The LHCb Experiment: First Results and Prospects

Mitesh Patel (Imperial College London)
RAL PPD Seminar, 8th June 2011
Outline

• An extended Higgs sector? ($B_d \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \mu^+\mu^-$)

• New CP violating phases in $B_s$ mixing? ($\phi_s$ from $B_s \rightarrow J/\psi\phi$)

• New particles, couplings? (angular observables in $B_d \rightarrow K^*\mu\mu$)

• A whistlestop tour…

• Will try and give you a feel for the prospects in each of these areas
  – Results from 2010 data $\sim 36 \text{ pb}^{-1}$
  – As of yesterday, $\sim 224 \text{ pb}^{-1}$ on tape, expectation is $200 \text{ pb}^{-1} \sim 300 \text{ pb}^{-1}$ for summer conferences, $\sim 1 \text{ fb}^{-1} \sim ???$ by the end of the year
The decays

$$B_d \rightarrow \mu^+ \mu^- \text{ and } B_s \rightarrow \mu^+ \mu^-$$
Introduction

- The branching ratios of the decays $B_d \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \mu^+\mu^-$ allow the parameters of an extended Higgs sector to be probed.

- The decays are doubly suppressed in the SM:
  - FCNC
  - Helicity suppression

However, rates well calculable – in the SM,

$$B(B_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9} \quad B(B_d \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

[Buras et al., arXiv:1007.5291]

- Sensitive to NP contributions in the scalar/pseudo-scalar sector:

$$\left( c_{S,P}^{MSSM} \right)^2 \propto \left( \frac{m_b m_\mu \tan^3 \beta}{M_A^2} \right)^2 \quad \text{MSSM, large tan}\beta \text{ approximation}$$
Motivation

• “fully complementary to direct searches at ATLAS/CMS”

\[ \tan\beta \text{ vs } M_A \text{ plane} \]

5\(\sigma\) discovery contours for observing the heavy MSSM Higgs bosons H, A in the three decay channels \( H, A \rightarrow \tau^+\tau^- \rightarrow \text{jets (solid line), jet}+\mu \) (dashed line), jet+e (dotted line) assuming 30-60 fb\(^{-1}\) collected by CMS.

Best fit contours in \( \tan\beta \) vs \( M_A \) plane in the NUHM1 model

[O. Buchmüller et al., arxiv:0907.5568]
Motivation

- “fully complementary to direct searches at ATLAS/CMS”

Measuring $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ at the $1 \times 10^{-8}$ level would be like probing similar region to that of $H,A \rightarrow \tau^+ \tau^-$ search with 30-60 fb$^{-1}$

- Believe this is possible with 2011 data, O(1fb$^{-1}$)

[F. Mahmoudi, arXiv: 08083144]
Current Experimental Results

- Limits from Tevatron @ 95% CL:
  - CDF (~3.7 fb$^{-1}$): $B_s (B_d) \to \mu^+ \mu^- < 43 \times 10^{-9}$
  - D0 (~6.1 fb$^{-1}$): $B_s \to \mu^+ \mu^- < 51 \times 10^{-9}$

CDF 6.9 fb$^{-1}$ exp, Beauty 2011
The Experimental Environment

• $\sigma_{\text{pp, inelastic}} @ \sqrt{s}=7$ TeV $\sim 60$ mb, only $1/200$ events contains a $b$ quark, looking for BR $\sim 10^{-9}$

• In nominal conditions LHCb would operate at an instantaneous luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, $50 \times$ lower than ATLAS/CMS, with a mean number of pp interactions per crossing $\sim 0.5$

• However, during 2010 pilot run, reduced number bunches; to get high luminosity $\rightarrow$ smaller $\beta^*$
  – Mean number of pp interactions per crossing up to $2.5$ ($5 \times$ design!)
  – Instantaneous luminosity $\sim 10^{32}$ cm$^{-2}$s$^{-1}$

• 2011 data-taking
  – Mean number of pp interactions of $1.5$ ($3 \times$ design)
  – Instantaneous luminosity $3 \times 10^{32}$ cm$^{-2}$s$^{-1}$ ($1.5 \times$ design)
  – Using “luminosity leveling” to keep this constant during fill
- 80 tracks per event in ‘high’-pile-up conditions (~2.5 pp interactions crossing)

Expect $0.7 \pm 0.08$ $B_s(B_d) \rightarrow \mu^+\mu^-$ events triggered and reconstructed in 37 pb$^{-1}$ if $BR = BR(SM)$ – is all about the background

