CP violation and mixing in beauty with LHCb

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On behalf of the LHCb collaboration
Direct CP violation in 3-body decays

- Direct CPV: only CPV manifestation in charged B mesons.
- At least two interfering amplitudes.
  - Weak phases (flip sign under CP).
  - Strong phases (CP invariant).
- 3-body charmless decays allow to study strong phases that can originate in:
  - Short distance processes.
  - Long distance processes with hadron-hadron interactions in the final state:
    - Final state $KK \leftrightarrow \pi\pi$ rescattering.
    - Interference between intermediate states.
- Eg.: Analysis of $B^\pm \to \pi^\pm K^- K^+$: [Phys.Rev.D90 (2014) 112004]
  - CP asymmetry in the phase space: $A_{CP} = -0.123 \pm 0.022$.
  - Large asymmetries in the $\pi\pi\leftrightarrow KK$ rescattering region.
Amplitude analysis of $B^{±} \rightarrow \pi^{±}K^-K^+$ decays

- $B^{±} \rightarrow \pi^{±}K^-K^+$ Dalitz Plot separated for $B^+$ and $B^-$.  
- DP amplitude analysis with Isobar model of seven components.

$$A(m_{\pi+K^{-}}, m_{K^{-}+K^{-}}) = \sum_{i=1}^{N} c_i M_{R_i}(m_{\pi+K^{-}}, m_{K^{-}+K^{-}})$$

- $c_i$ : complex isobar coefficients
- $M_{R_i}(m_{\pi+K^{-}}, m_{K^{-}+K^{-}})$: amplitudes for the $i$-th intermediate state.
- Observables:

$$A_{CP} = \frac{|\bar{c}_i|^2 - |c_i|^2}{|\bar{c}_i|^2 + |c_i|^2}$$

$$FF_i = \frac{\int |c_i M_i|^2 + |\bar{c}_i \bar{M}_i|^2 dm_{\pi^{±}K^{-}}^2 dm_{K^{-}+K^{-}}^2}{\int |A|^2 + |\bar{A}|^2 dm_{\pi^{±}K^{-}}^2 dm_{K^{-}+K^{-}}^2}$$

B$^+$ yield: 2052 ± 102  
B$^-$ yield: 1566 ± 84

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Fit Fraction(%)</th>
<th>$A_{CP}$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+(892)^0$</td>
<td>7.5 ± 0.6 ± 0.5</td>
<td>+12.3 ± 8.7 ± 4.5</td>
</tr>
<tr>
<td>$K_0^+(1430)^0$</td>
<td>4.5 ± 0.7 ± 1.2</td>
<td>+10.4 ± 14.9 ± 8.8</td>
</tr>
<tr>
<td>Single pole</td>
<td>32.3 ± 1.5 ± 4.1</td>
<td>-10.7 ± 5.3 ± 3.5</td>
</tr>
<tr>
<td>$\rho(1450)^0$</td>
<td>30.7 ± 1.2 ± 0.9</td>
<td>-10.9 ± 4.4 ± 2.4</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>7.5 ± 0.8 ± 0.7</td>
<td>+26.7 ± 10.2 ± 4.8</td>
</tr>
<tr>
<td>Rescattering</td>
<td>16.4 ± 0.8 ± 1.0</td>
<td>-66.4 ± 3.8 ± 1.9</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>0.3 ± 0.1 ± 0.1</td>
<td>9.8 ± 43.6 ± 26.6</td>
</tr>
</tbody>
</table>
Amplitude analysis of $B^\pm \rightarrow \pi^\pm K^- K^+$ decays

arXiv:1905.09244

- Main contributions $\sim 30\%$: non-resonant and $B^\pm \rightarrow \rho^0 (1450) \pi^\pm$.
- Large CP asymmetry in $K^+ K^-$ rescattering contribution $\sim 66\%$.
  - In agreement with the inclusive CP asymmetry reported in PRD 90, 112004 (2014).
Amplitude analysis of $B^+ \rightarrow \pi^+\pi^-\pi^+$ decays

