First observation of several sources of CP violation in $B^+ \to \pi^+\pi^+\pi^-$ decays at LHCb

EPS-HEP 2019

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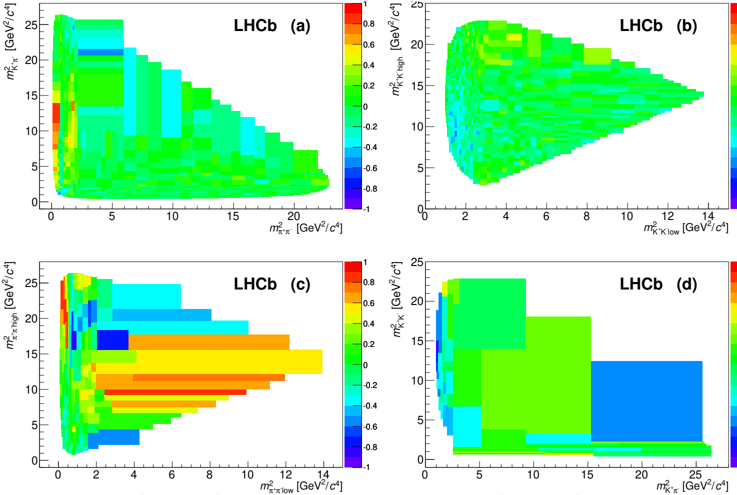
$B^{\pm} \to K^{\pm}h^{+}h^{-}$, $\pi^{\pm}h^{+}h^{-}$

Observed large CP violating effects in the phase space with Run 1 data

Phys. Rev. D **90**, 112004 (2014)

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



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

Conditions for CP Violation in Decay

In charged 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

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

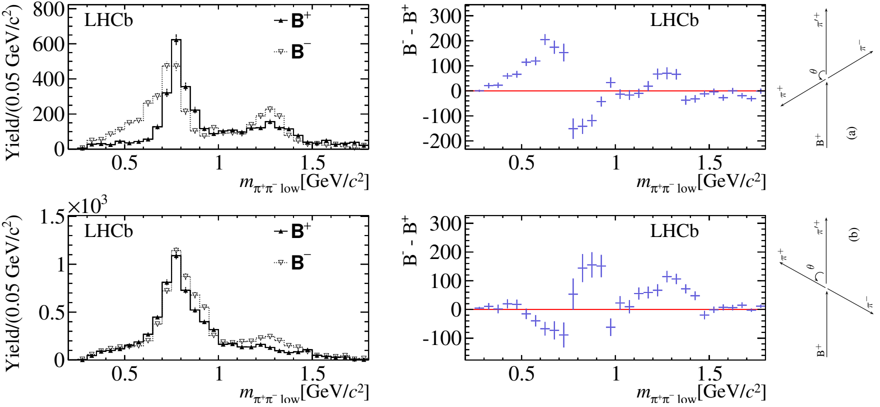
3 conditions required for CP violation in decay

- 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 Unitarity Triangle contributions to each amplitude

CP Asymmetry by Interference

Project onto $m_{\pi\pi}$ of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, Phys. Rev. D **90**, 112004 (2014)



Sign-flip in raw asymmetry and zero around ρ^0 pole

Opposite behaviour of raw asymmetry in each helicity half

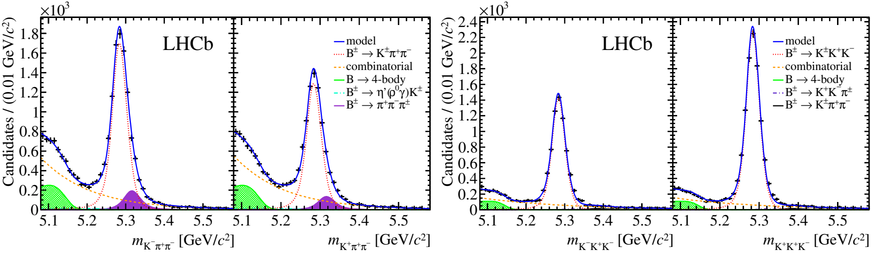
Characteristic of CP asymmetry generated by S-P interference

