Recent CP violation results in heavy flavour involving multibody decays

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J. Dalseno
jeremypeter.dalseno [AT] usc.es

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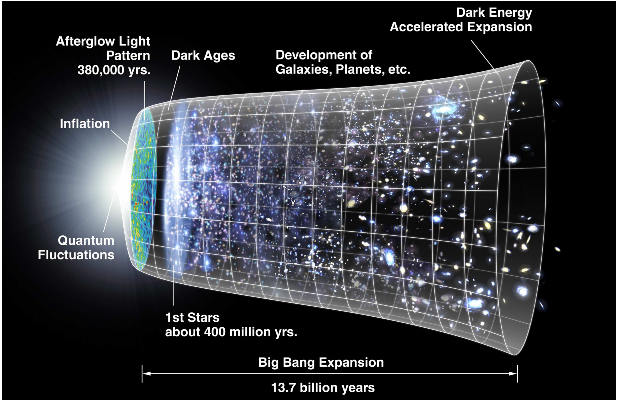
Introduction

The Standard Model (SM) of Particle Physics is incomplete

- Predicts almost all visible matter would annihilate right after the Big Bang

Cosmological observations show this is incorrect by $\mathcal{O}(10^9)$



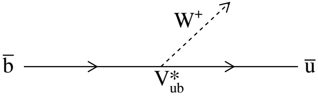
There must be new sources of matter-antimatter asymmetry

CP violation in the Standard Model

Matter-antimatter asymmetry manifests as violation of charge-parity (CP) symmetry

CP broken in the charged-current Lagrangian term of the weak interaction, $\mathcal{L}^{+}_{\mathrm{EW}}$

Up-type quark can transform to down-type quark mediated by W boson



Strength of transition described by the CKM matrix, V_{CKM}

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

For 3 quark generations, unitarity constraints leave V_{CKM} with a single complex phase

$\widehat{\mathbf{CP}}\mathcal{L}^{+}_{\mathrm{EW}} \neq \mathcal{L}^{+}_{\mathrm{EW}}$ if V_{CKM} complex

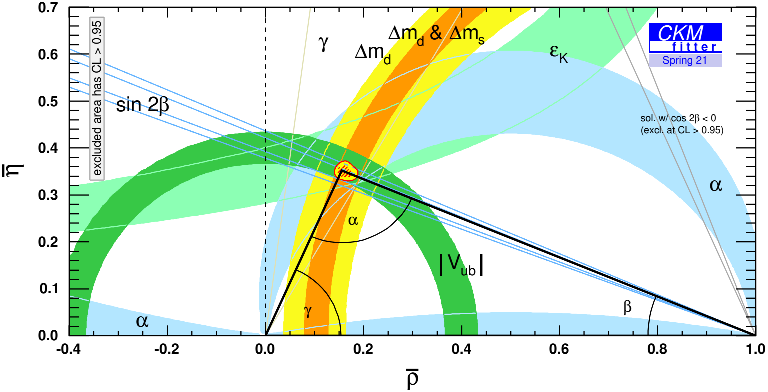
Single complex phase in V_{CKM} the source of all CP violation in the SM

Unitarity Triangle

Unitarity constraint: $V^{\dagger}_{\mathrm{CKM}} V_{\mathrm{CKM}} = \mathbf{1}$

$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$ - relevant for B decays

Convenient to represent as the Unitarity Triangle

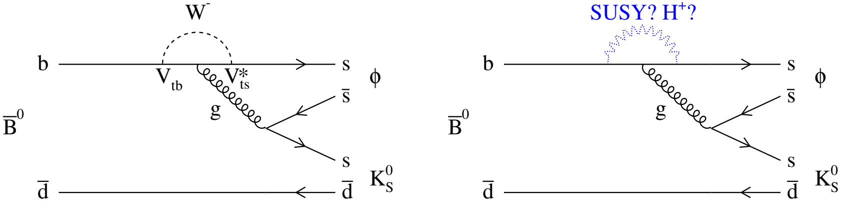


Angles and sides can be measured through various B decay processes

Experiment supports CKM mechanism, but room for New Physics at ∼20% level

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

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

Outline

1. Measurement of the CP-violating phase γ
   -ADS method
   -$B^{\pm} \to D[K^{-}\pi^{+}\pi^{+}\pi^{-}]K^{\pm}$

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

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

γ from B decays

Theoretically cleanest Standard Model measurement from $B^{\pm} \rightarrow DK^{\pm}$

