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# 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 that of electroweak symmetry breaking. It is a proton-proton collider making 27km in circumference, and it has provided the ATLAS detector with 4.7fb$^{-1}$of data ready for analysis in 2011 which represents about $5 \times 10^{15}$ inelastic proton-proton interactions.

The ATLAS detector[1] is a cylindrical apparatus of 25m in diameter composed of many subdetectors layered in an onion-like structure. At its very core is a high precision tracking system for charged particles in a 2T 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 dedicated magnetic field of 4T, provided by three air-core toroids (one for the middle section and two for the end caps).

### 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 $W \to \tau\nu$ [2] and $Z \to \tau\tau$ [3] signatures. ATLAS has also measured the $t\bar{t}$ cross-section with tau final states [4]. The $H \to \tau\tau$ 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 1.777GeV and a proper decay length of

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

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

87$\mu$m [6] which is just long enough so that it is possible under special circumstances[1] to resolve the tau decay vertex within the ATLAS detector.

Tau leptons decay via the weak interaction either to leptons and neutrinos only (leptonic decays, $\tau_\ell$[2]) 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 electromagnetically 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 they usually 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.

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[1] The tau decay must produce more than one charged particle for a secondary vertex to be reconstructed.

[2] 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 invariant mass that is usually larger than the tau mass is obtained. On the other hand, 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$-k_t$ 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 see 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 ∼300 for a signal efficiency of ∼35%. There is also a cut-based approach to electron background rejection, as well as a BDT approach. For both types of background, the BDT are doing best. The BDT method classifies regions in the multi-dimensional space determined by input discriminating variables according to their signal and background purities. The classification is the result of multiple successive trials, each new trial attempting to better classify regions that were misclassified in previous trials, a procedure referred to as boosting. The product of each trial is a binary decision tree. A specific tau candidate will receive a score that is a linear combination of the signal purities determined by each decision tree of the BDT. The BDT score for one prong taus is shown in Fig. 1.

### 2.5 Tau Identification Efficiency Measurements

ATLAS validated the different tau identification methods in data using $W \to \tau\nu$ and $Z \to \tau\tau$ 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[3] and their uncertainties are shown in Fig. 2. These earlier scaling factors have been used in the $Z \to \tau\tau$ cross-section measurement presented next. More recent measurements of these scaling

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[3] Ratio of the value measured in data over the expected value from simulation.

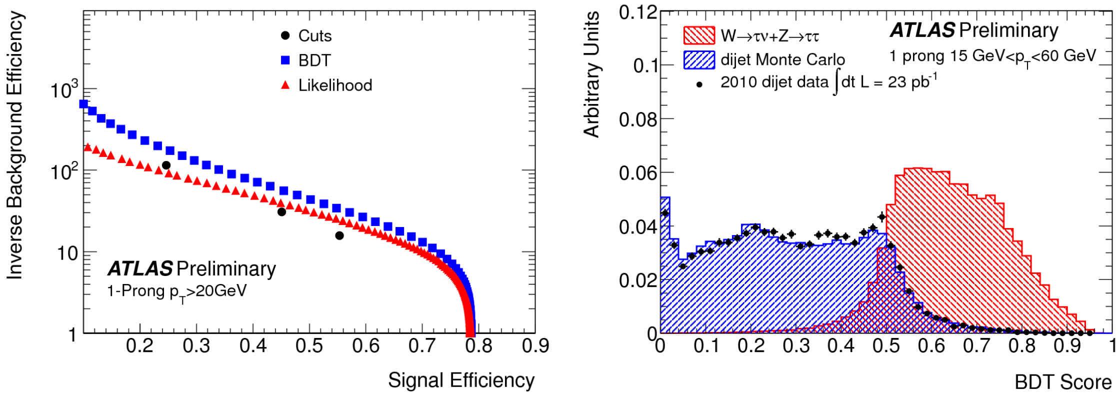

**Figure 1:** Performance of the different tau identification methods given as multijet background rejection vs. tau identification efficiency for one prong taus (left). Multijet background and tau signal distributions for the output BDT score for one prong taus (right) [9].

