Tau Physics with First Data in ATLAS

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Tau leptons, and particularly their hadronic decays, will play an important role at the LHC. The goals for early tau physics in ATLAS include collecting a sample of tau leptons from data with a purity as high as possible so that the identification efficiency of hadronically decaying tau leptons can be measured and the simulation can be tuned. Collecting data with an integrated luminosity of a few hundred pb^{-1} at an instantaneous luminosity of 10^{31} cm^{-2}s^{-1} will provide a unique opportunity in ATLAS to access and understand statistically significant tau samples from Standard Model processes at relatively low transverse momenta. Identification of tau leptons in ATLAS is particularly challenging due to overwhelming background coming from QCD dijet production. Processes like the production of W and Z bosons and top quark pairs will lead to samples of a few hundred to a few thousand identified hadronic tau decays. Hadronically decaying tau leptons will then become a well understood probe for discovery physics like searches for Higgs bosons, SUSY, or exotic phenomena. Feasibility studies for analyses which can be envisaged with an integrated luminosity of 100 pb^{-1} to 1 fb^{-1} are presented.

1. Introduction

The tau leptons are an excellent signature to probe new physics. As the heaviest leptons, they have the largest coupling to the Higgs boson both in the Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM). Their production and decay are well separated in time and they offer potential for measurements of the polarisation and parity of decaying heavier objects [1]. The signature of two tau leptons in the same event is important in the high mass resonance searches. In particular, there are models in which a hypothetical new resonance couples preferentially to third generation fermions [2]. For these models the branching fractions are such that the dielectron and dimuon channels are not viable, hence it is crucial to consider the two tau leptons channel.

The observation of tau leptons in the ATLAS [3] experiment will be possible already at the beginning of data taking with large statistics of $W \to \tau\nu$, $Z \to \tau\tau$ and $t\bar{t}$ events. These processes used as control channels will be important for detector calibration, background normalisation for Higgs boson and Beyond the Standard Model (BSM) searches, for tuning offline reconstruction and identification algorithms as well as estimating tau trigger efficiencies from data.

The tau lepton decays to hadronic states in 65% of all cases, and the remaining fraction of the decays are to lighter leptons (e or μ, accompanied by neutrinos). Amongst hadronic tau decays one distinguishes one- and three-prong decays resulting in one or three charged hadrons (predominantly pions) in the final state, respectively. At hadron colliders final states involving taus are challenging from the experimental point of view. In practice it will not be possible to discriminate between prompt light leptons and leptons from tau decays, the hadronic decay modes will be the signature of tau production. A very good identification of hadronically decaying tau leptons is thus decisive for the rejection of events from the overwhelming QCD dijet production. The energy of tau leptons cannot be measured directly as neutrinos in the tau decay carry off energy and give rise to missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). Excellent $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution in the ATLAS detector is important for channels requiring reconstruction of the invariant mass of the resonance decaying to tau leptons. All studies presented here refer to proton-proton collisions at a 14 TeV centre-of-

mass energy.

2. Tau leptons in SM processes

2.1. The $W \to \tau\nu$ inclusive production

The $W \to \tau\nu$ signal, produced with cross section times branching fraction of $1.7 \cdot 10^4$ pb, is the most abundant source of tau leptons in early running. The signal will be dominated by events with low p_T of the W-boson resulting in soft tau leptons with low missing transverse energy. The main background coming from QCD dijet production will exceed the signal production by six orders of magnitude. Other backgrounds comprise $W \to \ell\nu$, $(\ell = e, \mu)$, $t\bar{t}$, $Z \to \tau\tau$ and $Z \to ee$.

Events will be selected using a combined tau and missing E_T trigger. Given the allowed budget for the trigger rates, this configuration will be possible only for early running with an instantaneous luminosity of $10^{31} \text{cm}^{-2}\text{s}^{-1}$. The trigger efficiency will be measured from data using a multi-jet trigger as described in Sect. 2.3. The present trigger optimisation gives an overall trigger efficiency of 70% with respect to the offline analysis [4]. The signal will be extracted requiring one identified hadronic tau lepton (τ^{had}) with transverse energy E_T= 20-60 GeV, $E_T^{miss} > 60$ GeV and one jet in the event with $p_T > 15$ GeV. The backgrounds are further suppressed by rejecting events with an additional isolated electron or muon. To maximise the signal significance a veto on events with large fake missing E_T is applied by excluding those where the missing E_T direction is close to the direction of the identified tau lepton or the additional jet. The same trigger stream but with an identified electron instead of a hadronic tau will provide a control sample to model W-recoil and $W \to e\nu$ backgrounds in the identified tau sample.

