Status and physics at LHCb

Vienna Central European Seminar
Particle Physics and the LHC

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On behalf of the LHCb collaboration

Outline
• LHCb experiment and detector performance
• Selected physics results
• Outlook and summary
New physics effects in $B$ and $D$ decays

Strength of indirect approach

- New particles can appear as virtual particles in loop and penguin diagrams.
- Indirect searches have a high sensitivity to effects from new particles.
  - Can see NP effects before the direct searches.
  - Indirect measurements can access higher scales.
- Possible to measure the phases of the new couplings
  - New physics at TeV scale must have a flavour structure to provide suppression of FCNC.

→ Complementary to direct searches.
• **Incredible success** of CKM paradigm in last decades.
• All measurements coherent with CKM of SM.
  • Accuracy of angles determined by experiment
  • Accuracy of sides determined by theoretical uncertainties
• But, SM fails to explain matter-antimatter asymmetry in the Universe
  • New physics must hold additional sources of CP violation
• Effects are small but there is still room for NP effects.
  • Precision measurement of CKM elements.
  • Comparison between tree and penguin decays.
  • Not all CKM angles well constrained (e.g. $\gamma$ and $\beta_s$).

→ **CP violation and rare decays** of B hadrons and charm are the main focus of LHCb

😊 Large amounts of clean data available
😊 Precision tests: allow to look for small effects beyond SM

From CKMFitter

Current fit results:

$$\bar{\rho} = 0.144^{+0.023}_{-0.026}$$
$$\bar{\eta} = 0.343^{+0.015}_{-0.014}$$

(excl. at CL > 0.95)
LHCb detector

LHCb made for Heavy Flavour physics

- Good vertex resolution
  - Time-dependent measurements.
  - Suppress background from prompt decays.
- Good particle identification
  - Important for trigger, flavour tagging
  - Suppress background.
- Good momentum resolution
  - Mass resolution of heavy flavours.
  - Suppress background.

Tracking stations
- Velo
- RICH1+2
- Muon
- Calo
LHCb detector

- High $B$ hadron production at LHC
  - $\sigma_{bb} = 284 \pm 53 \, \mu b \ (\sqrt{s} = 7 \, \text{TeV}) \ [\text{PLB 694 209}]$
- Forward spectrometer
  - Most $B$ hadrons produced along beam axis.
  - Acceptance: $2 < \eta < 5$. Complementary to GPD’s.
  - Vertex detector close to beam.
  - Easy access to planar subdetectors.

Angular coverage optimised for $B$-physics.
Collaboration

760 members
15 countries
54 institutes
• LHCb recorded 1.1 fb$^{-1}$ in 2011
  • Data taking ended on 30 Oct.
  • Only ~340 pb$^{-1}$ used for most results shown here.
• Data taken with high efficiency ~90%
• Offline data quality rejects < 1%
• Sub-detectors all with > 98% active channels.

Luminosity leveling
• LHCb already running above design lumi
  • Average L$\sim$$3\times10^{32}$ cm$^{-2}$s$^{-1}$ (nominal $2\times10^{32}$)
• Need to cope with higher occupancies
  • More pile-up: average $\mu$~1.5 (nominal 0.5)
• Continuous, automatic adjustment of offset of colliding beams.
• Allows optimal conditions throughout a fill.
• VELO sensors only 8 mm from beam.
• Impact parameter resolution = 12 µm for high $p_T$ tracks.
• Good primary and secondary vertex resolution.
  • Suppress background from prompt decays.
• Good proper-time resolution
  • Important for time-dependent measurements.

Primary vertex resolution

for 25 tracks:
$\sigma_x \approx 16 \mu m$
$\sigma_y \approx 16 \mu m$
$\sigma_z \approx 76 \mu m$

VELO tomography with hadronic vertices

Decay time in $B_s \to J/\psi \phi$

Resolution from prompt $J/\psi$: $\sigma_t = 50$ fs

LHCb Preliminary
$\sqrt{s} = 7$ TeV, $L = 337$ pb$^{-1}$

$LHCb-CONF-2011-049$
Detector performance: PID

- Particle ID with RICH detectors
  - Kaon ID efficiency ≈ 96%,
  - misID π→K ≈ 7%
- Particle ID with Muon detector
  - Muon ID efficiency 97.3±1.2% (p>4 GeV/c)
  - misID π→μ ≈ 2.4%, p→μ ≈ 0.18%

