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Charmless multibody B decays at LHCb

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XUNTA DE GALICIA

LHCb

Conditions for CP violation in decay

Several other types of CP violation: in mixing, mixing-induced

In flavour-specific B decays, presence of multiple amplitudes may lead to (direct) CP violation in decay

$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$
$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |A_i| e^{i(\delta_i - \phi_i)}$

Strong phase (δ) invariant under CP

Weak phase (ϕ) changes sign under CP

$$\mathcal{A}_{CP}(B \to f) \equiv \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

3 conditions required for CP violation in decay

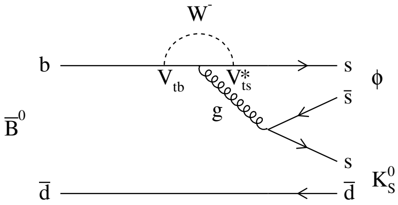
- At least 2 competitive amplitudes
- Non-zero strong phase difference, $\delta_i - \delta_j \neq 0$
- Non-zero weak phase difference, $\phi_i - \phi_j \neq 0$

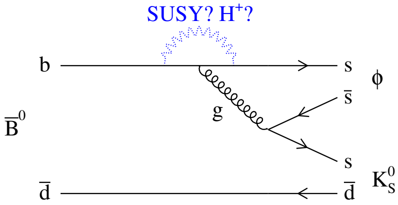
Weak phase comes from different CKM phases in each amplitude

Strong phase structure from decay amplitude in multibody phase space

New Physics mechanism

2nd-order loop diagrams potentially sensitive to New Physics





- Unknown heavy particle could be present in the loop
  - May carry a new CP violating phase
- Short time-scale in loop the key to accessing arbitrarily high energies
  - Heisenberg Uncertainty Principle: $\Delta E \Delta t \geq \hbar/2$
- Can reach higher mass scales than possible with direct searches at LHC

Mass scale of New Physics through loop processes a matter of statistics rather than CMS energy

- Deviation of measured CP violating phase and Standard Model expectation a clear signature of New Physics

Outline

1. Charmless 3-body B decays
   -Impact of strong phase motion on CP violation structure
   -Binned analysis of $B^+ \to h^+ h'^+ h'^-$

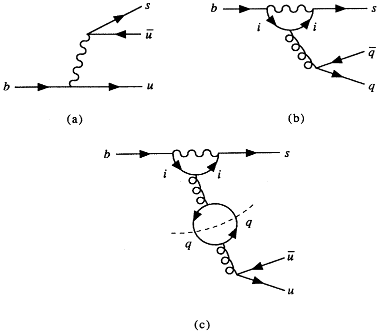
2. Charmless baryonic B decays
   -Triple-product asymmetries
   -$B^0 \to p\bar{p}K^+\pi^-$

Short-distance contributions

Direct CP violation more complicated in $B \to 3h$ decay channels compared to 2-body decays

- There are at least 4 possible sources of strong phase

1. Short-distance contributions (quark level)
   - BSS mechanism, PRL **43** (1979) 242
   - Tree contribution (a)
   - Penguin diagram (b) contains 3 quark generations in loop
   - From S-matrix unitarity, CPT conservation requires absorptive amplitude
   - Quark rescattering (c) generates a phase
   - If gluon in penguin is on-shell
     - Momentum transfer $q^2 > 4m_i^2$ where $i = u, c$
     - Imaginary part depends on quark masses
   - CP violation in 2-body processes caused by this effect
     - eg. $B^0 \to K^+\pi^-$



PRD **43** (1991) 2909

Long-distance contributions

Remaining sources more associated with multibody decays

Long-distance contributions (hadronic level)

2. Breit-Wigner phase

Propagator represents intermediate resonance states

$$T_R^{\mathrm{BW}}(s) = \frac{1}{m_R^2 - s - i m_R \Gamma_R(s)}$$

Phase varies across mass-squared, s

3. Relative CP-even phase in the isobar model

$$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$$
$$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |\bar{A}_i| e^{i(\delta_i - \phi_i)}$$

Related to final state interactions between different resonances

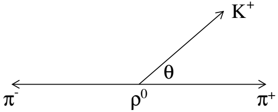
Manifestation of CP violation

Each source of strong phase leaves a unique signature in phase space

Illustrate with series of examples

Consider $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ with only 2 isobars

