CKM and CPV measurements in the beauty and charm sector

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On behalf of the LHCb collaboration

LHCP 2023
Large Hadron Collider Physics Conference
Outlines

- Introduction.
- Measurement of the CKM angle $\phi_s$
  - $B_s \rightarrow J/\psi \phi$
- Measurement of the CKM angle $\phi_s^{s\bar{s}s}$
  - $B_s \rightarrow \phi \phi$
- CKM angle $\gamma$ measurement
  - $B^\pm \rightarrow [h^+ h^- \pi^\pm \pi^\mp]_D h^\pm (h = K, \pi)$
- CP violation in charm sector.
  - CP violation in multibody $D$ decay.
- Summary.

ATLAS, CMS and LHCb

LHCb
CKM matrix and CP violation

- CKM matrix is a $3\times3$ unitary matrix, elements represent the strength of flavor-changing weak interactions.

\[
\begin{bmatrix}
d' \\
s' \\
b'
\end{bmatrix} = V_{\text{CKM}} \begin{bmatrix}
d \\
s \\
b
\end{bmatrix}, \text{ where } V_{\text{CKM}} = \begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix}
\]

- Parameterized by 3 mixing angles and CP violating phase.
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

- CKM phases are related to CP violation (CPV).
  - $\alpha = \arg \left( -\frac{V_{tb}}{V_{ub}} \right)$; $\beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)$; $\gamma = \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$.

- CKM matrix unitarity: test consistency of the CKM mechanism.
  - Sensitive to New Physics (NP).
CP violating $\phi_s$ and $\Delta \Gamma_s$ in $B_s \to J/\psi \phi$ decays

- $\phi_s$: weak phase difference between direct decays and decays through mixing of $B_s^0$.
- $\phi_s \approx -2\beta_s$, $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$.
- Sensitive to NP.

<table>
<thead>
<tr>
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<th>$\phi_s$</th>
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<tbody>
<tr>
<td>CKMfitter</td>
<td>$-0.0365^{+0.0013}_{-0.0012}\text{rad}$</td>
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<tr>
<td>UTfit</td>
<td>$-0.03700 \pm 0.0014\text{rad}$</td>
</tr>
</tbody>
</table>

- $\Delta \Gamma_s$: decay widths difference between mass eigenstates.
- Standard Model (SM) prediction: $(0.085 \pm 0.015)\text{ps}^{-1}$ [arXiv:1511.09466].
- Sensitive to NP.
Measurement with $B_s \to J/\psi K^+ K^-$ decay

LHCb | ATLAS | CMS
--- | --- | ---
Same-side (SS) and opposite-side (OS) tagger | OS tagger | 
Helicity | Transversity |

time-dependent angular analysis for signal from mass distribution.
Comparison between CMS, ATLAS and LHCb Results

<table>
<thead>
<tr>
<th>Measurement of $\phi_s$</th>
<th>CDF, D0, ATLAS and CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow J/\psi \phi$</td>
<td>$B_s \rightarrow J/\psi K^+ K^-$ (including $B_s \rightarrow J/\psi \phi$), $B_s \rightarrow \psi(2S)\phi$, $B_s \rightarrow J/\psi \pi^+ \pi^-$, $B_s \rightarrow D_s^+ D_s^-$</td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th>$\phi_s$ [rad]</th>
<th>$\Delta \Gamma_s$ [ps$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$-0.087 \pm 0.036 \pm 0.021$</td>
<td>$0.0657 \pm 0.0043 \pm 0.0037$</td>
</tr>
<tr>
<td>CMS</td>
<td>$-0.021 \pm 0.044 \pm 0.010$</td>
<td>$0.1032 \pm 0.0095 \pm 0.0048$</td>
</tr>
<tr>
<td>LHCb (all mumu)</td>
<td>$-0.042 \pm 0.025$</td>
<td>$0.0813 \pm 0.0048$</td>
</tr>
<tr>
<td>LHCb (ee)</td>
<td>$0.00 \pm 0.28 \pm 0.07$</td>
<td>$0.115 \pm 0.045 \pm 0.011$</td>
</tr>
</tbody>
</table>

Important check for the results with muons, because the systematic uncertainties are independent, while the studied mechanism of the CPV is the same.

