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LHCb trigger

O. SCHNEIDER[†]
and
T. NAKADA[†,§]

[†]*Institut de Physique des Hautes Energies, University of Lausanne, CH-1015 Lausanne*
[§] *European organization for nuclear research (CERN), CH–1211 Genève 23*

E-mail: `Olivier.Schneider@iphe.unil.ch, Tatsuya.Nakada@cern.ch`

LHCb is a hadron collider experiment in preparation at CERN, which plans to start taking data at its full potential as soon as the LHC machine becomes operational. It is dedicated to the study of CP violation and other rare phenomena with b hadrons produced copiously in the forward region. The design and realization of an efficient and selective trigger for both fully-hadronic and leptonic B decays in specific channels of interest is one of the major challenges of the experiment. Following a description of the LHCb detector and its environment at LHC, the current design of the trigger scheme is presented and its expected performance is discussed.

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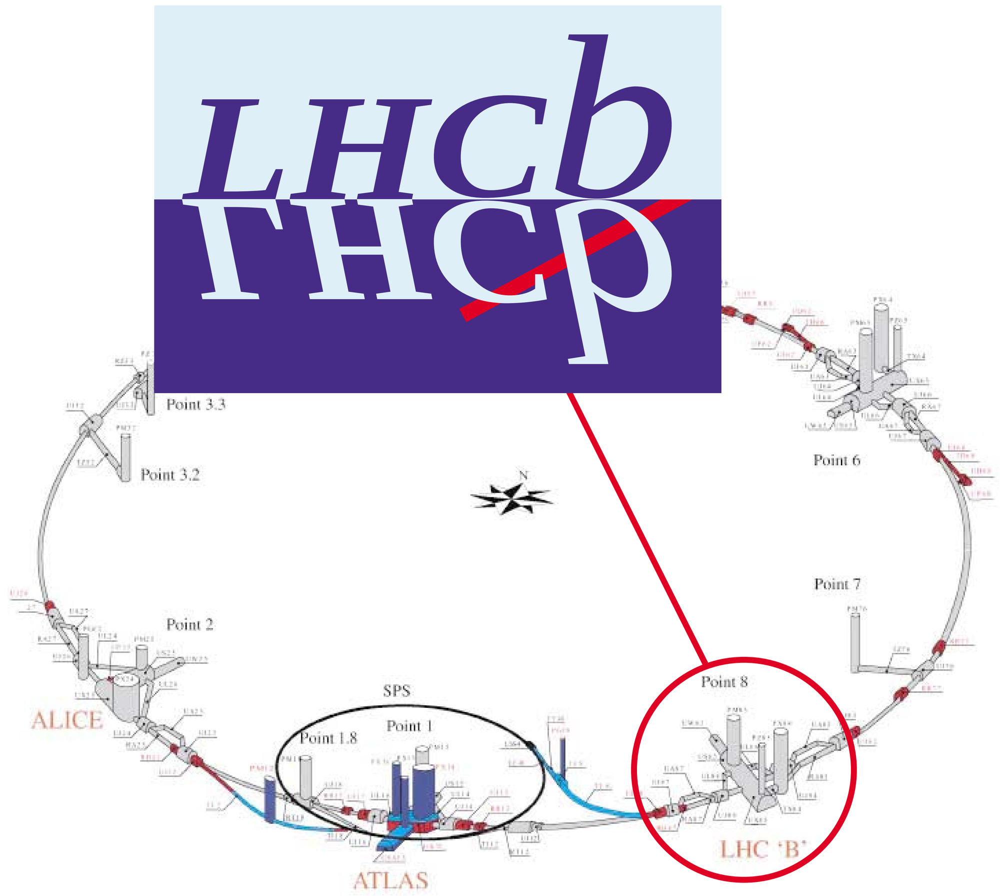
LHC parameters

$L_{\text{initial}} = 5\times10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
$L_{\text{design}} = 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
$L_{\text{LHCb}} = 2\times10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
$f_{\text{bunch crossings}} = 40$ MHz
$f_{\text{collisions@LHCb}} = 30$ MHz

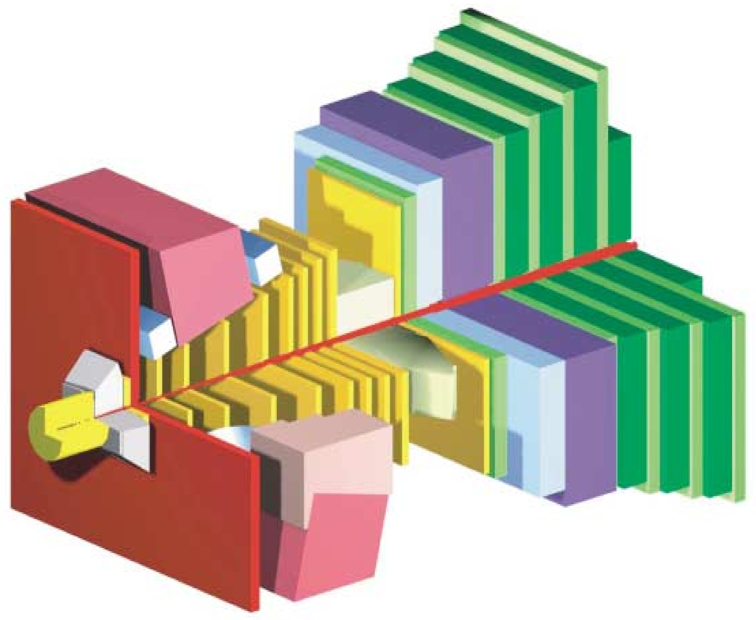
pp collisions at $\sqrt{s} = 14$ TeV
$\sigma_{\text{total}} = 100$ mb
$\sigma_{\text{inelastic}} = 80$ mb
$\sigma_{\text{inelastic}} - \sigma_{\text{diffraction}} = 55$ mb
$\sigma_{\text{visible in LHCb}} = 68$ mb
$\sigma_{c\bar{c}} = 1.5$ mb
$\sigma_{b\bar{b}} = 500\ \mu$b



