B-triggers at ATLAS and CMS

J. Kirk^a RAL]Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK.* On behalf of the ATLAS and CMS Collaborations

^a[

This paper describes the B -physics trigger strategies for the ATLAS and CMS experiments. The LHC will produce B events at an unprecedented rate allowing the possibility to study rare decays. Due to the high event rate at the LHC the trigger systems are required to be very selective, reducing the rate by about six orders of magnitude for recording. The B -trigger must be able to reject non- B background (only about one collision in a hundred will produce a $b\bar{b}$ pair) and select the B -decay channels of specific interest (often with low branching ratios). In addition the B -trigger must be flexible enough to cope with increasing luminosity during the period of LHC running. The different strategies used to achieve this flexibility are discussed in this paper.

1. INTRODUCTION

The Large Hadron Collider (LHC) is a proton-proton machine with a design centre-of-mass energy of 14 TeV. A pilot run at 900 GeV is planned for 2007 with running at the design energy due to start in 2008. From 2008 an initial “low-luminosity” running period is foreseen with a luminosity starting at about $10^{31} \text{ cm}^{-2}\text{s}^{-1}$ and rising to $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, this will allow 20 fb^{-1} of data to be collected per year. Later on the LHC will run at the design luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, recording 100 fb^{-1} of data per year.

At the LHC design energy the cross-section for $b\bar{b}$ production compared to the total cross-section is relatively high (with respect to that at previous lower energy machines) and about 1 in a hundred collisions will contain a $b\bar{b}$ pair. ATLAS and CMS are general-purpose experiments with an emphasis on high p_T physics beyond the Standard Model and as such have only a limited bandwidth for the recording of B -physics events. However, the experiments have a well defined B -physics programme and plan to study CP violation (in $B^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi \phi$), B_s^0 oscillations (using the channels $B_s^0 \rightarrow D_s \pi$ and $B_s^0 \rightarrow D_s a_1$) and to search for rare decays (e.g. $B_{s,d}^0 \rightarrow \mu^+ \mu^- (X)$ and $B_s^0 \rightarrow \phi \gamma$). The constraints applied to the B -triggers mean that they need to

be both efficient for the B -decays of interest and highly selective.

The B -triggers are based on single and di-muon triggers. Although the branching ratio for $b \rightarrow \mu$ is only about 10%, this channel has a clean signature early in the trigger chain and allows for flavour tagging which is needed in many of the analyses. In the higher levels of the trigger, different strategies are used in the different luminosity regimes. At design luminosity only di-muon events are used; this keeps the trigger rate low enough to be manageable whilst providing bandwidth for rare B decay channels containing two muons in the final state ($B_{d,s}^0 \rightarrow \mu\mu(X)$) and events containing $J/\psi \rightarrow \mu^+ \mu^-$. At lower luminosities (expected to be less than about $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$) additional triggers using a single muon will be added, allowing events containing hadronic and electromagnetic decays of the other b to be triggered.

2. ATLAS

Details of the ATLAS experiment can be found in Refs. [1, 2].

2.1. ATLAS trigger system

ATLAS has a three level trigger system [3] which reduces the 40 MHz bunch crossing rate to about 100 Hz of events to be recorded. The first level trigger (LVL1) is a hardware-based trigger which makes a fast decision (in $2.5 \mu\text{s}$) about

*Supported by the Daphne Jackson Trust and Particle Physics and Astronomy Research Council, UK.

which events are of interest for further processing. Coarse granularity information from the calorimeter and muon trigger systems are used at this stage of the trigger to identify regions of the detector which contain interesting signals (corresponding to high energy electrons, muons and taus and jets with large transverse or missing energy). These are called “Regions of Interest” (RoIs) and are used to guide the later stages of the trigger reconstruction. After LVL1 the trigger rate will be reduced to below 75 kHz (upgradeable to 100 kHz).

The LVL1 RoIs are used in the subsequent trigger levels to define regions of the detector in which to perform further reconstruction. The high level trigger (HLT) is software based and is split into two levels. At level 2 (LVL2) the full granularity of the detector is used to confirm the LVL1 signals and then to combine information from different sub-detectors within the RoIs identified at LVL1. Fast algorithms are used for the reconstruction at this stage and the rate is reduced to 1-2 kHz with an average execution time of about 10 ms. Lastly at the Event Filter (EF), the whole event is available and “offline-like” algorithms are used along with better alignment and calibration information to form a final decision about whether or not an event is accepted. With an execution time of about 1 s, the rate is reduced to 100 Hz.

