LHCb status report

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on behalf of the LHCb collaboration

University of Bristol

4 December 2013
Outline

1. LHCb in LS1
2. Physics@LHCb
3. LHCb Upgrade
4. Conclusions
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1. LHCb in LS1
2. Physics@LHCb
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The LHCb detector
LHCb in a nutshell

**TRACKING**

\[ \Delta p/p = 0.4 - 0.6\% \text{ at 5-100 GeV} \]


**PID**

\[ \epsilon(K \rightarrow K) \sim 95\% \quad \epsilon(\pi \rightarrow K) \sim 5\% \]


**CALO**

\[ \sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\% - \text{ECAL} \]
\[ \sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\% - \text{HCAL} \]


**MUON**

\[ \epsilon(\mu \rightarrow \mu) \sim 97\% \quad \epsilon(\pi \rightarrow \mu) \sim 1 - 3\% \]

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LS1 Status

- LS1 program achieved so far:
  - Significant consolidation of infrastructure: powering, cooling, gas.
  - Maintenance, repair and consolidation work for MUON, OT, IT and TT.
  - Two months delay in magnet consolidation because of procurement and technical difficulties - work ongoing.
  - 610 IMPACT work packages.
  - 350 visits, 4050 visitors (w-o open days).

- Program for 2014:
  - Exchange of part of the RICH1 and RICH2 HPD.
  - ECAL monitoring system exchange.
  - Continuation of MUON consolidation.
  - Reinstallation of the vacuum chamber with lighter supports foreseen for June.

- Conclusion:
  - The work is progressing as expected.
  - Expected to be completed in 2014 as scheduled.
Deferred trigger in 2012

- Software trigger performed in 2 steps: HLT1 and HLT2.
- HLT2 processes only events passing HLT1: it has a lower input rate and can run more time consuming code.
- So far HLT1 and HLT2 run in a single process.
Complete separate the HLT1 and HLT2 steps in 2 different processes.

Allows fully deferring HLT2 and perform online detector alignment/calibration before running it.
Computing news

- Re-stripping of 2011 and 2012 data
  - Bug fixes and new selection criteria added.
  - One more round foreseen for early 2014.

- Computing model updated and new document released with the other experiments.
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LHCb physics output

161 papers in total.

Talks at conferences

- 2013
- 2012
- 2011
- 2010
## Recent LHCb papers

<table>
<thead>
<tr>
<th>Title</th>
<th>arXiv:1309.6534</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of $D^0 - \bar{D}^0$ mixing parameters and search for CP violation using $D^0 \to K^+ \pi^-$ decays</td>
<td></td>
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<tr>
<td>Observation of $\bar{B}^{0}_{(s)} \to J/\psi f_1 (1285)$ decays and measurement of the $f_1 (1285)$ mixing angle</td>
<td>arXiv:1310.2145</td>
</tr>
<tr>
<td>Search for the decay $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$</td>
<td>arXiv:1310.2535</td>
</tr>
<tr>
<td>Search for the doubly charmed baryon $\Xi^{+}_{cc}$</td>
<td>arXiv:1310.2538</td>
</tr>
<tr>
<td>Measurement of CP violation in the phase space of $B^\pm \to K^+ K^- \pi^\pm$ and $B^\pm \to \pi^+ \pi^- \pi^\pm$ decays</td>
<td>arXiv:1310.4740</td>
</tr>
<tr>
<td>Measurements of indirect CP asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays</td>
<td>arXiv:1310.7201</td>
</tr>
<tr>
<td>Search for CP violation in the decay $D^+ \to \pi^- \pi^+ \pi^+$</td>
<td>arXiv:1310.7953</td>
</tr>
<tr>
<td>Study of forward Z+jet production in pp collisions at $\sqrt{s} = 7$ TeV</td>
<td>arXiv:1310.8197</td>
</tr>
<tr>
<td>Studies of beauty baryon decays to $D^0 p h^-$ and $\Lambda_c^+ h^-$ final states</td>
<td>arXiv:1311.4823</td>
</tr>
</tbody>
</table>
Measurement of $D^0 - \bar{D}^0$ mixing parameters ...

Exploit the interference between mixing and doubly-Cabibbo suppressed decay amplitudes.