Ise, Japan
19-23.2.2001

LHCb Trigger

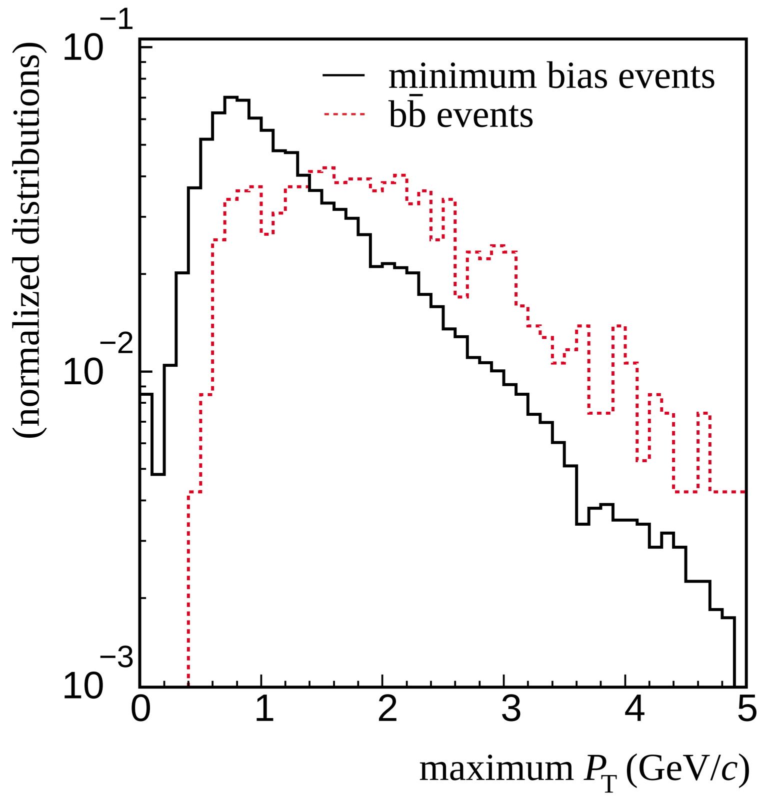
O.Schneider (Lausanne)
T.Nakada (CERN/Lausanne)
on behalf of the LHCb Collaboration

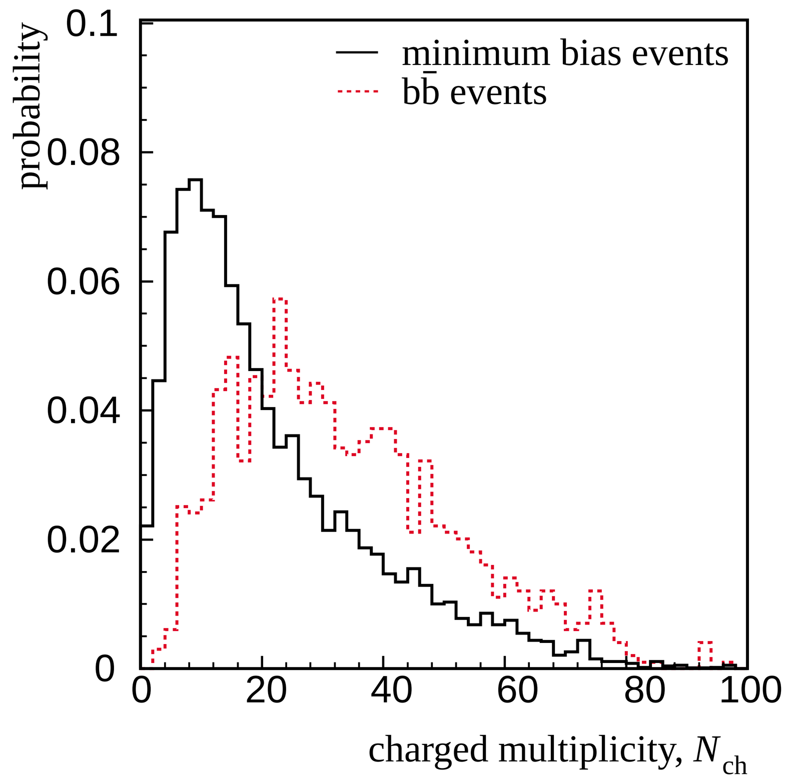


Vertex Locator (Si small r-φ strips)
Outer Trackers (straw chambers)
Inner Trackers (Si and Triple GEM)
RICH 1 (Aerogel + C_4F_{10} +HPD)
RICH 2 (CF_4 + HPD)
Calorimeter System
Preshower (Scintillator/Pb/Scintillator)
E Cal (Pb Scintillator Shashlik)
H Cal (Fe Scintillator tiles)
Muon System (RPC and MWPC)

Simulation of minimum bias and b events

Use PYTHIA with multiple parton-parton interactions model
tuned on charged track multiplicities observed at low energy
hadron colliders (SPS, Tevatron) in non single-diffractive events:
→ predictions at LHC for charged tracks in LHCb acceptance

