Study of the performance of the Level-1 track trigger in the $\text{H} \rightarrow \tau \tau \rightarrow \text{ee}$ channel in ATLAS at high luminosity LHC

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Abstract

The planned upgrade of the Large Hadron Collider, the HL-LHC, will increase the already excessive rates from the ATLAS first level (L1) trigger. The proposed increased luminosity is about five times higher than the design luminosity. This will increase the number of pile-up collisions in each event. This means that the L1 trigger must achieve a higher rejection factor to maintain current trigger thresholds. A higher threshold would lead to loss in sensitivity for interesting physics. The implementation of the proposed L1 track trigger will improve the selectivity of physics objects. This thesis presents the Monte Carlo simulation studies that demonstrate that the use of tracking information at the L1 trigger has a positive impact on ATLAS physics goals in the HL-LHC environment. The study is done with the current detector geometry and with fully simulated detector response. The simulation was done in pile-up environments corresponding to 69 and 92 simultaneous minimum bias events. Three methods for background rejection were studied: track matching, track isolation and $E_T/p_T$ matching between the electromagnetic calorimeter and the tracker. The study shows that the L1 track trigger can achieve a background rejection factor between 1 and 3 for a signal efficiency above 90%.
SUMMARY

The LHC provides the best opportunities in the exploration of the new physics and for precision measurements of the known phenomena. The LHC started its operation in 2009. It delivered data at a center of mass energy of 7 TeV in 2010-2011, and 8 TeV in 2012. The LHC machine will be upgraded in several steps over the next decade to extend the reach for new physics at the TeV energy scale and to improve the accuracy in the determination of Standard Model parameters, e.g. Higgs mass and couplings. The high-luminosity LHC (HL-LHC) is the final upgrade of the LHC where the instantaneous luminosity (number of collisions per square centimeter per second) increases beyond the design luminosity of LHC.

When the luminosity increases an optimal trigger system is required for maximum sensitivity to interesting physics and for rejection of background from pile-up. It is essential for the ATLAS detector to improve its performance in triggering for the HL-LHC luminosity. The Level-1 (L1) trigger rates at HL-LHC would require at least 500 kHz in order to maintain the same trigger thresholds as the current L1 trigger. The reduction in rates can be achieved by using the tracking information from the inner detector at the first level trigger. The combination of the tracking information from the inner detector and the information from the calorimeter is likely to provide a fast trigger system for electrons so that the ATLAS detector can exploit the new physics at HL-LHC.

A Monte Carlo simulation study was performed to investigate the performance of the L1 track trigger for electrons coming from H → ττ decays. The main focus of this study is to enhance the trigger performance by using tracking information together with electron trigger objects. Three different methods are studied to achieve a rejection of the background. The study shows that the L1 track trigger can achieve a background rejection factor between 1 and 3 for a signal efficiency above 90%.
Figure 1: Display of an event selected for the $H \rightarrow \tau_{lep}\tau_{lep}$ analysis in the vector boson fusion (VBF) category. One tau decays to an electron, indicated by the green track. The other tau decays to a muon, indicated by the red line. The two VBF jets are indicated by the cones. The dashed line represents the missing transverse energy $[i]$. 
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Introduction

The Standard Model (SM) of particle physics is a consistent, finite and computable theory that successfully explains the elementary particles and the interactions between them. The SM has been enormously successful in predicting a wide range of phenomena and it accurately describes the current experimental data. Despite the success of the SM, it is still not the final theory of matter. Several open questions remain that are not answered within this model. To mention a few, the model incorporates only three fundamental forces, omitting gravity. The model does not explain the nature of dark matter. It does not explain why there are three generations of quarks and leptons. Phenomena like neutrino oscillations, matter-antimatter asymmetry and strong CP violation are not accommodated by the SM theory. Therefore, there are many proposed theories beyond the SM such as Minimal Super Symmetric Standard Model, String Theory and extra dimensions.

The most essential component of the SM theory is a particle called the Higgs boson. The Brout-Englert-Higgs (BEH) mechanism is the leading idea to explain the phenomena of how particles gain mass by interacting with the scalar Higgs field [1, 2]. The recent discovery of the Higgs boson confirms the existence of the Higgs field. The search for the Higgs boson was one of primary goals of the Large Hadron Collider (LHC) [3] physics programme at CERN. On 4th July 2012, the ATLAS (A Toroidal LHC ApparatuS) experiment [4] together with the CMS (Compact Muon Solenoid) experiment [5] at the LHC announced that they had observed a new boson, consistent with the Higgs boson at a mass of 125-126 GeV [6]. Later on March 2013 it was confirmed that the new particle was indeed a Higgs boson.

The LHC extends our understanding of the fundamental nature of matter. It offers the opportunities both for the exploration of new physics and for precision measurements of known phenomena. The LHC started its operation in 2009. In its first year it delivered over 50 pb$^{-1}$ of data with a peak luminosity$^1$ of 230 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$ at a center of mass energy of 7 TeV. In 2012 which was the last year of running before the first long shut down (LS1) the LHC delivered over 23 fb$^{-1}$ of data with a peak luminosity of 7.73 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ at a center of mass energy of 8 TeV. The LHC machine will be upgraded to extend the reach for new physics at the TeV energy scale and to improve the accuracy in the determination of SM parameters, e.g. Higgs mass and couplings. The LHC upgrade will also provide exciting opportunities for discoveries in the high-mass region, such as multi-TeV squarks and gluinos, new gauge bosons, extra dimensions and it will extend the sensitivity to rare processes like Higgs pair production [7].

After LS1 that ends in spring 2015, the LHC will provide proton-proton collisions at the design luminosity of 10^{34} \text{cm}^{-2}\text{s}^{-1} and at a center of mass energy of 13 to 14 TeV (Phase-0). In 2018 the LHC will stop again its operation for a second shut down (LS2) to upgrade the beam optics

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$^1$ Luminosity is the number of collisions per square centimeter per second.
near the interaction point that will allow for higher luminosities than in Phase-0. The data taking will resume in 2019 (Phase-I) with an expected peak luminosity of $2 - 3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ aiming for an integrated luminosity of $300 - 400 \text{fb}^{-1}$ [8]. The ATLAS experiment will be upgraded during LS2 in order to take full advantage of the increase in luminosity. Improvements are planned in the forward muon spectrometers and by instrumenting a topological L1 calorimeter trigger.

In a third and final upgrade of LHC, the High-Luminosity LHC (HL-LHC) [9], the luminosity will reach $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. The HL-LHC is expected to begin collisions in 2024 (Phase-II) and will provide a total integrated luminosity of $3000 \text{fb}^{-1}$ to the ATLAS experiment over ten years [10]. The HL-LHC will increase the collision rates in the ATLAS detector producing 100-200 collisions per beam crossing. This will increase the pressure on the ATLAS trigger system. In order to manage the increase in data, the Level-1 (L1) trigger must achieve a high rejection rate in the harsh radiation environment. The high luminosity at HL-LHC will impact the experiment through increased occupancies in all parts of the experiment but the challenge is particularly demanding in the silicon detectors, compromising the tracking performance. Thus at the HL-LHC the ATLAS tracking system will be entirely replaced with a silicon tracker that has been developed, based on the experience with the current tracker [9].

The new ATLAS tracking system will improve the performance in track and vertex reconstruction, lepton identification and flavor tagging in the harsh environment of HL-LHC. In order to cope with the high occupancies at HL-LHC, the readout of the tracker system requires a higher bandwidth. To satisfy the bandwidth limitations, the $p_T$ thresholds for single leptons would have to be raised up to 60 GeV unless significant improvements are made to the L1 trigger system. With such high $p_T$ thresholds, a significant amount of physics at the electroweak scale will be lost. One way to improve the L1 trigger is by adding tracking information to the L1 trigger (L1Track) which will allow low $p_T$ thresholds for single leptons without saturating the L1 trigger bandwidth. A $p_T$ threshold of around 20 GeV for the single lepton trigger and for the acceptance of key signatures such as W and Z bosons, $t\bar{t}$ pairs is adequate for physics studies but would produce a total rate of 500 kHz at the HL-LHC if the performance of the current L1 trigger was not improved. This threshold cannot be sustained since the current L1 trigger accepts the events at a rate of 75 kHz. Some improvements will be done for the Phase-I where the L1 trigger will accept events at the rate of 100 kHz.

As seen, the Phase-I trigger bandwidth is far from sufficient for the HL-LHC. To manage the high rate, a new architecture has been proposed for the HL-LHC where a two-step L1 hardware trigger will reduce the event rates, in which the first step Level-0 will accept events at the rate of 500 kHz and the second step, a new L1 system, will reduce the rate to 200 kHz. By using the information from the tracker of the ATLAS experiment at the L1 trigger, the required reduction factor of rates can be achieved. The main challenge is thus to transfer the data from the tracker in time for the L1 trigger decision. The replacement of the detector readout electronics will accommodate the new two-step L1 hardware trigger architecture. More improvements will be made through the replacement of the calorimeter readout electronics which will provide the full
calorimeter granularity at L1. Also the muon $p_T$ resolution will be improved at L1 using the information from the monitored drift tubes and through the replacement of muon readout electronics. The combination of L1 track trigger and the information from calorimeter and muon systems will provide a fast trigger system allowing the ATLAS detector to exploit the new physics of the increased luminosity [9].

