CMS Conference Report

b Physics at LHC with the CMS detector

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Abstract

The perspectives for b-physics analyses with CMS are reviewed here and some of the related trigger and tracking issues are discussed.

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1 Introduction

Although the current theoretically-predicted $b\bar{b}$ cross-section is uncertain, the expected value at LHC is about five order of magnitude larger than that reachable with 2 TeV centre-of-mass energy of the Tevatron[1]. At the LHC design luminosity of $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$, it would translate into $10^5 b\bar{b}$ pairs/s and at the initial luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ into about $10^4 b\bar{b}$ pairs/s. The LHC collider thus provides a unique opportunity for b-physics analyses.

The amount of storage resources available at LHC is very small if compared to the amount of data produced. At CMS, the initial 40MHz p-p interaction rate will be brought down to 100 KHz by the Level-1 Trigger to finally reach about 100Hz stored on tape. In this scenario, the trigger strategy for b-physics studies is a major challenge.

The b-physics program with the CMS detector is intended to cover rare b decays, CP violation and $B_s - \bar{B}_s$ mixing. A benchmark channel for each of these items was chosen: $B_s \rightarrow \mu^+ \mu^-$, $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- \rightarrow K^+ K^-$ and $B_s \rightarrow D_s^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$. These channels were analysed to develop b-decay triggering strategies and to evaluate the physics outcome.

2 CMS trigger strategy for b physics

A detailed description of the CMS Trigger design and of the overall CMS Data Acquisition System is given in Refs. [2, 3, 4]. The features relevant to b-physics selection are mentioned here. The CMS trigger is divided into a Level-1 Trigger and High-Level Triggers (HLT). Coarse information from the calorimeters and the muon detectors are exploited at Level 1 to select basic physics objects subsequently refined (e.g., muon isolation) at HLT with the information provided by the tracking. The proton-proton interaction rate at LHC, 40MHz, is brought down to 100KHz at Level 1 and finally, after the HLT, to about 100Hz for final data storage. In the first LHC phase at low luminosity, the CMS DAQ System is planned to be staged so that it will be able to handle at most 50KHz Level-1 Trigger rate. However, the actual Level-1 Trigger rate so far considered for all HLT studies is only 16 KHz. A safety factor 1/3 was applied to account for possible surprises arising from the LHC beam conditions and the CMS detector as well as uncertainties in the simulation of the basic physics processes.

The available Level-1 Trigger rate must be allocated to the various physics objects (electrons/photons, muons, jets, τ jets) to cover the widest possible range of physics for discovery. For the low luminosity period, a prototype 'democratic' allocation of about 4KHz was made for the four categories and the P_T thresholds were optimized to fulfil this requirement.

The selection of b-physics processes can be triggered at Level 1 by the presence in the event of single or double muons produced in the b semileptonic decays; the Level-1 Trigger bandwidth allocated to the muons includes the single and di-muon triggers, the thresholds of which, $P_T^\mu > 14 \text{ GeV}/c$ and $P_T^\mu > 3 \text{ GeV}/c$, yield a rate of 2.7 KHz and 0.9 KHz respectively.

Particles originating from b-hadron decays are characterized by a relatively soft P_T spectrum and muons falling in the low P_T range can well be used for triggering. Muons are preferred to electrons because of their substantially lower P_T thresholds ($P_T^{el} > 29 \text{ GeV}/c$ and $P_T^{el} > 17 \text{ GeV}/c$).

At HLT a total of 30 Hz is allocated to muons (single + double). The muon isolation criteria bring further down the trigger rate and reject the majority of the b-hadron content; for the chosen single (double) muon threshold $P_T > 19 \text{ GeV}/c$ ($P_T > 7 \text{ GeV}/c$) a 25 Hz (5Hz) rate is achieved. Figure 1 shows the total muon rate at high luminosity as a function of the single muon P_T threshold after applying the isolation criteria. The contributions from different sources of muons to the total rate are also shown. At the working point chosen, the dominant contribution comes from the W leptonic decays. Only a small fraction (5Hz for the single muon) is accounted for by inclusive b and c decays.

