Measurement of CP violation and CKM matrix in LHCb

Marta Calvi

University of Milano Bicocca and INFN
Current laboratory measurements of CPV are in agreement with SM predictions, encoded in the CKM matrix, but observation of universe requires much more.

Unitarity relations represented by triangles.

Still space for finding effects due to NP in less constrained elements like $\gamma$ and $\beta_s$ angles.

UT constraints from tree measurements only.
The $B_s^0 \overline{B}_s^0$ mixing in $B_s^0 \to J/\psi \phi$

- A CP violating phase arises from interference between $B_s$ decay to $J/\psi \phi$ directly or via mixing

$$\Phi_{J/\psi \phi} \equiv \Phi \equiv - \arg(\eta_f \lambda_f) = \Phi_M - 2\Phi_D$$

$$\lambda_f = \frac{q}{p} = \eta_f e^{-i(\Phi_M - 2\Phi_D)}$$

- In the SM:

$B_s \to J/\psi \phi$ is dominated by a single weak phase, well predicted:

$$\Phi_{J/\psi \phi}^{SM} = -2\beta_s + \delta P$$

$$-2\beta_s = (-0.037 \pm 0.002) \text{ rad}$$

Penguin contribution estimated $\sim 10^{-4}$-$10^{-3}$ from UT fits

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\( B_0^s \bar{B}_0^s \) with New Physics

- New particles could contribute to the \( B_s-\bar{B}_s \) box diagram modifying the SM prediction, adding a new phase:

\[
M_{12}^{\text{tot}} = M_{12}^{\text{SM}} \Delta_s = M_{12}^{\text{SM}} |\Delta_s| e^{i\phi_s^\Delta}
\]

\[
\Phi_{J/\psi \phi} = \Phi_{\text{SM}} + \phi_s^\Delta
\]

- This new phase \( \phi_s^\Delta \) will also modify other measurements:

\[
\Delta \Gamma_s^{\text{meas}} = 2 |\Gamma_{12}^{\text{SM}}| \cos(\Phi_{M/\Gamma}^{\text{SM}} + \phi_s^\Delta)
\]

\[
\alpha_{fs}^{\text{meas}} = \frac{|\Gamma_{12}^{\text{SM}}|}{|M_{12}^{\text{SM}}|} \frac{\sin(\Phi_{M/\Gamma}^{\text{SM}} + \phi_s^\Delta)}{|\Delta_s|}
\]

where:

\[
\Phi_{M/\Gamma}^{\text{SM}} = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right)^{\text{SM}}
\]

is calculated in the SM:

\[
\Phi_{M/\Gamma}^{\text{SM}} = (3.40^{+1.32}_{-0.77}) \times 10^{-3}
\]
$B_s^0 \rightarrow J/\psi (\mu \mu) \phi (KK)$

P$\rightarrow$VV decay : mixture of CP-even ($\ell=0,2$) and CP odd ($\ell=1$) final states. An angular analysis allows to separate statistically the decay amplitudes.

3 angles $\Omega=(\theta,\phi,\psi)$ to describe the final decay products directions.

**Differential decay rate:**

$$\frac{d^4 \Gamma (B_s^0 \rightarrow J/\psi \phi)}{dt \, d\cos \theta \, d\phi \, d\cos \psi} = \frac{d^4 \Gamma}{dt \, d\Omega} \propto \sum_{k=1}^{6} h_k(t) f_k(\Omega)$$

- $A_0 (0) \rightarrow$ CP even
- $A_{||} (0) \rightarrow$ CP even
- $A_{\perp} (0) \rightarrow$ CP odd
Time dependent decay amplitudes

\[ |A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) - \sin \Phi \sin(\Delta m_s t) \right] \]

\[ |A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) + \sin \Phi \sin(\Delta m_s t) \right] \]

\[ |A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) - \sin \Phi \sin(\Delta m_s t) \right] \]

\[ \Im \{A_\parallel(t)A_\perp(t)\} = |A_\parallel(0)||A_\perp(0)| e^{-\Gamma_s t} \left[ - \cos(\delta_\perp - \delta_\parallel) \sin \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right.

\left. + \sin(\delta_\perp - \delta_\parallel) \cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel) \cos \Phi \sin(\Delta m_s t) \right] \]

\[ \Re \{A_0^*(t)A_\parallel(t)\} = |A_0(0)||A_\parallel(0)| e^{-\Gamma_s t} \cos \delta_\parallel \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right.

\left. + \sin \Phi \sin(\Delta m_s t) \right] \]

\[ \Im \{A_0^*(t)A_\parallel(t)\} = |A_0(0)||A_\parallel(0)| e^{-\Gamma_s t} \left[ - \cos \delta_\parallel \sin \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right.

