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On behalf of the LHCb Collaboration

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Discrete 2014, Kings College London

December 5th 2014
Outline

- The LHCb detector and running conditions
- Selected physics highlights:
  - Measurements based on 1 fb⁻¹ (2011) and 2 fb⁻¹ (2012) pp collision data at 7 & 8 TeV CM energy.
    - Parameters of the CKM matrix
    - Studies of CP violation in the Bs system
    - Mixing & CP violation in charm
    - Rare B decays (See also Fatima Soomro talk in parallel session)
    - New resonances
- Summary and Outlook
**LHCb- forward spectrometer**

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = $284 \pm 53 \mu b$ at $\sqrt{s} = 7$ TeV
  
  [PLB 694 209]

→ ~ 100,000 $b\bar{b}$ pairs produced/second ($10^4 \times B$ factories)
LHCb data taking

- Nominal luminosity = $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ : however, LHCb has learned to run at >2 times this.

- Continuous (automatic) adjustment of offset of colliding beams allows luminosity to be *levelled*
  
  • 37 pb$^{-1}$ collected in 2010
  • 1 fb$^{-1}$ in 2011
  • >2 fb$^{-1}$ recorded in 2012

2013/14 : currently in long shutdown
Selected physics highlights

- Parameters of the CKM matrix
- Studies of CP violation in the $B_s$ system
- Mixing & CP violation in charm
- Rare B decays
- New observed resonances
Quark mixing and CKM matrix

- In the SM charge $-1/3$ quarks (d, s, b) are mixed
- Mixing described by CKM matrix
  \[
  \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
  \end{pmatrix}
  =
  \begin{pmatrix}
  1-\lambda^2/2 & \lambda & A\lambda^3 (\rho - i\eta) \\
  -\lambda & 1-\lambda^2/2 & A\lambda^2 \\
  A\lambda^3 (1-\rho - i\eta) & -A\lambda^2 & 1
  \end{pmatrix} + O(\lambda^4)
  \]
- 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: 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

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

$$\phi = \phi_{\text{Mixing}} - 2 \phi_{\text{Decay}} = 2\beta$$
LHCb sin(2β) measurement

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

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

\[ S_{J/\psi K^0_S} = 0.73 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)} \]
\[ C_{J/\psi K^0_S} = 0.030 \pm 0.089 \pm 0.012 \text{ (syst)} \]


World average (Winter 2014) :
\[ \sin(2\beta) = 0.679 \pm 0.020 \]

New 3fb\(^{-1}\) results expected soon with much improved precision
... and $B_{(s)}$ mixing

\[
\frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow \bar{B}^0)}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow \bar{B}^0)}
\]

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

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


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 $D \to K_s^0 K^\pm K^\mp$
  - $B^\pm \to Dh^\pm$, $D \to \pi^\pm K^\mp \pi^\pm \pi^\mp$ and $D \to K^\pm \pi^\mp \pi^\mp \pi^\mp$
  - $B^\pm \to Dh^\pm$, $D \to \pi^\pm K^\mp$ and $D \to K^\pm \pi^\mp$
  - $B^\pm \to Dh^\pm$, $D \to K^\pm K^\mp$ and $D \to \pi^\pm \pi^\mp$

- Two paths to the same final state via $D^0$ and $\bar{D}^0$ → interference sensitive to gamma

- Methods:
  - “GGSZ”
    - JHEP 10 (2014) 097
  - “K3π”:
    - PLB 712 (2012) 203
  - “ADS”
    - Phys Lett B712 (2012) 203
  - “GLW”
    - Phys Lett B712 (2012) 203
\[ B^\pm \rightarrow D K^\pm \text{ and } B^\pm \rightarrow D \pi^\pm \text{ ADS & GLW modes} \]

\[ B^- \rightarrow (\pi^- K^+)_D K^- \quad B^+ \rightarrow (\pi^+ K^-)_D K^+ \]

\[ B^- \rightarrow (\pi^- K^+)_D \pi^- \quad B^+ \rightarrow (\pi^+ K^-)_D \pi^+ \]

\[ B^- \rightarrow (K^+ K^-)_D K^- \quad B^+ \rightarrow (K^+ K^-)_D K^+ \]

\[ B^- \rightarrow (K^+ K^-)_D \pi^- \quad B^+ \rightarrow (K^+ K^-)_D \pi^+ \]

\[ \text{ADS modes} \]

