Physics highlights from LHCb

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Outline

- The LHCb detector and running conditions
- Selected physics highlights
  
  Focus on current measurements from LHCb: based on 3 fb⁻¹ (2011&12) pp collision data at 7 & 8 TeV CM energy.
  
  • Parameters of the CKM matrix
  • Rare B decays
  • Studies of CPV in the Bₛ system
  • Mixing and CP violation in charm
  • Other highlights (pentaquarks).

- Summary and Outlook
LHCb- forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b \bar{b}$ cross-section = $284 \pm 20 \pm 49 \, \mu b$ at $\sqrt{s} = 7 \, \text{TeV}$  
- At $\sqrt{s} = 13 \, \text{TeV}$: $518 \pm 2 \pm 53 \, \mu b$ (EPS 2015)
- $\sim 100,000 \, b \bar{b}$ pairs produced/second ($10^4 \times B$ factories)

$10 \text{–} 300 \text{ mrad}$
A fish-eye view
LHCb data taking

- Nominal luminosity = $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ (50 times less than ATLAS/CMS) : however, LHCb has learned to run at >2 times this
  - 37 pb$^{-1}$ @ 7 TeV collected in 2010
  - 1 fb$^{-1}$ @ 7 TeV in 2011
  - 2 fb$^{-1}$ @ 8 TeV recorded in 2012

2015 at 13 TeV!!
Selected physics highlights

- Parameters of the CKM matrix

- Studies of CPV in the $B_s$ system

- CP violation in charm

- Rare B decays

- Pentaquarks
Quark mixing and CKM matrix

- In the SM charge $-1/3$ quarks ($d, s, b$) are mixed
- Mixing described by CKM matrix

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
$$

- 6 unitarity conditions of CKM matrix, 2 of which give triangles which do not have a side much shorter than the other two:

$$(V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td}) = 0$$

$$(V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb}) = 0$$
Unitarity triangle history: CKM fitter

- The CKM describes all the flavour-changing processes in the SM
- Amazing progress in the last 20 years; the SM remains intact, but still a whole lot still to learn

Measurement of angle $\beta$

- Interference between $B^0$ decay to $J/\psi K^0_s$ directly and via $B^0 \overline{B^0}$ oscillation gives rise to a CP violating phase

$$\phi = \phi_{\text{Mixing}} - 2 \phi_{\text{Decay}} = 2\beta$$
Spectacular results from $e^+e^-$ B factories on CP violation

Large CP violation effects: $\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_{S/L}$

**Babar**  
PRD 79 (2009) 072009

**Belle**  
PRL 108 (2012) 171802
LHCb now well into the game …

\[ \sin(2\beta) \text{ from } B^0 \rightarrow \jpsi K^0_S \]

\[
A_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(B^0(t) \rightarrow J/\psi K^0_S) - \Gamma(B^0(t) \rightarrow J/\psi K^0_S)}{\Gamma(B^0(t) \rightarrow J/\psi K^0_S) + \Gamma(B^0(t) \rightarrow J/\psi K^0_S)} = S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).
\]

\[
S_{J/\psi K^0_S} = 0.731 \pm 0.035 \text{ (stat)} \pm 0.020 \text{ (syst)}
\]

\[
C_{J/\psi K^0_S} = 0.0308 \pm 0.032 \text{ (stat)} \pm 0.005 \text{ (syst)}
\]

World average from (HFAG) all modes:

\[ \sin(2\beta) = 0.691 \pm 0.0170 \]

World average from \(B^0 \rightarrow \jpsi K^0_S\) (EPS 2015):

\[ \sin(2\beta) = 0.748 \pm 0.030 - 0.032 \]
... and $B_{(s)}$ mixing

$$\frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow B^0)}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow B^0)}$$

$\Delta m_d = 0.5156 \pm 0.0051 \pm 0.0033 \text{ ps}^{-1}$

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}$


J. Phys. 15 (2013) 053021
A measurement of $\gamma$ from $B^\pm \to DK^\pm$ and $D\pi^\pm$

- Four methods, comprising 14 $B^\pm$ decays included in a combined fit

- $B^\pm \to DK^\pm$, $D \to K_s^0 \pi^\pm \pi^\mp$ and $D \to K_s^0 K^\pm K^\mp$ "GGSZ"
  