The Experimental Environment

LHCb event display

Expect $0.7 \pm 0.08$ $B_s(B_d) \rightarrow \mu^+\mu^-$ events triggered and reconstructed in 37 pb$^{-1}$ if $BR = BR(SM)$ – is all about the background
The LHCb Detector
Key ingredients for $B_{s,d} \rightarrow \mu^+ \mu^-$

- Efficient trigger:
  - to identify leptonic final states

- Background reduction:
  - Excellent vertex & IP resolution: $\sigma(\text{IP}) \sim 25 \, \mu\text{m} \, @ \, p_T=2 \, \text{GeV/c}$
  - Particle identification: $\varepsilon(\mu \rightarrow \mu) \sim 97\%$ for $\varepsilon(h \rightarrow \mu)<1\%$ for $p>10 \, \text{GeV/c}$
  - Very good mass resolution: $\delta p/p \sim 0.35\% \rightarrow 0.55\%$ for $p=(5-100) \, \text{GeV/c}$

Signal = $2872 \pm 73 \, \sigma = (15.0 \pm 0.4) \, \text{MeV}$
Trigger for $B_{s,d} \rightarrow \mu^+ \mu^-$

- Half of the available 2 kHz bandwidth is given to the muon lines.
- $p_T$ cuts on muons kept low $\rightarrow \varepsilon(\text{trigger } B_{s,d} \rightarrow \mu^+ \mu^-) \sim 90\%$

### Muon Lines

<table>
<thead>
<tr>
<th>Level</th>
<th>Cut Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>Single-$\mu$: $p_T &gt; 1.4$ GeV/c [\mu\mu: p_{T1} &gt; 0.48$ GeV/c $p_{T2} &gt; 0.56$ GeV/c</td>
</tr>
<tr>
<td>HLT1</td>
<td>single-$\mu$: $p_T &gt; 0.8$ GeV/c IP &gt; 0.11 mm IPS &gt; 5</td>
</tr>
<tr>
<td>HLT2</td>
<td>Several di-muon lines with $M_{\mu\mu}$ cuts and/or displaced vertex</td>
</tr>
</tbody>
</table>

+ Global Event Cuts for events with high multiplicity
Analysis Strategy

• **Soft selection:**
  – Reduces the dataset to a manageable level

• **Discrimination between S and B via MultiVariate Discriminant variable (GL) and Invariant Mass (IM):**
  – Events in the sensitive region are classified in bins of the 2D plane Invariant Mass-GL

• **Normalisation:**
  – Convert the signal PDFs into a number of expected signal events by normalising to (several) channels of known BR

• **Extraction of the limit:**
  – Assign to each observed event a probability to be S+B or B-only as a function of the BR($B_{s,d} \rightarrow \mu^+\mu^-$) value; exclude (observe) the assumed BR value at a given confidence level using the **CLs binned method**
Soft Selection

- Isolate pairs of opposite charged muons with high quality tracks, which make a common vertex, displaced with respect to the primary proton-proton vertex (PV), with $M_{\mu\mu}$ in the range 4769-5969 MeV/c$^2$

- Keeps high efficiency for signal events

- Rejects the majority of bkgrd events
  - $\sim 3000$ background events in the large mass range 4769-5969 MeV/c$^2$
  - $\sim 300$ background events in the signal windows $m(B_{s,d}) \pm 60$ MeV/c$^2$

Signal regions blinded until analysis frozen
μ-ID performance & bkgrd composition

- μ-ID performance measured with samples of $\psi \to \mu \mu$, $K_s \to \pi \pi$, $\phi \to KK$, $\Lambda \to p\pi$

\begin{align*}
\text{Efficiency } &\sim (97.1 \pm 1.3)\% \\
\text{In the } B_q \to \mu \mu \ p \text{ range:} \\
\epsilon(\pi \to \mu) &\sim (7.1\pm0.5) \times 10^{-3} \\
\epsilon(hh \to \mu \mu) &\sim (3.5\pm0.9) \times 10^{-5}
\end{align*}

- Background is dominated by $bb \to \mu \mu X$ component i.e. double semileptonic decays and cascade processes
  - Mis-id $\mu$ + genuine $\mu \sim 10\%$ and double mis-id $\mu \sim 0.3\%$
  - Peaking bkgrd from $B \to hh'$ negligible, expect <0.1 evts in signal region
MVA: Geometrical Likelihood

- Main bkgrd is combinatorial, with two genuine muons

- Reduce by using variables related to the event geometry
  - vertex, pointing, $\mu$ IPS, lifetime, mu-isolation, B $p_T$

- Variables are decorrelated and the geometric likelihood (GL) built:
  - flat for signal
  - peaked at zero for bkgrd