2.2. ATLAS B trigger

The B -trigger is expected to account for 5-10% of the total ATLAS trigger resources. The core of the B -trigger is the LVL1 muon trigger which is based on a measurement of the muon transverse momentum (p_T). In the muon detector system the muon tracks are curved by the strong magnetic fields from the barrel and endcap toroids. The amount of curvature of the muon tracks (or displacement of the hits from a straight line) is determined by the muon p_T . The muon trigger requires hits in different layers of the muon chambers within a given coincidence window, the size of this window defines a p_T threshold for the triggered muon. The trigger logic allows for both high p_T and low p_T thresholds to be implemented, Fig. 1 shows the efficiency as a function of muon p_T for both the high and low thresh-

Figure 1. Efficiency of LVL1 muon trigger for high p_T (> 20 GeV) and low p_T (> 6 GeV) thresholds as a function of the muon p_T .

old muon triggers. Since muons from B decays are soft, it is the low p_T threshold (expected to be 6-8 GeV) which will be used for the B -physics trigger. Due to geometrical considerations such as the feet of the detector and other supporting structures, the efficiency of the muon trigger plateaus at about 85%. The rate for this trigger is predicted by convoluting the efficiency with the predicted cross-section as a function of p_T . A 6 GeV threshold is expected to give a rate of about 21 kHz at $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ of which about 15% is due to b events. The main background is due to real muons from π and K decays. The di-muon trigger (two muons with p_T above 6 GeV) is expected to have a rate of about 500 Hz (here the main background is from fake events where a single muon crosses overlapping areas of the detector and gives rise to two triggers).

The LVL1 di-muon trigger will be used to trigger events containing $J/\psi \rightarrow \mu^+ \mu^-$ and $B_{d,s}^0 \rightarrow \mu \mu(X)$. At LVL2 the muons will be confirmed firstly in the muon system (where the use of precision muon chambers means that a better momentum measurement is possible giving rise to a sharper p_T threshold) and then by combining muon and inner detector tracks. Finally the two muons can be combined and mass cuts are then applied. At the Event Filter the tracks are re-fit using more sophisticated track reconstruction al-

gorithms and vertex reconstruction is performed. Cuts are applied on the transverse decay length to reject prompt $J/\psi \rightarrow \mu^+ \mu^-$. For $B_{d,s}^0 \rightarrow \mu\mu$ events containing two muons both with p_T above 6 GeV, efficiencies of 60-70% are expected with an output rate of less than 10 Hz at $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

During the low-luminosity running period the trigger efficiencies for di-muon events can be improved by only requiring one LVL1 muon and searching for the second, lower p_T , muon in an enlarged region (RoI) around the LVL1 muon. After LVL2 confirmation of the LVL1 muon as described above, the rate is reduced to about 5 kHz. Then inner detector tracks are reconstructed within the muon RoI ($\Delta\eta \times \Delta\phi = 0.5 \times 0.5 \text{ rad}$) and are extrapolated to find matching hits within the muon system. This approach has been demonstrated for the $J/\psi \rightarrow \mu^+ \mu^-$ trigger; for events in which one muon has a p_T above 6 GeV and the other muon has a p_T above 3 GeV, efficiencies of 68-77% are expected with rates of 260-380 Hz predicted at $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

During the low-luminosity running, two different strategies are possible for extending the B -trigger to include hadronic and electromagnetic B -decays. In both cases a single muon is used to trigger the event at LVL1 and is confirmed at LVL2. In the high level trigger it is then possible to reconstruct tracks either within the entire inner detector (the “Fullscan” approach) or only within a certain volume of the detector around a low p_T “JET” or “EM” RoI identified at LVL1 (the RoI-guided approach). In both cases the track information is then used to reconstruct the decay products of the B . The RoI-guided approach should be faster due to the fact that it is using a smaller volume of the detector but the gain in speed will depend on the RoI size and the multiplicity of RoIs in an event. Figure 2 shows the mean multiplicity of LVL1 JET RoIs in background events (“ $b\bar{b} \rightarrow \mu 6X$ ” where one b decays to a muon of at least 6 GeV) as a function of the transverse energy (E_T) threshold used for the LVL1 JET RoI. The data are produced using a full GEANT-based detector simulation and include pile-up corresponding to a luminosity of $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. It can be seen that the mean number of RoIs per event increases rapidly for

Figure 2. The mean multiplicity of LVL1 JET RoIs in $b\bar{b} \rightarrow \mu 6X$ events as a function of the E_T threshold for JET RoIs.

lower thresholds. Thresholds for the LVL1 JET and EM RoIs used in this approach are chosen such that the RoI multiplicities for $b\bar{b} \rightarrow \mu 6X$ background events are about 1-2.

