Mixing induced CP violation in $B_d$ decays

Marta Calvi
University of Milano Bicocca and INFN
On behalf of the LHCb Collaboration
Large CPV is expected in interference between $B^0$ decays with or w/o mixing.

Measurements of CP phase provide constraints to SM parameters and probe for BSM physics.

$\beta = (21.9 \pm 0.7)^\circ$ wa

$\beta^{SM} = (24.3 \, ^{+1.3}_{-1.4})^\circ$

CKMFitter, all meas. except $\beta$
$B^0 \rightarrow J/\psi \ K_S$

- Dominated by tree $b \rightarrow c \bar{c} \ s$ transition in SM $S = \sin(2\beta)$

$$A(t) \equiv \frac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K^0_S) - \Gamma(B^0(t) \rightarrow J/\psi K^0_S)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K^0_S) + \Gamma(B^0(t) \rightarrow J/\psi K^0_S)} = S \sin(\Delta m t) - C \cos(\Delta m t)$$

- LHCb with RUN I data (3 fb$^{-1}$)
  41 560 ± 270 candidates

$$S = 0.731 \pm 0.035 \text{(stat)} \pm 0.020 \text{(syst)},$$

$$C = -0.038 \pm 0.032 \text{(stat)} \pm 0.005 \text{(syst)}$$

$$\rho(S,C) = 0.483$$

PRL 115 (2015) 031601
\( \mathbf{B}^0 \rightarrow \mathbf{J/\psi} \mathbf{K}_S \) prospects

- **2 fb\(^{-1}\) (2015+2016) at 13 TeV already on tape**
  - more than double data yield

### Origin systematics

<table>
<thead>
<tr>
<th>Origin</th>
<th>( \sigma_S )</th>
<th>( \sigma_C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background tagging asymmetry</td>
<td>0.0179 (2.5%)</td>
<td>0.0015 (4.5%)</td>
</tr>
<tr>
<td>Tagging calibration</td>
<td>0.0062 (0.9%)</td>
<td>0.0024 (7.2%)</td>
</tr>
<tr>
<td>( \Delta \Gamma )</td>
<td>0.0047 (0.6%)</td>
<td>—</td>
</tr>
<tr>
<td>Fraction of wrong PV component</td>
<td>0.0021 (0.3%)</td>
<td>0.0011 (3.3%)</td>
</tr>
<tr>
<td>( z )-scale</td>
<td>0.0012 (0.2%)</td>
<td>0.0023 (7.0%)</td>
</tr>
<tr>
<td>( \Delta m )</td>
<td>—</td>
<td>0.0034 (10.3%)</td>
</tr>
<tr>
<td>Upper decay time acceptance</td>
<td>—</td>
<td>0.0012 (3.6%)</td>
</tr>
<tr>
<td>Correlation between mass and decay time</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Decay time resolution calibration</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Decay time resolution offset</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Low decay time acceptance</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Production asymmetry</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>0.020 (2.7%)</td>
<td>0.005 (15.2%)</td>
</tr>
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</table>

- **Small systematic uncertainties, will decrease with increasing data samples.**
  - Currently dominated by background tagging asymmetry.

- **Higher tagging power available from new algorithms**
- **Control of penguin contributions from measurementts in other channels**
\( B^0_s \rightarrow J/\psi \ K_S \)

- Under approximated SU(3) symmetry allow to control size of penguin amplitudes in \( B^0 \rightarrow J/\psi \ K_S \)
- LHCb with 3 fb\(^{-1}\)
  
  \[ 908 \pm 36 \text{ signal candidates} \]

\[
\frac{B(B_s^0 \rightarrow J/\psi K_S^0)}{B(B^0 \rightarrow J/\psi K_S^0)} = 0.0431 \pm 0.0017 \text{ (stat)} \pm 0.0012 \text{ (syst)} \pm 0.0025 \text{ (} f_s/f_d \text{)}
\]

- Tagged time-dependent analysis

\[
C_{\text{dir}} = -0.28 \pm 0.41 \text{ (stat)} \pm 0.08 \text{ (syst)}
\]

\[
S_{\text{mix}} = -0.08 \pm 0.40 \text{ (stat)} \pm 0.08 \text{ (syst)}
\]

- Precision not yet sufficient to derive constraints on \( \Delta \phi_d \)
- Good prospects for RUN II
Flavour tagging at LHCb