- $B^{\pm} \to \rho^0 K^{\pm}$ and flat non-resonant (NR) component



ρ^0 lineshape a Breit-Wigner, T_{ρ}^{BW}

ρ^0 is a vector resonance, so angular distribution follows $\cos\theta$

$$B^{+}:\ A_{+} = |a_{+}^{\rho}|e^{i\delta_{+}^{\rho}}T_{\rho}^{\mathrm{BW}}\cos\theta + |a_{+}^{\mathrm{NR}}|e^{i\delta_{+}^{\mathrm{NR}}}$$

$$B^{-}:\ A_{-} = |a_{-}^{\rho}|e^{i\delta_{-}^{\rho}}T_{\rho}^{\mathrm{BW}}\cos\theta + |a_{-}^{\mathrm{NR}}|e^{i\delta_{-}^{\mathrm{NR}}}$$

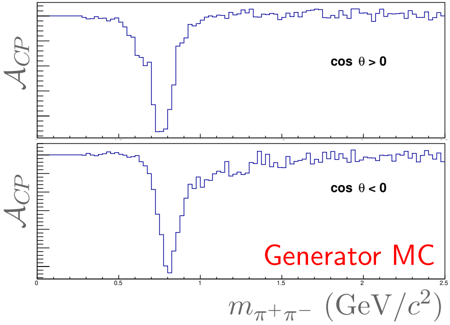
$$\begin{aligned}\mathcal{A}_{CP} &\propto |A_{-}|^2 - |A_{+}|^2 \\ &\propto (|a_{-}^{\rho}|^2 - |a_{+}^{\rho}|^2)|T_{\rho}^{\mathrm{BW}}|^2\cos^2\theta ... \\ &\quad -2(m_{\rho}^2 - s)|T_{\rho}^{\mathrm{BW}}|^2\cos\theta ... \\ &\quad +2m_{\rho}\Gamma_{\rho}|T_{\rho}^{\mathrm{BW}}|^2\cos\theta ...\end{aligned}$$

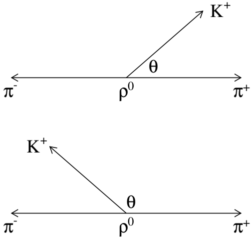
Short-distance effects

$$\mathcal{A}_{CP} \propto (|a_-^\rho|^2 - |a_+^\rho|^2)|T_\rho^{\rm BW}|^2\cos^2\theta ... \\ -2(m_\rho^2 - s)|T_\rho^{\rm BW}|^2\cos\theta ... \\ +2m_\rho\Gamma_\rho|T_\rho^{\rm BW}|^2\cos\theta ...$$

Only depends on ρ resonance

Maximum difference at ρ pole, quadratic in helicity





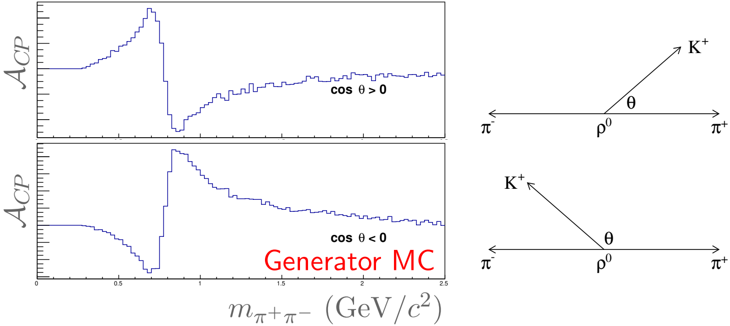
Only short-distance effects can create $|a_+^\rho| \neq |a_-^\rho|$

Long-distance effects

$$\mathcal{A}_{CP} \propto (|a_-^\rho|^2 - |a_+^\rho|^2)|T_\rho^{\rm BW}|^2 \cos^2\theta ...$$
$$-2(m_\rho^2 - s)|T_\rho^{\rm BW}|^2 \cos\theta ...$$
$$+2m_\rho \Gamma_\rho |T_\rho^{\rm BW}|^2 \cos\theta ...$$

Interference term from real part of Breit-Wigner

Zero at ρ pole, linear in helicity



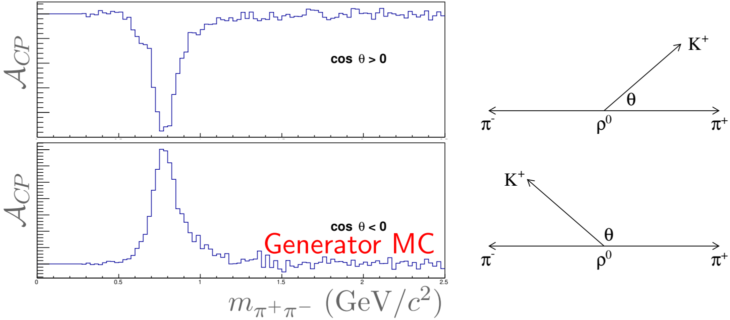
Caused by long-distance effects from final state interactions

