Observation of several sources of CPV in $B^+ \to \pi^+\pi^+\pi^-$ decays

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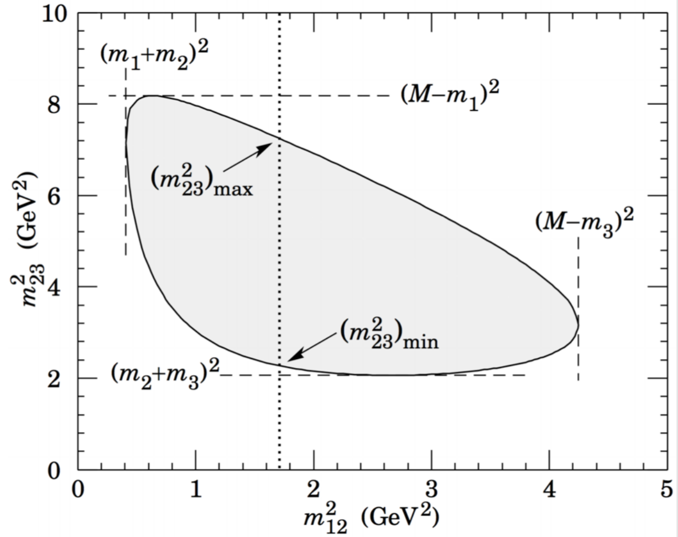
Motivations

- Suppressed in the Standard Model: penguin (loop) and tree diagrams of a similar magnitude
- $b \rightarrow s$ and $b \rightarrow d$ loop diagrams carry a different weak phase to those in the tree diagrams
- Different strong and weak phases can lead to large CP-violation in decay
- Intermediate resonances and short distance QCD effects result in a strong phase variation across the Dalitz plot

$$A_{CP} = \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)}$$
$$= \frac{2|A_1||A_2|sin\delta sin\phi}{|A_1|^2+|A_2|^2+2|A_1||A_2|cos\delta cos\phi}$$

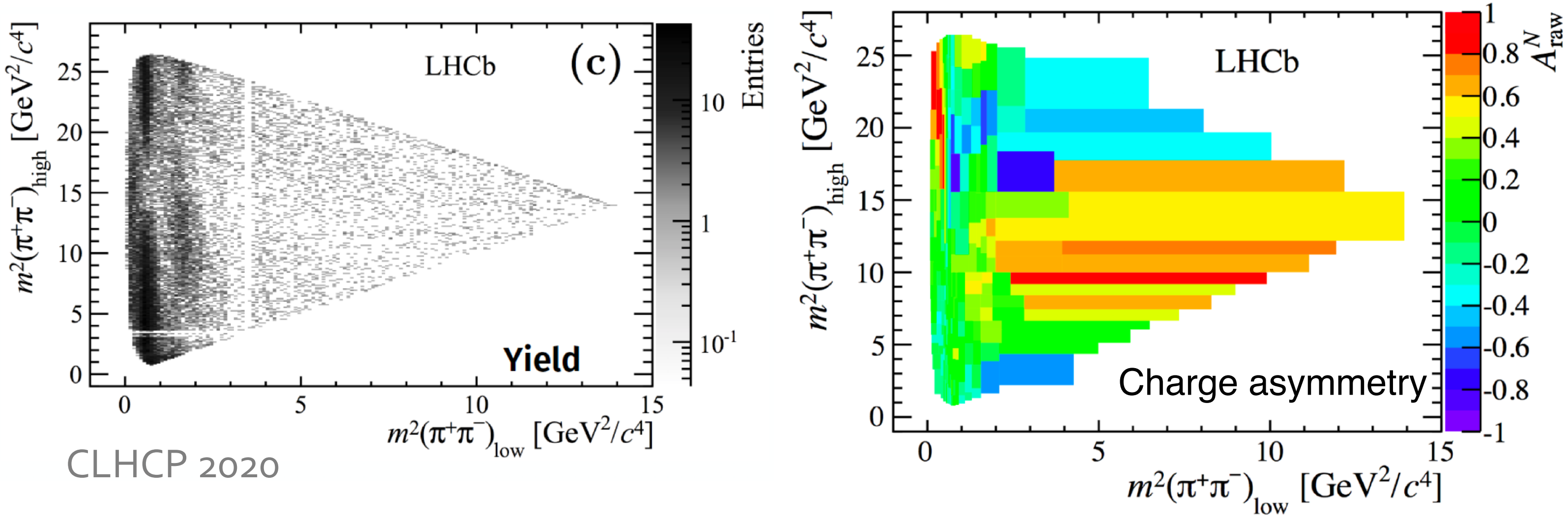
Phys. Rev. D 98.030001 (2018)



