

## Physics with Tau Lepton Final States in ATLAS

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The ATLAS detector records the high-energy proton-proton collisions produced by the Large Hadron Collider, probing an energy regime unexplored by previous experiments. Physics involving tau lepton signatures form an integral part of the ATLAS physics programme. Tau lepton identification is used in many analyses at ATLAS such as searches for exotic phenomena and Higgs bosons, as well as Standard Model measurements of cross-sections. The performance of the reconstruction and identification algorithms for hadronically decaying tau leptons is reviewed. The cross-section measurement of the Z boson decaying to a pair of tau leptons is discussed, as well as the search for heavier ditau resonances such as supersymmetric Higgs bosons.

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## 1. Introduction

### 1.1 The Standard Model of Particle Physics

The Standard Model of particle physics can be described as a collection of fundamental particles interacting with each other within the framework of quantum field theory. The Higgs boson is the final missing piece for which experimental evidence still has to be found. It is responsible for breaking the electroweak symmetry and giving mass to fundamental particles. A very potent way of looking for the Higgs boson is to detect pairs of tau leptons in high energy proton-proton collisions. Although the Higgs boson is certainly a priority for particle physicists, other sources of tau leptons beyond the Standard Model are also predicted. Tau leptons from known Standard Model sources such as the Z and W bosons must be very well understood if sources of tau leptons yet unseen are to be searched for.

### 1.2 The Large Hadron Collider and the ATLAS Experiment

The Large Hadron Collider (LHC) has been designed to enable particle physicists to provide a definitive statement on the existence of the Standard Model Higgs boson and to explore the unknown energy regime beyond electroweak symmetry breaking. It is the largest proton-proton collider on Earth, and it has so far provided the ATLAS detector with  $4.7\text{fb}^{-1}$  of good data in 2011 which represents about  $5 \times 10^{15}$  inelastic proton-proton interactions.

The ATLAS detector[1] is a seven story high machine with many subdetectors layered in an onion-like structure. At its very core is a high precision tracking system for charged particles in a solenoidal magnetic field, which does momentum measurement and vertex reconstruction. It can also measure transition radiation to distinguish electrons and charged pions. Surrounding this tracking system are the electromagnetic and hadronic calorimeters, dedicated to stopping all electrons, photons and hadrons and to measuring their energy. The only detectable particles not stopped by the calorimeters are muons, which are what the outermost system is dedicated to. The muon system is capable of tracking and triggering on muons. It has its own magnetic field, provided by three gigantic air-core toroids.

### 1.3 Tau Physics Programme

So far, the ATLAS collaboration has rediscovered the W and Z bosons as well as measured their cross-sections through the  $W \rightarrow \tau\nu$  [2] and  $Z \rightarrow \tau\tau$  [3] signatures. ATLAS has also measured the  $t\bar{t}$  cross-section with tau final states [4]. The  $H \rightarrow \tau\tau$  channel is currently playing an important role in the search for the Standard Model Higgs boson [5]. ATLAS is also looking for evidence of supersymmetry and grand unified theories which both have prominent signatures with tau final states such as heavy Higgs bosons or heavier counterparts to the Z and W bosons.

## 2. Tau Reconstruction and Identification

### 2.1 Tau Lepton Signature

The tau is the third generation lepton. It has a mass of  $1.777\text{GeV}$  and a proper decay length of  $87\mu\text{m}$  [6] which is just long enough so that it is possible under special circumstances<sup>1</sup> to resolve

<sup>1</sup>The tau decay must produce more than one charged particle for a secondary vertex to be reconstructed.

Decay mode	Branching ratio
Leptonic modes ( $\tau_\ell$ )	
$\tau^\pm \rightarrow e^\pm \nu_e \nu_\tau$	17.4%
$\tau^\pm \rightarrow \mu^\pm \nu_\mu \nu_\tau$	17.9%
Hadronic modes ( $\tau_h$ )	
1 prong	
$\tau^\pm \rightarrow \pi^\pm \nu_\tau$	10.9%
$\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$	25.5%
$\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_\tau$	9.3%
3 prongs	
$\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \nu_\tau$	9.3%
$\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \pi^0 \nu_\tau$	4.6%

**Table 1:** Branching ratios for the most frequent tau final states.

the tau decay vertex within the ATLAS detector.

