The ATLAS Tau Trigger

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Abstract. The ATLAS experiment at CERN’s LHC has implemented a dedicated tau trigger system to select hadronically decaying tau leptons from the enormous background of QCD jets. This promises a significant increase in the discovery potential to the Higgs boson and in searches for physics beyond the Standard Model. The three level trigger system has been optimized for efficiency and good background rejection. The first level uses information from the calorimeters only, while the two higher levels include also information from the tracking detectors. Shower shape variables and the track multiplicity are important variables to distinguish taus from QCD jets. At the initial luminosity of $10^{31} \text{cm}^{-2}\text{s}^{-1}$, single tau triggers with a transverse energy threshold of 50 GeV or higher can be run stand-alone. Below this level, the tau signatures will be combined with other event signatures. During the collection of a large sample of cosmic ray events in Autumn 2008, the tau trigger was operated as an integrated part of the ATLAS trigger system. This allowed the commissioning of technical aspects of the tau trigger.

1. Introduction

The ATLAS trigger system [2] comprises three levels of event selection: Level 1 (L1) [3] which is hardware-based using ASICs and FPGAs, Level 2 (L2) and Event Filter (EF) (collectively referred to as the High Level Trigger or HLT [4]) based on software algorithms analyzing the data on large computing farms. The three levels of the trigger system must reduce the output event storage rate to about 200 Hz from an initial LHC bunch crossing rate of 40 MHz. The challenge is to accomplish a large rejection against QCD processes while maintaining high efficiency for low cross section physics processes that include searches for new physics.

The tau trigger system is designed to select hadronic decays of tau leptons, which consist mainly of one or three charged pions accompanied by a neutrino and possibly neutral pions. Leptonics tau decays are selected by the electron or muon trigger systems.

ATLAS will collect data at different luminosities, starting at $10^{31} \text{cm}^{-2}\text{s}^{-1}$. At the lowest luminosity, the focus of tau triggers is to collect samples that are useful for understanding the detector and the tau reconstruction software. Tau signatures combined with missing transverse energy are essential to provide data samples enriched in $W \rightarrow \tau \nu$ events, which provide an important sample of real taus needed to refine tau identification algorithms. At higher luminosities, the tau trigger will cope with the event rate increase by using higher $E_T$ threshold requirements, stricter identification requirements, or by demanding a combination of different signatures, such as missing transverse energy, jets, or leptons. At high luminosity, tau triggers will be essential to enable the collection of data samples for searches based on single tau final states, like MSSM charged Higgs decays, $H^\pm \rightarrow \tau^\pm \nu$ [5]. They will also be used for final states

1 The full list of authors can be found in [1]
with more than one tau, like decays of the Standard Model or a MSSM neutral Higgs boson [6], or a new \( Z' \) gauge boson [7].

2. Tau trigger overview

2.1. Level 1 selection

The L1 tau trigger selection is fully documented in [8]. It is a hardware trigger based on information from the electromagnetic (e.m.) and hadronic calorimeters, and uses trigger towers of approximate size \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \), with coverage up to \( |\eta| < 2.5 \). Candidate selection is performed inside a Region of Interest (RoI) of \( 4 \times 4 \) towers logically divided into the 2 \( \times 2 \) towers central core and the isolation ring in the 12 towers surrounding the core. The candidate position is defined by the center of the RoI, and its transverse energy, \( E_T \), is calculated from the two most energetic neighboring towers in the core of the electromagnetic calorimeter plus the full core of the hadronic calorimeter. A maximum of 8 \( E_T \) thresholds can be defined. The rates for a luminosity of \( 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) have been estimated from simulations of the QCD backgrounds. The expected rate is given as a function of the \( E_T \) threshold in Fig. 1. The effect of an isolation cut of \( E_T < 6 \text{ GeV} \) in the electromagnetic calorimeter is also shown.

![Figure 1. Expected L1 trigger rate including all physics processes at a luminosity of \( 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) as function of the transverse energy threshold. Rates are shown without and with an isolation requirement of 6 GeV in the electromagnetic calorimeter.](image)

2.2. Level 2 selection

The Higher Level Triggers (HLT) are software based algorithms run on computer farms. Use is made of the full granularity calorimeter information and the tracking. While fast specialized algorithms are used at L2, slower, more sophisticated methods can be employed in the EF.

The L2 algorithm first refines the L1 position using the second sampling layer in the electromagnetic calorimeter. Then narrow jets are selected by means of a calorimeter shape variable again based on the second e.m. sampling only. Finally the total energy from all layers of the e.m. and hadronic calorimeters is computed. The shape variable used at this level (\( \text{EMRadius} \)), calculated with respect to the refined L2 position, is presented in Fig. 2 for low and high \( E_T \) samples. It is the energy-weighted squared radius \( (\Delta R)^2 = (\Delta \eta)^2 + (\Delta \phi)^2 \) in a region of size \( 0.6 \times 0.6 \). The distributions show, that it is difficult to distinguish QCD jets from taus at low \( E_T \), while the situation improves for higher \( E_T \). Other shape variables (as an isolation quantity in the second layer of the e.m. calorimeter and an \( \eta \) width in the first layer of the e.m. calorimeter) have been evaluated in addition to \( \text{EMRadius} \), but no significant further increase in rejection power was observed. The quantity \( \text{EMRadius} \) together with the total transverse energy are the base of the L2 calorimeter selection.