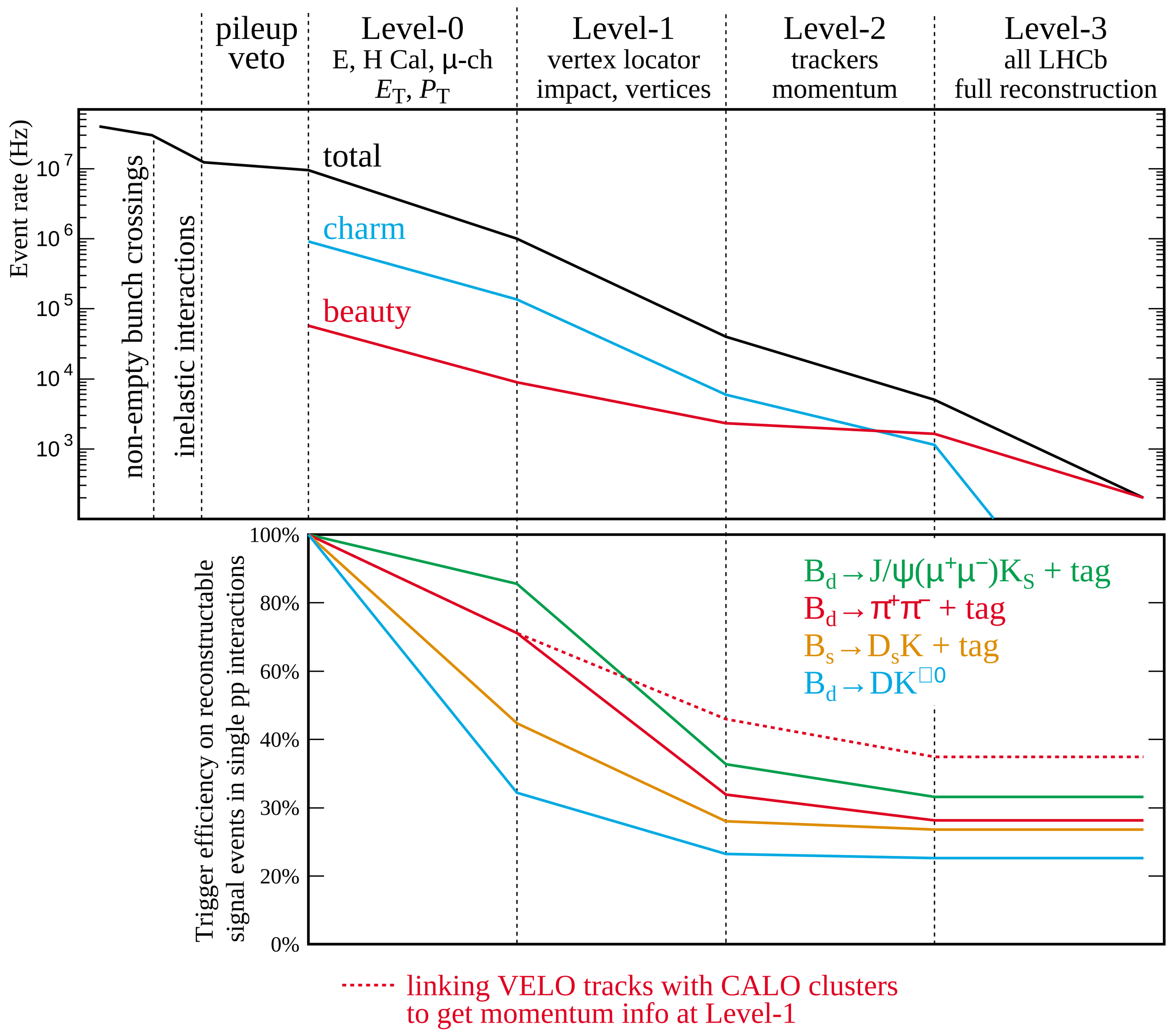


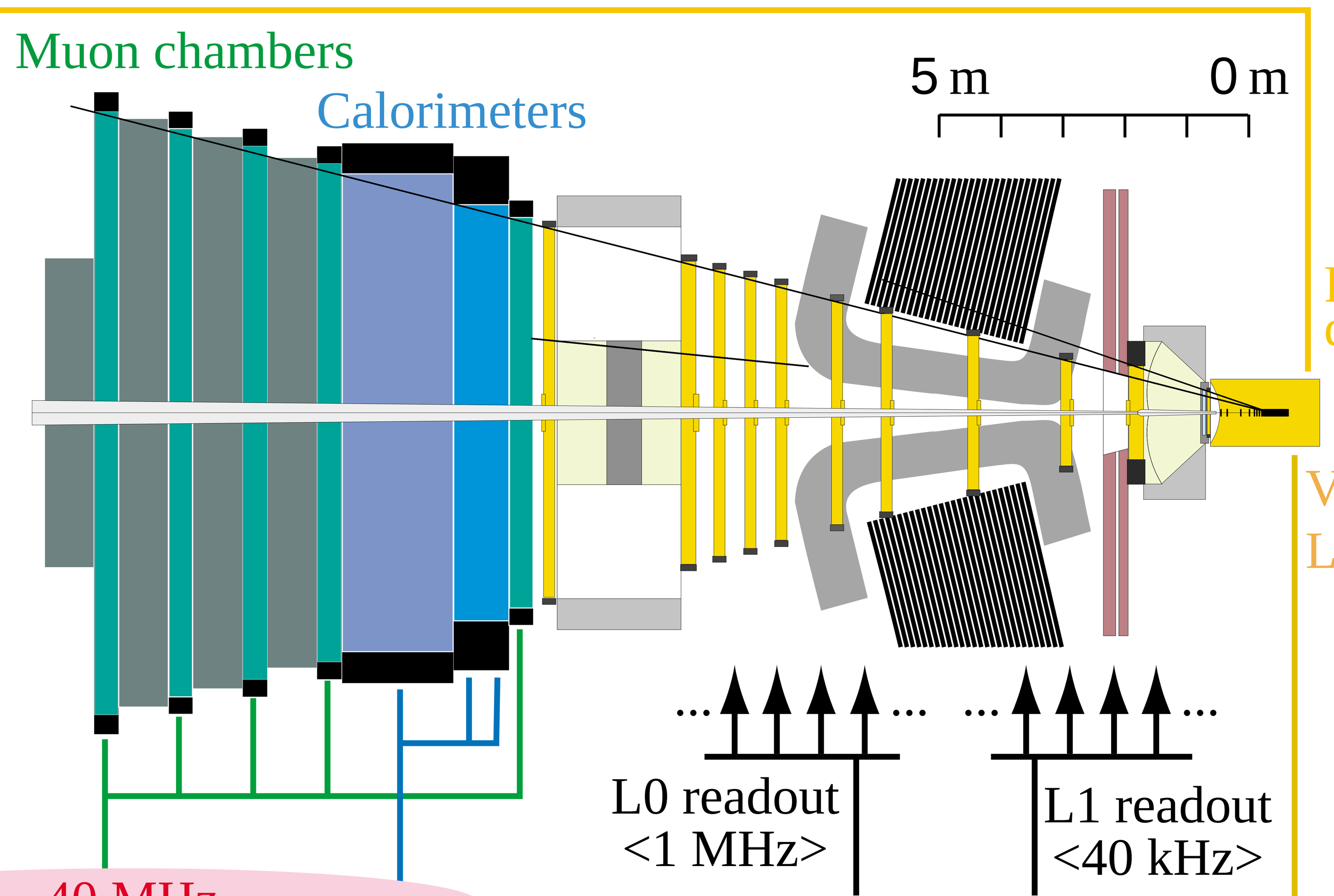


Special features

Reduction balanced between several levels
→ **robustness and flexibility**
Single high-P_T lepton, γ,
and hadron candidates at level 0
Vertex trigger at level 1
→ **good efficiency for both leptonic and hadronic B decay channels**

Summary of trigger performance





40 MHz

3.6 k channels | 26 k channels | 20k channels

Primary vertex candidates | High P_T $\mu^\pm$ candidates | High E_T hadron candidates, $e^\pm$ candidates, γ candidates

