Measurement of direct CP violation in the decay $B^+ \rightarrow K^+ \pi^0$

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on behalf of the LHCb collaboration
Implications Workshop
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Motivation

• Family of $B \to K\pi$ decays dominated by hadronic loop amplitudes, but diagrams contribute differently to decays
• Amplitudes expected to obey isospin relations, but measurements of CP asymmetries find $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.122 \pm 0.022$ (HFLAV 2018)
• More precise to incorporate all four CP asymmetries and branching fractions (Phys.Lett.B 627 (2005) 82)
• Tension in fit to $K\pi$ measurements can be resolved by enhancement of color-suppressed trees or NP in penguins (JHEP 01 (2018) 074, Phys.Lett.B 785 (2018) 525)

\[ A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0) \frac{2B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)} \]

$K\pi$ sum rule
Experimental Status

All four $B \to K\pi$ modes measured at B factories

Charged pion modes measured by LHCb

$B^+ \to K^+\pi^0$ is first analysis of a one-track $B$ decay at a hadron collider
  - Experimentally challenging – no secondary vertex
  - Secondary vertex a requirement for all Run I software triggers, dedicated trigger line developed for Run II

Proof of concept for other modes of similar topology such as $B^0 \to K^0\pi^0$

$A_{CP}$ measurements for the $B \to K\pi$ decay modes

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Sum rule prediction for $A_{CP}(K^0\pi^0)$: $-0.150 \pm 0.032$

References:

[1]: Phys.Rev.D 79, 052003
[2]: Phys.Rev.D 81, 011101(R)
[3]: Phys.Rev.Lett. 97, 171805
[4]: Phys.Rev.D 87, 031103(R)
[6]: Phys.Rev.D 87, 052009
[7]: Phys.Rev.D 98, 032004
[8]: Phys.Rev.D 76, 091102(R)
The LHCb Detector

- Forward spectrometer covering $10 < \theta < 300$ mrad
- $b\bar{b}$ production peaked forward/backward
  - 25% in ~4% solid angle

\[
\sigma_{pp} = \left(15 + \frac{29}{p_T[GeV]}\right) \mu m
\]

\[
\sigma_{\ell\ell} = \frac{1}{E} + 10%/\sqrt{E[GeV]}
\]

\[
\frac{\sigma_{pp}}{\ell} = 1\% \text{ at } 200 [\text{GeV/c}]
\]

Trigger

- Major challenge to suppress background in absence of displaced secondary vertex
- Dedicated trigger
  - Tight kinematic cuts
  - $\pi^0$ from photons merged into single calorimeter cluster
    - Higher energy, lower combinatorial background
  - $K^+$ impact parameter inconsistent with PV
  - $K^+$ distance of closest approach consistent with $B^+$ trajectory
Offline Selection

- Use boosted decision trees to overcome S/B of $\sim 3.3 \times 10^{-4}$
- Trained on high-mass and low-mass sidebands and simulated signal events
- Split and cross-validated to take advantage of full dataset and avoid overtraining
- Rely on kinematics, IP$\chi^2$(PV) and DOCA-$\chi^2$, and isolation (next slide)
Isolation Variables

- Events with other tracks pointing back to $B$ candidate are unlikely to be $B^+ \rightarrow K^+ \pi^0$ decays
- Combine each track individually with $K^+$: multiplicity of good vertices, $\chi^2$ of vertices formed
- Consider tracks in $\Delta R$ cone around $B^+$: $A_{p_T} \equiv \frac{p_T(B) - p_T(\text{cone})}{p_T(B) + p_T(\text{cone})}$
- Isolation depends on track multiplicity
  - Corrected by comparing $B^0 \rightarrow K^+ \pi^-$ data and simulation
• Split data by $B$ charge and magnet polarity
• Signal tails, some shape parameters of peaking and $B^+ \to \pi^+\pi^0$ from simulation
• Yields and asymmetries vary freely for all fit components (except $B^+ \to \pi^+\pi^0$)
• $8310 \pm 255$(MU), $8373 \pm 253$(MD) signal events
• $A_{\text{raw}} = 0.005 \pm 0.022$ (MU), $0.019 \pm 0.021$ (MD)
Production and Detection Asymmetry

\[ A_{CP}(B^+ \rightarrow K^+\pi^0) = A_{raw}(B^+ \rightarrow K^+\pi^0) - A_{prod}^B - A_{det}^K - A_{trig}^K - A_{reco}^K \]