Flavour tagging
- Tagging of production flavour (B or B̄)
- Important for mixing & CP analyses.
- Performance calibrated using control channels such as \( B^+ \rightarrow J/\psi K^+ \)
- Tagging power: \( \epsilon(1-2\omega)^2 = \)
  - (3.2 ± 0.8) % (opposite side)
  - (1.3 ± 0.4) % (same side)
from \( B_s \rightarrow D_s \pi \) mixing analysis preliminary [LHCb-CONF-2011-049]
Detector performance: mass resolution

- Integrated Bdl ~ 4 Tm
- Accurate field map and alignment
- Momentum resolution 0.4–0.6 %
- Mass resolution $J/\psi$: 13 MeV
  - MC: 10 MeV
→ Accurate mass measurements.

### Measured B masses [MeV/c²]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Mass [MeV/c²]</th>
<th>Error [MeV/c²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(B^+ \to J/\psi K^+)$</td>
<td>5279.27</td>
<td>0.11 (stat) ± 0.20 (syst)</td>
</tr>
<tr>
<td>$M(B^0 \to J/\psi K^{*0})$</td>
<td>5279.54</td>
<td>0.15 (stat) ± 0.16 (syst)</td>
</tr>
<tr>
<td>$M(B^0 \to J/\psi K_S^{*0})$</td>
<td>5279.61</td>
<td>0.29 (stat) ± 0.20 (syst)</td>
</tr>
<tr>
<td>$M(B^0_s \to J/\psi \Lambda)$</td>
<td>5366.60</td>
<td>0.28 (stat) ± 0.21 (syst)</td>
</tr>
<tr>
<td>$M(\Lambda_b \to J/\psi \Lambda)$</td>
<td>5619.49</td>
<td>0.70 (stat) ± 0.19 (syst)</td>
</tr>
<tr>
<td>$M(B^+_c \to J/\psi \pi^+)$</td>
<td>6268.0</td>
<td>4.0 (stat) ± 0.6 (syst)</td>
</tr>
</tbody>
</table>

**PDG**

5279.17 ± 0.29

**World-best mass measurements! (2010 data only)**
Measurement of $\Delta m_s$

- $\Delta m_s$: $B_s$-$\bar{B}_s$ mixing frequency using $B_s \rightarrow D_s \pi$
  - Flavour specific final state
  - High branching ratio (~0.3%)
- Important to resolve the fast $B_s$ oscillations.
  - Average decay time resolution ~45 fs
- Event selection based on kaon ID, track IP and vertex $\chi^2$
- $\Delta m_s$ extracted from unbinned ML fit to $B_s \rightarrow D_s \pi$ candidates
  - Uses mass, decay time and flavour tagging
  - Method includes now same side tagging (cf 2010 fit)

Event yield in 340 pb$^{-1}$

<table>
<thead>
<tr>
<th>decay mode</th>
<th>signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow D_s^- (\phi \pi^-) \pi^+$</td>
<td>4371 ± 91</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow D_s^- (K^* K^-) \pi^+$</td>
<td>2910 ± 89</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow D_s^- \pi^+$ non-resonant</td>
<td>1908 ± 74</td>
</tr>
<tr>
<td>total yield</td>
<td>9189 ± 147</td>
</tr>
</tbody>
</table>

\[\Delta m_s:\] $B_s-\bar{B}_s$ mixing frequency using $B_s \rightarrow D_s \pi$

- Flavour specific final state
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Measurement of $\Delta m_s$

$B_s$ oscillations

$\Delta m_s = 17.725 \pm 0.041\text{(stat)} \pm 0.025\text{ (sys)} \text{ ps}^{-1}$

Dilution of mixing amplitude from tagging and proper time

Dominant systematics uncertainty: $z$-scale and momentum scale

LHCb preliminary

$\sqrt{s} = 7\text{ TeV}, 341\text{ pb}^{-1}$

OST+SST

Most precise measurement of $\Delta m_s$

Preliminary

CDF 2006

LHCb 2010

LHCb 2011

WA
Measurement of $\phi_s$ from $B_s \to J/\psi \phi/f_0$

- $\phi_s$: interference phase between $B_s$ mixing and $b \to c\bar{c}s$ decay.
  - Small penguin pollution.
  - $B_s$ counterpart of $B_d \to J/\psi K^0$.
- Small in SM: $\phi_s = -0.036 \pm 0.002$
  - Prediction from CKMfitter 2011
  - New particles in box diagrams can modify measured phase $\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}$
Measurement of $\phi_s$

