The ATLAS Level-1 Trigger System

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Abstract. The ATLAS Level-1 Trigger is the first stage of event selection for the ATLAS experiment at the LHC. The Level-1 Trigger is implemented with custom-built electronics, and is designed to identify the interesting collision events to be passed on to the next selection stage, reaching a decision within a latency of less than 2.5 $\mu$s. Signals from the Calorimeter and Muon Trigger System are combined in the Central Trigger Processor which processes the overall L1 Accept (L1A) decision. The Level-1 Trigger identifies event features such as missing transverse energy, candidate electrons, photons, jets and muons. This paper presents how the Level-1 Trigger System has performed in 2011 and early 2012, covering techniques used to cope with the increasing LHC luminosity. This paper also covers some of the Level-1 Trigger upgrade plans with respect to managing the increasingly demanding LHC running conditions.

1. Introduction
The trigger system of the ATLAS Detector at the Large Hadron Collider at CERN is a three-stage system that is used to select events (snapshots of the detector) for recording at a final rate, in proton-proton collisions, of approximately 300 Hz. The physical event rate from which events must be selected is 40 MHz: the rate at which the beam bunches are delivered to the LHC experiments. The Level-1 trigger system is the first stage of the trigger, and is responsible for reducing the initial 40 MHz rate to less than 75 kHz.

The Level-1 trigger is a hardware-based, synchronous, pipelined system consisting of a Central Trigger Processor (CTP) fed by signals coming primarily from dedicated trigger hardware in the calorimeter (L1Calo) and muon (L1Muon) detector systems. The output of this trigger system is a single-bit ‘Level-1 Accept’ (L1A), which signals to the detector front-end readout systems, via the Trigger Timing and Control system (TTC), whether or not to read out the event information held in the pipelines of the front-end electronics. The readout of the accepted events is passed to the High Level Trigger (HLT), which consists of the software-based Level-2 and Event Filter stages of the ATLAS trigger system. A schematic diagram indicating the location of the Level-1 Trigger in the trigger system is shown in figure 1. A target latency for the Level-1 trigger is set at 2.0 $\mu$s, with a contingency of 500 ns, in order to reach a Level-1 trigger decision before the pipelines overflow. With much of that time spent transmitting signals between the on-detector electronics and the dedicated trigger electronics in the neighbouring cavern (see table 1), only about 0.5 $\mu$s is available for the hardware to process the input signals and reach a trigger decision. Further details on the design of the trigger system can be found in [1].

Most of the 75 kHz Level-1 trigger rate bandwidth is intended to be used for collision events (as opposed to background events where no protons are colliding in the detector), for which, in 2011 and 2012 data taking, there are typically 1000-1500 such ‘filled bunch crossings’ per full orbit of the LHC beam (the orbit frequency is 11.246 kHz). This corresponds to a colliding bunch rate of approximately 11-17 MHz, so simply by requiring the bunch crossing is filled can
reduce the input 40 MHz rate by 50-75%. However, the remaining rate reductions must be accomplished by the trigger system identifying events of interest, by performing a fast analysis of the detector signals generated by the colliding bunches. For each data taking period, the Level-1 trigger is loaded with a ‘trigger menu’, which is a list of up to 256 criteria (trigger items) upon which to determine if an event is accepted or not. The Level-1 trigger items include, among others, configurable algorithms to trigger on electrons/photons, hadronically decaying tau leptons, muons, jets and $E_{\text{miss}}$. As the luminosity is increased, these algorithm’s trigger rates will increase with at least a linear dependence on the luminosity. However, sometimes the dependence can be highly non-linear, such as with the $E_{\text{miss}} > 50 \text{ GeV}$ trigger L1\_XE50, shown in figure 2. The trigger menu and its associated trigger items must be continually refined in order to keep within the 75 kHz budget as the luminosity increases.

