LHCb upgrade

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Detectors and accelerators
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Present LHCb detector

Present LHCb detector conditions
- $\sqrt{s} = 10$-14 TeV
- $\sigma_{bb} = 350$-500 $\mu$b
- $\sigma_{inel} = 80$ mb
- $L = 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
  1 year at nominal lumi: $\sim 2$ fb$^{-1}$

Crucial for B physics
- optimised geometry and choice of luminosity
- trigger efficient in hadronic & leptonic modes
- excellent tracking and vertexing
- excellent particle ID - RICH (2-100 GeV/c)

TRIGGER: hardware - L0 & software - HLT
- L0: 40 MHz $\rightarrow$ 1 MHz (high $p_T$, $\mu,e,n^0,h,\gamma$)
- HLT: 1 MHz $\rightarrow$ 2 kHz (farm of 1800 CPU)

Performance
- mass resolution: 14 MeV ($B_s$)
- time resolution: 40 fs
- IP resolution: 30 $\mu$m
- PV resolution (z): 47 $\mu$m

both B in acceptance
$10^{12}$ bb/year

118-07-2009
LHCb detector status

Installation of all subdetectors finished
LHCb physics program \((10 \text{ fb}^{-1})\) \textit{wrt New Physics searches}

\begin{itemize}
  \item Precise measurement of mixing parameters \(B_s - \bar{B}_s\): \(\Delta m, \Delta \Gamma_s\)

    \(\rightarrow NP: \) mixing phase in \(B_s \rightarrow J/\Psi \phi \) (tree) & \(B_s \rightarrow \varphi \varphi \) (loop)

  \item Precise measurement of \(\gamma\) angle \((tree & loop)\)

    \(\rightarrow NP: \) \(B_s \rightarrow D_s K\) (tree) & \(B_d \rightarrow \pi^+ \pi^-\) (penguin)

  \item CP violation measurements

    \(\rightarrow NP: \) \(B_s \rightarrow \mu \mu\) at SM

    \(\rightarrow NP: \) compare CPV angle in \(\varphi K_s\) & \(J/\Psi K_s\)

  \item Rare decays with \(BR\) down to \(10^{-9}\)

    \(\rightarrow NP: \) Asymmetry \(FB\) of \(B_d \rightarrow K^* \mu \mu\)

    \(\rightarrow NP: \) \(B_s \rightarrow \mu \mu\) at SM

  \item Other New Physics searches

    \(B_d \rightarrow K^* \gamma, B_d \rightarrow K^{*0} \ell^+ \ell^-, B_s \rightarrow \varphi \gamma, b \rightarrow s \ell^+ \ell^-\)

  \item D meson physics

    \(CP, D - \bar{D}\) mixing

    \(+ \) \(B_c\) physics, Lepton Flavour Violation, ...
\end{itemize}
Physics motivation for LHCb upgrade

LHCb upgrade: 100 fb\(^{-1}\) (5 years at \(L=2\times10^{33}\text{cm}^{-2}\text{s}^{-1}\)) 2015/2016

- **LHCb & ATLAS & CMS/ONLY ATLAS & CMS/ONLY LHCb/NO EXPERIMENT** finds New Physics
  → worthwhile to continue exploration of flavour structure of NP / analyze flavour structure of NP for (tiny) deviations

- For many observables 10 fb\(^{-1}\) will not make us reach theoretical limits
  → theoretical progress in B physics + refined lattice calculations
  → New Physics effect may be subtle and need higher statistics to be elucidated

- **(Precise) angle measurements**
  - \(\Phi_d, \Phi_s, \gamma\) (knowledge of \(\gamma\) to a sub-degree level)
  - study nature of New Physics (\(\Phi_s, \gamma\))

- **\(b \rightarrow s\) transitions**
  - \(\sin(2\beta_{\text{eff}})\) down to 0.04 (\(B_d \rightarrow J/\psi K_s, B_d \rightarrow \phi K_s\))
  - very sensitive to NP  

- **\(B_s \rightarrow \phi \phi\)**
  - interesting \(b \rightarrow s\) penguin mode for LHCb
  - \(\beta_{\text{eff}}\) mixing phase in penguins \(\sigma \approx 0.015\) (SM=0)
  - yield (100 fb\(^{-1}\)): 0.3M  
    extrap. from LHCb-2007-130

- **\(B \rightarrow K^* \mu \mu\)**
  - zero for \(A_{FB}(s)\) to \(~2\%\) (but theoretical error: 9%)  
  - yield (100 fb\(^{-1}\)): \(~0.35M\)  
    extrap. from LHCb-2008-041

- **New Physics with \(B_s \rightarrow \mu \mu\)**

- **Lepton Flavour Violation searches in \(\tau \rightarrow \mu \mu \mu\) decays**

