The Upgrade of the LHCb Detector

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LHCb/CERN
LHCb

- LHCb is a collaboration of more than 700 people from 54 institutes of 15 countries
- LHCb is the dedicated B physics experiment at LHC devoted to precision measurement in CP violation and rare decays
- LHCb seeks to find the evidence of new particles via their interferences in b and c quarks decays
- b/anti-b production at LHC is very large especially in the forward region of the interaction points
- LHCb is a single-arm forward spectrometer
  - 1.9<\eta<4.9
  - \sigma_{bb} \sim 230 \, \mu b in detector coverage
  - Production of B^0, B^+/-, B_s, B_c, b-baryons
  - B's have a large momentum
    - Hadrons with both b and \bar{b} in the acceptance
    - Large displaced vertices
- Present “nominal” luminosity is 2x10^{32} \text{cm}^{-2} \cdot \text{s}^{-1}
  - At L=10^{33} \text{cm}^{-2} \cdot \text{s}^{-1}, 5x10^{12} B-hadrons produced per year (10^7 s)
The LHCb Detector
Introduction

- The present picture we have is very consistent with the Standard model
  - Still there many unanswered questions → New physics

- We may expect that NP will be seen at LHC
  - The first run (5/6 fb⁻¹, until 2015) could already give some hints
  - This is especially true in the heavy flavour sector (LHCb)

- If there are hints of NP after 5/6 fb⁻¹
  - Physics sensitivity is not sufficient to distinguish between different models

- Present operation of LHCb is very satisfactory
  - See the talk from Franz Muheim on Tuesday

- Upgrade done in 2 phases matching the LHC schedule

- Goal of first phase
  - Improve the trigger efficiency on b hadron (factor 2)
  - To accumulate 10 times more statistics (>50fb⁻¹)
  - Be flexible to be ready for the exploration of NP if found
CP asymmetry in $B_s \rightarrow J/\psi \Phi$

- $B_s \rightarrow J/\psi \Phi$ measures the $B_s$ mixing phase $-2\beta_s$ as $B \rightarrow J/\psi K_s$ provides the CPV phase $2\beta$

- $B_s \rightarrow J/\psi \Phi$ is a vector-vector final state
  - Angular analysis required
  - $\Delta \Gamma_s / \Gamma_s$ is a parameter of the fit

- LHCb should get 655k events in 10fb$^{-1}$
  - Projected errors
    - $2\beta_s \sim +/- 0.010$
    - $\Delta \Gamma_s / \Gamma_s \sim 0.005$

  - With 100fb$^{-1}$ errors on $2\beta_s$ is reduced to $+/-0.004$ (Extrapolation – Stat. errors only)
    - May imagine to distinguish among several supersymmetry models
B → s penguins

- $B_s \to \Phi\Phi$ is similar to $B \to \Phi K^0_s$

- Decay is dominated by penguins → very sensitive to NP

- SM predicts the decay phase cancels the mixing phase → this should be a “null measurement”

- $B_s \to \Phi\Phi$ is a vector-vector state
  - angular analysis is more difficult

- Estimated error in CP violating asymmetry
  - $B \to \Phi K^0_s$ for 100 fb$^{-1}$, +/-0.019-0.045 (20000 events)
  - $B_s \to \Phi\Phi$ for 100 fb$^{-1}$, +/-0.017 (0.6M events)
    (Extrapolation – Stat. errors only)

\[ \sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}}) \]

<table>
<thead>
<tr>
<th>Decay</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\to c\bar{c}s$ Word Average</td>
<td>0.67 ± 0.02</td>
</tr>
<tr>
<td>$\phi K^0$ Average</td>
<td>0.44 ± 0.17</td>
</tr>
<tr>
<td>$\eta' K^0$ Average</td>
<td>0.59 ± 0.07</td>
</tr>
<tr>
<td>$K^+ K^- K^0_s$ Average</td>
<td>0.74 ± 0.17</td>
</tr>
<tr>
<td>$\pi^0 K_s^0$ Average</td>
<td>0.57 ± 0.17</td>
</tr>
<tr>
<td>$\rho^0 K_s$ Average</td>
<td>0.54 ± 0.18</td>
</tr>
<tr>
<td>$\omega K_s$ Average</td>
<td>0.45 ± 0.24</td>
</tr>
<tr>
<td>$f_0 K_s$ Average</td>
<td>0.60 ± 0.13</td>
</tr>
<tr>
<td>$f_1 K_s$ Average</td>
<td>0.48 ± 0.53</td>
</tr>
<tr>
<td>$f_2 K_s$ Average</td>
<td>0.22 ± 0.53</td>
</tr>
<tr>
<td>$\pi^0 \pi^0 K_s$ Average</td>
<td>0.52 ± 0.41</td>
</tr>
<tr>
<td>$\phi \pi^- K_s$ Average</td>
<td>0.97 ± 0.22</td>
</tr>
<tr>
<td>$\pi^- \pi^+ K_s$ Average</td>
<td>0.21 ± 0.03</td>
</tr>
<tr>
<td>$K^+ K^- K^0$ Average</td>
<td>0.82 ± 0.07</td>
</tr>
</tbody>
</table>

Not yet a clear picture
Precision is needed
Standard model prediction for BR is precise and small
- $\text{Br}(B_s \rightarrow \mu\mu) = (3.35\pm0.32)\times10^{-9}$

But BR is very sensitive NP
- example of MSSM → goes as $\tan^6\beta$
SM Br will be reached with 10 fb⁻¹
- Br may be measured sooner if NP enhancement
- But certain models may also lead to BR suppression depending on phases
- Rate of \((B_d/B_s \rightarrow \mu\mu)\) is tightly constrained (distinction of SM and MFV)
- Can we hope to see \(B_d \rightarrow \mu\mu\) at the upgraded LHCb?