**Two decay modes**

### $B_s \to J/\psi \phi$

- **LHCb-CONF-049**
- **Diagram:** 
  - $B_s^0 \to J/\psi \phi(1020) \to K^+K^-$
- **Notes:**
  - ☀️ Narrow $\phi$ resonance (clean)
  - ☃️1 Vector-vector final state (requires angular analysis)

### $B_s \to J/\psi f_0(980)$

- **LHCb-CONF-051**
- **Diagram:** 
  - $B_s^0 \to J/\psi f_0(980) \to \pi^+\pi^-$
- **Notes:**
  - ☀️ CP odd final state (no angular analysis)
  - ☃️2 BR about 20% of $B_s \to J/\psi \phi$

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**First seen by LHCb last winter**

- **~8300 events**
- **~1400 events**
**Measurement of $\phi_s$**

Angular analysis of $B_s \rightarrow J/\psi \phi$

$B_s \rightarrow J/\psi \phi$ has vector-vector final state:
- Mixture of CP-odd and CP-even decay amplitudes
- Even and odd amplitudes can be disentangled using decay angles.

Decay amplitudes used in fit:

\[
\begin{align*}
A_0 & \quad \text{even} \\
A_\perp & \quad \text{even} \\
A_\parallel & \quad \text{odd} \\
A_s & \quad \text{odd} \\
\end{align*}
\]

- $A_0$ and $A_\perp$ are P wave
- $A_\parallel$ and $A_s$ are S wave
  - (non resonant $K^+K^-$)
Measurement of $\phi_s$

Angular analysis of $B_s \rightarrow J/\psi \phi$

PDF of unbinned ML fit described as:

$$\sum_{k=1}^{10} h_k(t; \phi_s, \Gamma_s, \Delta \Gamma_s) f_k(\theta, \psi, \phi)$$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$h_k(t)$</th>
<th>$f_k(\theta, \psi, \phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>2</td>
<td>$</td>
<td>A_\parallel(t)</td>
</tr>
<tr>
<td>3</td>
<td>$</td>
<td>A_\perp(t)</td>
</tr>
<tr>
<td>4</td>
<td>$\Im(A_\parallel(t)A_\perp(t))$</td>
<td>$- \sin^2 \psi \sin \theta \sin \phi \cos \phi$</td>
</tr>
<tr>
<td>5</td>
<td>$\Re(A_0(t)A_\parallel(t))$</td>
<td>$\sqrt{2} \sin 2 \psi \sin \theta \sin 2 \phi$</td>
</tr>
<tr>
<td>6</td>
<td>$\Im(A_0(t)A_\parallel(t))$</td>
<td>$\sqrt{2} \sin 2 \psi \sin \theta \cos \phi$</td>
</tr>
<tr>
<td>7</td>
<td>$</td>
<td>A_\phi(t)</td>
</tr>
<tr>
<td>8</td>
<td>$\Re(A_\phi^*(t)A_\parallel(t))$</td>
<td>$\frac{\sqrt{3}}{2} \sin \psi \sin \theta \sin 2 \phi$</td>
</tr>
<tr>
<td>9</td>
<td>$\Im(A_\phi^*(t)A_\parallel(t))$</td>
<td>$\frac{\sqrt{3}}{2} \cos \psi \sin \theta \cos \phi$</td>
</tr>
<tr>
<td>10</td>
<td>$\Re(A_\phi^*(t)A_0(t))$</td>
<td>$\frac{\sqrt{3}}{2} \cos \psi \left(1 - \sin^2 \theta \cos^2 \phi\right)$</td>
</tr>
</tbody>
</table>