The measurement is a counting experiment. It will be performed by observing an excess of events above the background level with the track multiplicity spectrum of identified tau leptons showing a characteristic behaviour (suppression of two-prong candidates with respect to one and three prong taus). For 100 pb^{-1} of integrated luminosity 1550 signal events are expected with a signal-to-background (S:B) ratio of 3:1. Figure 1 shows

the expected track multiplicity spectrum after the final selection.

The dominant source of systematic uncertainties comes from modelling of the dijet background in Monte Carlo. Hence the final optimisation of the tau identification and the E_T^{miss} cuts will be tuned with data. The signal-free region in the track multiplicity spectrum, populated by fake τ^{had} with more than three tracks, will be used to control the QCD background normalisation.
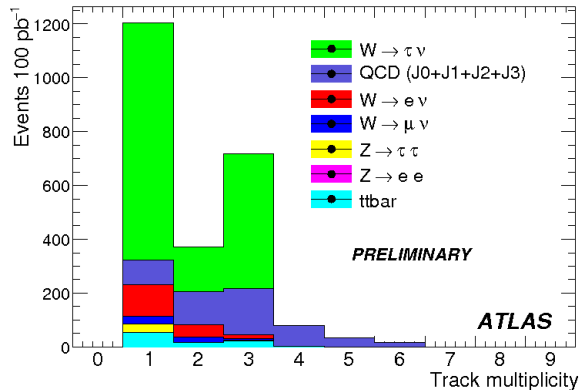

Figure 1. The track multiplicity spectrum for an integrated luminosity of 100 pb^{-1}.

2.2. The $Z \to \tau\tau$ inclusive production

The $Z \to \tau\tau$ process, although with a ten times lower rate compared to $W \to \tau\nu$, will have more robust prospects for analysis. Observation of the signal is foreseen in the lepton-hadron final state to provide the best signal to background ratio due to an isolated lepton. Events will be selected with a lepton trigger providing an unbiased sample of hadronic tau decays which can be used to understand efficiencies of the hadronic tau trigger.

The backgrounds for this analysis are the QCD dijet production, $W \to \ell\nu$, $Z \to \ell\ell$, $(\ell = e, \mu)$ as well as the $t\bar{t}$ processes. The signal will be extracted offline requiring one lepton with $p_T > 15$

GeV and one identified hadronic tau with $p_T>$ 15 GeV, which are well separated. A set of additional cuts is applied to suppress the backgrounds:

- $E_T^{miss}>$ 20 GeV (to suppress $Z \to \ell\ell$ and QCD backgrounds).

- Transverse mass (m_T) of the lepton and E_T^{miss} system $m_T < 30$ GeV (against W+jets background).

- Total transverse energy deposited in the calorimeter $E_T^{calo} < 400$ GeV (against $t\bar{t}$ and QCD backgrounds).

- No identified b-jet (against $t\bar{t}$ and QCD backgrounds).

Assuming 100 pb^{-1} of data, about 520 events are expected in the window in the invisible mass of 35-70 GeV with an S:B ratio of 5:1. The reconstructed visible mass is shown in Fig. 2.

The selection of $Z \to \tau\tau$ events allows to cross check channels with electron-τ^{had} and muon - τ^{had} final states to control the background, comparing the number of same-sign charge (SS) and opposite-sign charge (OS) events. Once the lepton identification and trigger efficiencies will be obtained from $Z \to \ell\ell(\ell = e, \mu)$ channels, the measured cross-section for the $Z \to \tau\tau$ process will allow studies of tau identification and mistagging efficiency.

Once the lepton energy scale is determined with the very first data, the invariant mass of the visible decay products of the tau lepton pair allows to calibrate the hadronic tau energy scale in situ. Figure 3 shows the sensitivity of the measured visible Z boson mass to the absolute tau energy scale assuming only signal events. Assuming 100 pb^{-1} of data and including statistical uncertainties only, the hadronic tau energy scale can be determined with a precision of 3 %.