Assuming the mixing parameters $|x|, |y| \ll 1$ and no CP violation:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2$$

where $x'$ and $y'$ are a linear combination of $x$ and $y$. 
Measurement of $D^0 - \bar{D}^0$ mixing parameters ...

Most systematics cancel in the ratio, remaining accounted for in the time dependent fit.

- $0.75 < |q/p| < 1.23$ at 68.3% confidence level.
- Most precise determination from a single experiment.
- No evidence of CP violation found.
Impact of LHCb results on $D^0$ mixing

HFAG average before LHCb results

HFAG average after LHCb results
Search for CP violation in the decay $D^+ \rightarrow \pi^- \pi^+ \pi^+$

- 3-body decays have rich resonance structures with interfering amplitudes modulated by strong-phase variations across the phase-space.
- Search of localized asymmetries can provide information on CPV.
- Study the Cabibbo suppressed $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay.
- Use $D^-_s \rightarrow \pi^- \pi^+ \pi^+$ as control channel.

**Binned method**

Measure the significance $S^{i}_{CP}$ of the difference of $D^+$ and $D^-$ in bins of the Dalitz plot.

**Unbinned method**

kNN nearest neighbor to compare $D^+$ and $D^-$ Dalitz plot distributions.

- Data selection common to both methods.
- Analysis carried out on 1 fb$^{-1}$ data.
Search for CP violation in the decay $D^+ \rightarrow \pi^- \pi^+ \pi^+$

- In absence of localized asymmetries $S_{CP}$ follows a Gaussian distribution.
- CPV can be detected as a deviation.
- All results show statistical agreement between the $D^+$ and $D^-$ samples.

- $k$NN method applied with 2 possible region definitions.
- The p-values for the CPV hypothesis are all above 20% consistent with no CP asymmetry.
Measurement of CPV in the phase space of $B^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm} \ldots$

- $B^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}$
- $B^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$

- $1.0 \text{ fb}^{-1}$ from 2011.
- $N(\pi\pi\pi) = 4904 \pm 148$ $A_{\text{raw}} = 0.124 \pm 0.020$
- $N(KK\pi) = 1870 \pm 133$ $A_{\text{raw}} = -0.143 \pm 0.040$
- $A_{CP} = A_{\text{raw}} - A_{D} - A_{P}$
- $A_{P}(B^{\pm})$ measured from $B^{\pm} \rightarrow J/\psi K^{\pm}$
- $A_{D}$ previously measured by LHCb: PLB713 (2012) 186

$$A_{CP}(\pi\pi\pi) = 0.117 \pm 0.021(\text{stat}) \pm 0.009(\text{sys}) \pm 0.007(J/\psi K) 4.9\sigma$$
$$A_{CP}(KK\pi) = -0.141 \pm 0.040(\text{stat}) \pm 0.018(\text{sys}) \pm 0.007(J/\psi K) 3.2\sigma$$
Measurement of CPV in the phase space of $B^\pm \rightarrow K^+K^-\pi^\pm$ ...

- $s\bar{s}$ resonant contribution strongly suppressed for $B^\pm \rightarrow K^+K^-\pi^\pm$.
- Asymmetries not uniformly distributed.
- A very large negative asymmetry is localized in the low $K^+K^-$ invariant mass region: $m_{K^+K^-}^2 < 1.5\text{ GeV}^2/c^4$.
- A large positive asymmetry is measured for $m_{\pi\pi}^2 \text{low} < 0.4\text{ GeV}^2/c^4$ $m_{\pi\pi}^2 \text{high} > 15\text{ GeV}^2/c^4$:

$$A_{CP}(\pi\pi\pi \text{ local}) = 0.584 \pm 0.082(\text{stat}) \pm 0.027(\text{sys}) \pm 0.007(J/\psi K)$$

$$A_{CP}(KK\pi \text{ local}) = -0.648 \pm 0.070(\text{stat}) \pm 0.013(\text{sys}) \pm 0.007(J/\psi K)$$

- Evidence of large direct CP violation observed.
- Interference between intermediate states does not seem to justify the results for $B^\pm \rightarrow K^+K^-\pi^\pm$. 

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Observation of $\bar{B}^0_{(s)} \rightarrow J/\psi f_1(1285)$ ...

