B Physics triggers at CMS

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The CMS detector is mainly designed to investigate hard events. Only few Level-1 Trigger conditions are suitable to select soft B-meson decays. The B-physics potential of CMS depends strongly on a selection strategy at High-Level Trigger. The selection algorithms for some benchmark B-decay channels that allow CMS to perform competitive B-physics program are presented.

1 Introduction

The CMS detector [1] is designed and optimized for discovery physics, in particular the observation of the Higgs boson(s) and the investigation of supersymmetry or other physics beyond the standard model. Nevertheless, B physics may be an interesting subject, especially during the low luminosity ($2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$) phase. The study presented in this note has been done for this phase.

The B-physics potential of the CMS detector depends on many factors but mostly on the trigger conditions that will be used to collect events for further offline analysis. While the main Level-1 triggers are almost defined, the High-Level Triggers (HLT) are currently under discussion and investigation. In this note, possible HLT selection algorithms for several B decay channels of interest are presented.

2 The CMS Trigger and Data Acquisition

The CMS Trigger and Data Acquisition System (TriDAS) is designed to inspect the detector information at the full beam crossing rate of 40 MHz and to select events at a maximum rate of $O(10^5)$ Hz for archiving and later offline analysis. The required rejection power of $O(10^5)$ is too large to be archived in a single processing step. For this reason, the full selection task is split in two steps. The first step (Level-1 Trigger) is designed to reduce the rate of events accepted for further processing to less than 100 kHz. The time available for actually processing the data is about 1 µs. Therefore the Level-1 Trigger can only process data from a subset of CMS sub-detectors, the calorimeters and muon chambers. Moreover, this data do not represent the full information recorded in the CMS front-end electronics, but only a coarse-granularity and lower-resolution set. The second step (High-Level Trigger) is designed to reduce the maximum Level-1 accept rate of 100 kHz to a final output rate of 100 Hz. The event selection at this stage takes advantage of the enhanced granularity and resolution available and makes use of information from tracking detectors. The HLT selection algorithms are actually almost as sophisticated as those used in the offline reconstruction of the events. The current best estimate for the total average processing time required for the design selection of 1:1000 (i.e. a rate reduction from 100 kHz to 100 Hz) is roughly 40 ms, with some events requiring up to one second.

The Level-1 Trigger is documented in the Volume I of the TriDAS Technical Design Report [2] and details of the architecture of the TriDAs related to the HLT can be found in the Volume II [3].

It is important to mention that the current CMS plan foresees only partial completion of the Data Acquisition system at the low luminosity phase (mainly during which the B-physics study will be performed). At startup, the DAQ system will therefore only be able to handle an event rate of 50 kHz or less. Moreover, to account for all uncertainties in the simulation of the basic physics processes, the CMS detector and the beam conditions, an additional safety factor of 3 is taken into account. Therefore, the maximum Level-1 Trigger rate of 16 kHz is considered for the HLT study.

In the following, the CPU time required for the algorithm execution at the HLT is also shown. This time is normalized on a Pentium-III 1 GHz processor and fits within the foreseen time budget if it is of the order of 500 ms/event [3].

3 The Level-1 Triggers

The allocation of the Level-1 Trigger bandwidth has been optimized in order to ensure the widest possible physics reach for the CMS experiment. An equal allocation (4 kHz) across the four categories of "objects", taken as 1) electrons/photons, 2) muons, 3) tau jets
(hadronic tau decays) and 4) jets plus combined channels (at least one jet plus other Level-1 signatures with lower thresholds), is made. The thresholds for each trigger were set to satisfy this requirement. Since the CMS detector is mainly oriented towards the investigation of events with high $p_T$ muons and electrons, very energetic jets and photons or significant missing $E_T$ values, the only suitable triggers which can collect reasonable amount of b events are the single-muon ($p_T > 14$ GeV/c), di-muon ($p_T > 3$ GeV/c) and possibly single-muon-plus-jet triggers.

4 Benchmark channels

According to the Level-1 triggers the B-meson-decay final states should contain one or two relatively high $p_T$ muon(s). Based on this requirements the following three benchmark channels have been selected:

$$B_s^0 \rightarrow J/\Psi \phi \rightarrow \mu^+ \mu^- K^+ K^-; \quad (1)$$

$$B_s^0 \rightarrow \mu^+ \mu^-; \quad (2)$$

$$B_s^0 \rightarrow D_s^- \pi^+ \rightarrow \phi \pi^- \pi^+ \rightarrow K^+ K^- \pi^- \pi^+. \quad (3)$$

The channels (1) and (2) are triggered by the di-muon Level-1 trigger and the channel (3) by the single-muon (which comes from the decay of the second B-meson in the event) Level-1 trigger.

