CP violation in $B_{(s)}^0 \rightarrow h^+ h'^-$

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on behalf of the LHCb collaboration

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Outline

- **Introduction**
  - Motivations
  - CPV observables
  - Current experimental status

- **Main ingredients of the analysis**
  - Event selection
  - Flavour tagging
  - Decay-time resolution
  - Decay-time acceptance
  - Final-state detection asymmetry

- **Final results**

- **Conclusions**
Motivations

- **CPV observables** are sensitive to CKM angles $\alpha/\phi_2$, $\gamma/\phi_3$, $\beta/\phi_1$ and $\beta_s/\phi_s$
- A rich set of physics processes contributes to the $H_b \rightarrow h^+ h'^-$ decays ($h = K, \pi$)
  - tree and penguin decay topologies
  - neutral $B$ mixing

Presence of loop diagrams:

- introduces **hadronic uncertainties** as additional parameters in the decay-amplitude
- makes the CPV observables sensitive to **New Physics** contributions

Decay diagrams

Mixing diagrams

PJC71(2011)1532  JHEP10(2012)029
EPJ C77(2017)574  JHEP03(2017)55
**CPV observables**

- Time-integrated CPV asymmetries in $B^0 \rightarrow K^+\pi^-$ and $B_s \rightarrow \pi^+K^-$ decays are defined as:

$$A_{CP} = \frac{|\tilde{A}_f|^2 - |A_f|^2}{|\tilde{A}_f|^2 + |A_f|^2}$$

- The main CPV observables are the time-dependent asymmetries of $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays:

$$A(t) = \frac{\Gamma_{B^0_{(s)} \rightarrow f}(t) - \Gamma_{B^0_{(s)} \rightarrow f}(t)}{\Gamma_{B^0_{(s)} \rightarrow f}(t) + \Gamma_{B^0_{(s)} \rightarrow f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta \Gamma_{d(s)}}{2}t\right) + A_f^{\Delta \Gamma} \sinh\left(\frac{\Delta \Gamma_{d(s)}}{2}t\right)}$$

- The knowledge of the flavour of the $B$ candidate at production is required $\Rightarrow$ flavour tagging tool is a key ingredient of the analysis
Status of art (TI $CPV$)

- Direct $CPV$ in $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ are dominated by LHCb measurement ($L = 1 \text{ fb}^{-1}$) [Phys. Rev. Lett. 110 (2013) 221601]

$$A_{CP}(B^0 \rightarrow K^+\pi^-) \quad A_{CP}(B_s^0 \rightarrow \pi^+K^-) \quad \text{Reference}$$

<table>
<thead>
<tr>
<th></th>
<th>$A_{CP}(B^0 \rightarrow K^+\pi^-)$</th>
<th>$A_{CP}(B_s^0 \rightarrow \pi^+K^-)$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$-0.107 \pm 0.016^{+0.006}_{-0.004}$</td>
<td>-</td>
<td>PRD 87 (2013) 052009</td>
</tr>
<tr>
<td>Belle</td>
<td>$-0.069 \pm 0.014 \pm 0.007$</td>
<td>-</td>
<td>PRD 87 (2013) 031103</td>
</tr>
<tr>
<td>CDF</td>
<td>$-0.083 \pm 0.013 \pm 0.004$</td>
<td>$0.22 \pm 0.07 \pm 0.02$</td>
<td>PRL 113 (2014) 242001</td>
</tr>
<tr>
<td>LHCb</td>
<td>$-0.080 \pm 0.007 \pm 0.003$</td>
<td>$0.27 \pm 0.04 \pm 0.01$</td>
<td>PRL 110 (2013) 221601</td>
</tr>
<tr>
<td>HFLAV average</td>
<td>$-0.082 \pm 0.006$</td>
<td>$0.26 \pm 0.04$</td>
<td></td>
</tr>
</tbody>
</table>
**Status of art (TD $CPV$)**

- First measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ performed by BaBar & Belle using the $B^0 \to \pi^+\pi^-$ decay

