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Tau Lepton Reconstruction in ATLAS

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Abstract

Tau leptons play a key role in many measurements and searches within and beyond the Standard Model of particle physics performed at the LHC. We present here the performance of the reconstruction, identification and energy measurement algorithms for hadronic tau lepton decays currently used by the ATLAS collaboration. We also introduce a new reconstruction method which uses the individual charged and neutral hadrons in tau decays to improve the 4-momentum resolution, while also providing increased sensitivity to tau polarization and Higgs CP state measurements.

Keywords: tau leptons, ATLAS

1. Reconstruction and identification of hadronic tau decays in Run 2 of the LHC at ATLAS

Tau leptons will play a very important role in the Run 2 physics program at the LHC. They offer the best channel to observe the Higgs boson directly decaying to fermions and also the best channel in searches for the neutral Higgs boson predicted by the Minimal Supersymmetric Standard Model. Furthermore, a number of extensions of the SM predict that processes involving these particles have significantly increased rates compared to those of other channels. Due to the relative complexity of data analyses involving tau leptons, a large phase space of these models remains unexplored to date.

The ATLAS detector [1] is one of the two general purpose detectors used to record the outcome of the proton-proton collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV delivered by the LHC. It measures 25x25x46 meters and has a cylindrical shape, being symmetrical around the collision point situated at its center. Several layers of subdetectors surround the beam pipe that traverses the detector along its central longitudinal axis of symmetry. Protons circulating through the beam pipe at almost the speed of light come from opposite directions and collide in the center of the detector at rates up to 1 billion Hz.

A tracking detector which records with a very high accuracy the tracks of most charged particles produced in the collisions, called the Inner Detector (ID), is placed at the very center immediately surrounding the beam pipe. It is surrounded by a calorimeter with a double function of measuring the energies of particles that interact with its material, including the neutral ones that leave no tracks in the Inner Detector, and of stopping most particles. The detector is completed by a muon spectrometer situated outside of the calorimeter. Only one in a million collisions is flagged by a multi-step trigger system as potentially interesting and recorded for further study.

With a mass of 1.78 GeV, taus are the heaviest of all leptons and the only ones heavy enough to decay hadronically. Their lifetime $c\tau$ is 87 μm , which means that they decay inside the beam pipe, before reaching any detector. The large variety of final states into which they decay makes them very challenging to reconstruct and identify at hadron colliders. Since the leptonic decay products of the tau lepton can not be distinguished from prompt electrons or muons, we will only discuss here the hadronic decays.

The typical signature of a hadronic decay of the tau in ATLAS is a narrow jet or spray of particles in the calorimeter, associated to one or three tracks in the ID.

The tau reconstruction [2] starts with a jet obtained using the anti- k_t algorithm with a distance parameter of 0.4. These jets are required to have a momentum transverse to the beam direction $p_T > 10$ GeV and to be within the acceptance of the tracking detectors by imposing $|\eta| < 2.5$, where $\eta = -\ln \tan(\frac{\theta}{2})$ and θ is the polar angle. A special Tau Vertex Association algorithm sums the p_T of the tracks in a cone with $\Delta R < 0.2$ around the jet direction to identify the vertex associated with the tau. The number of tracks reconstructed for true 1-prong and 3-prong taus is shown in Fig. 1. The tau reconstruction efficiency is about 70% up to 200 GeV, slowly decreasing towards 50% for 3-prongs of 500 GeV. The inclusion of a special prescription for merged hits increases the 3-prong reconstruction efficiency by 10% at high p_T [3]. The systematic uncertainty on reconstructing the true number of tracks is 2-5%.

Figure 1: The reconstructed number of tracks for true 1-prong and 3-prong taus [2].