Tau leptons decay via the weak interaction either to leptons and neutrinos only (leptonic decays,  $\tau_\ell$ <sup>2</sup>) or to hadrons and neutrinos (hadronic decays,  $\tau_h$ ). The leptonic decays are very difficult to use to identify tau leptons directly, although they are often used indirectly to detect tau pair production, such as first looking for the clear signature of a muon before probing for a hadronic tau decay in the same event. Hadronic decays have a more unique signature that can be used to ascertain the presence of tau leptons in an event. The branching ratios for the most important tau decay modes are shown in Table 1.

At ATLAS, muons and charged pions are considered final state (stable) particles. Muons almost always escape the detector before they decay while charged pions are forced to induce hadronic showers in the calorimeter. Neutral pions decay as soon as they are produced to pairs of photons more than 99% of the time and result in dense electromagnetic showers. Electrons are of course real stable particles which also make dense electromagnetic showers. Neutrinos escape the ATLAS detector unseen, leaving only an imbalance in the momentum in the transverse plane of the detector.

Tau hadronic decays with one charged pion are often referred to as one prong tau decays, while decays with three charged pions are called three prong decays.

## 2.2 Main Tau Backgrounds in ATLAS

In the proton-proton collisions of the LHC, hadronic tau decays must be distinguished primarily from two kinds of objects. Electrons can fake one prong tau decays but usually, they leave denser energy deposits than charged pions. Electrons also generate more radiation when transiting between different media which is picked up by the transition radiation tracker of the ATLAS inner detector.

<sup>2</sup>At ATLAS the symbol  $\ell$  is used to designate light leptons (electrons and muons).

Collimated showers of pions coming directly from the primary interactions are called multijets, and they are a more difficult background than electrons. The features differentiating them from tau hadronic decays are not as obvious. Multijets are usually wider than the pion showers from tau decays. They also have more pions in the final state. When the 4-vectors of these pions are summed, an arbitrarily large invariant mass is obtained, while the invariant mass of the visible decay products of a tau is bounded by the tau mass.

### 2.3 Tau Reconstruction

At ATLAS, hadronic tau decays are reconstructed by first gathering energy deposits in the form of topological clusters of cells [7] in the calorimeter. Then, these topological clusters are grouped together by using the anti- $k_r$  jet algorithm [8]. A tau candidate is a jet reconstructed in this way with a minimum transverse energy requirement of 10 GeV. Tracks from the inner detector that point to the energy deposits are associated with the tau candidate. From the calorimeter clusters and the tracks, a number of discriminating variables are calculated.