Input Variables to the GL

- MC $B_{d,s} \rightarrow \mu\mu$
- MC $bb \rightarrow \mu\mu X$
MVA: Geometrical Likelihood

- Main bkgrd is combinatorial, with two genuine muons

- Reduce by using variables related to the event geometry
  - vertex, pointing, $\mu$ IPS, lifetime, mu-isolation, $B p_T$

- Variables are decorrelated and the geometric likelihood (GL) built:
  → flat for signal
  → peaked at zero for bkgrd
Measuring the BR

- Use the $\text{CL}_s$ binned method
  - For each bin in the GL vs mass plane, the compatibility of the observed number of events with,
    - S+B [$\text{CL}_{S+B}$]
    - B only [$\text{CL}_B$]
  hypotheses is computed
- Get expected background from mass sidebands (in bins GL)
- For expected signal need mass and GL PDFs and an absolute normalisation
Expected Bkgrd in Signal Regions

- The expected background events in the signal plane is extracted from a fit of the mass sidebands divided into the appropriate GL bins.

Expected (observed) background events in $B_{s,d}$ mass regions

<table>
<thead>
<tr>
<th>GL bin</th>
<th>$B_s \rightarrow \mu\mu$</th>
<th>$B_d \rightarrow \mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bin1</td>
<td>329.1$\pm$6.4 (335)</td>
<td>351.6$\pm$6.6 (333)</td>
</tr>
<tr>
<td>bin2</td>
<td>7.4 $\pm$ 1 (7)</td>
<td>8.3$^{+1.1}_{-1.0}$ (8)</td>
</tr>
<tr>
<td>bin3</td>
<td>1.51$^{+0.41}_{-0.35}$ (1)</td>
<td>1.85$^{+0.45}_{-0.39}$ (1)</td>
</tr>
<tr>
<td>bin4</td>
<td>0.08$^{+0.10}_{-0.05}$ (0)</td>
<td>0.13$^{+0.13}_{-0.07}$ (0)</td>
</tr>
</tbody>
</table>
Signal Invariant Mass Calibration

- The $B_{s,d}$ mass line shapes are described by Crystal Ball function
- Parameters ($\mu, \sigma$) calibrated with $B \rightarrow hh'$ and di-muon resonances
  - $B \rightarrow hh'$ has similar kinematics/topology, select w/o PID → same seln
  - Interpolate from $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ to $B$ mass
    $\rightarrow \sigma(M) = 26.7 \pm 0.9 \text{ MeV/c}^2$

![Graphs showing invariant mass distributions for various $B$ decay modes]
Geometrical Likelihood calibration

- **B → hh’** sample is also used to calibrate the GL

  - The GL signal shape is given by the fractional yield of **B → hh’** in each GL bin

- GL shape for signal extracted from **B → hh’** is flat as expected
- Systematic error dominated by the fit model

![Graphs showing signal and background distributions with corresponding yields and fits.](image-url)
Normalisation

- The signal PDFs can be translated into a number of expected signal events by normalising to a channel with known BR

- Three different channels used:
  - 1) $\text{BR}(B^+ \rightarrow J/\psi(\mu^+\mu^-) K^+) = (5.98\pm0.22)\times10^{-5}$, 3.7% uncertainty
    - Similar trigger and PID. Tracking efficiency (+1 track) dominates the systematic in the ratio of efficiencies. Needs $f_d/f_s$ as input (13% uncertainty)
  - 2) $\text{BR}(B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)) = (3.35\pm0.9)\times10^{-5}$, 26% uncertainty
    - Similar trigger and PID. Tracking efficiency (+2 tracks) dominates the syst.
  - 3) $\text{BR}(B^0 \rightarrow K^+\pi^-) = (1.94\pm0.06)\times10^{-5}$, 3.1% uncertainty
    - Same topology as the signal. Different trigger dominates the syst. Needs $f_d/f_s$

- All three normalisation channels give compatible results:
  → Weighted avge accounting for correlated systematic uncertainties
**Results : \( B_s \rightarrow \mu^+ \mu^- \)**

<table>
<thead>
<tr>
<th></th>
<th>@ 90% CL</th>
<th>@ 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHCb</strong></td>
<td>(&lt; 43 (51) \times 10^{-9})</td>
<td>(&lt; 56 (65) \times 10^{-9})</td>
</tr>
<tr>
<td><strong>D0</strong></td>
<td>(&lt; 42 \times 10^{-9})</td>
<td>(&lt; 51 \times 10^{-9})</td>
</tr>
<tr>
<td><strong>CDF</strong></td>
<td>(&lt; 36 \times 10^{-9})</td>
<td>(&lt; 43 \times 10^{-9})</td>
</tr>
</tbody>
</table>