Buras: hep-ph/060450
Observable: forward-backward asymmetry of the angle between lepton and B in the di-lepton rest frame

Position of zero asymmetry crossing point will be measured by LHCb

LHCb measures 0 to +/-0.22 GeV^2 in 10 fb^{-1}

Other clean theoretical observables can only be extracted with more than 10fb^{-1}

Transverse polarization functions

\[
A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2},
\]

\[
A_T^{(3)} = \frac{|A_{0L}A^*_{1L} - A_{0R}A^*_{1R}|}{\sqrt{|A_0|^2 |A_1|^2}},
\]

\[
A_T^{(4)} = \frac{|A_{0L}A^*_{1L} - A_{0R}A^*_{1R}|}{|A_{0L}A^*_{1L} + A_{0R}A^*_{1R}|}.
\]

0.35 M yield at upgrade 100fb^{-1}
**B_s → Φγ**: Right-handed currents

- **SM predicts no right-handed currents**

\[
\tan \psi \equiv \left| \frac{\mathcal{A}(B_{s} \rightarrow Φ_{R} e^{-\frac{1}{2}}} \right| \text{ is null}
\]

\[
\begin{align*}
\Gamma_{B_{s}^{0} \rightarrow Φ_{R}γ}(t) & \approx |A|^{2} e^{-\frac{1}{2}} \left( \cosh \frac{\Delta \Gamma_{s}}{2} - A^{\Delta} \sinh \frac{\Delta \Gamma_{s}}{2} \right) \\
\Gamma_{\bar{B}_{s}^{0} \rightarrow Φ_{R}γ}(t) & \approx \Gamma_{B_{s}^{0} \rightarrow Φ_{R}γ}(t), \quad \text{Where } A^{\Delta} = \sin 2\psi
\end{align*}
\]

- **Sensitivity to A^Δ**
  (assume \(\Delta \Gamma_{s}/\Gamma_{s} \approx 0.12\))
  - \(\sigma(\sin 2\psi) = 0.22\) (2 fb^{-1})
  - \(\sigma(\sin 2\psi) = 0.02\) (100 fb^{-1})

(Extrapolation – Stat. errors only)
LHCb upgrade : the detector requirements

- The modern heavy quark experiments rely on
  - Favourable physics conditions
    - Essential to produce a large rate of (anti)b hadrons in the apparatus solid angle
  - Vertexing
    - Measure the displaced decay points, reduce background (*)
  - Particle identification
    - Kinematic constraints often do not permit to remove background contributions from other decay modes
  - Triggering
    - Need to select the interesting events with a high efficiency/purity (*)
  - Data acquisition and processing
    - The aim is to collect a large statistics

(*) vital for hadron colliders!

- LHCb was built to fulfil those requirements
- LHCb started to operate in very satisfactory conditions
  - The detector runs as expected
  - The present aim is to
    - consolidate the detector operations,
    - achieve fine calibrations and better understand LHCb
    - And of course : collect as much data as we can!
A flavour of the present LHCb
How can we upgrade?

- The goal is to collect up to 5 / 6 fb\(^{-1}\) during the present LHCb “first run” → 2015
  - We may expect to get first hints for new physics
  - The upgraded LHCb should adapt to new physics

- Upgrade is strongly coupled to the LHC schedule → 2 Phases

  (1) LHC long shutdown in 2015/2016
    - Increase the instantaneous luminosity from \(2 \times 10^{32}\) to \(10^{33} \text{ cm}^{-2} \text{.s}^{-1}\)
    - Complete re-design of the trigger scheme
    - New VELO
    - RICH photon detectors replacement
    - TT & IT replacement
    - New electronics for OT, calorimeter and muon system

(2) Second phase of the upgrade
- Torch / Super-Rich detector
- Better ECAL segmentation?
New Trigger Scheme (I)

- Only 1% of the inelastic cross-section is b production
- Not all the b hadrons are interesting
  - Present trigger is based on
    - L0: fully hardware trigger selecting events, 4μs latency, readout at 1MHz
      - high Pt muons
      - high Et hadrons, photons, electrons
      - Veto on multiple interactions
    - HLT: software trigger
      - L0 confirmation
      - Impact parameter, full tracking, ...
      - Exclusive decays
- Upgrade would consist in reading out the entire detector at 40MHz
  - Full software trigger
- The goal is to increase the current yield by a factor 5 to 10 in dileptonic and hadronic channels
  - Present $D_sK^-$ channels efficiency ~ 25%
    - L0 efficiency ~ 50%
    - HLT 1 / 2: ~ 60% / 85% in $D_sK^-$