Readout Supervisor

<1 MHz>
205 k channels

Level-0 decision unit — Level-0 Yes

latency 4 μs

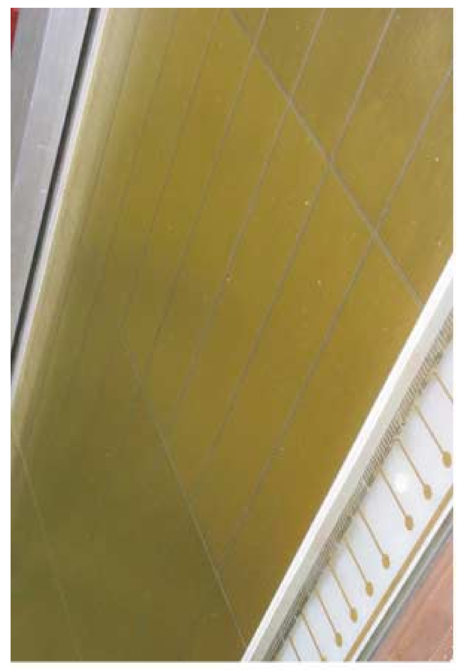
Detached Vertices

Level-0 information

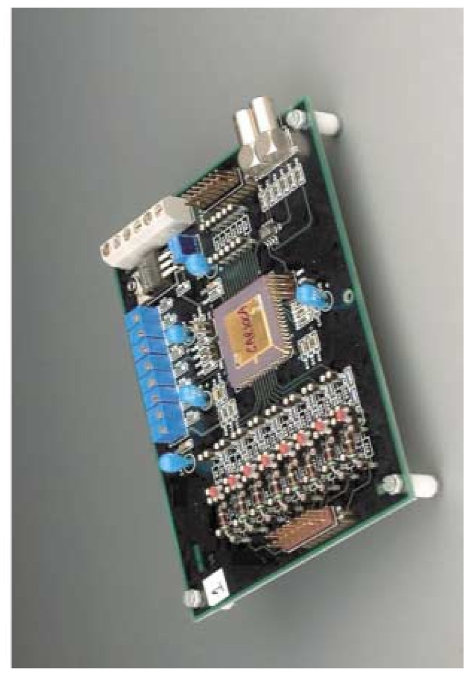
Level-1 Yes

Level-1 decision unit

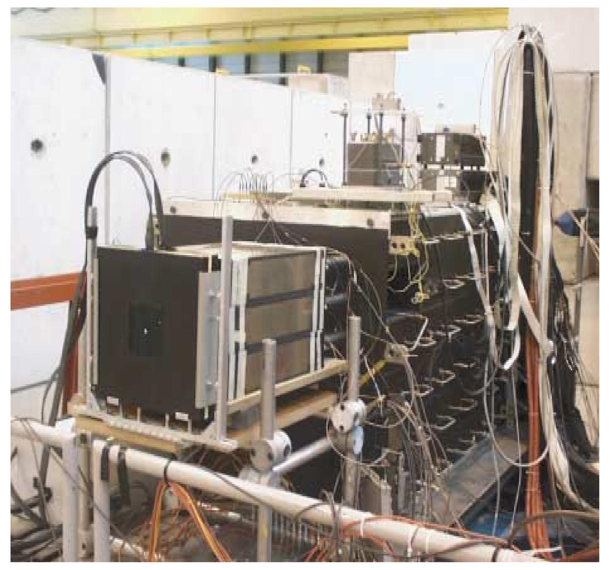
latency 1.7 ms



Muon MWPC prototype



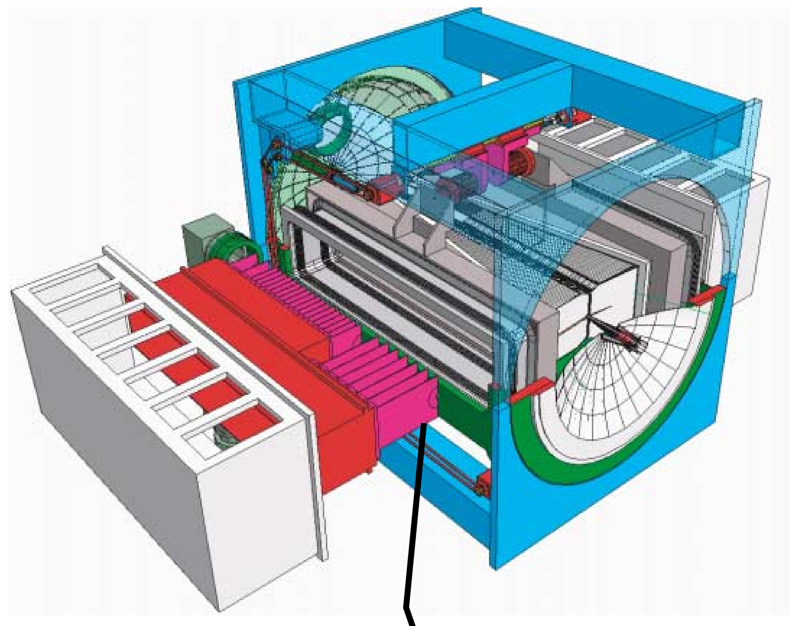
Muon MWPC frontend

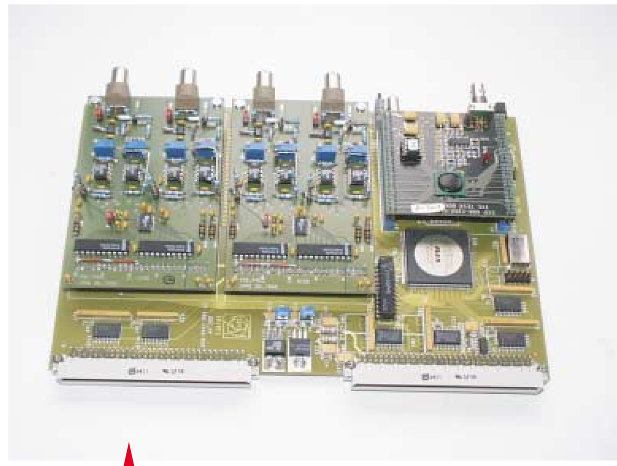


H Cal
E Cal
Level-0 electronics

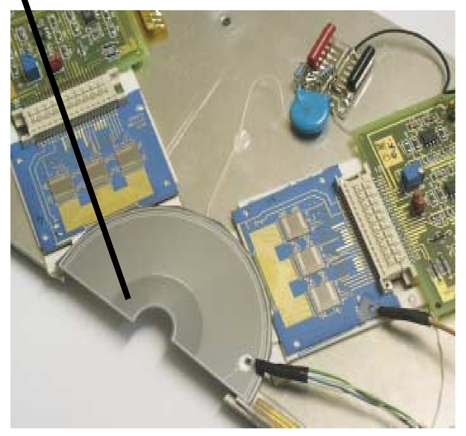
Preshower
E cal
H cal
prototypes

VELO vacuum tank





Off detector Level-1 electronics:
ADC
0 suppression
trigger interface
...



- Si detector
- Readout chip radiation hard 40MHz
- Hybrid

LHCb TRIGGER

O. SCHNEIDER[†] and T. NAKADA[†,§]
for the LHCb collaboration

[†] *Institut de Physique des Hautes Energies, University of Lausanne, Dorigny, CH–1015 Lausanne, Switzerland*
[§] *European organization for nuclear research (CERN), CH–1211 Genève 23, Switerland*
E-mail: Olivier.Schneider@iphe.unil.ch, Tatsuya.Nakada@cern.ch

LHCb is a hadron collider experiment in preparation at CERN, which plans to start taking data at its full potential as soon as the LHC machine becomes operational. It is dedicated to the study of CP violation and other rare phenomena with b hadrons produced copiously in the forward region. The design and realization of an efficient and selective trigger for both fully-hadronic and leptonic B decays in specific channels of interest is one of the major challenges of the experiment. Following a description of the LHCb detector and its environment at LHC, the current design of the trigger scheme is presented and its expected performance is discussed.

1 Introduction