Dedicated algorithms are used for track reconstruction at L2. To keep the execution time within budget, only the SCT and the Pixel detectors are used. Tracks with \( p_T < 1.5 \text{ GeV/c} \)
Figure 2. L2 variables to distinguish QCD background from low $E_T$ taus from $W \to \tau \nu$ decays (top) and from high $E_T$ taus from super-symmetric Higgs $A \to \tau \tau$ decays (bottom). The variables are: (left) calorimeter shape variable $\text{EMRadius}$, (middle) $p_T$ of leading track (in GeV), and (right) “$\text{Pt Iso/Core}$” (in GeV).

2.3. Event Filter selection

The Event Filter selection is based on the offline tau reconstruction algorithms [9]. For timing reasons, however, only data within a RoI of $0.8 \times 0.8$ around the L2 direction is being used. Calorimeter cells are collected and used to form topological clusters. All clusters within the RoI are then collected into a jet, and after an overall HI-style hadronic calibration [10] followed by a tau-specific jet calibration, the candidate position and transverse energy as well as a number of shower shape variables are derived. To investigate the best usage of the multiple shower shape variables use is made of the multi-variant analysis package, TMVA [11]. As at L2, the most important shower shape variable is $\text{EMRadius}$, the energy-weighted distance of cells inside a cone of 0.4 from the tau candidate position. For track reconstruction, the full offline algorithm is employed to tracking detector data within the RoI. Track quality criteria in accordance with the offline criteria are applied.

Figure 3 shows some relevant quantities for the EF selection. The quantities are $E_T$, $\text{EMRadius}$, and the track multiplicity. In addition, the EF selection uses the $p_T$ of the highest $p_T$ track and the invariant mass calculated from the tracks. Different selections for one- and multi-track candidates are used.

$^2$ For historical reasons, L2 uses distance squared whereas offline, and therefore EF, uses the distance to the first power.
Figure 3. EF variables to distinguish QCD background from low $E_T$ taus from $W \rightarrow \tau \nu$ decays (top) and from high $E_T$ taus from super-symmetric Higgs $A \rightarrow \tau \tau$ decays (bottom). The variables are: the calibrated $E_T$ (left), $EMRadius$ (middle), and the track multiplicity (right).

3. Tau trigger signatures

The single tau signatures are the basic elements of the ATLAS tau trigger menus. They are referred to as $\text{tauXXi}$, where $\text{tau}$ represents the particle we are aiming for, $XX$ is related to the $E_T$ threshold, and the $i$ is present if an isolation requirement has been applied. The tau signatures implemented for the earlier running period are $\text{tau12}$, $\text{tau16i}$, $\text{tau20i}$, $\text{tau29i}$, $\text{tau38i}$, $\text{tau50}$, and $\text{tau84}$.

The trigger efficiencies quoted in the following are normalized to hadronically decaying taus inside $|\eta|<2.5$ with visible momentum (i.e. momentum of all decay products except neutrinos) exceeding the value indicated by the trigger name for the given signature. Furthermore, the efficiencies are quoted with respect to those tau decays which are selected by the offline reconstruction program [9]. In order to optimize the acceptance to the desired physics sample at various luminosities, each signature is configured in three ways (loose, medium, and tight), which correspond, respectively, to a trigger efficiency of approximately 90%, 80%, and 70% with respect to offline reconstructed taus for each trigger level.

Figures 4 and 5, respectively, present as function of $E_T$ the overall trigger efficiency (L1 + L2 + EF) for each tau signature and the efficiency for the signature $\text{tau16i}$ at each trigger level.

3.1. Combined tau triggers

Due to the overwhelming QCD background, only single tau signatures with very high transverse energy ($\text{tau50}$, $\text{tau84}$) can be run stand-alone without saturating the available bandwidth. Lower threshold signatures have to be run prescaled or in combination with other trigger signatures. The combined trigger signatures are tailored to improve the sensitivity to specific physics channels. The following combined triggers are currently implemented:

- $\text{tau+missing } E_T$ ($\text{tau}+E_T^{\text{miss}}$). This trigger covers a wide spectrum of physics channels. At low luminosity, when the rejection can be relaxed, the selection of events with $W \rightarrow \tau \nu$ is the priority. $t\bar{t}$ events with semileptonic decays to taus are also selected. At design
luminosity the trigger is intended for SM and SUSY Higgs searches, as well as for searches for new exotic particles like a $Z'$ gauge boson.

- **tau$^+$-$\ell$ (+jets), $\ell = e, \mu$.** This trigger aims at selecting events with two taus in the final state, such as events with a $Z$ or a neutral Higgs boson. In addition it selects events with multiple leptons such as $t\bar{t}\ell$ events.

