Measurements of mixing and CP violation in charm and beauty at LHCb

Mirco Dorigo (EPFL) for the LHCb collaboration

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Accessing the next scale

Direct way

High energy production of new particles. Probe directly structure of matter and its interactions.

Indirect way (Flavour)

Low-energy precision measurements.
- NP can alter mixing dynamics
- NP can introduce new sources of CP violation
Neutral K (D, B and B_s) system: “particle mixture”, time-evolution governed by 2x2 Schrödinger’s equation

If CP is conserved, q and p are real, i.e. |q/p| = 1 and

Eigenstates superposition of flavour states, can have different masses and decay widths

\begin{equation}
|P_{L,H}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle
\end{equation}

\begin{align*}
x &= \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{(\Gamma_H + \Gamma_L)/2} \\
y &= \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}
\end{align*}

If CP is conserved, q and p are real, i.e. |q/p| = 1 and φ = arg(q/p) = 0
Review of $D$ mixing

Mass and width splittings \( \Delta M \) and \( \Delta \Gamma \) are determined by:

\[
\Delta M \equiv M_1 - M_2 = 2 \Re \left[ q_p (M_{12} - i/2 \Gamma_{12}) \right],
\]

\[
\Delta \Gamma \equiv \Gamma_1 - \Gamma_2 = -4 \Im \left[ q_p (M_{12} - i/2 \Gamma_{12}) \right],
\]

and therefore the characteristics of $D_0$-$\bar{D}_0$ mixing. We show the unmixed and mixed intensities as a function of the dimensionless variable, \( \Gamma t \), for initially pure states of $K_0$, $D_0$, $B_0$, and $B_s$, in Figs. 3(a–d), respectively. Of the four lowest-lying neutral pseudoscalar meson systems, the $D_0$-$\bar{D}_0$ system shows the smallest mixing, as noted earlier. In the $K_0$ system, both \( |x| \) and \( |y| \) are both of order 1; in the $D_0$ system, \( |x| \) and \( |y| \) are both of order 1%; in the $B_0$ and $B_s$ systems, \( |x| \gg |y| \).

\[
\langle P^0(0)|P^0(t)\rangle^2 \propto e^{-\Gamma t} \left[ \cosh(y \Gamma t) + \cos(x \Gamma t) \right]
\]

\[
\langle P^0(0)|\bar{P}^0(t)\rangle^2 \propto e^{-\Gamma t} \left[ \cosh(y \Gamma t) - \cos(x \Gamma t) \right]
\]

Fig. 3. The unmixed (blue) and mixed (red) intensities for an initially pure (a) $K_0$; (b) $D_0$; (c) $B_0$; (d) $B_s$ state. The vertical scale in (b) is logarithmic, the others linear. The values of the mixing parameters as defined in Eqs. 1 and 2 are obtained using data from Ref. 19, assuming \( |q/p| = 1 \).

Blue line:
given a $P^0$, at t=0, the probability of finding a $P^0$ at t

Red Line:
given a $P^0$, at t=0, the probability of finding a $P^0$ at t

[arXiv:1209.5806]
Blue line:
given a $P^0$, at $t=0$,
the probability of finding a $P^0$ at $t$

Red Line:
given a $P^0$, at $t=0$,
the probability of finding a $\bar{P}^0$ at $t$

$$|\langle P^0(0) | P^0(t) \rangle|^2 \propto e^{-\Gamma t} \left[ \cosh(y \Gamma t) + \cos(x \Gamma t) \right]$$

$$|\langle P^0(0) | \bar{P}^0(t) \rangle|^2 \propto e^{-\Gamma t} \left[ \cosh(y \Gamma t) - \cos(x \Gamma t) \right]$$
Crucial tracking and vertexing
- $\Delta p/p = 0.4\text{–}0.6\%$ at 5–100 GeV/c
- $O(20)$ $\mu$m IP resolution on tracks
- $O(50)$ fs decay-time resolution

Flavour at decay from final-state particles. Initial flavour:
- use $D^0$ coming from, $D^{*+} \rightarrow D^0\pi^+$ or $B \rightarrow D^0\mu^-X$
- for $B^0$ and $B_s^0$ more complicated...
Identifying the initial B flavour

Hadron collisions represent a challenging environments for B tagging

Don’t miss Vincenzo Battista’s talk at YSF!