In 2011, luminosities of up to $3.65 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ were delivered, corresponding to a maximum of approximately 24 average collisions in a single bunch (ATLAS uses a 71.5 mb inelastic cross-section for $\sqrt{s} = 7 \text{ TeV}$, and note that not all bunches contribute equally). In 2012, both the increase in centre of mass energy from $\sqrt{s} = 7 \text{ TeV}$ to 8 TeV, and the expected increases in instantaneous luminosity will put further pressure on the Level-1 trigger system. Section 2 discusses recent modifications to the L1Calo trigger system, designed to cope with the increasing luminosity being delivered to the ATLAS experiment. Section 3 presents a similar review of recent enhancements to the L1Muon system. Finally, section 4 reviews recent and planned changes to the CTP, in relation to the challenges outlined in this introduction.

### 2. L1Calo - Calorimeter Trigger

The L1Calo system is described in detail in [2], with a summary presented here. The L1Calo trigger is based on dedicated analogue trigger signals provided by the ATLAS calorimeters independently from the signals read out and used by offline reconstruction software. The calorimeters measure energy deposited in small cells of various sizes down to a granularity in $\Delta \eta \times \Delta \phi$ of 0.025 $\times$ 0.025. Rather than using the full granularity of the calorimeter, L1Calo uses information from analogue sums in regions of granularity ranging from 0.1 $\times$ 0.1 (central regions) up to 0.4 $\times$ 0.4 (forward regions), to form 7168 trigger towers. These are split between the EM and hadronic layers of the calorimeter. L1Calo digitizes these analogue signals at a sample rate of 40MHz, with the analogue-to-digital conversion calibrated so that the height of an analogue pulse generated by an energy deposit is measured in units of approximately one $ADC \ count$ per 250 MeV of $E_{\text{T}}$ deposited. The final conversion from ADC count to an $E_{\text{T}}$
Figure 2: Level-1 rates for the lowest-threshold unprescaled single object triggers at $3 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$. EM16VH is a trigger for an electron-photon with a threshold at 16 GeV; MU11 is a trigger for a muon with a threshold near 10 GeV, and requires a three station coincidence both in the barrel and the endcap parts of the detector; TAU30 is a trigger for a hadronically decaying tau above 30 GeV; XE50 is a trigger for missing ET above 50 GeV at the EM scale; and J75 is trigger for a jet above 75 GeV.

measurement with GeV precision is performed by a calibrated Finite Impulse Response (FIR) Filter, and Look Up Table (LUT). A sliding window algorithm then searches for local energy maxima across groups of the trigger towers (or coarser granularity jet elements, in the case of jet triggers), and tests these maxima against thresholds defined in the trigger menu. For example, an L1_EM16 trigger will require a pair of neighbouring trigger towers in the EM layer (this particular trigger only uses towers in the central region, $|\eta| < 3.2$) to have $E_T$ above 16 GeV. If the threshold is passed, this forms a single Region of Interest (RoI). The multiplicity (number of RoI) for each threshold is transmitted to the CTP. L1Calo uses the central trigger towers ($|\eta| < 3.2$) for the Electron/photon (EM), hadronic tau (TAU) and jet (J) trigger thresholds. Trigger towers in the forward calorimeter (FCAL) regions ($|\eta| > 3.2$) are used for forward-jet (FJ) triggers. Additionally, all trigger towers (central and forward) are used for ‘global’ trigger items: $E_{\text{miss}}^X$ (XE), $\Sigma E_T$ (TE) and $E_{\text{miss}}^X$-significance (XS).