- $|A_0|^2(t) = |A_0|^2 e^{-\Gamma t} \left[\cos\left(\frac{\Delta \Gamma}{2}t\right) + \sin\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$, $\cos\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)$
- $|A_\parallel|^2(t) = |A_\parallel|^2 e^{-\Gamma t} \left[\cos\left(\frac{\Delta \Gamma}{2}t\right) - \sin\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$, $\sin\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)$
- $|A_\perp|^2(t) = |A_\perp|^2 e^{-\Gamma t} \left[\cos\left(\frac{\Delta \Gamma}{2}t\right) + \cos\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$, $\sin\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)$
- $\Im(A_\parallel(t)A_\perp(t)) = |A_\parallel||A_\perp|e^{-\Gamma t} \left[-\cos(\delta_\perp - \delta_\parallel) \sin \phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$ $- \cos(\delta_\perp - \delta_\parallel) \sin \phi_s \sin(\Delta \Gamma t) + \sin(\delta_\perp - \delta_\parallel) \cos(\Delta \Gamma t)$
- $\Re(A_0(t)A_\parallel(t)) = |A_0||A_\parallel|e^{-\Gamma t} \cos(\delta_\parallel - \delta_0) \left[\cos\left(\frac{\Delta \Gamma}{2}t\right) - \cos \phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$ $+ \sin \phi_s \sin(\Delta \Gamma t)$
- $\Im(A_0(t)A_\parallel(t)) = |A_0||A_\parallel|e^{-\Gamma t} \left[-\cos(\delta_\parallel - \delta_0) \sin \phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$ $- \cos(\delta_\parallel - \delta_0) \cos \phi_s \sin(\Delta \Gamma t) + \sin(\delta_\parallel - \delta_0) \cos(\Delta \Gamma t)$
- $|A_\phi|^2(t) = |A_\phi|^2 e^{-\Gamma t} \left[\cos\left(\frac{\Delta \Gamma}{2}t\right) + \cos\phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$, $\sin \phi_s \sin(\Delta \Gamma t)$
- $\Re(A_\phi^*(t)A_\parallel(t)) = |A_\phi||A_\parallel|e^{-\Gamma t} \left[-\sin(\delta_\parallel - \delta_0) \sin \phi_s \sin\left(\frac{\Delta \Gamma}{2}t\right)\right]$ $- \sin(\delta_\parallel - \delta_0) \cos \phi_s \sin(\Delta \Gamma t) + \cos(\delta_\parallel - \delta_0) \cos(\Delta \Gamma t)$
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Complicated PDF: 3 independent implementations in LHCb
Main systematic errors from uncertainties in the description of angular and decay time acceptance and background angular distribution.
Measurement of $\phi_s$

Result of the two fits

$B_s \rightarrow J/\psi \phi$

Standard Model
(Lenz et. al, arXiv: 1008.1593)

$\sqrt{s} = 7$ TeV, $L = 337$ pb$^{-1}$

CL contours obtained using $\Gamma_s$ from $J/\psi \phi$.

Two solutions: PDF insensitive to

$(\phi_s, \Delta \Gamma_s) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s)$

$\phi_s^{J/\psi \phi} = 0.13 \pm 0.18$ (stat) $\pm 0.07$ (sys) rad,

$\Gamma_s = 0.656 \pm 0.009$ (stat) $\pm 0.008$ (sys) ps$^{-1}$,

$\Delta \Gamma_s = 0.123 \pm 0.029$ (stat) $\pm 0.011$ (sys) ps$^{-1}$.

$B_s \rightarrow J/\psi f_0(980)$

CL contours obtained using $\Gamma_s$ from $J/\psi \phi$.

CP-odd final state, cannot determine $\Gamma_s$ and $\Delta \Gamma_s$ simultaneously. When using both $\Gamma_s$ and $\Delta \Gamma_s$ from $B_s \rightarrow J/\psi \phi$:

$\phi_s = -0.44 \pm 0.44$(stat) $\pm 0.02$(syst)
Measurement of $\phi_s$

**Combined fit**

$\phi_s = -0.03 \pm 0.16$ (stat) $\pm 0.07$ (sys)

Preliminary
LHCb-CONF-2011-056

**Comparison with Tevatron**

Combined fit

$\phi_s^{J/\psi\phi} = -0.03$ $^{+0.16}_{-0.07}$ (stat) $^{+0.07}_{-0.07}$ (sys)

Preliminary results overlaid

68% CL
95% CL

**Next steps:**

- Resolve ambiguity by fitting S-wave phase in bins of $M(KK)$
  - Y. Xie et al., JHEP 0909:074 (2009)
- Include more data (2.5 times more data recorded)
- Include same-side tagging (~1.5x more tagging power)
  → Expect ~2x smaller statistical error.
Direct CP in $B_{d,s} \rightarrow K\pi$

Charmless charged two-body $B$ decays

Tree-penguin interference in $B_{d,s} \rightarrow K\pi$ decays allows to look for direct CP violation.

LHCb has a very good particle identification capability.