CP Asymmetry by Rescattering

$\pi\pi \leftrightarrow KK$ rescattering region: $1.0 - 1.5\ \mathrm{GeV}/c^2$

Phys. Rev. D **90**, 112004 (2014)

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



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

CPT conservation constrains hadron rescattering

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

Clear opposite sign CP asymmetry in $KK/\pi\pi$ - related channels

Physics Parameters

Dalitz Plot position, Φ_3

Construct amplitude model

Isobar coefficients c_i, free parameters of the model

$$A(\Phi_3) = \sum_i A_i(\Phi_3) = \sum_i c_i F_i(\Phi_3)$$

CP conjugate: $\bar{\Phi}_3 \equiv \Phi_3 \Rightarrow \bar{F}_i(\bar{\Phi}_3) = F_i(\Phi_3)$
Form factor F_i, contains only strong dynamics

$$\bar{A}(\bar{\Phi}_3) = \sum_i \bar{c}_i F_i(\Phi_3)$$

CP violation parametrised in free parameters
$c_i = (x_i + \Delta x_i) + i(y_i + \Delta y_i)$
$\bar{c}_i = (x_i - \Delta x_i) + i(y_i - \Delta y_i)$

Physics Parameters

Derived physical quantities

Fit fraction, essentially gives branching fractions

$$\mathcal{F}_i \equiv \frac{\int d\Phi_3 |A_i(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}_i(\Phi_3)|^2}{\int d\Phi_3 |A(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}(\Phi_3)|^2}$$

CP violation in decay

$$\mathcal{A}^i_{CP} \equiv \frac{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 - \int d\Phi_3 |A_i(\Phi_3)|^2}{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 + \int d\Phi_3 |A_i(\Phi_3)|^2}$$

3 approaches to analysis differing by S-wave description

Isobar Approach

- Each contribution has clear physical meaning

K-matrix Approach

- Interface with results from scattering experiments

QMI Approach

- Binned amplitude determined directly from data

Rescattering Lineshape

Inspired by $\pi\pi \leftrightarrow KK$ scattering in 2-body interactions

In the context of 3-body decays, production of one pair of mesons can affect the coupled channel

Attempt to account for this with phenomenological form factor

$$A(s) = \frac{\hat{T}}{1 + \frac{s}{\Delta^2_{PP}}}$$

I. Bediaga, T. Frederico and O. Lourenço, Phys. Rev. D **89**, 094013 (2014)

Intended to describe the partonic interaction that produces $\pi\pi$ and KK in 3-body final state

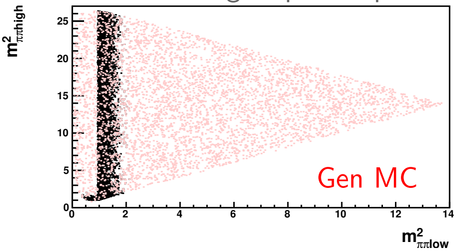
$\hat{T}$ is the observable amplitude related to the unitary S-matrix as, $\hat{S} = 1 + 2i\hat{T}$

$$\hat{S}(s) = \begin{pmatrix} \eta(s)e^{2i\delta_{\pi\pi}(s)} & i\sqrt{1-\eta^2(s)}e^{i(\delta_{\pi\pi}(s)+\delta_{KK}(s))} \\ i\sqrt{1-\eta^2(s)}e^{i(\delta_{\pi\pi}(s)+\delta_{KK}(s))} & \eta(s)e^{2i\delta_{KK}(s)} \end{pmatrix}$$