Figure 3 shows the trigger cross-section (unprescaled trigger rate $\div$ luminosity) for a selection of L1Calo-based trigger items, as a function of the average number of interactions per filled bunch crossing, $\langle \mu \rangle$. The L1Calo-based triggers form the bulk of the 75 kHz total Level-1 trigger rate budget, with a target of about 40-50 kHz (after prescaling). A trigger cross-section that is independent of $\langle \mu \rangle$ is one that scales linearly with luminosity, such as the L1_EM16VH or L1_J75 shown in figure 2. It is seen that the single-object trigger items (items which require at least one RoI passing the given threshold) have rates that are generally linear with luminosity. An exception is the L1_FJ75 trigger, which requires a jet in the forward region with $E_T$ above 75 GeV. This non-linearity is due to the larger size of the trigger towers in the FCAL regions, which therefore suffer from higher occupancy compared to the finer granularity central towers.
Section 2.2 discusses how trigger tower noise cuts in the forward regions were modified for 2012 running in order to calm the trigger rate for such items. The success of this action can be seen in figure 3, where a large rise in trigger cross-section was expected between \( \langle \mu \rangle \) of 15 and 25, but instead the cross-section has stayed relatively constant for 2012 running. These noise cuts also reduce the L1\_XE50 (an \( E_T^{\text{miss}} \) trigger) cross-section, as discussed in section 2.2 and seen in figure 3. In 2012, the XE50 trigger rate can be further calmed by including the requirement that the event pass a newly introduced bunch group mask (see section 4 for details), as seen in the cross-section of the new L1\_XE50\_BGRP7 trigger.

Figure 3: Trigger cross-sections (trigger rate ÷ luminosity) for a selection of L1Calo-based trigger items, as a function of the average number of inelastic interactions per filled bunch crossing. \( \langle \mu \rangle \) represents inelastic collisions, using a total cross-section of 71.5 mb for \( \sqrt{s} = 7 \) TeV data, and 73 mb for \( \sqrt{s} = 8 \) TeV data. Rates in the lefthand section were taken from two runs in mid-2011, with a typical LHC filling scheme involving filled bunches spaced 50 ns apart, in trains of bunches. The righthand section shows rates from a special high luminosity run in 2011 where well-separated bunches were made to collide with a high number of interactions per bunch. The central section shows rates taken from a 2012 run, at the higher centre-of-mass energy of \( \sqrt{s} = 8 \) TeV.

Multi-object triggers (the one shown in figure 3 is the L1\_4J10 trigger, which requires at least 4 jet RoI with \( E_T \) above 10 GeV) have a non-constant trigger cross-section with respect to luminosity (\( \langle \mu \rangle \)), which can be understood in terms of the following simple argument. Suppose the probability that a single interaction produces a particular type of trigger RoI above a given threshold is given by \( f \). Then for a bunch crossing with \( n \) interactions, the probability that the associated single-object trigger fires is given by:

\[
P_{\text{trigger}}^{\text{single-object}} = 1 - (1 - f)^n \approx fn
\]
where the approximation holds assuming $f$ is small. Since $n$ is proportional to the luminosity, and the trigger rate is proportional to the probability that a bunch crossing passes the trigger, it is seen that single-object triggers must therefore scale linearly with luminosity. If this exercise is repeated for a double-object trigger, for example, then the probability that a bunch crossing with $n$ interactions in it will fire this trigger is given by:

$$P_{\text{double-object trigger}} = 1 - (1 - f)^n - n(f(1 - f)^n) \approx fn - n(f - (n - 1)f) = (n^2 - n)f^2 \quad (2)$$

Note that Equation 2 is constructed under assumption that a double-object trigger would be caused by two separate interactions each giving a single triggerable object. The (linear) contribution from a single interaction producing two triggerable objects is assumed to be negligible. This equation therefore shows multi-object trigger rates pick up non-linear dependence on luminosity, consistent with what is seen in figure 3 and 9.

The small rise in trigger cross-section between the 2011 and 2012 running (seen at $\langle \mu \rangle = 15$ for many of the single-object trigger items) is due to the increase in centre of mass energy. Finally, the figure shows the 50% reduction in rate for the L1_EM16 trigger, which was accomplished with the introduction of variable eta thresholds and hadronic layer vetoes, as discussed in section 2.1.