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

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

\[ 1 \text{ fb}^{-1}, 7 \text{ TeV data} \]

\[ \text{GLW modes} \]

\[ A_{\text{GLW}} = (14.5 \pm 3.2 \pm 1.0)\% \]

$B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$ GGSZ & K(3\pi) modes

$B^- \rightarrow (\pi K^+\pi^+\pi^-)_{D}K^-$

$B^+ \rightarrow (\pi K^+\pi^+\pi^-)_{D}K^+$

$B^- \rightarrow (\pi K^+\pi^+\pi^-)_{D}\pi^-$

$B^+ \rightarrow (\pi K^+\pi^+\pi^-)_{D}\pi^+$

K(3\pi) modes

1 fb$^{-1}$

PLB 712 (2012) 203

JHEP 10 (2014) 097

GGSZ mode

$(K_S\pi^+\pi^-)_{D}$

3 fb$^{-1}$

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$B^\pm \rightarrow DK^\pm \gamma$ measurement

LHCb combined

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

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

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

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

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

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$  \hspace{1cm} \text{cos term (direct)}

$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$  \hspace{1cm} \text{sine term (indirect)}

- 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

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Selected physics highlights

- Parameters of the CKM matrix
- Studies of CP violation in the $B_s$ system
- Mixing & CP violation in charm
- Rare $B$ decays
- New observed resonances
**B_s weak mixing phase \( \phi_s \) in \( B_s \rightarrow J/\psi \phi \)**

- **Golden mode for this study is** \( B_s \rightarrow J/\psi \phi \)
- **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 \( B^0 - \overline{B^0} \) 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 \rightarrow J/\psi \phi \text{ angular analysis}

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

Need to perform $B_s \rightarrow J/\Psi \phi$ angular analysis

- LHCb 7 & 8TeV, 3fb^{-1}: 95,690 \pm 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 $B_s \rightarrow J/\psi \phi$

- 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

**CP-even**

**CP-odd**
Results correlated with $\Delta \Gamma_S = \text{width diff. of the } B_s \text{ mass eigenstates} \rightarrow \text{plot as contours in } (\phi_S \text{ vs } \Delta \Gamma_S) \text{ plane}$

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

World’s most significant direct measurement of $\phi_S$ & $\Delta \Gamma_S$, $\Delta \Gamma_S$

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

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

3 fb$^{-1}$ arXiv:1411.3104

PLB 736 (2014) 186
A combination of $\phi_S$ shows data not incompatible with the SM

Still much room for new physics in $\phi_S$, will continue improved precision
Selected physics highlights

- Parameters of the CKM matrix
- Studies of CP violation in the $B_s$ system
- Mixing & CP violation in charm
- Rare $B$ decays
- New observed resonances
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 to 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 (and CP-violation)

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

PRL 110, 101802 (2013)

CP violation in charm

Selected physics highlights

- Parameters of the CKM matrix
- Studies of CP violation in the $B_s$ system
- Mixing & CP violation in charm
- Rare B decays: See also Fatima Soomro talk in parallel session
- New observed resonances
Decays strongly suppressed in SM

Predicted BRs

\[ B^0_s \rightarrow \mu^+\mu^- = (3.65 \pm 0.23) \times 10^{-9} \]
\[ B^0 \rightarrow \mu^+\mu^- = (1.06 \pm 0.09) \times 10^{-10} \]

Bobeth et al. PRL 112 101801 (2014)

Very sensitive to new physics - e.g. MSSM
A needle in a haystack 

\[ B^0_s \rightarrow \mu^+\mu^- \]
- Results based on 2011/12 data: 3 fb$^{-1}$ blinded analysis