- Isolate decays contributing to $B \rightarrow hh'$ ($K,\pi,p$)

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

$$A_{CP}(B^0_s \rightarrow \pi K) = \frac{\Gamma(\bar{B}^0_s \rightarrow \pi^- K^+) - \Gamma(B^0_s \rightarrow \pi^+ K^-)}{\Gamma(\bar{B}^0_s \rightarrow \pi^- K^+) + \Gamma(B^0_s \rightarrow \pi^+ K^-)}$$
Direct $\mathcal{CP}$ in $B_{d,s} \to K\pi$

$B_{d,s} \to K^+\pi^-$: Clear asymmetry in raw distributions

$LHCb$ Preliminary
$s = 7$ TeV Data

$B^0 \to K^+\pi^-$

$\bar{B}^0 \to K^-\pi^+$

$LHCb$ Preliminary
$s = 7$ TeV Data

$B_s \to \pi^+K^-$

$\bar{B}_s \to \pi^-K^+$
Direct $CP$ in $B_{d,s} \rightarrow K\pi$

Raw asymmetry has to be corrected for detector and production asymmetry.

$$A_{RAW} = A_{CP} + A_{det} + \kappa \cdot A_{prod} = A_{CP} + A_{\Delta}$$

**Detector asymmetry**
- measured using charm control samples: $D^{*+} \rightarrow D^{0}(K\pi)\pi^{+}$, $D^{*+} \rightarrow D^{0}(KK)\pi^{+}$ and $D^{0} \rightarrow K\pi$.

**Production asymmetry**
- $\kappa$: dilution of $A_{prod}$ due to $B$ mixing, lifetime and acceptance $\kappa(B^0) \sim 0.3$, $\kappa(B_s^0) \sim -0.03$
- $A_{prod}$ measured using $B^0 \rightarrow J/\psi K^*(K\pi)$
  $$A_{prod}(B^0) = (-1.0 \pm 1.3)\%$$

**Interaction asymmetry**

<table>
<thead>
<tr>
<th>Asymmetries</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_I(K\pi)$</td>
<td>$-0.010 \pm 0.002$</td>
</tr>
<tr>
<td>$A_R(K\pi)$</td>
<td>$-0.0018 \pm 0.0002$</td>
</tr>
</tbody>
</table>

**Final correction factors:**
- $A_{\Delta}(B^0 \rightarrow K^+\pi^-) = (-0.7 \pm 0.6)\%$
- $A_{\Delta}(B^0_s \rightarrow \pi^+K^-) = (1.0 \pm 0.2)\%$
Direct $\mathbb{CP}$ in $B_{d,s} \rightarrow K\pi$

### $A_{CP}$ for $K\pi$ modes

$$A_{CP}(B^0 \rightarrow K\pi) = -0.088 \pm 0.011 \pm 0.008$$

→ Most precise, and first 5$\sigma$ observation of CP violation in hadronic machine.

$$A_{CP}(B_s \rightarrow \pi K) = 0.27 \pm 0.08 \pm 0.02$$

→ first 3$\sigma$ evidence of CP violation in $B_s^0 \rightarrow \pi K$

### Also measured BRs for CP eigenmodes

$$\mathcal{B}(B^0 \rightarrow K^+K^-) = (0.13^{+0.06}_{-0.05} \pm 0.07) \times 10^{-6}$$

$$\mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-) = (0.98^{+0.23}_{-0.19} \pm 0.11) \times 10^{-6}$$

→ First observation of $B_s \rightarrow \pi\pi$

Eventual goal to measure time-dependent asymmetries in e.g. $B_{(s)} \rightarrow \pi^+\pi^-$, $K^+K^-$

→ determine CKM angle $\gamma$ from loop decays

Compare to $\gamma$ measurements from tree decays, e.g.

- $B^{+/0} \rightarrow D^0K^{+/*}$: ADS+GLW and Dalitz method.
- $B_s \rightarrow D_sK$: Time-dependent, tagged analysis.

→ determine any contribution from new physics
Search for $B_{d,s} \rightarrow \mu^+ \mu^-$

The decay $B_{d,s} \rightarrow \mu^+ \mu^-$ provides sensitive probe for New Physics.