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

- Data set (3 fb-1 of Run 1 LHCb data):
- Construct an explicit amplitude model for the decay
- Three approaches, that differ in the S-wave (spin-0) description
  - K-matrix: Single unitarity conserving model, with parameters from scattering data
  - Isobar: Individual hand-engineered components for each contribution, does not conserve unitarity
  - Quasi-model-independent: Fit for a magnitude and phase in bins of the phase-space

LHCb-PAPER-2014-044



Yields

Simultaneous fit to the mass of B^+ and B^-

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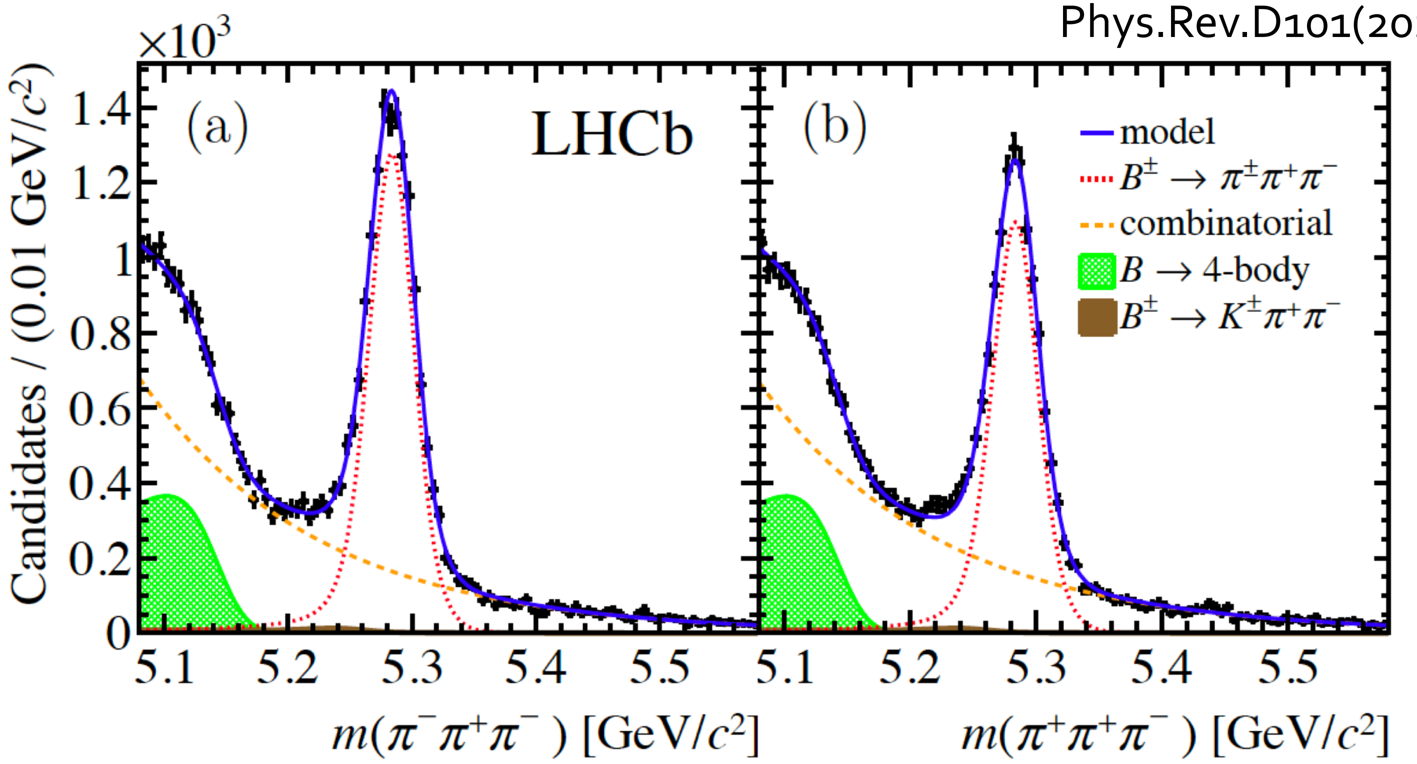


mass window

$[5.249, 5.317]$ GeV/c^2

Parameter	Value
Signal yield	$20\,600 \pm 1\,600$
Combinatorial background yield	$4\,400 \pm 1\,600$
$B^+ \to K^+\pi^+\pi^-$ background yield	143 ± 11
Combinatorial background asymmetry	$+0.005 \pm 0.010$
$B^+ \to K^+\pi^+\pi^-$ background asymmetry	0.000 ± 0.008