  JHEP 10 (2014) 097

- $B^\pm \to D\pi^\pm$, $D \to \pi^\pm K^\mp \pi^\pm \pi^\mp$ and $D \to K^\pm \pi^\mp \pi^\pm \pi^\mp$ "K3\pi";
  
  PLB 712 (2012) 203
  

- $B^\pm \to D\pi^\pm$, $D \to \pi^\pm K^\mp$ and $D \to K^\pm \pi^\mp$ "ADS"
  

- $B^\pm \to D\pi^\pm$, $D \to K^\pm K^\mp$ and $D \to \pi^\pm \pi^\mp$ "GLW"

- Two paths to the same final state via $D^0$ and $\bar{D}^0$ → interference sensitive to gamma
**B^± → DK^± and B^± → Dπ^± ADS & GLW modes**

**ADS modes**

\[ A_{ADS}(K) = (\pm 52 \pm 15 \pm 2)\% \]

\[ A_{ADS}(\pi) = (14.3 \pm 6.2 \pm 1.1)\% \]

1 fb\(^{-1}\), 7 TeV data

**GLW modes**

\[ A_{GLW} = (14.5 \pm 3.2 \pm 1.0)\% \]
**B^± → DK^± and B^± → Dπ^± GGSZ & K(3π) modes**

- **B^- → (πK^+π^+π^-)_D K^-**
- **B^+ → (πK^+π^+π^-)_D K^+**

**K(3π) modes**
- 1 fb^{-1}

**GGSZ mode**
- **(K_Sπ^+π^-)_D**
- 3 fb^{-1}

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**JHEP 10 (2014) 097**

**PLB 712 (2012) 203**

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**B^{±} → DK^{±} γ measurement**

LHCb combined

- **GLW** ($D^0 \rightarrow \pi^+\pi^-, K^+K^-$) 1 fb$^{-1}$
- **ADS** ($D^0 \rightarrow K^+\pi^-, K^+\pi^+\pi^-\pi^-$) 1 fb$^{-1}$
- **GGSZ** ($D^0 \rightarrow K_S\pi^+\pi^-, K_SK^+K^-$) 3 fb$^{-1}$

Combined: $\gamma = (72.9^{+9.2}_{-9.9})^\circ$

- **Compare:**
  - Belle ($69^{+17}_{-16})^\circ$
  - BaBar ($68^{+15}_{-14})^\circ$

**Indirect γ value from global CKM fit:** $\gamma = (66.5^{+1.3}_{-2.5})^\circ$
CP violation in $B \rightarrow \pi^+\pi^-$ & $B_s \rightarrow K^+K^-$ (angle $\alpha/\gamma$)

- 1 fb$^{-1}$ : ~9000 $B^0 \rightarrow \pi^+\pi^-$ events
- First time-dependent CP asymmetry plot of $B^0 \rightarrow \pi^+\pi^-$ at a hadron collider

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$ 
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$

- Also first ever time-dependent asymmetry seen in $B_s \rightarrow K^+K^-$

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$ 
$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$

JHEP 10 (2013) 183
LHCb measurement of $|V_{ub}|$

- Side opposite to $\beta$ proportional to $|V_{ub}| / |V_{cb}|$. Both $\beta$ and $|V_{cb}|$ known better than 3%.
- Closure test of UT mainly limited by $|V_{ub}|$
- The measurement of $|V_{ub}|$ has an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement: $B^0/B^+ \rightarrow X_u \mu^+ \nu$
- $|V_{ub}|/|V_{cb}|$ long thought to be impossible at a hadron colliders due to neutrinos

- **NEW** : LHCb measures $\Lambda_b \rightarrow p \mu^- \nu$

- LHCb measures

$$|V_{ub}| = (3.27 \pm 0.15 \text{(exp)} \pm 0.17 \text{(theory)} \pm 0.06 \times 10^{-3})$$

(relies on new $\Lambda_b \rightarrow p$ form factors from the lattice)