- Very rare decay (FCNC and helicity suppressed)
  \[ \text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9} \]  
  \[ \text{BR}(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.1 \pm 0.1) \times 10^{-10} \]  

- Sensitive to New Physics:
  - E.g. branching ratio in MSSM enhanced by sixth power of $\tan \beta$:
    \[ \text{BR}(B_{d,s} \rightarrow \mu^+ \mu^-) \sim \frac{\tan^6 \beta}{M_A^4} \]

Exclusion regions in MSSM (NUHM)

Recent excitement from CDF measurement:
\[ \text{BR}(B_s \rightarrow \mu^+ \mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8} \ (7 \ \text{fb}^{-1}) \]  
  arXiv:1107.2304

Blue: Allowed regions for given BR measurement
Selection & analysis strategy

- **Loose selection** to reduce data set
- Evaluate signal/background in a 2D-space of
  - Invariant mass $m_{\mu\mu}$
  - MVA classifier BDT combining kinematic and geometrical variables
- Data driven calibration through control channels and mass sidebands
- Normalize to channels with known BR
**Search for** $B_{d,s} \rightarrow \mu^+ \mu^-$

Expected mass resolution obtained from interpolation of dimuon resonances (from J/$\psi$ to $\Upsilon$'s)

$\sigma(B_s) = (24.6\pm0.2\pm1.0)$ MeV/c$^2$

$\sigma(B_d) = (24.3\pm0.2\pm1.0)$ MeV/c$^2$

- Mass distribution studied in 4 bins of BDT
- Expect ~ 1 event in each bin from SM.
- Main background from $b\bar{b}\rightarrow\mu\mu X$ and misidentified $B\rightarrow h^+h^-$

Small excess (2 events) in most sensitive bin, compatible with SM.
Search for $B_{d,s} \rightarrow \mu^+ \mu^-$
Search for $B_{d,s} \rightarrow \mu^+\mu^-$

The final branching ratio can be calculated as:

$$BR(B_{B_q}^0 \rightarrow \mu^+\mu^-) = BR_{\text{cal}} \times \frac{\varepsilon_{\text{cal}}}{\varepsilon_{\text{sig}}} \times \frac{f_{cal}}{f_{B_q^0}} \times \frac{N_{B_q^0 \rightarrow \mu^+\mu^-}}{N_{\text{cal}}} = \alpha_{\text{cal}} \times N_{B_q^0 \rightarrow \mu^+\mu^-}$$

Three complementary normalization channels with very different systematics:

- $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$
- $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- $B^0 \rightarrow K^+\pi^-$

Production ratio $f_s/f_d$ taken from LHCb's measurements using semileptonic and hadronic decays.

- Smaller error than HFAG average.
- Dominant systematic error.

$$\langle f_s / f_d \rangle = 0.267^{+0.021}_{-0.020}$$

<table>
<thead>
<tr>
<th></th>
<th>$B^+ \rightarrow J/\psi K^+$</th>
<th>$B_s^0 \rightarrow J/\psi \phi$</th>
<th>$B^0 \rightarrow K^+\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>$6.01 \pm 0.21$</td>
<td>$3.4 \pm 0.9$</td>
<td>$1.94 \pm 0.06$</td>
</tr>
<tr>
<td>$N_{\text{cal}}$</td>
<td>$107358 \pm 1759$</td>
<td>$5919 \pm 84$</td>
<td>$5732 \pm 506$</td>
</tr>
<tr>
<td>$\alpha_{cal}^{B_d \rightarrow \mu^+\mu^-}$</td>
<td>$2.58 \pm 0.16$</td>
<td>$3.39 \pm 0.98$</td>
<td>$2.47 \pm 0.57$</td>
</tr>
<tr>
<td>$\alpha_{cal}^{B_s \rightarrow \mu^+\mu^-}$</td>
<td>$0.966 \pm 0.096$</td>
<td>$1.27 \pm 0.35$</td>
<td>$0.92 \pm 0.22$</td>
</tr>
</tbody>
</table>

Values for $\alpha$ very compatible
Search for $B_{d,s} \rightarrow \mu^+ \mu^-$

- No significant excess observed in 0.3 fb$^{-1}$
- Upper limits (preliminary): [LHCb-CONF-2011-037]
  - $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-8}$ (95% CL)
  - $\text{BR}(B_d \rightarrow \mu^+ \mu^-) < 5.2 \times 10^{-9}$ (95% CL)

- CMS also set a limit this Summer with 1.1 fb$^{-1}$
  - $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.9 \times 10^{-8}$ (95% CL) arXiv:1107.5834

- LHCb + CMS analyses combined (preliminary)
  - $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-8}$ (95% CL)
  - This is $\sim 3.4 \times$ SM value
  - Most probable value $\sim 4 \times 10^{-9}$
  - Excess over SM not confirmed.

Future prospects

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Vienna Seminar, Particle physics and the LHC, 26.11.11
Status and physics at LHCb, Jeroen van Tilburg
Flipping the $b\rightarrow s$ diagram...