New algorithm SS Kaon
arXiv:1602.07252

Performance metrics
\[ \varepsilon = \frac{N(\text{tagged})}{N(\text{total})} \]
\[ \omega = \frac{N(\text{wrong tag})}{N(\text{tagged})} \]
\[ \varepsilon_{\text{eff}} = \varepsilon < (1 - 2\omega)^2 > \]

OS algorithms in EPJC 72 (2012) 2022

New OS Charm algorithm
JINST 10 (2015) 10005
Identifying the initial B flavour

Hadron collisions represent a challenging environment for B tagging

Don’t miss Vincenzo Battista’s talk at YSF!

<table>
<thead>
<tr>
<th>Tagging power [%]</th>
<th>2011</th>
<th>Run I</th>
<th>Improvement</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to J/\psi K_S$</td>
<td>2.38</td>
<td>3.03</td>
<td>+27%</td>
<td>PRL 115 (2015) 031601</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi KK$</td>
<td>3.13</td>
<td>3.73</td>
<td>+19%</td>
<td>PRL 114 (2015) 041801</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi \pi \pi$</td>
<td>2.43</td>
<td>3.89</td>
<td>+60%</td>
<td>PLB 736 (2014) 186</td>
</tr>
<tr>
<td>$B_s^0 \to \phi \phi$</td>
<td></td>
<td>5.33</td>
<td></td>
<td>PRD 90 (2014) 052011</td>
</tr>
<tr>
<td>$B_s^0 \to D_s K$</td>
<td></td>
<td>5.07</td>
<td></td>
<td>JHEP 11 (2014) 060</td>
</tr>
</tbody>
</table>

Impressive improvements
$\Delta m_d$ with high precision

Tagged $B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \mu^+ X$ (1.6M) and $B^0 \rightarrow D^{*-} (\rightarrow D^0 [K\pi] \pi^-) \mu^+ X$ (0.8M) decays reconstructed in the Run I dataset

$B^+ \rightarrow D^{(*)-} \mu^+ X$ major offending background. Develop a multivariate classifier to distinguish it from signal.

Use of OS tagging algorithm, tagging power of about 2.5%.

Biased estimate of the decay time, due to the unreconstructed neutrino ($B$ momentum partially reconstructed).

$$t = \frac{ML}{P_{\text{rec}} c} k(m_{D\mu})$$

Statistically correct by using simulation ($k$-factor). Decrease of the time resolution.
$\Delta m_d$ with high precision

**World's best measurement**

$\Delta m_d = (505.0 \pm 2.1 \text{ (stat)} \pm 1.0 \text{ (syst)}) \text{ ns}^{-1}$

Main sources of systematic related to the k-factor correction.

LHCb-PAPER-2015-031
**D^0 mixing from D^0 \rightarrow K^+ \pi^- \pi^- \pi^+**

**Prompt-tagged** decays from Run I data. 4-body final state, very challenging. Measure the ratio of **WS** to **RS** decays in bins of decay time.

\[ R(t) \approx \left( r_{D}^{K3\pi} \right)^2 - r_{D}^{K3\pi} \cdot y_{K3\pi} \cdot t + \frac{x^2 + y^2}{4} (t)^2 \]

\[ y_{K3\pi} = \frac{y \cos \delta_{D}}{x \sin \delta_{D}} \]

Sensitive to **mixing**, interference between CF and DCS amplitudes and their relative strength.

**Cabibbo Favoured**

**Doubly Cabibbo Suppressed**

**Oscillation**

**WS**

**Cabibbo Favored**

![Graphs showing D^0 mixing from D^0 \rightarrow K^+ \pi^- \pi^- \pi^+](image-url)

**LHCb**

- **RS candidates**
- **Fit**
- **Background**

**WS**

- **WS candidates**
- **Fit**
- **Background**

\[ \text{Candidates} / (0.1 \text{ MeV/c}^2) \]

**arXiv:1602.07224**
New mixing observation

Constraining $x$ and $y$ in the fit to known values (HFAG), measure

$$r_D^{K_3\pi} \quad (5.50 \pm 0.07) \times 10^{-2}$$

$$R_D^{K_3\pi} \cdot y_{K_3\pi}^{r} \quad (-3.0 \pm 0.7) \times 10^{-3}$$

World’s best results.