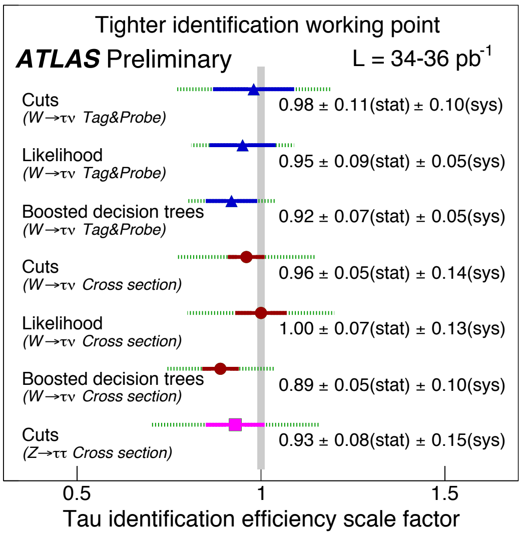

**Figure 2:** Tau Identification efficiency scaling factors between measured efficiency in data and efficiency predicted in simulation for the different ATLAS tau identification techniques. The scale factors are given for different efficiency measurement methods for a low signal efficiency, high background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

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.

### 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[4] (LC) that is applied on topolog-

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[4] The local hadronic calibration aims at calibrating one calorimeter topological cluster at a time according to their

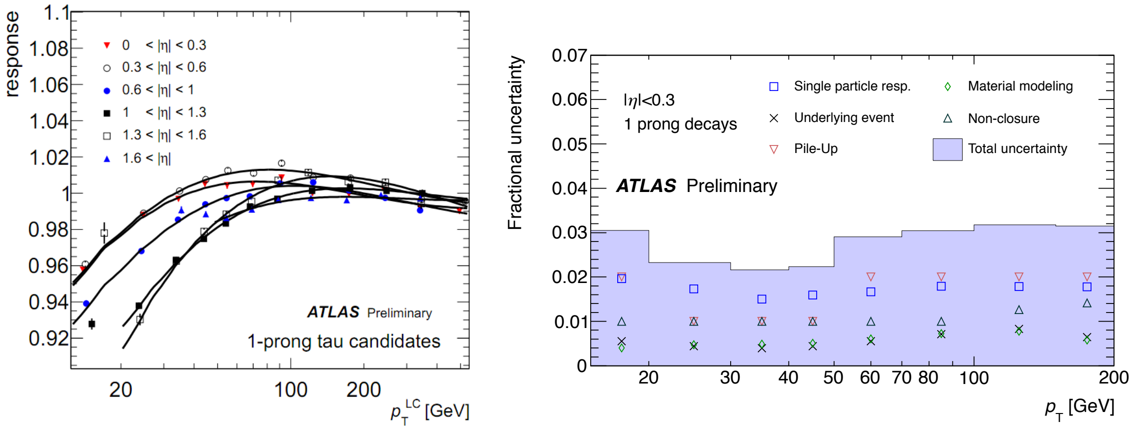

**Figure 3:** Simulated calorimeter response as a function of tau $p_{\mathrm{T}}$ for different pseudorapidity regions of the detector for 1 prong taus (left) [11]. Systematic uncertainty on the tau energy scale as a function of tau $p_{\mathrm{T}}$ for 1 prong taus in the central detector region broken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

ical 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 ($p_{\mathrm{T}}$) in different detector regions and it also shows an example of the systematic uncertainties on the tau energy scale, broken down by source of uncertainty.

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

ATLAS has been searching for $Z \to \tau\tau$ events in order to commission tau identification and reconstruction [3]. A $Z \to \tau\tau$ 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 $Z \to \ell\ell$ 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 events can still make it through a $Z \to \tau\tau$ 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.

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resemblance to hadronic-like showers or electromagnetic-like showers.

### 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 identified by the trigger system are recorded. Electrons are noticed if they have $p_{\mathrm{T}}$ greater than 20 GeV or 22 GeV, depending on the instantaneous luminosity, while muons are noticed if they have $p_{\mathrm{T}} > 18$ 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 $p_{\mathrm{T}}$ found in a ring around the lepton to the $p_{\mathrm{T}}$ of the lepton itself be small. Any imbalance of momentum in the transverse plane (called missing $E_{\mathrm{T}}$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 $E_{\mathrm{T}}$, 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 $Z \to \tau\tau$ 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 $Z \to \tau\tau$ channels are shown in Fig. 4, as well as the combined $Z \to \tau\tau$ 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