- The combined result is consistent with SM predictions.
CP violation in $B_s^0 \rightarrow \phi\phi$

- $b \rightarrow s\bar{s}s$ is benchmark to study CPV in FCNC decays.
- CPV arises from the interference between decay and mixing, characterised by the phase $\phi_s^{s\bar{s}s}$ and $|\lambda|$.
- Final state has 3 linear polarisation states.
- 6 fb$^{-1}$, 13 TeV
  - Flavour-tagged time-dependent angular analysis.
  - 15840 signal yields.
    - Signal weight is used to subtract background in the fit to decay-time and angular distributions.
    - $\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad
    - $|\lambda| = 1.004 \pm 0.030 \pm 0.009$

arXiv:2304.06198
Combined results in $B_s^0 \to \phi \phi$

- Combined with data taken in 2011 and 2012
  - $\phi_s^{ss} = -0.074 \pm 0.069 \text{ rad}$
  - $|\lambda| = 1.009 \pm 0.030$.
- The most precise measurement.
- Consistent with and supersedes the previous measurement.
- Agree with the SM expectation.
- The first time that the polarization-dependent CP-violation parameters are measured
  - Show no significant difference between the three polarization states of $B_s^0 \to \phi \phi$ decays.
  - Constrain new physics contributions in $b \to s$ transitions.
Direct measurement of $\gamma$

- CKM $\gamma$ is the only angle that can be determined using tree-level B meson decays with negligible theoretical uncertainty.

- Direct measurement of $\gamma$ can probe NP beyond SM.

- Several time-independent modes: $B \to D^{(*)}h$, $D^0$ and $\bar{D}^0$ decay to the same final state.
  - GLW: CP eigenstates ($D \to K^+K^-/\pi^+\pi^-$).
  - ADS: Cabibbo-favoured (CF) or Cabibbo-suppressed (CS) decays ($D \to K^+\pi^-$).
  - BPGGSZ: multi-body D decays, study CP asymmetry over phase space ($D \to K_S^0\pi^+\pi^-$).

- Time-dependent (interference between mixing and decay): $B^0 \to D^\mp\pi^\pm$...
Combination of $\gamma$ measurements

- Combination of measurements sensitive to the CP violation angle $\gamma$ and charm sector is performed.

- Include new and updated measurements from B decay
  - $B^\pm \rightarrow [K^\mp \pi^\pm \pi^+ \pi^-]_D h^\pm$ arXiv:2209.03692
  - $B^\pm \rightarrow [h^\pm h'^\mp \pi^0]_D h^\pm$ arXiv:2112.10617
  - $\gamma = (63.8^{+3.5}_{-3.7})^\circ$

- Compatibility with indirect determination
  - $\gamma = (65.5^{+1.1}_{-2.7})^\circ$ CKMfitter

- Compatible with previous combination
  - $\gamma = (65.4^{+3.8}_{-4.2})^\circ$ arXiv:2110.02350

- The most precise determination from a single experiment.
**γ measurement with** $B^\pm \to [h^+h^-\pi^\pm\pi^\mp]_D h^\pm$

• The first study of CP violation in $B^\pm \to [K^+K^-\pi^\pm\pi^\mp]_D h^\pm$ ($h = K, \pi$).

• Phase space integrated analysis for $K^+K^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$.  
  • supersed the previous $B \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$ measurement. [arXiv:2012.09903](https://arxiv.org/abs/2012.09903)

<table>
<thead>
<tr>
<th>CP-violating observable</th>
<th>Fit results</th>
</tr>
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<tbody>
<tr>
<td>$A_K^{KK\pi\pi}$</td>
<td>0.093 ± 0.023 ± 0.002</td>
</tr>
<tr>
<td>$A^-_{K^-K^+\pi^+\pi^-}$</td>
<td>-0.009 ± 0.006 ± 0.001</td>
</tr>
<tr>
<td>$A_{K^+K^-\pi\pi}$</td>
<td>0.060 ± 0.013 ± 0.001</td>
</tr>
<tr>
<td>$A_{\pi^-\pi^+\pi^+\pi^-}$</td>
<td>-0.0082 ± 0.0031 ± 0.0007</td>
</tr>
<tr>
<td>$R_{CP-K^+K^-\pi\pi}$</td>
<td>0.974 ± 0.024 ± 0.015</td>
</tr>
<tr>
<td>$R_{CP-\pi^-\pi^+\pi^+\pi^-}$</td>
<td>0.978 ± 0.014 ± 0.010</td>
</tr>
</tbody>
</table>
\( \gamma \) measurement with \( B^\pm \to \left[ h^+ h^- \pi^\pm \pi^\mp \right]_D h^\pm \)

- **Binned analysis for** \( K^+ K^- \pi^+ \pi^- \).
  - Local asymmetries confirm presence of CP violation effects.
  - \( \gamma = (116^{+12}_{-14})^\circ \) \( 3\sigma \) agreement with previous LHCb determinations using other channels.

Direct measurement of charm parameters allow the CP-violating observables to be determined model-independently.

External information on charm parameters, currently from amplitude model.

Result will evolve after charm model-independent measurement.

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arXiv:2301.10328

arXiv:2110.02350
CP violation in charm sector

• CP violation in up-type quark decays in charm sector.

• CP violation is expected to be tiny in Standard Model (SM) due to CKM elements and GIM mechanism: $A_{CP} \sim 10^{-4} - 10^{-3}$.