Important input for $\gamma$ measurement in $B \rightarrow D(\rightarrow K^- \pi^+ \pi^- \pi^+) K$ decay.
CPV: a two slits experiment

Quantum interference between two amplitudes

\[ A_{CP} \approx 2 |a_1 a_2| \sin(\delta_1 - \delta_2) \sin(\varphi_1 - \varphi_2) \]
CKM phase(s)

\[ u \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 \\ -\lambda + \frac{1}{2} A^2 \lambda^5 [1 - 2(\rho + i\eta)] \\ A\lambda^3 [1 - (1 - \frac{1}{2} \lambda^2)(\rho + i\eta)] \end{pmatrix} \quad s \begin{pmatrix} \lambda \\ 1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 (1 + 4A^2) \\ -A\lambda^2 + \frac{1}{2} A\lambda^4 [1 - 2(\rho + i\eta)] \end{pmatrix} \quad b \begin{pmatrix} A\lambda^3 (\rho - i\eta) \\ A\lambda^2 \\ 1 - \frac{1}{2} A^2 \lambda^4 \end{pmatrix} \]

\[ \lambda \approx 0.23 \]

\( \gamma \) less constrained angle

\( \beta \) mixing-induced CPV in \( B^0 \)

\( \beta_s \) mixing-induced CPV in \( B_s^0 \)

Charm CPV suppressed

[very small]

[extremely small]
\[ \gamma \text{ with } B^0 \rightarrow D^0 K^+ \pi^- \]

\[ \gamma \] constraints from pure tree \( B \rightarrow D h \) decays are robustly free from NP.

\[ \gamma \text{ uncertainty mainly statistical.} \]
Benefit from combining several inputs.

Latest LHCb combination:

\[ \gamma = \left(73^{+9}_{-10}\right)^\circ \]  

[\text{LHCb-CONF-2014-004}]  

Will be updated very soon!

using \( B^+ \rightarrow D^+ h^+ (h^- h^+) \) with

- \( D \rightarrow f_{\text{CP}} \) (GLW method)
- \( D \rightarrow f_{\text{sup}} \) (ADS method)
- \( D \rightarrow 3\text{-body} \) (GGSZ method)

and time-dependent \( B_s^0 \rightarrow D_s^- K^+ \).

First \( B^0 \rightarrow D^0 K^+ \pi^- \) Dalitz-plot analysis.
Despite low statistics, a new opportunity to access \( \gamma \) from interference of resonances in the DP.
$\gamma$ with $B^0 \rightarrow D^0 K^+ \pi^-$

**LHCb**

- $\bar{B}^0 \rightarrow D^0 K^\mp \pi^\mp$
  - $[\pi^\mp \pi^\pm$ and $K^- K^+]$

**LHCb**

- $B^0 \rightarrow D^0 K^\mp \pi^\mp$
  - $[\pi^\mp \pi^\pm$ and $K^- K^+]$

**Data**

- Total fit
- $K\pi$ S-wave
- $K_2^*(1430)^0$
- $D\pi$ S-wave
- $D\pi$ P-wave
- $D_s^*(2460)^-$
- $D_s^*(2700)^+$
- $\bar{B}^0$ bkgd.
- Mis-ID bkgd.
- Comb. bkgd.

**Total fit**

- $K^*(892)^0$
- $K^*(1410)^0$
- $D^0_s(2400)^-$
- $D^*_s(2460)^-$
- $D^*_s(2700)^+$
- $D^*$

**LHCb**

- $m^2(K^- \pi^+)$ [GeV$^2$/c$^4$]
- $m^2(K^+ \pi^-)$ [GeV$^2$/c$^4$]

**Weighted candidates / (60 MeV/c$^2$)**

- $m(K^- \pi^+)$ [GeV/c$^2$]
- $m(K^+ \pi^-)$ [GeV/c$^2$]

**arXiv:1602.03455**
From $B^0 \to D^0 K^*(892)^0$ extract the CP asymmetries

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

No evidence of CP violation.

While no value of is excluded at 95% C.L., this is a powerful new method which will be very important in Run 2 and beyond!
ΔACP in D⁰→h⁺h⁻

Probe CPV in charm with D⁰→K⁺K⁻ and D⁰→π⁺π⁻.