*(Nature Physics 10 (2015) 1038)*

Tension between inclusive and exclusive $|V_{ub}|$ persists
Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the $B_s$ system
- CP violation in charm
- Pentaquarks
Decays strongly suppressed in SM

Predicted BRs

\[ B^0_s \rightarrow \mu^+\mu^- = (3.66 \pm 0.23) \times 10^{-9} \]
\[ B^0 \rightarrow \mu^+\mu^- = (1.06 \pm 0.09) \times 10^{-10} \]

Very sensitive to new physics - e.g. MSSM

But it’s a bit like looking for a needle in a haystack

LHCb $\mu^+\mu^-$ mass spectrum

$B^0_s \rightarrow \mu^+\mu^-$?
History

- \( B^0_{(s)} \rightarrow \mu^+\mu^- \) sensitivity to NP has motivated searches since 1984 ...
- \( BR(B^0_s \rightarrow \mu^+\mu^-) \) has now surpassed the SM prediction
LHCb $B_s \rightarrow \mu^+\mu^-$ candidate
- Results based on 2011/12 data: 3 fb⁻¹ blinded analysis
- Selection based on multivariate estimator (BDT) combining vertex and topological information
- Cut on BDT > 0.5
- The known B masses and widths are fixed in the fit

\[ \beta(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0} st^{+0.3}_{-0.1} sy) \times 10^{-9} \]
Significance: 4.0 (Expected 5.0)

\[ \beta(B^0 \rightarrow \mu^+ \mu^-) = (3.7^{+2.4}_{-2.1} st^{+0.6}_{-0.4} sy) \times 10^{-10} \]
Significance: 2.0
Combining with CMS results

\[ B_d \rightarrow \mu^+\mu^-: \quad BR = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \]
3.0σ significance

\[ B_s \rightarrow \mu^+\mu^-: \quad BR = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]
6.2σ significance
First observation!

\[ B^0 \] compatible at 2.2σ with SM,
\[ B_s \] at 1.2σ
Constraints on new physics models

$B(B^0_s \rightarrow \mu^+ \mu^-)\, [10^{-9}]$

Modified from [Straub, 2012]

- MSSM-LL
- MSSM-RVV2
- MFV
- MSSM-AKM
- MSSM-AC
- CMS & LHCb
- SM4
- RSc
- SM

$B(B_s \rightarrow \mu^+ \mu^-) \propto \frac{\tan^6 \beta}{m_A^4}$

 Straub Moriond 2012
(http://phys.davidstraub.de/files/dstraub-moriond12.pdf)
FCNC decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

SM + New physics contributions

- LHCb has largest sample in world, as clean as the B Factories!
- Interesting anomaly seen in 1 fb$^{-1}$ dataset
- New 3fb$^{-1}$ sample now analysed, 7/8 TeV dataset

LHCb-CONF-2015-002

JHEP 08 (2013) 131
$B^0 \rightarrow K^*\mu^+\mu^-$ continued

- But forward-backward asymmetry $A_{FB}(q^2)$ in the $\mu\mu$ rest-frame is a sensitive NP probe ($q^2 = m_{\mu\mu}^2$)

- Measurement of zero crossing point with 3 fb$^{-1}$: $q^2 = 3.7^{+0.8}_{-1.0}$ GeV$^2$ [JHEP 01 (2012) 107]

- $A_{FB}$ measured by LHCb consistent with Standard Model
Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty ⇔ prevent NP from hiding under strong interaction effects.

Same 3 fb\(^{-1}\) 7/8 TeV dataset

Angular differential distribution given by:

\[
\frac{1}{\Gamma} \frac{d^3(\Gamma + \Gamma)}{d \cos \theta_\ell \, d \cos \theta_K \, d \phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right.

