

Search for Neutral MSSM Higgs Bosons in the $\tau_l\tau_h$ Decay Channel at the ATLAS Experiment

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In Fulfillment
of the Requirements of the Degree
Master of Science

Declaration

I declare that this Dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signed:

A handwritten signature in black ink, consisting of a series of loops and a long horizontal stroke extending to the right.

Date and Place:

28/05/2013 EDINBURGH, UK

Abstract

A thesis is presented for the study of the neutral Minimal Supersymmetric Standard Model (MSSM) Higgs sector in the decay channel $h/H/A \rightarrow \tau^+\tau^-$ at the LHC using the ATLAS detector. The case where one tau lepton decays to an electron or muon (τ_l) and the other decays hadronically (τ_h) is studied. Two production modes of these neutral Higgs bosons are investigated — gluon fusion and production in association with one or more b -quarks. The analysis is split into two categories based on whether or not a b -jet is identified in the event. The data used in this analysis is from centre-of-mass energy $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC during 2011 with an integrated luminosity of 4.66fb^{-1} . This is complemented by Monte Carlo simulations of the collisions. Comparisons between the data and simulations are done to validate reconstruction techniques and check background estimations. Different methods and algorithms for object and event identification are shown. Limits are placed on the MSSM parameters $\tan\beta$ and the mass of the pseudoscalar Higgs boson (A), m_A . The work done in this thesis formed part of an official ATLAS article (arXiv:1211.6956).

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1 Introduction

Electroweak symmetry breaking (EWSB) is one of the major areas of interest at the Large Hadron Collider (LHC) at CERN in Geneva. The LHC [1] is the world's largest particle collider with a design centre-of-mass energy of $\sqrt{s} = 14$ TeV, although in 2011 it ran at 7 TeV and in 2012 at 8 TeV.

The Higgs boson is a required single scalar particle needed for EWSB in the Standard Model (SM) [2–6]. Up until recently, there was little evidence for an SM Higgs boson. On July 4th 2012 an announcement of the discovery of a new boson [7] (see Figure 1) was made at CERN by the ATLAS and CMS experiments. It shows very good agreement with the expected characteristics of a Standard Model Higgs boson at 125 GeV, but is also compatible with the MSSM with $m_H \approx 125$ GeV [8]. An event display of a candidate Standard Model Higgs boson decaying to four muons is shown in Figure 2. However, the mass of the Higgs boson has quadratically divergent corrections in the SM at high energies [9].

The Minimal Supersymmetric Standard Model (MSSM) is a supersymmetric extension which solves the divergent mass problem by introducing a symmetry between fermions and bosons which provides cancelling corrections to the mass of the Higgs boson [12, 13]. There are two Higgs doublets which give five physical Higgs bosons in this model — two neutral and CP-even (h , H), one neutral and CP-odd (A) and two charged ($H^\pm$). Collectively the neutral Higgs bosons are denoted $\phi = h/H/A$.

The maximal mixing scenario in the MSSM is used, $m_h^{\max}$. The properties of the neutral Higgs bosons can be determined at tree level in terms of the ratio of vacuum expectation values of the Higgs doublets, $\tan\beta$, and the mass of the CP-odd Higgs boson, m_A and m_h . Here, m_h and M_A represent the masses of the h and A MSSM Higgs bosons. The Higgs sector coupling, μ , is constrained by $\mu > 0$. The variable properties in the $m_h^{\max}$ are calculated using terms such as $\tan\beta$, where $\tan\beta$ is chosen such that the maximal value of m_h is found as a function of $\tan\beta$ for maximal m_A [14]. These values are varied to give predictions that can be tested by experiment. This provides conservative exclusion limits since the largest mass of m_A is used. In regions with high $\tan\beta$ m_A is degenerate with either m_h (for $m_A \leq 130$ GeV) or m_H otherwise. In both cases the non-degenerate boson has a mass of approximately 130 GeV with m_A and m_H being degenerate and $m_h \approx 130$ GeV for $m_A \geq 130$ GeV. Regions with $\tan\beta \geq 20$ and $m_A > 130$ GeV are favoured since $m_h \leq 135$ GeV is constrained by theory [15]. In this low mass region the neutral Higgs bosons are referred to as $\phi = A/H/h$.

The variable $\tan\beta$ gives an indication of the couplings between the Higgs boson and fermions with differing hypercharge. Large and small $\tan\beta$ relate to negative and positive hypercharge, respectively. An increase in $\tan\beta$ enhances couplings between ϕ and up-type quarks as well as suppressing down-type quark and H/h couplings to vector bosons. A does not couple to vector bosons.

The main production mechanisms for the neutral MSSM Higgs bosons are gluon fusion and associated production with b -quarks (see Figure 8); gluon fusion production is higher in the low mass regions and the b associated production becomes the main production mechanism as $\tan\beta$ is increased. The branching ratios for the decays of ϕ , at high $\tan\beta (> 20)$ and for all $m_A \leq 1$ TeV, are: $\phi \rightarrow b\bar{b} \approx 90\%$, $\phi \rightarrow \tau\tau \approx 10\%$ and $\phi \rightarrow \mu\mu \approx 0.03\%$ [16] [17].

In this analysis we discuss di-tau decays where one tau decays leptonically (to a muon or electron and neutrino) and one decays hadronically into hadron showers (jets) and neutrinos. The analysis is separated into two parts: requiring the presence of at least one b -jet, and having a b -jet veto to further increase the sensitivity to the different production mechanisms. This is intended to further the work done on this channel done previously at LEP [18], the Tevatron [19–21] and the LHC [22, 23].

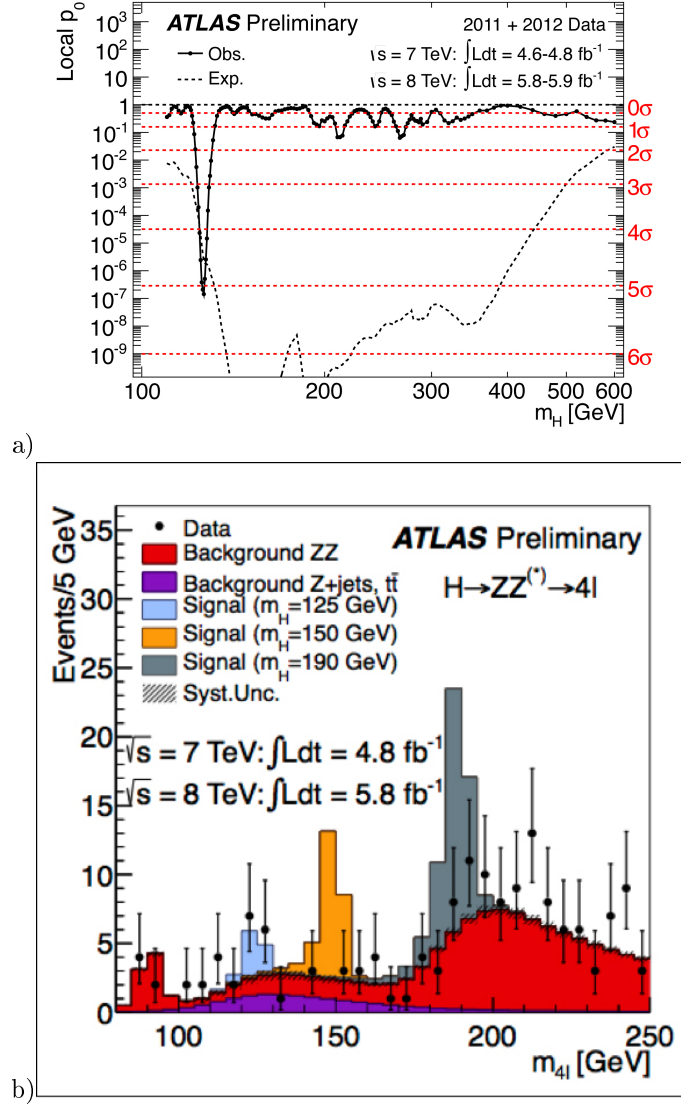


Figure 1: The p_0 distribution and the mass distribution in the four lepton channel showing the discovery of a new particle at 125 GeV and for the excess seen at 125 GeV [10]. The p_0 value shown here is the probability of seeing a fluctuation as extreme coming from a background fluctuation [11].

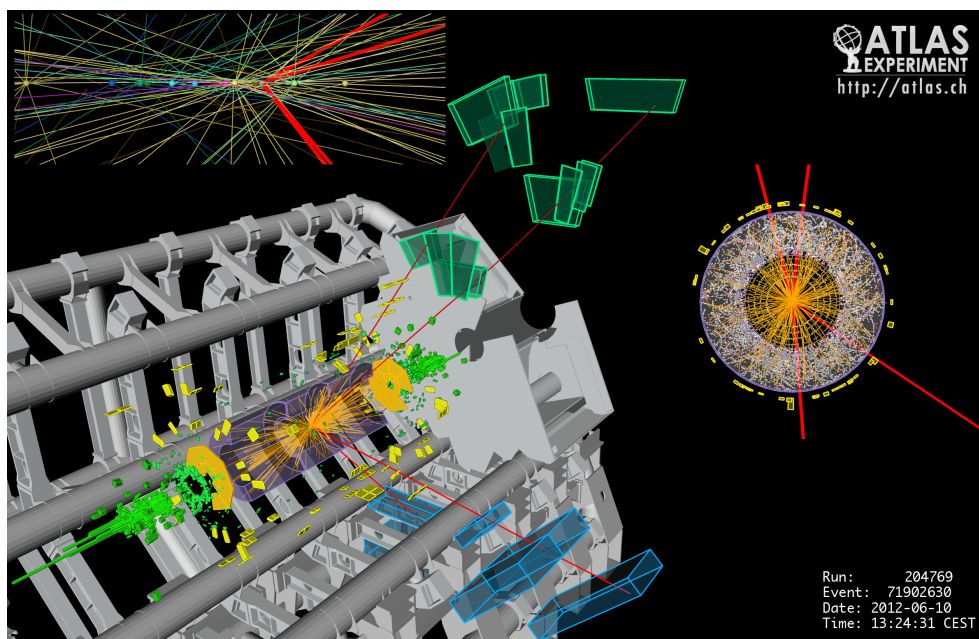


Figure 2: Candidate $H \rightarrow 4\mu$ event in the ATLAS detector [34].

2 Accelerator and Detector

2.1 LHC

The LHC [24] is located 50 to 175 m beneath the Swiss-Franco border and has a circumference of 27 km. The LHC is a proton-proton collider with a design centre-of-mass energy of $\sqrt{s} = 14$ TeV (7 TeV per beam). There is also a program for colliding heavy lead ions with a nucleon-nucleon center-of-mass energy of 2.76 TeV. At this energy the protons will be moving at $0.999999991c$ [25–27].

The LHC is trying to recreate the conditions that were apparent in the early universe, just after the Big Bang. It should be able to confirm or refute parts of the Standard Model of physics, including the discovery of the Higgs boson, which is the only as yet unconfirmed (see Introduction) particle from the Standard Model, and is responsible for mass generation through EWSB. There are many other searches at the LHC which include investigating symmetry breaking between matter and antimatter, models such as supersymmetry and their predicted particles and searching for the quark-gluon plasma that is predicted to have existed within billionths of a second after the Big Bang.

There are six detectors placed around the underground tunnel in four caverns (see Figure 3). There are two multipurpose detectors, A Toroidal LHC Apparatus (ATLAS) Experiment and Compact Muon Solenoid (CMS) Experiment [28–31]. These will be used to look for new physics and investigate EWSB and lead the search for the Higgs boson. The more specialised detectors include the LHC-beauty (LHCb) Experiment which is used to investigate why there is more matter than antimatter, A Large Ion Collision Experiment (ALICE) which is involved in the search for quark gluon plasma, LHC-forward (LHCf) which studies the origin of ultra-relativistic cosmic rays and the Total Cross Section, Elastic Scattering and Diffraction Dissociation (TOTEM) experiment which will be used to measure the size of the proton and the luminosity of the LHC [32, 33].

There are two beams of protons that run parallel to each other through the 27 km tunnel in opposite directions at centre-of-mass energies of up to $\sqrt{s} = 7$ TeV (although current energies are limited to 4 TeV after running at 3.5 TeV in 2011¹). The protons are sent through a number of pre-accelerators before entering into the main tunnel. The protons are collected in bunches of protons, rather than a constant beam. This is so that collisions will only take place at certain intervals and within the detector volume. A linear accelerator, LINAC2 (LINAC3 for ions), is used to accelerate the protons up to 50 MeV. They are subsequently sent to the 1 GeV Proton Synchrotron Booster (PSB) and on to the 25 GeV Proton Synchrotron (PS) and then before reaching main LHC ring, the Super Proton Synchrotron (SPS) which gives them their final boost of 450 GeV. The PS and SPS measure 628 m and 7 km in circumference, respectively. After they are injected into the LHC they are accelerated until they reach full speed after about 20 minutes. Magnets near the detectors are turned on which bring the particles from the opposing beams closer to each other and increase the probability of a collision. This is continued for up to ten hours per beam [36].

Superconducting magnets are used to bend the proton's paths around the collider. There are 1232 dipole magnets of 8.3 T each which are used to guide the proton bunches around the main ring. There are a further 392 quadrupole magnets of 6.5 T each which are used to focus the beam [37]. These magnets are kept at -271°C by liquid helium, increasing the strength of the magnetic fields.

The data generated by the LHC reaches up to 27 TB per day (700 MB/s) (previous citation [36]), which requires a large amount of storage space and computing power to process. The LHC Computing Grid is used to increase the capabilities of handling this task. It is a distributed computing network that is used to process the data from the LHC. It includes many university and research institute computing clusters situated throughout the world.

2.2 ATLAS Detector

There are many layers to the ATLAS detector (Figure 4a)) (see previous citations [28, 29, 32]). It has an "onion" type structure centred around the point of the collisions with each layer performing specialised

¹The LHC is only running at 4 TeV per beam currently. This following the liquid helium leak on 19 September 2008. There is also circuitry that must be upgraded and large problems with the superconducting magnets that must be fixed during the next maintenance period [35].

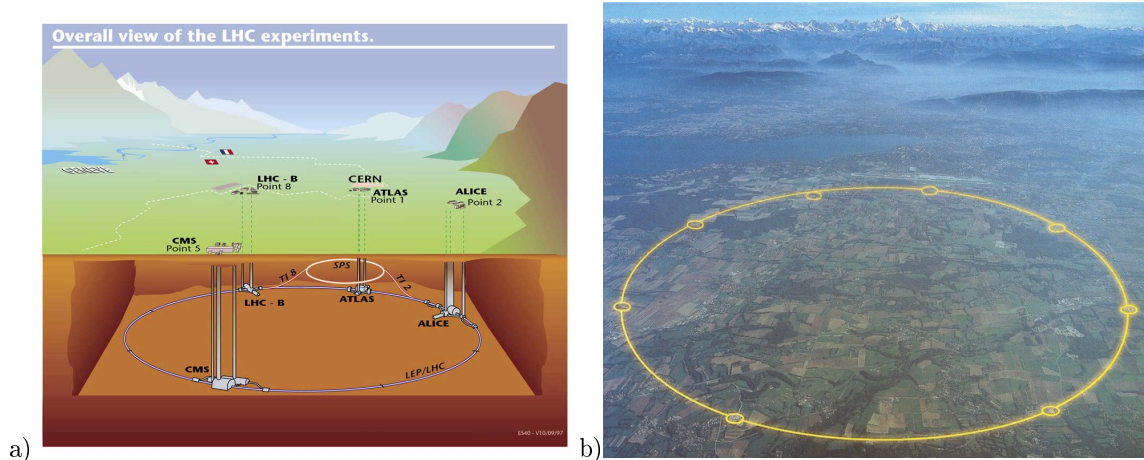


Figure 3: View of the LHC from a) the side [38] and b) above [39].

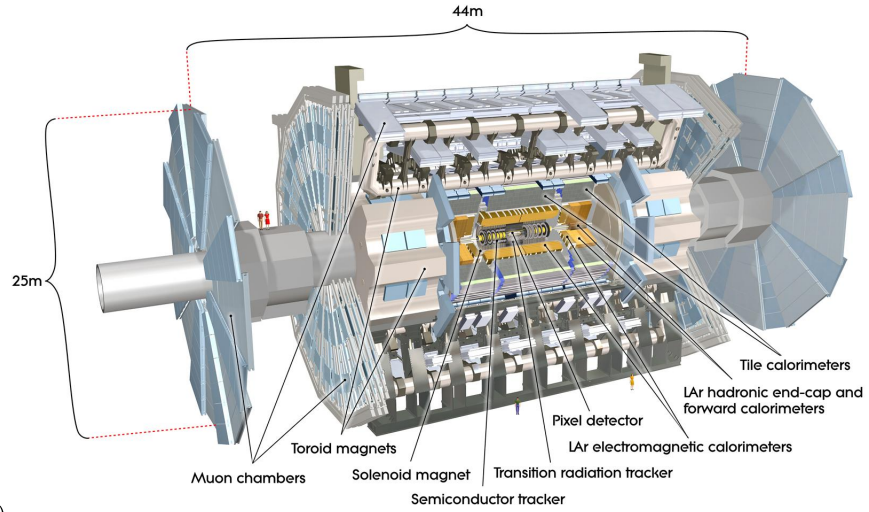
tasks. There are heavy particles produced in the proton-proton collisions which decay very rapidly and can only be detected by their decay products; the innermost detector layers are designed to track the paths of charged particles as they travel through the detector, and the presence of a magnetic field allows for measurements of their charge and transverse component of momentum. The calorimeters surround the inner detector and are used to measure the energy of the particles detected within the inner detector. Muons will move through the inner detectors and calorimeters undetected, but should be detected in the muon spectrometer. Neutrinos will travel through all of these detectors without detection, however, their presence can be inferred due to missing transverse momentum.

A right-handed coordinate system is used with the x -axis pointing towards the centre of the LHC ring, the y -axis pointing upwards and the z -axis along the beam direction. The polar (θ) and azimuthal (ϕ) angles are defined according to these axes. The pseudorapidity is used as a measure of the polar angle, defined as $\eta = -\ln(\tan \frac{\theta}{2})$, where points perpendicular to the beam axis have $\eta = 0$ and this tends towards infinity as this becomes parallel with the beam. Large magnets are used to bend the paths of charged particles along their trajectory, which is due to the Lorentz force.

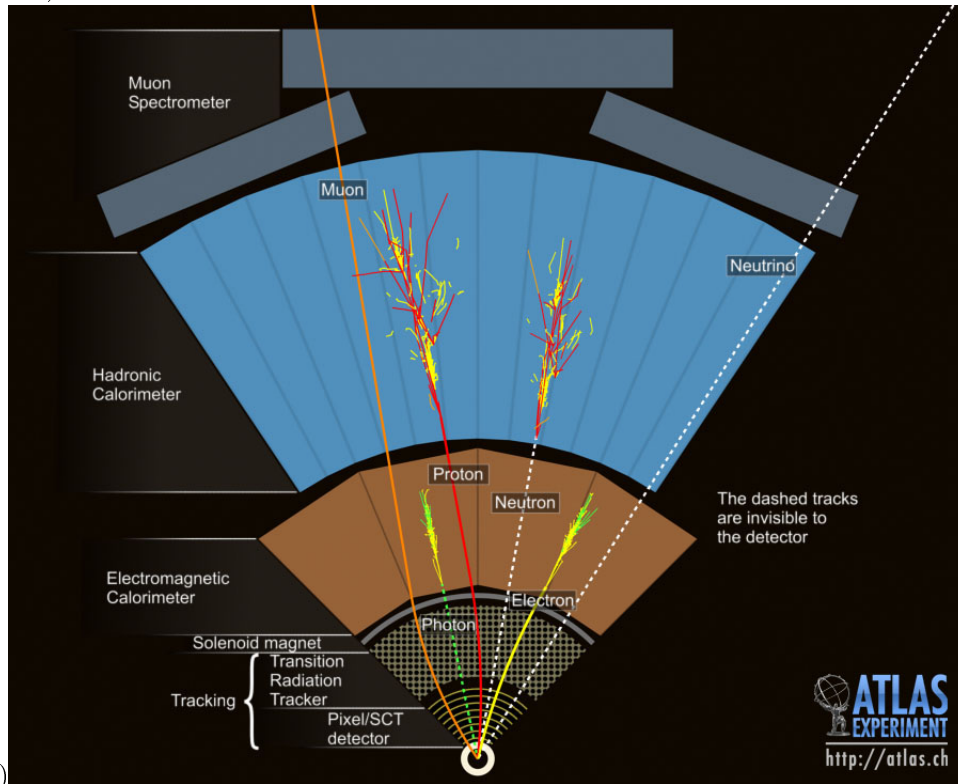
2.2.1 Inner Detector

The Inner Detector is used to detect charged particles. It consists of three sections, which get less accurate but can take readings over larger areas as the distance from the beam increases [40, 41].

Pixel Detector The Pixel Detector (Figure 5) is found closest to the interaction point and is the most sensitive and accurate of the Inner Detector components [42]. This provides critical tracking information which is useful when trying to find very short lived particles such as B-Hadrons. There are multiple layers of pixels in the detector system of differing accuracy and purpose. Pixel sensors are put in modules consisting of 46080 pixels on a silicon substrate, which has a potential difference applied to it and changes in the current can be recorded if a charged particle interacts with it. Each module consists of 16 read out channels, with each chip serving an array of pixels. The modules are either disk or barrel modules — the barrel modules are arranged into three cylindrical tubes of different radii that cover the length of the detector. The three disk modules go at the ends of the detector to ensure that particles moving out in all directions are measured. All modules overlap each other to ensure the detector is hermetic to ensure consistent and complete readings. There are a total of 1744 barrel modules within the detector which gives a total of about 80 million read out channels. The readings from the different layers in the pixel detector can be extrapolated to give an initial trajectory and find primary and secondary decay vertices. These detectors are exposed to huge amounts of radiation and have to be radiation hardened prior to insertion and need to be replaced every few years (this changes depending on the distance from the interaction point) in order to maintain the quality and accuracy of



a)



b)

Figure 4: a) The ATLAS Detector [43], b) schematic of particle interactions in the detector [44].

the readings.

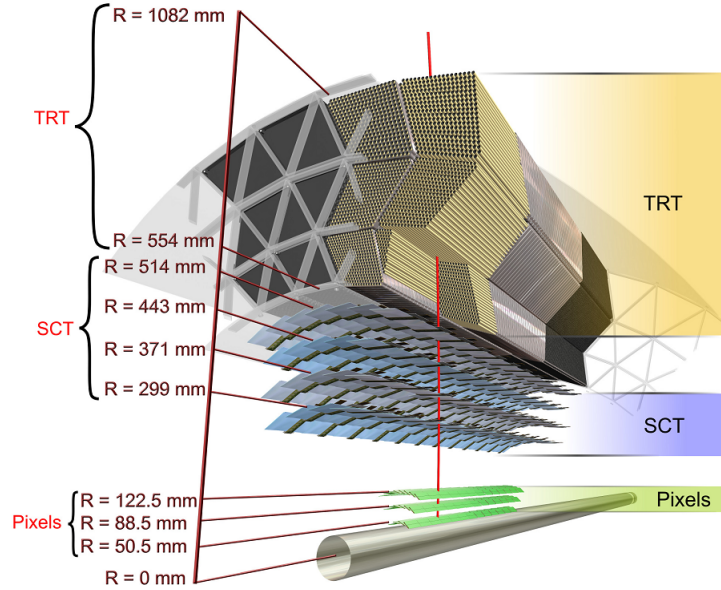


Figure 5: A cut out view of the Inner Detector [44].

Semi-Conductor Tracker The Semi-Conductor Tracker (SCT) [45] is the middle component within the Inner Detector and operates on a similar principle to the Pixel Detector, but instead of collections of pixels there are long silicon substrate strips. These longer strips increase the coverage area over the standard pixels, albeit with a lower resolution and granularity. The strips are single sided, but glued back to back. This gives a double sided sensor to give the position along the z-axis. Two of these sensors are glued together end to end. There are four double-sided layers in the SCT as opposed to the three in the Pixel Detector. Each of these silicon strips has 768 readout strips and this gives about 6.2 million channels in the entire SCT. The strips are aligned perpendicular to the radius of the beampipe and are thus able to track particles moving in the plane perpendicular to the beam's plane. Using the whole collection of modules, a charged particle's motion can be tracked through the SCT. The SCT consists of four barrel layers and two endcaps, each composed of nine of these disks. There are far fewer channels than the Pixel Detector and hence lower resolution, but it is able to cover a much larger area.

Transition Radiation Tracker The Transition Radiation Tracker (TRT) is the outermost component of the Inner Detector and works on the basis of straw detectors [46]. The straw detectors are used to measure drift velocity and track charged particles. Straw detectors are used to measure the transverse momentum of charged tracks with a high degree of precision. The straw detectors have a collection of hollow cylinders (straws) with a small diameter (4 mm) which are filled with a gas mixture of Xenon (70%), Carbon Dioxide (27%) and Oxygen (3%). When a particle comes into contact with this it ionises the gas within the straw and causes an electric pulse to flow down two thin wires twisted around the centre of the straw and is then recorded as a reading or hit. The number of straws in a module is dependent on position and ranges from about 300 to 800. There are approximately 5×10^4 straws in the barrel with two read out channels (one at the end and one in centre) and 3.2×10^5 radial straws which gives a combined output of 4.2×10^5 read out channels, which is a much lower resolution than the other Inner Detector layers. The straws are coated in materials of different thicknesses to maintain their electrical characteristics and so that Cherenkov radiation can be used to detect particles of different speeds. Ultra-relativistic particles will produce transition radiation as well as ionising the gas in the straw which will create stronger signals in the straws and allows for detection of ultra-relativistic

particles and their masses (since lighter particles will have a higher speed given the same amount of energy as a heavier particle).

Inner Solenoid The Inner Detector is surrounded by a 2 T solenoid magnet used to bend the trajectories of charged particles moving through the detector. The momentum and charge can be deduced from the amount of curvature using the Lorentz force. However, particles that are not travelling with very high momentum (< 400 MeV) escape detection because their paths are so tightly curved by the magnetic field that they do not move far enough away from the interaction point to be detected.

2.2.2 Calorimeters

The calorimeters are used for the measurement of energy and momentum of photons and electrons, measurement of direction and energy of jets and identifying these jets and finding missing momentum in order to infer the presence of particles such as neutrinos.

There are two parts to the calorimeter (Figure 6), both just outside the solenoidal magnet that surrounds the Inner Detector. When high energy particles come into contact with dense matter a particle shower starts, which is a result of the interaction between the high energy particles and the dense matter in the calorimeter. The particle showers consist of multiple particles that are produced during this interaction, which have lower energy than the initial particles. Eventually these particles are of a low enough energy to be absorbed by the calorimeter. This will change the charge and make up of the calorimeter, which can be measured. The particles produced in these showers are of two types — the types that will interact via the electromagnetic force, and those that will interact via the strong force (hadrons). Different calorimeters are needed for each of these types of showers. The final output signal of the calorimeter is proportional to the input energy, so that the total energy can be measure by the final output signal.

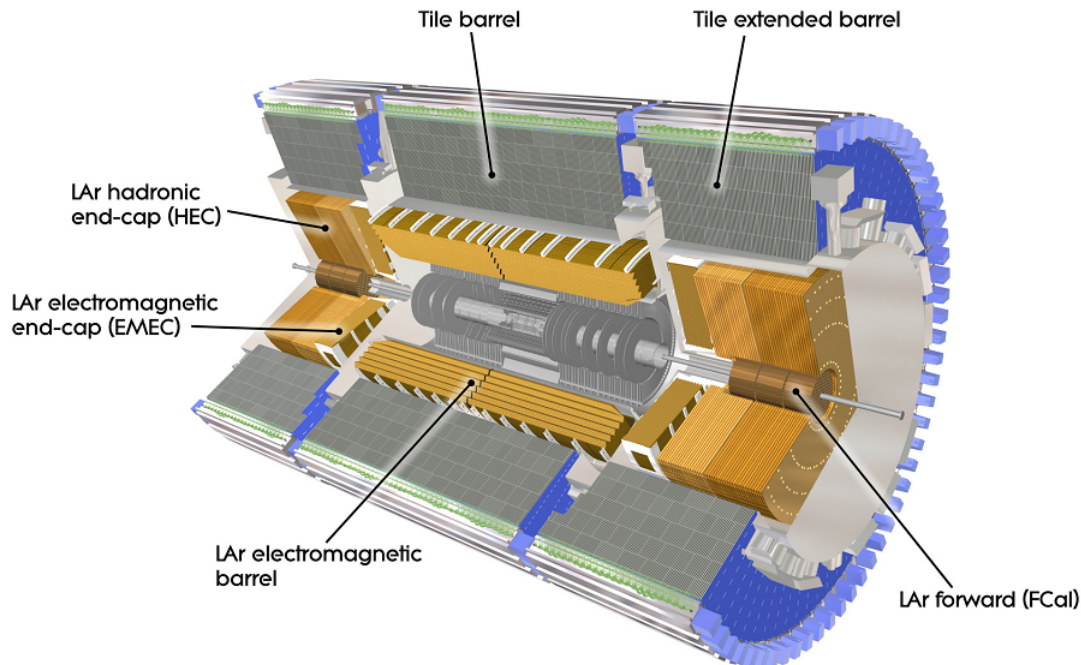


Figure 6: The ATLAS calorimeter system [44].

Electromagnetic Calorimeter The Electromagnetic (EM) calorimeter is designed to cover the range $|\eta| < 3.2$, with two subsections: the barrel detector which covers the range $|\eta| < 1.475$ and the end caps which cover $1.375 < |\eta| < 3.2$ [47]. The calorimeter has an accordion geometry to provide full azimuthal coverage whilst the lead absorber covers the entire area. There is a slight overlap so as to ensure complete hermiticity. The calorimeter is divided into longitudinal sections where sampling strips are placed to measure the energy and position of the particle showers as they move through the calorimeter. To correct for energy lost through the calorimeter a pre-sampler is included before the absorption plates. The detector has steel and lead as the absorbing materials and liquid argon as the sampling material [48]. The lead and steel absorbers must be thick enough to fully contain EM showers within the EM calorimeter to avoid leakage into the hadronic calorimeters.

Hadronic Calorimeter The absorption material used in the hadronic calorimeter (HCal) is mostly steel, with scintillating tiles used as the sampling material. Hadrons move through the EM calorimeter and into the HCal and are stopped before they enter the muon spectrometer.

There are three parts to the HCal: the barrel HCal (Figure 6) which covers $|\eta| < 1.7$, the end caps which cover $1.5 < |\eta| < 3.2$ and the forward detectors which cover $3.1 < |\eta| < 4.9$.

The tile calorimeter used in the barrel sections uses iron and scintillating tiles as the absorption material and sampling material respectively. The tiles are staggered around the barrel between iron sections with the barrel extending from 2.28 m to 4.23 m. There are 64 modules of tiles covering the entire barrel and extended barrels. The scintillators can be read out to give readings of the energy and position of the particle showers. In the forward calorimeters liquid argon is again used, as in the EM calorimeter.

Calorimeters can also be used to infer the presence of particles such as muons and neutrinos. Muons can leave an ionisation signal which, if the muon is solitary, can be identified as having come from the muon. This track can then be followed into the muon spectrometer to check that it was indeed a muon. Neutrinos can also be inferred with the calorimeter by considering momentum conservation of particles within the calorimeter. This requires high precision, so there must be as little leakage out of the HCal as possible.

2.2.3 Muon Spectrometer

The muon spectrometer [49, 50] has large dimensions and a layout such that any muons should pass through three detectors/ trigger planes of the spectrometer in order to accurately measure muons travelling through it. The detector extends from a radius of 4.25 m up to 11 m, which is the radius of the entire detector.

There are four types of detectors used in the muon spectrometer, each covering different radii and pseudorapidities. There are three concentric barrels consisting of the Cathode Strip Chambers (CSC) (5 m), the Monitored Drift Tube (MDT) Chambers (7.5 m) and the Resistive Plate Chambers (RPC) (10 m). For the end-caps there are Thin Gap Chambers (TGC) which are arranged as disks along the beam axis at distances of 7, 10, 14 and 21-23 m from the interaction point. Together they cover the range $1 < |\eta| < 2.7$.

The MDTs contain drift chambers which are collections of drift tubes filled with a combination of Ar-CH₄-N₂ (the choice of gas is important because a gas that ionises easily is needed). They are used to track the position of the muons that move through them and work on a similar principle to the straw detectors. They have a single W-Re, gold plated wire running through the centre of the tube and are held at a voltage of about 3200 V. There are multiple anodes within the tube that detect charged particles as they come in contact with the anode, causing sensors to fire, and measure the pulses along multiple tubes so that the particle can be tracked. Applying a magnetic field to this then allows for the charge to be calculated from the Lorentz force. The term "monitored" comes from the fact that they have fibre optics running through them to ensure that they remain straight and do not bend too much. These allow for good spatial resolution (of about 80 μm).