- **LHCb**
  - Observed (expected), \(37 \text{ pb}^{-1}\)
  - Expected upper limit
  - Very close to the best world’s best limits from Tevatron with ~100 (CDF) -200 (D0) times less luminosity

- **D0**
  - World best published, \(6.1 \text{ fb}^{-1}\)
  - Preliminary, Note 9892

- **CDF**
  - Preliminary, \(3.7 \text{ fb}^{-1}\)
  - Preliminary, Note 9892

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**CLs vs \( B(B_s \rightarrow \mu \mu) \)**

**Observed upper limit**

68% of possible experiments compatible with expected limit

90% exclusion

95% exclusion

**LHCb**

Expected upper limit
Results: $B_d \to \mu^+\mu^-$

<table>
<thead>
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<th>@ 90% CL</th>
<th>@ 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHCb</strong></td>
<td>Observed (expected), 37 pb$^{-1}$</td>
<td>$&lt; 12 \ (14) \times 10^{-9}$</td>
</tr>
<tr>
<td><strong>CDF</strong></td>
<td>World best, 2 fb$^{-1}$</td>
<td>$&lt; 15 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>PRL 100 101802 (2008)</td>
<td></td>
</tr>
<tr>
<td><strong>CDF</strong></td>
<td>Preliminary, 3.7 fb$^{-1}$</td>
<td>$&lt; 7.6 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>Note 9892</td>
<td></td>
</tr>
</tbody>
</table>

LHCb

Expected upper limit

CLs vs BR($B_d \to \mu \mu$)

68% of possible experiments compatible with expected limit

@ 90% CL

@ 95% CL

90% exclusion

95% exclusion
\( B_s \rightarrow \mu^+ \mu^- : \text{reach in 2011} \)

- With the data collected in 2011 we should be able to explore BR\( \sim 10^{-8} \) and below

\[ \begin{align*}
\text{BR} \times 10^9 & \leq 5.6 \times 10^{-8} \quad \text{(today)} \\
& \leq 2 \times 10^{-8} \quad \text{(summer 2011)} \\
& \leq 1 \times 10^{-8} \quad \text{(autumn 2011)} \\
& \leq 5 \times 10^{-9} \quad \text{(end 2011?)}
\end{align*} \]
The CPV Phase $\phi_s$
$B_s \to J/\psi \phi$ – Introduction

- $B_s \to J/\psi \phi$ decay dominated by $b \to c \bar{c} s$ transition
  - small penguin contribution, $\delta P$

- Interference between decay or mixing and then decay results in CP violating phase:
  - $\phi_S = \phi_M - 2\phi_D$

- SM prediction:
  - $\phi_S = -2\beta_s + \delta P \sim -2\beta_s = 0.04$

- $J/\psi \phi$ is not a CP eigenstate
  → required angular analysis (in transversity base) to statistically separate CP-even/odd
Experimental Status

<table>
<thead>
<tr>
<th>Signal yield (lumi)</th>
<th>$\phi^{J/\psi \phi}_{\tau}$ (rad)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF 6500 (5.2 pb$^{-1}$)</td>
<td>$-0.54 \pm 0.50^{(*)}$</td>
<td>CDF Note 10206</td>
</tr>
<tr>
<td>DØ 3400 (6.1 fb$^{-1}$)</td>
<td>$-0.76^{+0.38}_{-0.36}$ (stat) $\pm 0.02$ (syst)</td>
<td>DØ 6098-CONF</td>
</tr>
</tbody>
</table>

(*) CDF quotes $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ rad at 68% CL. "$-0.54 \pm 0.50$" is my estimate.
Principle of the measurement

- $P \rightarrow VV$, ang. mom. $\rightarrow$ in the B rest frame $J/\psi$ and $\phi$ have $l=0,1,2$
- $CP\mid J/\psi \phi \rangle = (-1)^l \mid J/\psi \phi \rangle \rightarrow$ mixture CP-even ($l=0,2$), CP-odd ($l=1$)
- Decay ampl. in terms of linear polarization when $J/\psi$ and $\phi$ are:
  - $A_\perp$ transversely polarised and $\perp$ to each other (CP-odd)
  - $A_\parallel$ transversely polarised and $\parallel$ to each other (CP-even)
  - $A_0$ longitudinally polarised (CP-even)
  - Three angles $\Omega=(\theta, \phi, \psi)$ describe directions of the $J/\psi$ and $\phi$