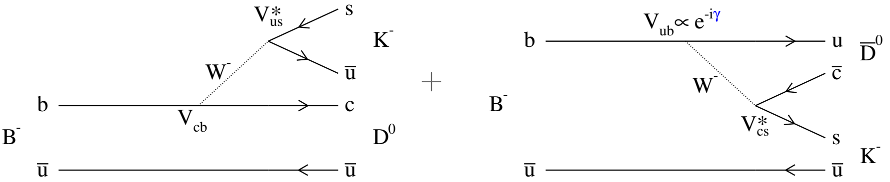
$|\delta\gamma|/\gamma \lesssim \mathcal{O}(10^{-7})$ from electroweak corrections

J. Brod and J. Zupan, JHEP **01** (2014) 51

D^0 and $\bar{D}^0$ decay to the same final state

Interference between $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ transitions

$$A_{B^-} \propto A_{D^0} \qquad + \qquad r_B e^{i\delta_B} e^{-i\gamma} A_{\bar{D}^0}$$



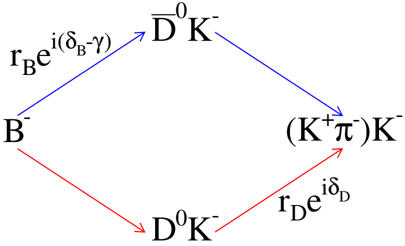
r_B: Ratio of Cabibbo-suppressed to Cabibbo-favoured diagrams

δ_B: Relative strong phase difference

Phase difference between A_{B+} and A_{B-} gives γ

ADS approach to γ

- Match suppressed B decay with favoured D decay and *vice versa*
  - D. Atwood, I. Dunietz and A. Soni, PRL **78** (1997) 3257



- Enhances observed CP asymmetries over other γ methods

$$\Gamma_{B^\pm} = r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B + \delta_D \pm \gamma)$$

- Cost is additional hadronic parameters from D decays, $r_De^{i\delta_D}$
  - Inputs typically taken from external measurements
    - Quantum-correlated $D\bar{D}$ production experiments: BESIII, CLEO-c
    - r_D from $D\bar{D}$ mixing measurements: LHCb
  - Significant source of systematic uncertainty

Multibody ADS-like approach to γ

Approach can be adapted to multibody D decays

$$\begin{tikzcd}
 & \overline{D}^0K^- \arrow[dr] & \\
B^- \arrow[ur, "r_Be^{i(\delta_B-\gamma)}"] \arrow[dr] & & (K^+\pi^-\pi^+\pi^-)K^- \\
 & D^0K^- \arrow[ur, "r_D^{K3\pi}e^{i\delta_D^{K3\pi}}"'] &
\end{tikzcd}$$

Hadronic D decay parameters $r_D^{K3\pi}e^{i\delta_D^{K3\pi}}$, vary across phase space

External measurements provide averages over phase space

- Dilution of decay rate asymmetry, $R_D^{K3\pi}$

$$R_D^{K3\pi}e^{i\delta_D^{K3\pi}} \propto \int A_{\bar{D}}(\Phi_4)A_D^*(\Phi_4)d\Phi_4$$

- Φ_4: Position in 4-body phase space

$$\Gamma_{B^\pm} = (r_B)^2 + (r_D^{K3\pi})^2 + 2r_Br_D^{K3\pi}R_D^{K3\pi}\cos(\delta_B + \delta_D^{K3\pi} \pm \gamma)$$