Closer to the point of interaction greater tracking accuracy is needed and CSCs are used. They differ from the MDTs in that they are multi-wire proportional drift chambers. In these the gas that is used is easily ionised and the magnetic field applied is used to cause the electrons and ions to drift towards

the electrodes such that they have enough energy to cause more ionisation in the collisions that are in the direction of the electrodes. They measure the energy of the particles, which is done by taking the difference in the timing of the readings between electrodes and taking into account that the number of ionised particles between them is proportional to the energy that they contain. They use a gas mixture of Ar-CO₂-CF₄ chosen specifically to allow a greater sensitivity to neutrons. However, they are more expensive to run and the gas needs to be replaced more frequently. The TGCs are very similar to these, except that they have slightly different dimensions and gaps between electrodes to provide a greater range of readings, but with a lower precision.

The RPCs are gaseous detectors (using C₂H₂F₄ and C₄H₁₀) and contain no wires as in the drift chambers. They are held at a constant high voltage with read out strips on either end. They provide good spatial/time resolution compared with the other chambers.

Outer Magnet The outer magnet is toroidal due to cost and because the tracking accuracy within the much larger muon spectrometer does not need to be as high as in the inner detector. A toroidal magnet does not produce a uniform magnetic field like the solenoidal one, which is the cause of this extra inaccuracy. The magnet is made up of a collection of 25 m long and 5 m wide coils. In total this magnet is able to store 1.1 GJ of energy.

2.3 Grid computing

The Worldwide LHC Computing Grid (WLCG) is a distributed computing and storage infrastructure set up around the world for the purposes of analysis of data from the LHC. The LHC produces about 15 petabytes [51] of data per year which requires large amount of storage and computing resources for the analysis of this data. Physicists from around the world need access to this data and the computing resources. The WLCG is set up to accomplish this task. There are multiple tiers to the WCLG [52]. More information on Grid computing can be found at Ref. [53].

Tier-0 is located at CERN. A copy of all data from the LHC is kept at Tier-0. There is a large computing cluster used for analysis called LXPLUS. LXPLUS consists of a few hundred nodes for users to use for analysis and to submit jobs to the Grid and the local batch system. These nodes are 64-bit machines running Scientific Linux 5 (SLC5). There are currently around 35000 CPU cores in the LXPLUS batch system, LXBATCH [54]. Data is stored on EOS [55], the CERN Disk Storage system. Users can access this directly from LXPLUS. Temporary space is available on each node for users, as well as a personal workspace of 20 GB. AFS [56,57] is used at CERN for users to access their data and workspaces. All data created is backed up on tape.

Tier-1 computing centres are situated at sites around the world. These are used for archival of datasets. This provides redundancy, so that CERN is not the only storage location and allows for faster access to data. Tier-1 clusters are required to provide services such as providing archival storage, a large amount of online disk storage, computing resources for analysis and must have a high availability. Tier-1 clusters provide data to Tier-2 centres.

Tier-2 computing centres are also situated around the world at many universities. These are used primarily for Monte Carlo simulations and user analyses. Data storage is available, but not for archival purposes. Data can be transferred from Tier-0 or Tier-1 sites for analysis.

Tier-3 computing centres are also found around the world at many universities. These are used for small scientific groups, providing access to large datasets on the Grid with local computational resources and batch queues. There is a computing cluster at the University of the Witwatersrand that is a Tier-3 Grid site.

Jobs or analyses submitted to the Grid has the code sent to a Grid site on the network where the required datasets are available and the job is run on that cluster. This can be at a Tier-1, Tier-2 or Tier-3 site. For example, if there is a dataset X available on the Wits Tier-3 cluster and it is required for a job that job will be sent to the Wits cluster and the analysis run on the Wits computers. When the job is finished the output is kept on the cluster temporarily and the user that submitted the job can download the output. If the datasets are available at more than one site the job can be run partially at both sites reducing the load for each site.

Specific tools are provided for data transfers and downloads of datasets. There are also tools (Panda [58], Ganga [59]) to monitor the progress of jobs on the Grid, wherever they may be running, and submit jobs to the Grid. Grid submission is done from any cluster where a user has access.

3 Theory

3.1 The Standard Model

The Standard Model is the current limit of the understanding of particle interactions [60]. This theory is able to explain a large amount of observed particle physics. It still does not explain gravity, but it is able to integrate current theories of electromagnetic, weak and strong forces into one theory. It predicts a number of fundamental particles with corresponding force mediating particles and from which all known matter is made. These particles have all been observed, and possibly the Higgs boson, which has not yet been confirmed.

Type of Fermion	Generation	Name	Gauge Boson	Symbol
Leptons	1st	Electron (e^-)		
	Generation	Electron neutrino (ν_e)		
	2nd	Muon (μ^-)		
	Generation	Muon neutrino (ν_μ)		
	3rd	Tau (τ^-)		
	Generation	Tau neutrino (ν_τ)		
Quarks	1st	Up (u)	Photon	γ
	Generation	Down (d)		
	2nd	Charm (c)	Gluon	g
	Generation	Strange (s)		
	3rd	Top (t)	Z Boson	Z^0
	Generation	Bottom (b)		
			W Bosons	$W^\pm$
			Higgs Boson*	H

* Nature of newly discovered Higgs-like boson not yet confirmed.

Table 1: Fundamental Particles and Gauge Bosons in the Standard Model.

Each of the particles listed in Table 3.1 has a corresponding antiparticle with the same properties but opposite-sign charge. Neutral particles can be their own antiparticles in some cases, but need not be identical otherwise.

As seen in Table 3.1 there are three generations of matter with different masses and quantum numbers between the generations. The heavier generation leptons decay into the lighter leptons of the lower generations via the weak force, however, neutrinos of each generation do not decay but do oscillate between generations. The quarks in different generations (known as different flavours of quarks) also decay to the first generation of quarks. All matter is made up of first generation quarks and leptons, however, the other generations are witnessed for very brief periods of time when there are very high energy interactions. All of these particles are fermions with spin $\frac{1}{2}$.

There are four known types of forces with differing ranges and strengths. These are gravity, the electromagnetic, strong and weak forces. The electromagnetic force is described by a $U(1)$ gauge symmetry and this combines with the weak force to give the electroweak force with an $SU(2) \times U(1)_\gamma$ to $U(1)_{em}$ symmetry (after symmetry breaking). This $SU(2) \times U(1)$ symmetry describes four gauge bosons – the B^0 , $W^\pm$ and W^0 bosons. When there is spontaneous symmetry breaking of the $SU(2)$ symmetry the B^0 and W^0 combine to give the Z boson and photon. However, in a gauge theory the gauge bosons are required to be massless, whilst the $W^\pm$ and Z bosons are not. There is a total symmetry of $SU(3) \times SU(2) \times U(1)$ for the Standard Model.

There are some major problems with the Standard Model which requires extensions to the model:

- The Hierarchy Problem – The Yukawa couplings that explain the fermion masses are not explained by the theory.
- CP Violation – The abundance of matter over anti-matter is not explained.
- Grand unified theories – The SM is not able to unify the electroweak and strong forces.
- No gravity – Gravity is not accounted for at all.

- Dark Matter/ Energy – The SM only accounts for 4% of the universe, the remaining dark energy and dark matter are not explained by the SM.

The Higgs mechanism is an important part of the SM which is a consequence of EWSB that brings about mass for the gauge bosons, Z and $W^\pm$. The Higgs mechanism is described in the following section.

3.1.1 Standard Model Higgs Sector

Generally, the Lagrangian formulation is used to explain the dynamics of a specific system, where the Lagrangian has a free and interaction part to it. It should describe all particles in the system as well. However, adding the required mass terms for the massive bosons to the EW Lagrangian results in an unrenormalisable theory. The mass has to arise naturally, through the breaking of symmetries. The symmetry breaking mechanism is described in this chapter. Global and local symmetries are both discussed, with their respective consequences.

For global symmetry breaking [62, 63] a Lagrangian density (which contains the kinetic and potential energy of the particle) for some complex scalar field describing the system $\Phi = (\phi_1 + i\phi_2)/\sqrt{2}$ can be written as:

$$\mathcal{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi - m^2 \Phi^\dagger \Phi.$$

A vacuum state is defined (Figure 7) by finding the minimum of this, and since m^2 is always positive this will happen when $\phi_1 = \phi_2 = 0$. If the sign of m^2 is changed this would be an unstable Lagrangian (not renormalisable, either) which can be stabilised by adding another term and making the final Lagrangian:

$$\mathcal{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi - \frac{m^2}{2\phi_0} (\Phi^\dagger \Phi - \phi_0^2)^2.$$

There is a minimum given the condition $\Phi^\dagger \Phi = \phi_0^2$. This Lagrangian is invariant under circle rotations which is a global symmetry. It can be shown the free Lagrangian is given by

$$\mathcal{L}_{free} = \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - m^2 \chi^2 + \frac{1}{2} \partial^\mu \psi \partial_\mu \psi.$$

Comparing this with the Klein Gordon (KG) equation,

$$\eta^{\mu\nu} \partial_\mu \partial_\nu \psi + \frac{m^2 c^2}{\hbar} \psi = 0,$$

it is seen that the term $m^2 \chi^2$ corresponds to a particle of spin 0 and of mass $\sqrt{2}m$, but there is no such quadratic term in the KG equation for the ψ . This spin 0 particle must therefore be a massless Goldstone boson. Since this broken global symmetry gives massless Goldstone bosons it is assumed that for EWSB there is a local (gauge) broken symmetry.

Since the EW Lagrangian has an $SU(2) \times U(1)$ symmetry, an attempt at breaking an $SU(2)$ gauge symmetry is made. The Lagrangian for the $SU(2)$ part of the EW sector is

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2.$$

Here the term ϕ is an $SU(2)$ doublet of complex scalar fields, as opposed to the singlet scalar field used in the global symmetry previously. ϕ is defined as:

$$\phi = \sqrt{\frac{1}{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}.$$

This is invariant under global $SU(2)$ transformations, but it must be invariant under local transformations

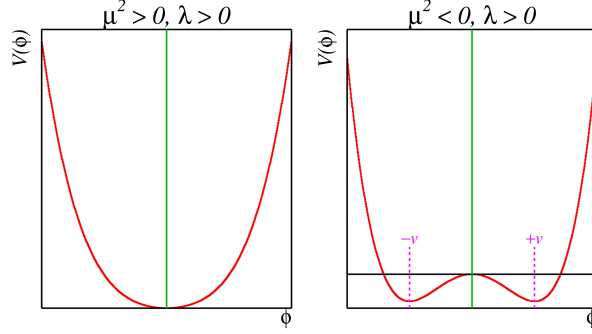


Figure 7: The Higgs potential before and after introducing stabilising terms to the Lagrangian [64].

$$\phi \rightarrow \phi' = e^{i\alpha_a(x)\tau_a/2} \phi.$$

This requires the introduction of a covariant derivative and the introduction of the gauge fields W_μ^a to keep the local invariance. The covariant derivative is given by

$$D_\mu = \partial_\mu + ig \frac{\tau_a}{2} W_\mu^a.$$

This gives a gauge invariant Lagrangian with the kinetic energy term of the gauge field added into it,

$$\mathcal{L} = (\partial_\mu \phi + ig \frac{1}{2} \tau \cdot W_\mu \phi)^\dagger (\partial^\mu \phi + ig \frac{1}{2} \tau \cdot W^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 - \frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu}.$$

The interaction potential in this is given by

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2.$$

This Lagrangian now describes a system of four scalar particles (from the definition of the complex SU(2) doublet), each having mass, as well as the three massless gauge bosons from the gauge field. Two cases need to be observed, $\mu^2 > 0$ (as in the global symmetry breaking) and $\mu^2 < 0$. The parameter λ needs to be positive in order to get a lower bound on the potential. Where $\mu^2 < 0$ there is a minimum of the potential at the point where

$$\phi^\dagger \phi = \frac{1}{2} (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda},$$

which can be expanded about a minimum choosing any three of the four ϕ_i independently to be 0 and the other to be $\sqrt{-\frac{\mu^2}{2\lambda}} = v$. This is the spontaneous symmetry breaking of SU(2). It can be shown that this gives a general answer, from gauge invariance, of

$$\phi(x) \rightarrow \phi(x) - \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix},$$

where $h(x)$ is the scalar Higgs field that corresponds to a non-zero mass, and it is from this that the Higgs boson comes, the associated particle for the Higgs field. The Higgs boson is theorised to be a massive spin 0 particle, with a possible discovery at CERN (see Introduction).

The basic idea behind this is that the gauge fields take the massless Goldstone bosons and they become massive by spontaneous symmetry breaking. This is known as the Higgs mechanism.

The four gauge fields introduced give the massive bosons $W^\pm$ and a combination of the B and W^0 boson to give a massive Z^0 and massless photon. The Higgs mechanism explains how $W^\pm$ and Z bosons acquire mass through symmetry breaking. When this happens the Higgs boson arises as another massive particle. Although the Higgs mechanism does not make a prediction for the mass of the Higgs boson, the discovery of a new boson of around $125 \text{ GeV}/c^2$ [65] looks very likely to be the Higgs boson. Detailed studies need to be done to confirm this is a Standard Model Higgs boson. This would also make the SM valid up to very high energy scales [62, 63, 66, 67].

3.2 The Minimal Supersymmetric Standard Model

Supersymmetry addresses some of the problems encountered by the Standard Model [68]. The Hierarchy Problem comes about whenever any particle couples to the Higgs field as it adds quadratic corrections to the Higgs mass term. The expectation value of the Higgs scalar field gives mass to all other quarks, leptons and massive bosons, which means that their masses will also be in disagreement with the Standard Model at high energies. In the Standard Model, corrections to Higgs mass term due to loops containing Dirac fermions with mass m_f with a coupling of $-\lambda_f H \bar{f} f$ give:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{\text{UV}}^2 + \dots,$$

where Λ_{UV} is the ultraviolet cut off — energy scale where new physics affects the high energy limit of the SM. This can give massive corrections to the Higgs mass. Since all particles get masses from the expectation of the Higgs, all of the particles will have masses sensitive to Λ_{UV} . Likewise, this can be calculated for a complex scalar particle S with mass m_S and coupling $-\lambda_S |H|^2 |S|^2$:

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} [\Lambda_{\text{UV}}^2 - 2m_S^2 \ln(\frac{\Lambda_{\text{UV}}}{m_S}) + \dots].$$

A new symmetry relating fermions to bosons is introduced to fix this. A transformation is required from a bosonic to a fermionic state, and vice versa. It is expected that *all* particles should have superpartners differing by spin $\frac{1}{2}$. The operator Q is defined to generate these transformations:

$$Q |\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q |\text{Fermion}\rangle = |\text{Boson}\rangle.$$

The rules for the generators Q and $Q^\dagger$ are:

$$Q, Q^\dagger = P^\mu,$$

$$Q, Q = Q^\dagger, Q^\dagger = [P^\mu, Q] = [P^\mu, Q^\dagger] = 0,$$

where P^μ is the four-momentum generator of spacetime translations. The commutation relations show members of the same supermultiplet will be proportional to a combination of Q and $Q^\dagger$ acting on another member of the supermultiplet. Further, since the P^2 operator commutes with the Q and $Q^\dagger$ operators the particles in a supermultiplet must have equal masses. Each supermultiplet contains and equal number of fermionic and bosonic degrees of freedom, shown in refMSSMprimer. A Weyl fermion with two fermionic degrees of freedom and two real scalars with one bosonic degree of freedom each give the simplest supermultiplet obeying these restrictions. This combination is known as a chiral supermultiplet. Single particle states exist in supermultiplets which contains both fermion and boson states that are superpartners of each other. The Higgs scalar boson is spin 0, so it exists in a chiral supermultiplet. However, two are needed to avoid gauge anomalies. Gauge anomalies in the electroweak gauge symmetry are cancelled if the $\text{Tr}[T_3^2 Y] \text{Tr}[Y^3] = 0$, where T_3 is the third component of weak isospin and Y is the weak hypercharge. Together these give the electric charge $Q_{EM} = T_3 + Y$. However, since there must be a fermionic partner in the chiral supermultiplet of the Higgs, there will be a $Y = \pm 1/2$. This will give a non-zero contribution to the Trace and give a gauge anomaly. Therefore there are two required with opposite hypercharge in order to cancel the anomaly. In addition, the $Y = 1/2$

supermultiplet will give masses to up-type quarks and $Y = -1/2$ to down-type quarks and leptons. The $Y = 1/2$ supermultiplet, H_u , has T_3 components of $\pm 1/2$, which give electric charges of 1 and 0, respectively. This gives $H_u = (H_u^+, H_u^0)$. Similarly, for the $Y = -1/2$, H_d is given by (H_d^0, H_d^-) . The SM Higgs boson is a combination of the H^0 components. The corrections that brought quadratically diverging terms to the mass of the Higgs are cancelled out by the symmetry between the fermions and bosons because of the opposite signs of the relative terms.

The Minimal Extension to the Standard Model (MSSM) is the supersymmetric extension that has the least particle content (and Higgs bosons) in order to make it a phenomenologically viable theory.

Particle	Spin	Sparticle	Spin
quark ($q_{L,R}$)	$\frac{1}{2}$	squark ($\tilde{q}_{L,R}$)	0
lepton ($l_{L,R}$)	$\frac{1}{2}$	slepton ($\tilde{l}_{L,R}$)	0
photon (γ)	1	photino ($\tilde{\gamma}$)	$\frac{1}{2}$
gluon (g)	1	gluino ($\tilde{g}$)	$\frac{1}{2}$
$W^\pm$	1	wino ($\tilde{W}^\pm$)	$\frac{1}{2}$
Z	1	zino ($\tilde{Z}$)	$\frac{1}{2}$
Higgs (H)	0	Higgsino ($\tilde{H}$)	$\frac{1}{2}$

Table 2: MSSM particles.

3.2.1 MSSM Higgs Sector

The theory is required to have symmetry breaking in accord with experiment, and further, since no evidence for superpartners has yet been observed. The Lagrangian is broken into two parts, $\mathcal{L}_{\text{SUSY}}$, a supersymmetric part (conserves supersymmetry), and $\mathcal{L}_{\text{soft}}$, a soft symmetry breaking part (spontaneously breaks supersymmetry). Any term that is associated with $\mathcal{L}_{\text{soft}}$ must have vanishing corrections to the mass term of the Higgs scalar when its largest mass term, m_{soft} , goes to 0, so that mass corrections are not quadratic. This addresses the Hierarchy Problem to a large extent. However, if the mass of the superpartners is too large the problem arises once again.

The soft supersymmetry breaking part of the Lagrangian, $\mathcal{L}_{\text{soft}}$, is given by:

$$\begin{aligned}
\mathcal{L}_{\text{soft}} = & -\frac{1}{2}(M_3\tilde{g}g + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}) \\
& -(\tilde{u})\mathbf{a}_u\tilde{Q}H_u - \tilde{d})\mathbf{a}_d\tilde{Q}H_d - \tilde{e})\mathbf{a}_e\tilde{L}H_d + \text{c.c.}) \\
& -\tilde{Q}^\dagger\mathbf{m}_Q^2\tilde{Q} - \tilde{L}^\dagger\mathbf{m}_L^2\tilde{L} - \tilde{u}\mathbf{m}_u^2\tilde{u}^\dagger - \tilde{d}\mathbf{m}_d^2\tilde{d}^\dagger - \tilde{e}\mathbf{m}_e^2\tilde{e}^\dagger \\
& -m_{H_u}^2H_u^*H_u - m_{H_d}^2H_d^*H_d - (bH_uH_d + \text{c.c.}).
\end{aligned}$$

M_1 is the bino mass term, M_2 is the wino mass term and M_3 is the gluino. The second line has scale cubic couplings. $\mathbf{a}$ terms are complex 3x3 matrices corresponding to Yukawa couplings of the superpotential. Third line has squark and slepton mass terms. Each mass term is a 3x3 matrix with complex entries, but hermitian to make $\mathcal{L}$ real. Last line has supersymmetry-breaking terms — squared mass terms. All $\mathbf{M}$ and $\mathbf{a}$ terms are $\approx m_{\text{soft}}$ and squared mass terms, including b are $\approx m_{\text{soft}}^2$. Lagrangian contains 105 masses, phases and mixing angles. These are restricted by CP violating and flavour mixing terms ruled out by experiment. ref 78-103.

The superpotential for the MSSM which contains Yukawa couplings for the Lagrangian is given by:

$$W_{\text{MSSM}} = \bar{u}\mathbf{y}_uQH_u - \bar{d}\mathbf{y}_dH_d - \bar{e}\mathbf{y}_eLH_d + \mu H_uH_d.$$

All chiral superfields (transform as left handed fields) corresponding to supermultiplets for the MSSM particles. The $\mathbf{y}$ terms are Yukawa coupling parameters. The μ value gives the supersymmetric version of the SM Higgs mass.

For spontaneous SUSY breaking $|0\rangle$ is not invariant: $Q_\alpha|0\rangle \neq 0$ and $Q_\alpha^\dagger|0\rangle \neq 0$. This has further consequences on the Hamiltonian and the equations of motion. The Hamiltonian, H , is given by

$H = P^0 = \frac{1}{4}(Q_1 Q_1^\dagger + Q_1^\dagger Q_1 + Q_2 Q_2^\dagger + Q_2^\dagger Q_2)$. For a broken symmetry, the vacuum must have positive energy: $\langle 0|H|0\rangle > 0$. This can be written $\langle 0|H|0\rangle = \langle 0|V|0\rangle$ if spacetime-dependent effects and fermion condensates are ignored. Here, V takes the usual value of the scalar potential. V for the MSSM is given by:

$$\begin{aligned} V = & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\ & + [b(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}] \\ & + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2) \\ & + \frac{1}{2}g^2(|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2). \end{aligned}$$

The g and g' are the electroweak gauge couplings (for $SU(2)_L$ and $U(1)_Y$). The μ term gives the dimensionful couplings in the supersymmetric part of the Lagrangian — the Higgs squared-mass terms in V . The other terms come from the soft supersymmetry breaking part of the Lagrangian.

To break EW symmetry, at the minimum of the potential, $H_u^+ = 0$. This requires $H_d^- = 0$, too. This gives a minimum where the b and $H_u^0 H_d^0$ terms are both real and positive. A restriction on b is given by bounding the potential from below: $2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$ and requiring the linear combination of H_u^0 and H_d^0 (which gives the SM Higgs boson) to have a negative squared mass, gives a further restriction of $b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2)$. However, here, $H_u^0 \neq H_d^0$, otherwise this equality cannot hold and the required symmetry breaking will not occur.

The non-zero vacuum expectation values of the H_u^0 and H_d^0 are then written as:

$$\nu_u = \langle H_u^0 \rangle, \quad \nu_d = \langle H_d^0 \rangle.$$

The ratio of these gives the parameter $\tan\beta = \nu_u/\nu_d$ which is one of the parameters varied in this analysis. These terms have a dependence on the Z mass of: $\nu_u^2 + \nu_d^2 = 2m_Z^2/(g^2 + g'^2) \approx (174 \text{ GeV})^2$.

When the EW symmetry is broken, the Higgs scalar fields in the MSSM, three of the eight degrees of freedom become the longitudinal modes of the Z^0 and $W^\pm$ and the other mass eigenstates give rise to the five scalar Higgs bosons. These other five scalars are the Higgs scalar mass eigenstates. These give the neutral CP-even Higgs H^0 , the neutral CP-odd Higgs A^0 and h^0 , and the charged Higgses $H^\pm$. Collectively the three neutral ones are known as ϕ . The mass eigenstate fields are then given by:

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} \nu_u \\ \nu_d \end{pmatrix} + \frac{1}{\sqrt{2}}R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}}R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix},$$

and

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_{\beta_\pm} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}.$$

The G terms are the Goldstone bosons from which the Z^0 and $W^\pm$ bosons come. The R matrices are rotation matrices given by:

$$R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix},$$

and

$$R_{\beta_{0/\pm}} = \begin{pmatrix} \sin\beta_{0/\pm} & \cos\beta_{0/\pm} \\ -\cos\beta_{0/\pm} & \sin\beta_{0/\pm} \end{pmatrix}.$$

Here, α is one of the mixing angles and is dependent on β , and the squared-masses of A^0 , H^0 , h^0 and Z .

In the maximal mixing scenario, m_h^{max} , analysed here, the largest possible mass is given to the lightest neutral Higgs, h . In this scenario the properties of the Higgs bosons can be determined at tree level from $\tan\beta$ and m_A . Large values of $\tan\beta$ ($\gtrsim 20$) are favoured because of the top to bottom quark mass ratio. The H and A bosons become degenerate in this limit and in the limit $M_A > 130 \text{ GeV}$ [70].

In total there are 120 parameters for the MSSM, which are mostly due to the soft symmetry breaking. A lot of these parameters lead to unrealistic scenarios, which makes the analysis much easier as there are fewer parameters to analyse.

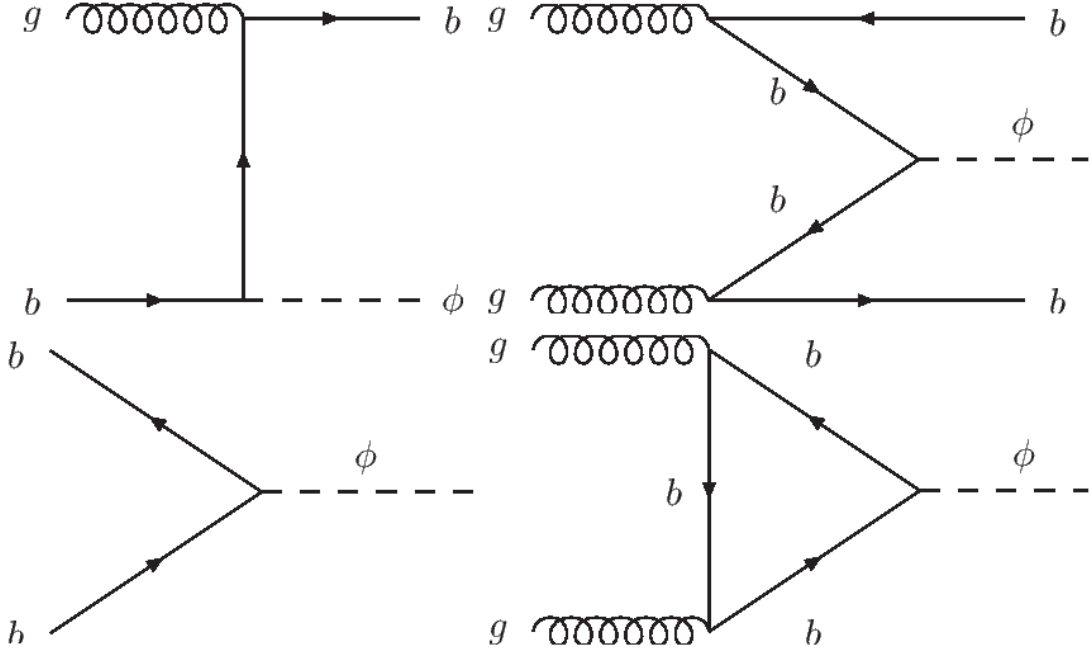


Figure 8: Feynman diagrams showing the different production mechanisms of the neutral MSSM Higgs bosons.

3.2.2 MSSM Higgs Production and Decay

MSSM Higgs production takes place through gluon fusion and via interaction with b -quarks (see Figure 8). Most of the couplings increase with mass, except for the gauge boson couplings, which get scaled by a factor $\cos(\beta - \alpha)$ for h^0 and $\sin(\beta - \alpha)$ for the heavy H^0 . There is no coupling to A . The mixing angle is given by α . This leaves the main production modes for the neutral MSSM Higgs as:

$$\begin{aligned} gg &\rightarrow b\bar{b}\phi \\ gb &\rightarrow b\phi \\ b\bar{b} &\rightarrow \phi \end{aligned}$$

The gluon fusion branch is higher in lower mass regions, but the b production modes become more apparent as mass increases.

The different free parameters in the Higgs sector at tree level that can be used to describe the theory are $\tan\beta$ and M_A . The exact masses predicted by the theory depend on the mixing scenario used. Large values of $\tan\beta$ are favoured because of the top to bottom quark mass ratio which is ≈ 35 . This is one of the reasons why the $\tan\beta \gtrsim 20$ region is preferred. The H and A bosons become degenerate in this limit and in the limit $M_A > 130$ GeV. The coupling to down type fermions and the production of b -jets ($\tan^2\beta$ in this case) is increased in these limits as well. For lower values of $\tan\beta$ their production comes mainly from gluon fusion. The cross sections for different processes are shown in Figure 10.

The branching ratios for the MSSM Higgs bosons are suppressed to W bosons, but the fermionic decay channel in regions with $M_A > 140$ GeV are direct and provides advantages. The main branching ratio, ϕ to $b\bar{b}$ occurs $\approx 90\%$ of the time, whilst $\phi \rightarrow \tau^+\tau^-$ is at $\approx 10\%$ and ϕ to $\mu^+\mu^-$ is at $\approx 0.03\%$. The different branching ratios are shown in Figure 11. The $b\bar{b}$ channel is difficult to analyse because of QCD backgrounds that dominate in this channel. The use of b -tagging of jets becomes an important technique that is used in this channel. The $\tau^+\tau^-$ channel also has a lot of background noise, however, it is manageable. In the low energy range most of the background comes from Z and W decays. The $\mu^+\mu^-$ channel provides a clean signature so it is also an option, despite its small branching ratio.

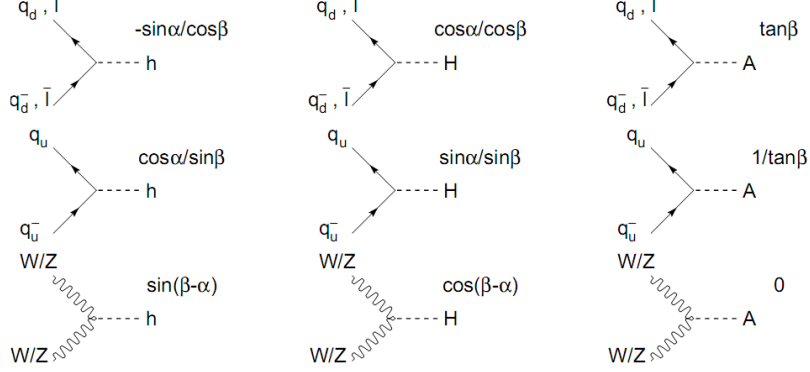
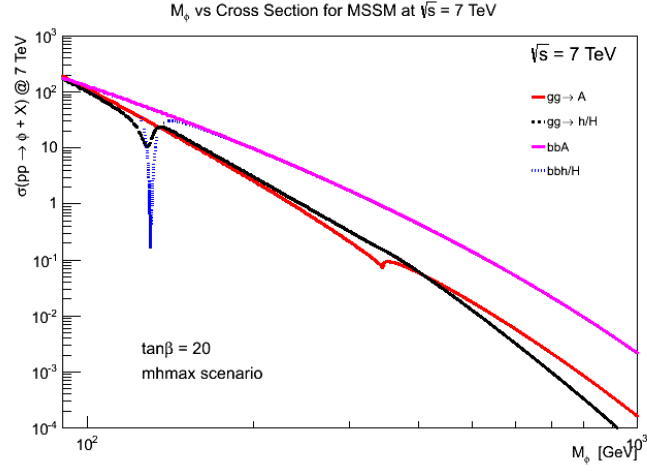


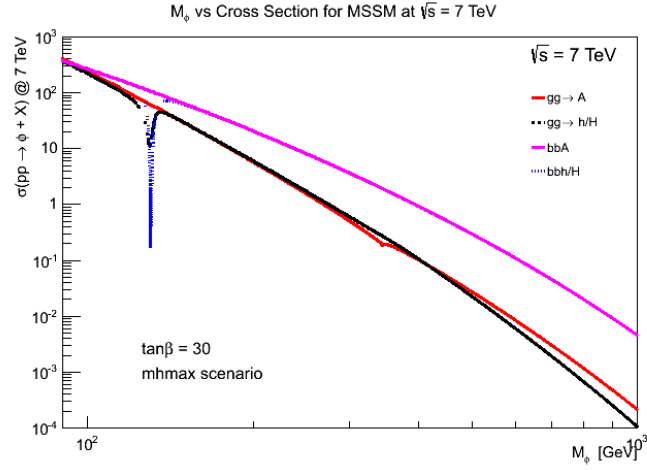
Figure 9: Scale factors for couplings of neutral MSSM Higgs bosons.