Signal event distribution:

$$S(\lambda, t, \Omega) = \epsilon(t, \Omega) \times \left( \frac{1 + qD}{2} \cdot s(\lambda, t, \Omega) + \frac{1 - qD}{2} \cdot \bar{s}(\lambda, t, \Omega) \right) \otimes R_t$$

Flavor tagging

acceptance

Physics parameters:

$$\lambda = (\Gamma_s, \Delta \Gamma_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp, \phi_s, \Delta m_s)$$

$$\Delta m_s = 17.77 \pm 0.12 \text{ ps}^{-1} \text{ (constraint)}$$
Road towards $\phi_S$ at LHCb

- Select signal and control channels
  - Determine lifetimes for: $B_s \rightarrow J/\psi \phi$, $B_d \rightarrow J/\psi K^*$, $B_d \rightarrow J/\psi K_S$, $\Lambda_b \rightarrow J/\psi \Lambda$

- Angular analysis and determination of $\Delta \Gamma_s$
  - Angular analysis of $B_d \rightarrow J/\psi K^*$
  - Untagged angular analysis of $B_s \rightarrow J/\psi \phi$

- Determination of $B$ production flavour
  - Determination of $B_s$ mixing frequency $\Delta m_s$

- Determination of $\phi_S$
  - Tagged analysis of $B_s \rightarrow J/\psi \phi$ decays
Selecting signal & control channels

• Similar selection for all channels: $B_s \rightarrow J/\psi \phi$, $B^+ \rightarrow J/\psi K^+$, $B_d \rightarrow J/\psi K^*$, $B_d \rightarrow J/\psi K_S$, $\Lambda_b \rightarrow J/\psi \Lambda \rightarrow$ Cross-check and systematics

• No lifetime biasing cuts (IP, decay length… ) $\rightarrow$ significant prompt background at small proper time

• Plots with $t>0.3\text{ps}$, $J/\psi$ mass constrained:

  - $B_s \rightarrow J/\psi \phi$
  - $B^0 \rightarrow J/\psi K^*$
  - $B^- \rightarrow J/\psi K^+$

  → Excellent mass resolution and low background
t resolution and t acceptance

- Prompt J/ψ separated from background using s-plot technique, use to extract proper time resolution
- Proper time acceptance also computed from data by using ratio between events selected with and without proper time bias
Lifetime measurements

\[ B^+ \rightarrow J/\psi \ K^+ \]

\[ B_d \rightarrow J/\psi \ K^* \]

\[ B_d \rightarrow J/\psi \ K^0_S \]

\[ B_S \rightarrow J/\psi \ \phi \]

\[ \Lambda_b \rightarrow J/\psi \ \Lambda \]

$36 \text{ pb}^{-1}$

Fit with single exponential

Unbiased trigger only

Systematics currently dominated by proper time acceptance uncertainty.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Yield</th>
<th>LHCb result $\tau [\text{ps}]^*$</th>
<th>PDG $\tau [\text{ps}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/\psi K^+$</td>
<td>$6741 \pm 85$</td>
<td>$1.689 \pm 0.022_{\text{stat.}} \pm 0.047_{\text{syst.}}$</td>
<td>$1.638 \pm 0.011$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^{*0}$</td>
<td>$2668 \pm 58$</td>
<td>$1.512 \pm 0.032_{\text{stat.}} \pm 0.042_{\text{syst.}}$</td>
<td>$1.5252 \pm 0.009$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^0_S$</td>
<td>$838 \pm 31$</td>
<td>$1.558 \pm 0.056_{\text{stat.}} \pm 0.022_{\text{syst.}}$</td>
<td>$1.525 \pm 0.009$</td>
</tr>
<tr>
<td>$B_S^0 \rightarrow J/\psi \phi$</td>
<td>$570 \pm 24$</td>
<td>$1.447 \pm 0.064_{\text{stat.}} \pm 0.056_{\text{syst.}}$</td>
<td>$1.477 \pm 0.046$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow J/\psi \ \Lambda$</td>
<td>$187 \pm 16$</td>
<td>$1.353 \pm 0.108_{\text{stat.}} \pm 0.035_{\text{syst.}}$</td>
<td>$1.391_{-0.037}^{+0.038}$</td>
</tr>
</tbody>
</table>
Angular Analysis & Acceptance Corrections

- Angular analysis in transversity basis:
  - Acceptance correction for reconstruction and selection
  - 3-dim. correction obtained from full simulation

- Cross-check of complete procedure using another $P \rightarrow VV$ decay $B^0 \rightarrow J/\psi K^*(K\pi)$
Flavour Tagging

- Use neural nets, trained on MC, to extract tagging decision and mis-tag probability, $\eta$

