Hidden Valley Search at ATLAS

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Abstract. A number of extensions of the Standard Model result in neutral and weakly-coupled particles that decay with macroscopic decay lengths to multiple hadrons or leptons. These particles with decay paths that can be comparable with ATLAS detector dimensions represent, from an experimental point of view, a challenge both for the trigger and for the reconstruction capabilities of the ATLAS detector. We will present a set of signature driven triggers for the ATLAS detector that target such displaced decays and evaluate their performances for some benchmark models and describe analysis strategies and limits on the production of such long-lived particles. A first estimation of the Hidden Valley trigger rates has been evaluated with 6pb-1 of data collected at ATLAS during the data taking of 2010.

1. The Hidden Valley Scenario

A number of extensions of the Standard Model (SM) result in particles that are neutral, weakly-coupled and have macroscopic decay lengths that can be comparable with LHC (Large Hadron Collider) detector dimensions.

The Hidden Valley (HV) scenario represents a possible extension of the SM where a new sector, neutral under SM forces and only weakly coupled to the SM sector, results in neutral long-lived HV particles ($\pi v$) that decay to heavy quark pairs and tau pairs. These particles can be produced in Higgs boson decays, SUSY processes or $Z$ decays, which allow the interactions between it and the SM sector.

A Hidden Valley model is structured as illustrated in figures 1 and 2. To the SM is appended a hidden sector, the “$v$-sector” for short, and a communicator (or communicators) which interacts with both sectors. A barrier (perhaps the communicator’s high mass, weak couplings or small mixing angles) weakens the interactions between the two sectors, making production even of light $v$-sector particles (“$v$-particles”) rare at low energy. At the LHC, by contrast, production of $v$-particles, through various possible channels, may be observable [1]. We present the results of a first study of the ATLAS Detector performance for the Higgs decay $h^0 \rightarrow \pi v \pi v$, where the $\pi$ is neutral and has a displaced decay mainly to bottom quarks, see figure 2.

Here we present results based on a simulation [2,3] of the process $h^0 \rightarrow \pi v \pi v$, with the following parameters: $m_{h0} = 140 \text{ GeV}$, $m_{\pi v} = 40 \text{ GeV}$ and $c_{\tau v} = 1500 \text{ mm}$. 

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2. The ATLAS Detector

ATLAS is one of the four large detectors at the proton-proton collider LHC, currently running at CERN, see figure 3.

![Figure 3. The ATLAS Detector. The position in ATLAS is defined by the cylindrical coordinate system (z,R,ϕ), where z is the position in the direction along the beam axis, R the radius, ϕ the azimuth angle, in addition we use η the pseudo-rapidity defined as η=−ln(tan(θ/2)), with θ the polar angle.](image)

Figure 1. A hidden sector, separated from the Standard Model sector by a barrier, becomes accessible at LHC energies. The mass gap stabilizes some v-particles, allowing them to decay slowly back through the barrier to Standard Model particles.

Figure 2. Neutral long lived HV particles (πv) model that decay to bb quark pairs (90%) and tau pairs (10%). Higgs bosons mediate the interaction between the Standard Model and the Hidden Valley sector.
interaction region is the Inner Detector (ID), followed by a calorimeter system (Electromagnetic and Hadronic calorimeter) and, in the outer region, by the Muon Spectrometer.

The ID provides pattern recognition and precise measurements of the decay vertex and momentum of charged particles. The calorimeter system measures with great accuracy the energy of the jet showers and the Muon Spectrometer, mounted around a large superconducting air-core toroid, provide a good momentum resolution of about 10% for a muon momentum of 1 TeV.

The enormous data flow arising from the high LHC design collision rate of $10^{34} \text{ Hz}$ must be reduced to about 300 MB/s, corresponding to a maximum trigger of about 200 Hz out of the ATLAS Trigger system.

In fact, the ATLAS trigger system has been designed to bridge this gap via a complex system of three different levels of selection algorithms optimized to efficiently select the interested events with a short latency time.

The first level trigger (LVL1) is designed to operate at a maximum pass rate of about 75 kHz, with a decision time (latency) less than 2.5 $\mu$s. The LVL1 decision is based on information with a coarse granularity of two sub-detector systems: the muon trigger chambers and the calorimeters. For events accepted by LVL1, the information of all sub-detector systems is pre-processed and stored in the Read-Out Buffers (ROBs).

The second level trigger (LVL2) uses both the LVL1 output and the data stored in the ROBs to further reduce the data rate to a maximum of 3 kHz. Even though the LVL2 has access to the full data, the selection is generally restricted to ‘Regions of Interest’ (ROI) flagged by the output of the LVL1. The LVL2 mean target processing time is about 40 ms (the time depends on the complexity of the event processed). For events accepted by the LVL2, the data fragments stored in the ROBs are collected by the so-called Event Builder and written into the Full Event Buffers.

The third trigger stage is called Event Filter and uses the information stored in the Full Event Buffers to keep the event rate sent to mass storage below 200 Hz, or about 300 MB/s. The Event Filter accesses the complete event information using complex offline selection algorithms.

### 3. Detector Signatures and Trigger Strategies for Displaced Decays

Hidden Valley events are characterized by highly displaced decays, leading to jets appearing throughout the volume of ATLAS. Due to the low Higgs mass resulting in soft jets, which are highly pre-scaled at the trigger level, and tracks that do not point to the IP (Interaction Point) coming from the highly displaced vertex, the standard ATLAS triggers select only a small fraction of these unique events.