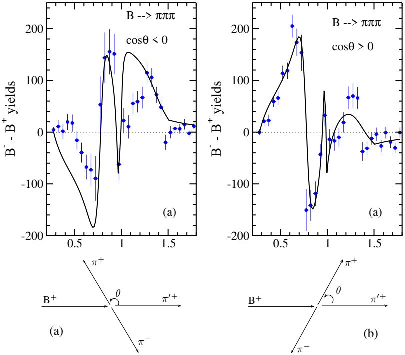
Rescattering Lineshape

- Only off-diagonal elements are relevant for amplitude analysis
- Use models for the phase shifts $\delta_{\pi\pi}(s)$, $\delta_{KK}(s)$ and inelasticity $\eta(s)$
  - J.R. Pelaez and F.J. Yndurain, Phys. Rev. D **71**, 074016 (2005)

Rescattering vs phase space

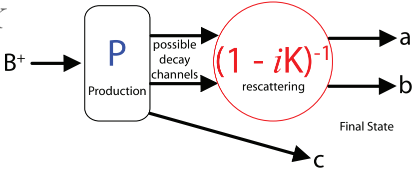


- Also tested on LHCb asymmetry
- ρ, $f_0(980)$ considered in addition
- Reproduces the main features
  - Exp: Phys. Rev. D **90**, 112004 (2014)
  - Th: Phys. Rev. D **92**, 054010 (2015)



K-Matrix

From unitarity of the S-matrix, physical transition amplitude given by
$\hat{T} = (\hat{I} - i\hat{K}\rho)^{-1}\hat{K}$



$\hat{K}$ parametrised by summation of base mass poles and a slowly varying part for non-resonant

$$(\rho\hat{K})_{ij}(s) \equiv \sqrt{\rho_i \rho_j}\left(\sum_R \frac{g_i^R g_j^R}{m_R^2 - s} + f_{ij}^{\rm scat}\frac{c - s_0^{\rm scat}}{s - s_0^{\rm scat}}\right) f_{A0}(s)$$

Parameters taken from global fit to scattering data
Eur. Phys. J. **A16** (2003) 229

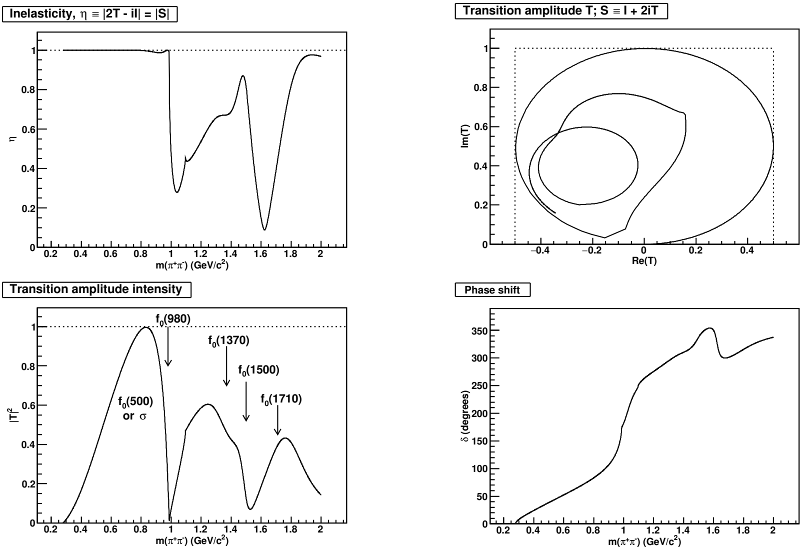
The production vector $\hat{P}$ takes on an analogous form to $\hat{K}$

$$\hat{P}_j(s) \equiv \sum_R \frac{\beta_R^{\rm prod} g_j^R}{m_R^2 - s} + f_j^{\rm prod}\frac{c - s_0^{\rm prod}}{s - s_0^{\rm prod}}$$

j: $\pi\pi$, KK, 4π, $\eta\eta$, $\eta\eta'$; $\beta_R^{\rm prod}$ and $f_j^{\rm prod}$ are the complex free parameters of the model