The affordable rate for final data storage on tape is only hundred events per second and they have to

Figure 1: Contributions to the High Level Trigger rate at high luminosity from all sources of muons after requiring the muon to be isolated.

include all physics processes relevant for discovery. The b events cannot be accepted inclusively for subsequent offline selection, since their amount would be too little to explore processes with branching ratios well below 10^{-4} . A selection at HLT, involving fast tracking, is henceforth needed to identify interesting exclusive b decays.

The HLT selection will be performed in an Event Filter Farm, where each single processor is devoted to the online data access, reconstruction and analysis of a single event. The CPU time constraints today (1 GHz Pentium-III processor) are about 300 ms/event. The primary task to be accomplished at HLT is then rejecting the event as fast as possible, while carefully retaining those with interesting physics content.

2.1 Tracking at High Level Trigger

The reconstruction of charged particles starts from the inner pixel detector which provides up to three accurate three-dimensional points. Track seeds are built out of pixel hit pairs compatible with a track originating from the primary interaction vertex and subsequently propagated outward in the silicon strip tracker. The full reconstruction is highly time consuming because of the large number of hit combinations. Although tracking at HLT is required to be robust, it does not need to be as accurate as for the offline reconstruction and substantial computing time can be saved by simplifying the reconstruction procedure.

In order to speed up the tracking procedure, the concepts of “regional” and “partial or conditional” tracking were developed with the aim of reducing the number of track seeds and the number of computational steps per seed respectively. With the regional tracking, tracks are reconstructed only in limited regions of interest in the tracker identified by the presence of a Level-1 Trigger object such as a muon. With the partial and/or conditional tracking, the track reconstruction can be stopped if, for instance, the measured P_T is below a certain threshold and no longer considered for further reconstruction, or when a certain optimal number of hits is already reconstructed. Figures 2 and 3 show the P_T and the transverse parameter resolution as a function of the number of hits reconstructed per track. The results are compared with those obtained with the full reconstruction. The asymptotic value of the resolution is almost reached by reconstructing five or six hits per track while reducing by about half the reconstruction time.

Figure 2: The P_T resolution for partial track reconstruction as a function of the number of reconstructed hits. The markers at zero on the horizontal axis show the resolution achieved with the full tracker reconstruction.

Figure 3: The resolution of the transverse impact parameter for partial track reconstruction as a function of the number of reconstructed hits. The markers at zero on the horizontal axis show the resolution achieved with the full tracker reconstruction.

3 Exclusive B decay channels

3.1 $B_s \rightarrow \mu^+ \mu^-$

The decay channel $B_s \rightarrow \mu^+ \mu^-$ is a Flavour-Changing-Neutral-Current process described at loop level by the Standard Model (SM). The experimental signature is unique and clean. Unfortunately, the SM predicts a tiny branching ratio ($O(10^{-9})$). It is unlikely that $B_s \rightarrow \mu^+ \mu^-$ will be observable before the LHC starts, unless a drastic enhancement of the branching ratio, due to contributions from new physics, shows up.

Events are triggered at Level 1 by two opposite charge muons with $P_T > 3 \text{ GeV}/c$. Pixels seeds are built out of pixels hit pairs compatible with $P_T > 4 \text{ GeV}/c$ and transverse impact parameter below 1 mm. The

seeds so obtained are used for a first reconstruction of the primary vertex. Hit pairs are then filtered with the vertex constraint and the region of interest around the Level-1 di-muon direction and used for partial/conditional track reconstruction, i.e., the reconstruction is stopped if either the track P_T is lower than 4 GeV/ c at 5σ , or six hits are reconstructed along the track, or the relative P_T resolution is below 2%. When two tracks with opposite charge are found, the invariant mass is calculated and required to be within 150 MeV/ c^2 around the B_s mass. Figures 4 and 5 show the B_s mass resolution achievable at HLT and offline respectively.

Figure 4: Decay channel $B_s \rightarrow \mu^+ \mu^-$: B_s mass resolution with the HLT selection and reconstruction.