Long-distance effects

$$\mathcal{A}_{CP} \propto (|a_-^\rho|^2 - |a_+^\rho|^2)|T_\rho^{\rm BW}|^2\cos^2\theta ... \\ -2(m_\rho^2 - s)|T_\rho^{\rm BW}|^2\cos\theta ... \\ +2m_\rho\Gamma_\rho|T_\rho^{\rm BW}|^2\cos\theta ...$$

Interference term from imaginary part of Breit-Wigner

Maximum at ρ pole, linear in helicity



Caused by long distance effects from Breit-Wigner phase and final state interactions

Rescattering contributions

Last source of strong phase

4. Final state $KK \leftrightarrow \pi\pi$ rescattering

Can occur between decay channels with the same flavour quantum numbers

- eg. $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

CPT conservation constrains hadron rescattering

- For given quantum numbers, sum of partial widths equal for charge-conjugate decays

$KK \leftrightarrow \pi\pi$ rescattering generates a strong phase

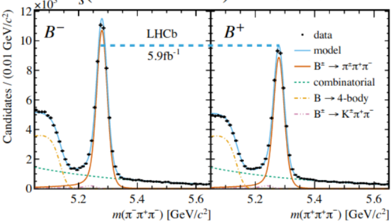
Look into rescattering region

If rescattering phase in one decay channel generates direct CP violation in this region

Rescattering phase should generate opposite sign direct CP violation in partner decay channel

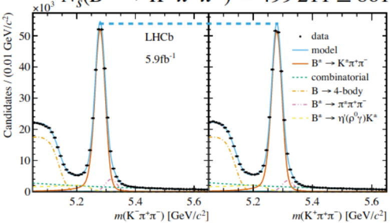
$B^+ \to h^+ h'^+ h'^-$ at LHCb

$N_s(B^\pm \to \pi^\pm \pi^+ \pi^-) = 100\,999 \pm 527$



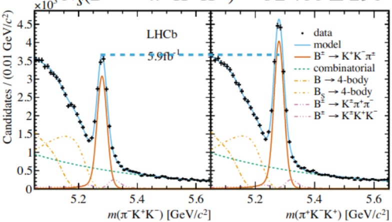
$A_{CP} = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$ (14.1σ)

$N_s(B^\pm \to K^\pm \pi^+ \pi^-) = 499\,211 \pm 861$



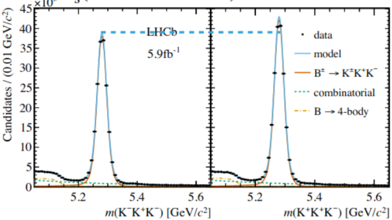
$A_{CP} = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$ (2.4σ)

$N_s(B^\pm \to \pi^\pm K^+ K^-) = 32\,466 \pm 296$



$A_{CP} = -0.114 \pm 0.007 \pm 0.003 \pm 0.003$ (13.6σ)

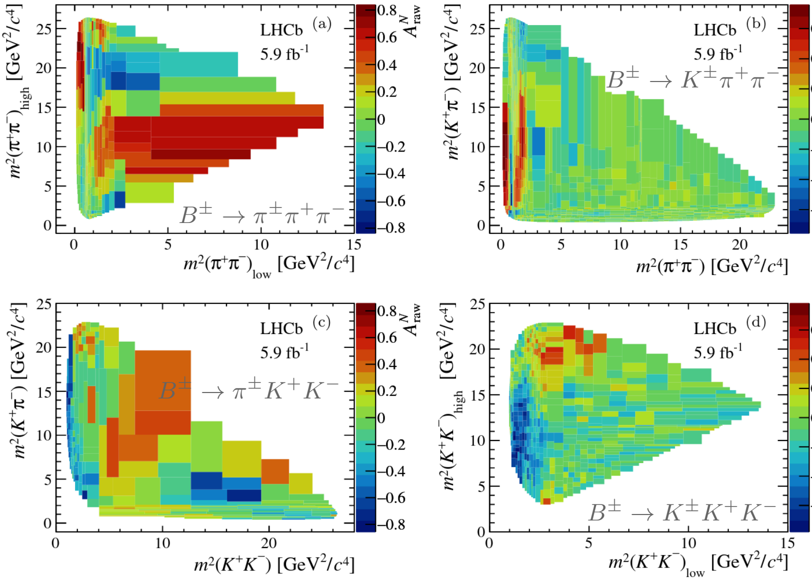
$N_s(B^\pm \to K^\pm K^+ K^-) = 364\,883 \pm 979$