2.1. VH Thresholds
In mid-2011, modifications were made to some of the electron/photon trigger thresholds to correct for dead-material variations causing non-uniform trigger efficiency across the $\eta$ range of the calorimeter. It is possible to raise the trigger threshold in regions of highest trigger efficiency (as measured with respect to offline reconstructed electrons, using a Z tag and probe method), without significantly altering the overall trigger efficiency turn-on curve, because the turn-on position is primarily determined by the regions of lowest trigger efficiency. Furthermore, electrons and photons deposit the majority of their energy in the electromagnetic layer of the calorimeter, so introducing a veto on energy deposits (allowing no more than 1 GeV) in the hadronic layer towers behind an EM layer deposit could further decrease the trigger rate for this trigger item without significantly affecting efficiency. Figure 4(a) shows the trigger efficiency for the electron/photon trigger with a 16 GeV threshold trigger item with the variable eta threshold and hadronic veto (L1_EM16VH) and without these two new enhancements (L1_EM16). Strictly, the L1_EM16VH trigger has a threshold of 16 GeV only in a few regions of the detector, whereas in other regions across the $\eta$ range the threshold will be higher (the regions with higher trigger efficiency).

Figure 4: (a) Efficiencies of the L1_EM16 and EM16VH triggers as a function of offline electron $p_T$. (b) Efficiencies as a function of offline electron $\eta$ [3]
It can be seen that the $E_T$ at which the trigger reaches full efficiency is not significantly altered by the introduction of these tighter trigger requirements. Figure 4(b) shows that the trigger efficiency for the new VH trigger is less dependent on $\eta$ than the non-VH trigger. From figure 3 it can be seen that the rate for this trigger item was reduced by about 50% by the introduction of variable eta thresholds with an hadronic layer energy veto.

Further information regarding the VH thresholds can be found in [3]

2.2. Increasing tower noise cuts

A cut is applied to the $E_T$ measurements of the trigger towers, designed to suppress the random electronic noise fluctuations present in the analogue signals. The default noise cut used for towers corresponds to approximately 1 GeV $E_T$ measurement. However, an additional source of ADC fluctuations are the pulse shapes of energy deposits of neighbouring bunch crossings: the ATLAS calorimeter pulse shapes are bipolar (a narrow peak followed by an undershoot such that the integral across the whole signal is zero) and span up to approximately 750 ns (about 150 ns of this is the positive peak, and the remainder of the signal is the long undershoot. The shortest pulse shapes are in the FCAL region, but these still span several filled bunches), whereas the filled bunch crossings are separated by 50 ns (in 2011 and 2012. This will eventually be reduced to 25ns spacing). With pulse shapes spanning many crossings, it is easy for high-occupancy towers to experience overlapping pulse shapes, which can result in a low-energy deposit being measured with a higher value when its pulse sits on top of the positive part of another.

The highest tower occupancies occur in the largest trigger towers, located in the high $|\eta|$ regions (the FCAL and inner wheel of the electromagnetic endcap, EMEC-IW). This can be seen from figure 5(a), which shows the ADC count distribution, in bins of $|\eta|$, as measured using randomly selected events to discount bias from any underlying physics (the Level-1 Trigger CTP is programmed to accept a small number of randomly selected events from filled bunches, regardless of what trigger items have fired). The largest trigger towers (labeled bin 3 and 4 in the figure) experience the largest fluctuations away from the nominal ADC count value when no energy deposit is present. This has been subtracted from the ADC counts used for the figure so that the nominal (zero-energy) value is 0 ADC counts. Figure 5(b) shows how the RMS standard deviation of the ADC distribution varies as a function of the number of interactions per bunch crossing. The largest trigger towers are seen to have the strongest dependence on the number of interactions.

From results shown in figure 5(b), and similarly for other trigger towers in the FCAL and EMEC-IW regions, new noise cuts are derived for the different trigger tower $|\eta|$ bins, using the formula:

$$Cut(\mu) = \sqrt{(A \times \sigma(\mu))^2 + 1.0^2} \text{ [GeV]}$$

where $A$ is a scale factor chosen such that the equation gives a predefined value for the cut at a particular choice of $\mu$ - specifically, the predefined values come from a complementary body of work (not discussed here) where a set of cuts for the different $\eta$ bins were determined manually for conditions where $\mu = 15$. This set of cuts form an effective reference point about which cuts for different values of $\mu$ are calculated using equation 3. The effect of these reference value cuts on the XE trigger rates are shown as the loose noise cuts in figure 6. This figure shows that the XE trigger rate after applying these increased noise cuts is virtually identical to excluding all the forward region trigger towers from the XE algorithm.