Amplitude analysis formalism

Amplitude for B^+ and B^- signal decays is constructed as the sum over N resonant contributions and the S-wave component

- $A^{\pm}(m_{13}^2, m_{23}^2) = \sum_j^N c_j^{\pm} F_j(m_{13}^2, m_{23}^2) + A_S^{\pm}(m_{13}^2, m_{23}^2)$

Typical model for resonances for a product of 3 terms: mass lineshape angular dependence and Blatt-Weisskopf barrier factors

- $F_j(m_{13}^2, m_{23}^2) = \mathrm{R(m_{13})}\, T(\vec{p}, \vec{q}) X(|\vec{p}| r_{BW}^P)\, X(|\vec{q}| r_{BW}^R)$

- P-wave: $\rho(770)^0, \omega(782), \rho(1450)$(Relativistic Breit-Wigner)
  - $\rho(770)^0$lineshape modelled by Gounaris-Sakurai amplitude
  - $\rho(770)^0$pole parameters free in nominal fit
  - $\rho(770)^0$ and , $\omega(782)$ bound together in a mixing amplitude
- D-wave: $f_2(1270)$ Relativistic Breit-Wigner
- F-wave: $\rho_3(1690)^0$ Relativistic Breit-Wigner

Isobar Model

- Analytical description of the S-wave
  - Form factors associated with physical contributions
  - Direct physical interpretation
- $\sigma/f_0(500)$
  - $T(m) = \frac{1}{m_\sigma^2 - m^2}$
- $\pi\pi - KK$ Rescattering
  - Phys.Rev. D 71 (2005) 074016
  - Ported to 3-body decays from 2-body interactions
  - Scattering phase respects unitarity and analyticity
  - Pair of mesons produced here will also appear in $B^+ \to K^+\pi^+K^-$
    - $A_{source}(m; \Delta^2_{\pi\pi}, \Delta^2_{KK}) = \frac{1}{1+(m/\Delta^2_{\pi\pi})} \frac{1}{1+(m/\Delta^2_{KK})}$
  - $T(m) = A_{source}(m) f_{rescattering}$
    - $f_{rescattering}(\mathrm{s}) = \sqrt{1 - \eta^2(s)}\mathrm{e}^{2i\delta(s)}$
    - Inelasticity $\eta(s)$, and strong phase variation $\delta(s)$ from external data

The 'K-matrix' S-wave model

arXiv:hep-ph/0204328
(Anisovich & Sarantsev)

- Analytical description of the S-wave
  - Resonant contributions and their decay channels intertwined in a global form factor, inspired by conservation of unitarity in rescattering analyses

Sum over resonance poles

$$\mathcal{F}_u = \sum_{v=1}^{n} [I - i\hat{K}\rho]^{-1}_{uv} \cdot \hat{P}_v$$

- $\widehat{K}_{\mu\nu}$(fixed): K-matrix fixed from external scattering data
- ρ_μ: Amount of phase space available to decay channel
- $\widehat{P}_\nu$: Production vector comprised of mass poles and non-resonant

$$\hat{P}_v(s) = \sum_{\alpha=1}^{N} \frac{\beta_\alpha g_v^{(\alpha)}}{m_\alpha^2 - s} + f_v^{\text{prod}} \frac{m_0^2 - s_0^{\text{prod}}}{s - s_0^{\text{prod}}}$$