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Expected sensitivity for LHCb upgrade (100 fb\(^{-1}\))

<table>
<thead>
<tr>
<th>Observable</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S(B_s \rightarrow \phi \phi))</td>
<td>0.01 – 0.02</td>
</tr>
<tr>
<td>(S(B_d \rightarrow \phi K^0_s))</td>
<td>0.025 – 0.035</td>
</tr>
<tr>
<td>(\phi_s (J/\psi \phi))</td>
<td>0.003</td>
</tr>
<tr>
<td>(\sin(2\beta) (J/\psi \phi K^0_s))</td>
<td>0.003 – 0.010</td>
</tr>
<tr>
<td>(\gamma (B \rightarrow D^{(<em>)} K^{(</em>)}))</td>
<td>(&lt; 1\degree)</td>
</tr>
<tr>
<td>(\gamma (B_s \rightarrow D_s K))</td>
<td>(1 – 2\degree)</td>
</tr>
<tr>
<td>(B(B_s \rightarrow \mu^+ \mu^-))</td>
<td>5 – 10%</td>
</tr>
<tr>
<td>(B(B_d \rightarrow \mu^+ \mu^-))</td>
<td>3\sigma</td>
</tr>
<tr>
<td>(A^{(2)}_{FB} (B \rightarrow K^{*0} \mu^+ \mu^-))</td>
<td>0.05 – 0.06</td>
</tr>
<tr>
<td>(A_{FB} (B_s \rightarrow \phi K^0_s))</td>
<td>0.07 GeV(^2)</td>
</tr>
<tr>
<td>(S(B_s \rightarrow \phi \gamma))</td>
<td>0.016 – 0.025</td>
</tr>
<tr>
<td>(A^{\Delta_{FB}} (B_s \rightarrow \phi \gamma))</td>
<td>0.030 – 0.050</td>
</tr>
<tr>
<td>charm</td>
<td>(x^{c2})</td>
</tr>
<tr>
<td>mixing</td>
<td>(y_d)</td>
</tr>
<tr>
<td>CP</td>
<td>(y_{CP})</td>
</tr>
</tbody>
</table>
Examples of NP with 100 fb⁻¹

- **Precise measurement of \( \Phi_s \)**
  \[ \Phi_s = -2\eta\lambda^2 \ (in \ SM) \]
  New Physics may manifest itself with e.g. \( B_s \to J/\Psi\phi \) through significantly larger value wrt very small SM expectation
  Precise measurement with 100 fb⁻¹, noting that in SM \( \Phi_s \) is very well constrained:
  \[ \Phi_s \ (indirect) = -0.037 \pm 0.002 \]

<table>
<thead>
<tr>
<th>(upgraded-) LHCb</th>
<th>2 fb⁻¹</th>
<th>10 fb⁻¹</th>
<th>100 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical error</td>
<td>0.021</td>
<td>0.009</td>
<td>0.003</td>
</tr>
</tbody>
</table>

(extrapolation from LHCb-2003-119)

Here we must worry about penguins, and their relative effect could be large compared with this precision. Control with \( B_d \to J/\psi\rho \) (Fleischer, Phys.Rev. D60 (1999) 073008)

- **\( B_s \to \phi\phi \)**
  Fully hadronic decay
  Yield (100 fb⁻¹): 0.3M

Time dependent CPV
\( \to \) full angular fits needed \( \to \) statistics

\[ \beta_s^{\text{eff}} \text{ mixing phase in penguins} \] \( \sigma = 0.015 \) \( (SM=0) \)

(extrapolation from LHCb-2007-047)
LHCb upgrade strategy

- Goal: 5 years with $L = 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ ($100 \text{ fb}^{-1}$)

  $\Rightarrow$ 30 MHz of crossing with $\geq 1$ interaction
  (10 MHz for $L = 2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$)

  $\Rightarrow$ <number> of visible interactions / x-ing: $\sim 5$
  ($\sim 1.2$ for $L = 2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$)

Upgrade strategy

- improve $\times 2$ hadron trigger efficiencies
- move L0 to a fully software trigger
- improve resolutions (photon detector, RICH)
  - all detector information to be used in trigger
  - replace front-end electronics of most detectors
  - replace all silicon detectors: VELO, TT, IT
  - replace RICH photon detectors
Trigger & DAQ

Trigger needs for upgrade

- reconstruct all primary vertices per bunch crossing
- measure track impact parameter (IP) to any PV
- measure track $p_T$ with significant IP

Proposal for “upgraded” trigger

Cut on $p_T$ & $IP/track$ simultaneously

→ software trigger on large CPU farm to deal with input rate to 30 MHz
→ need to improve detector granularity to deal with CPU time required for upgraded trigger

**Example**: $B_s \rightarrow \phi \phi$ (after first step of current High Level Trigger)

L = $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
$E_T > 3.5$ GeV $\rightarrow$ efficiency = 22%
Minimum bias retention: 10 kHz