Before applying these increased noise cuts, which would significantly reduce the rate of both forward jet (FJ) and missing energy (XE) triggers, it was necessary to check if there was any impact on the trigger efficiency. The XE trigger efficiency was tested using a sample of candidate $W$ boson events (single lepton events with a transverse mass $M_T > 40$ GeV). For a

$^1$ Transverse mass is defined as $M_T = \sqrt{2p_T^l E_T^{miss} (1 - \cos \Delta \phi_{l,E_T^{miss}})}$, where $l$ is the lepton.
Figure 5: (a) The ADC count distribution for trigger towers from the FCAL1 region of the forward calorimeters (all $\mu$ values). The binning is approximately in terms of tower $\eta$, and represent the approximate physical size of the towers in this region: 3.1-3.2 (bin 1), 3.2-3.5 (bin 2), 3.5-4.2 (bin 3), 4.2-4.9 (bin 4). (b) The RMS standard deviation of the ADC count distributions, after binning the data according to the number of interactions per bunch crossing, $\mu$.

Figure 6: Level-1 $E_{\text{miss}}^T$ rates as a function of threshold for several pile-up noise cut scenarios. The rates are estimated by applying noise cuts to ZeroBias events from a single run with a $\mu$ of 15.

selection of different choices of noise cuts, negligible difference in the XE efficiency with respect to the offline reconstructed $E_{\text{miss}}^T$ (using topological clusters) was seen, as shown in figure 7.

3. L1Muon - Muon Trigger
The L1Muon system searches for a coincidence of hits across multiple layers (stations) of trigger chambers, which are consistent with the combination of hits expected from muons originating from an interaction point at the origin. For each location (RoI - region of interest) in one station (the pivot plane), there is a pre-calculated window of locations in other stations (up to two other stations) for which a muon above a certain $p_T$ threshold is believed to be able to pass through.
Figure 7: L1_XE50 trigger efficiency as a function of offline topological cluster-based $E_T^{\text{miss}}$, measured for a sample of candidate W events. Four different choices of noise cuts were simulated offline: one with FCAL noise cuts optimized to conditions with $\mu = 15$, one with FCAL noise cuts optimized to $\mu = 20$, one with both FCAL and EMEC-IW noise cuts optimized to $\mu = 20$, and one with FCAL and EMEC-IW noise cuts optimized to $\mu = 25$. Unoptimized noise cuts have a value of approximately 1 GeV.

These coincidence windows are calculated using Monte Carlo simulation of single muon events, identifying the regions where some fraction (e.g. 90%) of true muon hits lie on the non-pivot stations. Up to six different $p_T$ thresholds are supported. Of the 75 kHz Level-1 trigger rate budget, approximately 15 kHz is allocated for L1Muon-based triggers. A cross-section through the ATLAS detector, showing the location of the L1Muon trigger chambers, organized in their respective layers, is shown in figure 8.

Figure 8: Cross-section through the ATLAS detector, showing the locations of the L1Muon trigger chambers. The barrel region ($|\eta| < 1.05$) uses Resistive-Plate Chambers (RPC), and the endcap regions ($1.05 < |\eta| < 2.4$) use Thin-Gap Chambers (TGC).
L1Muon uses two types of trigger chamber: Resistive-Plate Chambers (RPC), used in the barrel region ($|\eta| < 1.05$) and Thin-Gap Chambers (TGC), used in the endcap regions ($1.05 < |\eta| < 2.4$). The chambers are divided into sectors. In both regions there are three stations, with the middle station in the RPC system and outer station of the TGC used as the pivot planes respectively. Further details on the L1Muon trigger design can be found in [1] and [4].