3.3 Tau leptons

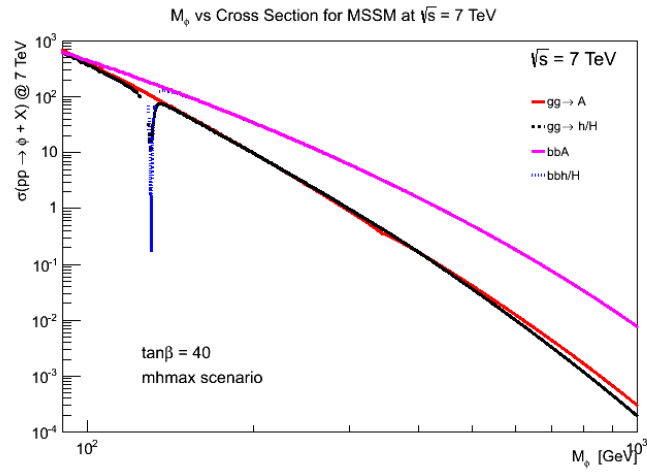
Tau leptons are massive third generation leptons (1.776 GeV) with a lifetime of 2.9×10^{-13} s. Taus can decay either leptonically (Branching Ratio (BR) = 35%) or hadronically (BR = 64%). Hadronic taus typically decay to an odd number of charged pions (one or three most often) and any number of neutral pions and a neutrino. These are referred to as n-prong taus, where n is the number of charged particles in the decay. Higher prong tau decays can be difficult to detect in an environment with a lot of jets, as well as being very rare. Tau decays involve the emission of either one or two neutrinos, so events with tau decays will be characterised by a large amount of missing transverse energy. Schematics for the leptonic and hadronic decay modes are shown in Figure 12.



(a) $\tan\beta = 20$.



(b) $\tan\beta = 30$.



(c) $\tan\beta = 40$.

Figure 10: Cross sections for the H MSSM Higgs for different production mechanisms [17].

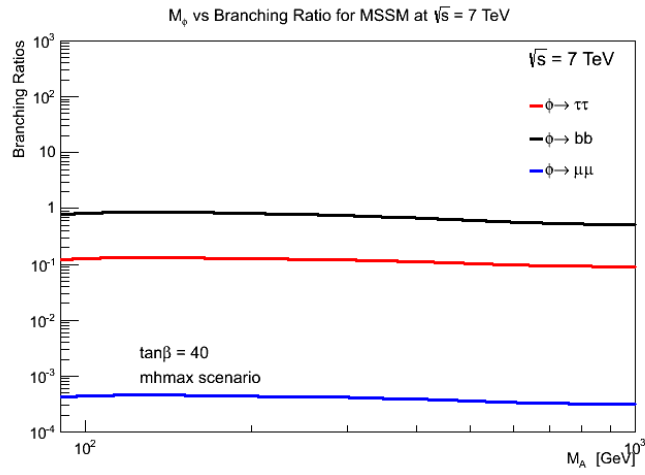
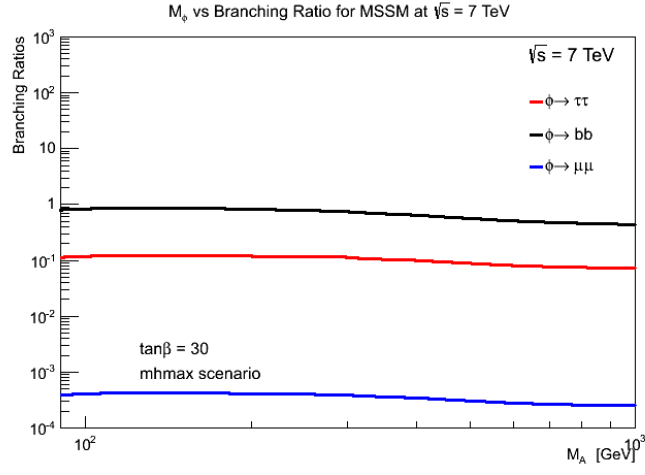
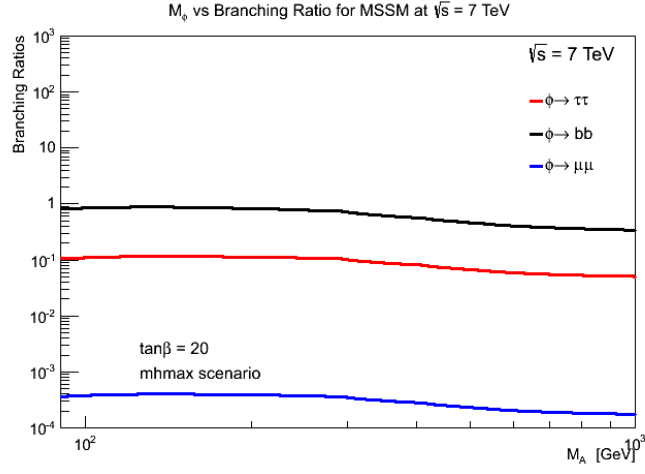


Figure 11: Higgs branching ratios as a function of the Higgs mass for different production processes [17].

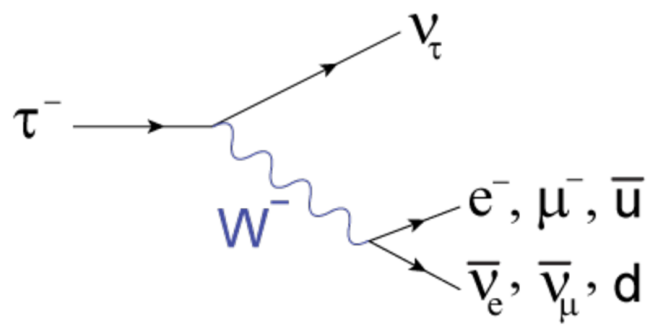


Figure 12: Feynman diagram of the decay of a tau.

4 Data and Monte Carlo Samples

All Monte Carlo (MC) and embedded samples are listed in Appendix A.

4.1 Data Samples

The results presented here are based on proton-proton collisions from the LHC in 2011 with a centre-of-mass energy $\sqrt{s} = 7$ TeV for this period, although it was increased to 8 TeV for the 2012 run. The integrated luminosity for this period collected by ATLAS is 4.66 fb^{-1} .

All data samples use a trigger to pre-select $e\tau_h/\mu\tau_h$ events. Electron stream events apply a trigger on E_T of clusters from the electromagnetic calorimeter with an associated track. The threshold was raised from $E_T > 20$ GeV to > 22 GeV through the year to control bandwidth as collision and data taking rates increased. The muon stream events are triggered by a muon candidate with $p_T > 18$ GeV. Trigger efficiencies are higher in MC samples than data and must be scaled down by 0.995 for electrons [72] and 0.992 for muons [73].

4.2 Monte Carlo Samples

MC event generators [74] are used to model the proton-proton collisions. These, together with detector simulations (like GEANT, mentioned below), provide a method of estimating the detector response, in estimating high energy processes and understanding the physical processes. Since not all of the modelling can be done perturbatively and many processes often contain loop diagram corrections, Monte Carlo methods are used to evaluate these scenarios. MC methods use random sampling to obtain numerical results. This can be used as a numerical integration method, for example, which works well as an event generator when the function being integrated is a probability density function for some physical process. The software used to do this is factorised into parts that focus on different parts of the collision. The first step is generally short-distance QCD calculations which can be done perturbatively, including the hard process (the actual event that is being simulated), parton showering (the subsequent decay of the particles created in the high energy collision) and initial and final state radiation (emissions from incoming and outgoing partons). The second step involves hadronisation of the parton showers, this is the formation of hadrons from the particles in the parton shower. The third step is soft hadronic phenomena such as the underlying event, which is the description of interactions happening in the collision that are not of interest in the current study (initial and final state radiation can also contribute to this). Further to this decays of the unstable partons formed in the previous steps can be calculated. An example of the factorisation of an LHC event is given in Figure 13. Many event generators exist with different methods of handling the outlined steps, with some doing certain types of events better than others. The generators used in this analysis are listed and discussed below.

The ALPGEN [76–78], AcerMC [79], MC@NLO [80], Sherpa [81], POWHEG [82–85], JIMMY [86], PYTHIA [87] and HERWIG [88, 89] generators were used to simulate different signal and background processes. The generation is done in two steps: hard processes and then parton shower and hadronisation.

For the hard process generation, we use SHERPA, MC@NLO, ALPGEN, gg2WW and PYTHIA. The parton shower and hadronisation are done with SHERPA. The steering parameters for the HERWIG, JIMMY and PYTHIA generators are described in Ref. [90].

ALPGEN was used to simulate the production of W and Z bosons in association with jets. MC@NLO (interfaced with HERWIG for parton showering, and JIMMY for the underlying event) was used to produce the $t\bar{t}$ and diboson processes. AcerMC was used to simulate single-top s- and t-channel background processes. The di-boson process, $gg \rightarrow WW$, was generated with gg2WW [92].

The signal process $gg \rightarrow A/H/h$ was simulated with POWHEG and $b\bar{b}A/H/h$ with SHERPA. For b -associated production the 4 [93, 94] and 5 flavour [95] calculations are combined using the matching scheme described here [96]. FeynHiggs [97] is used to calculate the masses, coupling constants and branching ratios of $A/H/h$. Since the mass of A is not known a number of samples were created with different masses from 90 GeV to 600 GeV with $\tan\beta = 20$. Since there is degeneracy between $A/H/h$

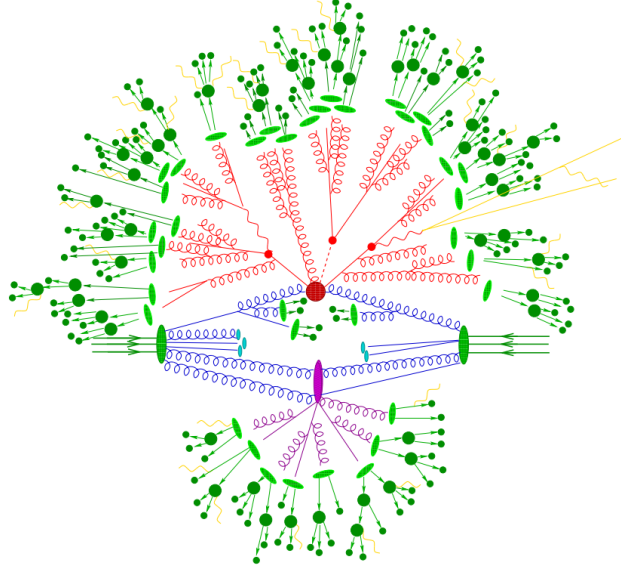


Figure 13: Monte Carlo event generation for a Standard Model $t\bar{t}H$ event. The large red circle indicates the hard process or actual interesting interaction, the purple object is another process taking place in the collision, the red lines indicate QCD radiation, with the smaller red circles being the top quarks and SM Higgs boson. The light green objects represent partons hadronising, with the dark green objects being the hadrons decaying. Photons are represented by the yellow lines and give off final state radiation. [75].

in a large region, the same samples are used for all signal processes. Where there is no degeneracy the mass of H/h can be approximated. These masses are based on the m_h^{max} MSSM scenario.

TAUOLA [98] and PHOTOS [99] were used to simulate the tau decays and photon radiation from charged leptons for all samples except those generated with SHERPA.

GEANT4 [100,101] is detector simulation software which was used to provide a detailed simulation of the ATLAS detector response.

Since all of the processes have different cross sections they must be weighted accordingly when comparing results between different event samples.

Some issues in data that are due to dynamic physical processes in the detector which must be accounted for in MC. One such issue is pile-up which poses a significant challenge for data analysis. Pile-up refers to activity in the detector from other events. This can be out-of-time (from previous bunches) or in-time (activity from the current bunch). It can make it difficult to determine from which event a measurement comes from. The number of reconstructed vertices is often used as a measure of the pile-up, as more vertices indicates more activity in the event. This is generally due to an increase in the number of jets in the event.

The number of vertices was previously used for the pile-up variable, but this is no longer sufficient in 2011 data where there is out-of-time pile-up. The average number of interactions per crossing, $\langle\mu\rangle$, is now used instead. This is a measure of how many interactions there are per event. The smallest chunk of data that is used for luminosity calculations is one luminosity block (defined as a time interval in which the luminosity remains constant during data-taking, typically about 60 seconds). This means μ is an average over the luminosity block. The pile-up in the event can be changed in the generator settings which allows for algorithms to be tested on more complicated event topologies.

4.3 Embedded Samples

In this analysis, the $Z \rightarrow \tau\tau$ background is largely irreducible, especially for a low mass Higgs. It is critical that this is well understood. Whilst this can be simulated using Monte Carlo generators, methods to estimate this directly from data are preferred. MC methods were used to model distribution

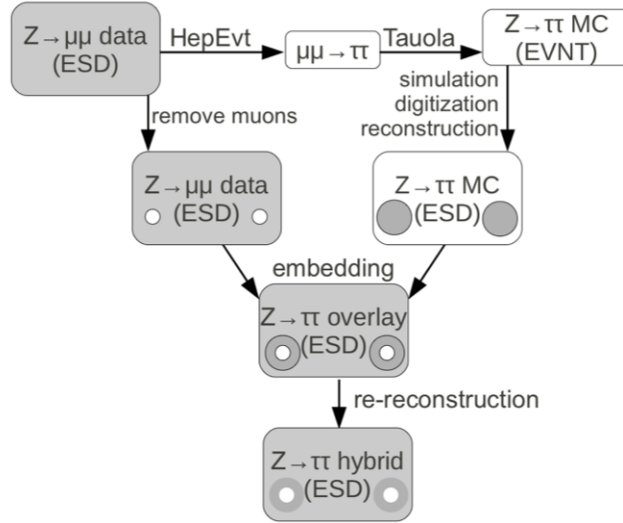


Figure 14: Overview of a *mini event* in the embedding process [90].

shapes and test selection efficiencies. An embedding method is used where a pure sample of $Z \rightarrow \mu\mu$ events is taken from data.

$Z \rightarrow \mu\mu$ processes are identical to $Z \rightarrow \tau\tau$ except for the tau mass. In addition, this process is very unlikely to have signal events in it because of the very low branching ratio of $\phi \rightarrow \mu\mu$.

The $Z \rightarrow \mu\mu$ events are modified by taking simulated tau decays and replacing the muons in the event. The kinematics of the decay are taken from the muons, but the tau decays are then taken from MC to give a more accurate description of data-taking conditions. This is illustrated in Figure 14. The embedded sample must be normalised to the ALPGEN MC samples since the trigger information is lost during the embedding process.

Events with two muons are selected with cuts on the momentum, track isolation, the invariant mass of the system and a common primary vertex for the two muons. The invariant mass of the Z is reconstructed by adding up all of the masses of the decay products. The muons are replaced by taus in the sample and the four-momenta of the taus is scaled in the reconstructed Z rest frame to account for the mass difference between muon and tau. The event is then processed with TAUOLA and PHOTOS and passed through GEANT4 to get the detector response. This is called a *mini event*. The data models used, Event Summary Data (ESD) and Analysis Object Data (AOD), are described in reference [91]. ESD has more event information than AOD, which has been reprocessed with the next iteration of event reconstruction taking place.

The final steps involve removing all of the muon tracks from the data event and accordingly adjusting the energy in the event. This is done by creating a *mini event* with the original kinematics and subtracting the energy from this simulated event. The calorimeter cell energies and tracks from the first *mini event* are copied to the data event. Lastly a full offline reconstruction must be done on this new sample to recalculate the missing transverse energy and all objects. This gives a fully reconstructed simulated $Z \rightarrow \tau\tau$ event by using data-driven methods.

5 Object Reconstruction

5.1 Triggers

Triggers are needed to make fast decisions about events so that it can be kept or discarded. Not all events are kept, since some of them do not pass quality requirements and there are far too many events produced per second for all of them to be recorded. The LHC had an initial bunch crossing rate of 400 MHz — the triggers help to reduce this to ≈ 200 Hz [102]. Other important uses of triggers are to reject QCD multi-jet events and keep low cross section events.

There are three hardware and software triggers implemented in the ATLAS detector:

- Level 1 (L1) is a hardware based trigger,
- Level 2 (L2) is a software based trigger,
- and the Event Filter (EF) is also based in software.

L2 and EF together are known as the High Level Trigger (HLT).

The L1 calorimeter trigger makes decisions in $2.5 \mu\text{s}$ based on objects in the calorimeters. Some of these objects are EM clusters, taus, jets and missing transverse energy which are calculated using E_T from trigger towers of 0.1×0.1 granularity in $\Delta\phi \times \Delta\theta$. The L1 muon trigger uses trajectories from the muon detector. In total there are 256 different configurations for the L1 trigger based on the multiplicity and thresholds of the different objects reconstructed by the trigger. A p_T and $\eta - \phi$ dependent seed is created by the L1 trigger for the L2 trigger.

The L2 trigger runs a number of algorithms in the regions identified by the L1 trigger. More data is used to do a more intensive analysis of this candidate, producing a higher resolution picture of the candidate than the L1 trigger. The L2 trigger also uses data from the Inner Detector. The decision time is increase at the L2 trigger to 40 ms.

The EF uses seeds from the L2 trigger, but has access to the complete set of data for tracking, typically running the same sort of analysis as offline reconstruction software. This increases rejection of unwanted data and keeps the output rate at a manageable level.

All reconstructed objects — electrons, muons, taus, etc. — are required to pass certain triggers before further selection is done.

5.2 Electrons

Electron candidates are identified by matching a track in the inner detector with a cluster of cells in the EM calorimeter. Depending on whether *loose*, *medium* or *tight* selection is applied the requirements change on the shower shape, hadronic leakage (ratio of energy in the transverse plane, E_T , in the hadronic calorimeter to the EM calorimeter), the number of pixel and SCT sensor readings (hits), the impact parameter, shower width, number of hits in the TRT and the innermost layer of the Pixel Detector (Blayer) [103], track matching (using cuts on $\Delta\phi$, E/p and η) and rejection of electrons matching photon conversions.

Since the initial momentum is not known in the beam direction the momentum in the transverse plane is used for missing energy and momentum measurements. All of the initial momentum is along the axis of the beam direction, with no momentum in the transverse plane, which must be conserved. Electrons are required to have:

- Transverse momentum $p_T > 15$ GeV.
- $|\eta| < 1.32$ or $1.52 < |\eta| < 2.47$ which places it in the barrel or endcaps.
- Isolation is evaluated a hollow cone of radius ² $\Delta R < 0.2$ of the electron candidate axis with the 5×7 cell area in the centre excluded.

² $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ for the two objects being compared. This defines a cone around an axis of a track.

- The energy in the cone around the electron is required to be $< 8\%$ of the total p_T of the electron. This ensures that the energy deposits are well collimated.
- Track isolation requirements – all tracks within a cone of $\Delta R < 0.4$ of the electron candidate with $p_T > 1$ GeV should have a total p_T that is $< 6\%$ of the electron track p_T .

Corrections are applied to the energy resolution, reconstruction and identification efficiencies and calorimeter isolation to account for mis-modelling in MC simulations.

5.3 Muons

Muons are identified using tracks in the inner detector and muon spectrometer. In this analysis muons identified with the Staco [102] family of algorithms. There are three different strategies that are used:

- *Standalone* muons are found by extrapolating tracks in the muon spectrometer to the beam line, taking into account energy loss and scattering. This Staco algorithm is called Muonboy. These have the advantage that they have greater η coverage, but might miss lower momentum muons that don't reach the outermost detectors.
- *Combined* muons are identified by tracks in the muon spectrometer that are matched to tracks found in the inner detector.
- *Tagged* muons are done in the opposite way to the Standalone muons so inner detector tracks are extrapolated out to the muon spectrometer and hits are looked for around this point in the spectrometer.

In all scenarios the muon kinematics are measured using inner detector tracks.

Muons are required to have:

- Transverse momentum $p_T > 10$ GeV.
- Pseudorapidity $|\eta| < 2.5$.
- As for the electrons there are track and calorimeter isolation requirements. For the calorimeter isolation the energy in the calorimeters in a cone of $\Delta R < 0.2$ should be $< 4\%$ of the muon's p_T .
- Track isolation requires the total p_T of all tracks within $\Delta R < 0.4$ with $p_T > 1$ GeV to be less than 8% of the muon candidate's track p_T .
- The point of closest approach along the z -axis of the muon must be less than 1 cm from the primary vertex to remove cosmic ray contamination.

As for the electron, there are corrections applied to the p_T , identification efficiency and the calorimetric isolation.

5.4 Taus

Hadronic tau decays have different decay modes for different prong decays. In single prong decays the dominant modes are $\tau \rightarrow \pi^\pm \nu$ (22.4%) and $\tau \rightarrow n\pi^0 \pi^\pm \nu$ (73.5%). In three prong decays the dominant modes are $\tau \rightarrow 3\pi^\pm \nu$ (61.6%) and $\tau \rightarrow n\pi^0 3\pi^\pm \nu$ (33.7%). However, some tau decays involve a kaon instead of a pion. Charged kaons, $K^\pm$ have the same sort of signature in the detector, however, neutral kaons, K_S^0 can be difficult to identify as one or three prong decays.

Hadronic tau decays have a signature of a well collimated jet with low track multiplicity and a displaced secondary vertex. The collimation is due to a Lorentz boost which causes the decay products to have less angular separation in the lab frame and gives a longer flight time. This collimation and low track multiplicity as well as other track characteristics and calorimeter shapes distinguish hadronic taus from QCD jets. An illustration of a tau decay is shown in Figure 15.

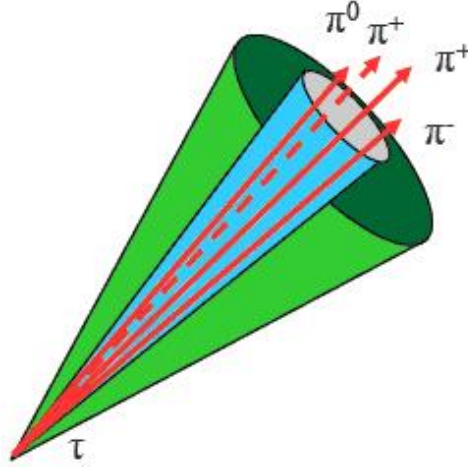


Figure 15: An illustration of a hadronic tau decay [71].

Requiring the tau to be isolated removes other backgrounds and makes identification easier and more reliable. Using the track and calorimeter measurements variables can be used to identify the hadronic taus.

There are two main algorithms used to identify taus – calorimeter seeded and track seeded. In both cases track and calorimeter measurements are used. These are discussed in the next section.

Calorimeter based algorithms start with energy deposits in the calorimeters and build up from there by using tracking information.

Tracking based algorithms are seeded by tracks that come from low multiplicity tracks surrounding, with good collimation, the leading track. The energy of the tau is calculated using an energy-flow algorithm based on tracks and electromagnetic calorimeter deposits.

The inner detector is used to find the charged tracks in the decay. These should show isolation from the rest of the event and not have any matching tracks in the muon detector or show characteristics of electrons listed previously. Furthermore, the tracks should show little separation and be well collimated in the (ϕ, η) space.

The calorimeter gives measurements of the energy deposits and shower shapes from the decay products. Whilst the resolution in the calorimeter is not as high as in the inner detector the shapes of the showers in the calorimeter are still able to be used for identification. Hadronic tau decays have narrow shower shapes in the electromagnetic calorimeter.

Taus are first seeded from all jets reconstructed with the anti- k_t algorithm (discussed in subsection 5.5). From here the identification variables are calculated and a number of quality criteria are required. The distance parameter used is $R = 0.4$, which is the distance from the topological clusters to the centre of the tau candidate. All jets with $p_T > 10$ GeV and within $|\eta| < 2.5$ are used as seeds.

The four-momentum of the tau is defined by the transverse momentum, p_T , the pseudorapidity, η , the azimuthal angle, ϕ . η and ϕ are calculated using the sum of four-vectors of the topological clusters from the seed jet. The E_T and p_T of the tau candidate are equal since the four-vectors of the tau are massless.

Track quality criteria for the tau candidate are listed below:

- $p_T > 1$ GeV,
- Number of pixel hits ≥ 2 ,
- number of pixel + SCT hits ≥ 7 ,
- $|d_0| < 1.0$ mm,
- $z_0 \sin \theta < 1.5$ mm.

Where d_0 is the impact parameter, defined in the next section and z_0 is the longitudinal distance of the closest approach of the track to the reconstructed primary vertex in the transverse plane. The isolation annulus is defined as $0.2 < \Delta R < 0.4$ and the core cone as $\Delta R < 0.2$.

In addition to the track quality criteria a number of further cuts and decisions must be made to identify a jet seed as a tau. These are a $p_T > 20$ GeV requirement, $|\eta| < 2.5$, one or three charged tracks and the overall charge should be ± 1 . There are muon and electron vetoes applied to remove fakes from the lighter leptons. The tracks and calorimeter deposits should match. The invariant mass of the tau candidate should be less than the actual tau mass, since there will be missing energy.

A number of identification variables are calculated and then cut based and multivariate discriminants are used to reject jets which fake hadronic tau decays. These identification variables are fed into a boosted decision tree (BDT) to make a decision on the identification of the tau. A working point with 45% identification efficiency is used.

The inner detector is used to find the charged tracks in the decay. These should show isolation from the rest of the event as well not having any matching tracks in the muon detector or show characteristics of electrons (as defined above). The tracks should show little separation and be well collimated in the (ϕ, η) space.

The calorimeter gives measurements of the energy deposits from the decay products. Whilst the resolution in the calorimeter is not as high as in the inner detector the shapes of the showers in the calorimeter are still able to be used for identification. Hadronic tau decays have narrow shower shapes in the electromagnetic calorimeter.

5.4.1 Seeding Algorithms

Tracking Based Algorithms

As discussed above, a well collimated, low multiplicity object of neutral and charged pions is used as a seed. The leading pion (large p_T and well defined direction) should be charged. Low multiplicity must be observed in the core region of the tau candidate, with more tracks allowed in the isolation region and the charge must be ± 1 or 0.

Generally only one- and three-track candidates are used, however two-track candidates can be used to recover three-prong candidates which have not been identified properly, however, this also increases contamination from QCD jets [105].

The direction of the vertex of the leading track(s) is used to calculate the position of the candidate. The energy is calculated using the energy-flow method described below.

Energy-flow Algorithm

Multiple categories are used to discriminate different types of cell energy deposits. These are listed here:

- E_T^{emcl} , the electromagnetic energy, seeded by an isolated EM cluster, isolated from tracks passing all quality requirements with no hadronic leakage (all energy is within the EM calorimeter).
- E_T^{chrgEM} and E_T^{chrgHad} , the *charged* EM energy in the EM and Hadronic calorimeters.
- E_T^{neuEM} , the *neutral* EM energy in the EM calorimeter. The energy comes from cells not used in the charged EM energy definition.

The charged EM energy deposits are replaced by the track p_T in the energy-flow algorithm to define the energy scale. The neutral contribution from π^0 s is included in E_T^{emcl} and E_T^{neuEM} and two terms are added to correct for π^0 s and $\pi^\pm$ s depositing energy in the same cells: $\sum \text{res} E_T^{\text{chrgEM}}$ and $\text{res} E_T^{\text{neuEM}}$ where the energy response (res) is defined as $(E_{\text{rec}} - E_{\text{truth}})/E_{\text{truth}}$. The final equation for the energy-flow algorithm is given by:

$$E_T^{\text{eflow}} = E_T^{\text{emcl}} + E_T^{\text{neuEM}} + \sum p_T^{\text{track}} + \sum \text{res} E_T^{\text{chrgEMtrk}} + \text{res} E_T^{\text{neuEM}}.$$

This works well for hadronic taus where the energy scale definition used has benefits in the reduction of fake hadronic tau candidates. QCD jets will not generally contain their energy in a cone of $\Delta R = 0.2$,

so contamination is small [105]. This should give smaller tails on the mass distribution compared with the calorimeter based algorithm.

Calorimeter Based Algorithms

Calorimeter clusters are used as seeds in this approach. A grid on the calorimeter layers is used to form calorimeter towers of cell energy deposits. The position and energy of all the cell deposits are used to identify clusters of cells. The identification efficiency can be increased by raising the limits on the E_T [105]. An associated momentum for each cluster is calculated using the assumption of the tau candidate being massless. However, in events where there are neutrinos this will cause slight differences.

All cells are calibrated and weighted according to the cell energy density, the cell's η and the region of the calorimeter the cell is in. This must be corrected further, since this is generally done for jets and not taus.

The identification variables defined below are used in a likelihood function, similar to the methods used in the anti- k_T algorithm. This is done to discriminate QCD jets from true hadronic tau decays. There is a generally a strong E_T dependence in the identification variables [105].

5.4.2 Identification variables

A number of variables are used for hadronic tau identification. Some of these are calorimetric based variables and others track based variables. The hadronic tau is assumed to be massless, and so an associated energy can be found for each candidate. However, due to the presence of neutrinos the energy scale of the tau must be corrected.

Tracking Variables:

- Charge of tau candidate:

The charge is given as a sum over the charges of the associated tracks.

- Number of associated tracks (N_{tr}): The number of tracks associated with the tau candidate within a radius of $\Delta R < 0.4$. These tracks have no quality criteria other than $p_T > 1$ GeV.
- Track radius or track average distance (R_{track}):

$$R_{track} = \frac{\sum_i^{\Delta R_i < 0.4} p_{T,i} \Delta R_i}{\sum_i^{\Delta R_i < 0.4} p_{T,i}},$$

which is the track width, or distance between the tau candidate and track, ΔR_i , weighted by track transverse momentum, p_T , for all the core and isolation tracks, i , around the tau candidate.

- Number of tracks within the isolation annulus around the tau candidate, N_{track}^{iso} .
- Track mass (m_{tracks}):

$$m_{tracks} = \sqrt{(\sum_{tracks} E)^2 - (\sum_{tracks} p)^2},$$

the invariant mass of the tracking system using the isolation and core tracks and the associated energy deposits and measured transverse momentum.

- Signed decay length (L_T^{flight}): The distance between the primary and secondary vertex in a multi-prong decay.

- Track flight path significance (S_T^{flight}):

$$S_T^{\text{flight}} = \frac{L_T^{\text{flight}}}{\delta L_T^{\text{flight}}}.$$

The significance of the decay length for the secondary vertex, using only core tracks, in multiprong decays. Here, $\delta L_T^{\text{flight}}$ is the estimated uncertainty.

- Impact parameter (d_0): Closest approach of the track to the reconstructed primary vertex in the transverse plane.
- Leading track IP significance ($S_{\text{lead track}}$):

$$S_{\text{lead track}} = \frac{d_0}{\delta d_0}.$$

The significance of the impact parameter of the leading track (highest p_T track).

- Maximum ΔR (ΔR_{max}): The maximum distance or radius between a core track and the tau candidate central axis.
- TRT HT fraction (f_{HT}):

$$f_{\text{HT}} = \frac{\text{High-threshold TRT Hits}}{\text{Low-threshold TRT Hits}}.$$

The ratio of high- to low-threshold hits in the TRT. Electrons are likely to produce more high-threshold hits than pions, so this ratio can be used to discriminate one prong taus and electrons.

- Jet vertex fraction (JVF) [104]:

$$\text{JVF} = \frac{\sum_{\text{PV}} p_T(\text{track})}{\sum_{\text{all}} p_T(\text{track})}.$$

This is the fraction of track p_T from the primary vertex. This is used as a local measure of pileup.

- Number of wide tracks ($N(\text{wide tracks})$): A wide track is a track within the isolation annulus of $\Delta R < 0.4$ but outside the core annulus of $\Delta R < 0.2$. This is the number of wide tracks associated with the tau candidate.

Calorimeter Variables:

- Electromagnetic fraction (f_{EM}):

$$f_{\text{EM}} = \frac{\sum_{i \in \{\text{EM 0-2}\}}^{\Delta R_i < 0.4} E_{T,i}}{\sum_{j \in \{\text{all}\}}^{\Delta R_j < 0.4} E_{T,j}}.$$

The transverse energy deposited in the first three layers of the EM calorimeter (EM 0-2) as a fraction of the energy deposited in all layers of the calorimeter.

- Hadronic radius (R_{Had}):

$$R_{\text{Had}} = \frac{\sum_{i \in \{\text{Had, EM3}\}}^{\Delta R_i < 0.4} E_{T,i} \Delta R_i}{\sum_{i \in \{\text{Had, EM3}\}}^{\Delta R_i < 0.4} E_{T,i}}.$$

Shower width, ΔR_i , in the hadronic calorimeter (denoted Had here) and layer three of the EM calorimeter (EM3) weighted by the transverse energy in a cone of $\Delta R < 0.4$ from the tau candidate axis.

- Electromagnetic radius (R_{EM}):

$$R_{\text{EM}} = \frac{\sum_{i \in \{\text{EM } 0-2\}}^{\Delta R_i < 0.4} E_{\text{T},i} \Delta R_i}{\sum_{i \in \{\text{EM } 0-2\}}^{\Delta R_i < 0.4} E_{\text{T},i}}.$$

Shower width, ΔR_i , in the pre-sampler, layer one and layer two of the EM calorimeter (EM 0-2) weighted by the transverse energy in a cone of $\Delta R < 0.4$ from the tau candidate axis.

- Corrected cluster isolation energy ($E_{\text{T,corr}}^{\text{iso}}$):

$$E_{\text{T,corr}}^{\text{iso}} = E_{\text{T}}^{\text{iso}} - \delta E_{\text{T}}^{\text{iso}} = \sum_i^{0.2 < \Delta R_i < 0.4} E_{\text{T},i} - \delta E_{\text{T}}^{\text{iso}}.$$

Transverse energy of the isolated clusters. $\delta E_{\text{T}}^{\text{iso}} = (1 - \text{JVF}) \times \sum p_{\text{T},\text{trk}}$ is a pileup correction term. JVF is the jet vertex fraction of the jet seed of the tau and $\sum p_{\text{T},\text{trk}}$ the sum of the transverse momentum of that jet's associated tracks.