L = $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
$E_T > 2$ GeV $\rightarrow$ efficiency = 45%
Minimum bias retention: 28 kHz

MC studies started
Vertex detector

Needs for upgrade
- radiation hard solutions
  flux \((100 \text{ fb}^{-1}) : 1.4 \times 10^{16} \text{n}_{\text{eq}} \text{ cm}^{-2}\)
- lower occupancy
- improved pattern recognition

Design optimum detector

→ **Pixel-based system**
  
  Two geometries are studied:
  - rectangular pixel cells \((50 \times 400 \ \mu \text{m}^2)\), readout with ASIC based on FPIX2
  - square pixel cells \((50 \times 50 \ \mu \text{m}^2)\), readout with ASIC based on TIMEPIX / MEDIPIX

→ **Pixel system offers advantages**
  - better resistance to radiation
  - noise immunity
  - better ghost reduction

Under study
- radiation hardness
- sensor & electronic thinning
- cooling \((CVD \ Diamond?)\)
- new geometry \((smaller \ radius?)\)
- optimisation of RF foil design \((towards \ minimization \ of \ the \ material \ in \ front \ of \ the \ first \ position \ measurement?)\)
Tracking system

- Higher luminosity has stronger effect on occupancy & ghosts in tracking system
  - especially in Outer Tracker (OT) → gas technique used
- Increase area covered by Inner Tracker (silicon)
- Request for 40 MHz readout → change design of IT
  - new sensor, new FEE chip, ...
- Material reduction (if possible)
  - crucial for momentum resolution & occupancy

NEW POSSIBILITY FOR TRACKING

FIBER TRACKER WITH MIXED FIBER DIMENSIONS
- Inner Tracker: 250 µm, Outer Tracker: 700-1000 µm
- readout with SiPM and/or conventional MAPMT

ADVANTAGES
- simplified services configuration: no cables, no cooling, thinner frames, FEE outside → less material budget
- good timing performance
- increase granularity in x (good spatial resolution)

Possible problems (fibers)
- SiPM readout and its optimisation
- radiation
- mechanics

OTHER POSSIBILITY - SILICON STRIPS
- enlarge IT - remove inner section of OT & increase IT
- lower tracking system occupancy
- lower material (when possible)
RICH / TORCH

RICH wrt upgrade
- Maintain RICH 1 & 2
- New possibility replacing aerogel in RICH 1 with TORCH

- In any case NEW PHOTO SENSORS - two options:
  - new HPD (needs R&D to study ion feedback rate)
  - MAPMT (Multi-Anode Photomultiplier Tubes)
  
  both options with new independent chip readout

TORCH - combination of TOF & RiCH
- quartz plane at the entrance of calorimeters
  - TOF performance at 40ps level
  - MicroChannel Plate PM
  - multianode readout

- idea is to measure time and position of Cherenkov $\gamma$'s
  - focusing system needed

- A lot of R&D needed
  (quartz plane mechanics, aging of MCP, electronics etc.)

- project independent of RICH layout

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EM Calorimeter

- At $2 \times 10^{33}$ worst place has 2.5 Mrad/year
  → projected useful life is only 2 years
  → no data for higher doses (up to factor 5)

- Need replacement with radiation hard technology

- Useful would be increased segmentation in inner part
  → dense detection medium material: PbWO$_4$

ELECTRONICS

- FEE readout already at 40MHz
- need to lower PM gain ($\times 5$)
- need to increase preamplifier sensitivity
- need to reduce noise
Muon system

● Major part of the muon detector can operate at $2 \times 10^{33}$ for 5 years
  → FE electronics is already at 40 MHz

● Upgrade of M1 station is not required
  → it will likely be removed
  → background / updated L0

● Ageing tolerable up to 100 fb$^{-1}$
  → possible exception of region M2R1
  → possibility of replacement of the inner parts with large area
    GEM ($70 \times 30 \text{ cm}^2$) or with MWPC

● Transition to a fully 3D muon projective readout
  → could reduce fake associations

Limitations of present design at higher luminosities
● dead time caused by high rate in inner regions
● aging due to radiation in inner regions

Effects evaluated with first data
Conclusions

- LHCb installed and ready for data taking
  - initial plan: collect 10 fb\(^{-1}\) in first 5 years

- For upgrade leading to a factor of ≥10 improvement in sensitivity
  - broader scope of NP exploration

- LHCb upgrade foreseen for 2015/16
  - schedule coupled with LHC long shut-down planned for ~2014
  - luminosity increased to 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}
  - expected 100 fb\(^{-1}\) after 5 years of data taking

- Main challenges for higher luminosity have been identified
  - trigger & detector simulations have been started
  - R&D on subdetector projects is under way