Rate further corrected to account for neutral D^0-$\bar{D}^0$ oscillations

$B^{\pm} \to D[K^{-}\pi^{+}\pi^{+}\pi^{-}]K^{\pm}$ at LHCb

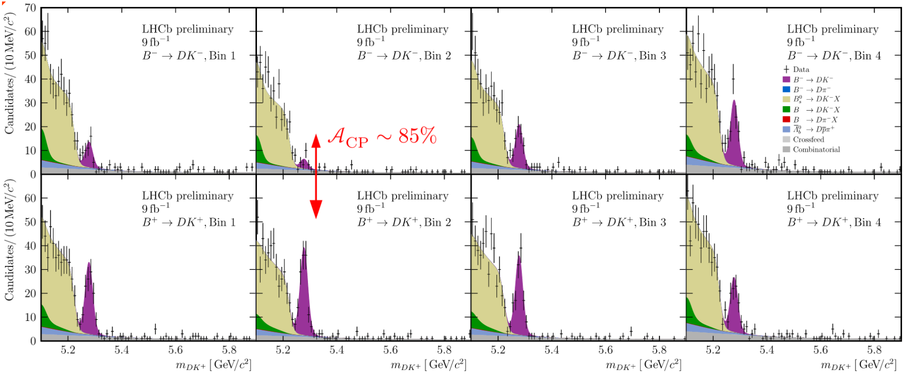
Multibody ADS-like approach further refined to recover sensitivity to γ

Determine hadronic D decay parameter averages in bins of phase space

- Driven by $D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ amplitude analysis
- LHCb collaboration, EPJC **78** (2018) 443

$r_D^{K3\pi}$, $\delta_D^{K}3\pi$ and $R_D^{K3\pi}$ averages from BESIII, CLEO-c and LHCb input

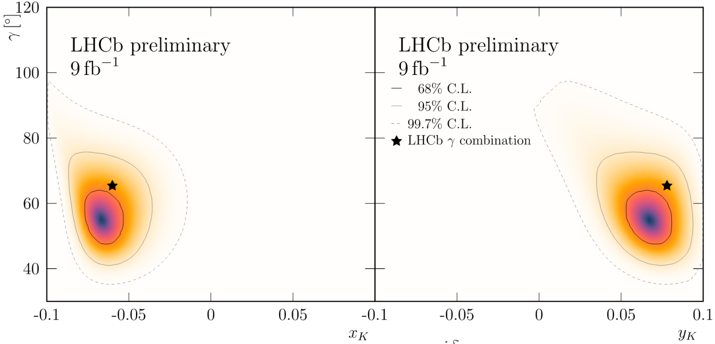
- LHCb-PAPER-2022-017 in preparation



$\mathcal{A}_{\rm CP} \sim 85\%$

$B^{\pm} \to D[K^-\pi^+\pi^+\pi^-]K^{\pm}$ at LHCb

Combine $B^{\pm}$ decay rates and D decay parameters to measures γ



$$x_K + iy_K = r_B e^{i\delta_B}$$

$$\boxed{\begin{array}{c} r_B = [94.6^{+3.1}_{-3.1}\ (\text{stat})\ ^{+0.5}_{-0.5}\ (\text{syst})\ ^{+3.0}_{-2.3}\ (\text{ext})] \times 10^{-3} \\ \delta_B = [134.6^{+6.0}_{-6.0}\ (\text{stat})\ ^{+0.7}_{-0.7}\ (\text{syst})\ ^{+8.6}_{-8.7}\ (\text{ext})]^{\circ} \\ \gamma = [54.8^{+6.0}_{-5.8}\ (\text{stat})\ ^{+0.6}_{-0.6}\ (\text{syst})\ ^{+6.7}_{-4.3}\ (\text{ext})]^{\circ} \end{array}}$$

Limited by external measurements of hadronic D decay parameters

Expected to be improved by BESIII in near future

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Triple-product asymmetries

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

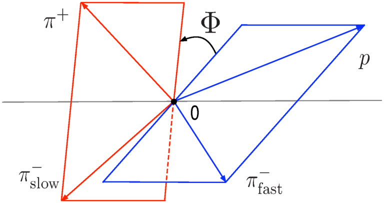
Amplitude analysis ambitious, begin with model-independent approach

Probe CP violation with triple-product asymmetry measurements

P-odd triple products

B: $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+}) \propto \sin\Phi$

$\bar{B}$: $\bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi^+_{\text{fast}}} \times \vec{p}_{\pi^-}) \propto \sin\bar{\Phi}$



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

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

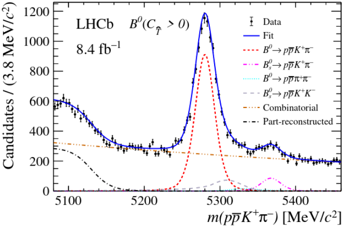
CP-odd observable

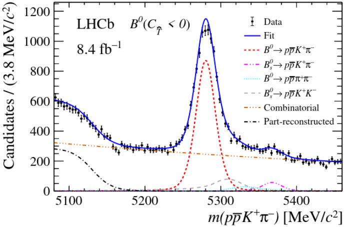
$$a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$$