- The ratio of the leading two (three) clusters (by energy) to the total energy of all clusters associated with the tau candidate ($f_{2(3) \text{ lead clusters}}$).
- Centrality or core energy fraction (f_{core}):

$$f_{\text{core}} = \frac{\sum_{i \in \{\text{all}\}}^{\Delta R_i < 0.x_1} E_{\text{T},i}}{\sum_{j \in \{\text{all}\}}^{\Delta R_j < 0.x_2} E_{\text{T},j}}.$$

This gives the fraction of the transverse energy, E_{T} , within $\Delta R < 0.x_1$ of the tau candidate compared with the total transverse energy within $\Delta R < 0.x_2$. i and j run over the calorimeter cells in the respective ΔR regions. Calorimeter cells are defined by whether or not they come from the topological clusters from the jet seeding the tau.

- Calorimetric radius (R_{cal}):

$$R_{\text{cal}} = \frac{\sum_{i \in \{\text{all}\}}^{\Delta R_i < 0.4} E_{\text{T},i} \Delta R_i}{\sum_{i \in \{\text{all}\}}^{\Delta R_i < 0.4} E_{\text{T},i}}.$$

The shower width for each i cell within $\Delta R < 0.4$ within the calorimeters weighted by the transverse energy, E_{T} , of each cell.

- Ring isolation (f_{iso}):

$$f_{\text{iso}} = \frac{\sum_{i \in \{\text{EM } 0-2\}}^{0.1 < \Delta R_i < 0.2} E_{\text{T},i}}{\sum_{j \in \{\text{EM } 0-2\}}^{\Delta R_j < 0.4} E_{\text{T},j}}.$$

Here i is the index of the cell within the first three layers of the EM calorimeter (EM 0-2) in the region $0.1 < \Delta R < 0.2$. The index j runs over all cells within the wide cone $\Delta R < 0.4$.

- Effective topological cluster mass ($m_{\text{eff,clusters}}$):

$$m_{\text{eff,clusters}} = \sqrt{\left(\sum_{\text{clusters}} E\right)^2 - \left(\sum_{\text{clusters}} p\right)^2}.$$

- The invariant mass of the clusters making up the seed jet at the local calibration scale (using only topological clusters in the calorimeter). Only the first N clusters are used where N is defined as:

$$N = \frac{(\sum_i E_{Ti})^2}{\sum_i E_{Ti}^2}.$$

Tracking and Calorimeter Variables:

- Leading track momentum fraction (f_{track}):

$$f_{\text{track}} = \frac{p_{T,1}^{\text{track}}}{p_T^\tau}.$$

The ratio of the leading p_T core track, $p_{T,1}^{\text{track}}$ to the p_T of the tau candidate, p_T^τ . π^0 s might deposit energy in the calorimeter, so the track p_T will only be a fraction of the total transverse momentum of the tau candidate.

- Hadronic track fraction ($f_{\text{Had}}^{\text{track}}$):

$$f_{\text{Had}}^{\text{track}} = \frac{\sum_{i \in \{\text{Had}\}}^{\Delta R_i < 0.4} E_{T,i}}{p_{T,1}^{\text{track}}}.$$

The ratio of transverse energy in the hadronic calorimeter (denoted Had here) to the transverse momentum of the leading track within $\Delta R < 0.4$.

- Maximum strip E_T ($E_{T,\text{max}}^{\text{strip}}$): Maximum transverse energy deposited in the pre-sampler of the EM calorimeter not associated to the leading track.
- Electromagnetic track fraction ($f_{\text{EM}}^{\text{track}}$):

$$f_{\text{EM}}^{\text{track}} = \frac{\sum_{i \in \{\text{EM}\}}^{\Delta R_i < 0.4} E_{T,i}}{p_{T,1}^{\text{track}}}.$$

The ratio of the transverse energy within a cone of $\Delta R < 0.4$ in the EM calorimeter to the transverse momentum of the leading track.

5.4.3 Energy Calibration

The energy of the reconstructed hadronic tau candidate must be corrected to account for calorimeter response. The energy is reconstructed at the EM scale by summing over the energy of all cells within a cone of $\Delta R < 0.4$ of the tau candidate axis. Response functions for the calorimeter are determined using EM scale p_T measurements compared with p_T measurements from MC samples. Tau candidates are then calibrated to the tau energy scale (TES) using:

$$p_T^{\text{TES}} = \frac{1}{R(p_T^{\text{EM}})} p_T^{\text{EM}},$$

where $R(p_T^{\text{EM}}) = \frac{p_T^{\text{EM}}}{p_T^{\text{true}}}$.

5.4.4 Tau Candidate Identification Algorithms

There are a number of methods used for tau candidate identification. These include cut based and multivariate methods. In the cut based method the identification is made by making cuts on variables that should give good discrimination against fake tau candidates. In the multivariate methods a Boosted Decision Tree (BDT) is trained on MC samples to recognise patterns in tau variables. Log-likelihood (LLH) methods are used to maximise the likelihood of identifying a tau based on a selection of variables.

Cut Based Identification

Cut based methods work by cutting on selected discriminating variables. The main variables used, as defined above, are R_{EM} , R_{track} and f_{track} . These are used to discriminate between one- and three- prong candidates. These cuts are p_{T} dependent [106].

These cuts rely on the shape of the hadronic shower produced in tau decays where the narrow width is a major consideration. Since there is a Lorentz boost to the tau in the laboratory frame, the width-like variables, R_{EM} , R_{track} , should be inversely proportional to the p_{T} . There is also linear dependence on the angular relation between the jet seed axis and the momentum vector of the decay pions. For small angles this gives $\Delta\phi \approx \tan\Delta R$. The term $\tan\Delta\phi$ is defined as $\frac{k_{\text{T}}}{p_{\text{T}}}$, where p_{T} has its usual meaning and k_{T} is defined as the jet seed transverse momentum. Thus the variables, R_{EM} , R_{track} , are p_{T} dependent, however, this dependence can be reduced by multiplying the R variables by p_{T} . This is done for background and signal MC samples and cut curves are defined based on a linear combination of the background and signal distributions.

Multivariate Identification

The most common multivariate technique used is a Boosted Decision Tree. This works in much the same way as a cut-based method by cutting on identification variables. However, if a cut is failed the identification does not immediately fail. By looking at truth information from the MC samples the event might be kept even if it fails a cut and the cuts that it does pass are recorded. In this way a score can be assigned (between 0 and 1) to each event to classify it as background- (closer to 0) or signal-like (closer to 1). This is only done for training on MC samples. To classify events after training, all of the input variables are used to assign a score. This classification can be done on data.

A decision tree is constructed by taking each variable and calculating the best variable to split the tree on. This is done by calculating a score for each variable and taking the one with the highest signal purity [107]. This is done using the Gini index [108]. This builds up a binary decision tree, with each node representing a decision of signal or background. A boosted decision tree expands on this and has multiple trees. The trees get weighted by a factor when an event is misclassified. This makes the new tree more likely to identify this event correctly. The BDT is trained using MC samples since these have truth information. Overtraining must be avoided as the BDT learns to identify the training dataset and cannot generalise properly [109].

BDTs are trained separately on one- and three-prong tau decays. The three-prong tree is used to identify any tau candidate with two or more tracks. The final BDT score between 0 and 1 that is used as the final selection variable is found using the signal and background efficiency. A signal efficiency is chosen as a cut-off value and a BDT score that obtains that efficiency is used as the discriminating variable.

New BDT Variables for 2012

As the energy of the collisions is increased and the bunch spacing decreased at the LHC the pile-up is expected to increase. This means pile-up independent methods of particle identification are very important. A study was done into how to reduce pile-up dependence of current hadronic tau identification using BDTs.

The idea was to find identification variables for which there was a good tau identification efficiency that had no dependence on the number of vertices or μ , or a linear dependence which is relatively easy to correct for.

For this study the signal was a true tau (using truth information from MC samples) and the background was a tau candidate, but not a true tau. The signal efficiency was defined by the number of true taus identified as a fraction of the total number of true taus, similarly for the background where the number of taus as a fraction of the total number of true taus was used. A good signal efficiency was required with a low background efficiency.

Identification variables were tested to find out which ones showed the most sensitivity to pile-up. The least sensitive variables were used as possible variables to use for tau identification. New variables were used to reduce pile-up dependency. The new identification incorporating these is known as tau++.

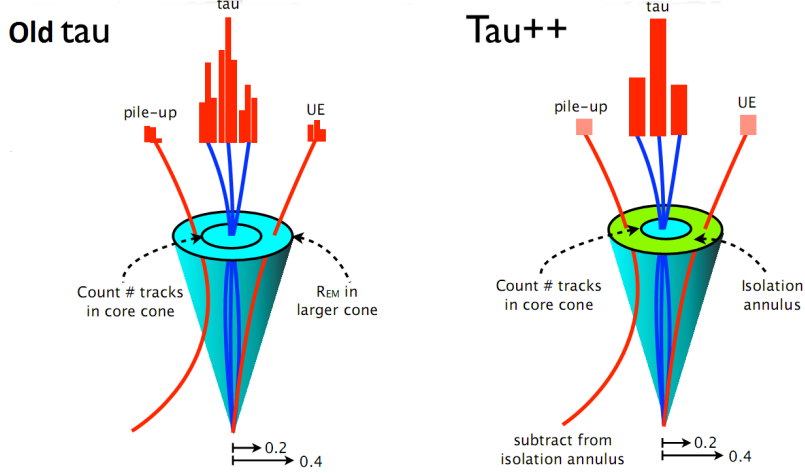


Figure 16: An illustration showing the difference between the old and new (tau++) methods of calculating identification variables for taus [104].

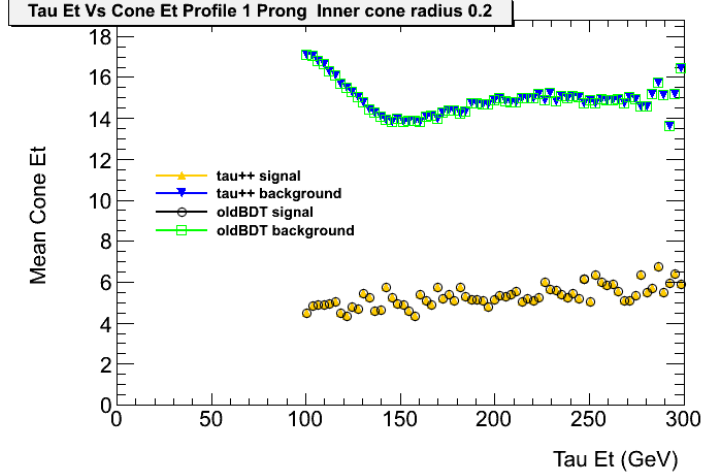
These focus on the isolation cone around the tau candidate, where the largest effect from pile-up will be noticed. The tau structure is separated from the isolation of the tau candidate. An example of the new methods is shown in Figure 16. As discussed in the tau identification algorithms, the current identification is based on the width of a tau candidate within a cone of $\Delta R < 0.4$. Tau decays should be narrow, so a decrease in this cone size should be used, getting narrower at higher p_T . The width of the cone and the identification variables calculated in this cone (calorimeter based), are sensitive to pile-up. Instead of having a core cone of $\Delta R = 0.2$ with the outer cone of $\Delta R = 0.4$ it is proposed that the variables are all calculated within a smaller inner cone and an isolation annulus is constructed around this inner cone where there should be a restriction on the amount of energy to reduce contamination from pile-up. BDTs were trained separately for one prong and three prong tau decays due to their different topologies.

The old set of identification variables used in BDT decisions in a $\Delta R = 0.4$ cone were:

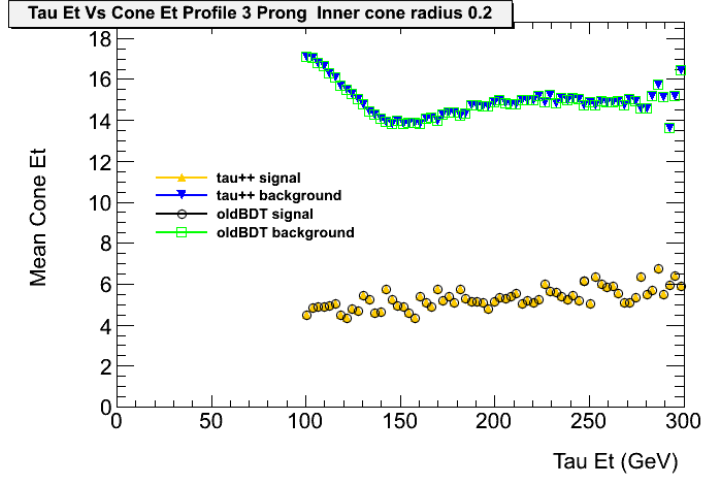
- Centrality fraction, f_{core} .
- Calorimetric radius, R_{cal} .
- Cluster energy of the leading three clusters as a fraction of the total cluster energy, $f_{2(3) \text{ lead clusters}}$.
- Effective topological invariant mass, $m_{\text{eff.clusters}}$.
- Transverse energy as a fraction of the leading track's p_T .
- Track average distance, R_{track} .
- Number of wide tracks, $N(\text{wide tracks})$.
- Impact parameter significance for the leading track (one prong only), $S_{\text{lead track}}$.
- Maximum dR (three prong only), ΔR_{max} .
- Mass of the tracking system (three prong only), m_{tracks} .
- Track flight path significance (three prong only), S_T^{flight} .

These variables are defined in Section 5.4.2.

The old variables were calculated with cell based definitions instead of cluster based and these were used to train a BDT (implemented in TMVA [110]) to identify taus. Here a tau is defined as in the



(a) 1 Prong.



(b) 3 Prong.

Figure 17: Small correlation between tau total E_T and cone E_T , shown for 1 and 3 prong taus in a cone size of $0.2 < \Delta R < 0.4$.

object selection above, without the tau identification BDT decision. The relative power of a variable could be found during training and testing the BDT. The new variables were calculated in variable cone sizes and tested on cone sizes ranging from $\Delta R = 0.1 - 0.4$. At the same time the isolation annulus was varied. There were many combinations of cone sizes and subsets of the old variables tried as cell or cluster based.

Additional ideas were tried such as cutting on the E_T of the tau, but no correlation was found between the tau E_T and the isolation annulus E_T . This is shown in Figure 17.

All new variables were calculated using cell based definitions, except for the effective cluster mass. The leading cluster fraction was changed to the energy of the leading 40 cells as a fraction of the energy of all the cells in the cone instead of the leading three clusters as a fraction of the energy of all the clusters in the cone.

The distributions from the variables used are shown in Figures 19 - 37 vs. the number of reconstructed vertices and vs. the mean number of reconstructed vertices for that variable. These figures shown are for a cone of size $0.2 < \Delta R < 0.4$. The centrality fraction plots, Figures 19 and 20, show a much higher number of high pile-up events being selected, however, a lot of the sensitivity is lost as there are fewer events with low centrality fractions being selected by the new method. The difference between one and

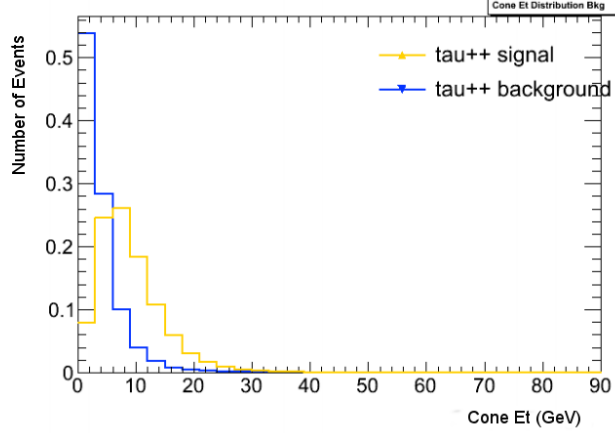


Figure 18: Good separation is shown for the cone E_T between background and signal.

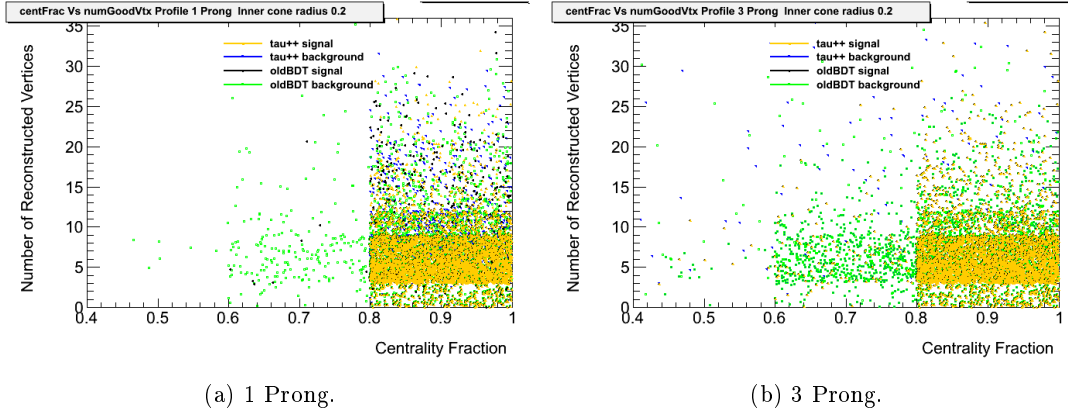


Figure 19: Centrality fraction vs. the number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

three prong plots here is expected, as more of the energy will be in the central cone in one prong decays. The difference between the variables in most of these plots indicates that there is similar performance between the old and new identification methods for three prong decays. Some variables have significant differences between the old and new identification method for one prong decays. However, whilst higher pile-up events are being selected, the identification efficiency is not as badly effected as it was for the older method. This is discussed in the next paragraph. The calorimetric radius variable (Figures 37 and 38) was removed and not used as it showed heavy pile-up dependence and very little discrimination between signal and background.

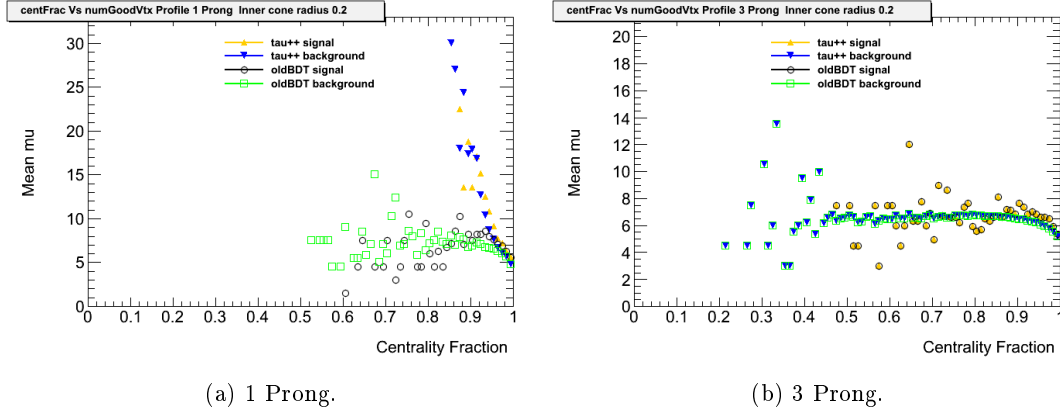


Figure 20: Centrality fraction vs. the mean number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

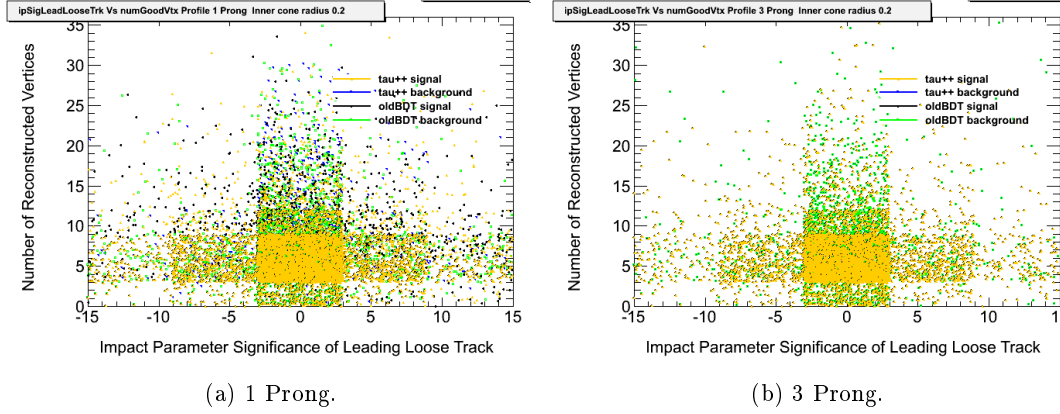


Figure 21: Leading track impact parameter significance vs. the number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

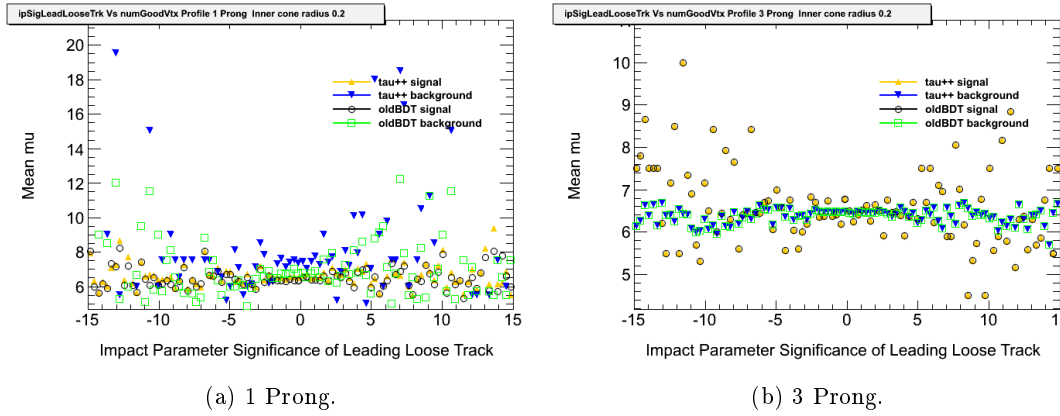


Figure 22: Leading track impact parameter significance vs. the mean number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

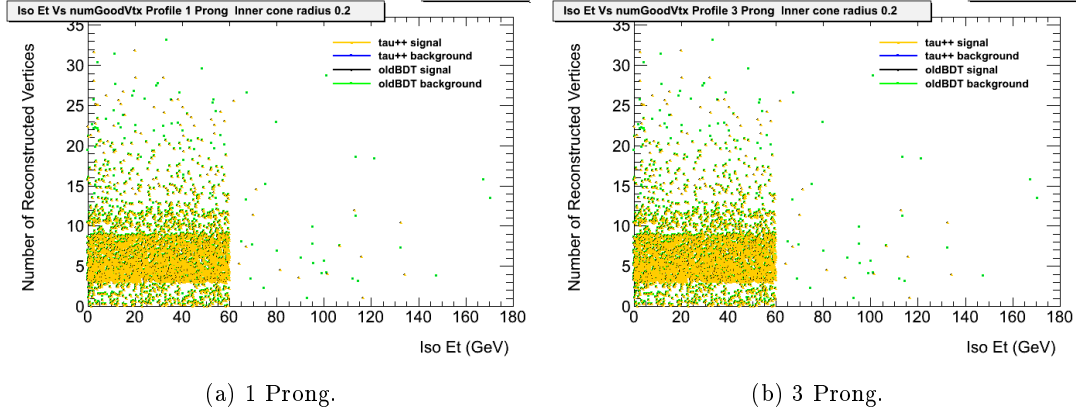


Figure 23: Isolation cone energy vs. the number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

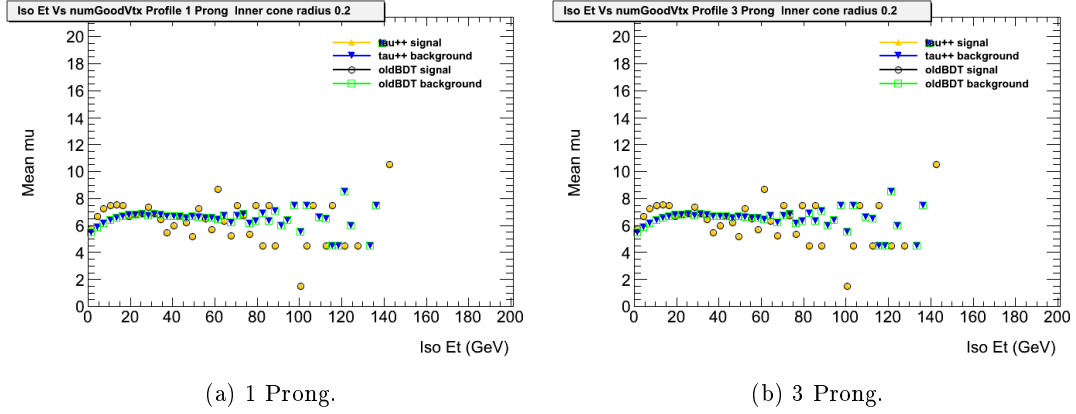


Figure 24: Isolation cone energy vs. the mean number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

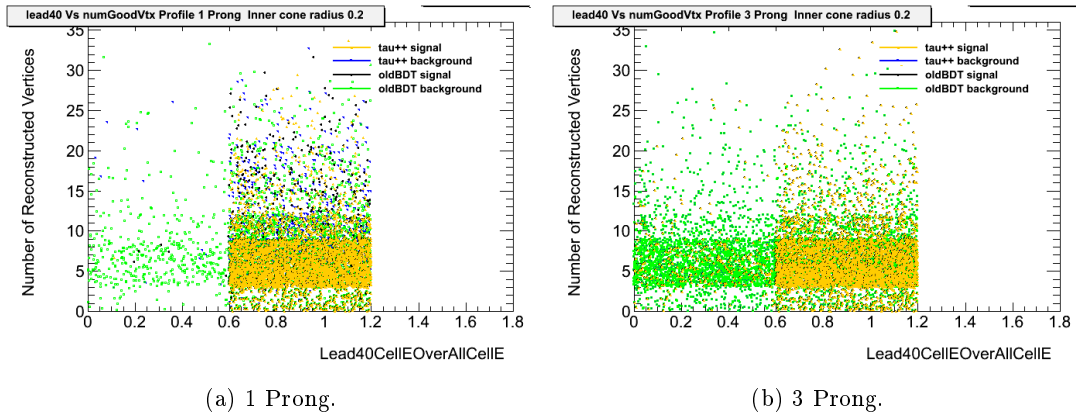


Figure 25: Energy of leading 40 cells as a fraction of energy of all cells vs. the number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

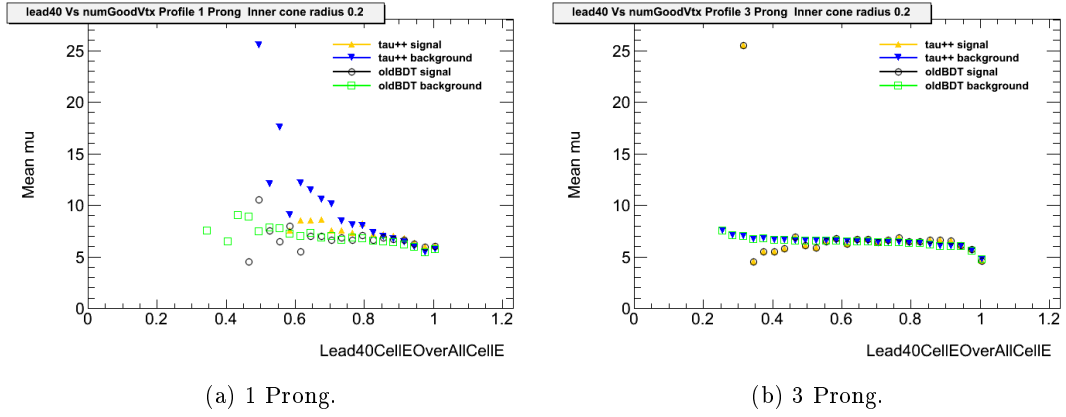


Figure 26: Energy of leading 40 cells as a fraction of energy of all cells vs. the mean number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

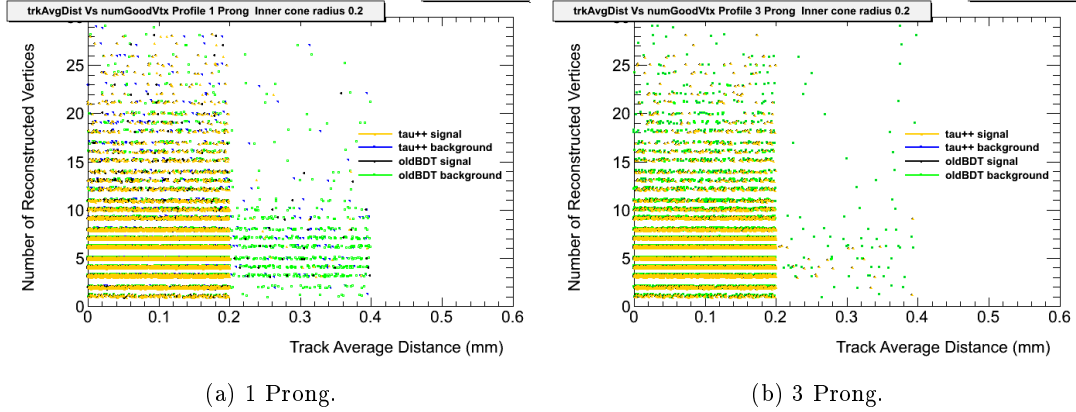


Figure 27: Track average distance vs. the number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

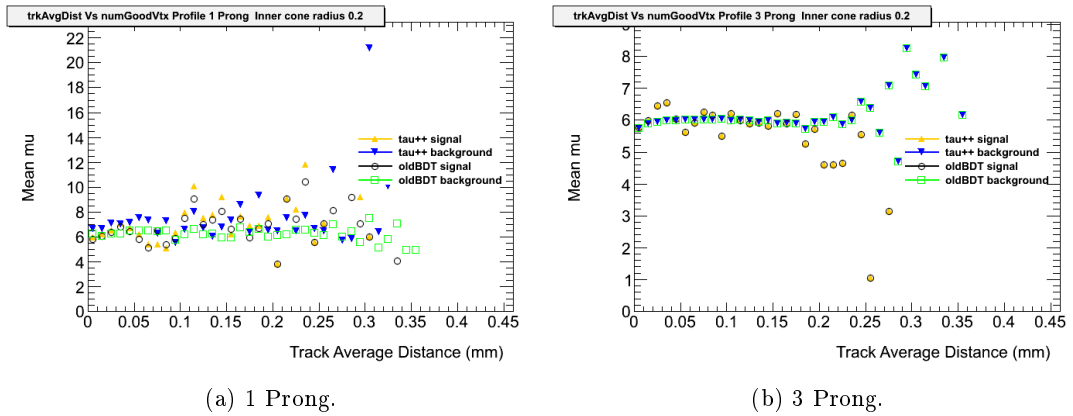


Figure 28: Track average distance vs. the mean number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

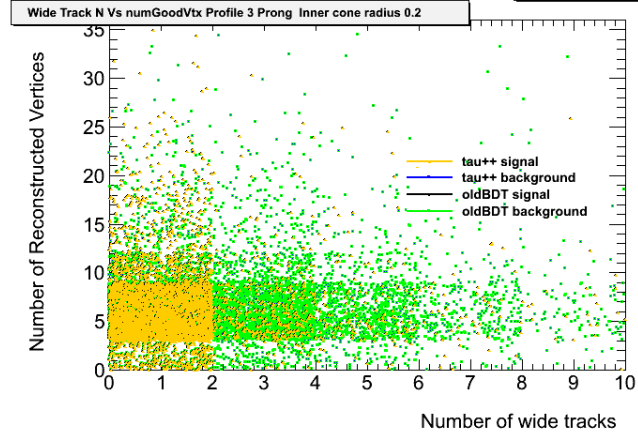


Figure 29: Number of wide tracks vs. the number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

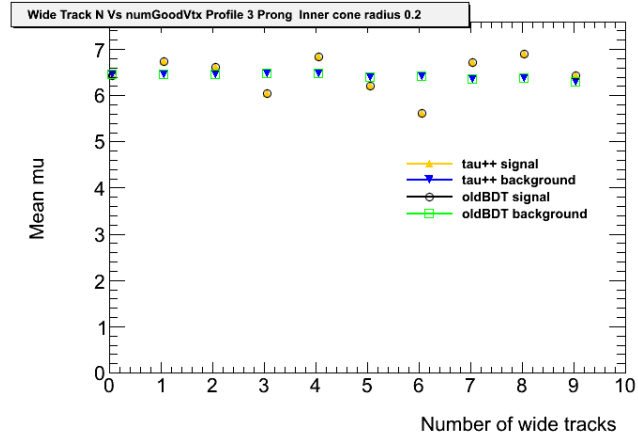


Figure 30: Number of wide tracks vs. the mean number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

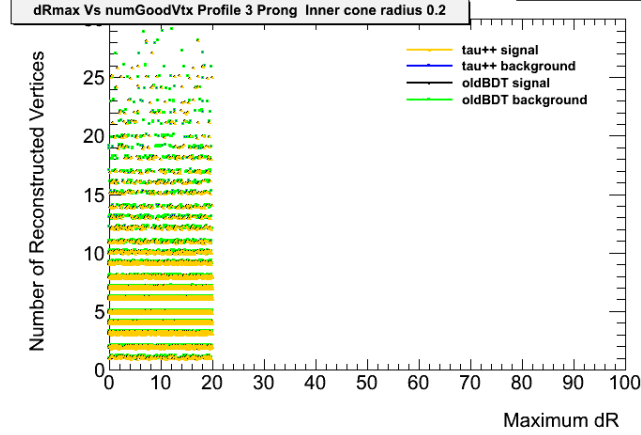


Figure 31: Maximum difference in radius vs. the number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

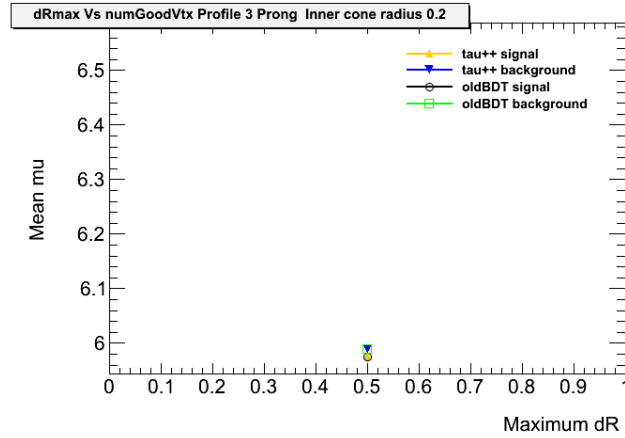


Figure 32: Maximum difference in radius vs. the mean number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

The shrinking cone size showed improved results for a cone size of $\Delta R = 0.2$. This is shown in the efficiency plots in Figures 40 - 43. There was a large improvement in background efficiency over the old variable set, however, for a large portion of this region the signal efficiency was lower. The efficiency is taken from the BDT score vs efficiency graphs produced during the training, shown in Figure 39. For a 50% efficiency the BDT score is taken, and then when selecting signal events with the BDT this is used as a cut to remove background events. This is different for one prong and three prong events. For a given signal efficiency the dependence on the pile-up is plotted. For one prong events a BDT score of 0.8 was used and for three prong events a BDT score of 0.68 was used. The number of events passing for a given number of good vertices (μ) is given as a fraction of all events with that number of vertices. This is shown in Figures 40 - 42. A linear fit was applied to the μ vs. efficiency distributions (see Tables 3 - 6, which can then be corrected for. This showed much better performance for the larger inner cone size of 0.2. A correction factor of $0.033 \times \mu$ was added to the BDT score. This had a large impact on the signal efficiency, bringing it close to linear for high pile-up, as can be seen in Figures 41 and 43. This is shown for the smaller inner radius as well, but there is a worse fit, see Figures 40 and 42.

