LHCb results on CP violation in $B^0_{s/d}$ mixing and in the interference with decays

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on behalf of the LHCb collaboration

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Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm

Tracking system
momentum resolution
\[ \Delta p/p = 0.4\%-0.6\% \]

Dipole Magnet
normal conducting
bending power: 4 Tm
regular polarity switches

RICH detectors
K/\pi/p separation

Calorimeters
energy measurement
particle identification

Muon System
\( \sin 2\beta \)

- \( \beta \) best constrained angle in the CKM triangle (\( b \to c\bar{c}s \) transitions)
- Complementary measurements in \( b \to c\bar{c}d \) possible

\[
A_{DD}(t) = \frac{\Gamma(\bar{B}^0(t) \to D^+D^-) - \Gamma(B^0(t) \to D^+D^-)}{\Gamma(\bar{B}^0(t) \to D^+D^-) + \Gamma(B^0(t) \to D^+D^-)}
= S_{CP} \sin(\Delta m_d t) - C_{CP} \cos(\Delta m_d t)
\]

- \( S_{CP} / \sqrt{1 - C_{CP}^2} = - \sin(\varphi_d + \Delta \varphi) \)
- SM: \( \varphi_d = 2\beta \)
- \( B^0 \to D^+(K^-\pi^+\pi^+)D^- (K^+\pi^-\pi^-) \)
- \( B^0 \to D^\pm (K\mp K^\pm \pi^\pm)D^\mp (K^\pm \pi^\mp \pi^\mp) \)
- 1610 \pm 50 candidates in run 1 (2011+2012)

[\text{LHCb-PAPER-2016-037}] \text{in prep.}
first application of OS charm tagger, SS proton tagger, and optimised SS pion tagger

calibrate with
$B^0 \rightarrow D^+_s (K^+K^-\pi^+)D^- (K^+\pi^-\pi^-)$

unprecedented tagging power at LHCb
$\varepsilon(1 - 2\omega)^2 = (8.1 \pm 0.6)\%$

more on flavour tagging at LHCb → poster by Vanessa Müller
\( B^0 \rightarrow D^+D^- \) result

\[ S_{CP} = -0.54 \pm 0.17 \text{ (stat)} \pm 0.05 \text{ (sys)} \]

(HFAG: \(-0.98 \pm 0.17\))

\[ C_{CP} = 0.26 \pm 0.17 \text{ (stat)} \pm 0.02 \text{ (sys)} \]

(HFAG: \(-0.31 \pm 0.14\))

correlation stronger than at B factories:
\( \varrho = 0.48 \)

leading systematics: prediction for \( CP \) violation in \( B^0 \rightarrow DKK\pi \)
$B^0 \rightarrow D^+D^-$ result

$S_{CP} = -0.54 \pm 0.17 \text{ (stat)} \pm 0.05\text{ (sys)}$
(HFAG: $-0.98 \pm 0.17 \rightarrow -0.84 \pm 0.12$)

$C_{CP} = 0.26 \pm 0.18 \text{ (stat)} \pm 0.02\text{ (sys)}$
(HFAG: $-0.31 \pm 0.14 \rightarrow -0.13 \pm 0.10$)

- correlation stronger than at B factories: $\varrho = 0.48$
- leading systematics: prediction for $CP$ violation in $B^0 \rightarrow DKK\pi$

[LHCb-PAPER-2016-037] in prep.
Implications

Study of bottom to double charm have additional theory motivation

- comparison of $B^0 \rightarrow J/\psi K_S$ and $B^0 \rightarrow D^+D^-$ constrains penguin contributions to $B \rightarrow DD$ topologies (compatible with 0)
- with $U$-spin this gives control to higher order contributions in the $\phi_s$ measurement in $B_s^0 \rightarrow D_s D_s$

\[
\sin 2\beta
\]

- Paul Seyfert (INFN MIB)
- CP violation in B mixing at LHCb
\[ \phi_s \] in \( B_s^0 \rightarrow \psi(2S)\phi \)

