Calorimeter Performance for Tau Reconstruction and Identification at ATLAS

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Abstract. The ATLAS physics program involving tau final states ranges from Standard Model measurements involving W, Z, and top pair production, to searches for the Higgs, Supersymmetry and other beyond the Standard Model signatures. The ATLAS calorimeter plays a crucial role in the reconstruction and identification of hadronically decaying tau leptons in ATLAS. This proceeding discusses the role of the calorimeter in reconstructing the tau energy, as well as methods to measure the systematic uncertainties on the tau energy scale. The calorimeter is further a key component in building identification variables used to differentiate tau candidates from hadronic jets. The role of these variables is presented, and the use of variables in high luminosity environments is also discussed. A brief overview of the impact of the tau energy scale and identification efficiency uncertainties in searches for new physics with tau-based signatures is also given.

1. Introduction

Tau leptons play a significant role in the LHC [1] physics program. For example, it is an important signature for the Higgs boson. Tau leptons decay hadronically 64.7% of the time, predominantly to one or three charged pions, a neutrino and often additional neutral pions. Hadronically decaying tau, are categorised by the number of charged decay products observed or prongs. Hadronic 1-prong decays are the most common (BR = 49.5%) followed by 3-prong decays (BR = 15.2%) [2].

The challenge in identifying hadronic tau decays at the LHC is that the cross section for multijet QCD production, which can be falsely identified as hadronic tau decays, is many orders of magnitude above the cross sections for weak interaction processes involving tau leptons. The most discriminating features for identifying taus among this background are the characteristic 1 or 3-prong hadronic tau signature, consequently low track multiplicity, and relatively narrow clustering of tracks and depositions in the calorimeters. Calorimeter and tracking information are combined into hadronic tau decay identification variables capturing these distinct features.

2. Reconstruction

Hadronic tau candidates [3] are seeded by jets with a transverse energy at the electromagnetic scale higher than 10 GeV. Tracks in the angular vicinity of the jet barycenter ($\Delta R = 0.2$) are associated with the hadronic tau candidate. The number of tracks within $\Delta R < 0.2$ is used

$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$

where the pseudorapidity, $\eta$, is defined as $\eta = -\ln(\tan(\frac{\theta}{2}))$ and the cylindrical coordinates $\phi$ and $\theta$ are defined in the usual way.
to classify the hadronic tau candidate into 1 or 3-prong categories. The collected tracks and calorimeter clusters from the jet are then used to calculate a number of identification variables. Variables based on calorimeter information are calculated from calorimeter cells in $\Delta R < 0.4$ around the hadronic tau candidate axis.

3. Identification

The track and calorimeter variables are combined into multivariate discriminants to reject misidentified jets and electrons. These algorithms take as inputs various quantities built from the calorimeters or the inner detector. While the tracking variables are less sensitive to pile-up due to vertex association, the calorimeter variables have higher sensitivity to the activity from pile-up interactions. To reduce the impact of the pile-up in calorimeter quantities, the hadronic tau cone is chosen to be as small as possible ($\Delta R < 0.4$). An example variable used for jet-tau discrimination is $R_{\text{cal}}$, the distribution of which is shown in Fig. 1. The fraction of transverse energy of the hadronic tau candidate deposited in the electromagnetic calorimeter is an example of a variable used to reject electrons (Fig 2).

**Figure 1.** Energy weighted shower width in the calorimeter, $R_{\text{cal}}$, for hadronic tau signal Monte Carlo (red) and compared to QCD di-jet data (black) [3].

**Figure 2.** The ratio of the transverse energy deposited in the electromagnetic calorimeter over the transverse momentum of the leading track for signal ($Z \rightarrow \tau\tau$ sample) and background ($Z \rightarrow ee$ sample) [3].