<table>
<thead>
<tr>
<th>$C_{\pi\pi}$</th>
<th>$S_{\pi\pi}$</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>BaBar</td>
<td>$-0.25 \pm 0.08 \pm 0.02$</td>
<td>$-0.68 \pm 0.10 \pm 0.03$</td>
</tr>
<tr>
<td>Belle</td>
<td>$-0.33 \pm 0.06 \pm 0.03$</td>
<td>$-0.64 \pm 0.08 \pm 0.03$</td>
</tr>
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- LHCb performed a measurement using 1 fb$^{-1}$ at 7 TeV on $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays

  [JHEP 1310 (2013) 183]

  $B^0 \to \pi^+\pi^-$

  $C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$
  $S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$

  $B_s \to K^+K^-$

  $C_{KK} = 0.14 \pm 0.11 \pm 0.03$
  $S_{KK} = 0.30 \pm 0.12 \pm 0.04$

- No measurement available for $A_{KK}^{\Delta \Gamma}$
Main ingredients of the analysis

- Analysis performed using full Run 1 data sample ($\sim 3 \text{ fb}^{-1}$)
- Main steps of TD CPV in $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$
  - flavour tagging
  - decay-time resolution
  - decay-time acceptance

$$A_{\text{raw}}(t) \sim D_{\text{tag}}D_{\text{reso}}A(t)$$

- Main ingredients of TI CPV in $B^0 \rightarrow K^+\pi^-$ and $B^0_s \rightarrow \pi^+K^-$:
  - final state detection asymmetries ($A_F$)
  - production asymmetry ($A_P$)
    $\implies$ extrapolated directly from $A_{\text{CP}}$ by means of the time-dependent fit

$$A_{\text{raw}} \sim A_{\text{CP}} + A_F + A_P$$
Event selection

- All the CP parameters are determined with a multidimensional fit performed simultaneously on the $K^\pm \pi^\mp$, $\pi^+\pi^-$ and $K^+K^-$ spectra.

- A PID selection is applied to separate the three final states and reduce the amount of cross contamination from the other $H_b \to h^+h'^-$ to a $\sim 10\%$ of the signal.

- A MVA algorithm based on a BDT is used to reduce the combinatorial background $\implies$ F.O.M. = $S/\sqrt{S+B}$

\begin{align*}
B^0 \to \pi^+\pi^- & \quad B_s \to K^+K^- \\
\sim 28 \, 600 & \quad \sim 36 \, 800 \\
B^0 \to K^+\pi^- & \quad B_s \to \pi^+K^- \\
\sim 94 \, 200 & \quad \sim 7 \, 000
\end{align*}

Flavour tagging

- **"Same Side" (SS)** if the tagging particle comes from the signal B fragmentation:
  - SS$\pi$ & SS$p$ for $B^0$
  - SSK for $B_s^0$

- **"Opposite Side" (OS)** if the tagger exploits the charge information of the opposite B decay

Each tagger provides a tagging decision and a mistag rate ($\omega$)

\[ \Rightarrow \text{tagging dilution: } D_{tag} = (1 - 2\omega) \]

- Tagging efficiency: $\varepsilon_{tag}$
- Tagging power: $\varepsilon_{eff} = \varepsilon_{tag}D_{tag}^2$

\[ \sigma_{stat} (CP \text{ asym}) \propto \frac{1}{\sqrt{\varepsilon_{eff} N}} \]

Flavour tagging calibration

- Calibration of the predicted mistag rate $\eta$ is crucial step in order to obtain an unbiased estimation of the mistag probability $\omega$
- Natural control samples are $B^0 \rightarrow K^+\pi^-$ and $B^0_s \rightarrow \pi^+K^-$
- OS tagger is calibrated on the fly using $B^0 \rightarrow K^+\pi^-$: no distinction between $B^0$ and $B^0_s$
- $SS_\pi$ and $SS_p$ calibrated using $B^0 \rightarrow K^+\pi^-$ and then combine into an unique tagging algorithm $SS_{comb}$.
- $SS_{comb}$ calibrated on the fly using $B^0 \rightarrow K^+\pi^-$ ($B^0$ only)
- $SS_K$ calibrated using a sample of $B^0_s \rightarrow D^-\pi^+$ decays ($B^0_s$ only)
  $\Rightarrow$ yield of $B^0_s \rightarrow \pi^+K^-$ not sufficient to obtain a reliable calibration