### 2.4 Tau Identification

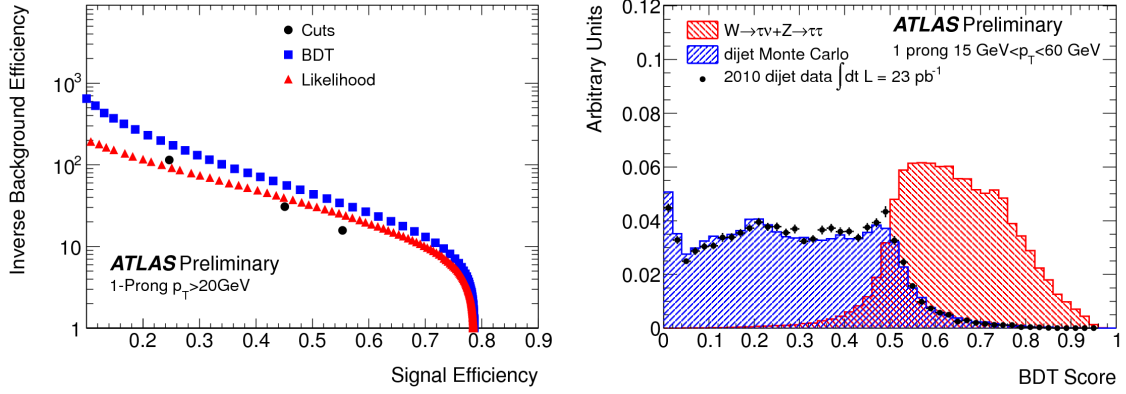
The discriminating power of the variables calculated at reconstruction level against electrons and jets is exploited with multi-variate techniques. Quantities such as the width of the energy deposits, the invariant mass of all calorimeter clusters, the transverse flight path significance to the primary vertex and the fraction of energy in the electromagnetic calorimeter to the momentum of the leading track are used in this way. Against multijets, ATLAS uses a simple cut-based method, a log likelihood discriminant (LLH) or boosted decision trees (BDT) [9]. A comparison of the performance of these three techniques can be seen in Fig. 1 for one prong taus. The BDT identification method is doing best with a background rejection factor in the range 20 – 50 for a signal efficiency of 60%, and a rejection factor of up to  $\sim 300$  for a signal efficiency of  $\sim 35\%$ . There is also a cut-based approach to electron background rejection, as well as an electron BDT. For both types of background, the BDT are doing best. The BDT method results in a continuous score on which one can choose a signal efficiency. The BDT score for one prong taus is also shown in Fig. 1.

### 2.5 Tau Identification Efficiency Measurements

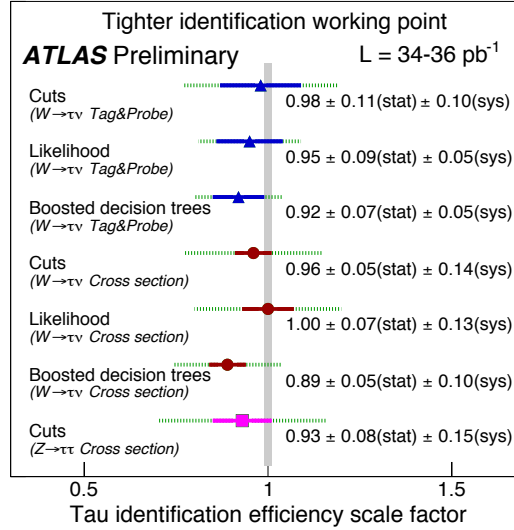
ATLAS validated the different tau identification methods in data using  $W \rightarrow \tau\nu$  and  $Z \rightarrow \tau\tau$  events [10]. The tau identification efficiency measured in data using these techniques is found to agree with the simulation expectations. Examples of tau identification efficiency scaling factors<sup>3</sup> and their uncertainties are shown in Fig. 2. These earlier scaling factors have been used in the  $Z \rightarrow \tau\tau$  cross-section measurement presented next. More recent measurements of these scaling factors show an agreement between simulation and measurement within 5% [11]. These more recent measurements have been used in the MSSM Higgs search presented next.

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<sup>3</sup>Ratio of the value measured in data over the expected value from simulation.



**Figure 1:** Performance of the different tau identification methods given as multijet background rejection vs. tau identification efficiency for one prong taus (left). Multijet background and tau signal distributions for the output BDT score for one prong taus (right) [9].