K-Matrix

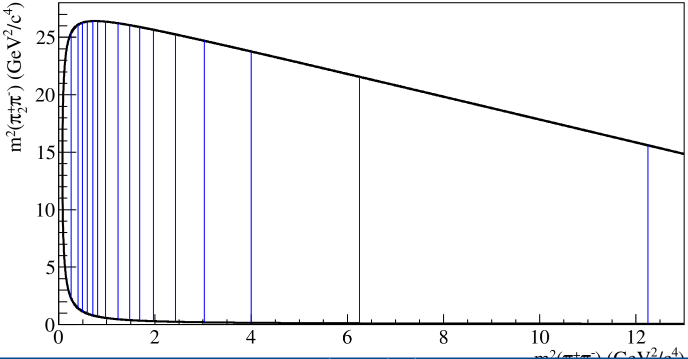
Elastic scattering on the physical boundary, inelastic scattering inside



Resonances don't necessarily manifest as Breit-Wigner structure

Quasi-Model-Independent Approach

- Construct spin-1 and spin-2 resonances with the isobar model as usual
- Model $\pi\pi$ S-waves with adaptive binning method
- Equal number of events in each bin
- 1D bins in $m^2(\pi^+\pi^-)$, 15 bins below charm veto, 2 bins above
- In each bin, float amplitude magnitude and phase, 83 free parameters in total
- Bose-symmetric amplitude implied

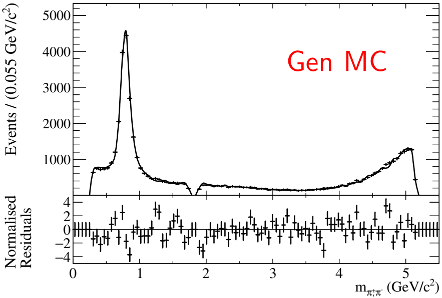


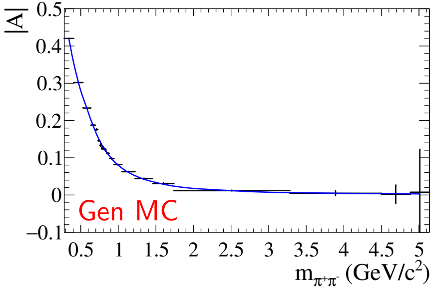
Quasi-Model-Independent Approach

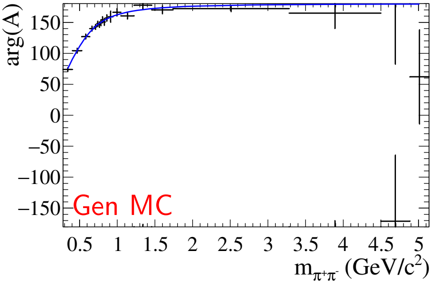
- Quasi-model-independent method
  - Reminiscent of partial wave analysis
- Divide the data into bins
- Free magnitude/phase in each bin

- Data points: Fit results
- Blue Curve: Generated $f_0(500)$ Breit-Wigner

MC generated with ρ, $f_0(500)$

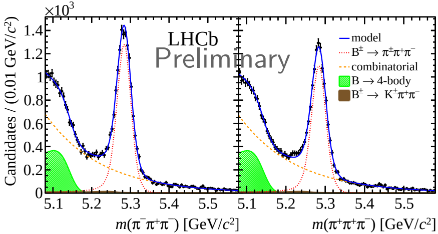






Data Sample

Only Run 1 data from 2011+12 used, LHCb-PAPER-2019-017

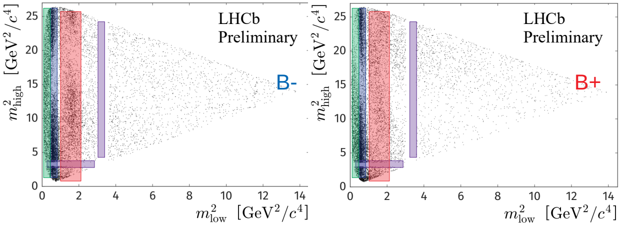


LHCb-PAPER-2019-018

Parameter	Value
Signal yield	$20\,594 \pm 1\,569$
Combinatorial bkg yield	$4\,409 \pm 1\,634$
$B^+ \to K^+\pi^+\pi^-$ bkg yield	143 ± 11
Combinatorial bkg asym	$+0.005 \pm 0.010$
$B^+ \to K^+\pi^+\pi^-$ bkg asym	$+0.000 \pm 0.008$