The Fullscan and RoI-guided approaches have been compared in detail for the case of a trigger for $B_s^0 \rightarrow D_s \pi$ events containing the hadronic decay $D_s \rightarrow \phi(K^+ K^-) \pi$ [4]. In the RoI-guided approach, the efficiency for there to be a JET RoI produced by the B in these events is 78% if the p_T of the B is above 10 GeV, and full efficiency is achieved once the p_T of the B is above 20 GeV. At LVL2 the track reconstruction is performed either within the JET RoI (with $\Delta\eta \times \Delta\phi = 1.5 \times 1.5 \text{ rad}$) or over the entire inner detector and the resulting tracks are combined to form first ϕ and then D_s candidate particles. In both cases, 3σ mass cuts are applied to identify the particles. For events where the p_T of the B is above 10 GeV (the offline selection cut), the LVL2 efficiency is 60% for the RoI-guided approach and 68% for the Fullscan with background rates of less than 200 Hz at $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. Figure 3 shows

the efficiencies for the two different approaches as a function of the p_T of the B meson. As expected the Fullscan approach performs better for lower energy B 's.

Figure 3. The LVL2 trigger efficiency as a function of $B p_T$ for the $D_s \rightarrow \phi(K^+K^-)\pi$ trigger for the RoI-guided (full line) and the Fullscan (dotted line) approaches.

The time taken for the different approaches is also important and studies show that the track reconstruction is about eight times faster within a single RoI than for the Fullscan (this is due to the smaller geometrical volume of the detector being used). When the RoI multiplicity is also taken into account, the RoI approach is about four times faster than the Fullscan. While the Fullscan may be possible during the earliest LHC running periods, the RoI-guided approach should provide significant resource savings which will allow this trigger to be used during the full low-luminosity period.

The RoI-guided approach has also been investigated for events with electromagnetic (EM) RoIs which would enable triggering on events such as those containing $J/\psi \rightarrow e^+e^-$ and the rare radiative decays $B^0 \rightarrow K^*\gamma$ and $B_s^0 \rightarrow \phi\gamma$. In these cases additional information from the calorimeter and the Transition Radiation Tracker (TRT) can be

used at LVL2 for electron and photon identification. For the $J/\psi \rightarrow e^+e^-$ trigger, track reconstruction is performed in an enlarged region around the LVL1 EM RoI and pairs of tracks are combined to form the J/ψ . For events in which both electrons have p_T above 5 GeV, the LVL2 efficiency is 68% with a rate of 170 Hz at $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The radiative decays have been studied using offline code to predict the trigger performance. For 30 fb^{-1} of data, 15,000 $B^0 \rightarrow K^*\gamma$ and 4,800 $B_s^0 \rightarrow \phi\gamma$ decays are expected to be collected with a trigger rate of less than $\sim 1 \text{ Hz}$.

3. CMS

Details of the CMS experiment can be found in Refs. [5, 6].

3.1. CMS trigger

CMS has a two level trigger [5] which reduces the bunch crossing rate down to about 150 Hz for recording. The Level-1 trigger uses muon and calorimeter information and is hardware based with an output rate of about 100 kHz and a latency time of $3.2 \mu\text{s}$. The High Level Trigger (HLT) is software based and uses similar reconstruction algorithms to those which are available offline, this runs in about 1 s and reduces the rate to the required 150 Hz. To speed up reconstruction in the HLT, a partial track reconstruction is used. This makes use of the fact that as additional hits are added to a track, the resolutions become asymptotic after about 5 or 6 hits. Therefore in the trigger the reconstruction is stopped once enough information about a track, is available to answer a specific question (i.e. the momentum resolution is good enough) and this is known as partial reconstruction.

3.2. CMS B trigger

As in ATLAS, CMS triggers B events using single and di-muon triggers. The di-muon trigger has a low p_T threshold of 3 GeV which ensures a high efficiency for events with two muons in the final state with a rate of only 0.9 kHz at $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The single muon trigger rate for a p_T threshold of 14 GeV is expected to be about

3.2 kHz, a lower threshold may be possible if a jet is also required in the events. In the HLT, exclusive b -decays are reconstructed around the level 1 muon using the partial track reconstruction technique described above.