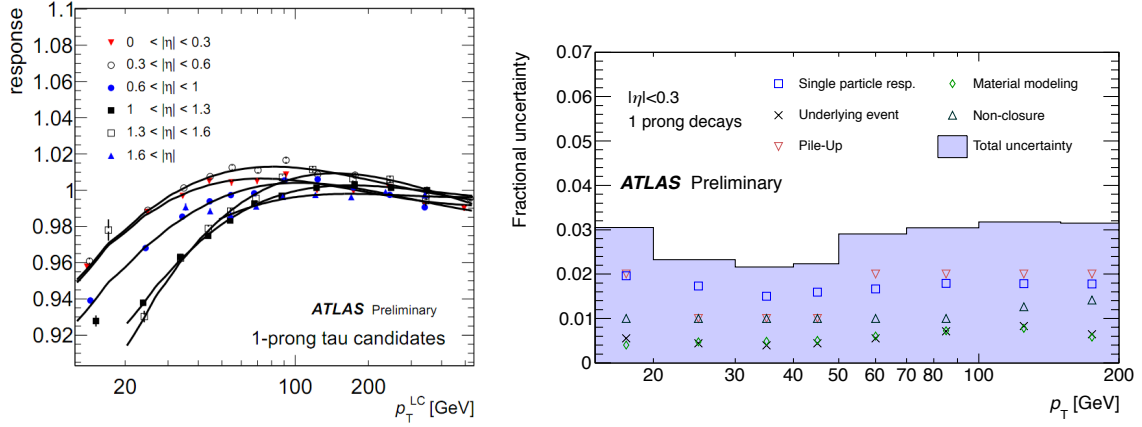


**Figure 2:** Tau Identification efficiency scaling factors between measured efficiency in data and efficiency predicted in simulation for the different ATLAS tau identification techniques and efficiency measurement methods for a low efficiency, high rejection (tight) working point. The solid bars are for the statistical uncertainty while the green dotted bars are for the systematic uncertainties [10].

## 2.6 Tau Energy Scale

The energy of reconstructed taus at ATLAS is calibrated using simulation. The tau energy scale correction is applied on top of the local hadronic calibration<sup>4</sup> (LC) that is applied on topological clusters. The correction is derived from inverted response functions calculated in simulation. Figure 3 shows such response functions as a function of tau transverse momentum ( $p_T$ ) in different detector regions and it also shows an example of the systematic uncertainties on the tau energy

<sup>4</sup>The local hadronic calibration aims at calibrating one calorimeter topological cluster at a time according to their resemblance to hadronic-like showers or electromagnetic-like showers.



**Figure 3:** Simulated calorimeter response as a function of tau  $p_T$  for different pseudorapidity regions of the detector for 1 prong taus (left) [11]. Systematic uncertainty on the tau energy scale as a function of tau  $p_T$  for 1 prong taus in the central detector region broken down by source (right) [12].

scale, broken down by source of uncertainty.

### 3. $Z \rightarrow \tau\tau$ Cross-section Measurement

ATLAS has been searching for  $Z \rightarrow \tau\tau$  events in order to commission tau identification and reconstruction [3]. A  $Z \rightarrow \tau\tau$  event can have fairly different signatures depending on how the taus decay. Ditau signatures are grouped in three categories:  $\tau_e\tau_\mu$ ,  $\tau_\ell\tau_h$  and  $\tau_h\tau_h$ . The  $\tau_\mu\tau_h$  is the most sensitive signature at ATLAS, having a clear muon signal and a large enough branching fraction.

#### 3.1 Most Important Background Events

Many Standard Model processes can look like ditau production. A  $W$  decaying to a light lepton can be accompanied by a jet which fakes a hadronic tau decay. This background is especially important in the  $\tau_\ell\tau_h$  channel. Muons and electrons in  $Z \rightarrow \ell\ell$  events can occasionally fake hadronic tau decays as well, which constitute the second most difficult background for all channels considered.  $t\bar{t}$  events are complex, and they feature various jets and leptons. They are easier to eliminate due to the larger number of objects and larger transverse momentum in the event, but incompletely reconstructed  $t\bar{t}$  events can still make it through a  $Z \rightarrow \tau\tau$  event selection. Finally, the multijet background is the most difficult for all channels. It can happen that one jet fakes an electron or even have a pion decay to a muon, while another jet fakes a hadronic tau decay. However, The reconstructed leptons from multijets, faked or real, often have other jet particles in their immediate neighbourhood. Leptons from real ditau events are usually isolated.