- Analysis in high and low ($\pi^+\pi^-$) pairs mass.
- Bose-symmetric amplitude.
- Isobar model of Non S-wave and S-wave cont.
- Non S-wave cont.: $\rho(770)^0$-$\omega(782)$, $f_2(1270)$, $\rho(1450)^0$ and $\rho_3(1690)^0$.
- S-wave cont.: $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$.
- Three S-wave approaches:
  - Isobar Approach.
    - Includes rescattering component and pole for $f_0(500)$.
  - K-matrix Approach.
    - Unitary by construction.
  - QMI Approach.
    - Fit magnitude and phase in regions of the DP.
- General agreement between the three S-wave approaches.

Combined signal yield
20600 ± 1600 events

Lepton–Photon 2019
Toronto, August 5–10

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Amplitude analysis of $B^+ \rightarrow \pi^+\pi^-\pi^+$ decays

Phases:
- Largest difference between $B^-$ and $B^+$ in $f_2(1270)$ (~55°).
- Originates some large CPV in DP.

Fit fractions:
- Dominant $\rho(770)^0$ (~0.56) and S-wave (~0.26).
- Significant $f_2(1270)$ (~0.09).

CP asymmetries:
- No asymmetry observed in $\rho$-$\omega$ mixing.
- Clear asymmetry in $m(\pi^+\pi^-)$ below $\rho(770)^0$ mass.
  - Flips sign at $K^+K^-$ threshold.
- Large asymmetry in helicity angle.
  - Reveals CPV in S-P waves interference.
  - **First observation** (>25σ) of CPV in a quasi-two-body interference.
- Large asymmetry ~40% in $f_2(1270)$.
  - **First observation** (>10σ) of CPV involving a tensor.
$B_s^0 \rightarrow VV$ time dependent analyses

\[ \phi^{c\bar{s}s}_{s} \equiv \arg \lambda \ \approx \ \arg \left( \frac{V_{ts}^* V_{tb} V_{ts}^* V_{tb}^*}{V_{cs}^* V_{cb} V_{cs}^* V_{cb}^*} \right) = -36.8^{+1.0}_{-0.8} \text{ mrad} \]

- $B_s^0 - \bar{B}_s^0$ mixing interference between:
  - Decay.
  - Decay after mixing.
- Observable phase $\phi_s = \Phi_M - 2 \Phi_D$.
- Different decays $\rightarrow$ different $\phi_s$.
- NP can appear in $\Phi_M$.
- Tree decays (no NP in $\Phi_D$): $b \rightarrow scc$ transitions.
- Loop decays (potential NP in $\Phi_D$): $b \rightarrow sss$ and $b \rightarrow sdd$ transitions.

Direct CPV also possible if $|\lambda| = \left| \frac{q}{p} \cdot \frac{\bar{A}}{A} \right| \neq 1.$
\( B_s^0 \rightarrow VV \) time dependent analyses

- Deviation of \( \phi_s \) from SM would imply NP.
- Decay rate depends on \( \phi_s, \Delta \Gamma_s \) and \( \Delta m_s \).
- Vector and S-wave final states: admixture of CP-even and CP-odd eigensates.
- Full amplitude analyses applied with dependencies on:
  - Mass.
  - Helicity angles.
  - Time.
- Require tagging.
- Time resolution and tagging power enter in the experimental PDF.
- Unbinned maximum likelihood fits.
• $B^0_s \rightarrow J/\psi K^+K^-$ and $B^0_s \rightarrow J/\psi \pi^+\pi^-$
  
- 1.9 fb$^{-1}$ (2015: 0.3 fb$^{-1}$ & 2016: 1.6 fb$^{-1}$) Run-II data.
- $B^0_s \rightarrow J/\psi K^+K^-$ around $\phi(1020)$.
  - Modest S-wave contribution.
- $B^0_s \rightarrow J/\psi \pi^+\pi^-$: mainly $B^0_s \rightarrow J/\psi f_0(980)$.
- Decay-time resolution
  - $\sigma_{\text{eff}}(B^0_s \rightarrow J/\psi K^+K^-) \approx 45.5$ fs,
  - $\sigma_{\text{eff}}(B^0_s \rightarrow J/\psi \pi^+\pi^-) \approx 41.5$ fs.
- Decay-time and angular efficiencies
  - Estimated with simulation.
  - Corrected with data methods.
- Flavour tagging
  - 30% higher tagging power than Run-1.