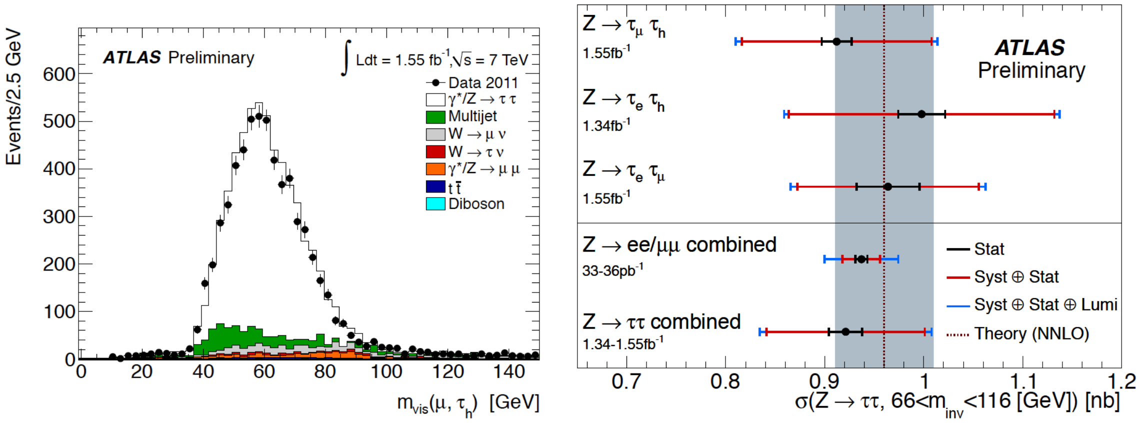

**Figure 4:** Data vs. simulation comparison for the invariant mass of the visible parts of the tau decays after full $Z \to \tau\tau$ event selection (left). Cross-section measurements for $Z \to \tau\tau$ broken down by signature and for the combined signatures (right) [13]. The theoretical cross-section is given for $Z$ invariant masses between 66 and 116 GeV.

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 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, $Z \to \tau\tau$ 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 makes 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 $Z \to \tau\tau$ 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.

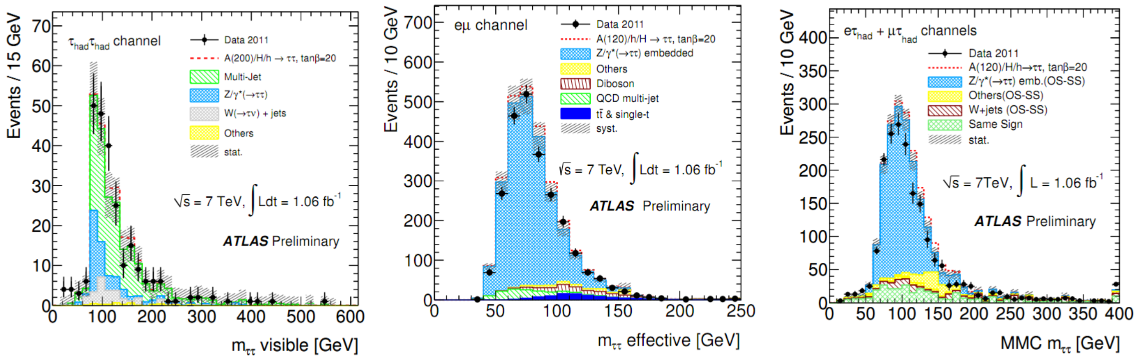

**Figure 5:** Visible mass spectrum in the MSSM $A/H/h \to \tau_h \tau_h$ search (left). Effective mass spectrum in the MSSM $A/H/h \to \tau_e \tau_\mu$ search (middle). Missing mass calculator mass spectrum in the MSSM $A/H/h \to \tau_\ell \tau_h$ search (right) [14].