In this thesis, based on the Phase-II ATLAS upgrade, a simulation study was performed to investigate the performance of the L1 track trigger for electrons coming from the $H \rightarrow \tau_{lep}\tau_{lep}$ decay channel. The brief description of the LHC and its major experiments, as well as the physics potential of the current and future LHC are detailed in chapter 2. In chapter 3 the theoretical aspects of Higgs physics such as the BEH mechanism are described. Also various Higgs production channels at LHC and the experimental importance of the decay channel $H \rightarrow \tau\tau \rightarrow ee$ are explained. In chapter 4 a brief overview of the ATLAS detector and its sub-detectors is given. Especially the relevant parts of the detector for this study such as the calorimeter and the inner detector are explained. In chapter 5 the current ATLAS trigger system and the important aspects of its first level L1 are described. The main challenges for the proposed ATLAS L1 trigger upgrade are also described in this chapter. The L1 electron trigger studies for one of the benchmark channels $H \rightarrow \tau_{lep}\tau_{lep}$ for upgrade physics are described in chapter 6. The main method used for calculating the efficiencies of the L1 track trigger is by matching the tracks with electron trigger objects in a region of interest. Also, isolation criteria were applied to electromagnetic (EM) clusters in order to find an optimal isolation cut at which the signal efficiency would be high with a good rejection of the background. Simulation studies by using $E_T/p_T$ selection cuts were also performed. The conclusions of these studies are presented in chapter 7.
The Large Hadron Collider (LHC) built near Geneva (Switzerland) is the world’s most powerful particle accelerator. It is one of the largest and most complex experimental facilities ever built. It consists of a 27 kilometer superconducting ring installed in the tunnel that was built for its predecessor, the Large Electron Positron (LEP) collider. Inside the superconducting ring, protons are accelerated in opposite directions in two separate ultra-high vacuum pipes and collide at four points where the two beams intersect. At each point, the experiments ATLAS, CMS, ALICE and LHCb are installed in huge underground caverns. The two major experiments, ATLAS and CMS, are designed to search for new phenomena in high-energy proton collisions at the LHC. The description of ATLAS will be given in chapter 4. The major difference between the ATLAS and CMS experiment are in the design of their calorimeter and muon spectrometer. The ATLAS experiment uses a liquid argon based calorimeter while the CMS experiment uses a crystal based calorimeter. The muon spectrometer in ATLAS is embedded in an air-toroid field while the spectrometer of CMS is embedded in an iron yoke with a solenoid field. The acceleration of the protons is done using a number of steps where the beam energy is increased gradually. The LHC accelerates protons taken from a bottle of hydrogen gas, first in a linear accelerator followed by the Proton Synchrotron (PS) up to 26 GeV. The proton beam is then injected into the Super Proton Synchrotron (SPS). After being accelerated to 450 GeV in the SPS the proton beam is injected into the main ring of LHC. The LHC main ring consists of two beam tubes, one for each proton beam. Radio frequency (RF) cavities operating at 400 MHz are used to accelerate up to 2808 proton bunches. The protons in bunches are distributed in both position and momentum. The spread of bunches is measured by the emittance. The longitudinal emittance measures the bunch length and the transverse emittance measures the width of the bunches. The LHC beam pipes are contained in the superconducting cold mass and cryostat. In this twin-bore design the magnetic fields of the dipoles point in opposite directions to provide the Lorentz bending force toward the center of the ring. The separation of the two beams is small so they are coupled both magnetically and mechanically. The LHC dipoles use Niobium-Titanium cables which become superconducting below the temperature 2K. The number of interactions generated in the LHC collisions is given by

\[ N = L\sigma \]  \hspace{1cm} (2.1)

Here N is the total number of events, L is the luminosity and \( \sigma \) is the cross section of the studied process. The product \( L\sigma \) is used to estimate the rates of physics interactions.
The instantaneous luminosity is used to calculate the expected rate of collisions at the LHC. Since the experiments at LHC collect data over a period of time the integrated luminosity is defined in units of $\text{fb}^{-1}$ as\(^2\)

$$\mathcal{L} = \int L dt$$

(2.2)

The instantaneous luminosity of the LHC machine depends on the beam parameters and is defined as

$$L = \frac{N_b n_b f_{\text{rev}} \gamma_r}{4\pi \varepsilon_n \beta^*} F$$

(2.3)

where $N_b$ is the number of particles per bunch and $n_b$ is the number of bunches per beam. $f_{\text{rev}}$ is the revolution frequency, $\gamma_r$ is the relativistic gamma factor, $\varepsilon_n$ is the normalized beam emittance and $\beta^*$ is the beta function at the interaction point. $F$ is the geometric luminosity factor due to the crossing angle at the interaction point. The instantaneous luminosity will be increased through major upgrades in various phases to exploit the full physics capabilities of the LHC. In a future phase of LHC named as High Luminosity LHC, a total integrated luminosity of 3000 $\text{fb}^{-1}$ will be collected in 10-12 years. This will be achieved by increasing the instantaneous luminosity and by luminosity leveling [3, 10]. Figure 2.1 shows the possible evolution of the peak and integrated luminosity of the LHC.

![Figure 2.1: The peak and integrated luminosity increase of LHC over 12 years. The three shut down periods of LHC are also shown [10].](image)

\(^2\) 1 barn ($\text{barn}$) = $10^{-24} \text{cm}^{-2}$
Theoretical foundation

3.1 The Standard Model
The fundamental constituents of matter are tiny elementary particles. In nature there are four fundamental forces interacting between these elementary particles. The theory that describes the origin of the elementary particles and the interactions they experience in a mathematically strict and detailed way is called the Standard Model (SM) of particle physics [11, 12, 13]. The SM classifies the elementary particles into groups of fermions and bosons. Particles with half integer spin obeying the Fermi-Dirac statistics are called fermions and they are further divided into quark and lepton families. The leptons are the electron $e^-$, the muon $\mu^-$, the tau $\tau^-$, three associated neutrinos ($\nu_e, \nu_\mu$ and $\nu_\tau$) and their anti-particles. The leptons have electric charges of -1 for charged leptons and 0 for neutrinos. There are six types of quarks known as up, down, strange, charm, top, and bottom. Each quark comes in one of three “colour” flavors. The quarks have fractional electric charges, with $+2/3$ for up-type quarks and $-1/3$ for down-type quarks. The leptons and quarks are grouped into three generations with different masses as listed in Table 3.1.

The electromagnetic force, the weak force and the strong force are fundamental interactions explained by the SM. The SM does not incorporate the gravitational force. All forces have associated particles which act as a mediator between the elementary particles when they interact. These particles are called bosons. Bosons are particles obeying the Bose-Einstein statistics and have an integer spin. In the SM the forces are described by a local gauge theory so the bosons in the SM are called gauge bosons. The local gauge group is a direct product of three symmetry groups $SU(3) \otimes SU(2)_L \otimes U(1)_Y$. The gauge group $SU(2)_L \otimes U(1)_Y$ is the group of the unified weak and electromagnetic force. The weak interaction between fermions are mediated by the three massive gauge bosons $W^\pm$ and $Z^0$. Based on the $U(1)$ symmetry group the electromagnetic force is described by the quantum electrodynamics (QED) and affects all charged particles. The photon $\gamma$ is the mediating gauge boson in QED. The photon has no mass in order to preserve local gauge symmetry and it cannot self-interact. The group $SU(3)$ is the symmetry group of the strong force. The strong force acts on the quarks via gauge bosons called gluons. The strong force is described by the quantum chromo dynamics (QCD). The properties of the gauge bosons are listed in Table 3.2.
Table 3.1: Fermions in the Standard Model [14].

<table>
<thead>
<tr>
<th>Generation</th>
<th>Leptons</th>
<th></th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fermion</td>
<td>Electric charge</td>
<td>Mass (MeV)</td>
</tr>
<tr>
<td>First</td>
<td>e^-</td>
<td>-1</td>
<td>0.511</td>
</tr>
<tr>
<td></td>
<td>ν_e</td>
<td>0</td>
<td>&lt;2 x 10^-6</td>
</tr>
<tr>
<td>Second</td>
<td>μ^-</td>
<td>-1</td>
<td>105.65</td>
</tr>
<tr>
<td></td>
<td>ν_μ</td>
<td>0</td>
<td>&lt;0.19</td>
</tr>
<tr>
<td>Third</td>
<td>τ^-</td>
<td>-1</td>
<td>1776.82±0.16</td>
</tr>
<tr>
<td></td>
<td>ν_τ</td>
<td>0</td>
<td>&lt;18.2</td>
</tr>
</tbody>
</table>

Table 3.2: Bosons in the Standard Model [14].

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Boson</th>
<th>Electric charge</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>γ</td>
<td>0</td>
<td>&lt;10^-27</td>
</tr>
<tr>
<td>Weak</td>
<td>W^±</td>
<td>±1</td>
<td>80.385 ± 0.015</td>
</tr>
<tr>
<td>Strong</td>
<td>Z^0</td>
<td>0</td>
<td>91.1876 ± 0.0021</td>
</tr>
<tr>
<td></td>
<td>Gluons</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

3.2 BEH mechanism

In the SM the electroweak symmetry breaking is achieved by the Brout-Englert-Higgs (BEH) mechanism, which in turn predicts the existence of a Higgs boson [1, 2]. The Higgs boson is a neutral spin-0 particle. Without the Higgs field, gauge invariance\(^3\) requires that spin-1 gauge bosons have zero masses. In quantum electrodynamics and quantum chromodynamics, the gauge bosons are photons and gluons, both of which have a zero mass. However, \(W^\pm\) and \(Z^0\) gauge bosons are massive. Thus it is assumed that particles interact with a scalar field, called the Higgs field which has a non-zero expectation value in the vacuum state\(^4\) [1, 15]. The interaction of the gauge bosons with the Higgs field is gauge invariant. Due to the non-uniqueness of the vacuum state the symmetry breaks. Such a spontaneous symmetry breaking occurs in other fields of physics whenever the vacuum state is not unique. The simplest theory exhibiting the spontaneous symmetry breaking is the Goldstone model. Consider a real scalar field \(\phi\) described by the Lagrangian.

\[
\mathcal{L} = \frac{1}{2} \left( \partial_\mu \phi \right)^2 - V(\phi)
\]  

(3.1)

where \(V(\phi) = \left( \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4 \right)\).

In the potential term \(\mu^2\) and \(\lambda\) are real parameters. The Lagrangian is invariant under global phase transformation \(\varphi(x) \rightarrow e^{i\alpha} \varphi(x)\), where \(\alpha\) is an arbitrary phase parameter. To find the vacuum state of the system, one has to find the minima of the potential \(V(\phi)\). The system has

---

\(^3\) If the Lagrangian of a system including gauge fields is invariant under local group transformation, there is gauge invariance.

\(^4\) The vacuum state is a quantum state of lowest energy.
minimal energy when its kinetic and potential energies are separately minimal. The kinetic energy is minimum when $\phi$ is constant. Also the potential energy of the field should be bounded from below for $\lambda > 0$. Now two different situations occur depending on the sign of $\mu^2$.

When $\mu^2 > 0$, the terms in the potential $V(\phi)$ are positive definite and it has a minimum at $\phi = 0$ as shown in Figure 3.1 (left). The Lagrangian is invariant under phase transformation and hence the spontaneous symmetry breaking does not occur.