Large sample of $B^0_{(s)} \rightarrow J/\psi \pi \pi \pi \pi$ identified in 3 fb$^{-1}$ data.

$N_{\bar{B}^0} = 1197 \pm 41$

$N_{B^0} = 836 \pm 39$

- Clear signals at 1285 MeV/c$^2$ with structure at higher mass.
- Angular distribution of $J/\psi$ studied to probe the spin of the four-pion state

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Observation of $\bar{B}^0_s \rightarrow J/\psi f_1(1285)$... 

$N_{\bar{B}^0_s} = 110.2 \pm 15.0 \, 7.6 \sigma$  
$N_{B^0} = 49.2 \pm 29.5 \, 5.4 \sigma$ 

First observation of $f_1(1285)$ in b-hadron decays.

\[
\frac{\mathcal{B}(B^0_s \rightarrow J/\psi f_1(1285))}{\mathcal{B}(B^0_s \rightarrow J/\psi \pi^+\pi^-)} = (3.82 \pm 0.52^{+0.29}_{-0.32})% \\
\frac{\mathcal{B}(B^0 \rightarrow J/\psi f_1(1285))}{\mathcal{B}(B^0 \rightarrow J/\psi \pi^+\pi^-)} = (2.32 \pm 0.54 \pm 0.11)% \\
\frac{\mathcal{B}(\bar{B}^0 \rightarrow J/\psi f_1(1285))}{\mathcal{B}(\bar{B}^0 \rightarrow J/\psi f_1(1285))} = (11.6 \pm 3.1^{+0.7}_{-0.8})% 
\]

Assuming $f_1(1285)$ is a mixed $q \bar{q}$ state the mixing angle $\Phi$ is measured:

\[
|f_1(1285)\rangle = \cos \Phi \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}} - \sin \Phi |s\bar{s}\rangle \\
\Phi = \pm (24.0^{+3.1+0.6}_{-2.6-0.8})^\circ
\]
Studies of beauty baryon decays...

- Study $\Lambda_c^+\pi^-$, $\Lambda_c^+K^-$, $D^0p\pi^-$, and $D^0pK^-$ spectra.
- Measure yields of $\Xi_b$ and $\Lambda_b$ both in Cabibbo favored and Cabibbo suppressed channels:
Studies of beauty baryon decays...

- Efficiency calculated separately for selection, PID and phase-space.
- PID efficiency is data driven as much as possible, remaining components measured from simulation

$D^0 p\pi$ Dalitz plots

- Non zero spin particles involved in initial and final states.
- Angular corrections found to be negligible.
First observation of $\Xi_b \rightarrow D^0 p K^-$ and of $\Lambda_b \rightarrow D^0 p K^-$

$m_{\Xi_b} - m_{\Lambda_b} = 174.8 \pm 2.4 \pm 0.5 \text{ MeV}/c^2$

$m_{\Xi_b} = 5794.3 \pm 2.4 \pm 0.7 \text{ MeV}/c^2$
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Why an upgrade?

Expected precisions on several Heavy Flavour related quantities from ECFA workshop, Aix-les-Bain Octobr 2013.

$q_0^2$ from $B \to K^* l^+ l^-$

$\Phi_s$ from $B^0_s \to \Phi \Phi$ and $B^0_s \to J/\psi \Phi$

$\gamma$ from tree decays

$A_\Gamma$ from $D^0 \to h^+ h^-$

LHCb upgrade more sensitive than competition for key flavour physics observables
LHCb Upgrade

- Luminosity: $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
- 40 MHz readout with software base trigger running on a PC farm.
LHCb Upgrade TDR’s

LHCb Upgrade TDR 14
28 November 2013

CERN/LHCC 2013-022

Particle Identification

Technical Design Report
Overall structure still based on 2 detectors

Remove aerogel from RICH 1 $\Rightarrow$ reduced maximum ring size and increase of Cherenkov photons by about 15%.

Focal length of spherical mirrors increased by $a \approx \sqrt{2} \Rightarrow$ halved occupancy and reduced aberration.

Distance between spherical and plane mirrors also increased $\Rightarrow$ further increase in Cherenkov photons.

Tilt of spherical mirrors reduced $\Rightarrow$ reduced aberration.
RICH PD & performance

- Baseline R11265 Hamamatsu MaPMT.
- $8 \times 8$ pixel, 26.2 mm square device.