5 High-Level Trigger strategy

The HLT strategy is common for all three benchmark channels. The CMS Tracker information is used to reconstruct tracks, compute invariant masses and select events on the basis of kinematical and topological properties of the final states of the benchmark channels. A difference between algorithms is related to the track reconstruction procedure. Due to the physically limited HLT processing time, it is not possible to reconstruct all tracks with $p_T > 1$ GeV/c in the full rapidity coverage. Nevertheless, for the channels (1) and (2) there is a natural, so-called, Region of Interest (RoI) around the two Level-1 muons. Moreover, the large magnetic field yields a satisfactory momentum resolution for these muons even with a limited number of hits. The resulting accuracy of the track parameters obtained with a partial track reconstruction is shown in Fig. 1. The three cases shown in this figure differ by the number of layers hit in the pixel detector used in the reconstruction: 1) only two innermost layers hit; 2) all three layers hit; 3) at least two layers hit. For the channels (1) and (2), the track reconstruction is performed in the RoI and stopped if one of the conditions is fulfilled: 1) either six hits along the trajectory are found, or 2) the relative transverse momentum resolution is better then 2%. For the channel (3), the di-

![Figure 1. The resolution on a) $p_T$ and b) impact parameter for partial track reconstruction, compared with full track resolution, as a function of the number of smoothing steps in different $p_T$ and for the barrel region. The leftmost points at "0" reconstructed hits show the full tracker performance.](attachment:image.png)

5.1 The $B_s^0 \rightarrow \mu^+ \mu^-$ channel

Events are required to have two oppositely charged isolated muons coming from a common displaced vertex with an invariant mass close to the nominal $B_s^0$ mass. First, a fast algorithm creates track seeds from pairs of hits in the pixel detector which can be assigned to tracks with $p_T > 4$ GeV/c with transverse impact parameter smaller than 1 mm. The reconstructed track pairs are used for a first reconstruction of the primary vertex. Then, pairs of hits are filtered using a vertex constraint and the RoI around the Level-1 muon momentum directions ($\Delta \eta \leq 0.5$ and $\Delta \phi \leq 0.8$). These pairs are used for the conditional track reconstruction as described above.

The reconstructed tracks are propagated back to the origin using a standard smoothing procedure. If and only if two oppositely charged particle tracks are reconstructed, it is checked that the invariant mass formed by the two particles is within 150 MeV/c$^2$ of the $B_s^0$ mass. In order to suppress combinatorial background, tracks are vertexed and retained if the vertex
5.2 The $B^0_s \to J/\Psi \phi$ channel

Muons from $J/\Psi$ are reconstructed in the same way as described above, except for the fact that slightly tighter cuts on the di-muon mass and the secondary vertex are put to keep the background rate at an acceptable level. The mass window is decreased to 100 MeV/$c^2$ and the secondary vertex has to be at least 200 \( \mu \text{m} \) from the beam with the vertex $\chi^2 < 10$. The di-muon selection leads to an inclusive rate of about 15 Hz, 90\% is due to a $J/\Psi$ from b decays.

To select the kaons, coming from the $\phi$ meson, all track seeds within a cone $\Delta R < 1.5$ around the $J/\Psi$ candidate direction are reconstructed using the conditional track reconstruction. Charged-particle tracks of opposite sign are paired and retained if their invariant mass is within 10 MeV/$c^2$ of the $\phi$ mass. The $B^0_s$ candidate is retained if the mass formed by the $J/\Psi$ and $\phi$ candidates is within 60 MeV/$c^2$ of the $B^0_s$ mass. The mass resolutions for the $J/\Psi$ and the $B^0_s$ candidates are shown in Fig. 2.

The global HLT selection efficiency is about 8.7\% and the yield is about 160000 events for a low-luminosity year. The background rate is estimated to be less than 2 Hz.

5.3 The $B^0_s \to D_s^- \pi^+$ channel

A single muon or a combination of a low $p_T$ muon and a relatively low $E_T$ jet can be used as a Level-1 trigger to select this decay channel. Table 1 shows the expected trigger rates as a function of the different cuts on the muon and the jet transverse momentum and energy. The corresponding yields for signal events are shown in Table 2. The machine conditions and the instantaneous luminosity may well allow the Level-1 Trigger to be run with lower thresholds than the nominal ones, which have been determined for the luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

![Figure 2](image)

**Figure 2.** Mass resolutions for $J/\Psi$ and $B^0_s$ candidates for the $B^0_s \to J/\Psi \phi$ decay channel.

| $p_T^\mu$ (GeV/c) | Background rate (Hz) |
|------------------|---------------------|
|                  | No jet | $E_T^{jet} \geq 30 \text{ GeV}$ |
| 4                | 270 (50K) | 80 (5.7K) |
| 7                | 110 (18K) | 50 (2.7K) |
| 10               | 40 (6.4K) | 10 (1.3K) |
| 14               | 17 (3.2K) | 8 (0.7K) |

**Table 1.** HLT (Level-1) rates as a function of trigger $\mu$ momentum and trigger jet $E_T$ for an integrated luminosity of 20 $\text{fb}^{-1}$.