When $\mu^2 < 0$, the potential $V(\phi)$ has a minimum at $\partial V / \partial \phi = \mu^2 \phi + \lambda \phi^3 = 0$ as shown in Figure 3.1 (right). Now the system has two states with the lowest energies.

$$\phi_1 = \sqrt{-\frac{\mu^2}{\lambda}} \equiv + \nu, \quad \text{and} \quad \phi_2 = -\sqrt{-\frac{\mu^2}{\lambda}} \equiv - \nu$$

The quantity $\pm \nu$ is called the vacuum expectation value of the scalar field $\phi$. Now $\phi_1$ is not invariant under global phase transformation and the symmetry is spontaneously broken.

![Figure 3.1: The potential $V(\phi)$ of the scalar field $\phi$ in the case $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right) [17].](image)

The gauge bosons $W^\pm$ and $Z^0$ acquire masses from the interaction with the Higgs field. One can moreover show that the ratio of their masses is

$$M_W / M_Z = \cos \theta_W$$

where $\theta_W$ is the weak mixing angle. The interaction of fermions with the Higgs field has a dimensionless coupling constant related to the fermion mass by

$$g_{Hff} = \sqrt{2} g_w (m_f / M_W)$$

where $m_f$ is the mass of fermions and $g_w$ is the coupling constant of weak interactions [16, 17].
3.3 Higgs boson production at LHC

The dominant production channel for the Higgs boson at the LHC is the gluon-gluon fusion channel $gg \rightarrow H$. It provides the largest production cross section for the entire Higgs mass range, $100 \text{ GeV} < m_H < 1 \text{ TeV}$. For experimental measurements the gluon-gluon fusion production channel is challenging because of a large QCD jets background due to gluons. The SM Higgs production via vector boson (WW, ZZ) fusion $qq \rightarrow qqH$ (VBF) and via Higgs-strahlung $qq \rightarrow VH$ where the vector boson V decays hadronically are important experimental channels as they suffer from less QCD background in the central rapidity regions and hence provide a clean experimental signature. The production cross section of the Higgs boson depends on the Higgs mass and the center of mass energy of the colliding particles [18]. Figure 3.2 shows the production cross section of several Higgs boson channels as a function of the Higgs mass at 14 TeV [18].

![Figure 3.2](image1.png)

**Figure 3.2:** The cross section for the production channels of the SM Higgs boson as function of the Higgs mass at 14 TeV [19].

The VBF channel is used in this thesis study. The production of the Higgs boson occurs in association with two hard jets in the forward regions of the detector, with a large rapidity separation. The Higgs production via VBF plays an important role in the determination of the Higgs couplings at the LHC. Figure 3.3 shows a Feynman diagram for the VBF process.

![Figure 3.3](image2.png)

**Figure 3.3:** VBF production channel of the SM Higgs boson in the decay mode of $H \rightarrow \tau^+ \tau^-$. 
3.4 Higgs boson decays

The branching ratios for important decay modes of the SM Higgs boson are shown in Figure 3.4 as a function of the Higgs mass. The recent discovery of a Higgs boson at 125-126 GeV in the $\gamma\gamma$, $WW$ and $ZZ$ channels is described in [6]. The Higgs boson decay into $H \to \gamma\gamma$ is despite the low branching ratio the main signature for a mass below 130 GeV. The signal is relatively clean and the main background for this channel is the $\gamma$-jet and jet-jet production, where jets are misidentified as photons. These backgrounds are eliminated by the help of excellent $\gamma$–jet separation and $\gamma$ energy resolution. A jet is a narrow cone of hadrons and other particles produced by a quark or gluon. The Higgs boson decay into $H \to ZZ \to 4l$, where $l = e$ or $\mu$, also provides good sensitivity over a wide mass range. The largest background comes from $ZZ^*$ for this channel. The signal events are selected either by using single lepton or di-lepton final states. The Higgs boson decay $H \to WW$ provides a clean signature by producing two opposite charged leptons with large missing transverse momentum coming from neutrinos. The main background comes from $WW$ and $t\bar{t}$ production for this channel. The Higgs boson has not yet been discovered in $\tau\tau$ and $bb$ final states.

The decay of a Higgs boson into a $\tau^+\tau^-$ pair is an important channel in the low Higgs mass region $m_H < 160$ GeV. The mass of the Higgs boson can be reconstructed using the $\tau$ decay products (usually in the same direction as the $\tau$ lepton). Backgrounds for this process are reducible $W +$ jets and $t\bar{t} +$ jets events. For the study of $H \to \tau^+\tau^-$, the VBF production channel of a Higgs boson with two hard jets gives a clean signature. Due to additional high $p_T$ jets in the event, the Higgs boson is boosted in the transverse plane, which increases the momentum of $\tau$ decay products and gives a discrimination against background processes. The reconstruction and identification of $\tau$ leptons play an important role for Higgs boson searches. $\tau$ is the heaviest lepton and the only one that can decay both leptonically and hadronically, which gives the possibility to use the electron or muon trigger. Several decay modes of the $\tau$ lepton are listed in Table 3.3.

![Figure 3.4](image_url)

Figure 3.4: The branching ratios of the SM Higgs boson decay modes [19].
It decays about 35% of the time leptonically, either with an electron or muon in the final state. Hadronically τ lepton decay with one charged particle (1-prong) or with three charged particles (3-prong). The hadronic decay products of τ leptons are dominated by π± and π⁰ mesons and also by a small fraction of K± and K⁰ mesons in the final state. Figure 3.5 shows the Feynman diagrams of a τ lepton decaying leptonically and hadronically. The Higgs boson can be searched for in the channel $H \rightarrow \tau^+\tau^-$ for any of the final states of the τ decay. However, the purely hadronic final state is very challenging because of the massive QCD background from the soft p-p collisions. While the leptonic final states are easier to separate from the background, the weak decay of τ softens the detected leptons since the neutrinos escape with a part of the transverse energy.

**Figure 3.5:** Feynman diagram of the $\tau^-$ lepton decay modes. The $\tau^+$ decay modes are charge conjugated.
Table 3.3: The $\tau^-$ lepton decay modes. The $\tau^+$ decay modes are charge conjugated [14].

<table>
<thead>
<tr>
<th>$\tau^-$ decay modes</th>
<th>Branching Ratio %</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-\bar{\nu}<em>e \nu</em>\tau$</td>
<td>$17.83 \pm 0.04$</td>
<td>Leptonic decays</td>
</tr>
<tr>
<td>$\mu^-\bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>$17.41 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>$\pi^-\pi^0 \nu_\tau$</td>
<td>$25.52 \pm 0.09$</td>
<td>1-prong hadronic decays</td>
</tr>
<tr>
<td>$\pi^-\nu_\tau$</td>
<td>$10.83 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td>$\pi^-2\pi^0 \nu_\tau$</td>
<td>$9.30 \pm 0.11$</td>
<td></td>
</tr>
<tr>
<td>$K^-\pi^0 \nu_\tau$</td>
<td>$(4.29 \pm 0.15) \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$K^-2\pi^0 \nu_\tau$</td>
<td>$(6.5 \pm 2.3) \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\pi^-\pi^+\pi^- \nu_\tau$</td>
<td>$9.31 \pm 0.06$</td>
<td>3-prong hadronic decays</td>
</tr>
<tr>
<td>$\pi^-\pi^+\pi^-\pi^0 \nu_\tau$</td>
<td>$4.62 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td>$K^-\pi^+\pi^- \nu_\tau$</td>
<td>$(3.49 \pm 0.16) \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$K^+K^-\pi^0 \nu_\tau$</td>
<td>$&lt; 4.8 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$K^-K^+K^- \nu_\tau$</td>
<td>$(2.1 \pm 0.8) \times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>
The ATLAS Detector

4.1 Overview of the ATLAS Detector

ATLAS (A Toroidal LHC ApparatuS) [4] is a general purpose detector built for probing $p\bar{p}$ collisions. The detector is designed to accommodate a wide spectrum of possible physics signatures and to explore the TeV mass scale where discoveries are expected. The ATLAS detector is optimized for maximum sensitivity to e.g. particles from Higgs boson decays. Also in focus are investigations of signatures expected from various types of particles in Beyond Standard Model (BSM) theories. In addition ATLAS is a hermetic detector designed to observe and reconstruct the energy of neutrinos and weakly interacting massive particles predicted by the BSM theories, through the missing transverse momentum. The basic design of the detector is as follows:

- An inner tracker is used for measuring charged particle momenta with high resolution and reconstruction efficiency. The vertex detectors near the interaction region are used to observe the secondary vertices from decaying short lived particles.
- For the identification and measurement of electrons and photons, an electromagnetic calorimeter is used. It is surrounded by the hadronic calorimeter, for the measurement of jets.
- A high-precision muon spectrometer is used for the identification and momentum measurement of muons over a wide range of momenta.
- Events are triggered, based on the low transverse-momentum particles, with a sufficient background rejection, providing high efficiency for most physics processes at LHC.

The layout of the detector is shown in Figure 4.1. The detector is forward-backward symmetric with respect to the interaction point and it covers almost all the solid angle $4\pi$. The dimensions of the detector, defined by the muon spectrometer toroid magnets, are 25 m in height and 44 m in length, for an overall weight of approximately 7000 tons. The magnetic configuration based on air-core superconducting toroids, one barrel and two end-caps arranged with an eight-fold azimuthal symmetry around the calorimeter, generates a large magnetic field with a strong bending power within a light and open structure. As for the inner detector, it is surrounded by a thin superconducting solenoid with a magnetic field of 2 T [4, 19, 20].