2.3. The tau leptons from $t\bar{t}$ production

The process $t\bar{t} \to W(\to \tau\nu)W(\text{inclusive})b\bar{b}$, with a cross section times branching fraction of 165 pb is an additional large source of tau leptons from SM processes. The hadronic taus from this sample have a larger p_T range, complementary to that available from $W \to \tau\nu$ and $Z \to \tau\tau$ processes.
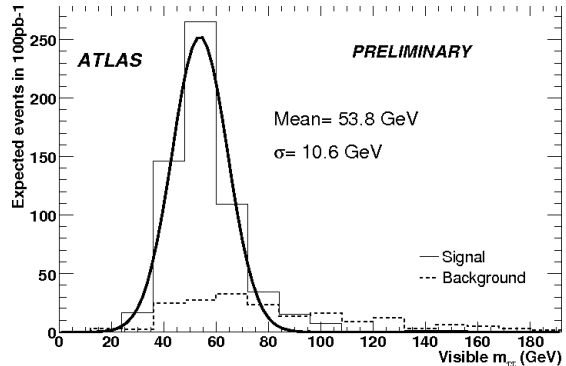
Figure 2. The reconstructed visible mass of the lepton-τ^{had} pair for a $Z \to \tau\tau$ signal (solid line) and backgrounds (dashed line). The fitted function is a single Gaussian.

The decay chain $t\bar{t} \to W(\to \tau\nu)W(q\bar{q})b\bar{b}$ can be selected using either tau triggers or multi-jet triggers. In the latter case this will lead to an unbiased sample of tau candidates which can be used to study the tau identification efficiency and to commission the tau and combined tau and missing E_T triggers. For 100 pb^{-1} of data roughly 300 signal events with S:B of 20:1 are expected.

The decay chain $t\bar{t} \to W(\to \tau\nu)W(\ell\nu)b\bar{b}$ is strongly dominated by $W \to \ell\nu+3$ jets events production. Using b-tagging techniques to suppress the background, 67 events can be observed for 100 pb^{-1} of data, with S:B of the order of 1:1.

3. Discovery physics with early data

In this section a generic two tau leptons resonance search for the first 100 pb^{-1} to 1 fb^{-1} of data is discussed. A wide range of models predict extra neutral gauge bosons; as a reference for these studies, the Sequential Standard Model (SSM) was assumed. Current experimental lower limits on the mass of the SSM Z' boson are derived from searches using high-mass tau pairs at the Tevatron experiments and are set to 400 GeV [5] at 95% confidence level. To study the potential for observing a Z' over a large mass
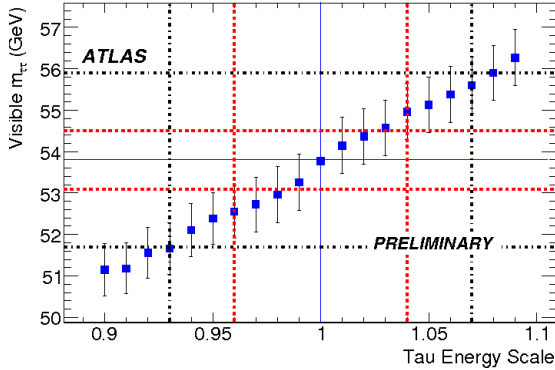
Figure 3. The reconstructed visible mass of the lepton-tau hadron pair from $Z \to \tau\tau$ decays as a function of the hadronic tau energy scale. The dashed lines correspond to $\pm 1\sigma$ and $\pm 3\sigma$ with respect to the reconstructed peak position.

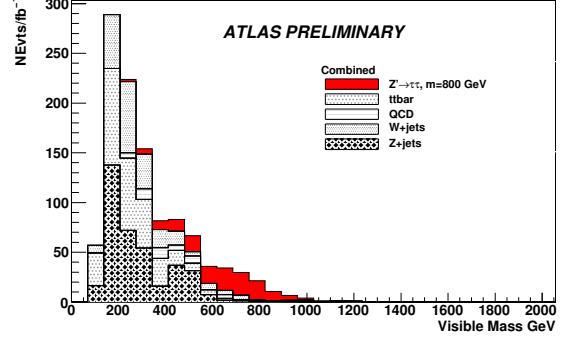Figure 4. The visible mass distributions obtained for all the final states and a Z' signal mass of 800 GeV for 1 fb^{-1} of data.

range, four different samples of a Z' in the SSM with masses equal to 600, 800, 1000 and 2000 GeV were considered.