- Determines $B^0$ signal flavour at production, using information from the rest of the event
- Sensitivity $\sigma_{\text{stat}} \sim 1 / \sqrt{\varepsilon(1-2\omega)^2 N}$
  - $\varepsilon$ tagging efficiency
  - $\omega$ wrong tag rate
- Many algorithms combined
- Recently added/retuned: OS charm, SS pion, SS proton taggers

Same Side

Opposite Side
**Same Side B^0 flavour tagging**

- Exploit correlation of signal B flavour with charge of pions (protons) from the hadronization process

- Tagging algorithms tuned and calibrated on data using flavour specific B^0 decay modes

or decays of excited states, eg. B^{**+} \rightarrow B^0 \pi^+

\[\begin{align*}
B^0 & \quad \pi^+ \\
\bar{b} & \quad \bar{d} \\
d & \quad u
\end{align*}\]

\[\begin{align*}
B^0 & \quad \bar{p} \\
\bar{b} & \quad \bar{d} \\
d & \quad u \quad u
\end{align*}\]
• Select pions (protons) from primary vertex and train a BDT to separate right tag/wrong tag candidates

• Convert the BDT output into a mistag probability associated to that particle with a time-dependent analysis of flavour oscillations

\[ A(t) = \frac{N^{\text{unmix}}(t) - N^{\text{mix}}(t)}{N^{\text{unmix}}(t) + N^{\text{mix}}(t)} = (1-2\omega) \cos(\Delta m t) \]

arXiv:1610.06019
• Mistag calibration checked on control samples
  • Assume linear relation between true and predicted mistag

• SS pion tagger gives +60% in tagging power wrt SS algorithm used for RUNI \( B^0 \to J/\psi K_S \) analysis.
• SS proton provides an additional +25%
• Final performance depends on the kinematic properties of the selected \( B^0 \) decays.
$B^0 \rightarrow D^+ D^-$

- Measure $\sin(2\beta)$ from dominant, tree level, $b \rightarrow c \bar{c} d$ transition
- Sensitivity to higher order contributions provide constraints to possible additional CP phases.

- Time-dependent decay rate

$$\frac{d\Gamma(t, d)}{dt} \propto e^{-t/\tau} \left( 1 - d S \sin(\Delta m t) + d C \cos(\Delta m t) \right)$$

$$S / \sqrt{1 - C^2} = - \sin(\phi_d + \Delta \phi)$$

- SM, at tree level:

$$\phi_d = 2\beta \quad C = 0$$

$d = \pm 1$

$B^0$ flavour at production
$B^0 \rightarrow D^+ D^-$ previous results

**BaBar**  
PRD 79 (2009) 032002  
$N(BB) = 467$ M  
$S = -0.63 \pm 0.36 \pm 0.05$  
$C = -0.07 \pm 0.23 \pm 0.03$

**Belle**  
PRD 85 (2012) 091106  
$N(BB) = 772$ M  
$S = -1.06 ^{+0.21}_{-0.14} \pm 0.08$  
$C = -0.43 \pm 0.16 \pm 0.05$

- Not yet a constraint to additional SM phases.
• $B^0 \rightarrow D^+ D^- \rightarrow (K^- \pi^+ \pi^+) (K^+ \pi^- \pi^-)$
  \rightarrow (K^- K^+ \pi^+) (K^+ \pi^- \pi^-), (K^- \pi^+ \pi^+) (K^+ K^- \pi^-)$
  
• Two BDTs used to suppress combinatorial background.
• Requirements on decay time significance of each D to suppress contamination of $B \rightarrow D K\pi$ and $B \rightarrow D K\bar{K}\pi$ decays

RUN I data (3 fb$^{-1}$)

1610 ± 50 signal candidates

arXiv:1610.06620
$B^0 \rightarrow D_s^+ D^-$ as control channel

- Mistag probability calibrated on $B^0 \rightarrow D_s^+ D^-$ decays.
- Similar selection as signal, to minimize kinematic differences
  16 736 ± 134 signal candidates
- Decay-time fit to $B^0$ flavour oscillations to calibrate all taggers
**B^0 \rightarrow D^+D^-** decay-time fit

- Convoluted with a decay-time resolution derived from simulation (~50 ps) and time acceptance with free parameters

\[
\frac{d\Gamma(t,d)}{dt} \propto e^{-t/\tau} \left(1 - dS \sin(\Delta mt) + dC \cos(\Delta mt)\right)
\]

- \(\epsilon(1-2\omega)^2 = 8.1 \pm 0.6\%\)
- \(\epsilon = 87.6 \pm 0.8\% \quad \omega = 34.8 \pm 0.6\%\)
- High tagging power due to improved algorithms and high \(p_T\) of selected \(B^0\)

arXiv:1610.06620
Stat. correlation coeff. $\rho = 0.48$, larger than at B factories.