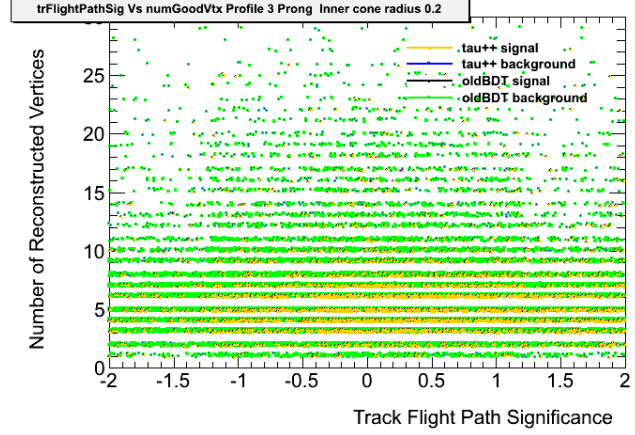


Figure 33: Flight path significance vs. the number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

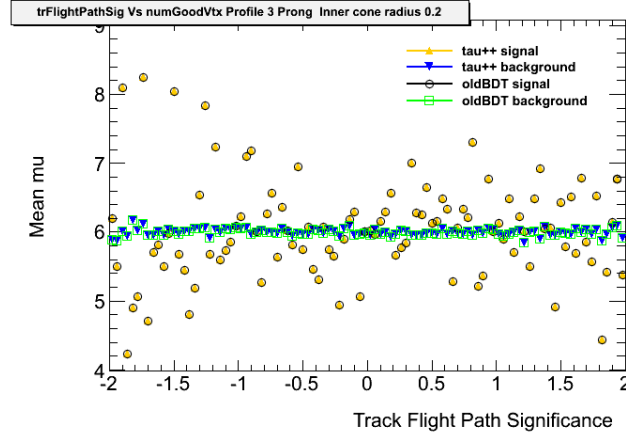


Figure 34: Flight path significance vs. the mean number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

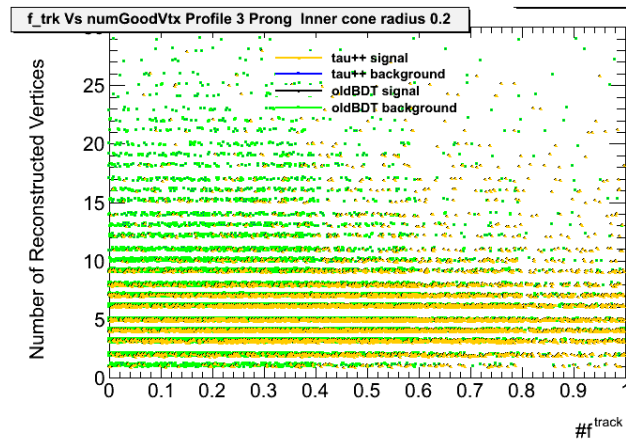


Figure 35: f_{track} vs. the number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

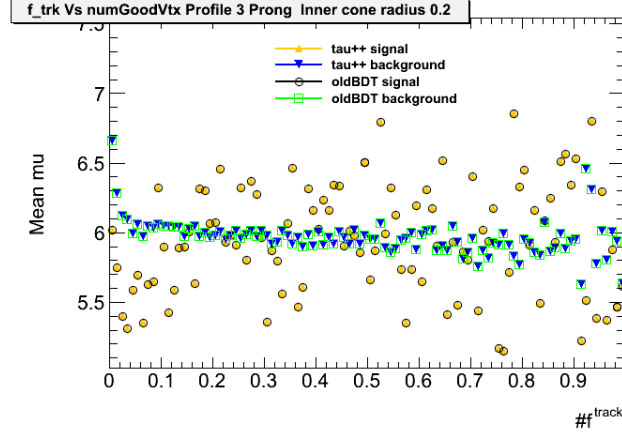


Figure 36: f_{track} vs. the mean number of reconstructed vertices for 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

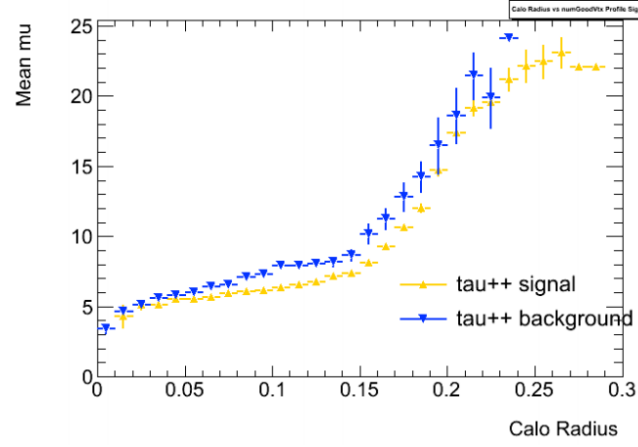


Figure 37: Calorimetric radius for 1 prong taus using the new BDT in a cone of size $0.2 < \Delta R < 0.4$. A strong pile-up dependence is shown here.

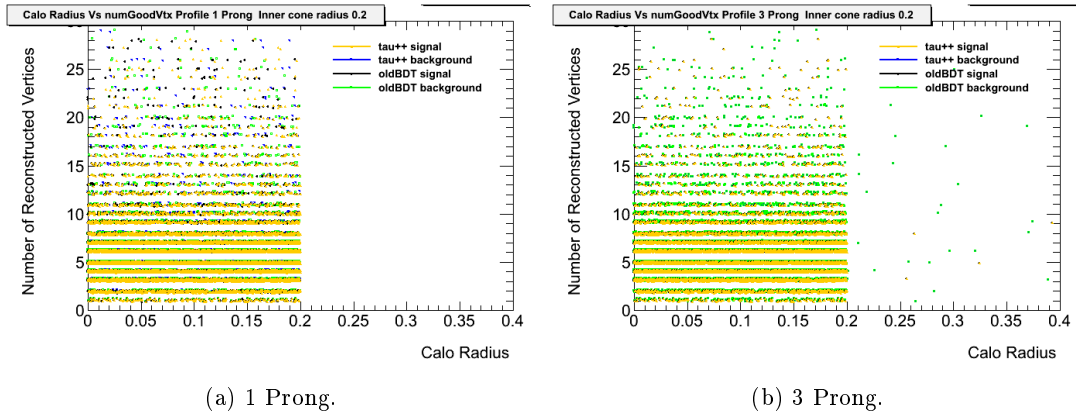


Figure 38: Calorimetric radius vs. the number of reconstructed vertices for 1 and 3 prong taus using the new BDT in a cone of radius $0.2 < \Delta R < 0.4$.

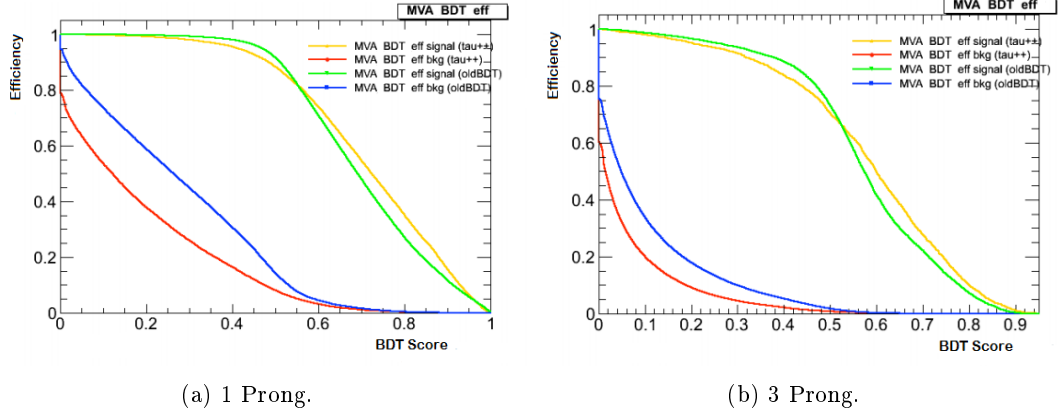


Figure 39: BDT score vs efficiency for signal and background samples for 1 and 3 prong taus in a cone size of $0.2 < \Delta R < 0.4$ from BDT training.

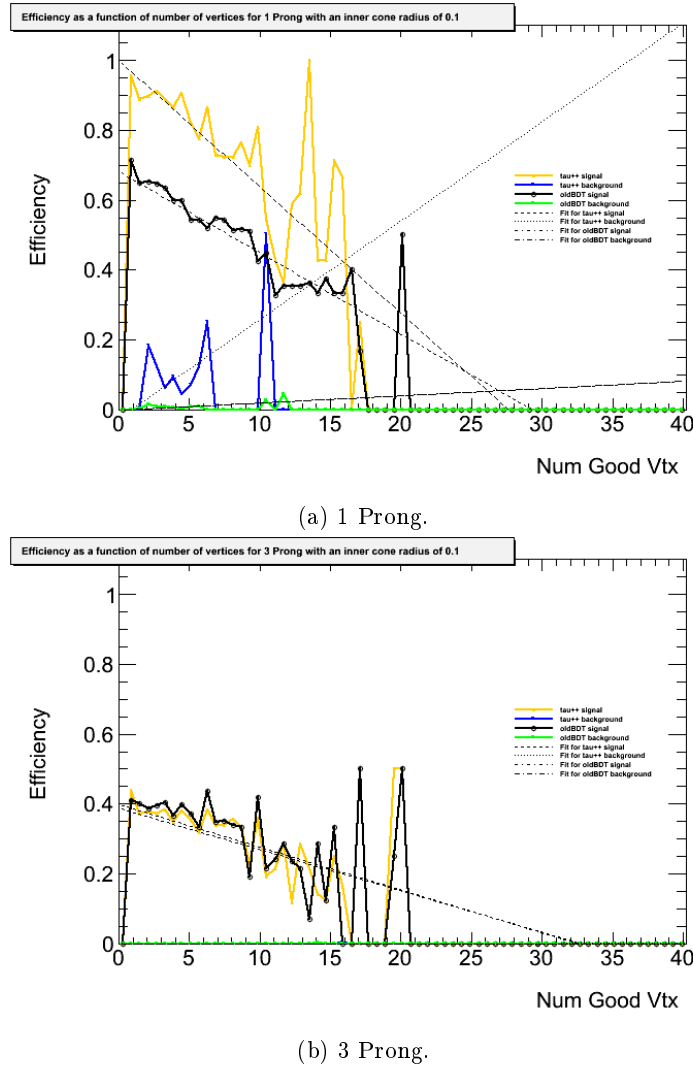
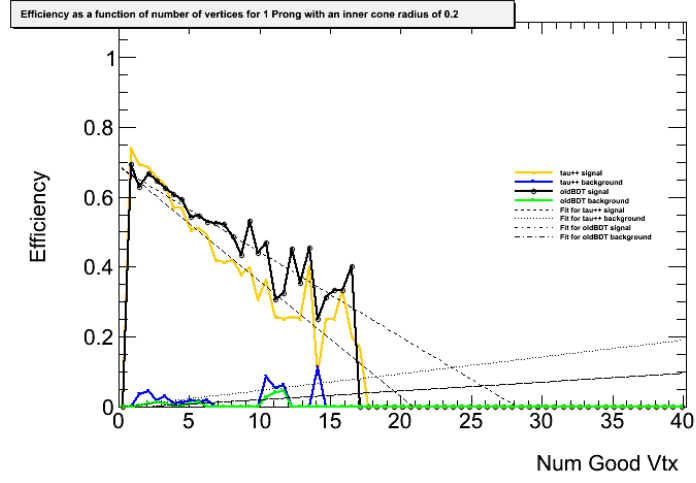
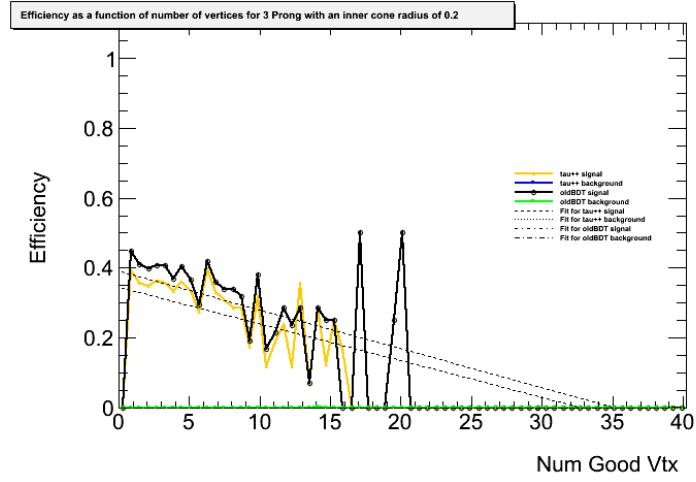


Figure 40: Uncorrected number of reconstructed vertices vs efficiency for tau identification for 1 prong and 3 prong using a cone of $0.1 < \Delta R < 0.4$.

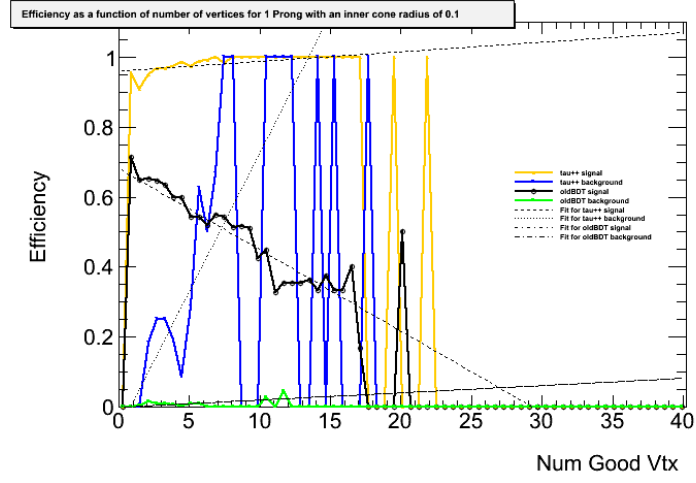


(a) 1 Prong.

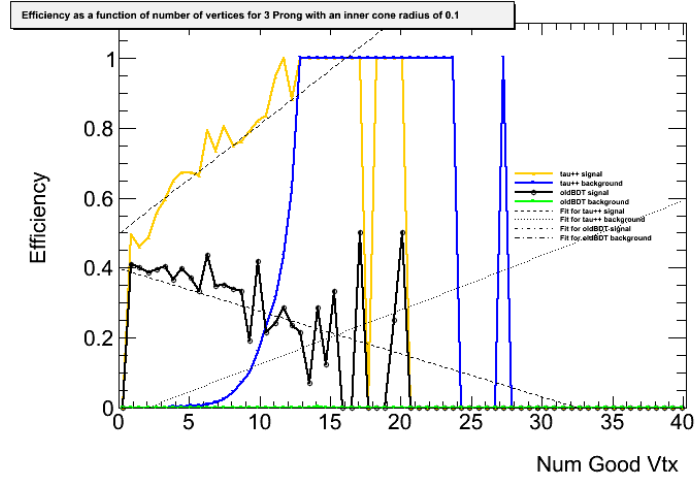


(b) 3 prong.

Figure 41: Uncorrected number of reconstructed vertices vs efficiency for tau identification for 1 prong and 3 prong using a cone of $0.2 < \Delta R < 0.4$.

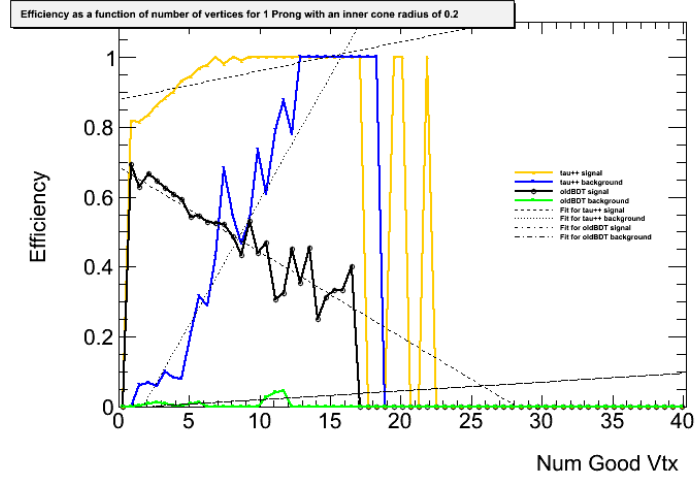


(a) 1 Prong.

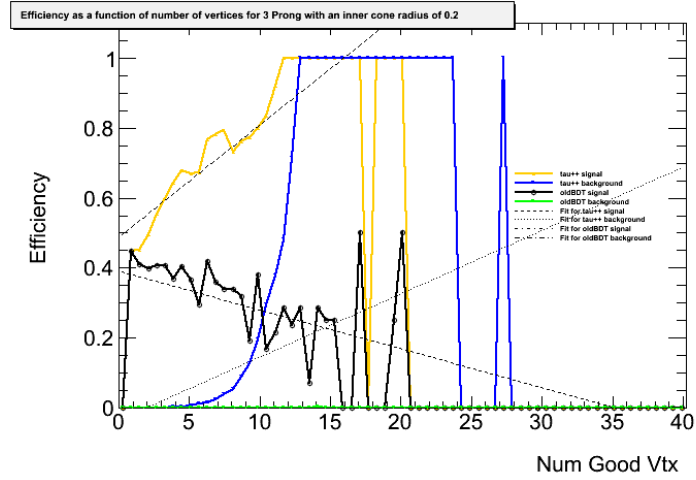


(b) 3 Prong.

Figure 42: Corrected number of reconstructed vertices vs efficiency for the new BDT for tau identification for 1 prong and 3 prong using a cone of $0.1 < \Delta R < 0.4$.



(a) 1 Prong.



(b) 3 Prong.

Figure 43: Corrected number of reconstructed vertices vs efficiency for the new BDT for tau identification for 1 prong and 3 prong using a cone of $0.2 < \Delta R < 0.4$.

Table 3: Linear fits for 1 prong taus using uncorrected BDT score.

Fit for signal sample for 1 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	7.896×10^{-1}	N/A
NDf	25	N/A
p0	9.993×10^{-1}	$\pm 3.586 \times 10^{-1}$
p1	-3.618×10^{-2}	$\pm 3.241 \times 10^{-2}$
Fit for background sample for 1 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	4.183×10^{-1}	N/A
NDf	7	N/A
p0	-2.325×10^{-2}	$\pm 3.363 \times 10^{-1}$
p1	2.824×10^{-2}	$\pm 7.389 \times 10^{-2}$
Fit for signal sample for 1 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	4.751×10^{-1}	N/A
NDf	26	N/A
p0	6.897×10^{-1}	$\pm 2.856 \times 10^{-1}$
p1	-3.308×10^{-2}	$\pm 2.391 \times 10^{-2}$
Fit for background sample for 1 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	1.271×10^{-1}	N/A
NDf	11	N/A
p0	-8.137×10^{-4}	$\pm 9.174 \times 10^{-2}$
p1	4.789×10^{-3}	$\pm 1.639 \times 10^{-2}$

Table 4: Linear fits for 3 prong taus using uncorrected BDT score.

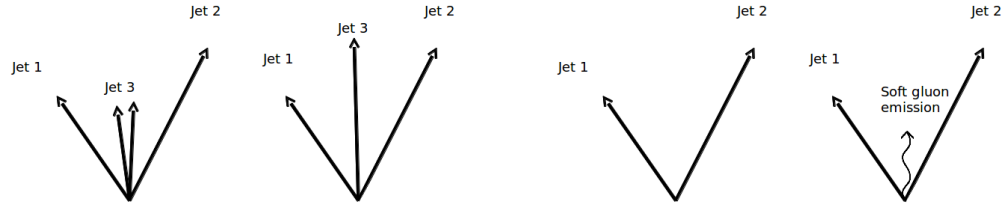
Fit for signal sample for 3 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	8.766×10^{-1}	N/A
NDf	26	N/A
p0	3.875×10^{-1}	$\pm 2.316 \times 10^{-1}$
p1	-1.18×10^{-2}	$\pm 2.056 \times 10^{-2}$
Fit for background sample for 3 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	3.334×10^{-3}	N/A
NDf	15	N/A
p0	1.056×10^{-4}	$\pm 8.9 \times 10^{-3}$
p1	4.196×10^{-5}	$\pm 1.435 \times 10^{-3}$
Fit for signal sample for 3 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	1.276	N/A
NDf	27	N/A
p0	3.449×10^{-1}	$\pm 2.19 \times 10^{-1}$
p1	-1.05×10^{-2}	$\pm 1.904 \times 10^{-2}$
Fit for background sample for 3 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	1.488×10^{-3}	N/A
NDf	13	N/A
p0	1.285×10^{-4}	$\pm 8.998 \times 10^{-3}$
p1	2.316×10^{-5}	$\pm 1.613 \times 10^{-3}$

Table 5: Linear fits for 1 prong taus using corrected BDT score.

Fit for signal sample for 1 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	6.618×10^{-3}	N/A
NDf	28	N/A
p0	9.611×10^{-1}	$\pm 3.653 \times 10^{-1}$
p1	2.734×10^{-3}	$\pm 3.27 \times 10^{-2}$
Fit for background sample for 1 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	1.400	N/A
NDf	16	N/A
p0	-6.469×10^{-2}	$\pm 2.668 \times 10^{-1}$
p1	7.931×10^{-2}	$\pm 4.033 \times 10^{-2}$
Fit for signal sample for 1 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	4.947×10^{-2}	N/A
NDf	29	N/A
p0	8.791×10^{-1}	$\pm 3.458 \times 10^{-1}$
p1	8.288×10^{-3}	$\pm 0.0303 \times 10^{-2}$
Fit for background sample for 1 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	7.391×10^{-1}	N/A
NDf	27	N/A
p0	-1.197×10^{-1}	$\pm 1.462 \times 10^{-1}$
p1	7.116×10^{-2}	$\pm 2.254 \times 10^{-2}$

Table 6: Linear fits for 3 prong taus using corrected BDT score.

Fit for signal sample for 3 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	1.463×10^{-1}	N/A
NDf	30	N/A
p0	4.988×10^{-1}	$\pm 2.889 \times 10^{-1}$
p1	3.121×10^{-2}	$\pm 2.716 \times 10^{-2}$
Fit for background sample for 3 Prong using tau++, cone size 01-04.		
Parameter	Value	Error
χ^2	15.39	N/A
NDf	38	N/A
p0	-3.099×10^{-2}	$\pm 1.748 \times 10^{-2}$
p1	1.558×10^{-2}	$\pm 6.12 \times 10^{-3}$
Fit for signal sample for 3 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	1.675×10^{-1}	N/A
NDf	30	N/A
p0	4.888×10^{-1}	$\pm 2.865 \times 10^{-1}$
p1	3.214×10^{-2}	$\pm 2.703 \times 10^{-2}$
Fit for background sample for 3 Prong using tau++, cone size 02-04.		
Parameter	Value	Error
χ^2	14.66	N/A
NDf	38	N/A
p0	-3.492×10^{-2}	$\pm 1.794 \times 10^{-2}$
p1	1.808×10^{-2}	$\pm 6.566 \times 10^{-3}$



(a) Collinear safe method.

(b) Infrared safe methods.

Figure 44: Collinear safe methods (a) should return Jet 3 as one jet in both situations. Infrared safe methods should return the same two jets even with soft emissions present.

5.5 Jets

Jets are showers of partons in the detector that are reconstructed using the anti- k_t algorithm [111]. This algorithm is discussed below. $\Delta R = 0.4$ was used for the jet reconstruction.

5.5.1 Anti- k_t algorithm

The anti- k_t algorithm is a jet clustering algorithm used to identify jets in hadron colliders. This is one of many sequential recombination clustering algorithms available, but for many reasons this is used in the $\phi \rightarrow \tau\tau$ search. It is both collinear and infrared safe (IRC-safe) [112] and provides well defined conical jets centred around hard particles with only the softer jets having more irregular, complex shapes. These are the main reasons it is used in this analysis. This gives it the advantage of having regular boundaries like cone jet algorithms but includes collinear safety. Where jets overlap the harder jet will be conical and the softer jet is cut off on the edge, or in the case where the two are equal hardness a straight line boundary can be produced. The algorithm gives a good representation of the Underlying Event (UE) which can then be used for calibration with MC samples. The UE refers to all activity in the event that is not a hard scattering process such as beam-beam remnants.

Collinear safety means that the collinear splitting of jets should not alter the overall jet identification. Infrared safety means the jet is not altered by the emission of soft emissions. This is illustrated in Figure 44.

The algorithm works like the k_t [113] and Cambridge/ Aachen [114] algorithms, with a slight change to the distance measurements. The distance measures are defined as

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2},$$

$$d_{iB} = k_{ti}^{2p}.$$

Here i and j are jet candidate indices, $\Delta R_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti} the transverse momentum, y_i the rapidity and ϕ_i the azimuthal angle of particle i . In the anti- k_t algorithm the parameter $p = -1$, whilst it is $p = 0$ for Cambridge/ Aachen and $p = 1$ for the k_t algorithm.

For each particle i (or cluster of energy in the calorimeter) the distance d_{ij} is calculated and vanishes when i is parallel to j or either is soft. The two closest partons are combined into one by adding the momentum. This is called a proto-jet. This is repeated on all of the remaining proto-jets and partons. and continued until all distances are greater than some cut off distance. Once all of the d_{ij} are above this cut-off the remaining objects are jets. The lower this cut-off the more jets will be found.

The algorithm finds the hardest p_T particles first and clusters softer particles around them, due to the definition of the distance parameter d_{ij} where the minimum of the inverse of the p_T is used as a

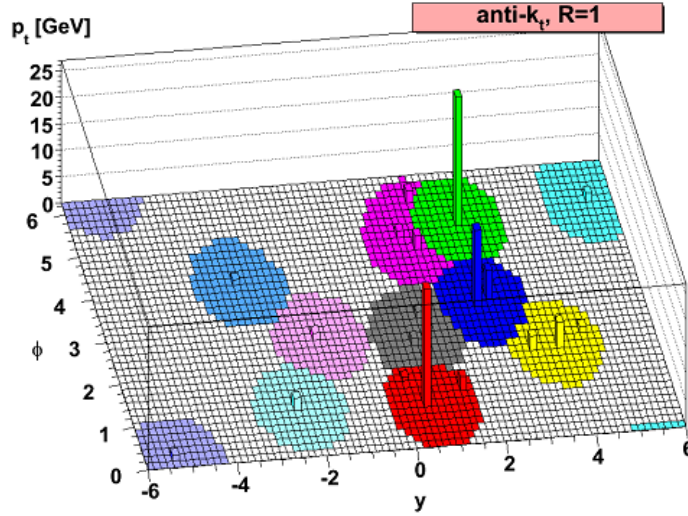


Figure 45: The clustering done with the anti- k_T method produces conical jets with regular boundaries except for the boundaries between two jets of approximately equal momentum [111].

scaling factor. Softer particles are more likely to cluster with hard particles rather than alone which results in conical jets. If there are two hard particles within the same radius and they have $k_{t1} \approx k_{t2}$ the two jets will not be conical and have irregular boundaries. An example is shown in Figure 45.

The jet clustering algorithm is used with topological clusters in the calorimeter [115]. The clusters are calibrated using the p_T and η in MC samples to convert the EM ATLAS calibration to the hadronic scale [116]. Corrections are applied to clusters to account for dead material and energy losses [117].

Jets are required to have $p_T > 20$ GeV and $|\eta| < 2.5$, and to suppress pile-up, jets with $|\eta| < 2.4$ must have $|JVF| > 0.75$ (JVF is described in Section 5.4.2).

Flavour tagging is used to identify b -jets. These are jets produced from the hadronization of a b -quark. The tagger used in this search is the MV1 tagger (discussed under the section on b -jet tagging). A b -jet is identified if the jet has an MV1 tagger score of $\omega_{MV1} > 0.601713$. This working point from this tagger has an efficiency of 70%. The MV1 tagger algorithm is discussed below.

5.5.2 b -Jet Tagging

There are several properties of b -jets which allow them to be distinguished from lighter quark jets. When the b -quark fragments and hadronises the resulting b -hadron keeps about 70% of the original momentum. These b -hadrons will have a large transverse momentum and have a large mass of > 5 GeV. Since b -hadrons have a long lifetime there will be a long flight path length which gives a displaced secondary vertex.

Algorithms used to find b -jets take advantage of these properties by looking for large impact parameters of the tracks, d_0 , from the b -hadron decay products, or by reconstructing the secondary displaced vertices. In both cases a large number of tracks are required to accurately reconstruct the primary vertex as pile-up can cause significant errors. Semi-leptonic decays of b -hadrons can be identified by the reconstruction of a high p_T muon close to the jet axis, or within the jet.

An example of an impact parameter (defined in Section 5.4.2) tagging algorithm is the IP3D algorithm. Here the signed impact parameter significance, as defined above, is calculated for each track. These are combined and weighted depending on the accuracy using Santander matching [118]. The same is done for the signed longitudinal impact parameter significance. Distributions of the two variables are taken from MC and put into a 2-d histogram for both the b -jet and light-jet possibilities. For each discriminating variable a probability is calculated and a likelihood ratio test is used to assign a weight

for each jet. The weight is then defined as

$$W_{jet} = \sum_{i=1}^{N_T} \frac{b(S_i)}{u(S_i)},$$

where N_T is the track, S_i is the discriminating variable, the signed impact or longitudinal parameter significance, and the probabilities for the b -jet and light-jet hypothesis are $b(S_i)$ and $u(S_i)$, respectively. A cut on W_{jet} is placed to identify a b -jet with a given efficiency.

A secondary vertex algorithm used is SV1. This reconstructs the secondary vertex, or the vertex of the b -hadron decay, using the b -hadron and c -hadron decay products. The invariant mass of the tracks associated to the secondary vertex, the ratio of the energy of the tracks to the energy of the entire jet and the number of two-track vertices (two-track pairs forming a good vertex) are used as discriminating variables. A 2-d histogram of the first two variables and 1-d distribution of the last variable are used as the distributions for the b -jet and light-jet hypothesis in a likelihood ratio test as in the IP3D algorithm. Again a weight is assigned to each jet with a given efficiency.