- $3.9 \times 10^{32}$ cm$^{-2}$s$^{-1}$ current geometry
- $10.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$ current geometry
- $20.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$ current geometry
- $20.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$ updated geometry
Calorimeter

- Maintain the same photo-multipliers: reduce gain by factor 5 to increase their lifetime.
- Change in electronics to compensate the reduced gain.
- Degradation with radiation will require replacement of the innermost part of ECAL.

- Remove SPD and PS.
- Pile-up
- $\implies$ change in reconstruction.

**Photon efficiency for various luminosities**

![Graph showing photon efficiency for various luminosities]
New off-detector electronics with 40 MHz readout.
Removal of station M1.
Additional shielding around the beam pipe in front of M2.
Change in identification algorithm needed to recover increased misidentification.

**μ** id. efficiency

<table>
<thead>
<tr>
<th>p (MeV/c)</th>
<th>0</th>
<th>20000</th>
<th>40000</th>
<th>60000</th>
</tr>
</thead>
<tbody>
<tr>
<td>efficiency</td>
<td>1</td>
<td>0.95</td>
<td>0.9</td>
<td>0.85</td>
</tr>
</tbody>
</table>

MuonID efficiency at $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, $\sqrt{s} = 14$ TeV

- 2012 conditions: $4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$, 50 ns, $\sqrt{s} = 8$ TeV
- Upgrade conditions: $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, 25 ns, $\sqrt{s} = 14$ TeV
- Upgrade conditions and DLL$\mu > -4$

**μ** misidenticalation

<table>
<thead>
<tr>
<th>Pion MisID Probability (%)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>p (MeV/c)</td>
<td>0</td>
<td>20000</td>
<td>40000</td>
<td>60000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 2012 IsMuon
- $L=2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ IsMuon
- $L=2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ IsMuon & DLL$\mu > -4$
VELO requirements

Physics performance
- Fast and robust reconstruction with excellent IP resolution at $20.0 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$.
- First measured point as close as possible to interaction point: $\Rightarrow$ as close to the beam as $\pm 5.1$ mm.
- Material in acceptance kept at minimum.
- Geometric acceptance $> 99\%$ for track within $\pm 2\sigma_{\text{lumi}} = \pm 126$ mm.

Sensors
- Hottest sensor exposed to fluence of $8 \times 10^{15.1} \text{MeV} \text{n}_{\text{eq}} \text{cm}^{-2}$ after 50 fb$^{-1}$.
- Must be able to withstand 1000 V.
- Will be kept at $<-20$ °C.

ASIC
- Output rate up to 15.1 Gbit/s.
- Power consumption $\leq 3$ W.
VELO performance: pattern recognition

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ events at $\mathcal{L} = 20.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$.
- Improved efficiency and ghost rate compared to current VELO.
- Flatter efficiency over $p$, $p_T$, $\eta$, $\phi$...
- Comparison between current (black) and upgraded (red).

**Efficiency vs. $p_T$**

- LHCb simulation

**Efficiency vs. $\eta$**

- LHCb simulation

**Efficiency vs. $\phi$**

- LHCb simulation
**VELO performance: primary vertex and IP**

- $B^0 \rightarrow K^*\mu^+\mu^-$ events at $\mathcal{L} = 20.0 \times 10^{32}$ cm$^{-2}$s$^{-1}$.
- PV and IP resolution after full reconstruction.
- Intercept of IP resolution vs $1/p_T$ similar for current (black) and upgraded (red). Slope reduced significantly.

### PV resolution in X

<table>
<thead>
<tr>
<th>Number of tracks</th>
<th>Average resolution [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

LHCb simulation

### IP resolution

<table>
<thead>
<tr>
<th>$1/p_T$ [GeV$^{-1}$c]</th>
<th>IP$_{3D}$ resolution [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
</tr>
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</table>

LHCb simulation
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Conclusions

- LHCb continues to produce a wealth of high-quality physics results.
- Full dataset of 3 fb$^{-1}$ not yet fully exploited.
- At the same time work is in progress to prepare for Run 2.
- VELO and PID TDR submitted to LHCC: major milestones on upgrade for achieved.