There are three independent methods for tau identification in ATLAS [4]: a cut based approach, placing cuts on variables, a projective likelihood method, using the log likelihood ratio of signal and background, and boosted decision trees (BDT), to find the optimal separation in a multi dimensional phase space. The methods have a different sets of identification variables and are separately trained for 1 and 3-prong hadronic tau candidates. Three dedicated working points with signal efficiencies with target efficiencies of approximately 60%, 45% and 30% (loose, medium, tight) are provided for all hadronic tau vs QCD jets identification. For the training of the identification algorithms, the QCD background is obtained from data, while the hadronic tau decay signal is simulated in $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ Monte Carlo samples. The inverse background efficiency versus signal efficiency for all three methods is shown for 1-prong in Fig 3. Electrons can also be misidentified as a hadronic tau due to the signature in the detector. They will be reconstructed mostly as a 1-prong hadronic tau decays.

\(^2\) Pile-up in the following refers to the contribution of additional $pp$ collisions superimposed on the hard physics process.
Selection on the output of the discriminants is used to select a sample of hadronic tau candidates with the desired level of background rejection or signal efficiency.

4. Identification efficiency measurements in data
The performance and systematic uncertainties of the hadronic tau identification methods are evaluated on data using two different signal channels [3]. The first method uses \( Z \rightarrow \tau\tau \) events in 800 pb\(^{-1}\) of ATLAS data and relies on a tag-and-probe method [5]. Events are tagged with a muon from a tau decay, and the other tau lepton in the event is required to decay hadronically, forming the probe that is used to measure the identification efficiency. The background is dominated by QCD multijet events estimated using a data driven method. The other backgrounds are estimated through simulation. The signal efficiency is derived by counting events before and after the hadronic tau identification is applied. The visible mass of the muon and the hadronic tau is shown for data before (Fig 4) and after (Fig 5) applying the tight BDT tau identification and agrees well with Monte Carlo predictions. The second method to measure the hadronic tau identification efficiency uses \( W \rightarrow \tau\nu \) events collected in 1.37 fb\(^{-1}\) of ATLAS data [3]. The measured efficiencies in both methods are in good agreement with Monte Carlo predictions within 5% (8 - 12%) for the \( W \rightarrow \tau\nu \ (Z \rightarrow \tau\tau) \) method.

**Figure 3.** Background rejection power with respect to QCD jets is shown as a function of signal efficiency for each discriminant for 1-prong hadronic tau in the region \( 20 \text{ GeV} < p_T < 40 \text{ GeV} \) [3].

**Figure 4.** Visible mass distribution after full event selection without any identification requirement on the hadronic tau [3].

**Figure 5.** Visible mass distribution after full event selection and requiring the hadronic tau to pass tight BDT identification [3].
5. Energy calibration

The energy of the visible hadronic tau decay products is calculated using all calorimeter clusters calibrated at the Local Hadron Calibration (LC) [6], within a core of $\Delta R < 0.2$ around the 4-vector sum of clusters associated with the jet seed. LC takes into account the difference of the response of the ATLAS calorimeters to hadronic and electromagnetic energy depositions due to non-compensation of the ATLAS calorimeters.

The LC improves the hadronic tau decay energy resolution (Fig. 6) but does not fully restore the hadronic tau energy scale, due to particles that do not reach the calorimeters and imperfections within the LC itself.

An additional correction is derived from simulation of various physics processes with hadronic taus and applied on top of LC calibration. Calibration factors [7] are derived from response functions, which are the ratio of reconstructed tau energy to true visible tau energy. Response functions (Fig. 7) depend on the reconstructed tau energy at LC scale, and are calculated separately for 1 and 3-prong hadronic tau, as well as for different detector regions.

The systematic uncertainty on the tau energy scale (TES) [7] is derived from a combination of simulation and data.

Single particle response measurements can be used to determine the calorimeter response uncertainty by decomposing the reconstructed hadronic tau decay into its decay products and convolving the constituents’ response with the hadronic tau particle composition.