Figure 5: Decay channel $B_s \rightarrow \mu^+ \mu^-$: B_s mass resolution with the offline reconstruction.

The combinatorial background is suppressed by constraining the two tracks to a common secondary vertex and imposing suitable cuts on the vertex fit χ^2 and on the transverse impact parameter. The HLT selection efficiency is about 33% while the Level-1-plus-HLT efficiency is about 5% with a yield of 47 events with 10 fb $^{-1}$. The average time required for reconstructing a $B_s \rightarrow \mu^+ \mu^-$ event is 240 ms.

The HLT selection is identical to the offline procedure described in Ref.[5]. It does, however, apply much looser cuts. The events selected by the offline analysis (seven signal events with one background

event with 10 fb^{-1}) are then expected to pass the HLT selection. In such conditions a 5σ observation would be possible with about 15 fb^{-1} .

3.2 $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$

The decay channel $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ is the gold-plated mode for probing CP violation. It allows $\Phi_s = -2\lambda^2\eta$, the value of the CP violation weak phase, to be measured. This value is predicted to be extremely small, $O(0.03)$, by the Standard Model. An enhancement of Φ_s would imply contributions from new physics.

As for the previous channel, $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ is triggered at Level 1 by the presence of a di-muon. The reconstruction is, in this case, more complicated and more time consuming. It can be divided into two steps, referred to as HLT step 1 and HLT step 2 in the following.

At the HLT step 1, muons from the J/ψ are reconstructed as described in the previous section. Slightly tighter cuts, however, are applied to the di-muon invariant mass and on the secondary vertex to keep under control the background level. The J/ψ mass resolution is shown in Fig. 6.

Figure 6: Decay channel $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$: J/ψ mass resolution achieved with the HLT selection.

The di-muon reconstruction gives an inclusive rate of 15 Hz at low luminosity. The contribution from J/ψ produced in b decays is about 90%. The HLT step 1 takes on average 260 ms per event. The HLT step 2, concerning the ϕ and B_s reconstruction, is more time demanding. First, the ϕ is reconstructed out of charged particle tracks in a cone around the J/ψ . Partial tracking is used for their reconstruction. Oppositely-charged particle track pairs with invariant mass within $10 \text{ MeV}/c^2$ of the ϕ are retained as candidates. Finally the invariant mass of the J/ψ and the ϕ is calculated and required to be within $60 \text{ MeV}/c^2$ of the B_s mass. The B_s mass resolution so obtained is shown in Fig. 7.

The combined HLT-step-1 and HLT-step-2 efficiency is about 8.7%. A yield of about 84K events is expected with 10 fb^{-1} at low luminosity with a background rate smaller than 2 Hz. The total average reconstruction time is about 800 ms. The $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ offline reconstruction is expected to select 60% to 70% of the HLT signal. This translate to about 200K signal events with 30 fb^{-1} . Past studies [6], involving the time-dependent angular analysis of the decay products, predict a relative uncertainty on $\Delta\Gamma_s$ of about 15% and an uncertainty of about 0.0025 on Φ_s for $x_s=20$.

Figure 7: Decay channel $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$: B_s mass resolution achieved with the HLT selection.

3.3 $B_s \rightarrow D_s^+ \pi^- \rightarrow \phi \pi^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$

The Standard Model prediction for ΔM_s in the $B_s - \bar{B}_s$ system is $14.8 \leq \Delta M_s \leq 25.9 \text{ ps}^{-1}$ at 99% C.L. The present experimental 95% C.L. lower limit is $\Delta M_s \geq 14.4 \text{ ps}^{-1}$. The study of the decay channel $B_s \rightarrow D_s^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$ at LHC allows the whole predicted ΔM_s range to be spanned.

A fully hadronic decay channel such as $B_s \rightarrow D_s^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$ can be triggered at Level 1 by the muon produced in the semileptonic decay of the other b hadron present in the event. For this channel, the muon also serves for tagging the CP state of the B_s at production time. Alternatively, a combination of a low- P_T muon and a low- E_T jet can be used with different threshold scenarios and trigger rates.