For the first half of 2011, L1Muon was configured with the following trigger thresholds:

- **MU0** Trigger for a muon of any $p_T$. This threshold required hits anywhere in two stations within the same sector.
- **MU6** Trigger for muons with $p_T$ above approximately 6 GeV. Required coincidence hits in three stations in the TGC, but only two stations in RPC.
- **MU10** Trigger for muons with $p_T$ above approximately 10 GeV. Coincidence requirements as for MU6, but with smaller coincidence windows.
- **MU11** Trigger for muons with $p_T$ above approximately 11 GeV. This threshold shares coincidence windows with MU10 for two stations, but now requires a three-station coincidence in the RPC. Hence the MU10 and MU11 triggers are actually the same energy threshold, but MU11 has a tighter trigger requirement than MU10.
- **MU15** Trigger for muons with $p_T$ above approximately 15 GeV. Required three-station coincidence in all regions.
- **MU20** Trigger for muons with $p_T$ above approximately 20 GeV. Coincidence requirements as for MU15, but with smaller coincidence windows.

In mid-2011, the MU0 threshold was replaced by a two-station MU4 threshold with a coincidence window for muons with $p_T$ approximately 4 GeV and above. At the same time, a reoptimization of the coincidence windows for the MU6 and MU10 thresholds was deployed - the new coincidence windows were based on the hit clusters of simulated muons, as opposed to the individual hits as were used for the first set of coincidence windows. Using the clusters to define the coincidence windows results in a smaller window and hence a reduced rate. The effect of these changes can be seen in the left-hand section of figure 9, which shows the trigger cross-sections for the various muon thresholds as well as two multi-object muon triggers (L1_2MU4 and L1_2MU6). All the single-object triggers have constant trigger rates, whereas the two-object triggers have a slight dependence on the luminosity, as expected (see section 2). The lower cross-sections seen in the special high-luminosity run shown in the right-hand section of the figure are due to the absence of bunch trains in this particular LHC fill - it is known that there is a contribution to muon trigger rates (particularly the two-station thresholds) from late trigger chamber hits coming from neighbouring filled bunch crossings. For this special high-luminosity run, the filled bunches were spaced far apart from one another, so there is no contribution from late hits to the trigger rate.

Further coincidence window reoptimizations were made between 2011 and 2012 data taking, in particular for the TGC region where it was possible to significantly decrease the window sizes. The first set of windows that were calculated for this region were done using monte carlo that did not include simulation of the crosstalk between TGC chamber signals. As a result, the windows that were derived resulted in lower trigger efficiencies in the data than were originally targeted. To recover this efficiency the windows were artificially enlarged, but this was at the expense of an increased trigger rate. Crosstalk simulation was later added to the monte carlo, and smaller coincidence windows could be derived that were able to deliver the target trigger efficiency at a lower trigger rate than the artificially enlarged windows. This is seen in the high-$p_T$ thresholds at the transition from 7 TeV to 8 TeV running of figure 9.
The L1_MU10 trigger shows a particularly large trigger rate decrease between 2011 and 2012 running due to the installation of additional shielding between the barrel and endcap regions of the detector. It was seen in 7 TeV data taking that a large fraction of MU10 trigger RoI were located at approximately $\eta = 1.0$, and this was diagnosed, through simulation, to be due to inadequate shielding in this region allowing gamma rays from the beam to reach the muon chambers and trigger the MU10 threshold. With the additional shielding installed at the beginning of 2012, the MU10 trigger rate contribution from this region was significantly decreased, as shown in figure 10.