The nominal collision point is the origin of the ATLAS cartesian coordinate system. The beam direction defines the z-axis, while the positive x-axis points towards the center of the LHC ring and the y-axis upwards. The azimuthal angle $\phi$ is the angle defined around the beam axis. The polar angle $\theta$ is the angle measured from the beam axis. The polar angle can be replaced by the pseudorapidity defined as $\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$. The distance between two objects in the pseudorapidity-azimuthal plane is defined as
21

\[
\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}.
\]  \hspace{1cm} (4.1)

The transverse momentum \(p_T\) in the \(x-y\) plane is defined as

\[
p_T = \sqrt{p_x^2 + p_y^2}
\]  \hspace{1cm} (4.2)

\[\text{Figure 4.1: General layout of the ATLAS detector and its sub-systems [ii].}\]

4.2 Inner Detector

The inner detector (ID) [21] is designed for high-precision measurements of the track momenta of charged particles and for finding vertices with a high resolution. The ID consists of three detectors: a Pixel Detector of silicon pixel sensors; a Semiconductor Tracker (SCT) of narrow silicon micro-strip detectors; a Transition Radiation Tracker (TRT) containing straw tubes. The high granularity and short distance to the interaction point of the Pixel Detector allows for clean reconstruction of secondary vertices as well as vertices from additional proton-proton interactions (pile-up) which is important for the study presented in this thesis. The ID operates within a solenoid magnetic field of 2 Tesla covering a pseudorapidity range of \(|\eta| < 2.5\). A three-dimensional cutaway view of the ID is shown in Figure 4.2. The proximity to the interaction point makes the ID subject to high radiation which limits the life time of the instrument to about 10 years.
Figure 4.2: Cutaway view of the ATLAS inner detector [ii].

4.2.1 Pixel Detector
The Pixel Detector [22, 23, 24] is the innermost part of the ID. It contains approximately 80 million readout channels. The Pixel Detector uses silicon diodes as detection technology. The pixels are arranged in three layers and determine track trajectories with an intrinsic accuracy of 10 μm in the R-ϕ direction and 115 μm in the beam direction. The innermost pixel layer, called b-layer is located as close as possible to the interaction point to improve the performance of secondary vertex measurements. With four disk layers of Pixel Detector at each end of the central barrel, the coverage extend to |η| < 2.5. For operation in high pile-up environment, the spatial resolution for reconstructing vertices coming from soft proton-proton interactions along the beam direction becomes important in order to discriminate physics signal processes from background.

4.2.2 Semiconductor Tracker
The Semiconductor Tracker (SCT) [24, 25] consists of a barrel detector and two symmetric end-cap detectors. The barrel region consists of four layers and covers the pseudorapidity range |η| < 1.4. Each end-cap has nine disks and extends the pseudorapidity coverage to |η| < 2.5. The SCT is based on silicon micro-strip detector technology. It provides four space-point precision measurements by combining hits from axial layers with hits from layers rotated with 40 mrad with respect to the beam axis called stereo layers. The intrinsic resolution is 17 μm in the R-ϕ direction and 580 μm in the beam direction. The SCT has in total around 6.3 million readout channels. Both the pixel and SCT systems have to be cooled down to a temperature 60K to maintain the adequate signal-to-noise performance and to reduce the effect of radiation damage.

4.2.3 Transition Radiation Tracker
The Transition Radiation Tracker (TRT) system [24, 26] is a combination of a straw tracker and a transition radiation detector. It consists of three parts, a barrel and two end-caps. In the barrel the straw tubes are arranged parallel to the beam direction. In the end-caps the tubes are oriented radially. The straw tubes are filled with a Xenon based gas mixture that is ionized at the passage
of charged particle. A wire with a positive potential collects the electrons from the ionized gas in the center of the straw tube and produces a current signal to be read out. Electrons that pass through the tube wall create additional electrons through transition radiation that will result in higher signal amplitude. The transition radiation detection enhances the capability of electron identification and discrimination against pions. The geometry of the TRT detector provides continuous tracking at larger radii. The TRT system has an intrinsic radiation hardness but lacks capability to operate at luminosities expected at HL-LHC because of high occupancies.

4.3 Calorimeter
The calorimeter system [27, 28] of the ATLAS detector is designed to measure the energy and position of electrons, photons and hadrons. The calorimeter has a fast readout that is used in the trigger system. The region of the calorimeter which overlaps with the inner detector has a fine grained structure. Due to a wide range of acceptance $|\eta| < 4.9$ and the high granularity, the calorimeter allows the reconstruction of missing transverse energy. The main parameters of the calorimeter system are listed in Reference [4, Table 1.3]. It is divided into several parts with specific properties and tasks.

4.3.1 Electromagnetic Calorimeter
The Electromagnetic (EM) calorimeter is a high granularity, sampling liquid argon (LAr) calorimeter that measures electrons and photons. It is divided into three parts, a barrel that covers $|\eta| < 1.47$ and two end-caps that cover $1.37 < |\eta| < 3.2$. The EM calorimeter uses LAr as an active material and lead as a converter over the full coverage. The particles traveling through the lead absorber initiate a cascade, depositing all their energies in the calorimeter by the ionization of the active material. The EM calorimeter uses an accordion geometry to provide a complete coverage and to ensure a uniform response. It shows an excellent performance in terms of energy and position resolution. A presampler detector is installed in front of the first layer within $|\eta| < 1.8$ to correct for energy losses in the material of the inner detector [27].

4.3.2 Hadronic Calorimeter
The Hadronic Calorimeter (HC) is installed outside the EM calorimeter. Its barrel region covers the range $|\eta| < 1.0$ and two extended barrels cover the range $0.8 < |\eta| < 1.7$. It is a sampling calorimeter which uses steel as a converter and scintillating tiles as active material. The thickness of the HC provides a good containment and prevents punch-through of non-muon particles into the muon system. The Hadronic End-Cap Calorimeter (HEC) consists of two independent end-cap wheels. In contrast to the HC, the HEC is LAr based and covers $|\eta| > 1.5$ [27].

4.3.3 LAr Forward Calorimeter
In the very forward region, the liquid argon Forward Calorimeter (FCal) provides coverage up to $|\eta| = 4.9$ and reduces the radiation background in the muon system. The FCal consists of three modules in each end-cap. Due to the high radiation density in the forward region, a radiation hard material is used in FCal. The first module is made of copper while the other two modules are made of tungsten. The FCal is able to measure the energy of electromagnetic and hadronic
interactions. The large $\eta$ coverage of the hermetic calorimeter provides good missing transverse energy measurements [28].

4.4 Muon System
The muon system is a large tracking and trigger system, installed around the calorimeter for high precision measurement and identification of muons. Because of their high mass in comparison to electrons, muons do not initiate a cascade in calorimeters. The system covers the pseudorapidity range of $|\eta| < 2.7$. The muon system uses four different chambers. In the barrel region, the chambers are arranged in three cylindrical layers parallel to the beam axis and, in the end cap regions, the chambers are arranged in planes perpendicular to the beam axis. The four muon chambers are: Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC) which deliver the precision tracking information within the barrel pseudorapidity range; Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) which deliver fast signals for triggering purposes in the barrel and end-caps respectively. The whole muon system is located inside three large air-core toroid superconducting magnets that generate the magnetic field in the muon spectrometer, 0.5 T in the barrel region and 1 T in the end-caps [4].

4.5 Forward Detectors
Special detectors are installed in the forward region of the ATLAS detector. The LUCID (Luminosity measurement Using Cerenkov Integrating Detector) is installed at 17 m from the interaction point, in order to detect the inelastic p-p collisions in the forward region. The LUCID detector is primarily dedicated to online luminosity monitoring. The BPTX system [29] is installed at 175 m from the interaction point to monitor the timing of the beam. The system has four electrostatic pick-up detectors, arranged symmetrically in the transverse plane around the LHC beam pipe. To detect the forward photons and neutrons, the ZDC (Zero-Degree Calorimeter) system is located at 140 m from the interaction point. The ZDC plays an important role in heavy-ion collisions by determining the centrality of such collisions [4].

4.6 ATLAS Upgrade
At the high-luminosity LHC (HL-LHC) the instantaneous luminosity will increase the number of interactions from 55 per bunch crossing at $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (Phase-I) to 140 per bunch crossing at $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (Phase-II). It will deliver over 3000 fb$^{-1}$ of data over ten years of operation to ATLAS around year 2024. The Phase-I ATLAS upgrade programme is described in [8]. The additional luminosity in the Phase-I upgrade will increase the occupancies in both the silicon tracker and the transition radiation tracker. Therefore it is essential for ATLAS to improve the performance in triggering and reconstructing the physics objects at the HL-LHC and to ensure operation in a harsh radiation environment. In the Phase-II upgrade, it is planned to replace the complete inner detector system. The readout for the new tracker system will be challenging because the number of hits per event will be larger. At HL-LHC, the particle fluxes and the average energy deposited in the calorimeters are expected to be higher than the design values. At the start of operation the front-end electronics would be 15-20 years old and have to
be replaced. To meet the requirements of the front-end readout electronics and to provide the higher granularity information to the trigger processors the readout electronics of the hadronic Tile Calorimeter will also be replaced.

The high pile-up will increase the pressure on the trigger system. Therefore the L1 trigger must achieve a higher rejection factor than before, for the same trigger $p_T$ threshold, even if the collision environment is more demanding. If the operation at HL-LHC preserves the $p_T$ thresholds, a total L1 trigger rate of 500 kHz would be expected. The proposed baseline architecture in Phase-II consists of a two-step Level-0/Level-1 hardware trigger. The Level-0 accepts the events at a rate of 500 kHz and the new Level-1 system reduces the rate to 200 kHz. To reduce the rate while maintaining the low single lepton threshold at around 20 GeV, the tracking information of the L0/L1 system will be used together with the calorimeter and muon trigger systems. Improved background rejection will be achieved by matching the tracks from the inner detector to the objects in the calorimeter or muon spectrometer. Hence the L0/L1 system allows the reconstruction of tracks at very low momenta and to perform the track based isolation for L1 electron, muon or tau candidates. The track trigger at L1 has more flexibility and redundancy, hence it should ensure full exploitation the physics potential at HL-LHC [9].
The ATLAS trigger and data acquisition system

5.1 Introduction
The ATLAS trigger and data acquisition system (TDAQ) is a multilevel system. The system is divided into three levels: Level 1 (L1) [30], Level 2 (L2) and Event Filter (EF). The L2 and EF levels are collectively known as High Level Trigger (HLT) [31]. The L1 trigger receives data at the full LHC bunch crossing rate of maximum 40 MHz. It uses limited detector information to make a decision within 2.5 μs, reducing the rate to 75 kHz. The HLT uses more detector information to reduce the rate up to 200 Hz with an average event size of 1.3 Mbyte. Each trigger level refines the decisions made at previous levels and applies new selection criteria. The data acquisition system TDAQ receives and buffers the events at the L1 acceptance rate. The system transmits the data corresponding to specific region of interests (RoIs) to the L2 trigger. The event building performed for those events is selected at L2. The TDAQ system moves the assembled events to the next trigger chain EF. The events selected at EF are then moved by the TDAQ system for permanent storage. Figure 5.1 shows a functional view of the ATLAS TDAQ system.