$A_{CP} = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$ (8.5σ)

Phys. Rev. **D108** (2023) 012013, Phys. Rev. **D108** (2023) 012008

$B^+ \to h^+ h'^+ h'^-$ at LHCb



Phys. Rev. **D108** (2023) 012013, Phys. Rev. **D108** (2023) 012008

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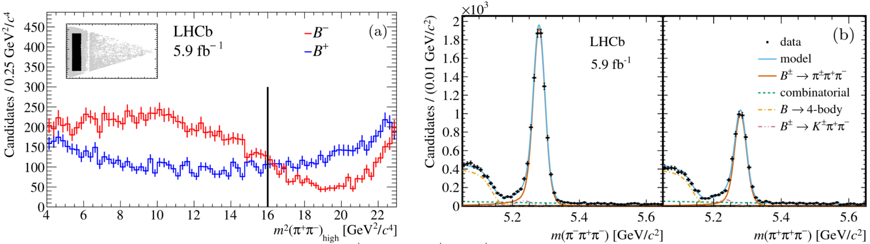
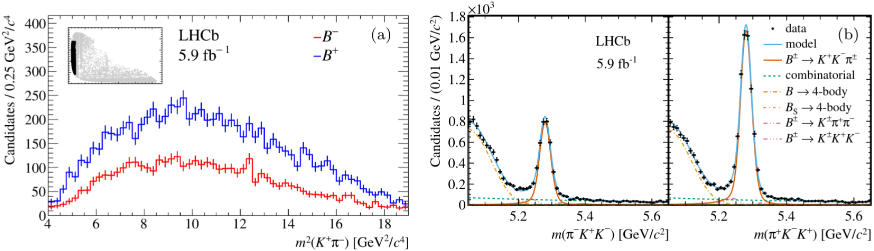
$B^+ \to \pi^+ h'^+ h'^-$ rescattering region

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



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

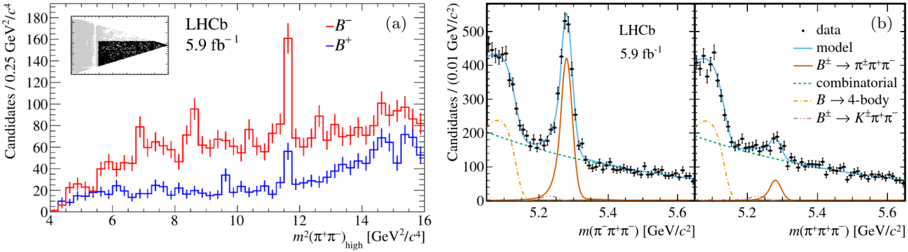


Phys. Rev. **D108** (2023) 012013, Phys. Rev. **D108** (2023) 012008

Clear opposite sign CP asymmetry in CPT-coupled $KK \leftrightarrow \pi\pi$ channels

$B^+ \to \pi^+ h'^+ h'^-$ charmonium region

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



Phys. Rev. **D108** (2023) 012013, Phys. Rev. **D108** (2023) 012008

Large amount of CP violation observed

Double-charm rescattering mechanism proposed

- I. Bediaga, T. Frederico and P.C. Magalhães, PLB **806** (2020) 135490

Clear CP violation involving $\chi_{c0}(1P)$

- Short-distance CP violation not expected
- Large long-distance CP violation through interference predicted long ago
- G. Eilam, M. Gronau and R.R. Mendel, PRL **74** (1995) 4984

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Triple-product asymmetries

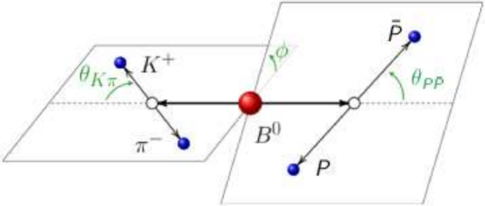
Rich resonant structure in 4-body decays conducive to CP violation