Figure 11 shows that the majority of fake muon triggers come from the TGC endcap region of the L1Muon trigger system. It is believed that this is due to low-momentum protons from secondary interactions near the endcap toroid, which are bent by the magnetic field in such a way as to traverse the same path through the TGC stations as a high-$p_T$ muon coming from the origin. There are additional TGC chambers installed on the inner side of the endcap toroid, which, to-date, have not been incorporated into the trigger algorithms. However, simulations have shown that by using the hit information coming from these TGC-inner chambers, it is expected that these low-momentum protons can be vetoed and the fake rate (and hence trigger rate) can be significantly reduced in these regions. Implementation of this new trigger configuration is expected to take place as part of the 2014 shutdown of the LHC.

4. CTP - Central Trigger Processor
The CTP is implemented as a set of VME modules in a single hardware crate. The CTP takes trigger inputs (thresholds passed and multiplicities) from the L1Calo and L1Muon trigger

Figure 9: Trigger cross-sections (trigger rate ÷ luminosity) for a selection of L1Muon-based trigger items, as a function of the average number of inelastic interactions per filled bunch crossing.
Figure 10: Distribution of Level-1 RoI $\eta$, for RoI passing the MU10 threshold.

Figure 11: Distribution of Level-1 RoI $\eta$, for RoI passing the MU11 threshold. Also shown are the fraction of such RoI that are $\Delta R(< 0.2)$ matched to an offline reconstructed muon.

systems (as well as other specialized detectors which are not discussed here, see [1]) and uses them to form the L1A trigger decision. Up to 372 trigger inputs are received and aligned in time by the three CTPIN modules. Of these trigger inputs, up to 160 are selected for transmission over the Pattern-In-Time (PIT) bus to the CTPCORE module. A lookup table and content addressable memory is used to form up to 256 trigger items from these 160 trigger inputs. A trigger item can consist of a combination of logical OR and AND of the various trigger inputs and bunch group masks, which identify what type of bunch crossing the current event comes from (e.g. empty or filled). The trigger items can then be individually prescaled (e.g. a prescale of 5 will mask 4 out of every 5 positive results of a particular trigger item). A veto can be applied to the trigger items, which is necessary in the few bunch crossings following an L1-accepted bunch crossing in order to prevent requests for data readout more than once; some parts of the detector, particularly the calorimeters, require readout of the data corresponding to a given trigger, as well as the data from the neighbouring bunch crossings. The hardware is designed to only readout the data once, so triggered bunches are required to be separated by a minimum amount of time. This is known as simple deadtime (programmed to veto the five bunches (125 ns) after an L1A in 2011, four bunches in 2012), as opposed to complex deadtime that consists of a leaky-bucket algorithm to limit the number of L1As occurring in a given time window (configured in 2011 and 2012 to limit up to 7 accepted events every 2905 bunch crossings). The trigger items, after prescaling and vetoing, are combined in a logical OR to form the L1A decision. Figure 12 shows an outline of the CTP, and further information on the CTP can be found in [5].

4.1. The BGRP7 Bunch Group Mask

For 2012 running, a new bunch group mask was created to mask the first few bunches of a bunch train. This was motivated by the observation that some trigger items, in particular the L1XE triggers, exhibit a strong trigger rate dependence on the position in the bunch train, as shown in figure 13.

The XE trigger has a much higher rate at the start of the bunch trains because of the unbalanced overlaying of the bipolar calorimeter pulse shapes that are used as the input for the L1Calo trigger system. At the start of the bunch trains, these pulse shapes constructively overlay each other, and can result in large fake missing energy measurements. By the time the middle of the train has been reached, the negative contributions from the bipolar pulse shape
Figure 12: Outline of the ATLAS Level-1 Central Trigger Processor. Each section represents one VME module in the CTP system.

Figure 13: Trigger rate per bunch, relative to the rate in bunch crossing ID=141, for a typical bunch train with 50 ns spacing, as used in the LHC for 2011 and 2012 data taking. The trigger rates have been normalized to account for variations in the luminosity within each individual bunch.