\left. + \sin \delta_\parallel \cos(\Delta m_s t) - \cos \delta_\parallel \cos \Phi \sin(\Delta m_s t) \right] \]

High sensitivity to small \( \Phi \) values when \( B/\bar{B} \) initial state is determined by Flavour tagging (\( \Delta m_s \) terms)

Depend on 8 physics parameters:

\( \Phi, \Gamma_s, \Delta \Gamma_s, \Delta m_s, R_\perp, R_\parallel, \delta_\perp, \delta_\parallel \)

From Tevatrons results:

\( \Delta m_s \) well measured, hints of deviation from SM in \( \Phi \)

\[ \Phi = \Phi^{\text{SM}} \quad |\phi_s^\Delta| \]

\[ \Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \]

\[ \Delta \Gamma = \Gamma_L - \Gamma_H \]

\[ \Delta m_s = M_H - M_L \]

\[ R_\perp = \frac{|A_\perp(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2} \]

\[ R_\parallel = \frac{|A_\parallel(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2} \]

\[ \delta_\perp = \arg(A_\perp(0)A_0^*(0)) \]

\[ \delta_\parallel = \arg(A_\parallel(0)A_0^*(0)) \]
LHCb @ LHC

High $b\bar{b}$ production in pp collisions at $\sqrt{s}=14$ TeV

$\sigma_{\text{inel}} = 80$ mb

$\sigma_{bb} = 500$ $\mu$b $\rightarrow N \sim 10^{12}$ $b\bar{b}$ events in $L_{\text{int}} = 2$ fb$^{-1}$

(1 nominal year $10^7$ s at $2x10^{32}$ cm$^{-2}$s$^{-1}$)

$\sim 40\%$ in the forward region

LHCb single arm forward detector

Detector ready and operational

TED data June 2009
(secondary particles downstream LHC beam stopper)
$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$ reconstruction

Full MC simulation all trigger levels included:

<table>
<thead>
<tr>
<th>Signal yield (2 fb$^{-1}$)</th>
<th>117 k</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$(long-lived) /S</td>
<td>0.5</td>
</tr>
<tr>
<td>$B$(prompt $J/\psi$) /S</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- High efficiency for di-muon trigger $\varepsilon_{\text{tot}} \sim 70\%$
- Baseline event selection is lifetime-unbiased:
  - small proper time and angular acceptance corrections needed.
  - High background from prompt $J/\psi$: harmless in $\beta_s$ fit, can allow the determination of proper time resolution.
  - Alternative analysis under study: higher statistic sensitivity.

- Large use of control channels:
  Measure resolution and acceptance for proper time and angular distributions. Flavour tagging

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield (2 fb$^{-1}$)</th>
<th>B/S total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow J/\psi K^*$</td>
<td>490 k</td>
<td>6.7</td>
</tr>
<tr>
<td>$B_u \rightarrow J/\psi K^+$</td>
<td>940 k</td>
<td>1.9</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s\pi$</td>
<td>~70k</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Flavour Tagging

From combination of several methods (electron, muon, kaon, inclusive vertex, same side kaon)

<table>
<thead>
<tr>
<th>Tagger</th>
<th>Tag eff.</th>
<th>mistag</th>
<th>$\epsilon(1-2\omega)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite side</td>
<td>45%</td>
<td>36.5%</td>
<td>3.3%</td>
</tr>
<tr>
<td>+ same side</td>
<td>56%</td>
<td>33.3%</td>
<td>6.2%</td>
</tr>
</tbody>
</table>

Calibration and validations on control channels

$B^0 \to J/\psi(\mu\mu)K^*(K\pi)$ oscillations for opposite side taggers

$B_s \to D_s (KK\pi) \pi$ oscillations for same side tagger
\( B_s^0 \rightarrow J/\psi\phi : \) fits results

- **Sensitivity studies** with 2fb\(^{-1}\) (one nominal year) : \( \sigma(2\beta_s) \sim 0.03 \)
  Good convergence for all physics parameters, all “detector parameters” can also be fitted.

- **Systematics:**  
  Angular distortions (\( \pm \ 5\% \))  \( \Delta \beta_s/\beta_s \)
  Proper time resolution (40 \( \pm \ 4 \) fs)  \( 5\% \)
  Mistag rate (0.34 \( \pm \ 0.01 \))  \( 7\% \)

Ignoring a possible 5-10\% S-wave contamination will introduce a \( \sim 15\% \) bias on \( \beta_s \).