CERN's Large Hadron Collider (LHC) is presently planned to come into operation in 2006 and will provide the LHCb detector with high luminosity proton-proton collisions at $\sqrt{s} = 14$ TeV. The main goal of the LHCb experiment is to accumulate large statistics of B decays in a wide set of specific channels suitable for a detailed study of CP violation. Some of these channels correspond to final states without leptons, like $\mathrm{B_s^0} \to \mathrm{D_s^{\mp}K^{\pm}}$ and $\mathrm{B_d^0} \to \pi^+\pi^-(\pi^0)$, or have visible branching ratios as low as 10^{-7}, like $\mathrm{B_d^0} \to \mathrm{D^0K^{*0}}$. Together with the machine parameters and cross sections given in Table 1, from which one expects of the order of 10^{12} $\mathrm{b\bar{b}}$ pairs produced in a nominal year of 10^7 s, this sets very challenging requirements on the LHCb trigger: being able to maintain high efficiency for the B decay channels of interests while reducing a 40 MHz input rate by several orders of magnitude.

This document gives an overview of the LHCb detector, before presenting and discussing the LHCb trigger scheme and performance. The CP violation reach and B physics programme of LHCb (and of ATLAS and CMS, the two general purpose experiments operating in LHC's central region) are described elsewhere.[1]

initial luminosity ($\mathrm{cm^{-2}s^{-1}}$)	5×10^{32}
design luminosity ($\mathrm{cm^{-2}s^{-1}}$)	1×10^{34}
LHCb luminosity ($\mathrm{cm^{-2}s^{-1}}$)	2×10^{32}
nominal bunch crossing rate	40 MHz
non-empty bunch crossing rate at LHCb	30 MHz
total cross section	100 mb
inelastic cross section	80 mb
non-diffractive inelastic cross section	55 mb
"visible" cross section in LHCb	68 mb
$\mathrm{c\bar{c}}$ production cross section	1.5 mb
$\mathrm{b\bar{b}}$ production cross section	0.5 mb

Table 1: Some LHC parameters and expected cross sections for pp collisions at 14 TeV. The latter suffer from rather large theoretical or extrapolation uncertainties.