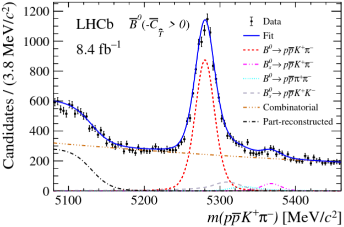
Sensitive to interference between P-even and P-odd amplitudes

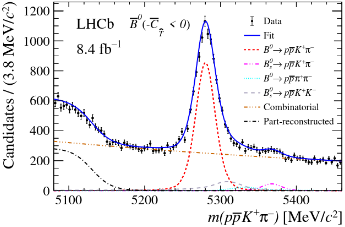
$B^0 \to p\bar{p}K^+\pi^-$ at LHCb

LHCb-PAPER-2022-003







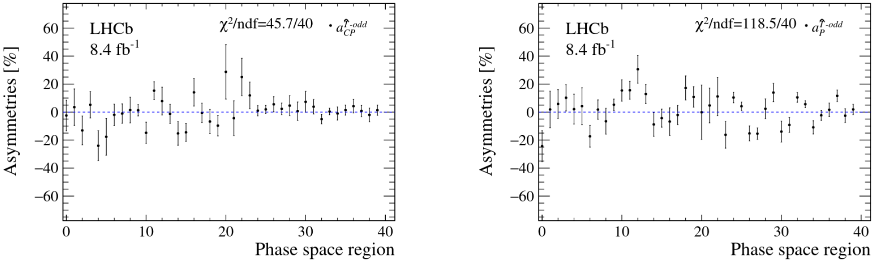


$$\boxed{\begin{aligned} a_P^{\hat{T}-\text{odd}} &= [1.49 \pm 0.85 \text{ (stat)} \pm 0.08 \text{ (syst)}]\% \\ a_{CP}^{\hat{T}-\text{odd}} &= [0.51 \pm 0.85 \text{ (stat)} \pm 0.08 \text{ (syst)}]\% \end{aligned}}$$

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

Can enhance sensitivity by dividing phase space into bins

LHCb-PAPER-2022-003



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

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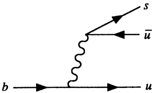
Short-distance contributions

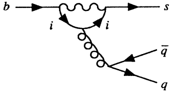
Direct CP violation more complicated in $B \to 3h$ decay channels compared to 2-body decays

- There are at least 4 possible sources of strong phase

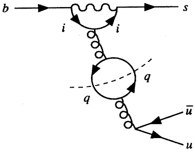
1. Short-distance contributions (quark level)
   - BSS mechanism, PRL **43** 242 (1979)



(a)



(b)



(c)

Tree contribution (a)

Penguin diagram (b) contains 3 quark generations in loop

S-matrix unitarity, CPT require absorptive amplitude

If gluon in penguin is timelike (on-shell)

- Momentum transfer $q^2 > 4m_i^2$ where $i = u, c$
- Imaginary part depends on quark masses

- Particle rescattering (c) generates a phase difference

CP violation in 2-body processes caused by this effect

- eg. $B^0 \to K^+\pi^-$

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

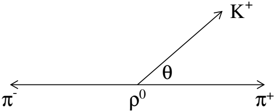
Manifestation of CP violation

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 $\cos\theta$

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

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

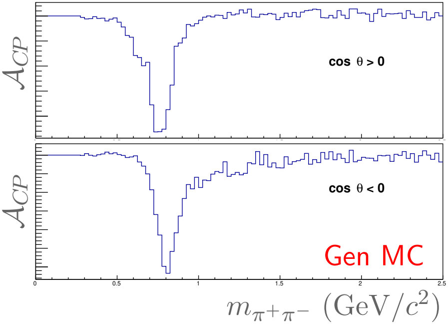
$$\begin{aligned} \mathcal{A}_{CP} &\propto |A_{-}|^2 - |A_{+}|^2 \\ &\propto (|a_{-}^{\rho}|^2 - |a_{+}^{\rho}|^2)|T_{\rho}^{\mathrm{BW}}|^2 \cos^2\theta \ldots \\ &\quad -2(m_{\rho}^2 - s)|T_{\rho}^{\mathrm{BW}}|^2 \cos\theta \ldots \\ &\quad +2m_{\rho}\Gamma_{\rho}|T_{\rho}^{\mathrm{BW}}|^2 \cos\theta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