We use the simulation to determine the composition of the decay products of the reconstructed tau, namely charged and neutral pions, then we fluctuate them according to measured responses in data.

The uncertainties on particle responses in the calorimeter is derived by varying the response of single particles within uncertainties measured in-situ with isolated single hadrons ($<E/P>$).

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$^{3}$ All tau decay daughters, except neutrinos.

$^{4}$ The mean energy response for low momentum charged hadrons is measured by comparing their calorimeter energy (E) depositions to the momentum (P) measured by the inner detector ($<E/P>$).
and combined test beam data. Unfortunately the combined test beam data is not available besides $|\eta| > 0.8$. Then the systematic uncertainty on the calorimeter response is given by a mixture of in-situ $<E/P>$ and combined test beam measurements in the central region and a combination of in-situ $<E/P>$ measurements and Monte Carlo simulation in the other detector regions. The comparison of the mean energy response $<E/P>$ between data and Monte Carlo is used to determine a relative response bias in the simulation. The $<E/P>$ analysis uses data collected in 2011 and follows the analysis method described in [8] [9]. Fig. 8 shows the $E/P$ distribution for particles at low momentum. Fig. 9 shows the background-subtracted $<E/P>$ for isolated tracks with at least one associated cluster. This figure shows also that the Monte Carlo simulation describes the calorimeter energy response well, with deviations up to 5% at low momentum.

Figure 8. $E/P$ distribution for isolated tracks with momentum $1.8 < P < 2.2 \text{ GeV}$. The bin at 0 in the left plot contains tracks which have no associated cluster [7].

Figure 9. The background subtracted $<E/P>$ distribution as a function of the track momentum [7].

Additional uncertainties on the hadronic tau energy scale are fully derived from Monte Carlo and they are evaluated from five distinct sources: knowledge of the dead material in front of the calorimeters, underlying event model, shower shape modeling, non-closure of the calibration method and pile-up. The uncertainty due to the dead material, underlying event model, shower shape modeling are obtained by comparing the TES of the nominal sample with a dataset generated using a dedicated Monte Carlo with these various systematic effect varied. Uncertainties related to the numerical inversion used in determining the calibration constants are referred to as non-closure uncertainties. These account for deviations in the reconstructed hadronic tau candidates kinematics from the true kinematics. The pile-up uncertainty is estimated by dividing up the nominal samples into seven bins according to the average number of primary vertices. The difference in the highest and lowest closure $5$ is taken as the pile-up uncertainty. The final systematic uncertainty (Fig. 10) is found to be less than 3% for 1-prong hadronic tau decay central region and slightly larger than 3% for $1.3 < |\eta| < 1.6$. The final

$5$ We define the closure as the difference between the reconstructed transverse momentum and the true visible transverse momentum divided by the true visible transverse momentum.
systematic uncertainty for 3-prong, is on average 3%, and up to 5% at low momentum for $1.3 < |\eta| < 1.6$.

![Figure 10. TES uncertainty for 1-prong decays in the forward region. The individual contributions are shown as points and the combined uncertainty is shown as a filled band [7].](image)

5.1. *In-situ TES cross check systematic*

The reconstructed visible mass peak of $Z$ decays can be used to measure both the TES and its uncertainty in-situ. However, with the luminosity available in 2011, there are not enough data for a competitive data driven TES determination. Instead, this method is used to verifying that the TES systematics in the region where no combined test beam data are available covered any possible uncertainty.

6. Summary

ATLAS has an important physics program with tau lepton final states, and a well performing tau identification is a essential part of these analyses. Different techniques are used to separate tau leptons from the quark and gluon initiated jet background. The corresponding efficiencies and systematic uncertainties of the tau identification methods have been studied using Standard Model processes. The energy scale of tau leptons decaying to hadrons is also well understood, with an average uncertainty of 3% calculated on data driven and Monte Carlo driven methods.

References

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