Decay-time resolution

- Calibration is performed measuring simultaneously the time-dependent asymmetries of $B^0 \to D^- \pi^+$ and $B^0_s \to D_s^- \pi^+$
- Raw asymmetries diluted by:
  - **flavour tagging**: $D_{tag} = (1 - 2\omega)$
  - **decay-time resolution**: $D = \exp(-\sigma_t^2 \Delta m^2 / 2)$
- $B^0 \to D^- \pi^+$ decay used to calibrate tagging dilution
- $B^0_s \to D_s^- \pi^+$ decay used to calibrate the decay-time resolution
  - $\Rightarrow$ dilution from $\sigma_t$ negligible for $B^0$ due to small $\Delta m_d$
- Portability from $B^0_{(s)} \to D^-_{(s)} \pi^+$ to $B^0_{(s)} \to h^+ h'^-$ studied using fully simulated events

![Graphs](https://example.com/graphs.png)
Decay-time acceptance

- Reconstruction efficiency as a function of decay-time is determined using $B^0 \rightarrow K^+ \pi^-$ decays
- Untagged decay rate of $B^0$ as a function of time is a pure exponential
- Fully simulated samples are used to study the differences of the other decay modes w.r.t. $B^0 \rightarrow K^+ \pi^-$

Other sources of asymmetry

- The time dependent asymmetry is measured as:

\[ A_{\text{raw}}(t) \approx A_{\text{CP}} + A_{D} + A_{\text{PID}} + A_{P} \cos(\Delta m_{d(s)} t) \]

- The **production asymmetry** \( A_{P} \) can be extracted by means of the time-dependent fit from the \( CP \) asymmetries in \( B^0 \rightarrow K^+ \pi^- \) and \( B_s \rightarrow \pi^+ K^- \) decays.

- A correction is required taking into account:
  - asymmetry induced by the PID requirements \( A_{K\pi}^{\text{PID}} \)
  - detection asymmetry \( A_{D}^{K\pi} \)

- \( A_{K\pi}^{PID} \) estimated using \( D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+ \)

- \( A_{D}^{K\pi} \) measured using raw asymmetries of Cabibbo-favoured charm decays \( D^+ \rightarrow K^- \pi^+ \pi^+ \) and \( D^+ \rightarrow K^0 \pi^+ \) [JHEP 07 (2014) 041]

- Asymmetries are convoluted with the \( B_{(s)}^0 \rightarrow h^+ h'^- \) phase space

\[
\begin{align*}
A_{K\pi}^{PID}(B_{(s)}^0 \rightarrow K^\pm \pi^{\mp}) &= (-0.04 \pm 0.25)\% \\
A_{D}^{K\pi}(B^0 \rightarrow K^+ \pi^-) &= (-0.900 \pm 0.141)\% \\
A_{D}^{K\pi}(B_s \rightarrow \pi^+ K^-) &= (-0.924 \pm 0.142)\%
\end{align*}
\]

Results of the $K^{\pm}\pi^{\mp}$ final state

- Most precise measurement from a single experiment
  

\[ A_{CP}^{B^0} = (-8.4 \pm 0.4 \pm 0.3)\% \]
\[ A_{CP}^{B^0_s} = (21.3 \pm 1.5 \pm 0.3)\% \]

- Production asymmetry is subtracted by means of the time-dependent fit

\[ A_P(B^0) = (0.19 \pm 0.60)\% \quad A_P(B^0_s) = (2.4 \pm 2.1)\% \]

(compatible with expectation from Phys. Lett. B 774 (2017) 139)

- SM test assuming U-spin validity [PLB 621 (2005) 126]

\[ \Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B^0_s}} + \frac{B(B^0_s \to \pi^+K^-)}{B(B^0 \to K^+\pi^-)} \frac{\tau_d}{\tau_s} = -0.11 \pm 0.03 \pm 0.04 \text{ (from } A_{CP}) \]
Results of the $\pi^+\pi^-$ final state