![Figure 5.1: Block diagram of the trigger/DAQ system [30].](image)

The L1 trigger identifies the physics signatures from jets, electrons, photons, high p_T muons and τ leptons decaying into hadrons. It also selects events with large missing transverse energy and total transverse energy. The L1 selection is based on information from a subset of detectors. The high p_T muons are identified using fast trigger chambers in the barrel and end-cap regions of the spectrometer. The electromagnetic clusters, jets, τ leptons and missing transverse energies are
selected by using all the sub-systems of the calorimeter but with reduced granularity information. The decisions of the L1 trigger are rapidly transferred to readout buffers of the front end electronics in the detector because of limited time for storing all data. The L1 trigger is fully implemented in hardware to meet a required short latency. The L1 trigger will be described in more detail in section 5.2.

The L2 trigger is a software based trigger. The L2 selection is based on RoIs identified at L1. For each event accepted by the L1 trigger, the information on each object is passed to the L2 trigger. The L2 trigger uses the RoIs information on coordinates and energy to limit the amount of data to process which significantly reduces the required computing resources. The L2 trigger reduces the event rate to below 3.5 kHz. Each region of interest (RoI) from the muon or calorimeter systems is examined at L2 together with tracking information from the ID to confirm if it is a valid trigger object. For example the track reconstruction in the ID enhances the distinction between electrons and photons.

The last trigger in the chain is EF which precedes the online selection step. It is a computer farm that receives an independent number of tasks on each processing node and processes the events. These tasks are very similar to the standard ATLAS event reconstruction that is done offline on stored data. For example, algorithms used at EF are the track fitting, vertex reconstruction, bremsstrahlung recovery for electrons, etc. The events are received at the maximum L2 rate of 3.5 kHz and the EF provides an additional rejection leading to a final output rate of ~ 200 Hz (which is limited by the storage capacity). For those events which fulfill the selection criteria at EF, a tag is added for identifying the physics stream in which the event has been classified and accepted events are stored in a database [4, 20, 30].

5.2 Level-1 trigger
The flow of the L1 trigger system is shown in Figure 5.2. The L1 trigger uses muon and calorimeter algorithms to make fast decisions. The tracking detectors have too many readout channels to be read out fast enough for the L1 trigger in the current detector. The L1 calorimeter trigger (L1Calo) selection is based on information from electromagnetic and hadronic calorimeters in the barrel, end-caps and forward regions. The L1Calo identifies the events with large missing and total transverse energies, electrons, photons, jets and τ leptons decaying into hadrons. For the triggered events with electrons, photons and τ leptons, isolation can be required, which aims at separating, the desired processes from the QCD jet production and other backgrounds. The observed L1Calo objects are computed using the $E_T$ values in trigger towers of $0.1 \times 0.1$ granularity in $\Delta\eta \times \Delta\phi$. The L1 muon trigger is based on signals in the different stations of muon trigger detectors: the Resistive Plate Chambers (RPC) in the barrel region and the Thin Gap Chambers in the end-cap region.

The Central Trigger Processor (CTP) combines the information from calorimeter and muon triggers for different objects and makes the decision. This trigger decision is then distributed to
the detector front end and readout systems via the Timing, Trigger and Control (TTC) system. The events accepted by the L1 trigger are sent as RoIs to the L2 trigger.

Figure 5.2: Block diagram of the L1 trigger [4].

The number of configuration choices is limited at L1, which requires a careful selection of thresholds. The total number of thresholds allowed for EM and tau objects is 16. Table 5.1 gives the total number of thresholds for each object at L1. The number of allowed L1 configurations that can be programmed is up to 256 distinct items. Each of these L1 items programmed in the CTP is a combination of one or more configured L1 thresholds. For example L1_EM18 is a single L1 EM object with threshold \( E_T > 18 \text{ GeV} \).

Table 5.1: Number of thresholds set for L1 objects [19].

<table>
<thead>
<tr>
<th>Object</th>
<th>EM</th>
<th>Taus</th>
<th>Jets</th>
<th>( E_T )</th>
<th>( \sum E_T )</th>
<th>( \sum E_T(jets) )</th>
<th>( \mu \leq 10 \text{ GeV} )</th>
<th>( \mu &gt; 10 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td># of thresholds</td>
<td>8-16</td>
<td>0-8</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

A very short 25 ns bunch-crossing interval makes a challenging task for processing and selecting events by L1. The front-end buffers in the detector are finite and can hold the data with full resolution only for a limited time of \( \sim 3\mu s \). If a signal accepted at L1 is not recorded within this time, the data is lost. The time between a proton-proton collision and the corresponding L1 trigger decision is called L1 latency [4, 19, 30].
5.3 Electron/Photon trigger at L1

The L1 calorimeter trigger (L1Calo) [32] uses a set of trigger towers of reduced granularity \(0.1 \times 0.1\) in \(\Delta \eta \times \Delta \phi\) as input and processes the data by using a pipelined digital system. It covers the rapidity \(|\eta| < 5.0\) and \(\phi = 0\) to \(2\pi\). The electromagnetic and isolated hadron cluster trigger covers only up to \(|\eta| < 2.5\), the same region where tracking information is provided by the ID. The total number of trigger towers is 7200, of which 6400 are used for the electromagnetic and isolated hadron cluster trigger. The L1Calo operates at the LHC bunch crossing frequency of 40 MHz. It takes a snapshot of the energy deposited in trigger towers. The L1Calo must select different types of high \(E_T\) objects such as electrons, jets, hadrons from tau decays, missing and total transverse energy. The L1Calo uses different types of algorithms for triggering and delivering the RoIs to L2. The algorithms used in L1Calo are limited but they are fully programmable at the level of parameters (\(\eta\) and \(\phi\)). The electron/photon algorithm [33] is shown in Figure 5.3.

![Electron/photon trigger algorithm](image)

**Figure 5.3:** Electron/photon trigger algorithm [4].

The electron/photon trigger algorithm is based on \(4 \times 4\) towers in the electromagnetic and hadronic calorimeters. The trigger towers within such windows are as follows:

- Each electromagnetic trigger tower has its own window named as Reference Trigger Tower.
- The central electromagnetic and hadronic calorimeter trigger towers build a \(2 \times 2\) array.
- The isolation ring consists of 12 electromagnetic and hadronic trigger towers around the central ones.
By combining the transverse energies of the above trigger towers, the following trigger elements are formed:

- Electromagnetic clusters are formed by the four possible sums of two contiguous central electromagnetic trigger towers. The four possible sum of two of these electromagnetic central trigger towers together with the sum of four central hadronic trigger towers make the hadronic cluster.
- The electromagnetic and hadronic isolation sum is computed using 12 electromagnetic and hadronic calorimeter isolation ring trigger towers respectively.
- A central RoI is the sum of four central electromagnetic and hadronic trigger towers.

The electromagnetic and isolated hadronic triggers formed from these trigger elements must fulfill the following requirements:

- One of the most energetic sums of the electromagnetic and hadronic cluster must pass the trigger threshold.
- The central RoI must be a local transverse energy maximum.
- The electromagnetic and hadronic isolation sum must be below specified thresholds.

All these thresholds are given in Table 5.1 and they are fully programmable [33]. If an electron/photon or tau object meets these requirements, then the window is considered to contain electromagnetic or hadronic cluster respectively. The algorithms are based on 4 × 4 windows that can slide and overlap by steps of 0.1 in both η and φ. This implies that a cluster from an electron/photon or τ satisfy the conditions in two or more adjacent windows. To avoid this multiple counting of clusters the sum of the four central electromagnetic and hadronic towers is required to be a local maximum with respect to its eight nearest overlapping neighbours. The multiplicity of candidates passing the sets of threshold and isolation criteria is counted and passed to Central Trigger Processor as an input [4, 30, 32, 33].

Most of the calorimeter trigger rates will increase linearly with the LHC luminosity increase. The current ATLAS L1Calo trigger system is not able to provide acceptable rates at low p_T thresholds for electron and photon triggers. So ATLAS is planning to implement various algorithms, used in existing high level trigger, in the L1Calo trigger system during Phase-I. This will lower the rates for the EM objects at low p_T thresholds. Figure 5.4 shows the EM thresholds as a function of the instantaneous luminosity. The three curves in Figure 5.4 correspond to different noise suppression thresholds. For a 20 kHz L1 trigger rate the predicted EM threshold is around 40-45 GeV, which will eliminate most of the W and Z signals. For the same 20 kHz L1 trigger rate the isolation requirements on the L1 EM cluster described above in this section would reduce the rates but this is far from sufficient to preserve the low thresholds. Figure 5.5
shows the expected rates for the EM18VH\textsuperscript{5} trigger for different number of interactions (pile-up) at a center of mass energy of 14 TeV. For an EM threshold below 30 GeV the integrated rate exceeds 200 kHz which is far from the L1 output rate in Phase-I.

![Graph showing expected rates for EM18VH trigger.]

**Figure 5.4:** The predicted EM thresholds as a function of the instantaneous luminosity at 20 kHz L1 trigger rate [8].

![Graph showing differential rate of L1 EM18VH for minimum bias sample of different pile-ups.]

**Figure 5.5:** The differential rate of L1 EM18VH for minimum bias sample of different pile-ups [iii].

For an acceptable L1 trigger rate at low $p_T$ threshold, the granularity of the EM trigger towers does not allow to discriminate against low $p_T$ jets. Shower shape algorithms are used in the current offline reconstruction to improve the identification between electrons and photons as well as the rejection against $\pi^0$s. The algorithms use the information from the second layer of the EM calorimeter cells. Studies shows that the shower shape algorithms using the information from the

\textsuperscript{5}The “VH” is an algorithm applied to see the response of electrons in ATLAS detector, due to the variation in material in front of the calorimeter: “V” represents threshold values in different $\eta$ regions and “H” is a hadronic core cut. Further details and results are given in appendix B.
fine granularity cells $\Delta \eta \times \Delta \phi = 0.025 \times 0.1$ in the second layer of the EM calorimeter can achieve a better background rejection. The information from the second layer of the EM calorimeter cells are the ratio of energies deposited in the clusters in $\eta, \phi$. Figure 5.6 shows the distribution of the ratio of the energy in the clusters of the second layer of EM calorimeter cells for electrons and jets [8].