- F_L \cos^2 \theta_K \cos 2\theta_\ell + \frac{1}{2} (1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi +

\sqrt{F_L(1 - F_L)} P_4' \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \sqrt{F_L(1 - F_L)} P_5' \sin 2\theta_K \sin \theta_\ell \cos \phi +

(1 - F_L) A_{Re}^T \sin^2 \theta_K \cos \theta_\ell + \sqrt{F_L(1 - F_L)} P_6' \sin 2\theta_K \sin \theta_\ell \sin \phi +

\sqrt{F_L(1 - F_L)} P_8' \sin 2\theta_K \sin 2\theta_\ell \sin \phi + (S/A)_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \]

JHEP 08 (2013) 131 : 1 fb\(^{-1}\)
LHCb-CONF-2015-002 : 3 fb\(^{-1}\)
New observables in $B^0 \rightarrow K^* \mu^+ \mu^-$ cont'

- Local discrepancy of $3.7\sigma$ in 2 bins of $P_5$
  (SM prediction J.Mathias et al, JHEP 05 (2013) 137)

- A flavour changing $Z'$ boson, QCD effects, or just statistical fluctuation?

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Lepton universality test in $B^+ \rightarrow K^+ \mu^+ \mu^-$

- Due to lepton universality, the $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^+ \rightarrow K^+ e^+ e^-$ decays should have same BF to within a factor $10^{-3}$

- The ratio

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}$$

is sensitive to lepton flavour violating NP

- The electron mode is a challenge for LHCb
Lepton universality test in $B^+ \rightarrow K^+ \ell^+ \ell^-$

- Define $R_K$ as:
  $$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3}) \text{ in SM}$$

- To cancel systematics, form double ratios with $B^+ \rightarrow K^+ J/\psi(\rightarrow \ell^+ \ell^-)$ (assuming lepton universality for $J/\psi \rightarrow \ell^+ \ell^-$)

- The result for $R_K$ differs from SM at 2.6 sigma level. This is using the 3 fb$^{-1}$ of data.

- This is the most precise measurement of $R_K$ to date.

$$R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$$
Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the $B_s$ system
- CP violation in charm
- Pentaquarks
Golden mode for this study is $B_s \to J/\psi \phi$

Analogue of $2\beta$ (phase of $B^0$ mixing) but in the $B_s$ system

Interference between $B^0$ decay to $J/\psi \phi$ directly and via $B^0 - \bar{B}^0$ oscillation gives rise to a CP violating phase

$$\phi = \phi_{\text{Mixing}} - 2 \phi_{\text{Decay}} = -2\phi_s$$

$\phi_s$ is expected to be very small in the SM and precisely predicted:

$$\phi_s = -0.036 \pm 0.002$$

(see eg Charles et al PRD84 (2011) 033005)
\[ B_s \to J/\psi \phi \] angular analysis

- \( \phi \) is a vector meson (spin 1)
- Vector-vector final state: mixture of CP-odd and CP-even components

Need to perform \( B_s \to J/\psi \phi \) angular analysis

- LHCb 7 & 8 TeV, 3 fb\(^{-1}\): 95,690 ± 350 candidates
- Tagging: Opposite side tagging power 2.55% (+15% w.r.t. 2011)
  
  Same Side Kaon Tagger 1.25% (+40% w.r.t. 2011)
“Visualizing” the effect of $\phi_s$ in $B_s \to J/\psi \phi$

- Amplitude of asymmetry $\propto \sin \phi_s$
- Frequency is the same as in $B_s$ mixing

$\phi_s = 0.4$

$\phi_s = 0.04$ (SM)
$B_s \rightarrow J/\psi \phi$: fit projections
Results correlated with $\Delta \Gamma_s = \text{width diff. of the } B_s \text{ mass eigenstates}$ → plot as contours in $(\phi_s \text{ vs } \Delta \Gamma_s)$ plane

- $\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1}$
- $\Delta \Gamma_s = 0.0805 \pm 0.0091 \pm 0.0033 \text{ ps}^{-1}$
- CP-violating phase:
  - $\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$

Also add in $B_s \rightarrow J/\psi \pi\pi$

- $\phi_s = -0.010 \pm 0.039 \text{ rad}$

World’s most significant direct measurement of $\phi_s$ & $\Delta \Gamma_s$

PLB 736 (2014) 186

3 fb$^{-1}$ arXiv:1411.3104
Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the $B_s$ system
- CP violation in charm
- Pentaquarks
Mixing (and CP-violation) in charm decays

Short Range

\[ c \rightarrow W \rightarrow d, s, b \rightarrow d, s, b \rightarrow u \]

\[ u \rightarrow W \rightarrow c \]

Long Range

\[ D^0 \rightarrow \pi^+, K^+ \rightarrow \overline{D^0} \]

\[ \pi^-, K^- \]

NP?