- Most precise measurement from a single experiment
- Uncertainties halved with respect to previous LHCb results

\[ \mathbf{C}_{\pi\pi} = -0.34 \pm 0.06 \pm 0.01 \]
\[ \mathbf{S}_{\pi\pi} = -0.63 \pm 0.05 \pm 0.01 \]
\[ \rho(\mathbf{C}_{\pi\pi}, \mathbf{S}_{\pi\pi}) = 0.448 \]
Results for the $K^*K^-$ final state

- Very first measurement of $A_{KK}^{\Delta\Gamma}$ [Phys. Rev. D 98 (2018) 032004]
- Strongest evidence of CPV in $B_s^0$ sector: confirmed at $4\sigma$

\[ C_{KK} = 0.20 \pm 0.06 \pm 0.02 \]
\[ S_{KK} = 0.18 \pm 0.06 \pm 0.02 \]
\[ A_{KK}^{\Delta\Gamma} = -0.79 \pm 0.07 \pm 0.10 \]
### Systematic uncertainties

- **Summary of the systematic uncertainties taken into account**
- **Main contribution highlighted in red**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$C_{\pi^+\pi^-}$</th>
<th>$S_{\pi^+\pi^-}$</th>
<th>$C_{K^+K^-}$</th>
<th>$S_{K^+K^-}$</th>
<th>$A^\Delta_{K^+K^-}$</th>
<th>$A_{CP}(B^0 \rightarrow K^+\pi^-)$</th>
<th>$A_{CP}(B_s \rightarrow \pi^+K^-)$</th>
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</thead>
<tbody>
<tr>
<td>Time-dependent efficiency</td>
<td>0.0011</td>
<td>0.0004</td>
<td>0.0020</td>
<td>0.0017</td>
<td><strong>0.0778</strong></td>
<td>0.0004</td>
<td>0.0002</td>
</tr>
<tr>
<td>Time-resolution calibration</td>
<td>0.0014</td>
<td>0.0013</td>
<td>0.0108</td>
<td>0.0119</td>
<td>0.0051</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Time-resolution model</td>
<td>0.0001</td>
<td>0.0005</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0003</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Input parameters</td>
<td>0.0025</td>
<td>0.0024</td>
<td>0.0092</td>
<td>0.0107</td>
<td><strong>0.0480</strong></td>
<td>negligible</td>
<td>0.0001</td>
</tr>
<tr>
<td>OS tagger calibration</td>
<td>0.0018</td>
<td>0.0021</td>
<td>0.0018</td>
<td>0.0019</td>
<td>0.0001</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>SSK tagger calibration</td>
<td>n/a</td>
<td>n/a</td>
<td>0.0061</td>
<td>0.0086</td>
<td>0.0004</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>SS tagger calibration</td>
<td>0.0015</td>
<td>0.0017</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Cross-feed time model</td>
<td><strong>0.0075</strong></td>
<td><strong>0.0059</strong></td>
<td>0.0022</td>
<td>0.0024</td>
<td>0.0003</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Three-body bkg.</td>
<td><strong>0.0070</strong></td>
<td><strong>0.0056</strong></td>
<td>0.0044</td>
<td>0.0043</td>
<td>0.0304</td>
<td>0.0008</td>
<td><strong>0.0043</strong></td>
</tr>
<tr>
<td>Comb. bkg. time model</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0004</td>
<td>0.0002</td>
<td>0.0019</td>
<td>0.0001</td>
<td>0.0005</td>
</tr>
<tr>
<td>Signal mass model (reso)</td>
<td>0.0027</td>
<td>0.0025</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0023</td>
<td>0.0001</td>
<td><strong>0.0041</strong></td>
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<tr>
<td>Signal mass model (tails)</td>
<td>0.0007</td>
<td>0.0008</td>
<td>0.0013</td>
<td>0.0013</td>
<td>0.0016</td>
<td>negligible</td>
<td>0.0003</td>
</tr>
<tr>
<td>Comb. bkg. mass model</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0016</td>
<td>negligible</td>
<td>0.0001</td>
</tr>
<tr>
<td>PID asymmetry</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td><strong>0.0025</strong></td>
<td><strong>0.0025</strong></td>
</tr>
<tr>
<td>Detection asymmetry</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.0115</td>
<td>0.0095</td>
<td>0.0165</td>
<td>0.0191</td>
<td>0.0966</td>
<td>0.0030</td>
<td>0.0066</td>
</tr>
</tbody>
</table>