The $B \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \phi(\rightarrow K^+ K^-)$ trigger [7] is presented here as an example of the CMS B -trigger. A level 1 di-muon trigger is required and the HLT is split into two parts; at level 2 the J/ψ is found and at level 3 further reconstruction identifies the ϕ and then the B . At level 2, partial track reconstruction up to a maximum of five hits is performed in cones around the level 1 muons. Muon candidate tracks are required to have a p_T of at least 2.5 GeV for $|\eta| < 1.2$ or 2 GeV for $|\eta| \geq 1.2$. Opposite sign muon tracks are then combined to form J/ψ candidates and mass cuts are applied. Figure 4 shows the reconstructed

Figure 4. Reconstructed invariant mass for J/ψ candidates for signal events. The hashed histogram shows the combinatorial background from signal events.

invariant mass for J/ψ candidates, the mass resolution is 51 MeV and candidates are required to have a mass within 150 MeV of the world average J/ψ mass. In addition the p_T of the J/ψ must

Figure 5. Transverse decay length (L_T^{rec}) significance for signal events (solid line), inclusive $b \rightarrow J/\psi X$ events (dashed line) and prompt J/ψ events (dotted line). The signal events are scaled up by a factor 10^3 .

be at least 4 GeV. A vertex fit is performed and to reduce the background from prompt J/ψ the decay length significance is required to be above a value of 3. Figure 5 shows the transverse decay length significance (which is the transverse decay length itself divided by its error) for signal and background events. This J/ψ trigger has an efficiency of 28% for a generated event sample with $p_T(\text{muon}) > 3(2)$ GeV in the barrel(endcap) and $p_T(K) > 0.8$ GeV (It should be noted that the efficiency is dependent on the the signal sample; the p_T cut on the generated particles is lower in the case of CMS and low p_T particles are more difficult to reconstruct, which leads to a lower efficiency). The acceptance rate is reduced to about 15 Hz and about 80% of the triggered J/ψ 's originate from B decays.

At level 3 a further rate reduction is achieved by doing a full reconstruction of the B . A search for the kaons is made in a cone around the J/ψ and first the ϕ and then the B_s^0 are reconstructed. The p_T of each kaon candidate track is required to be above 0.7 GeV and the invariant mass of

Figure 6. Reconstructed invariant mass for B_s^0 candidates. The hashed histogram shows the combinatorial background from signal events.

opposite-sign track pairs is required to be within 20 MeV of the world average ϕ meson mass (the mass resolution is 4.5 MeV). For ϕ candidates with a p_T above 1 GeV, the two muon candidates from the J/ψ are added and the four-track invariant mass is required to be within 200 MeV of the world average B_s^0 meson mass. Figure 6 shows the B_s^0 candidate invariant mass and the resolution is 65 MeV. In addition the p_T of the B_s^0 candidate is required to be above 5 GeV and a vertex fit is made to the four tracks, with similar requirements applied as those for the J/ψ . A final rate of about 0.03 Hz is expected at $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with an efficiency of 20% for the signal sample described above.

4. PILOT RUN

For the low energy (900 GeV) pilot run in 2007, the fraction of the total cross-section which is due to $b\bar{b}$ events will be smaller than at the design energy (14 TeV). This and the expected lower luminosity ($\sim 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$) means that there will be very few B -physics events, e.g. less than 10 $b \rightarrow J/\psi X$ events are expected assuming 30 days running and 30% data-taking efficiency. However

this period will be useful for commissioning and testing the triggers. It is likely that the experiments will run loose level 1 triggers (e.g. single LVL1 muon or minimum bias triggers) and have a pass-through high level trigger where information about the trigger reconstruction and decisions is recorded but not used to reject events. A few hundred prompt J/ψ and Υ events are expected and these can be used to study the mass reconstruction in the trigger.

5. SUMMARY

We have presented flexible strategies for the triggering of B -physics events at ATLAS and CMS from the initial running to final design luminosities. A broad programme of B -physics is planned during the low-luminosity running and studies using di-muon channels will continue at high-luminosity. Final trigger menus to maximise the B -physics potential of the experiments are now being prepared and we are looking forward to the first LHC data.

REFERENCES

- 1 ATLAS Collaboration, *ATLAS Detector and Physics Performance Technical Design Report*, CERN/LHCC/99-14 (1999).
- 2 H. Burckhart, *The ATLAS detector*, these proceedings.
- 3 ATLAS Collaboration, *ATLAS High Level Trigger Data Acquisition and Controls Technical Design Report*, CERN/LHCC/2003-22, 2003.
- 4 J. Baines, J. Kirk, A. Watson, *ATLAS B-physics trigger studies using EM and Jet RoIs*, ATL-DAQ-PUB-2006-004 (2006).
- 5 CMS Collaboration, *CMS physics : Technical Design Report v.1 : Detector performance and software*, CERN/LHCC/2006-001, CMS TDR 8.1 (2006).
- 6 O. Buchmuller, *The CMS detector*, these proceedings.
- 7 CMS Collaboration, *CMS physics : Technical Design Report v.2 : Physics performance*, CERN/LHCC/2006-021, CMS TDR 8.2 (2006).