First, the primary vertex is reconstructed based on the pixel information. Then, all tracks with $p_T > 0.7$ GeV/c are reconstructed from three hits only: two hits are taken from the pixel detector and one from the first silicon strip layer. To reduce the execution time, seeds are requested to come from the primary vertex $z$ location within $\pm 1 \text{ mm}$. A search is then made for the $\phi$, $D_s$ and $B^0_s$ candidates using following topological requirements: $\Delta R(K, K) < 0.3$, $\Delta R(\phi, \pi) < 1.2$ and $\Delta R(D_s, \pi) < 3.0$. The invariant mass distributions are shown in Fig. 3 for the $\phi$ and the $D_s$ candidates and in Fig. 4 for the $B^0_s$ candidate. The main cuts are placed on the invariant masses and the transverse momenta of the three resonances. A three-dimensional reconstruction of the $D_s$ decay vertex is also performed.

| $p_T^\mu$ (GeV/c) | Number of Signal events |
|------------------|-------------------------|
|                  | No jet | $E_T^{jet} \geq 30 \text{ GeV}$ |
| 4                | 11K (106K) | 2.3K (14K) |
| 7                | 5.6K (48K) | 1.3K (9.4K) |
| 10               | 2.0K (20K) | 0.6K (5.3K) |
| 14               | 1.0K (11K) | 0.3K (3K) |

**Table 2.** Number of signal events after HLT (Level-1) as a function of trigger $\mu$ momentum and trigger jet $E_T$ for an integrated luminosity of 20 $\text{fb}^{-1}$.
The signal efficiency after all cuts is about 10%, while the background is suppressed by a factor of 250. The mean execution time shown in Fig. 4 is about 460 ms for signal events and about 640 ms for background. The number of signal events depends on the bandwidth allocated to this channel, according to the instantaneous luminosity of LHC. From the above tables even a relatively high threshold of 14 GeV/c gives a rate of 3 kHz after Level 1. Since the allowed bandwidth may be lower than 3 kHz, it is necessary to scale the rate. This can be done by scaling either the rate of events with the lowest possible $p_T$ threshold of the trigger muon or the rate of events in all $p_T$ bins so that the overall sum matches the allowed bandwidth. On the other hand, the quality of the analysis depends on the total number of events, the fraction of signal events and their dilution factor. By rising the muon $p_T$ the signal fraction and the dilution factor increases mildly, while the total number of events decreases. Therefore, it is better to fill the allowed bandwidth with events with the lowest possible muon $p_T$ and, if it is needed, downscale only the next lower bin. For example, referring to Table 1 for an allowed bandwidth of 4 kHz, all events with a muon of $p_T > 14$ GeV/c should be kept, while events with 10 GeV/c $< p_T < 14$ GeV/c should be scaled by a factor of 4. Details of this study can be found in [7]. As mentioned above, the number of signal events collected per one year depends on the bandwidth allocated for this decay channel at Level 1. For a Level-1 Trigger rate of 1 KHz the number of selected signal events ranges from 300 to 400 for the integrated luminosity of 20 fb$^{-1}$ and depends on the type of the Level-1 trigger. With such an amount of events CMS will be sensitive up to $\Delta m_s = 20$ ps$^{-1}$ [S].

6 Conclusion

Although B physics at a general-purpose detector like CMS is not a first priority task, a proper design of the sub-detectors and the TriDAS system allow CMS to be competitive for a number of B-decay channels. Single-muon and di-muons final states of B decays can be successfully triggered both at Level-1 and HLT, with enough signal events for the offline analysis. The HLT algorithms presented in this note are based on the CMS Tracker information used to perform a fast and precise primary/secondary vertex, track and invariant mass reconstruction. All algorithms are channel specific and very similar to the offline ones with slightly looser cuts. The use of the conditional track reconstruction in a Region of Interest or the track reconstruction in the full detector acceptance with only three innermost hits allows the algorithms to be fast enough to fit within the HLT time budget.

More studies will be done to optimize the selection procedure for the decay mode $B_s^0 \rightarrow D^- \pi^+$ and to decrease the HLT execution time for the decay mode $B_s^0 \rightarrow J/\Psi \phi$.

References

1. The CMS Collaboration, The Compact Muon Solenoid, Technical Proposal, CERN/LHCC 94-38
2. The CMS Collaboration, The Trigger and Data Acquisition Project, Volume I, The Level-1 Trigger, Technical Design Report, CERN/LHCC 2000-038
3. The CMS Collaboration, The Trigger and Data Acquisition Project, Volume II, Data Acquisition & High-Level Trigger, Technical Design Report, CERN/LHCC 2002-26
4. The CMS Collaboration, The Tracker Project, Technical Design Report, CERN/LHCC 98-6
5. S.Gennai, R.Dell’Orso, F.Palla and A.Starodumov A Study of bb Production Mechanisms in PYTHIA, CERN-2000-004, CMS NOTE 2000/037
6. D. Kotlinski and A. Starodumov, *High Level Tracker Triggers for CMS*, Nucl. Instrum. and Methods A501 (2001) 222-228, hep-ph/0203101

7. A. Giassi, F. Palla and A. Starodumov, *Study for a High-Level Trigger for the decay channel B^0_s → D_s π → φ(KK) π π*, CMS Note 2002/045

8. Z. Xie, F. Palla and A. Starodumov, *B^0_s oscillation sensitivity study in CMS*, CMS Note 2000/038