Conclusions

- The latest measurements of $CPV$ in $B_{(s)}^{0} \rightarrow h^+ h'^-$ decays at LHCb have been shown [Phys. Rev. D 98 (2018) 032004]

- Analysis is based on the full Run 1 sample corresponding to an integrated luminosity of $1 \text{ fb}^{-1}$ at 7 TeV and $2 \text{ fb}^{-1}$ at 8 TeV

- **Significant improvement with respect to previous measurements**
  - Best measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ from a single experiment
  - Best measurement of $A_{CP}^{B_{0}}$ and $A_{CP}^{B_{s}}$ from a single experiment
  - Strongest evidence of $CPV$ in $B_{s}^{0} \rightarrow K^+ K^-$ decay at $4\sigma$

\[
\begin{align*}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01 \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01 \\
C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02 \\
S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02 \\
A_{\Delta \Gamma}^{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10 \\
A_{CP}^{B_{0}} &= (-8.4 \pm 0.4 \pm 0.3)\% \\
A_{CP}^{B_{s}^{0}} &= (21.3 \pm 1.5 \pm 0.3)\%
\end{align*}
\]
Thank you for your attention!
Backup
The Large Hadron Collider beauty (LHCb) Experiment

- LHCb detector is a single-arm forward spectrometer optimised for $b$ and $c$ hadron physics
  - pseudorapidity range: $\Delta \eta = [2,5] \Rightarrow \sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
  - Run1 (2010-2012) $\Rightarrow \approx 3$ fb$^{-1}$
  - Run2 (2015-2018) $\Rightarrow \approx 4$ (already taken) $+ 2$ (expected) fb$^{-1}$

- Excellent performances
  [Int. J. Mod. Phys. A 30, 1520022 (2015)]:
  - **Momentum resolution**:
    $\frac{\sigma_p}{p} \approx 0.5 - 0.8\%$ ($p < 100$ GeV/c)
  - Impact Parameter (IP) resolution:
    $\sigma_{IP} \approx 20$ $\mu$m (at high $p_T$)
  - Decay time resolution:
    $\sigma_t \approx 50$ fs
  - **Particle Identification (PID)**:
    $\varepsilon(K) \approx 95\%$, $\pi$ mis-ID $\approx 5\%$ ($p < 100$ GeV/c)
    $\varepsilon(\mu) \approx 97\%$, $\pi$ mis-ID $\approx 1-3\%$
Flavour Tagging algorithms

- "Same Side" (SS): exploit the charge of the particle ($\pi$, $p$, $K$) produced in the fragmentation of the signal b-hadron to infer its flavour at production.
- "Opposite Side" (OS): exploit the charge of the particle ($l$, $K$, $c$-decays) or of the reconstructed secondary vertex produced from the opposite b-hadron to infer the signal b-hadron flavour at production.
Tagging performance

- **Tagging Efficiency**: fraction of tagged events
  \[ \varepsilon_{\text{tag}} = \frac{N_{\text{wrong}} + N_{\text{right}}}{N_{\text{wrong}} + N_{\text{right}} + N_{\text{untag}}} \]

- correlated with the transverse momentum of the signal B

- **Mistag probability**: fraction of the events with wrong tag decision, defined in range [0, 0.5].
  \[ \omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}} \]

- **Dilution**: \( D = (1 - 2\omega) \) of asymmetries and decay rates.