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>Dataset</th>
<th>( \phi_s^{\text{ee}} )</th>
<th>( \Delta \Gamma_s ) (ps(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>( J/\psi \phi )</td>
<td>9.6 fb(^{-1})</td>
<td>([-0.60, +0.12]), 68% CL</td>
<td>+0.068 ± 0.026 ± 0.009</td>
</tr>
<tr>
<td>D0</td>
<td>( J/\psi \phi )</td>
<td>8.0 fb(^{-1})</td>
<td>(-0.55^{+0.38}_{-0.36})</td>
<td>+0.163^{+0.065}_{-0.064}</td>
</tr>
<tr>
<td>ATLAS</td>
<td>( J/\psi \phi )</td>
<td>4.9 fb(^{-1})</td>
<td>+0.12 ± 0.25 ± 0.05</td>
<td>+0.053 ± 0.021 ± 0.010</td>
</tr>
<tr>
<td>ATLAS</td>
<td>( J/\psi \phi )</td>
<td>14.3 fb(^{-1})</td>
<td>-0.123 ± 0.089 ± 0.041</td>
<td>+0.096 ± 0.013 ± 0.007</td>
</tr>
<tr>
<td>ATLAS</td>
<td>above 2 combined</td>
<td></td>
<td>-0.098 ± 0.084 ± 0.040</td>
<td>+0.083 ± 0.011 ± 0.007</td>
</tr>
<tr>
<td>CMS</td>
<td>( J/\psi \phi )</td>
<td>19.7 fb(^{-1})</td>
<td>-0.075 ± 0.097 ± 0.031</td>
<td>+0.095 ± 0.013 ± 0.007</td>
</tr>
<tr>
<td>LHCb</td>
<td>( J/\psi K^+K^- )</td>
<td>3.0 fb(^{-1})</td>
<td>-0.058 ± 0.049 ± 0.006</td>
<td>+0.0805 ± 0.0091 ± 0.0033</td>
</tr>
<tr>
<td>LHCb</td>
<td>( J/\psi \pi^+\pi^- )</td>
<td>3.0 fb(^{-1})</td>
<td>+0.070 ± 0.068 ± 0.008</td>
<td>—</td>
</tr>
<tr>
<td>LHCb</td>
<td>above 2 combined</td>
<td></td>
<td>-0.010 ± 0.039(tot)</td>
<td>—</td>
</tr>
<tr>
<td>LHCb</td>
<td>( D_s^-D_s^- )</td>
<td>3.0 fb(^{-1})</td>
<td>+0.02 ± 0.17 ± 0.02</td>
<td>—</td>
</tr>
<tr>
<td>All combined</td>
<td></td>
<td></td>
<td>-0.033 ± 0.033</td>
<td>+0.084 ± 0.007</td>
</tr>
</tbody>
</table>

- \( \phi_s \) measurements traditionally done in \( B_s^0 \rightarrow J/\psi \phi \)
- never done at a higher \( c\bar{c} \) resonance

\rightarrow First measurement of \( \phi_s \) in \( B_s^0 \rightarrow \psi(2S)\phi \)

- final state no \( CP \) eigenstate
- \( \rightarrow \) angular analysis

\[ CP | J/\psi \phi \rangle_\ell = (-1)^\ell | J/\psi \phi \rangle_\ell \]
$B_s^0 \rightarrow \psi(2S)\phi$ data (full Run 1)

$B_s^0 \rightarrow \psi(2S)\phi$

![Graph showing signal yield 4697±71](image)

- Multivariate selection for optimal statistical power
  - new wrt. $J/\psi\phi$

$B^0 \rightarrow \psi(2S)K^*$

![Graph showing data driven time acceptance from control mode](image)

- Data driven time acceptance from control mode
  - new wrt. $J/\psi\phi$

- time resolution from prompt $J/\psi \rightarrow \mu\mu$ decays
- angular acceptance for all 10 fit components from simulation
- flavour tagging $\varepsilon(1 - 2\omega)^2 = (3.88 \pm 0.18)\%$ ($B_s^0$ system, softer than $B \rightarrow DD$)

[Addendum: LHCb-PAPER-2016-027 in prep.]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$]</td>
<td>$0.668 \pm 0.011 \pm 0.006$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>$0.066^{+0.041}_{-0.044} \pm 0.006$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta</td>
<td></td>
</tr>
<tr>
<td>$\delta \perp$ [rad]</td>
<td>$3.29^{+0.43}_{-0.39} \pm 0.04$</td>
</tr>
<tr>
<td>$\phi_s$ [rad]</td>
<td>$0.23^{+0.29}_{-0.28} \pm 0.02$</td>
</tr>
<tr>
<td>$</td>
<td>A</td>
</tr>
<tr>
<td>$F_S$</td>
<td>$0.061^{+0.026}_{-0.025} \pm 0.007$</td>
</tr>
<tr>
<td>$\delta_S$ [rad]</td>
<td>$0.03 \pm 0.14 \pm 0.02$</td>
</tr>
</tbody>
</table>