2 LHCb detector design

The design of the LHCb detector is driven by several requirements. First, a good acceptance is needed for both b-hadrons in a $\mathrm{b\bar{b}}$ event, providing the ability to tag the production flavour of the decaying B of interest using the other b-hadron. Since the two b-hadrons are produced predominantly at low polar angle, either both forward or both backward, a forward geometry with a single-arm spectrometer is chosen, as shown in the upper part of Figure 1 and described in detail in the Technical Proposal.[2] Polar angles from 300 mrad down to 15 mrad are covered, corresponding to a pseudo-rapidity range from 1.9 to 4.9 and representing a $\mathrm{b\bar{b}}$ acceptance of the same order as the one of a large central detector like ATLAS or CMS. The overall length of the LHCb apparatus (consisting of a vertex detector, a tracking system with a dipole magnet, RICH counters, calorimeters and a muon system) is determined by the size of the already existing experimental hall on the LHC ring assigned to LHCb.

Secondly, an efficient trigger is needed for the fully-hadronic final states of interest like $\mathrm{B^0} \to \pi^+\pi^-$ or $\mathrm{B_s^0} \to \mathrm{D_s^{\mp}K^{\pm}}$. In addition to the traditional lepton triggers, a hadron trigger is therefore foreseen at the first level based on calorimeter information, as well as a displaced vertex trigger at the second level based on vertex detector information. The trigger scheme is discussed in Section 3.

High rates of backgrounds will have to be rejected, even after the lower level triggers. This can be done very effectively by identifying charged particles. Two Ring Imaging Cherenkov (RICH) detectors have been designed.[3] The first one, located just in front of the magnet, will cover polar angles up to 330 mrad and contain two radiators: $\mathrm{C_4F_{10}}$ gas and aerogel. The latter has a

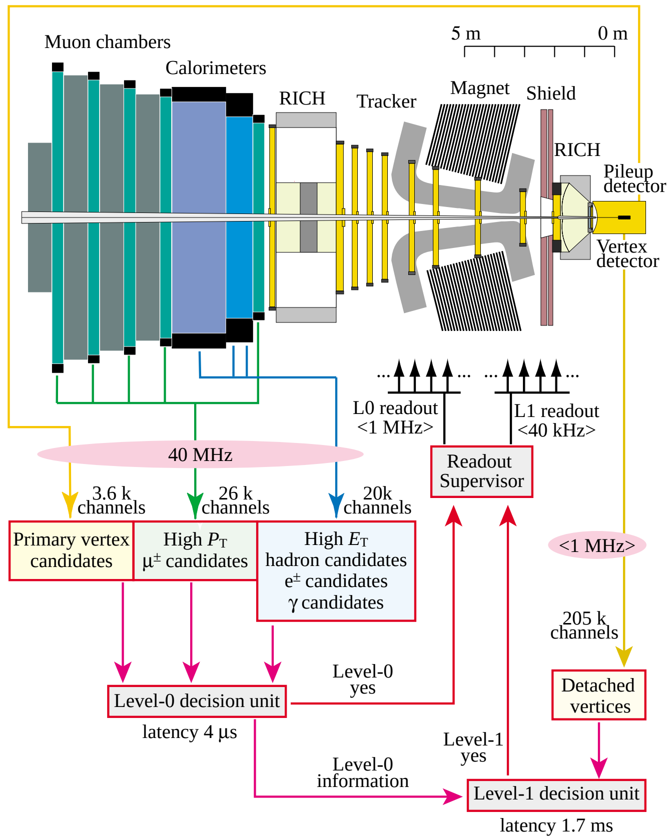


Figure 1: Side view of the LHCb detector (in the non-bending plane) and overall scheme of the first two trigger levels.

higher refractive index, ensuring a good $\mathrm{K}-\pi$ separation down to ~ 1 GeV/c, and thereby efficient flavour tagging with charged kaons from $\mathrm{b} \to \mathrm{c} \to \mathrm{s}$ decays of the other b-hadron. High momentum tracks, which tend to be emitted at low angles, will be identified in front of the calorimeter by a second RICH detector with $\mathrm{CF_4}$ gas. This will extend the $\mathrm{K}-\pi$ separation capability up to ~ 100 GeV/c, covering a large fraction of the momentum spectrum of tracks from two-body B decays.

Other means of reducing the background include a good mass resolution. Because of the high particle density close to the beam axis, the tracking system is split into outer and inner subsystems at a radius of approximately 30 cm. Straw-tude drift chambers with 5 mm cell diameter will be used for the outer tracker, while two different technologies with much finer granularity (typically 250 μm) are still under study for the inner tracker: silicon detectors and micro-strip gas chambers with gaseous electron multipliers. Together with a warm dipole magnet of 4 Tm bending power,[4] this will provide a momentum resolution of $\sigma_p/p = (0.33 \oplus 0.0036\ p/\mathrm{GeV})\%$ and average mass resolutions of 11 and 17 MeV/c^2 for reconstructed $\mathrm{B^0_s} \to \mathrm{D^-_s}\pi^+$ and $\mathrm{B^0} \to \pi^+\pi^-$ decays respectively.

A good proper time resolution is also necessary to resolve the fast $\mathrm{B^0_s} - \mathrm{\bar{B}^0_s}$ oscillations, as needed for the observation of time-dependent asymmetries in $\mathrm{B^0_s}$ decays. This is provided by the vertex detector, which (as most other sub-detectors) has been re-optimized since the Technical Proposal. It now consists of 25 silicon stations (disks) spread on the beam axis around the interaction point; they will be mounted perpendicular to that axis on Roman pots inside the vacuum tank and can be retracted from the beams during injection. The 220 μm thick single-sided silicon detectors will have small r and ϕ strips with an active radius from 8 to 45 mm, and an analogue readout. This device will provide a 40 μm resolution on the interaction point along the beam axis. The proper time resolution for $\mathrm{B^0_s} \to \mathrm{D^-_s}\pi^+$ is estimated to be 43 fs.