The $B_s \rightarrow D_s^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$ selection at HLT starts with the primary vertex reconstruction as for the $B_s \rightarrow \mu^+ \mu^-$. Since the Level-1 Trigger muon direction has no correlation with the B_s direction, no region of interest can be used for applying regional tracking. Hence all tracks with P_T above $0.7 \text{ GeV}/c$ have to be reconstructed. To reduce the reconstruction time, only three hits, two in the pixel detector and one in the innermost layer of the silicon strip detector, are used for creating the seed tracks. Also, seeds are requested to be compatible with the primary vertex along the z direction.

Topological cuts are applied to select the ϕ , D_s^+ and B_s candidates as well as cuts are applied to their invariant masses and transverse momenta. The three mass distributions after the HLT selection are shown in Fig. 8, 9 and 10. The HLT selection efficiency is about 9% and the average execution time is 250 ms per event.

The number of selected signal events depends on the HLT bandwidth available for this channel which almost likely cannot exceed 5Hz. With this assumption, about 300 events are expected with 20 fb^{-1} which would allow the exploration of the ΔM_s range up to $\Delta M_s \sim 20 \text{ ps}^{-1}$. About 1000 events would be needed to extend the sensitivity to the upper limit allowed by the Standard Model ($\Delta M_s \leq 26 \text{ ps}^{-1}$). More details concerning the $B_s \rightarrow D_s^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$ study are presented in Ref. [7].

Figure 8: Invariant mass distribution of the ϕ in the decay channel $B_s \rightarrow D_s^+ \pi^+ \rightarrow K^+ K^- \pi^+ \pi^-$

Figure 9: Invariant mass distribution of the D_s^+ in the decay channel $B_s \rightarrow D_s^+ \pi^+ \rightarrow K^+ K^- \pi^+ \pi^-$

4 High-Level Trigger bandwidth for exclusive b decay channels

The present prototype HLT table does not include explicitly the b-physics item since the allocation of b-physics triggers is likely going to be a rather dynamic process. The rate of events selected by reconstructing online exclusive b decays is few Hz and an optimization of the reconstruction strategies might reduce it further. The main limitation comes from the Level-1 Trigger rate actually sustainable by the HLT reconstruction algorithms. The present average HLT processing time, including all Level-1 physics objects, is about 300 ms/event. This was used to get an estimate of the computing power needed in the low luminosity period to process the Level-1 output at 50 KHz.

Any improvement either of the processor performance (Moore's law would suggest 300 ms/event might become 30 ms/event in 2007) and of the software performance (refined algorithms as well as optimized software) would open more space for b-physics triggers.

Figure 10: Invariant mass distribution of the B_s in the decay channel $B_s \rightarrow D_s^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$

Another point to bear in mind is that the Level-1 Trigger thresholds were designed in order to account for a factor 1/3 of the first-phase design Level-1 output rate. The safety factor might turn out to be pessimistic: either 30 KHz become available or the time for processing each event at HLT would be three times larger than nowadays expected.

The bandwidth which can be allocated for b physics is likewise dependent on the actual value of the luminosity. The nominal low luminosity is $2 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, however, at the LHC start up it is likely to expect a somehow lower value. Such an occurrence would imply a lower HLT output and larger trigger rate might be allocated to the exclusive b-physics processes.

5 Conclusions

The huge $b\bar{b}$ statistics at LHC render possible the first observation of the $B_s \rightarrow \mu^+ \mu^-$ decay and very accurate measurements such as the extraction of the weak mixing phase Φ_s from $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ and ΔM_s from $B_s \rightarrow D_s^+ \pi^- \rightarrow \phi \pi^+ \pi^- \rightarrow K^+ K^- \pi^+ \pi^-$.

Although CMS was not specifically designed for b-physics studies, it can surely support a competitive program. The powerful tracking device can be exploited at HLT by designing suitably fast algorithms.

The bandwidth allocated to b-physics triggers crucially depends on the technological evolution of commercial processors on one side and on the LHC beam conditions on the other.

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