Figure 5.6: The distribution of $R_{\eta} = \frac{E_{3 \times 2}}{E_{7 \times 2}}$ ratio of energies measured in $3 \times 2$ over $7 \times 2$ cells of the second layer of the EM calorimeters for electrons and jets. The size of each cell in the cluster is $\Delta \eta \times \Delta \phi = 0.025 \times 0.1$ [8].

5.4 Level-1 Calorimeter Trigger
The ATLAS physics goals require an upgrade of the trigger and TDAQ systems. To keep the single lepton $p_T$ thresholds low, many parts of the L1 trigger system need to be improved to achieve sufficient background rejection. The Phase-II trigger architecture is a split L0/L1 hardware trigger. The acceptance rate at L0 is 500 kHz within a latency of 6 $\mu$s. The L1 reduces the rate to 200 kHz within 20 $\mu$s by using tracking information within a RoI of calorimeter granularity. The L0 trigger is functionally the same as the Phase-I L1 trigger system. It also incorporates the topological trigger system. The information processed by the L1 topological trigger is the transverse energy of the RoIs identified by the L1Calo trigger and $\eta - \phi$ coordinates. The topological algorithms are used in the development of the L1 trigger to retain the low $p_T$ thresholds. A selection based on di-lepton, jet topology and missing transverse energy allows to achieve the rate reduction of 2-5 in the concerned channels. Two topological algorithms are currently being studied. One of them improves the performance of single lepton triggers by including the separation between electron and jet signatures. The second one
improves the multiple trigger objects to identify the W or Z lepton decay candidates by computing the (transverse) mass.

In Phase-II the L1 calorimeter trigger system (L1Calo) will have access to the full granularity of the calorimeter. This will improve the measurements of the energies and provide sharp turn-on curves. In turn, this will help match clusters to tracks found by the L1 track trigger system. The increase in granularity will provide additional background rejection for electron triggers and a finer resolution of the η coordinate of any EM region of interest. The improved measurement of the transverse energy of each object could also apply to jet finding algorithms. Two methods can be used to refine the identification of electrons and photons. In the first method the η × φ granularity in the second sampling layer of the EM calorimeter is 0.025 × 0.025 in L1Calo and 0.025 × 0.1 in L0Calo as shown in Figure 5.7.

![Figure 5.7: The EM calorimeter granularity in Phase-II EM triggers [9].](image)

In addition the fake EM trigger rate due to photons from π⁰ → γγ can be suppressed by using the granularity 0.003125 × 0.1 in the first η − φ liquid-argon strip layer. As shown in Figure 5.8 a single electron or photon is concentrated in a single region of the strip layer while photons from π⁰ decays are found in two strip layers [9].

![Figure 5.8: The fine granularity information from the first sampling layer of the EM calorimeter for electron/photon on the left and for π⁰ decays on the right [9].](image)

5.5 Level-1 Track Trigger
In HL-LHC the L1 electron trigger rates would be unsustainable with a threshold of 20 GeV. The proposed L1Calo trigger Phase-II upgrade alone is insufficient to meet requirements on the
ATLAS physics goals. So the only other source of information that has the potential to enhance the purity of events selected at L1 is the inner tracker. Currently the tracking information is used by the L2 trigger system for background rejection. In the Phase-I upgrade the Fast Track Reconstruction system called FTK [34] will implement a hardware trigger to provide information on the reconstructed tracks to the high level trigger. An FTK-like system may be used as a base for a L1 track trigger as a part of the tracker upgrade. For Phase-II, two L1 track trigger designs are discussed: a RoI-driven L1 track trigger and a self-seeded L1 track trigger.

In the RoI-driven approach, the tracks are provided in regions of the inner detector defined by the EM RoIs from the L0 trigger. The full data of ID cannot be readout at the L0 rate of 500 kHz. The RoI-driven design solves the problem by reading out the data, first from L0 trigger RoIs and then a subset of the tracker data. The main advantage of the RoI-driven approach is that it has little impact on the inner detector layout and can be optimized independently. The RoI-driven also has to fit within the latency of 20 μs in Phase-II trigger system. The RoI system is studied in this thesis.

In the self-seeded approach, hits from high momentum tracks are detected through correlation of hits between closely spaced silicon layers. A sufficient reduction of low $p_T$ hits is required for the rate to stay inside the bandwidth of data links. As the large amount of data makes it impossible to process all hit information in the tracker, a subset of selected strip layers are used for trigger processing. A data reduction scheme is applied to remove the hits of low-momentum tracks for the self-seeded L1 track trigger. For this reduction two methods are exploited, first using the hits from small size clusters and second inferring the transverse momenta of charged particles from the angle between the hits of double strip layers and apply a $p_T$ cut. These two methods can reduce the bandwidth by two orders of magnitude for $p_T > 20$ GeV. But the exact performance depends on the design of the ID layers. The instrumentation of a self-seeded trigger requires a complete redesign of the ID and no studies have yet proven that this method will work in the EC region. At this moment the RoI based track trigger seems more feasible [9].
Analysis

6.1 Signal and background samples
The observation of the SM Higgs boson by the ATLAS and CMS experiments at the LHC is a great success in experimental particle physics. The Higgs decay mode $H \rightarrow \tau^+ \tau^-$ is an important decay channel to measure because it probes the coupling of the Higgs boson to fermions [35]. The $H \rightarrow \tau^+ \tau^-$ channel has a branching ratio of 6.3% for a Higgs mass of 125 GeV and is one of the leading decay modes of the SM Higgs boson not yet discovered at the LHC. The $H \rightarrow \tau^+ \tau^-$ channel is selected as one of the benchmark channels for the ATLAS upgrade and it is a particularly interesting channel for the L1 track trigger studies because of the leptonic decay of the $\tau$ lepton, which lead to low $p_T$ tracks matched with the calorimeter or muon spectrometer signals. In this analysis, the performance of the L1 track trigger for the channel $H \rightarrow \tau^+ \tau^-$ where $\tau$ decays into electrons has been studied. The single electron trigger is used to select the data and to maximize the electron acceptance. The data files used in the analysis are produced in Athena by a D3PD maker. Athena is a software framework which digitizes and reconstructs raw data from the detector or a Monte Carlo generator and provides a convenient output. The operator input to Athena is a set of algorithms defined by the user for the reconstruction and identification of specific physics objects and the output is a useful chain of variables in ROOT format. Athena uses algorithms written in C++ or Python for building the physics objects e.g. tracks or clusters of EM calorimeter cells. ROOT is an object-oriented framework that is used for solving data analysis challenges in high energy physics. It handles and analyses large amounts of data in a very efficient way. It also provides a large selection of specific utilities such as histograms and fitting. It has the built-in C++ interpreter CINT that provides fast prototyping of macros. The LHC started its operations at a luminosity of $3 \times 10^{33} \text{cm}^{-1}\text{s}^{-1}$ in 2009. It will eventually deliver data at the design luminosity of $10^{34} \text{cm}^{-1}\text{s}^{-1}$ before the end of the decade. In this environment, more than one proton-proton collision is expected per bunch crossing. This is called pile-up. In general it implies that, when an event with interesting physics fires a trigger, there are additional traces in the detector from additional soft proton-proton collisions (called minimum-bias events) that are not related to the main physics event. Hence the events with interesting physics contain a superposition of tracks coming from different events. In addition to the minimum-bias events from the pile-up, cavern background interactions are also added [36]. PYTHIA [37] is used to produce these pile-up Monte Carlo samples with 69 or 92 minimum-bias events per bunch crossing. The minimum-bias events are simulated corresponding to the luminosity of $3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. For the details of samples see appendix A.

6.2 Physics objects
The electromagnetic calorimeter measures the energy from particles that dominantly interact electromagnetically, namely electrons and photons. Associating a track from the inner detector to the energy deposit in the electromagnetic calorimeter will form electron candidates. An initial
selection of events is performed by triggering on electrons at a threshold of 18 GeV at Level-1. The selection of physics objects is then based on the requirements applied to offline electrons for current Higgs studies in ATLAS. The details of electron identification cuts are described in [38]. The transverse energy cut of offline electrons is $E_T > 15$ GeV, within the rapidity $|\eta| < 2.47$. The selected electrons are then required to be isolated. For isolation the additional transverse energy in a cone of radius $\Delta R < 0.2$ around the electron direction must be less than 8% of the electron transverse energy [39]. Figure 6.1 shows the $E_T$ distribution of offline reconstructed electrons after the physics selection cuts for the Monte Carlo signal sample with pile-up (69 minimum-bias events are used).

In the EM calorimeter the cluster energy is defined as the sum of all energies in the calorimeter cells as described in section 5.3. The L1 calorimeter trigger information is used for trigger matching. The minimum $p_T$ threshold used for triggering is 18 GeV. In the Phase-II ATLAS upgrade the L1 calorimeter trigger system will use the full granularity of the calorimeter for the improved measurements of energies of trigger objects. Hence, in the current analysis, to see the effect of granularity, the calorimeter Level-2 (L2) trigger information is also used for trigger matching. Figure 6.2 shows the distribution of energy deposited in the L1 cluster after triggering and the distribution of transverse energy at L2 for the signal sample with pile-up. With the existing L2 trigger the calorimeter has access to the full granularity which resolves two nearby energy deposits that would be merged into one at L1 because of the coarser granularity. After triggering at 18 GeV at L1, the L2 cluster contains objects with energy below 18 GeV. Above an energy of 18 GeV the L2 cluster has almost the same energy distribution as the L1 cluster. Overall the L2 cluster finds more objects compared to the L1 cluster. The matching of L1 and L2 electromagnetic clusters with the selected offline reconstructed electrons in a cone of $\Delta R = \sqrt{(\eta_{\text{offel}} - \eta_{\text{clus}})^2 + (\phi_{\text{offel}} - \phi_{\text{clus}})^2} < 0.2$ defines the (non-isolated) RoI. Figure 6.3 shows
the distribution of energy deposited in the L1 and L2 clusters after matching to the offline electrons. The red curve represents the L1 cluster and the blue curve represents the L2 cluster in Figure 6.3. The L2 cluster has more electrons below an energy of 18 GeV because of the finer granularity. Above an energy of 20 GeV the distributions are very similar for L1 and L2 clusters.