- Calibrate on self-tagging decay modes such as $B^+ \rightarrow J/\psi K^+$

- Using only OS taggers, tagging power $\varepsilon D^2 = 2.2 \pm 0.5\%$
B_s mixing frequency $\Delta m_s$

- Once tagging established can measure the B_s mixing frequency $\Delta m_s$

- See a clear dip in mixing frequency at 17.6 ps$^{-1}$, 4.6$\sigma$ significance

- Comparable precision to CDF measurement with 36 pb$^{-1}$

\[ \Delta m_s = 17.63 \pm 0.11 \text{(stat)} \pm 0.04 \text{(sys)} \hspace{1cm} \text{ps}^{-1} \]

\[ \Delta m_s = 17.77 \pm 0.10 \text{(stat)} \pm 0.07 \text{(sys)} \hspace{1cm} \text{ps}^{-1} \hspace{1cm} \text{CDF, 2006 [2]} \]

$^a$Assumption: $\Delta \Gamma_s = 0.1 \times \Gamma_s$
Constraints on phase $\phi_s$

- No meaningful point-estimate $\Rightarrow$ Confidence contours using Feldman-Cousins method.
- **Statistical error only**: Accounts for syst. uncertainty of tagging (small).
- Compared to statistical error all systematic effects are negligible

$\phi_s \in [-2.7, -0.5]$ rad at 68% CL
$\phi_s \in [-3.5, 0.2]$ rad at 95% CL

SM P-value: 22% ("1.2$\sigma$")

Standard Model:
$\Delta \Gamma_s = 0.087 \pm 0.021$ ps$^{-1}$
$\phi_s = -0.0363 \pm 0.0017$ rad (CKMfitter)
Prospects for 2011

• Current performance:

<table>
<thead>
<tr>
<th>Event</th>
<th>LHCb $36 \text{ pb}^{-1}$</th>
<th>CDF $5.2 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to J/\psi \phi$</td>
<td>836</td>
<td>6500</td>
</tr>
<tr>
<td>Proper time resolution</td>
<td>50 fs</td>
<td>100 fs</td>
</tr>
<tr>
<td>OS tagging power</td>
<td>$2.2 \pm 0.5%$</td>
<td>$1.2 \pm 0.2%$</td>
</tr>
<tr>
<td>SS tagging power</td>
<td>work ongoing</td>
<td>$3.5 \pm 1.4%$</td>
</tr>
</tbody>
</table>

• With current performance and only OS tagger expected $\phi_s$ sensitivity for $1\text{fb}^{-1}$ is $0.13$ rad

• SS tagger will improve sensitivity significantly, expect to have world’s best measurement with the 2011 data
$B_d \rightarrow K^* \mu \mu$
$B_d \to K^* \mu \mu$ – Introduction

• Flavour changing neutral current → loop

• Sensitive to interference between $O_{7\gamma}$ and $O_{9,10}$ and their primed counterparts

• Exclusive decay → theory uncertainty from form factors

• Multitude of observables in which uncert. cancel to some extent e.g. $A_{FB}$, $A_T^{(i)}$
  • zero-crossing point of $A_{FB}$
Experimental Status

- Babar, Belle and CDF have all measured angular asymmetry $A_{FB}$:

  \[ A_{FB} = 0.24^{+0.18}_{-0.23} \pm 0.05 \] 

  \[ A_{FB} = 0.26^{+0.27}_{-0.30} \pm 0.07 \] 

  \[ A_{FB} = 0.43^{+0.36}_{-0.37} \pm 0.06 \]

- Measurements look consistent with each other but errors too large to give real discrimination between SM and NP models.

BABAR: PRL 102, 091803 (2009); CDF: Note 10047 (2010); Belle: PRL 103, 171801 (2009)
LHCb data

• Selection tuned on $B_d \rightarrow K^*J/\psi$ without use of signal decay

• 36pb$^{-1}$ 2010 data yielded $23\pm6$ signal events with $B/S=0.2$
  $\rightarrow 200pb^{-1}$: $127\pm31$ events
  $\rightarrow 1fb^{-1}$: $635\pm154$ events
  (cleanest bin of multivariate discriminant, further $\sim50\%$ of statistics with $B/S=1$)

• cf.
  – Babar 60 events with $B/S=0.3$
  – Belle 230 $0.25$
  – CDF 100 $0.4$
Prospects for 2011

• Measurement requires:
  – Signal selection
  – Acceptance correction
  – Angular fit

• Former items being validated on $B_d \to K^* J/\psi$ decay

• Assuming that with $1 \text{fb}^{-1}$ of data LHCb sees the same central value as Belle in the low $q^2$ region, would exclude the SM at $4\sigma$
**B_d → K^*μμ – Outlook**

- More data will enable a full angular fit to extract complete information from $B_d \rightarrow K^*\mu\mu$ decays → host of theoretically well calculable observables
- Correlation between measurements also of interest...