15 November 2011 Last updated at 12:18 GMT

LHC reveals hints of 'new physics' in particle decays

By Jason Palmer
Science and technology reporter, BBC News

Large Hadron Collider researchers have shown off what may be the facility's first "new physics" outside our current understanding of the Universe.

Particles called D-mesons seem to decay slightly differently from their antiparticles, LHCb physicist Matthew Charles told the HCP 2011 meeting on Monday.

The result may help explain why we see so much more matter than antimatter.
Mixing in charm decays

- Charm mixing was confirmed by BaBar, Belle & CDF, but LHCb shows clear observation in a single experiment.
- LHCb measures the time-dependent ratio of $D^0$ decays to **Wrong Sign** over **Right Sign** (will have contribution from mixing)
  
  $$R(t) = \frac{N(D^0 \rightarrow K^+ \pi^-)}{N(D^0 \rightarrow K^- \pi^+)}$$

- Use the sign of the slow pion from $D^{*+} \rightarrow D^0 \pi^+_s$ and $D^{*-} \rightarrow \bar{D}^0 \pi^-_s$ to tag the initial $D^0$ flavour.
Charm mixing measurement

\[ R(t) = \frac{N(D^0 \rightarrow K^+\pi^-)}{N(D^0 \rightarrow K^-\pi^+)} \]

- New analysis uses 3 fb\(^{-1}\) of data (results coming soon)
- Huge samples of D candidates: 230k WS and 54M RS
Charm mixing measurement (2011 data)

The no mixing hypothesis is excluded at the 9.1σ level in a single experiment.

PRL 110, 101802 (2013)
CP violation in charm

Consistent with no CP violation in charm sector

Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the $B_s$ system
- CP violation in charm
- Pentaquarks
NEW ... pentaquarks!

- Unexpected narrow resonance in $m(J/\psi p)$ where $\Lambda_b \rightarrow (J/\psi p) K^-$
- Consistent with pentaquarks: allowed by QCD, but not seen for 50 years.
Pentaquarks – full amplitude analysis

(a) LHCb

(b) LHCb

\[ P_c^+ (4380): M = 4380 \pm 8 \pm 29 \text{ MeV} \quad \Gamma = 205 \pm 18 \pm 86 \text{ MeV} \]

\[ P_c^+ (4450): M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV} \quad \Gamma = 39 \pm 5 \pm 19 \text{ MeV} \]

9 sigma
12 sigma
The preferred $J^P$ assignments are of opposite parity, with $P_c^+(4380)$ having $3/2^-$ and the $P_c^+(4450)$ having $5/2^+$. Good evidence for the resonant character of $P_c^+(4450)$.

Too large errors for $P_c^+(4380)$: hard to make a definitive conclusion.
Summary and Outlook

- The LHCb experiment is performing spectacularly well

- So far all is in good agreement with the Standard Model
  → New physics is becoming constrained in the flavour sector
  → Hints of new physics await more data

- Up to 2017 we expect 7-8 fb⁻¹ of data in total, much of this at nearly double the beam energy (now $\sqrt{s} = 13$ TeV) giving ~twice the 8 TeV heavy-flavour production cross-section

- Still much room for new physics, higher precision required …
  → preparing for LHCb Upgrade beyond 2020 !
Looking to the future …

Charm from the first July 2015 run

\[
\begin{align*}
\text{Corfu Summer Institute} & \quad 2 \text{ September 2015} & \quad \text{N.Harnew}
\end{align*}
\]
Spare slides from here on
### LHCb 2012 data-taking in numbers