- $B_d \rightarrow \mu^+\mu^-K^*$ rare decay in the SM.
  - $\text{BR} (B_d \rightarrow l^+l^-K^*) \sim 1.0 \times 10^{-6}$
- SM diagrams can be easily modified in presence of NP
- Angular distributions contain a lot of information.
  - Many observables probe helicity structure of NP
- Zero crossing point of $A_{FB}(q^2)$ well predicted in SM
  - Hadronic uncertainties are minimized
- Sensitive to SUSY, graviton exchanges, extra dimensions...

$F_L$: fraction of $K^*$ long. pol.
$A_{FB}$: $\mu$ forward-backward asym.
$A_T^{(2)}$: transverse pol. asym.
$A_{im}$: $T$-odd $CP$ asym.
Results from CDF & B-factories show intriguing behaviour at low $q^2$:
→ however, precision is limited.

$A_{FB}$

$C_7 = -C_7^{SM}$
Angular distributions in $B_d \rightarrow \mu^+\mu^-K^*$

Event selection

- 309 pb$^{-1}$ in 2011
- 302 signal candidates
- B/S $\sim 0.3$

Selection using BDT

- BDT variables chosen to minimize acceptance effects
- Angular acceptance from MC
- Trained on $B_d \rightarrow J/\psi K^*$ for signal and mass sidebands for background

$LHCb$ Preliminary

302 signal events
Angular distributions in $B_d \rightarrow \mu^+ \mu^- K^*$

Angular fit

Not enough data yet to perform full angular analysis.

→ Measure in 6 $q^2$ bins:
  - $A_{FB}$
  - Longitudinal polarisation, $F_L$
  - Differential branching fraction $d\Gamma/dq^2$

→ Fit $A_{FB}$ and $F_L$ using the 1D projections of $\theta_\ell$ and $\theta_K$

$$
\frac{1}{\Gamma} \frac{d^2\Gamma}{d\cos \theta_\ell dq^2} = \frac{3}{4} F_L (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell
$$

$$
\frac{1}{\Gamma} \frac{d^2\Gamma}{d\cos \theta_K dq^2} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L) (1 - \cos^2 \theta_K)
$$

Used $B_d \rightarrow J/\psi K^*$ to validate fitting procedure and angular acceptance
Angular distributions in $B_d \to \mu^+ \mu^- K^*$

In bin $1 < q^2 < 6 \text{ GeV}^2$

**LHCb**
- $A_{FB} = -0.10^{+0.14}_{-0.14} \pm 0.05$
- $F_L = 0.57^{+0.11}_{-0.10} \pm 0.03$
- $d\mathcal{B}/dq^2 = 0.39 \pm 0.06 \pm 0.02$

**Theory**
- $A_{FB} = -0.04^{+0.03}_{-0.03}$
- $F_L = 0.74^{+0.06}_{-0.07}$
- $d\mathcal{B}/dq^2 = (0.50^{+0.11}_{-0.10}) \times 10^{-7}$
Angular distributions in $B_d \to \mu^+\mu^-K^*$

Data consistent with SM predictions at present sensitivity and indicate that $A_{FB}$ is changing sign as predicted by the SM (most recent CDF result also has negative first bin: arXiv:1108.0695)

Next steps
- Determine zero-crossing point in $A_{FB}(q^2)$
- Add phi angle and $A_T^{(2)}$
- Include full 2011 data set.
- With > 2 fb$^{-1}$ do full angular analysis

Already effective in constraining NP
arXiv:1111.1257
Charm physics

Mixing established in the charm sector. Next step: look for CP violation

- No mixing excluded at 10.2σ
- Presence of mixing allows to search for indirect CPV
- CP violation expected to be very small in SM
- Good place to look for new physics effects.

Many opportunities for charm physics at LHCb

- Dedicated trigger lines for charm decays
  - Yield of O(10^8) events per fb^-1
  - Flavour tag from charge of slow pion.
- Large statistics available
  - > 10^6 D^0 → K^+K^- from D^*+ → D^0 π^+

HFAG averages
x = (0.63 ± 0.19)%
y = (0.75 ± 0.12)%

D^0 → K^+K^-
Charm physics

\[ y_{CP} \text{ in } D^0 \rightarrow K^+K^- \text{ (CPV in mixing)} \]

\[ y_{CP} = \frac{\hat{\Gamma}(D^0 \rightarrow K^+K^-)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+)} - 1 \approx y \cos \varphi - x \frac{A^m}{2} \sin \varphi \]

Combined with measurement of \( y \) gives access to CPV.