![CP-averaged angular coeff.](image)

Two more observables with a zero: $S_4, S_5$

$S_6 \sim A_{FB}$

$S_2 \sim A_T^2$

$\sim A_T^3$

$\sim A_T^4$

Ball *et al.* arXiv:0811.1214v2
$B_d \rightarrow K^* \mu\mu$ – Outlook

- More data will enable a full angular fit to extract complete information from $B_d \rightarrow K^* \mu\mu$ decays
  $\rightarrow$ host of theoretically well calculable observables

- Correlation between measurements also of interest…

$S_6 \sim \text{Re}(C_5-C_5')$, if phase of $C_5$ modified...

$C_p/C_S=0$ i.e. NP only from $S$ terms

$S_6 \sim \text{Re}(C_5-C_5')$, if phase of $C_5$ modified...

$C_p/C_S=-1$ (MSSM)

$\mu>0$, CMSSM with large $\tan\beta$

$\mu<0$, CMSSM with large $\tan\beta$
A whistlestop tour…
CKM Measurements

- $B_s \rightarrow J/\psi \phi$ measurement about looking for NP in $B_s$ mixing
- Still scope for NP in $B_d$ mixing?
  - CKM angle $\gamma$ determined indirectly $(68 \pm 4)^\circ$
  - Loop processes $\rightarrow$ sin $(2\beta + \phi_{bd}^{NP})$
  - cf. direct measurement of $\gamma$ from tree processes (currently $(70 +14 -21)^\circ$)
CKM Measurements

• Time independent strategies:
  - $B^+ \rightarrow D(\text{hh})K^+ $
  - $B^0 \rightarrow D(\text{hh})K\pi^+$
  - $B^+ \rightarrow D(K_S\pi\pi)K^+$
  - $B^+ \rightarrow D(K\pi\pi\pi)K^+$
  - $B_s \rightarrow D_s\phi$

- Time dependent strategies:
  - $B_s \rightarrow D_s^-K^+$
  - $B \rightarrow \text{hh} \quad \text{[loops]}$

$\sigma_{\gamma} \sim 10^o$ with $1\text{fb}^{-1}$
First sign of CPV at LHCb

$B^0 \rightarrow K^+\pi^-, \ L=37 \text{ pb}^{-1}$

$\bar{B}^0 \rightarrow K^-\pi^+, \ L=37 \text{ pb}^{-1}$

<table>
<thead>
<tr>
<th>LHCb</th>
<th>world average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{CP}(B^0 \rightarrow K^+\pi^-)$</td>
<td>$-0.077^{+0.033}_{-0.007}$</td>
</tr>
<tr>
<td>$A_{CP}(B_S \rightarrow \pi^+K^-)$</td>
<td>$0.15^{+0.19}_{-0.02}$</td>
</tr>
</tbody>
</table>

- Interference of penguin and tree diagms … no measurement of $\gamma$ yet
\[
\frac{f_d}{f_s} = \frac{253 \pm 21}{670 \pm 34} = 0.374 \pm 0.031
\]

\[
\frac{f_s}{f_d} = 0.242 \pm 0.024^{\text{stat}} \pm 0.018^{\text{syst}} \pm 0.016^{\text{theor}}
\]

\[
\frac{f_s}{f_d} = 0.249 \pm 0.013^{\text{stat}} \pm 0.020^{\text{syst}} \pm 0.025^{\text{theor}}
\]

Combined:
\[
\frac{f_s}{f_d} = 0.245 \pm 0.017^{\text{stat}} \pm 0.018^{\text{syst}} \pm 0.018^{\text{theor}}
\]

(LHCb preliminary)
First observation of $B_s \rightarrow K^* K^*$

- Observed with $7.4\sigma$ significance
- Sensitivity to NP in mixing box and penguin diagram
- No measurement of CPV, yet

$$B(B_s \rightarrow K^* \bar{K}^*) = (1.95 \pm 0.47_{\text{stat.}} \pm 0.66_{\text{syst.}} \pm 0.29_{f_d/f_s}) \cdot 10^{-5}$$
First Observation of $B_s \rightarrow J/\psi f_0(980)$

- Measurement of the BR of the two interfering resonances $f_0(980)$ and $f_0(1370)$
- CP-odd final state, therefore possible measurement of $\phi_s$ w/o angular analysis
- Ratio to $J/\psi$ production determined,
  
  $$R_{f_0/\phi} = \frac{\Gamma(B_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+\pi^-)}{\Gamma(B_s \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$