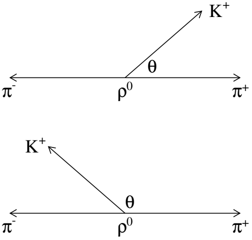
Short-distance effects

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

Only depends on ρ resonance

Maximum difference at ρ pole, quadratic in helicity





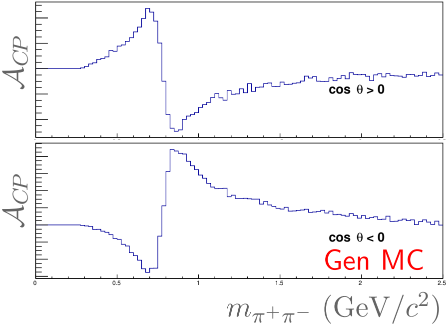
Only short-distance effects can create $|a^{\rho}_{+}| \neq |a^{\rho}_{-}|$

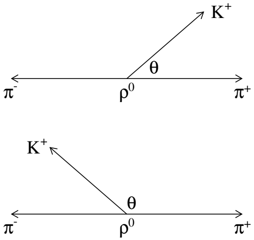
Long-distance effects

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

Interference term from real part of Breit-Wigner

Zero at ρ pole, linear in helicity





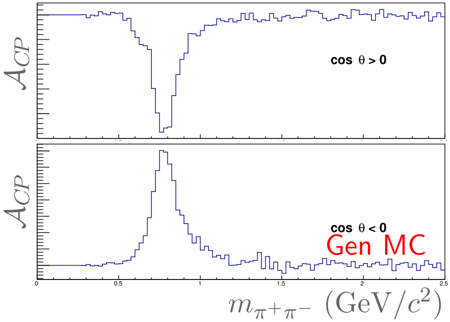
Caused by long-distance effects from final state interactions

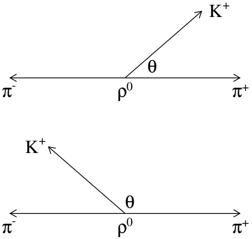
Long-distance effects

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

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

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

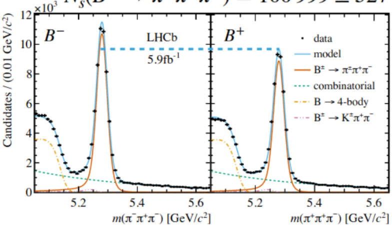
Look into rescattering region

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

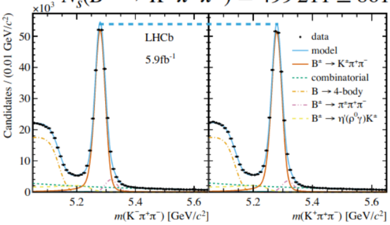
$B^+ \to h^+ h'^+ h'^-$ at LHCb

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



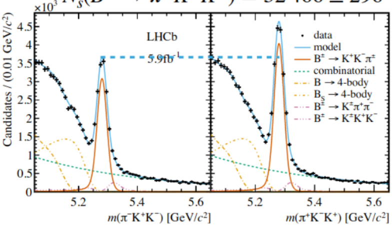
$A_{CP} = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$ (14.1σ)

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



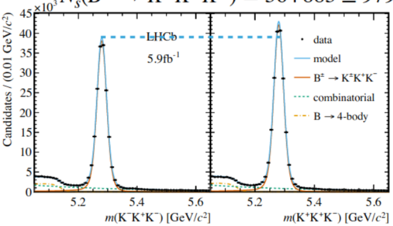
$A_{CP} = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$ (2.4σ)