The LHCb calorimetric system includes a preshower, an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL).[5] The preshower consists of 2 radiation lengths (X_0) of lead sandwiched between two scintillator planes. The energy resolution of the ECAL (25 X_0 lead-scintillator "shashlik") and HCAL (5.6 interaction lengths of iron with scintillating tiles) are $\sigma_E/E = 10\%/\sqrt{E/\mathrm{GeV}} \oplus 1\%$ and $80\%/\sqrt{E/\mathrm{GeV}} \oplus 10\%$ respectively.

The muon filter, with a total thickness of 21 interactions lengths, is equipped with 5 double-layer stations, divided in a low occupancy region with resistive plate chambers and a high occupancy region (at small radius) with multiwire proportional chambers. This system provides good muon identification with a modest momentum resolution of $\sim 25\%$.

3 Trigger design

The 25 ns bunch spacing at LHC implies that the pipeline of the front-end electronics will have to be clocked at 40 MHz. However, some of the bunch crossings in LHCb will involve empty bunches, reducing the real bunch crossing rate to an effective average value of 30 MHz.

At high luminosities, several proton-proton interactions are expected in a single bunch crossing. However, LHCb is planning to reach its physics goal using only events with single interactions. This is motivated by radiation damage, detector occupancy, pattern recognition, flavour tagging and trigger issues. The detector will therefore be operated at a modest luminosity of 2×10^{32} cm^{-2}s^{-1} (the beams will be defocused at the LHCb interaction point as the LHC machine gradually delivers its design luminosity of 10^{34} cm^{-2}s^{-1} to ATLAS and CMS). Under these conditions, and assuming an inelastic cross section of 80 mb, 30% (10%) of the bunch crossings will have one (more than one) proton-proton interaction.

In addition, a pile-up veto system is foreseen at the earliest trigger level: two dedicated silicon disks located upstream of the vertex detector will be used to reconstruct the longitudinal position of the interaction vertices and reject events with two or more such vertices. After this cut, the event rate is approximately 10 MHz, with more than 90% single interactions. Assuming a $b\bar{b}$ production cross-section of 500 μb, this represents 5.6×10^{11} $b\bar{b}$ pairs per year (10^7 s) available in single interactions.

The high trigger selectivity will be achieved in several steps (trigger levels). The lower level triggers (Levels 0 and 1), represented schematically in Figure 1, will aim at rejecting non-b events. They will merely rely on two main features of the b-hadron decays: long lifetime and significant transverse momentum release due to the high b-quark mass. The higher level triggers (Levels 2 and 3) will consist of software algorithms running on farms of commercial computers, and reject uninteresting $b\bar{b}$ events as well.

The first level of triggering (Level 0), based on calorimeter and muon chamber information only, will reduce the event rate to 1 MHz by requiring a muon, an electron or a hadron with a transverse momentum (p_T) or energy (E_T) above some threshold, typically 1, 2.4 and 3.4 GeV respectively: tracks from b-hadron decays have indeed a harder p_T spectrum than tracks from non-b events. The fractions of the bandwidth attributed to the muon, electron and hadron triggers are chosen to maximize the overall CP reach and will approximately be 20%, 10% and 60% respectively, the rest being allocated to other triggers (high E_T photon, dimuon, ...). The Level-0 decision will take 4 μs during which the data will be kept in the pipeline of the front-end electronics.

The Level-1 trigger achieves a further reduction in rate by a factor of 25. It uses vertex detector information to identify secondary vertices produced by the b decays.[6] Tracks are found from the hits in the silicon and a primary vertex is reconstructed; secondary vertices are then formed with large impact parameter tracks. The Level-1 buffer will reside on off-detector electronics, with a depth allowing for a maximum latency of 1.7 ms. After a Level-1 accept, the zero-suppressed data are transferred to the data acquisition (DAQ) system and the full event buffer made available to the high level software triggers.

Some secondary vertices found at Level 1 are fake, due to low momentum tracks undergoing multiple scattering. The aim of the Level-2 trigger is to reconstruct large impact parameter tracks in the silicon and the first tracking chambers, and use the momentum information to refine the secondary vertex requirement. At Level 3, specific b-hadron decay modes will be reconstructed and selected with loose cuts, using all available information. Approximately 200 events per second will be written to tape at a rate of 20 Mbytes/s.

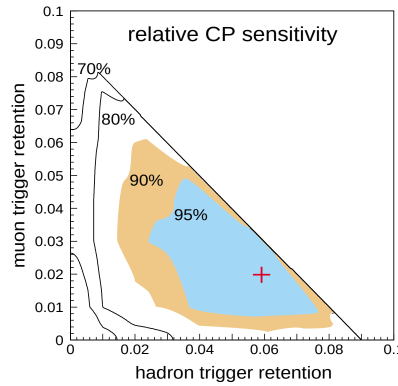


Figure 2: This plot shows how the expected significance of the CP asymmetry measured with $B^0 \to \pi^+\pi^-$ decays, proportional to $\sqrt{\epsilon}(1-2\omega)$ where ϵ is the efficiency and ω the mistag probability, varies as a function of the fractions of events accepted at Level 0 by the muon and the hadron triggers, for a fixed total fraction of 9% (including the electron trigger). In the two shaded areas, the significance exceeds 90% or 95% of its maximal value. The cross indicates the optimal operating point that maximizes the overall CP sensitivity of the experiment.