An algorithm which doesn't fall into either of the other categories is the JetFitter algorithm. This finds a common line on which all vertices (primary and b and c -hadron vertices) lie. The positions of the vertices on this line are used to reconstruct the b -hadron flight path. The same discriminating variables used in the SV1 algorithm as well as the flight length significance are used in a likelihood ratio test to obtain a weight for each jet.

The MV1 tagging algorithm is based on a combination of these three b -taggers—IP3D, SV1 and JetFitter+IP3D. An artificial neural network is used to combine all of these using MC truth information as training samples. The weight is assigned as a combination of the individual weights.

A fuller description of these b -tagging techniques is discussed in Ref. [119].

5.5.3 Missing LAr FEB

The Liquid Argon Front End Boards (LAr FEB) in the ATLAS detector are used for interfacing with the liquid argon calorimeter. They are used for amplifying and sampling the signal and then digitising the analogue signal [120]. For part of the data taking period the Liquid Argon Front End Board was not working. Before overlap removal all objects are tested to see if they fall in this region.

All events from the runs where this was an issue were vetoed if jets were found within a rectangle of $\Delta R = 0.2$ ($-0.2 < \eta < 1.6$, $-0.988 < \phi < -0.392$). The jets were required to have $p_T > 20$ GeV, even though in general selection the jets have this requirement at 25 GeV. This reduces mismeasurements from missing energy deposited in the region. The event was also vetoed if the τ_{had} or electron was reconstructed within $\Delta R = 0.1$ ($-0.1 < \eta < 1.55$, $-0.9 < \phi < -0.5$).

5.6 Missing Transverse Energy

Not all decay products are detected and this can appear as missing energy. The energy in the calorimeters and muon detector is summed in the transverse plane to give a visible transverse energy.

The colliding protons do not have a transverse component, so the decay products should have a summed total transverse momenta that disappears. This means that the visible transverse momenta should give the negative transverse momenta of the neutrinos. Corrections are applied for problems with the detector that might cause energy loss. An example of this is the Liquid Argon Calorimeter cryostat walls.

The transverse energy not accounted for by the visible decay products is known as the missing transverse energy, E_T^{miss} .

5.7 Overlap Removal

A reconstructed object can sometimes pass the requirements for more than one type of object. In order to deal with this problem an order of precedence for identification is defined. This is muon, electron, taus and then jets in this order. In this analysis the muon isolation requirements are not enforced for the

overlap removal with electrons and taus and a looser electron identification is used. For muon overlap removal with jets the isolation is kept to identify muons in b -hadron decays.

6 $\phi(= A/H/h) \rightarrow \tau_l \tau_h$

6.1 Introduction

This chapter details the neutral MSSM Higgs boson decaying to a leptonic and hadronic tau. The $A \rightarrow \tau\tau$ process was simulated to model the $\phi \rightarrow \tau\tau$ process.

The analysis was performed at $\sqrt{s} = 7$ TeV with an integrated luminosity of 4.66fb^{-1} . Where the MC samples were of a lower amount of pile-up the events were scaled up by a factor to match the data luminosity.

The signal signature being searched for is one tau decaying leptonically (τ_{lep}) to a muon or electron and one hadronically decaying tau (τ_{had}). Both of these decays are accompanied by neutrinos, creating a large missing transverse energy in the event. Further cuts, as described in section 6.3, below, are done to remove background and take advantage of the expected topology of the decay process.

The code to do this analysis was written in C++ interfacing to ROOT [123] for the analysis of the datasets. Python and ROOT were used for most of the plots done here. Parts of the analysis were run locally, on the Grid, on the LXPLUS batch system and the University of the Witwatersrand (Wits) computing cluster. When the analysis code was run over larger datasets, such as the backgrounds, this was done on the Grid. Smaller scale studies were done on LXPLUS and the Wits cluster. Testing the code on the signal sample was done locally.

In order to make sure the recommendations and object / event selections were done properly a number of research groups involved in the analysis wrote analysis code to do the same selection until the event yields converged. This acceptance challenge was done on the SherpabbAtautaulhMA120TB20 (SHERPA MC generator for the bbA production where two taus are produced and one decays hadronically, one leptonically, for $M_A = 120$ GeV and $\tan\beta = 20$) and the PowHegPythia_ggHtautaulh_MA120TB20 samples (PowHeg with Pythia simulating ggH production at $M_A = 120$ GeV and $\tan\beta = 20$). The results of the acceptance challenge are given in Table 9.

Once a lepton-hadron final state has been reconstructed there are further cuts that can be applied to separate background and signal. Mass reconstruction is one of the key techniques used for this.

6.2 Mass Reconstruction

One of the discriminants to identify the parent particle of the two reconstructed taus, one leptonic and one hadronic, is the invariant mass of the two taus. However, this is not always possible due to the presence of missing energy and the invariant mass can only be estimated. With better sensitivity and resolution of the reconstructed mass, a more reliable and efficient identification of the parent particle becomes available. The invariant mass of the parent particle can be estimated by using a variety of techniques. Three methods are discussed below. In this analysis the Missing Mass Calculator (MMC) [121] is used.

6.2.1 Transverse Mass

The transverse mass refers to the invariant mass of a reconstructed lepton and the E_T^{miss} . It is given by the following equation:

$$m_T = \sqrt{2p_T^{\text{lep}} E_T^{miss} (1 - \cos\Delta\phi)}.$$

The $\Delta\phi$ is between the lepton and the E_T^{miss} . A $\Delta\phi$ of ≈ 0 will give a large m_T since the lepton and E_T^{miss} are perpendicular, whilst a $\Delta\phi \approx \pi$ gives a small m_T since they lepton and the E_T^{miss} are aligned.

Since this method does not take into account the neutrino momenta the reconstructed mass of the system will be broader than it should be, giving decreased sensitivity. However, it can be used effectively to discriminate between QCD jets, signal and $Z \rightarrow \tau\tau$ from W +jets as it has a much higher m_T .

This method can be defined for all events, increasing the statistical power of the analysis.

6.2.2 Visible Mass

This is the easiest method to implement and understand. Only the visible decay products are used to calculate the invariant mass. This has serious shortfalls since this does not make any correction for the missing energy. There will be a large shift in the mass distributions as the invariant mass will always be too low. Further, the resolution of the mass distribution will be very broad and have limited sensitivity. This is denoted m_{vis} .

Both the visible mass and transverse mass are not very effective at separating signal, $\phi \rightarrow \tau\tau$, from the broad $Z \rightarrow \tau\tau$ background which is much larger.

6.2.3 Collinear Mass

This method is a good approximation when the parent particle of the decay products is boosted. The basic assumption is that the tau and its decay products are collinear and that all missing energy is due to neutrinos. Using this assumption, the mass, including the missing energy contribution, can be estimated. The invisible momentum from the neutrinos can be approximated using the following equations:

$$\begin{aligned} E_{T_x}^{miss} &= p_{miss_1} \sin\theta_{vis_1} \cos\phi_{vis_1} + p_{miss_2} \sin\theta_{vis_2} \cos\phi_{vis_2}, \\ E_{T_y}^{miss} &= p_{miss_1} \sin\theta_{vis_1} \sin\phi_{vis_1} + p_{miss_2} \sin\theta_{vis_2} \sin\phi_{vis_2}. \end{aligned}$$

Here $E_{T_x}^{miss}$ and $E_{T_y}^{miss}$ are the x and y components of the missing transverse energy, p_{miss_i} are the invisible momenta, θ_{vis_i} and ϕ_{vis_i} are the polar and azimuthal angles of the visible decay products.

The fraction of visible momentum is given by $x_{1,2} = p_{vis_{1,2}} / (p_{vis_{1,2}} + p_{miss_{1,2}})$. The invariant mass is then calculated using this fraction, $x_{1,2}$, and m_{vis} as $M_{\tau\tau} = m_{vis} \sqrt{x_1 x_2}$.

However, this method only works for a small fraction of $\phi \rightarrow \tau\tau$ events since most of these events will have the taus back to back, leaving the above equations degenerate. In addition, the invariant di-tau mass often gets over estimated, leaving long tails in the mass distribution. Full details can be found in reference [122].

6.2.4 Missing Mass Calculator

This method provides improved invariant mass and neutrino momentum resolutions over the collinear mass approximation, without the angular limitations on the decay products. This is a method only recently used for this analysis.

The assumptions used here are perfect detector resolution and that all missing energy is from neutrinos, and these neutrinos are only from $\tau\tau$ decays.

The unknowns in the decay — the components of the neutrino's momentum for each tau in the event and the invariant mass of the neutrinos from each leptonic tau decay — are represented by four equations:

$$\begin{aligned} E_{T_x}^{miss} &= p_{miss_1} \sin\theta_{miss_1} \cos\phi_{miss_1} + p_{miss_2} \sin\theta_{miss_2} \cos\phi_{miss_2}, \\ E_{T_y}^{miss} &= p_{miss_1} \sin\theta_{miss_1} \sin\phi_{miss_1} + p_{miss_2} \sin\theta_{miss_2} \sin\phi_{miss_2}, \\ M_{\tau_1}^2 &= m_{miss_1}^2 + m_{vis_2}^2 + 2\sqrt{p_{vis_1}^2 + m_{vis_1}^2} \sqrt{p_{miss_1}^2 + m_{miss_1}^2} - 2p_{vis_1} p_{miss_1} \cos\Delta\phi_{\nu m_1}, \\ M_{\tau_2}^2 &= m_{miss_2}^2 + m_{vis_1}^2 + 2\sqrt{p_{vis_2}^2 + m_{vis_2}^2} \sqrt{p_{miss_2}^2 + m_{miss_2}^2} - 2p_{vis_2} p_{miss_2} \cos\Delta\phi_{\nu m_2}, \end{aligned}$$

where $E_{T_x}^{miss}$, $E_{T_y}^{miss}$, $p_{vis_{1,2}}$, $m_{vis_{1,2}}$, $\theta_{vis_{1,2}}$ and $\phi_{vis_{1,2}}$ have the same meanings as in the collinear mass approximation, $M_\tau = 1.777 \text{ GeV}/c^2$, and the rest are unknowns—the missing neutrino momenta, $p_{miss_{1,2}}$, and the invariant mass of the neutrinos, $m_{miss_{1,2}}$. $\Delta\phi_{\nu m_{1,2}}$ is the angle between p_{miss} and p_{vis} for each tau lepton.

The system of equations is under-constrained so tau decay kinematics are used to find more likely solutions. This additional knowledge is applied by using probability density functions in a globally defined event likelihood. These are calculated using MC simulations of tau decays. Different parameters can be parameterised and fitted to give the probability of a particular tau topology. An example of this would be $\Delta R = \sqrt{(\eta_{vis} + \eta_{mis})^2 + (\phi_{vis} - \phi_{mis})^2}$ for each type of decay topology (1, 3 prong, etc.).

The log-likelihood is defined as:

$$L = -\log(P(\Delta R_1, p_{\tau 1}) \times P(\Delta R_2, p_{\tau 2})).$$

Where P are probability functions defined for different decay types. Each point in the parameter space that is scanned has L calculated and the best value is chosen. The mass of the di-tau system, $m_{\tau\tau}$, is then taken from the probability functions.

6.3 Event Selection

All objects – electrons, muons, taus and jets, must pass the object selection requirements and overlap removal.

6.3.1 Triggers

Triggers are applied as simple and robust methods to find events where there are electrons with $p_T > 25$ GeV or muons with $p_T > 20$ GeV.

6.3.2 Good Runs List

When running over an event it must be checked to see if it was during a physics run where there were no problems with the detector. A physics run is defined as a period during which maximal energy is reached with beam collisions with the luminosity optical configuration (powering of the LHC magnets such that they are in a configuration to maximise luminosity). The Good Runs List checks for problems with the detector in a single luminosity block.

6.3.3 Vertex Requirements

A primary vertex with at least four tracks is required. This ensures that the vertex is well described and the position well known.

6.3.4 Event Cleaning

Jet cleaning is done to remove jets that are in bad regions of the detector or noise bursts and data integrity errors.

6.3.5 Lepton Selection

Exactly one light lepton (electron or muon) passing the object selection requirements and the trigger is required. The momentum requirements are an electron with $p_T > 25$ GeV or muon with $p_T > 20$ GeV. The requirement of no more than one lepton suppresses background contributions from $Z \rightarrow ee, \mu\mu, t\bar{t}$ and Wt where there can be multiple electrons or muons.

6.3.6 Tau Identification

Exactly one reconstructed hadronic tau is required. This hadronic tau must have the opposite charge of the selected electron or muon in the event.

6.3.7 Transverse Mass

The cut on the transverse mass is $m_T \leq 30$ GeV. This reduces contamination from W +jets and $t\bar{t}$ processes where there is a large m_T (see Figure 46). This is because the angle between the τ and ν_τ in these decays will be large, giving a very large m_T . This is illustrated in Figure 47.

6.3.8 b -Jet Cut

After passing the above selection criteria the analysis is split into two categories, one where the leading p_T jet is identified as a b -jet and one where it is not. Only one of these cuts is applied.

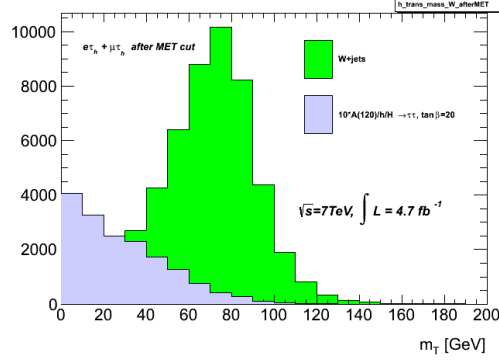


Figure 46: The m_T in the W background sample (after normalisation) and the Sherpa signal sample for $m_A = 120$ GeV at $\tan\beta = 20$. The cut at 30 GeV provides good rejection of the W background.

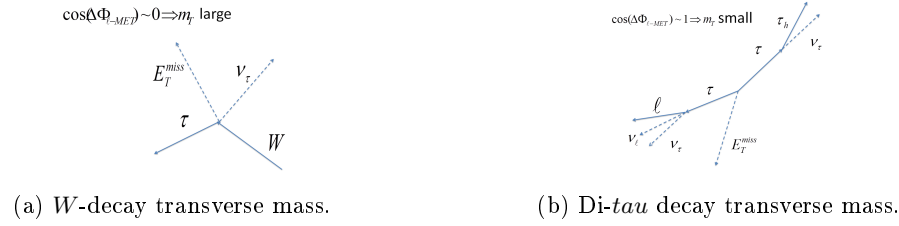


Figure 47: The calculation of the transverse mass is shown for a) W decays and b) di- τ decays. m_T is higher for W decays.

b -Jet Veto This category contains events where the leading p_T jet is not identified as a b -jet.

b -Jet Requirement This category includes events where the leading jet has $20 < p_T < 50$ GeV and is identified as a b -jet. This reduces background contamination from top decays where the b -jets typically have a large transverse momentum. This is illustrated in Figure 48.

Only one b -jet is required. If there is a second b -jet in the event it will most likely be a very soft jet.

6.3.9 Missing Energy

A restraint is placed on the missing transverse energy in the event for the b -vetoed analysis. This removes contamination from QCD jets, where there will be fake hadronic taus with, in general, less E_T^{miss} than in true hadronic decays where there is a lot of missing energy due to neutrinos. The cut here was $E_T^{\text{miss}} > 20$ GeV.

There is no cut on the b -tagged analysis since the b -jet ensures less QCD contamination already.

6.3.10 Mass Reconstruction

Due to the large amount of missing energy in di-tau decays a good mass reconstruction method is needed with good mass resolution. For this the Missing Mass Calculator was used to reconstruct the mass. This is slower computationally than the other methods, but it provides better mass resolution. In most cases the algorithm will converge and give a good reconstructed mass. It is possible that this does not happen and it doesn't converge, however, and some of the events are lost, on average $\approx 1\text{-}3\%$ [121]. This is used as the final discriminating variable in the di-tau reconstruction.

6.4 Backgrounds

The different backgrounds are described here. The main background is $Z/\gamma^* \rightarrow \tau^+\tau^-$ (where the $*$ indicates an off-shell or virtual particle), with significant contributions from $W \rightarrow e\nu/\mu\nu + \text{jets}$ due to

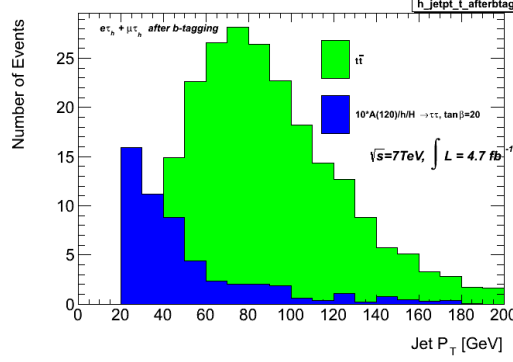


Figure 48: The p_T of the identified b -jet in the $t\bar{t}$ MC sample (after normalisation) and the Sherpa signal sample for $m_A = 120$ GeV at $\tan\beta = 20$. The cut at 50 GeV should provide good rejection of the $t\bar{t}$ background.

the large cross section. The cross sections can be found in Appendix A.

6.4.1 QCD multi-jet

Di-jet events are produced through QCD interactions at a much higher rate than the signal events. This large difference in cross section can contaminate the signal region even though the signature might be very different from the signal. QCD jets can contaminate the signal region if they are misidentified as hadronic taus.

6.4.2 $W \rightarrow e\nu/\mu\nu + \text{jets}$

This process has a large cross section, and when combined with the charged lepton and missing transverse energy in the decay, as well as hadronic jets in the decay that fake hadronic taus, this can create a significant background.

6.4.3 $Z/\gamma^* \rightarrow e^+e^-/\mu^+\mu^- + \text{jets}$

These decays, or Z boson and Drell-Yan events with lepton pairs can contribute to the background if one of the leptons or a jet is misidentified as a hadronic tau. The rate at which leptons fake taus is much lower than the rate at which jets fake taus. The vetoes for fake taus from leptons have very high efficiencies of over 90%.

6.4.4 $Z/\gamma^* \rightarrow \tau^+\tau^- + \text{jets}$

This is the largest background for this analysis and is largely irreducible. The reconstructed mass could be used as a discriminant, provided that the Higgs mass is not too low and the tail from the Z mass distribution is not too long.

6.4.5 $t\bar{t}$ production

Decays of $t\bar{t}$ to $W^-bW^+\bar{b}$ provides a complex background process. Events may contain a real electron or muon from leptonic W decays ($W \rightarrow e\nu$, $W \rightarrow \mu\nu$, $W \rightarrow \tau\nu \rightarrow e/\mu + 3\nu$), and also real hadronic tau decays from $W \rightarrow \tau_{had} + 2\nu$. In a significant fraction of events, the W -boson decays hadronically and one of the jets is reconstructed incorrectly as a hadronic tau decay. Neutrinos accompanying leptonic W -decays and tau decays provide missing transverse energy in the event.

Additionally, the presence of b -jets can add a background for the b -tagging methods. b -jets produced from $t\bar{t}$ decays are generally much harder than those produced in $\phi \rightarrow \tau\tau$ decays, so a cut on the b -jet p_T can reduce this background.

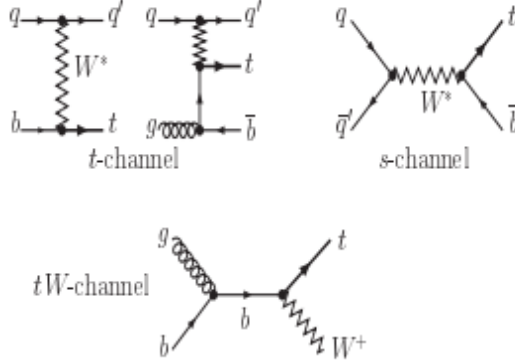


Figure 49: Feynman diagrams for the t , s and tW single top production mechanisms.

6.4.6 Single top production

A single top produced in association with a W boson contributes when the W decays leptonically and a hadronic jet is misidentified as a tau.

This happens in two channels. The s -channel refers to when a W -boson decays into a top and anti-bottom quark. The t -channel refers to when a bottom quark exchanges an up or or down quark with a W -boson and produces a top quark. Further, there is the tW channel where a b quark decays to a W -boson and a top. These are shown in Figure 49.

6.4.7 Diboson production

WW , WZ and ZZ pairs can give final states with a number of charged leptons and jets that fake taus and contribute to the background.

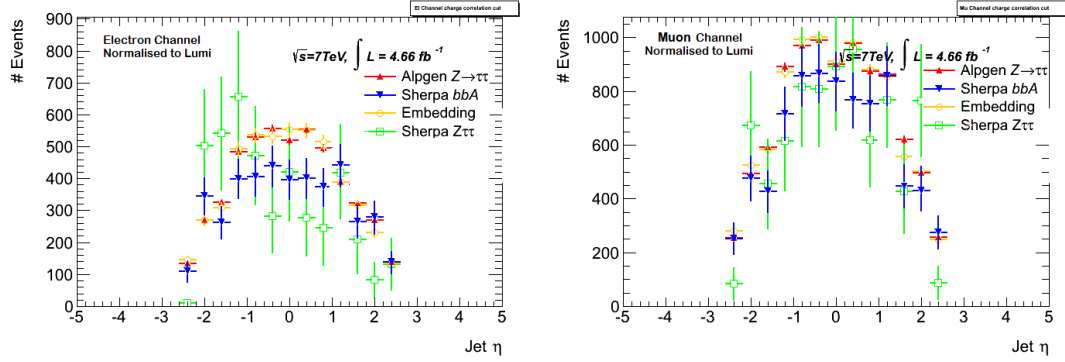
6.5 Monte Carlo Signal Samples

The generators used for the signal sample are described in Section 4. As three different generators were being used to describe di-tau decays, Alpgen, Sherpa and embedded, a cross check was done between all three to check that the shapes of the distributions were consistent with each other. The Embedding method had to be normalised to the Alpgen $Z \rightarrow \tau\tau$ sample as the cross section was not reliably known. Some of the distributions are shown in Figures 50—56. As can be seen, there is generally very good agreement in the shapes. However, in the b -tagged regions the statistics become much lower and the distributions start to show disagreement. This is due to the low statistics. The η distributions show strange behaviour in the Sherpa $Z \rightarrow \tau\tau$ sample, however, the signal sample does not suffer from these problems. The Sherpa $Z \rightarrow \tau\tau$ sample was not used but was used as a check to see how this deviated from the other samples. The samples show better agreement after being normalised to luminosity than to unity. This is most likely just a scale issue, but the shapes can be better compared using the plots normalised to unity.

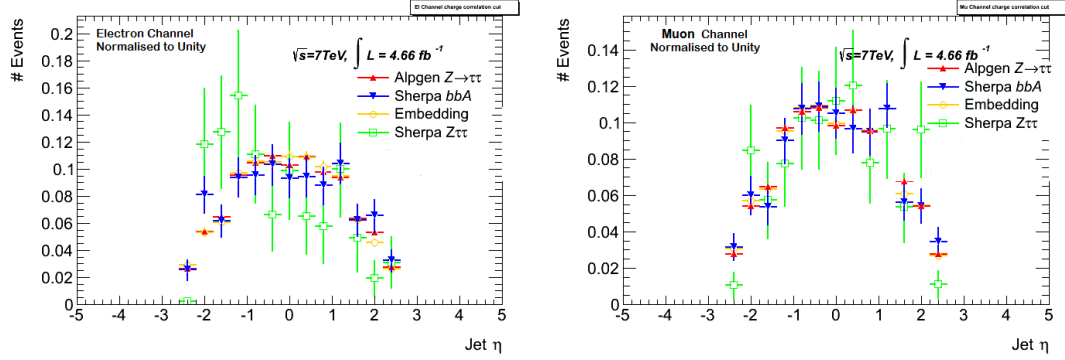
The Sherpa signal samples were enriched with b - and c -jets to increase the sensitivity of the b -tagging methods. The events where this was the case were scaled by a factor to get the cross section in line with the rest of the events.

6.6 Monte Carlo Background Samples

For most of the backgrounds the samples were simulated. These are listed in Section 4. For some of them a data-driven method was necessary since there were not enough statistics available in the simulated

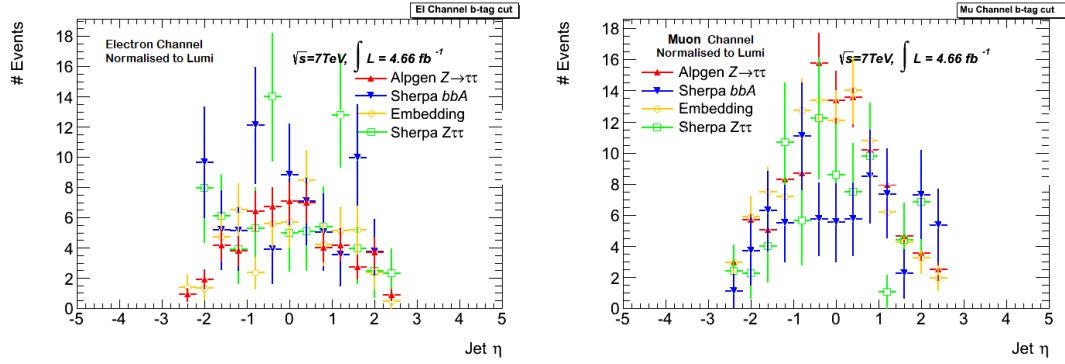


(a) Normalised to luminosity.

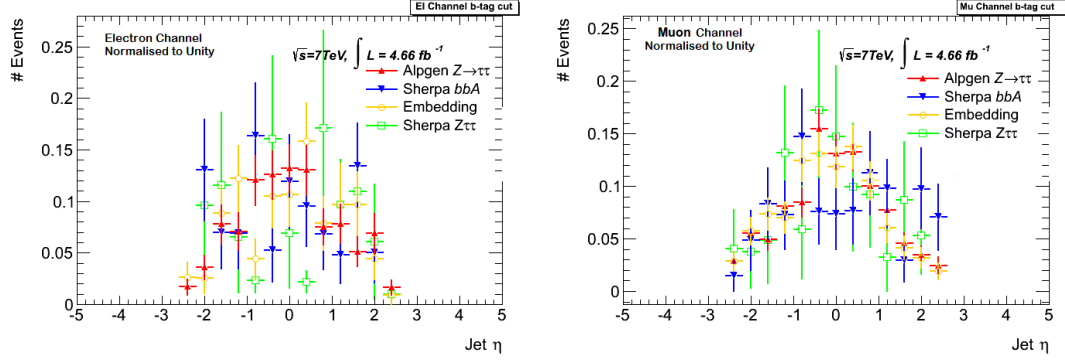


(b) Normalised to unity.

Figure 50: The jet eta distributions after the charge correlation cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right.

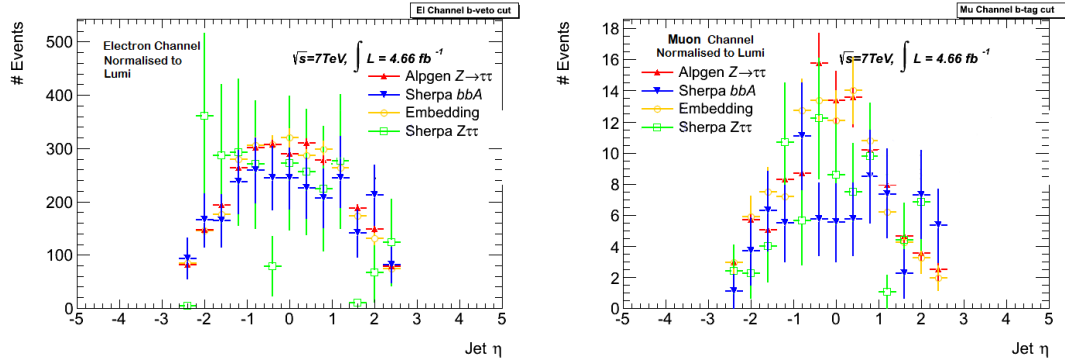


(a) Normalised to luminosity.

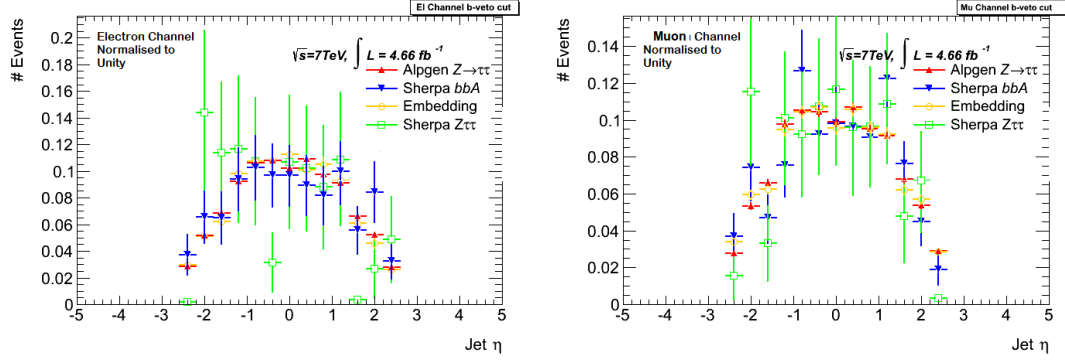


(b) Normalised to unity.

Figure 51: The jet eta distributions after the b -tagged cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right



(a) Normalised to luminosity.



(b) Normalised to unity.