Dalitz plot analysis performed in the signal region,

$5.249 < m(\pi^{\pm}\pi^{+}\pi^{-}) < 5.317\ \mathrm{GeV}/c^2$



- Sample correspond to 3fb^{-1} from Run 1.
- Charm veto.
- $f_2(1270)$ region.
- $\rho(770)$ region.
- low scalar $m(\pi\pi)$.

Phases

B^+

LHCb-PAPER-2019-017, LHCb-PAPER-2019-018

Component	Isobar	K-matrix	QMI
$\omega(782)$	$-19 \pm 6 \pm 1$	$-15 \pm 6 \pm 4$	$-25 \pm 6 \pm 27$
$f_2(1270)$	$+5 \pm 3 \pm 12$	$+19 \pm 4 \pm 18$	$+13 \pm 5 \pm 21$
$\rho(1450)^0$	$+127 \pm 4 \pm 21$	$+155 \pm 5 \pm 29$	$+147 \pm 7 \pm 152$
$\rho_3(1690)^0$	$-26 \pm 7 \pm 14$	$+19 \pm 8 \pm 34$	$+8 \pm 10 \pm 24$

B^-

Component	Isobar	K-matrix	QMI
$\omega(782)$	$+8 \pm 6 \pm 1$	$+8 \pm 7 \pm 4$	$-2 \pm 7 \pm 11$
$f_2(1270)$	$+53 \pm 2 \pm 12$	$+80 \pm 3 \pm 17$	$+68 \pm 3 \pm 66$
$\rho(1450)^0$	$+154 \pm 4 \pm 6$	$-166 \pm 4 \pm 51$	$-175 \pm 5 \pm 171$
$\rho_3(1690)^0$	$-47 \pm 18 \pm 25$	$+5 \pm 8 \pm 46$	$+36 \pm 26 \pm 46$

Phases given in degrees, measured relative to the $\rho(770)^0$

Broad agreement between different S-wave approaches

Largest phase difference between B^+ and B^- in $f_2(1270)$

Responsible for some of the large CP seen in the Dalitz plot

Fit fractions and CP asymmetries

CP conserving fit fractions

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.7 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.03 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.8 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.4 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.7 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

First error: statistical, Second: systematic, Third: Model uncertainty

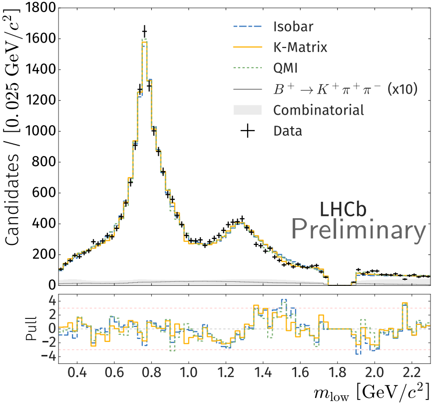
$\rho(770)^0$ and S-wave dominant, significant $f_2(1270)$ contribution

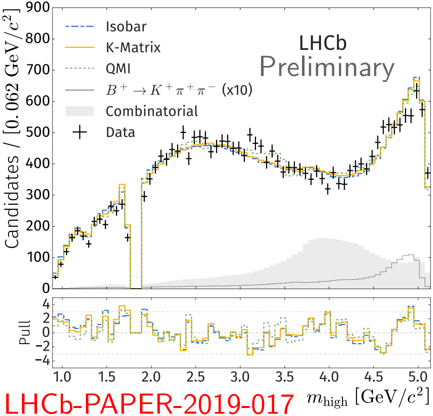
Direct CP asymmetries LHCb-PAPER-2019-017, LHCb-PAPER-2019-018