However, it is possible to use the displaced vertex signature as a trigger object in order to increase the fraction of events accepted. In this section we discuss the $b$-jet signatures that are observed in different parts of the ATLAS detector from decays of $\pi$’s to $bb$ pairs. We consider four detector regions:

- Decays from end of the Hadron Calorimeter (HCal) to the first Muon Spectrometer trigger plane;
- Decays in the calorimeters;
- Decays in the Inner Detector beyond the pixel layers to the end of the Transition Radiation Tracker (TRT);
- Decays in the beam pipe and pixel layers.

#### 3.1. Decays in the Muon Spectrometer

Decays occurring near the end of the HCal and before the first muon trigger plane are characterized by a large number of charged hadrons traversing a narrow ($\eta, \phi$) region of the Muon Spectrometer and result in a large number of clustered LVL1 “muon” RoIs (ATLAS LVL1 trigger object which
describes a Region of Interest in \((\eta, \phi)\) to be examined at LVL2. The cluster of LVL1 RoIs will be accompanied by a lack of activity in the ID and Calorimeters.

These events are rejected by the current ATLAS LVL2 trigger which requires a matching ID track for the LVL1 muons.

The algorithm implemented for a stand-alone HV LVL2 trigger requires that the cluster contains at least three muon RoIs in a cone of \(\Delta R = 0.4\), no jets in a cone of \(\Delta R = 0.7\) centered on muon RoI cluster and no inner detector track in \((\Delta \eta, \Delta \phi)\) region of \((0.2x0.2)\).

The efficiency obtained is about 70% in barrel and 25% in the endcap of the muon system using this new LVL2 algorithm, see figure 4.

Figure 4. Efficiency distribution obtained in the barrel (left plot) and in the endcap region (right plot) by the Hidden Valley LVL2 trigger based on the Muon Spectrometer.

3.2. Decays in Calorimeters

If the \(\pi^0\) decays beyond the Electromagnetic calorimeter (ECal) the ratio of energy deposited in the HCal to that in ECal will be larger than that which is normally observed for jets originating at the IP.

This suggests to use the ratio between the energy deposited in the HCal and ECal, \(\log(E_{\text{HAD}}/E_{\text{EM}})\), as a trigger object. Figure 5 shows the energy ratio as a function of the \(\pi^0\) decay point; making very clear that for this type of event the ECal records little or no energy, while the HCal has a large energy deposition. No visible track connects this jet with the IP.

Figure 5. Distribution of the \(\log_{10}(E_{\text{HAD}}/E_{\text{EM}})\) variable. Jets from the decay of \(\pi^0\)'s in the HCal have \(\log_{10}(E_{\text{HAD}}/E_{\text{EM}}) \approx 1.5\), while decays in the ID and ECal have a value less than 1.

Figure 6. Efficiency distribution obtained in the barrel region by the “Calo Ratio” Hidden Valley LVL2 trigger.
The HV trigger algorithm requires:
- \( \log_{10}(E_{\text{HAD}}/E_{\text{EM}}) > 1 \)
- No ID tracks in region around jet direction

The efficiency obtained in barrel is about 60% (see figure 6) and about 35% in endcap regions.

3.3. Decays in TRT
Decays in the outer Silicon layers and TRT (Transition Radiation Tracker) lead to jets with no connecting track to the IP (trackless jets). Selecting such events at LVL2 requires a robust LVL2 TRT vertex finding algorithm, which unfortunately is not currently available. Thus we examine trackless jets as trigger objects for this event signature and we added the new trigger chain. We require a jet of energy greater than 35 GeV and no tracks matching it in the ID. The efficiency obtained by this selection algorithm is still not optimized and requires further improvements in the future.

3.4. Decays in the Beam Pipe and Pixels
Decays in this region will look very much like decays of heavy flavor particles produced in Standard Model processes. The b-tagging algorithms should find these events with good efficiency and consequently special LVL2 triggers are not needed (not used).

3.5. Dependence of Trigger Efficiencies on \( \pi_v \) Decay Length
The relative efficiency of the new signature driven LVL2 triggers as a function of the \( \pi_v \) decay length is shown in figure 7. From the efficiency for triggering on a \( \pi_v \) as a function of its decay position, we predict the fraction of Higgs decays that would be accepted by our triggers as a function of the \( \pi_v \) proper lifetime \( c \tau \), assuming a 100% branching fraction for \( h^0 \rightarrow \pi_v \pi_v \).

Figure 7 shows the expected fraction of events vs the \( \pi_v \) lifetime for each of our three triggers, and the total fraction accepted. The right scale gives the number of expected events for an integrated luminosity of 100pb\(^{-1}\).

Figure 7. \( h^0 \rightarrow \pi_v \pi_v \) events accepted by our long-lived particle triggers vs the \( \pi_v \) lifetime for \( m_{h^0}=140 \) GeV and \( m_{\pi_v}=40 \) GeV. Left axis: fraction of events accepted. Right axis: number of events for an integrated luminosity of 100 pb\(^{-1}\) assuming Br \( (h^0 \rightarrow \pi_v \pi_v) = 100\% \).
4. Trigger Performance with Early Data
The new HV algorithms have been tested during the first period of ATLAS Data taking. We measured the final trigger rate for all the three trigger algorithms; as results of this measurement, we obtained trigger rates well inside the experimental data taking limits at the luminosity of $10^{32}$.

Figure 8 shows the luminosity achieved in the run analyzed while in the figures 9, 10 and 11 the rates obtained for each trigger menu are shown.

5. Conclusions
Different models predict extensions of the Standard Model with new particles that are neutral and have lifetimes comparable with ATLAS detector dimensions. In this work we have shown that it is necessary to define a set of signature-driven triggers in order to select these types of events with a reasonable efficiency. Algorithms for these triggers have been implemented in the ATLAS High Level Trigger framework. Rate studies of these new triggers using 6pb$^{-1}$ of data have been presented. Studies on QCD di-jets and cosmic backgrounds are ongoing.

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