- systematics $< 0.2\sigma_{\text{stat}}$ (except $\Gamma_s$)
- limited by statistics in control mode for time acceptance
- compatible but not competitive with $J/\psi \phi$ (HFAG: $\sigma_{\phi_s} = 0.033$)
- exploration of additional $\phi_s$ modes and new techniques
Another alternative to $\phi_s$ measurement in $B_s^0 \rightarrow J/\psi \phi$:

$B_s^0 \rightarrow J/\psi \eta (\gamma\gamma)$

**pro**

- $CP$ eigenstate $\rightarrow$ no angular analysis necessary

**con**

- low statistics
- mass resolution worse with neutrals in the final state

Not attractive for direct $\phi_s$ measurement

**BUT:** effective lifetime holds sensitivity to $\phi_s$

$CP$ conservation $\leadsto B_s^0 \rightarrow J/\psi \eta$ is a $B_{s,L}$ decay

$[arXiv:1607.06314]$

3021 $\pm$ 73 $B_s^0$ candidates
\[ \tau(B_s^0 \rightarrow J/\psi \eta) \]

- constrain \(B_s^0/B^0\) production fractions,
- \(B_q \rightarrow J/\psi \eta\) branching fractions, and \(B^0\) lifetime
- dedicated calorimeter calibration for \(\eta \rightarrow \gamma \gamma\)

\[ \tau(J/\psi \eta) = 1.479 \pm 0.034(\text{stat}) \pm 0.011(\text{sys}) \text{ps} \]

SM prediction: \(\tau = (1.43 \pm 0.03) \text{ ps}\)

Compatible with previous measurements (at same precision) and compatible with SM
Conclusion

- expanded CPV measurements beyond golden modes

- \( \sin 2\beta_{\text{DD}} \) precision close to world average for \( B^0 \rightarrow \text{DD} \)

\[ \text{[LHCb-PAPER-2016-037] in prep.} \]

\[ B_s^0 \rightarrow \psi(2S)\phi \]

- first \( \phi_s \) measurement with higher \( c\bar{c} \) resonance than \( \psi \)

\[ \text{[LHCb-PAPER-2016-027] in prep.} \]

- \( B_s^0 \) lifetime measurement in \( B_s^0 \rightarrow \psi/\psi \eta \)

\[ \text{[arXiv: 1607.06314]} \]

- update on semileptonic asymmetry \( a_{s1} \): talk by Suzanne Klaver later today
GIVE UP

DON´T GIVE UP
$B^0 \rightarrow D_s D$ calibration sample

- 16736 ± 134 candidates for tagging calibration
- Assume maximum oscillation and compare to observed oscillation
- Calibrate tagging performance
$B^0 \rightarrow DD$ mass model

- signal: triple crystal ball
  - shape (except one resolution factor) fixed from simulation
- $B_s^0$ and $B^0$ share shape
- $B_s^0 - B^0$ mass difference fixed
- not included $B^0 \rightarrow D hhh$ or $B^0 \rightarrow hhhhhh$
  - same position in mass as signal, wider resolution
  - estimated up to 2% of signal yield (invert D mass window)
  - unknown CP parameter
  - treated as systematic (generate with CP parameters opposite to signal)

[LHCb-PAPER-2016-037] in prep.
# $B^0 \rightarrow DD$ systematics

<table>
<thead>
<tr>
<th>$B^0 \rightarrow Dhhh$</th>
<th>±0.05</th>
<th>±0.013</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Gamma_d = 0$</td>
<td>±0.014</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon(t)$</td>
<td>±0.007</td>
<td></td>
</tr>
<tr>
<td>mass time factorisation</td>
<td></td>
<td>±0.007</td>
</tr>
<tr>
<td>time resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>length scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>production asymmetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mass models</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total sys</td>
<td>±0.05</td>
<td>±0.02</td>
</tr>
<tr>
<td>stat</td>
<td>±0.17</td>
<td>±0.18</td>
</tr>
</tbody>
</table>
$B^0_s \rightarrow \psi(2S)\phi$ BDT optimisation

- modified $\frac{s}{\sqrt{s+b}}$
- take tagging behaviour into account (weight events with low predicted mistag probability higher)
- take time resolution into account (weight events with good predicted decay time resolution higher)
\[ \frac{d^4 \Gamma(B_s^0 \to \psi(2S)\phi)}{dt \, d\Omega} \propto \sum_{k=1}^{10} h_k(t) \, f_k(\Omega) \]

\[ h_k(t) = N_k e^{-Gt} \left[ a_k \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) + b_k \sinh \left( \frac{1}{2} \Delta \Gamma_s t \right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) \right] . \]