The new bunch group mask (BGRP7), provided for 2012 running, can be used to mask the events at the start of each bunch train. This new mask has been used with the XE50 trigger input to form a new $E_T^\text{miss}$ trigger item, which has a significantly reduced trigger rate compared to an equivalent trigger which is combined with the mask that accepts any filled bunch. See figure 3 for a comparison of the trigger cross-sections of L1_XE50 and L1_XE50_BGRP7. Both triggers...
are available in the 2012 trigger menu, however the XE50_BGRP7 trigger will be much more stable as luminosity increases compared to the XE50 trigger, which will need to be prescaled much sooner.

The turn-on effect seen at the start of the bunch crossing in the rate of the L1_MU10 single muon trigger is indicative of the contribution to muon trigger rate from late hits coming from previous bunches, which is particularly prominent in 2011 in the poorly shielded region between the barrel and endcap. This is consistent with the lower trigger rates of the special high luminosity run shown in the righthand section of figure 9, where there were no bunch trains and so no contribution from late trigger chamber hits to the level-1 muon trigger rate.

4.2. Preliminary Upgrade Plans
During the 2013-2014 LHC shutdown, planned upgrades to the CTP modules will almost double the capacity of the Level-1 CTP Trigger. Of particular note are:

- Multiplexing the 160 PIT bus lines to deliver double data rate at 80 MHz on the existing backplane - effectively increasing the number of PIT bus lines to 320.
- Additional optical inputs to CTPCORE (using SNAP12 ribbon-fiber receivers) for new trigger inputs, such as a new L1Calo topological processor. In time, the electrical PIT bus inputs from the CTPIN modules can be migrated over to the optical inputs.
- Allow partitioning of the L1A generation, so that secondary partitions can be used for detector commissioning. This involves each partition having their own trigger menu with separate Veto, Deadtime and OR stages as shown in figure 12. Up to three additional partitions are expected to be made available.

Table 2 lists some key statistics related to the CTP hardware, and how these values are expected to change with the planned upgrades.

|                  | Used Now | Available Now | Planned Upgrade |
|------------------|----------|---------------|-----------------|
| CTPIN Input Signals | 212      | 372           |                 |
| CTPIN Integrating monitoring counters | 138      | 768           |                 |
| PIT Bus Lines     | 160      | 160           | 320             |
| CTPCORE Trigger items | 241      | 256           | 512             |
| CTPCORE Bunch group masks | 8        | 8             | 16              |
| CTPCORE Max number of AND terms | 6        | 256           |                 |
| CTPCORE Max number of OR terms | 6        | 12            |                 |
| CTPCORE per-bunch trigger item counters | 12       | 12            | 256             |
| CTPOUT Cables to TTC partitions | 20       | 20            | 25              |
| CTPMON per-bunch monitoring counters | 88       | 160           |                 |

Table 2: Key statistics of CTP hardware, with planned improvements shown for some critical values.

5. Conclusion
The ATLAS Level-1 Trigger continues to meet the challenges faced by the increasing luminosities being delivered at the LHC. Deployment of electron/photon objects in L1Calo with thresholds that vary in η and include hadronic layer vetoes have shown to halve the single item trigger rate without significantly shifting the energy at which the trigger becomes fully efficient. Increased noise cuts in the forward calorimeter regions have significantly reduced forward-jet and \( E_{\text{miss}} \) trigger rates, without impacting trigger efficiency. The introduction of a new bunch group mask to exclude events from the beginning of bunch trains is seen to deliver a significant reduction
in the $E_T^{miss}$ trigger rate. Continued reoptimization of the L1Muon coincidence windows have provided further rate reductions and additional shielding installed at the beginning of 2012 has significantly reduced a major source of fake muon triggers. Upgrades to the muon trigger are planned to deliver further reduction of fake muon triggers in the endcap region, and upgrades to the CTP modules will allow for more trigger inputs to be used in larger trigger menus, with scope for multiple trigger partitions for commissioning new detector systems in parallel to normal physics running.

[1] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider (http://stacks.iop.org/1748-0221/3/i=08/a=S08003)
[2] ATLAS Collaboration, The ATLAS Level-1 Calorimeter Trigger (http://stacks.iop.org/1748-0221/3/i=03/a=P03001)
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