Since many jets formed by quarks or gluons can fake the signature of tau leptons, a multivariate analysis algorithm based on Boosted Decision Trees (BDT) is used to distinguish between taus and jets due to other particles. It is trained separately for 1-prong and 3-prongs using taus from $Z \rightarrow \tau^+ \tau^-$ Monte Carlo (MC) simulations as signal and jets from MC multijet events as background. The input variables are chosen mostly among shower shape variables that use the narrowness of the tau jet to distinguish it from other jets. The output of the BDT is shown in Fig. 2 for both 1-prong and 3-prong taus.

Three working points called Loose, Medium and Tight are chosen such that they deliver an efficiency approximately constant as a function of p_T for reconstruction and identification of true tau leptons of 60 (50), 55 (40) and 45 (30)% for 1-prong (3-prong) tau candidates, while the acceptance for background jets is about 5%, 1% and 0.3% respectively.

Figure 2: The BDT output distribution for 1-prong (left) and 3-prong (right) tau leptons (red), as well as for background jets (black) [2].

The uncertainty on the tau identification efficiency is evaluated using dedicated $Z \rightarrow \tau^+ \tau^-$ MC samples generated with different configurations for inner detector material, calorimeter performance and calibration, underlying event tunes, shower model and pileup model. It has values of 5-15% for 1-prong taus, and 6-19% for 3-prong taus.

The energy of the tau candidate is measured in a $R < 0.2$ cone and calibrated to true visible energy using a η and p_T dependent scale factor called the Tau Energy Scale (TES). The energy resolution of 1-prong and 3-prong taus is shown in Fig. 3. The uncertainty on the tau energy measurement is 4% for 1-prong taus and 4-6% for 3-prong taus.

Figure 3: The energy resolution for 1-prong (top) and 3-prong (right) tau leptons [2].

2. The Tau Particle Flow algorithm

A new algorithm called Tau Particle Flow, based on reconstructing the individual charged and neutral hadrons in tau lepton decays, was recently published by ATLAS [4]. The $\pi^\pm$ originating from the decay of a tau lepton are reconstructed using the tracks in a $R < 0.2$ cone around the direction of the tau candidate. The estimated energy deposited in the calorimeter by the $\pi^\pm$ is subtracted from the energy of the tau jet, and from the remaining clusters the π^0 s are reconstructed and identified using a multivariate analysis based on BDT. The final decay mode classification is done using another BDT which incorporates all the available information regarding that particular tau candidate.

The algorithm provides a more detailed classification of tau decay modes than the reconstruction algorithm used in Run 1 and referred to as Baseline in this section, which only distinguished between 1-prong and 3-prong taus. The new categories are $h^\pm$, $h^\pm\pi^0$, $h^\pm\geq 2\pi^0$, $3h^\pm$ and $3h^\pm\geq 1\pi^0$. This feature is expected to be fully exploited by the measurement of the CP mixture of the Higgs boson via spin effects in $H \rightarrow \tau^+\tau^-$ decays, one of the key results expected in Run 2 of the LHC, which relies on selecting with high purity events in which the tau lepton decays to $\pi^-\nu$, $\pi^-\pi^0\nu$ or $\pi^-\pi^+\pi^-\nu$ [5].

The efficiency of correctly identifying a certain decay mode is given in Fig. 4, which shows for each generated decay mode, listed on the horizontal axis, the probability of being classified as a certain reconstructed decay mode, as listed on the vertical axis. Overall, 74.7% of the tau candidates are correctly classified.

Reconstructed decay mode	ATLAS Simulation				
	Tau Particle Flow				
	Diagonal fraction: 74.7%				
	$Z/\gamma^* \rightarrow \tau\tau$				
$3h^\pm\geq 1\pi^0$	0.2	2.5	3.6	5.3	56.6
$3h^\pm$	0.2	0.6	0.3	92.5	40.2
$h^\pm\geq 2\pi^0$	0.4	6.0	35.4	0.1	0.4
$h^\pm\pi^0$	9.4	74.8	56.3	0.9	2.5
$h^\pm$	89.7	16.0	4.3	1.2	0.3
	$h^\pm$	$h^\pm\pi^0$	$h^\pm\geq 2\pi^0$	$3h^\pm$	$3h^\pm\geq 1\pi^0$
Generated decay mode					

Figure 4: Efficiency matrix for the decay mode classification [4].