• Types of CP violation.

• LHCb has reported the first observation of CP asymmetry in $D^0 \rightarrow h^+ h^-$ decays in March 2019 [PRL 122 (2019) 211803].

• Further studies are ongoing in charm sector.

More will be given by D. Friday’s talk on CPV and mixing in c decays.
Search for CP violation in multi-body $D$ decays

• Direct CPV arises from different weak and strong phases between the amplitudes involved in the decay

• 3-body charm decays
  • Resonances provide a source of strong phase difference.
  • Enhance sensitivity to CPV in localized regions of the phase space.
Search for CP violation in multi-body $D$ decays

• model-independent approach.
  • Compare Dalitz distributions of $D^0$ and $\bar{D}^0$ decays.
    • $D^0 \rightarrow \pi^-\pi^+\pi^0$ decay (unbinned) LHCb-PAPER-2023-005
    • $p$-value is obtained by comparing nominal result to the expected distribution under CP symmetry.
      • $p$-value is 0.62
    • No indication of any CPV in localized region of the phase space.
    • $D^{+}_{(s)} \rightarrow K^-K^+K^+$ decay (binned) arXiv: 2303.04062
      • $p$-value is defined as the probability of obtaining a test variable (Dalitz-plot distribution comparison of $D^0$ and $\bar{D}^0$) that is at least as high as the value observed under CP conservation.
        • $D^+_s$ mode: $p$-value = 13.3%
        • $D^+$ mode: $p$-value = 31.6%
  • No local CP violation observed and the first search for CP violation in the $D^{+}_{(s)} \rightarrow K^-K^+K^+$ decays.
Summary

- The measurements of $\phi_s$ from LHCb and so on are in agreement with the SM, results with final state containing electrons are an important check.

- New precise $\phi_s^{S\bar{S}S}$ tests of SM in $B_s$ decay, in agreement with the SM.

- The most precise single measurement of $\beta$ is performed.

- Direct measurement of $\gamma$ in $B$ decays improve precision in LHCb.
  - Uncertainty $< 4^\circ$
  - Further improvements expected with other decay modes and more knowledge of charm hadronic parameters.

- New search of local CP violation in charm sector.
Thanks for your attention!
BACKUP
LHCb Result - $B_s \rightarrow J/\psi (e^+ e^-) \phi$ decay

- $3 \text{ fb}^{-1}, 7\&8$ TeV  

- Admixture of CP-even and CP-odd components, disentangled by time-dependent angular analysis.

- $(1.27 \pm 0.05) \times 10^4 B_s \rightarrow J/\psi (e^+ e^-) \phi$ decays from the fit to $m(e^+ e^- K^+ K^-)$ distribution.

- CP observables are determined by fit to background-subtracted candidates in $B_s^0$ decay time and helicity angles distributions.
  - $\phi_s = 0.00 \pm 0.28 \pm 0.07 \text{ rad}$
  - $\Delta \Gamma_s = 0.115 \pm 0.045 \pm 0.011 \text{ ps}^{-1}$

- The first time that $\phi_s$ measured with the final state containing electrons

- No evidence for direct CPV.
$\gamma$ measurement with $B^\pm \to [K^\mp \pi^\pm \pi^\pm \pi^\mp]_D h^\pm$

- 9 fb$^{-1}$, 7,8 and 13 TeV
- Through CF and DCS amplitudes
  - high branching fractions and only charged particles
- First measurement of parameters in this decay in bins of phase space of $D^0$ decay
  - Magnitude of CP violation in one of bins is the largest yet observed.
  - $\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3})^\circ$
    - One of the most precise determinations (2nd).
    - Compatible with current averages.
  - Have a strong impact on the overall knowledge of $\gamma$.

From external inputs for hadronic $D$ decay parameters determined from CLEO-c and BESIII

Improvement from incoming BESIII $\psi(3770)$ data.
Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$

arXiv:2209.03179

- 5.7 fb$^{-1}$, 13 TeV
  - $A_{CP}(K^- K^+) = [6.8 \pm 5.4 \text{ (stat)} \pm 1.6 \text{ (syst)}] \times 10^{-4}$
  - Consistent with the previous LHCb results.
  - Comparison with the world average gives a compatibility of 1.3$\sigma$.
  - The most precise measurement of time-integrated CP asymmetry in $D^0 \rightarrow K^- K^+$.

- Combination of charm CP asymmetries by LHCb
  - $a_{K^- K^+}^d = (7.7 \pm 5.7) \times 10^{-4}$
  - $a_{\pi^- \pi^+}^d = (23.2 \pm 6.1) \times 10^{-4}$
  - Departure from U-spin symmetry is 2.7$\sigma$.
  - The first evidence of direct CP violation in $D^0 \rightarrow \pi^+ \pi^-$ at the level of 3.8$\sigma$. 

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