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 1.2 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 6.6 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 3.6 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 7.0 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 13.5 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 2.1 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

Large CP violation in $f_2(1270)$ and S-wave

Full Charmless Fit Projection





LHCb-PAPER-2019-017

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

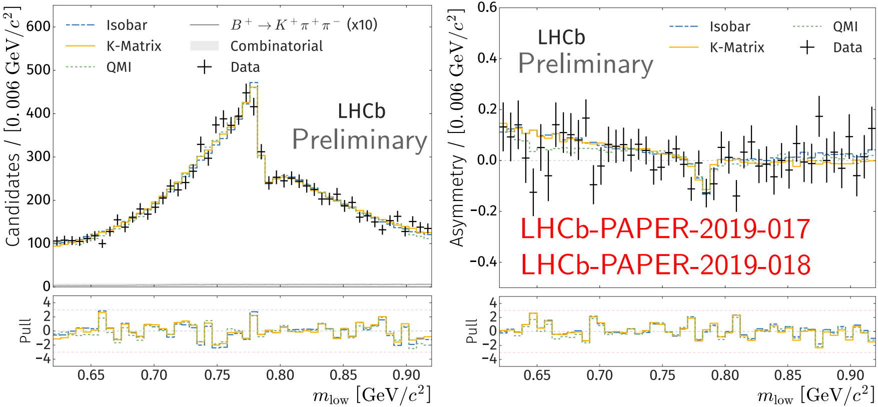
m_{low} is the lower $\pi^+\pi^-$ invariant mass combination

- Enhances resonance visibility

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

- Shows spin structure

$\rho(770)^0$ Region: $m(\pi^+\pi^-)$

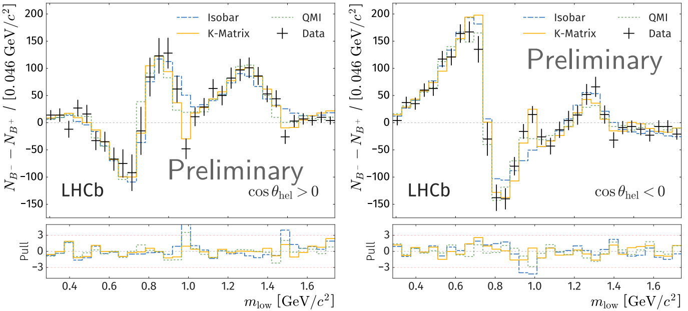


Clear ρ-ω interference

Rapid sign flips of $\mathcal{A}_{CP}$ in small region, attribute to $\rho - \omega$ mixing

No charge asymmetry observed as a function of $m(\pi^+\pi^-)$

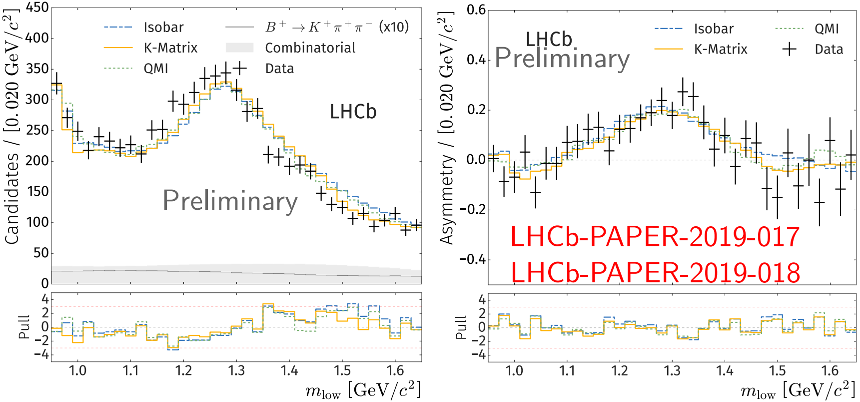
$\mathcal{A}_{CP}$ About $\rho(770)^0$ Pole