Room for improvement especially in Hadronic channels $\rightarrow x2$
At $2 \times 10^{32} \text{ cm}^{-2} \cdot \text{s}^{-1}$ (nominal conditions)
- 30 MHz of crossings
- Most crossings have no interaction
- L0 reduces data to 1MHz
- HLT output is 2kHz → on tape

At $10^{33} \text{ cm}^{-2} \cdot \text{s}^{-1}$
- On average 2.3 interactions/crossings

Software trigger
- 16000 processors in the farm
- $25 \text{ ns} \times 16000 = 0.4 \text{ ms}$ on average to
  - Reduce background
  - Maximize the signal efficiency

Aim is
- $\sim 20 \text{ kHz}$ on tape
- Reduction factor of 100000 on min-bias
- Hadronic trigger efficiency $\sim 50\%$
Electronics and readout completely re-designed to permit readout @ 40MHz
The events are zero-suppressed / packed at the front-end level
The GBT technology is used to send the data from the FE to the readout syst.
The readout boards are common to all the sub-detectors
A throttling mechanism (Calo/Muon/Farm) is implemented to cope with
  • A staged DAQ which cannot handle the full rate
  • Unexpected high occupancies which prevent a full readout
The VErtex LOcator

- Present VELO has to be replaced (radiation)
- Precise measurement of the vertices
  - Aim is pattern recognition for the trigger
- The baseline is VELOPix, based on Medipix/TimePix readout chip
  - 256x256 pixels, 55μm square
  - 3 side buttable chip
  - TSV (Through Silicon Via) → dead side may be reduced to 0.8mm (Medipix3)

- Benefit from the 3D information
  - Less combinatorial for tracking reconstruction
- Very low occupancy of the detector
- But very high data rate (15Gbit/s/chip)
Tracking

- Running at $2 \times 10^{33}$ is not acceptable for the present Outer tracker
  - Too high occupancy
  - Decide to limit the luminosity to $10^{33}$ for phase I of upgrade (2016)

- Still the OT electronics has to be changed to cope with the 40MHz readout
  - First prototypes are being designed

- Two options are still envisaged for the ST (TT and IT)
  1. Si options
     - Keep the existing modules unchanged
       - Need re-equip them with an upgraded electronics
       - Development of a new rad-hard FE chip @ 40MHz
     - Build new modules identical to the existing ones
  2. Fiber option
     - Several layers of scintillating fibers
     - Light collections with SiPM
     - Electronics is out of the acceptance (rad. tolerance)
     - First simulations show equivalent performances as Si
     - Requires important R&D but several labs are interested
Rich (+TOF)

- Rich HPD tied to 1MHz readout → must be replaced
- Baseline candidate is the MA-PMT (Hamamatsu)
  - 8x8 pixels (of 2.0x2.0 mm$^2$)
  - Characterisation of the chip shows good properties
    - Single photon response,
    - Uniformity,
    - Cross-talk,
    - Dark current.
  - Behaviour under magnetic field still to be checked
  - Temperature
- A front-end electronics is being designed
  - Target is
    - no pile-up (25ns)
    - Low consumption
- TOF (Torch)
  - TOF measurement could be coupled to the RICH for PID
  - 1 cm thick quartz plate at z=12m
  - 30ps resolution
  - Probably for the second upgrade phase
Calorimeter and Muon system

- The front-end electronics of the calorimeter to be replaced (40MHz readout)
  - The PMT have to be operated at lower gain
  - The electronics will compensate but need to maintain the same noise as before
    - 2 directions: ASIC and discrete components → prototype being delivered
  - The L0 uses calo information (40MHz)
    - Plan is to keep on providing this to the farm to help software trigger (seeds)

- Radiation tolerance of the calorimeter inner modules
  - 2 modules irradiated at Protvino (Russia) and 2 other in the LHC tunnel

- Muon front-end electronics can basically be kept (already @ 40MHz)
  - The M1 chamber should be removed (background and upgraded L0)
  - The interface to the common readout has most probably to be adapted
  - The muon system should provide information to the throttling mechanism
    - Based on the present L0
Conclusion

- LHCb is being operated in very satisfactory conditions since day 1
- LHCb physics program is largely not affected by the present running conditions
- Physics sensitivity for LHCb gives good chance of seeing NP after $5 \text{ or } 6 \text{ fb}^{-1}$
  - But we need high precision to
    - understand NP
    - Distinguish between different models
- We want a flexible trigger (software) to be able to study any kind of NP signal
- The phase I upgrade is mainly a trigger and readout upgrade
  - Better trigger performances (fully software trigger)
  - Readout @40MHz
  - and a new VELO, a new RICH photo-detection
- The letter of intent should be sent to the LHCC this year
The LHCb detector

Muon System

Calorimeters: PID: e, γ, π₀

RICHES: PID: K, π separation

Trigger Tracker: p for trigger and K_s reco

VELO: primary vertex, impact parameter, displaced vertex

Tracking Stations: p of charged particles

PileUp System

IP