#### 3.2 Event Selection

The following event selection is applied to suppress the various backgrounds. First, only collisions in which an electron or a muon has been noticed by the trigger system are recorded. Electrons are noticed if they have  $p_T$  greater than 20 GeV or 22 GeV, depending on the instantaneous luminosity, while muons are noticed if they have  $p_T > 18$  GeV. Non-collision events, misreconstructed

or noisy events are then identified and removed. Then, one identified hadronic tau decay is required with exactly one isolated electron or muon of opposite charge. The isolation criteria consist in requiring that the ratio of the  $p_T$  found in a ring around the lepton to the  $p_T$  of the lepton itself be small. Any imbalance of momentum in the transverse plane (called missing  $E_T$  at ATLAS) in the event must be found between the taus, which is a clear sign that the imbalance is real and caused by the neutrinos of the tau decays. An upper bound of 50 GeV is applied on the transverse mass of the lepton and the missing  $E_T$ , which is a good discriminant against  $W$  events. Then, an invariant mass from the visible decay products of the two taus is reconstructed, which is shown in Fig. 4. A window between 35 and 75 GeV on this so-called visible mass is chosen as the signal region.

### 3.3 Background Estimation Methods

The number of background events that survive the selection must be precisely estimated. For  $W$  production with accompanying jets, the shape of the distribution in the visible mass signal window is estimated from simulation but the normalization is taken from a control region in data defined by large transverse mass values. For the multijet background, a so-called ABCD method is used. Four regions are defined by whether or not the lepton opposite to the hadronic tau is isolated, and whether or not it has the same charge as the hadronic tau decay. Both requirements, when inverted, produce control regions with large dominant multijet production. The ratio of opposite charge to same charge jets is taken from the non-isolated regions (C and D), and then the ratio is applied to the number of events found in region B (same charge, isolated lepton) to find the contamination from multijets in the signal region A (opposite charge, isolated lepton). This method assumes that lepton charge and isolation are uncorrelated. The contamination from electroweak and  $t\bar{t}$  must also be estimated in regions B, C and D. The  $Z$  and  $t\bar{t}$  backgrounds are estimated directly from simulation.

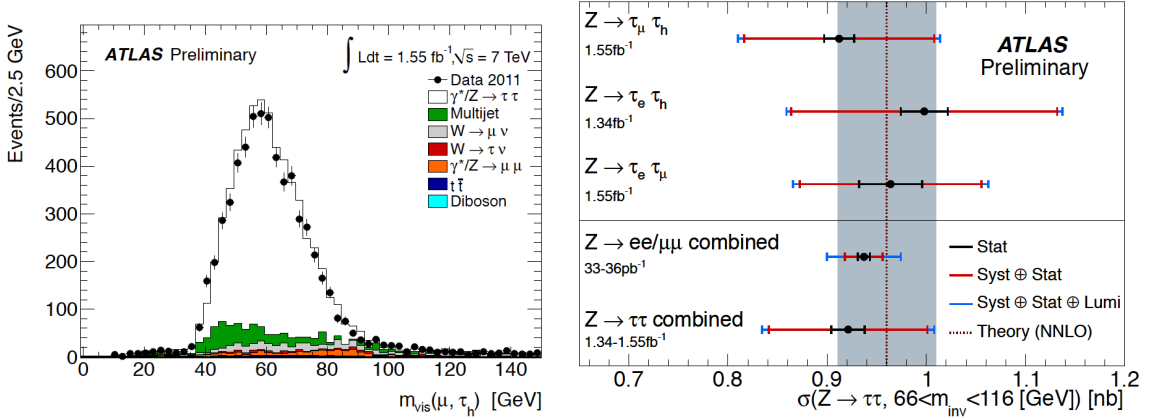
### 3.4 Cross-section

The resulting measured  $Z \rightarrow \tau\tau$  cross-section is obtained by subtracting the estimated number of background events from the number of observed events in the signal region, and then taking into account factors for the geometrical acceptance of the detector and the kinematic region probed by the analysis, the efficiency of the event selection, and the luminosity. The measured cross-sections for the different  $Z \rightarrow \tau\tau$  channels are shown in Fig. 4, as well as the combined  $Z \rightarrow \tau\tau$  cross-section.