4 Trigger performance and discussion

As shown in the upper part of Figure 3, the overall triggering scheme is well balanced between the various levels. It is also robust and flexible: the exact operating point can be adjusted to running conditions without significant loss in physics. As an example, Figure 2 shows that, for a fixed output rate, the Level-0 thresholds can be varied in a reasonably wide range without degrading substantially the CP asymmetry measurement in the $B^0 \to \pi^+\pi^-$ channel.

The hadron trigger is essential for the fully-hadronic decay modes. As can be seen from the lower part of Figure 3, the overall trigger efficiencies for useful events in such modes are comparable to the ones obtained for other b-decay channels involving leptons, i.e. around 30%. It should be noted that the Level-0 trigger can not only be fired by a track from a decaying B of interest, but also by a track from the other b hadron; in this case, the charge of the track can be used for tagging if it is identified as a lepton or a kaon. The trigger therefore also ensures a respectable tagging efficiency of 40%, using these simple tags alone. The average tagging purity has been estimated to be approximately 30%.

The results of Figure 3 have been obtained with the Monte Carlo event generator, detector configuration, and event reconstruction used at the time of the Technical Proposal.[2] In particular, the default PYTHIA generator was used and the effect of pattern recognition in the tracking was not included. The latter is under study and still being minimized, until the design of the tracking system is finalized at the end of 2001, when the corresponding Technical Design Reports should be submitted.

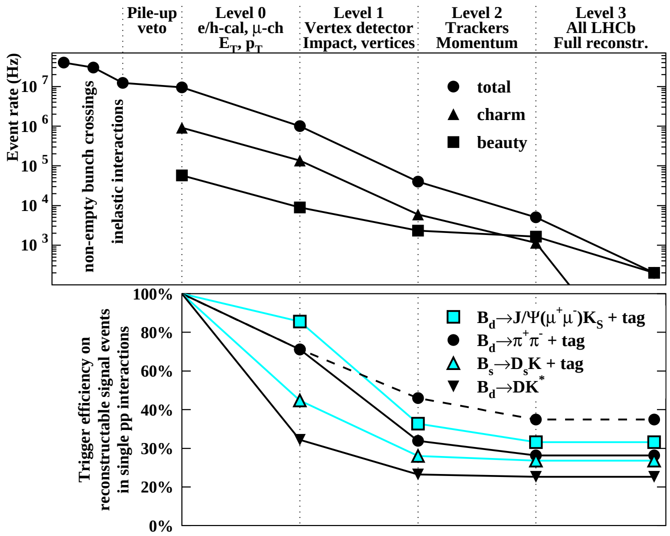


Figure 3: Summary of the LHCb trigger performance, with event rates (top) and efficiencies for signal events usable in the offline analysis (bottom) after each trigger level. The dashed line shows the effect of using Level-0 information for the Level-1 trigger.[6]

In order to improve the description of the events produced at $\sqrt{s} = 14$ TeV, the PYTHIA generator has been tuned[7] to reproduce measurements performed at lower energy hadron colliders (SPS, Tevatron) on non-single diffractive events. The total charged track multiplicity distribution in these events can be better reproduced in the framework of a model for multiple parton-parton interactions which assumes a varying impact parameter between the two colliding protons. Predictions obtained for charged tracks in the LHCb acceptance are shown in Figure 4. Transverse momentum distributions are affected, requiring the need to retune the Level-0 trigger thresholds. Furthermore, the charged track multiplicity now appears to have a much larger tail with a higher average for $b\bar{b}$ events than for minimum bias events, with possible implications on occupancies and triggering. First studies give however confidence that a Level-0 trigger performance close to the one shown in Figure 3 is achievable.

On the other hand, improvements are still possible. For example, the Level-1 trigger efficiency could be boosted significantly if momentum information was available at this stage. This is possible by linking vertex detector tracks found at Level 1 with calorimeter clusters found at Level 0. First studies[6] show that the $B^0_d \to \pi^+\pi^-$ yield can be increased by 50% using this "super Level 1" trigger (see dashed line of Figure 3).

Another improvement, presently under study, can be the implementation of a π^0 trigger at Level 0 to complement the single photon trigger and increase the efficiency for B decay final states containing neutral pions.

The trigger Technical Design Report will be submitted early 2002.

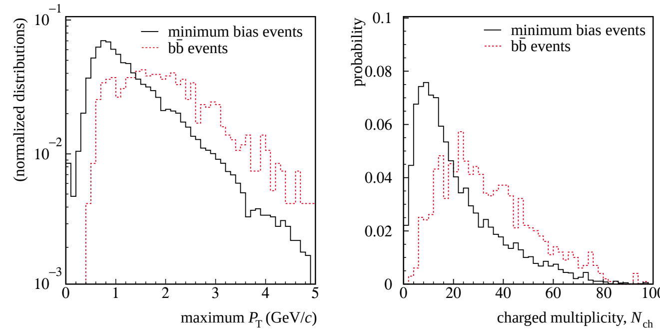


Figure 4: PYTHIA predictions for charged tracks in the LHCb acceptance, using the CTEQ4L parton distribution functions and a tuned model for multiple parton-parton interactions,[7] for minimum bias events (solid histograms) and $b\bar{b}$ events (dotted histograms). Left: maximum transverse momentum. Right: multiplicity.

5 Summary

The LHCb experiment will take data in the forward region at its design luminosity from the start of LHC operation. It will trigger at Level 0 on single lepton, photon and hadron candidates with a minimum transverse energy, and at Level 1 on secondary vertexes. Higher level triggers will select fully reconstructed B decays in many different channels, using the full potential of the LHCb detector, including excellent particle identification. This scheme is robust and flexible. Sufficiently high efficiencies will be achieved to enable LHCb to perform a full programme of precision CP violation and B physics.

Acknowledgments

It is a pleasure to thank the organizers of this wonderful conference. H. Dijkstra is acknowledged for his careful reading of this writeup and useful comments.

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