3.1. Event selection

Events in the hadron-hadron (hh) channel are selected using a combined tau and missing E_T trigger whereas single lepton triggers are foreseen for the lepton-hadron (ℓh) and the lepton-lepton ($\ell\ell$) final states. In the analysis, hadronic tau candidates, electrons and muons must have $p_T > 60$ GeV, $p_T > 27$ GeV and $p_T > 22$ GeV respectively and fulfill the selection criteria described in [4].

To select events in the hh, ℓh and $\ell\ell$ final states, two τ^{had}, one τ^{had} and one lepton or two leptons of opposite charge are required respectively. The backgrounds to the two tau lepton channel comprise Drell-Yan (DY) production, W+jets, $t\bar{t}$ and QCD dijet events. After the initial object selection further requirements are imposed to maximise the signal significance:

- Significant E_T^{miss} (against DY processes, $Z \to \ell\ell$, ($\ell = e, \mu$) and QCD dijets with relatively low p_T).

- An upper bound on m_T (against W+jets).

- An upper bound on p_T^{tot} - total p_T of the event (against $t\bar{t}$ and QCD dijets).

- No identified b-jet (against $t\bar{t}$, $\ell\ell$ channel only).

In the case of the two tau leptons final state one cannot simply reconstruct the invariant mass of the resonance as energy is taken away from the event by the neutrinos. For all events selected by the above cuts a visible mass variable (m_{vis}) is constructed by adding the four momenta of the two identified tau visible decay products to the E_T^{miss} four-momentum (for which the z component is set to zero), and then calculating the visible mass of the sum [5]. To greatly help the background rejection and to restrict our search to the region of interest we require a lower cut on m_{vis}. The reconstructed mass (m_{col}) is calculated using the collinear approximation as $m_{\mathrm{col}} = m_{\tau\tau}^{\mathrm{vis}}/\sqrt{x_{\tau_1} \cdot x_{\tau_2}}$ [6] where $m_{\tau\tau}^{\mathrm{vis}}$ is the invariant mass of the two identified tau visible decay products and x_{τ_1} and x_{τ_2} are the fractions of the tau momenta carried by the visible decay daughters.

Since the collinear approximation becomes numerically instable when the two tau leptons are
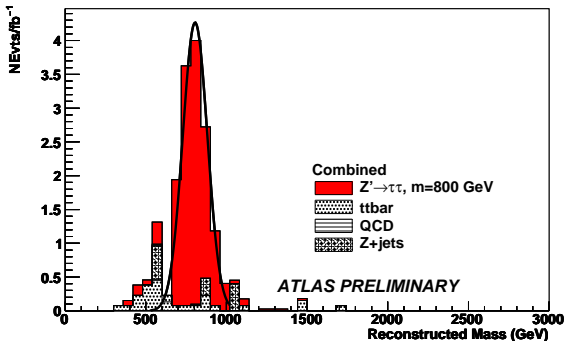
Figure 5. The reconstructed mass distributions obtained for all the final states and a Z' signal mass of 800 GeV for 1 fb^{-1} of data.

back-to-back, we impose the requirement that $\cos \Delta\phi_{12} > -0.99$, where $\Delta\phi_{12}$ is the opening angle in the transverse plane of the visible decay products of the two taus. Since a very heavy particle tends to be produced at rest, the decay objects are mostly back-to-back, leading to a highly inefficient mass reconstruction. Hence, it is expected that the search will proceed by looking at the visible mass. If a significant excess over the background is observed, the collinear approximation will then be used to help establish the presence of a new resonance.

3.2. Discovery potential

Figures 4 and 5 show the visible and the reconstructed mass shape obtained from the combination of all three final-states. In 1 fb^{-1} of ATLAS data we estimate in the $hh/\ell h/\ell\ell$ channel, 50.6/59.1/14.9 signal events and 22.6/35.1/18.2 background events after imposing the event selection up to the requirement of the visible mass. Here an 800 GeV Z' and the SSM cross section are assumed.