## 4. Search for neutral MSSM Higgs bosons decaying to pairs of tau leptons

### 4.1 Introduction to the MSSM Higgs search

Tau leptons are very important for supersymmetry searches at ATLAS [14]. The Minimally Supersymmetric Standard Model (MSSM) requires two scalar Higgs doublets. The doublets decompose in 5 Higgs bosons which break electroweak symmetry, three of which are neutral (referred to as  $h$ ,  $H$  and  $A$ ) and two of them are charged ( $H^\pm$ ). The masses, widths and branching ratios of the five Higgs bosons are functions of only two parameters at leading order typically chosen to be  $m_A$ , which is the mass of the  $A$  and  $\tan\beta$ , which is the ratio between the vacuum expectation values



**Figure 4:** Data vs. simulation comparison for the invariant mass of the visible parts of the tau decays after full  $Z \rightarrow \tau\tau$  event selection (left). Cross-section measurements for  $Z \rightarrow \tau\tau$  broken down by signature and for the combined signatures (right) [13].

of the two Higgs doublets. For all these Higgs bosons, signatures with tau lepton final states are enhanced for large portions of the  $(m_A, \tan\beta)$  parameter space. In the search for neutral MSSM Higgs bosons, the  $\tau_e \tau_\mu$ ,  $\tau_\ell \tau_h$  and  $\tau_h \tau_h$  signatures are all considered.

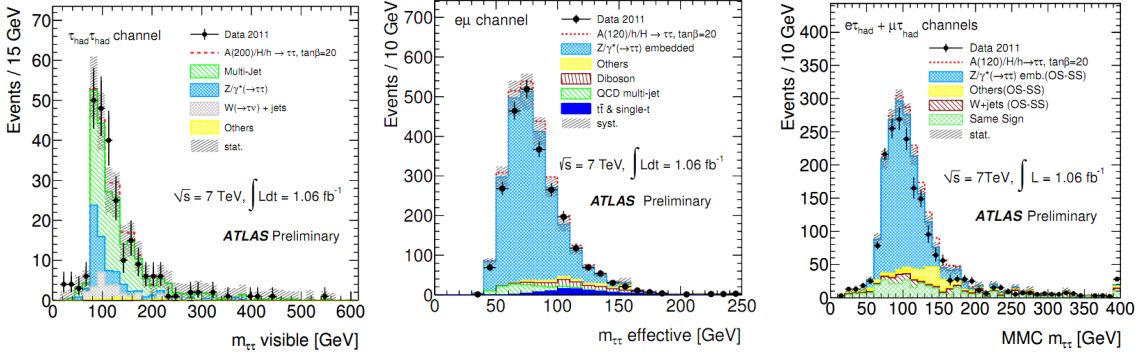
#### 4.2 Most Important Background Events

The most important backgrounds to the search for neutral MSSM Higgs bosons are essentially the same as that for the  $Z$  boson, except that more rare and more energetic events like single top production and diboson production also become important. Of course,  $Z \rightarrow \tau\tau$  itself becomes a background. The multijets are especially important in the  $\tau_h \tau_h$  channel.