Amplitude analysis ambitious, begin with model-independent approach

Probe CP violation with triple-product asymmetry measurements

P-odd triple products

B: $C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p) \propto \sin\phi$
$\bar{B}$: $\bar{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}}) \propto \sin\bar{\phi}$



P-odd asymmetries of $\hat{T}$ operator

$$B: \; A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\bar{B}: \; \bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$

P-odd observable

$$a_P^{\hat{T}-\mathrm{odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

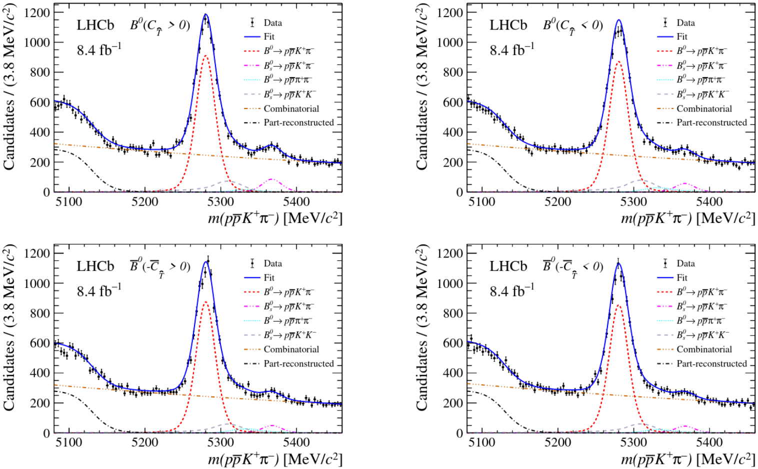
CP-odd observable

$$a_{CP}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$$

Sensitive to interference between P-even and P-odd amplitudes

$B^0 \to p\bar{p}K^+\pi^-$ at LHCb

Phys. Rev. **D108** (2023) 032007



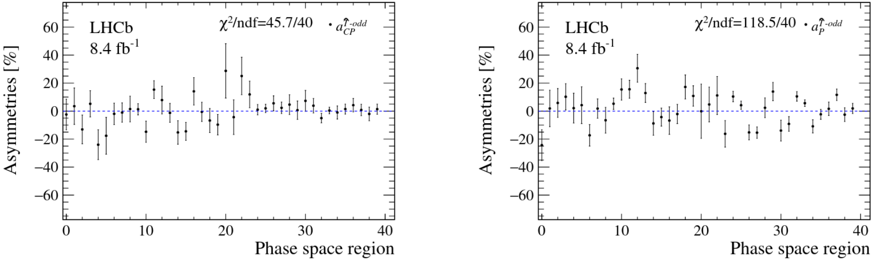
$$a_P^{\hat{T}-\mathrm{odd}} = [1.49 \pm 0.85\ (\mathrm{stat}) \pm 0.08\ (\mathrm{syst})]\%$$
$$a_{CP}^{\hat{T}-\mathrm{odd}} = [0.51 \pm 0.85\ (\mathrm{stat}) \pm 0.08\ (\mathrm{syst})]\%$$

$B^0 \to p\bar{p}K^+\pi^-$ at LHCb

Can enhance sensitivity by dividing phase space into bins

- Based on $K^+\pi^-$ mass and helicity angles

Phys. Rev. **D108** (2023) 032007



Control sample $B^0 \to p\bar{p}\bar{D}^0[K^+\pi^-]$ estimates detection asymmetry

Significant P violation in low $p\bar{p}$ and $K^*(892)^0$ mass regions

- P conservation rejected at $\sim 6\sigma$

CP conserved within $\sim 1\sigma$

- Theoretical prediction up to 20% level not excluded
- Int. J. Mod. Phys. **23** (2008) 3290, Phys. Rev. Lett. **98** (2007) 011801, Eur. Phys. J. **C80** (2020) 565

Summary

Multibody decays provide excellent environment for CP violation studies

- Large-valued measurements more accessible
- Diverse structures provide another view to strong phase motion

Recent results from LHCb

Model-independent study of 3-body charmless hadronic $B^{\pm}$ decays

- Attention should turn to modelling rescattering regions
- CP violation driven by long-distance $\chi_{c0}(1P)$ interactions foreseen

Triple-product asymmetries in $B^0 \to p\bar{p}K^+\pi^-$ decays

- World-first measurement
- Still no observation of CP violation in baryonic B decays at this time
- Predicted up to the 20% level