- **tau+tau (+jets).** This trigger selects events where two taus decay hadronically. While the rejection rate is less favorable than in the tau$^+$-$\ell$ case, the sample collected is complimentary allowing for increased statistics. The trigger is relevant for searches for a Higgs boson and new exotic particles like a $Z'$.

- **tau+jets, tau$^+$-b-jets.** This is an interesting alternative trigger for $t\bar{t}$ studies. At low luminosity, it allows the study of events with low jet $E_T$ thresholds.

### 3.2. Tau trigger performance

Figure 6 and 7 show for the single tau signatures and the combined tau triggers, respectively, the background rates estimated at a luminosity of $10^{31}$ cm$^{-2}$s$^{-1}$ and the efficiencies for signal events of the types $W \to \tau \nu$, $Z \to \tau \tau$, and $t\bar{t}$. The efficiencies are calculated per event, with the references:

- Trigger with one (two) taus: at least one (two) tau decays at generator level with visible $E_T$ greater than the tau trigger threshold(s) should be required. Furthermore, the generated taus are identified by the offline reconstruction algorithms.

- Trigger with tau$^+$-$\ell$ and tau$^+$-$\mu$: besides the tau lepton requirement (see above item), the additional lepton is required at generator level to have an $E_T$ greater than the chosen lepton trigger threshold. The generated lepton should be identified by the offline reconstruction algorithm according the “loose” criteria.

- Trigger tau$^+$+$E_T^{\text{miss}}$: besides the tau lepton requirement (see item above), the missing $E_T$ at generator level as well as the missing $E_T$ reconstructed by the offline reconstruction algorithms are required to be above the chosen trigger threshold.
Figure 6. Performance of the single tau signatures (“loose” selection). Left: unprescaled trigger rates at $\mathcal{L} = 10^{31} \text{cm}^{-2}\text{s}^{-1}$. Right: trigger efficiency for three benchmark physics channels. As discussed in Sect. 3.2, the trigger efficiency is defined with respect to events which at generator level have a tau lepton with visible $E_T$ exceeding the relevant trigger threshold.

Figure 7. Performance of the combined tau trigger signatures. Left: trigger rates at L1, L2, and EF (“loose” selection). Right: trigger efficiency for three benchmark physics channels. (xe indicated a $E_T^{\text{miss}}$ requirement. EFxe indicates a $E_T^{\text{miss}}$ requirement at EF level only.)

4. Trigger timing
The timing performance of the trigger is a crucial ingredient in the optimization. The trigger system design constraints the total executing time per event to 40 ms at L2 and 1 s at EF for the complete trigger. Estimates based on simulated minimum bias events indicate that the current algorithms at running conditions corresponding to a luminosity of $10^{31} \text{cm}^{-2}\text{s}^{-1}$ are comfortably
Table 1. Mean algorithm execution time per RoI. Measurements from a simulated sample of QCD dijet events with the transverse momentum in the hard scattering process within $35 < p_T < 70$ GeV/c. Test performed on a Intel(R) XEON(TM) CPU 2.20 GHz machine.

| Algorithm       | Time (ms) |
|-----------------|-----------|
| L2 Calo         | 8         |
| L2 Tracking     | 15        |
| L2 Combined     | 2         |
| EF Calo         | 13        |
| EF Tracking     | 270       |
| EF Combined     | 81        |

within this budget with total executing times of about 20 ms at L2 and 110 ms at EF. Of this the tau trigger is in both cases responsible for less than 5%.

Table 1 shows a break down of the processing time per RoI for the tau trigger algorithm.

5. Cosmic ray commissioning
During Autumn 2008, the ATLAS experiment recorded large samples of cosmic ray events. During this data-taking period, the tau trigger was being operated as an integrated part of the ATLAS trigger system. Even though very few cosmic ray events passed the tau trigger requirements, this allowed a thorough break-in of the technical aspects of the trigger system. Online and offline monitoring of the trigger behaviour was consolidated. Trigger decisions were saved together with the recorded data allowing a detailed validation of the on-line functionality of the trigger algorithms. Furthermore, the recorded data allowed early studies of the performance of the ATLAS calorimeters, especially their noise characteristics.

6. Conclusion
A three-level hadronic tau trigger has been developed for ATLAS. At each level of the three-level trigger system, the narrowness of tau jets as compared to QCD jets is exploited in order to reduce the overwhelming background rate. At the higher trigger levels, also the low charged particle multiplicity of tau decays is exploited. The trigger rate at low transverse energy thresholds are too large to be run stand-alone, but in combination with other trigger signatures low $E_T$ triggers can be run unprescaled. Single tau triggers with a transverse energy threshold of 50 GeV or higher can be run unprescaled at the initial luminosity of $10^{31}$ cm$^{-2}$s$^{-1}$.

At initial LHC running the emphasis will be on commissioning of the detector and the trigger system. Thus, focus will be on Standard Model physics processes such as $W \rightarrow \tau \nu$, $Z \rightarrow \tau \tau$, and $t\bar{t}$. The single tau signatures will be later used as ingredients in more complex signatures for use in searched for new physics.

The tau trigger system has been thoroughly exercised during a large ATLAS cosmic ray run in Autumn 2008.

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