The hadron-hadron and lepton-hadron final-states are the most promising channels due to the larger branching fractions and higher signal-to-background ratios. The best mass resolution comes from the hadron-hadron channel (via the

collinear approximation) due to the fact that this final-state contains the fewest neutrinos (a Gaussian fit to the reconstructed signal peak for an 800 GeV Z' yields a mass resolution of $\sim 10\%$ in the hadron-hadron and 15% in the lepton-hadron final-state respectively). A total of four neutrinos from tau decays in the lepton-lepton final-state adversely affects the mass resolution in this channel. Since the SSM Z' is very narrow, the width of the resonance observed is completely dominated by the detector resolution.

3.2.1. Systematic Uncertainties

For an analysis of 1 fb^{-1} of data the dominant source of systematic uncertainties on the signal, just over $\pm 18\%$, comes from the uncertainty on the luminosity. The second most dominant systematic is the hadronic tau energy scale. The lowest mass signal is affected by 10%. The effect is less severe for higher masses due to the harder nature of taus coming from the Z' decay, which lie much further away from the p_T threshold used in the hadronic tau selection. Summing in quadrature the effects of all systematic uncertainties on the signal Monte Carlo sample results in a total systematic uncertainty of about $\pm 20\%$. As a conservative estimate, the total systematic uncertainty on the backgrounds is assumed to be identical to that observed in the signal Monte Carlo. This is a conservative estimate because the majority of the backgrounds in the data have very large cross-sections (dijets, W+jets, etc.) and the evaluation of systematic uncertainties there should be less sensitive to statistical fluctuations than for the signal events.

3.2.2. Significance

The significance is estimated using a formula based on the likelihood ratio method and assuming the Poisson distribution: $S = \sqrt{2\big((s+b)\ln(1+\frac{s}{b}) - s\big)}$. To gauge the discovery reach of these analyses, Fig. 6 shows the amount of integrated luminosity required for a 3σ evidence or a 5σ discovery as a function of the true mass of the Z'. If a Z' exists with a relatively low mass, and couples to the third family, it could be discovered in the two tau leptons final state with only a few hundred pb^{-1} of data.
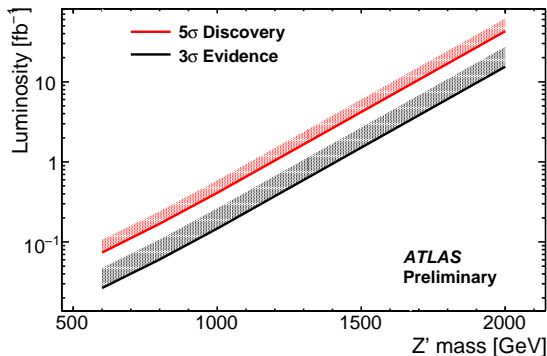
Figure 6. The luminosity required for a 3σ evidence or a 5σ discovery (all channels combined) as a function of the true Z' mass including 20% systematic uncertainty.

Figure 7 shows the cross-section required for a 3σ evidence or a 5σ discovery (all channels combined) as a function of the Z' mass given 1 fb^{-1} of data. The cross-section from the SSM, as a function of the true Z' mass, is superimposed. Assuming SSM couplings of the extra gauge boson to taus, we can reach a 5σ discovery limit if the Z' has a mass up to roughly 1200 GeV.

4. Summary

The ATLAS experiment has a well developed technique to extract tau signals in very early data from $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$ and $t\bar{t}$ events. Once a measurement of the identification and mis-tagging efficiencies as well as a calibration of the tau energy scale are performed, the tau leptons will then be used to search for new physics. If an extra gauge boson exists in the SSM, ATLAS could observe it in a relatively low mass region already with 100 pb^{-1} of data.

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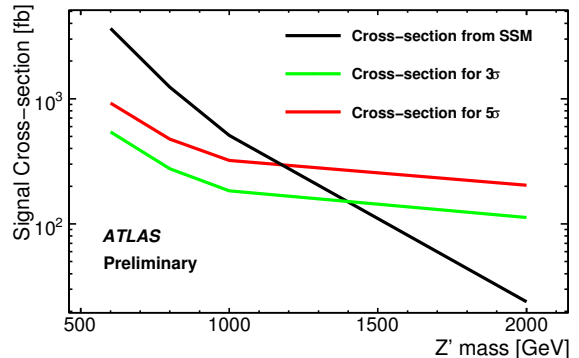
Figure 7. The signal cross-section required for a 3σ evidence or a 5σ discovery (all channels combined) as a function of the true Z' mass assuming 1 fb^{-1} of data. The signal cross-section from the SSM, as a function of the Z' mass, is superimposed.