Figure 52: The jet eta distributions after the b -veto cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right

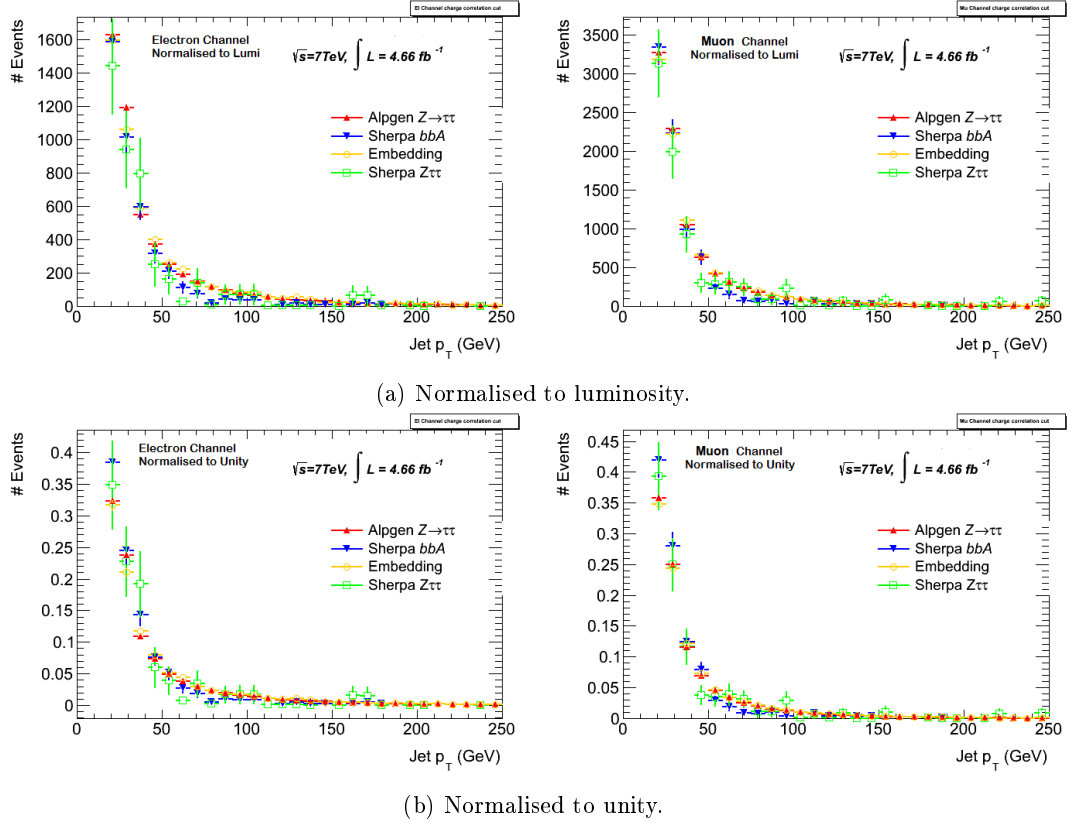


Figure 53: The jet p_T distributions after the charge correlation cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right

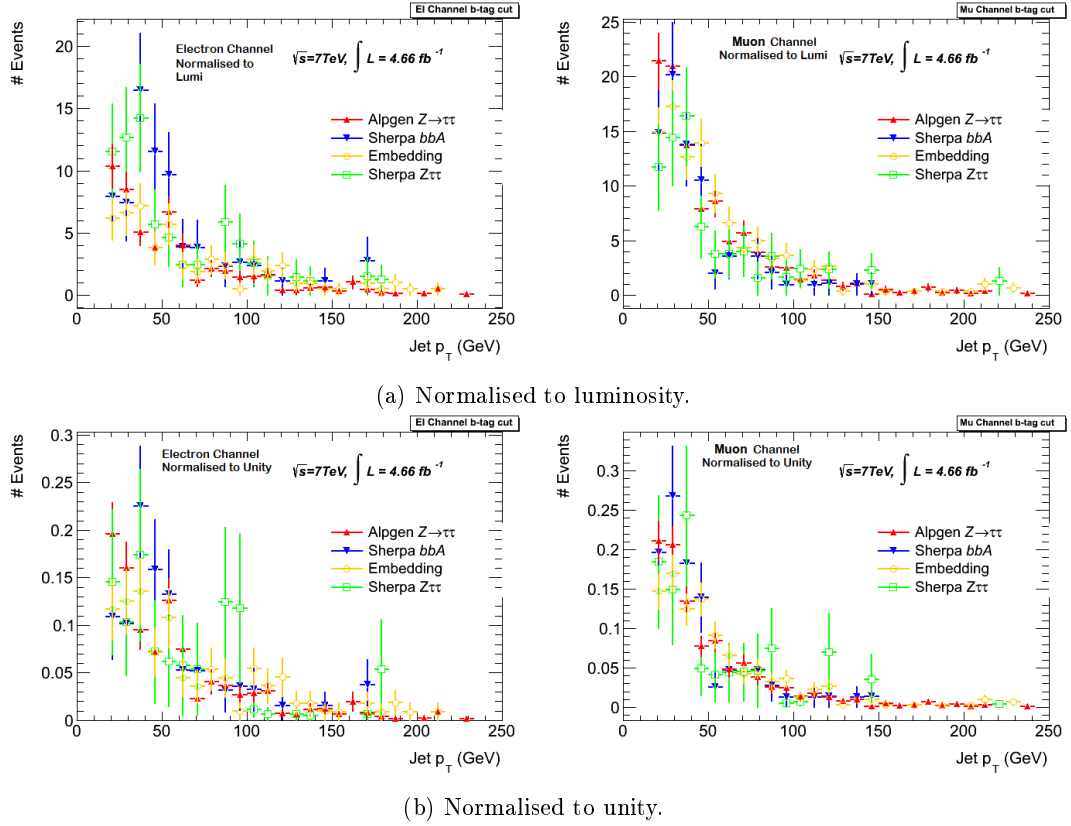
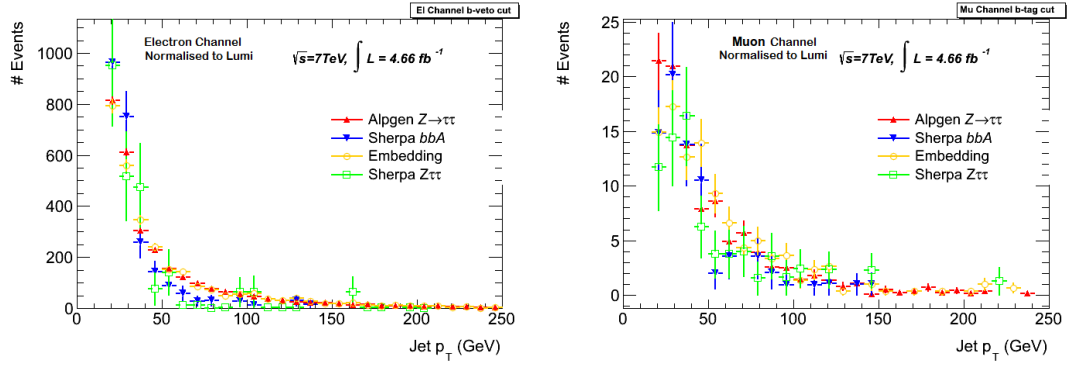
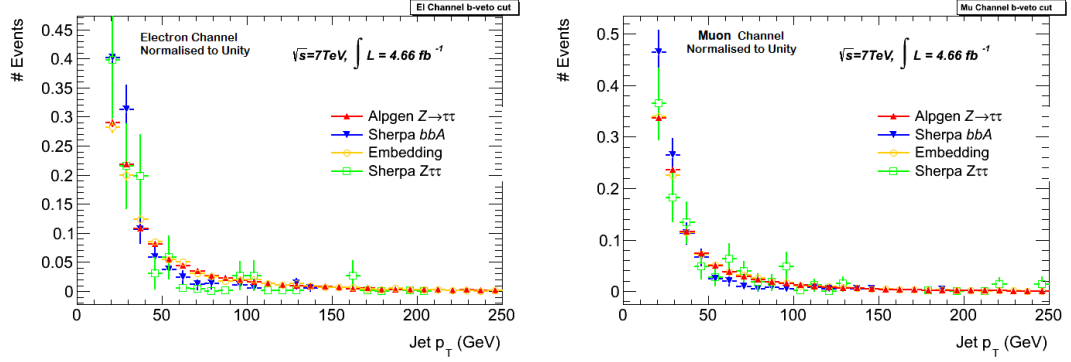


Figure 54: The jet p_T distributions after the b -tag cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right

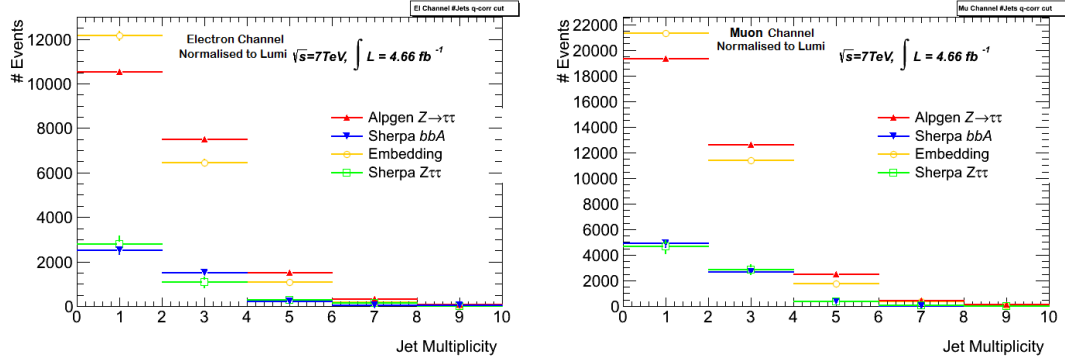


(a) Normalised to luminosity.

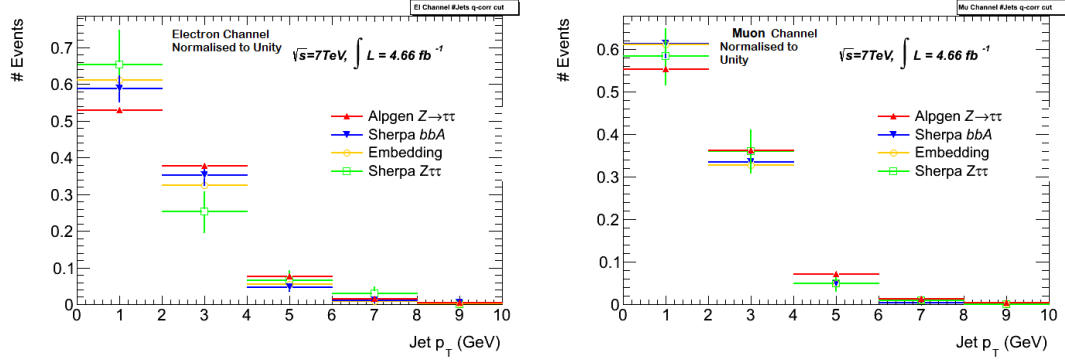


(b) Normalised to unity.

Figure 55: The jet p_T distributions after the b -veto cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right



(a) Normalised to luminosity.



(b) Normalised to unity.

Figure 56: The jet multiplicity distributions after the charge correlation cut normalised to luminosity a) and unity b) for Sherpa, AlpGen and embedded di-tau samples. The electron channel is shown on the left and the muon channel on the right

samples. The data-driven backgrounds are discussed in this section. The systematic uncertainties for the data-driven backgrounds are described in Section 7.

6.6.1 $Z \rightarrow \tau\tau$

As discussed in Section 4, the tau embedded $Z \rightarrow \mu\mu$ is normalised to the Alpgen $Z \rightarrow \tau\tau$ sample.

Comparisons between SHERPA, ALPGEN and Embedding are shown in Figures 50–56. A cross-check of the simulated $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ samples was done to check the b -jet properties. Since the embedded sample comes directly from data and the jet activity in the process is the same for all $Z \rightarrow ll$ decays (where l represents either an electron or muon), the ratio of b -jets in the embedded and Alpgen $Z \rightarrow \tau\tau$ are compared to give a correction factor to be applied to the embedded event yields after the b -jet requirement.

The correction factors found were $f_{Zb}^e = 1.08 \pm 0.23$ and $f_{Zb}^\mu = 1.11 \pm 0.13$ for the electron and muon channels respectively [90].

6.6.2 W +jets

These backgrounds are estimated using ALPGEN. However, simulation has been shown to overestimate the jet to tau fake rate [124] contribution. Jets are not simulated well enough to describe the jet to tau fake rate. The simulated method only allows up to five jets.

A control region in data is used to find a normalisation factor. W +jets events generally have a high m_T (see section 6.2.1) and this knowledge is used to create a control region with a high purity of W +jets events. Here this control region was set up so that $70 \text{ GeV} < m_T < 110 \text{ GeV}$ with the W mass in this middle of this region.

The normalisation factor is calculated by using the ratio of W +jets events in the data control region to the number found in the MC samples. Since the control region cannot be guaranteed to be completely pure an estimate of the number of other events is subtracted from the control region using MC samples. The MC samples of other processes are used for this purpose. The factor is then defined as:

$$f_W^l = \frac{n_{data}^{CR} - n_{rest MC}^{CR}}{n_{W MC}^{CR}}.$$

This is done separately for the electron and muon streams. This correction factor is applied to all W +jet MC events passing the cuts in the signal region. The normalisation factors were found to be $f_W^e = 0.587 \pm 0.009$ and $f_W^\mu = 0.541 \pm 0.008$ with statistical uncertainty quoted [90].

The systematic uncertainties come from the jet energy scale variation and the b -jet identification. The jet-to-tau fake rate is dependent on the quark flavour, thus b -tagged events will have a different jet to tau fake rate that is accounted for as a systematic uncertainty. Furthermore, there are correction factors due to the systematic uncertainties in the MC samples used to subtract the non- W contribution in the control region.

6.6.3 QCD multi-jet

The QCD background is difficult to model since the high cross-section and low selection efficiency means that the number of events needed to get enough statistics would be impractical to simulate for an integrated luminosity of 4.66 fb^{-1} . The cross section for the QCD multi-jet background is many magnitudes higher than the signal process so a data-driven technique to estimate the QCD jet contamination is therefore essential. In addition, the jet-to-tau fake rate is overestimated in simulation.

A sideband extrapolation method, the ABCD method [125], is used to extrapolate the number of events in a sideband to the signal region. Multiple control regions are used to correct for the first sideband having a different shape to the signal region.

Two uncorrelated variables for the QCD background are used to define a signal region and three other control regions. The charge correlation and lepton isolation are used as the identification variables [126]. All of the event selection criteria are applied as described in Section 6.3, except the events are then split on the charge correlation, opposite sign (OS) or same sign (SS), and lepton isolation. There are four subsets of events used illustrated in Table 7.

	Isolated Lepton	Inverted Isolated Lepton
OS	A(Signal)	B
SS	C	D

Table 7: Signal and control regions used for the ABCD method for QCD background estimation. These are based on the charge correlation and isolation of the leptons in the event.

The QCD contribution to regions B, C and D are estimated using data and subtracting contributions to this region from other processes simulated with MC. A similar method to that used to define the normalisation factors for the $t\bar{t}$ and W +jets control regions is used to find the estimated number of events in the signal region, A. This is done separately for the b -tagged and b -vetoed analyses. The estimated number of events is given by:

$$n_A^{QCD} = n_C \frac{n_B}{n_D} \equiv r_{B/D} n_C.$$

Where the ratio of event yields between regions A and B is assumed to be the same as the ratio between regions C and D. This assumes the ratio of opposite to same sign event yields is the same whether for both isolated and un-isolated leptons, which is based on the identification variables being uncorrelated for the background.

6.6.4 $t\bar{t}$

As for the W +jets region the jets are not simulated well and this leads to an overestimation of jets being misidentified as taus. This is particularly important for this search since there is a b -jet requirement, which will pick up contamination from $t\bar{t}$. Again as in the W +jets region a control region is defined to calculate a normalisation factor to apply to the MC simulations.

The b -jets produced in $t\bar{t}$ events will be of a much higher p_T than in the signal region, so a control region can be defined in which there is a high p_T requirement for any identified b -jets. The region used here for the b -jet is $50 \text{ GeV} < p_T < 150 \text{ GeV}$. A second b -jet is also required to further enhance the purity of the control region. A second b -jet coming from any signal processes will be soft and is unlikely to be identified as a b -jet. The m_T cut is not applied to increase the statistics.

A similar definition as used for the W -jets normalisation is used for the normalisation factor for this control region:

$$f_{t\bar{t}} = \frac{n_{data}^{CR} - n_{rest}^{MC}}{n_{W}^{CR}}.$$

The correction factor was measured to be $f_{t\bar{t}} = 0.88 \pm 0.04$ [90].

Systematic uncertainties are due to MC samples used for the non- $t\bar{t}$ contribution in the control region and the jet energy scale and b -jet identification, as was described for the W +jets background estimation.

7 Systematic Uncertainties

Errors quoted on measurements are either statistical, coming from random fluctuations in the measured quantity, or systematic, coming from inaccurate measurements due to imperfect descriptions of the ATLAS detector in MC simulations.

Corrections can be applied to account for these systematic uncertainties by studying the cause of the error. This is often done by applying a scale factor or a correction to variables used for object and event selection. All events are weighted by the product of the scale factors for that event. Furthermore, the systematic uncertainties for each event scale factor are evaluated by running the full analysis chain when varying scale factors individually by $\pm 1 \sigma$.

7.1 Corrections and Systematic Uncertainties for Object and Event Selection

Many corrections and scale factors need to be applied to events to account for differences between data and MC, for example. Tools are provided by the ATLAS Collaboration for most of the object scaling and corrections as well as tools to calculate the systematic uncertainty for each correction.

Electron Energy Scale

The electromagnetic cluster energy is scaled based on the η and ϕ of the electron. Resonances of $Z \rightarrow ee$, $J/\psi \rightarrow ee$ or other similar decays are used to calculate the η/ϕ dependence of the cluster energy based on the position of the deposition. This is done for data, embedded and MC samples. MC and embedded electron energy is smeared to reproduce the resolution in data. The energy scaling is done before any other corrections and the other corrections use the corrected energy. Systematic uncertainties are independently applied for the energy scale and resolution. The uncertainties range from 1% for electrons in the central region to 3% for those in the endcaps [127, 128].

Muon Momentum Smearing

The muon transverse momentum is smeared in the same way as the electron energy is scaled. The scale factors for MC and embedded samples are determined by using di-muon resonances. Combined and tagged muons are scaled differently because of the differences in the reconstruction techniques. Systematic uncertainties from this are calculated and added to (subtracted from) the corrected term to provide the upwards (downwards) fluctuation [129]. Generally these corrections are less than 10% and are p_T and η dependent.

Muon and Electron Calorimeter Isolation

The muon/electron transverse energy in the isolation cone around the muon candidate must be corrected to account energy leakage and the electron candidate corrected for pile-up. These corrections are applied during the object selection. However, these the corrections are negligible since the di-lepton backgrounds have a small contribution to the overall background [90].

Muon and Electron Efficiency Corrections

Due to differences in MC and data there are slight differences in the efficiencies of the object selection algorithms. These differences in efficiencies for electron are calculated using bins of η integrated over the E_T . A further correction is applied to account for the E_T dependence. The scale factors for muons are done in the same way, using the η and p_T of the muon. These scale factors are applied at the di-lepton veto.

An identification uncertainty is applied for both electrons and muons. The systematic uncertainty on the electron efficiency and identification scale factors are varied up and down and the results are added in quadrature with a 2% uncertainty on the isolation efficiency. The corrections are obtained from tools provided by the ATLAS Electron/Gamma Performance group.

The electron identification efficiency scale factor was found to vary between 0.87 and 0.99 with 3-6% uncertainty [130]. The muon scale factors were 1 with a small uncertainty of 1.8% [131, 132].

Trigger Efficiency Corrections

These were found to be $\approx 1\%$ for both electron and muon triggers, using data and MC. The scale factors were very close to unity for both electron and muon triggers—0.995 and 0.992 respectively. Electron and muon trigger efficiency correction factors are calculated from data using $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events. The correction factors and scale factors are both provided by the ATLAS Trigger Group.

Jet Uncertainties

The Jet Energy Scale uncertainty is used as systematic uncertainty on the jet energy. This is scaled up and down for to find the effect on the jet acceptance. The Tau Energy Scale is fully correlated with this and both changes are done at the same time. The typical uncertainty for the jet and tau energy scales was found to be about 5% [127, 128].

Tau Uncertainties

Efficiencies for hadronic taus are measured in the same way as for the electrons and muons, but there is a strong p_T dependence. The efficiency for $p_T > 22$ GeV taus is 4% and 8% for lower p_T taus [133]. The Tau Energy Scale, which is fully correlated with the Jet Energy Scale, is varied by smearing the taus depending on η , number of tracks and energy.

Tau Electron Fake Rate Correction

This is a scale factor that should be applied to MC if a 1-prong tau is truth-matched to a truth electron within $\Delta R < 0.2$. This is based on the electron misidentification probability and is used to account for electrons faking taus. This uncertainty ranged from 30%-100% [90].

b -jet Scale Factors

Scale factors are derived for the identification efficiency and the mistag rate. This is done using a tag and probe method in data and MC [135]. Scale factors and uncertainties are applied for both positive and negative outcomes of the b -tagger. The uncertainties were found to vary from 4-10% for signal in the b -tagged category with the background uncertainty going up to 30%. These were lower in the negative outcome where they were 1% and 10% for the signal and background, respectively [90].

7.2 Corrections for MC samples only

Pile-up Reweighting

MC is generated with different amounts of pile-up and in order to match data-taking conditions events are reweighted to take into account the amount of pile-up in the event. The instantaneous luminosity is directly correlated to the pile-up in the event. For increased pile-up the event must be reweighted to account for the higher instantaneous luminosity.

Luminosity

The uncertainty used was 3.9% [134].

MC Sample Cross Sections

Systematic uncertainties for the background samples are calculated by varying the tuning parameters when generating the MC samples. The signal cross section is further dependent on $\tan\beta$, and the masses of $A/H/h$. This is described more fully in [136]. The final uncertainties for all samples are listed in Table 8.

Table 8: Production cross section uncertainties for signal at $m_A = 200$ and $m_A = 300$ GeV and background.

Sample	Uncertainty
$b\bar{b}A$ ($m_A = 200$) GeV	+9% / - 12%
$b\bar{b}A$ ($m_A = 300$) GeV	+8.6% / - 10.7%
$gg \rightarrow A$ ($m_A = 200$) GeV	+15.4% / - 14.8%
$gg \rightarrow A$ ($m_A = 300$) GeV	+16.1% / - 15.0%
W/Z	$\pm 5\%$
$t\bar{t}$	$\pm 10\%$
single top	$\pm 13\%$
WW, ZZ, WZ	$\pm 7\%$

7.3 Corrections for Background Estimation

QCD Background Estimation Systematic Uncertainties

Uncertainties in the ABCD method outlined in Section 6.6.3 come from the errors in the simulated samples that were subtracted from data in the B, C and D regions. Tests of the ratio of region B to region D showed a variation which gives a 20% systematic uncertainty. These uncertainties are used to get upper and lower limits on the event yields in the signal region A.

The results of these are a 15% uncertainty in the electron channel and a 7.5% uncertainty in the muon channel.

W +jets Background Estimation Systematic Uncertainties

Variations in the control region definition have been used to assign an uncertainty of 5%. Furthermore, the correction factor has uncertainties from jet energy scale variations and the electron to tau fake rate. Overall the correction factors were found to be $f_W^e = 0.59$ with a 7% uncertainty and $f_W^\mu = 0.54$ with a 8% uncertainty.

$t\bar{t}$ Background Estimation Systematic Uncertainties

Systematic errors in this background estimation come from the b -jet identification efficiency, the JES variations and the choice of control region. There is a 16% relative uncertainty on the scale factor.

$Z \rightarrow \tau\tau$ Embedding Background Estimation Systematic Uncertainties

The error is found by varying the muon isolation requirements in new embedded samples for a shape uncertainty, and in the embedding procedure the calorimeter energy is scaled up and down to derive a normalisation uncertainty. A correction of 7% is assigned to the $Z/\gamma^* \rightarrow \ell\ell$ corrections after the b -jet p_T requirement.

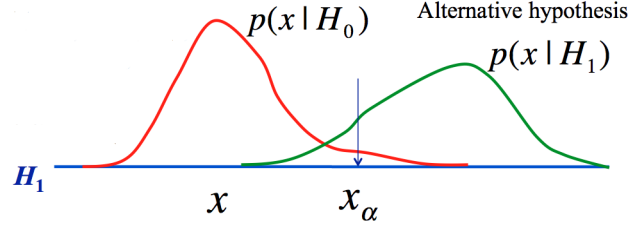


Figure 57: Two possible hypotheses are shown, the null hypothesis H_0 which is the red curve and the alternative hypothesis H_1 which is the green curve. A test must be able to determine whether for a given value x_α it matches the null or alternative hypothesis and at what confidence level [138, 139].

8 Statistical Analysis and Exclusion Limits

As there was no significant excess seen in the mass distributions and event yields an exclusion limit is calculated instead. This is done to put limits on where the neutral Higgs boson, ϕ , will not be found up to a very high confidence level.

In order to evaluate a model, multiple hypotheses need to be compared. In this case analysis there is a background hypothesis or model which is the Standard Model scenario without any Higgs boson. The signal hypothesis or model includes the MSSM Higgs bosons. The background hypothesis needs to be separated from an alternative hypothesis (signal). An example of this is shown in Figure 57. A number of statistical methods discussed below are used to quantify the compatibility between these two, see Ref. [137].

The likelihood for some observation given the parameters it is based on refers to the probability that this outcome is achieved for the same parameters. The definition of the likelihood function, $\mathcal{L}(\mu, \theta)$, is given as a function of the signal strength μ and the nuisance parameters θ . μ is the signal strength, where $\mu = 0$ is a background only hypothesis and $\mu = 1$ is the background and signal hypothesis. For $\mu = 1$ the masses and cross-sections are used for a specified point in the $m_A - \tan\beta$ plane. The set of nuisance parameters, θ , that parameterise the systematic uncertainties is constrained by Gaussian distributions. The Poisson distribution of the signal and background distribution is determined using the total number of events N_j , the total number of signal events s_j and the number of background events b_j where the subscript refers to the bin number.

$$\mathcal{L}(\mu, \theta) = \prod_j \text{Poisson}(N_j | \mu \cdot s_j + b_j) \prod_\theta \text{Gaussian}(\theta | 0, 1)$$

Here, the Poisson and Gaussian probability functions have their normal definitions. A likelihood function is calculated for both the b -tagged and b -vetoed categories. The overall likelihood is calculated using the product of a Poisson and Gaussian distribution for each bin in the MMC mass distributions.

The maximum likelihood estimation (MLE) is done by maximising the likelihood for the different parameters, μ and θ :

$$\frac{\partial \ln \mathcal{L}(\mu, \theta)}{\partial \mu} = \frac{\partial \ln \mathcal{L}(\mu, \theta)}{\partial \theta} = 0.$$

The MLE will find any unbiased estimate of a parameter, but is itself biased [138].

The values for the estimators of μ and θ are denoted by $\hat{\mu}$ and $\hat{\theta}$ respectively. These are then used in the test statistic which is the ratio of log-likelihoods multiplied by a factor of two. This gives a comparison of the likelihoods for two different hypotheses. The test statistic $\tilde{q}_\mu$ was calculated using this definition and approximated using the asymptotic approximation [140]:

$$\tilde{q}_\mu = \begin{cases} -2 \ln \left(\frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(0, \hat{\theta}_\mu)} \right) & \text{if } \hat{\mu} < 0, \\ -2 \ln \left(\frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right) & \text{if } 0 \leq \hat{\mu} \leq \mu, \\ 0 & \text{if } \hat{\mu} > \mu, \end{cases}$$

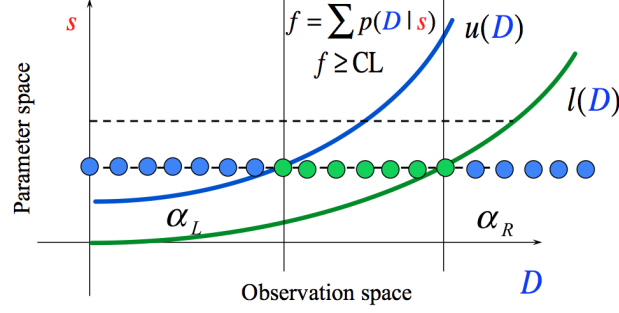


Figure 58: Example of how a confidence level is built up. This is for one point, this must be done for multiple points in the $m_A - \tan \beta$ plane [138]. For a 95% confidence level, the fraction of all events, f , in the bounded region must be greater than 95%. This corresponds to the probability that the true value lies within this region. Thus α_L and α_R must be 2.5% of the observation space on the x -axis each. The two curves $u(D)$ and $l(D)$ are the functions that describe the upper and lower bounds of the observation parameter D that is being searched for. The parameter space variable, s , is presumed to be a constant for each iteration, and in this analysis it would be $\tan \beta$. For a particular value of s there is a set of values for D that correspond to this within the bounds f . This is done in this analysis for each $m_A - \tan \beta$ point.

Here the value $\hat{\theta}_\mu$ is a conditional maximum likelihood of θ for a given μ . The conditional maximum likelihood estimate (CMLE) means that the nuisance parameters are replaced in the likelihood function by their estimates. In general this allows for a likelihood for the signal that is not dependent on the nuisance parameters, however this can be difficult if the CMLE is not solved exactly and an approximation is used.

A confidence interval is used to say that a fraction $f \geq p$ of all statements are true for a given ensemble of statements. Here, f is the coverage probability and p the confidence level. The CL_S method [141] is used to obtain the upper limit. This is a test of the compatibility between the background and signal hypothesis with the background only hypothesis. It works as follows: for every value of m_A (our observed value) the test statistic is calculated for all values of the cross section times branching ratio ($\sigma \times BR \rightarrow \tau_l \tau_h$). Only values that correspond to a confidence level of 95% or greater are selected. An example of this for a single point is shown in Figure 58. These are calculated using results from a background only ($\mu = 0$) Asimov dataset, which is a dataset with a large number of statistics and not much variance so a good median value for the cross section is obtained. Points within 1 and 2σ (standard deviations) are calculated and plotted as bands where there is a 1 or 2σ deviation from the expected value given by the Asimov dataset. This is then compared with the observed data and the limits are once again calculated with the test statistics. The median line in the exclusion limit plots shows what cross section times branching ratio values are excluded for a process at a particular m_A at a 95% confidence level. Any points below the observed points are excluded. This is shown in Figure 59. This is done for both production mechanisms. Since in the MSSM the parameter $\tan \beta$ is related to the cross section exclusion limits can then be placed on values of $\tan \beta$ for every value of m_A . This is shown in Figure 60.

To judge the significance of an excess of events over the background only hypothesis a p_0 -value is calculated. This gives an indication of the probability that the background only hypothesis has produced a value as extreme as the observed value. For this the test statistic used is:

$$\tilde{q}_\mu = \begin{cases} -2 \ln \left(\frac{\mathcal{L}(0, \hat{\theta}_0)}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right) & \text{if } \hat{\mu} \geq 0, \\ 0 & \text{if } \hat{\mu} < 0. \end{cases}$$

For some observed quantity, x_0 , the p_0 -value is calculated with:

$$p_0 = \int_{q_0}^{\infty} \mathcal{L}(q_0 | \mu = 0) dq_0,$$

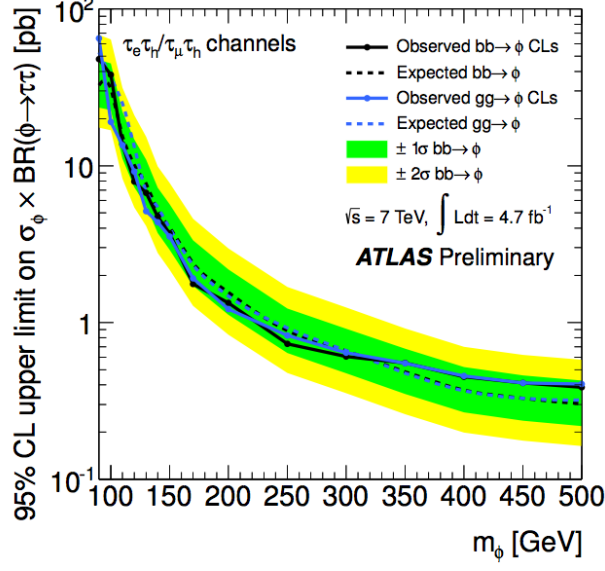


Figure 59: Expected (dashed line) and observed (solid line) 95% confidence level cross section exclusion limits as a function of m_ϕ , where again $\phi = A/H/h$. Also shown are the $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands of the expected limit [90].

where $\mathcal{L}(q_0|\mu = 0)$ is the probability density function for q_0 for the background only hypothesis.

At a specified p_0 the probability is small enough to say that the null hypothesis, or background only hypothesis, can be rejected, meaning there must be some signal. The local significance is calculated from the p_0 -value by using the number of standard deviations that this corresponds to using:

$$Z_0 = \Phi^{-1}(1 - p_0).$$

Where Φ^{-1} is defined as the inverse of the Normal distribution. A 5σ significance is used as the benchmark to claim discovery to ensure that an observed excess is not a statistical fluctuation from the background only hypothesis.

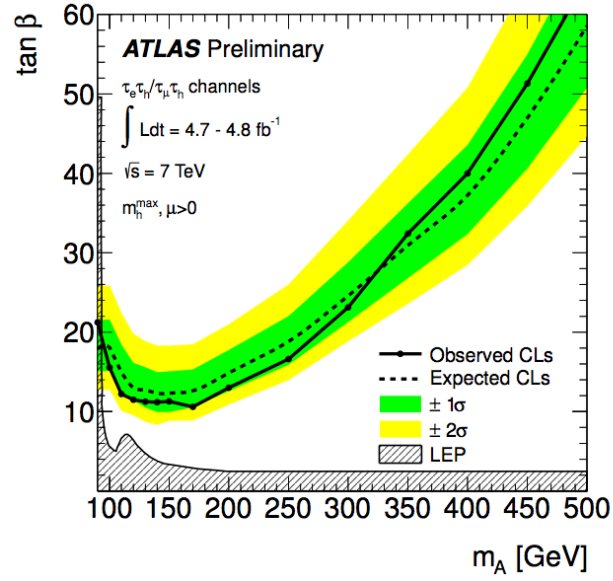
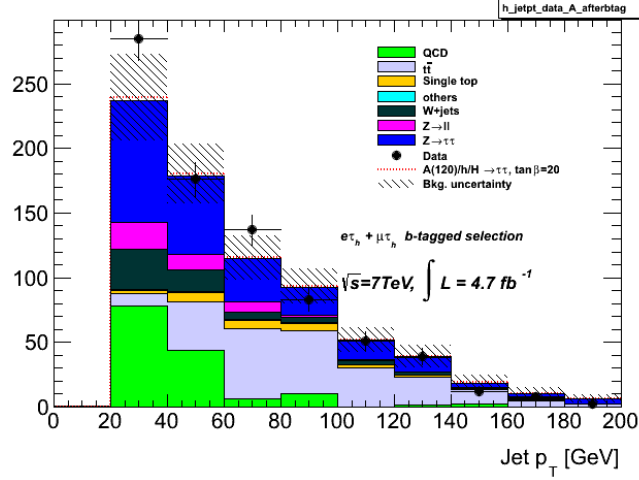
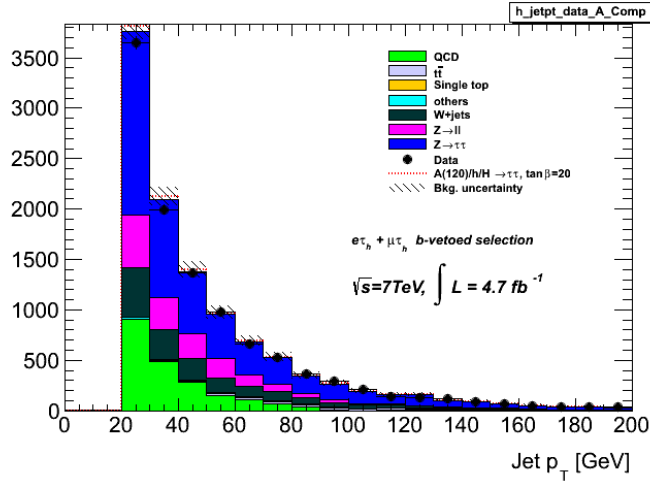


Figure 60: Expected (dashed line) and observed (solid line) 95% confidence level of $\tan\beta$ exclusion limits as a function of m_A . Also shown are the $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) bands of the expected limit [90].



(a) b -tagged.



(b) b -vetoed.