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\[ B^0_s \to J/\psi K^+K^- \quad \text{and} \quad B^0_s \to J/\psi \pi^+\pi^- \]

Results in agreement with previous measurements and SM prediction.
Exp. unc. of \( \phi_s \) average: 31 → 21 mrad.
Exp. unc. of \( \Delta \Gamma_s \) average: 0.005 → 0.0034 ps\(^{-1}\).

\[ B^0_s \to J/\psi K^+K^- \]
\[ \phi_s = -83 \pm 41 \pm 6 \text{ mrad} \]
\[ |\lambda| = 1.012 \pm 0.016 \pm 0.006 \]
\[ \Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1} \]

\[ B^0_s \to J/\psi \pi^+\pi^- \]
\[ \phi_s = -57 \pm 60 \pm 11 \text{ mrad} \]
\[ |\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03 \]
\[ \Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1} \]

Average LHCb
\[ \phi_s = -41 \pm 25 \text{ mrad} \]
\[ |\lambda| = 0.093 \pm 0.010 \]
\[ \Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1} \]

HFLAV combination
\[ \phi_s = -55 \pm 21 \text{ mrad} \]
\[ \Delta \Gamma_s = 0.0764 \pm 0.0024 \text{ ps}^{-1} \]
$B_s^0 \rightarrow \phi \phi$

- Run 1 (3 fb$^{-1}$) + part. Run 2 (2 fb$^{-1}$) data
- 4-dimension: 3 angles + time:
  - $\Gamma_s$ and $\Delta \Gamma_s$ and $\Delta m_s$ from external input (PDG and HFLAV).
- CP-even and CP-odd S-wave contributions.
- Detector efficiency and decay-time resolution determined with simulated events.
- Decay-time efficiency determined with data method.
- Angular observables measured.
  - Pure penguin decays show small longitudinal polarisation ($A_0$ or $f_L$) with one exception.

~8500 signal events.
$B_s^0 \rightarrow \phi\phi$

\[ |A_0|^2 = 0.381 \pm 0.007 \text{ (stat)} \pm 0.012 \text{ (syst)}, \]
\[ \phi_s^{\text{SSS}} = -0.073 \pm 0.115 \text{ (stat)} \pm 0.027 \text{ (syst)} \text{ rad}, \]
\[ |\lambda| = 0.99 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)}. \]

Stat. unc. of $\phi_s$: 15→11.5 mrad.
Stat unc. of $|A_0|^2$: 0.012 →0.007

Total CP–even  CP–odd  S–wave
• TD 2018 analysis of $B^0_s \rightarrow K^{*0} \bar{K}^{*0}$ determined [JHEP 1803 (2018) 140]:

$$\phi_{d\bar{d}s} = -0.10 \pm 0.13 \text{ (stat.)} \pm 0.14 \text{ (syst.)} \text{ [rad]}$$

$$|\lambda| = 1.035 \pm 0.034 \text{ (stat.)} \pm 0.089 \text{ (syst.)}$$

• Prospects: repeat the study with Run 2 (6 fb$^{-1}$) and upgraded LHCb data.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>3 fb$^{-1}$</th>
<th>23 fb$^{-1}$</th>
<th>50 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow \phi \bar{\phi}$</td>
<td>0.154</td>
<td>0.039</td>
<td>0.026</td>
<td>0.011</td>
</tr>
<tr>
<td>$B^0_s \rightarrow (K^+\pi^-)/(K^-\pi^+)$ (inclusive)</td>
<td>0.129</td>
<td>0.033</td>
<td>0.022</td>
<td>0.009</td>
</tr>
<tr>
<td>$B^0_s \rightarrow K^* (892)^0 \bar{K}^* (892)^0$</td>
<td>–</td>
<td>0.127</td>
<td>0.086</td>
<td>0.035</td>
</tr>
</tbody>
</table>