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>TDR</th>
<th>2011</th>
<th>2012</th>
<th>2012/TDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Luminosity</td>
<td>$\mu$b^{-1}/s</td>
<td>280</td>
<td>400</td>
<td>400</td>
<td>142%</td>
</tr>
<tr>
<td>Average Luminosity</td>
<td>$\mu$b^{-1}/s</td>
<td>200</td>
<td>265</td>
<td>390</td>
<td>195%</td>
</tr>
<tr>
<td>Seconds of running time $t$</td>
<td>$10^7$s</td>
<td>1</td>
<td>0.46</td>
<td>0.63</td>
<td>63%</td>
</tr>
<tr>
<td>Integrated luminosity $\int L dt$</td>
<td>fb^{-1}</td>
<td>2.0</td>
<td>1.2</td>
<td>2.1</td>
<td>105%</td>
</tr>
<tr>
<td>Bunches</td>
<td></td>
<td>2600</td>
<td>1300</td>
<td>1300</td>
<td>50%</td>
</tr>
<tr>
<td>CM energy</td>
<td>TeV</td>
<td>14</td>
<td>7</td>
<td>8</td>
<td>57%</td>
</tr>
<tr>
<td>Inelastic cross sec $\sigma_{\text{inel}}$</td>
<td>mb</td>
<td>80</td>
<td>64</td>
<td>67</td>
<td>84%</td>
</tr>
<tr>
<td>$b\bar{b}$ cross sec $\sigma_{b\bar{b}}$</td>
<td>$\mu$b</td>
<td>500</td>
<td>284</td>
<td>$\sim$330</td>
<td>58%</td>
</tr>
<tr>
<td>pp interactions/BeamX</td>
<td></td>
<td>0.55</td>
<td>1.15</td>
<td>1.65</td>
<td>272%</td>
</tr>
<tr>
<td>Average min bias rate</td>
<td>MHz</td>
<td>16</td>
<td>17</td>
<td>22</td>
<td>131%</td>
</tr>
<tr>
<td>$b\bar{b}$ yield: $\sigma_{b\bar{b}}\int L dt$</td>
<td>$10^{12}$</td>
<td>1</td>
<td>0.35</td>
<td>0.63</td>
<td>63%</td>
</tr>
<tr>
<td>HLT rate $\lambda_{\text{HLT}}$</td>
<td>kHz</td>
<td>2</td>
<td>2.45</td>
<td>4.1</td>
<td>205%</td>
</tr>
<tr>
<td>Stored events $\lambda_{\text{HLT}} t$</td>
<td>$10^9$</td>
<td>20</td>
<td>11</td>
<td>26</td>
<td>130%</td>
</tr>
</tbody>
</table>
Flavour tagging

- Tagging of production flavour (B or \(\bar{B}\)) important for mixing and CP analyses. Performance calibrated using control channels such as \(B^+ \rightarrow J/\psi \ K^+\)

- Current opposite side tagging power:
  \[\varepsilon (1 - w)^2 = (2.10 \pm 0.08 \pm 0.24)\%\]
**CP violation in $B \to K\pi$ and $B_s \to K\pi$**

\[
A_{CP}(B^0 \to K\pi) = \frac{\Gamma(B^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} \\
A_{CP}(B^0_s \to \pi K) = \frac{\Gamma(B^0_s \to \pi^-K^+) - \Gamma(B^0_s \to \pi^+K^-)}{\Gamma(B^0_s \to \pi^-K^+) + \Gamma(B^0_s \to \pi^+K^-)}
\]

- Using 1/fb (2011) @ $\sqrt{s} = 7$ TeV.

\[\mathcal{A}_{CP}(B^0) = -0.080 \pm 0.007 \pm 0.003\] (most precise measurement, 10.5σ)

\[\mathcal{A}_{CP}(B^0_s) = -0.27 \pm 0.04 \pm 0.01\] (first observation of CPV in $B^0_s$ decays, 6.5σ)

LHCb PRL 110, 221601 (2013)
Charm mixing formulism

mass difference $x$:
$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}$$

decay width difference $y$:
$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma}$$

In the limit of small mixing $|x|, |y| \ll 1$ and assuming negligible CPV:
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D \cdot y'} \cdot t + \frac{x'^2 + y'^2}{4} \cdot t^2$$

- the ratio of DCS to CF decay rates
- the interference of the DCS and mixed decays
- mixing parameters

$$x' = x \cos \delta + y \sin \delta \quad y' = y \cos \delta - x \sin \delta$$

$\delta$ is a strong phase difference between DCS and CF amplitudes
W/Z production

LHCb’s unique forward and low p_T acceptance equips it to perform EW / QCD measurements which are highly complementary to those of mid-rapidity GPDs.