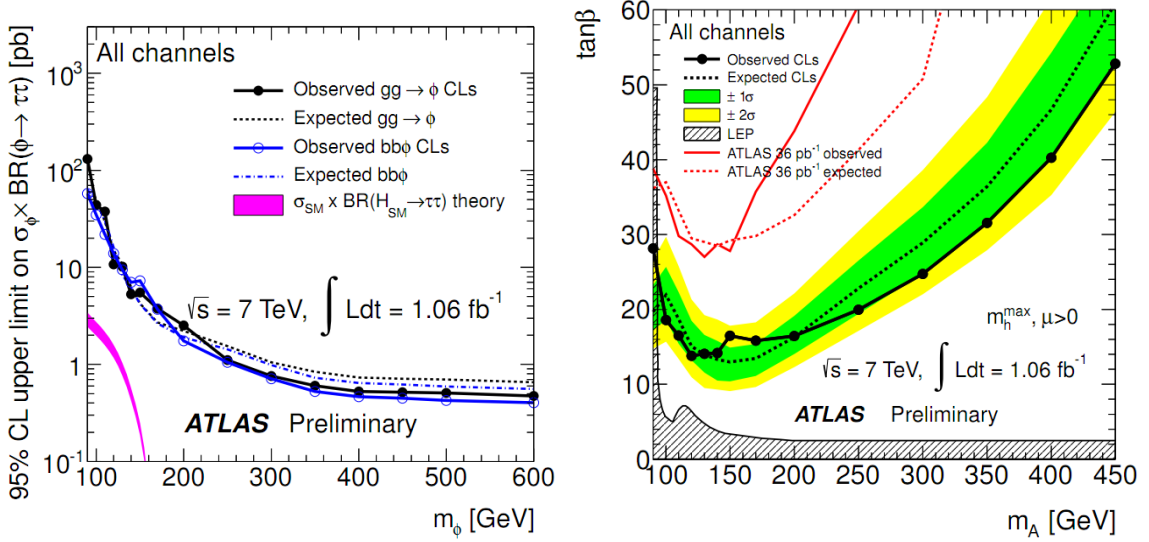
#### 4.3 Ditau Invariant Mass Reconstruction Techniques

An interesting aspect of the search for a ditau signature is the reconstruction of the invariant mass of the source of the pair of taus. Since neutrinos are always part of tau decays, special invariant mass reconstruction techniques are sometimes used. The current search of the MSSM Higgs bosons made use of three different techniques. The first, used in the  $\tau_h \tau_h$ , consists in simply ignoring the neutrinos, by calculating the invariant mass using only the visible decay products. This has also been done in the  $Z \rightarrow \tau\tau$  analysis previously discussed. The second technique, called the effective mass, consists in taking the two transverse components from the missing  $E_T$  and summing them (as a 4-vector with no mass or longitudinal component) with the visible four-momenta of the two taus. The third technique, used in the  $\tau_\ell \tau_h$  is the missing mass calculator [15], which uses the measured kinematics in the event to constrain the 4-vector of the neutrinos from the tau decays. By using probability distributions for the angle between the visible and invisible decay products of the taus, additional constraints are added and the most likely solution is chosen. The missing mass calculator is becoming more and more popular in ditau searches at ATLAS because of its superior performance. Reconstructed masses for the different techniques used in the different channels are shown in Fig. 5.





**Figure 5:** Visible mass spectrum in the MSSM  $A/H/h \rightarrow \tau_h \tau_h$  search (left). Effective mass spectrum in the MSSM  $A/H/h \rightarrow \tau_e \tau_\mu$  search (middle). Missing mass calculator mass spectrum in the MSSM  $A/H/h \rightarrow \tau_\ell \tau_h$  search (right) [14].



**Figure 6:** Exclusion limits for a generic resonance to a pair of tau leptons with the Standard Model Higgs boson as a reference (left). Exclusion limits on the MSSM  $(m_A, \tan\beta)$  parameter space (right) for the  $m_h^{\max}$ . In both plots, the region above the observed limit is excluded to 95% confidence [14].

#### 4.4 Exclusion Limits

The search for a neutral MSSM Higgs boson yields two exclusion results. The first is for the cross-section of a generic Higgs boson. The second is excluding regions in the  $(m_A, \tan\beta)$  parameter space. Both are shown in Fig. 6. ATLAS has yielded no positive results for supersymmetry so far. The experimental constraints are being tightened and the search is still ongoing.

#### 5. Conclusion

ATLAS has a very active programme in tau physics, which include both Standard Model and new physics measurements. The tau reconstruction and identification algorithms used by the experiment have proven effective at providing discrimination against QCD jets and electrons in such

measurements, which is crucial to establish the presence of taus in any event. These algorithms are fully commissioned and validated in data. ATLAS is already producing exclusion results in supersymmetry. Tau reconstruction and identification at ATLAS are in constant evolution. Any improvement in reconstructing and identifying taus results in higher sensitivity in any search for which taus are an important part of the event signature.

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