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}\text{ st }^{+0.3}_{-0.1}\text{ sy}) \times 10^{-9}
\]

Significance : 4.0 (Expected 5.0)

\[
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}\text{ st }^{+0.6}_{-0.4}\text{ sy}) \times 10^{-10}
\]

Significance : 2.0
Combining with CMS results

$BR(B_s \to \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

$BR(B^0 \to \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

$B^0$ compatible at 2.2$\sigma$ with SM, $B_s$ at 1.2$\sigma$
FCNC decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- LHCb has largest sample in world, as clean as the B Factories!

- Analysis presented here based on $883 \pm 34$ events ($1\text{fb}^{-1}$ at 7 TeV)
Observables in $B^0 \rightarrow K^*\mu^+\mu^-$

- 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 1 fb$^{-1}$ 7 TeV dataset
- Angular differential distribution given by:

\[
\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell d \cos \theta_K d \phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell 
\right.
\]
\[
- F_L \cos^2 \theta_K \cos 2\theta_\ell + \frac{1}{2} (1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + 
\]
\[
\sqrt{F_L(1 - F_L)} P_4' \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \sqrt{F_L(1 - F_L)} P_5' \sin 2\theta_K \sin \theta_\ell \cos \phi + 
\]
\[
(1 - F_L) A_T^{(2)} \sin^2 \theta_K \cos \theta_\ell + \sqrt{F_L(1 - F_L)} P_6' \sin 2\theta_K \sin \theta_\ell \sin \phi + 
\]
\[
\sqrt{F_L(1 - F_L)} P_8' \sin 2\theta_K \sin 2\theta_\ell \sin \phi + (S/A)_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \]
\]

PRL 111 (2013) 191801
New observables in $B^0 \to K^{*}\mu^+\mu^-$ cont’

- Local discrepancy of $3.7\sigma$ in 3rd bin of $P_5'$
  (SM prediction J. Mathias et al, JHEP 05 (2013) 137)

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

- More data required
Lepton universality test in $B^+ \rightarrow K^+ \ell^+ \ell^-$

- 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
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Two new baryons recently observed

- Spectrum of known b-baryons still sparsely populated.
- For the \( \Xi_b \) (bsd, bsu) states only the ground states, \( \Xi_b^- \) & \( \Xi_b^0 \), and one resonance, \( \Xi_b^0 \) (5945), observed.
- cf. the \( \Xi_c \) pattern, there must be
  - \( \Xi_b^- \) \( J^P = 1/2^+ \), \( \text{spin}(sd) = 1 \)
  - \( \Xi_b^{*-} \) \( J^P = 3/2^+ \), \( \text{spin}(sd) = 1 \)
- Study the ( \( \Xi_b^0 \pi^- \) ) mass spectrum, with \( \Xi_b^0 \rightarrow \Xi_c^+ \) (\( \rightarrow p K^- \pi^+ \)) \( \pi^- \).
- Require good tracks and vertices; PID on kaon and proton; exploit the long \( \Xi_b^0 \) lifetime
- Require soft \( \pi_s^- \) and \( \Xi_b^0 \) from PV.

LHCb-PAPER-2014-061
Two new baryons cont’

\[ \Xi_b' - \Xi_b^* - \Xi_b \]

\[ \delta m = m_{\text{cand}}(\Xi_b^0 \pi^-) - m_{\text{cand}}(\Xi_b^0) - m(\pi^-) \]

\[ m(\Xi_b') = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50 \text{ MeV} \]
\[ \Gamma(\Xi_b') < 0.08 \text{ MeV at 95\% CL} \]

\[ m(\Xi_b^*) = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50 \text{ MeV} \]
\[ \Gamma(\Xi_b^*) = 1.65 \pm 0.31 \pm 0.10 \text{ MeV} \]
And finally … the Z(4430) tetraquark

- First observed by Belle (but not seen by Babar)
- LHCb: use very clean sample of 25,200 $B^0 \to \psi' K^+\pi^-$, ($\psi' \to \mu^+\mu^-$) 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) state. The minimal quark content of the $Z(4430)$ is $cc$(bar)$du$(bar). It is therefore a two-quark plus two-antiquark state

$$m = 4475 \pm 7^{+15}_{-25} \text{ MeV}/c^2$$
$$\Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}/c^2$$

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
  → Possible hints of new physics await more data.