Isospin asymmetry in $B^0 \rightarrow K^{0(*)}\mu^+\mu^-$

- LHCb measure “isospin asymmetry”
\[
\frac{\Gamma(B^0 \rightarrow K^0 \mu^+\mu^-) - \Gamma(B^+ \rightarrow K^+ \mu^+\mu^-)}{\Gamma(B^0 \rightarrow K^0 \mu^+\mu^-) + \Gamma(B^+ \rightarrow K^+ \mu^+\mu^-)}
\]

- Expected to be $\sim$zero in SM

- Significant had emerged ($4.6\sigma$ from zero) in early $K^0$ data not in $K^*$.)

- With full 3 fb$^{-1}$ data set the isospin asymmetry is compatible with zero at the 1.5$\sigma$ level

arXiv:1403.8044

JHEP 7 (2012) 133
**CP-violating asymmetry** $a_{s,l}^s$ in $B_s$ decays

- CPV in mixing $P(B \to \bar{B}) \neq P(\bar{B} \to B)$

- First step to resolving the issue of the D0 di-muon asymmetry anomaly.


- LHCb 1 fb$^{-1}$ result for $a_{s,l}^s$

$$a_{s,l}^s \equiv \frac{\Gamma(B_s^0 \to D_s^- \mu^+) - \Gamma(\bar{B}_s^0 \to D_s^+ \mu^-)}{\Gamma(B_s^0 \to D_s^- \mu^+) + \Gamma(\bar{B}_s^0 \to D_s^+ \mu^-)}$$

$$a_{s,l}^s[\text{LHCb}] = (-0.06 \pm 0.50 \pm 0.36)\%$$

[arxiv: 1308.1048](http://arxiv.org/abs/1308.1048)

- D0 result not confirmed nor ruled out.
The Z(4430) tetraquark

- First observed by Belle (but not seen by Babar)
- LHCb: use very clean sample of 25,200 $B^0 \rightarrow \psi' K^+\pi^-$, $(\psi' \rightarrow \mu^+\mu^-)$ decays observed in 3 fb$^{-1}$ of data (7 and 8 TeV).
- $Z(4430)^-$ peak seen in $\psi' \pi^-$ mass with significance of the signal 13.9$\sigma$
- Spin-parity $J^P = 1^+$ at 9.7$\sigma$
- Being charged, it cannot be a $cc(\bar{c}c)$ state. The minimal quark content of the $Z(4430)$ is $cc(\bar{c}c)du(\bar{d}u)$. It is therefore a two-quark plus two-antiquark state

$m = 4475 \pm 7^{+15}_{-25} \text{ MeV}/c^2$

$\Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}/c^2$

**R(D) and R(D*)**

**BaBar**

\[
R(D) = 0.440 \pm 0.058 \pm 0.042 \\
R(D^*) = 0.332 \pm 0.024 \pm 0.018
\]

**Belle**

\[
R(D) = 0.375 \pm 0.064 \pm 0.026 \\
R(D^*) = 0.293 \pm 0.038 \pm 0.015
\]

**LHCb**

\[
R(D^*) = 0.336 \pm 0.027 \pm 0.030
\]

- Combination is **3.9σ** from the SM expectation:

\[
R(D) = 0.297 \pm 0.017 \quad , \quad R(D^*) = 0.252 \pm 0.003
\]

Possible anomaly in $B_s^0 \rightarrow \phi \mu^+ \mu^-$ decays?