Taking advantage of the superior resolution provided by the $\pi^\pm$ tracks, the Tau Particle Flow pro-

vides significantly improved angular and energy resolution compared to Baseline, which makes use only of the calorimeter for these measurements. The tau lepton E_T measurement provided by Tau Particle Flow is based on adding the 4-momentum of all reconstructed constituents, calibrating the result using E_T dependent scale factors obtained from MC and combining the result with the Baseline method by weighting each measurement with the inverse-square of their respective E_T -dependent core resolutions.

Figure 5 shows a comparison of the resolution in azimuthal angle ϕ and p_T for the two algorithms. The Tau Particle Flow algorithm brings a resolution improvement of a factor of 5 in the ϕ angle, and a factor of 2 in E_T for taus with visible E_T in the range 15-20 GeV with respect to Baseline, the difference in energy resolution between the two methods decreasing at higher E_T as the calorimeter energy resolution improves.

Figure 5: The resolution of the azimuthal angle ϕ (top) and the half-widths spanned by the 68% and 95% quantiles, i.e. the core and tail resolutions, of the relative E_T residual distributions as a function of the generated E_T of the visible decay products of the tau lepton decay (bottom) for the Tau Particle Flow and Baseline algorithms [4].

An alternative E_T measurement, similar to the one used by the D0 experiment in [6], was also developed based on the classification provided by the Tau Particle Flow algorithm. In the absence of π^0 s in the tau lepton decay, this method is similar to the Tau Particle Flow one in the sense that it calculates the E_T using exclusively the tracks momentum. In the case of decays with π^0 s, the energy of the charged pions is measured using the tracks while the energy of the π^0 s is estimated as the difference between the E_T of the tau jet and the E_T of the summed momenta of all $\pi^\pm$, scaled by their expected calorimeter response $R_{Ch.Pion}(\eta, p_T^{trk})$ as measured in Ref. [7]. The formula for tau p_T measurement becomes: $p_T^\tau = E_T^{CAL} + \sum p_T^{trk} - \sum R_{Ch.Pion}(\eta, p_T^{trk}) * p_T^{trk}$. The result of this calculation is then averaged with the Baseline measurement to further improve slightly the energy resolution. In spite of being a much simpler method, the resulting energy resolution obtained this way is very similar to that of the Tau Particle Flow.

When comparing simulation with data, good modelling of the classification efficiency is observed for both true taus as well as jets that fake tau lepton decays. Figure 6 shows this for true tau lepton decays in $Z \rightarrow \tau^+ \tau^-$ events.

Figure 6: The number of tau candidates for each reconstructed decay mode in $Z \rightarrow \tau^+ \tau^-$ events, for both data and MC simulations. The background in the $Z \rightarrow \tau^+ \tau^-$ analysis is dominated by multijet and $W(\rightarrow \mu\nu)$ +jets production [4].

Finally, good kinematic modelling is also observed when reconstructing the tau lepton mass and the invariant mass of the muon and tau candidate in the $Z \rightarrow \tau^+ \tau^-$ analysis performed using 5 fb^{-1} of data from Run 1 collected at $\sqrt{s} = 8 \text{ TeV}$, as shown in Fig. 7.

Figure 7: The reconstructed tau lepton mass and the invariant mass of the muon and tau candidate in the $Z \rightarrow \tau^+ \tau^-$ analysis [4].

3. Conclusion

The reconstruction of hadronic decays of the tau lepton in ATLAS resumed in Run 2 with algorithms and performance similar to Run 1, in spite of increased instantaneous luminosity. A new algorithm which identifies π^0 s in tau decays is now available, leading to a better decay mode classification, significant improvement in angular and energy resolution, and new possibilities of measuring the Higgs boson CP with tau leptons.

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