![Figure 6.2: Distribution of energy in the EM L1 and L2 clusters. The L1 EM cluster has been triggered at a threshold of 18 GeV.](image1)

![Figure 6.3: Distribution of energy in the L1 and L2 EM clusters after matching to the offline electrons.](image2)

As a comparison, in the case of pile-up samples, Figure 6.4 shows the distribution of the energy in the EM clusters at L1 and L2 after triggering, for samples with 69 minimum-bias events. The cyan curve in Figure 6.4 represents the L1 cluster while the magenta curve represents the L2 cluster.
Figure 6.4: Distribution of energy in the L1 and L2 EM clusters for the sample with 69 minimum-bias events. The L1 EM cluster has been triggered at a threshold of 18 GeV.

6.3 Level-1 track trigger studies

Three different methods are used in this analysis to study the performance of the L1 track trigger in the $H \to \tau^+\tau^- \to e^+e^-$ channel. These methods were studied and optimized for high signal efficiency and good background rejection. The analysis is carried out with the current geometry of the ATLAS detector because the upgraded detector geometry for HL-LHC is still not implemented fully in Athena. In the first method, the matching of tracks from the ID to EM calorimeter clusters is used to reject background. For each electron a matching track is sought in a matching cone $\Delta R = \sqrt{(\eta_{\text{clus}} - \eta_{\text{track}})^2 + (\phi_{\text{clus}} - \phi_{\text{track}})^2}$. The EM clusters which do not have a matched track are treated as background and rejected. In this method the signal and background efficiencies are calculated for different matching cone sizes and different track transverse momenta. To enhance the performance of the trigger, a track based isolation method is then studied. In this second method, additional tracks are searched for inside the so-called isolation cone which is larger than the matching cone. By varying various parameters in this method one can find an optimal isolation cut with a high signal efficiency and low background. Finally, in the third method, a $E_T/p_T$ based selection cut is used to further reject the background, where $E_T$ is the transverse energy deposited in the EM calorimeter by an electron with an associated track transverse momentum $p_T$. In this method, after matching tracks to the electrons in just one matching cone, an additional selection based on $E_T/p_T$ is made. Using these methods in the trigger, the aim is to get background rejection factors of about 2-5 because the luminosity at HL-LHC increases by a factor of five.

6.3.1 Track matching study

The use of L1 track matching to the EM calorimeter clusters is expected to reduce the rates from objects in minimum-bias events while maintaining a high efficiency for electron candidates.
Figure 6.5 shows the $\Delta R$ distribution between the offline tracks passing the criteria $p_T > 6, 10, 14$ GeV and the L1 or L2 electromagnetic cluster for both signal and pile-up samples where 69 minimum-bias events are used.

![Signal](image1)

![Background](image2)

**Figure 6.5:** The $\Delta R$ distribution for offline tracks with respect to the L1 and L2 EM clusters for signal (left) and for pile-up (right).

The $\Delta R$ distribution of offline tracks with respect to L1 clusters has a long tail for both samples. The L1 calorimeter $\eta$ granularity is expected to be improved after the Phase-I upgrade, while the $\phi$ granularity will remain the same. So the corresponding $\Delta R$ distribution is not expected to become as the present one for L2 clusters but in between the distributions for L1 and L2 clusters.
As it can be seen from the left plots in Figure 6.5, for the signal sample most tracks are inside the cone of radius 0.2 for the L1 cluster and in a cone of radius 0.1 for the L2 cluster. The shape of the ΔR distribution in the pile-up sample (right plots in Figure 6.5) also has a long tail due to matching of tracks to EM clusters from π⁰ conversions and bremsstrahlung.

Figure 6.6 shows the total number of tracks matched to the L1 EM cluster in a cone of ΔR < 0.2 with a track p_T cut of 6, 10 and 14 GeV for signal and pile-up. At low track momenta, the signal electrons with one matched track dominate over electrons that have no matched track at all. The number of electrons with only one matched track increases as the p_T cut is tightened. In minimum bias events, most electrons have more than one matched track at low momentum and at high transverse track momenta electrons have no tracks. The electrons for which no tracks are found are mainly background coming from processes like bremsstrahlung.

**Signal**

- Track $p_T > 6 \text{ GeV}, \Delta R < 0.2$
  - No track: 37.1%
  - One track: 65.0%
  - More than one tracks: 7.9%
- Track $p_T > 10 \text{ GeV}, \Delta R < 0.2$
  - No track: 22.5%
  - One track: 73.4%
  - More than one tracks: 4.1%
- Track $p_T > 14 \text{ GeV}, \Delta R < 0.2$
  - No track: 16.7%
  - One track: 83.3%
  - More than one tracks: 0%

**Background**

- Track $p_T > 6 \text{ GeV}, \Delta R < 0.2$
  - No track: 53.1%
  - One track: 36.5%
  - More than one tracks: 10.4%
- Track $p_T > 10 \text{ GeV}, \Delta R < 0.2$
  - No track: 25.2%
  - One track: 52.2%
  - More than one tracks: 22.6%
- Track $p_T > 14 \text{ GeV}, \Delta R < 0.2$
  - No track: 33.7%
  - One track: 52.2%
  - More than one tracks: 14.0%

**Figure 6.6:** Track multiplicities with respect to the L1 EM cluster in a cone of ΔR < 0.2 with different p_T cuts for signal (top) and for minimum-bias events (bottom).

Figure 6.7 shows the total number of tracks matched to the L2 EM cluster in a cone of ΔR < 0.1 with a track p_T cut of 6, 10 and 14 GeV for signal and minimum-bias events. For the signal sample, more than 70% of electrons have one matched track. Only for a few electrons, no matched tracks have been found for the L2 cluster. In the pile-up sample the electrons with no matched tracks are more abundant than the electrons with one matched track at low and high track momenta.
Figure 6.7: Track multiplicities with respect to the L2 EM cluster in a cone of $\Delta R < 0.1$ with different $p_T$ cuts for signal (top) and for minimum-bias events (bottom).

After matching tracks to the EM cluster, for each electron a matched highest $p_T$ track (leading track) is searched for. The corresponding efficiency is then calculated for both signal and background samples as

$$\epsilon_{\text{lead track}} = \frac{N_e^{\text{matched}}}{N_e^{\text{total}}}$$  \hspace{1cm} (6.1)

where $N_e^{\text{matched}}$ is the number of electrons passing the track trigger criteria ($p_T > \text{threshold}$, $\Delta R < 0.1 - 0.4$) and $N_e^{\text{total}}$ is the total number of electrons after physics selection. Figure 6.8 shows the signal efficiency versus the background efficiency for different matching cones and for different track $p_T$ cuts, for both L1 and L2 EM clusters. Clearly the signal efficiency with respect to the L1 EM clusters is high for a cone of $\Delta R < 0.2$ (red curve in the left plot of Figure 6.8), while for the L2 EM clusters, the cone $\Delta R < 0.1$ has a high signal efficiency for different track $p_T$ cuts (blue curve in the right plot of Figure 6.8). The signal and background efficiency decreases with the high track $p_T$ cuts for each cone size for both L1 and L2 EM clusters. The signal efficiency in the narrow cone size of $\Delta R < 0.1$ is larger for the L2 EM clusters than for the L1 EM clusters. For a cone size of $\Delta R < 0.3$ or 0.4 the signal versus background efficiency at different track $p_T$ cuts is very high for the L1 EM clusters and even slightly better for the L2 EM clusters. The overall signal efficiency is thus better for the L2 EM clusters as compared to the L1 EM clusters. Figure 6.8 shows that the track matching method works very well providing a signal efficiency of above 90% with a background rejection factor of between 1 and 3.
Figure 6.8: The signal efficiency versus the background efficiency for different matching cones with respect to the L1 EM clusters (right) and L2 EM clusters (left). The numbers next to the curve represents the minimum track $p_T$ cut.

6.3.2 Track isolation study

One goal of this second simulation study is to find an optimal isolation cut while maintaining the high signal efficiency and rejecting the background. As described in section 6.3.1, the highest $p_T$ track was identified for each electron. For the isolation study the leading tracks with a $p_T$ of 8 and 12 GeV have been considered. The blue curves in Figure 6.9 are the efficiency curves for the leading track found in the matching cone of $\Delta R < 0.2$ and $\Delta R < 0.1$ with respect to the L1 EM clusters (right) and L2 EM clusters (left) respectively. These curves correspond to, respectively, the red curve in Figure 6.8 (left) and the blue curve in Figure 6.8 (right). From these curves the efficiencies of lead tracks with $p_T$ of 8 and 12 GeV are taken as a reference for the isolation study.

To isolate the leading tracks with a $p_T$ of 8 and 12 GeV, sub-leading tracks are searched for in an isolation cone having a larger radius i.e. $\Delta R < 0.3$ (0.2) for a matching cone with radius $\Delta R < 0.2$ (0.1). Then the sub-leading tracks in each isolation cone are searched for and those that pass the isolation criteria ($p_T$ of sub-leading track < threshold) are then used for calculating the efficiency:

$$\varepsilon_{\text{isolated track}} = \frac{N^e_{\text{isolated}}}{N^e_{\text{matched}}} \quad (6.2)$$

where $N^e_{\text{isolated}}$ is the number of electrons passing the isolation criteria and $N^e_{\text{matched}}$ is the total number of electrons after passing the track trigger criteria. The total efficiency is then calculated as:

$$\varepsilon_{\text{Total}} = \varepsilon_{\text{lead track}} \times \varepsilon_{\text{isolated track}} \quad (6.3)$$

where $\varepsilon_{\text{lead track}}$ is the efficiency of leading tracks with a $p_T$ of 8 and 12 GeV. The magenta and red curves in Figure 6.9 are the efficiency curves for isolated tracks in the isolation cones of $\Delta R < 0.3$ and $\Delta R < 0.2$ with respect to L1 (left) and L2 (right) EM clusters around the leading
tracks of 8 and 12 GeV. The isolation works well for the L1 EM clusters but it has a very small effect for L2 EM clusters. The reason is the track multiplicity with respect to both L1 and L2 EM clusters. As it can be seen in Figures 6.6 and 6.7, the fraction of events with more than one track matched to the cluster is greater for L1 EM clusters than for L2 EM clusters. So there are more tracks available in isolation cones for L1 EM clusters than for L2 EM clusters. Increasing the isolation cone size to $\Delta R < 0.4$ for L1 EM clusters and $\Delta R < 0.3$ for L2 EM clusters does not yield much difference.