LHCb prelinary

SM from DHMV

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

$B_s^0 \rightarrow \phi \mu^+ \mu^-$ decays

Corfu Summer Institute 2 September 2015 N.Harnew
Detector performance – VELO

- **Vertex Locator (VELO):**
  21 modules of back-to-back silicon sensor disks, $R$-$\phi$ strip geometry

- **Silicon is only 8 mm from beams. Must be retracted for safety during beam injection**

- **300 $\mu$m-thick silicon**
  2048 strips/sensor, 40 $\mu$m inner pitch
Vertex reconstruction performance

- Impact parameter resolution = 12 µm for high $p_T$ tracks from VELO detector.
- Proper-time resolution: $\sigma_t = 45$ fs for eg. $B_s \rightarrow J/\psi\phi$
Tracking performance

- Integrated field strength 4 Tm from dipole magnet
- Planes of straw tubes

\[ \sigma(m_{J/\psi}) = 13 \text{ MeV/c}^2 \]

\[ \sigma(m_{Y(1S)}) = 43 \text{ MeV/c}^2 \]
Particle identification

- Charged particles identified with two Ring-Imaging Cherenkov detectors covering $2 < p < 100$ GeV/c
- Cherenkov angle resolution 0.66 mrad per photon achieved (in RICH 2)
**PID performance**

- Kaon identification efficiency > 90% for pion misidentification < 5% over a large momentum range ($2 < p < 100 \text{ GeV/c}$)

**Calibration data**

- Allows strong suppression of combinatorial background
  - eg for $\phi \rightarrow K^+K^-$

---

![Efficiency graph](image)

- LHCb $\sqrt{s} = 7 \text{ TeV Data}$
  - $K \rightarrow K$
  - $\pi \rightarrow K$

![Mass spectrum](image)

- LHCb $\sqrt{s} = 900 \text{ GeV Data}$
  - $\phi \rightarrow K^+K^-$

---

*arXiv:1211.6759*
The LHCb trigger performance

Hardware level (L0):
- 4 μs latency @ 40MHz
- high-\(p_T\) μ, e, γ, hadron candidates, typically \(p_T(\mu)>1.4; E_T(e/\gamma)>2.7; E_T(\text{hadron})>3.6\) [GeV]

Software level (HLT):
- ~30000 tasks in parallel on ~1500 nodes

Combined efficiency (L0+HLT):
- ~90 % for di-muon channels
- ~30 % for multi-body hadronic final states

Offline processing:
- ~10^{10} events, 700 TB recorded per year
- ~800 “stripping” selections to reduce to samples with 0(10^7) events for analyses
Outlook: LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau
- Proposed upgrade is to remove hardware trigger: read out detector at 40 MHz (bunch crossing rate). Trigger fully in software in CPU farm. Requires replacing all front-end electronics
- Will allow to increase luminosity by factor ~ 10 to $1 - 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- TDRs being approved by CERN: Physics case enthusiastically endorsed, detector R&D underway

Upgrade of LHCb detector planned for 2019 to take at least
10× more data: 50 fb$^{-1}$
## Upgrade sensitivities 50 fb⁻¹

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \to J/\psi \phi)$</td>
<td>0.10 [24]</td>
<td>0.025</td>
<td>0.008</td>
<td>~ 0.003</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \to J/\psi f_0(980))$</td>
<td>0.17 [26]</td>
<td>0.045</td>
<td>0.014</td>
<td>~ 0.01</td>
</tr>
<tr>
<td></td>
<td>$A_{fs}(B_s^0)$</td>
<td>$6.4 \times 10^{-3}$ [41]</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to \phi \phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to K^{*0} \bar{K}^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to \phi K_S^0)$</td>
<td>0.17 [41]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \to \phi \gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>currents</td>
<td>$\tau^{\text{eff}} (B_s^0 \to \phi \gamma) / \tau_{B_s^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$s_3 (B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.08 [42]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$s_0 A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-)$</td>
<td>25% [42]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.25 [9]</td>
<td>0.08</td>
<td>0.025</td>
<td>~ 0.02</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B^+ \to K^+ \mu^+ \mu^-)$</td>
<td>25% [43]</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [4]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>Penguin</td>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>–</td>
<td>~ 100%</td>
<td>~ 35%</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma (B \to D^{(<em>)} K^{(</em>)})$</td>
<td>~ 10–12° [28, 29]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td>Triangle</td>
<td>$\gamma (B_s^0 \to D_s K)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td>Angles</td>
<td>$\beta (B^0 \to J/\psi K_S^0)$</td>
<td>0.8° [41]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_\Gamma$</td>
<td>$2.3 \times 10^{-3}$ [41]</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>$CP$ violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [8]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>