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



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

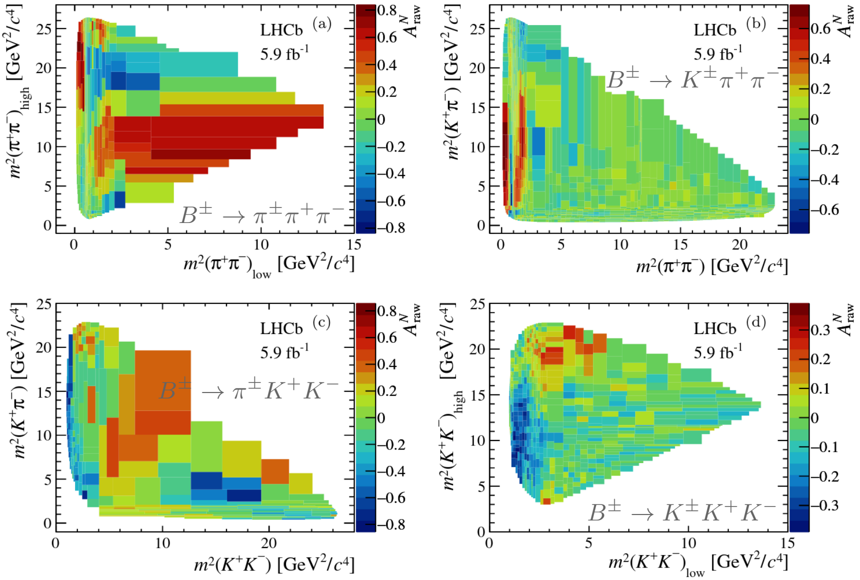
$N_s(B^\pm \to K^\pm K^+K^-) = 364\,883 \pm 979$



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

LHCb-PAPER-2021-049

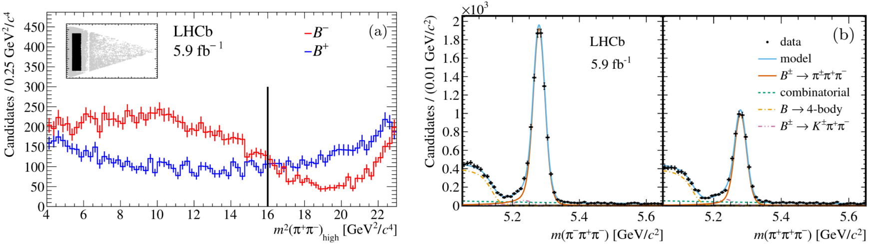
$B^+ \to h^+ h'^+ h'^-$ at LHCb



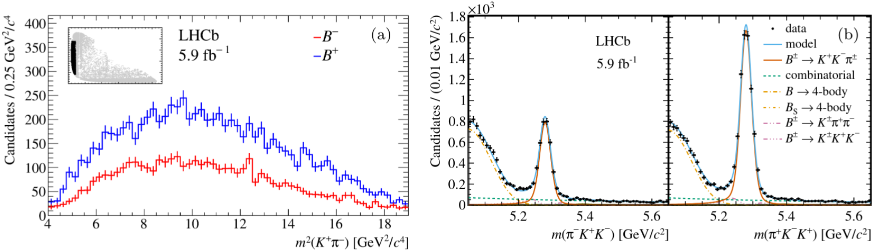
LHCb-PAPER-2021-049

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

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



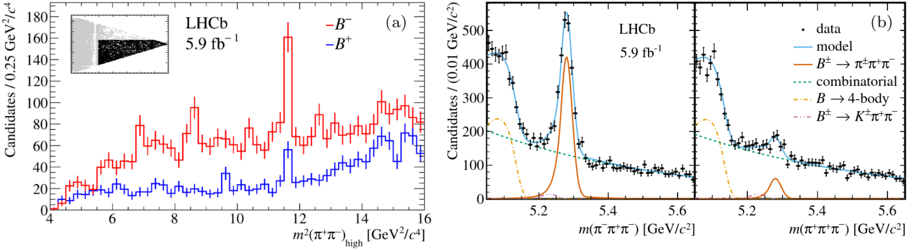
$B^+ \to \pi^+K^+K^-$



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

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

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



- 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

Amplitude Analysis

Amplitude model sum of contributions to the phase space

$$A^{\pm}(\Phi_3) = \sum_i A_i^{\pm}(\Phi_3) = \sum_i c_i^{\pm} F_i(\Phi_3)$$

Φ_3: position in phase space

$c_i^{\pm}$: complex free parameters of the model

F_i: Decay form factor comprised of several components

- Dynamic lineshape, *eg*. Breit-Wigner
- Spin amplitude
- Production and decay barrier factors