- Raw asymmetry is a combination of physical CP asymmetry, \( B^\pm \) production asymmetry and \( K^\pm \) detection, reconstruction, and triggering
- Can measure the same combination of effects in \( B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+ \) decays
  - \( \pi^0 \) neutral, \( \mu^\pm \) symmetric
  - \( K^+ \) trigger, selection, reco. matches signal
  - Weight \( p/p_T(B^+/K^+) \) distributions of
    \[ B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+ \] to match signal
- \( A_{CP}(B^+ \rightarrow J/\psi K^+) = 0.002 \pm 0.003 \) (PDG), introduces small external uncertainty to \( A_{CP}(B^+ \rightarrow K^+\pi^0) \) measurement
Prod./Det. Asymmetry Correction

- Split data by $B$ charge and magnet polarity
- $\sim$99% signal purity
- $A_{\text{raw}}(B^+ \to J/\psi K^+) = -0.009 \pm 0.002$ (MU), $-0.012 \pm 0.002$ (MD)

\[
A_{CP}(B^+ \to K^+\pi^0) = A_{\text{raw}}(B^+ \to K^+\pi^0) - (A_{\text{raw}}(B \to J/\psi K^+) - A_{CP}(B \to J/\psi K^+)) = 0.016 \pm 0.022$ (MU), $0.033 \pm 0.021$ (MD)
Systematic Uncertainties

- Fit variation systematics determined from pseudoexperiments
- Dominant source of uncertainty modeling of signal tails
- Common value of 0.0013 from pseudoexperiment statistics
- Effect of $B^+ \to J/\psi K^+$ weighting used to estimate residual differences in asymmetries
- Averaging Magnet Up and Magnet Down results and adding systematic uncertainties in quadrature:
  \[
  A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015\text{(stat.)} \pm 0.006\text{(syst.)} \pm 0.003\text{(ext.)}
  \]

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<th>Systematic</th>
<th>Value</th>
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<tr>
<td>Combinatorial bkg.</td>
<td>Shape</td>
<td>0.0013</td>
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<td>Low-mass bkg.</td>
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<tr>
<td>Peaking bkg.</td>
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<td>Resolution</td>
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<tr>
<td>$B^+ \to \pi^+\pi^0$</td>
<td>Yield</td>
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<tr>
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<td>$CP$ Asymmetry</td>
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<tr>
<td>Signal modeling</td>
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<td>Multiple candidates</td>
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<tr>
<td>Sum in quadrature</td>
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<td>0.0061</td>
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Conclusion

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Previous sum rule prediction for $A_{CP}(K^0\pi^0)$: $-0.150 +/- 0.032$

- Most precise measurement of direct CP violation in $B^+ \to K^+\pi^0$ decays
- Consistent with world average, consistent with 0 at 1.5$\sigma$
- Combining with world average $A_{CP}(B^+ \to K^+\pi^0) = 0.031 \pm 0.013$ and $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$, non-zero at 8$\sigma$
- New sum rule prediction for $A_{CP}(K^0\pi^0)$: $-0.138 +/- 0.025$, non-zero at 5.5$\sigma$
- Similar trigger in place for $B^0 \to K^0\pi^0$
- Much more data coming with upgrade
  - Plan to migrate triggers to Run III Real Time Analysis
Backup
Consistency Checks

- Consistent between years and magnet polarities
- Additional checks: Binning by kaon $p_T$ and magnet polarity, allowing shape parameters to vary between charges and magnet polarities
- Raw asymmetry consistent in all cases