- Up to 2017 in Run 2 we expect 7-8 fb\(^{-1}\) of data in total, and much of this at \sim double the current heavy-flavour production cross-section (since \(\sqrt{s}: 8 \rightarrow 14\) TeV)

- Still much room for new physics, higher precision required …
  → LHCb upgrade.
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 $\rightarrow$ 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 $\sim 10$ to $1-2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$.
- All TDRs approved by CERN: Physics case enthusiastically endorsed, detector R&D and design well underway.

Upgrade of LHCb detector planned for 2019 to take at least $10\times$ 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><strong>$B_s^0$ mixing</strong></td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$</td>
<td>0.10 [24]</td>
<td>0.025</td>
<td>0.008</td>
<td>~ 0.003</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$</td>
<td>0.17 [26]</td>
<td>0.045</td>
<td>0.014</td>
<td>~ 0.01</td>
</tr>
<tr>
<td></td>
<td>$\Delta_f(B_s^0)$</td>
<td>$6.4 \times 10^{-3}$ [41]</td>
<td>$6.0 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Gluonic penguin</strong></td>
<td>$2\beta_{\phi\phi}^s (B_s^0 \rightarrow \phi\phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{K^{*0}K^{*0}}^s (B_s^0 \rightarrow K^{*0}K^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{\phi K_s}^s (B_s^0 \rightarrow \phi K_s)$</td>
<td>0.17 [41]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Right-handed currents</strong></td>
<td>$2\beta_{\phi\gamma}^s (B_s^0 \rightarrow \phi\gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\phi\gamma}^s (B_s^0 \rightarrow \phi\gamma) / \tau_{B_s^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Electroweak penguin</strong></td>
<td>$S_3 (B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.08 [42]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</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>$B(B^+ \rightarrow \pi^+\mu^+\mu^-)/B(B^+ \rightarrow K^+\mu^+\mu^-)$</td>
<td>25% [43]</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td><strong>Higgs penguin</strong></td>
<td>$B(B_s^0 \rightarrow \mu^+\mu^-)$</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></td>
<td>$B(B^0 \rightarrow \mu^+\mu^-)/B(B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>~ 100%</td>
<td>~ 35%</td>
<td>~ 5%</td>
<td></td>
</tr>
<tr>
<td><strong>Unitarity</strong></td>
<td>$\gamma (B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>~ 10–12° [28,29]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K_s)$</td>
<td>0.8° [41]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Charm</strong></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></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>

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*Discrete 2014, King’s College London 5th December 2014 N.Harnew*
In 2025 with the LHCb upgrade ...

- \(|V_{ub}|/|V_{cb}|\) and the angle \(\gamma\) will be precision measurements in the future.
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 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 lumi $\int L dt$</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>$bb(\bar{b})$ cross sec $\sigma_{bb(\bar{b})}$</td>
<td>$\mu$b</td>
<td>500</td>
<td>284</td>
<td>~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>$bb(\bar{b})$ yield: $\sigma_{bb(\bar{b})}\int L dt$</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>
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. $B_s \rightarrow J/\psi \phi$

![Prompt J/ψ graph](image)
Tracking performance

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

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

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

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

- Allows strong suppression of combinatorial background eg for φ → K⁺K⁻

**Calibration data**

![Graphs showing calibration data](LHCb_data.png)
The LHCb trigger performance

Hardware level (L0):
- 4 μs latency @ 40MHz
- high-$p_T$ μ, e, γ, hadron candidates, typically $p_T(\mu)>1.4$; $E_T(e/\gamma)>2.7$; $E_T$(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
Flavour tagging