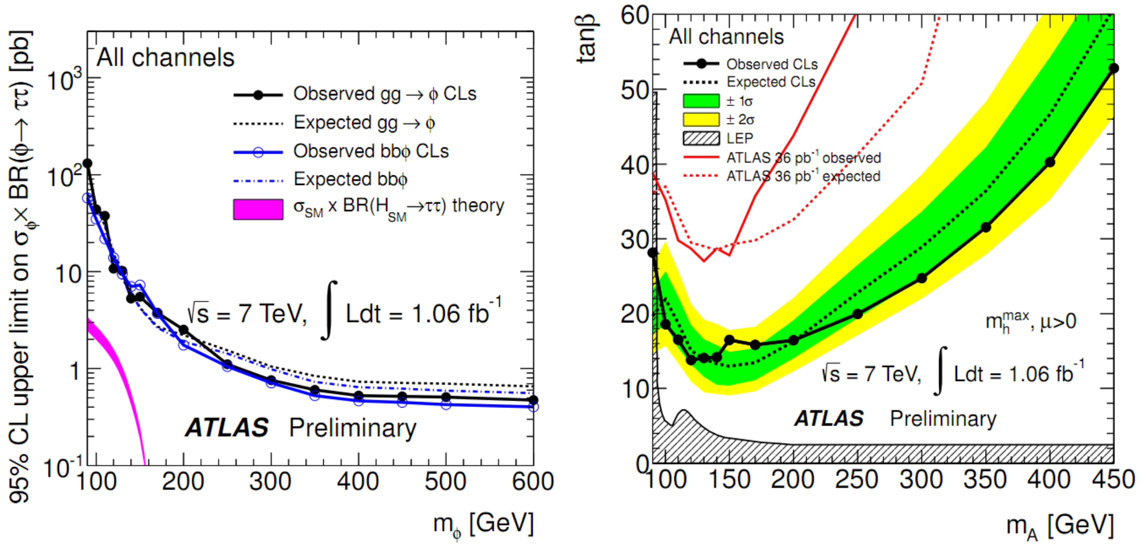

**Figure 6:** Exclusion limits for a generic resonance to a pair of tau leptons with the Standard Model Higgs boson as a reference (left). Exclusion limits on the MSSM $(m_A, \tan\beta)$ parameter space (right) for the $m_h^{\max}$. In both plots, the region above the observed limit is excluded to 95%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

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.

### 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.

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## 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.

## References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* 2008 3 S08003

[2] ATLAS Collaboration, *Measurement of the W to tau nu Cross Section in pp Collisions at sqrt(s) = 7 TeV with the ATLAS experiment*, *Phys.Lett. B* **706** (2012) 276-294 [`hep-ex/1108.4101`]

[3] ATLAS Collaboration, *Measurement of the Z to tau tau Cross Section with the ATLAS Detector*, *Phys.Rev. D* **84** (2011) 112006 [`hep-ex/1108.2016`]

[4] ATLAS Collaboration, *Measurement of the $t\bar{t}$ production cross section in the final state with a hadronically decaying tau lepton and jets using the ATLAS detector*, CERN, Geneva 2011 [`ATLAS-CONF-2012-032`]

[5] ATLAS Collaboration, *Combined search for the Standard Model Higgs boson using up to 4.9fb$^{-1}$ of pp collision data at $\sqrt(s) = 7$TeV with the ATLAS detector at the LHC*, *Phys. Lett. B* **710** (2012) 49-66

[6] K. Nakamura et al. (Particle Data Group), *The Review of Particle Physics*, *J. Phys.* **G 37** (075021) (2010) and 2011 partial update for the 2012 edition.

[7] ATLAS Collaboration, *Calorimeter Clustering Algorithms : Description and Performance*, CERN, Geneva 2008 [`ATL-LARG-PUB-2008-002`]

[8] M. Cacciari, G. P. Salam and G. Soyez, *The anti-$k_t$ jet clustering algorithm*, *JHEP* 0804:063 2008 [`hep-ph/0802.1189v2`]

[9] ATLAS Collaboration, *Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment*, CERN, Geneva 2011 [`ATLAS-CONF-2011-077`]

[10] ATLAS Collaboration, *Measurement of hadronic tau decay identification efficiency using Wtaunu events*, CERN, Geneva 2011 [`ATLAS-CONF-2011-093`]

[11] ATLAS Collaboration, *Performance of the Reconstruction and Identification of Hadronic Tau Decays with ATLAS*, CERN, Geneva 2011 [`ATLAS-CONF-2011-152`]

[12] ATLAS Collaboration, *Tau Energy Scale Uncertainty plots for Winter 2012*, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauPublicCollisionResults

[13] ATLAS Collaboration, *$Z \rightarrow \tau\tau$ cross section measurement in proton-proton collisions at 7 TeV with the ATLAS experiment*, CERN, Geneva 2012 [`ATLAS-CONF-2012-006`]

[14] ATLAS Collaboration, *Search for neutral MSSM Higgs bosons decaying to tau+tau- pairs in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector*, CERN, Geneva 2011 [`ATLAS-CONF-2011-132`]

[15] A. Elagin, P. Murat, A. Pranko and A. Safonov, *A New Mass Reconstruction Technique for Resonances Decaying to di-tau*, *Nucl.Instrum.Meth.* **A654** (481-489) [`hep-ex/1012.4686`]