Main systematic from residual $2\% \ B^0 \rightarrow D^+ K^+ K^- \pi^-$ background (assumed with maximal CP violation, opposite to signal).

This result constrains the phase shift due to higher-order SM corrections to

$$\Delta \phi = -0.16^{+0.19}_{-0.21} \text{ rad}$$

Exclude CP symmetry conservation by $4\sigma$
• SU(3) symmetry relates $\Delta \phi_d$ to $\Delta \phi_s$.

$B^0 \rightarrow D^+ D^-$ controls size of penguin contributions to $B^0_s \rightarrow D^+_s D^-_s$.

Bel et al. arXiv:1505.01361,
Jung and Schacht arXiv:1410.8396
Gronau et al. arXiv:0805.4601

$\rightarrow$ see S. Akar’s talk

• LHCb result compatible with BaBar one.

• Comparison with Belle hampered by non-Gaussian uncertainties.
Penguin contributions are predicted to be enhanced in $B^0 \to J/\psi \pi^+\pi^-$ wrt to $B^0 \to J/\psi K_S$

Six resonances considered in the $B^0 \to J/\psi \pi^+\pi^-$ final state as in a previous amplitude analysis  

Largest rate ($\sim 66\%$) for $B^0 \to J/\psi \rho^0(770)$
• **Time-dependent measurement, in each resonant final state**

  • Assume equal CP parameters for the three transversity states of $B^0 \rightarrow J/\psi \rho^0(770)$ and a common CP parameter for all other resonances

<table>
<thead>
<tr>
<th>$2\beta_i^{\text{eff}}$ (°)</th>
<th>$\alpha_{CP}^i (\times 10^{-3})$</th>
<th>$\alpha_{CP}^i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$41.7 \pm 9.6^{+2.8}_{-6.3}$</td>
<td>-32 ± 28^{+9}_{-7}</td>
</tr>
<tr>
<td>other − $\rho$</td>
<td>$3.6 \pm 3.6^{+0.9}_{-0.8}$</td>
<td>$-1 \pm 25^{+7}_{-14}$</td>
</tr>
</tbody>
</table>


• **Difference wrt to $B^0 \rightarrow J/\psi K_S$**

\[
\Delta 2\beta_f = 2\beta_{J/\psi \rho} - 2\beta_{J/\psi K_S^0} = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ
\]

• Approximated SU(3) symmetry relates penguin contribution in $B^0 \rightarrow J/\psi \rho^0$ and $B^0_s \rightarrow J/\psi \phi$ decays. Can limit the size of penguin contributions in $B^0_s \rightarrow J/\psi \phi$ to

\[
\delta_p = (0.05 \pm 0.56)^\circ
\]
Conclusion

- Several mixing-induced CPV measurements in $B^0$ decays at LHCb with RUN I data
- Charmonium:
  - $B^0 \rightarrow J/\psi K_S$, $B^0 \rightarrow J/\psi \pi^+\pi^-$, $B^0 \rightarrow J/\psi K^+\pi^-$
- Open charm:
  - $B^0 \rightarrow D^+ D^-$, $B^0 \rightarrow D^+ \pi^-$ (see A. Birnkraut’s talk)
- Exciting prospects with new RUN II data and improved analysis techniques.
- Higher trigger efficiency for hadronic modes will also come with LHCb Upgrade
backup
### Table 8
Comparison of $S_f$ and $C_f$ between different measurements.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$f$</th>
<th>$S_f$</th>
<th>$C_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$\bar{B}^0 \rightarrow J/\psi \rho^0$</td>
<td>$-0.66^{+0.13+0.09}_{-0.12-0.03}$</td>
<td>$-0.063 \pm 0.056^{+0.019}_{-0.014}$</td>
</tr>
<tr>
<td>Belle [33]</td>
<td>$B^0 \rightarrow J/\psi \pi^0$</td>
<td>$-0.65 \pm 0.21 \pm 0.05$</td>
<td>$-0.08 \pm 0.16 \pm 0.05$</td>
</tr>
<tr>
<td>BaBar [34]</td>
<td>$B^0 \rightarrow J/\psi \pi^0$</td>
<td>$-1.23 \pm 0.21 \pm 0.04$</td>
<td>$-0.20 \pm 0.19 \pm 0.03$</td>
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