S-wave description difficult, increasingly turning to multiple approaches

Isobar

- Each contribution has clear physical meaning

K-matrix

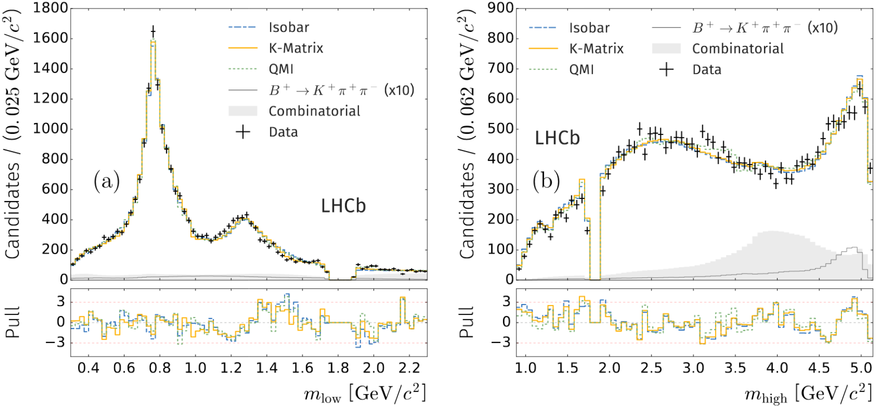
- Experimental interface scattering results that enforce 2-body unitarity

Quasi-model-independent

- Binned amplitude determined directly from data

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ at LHCb

LHCb Collaboration, PRD **101** (2020) 012006



$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ has two identical pions

m_{low} is the lower $\pi^{+}\pi^{-}$ invariant mass combination

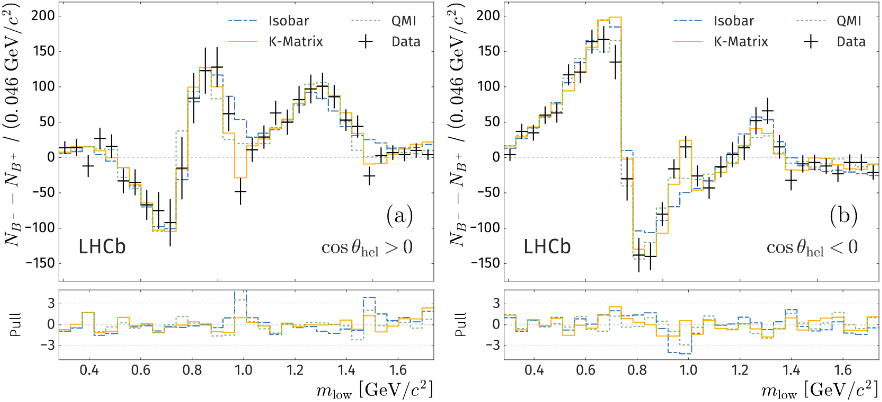
- Enhances resonance visibility

m_{high} is the higher $\pi^{+}\pi^{-}$ invariant mass combination

- Shows spin structure

Long-distance CP violation by interference

LHCb Collaboration, PRD **101** (2020) 012006



Asymmetry sign-flip across $\rho(770)^0$ pole in opposing helicity halves

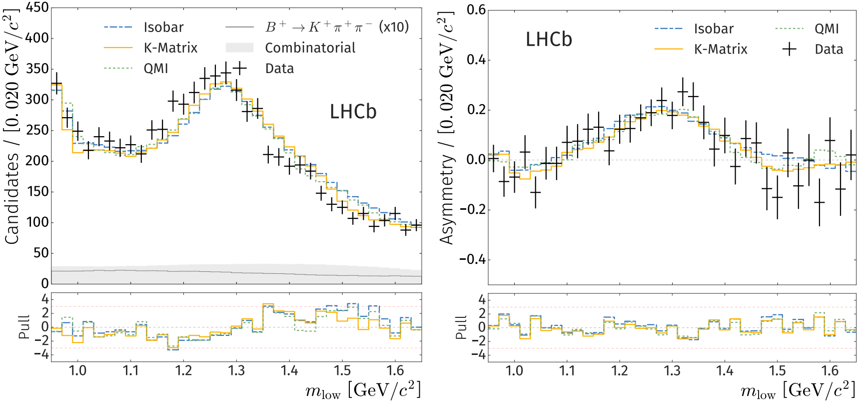
CP violation generated by interference between overlapping S- and P-waves