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

- Opposite side tagging power (2011):
  $$\varepsilon (1-w)^2 = (2.10 \pm 0.08 \pm 0.24)\%$$
The sign of $\Delta \Gamma_s$

- To resolve ambiguity
  
  $(\phi_s, \Delta \Gamma_s, \delta_{||}, \delta_{\perp}) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s, 2\pi - \delta_{||}, -\delta_{\perp})$
  
  study strong phase difference $\delta_{s\perp} = \delta_s - \delta_{\perp}$
  
  between $K^+K^-$ P-wave and S-wave amplitudes as a function of $m(K^+K^-)$ around the $\phi(1020)$

- P-wave: $\phi(1020)$, going through resonance
  
  → expect rapid positive phase shift

- S-wave: non-resonant and tail from $f_0(980)$
  
  → expect no fast variation of phase

- Analysis based on $0.37 \text{ fb}^{-1}$

- Determine $\delta_{s\perp}$ in four $K^+K^-$ mass bins

Solution corresponding to $\Delta \Gamma_s > 0$

preferred with $4.7\sigma$ significance
CP violation in $\mathbf{B \to K\pi}$ and $\mathbf{B_s \to K\pi}$

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

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

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

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

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

LHCb

PRL 110, 221601 (2013)
CP violation in charm

Measure $D^0/\overline{D}^0$ decay asymmetries – charge of $\pi$ from $D^*$ decay determines production state of the $D^0$. Also include events with muon tag on opposite side.

$$A_K = \frac{N(D^0 \rightarrow K^+K^-) - N(\overline{D}^0 \rightarrow K^+K^-)}{N(D^0 \rightarrow K^+K^-) + N(\overline{D}^0 \rightarrow K^+K^-)}$$

$$A_\pi = \frac{N(D^0 \rightarrow \pi^+\pi^-) - N(\overline{D}^0 \rightarrow \pi^+\pi^-)}{N(D^0 \rightarrow \pi^+\pi^-) + N(\overline{D}^0 \rightarrow \pi^+\pi^-)}$$

In the Standard Model these asymmetries should be very close to zero

The quantity $\Delta A_{CP} = A_K - A_\pi$ is measured (since systematics largely cancel)
CP violation in charm

- $\Delta A_{CP} = A_K - A_\pi$

$$\Delta A_{CP} = (+0.14 \pm 0.16 \text{ (stat)} \pm 0.08 \text{ (syst)})\%$$

Combination consistent with zero CP violation
Charm mixing formulism

$$\begin{align*}
\text{mass difference } x: \\
x & \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}
\end{align*}$$

death width difference } y:
\begin{align*}
y & \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma}
\end{align*}

In the limit of small mixing $|x|, |y| \ll 1$ and assuming negligible CPV:

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

- 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.
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
Constraints on new physics models

\[ B(B_s^0 \rightarrow \mu^+ \mu^-) \propto \frac{\tan^6 \beta}{m_A^4} \]

Straub Moriond 2012
(http://phys.davidstraub.de/files/dstraub-moriond12.pdf)
But forward-backward asymmetry $A_{FB}(q^2)$ in the $\mu\mu$ rest-frame is a sensitive NP probe ($q^2 = m_{\mu\mu}^2$)

First measurement of zero crossing point: $q^2 = 4.9 \pm 0.9 \text{ GeV}^2$

$A_{FB}$ measured by LHCb (and now ATLAS & CMS) consistent with Standard Model
**B^+ \rightarrow \pi^+\mu^+\mu^- rare penguin decay**

- **B^+ \rightarrow \pi^+\mu^+\mu^-**

  First observation – (rarest B decay ever observed that has >5\(\sigma\) significance)

  - **SM prediction**: \((2.0 \pm 0.2) \times 10^{-8}\)
  - **BR measured**: \((2.4 \pm 0.6 \pm 0.2) \times 10^{-8}\)

  - **FIGURE**: 
    - **25\pm6 events**
    - **5.2 \(\sigma\) significance**
    - **LHCb (a)**
    - **PRD77 (2008) 014017**
CP-violating asymmetry $a_{s\ell}^s$ in $B_s$ decays

- CPV in mixing $P(B \rightarrow \bar{B}) \neq P(\bar{B} \rightarrow B)$
- First step to resolving the issue of the D0 di-muon asymmetry anomaly.
  