Measurement (2010 only; 28 pb\(^{-1}\)):

\[ y_{CP} = (5.5 \pm 6.3_{stat} \pm 4.1_{syst}) \times 10^{-3} \]

\[ A_{\Gamma} \text{ in } D^0 \rightarrow K^+K^- \text{ (CPV in mixing)} \]

\[ A_{\Gamma} = \frac{\hat{\Gamma}(D^0 \rightarrow K^+K^-) - \hat{\Gamma}(\overline{D}^0 \rightarrow K^+K^-)}{\hat{\Gamma}(D^0 \rightarrow K^+K^-) + \hat{\Gamma}(\overline{D}^0 \rightarrow K^+K^-)} \approx -a_{\Gamma}^{ind} \]

Measurement (2010 only; 28 pb\(^{-1}\)):

\[ A_{\Gamma} = (-5.9 \pm 5.9_{stat} \pm 2.1_{syst}) \times 10^{-3} \]

LHCb is currently updating with more statistics.
Charm physics

**ΔA_{CP} in D^0 \rightarrow h^+h^- (CPV in decay)**

\[
\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta a_{CP}^{\text{dir}} - 0.1a_{CP}^{\text{ind}}
\]

Production and detector asymmetry cancel.
Measurement (2011 only; 580 pb\(^{-1}\)):

\[
\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})] \%
\]

Significance 3.5σ

First evidence of CP violation in charm sector!

New result!
Only presented last week at HCP

• 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.

• Will allow to increase luminosity by factor $\sim 5$ to $1-2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

• Requires replacing front-end electronics and part of tracking system. Planned for the long shutdown in 2018. Running for 10 years will then give $\sim 50 \text{ fb}^{-1}$

• Letter of Intent recently submitted to the LHCC. Physics case endorsed, detector R&D underway (e.g. scintillating-fibre tracking, TOF, …)
## LHCb Upgrade

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb (5 fb⁻¹)</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluonic penguin</td>
<td>$S(B_s \rightarrow \phi\phi)$</td>
<td>-</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$S(B_s \rightarrow K^{*0}\bar{K}^{*0})$</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$S(B^0 \rightarrow \phi K_S^0)$</td>
<td>0.17</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$B_s$ mixing</td>
<td>$2\beta_s (B_s \rightarrow J/\psi\phi)$</td>
<td>0.35</td>
<td>0.019</td>
<td>0.006</td>
<td>~ 0.003</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$S(B_s \rightarrow \phi\gamma)$</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$A^{\Delta s}(B_s \rightarrow \phi\gamma)$</td>
<td>-</td>
<td>0.14</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>E/W penguin</td>
<td>$A_T^{(2)}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>-</td>
<td>0.14</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>-</td>
<td>4%</td>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s \rightarrow \mu^+\mu^-)$</td>
<td>-</td>
<td>30%</td>
<td>8%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td></td>
<td>$\frac{B(B^0 \rightarrow \mu^+\mu^-)}{B(B_s \rightarrow \mu^+\mu^-)}$</td>
<td>-</td>
<td>-</td>
<td>~ 35%</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>$\gamma (B \rightarrow D^{(<em>)}\bar{K}^{(</em>)})$</td>
<td>~ 20°</td>
<td>~ 4°</td>
<td>~ 4°</td>
<td>0.9°</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s \rightarrow D_s\bar{K})$</td>
<td>-</td>
<td>~ 7°</td>
<td>1.5°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K^0)$</td>
<td>1°</td>
<td>0.5°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CPV</td>
<td>$A_\Gamma$</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$2 \times 10^{-4}$</td>
<td>$4 \times 10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$A_{CP}^{dir}(K\bar{K}) - A_{CP}^{dir}(\pi\pi)$</td>
<td>$4.3 \times 10^{-3}$</td>
<td>$4 \times 10^{-4}$</td>
<td>$8 \times 10^{-5}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Integrated luminosity of order 50 fb⁻¹ allows to measure NP effects below the % level.
Conclusion

- LHCb will have huge contribution to flavour physics in the years to come.
- LHCb will perform the precision measurements needed to see effects from new physics.
- The future will bring an even better understanding of our detector and much more statistics!
- Hope to see first hints from new physics soon.
- Expect more interesting results this Winter.

No time to mention:
- $B_s \rightarrow \phi \gamma$ and other radiative $B$ decays.
- Semileptonic $B$ decays
- Electroweak physics.
- Higgs and exotica.
- LFV tau decays
- And much, much more…