Over 25σ statistical significance

First observation of CP violation in S-P interference

Short-distance CP violation in $f_2(1270)$ region

LHCb Collaboration, PRD **101** (2020) 012006



Mass poorly described by all 3 S-wave approaches

Can be resolved, but requires more statistics to confirm

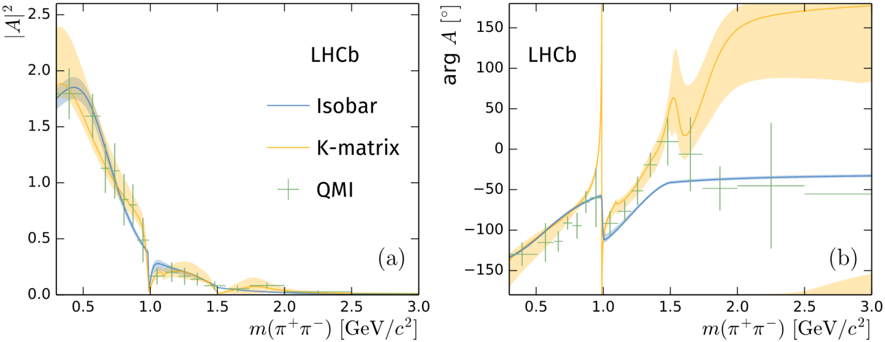
Very large CP asymmetry well-described by all 3 S-wave approaches

Observation of CP violation ranges from exceeds 14σ (statistical)

First observation of CP violation in any process involving a tensor

S-wave comparison

LHCb Collaboration, PRD **101** (2020) 012006



Good agreement on structures in $|A|^2$

Structure in phase motion qualitatively agreed on

Potential to drive further theoretical work

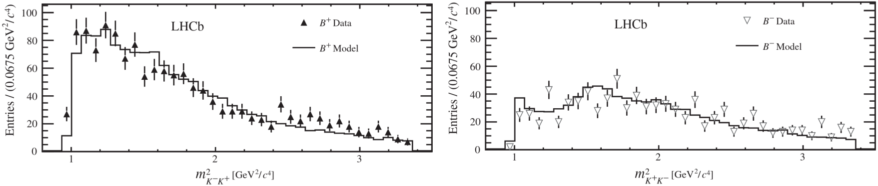
Need Isobar form factors to improve as these have physical meaning

$B^\pm \to \pi^\pm K^+ K^-$ at LHCb

$\pi\pi \leftrightarrow KK$ rescattering model for the low K^+K^- mass

J. R. Peláez and F. J. Ynduráin, PRD **71** (2005) 074016

LHCb Collaboration, PRL **123** (2019) 231802



Largest CP violation in a single amplitude ever observed

$$\boxed{\mathcal{A}_{CP} = (-66.4 \pm 3.8\ (\text{stat}) \pm 1.9\ (\text{syst}))\%}$$

Summary

- Multibody decays provide excellent environment for CP violation studies
  - Large measurements more accessible
  - Diverse structures provide another view to strong phase motion

Recent results from LHCb

- Model-independent measurement of γ in $B^{\pm} \rightarrow D[K^{-}\pi^{+}\pi^{+}\pi^{-}]K^{\pm}$
  - Significant contributor to the γ average
  - Cooperation with BESIII required to reduce dominant systematic
- Triple-product asymmetries in $B^{0} \rightarrow p\bar{p}K^{+}\pi^{-}$ decays
  - Still no observation of CP violation in baryonic B decays at this time
  - Predicted up to the 20% level
- Model-independent study of 3-body charmless hadronic $B^{\pm}$ decays
  - Attention should turn to modelling rescattering regions
  - CP violation driven by $\chi_{c0}(1P)$ foreseen
- Amplitude analysis of 3-body charmless hadronic $B^{\pm}$ decays
  - First observation of CP violation involving S-, D-waves and S-P interference
  - Quasi-model-independent results feed back into the theoretical community