Prompt-tagged decays from full Run I dataset. Measure:

\[ A_{\text{raw}}[hh] \equiv \frac{N(D^{*+} \rightarrow D_{[hh]}^0 \pi^+_s) - N(D^{*-} \rightarrow \bar{D}_{[hh]}^0 \pi^-_s)}{N(D^{*+} \rightarrow D_{[hh]}^0 \pi^+_s) + N(D^{*-} \rightarrow \bar{D}_{[hh]}^0 \pi^-_s)} \]

\[ \approx A_{\text{CP}}[hh] + A_{\text{prod}}[D^*] + A_{\text{det}}[\pi_s] \]

Provided equal kinematic distributions for decays to K⁺K⁻ and π⁺π⁻ decays, spurious asymmetries cancel in the difference

\[ \Delta A_{\text{CP}} = A_{\text{raw}}(K^- K^+) - A_{\text{raw}}(\pi^- \pi^+) \]
\[ \Delta A_{CP} \text{ in } D^0 \rightarrow h^+h^- \]

\[ \Delta A_{CP} = (-0.10 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)}) \% \]

$2\beta_s$ and $2\beta$ quick reminder

$2\beta_s$

- $B_s^0 \rightarrow J/\psi KK$ PRL 114 (2015) 041801
- $B_s^0 \rightarrow J/\psi\pi\pi$ PLB 736 (2014) 186
- $B_s^0 \rightarrow D_s^- D_s^+$ PRL 114 (2015) 041801

$2\beta_s^{\text{eff}} B_s^0 \rightarrow \phi\phi$ PRD 90 (2014) 052011

$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$ with $B^0 \rightarrow J/\psi K_S$ PRL 115 (2015) 031601

+ Control of penguin pollution

- $2\beta^{\text{eff}} B^0 \rightarrow J/\psi \rho$ PLB 742 (2015) 38
- CPV in $B_s^0 \rightarrow J/\psi K^*$ JHEP 11 (2015) 082
- CPV in $B_s^0 \rightarrow J/\psi K_S$ JHEP 06 (2015) 131
Conclusions

✧ LHCb continues to harvest rich results from Run I.

High precision measurements of mixing of neutral B mesons. Continuing the exploration of the D mixing dynamics.

Measurements of CPV in B and D mesons in good agreement with the SM, but (almost all) limited by statistics.

Full data sample not (yet) completely exploited, many important results foreseen very soon (e.g. new γ measurements, CPV in b baryons)

✧ LHCb ready and fully operational for Run II. Eager to exploit the physics potential of new data!
Backup
\[ \Delta A_{CP} \text{ in } D^0 \rightarrow h^+ h^- \]

Going to sub-per-mill precision.

Analysis of 8 disjoint subsamples
Split by:
  - magnet polarity: test cancellation of detector-related asymmetries
  - year: data taking condition
  - LO trigger: different kinematic of the decays

Numerous stability checks.

Asymmetries as a function of
  - number of primary vertices
  - quality of the D* vertex
  - \( \pi \) soft kinematics
  - \( D^0 \) kinematics
  - PID requirements
  - \( D^0 \) mass
  - time (run numbers)
  - ...
\[ \sin 2\beta_{SM} = 0.771^{+0.017}_{-0.041} \]

[CKMFitter arXiv:1501.05013]

A long history of \( \sin 2\beta \) measurements at the B factories, started in 1999.

BaBar: \( 0.687 \pm 0.028 \pm 0.012 \)

[PRD 79, 072009 (2009)]

Belle: \( 0.667 \pm 0.023 \pm 0.012 \)

[PRL 108, 171802 (2012)]

Intriguing tension between direct and indirect determinations
**\( \beta_s \) angle**

Another unitary relation of CKM matrix, concerning \( B_s \)

Indirect determination:
\[
2\beta_s^{SM} = 0.0363 \pm 0.0013 \text{ rad}
\]
[CKMFitter arXiv:1501.05013]

Early measurements by Tevatron experiments showed interesting 2\( \sigma \) deviation from indirect determination, but large uncertainties.

Moved to high precision era with LHC “\( B_s \) factory”.
Outlooks

We expect a huge increase in precision in the LHCb upgrade!

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi)$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0)$ ($10^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>$0.03$</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi_{s\text{eff}}(B_s^0 \to \phi \phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_{s\text{eff}}(B_s^0 \to K^{*0}K^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{\text{eff}}(B_s^0 \to \phi K_s^{0})$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_{s\text{eff}}(B_s^0 \to \phi \gamma)$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{eff}}(B_s^0 \to \phi \gamma) / \tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$q_0^2 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+\mu^+\mu^-) / B(B^+ \to K^+\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s^0 \to \mu^+\mu^-) (10^{-9})$</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+\mu^-) / B(B_s^0 \to \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \to D^{(<em>)}K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma(B_s^0 \to D^\pm K^\mp)$</td>
<td>17°</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
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<tr>
<td>angles</td>
<td>$\beta(B^0 \to J/\psi K_S^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T(D^0 \to K^+K^-) (10^{-4})$</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP} (10^{-3})$</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>–</td>
</tr>
</tbody>
</table>