**Figure 6.9:** The signal versus background efficiency in the isolation study with respect to the L1 (left) and L2 (right) EM cluster. The blue curve on both plots represents the efficiency curve for leading tracks. The red and magenta curves in the left plot (L1 EM cluster) are efficiency curves for an isolation cone of $\Delta R < 0.3$ and track $p_T$ cuts up to 17 GeV. The red and magenta curves in the right plot (L2 EM cluster) are efficiency curves for an isolation cone of $\Delta R < 0.2$ and track $p_T$ cuts up to 17 GeV. The numbers next to each curve represents the track $p_T$ cut.

### 6.3.3 Study of $E_T/p_T$ matching

The electrons coming from $H \rightarrow \tau^+\tau^-$ deposit their energies in the EM calorimeter. For a true electron with some transverse momentum $p_T$ depositing its transverse energy in the calorimeter, the ratio $E_T/p_T$ should ideally be equal to 1. The distribution of $E_T^{\text{cluster}}/\text{track } p_T$ with a track $p_T$ cut of 6, 10 and 14 GeV using L1 and L2 EM clusters are shown in Figure 6.10 for both signal and pile-up samples. At low momentum the resolution of the peak is dominated by the calorimeter $E_T^{\text{cluster}}$ resolution and at high momentum it is dominated by the track $p_T$ resolution. For both the signal and pile-up samples the distribution has a long tail. For the signal it is mainly due to the energy loss of electrons through bremsstrahlung. Using the $E_T^{\text{cluster}}/\text{track } p_T$ cuts would allow good discrimination against minimum-bias events. Figure 6.11 shows the signal versus background efficiency using different $E_T^{\text{cluster}}/\text{track } p_T$ cuts on both signal and pile-up samples with 69 minimum-bias events. The efficiency is calculated after applying different cuts on $E_T^{\text{cluster}}/\text{track } p_T$ for the leading track as:

$$
\varepsilon = \frac{N^F_{\text{matched after cuts}}}{N_{\text{Total}}} \tag{6.4}
$$
where \( N_{\text{matched after cuts}} \) is the number of electrons passing the \( E_T^{\text{cluster}}/\text{track} \ p_T \) cuts together with track trigger criteria and \( N_{\text{total}} \) is the total number of electrons after physics selection. The efficiency is low if \( E_T^{\text{cluster}}/\text{track} \ p_T \) cuts harshly on the bremsstrahlung tail for low \( E_T \) electrons, as shown by the blue curves in Figure 6.11. If \( E_T^{\text{cluster}}/\text{track} \ p_T \) cuts loosely then the signal versus background efficiency is not very affected by different \( E_T^{\text{cluster}}/\text{track} \ p_T \) cuts. As it can be seen from Figure 6.11 for track \( p_T \) cut above 8 GeV the efficiency curves are almost the same just slightly drifting downwards for each \( E_T^{\text{cluster}}/\text{track} \ p_T \) cut. The \( E_T^{\text{cluster}}/\text{track} \ p_T \) matching method does not give the expected background rejection factor. It shows a bad discrimination against background for both L1 and L2 EM clusters.
Figure 6.10: The $E_T^{\text{cluster}}/\text{track } p_T$ distribution for signal and background for track $p_T$ cuts of 6, 10 and 14 GeV.
Figure 6.11: Signal versus background efficiency for the different cuts on $E_T^\text{cluster}/\text{track } p_T$ for a matching cone of $\Delta R < 0.2$ (left) with respect to a L1 EM cluster and for a matching cone of $\Delta R < 0.1$ with respect to a L2 EM cluster. The red curve on both plots represents the efficiency curve for leading tracks without $E_T^\text{cluster}/\text{track } p_T$ cuts. The numbers next to each curve represents the minimum track $p_T$ cut.
Conclusions

This study demonstrates that using tracking information would greatly improve the performance of the L1 trigger while keeping the electron signatures at low p_T thresholds. The ultimate background rejection factor for electrons is possibly between 1 and 3. It has been demonstrated in terms of single electron trigger that the track matching to the EM cluster maintains the high signal efficiency for matching cones with ΔR < 0.2 with respect to L1 clusters and matching cones ΔR < 0.1 with respect to L2 clusters. With a lead track p_T > 10 GeV in a matching cone of ΔR < 0.2 the signal efficiency is 94% with a background efficiency of 63%, thus providing a maximum background rejection of 1.58 for L1 clusters. With the same lead track p_T > 10 GeV in a matching cone of ΔR < 0.2 with respect to L2 clusters, the signal efficiency is 92% with a background efficiency of 52%, providing a background rejection factor of 1.92. For a lead track p_T > 10 GeV in a matching cone of ΔR < 0.1 with respect to L2 clusters the signal efficiency is 91% with a background efficiency of 44%, hence the background rejection factor is 2.27. Therefore, by using L2 clusters with high granularity information, in the track matching method, a better signal efficiency and a higher background rejection are obtained.

Additionally, a track based isolation method can be used to increase the background rejection factors. The isolation works better for L1 clusters than for L2 clusters. Different isolation cone sizes were used, together with different track p_T cuts, to find the optimal isolation cut at which the signal efficiency would be high and the required background rejection would be achieved. For example, for EM L1 clusters in an isolation cone of ΔR < 0.3 around the lead track with p_T > 8 GeV, the signal efficiency for a sub-leading track p_T cut of 8 GeV is 58% with a background efficiency of 32%. The total background rejection factor achieved is 3.1. For EM L2 clusters with an isolation cone of ΔR < 0.2 around the lead track with p_T > 8 GeV, the signal efficiency for a sub-leading track p_T cut of 8 GeV is 68% with the background efficiency of 35%. A background rejection factor of 2.85 is achieved. Hence, one can obtain a high background rejection factor even in larger isolation cones with respect to L1 clusters than in narrow isolation cones with respect to L2 clusters.

Finally, to improve the background rejection different E_T^{cluster}/track p_T cuts were applied after track matching to clusters. Very small effects are seen for E_T^{cluster}/track p_T < 4-10 for both L1 and L2 clusters, so the E_T^{cluster}/track p_T based selection does not show a good discrimination against background. The signal efficiency drops rapidly for E_T^{cluster}/track p_T < 3.

The parameters used for the track matching and track isolation methods are the cone sizes and the track p_T cuts. One can optimize these parameters to in different physics channels to see the performance of the L1 track trigger. In this study reconstructed offline tracks were used rather than unreconstructed detector hits. A more significant effect is the possible increase of fake tracks or loss of efficiency if the reconstruction is done in a coarse and fast way, as it will be
necessary in the L1 track trigger. The understanding of the prospective L1 track trigger performance will depend upon the final design parameters of ATLAS detector and of the L1 trigger after the upgrade.
Appendix A

High Luminosity Datasets

<table>
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<th>Dataset ID</th>
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<th>Reconstruction Tag</th>
<th>Events</th>
<th>Description</th>
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<td>7496</td>
<td>MC09 PU 46</td>
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<td>MC11 14TeV PU 69</td>
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<td>MC11 14TeV PU 92</td>
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<td>108351</td>
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<td>e842_s1321_d602_r2887</td>
<td>389200</td>
<td>MC11 14TeV PU 69</td>
</tr>
</tbody>
</table>

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mc11_14TeV.108351.Pythia8_minbias_Inelastic.recon.AOD.e842_s1321_d671_r3300.D3PD
mc11_14TeV.108351.Pythia8_minbias_Inelastic.recon.AOD.e842_s1321_d602_r2887.D3PD
Appendix B

The response to electrons varies in the ATLAS detector with $\eta$ due to the variation of the material in front of the calorimeter. To see the effect, an algorithm called VH is applied: “V” corresponds to different threshold values in different eta $\eta$ regions and “H” is the hadronic core cut used for $e/\gamma$ isolation. Figure 1 shows the distribution of energy deposited in the L1 EM cluster after triggering at 18 GeV and applying the VH algorithm. After applying the VH algorithm the L1 EM cluster contains fewer objects than the L1 EM cluster without a VH algorithm shown in Figure 6.2. The objects in the L1 EM cluster after the VH algorithm are matched to the offline electrons in a cone of $\Delta R < 0.2$. Figure 2 shows the distribution of energy in the L1 EM cluster after matching to the offline electrons.

![Figure 1](image1.png)

**Figure 1:** Distribution of energy in the L1 EM cluster after applying the VH algorithm for signal sample.

![Figure 2](image2.png)

**Figure 2:** Distribution of energy in the L1 EM cluster after matching to the offline electrons and after applying the VH algorithm for signal sample with 69 minimum-bias events.
As a comparison, in the case of the pile-up sample with 69 minimum-bias events, Figure 3 shows the distribution of energy deposited in the L1 EM cluster after the VH algorithm.

![Figure 3](image)

**Figure 3:** Distribution of energy in the L1 EM cluster after applying the VH algorithm for the sample with 69 minimum-bias events.

The different methods described in section 6.3 were also used to study the L1 track trigger after applying the VH algorithm. Figures 4, 5 and 6 show the signal versus background efficiencies for the three methods; track matching, track isolation and $E_T/p_T$, respectively.

![Figure 4](image)

**Figure 4:** The signal versus background efficiency for different matching cones and for the minimum required track $p_T$ with respect to the L1 EM cluster after applying the VH algorithm. The numbers next to the curve represents the minimum track $p_T$ cut.
Figure 5: The signal versus background efficiency in an isolation study with respect to the L1 EM clusters after applying the VH algorithm. The red curve on the plot represents the efficiency curve for leading tracks in a matching cone of radius $\Delta R < 0.2$. The green, black and blue curves are efficiency curves in an isolation cone of $\Delta R < 0.3$ with track $p_T$ cuts up to 17 GeV. The numbers next to each curve represents the minimum track $p_T$ cut.

Figure 6: The signal versus background efficiency for the different cuts on $E_{T \text{cluster}}/\text{track } p_T$ for a matching cone of $\Delta R < 0.2$ at L1 after applying the VH algorithm. The red curve represents the efficiency curve for leading track without $E_{T \text{cluster}}/\text{track } p_T$ cuts. The numbers next to each curve represents the minimum track $p_T$ cut.
References

Figure References

i. ATLAS-CONF-2012-160.

ii. ATLAS Experiment © 2012 CERN.

iii. F. Pastore and V. Boisver, “Talk on L/Track trigger studies for di-leptons signatures: rate comparisons”.