Conclusions

• $B_d \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \mu^+\mu^-$
  – Very close to the world’s best limits with $\sim 100\times$ less luminosity than CDF
  – With the data collected in 2011 we should be able to explore $\text{BR} < \sim 10^{-8}$

• $\phi_s$ from $B_s \rightarrow J/\psi\phi$
  – Full measurement chain established – currently OS-tagger only
  – Expect to have world’s best measurement with the 2011 data

• $B_d \rightarrow K^*\mu\mu$
  – First signal isolated, very clean
  – $A_{FB}$ measurement competitive with B-factories, CDF with $\sim 200 \text{ pb}^{-1}$

• Large number of other analyses in progress
  – CKM angle $\gamma$, charm physics, exotics … should be a range of results for summer conferences
Signal Invariant Mass calibration

Mass resolutions $\sigma(M(B_{d,s}))$ from:

1) $B \rightarrow hh'$ inclusive sample:
2) Interpolation from dimuon resonances

- similar kinematics/topology
- Selection identical to the signal one:
  $\rightarrow$ Avoid to using PID and use only events triggered by the other $b$ to avoid bias in the phase space [eg resolution]

The $\Upsilon$ family: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
<table>
<thead>
<tr>
<th>Invariant Mass bins (MeV/c²)</th>
<th>Geometrical Likelihood Bins</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[0, 0.25]</td>
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<tr>
<td></td>
<td>[0.25, 0.5]</td>
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<td>[0.5, 0.75]</td>
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<td>[0.75, 1]</td>
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</tbody>
</table>

| [−60, −40] Exp. bkg. | 56.9±1.1                 |
| Exp. sig. Observed   | 0.0076±0.0034             |
|                      | 39                        |
|                      | 1.31±0.19                 |
|                      | 0.0050±0.0027             |
|                      | 2                         |
|                      | 0.282±0.076               |
|                      | 0.0037±0.0015             |
|                      | 1                         |
|                      | 0.016±0.021               |
|                      | 0.0047±0.0015             |
|                      | 0                         |

| [−40, −20] Exp. bkg. | 56.1±1.1                 |
| Exp. sig. Observed   | 0.0220±0.0084             |
|                      | 55                        |
|                      | 1.28±0.18                 |
|                      | 0.0146±0.0066             |
|                      | 2                         |
|                      | 0.269±0.072               |
|                      | 0.0107±0.0036             |
|                      | 0                         |
|                      | 0.015±0.020               |
|                      | 0.0138±0.0034             |
|                      | 0                         |

| [−20, 0] Exp. bkg.  | 55.3±1.1                 |
| Exp. sig. Observed  | 0.038±0.015               |
|                     | 73                        |
|                     | 1.24±0.17                |
|                     | 0.025±0.012              |
|                     | 0                         |
|                     | 0.257±0.069              |
|                     | 0.0183±0.0063            |
|                     | 0                         |
|                     | 0.014±0.018              |
|                     | 0.0235±0.0059            |
|                     | 0                         |

| [0, 20] Exp. bkg.   | 54.4±1.1                 |
| Exp. sig. Observed  | 0.03761±0.0015           |
|                     | 60                        |
|                     | 1.21±0.17                |
|                     | 0.025±0.012              |
|                     | 0                         |
|                     | 0.246±0.066              |
|                     | 0.013±0.017              |
|                     | 0                         |
|                     | 0.012±0.015              |
|                     | 0.0235±0.0060            |
|                     | 0                         |

| [20, 40] Exp. bkg.  | 53.6±1.1                 |
| Exp. sig. Observed  | 0.0220±0.0084            |
|                     | 53                        |
|                     | 1.18±0.17                |
|                     | 0.0146±0.0067            |
|                     | 2                         |
|                     | 0.235±0.063              |
|                     | 0.0138±0.0035            |
|                     | 0                         |
|                     | 0.012±0.015              |
|                     | 0.0138±0.0035            |
|                     | 0                         |

<p>| [40, 60] Exp. bkg.  | 52.8±1.0                 |
| Exp. sig. Observed  | 0.0076±0.0031            |
|                     | 55                        |
|                     | 1.15±0.16                |
|                     | 0.0050±0.0025            |
|                     | 1                         |
|                     | 0.224±0.060              |
|                     | 0.0037±0.0013            |
|                     | 0                         |
|                     | 0.011±0.014              |
|                     | 0.0047±0.0010            |
|                     | 0                         |</p>
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