LHCb-PAPER-2019-017

- Described well by all 3 S-wave approaches
- Large amounts of direct CP violation seen
- Opposite behaviour in helicity between B^+ and B^-
- Characteristic of CP violation in interference between broad and dominant S- and P-waves
  - $\mathcal{A}_{CP}$ linear in helicity, yet invisible in full $m(\pi^+\pi^-)$ projection
- Over 25σ statistical significance
- First observation of CP violation in S-P interference

$f_2(1270)$ Region



Poorly described by all 3 S-wave approaches, can be fixed in 2 ways

Free $f_2(1270)$ pole parameters

- Inconsistent with PDG values, disagreement between 3 approaches

Additional D-wave contribution

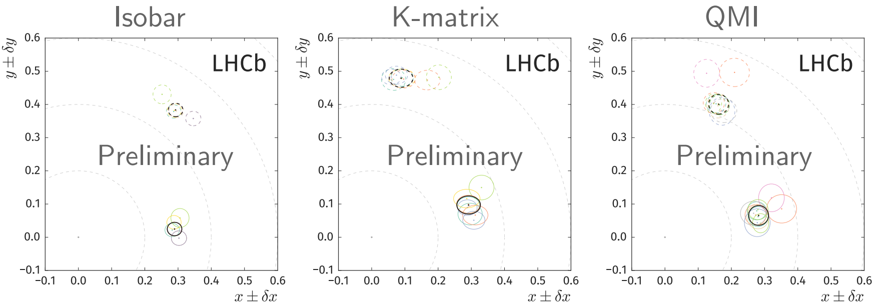
- Fit with additional D-wave, $f_2(1430)$ state not well established

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

$f_2(1270)$ Region

Quantify quasi-two-body CP violation by plotting isobar parameters in the Argand plane

Magnitude and phase for $B^+ \to f_2(1270)\pi^+$ and $B^- \to f_2(1270)\pi^-$



LHCb-PAPER-2019-017

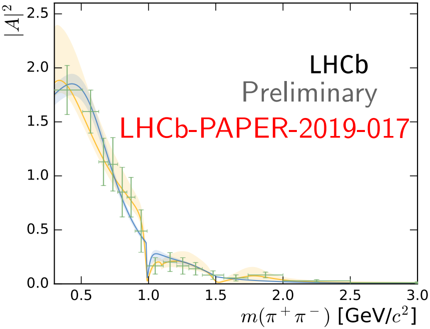
Black ellipse: Nominal fit

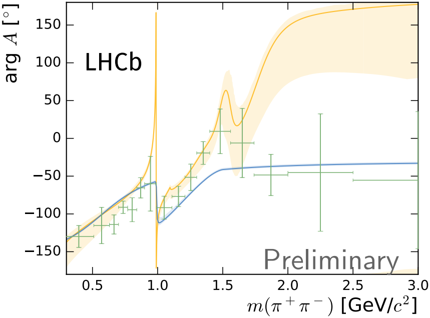
Coloured ellipses: Various systematic variations

Observation of CPV ranges from $14 - 19\sigma$ (statistical only)