Included in the fit will reduce the resolution \( \sim 20\% \) but allows cos\( 2\beta_s \) measurement.
If true $\beta_s$ value is the current Tevatron measurement (NP-like) we should measure it from $B_s \rightarrow J/\psi(\mu\mu)\phi$ with 200 pb$^{-1}$!

With 10 fb$^{-1} > 3\sigma$ evidence of non-zero $\beta_s$ even if only SM.

Other channels also under study: $B_s \rightarrow J/\psi(ee)\phi$, $B_s \rightarrow J/\psi\eta$, $B_s \rightarrow D_s^+D_s^-$...
\[
\sin(2\beta) \text{ with } B^0 \to J/\psi(\mu\mu)K_S(\pi\pi)
\]

Will be the first time dependent CP asymmetry measurement at LHCb:
with 200 pb\(^{-1}\) expect \(\sigma(\sin 2\beta) \approx 0.06\)

<table>
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<tr>
<th>Channel</th>
<th>Signal yield (2 fb(^{-1}))</th>
<th>B/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_d \to J/\psi K_S)</td>
<td>94 k</td>
<td>0.6</td>
</tr>
</tbody>
</table>

\(\sigma(\sin 2\beta) \approx 0.020\) in 2 fb\(^{-1}\)

With additional luminosity will give insight into possible NP contributions to \(b \to c\bar{c}s\). Will also constrain direct CP asymmetry.

**NP from \(b \to s\bar{s}s\bar{s}\) penguin decays**

Good perspective at LHCb for \(B_s \to \phi\phi\).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield (2 fb(^{-1}))</th>
<th>B/S (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s \to \phi\phi)</td>
<td>3100</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>(B_d \to \phi K_S)</td>
<td>920</td>
<td>&lt; 1.1</td>
</tr>
</tbody>
</table>

Time dependent analysis of angular distribution of flavour tagged events:

\[
\sigma_{\text{stat}}(\phi B_s \to \phi^{NP}) = 0.11 \text{ in } 2 \text{ fb}^{-1}
\]

From \(B_d \to \phi K_S\) expect \(\sigma(\sin 2\beta_{\text{eff}}) \approx 0.23\)

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\(\gamma\) measurements

- Many approaches to \(\gamma\) angle measurements. Most powerful through ‘B\(\rightarrow\)DK’ strategies (charged and neutral B modes). D final state is common to D\(^0\) and D\(^0\).

- Opportunity for LHCb to make a contribution already with 200 pb\(^{-1}\):
  expect \(\sim 10k\) events B\(\rightarrow\)D(hh)K.

- Dalitz plot analysis giving currently the single best \(\gamma\) results: LHCb will reconstruct in B\(\rightarrow\)D(K\(_S\)\(\pi\pi\))K \(\sim 6.800\) events /2 fb\(^{-1}\) with B/S<1.5 90%CL.

- B\(_s\)\(\rightarrow\)D\(_s\)K time dependent CP asymmetry is unique to LHCb: exploit good PID for separation from B\(_s\)\(\rightarrow\)D\(_s\)\(\pi\) and excellent proper time resolution.

Global fit to all measurements of \(\gamma\) from tree decays only:

\[\sigma(\gamma) \sim 4^{\circ} \text{ with } 2 \text{ fb}^{-1}\]
Conclusions

• LHCb detector is on place and operational, ready for data taking at LHC start-up.

• $2\beta_s$ value could bring good news for NP: first LHCb results could come already from 2010 running. Expected sensitivity $\sim 0.03/2 \text{ fb}^{-1}$

• Extensive LHCb program includes studies on many hadronic channels for measurements on all CKM matrix parameters, as well as searches for rare decays.

• First year data will also provide a lot of inclusive measurements and studies on control channels.

• In the coming years LHCb results will finally provide a strong improvement to flavour physics, in particular to the knowledge of the $B_s$ sector.
BACKUP
Angular acceptance checks with $B^0 \to J/\psi K^*$

- Measurement of polarization amplitudes and phases in the $B^0 \to J/\psi K^*$ decay from fit to time dependent angular distributions.

- Comparison with existing results from B Factories and Tevatron will validate the use of simulated acceptance functions and allow estimation of systematic uncertainties to $2\beta_s$ related to angular acceptance.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Expected uncertainty $\pm 5%$ modification of acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$\delta_\parallel$ [rad]</td>
<td>$0.006 \pm 0.006$</td>
</tr>
<tr>
<td>$\Gamma_d$ [ps$^{-1}$]</td>
<td>$0.0009 \pm 0.0009$</td>
</tr>
</tbody>
</table>

- Strong constrain already for a $\pm 5\%$ modified angular acceptance.