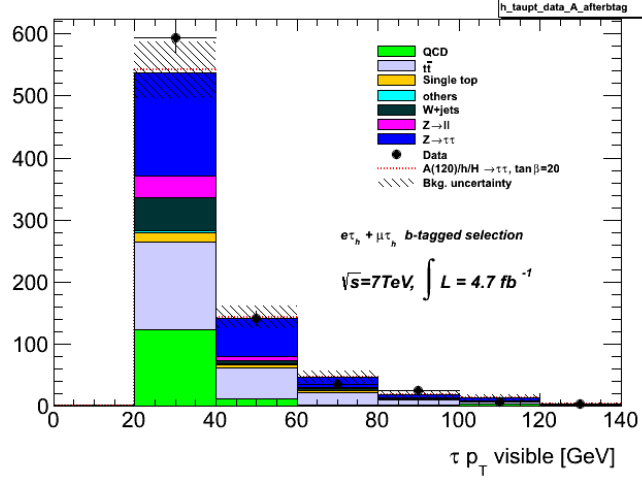
Figure 61: Distributions for signal and background samples for the jet p_T in the two categories, (a) b -tagged and (b) b -vetoed.

9 Results

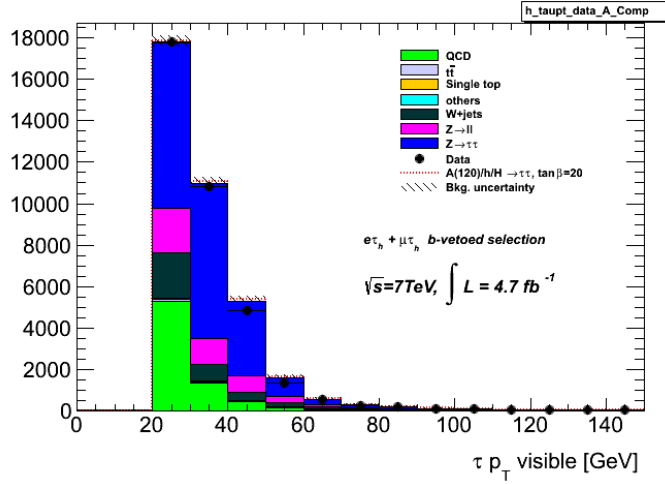
Comparisons between data and MC for the m_T , m_{vis} , E_T^{miss} , jet and tau p_T and m_{MMC} for the b -vetoed and b -tagged categories are shown in Figures 61 - 66. Although in many cases there is an excess in the number of data events, this is always within statistical and systematic uncertainty.

No significant excesses are seen in the collected data with luminosity 4.66 fb^{-1} in proton-proton collisions running at $\sqrt{s} = 7 \text{ TeV}$. However, exclusion limits were produced for $\tan\beta$ using the CL_s method of finding confidence intervals. This was done for every m_A point. The cross-sections used for the Higgs bosons were calculated for the m_h^{max} maximal mixing scenario with $\mu > 0$. These limits on $\tan\beta$ are shown in Figure 60. The tightest constraint on $\tan\beta$ is at $m_A = 170 \text{ GeV}$.

The constraints on the cross sections times branching ratio was shown for both production mechanisms of ϕ . This is shown in Figure 59.



(a) b -tagged.

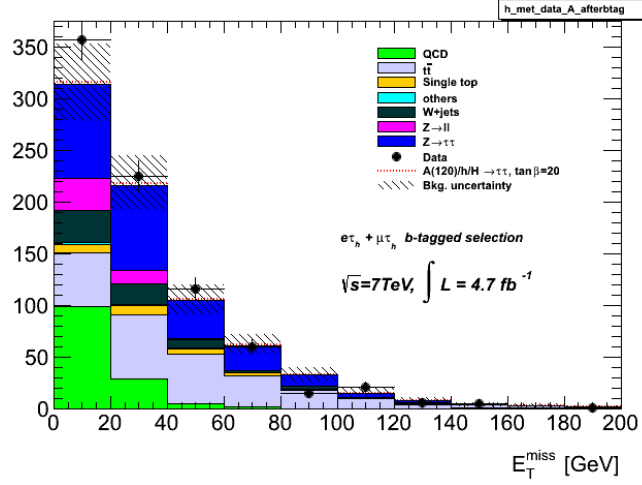


(b) b -vetoed.

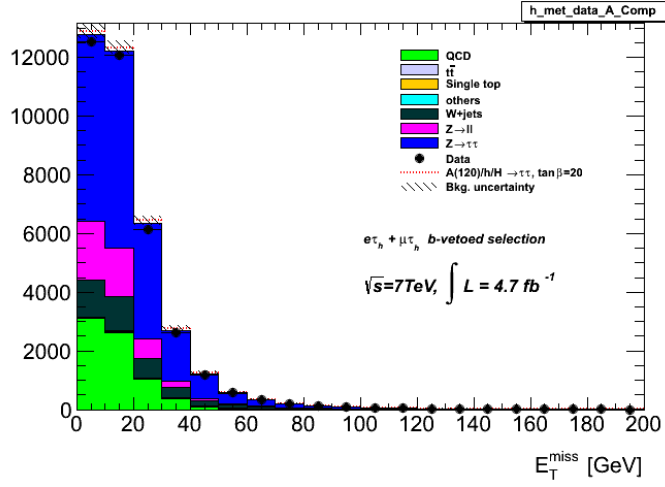
Figure 62: Distributions for signal and background samples for the tau p_T in the two categories, (a) b -tagged and (b) b -vetoed.

Cut	e^- Channel Raw	e^- Channel Scaled	μ^- Channel Raw	μ^- Channel Scaled
Trigger	6305	6329.85	7308	7310.21
Vertex cleaning	6286	6223.20	7276	7237.06
Jet cleaning	6264	6202.07	7256	7216.67
LAr cleaning	6164	6081.43	7182	7127.23
1 loose lepton	3622	3580.86	5279	5162.54
Di-lepton veto	3549	3507.87	5205	5089.62
1 Tau	1042	1027.21	1523	1489.69
Charge correlation	1034	1019.25	1513	1480.19
m_T	592	583.54	886	866.61
b -veto	532	523.68	810	792.89
b -tag	60	59.87	76	73.72
Jet p_T cut	36	37.78	60	57.92

Table 9: Results from the acceptance challenge for the electron and muon channels without scaling (raw) and with scaling, using the Sherpa bbA ($m_A = 120$ GeV) at $\tan\beta$.

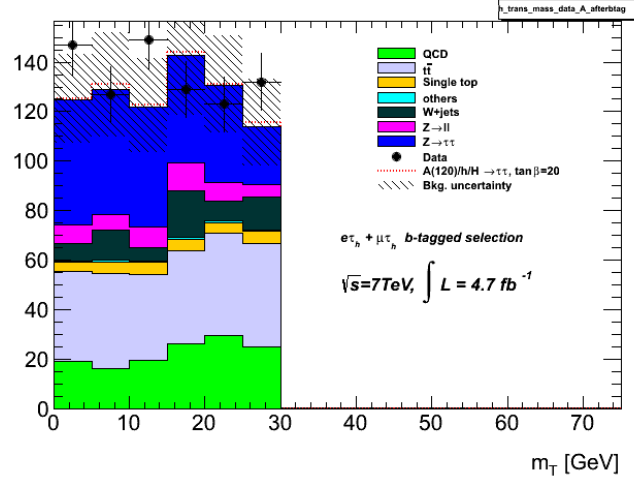


(a) *b*-tagged.

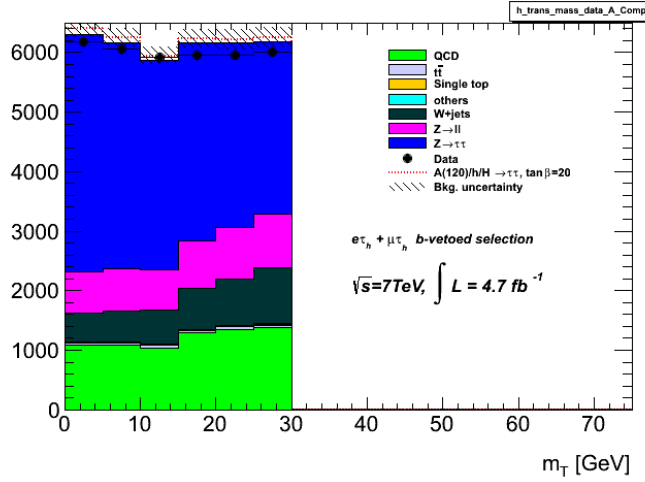


(b) *b*-vetoed.

Figure 63: Distributions for signal and background samples for the E_T^{miss} in the two categories, (a) *b*-tagged and (b) *b*-vetoed.

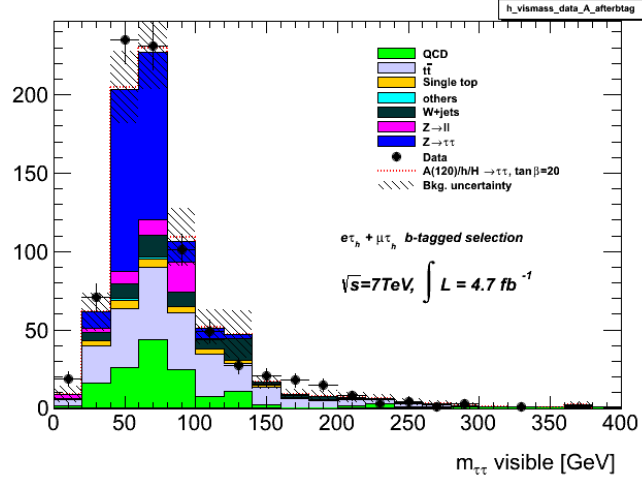


(a) *b*-tagged.

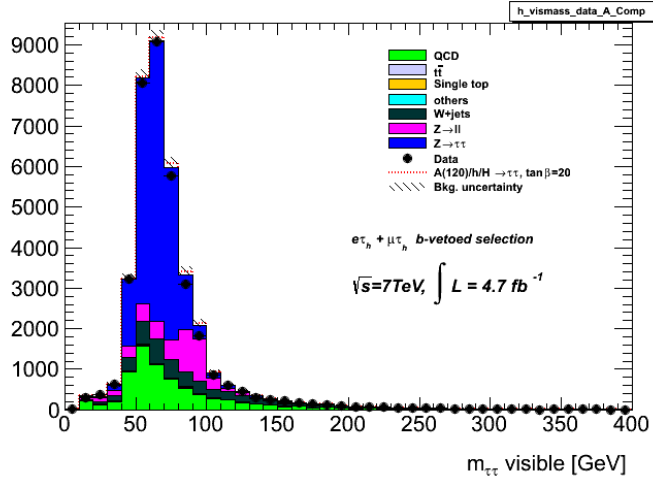


(b) *b*-vetoed.

Figure 64: Distributions for signal and background samples for the m_T in the two categories, (a) *b*-tagged and (b) *b*-vetoed.

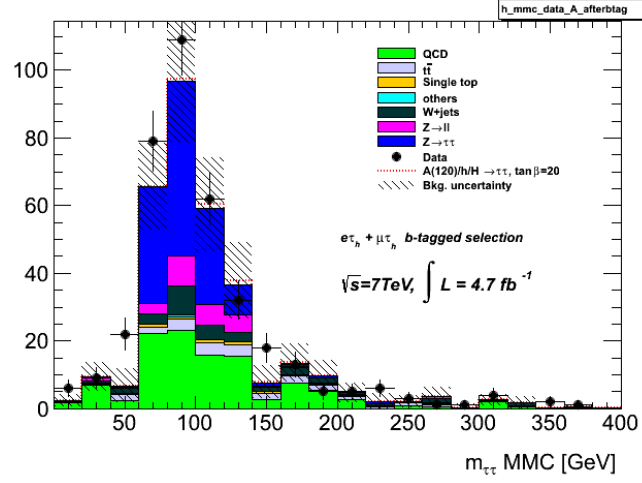


(a) *b*-tagged.

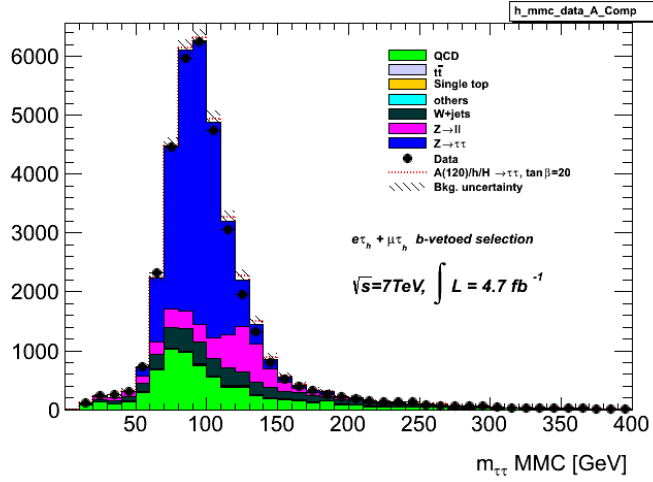


(b) *b*-vetoed.

Figure 65: Distributions for signal and background samples for the m_{vis} in the two categories, (a) *b*-tagged and (b) *b*-vetoed.



(a) *b*-tagged.



(b) *b*-vetoed.

Figure 66: Distributions for signal and background samples for the m_{MMC} in the two categories, (a) *b*-tagged and (b) *b*-vetoed.

10 Summary and Outlook

A report on the search for neutral MSSM Higgs bosons in proton-proton collisions at the LHC and recorded with the ATLAS experiment is presented. The data used corresponds to an integrated luminosity of 4.66 fb^{-1} . The analysis was increased in sensitivity by considering the gluon fusion and b -associated production mechanisms in different categories by requiring the presence (or lack thereof) of a b -jet. Further to this the electron and muon channels were separated as well.

There was no excess seen in the data and 95% confidence level limits were set in the m_A - $\tan\beta$ plane. A large area of this parameter space has now been excluded.

The methods used to remove the background contamination were effective for most processes, although the dominant $Z \rightarrow \tau\tau$ background was largely irreducible. Most of the selection was done using cut based methods. Advantage was taken of the transverse mass, reconstructed mass and missing transverse energy distributions, and the presence of b -jets, to reject backgrounds.

The Monte Carlo simulated data samples used were checked thoroughly with data control regions and were corrected where needed. The systematic uncertainties were evaluated for all samples and all corrections done to the samples.

This analysis relies strongly on the ability to accurately reconstruct hadronic tau decays. Research into a pile-up independent tau identification scheme with multivariate techniques is promising, with some preliminary results shown here. There is further work to be done on this and new methods to be tested. These include changing the number of variables used for the identification, applying vetoes on isolation energies in the isolation cone and this both with and without the shrinking cone technique used here. More work will also be carried out on much higher energy taus, where the collimation makes it more difficult to identify them.

This work could be furthered by including an analysis of the 2012 data which is of a much greater luminosity and higher centre-of-mass energy. This would require some changes to the methods used as the detector conditions will have changed and there are large changes in the collision kinematics due to the higher energies. The pile-up will have increased substantially making the tau identification and b -jet identification more difficult, specifically. It might be worthwhile investigating boosted topologies of decay products at these higher energies as well. The presence of the newly discovered SM Higgs boson has constrained the MSSM parameter space somewhat, however, but this reduces the amount of parameter space that needs to be searched.

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A Appendix

A.1 MC Samples and Cross Section

A.1.1 Signal MC samples and cross-sections

The pseudoscalar A boson samples for gluon fusion and b associated production are generated for $\tan\beta = 20$ at several mass points. Specific m_A and $\tan\beta$ points are approximated using a combination 4- and 5-flavour schemes. This is done by mixing the samples and weighting them by cross section.

MSSM Higgs cross-sections in the m_A vs $\tan\beta$ plane are shown in Table 10 for $b\bar{b}A/H/h$ production and in Table 11 for $gg \rightarrow A/H/h$ production.

Table 10: MSSM Higgs $b\bar{b}A/H/h$ production cross section as a function of $\tan\beta$ and m_A . The cross sections are multiplied by the branching ratio $\text{BR}(H \rightarrow \tau\tau)$. Another factor of 0.456 is needed in order to estimate the cross-sections used for the $\pi_{lep}\tau_{had}$ channel.

$\tan\beta = 20$					
m_A (GeV)	$\text{BR} \times \sigma$ (fb)	m_H (GeV)	$\text{BR} \times \sigma$ (fb)	m_h (GeV)	$\text{BR} \times \sigma$ (fb)
90	19195	130.583	38.7695	89.5643	19453.1
100	13810.7	130.772	84.8797	99.3745	14090
110	10161.1	131.126	212.999	109.019	10342.6
120	7619.21	131.989	690.246	118.155	7291.64
130	5807.73	134.917	2472.95	125.224	3568.64
140	4490.74	142.081	3586.15	128.06	1022
150	3516.68	151.242	3197.97	128.897	397.415
170	2228.11	170.717	2139.57	129.419	133.8
200	1173.38	200.482	1170.53	129.654	57.384
250	453.861	250.388	474.332	129.786	28.4403
300	181.619	300.43	207.782	129.84	19.8454
350	72.2479	350.194	91.638	129.865	16.2317
400	35.4993	399.937	43.3885	129.881	14.1262
450	18.3892	449.762	19.1608	129.892	12.8272
500	9.93865	499.787	9.53661	129.9	11.8836

A.1.2 Background MC samples and cross-sections

Tables 12-16 list the background MC samples.

Table 17 summarises numbers used in our final results.

Table 11: MSSM Higgs $ggA/H/h$ production cross section as a function of $\tan\beta$ and m_A . The cross sections are multiplied by the branching ratio $\text{BR}(H \rightarrow \tau\tau)$. Another factor of 0.456 is needed in order to estimate the cross-sections used for the $\tau_{lep}\tau_{had}$ channel.

$\tan\beta = 20$					
m_A (GeV)	$\text{BR}\times\sigma$ (fb)	m_H (GeV)	$\text{BR}\times\sigma$ (fb)	m_h (GeV)	$\text{BR}\times\sigma$ (fb)
90	20482.1	130.583	1399.65	89.5643	19160.4
100	12261.6	130.772	1607.44	99.3745	11491.8
110	7640.37	131.126	1837.43	109.019	7027.42
120	4927.53	131.989	2208.56	118.155	4102.36
130	3269.7	134.917	2776.23	125.224	1879.12
140	2223.74	142.081	2381.39	128.06	1202.21
150	1545.17	151.242	1705.38	128.897	1179.07
170	787.406	170.717	884.594	129.419	1169.61
200	311.57	200.482	372.08	129.654	1094.49
250	80.1543	250.388	110.172	129.786	977.97
300	22.1582	300.43	38.8445	129.84	903.116
350	8.00301	350.194	15.2168	129.865	856.159
400	4.74617	399.937	6.02613	129.881	825.384
450	2.42182	449.762	2.14469	129.892	804.103
500	1.24758	499.787	0.863687	129.9	789.001

Table 12: Background MC samples (part1) : W +jets samples

Process	Dataset number	$\sigma \times \text{BR}$ (pb)	k-factor	ϵ_{filter}	Generator
$W \rightarrow e\nu + \text{Np0}$	107680	6921.60	1.20	1	ALPGEN
$W \rightarrow e\nu + \text{Np1}$	107681	1304.30	1.20	1	ALPGEN
$W \rightarrow e\nu + \text{Np2}$	107682	378.29	1.20	1	ALPGEN
$W \rightarrow e\nu + \text{Np3}$	107683	101.43	1.20	1	ALPGEN
$W \rightarrow e\nu + \text{Np4}$	107684	25.87	1.20	1	ALPGEN
$W \rightarrow e\nu + \text{Np5}$	107685	7.00	1.20	1	ALPGEN
$W \rightarrow \mu\nu + \text{Np0}$	107690	6919.60	1.20	1	ALPGEN
$W \rightarrow \mu\nu + \text{Np1}$	107691	1304.20	1.20	1	ALPGEN
$W \rightarrow \mu\nu + \text{Np2}$	107692	377.83	1.20	1	ALPGEN
$W \rightarrow \mu\nu + \text{Np3}$	107693	101.88	1.20	1	ALPGEN
$W \rightarrow \mu\nu + \text{Np4}$	107694	25.75	1.20	1	ALPGEN
$W \rightarrow \mu\nu + \text{Np5}$	107695	6.92	1.20	1	ALPGEN
$W \rightarrow \tau\nu + \text{Np0}$	107700	6918.60	1.20	1	ALPGEN
$W \rightarrow \tau\nu + \text{Np1}$	107701	1303.20	1.20	1	ALPGEN
$W \rightarrow \tau\nu + \text{Np2}$	107702	378.18	1.20	1	ALPGEN
$W \rightarrow \tau\nu + \text{Np3}$	107703	101.51	1.20	1	ALPGEN
$W \rightarrow \tau\nu + \text{Np4}$	107704	25.64	1.20	1	ALPGEN
$W \rightarrow \tau\nu + \text{Np5}$	107705	7.04	1.20	1	ALPGEN
$W + c + \text{Np0}$	117293	644.4	1.20	1	ALPGEN
$W + c + \text{Np1}$	117294	205.0	1.20	1	ALPGEN
$W + c + \text{Np2}$	117295	50.8	1.20	1	ALPGEN
$W + c + \text{Np3}$	117296	11.4	1.20	1	ALPGEN
$W + c + \text{Np4}$	117297	2.8	1.20	1	ALPGEN
$W + cc + \text{Np0}$	117284	127.53	1.20	1	ALPGEN
$W + cc + \text{Np1}$	117285	104.68	1.20	1	ALPGEN
$W + cc + \text{Np2}$	117286	52.08	1.20	1	ALPGEN
$W + cc + \text{Np3}$	117287	16.96	1.20	1	ALPGEN
$W + bb + \text{Np0}$	107280	47.35	1.20	1	ALPGEN
$W + bb + \text{Np1}$	107281	35.76	1.20	1	ALPGEN
$W + bb + \text{Np2}$	107282	17.33	1.20	1	ALPGEN
$W + bb + \text{Np3}$	107283	7.61	1.20	1	ALPGEN

Table 13: Background MC samples (part2) : Z +jets samples

Process	Dataset number	$\sigma \times \text{BR}$ (pb)	k-factor	ϵ_{filter}	Generator
$Z \rightarrow ee$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np0	107650	668.32	1.25	1	ALPGEN
$Z \rightarrow ee$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np1	107651	134.36	1.25	1	ALPGEN
$Z \rightarrow ee$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np2	107652	40.54	1.25	1	ALPGEN
$Z \rightarrow ee$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np3	107653	11.16	1.25	1	ALPGEN
$Z \rightarrow ee$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np4	107654	2.88	1.25	1	ALPGEN
$Z \rightarrow ee$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np5	107655	0.83	1.25	1	ALPGEN
$Z \rightarrow \mu\mu$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np0	107660	668.68	1.25	1	ALPGEN
$Z \rightarrow \mu\mu$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np1	107661	134.14	1.25	1	ALPGEN
$Z \rightarrow \mu\mu$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np2	107662	40.36	1.25	1	ALPGEN
$Z \rightarrow \mu\mu$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np3	107663	11.19	1.25	1	ALPGEN
$Z \rightarrow \mu\mu$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np4	107664	2.75	1.25	1	ALPGEN
$Z \rightarrow \mu\mu$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np5	107665	0.77	1.25	1	ALPGEN
$Z \rightarrow \tau\tau$	106052	989	1	1	PYTHIA
$Z \rightarrow \tau\tau$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np0	107670	668.40	1.25	1	ALPGEN
$Z \rightarrow \tau\tau$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np1	107671	134.81	1.25	1	ALPGEN
$Z \rightarrow \tau\tau$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np2	107672	40.36	1.25	1	ALPGEN
$Z \rightarrow \tau\tau$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np3	107673	11.25	1.25	1	ALPGEN
$Z \rightarrow \tau\tau$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np4	107674	2.79	1.25	1	ALPGEN
$Z \rightarrow \tau\tau$ (40 GeV < $m_{\ell\ell}$ < 2 TeV) + Np5	107675	0.77	1.25	1	ALPGEN
$Z \rightarrow ee + bb$ + Np0	109300	6.57	1.25	1	ALPGEN
$Z \rightarrow ee + bb$ + Np1	109301	2.48	1.25	1	ALPGEN
$Z \rightarrow ee + bb$ + Np2	109302	0.89	1.25	1	ALPGEN
$Z \rightarrow ee + bb$ + Np3	109303	0.39	1.25	1	ALPGEN
$Z \rightarrow \mu\mu + bb$ + Np0	109305	6.56	1.25	1	ALPGEN
$Z \rightarrow \mu\mu + bb$ + Np1	109306	2.47	1.25	1	ALPGEN
$Z \rightarrow \mu\mu + bb$ + Np2	109307	0.89	1.25	1	ALPGEN
$Z \rightarrow \mu\mu + bb$ + Np3	109308	0.39	1.25	1	ALPGEN
$Z \rightarrow \tau\tau + bb$ + Np0	109310	6.57	1.25	1	ALPGEN
$Z \rightarrow \tau\tau + bb$ + Np1	109311	2.49	1.25	1	ALPGEN
$Z \rightarrow \tau\tau + bb$ + Np2	109312	0.89	1.25	1	ALPGEN
$Z \rightarrow \tau\tau + bb$ + Np3	109313	0.39	1.25	1	ALPGEN
$Z \rightarrow ee$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np0	116250	3055.20	1.22	1	ALPGEN
$Z \rightarrow ee$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np1	116251	84.92	1.22	1	ALPGEN
$Z \rightarrow ee$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np2	116252	41.40	1.22	1	ALPGEN
$Z \rightarrow ee$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np3	116253	8.38	1.22	1	ALPGEN
$Z \rightarrow ee$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np4	116254	1.85	1.22	1	ALPGEN
$Z \rightarrow ee$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np5	116255	0.46	1.22	1	ALPGEN
$Z \rightarrow \mu\mu$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np0	116260	3054.90	1.22	1	ALPGEN
$Z \rightarrow \mu\mu$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np1	116261	84.87	1.22	1	ALPGEN
$Z \rightarrow \mu\mu$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np2	116262	41.45	1.22	1	ALPGEN
$Z \rightarrow \mu\mu$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np3	116263	8.38	1.22	1	ALPGEN
$Z \rightarrow \mu\mu$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np4	116264	1.85	1.22	1	ALPGEN
$Z \rightarrow \mu\mu$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np5	116265	0.46	1.22	1	ALPGEN
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 60 GeV)	107055	3971	1	1	PYTHIA
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np0	116270	3055.10	1.22	1	ALPGEN
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np1	116271	84.93	1.22	1	ALPGEN
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np2	116272	41.47	1.22	1	ALPGEN
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np3	116273	8.36	1.22	1	ALPGEN
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np4	116274	1.85	1.22	1	ALPGEN
$Z \rightarrow \tau\tau$ (10 GeV < $m_{\ell\ell}$ < 40 GeV) + Np5	116275	0.46	1.22	1	ALPGEN

Table 14: Background MC samples (part3) : $t\bar{t}$ and single top samples

Process	Dataset number	$\sigma \times \text{BR}$ (pb)	k-factor	ϵ_{filter}	Generator
$t\bar{t}$ (no fully hadronic decays)	105200	164.570	1	0.556	MC@NLO
$t\bar{t}$ (fully hadronic decays)	105204	164.570	1	0.444	MC@NLO
single top : t -channel $W \rightarrow e\nu$	117360	6.93	1	1	AcerMC
single top : t -channel $W \rightarrow \mu\nu$	117361	6.93	1	1	AcerMC
single top : t -channel $W \rightarrow \tau\nu$	117362	6.93	1	1	AcerMC
single top : t -channel $W \rightarrow e\nu$	108340	6.34	1	1	MC@NLO
single top : t -channel $W \rightarrow \mu\nu$	108341	6.34	1	1	MC@NLO
single top : t -channel $W \rightarrow \tau\nu$	108342	6.34	1	1	MC@NLO
single top : s -channel $W \rightarrow e\nu$	108343	0.50	1	1	MC@NLO
single top : s -channel $W \rightarrow \mu\nu$	108344	0.50	1	1	MC@NLO
single top : s -channel $W \rightarrow \tau\nu$	108345	0.50	1	1	MC@NLO
single top : Wt -channel	108346	13.10	1	1	MC@NLO
single top : Wt -channel	105500	15.6	1	1	AcerMC

Table 15: Background MC samples (part4) : WW samples

Process	Dataset number	$\sigma \times \text{BR}$ (pb)	k-factor	ϵ_{filter}	Generator
$q\bar{q}' \rightarrow W^+W^- \rightarrow e^+\nu e^-\nu$	105921	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow e^+\nu\mu^-\nu$	105922	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow e^+\nu\tau^-\nu$	105923	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow \mu^+\nu\mu^-\nu$	105924	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow \mu^+\nu e^-\nu$	105925	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow \mu^+\nu\tau^-\nu$	105926	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow \tau^+\nu\tau^-\nu$	105927	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow \tau^+\nu e^-\nu$	105928	0.524	1	1	MC@NLO
$q\bar{q}' \rightarrow W^+W^- \rightarrow \tau^+\nu\mu^-\nu$	105929	0.524	1	1	MC@NLO
$gg \rightarrow W^+W^- \rightarrow e^+\nu e^-\nu$	106011	0.0155	1	0.9895	gg2WW
$gg \rightarrow W^+W^- \rightarrow e^+\nu\mu^-\nu$	106012	0.0155	1	0.9899	gg2WW
$gg \rightarrow W^+W^- \rightarrow e^+\nu\tau^-\nu$	106013	0.0155	1	0.9232	gg2WW
$gg \rightarrow W^+W^- \rightarrow \mu^+\nu\mu^-\nu$	106014	0.0155	1	0.9890	gg2WW
$gg \rightarrow W^+W^- \rightarrow \mu^+\nu e^-\nu$	106015	0.0155	1	0.9869	gg2WW
$gg \rightarrow W^+W^- \rightarrow \mu^+\nu\tau^-\nu$	106016	0.0155	1	0.9288	gg2WW
$gg \rightarrow W^+W^- \rightarrow \tau^+\nu\tau^-\nu$	106017	0.0155	1	0.3269	gg2WW
$gg \rightarrow W^+W^- \rightarrow \tau^+\nu e^-\nu$	106018	0.0155	1	0.9219	gg2WW
$gg \rightarrow W^+W^- \rightarrow \tau^+\nu\mu^-\nu$	106019	0.0155	1	0.9289	gg2WW

Table 16: Background MC samples (part5) : ZW and ZZ samples ($\ell=e$ or μ)

Process	Dataset number	$\sigma \times \text{BR}$ (pb)	k-factor	ϵ_{filter}	Generator
$W^+Z \rightarrow \ell\nu qq$	105940	1.696	1	1	MC@NLO
$W^+Z \rightarrow \ell\nu \ell\ell$	105941	0.161	1	1	MC@NLO
$W^+Z \rightarrow qq\ell\ell$	105942	0.506	1	1	MC@NLO
$W^+Z \rightarrow \tau\nu\ell\ell$	106024	0.081	1	1	MC@NLO
$W^+Z \rightarrow \ell\nu\tau\tau$	106025	0.082	1	1	MC@NLO
$W^+Z \rightarrow \tau\nu\tau\tau$	106026	0.041	1	1	MC@NLO
$W^+Z \rightarrow qq\tau\tau$	113190	0.255	1	1	MC@NLO
$W^-Z \rightarrow \ell\nu qq$	105970	0.920	1	1	MC@NLO
$W^-Z \rightarrow \ell\nu \ell\ell$	105971	0.088	1	1	MC@NLO
$W^-Z \rightarrow qq\ell\ell$	105972	0.274	1	1	MC@NLO
$W^-Z \rightarrow \tau\nu\ell\ell$	106027	0.044	1	1	MC@NLO
$W^-Z \rightarrow \ell\nu\tau\tau$	106028	0.044	1	1	MC@NLO
$W^-Z \rightarrow \tau\nu\tau\tau$	106029	0.022	1	1	MC@NLO
$W^-Z \rightarrow qq\tau\tau$	113191	0.137	1	1	MC@NLO
$ZZ \rightarrow \ell\ell qq$	105930	0.533	1	1	MC@NLO
$ZZ \rightarrow \ell\ell\ell\ell$	105931	0.026	1	1	MC@NLO
$ZZ \rightarrow \ell\ell\nu\nu$	105932	0.152	1	1	MC@NLO
$ZZ \rightarrow \ell\ell\tau\tau$	106036	0.026	1	1	MC@NLO
$ZZ \rightarrow \tau\tau\tau\tau$	106037	0.006	1	1	MC@NLO
$ZZ \rightarrow \tau\tau\nu\nu$	113192	0.077	1	1	MC@NLO
$ZZ \rightarrow \tau\tau qq$	113193	0.266	1	1	MC@NLO

Table 17: Summary of uncertainties of production cross section of BG processes. Cross section of W , Z and diboson with higher order corrections is summarized in [142].

W/Z	$\pm 5\%$
$t\bar{t}$	$\pm 10\%$
Single top	$\pm 13\%$
Diboson (WW , ZZ , WZ)	$\pm 7\%$