First observation of CP violation in any process involving a tensor

S-wave Comparison





Green data points: QMI S-wave

Blue curve: Isobar S-wave, Orange curve: K-matrix S-wave

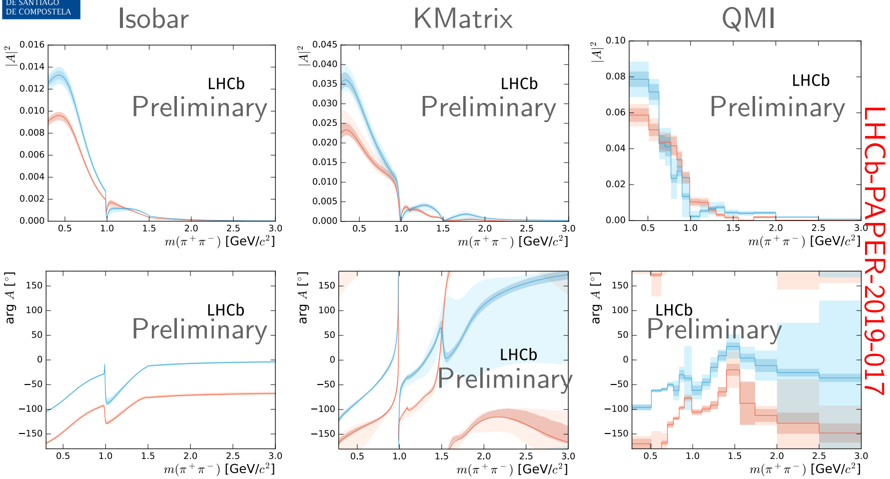
Total uncertainties shown

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

Structure in phase motion qualitatively agreed on

Deviation from QMI indicates more theoretical work needed

S-wave Amplitude



Red: B^+, Blue: B^-, Dark (light) shading: Statistical (Total) error

First CP violation in S-wave, over 10σ statistical significance

Elastic region, could be generated by short-distance effects

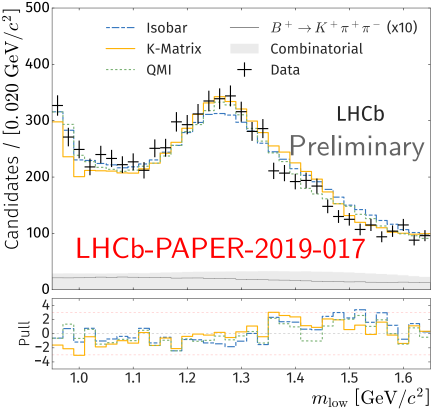
If phase difference non-constant, could indicate new dynamics

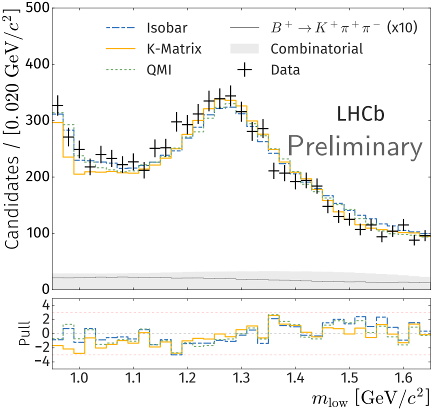
Summary

- Amplitude analysis of $B^+ \to \pi^+\pi^+\pi^-$
- 3 approaches to the complicated S-wave, which broadly agree
  - Isobar: Each lineshape has physical meaning
  - K-matrix: Interface with results from scattering experiments
  - QMI: Determine directly from the data
- Theoretical speculation on cause of large localised CP violation
  - Low-mass S-wave interference with $\rho(770)^0$: yes
  - $\rho - \omega$ mixing: no
  - $KK \to \pi\pi$ rescattering: not yet
- 3 different kinds of CP violation observed for the first time
  - In S-P interference around the $\rho(770)^0$ pole
  - In the $f_2(1270)$
  - In the S-wave at low $m(\pi^+\pi^-)$
- Significant new insight into CP violation in multi-body B-hadron decays
- Motivates further study into the processes that govern CP violation
- LHCb-PAPER-2019-017 and LHCb-PAPER-2019-018 in preparation

Backup

$f_2(1270)$ Region





Bad fit in $f_2(1270)$ region can be fixed in 2 ways

Left: Free $f_2(1270)$ pole parameters

- Inconsistent with PDG values, disagreement between 3 approaches

Right: Additional D-wave contribution

- Fit with additional $f_2(1430)$, state not well established