• $B^0 \rightarrow K^{*0} \bar{K}^{*0}$ U-spin partner of $B^0_s \rightarrow K^{*0} \bar{K}^{*0}$ decay.
  – Can be used to control penguin pollution from subleading amplitudes.
• First LHCb analysis of $B^0 \rightarrow K^{*0} \bar{K}^{*0}$.
• High $f_L$ compared with $B^0_s \rightarrow K^{*0} \bar{K}^{*0}$.
• Complete Run-I (3 fb$^{-1}$) data.
• Untagged and time-integrated analysis.
• Assuming $\Delta \Gamma \sim 0$ and negligible CPV in the mixing and in the decay.


\[ \mathbf{B}^0 \rightarrow \mathbf{K}^{*0} \mathbf{K}^{*0} \]

- Large longitudinal polarisation: \( f_L = 0.724 \pm 0.051 \) (stat) \( \pm 0.016 \) (syst).
  - S–wave fraction: \( 0.408 \pm 0.050 \) (stat) \( \pm 0.023 \) (syst).
- Parallel study of the \( \mathbf{B}_s^0 \rightarrow (\mathbf{K}^+\pi^-)(\mathbf{K}^-\pi^+) \) performed.
  - Small \( f_L = 0.240 \pm 0.031 \) (stat) \( \pm 0.025 \) (syst).
  - Large S–wave contribution: \( 0.694 \pm 0.016 \) (stat) \( \pm 0.012 \) (syst).
  - Compatible with LHCb time dependent study.

\( \mathbf{B}^0 \rightarrow \mathbf{K}^{*0} \mathbf{K}^{*0} \) branching fraction measured

\[ \mathcal{B}(\mathbf{B}^0 \rightarrow \mathbf{K}^{*0} \overline{\mathbf{K}}^{*0}) = (8.04 \pm 0.87 \) (stat) \( \pm 0.41 \) (syst)) \( \times 10^{-7} \]

- Using averages \( y = \Delta \Gamma_s/(2 \Gamma_s) = 0.064 \pm 0.005 \) and \( \phi_s = -0.021 \pm 0.031 \)

\[ R_{sd} = \frac{\mathcal{B}(\mathbf{B}_s^0 \rightarrow \mathbf{K}^{*0} \overline{\mathbf{K}}^{*0}) f_L(\mathbf{B}_s^0 \rightarrow \mathbf{K}^{*0} \overline{\mathbf{K}}^{*0})}{\mathcal{B}(\mathbf{B}^0 \rightarrow \mathbf{K}^{*0} \overline{\mathbf{K}}^{*0}) f_L(\mathbf{B}^0 \rightarrow \mathbf{K}^{*0} \overline{\mathbf{K}}^{*0})} \frac{1 - y^2}{1 + y \cdot \cos \phi_s} \]

found to be \( R_{sd} = 3.43 \pm 0.38 \).
- There is a theoretical prediction:

\[ R_{sd}^{\text{theory}} = 16.4 \pm 5.2 \quad [\text{Phys.Rev.D76 (2007) 074005}] \]
Conclusions

• Very large direct CPV effects are observed in DP regions of charmless 3-body decays.
  – Possibly due to strong phases originated in rescattering.

• In particular, in $B^+ \rightarrow \pi^+ \pi^- \pi^+$ decays, large asymmetry in helicity angle.
  – First observation of CPV in the interference of S and P waves contributions.
  – Large asymmetry $\sim 40\%$ in $f_2(1270)$ which is the first observation of CPV involving a tensor.

• TD analyses compatible with the SM and produce the strongest constraints in the different $\phi_s$.

• The $B \rightarrow VV$ longitudinal polarisation puzzle continues with the very different $f_L$ values of of $B^0 \rightarrow K^*0\bar{K}^*0$ and $B_s^0 \rightarrow K^*0\bar{K}^*0$.
  – Questions U-spin symmetry.