<table>
<thead>
<tr>
<th>(k)</th>
<th>(f_k(\theta_\mu, \theta_K, \phi_h))</th>
<th>(N_k)</th>
<th>(a_k)</th>
<th>(b_k)</th>
<th>(c_k)</th>
<th>(d_k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2 \cos^2 \theta_K \sin^2 \theta_\mu)</td>
<td></td>
<td>1</td>
<td>(D)</td>
<td>(C)</td>
<td>(-S)</td>
</tr>
<tr>
<td>2</td>
<td>(\sin^2 \theta_K (1 - \sin^2 \theta_\mu \cos^2 \phi_h))</td>
<td>(</td>
<td>A_0(0)</td>
<td>^2)</td>
<td>(</td>
<td>A_0(0)</td>
</tr>
<tr>
<td>3</td>
<td>(\sin^2 \theta_K (1 - \sin^2 \theta_\mu \sin^2 \phi_h))</td>
<td>(</td>
<td>A_\perp(0)</td>
<td>^2)</td>
<td>(</td>
<td>A_\perp(0)</td>
</tr>
<tr>
<td>4</td>
<td>(\sin^2 \theta_K \sin^2 \theta_\mu \sin 2\phi_h)</td>
<td>(</td>
<td>A_\parallel(0)A_\perp(0)</td>
<td>)</td>
<td>(C \sin(\delta_\perp - \delta_\parallel))</td>
<td>(S \cos(\delta_\perp - \delta_\parallel))</td>
</tr>
<tr>
<td>5</td>
<td>(\frac{1}{2} \sqrt{2} \sin 2 \theta_K \sin 2 \theta_\mu \cos \phi_h)</td>
<td>(</td>
<td>A_0(0)A_\perp(0)</td>
<td>)</td>
<td>(\cos(\delta_\parallel - \delta_0))</td>
<td>(D \cos(\delta_\parallel - \delta_0))</td>
</tr>
<tr>
<td>6</td>
<td>(-\frac{1}{2} \sqrt{2} \sin 2 \theta_K \sin 2 \theta_\mu \sin \phi_h)</td>
<td>(</td>
<td>A_0(0)A_\perp(0)</td>
<td>)</td>
<td>(C \sin(\delta_\parallel - \delta_0))</td>
<td>(S \cos(\delta_\parallel - \delta_0))</td>
</tr>
<tr>
<td>7</td>
<td>(\frac{2}{3} \sin^2 \theta_\mu)</td>
<td>(</td>
<td>A_\parallel(0)</td>
<td>^2)</td>
<td>(</td>
<td>A_\parallel(0)</td>
</tr>
<tr>
<td>8</td>
<td>(\frac{1}{3} \sqrt{6} \sin \theta_K \sin 2 \theta_\mu \cos \phi_h)</td>
<td>(</td>
<td>A_\parallel(0)A_\perp(0)</td>
<td>)</td>
<td>(C \cos(\delta_\parallel - \delta_S))</td>
<td>(S \sin(\delta_\parallel - \delta_S))</td>
</tr>
<tr>
<td>9</td>
<td>(-\frac{1}{3} \sqrt{6} \sin \theta_K \sin 2 \theta_\mu \sin \phi_h)</td>
<td>(</td>
<td>A_\parallel(0)A_\perp(0)</td>
<td>)</td>
<td>(C \sin(\delta_\parallel - \delta_S))</td>
<td>(-D)</td>
</tr>
<tr>
<td>10</td>
<td>(\frac{4}{3} \sqrt{3} \cos \theta_K \sin^2 \theta_\mu)</td>
<td>(</td>
<td>A_\parallel(0)</td>
<td>^2)</td>
<td>(</td>
<td>A_\parallel(0)</td>
</tr>
</tbody>
</table>

\[ \phi_s = -\arg(\eta_f \lambda_f) \]
\[ C = \frac{1 - \left| \lambda_f \right|^2}{1 + \left| \lambda_f \right|^2} \]
\[ S = -\frac{2 \left| \lambda_f \right|}{1 + \left| \lambda_f \right|^2} \Im(\lambda_f) \]
\[ D = -\frac{2 \left| \lambda_f \right|}{1 + \left| \lambda_f \right|^2} \Re(\lambda_f) \]