- Predicted mistag probability \( \eta \) computed by taggers needs calibration \( \omega(\eta) \) to provide unbiased estimate of the mistag probability \( \omega \)

- **Tagging power**: statistical degradation of CP asymmetries
  \[ \varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} D^2 = \varepsilon_{\text{tag}} \langle (1 - 2\omega)^2 \rangle \]
  \[ \sigma^{\text{stat}}(\text{CP asym}) \propto \frac{1}{\sqrt{\varepsilon_{\text{eff}} N}} \]
How to exploit $H_b \rightarrow h^+ h'^-$ decays

- $CP$ asymmetries of $B^0 \rightarrow \pi^+ \pi^-$ decays
  - fundamental input to the isospin analysis to determine the CKM angle $\alpha/\phi_2$
- First proposal to include also $B^0_s \rightarrow K^+ K^-$ decays dates back to 1999
  - exploiting U-spin symmetry to constraint QCD uncertainties and determine $\gamma/\phi_3$ and $-2\beta_s/\phi_s$
- $A_{CP}$ of $B^0 \rightarrow K^+ \pi^-$ and $B_s \rightarrow \pi^+ K^-$ provide a test of the SM assuming U-spin symmetry:

\[
\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B^0_s}} + \frac{B(B^0_s \rightarrow \pi^+ K^-)}{B(B^0 \rightarrow K^+ \pi^-)} \frac{\tau_d}{\tau_s} = 0 \quad \text{[PLB 621 (2005) 128]}
\]

- More recent studies aimed to reduce the impact of the uncertainty due to U-spin breaking:
  - combined analysis of $B^0, \pm \rightarrow \pi^0, \pm \pi^0, \mp$ and $B^0_s \rightarrow K^+ K^-$
- Combining $CP$ asymmetries of $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+ K^-$ with information from semileptonic $B^0 \rightarrow \pi l \nu$ and $B_s \rightarrow K l \nu$ allow to reduce the usage of U-spin symmetry [arXiv:1608.00901, arXiv:1612.07342]
Systematic uncertainties

- Two main strategies:
  - Fixed parameters: repeat the fit to data 100 times changing the parameter values according to their uncertainties and correlations with the other parameters
  - Models: generating pseudo-experiments with the default model, then repeating the fit both with the default and the modified models
- The squared sum of the mean and the RMS of the variation is taken as systematic uncertainties

<table>
<thead>
<tr>
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<th>$C_{\pi^+\pi^-}$</th>
<th>$S_{\pi^+\pi^-}$</th>
<th>$C_{K+K^-}$</th>
<th>$S_{K+K^-}$</th>
<th>$A_{K+K^-}^{\Delta}$</th>
<th>$A_{\alpha}(B^0 \rightarrow K^+\pi^-)$</th>
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<tr>
<td>SS tagger calibration</td>
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<td>0.0017</td>
<td>n/a</td>
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<td>negligible</td>
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<tr>
<td>Cross-feed time model</td>
<td><strong>0.0075</strong></td>
<td><strong>0.0059</strong></td>
<td>0.0022</td>
<td>0.0024</td>
<td>0.0003</td>
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<tr>
<td>Three-body bkg.</td>
<td><strong>0.0070</strong></td>
<td><strong>0.0056</strong></td>
<td>0.0044</td>
<td>0.0043</td>
<td>0.0304</td>
<td>0.0008</td>
<td><strong>0.0043</strong></td>
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<tr>
<td>Comb. bkg. time model</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0004</td>
<td>0.0002</td>
<td>0.0019</td>
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<tr>
<td>Signal mass model (reso)</td>
<td>0.0027</td>
<td>0.0025</td>
<td>0.0015</td>
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<td>0.0023</td>
<td>0.0001</td>
<td><strong>0.0041</strong></td>
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<tr>
<td>Signal mass model (tails)</td>
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<td>0.0008</td>
<td>0.0013</td>
<td>0.0013</td>
<td>0.0016</td>
<td>negligible</td>
<td>0.0003</td>
</tr>
<tr>
<td>Comb. bkg. mass model</td>
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<td>0.0003</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0016</td>
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<td>negligible</td>
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<td>PID asymmetry</td>
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<td>n/a</td>
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<tr>
<td>Detection asymmetry</td>
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<td>Total</td>
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<td>0.0095</td>
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<td>0.0191</td>
<td>0.0966</td>
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