- LHCb 1 fb$^{-1}$ result for $a_{s\ell}^s$
  
  $a_{s\ell}^s \equiv \frac{\Gamma(B_s^0 \rightarrow D_s^- \mu^+) - \Gamma(\bar{B}_s^0 \rightarrow D_s^+ \mu^-)}{\Gamma(B_s^0 \rightarrow D_s^- \mu^+) + \Gamma(\bar{B}_s^0 \rightarrow D_s^+ \mu^-)}$

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

  arxiv:1308.1048

- D0 result not confirmed nor ruled out.

\[ \begin{align*}
  a_{s\ell}^s &= (1.9 \pm 0.3) \times 10^{-5} \\
  a_{s\ell}^d &= (-4.1 \pm 0.6) \times 10^{-4}
\end{align*} \]

arXiv:1205.1444

Discrete 2014, King’s College London 5th December 2014

N.Harnew
$B^0_s \to \phi\phi$

- Current status of LHCb's $B^0_s \to \phi\phi$ measurement
  
  - $B^0_s \to \phi\phi$
  - Combinatorial
  - $\Lambda^0_b \to \phi p K$
  - $B^0 \to \phi K^*$

  - $N_{\text{events}} \sim 4000$ of $B^0_s \to \phi(K^+K^-)\phi(K^+K^-)$

  - A vector-vector decay; a mixture of CP even and CP odd distributions

- No significant CP violation observed

$$\phi_s = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst) rad}$$
**B_s weak mixing phase \( \phi_s \) in \( B_s \to J/\psi \phi \)**

- **Measurements by ATLAS, CMS and LHCb:**
  - **LHCb (50 fb\(^{-1}\)):** \( \delta\phi_s \approx \pm 0.009 \) (SM \(-0.036 \pm 0.003\)) (current meas. \(\pm 0.07\))
Complementarity with Belle-II

LHCb

• Rare decays: $B_{d,s} \rightarrow \mu\mu$
• $B_s$ system
• b-baryons

• Spectroscopy
• CKM phases ($\beta$, $\gamma$)
• Gluonic penguins
• EW penguins
• Charm physics
• Semileptonics: Mixing, $A_{SL}$

On-going

• Semileptonics: $V_{xb}$
• $B \rightarrow \tau\nu, D\tau\mu,$
• $B \rightarrow K^*\nu\nu$
• $\tau$-physics

ATLAS & CMS

Some only LHCb, some only Belle II

Belle II
Why upgrade: current LHCb limitations

- No evidence for New Physics in LHC Run I
  - Need more (x10 or more) data, aiming at experimental sensitivities comparable to theoretical uncertainties

- Need to increase levelled luminosity from $0.4 \times 10^{33}$ up to $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ (pile-up $\sim 8$)

- However the current 1 MHz level-0 trigger output is a severe limitation!

- If we increase the luminosity
  - Need harder cuts on $P_t$ due to the 1 MHz bandwidth limit
  - The trigger yield of hadronic events saturates
  - there’s no real gain in statistics

Need a radical change in the trigger strategy to get to 5pb$^{-1}$ per year
The timeline ...

ATLAS & CMS ~100 fb⁻¹ → Phase 1 Upgrade → ~300 fb⁻¹ → Phase 2 HL - Upgrade → ~3000 fb⁻¹

LHCb >8 fb⁻¹ → Upgrade → >23 fb⁻¹ → >50 fb⁻¹

LHC Run 2: 13-14 TeV → LS 2 → Run 3: 14 TeV → LS 3 → Run 4+5

SuperKEKb & Belle II → 50 ab⁻¹

BES III