- $Pole\ i$: $f_0(500), f_0(980), f_0(1370), f_0(1500), f_0(1710)$

The K-matrix S-wave model

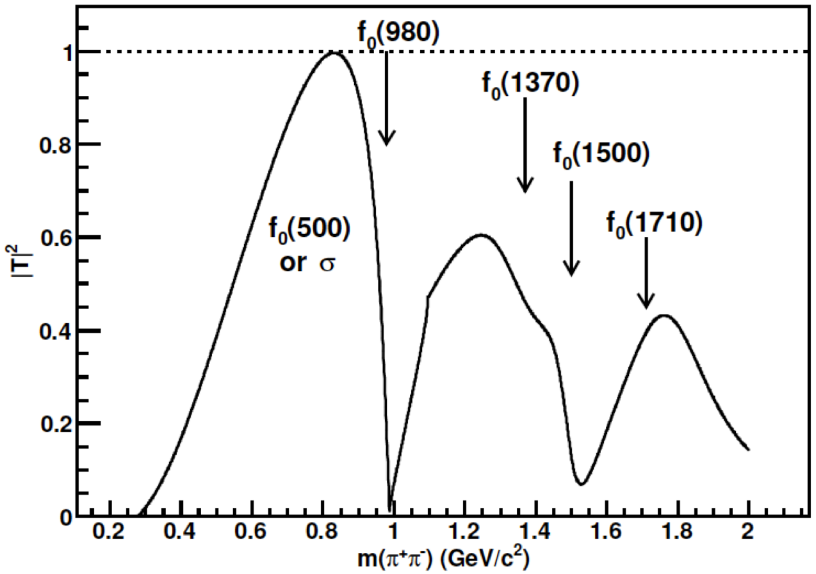
Parameters: Phys. Rev. D78 (2008) 034023, arXiv:0804.2089
Data: Eur. Phys. J. A16 (2003) 229, arXiv:hep-ph/0204328.
S_o^{prod} : Phys. Lett. B585 (2004) 200, arXiv:hep-ex/0312040

Poles

Channels

Couplings

α	m_α	$g_1^\alpha[\pi\pi]$	$g_2^\alpha[K\bar{K}]$	$g_3^\alpha[4\pi]$	$g_4^\alpha[\eta\eta]$	$g_5^\alpha[\eta\eta']$
1	0.65100	0.22889	−0.55377	0.00000	−0.39899	−0.34639
2	1.20360	0.94128	0.55095	0.00000	0.39065	0.31503
3	1.55817	0.36856	0.23888	0.55639	0.18340	0.18681
4	1.21000	0.33650	0.40907	0.85679	0.19906	−0.00984
5	1.82206	0.18171	−0.17558	−0.79658	−0.00355	0.22358
	s_0^{scatt}	f_{11}^{scatt}	f_{12}^{scatt}	f_{13}^{scatt}	f_{14}^{scatt}	f_{15}^{scatt}
	3.92637	0.23399	0.15044	−0.20545	0.32825	0.35412
	s_0^{prod}	m_0^2	s_{A0}			
	3.0	1.0	−0.15			

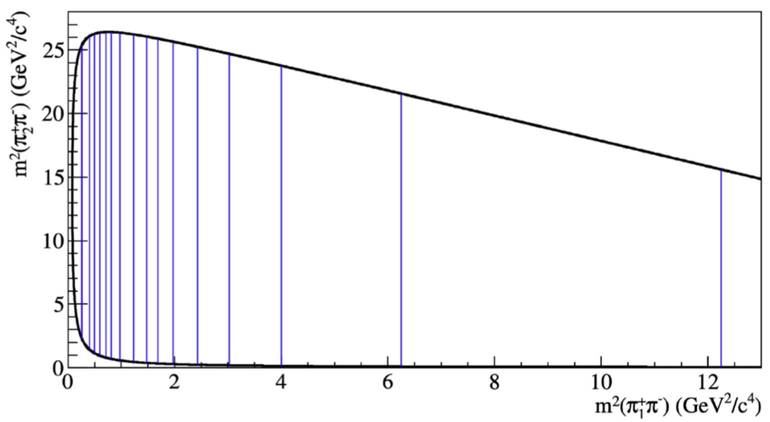


Arxiv: 1711.09854

- amplitude squared (showing the location of various resonance structures")
- Describes entire S-wave in a single model

QMI Model

- Numerical quasi-model-independent (QMI) description of the S-wave
- Divide phase space for equal number of events in each bin initially
- Free amplitude and phase in each bin for B^+ and B^-
- Test bin performance on large statistics pseudo-experiment generated from Isobar result
- Merge biased bins unable to reproduce Isobar S-wave with neighbor
- Settle on 13 bins below D0 veto, 4 above
- Amplitude and phase motion can vary rapidly within a bin particularly when crossing channel openings
    - Spline interpolation not appropriate



Fit result

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Fit fractions

$$\mathcal{F}_j = \frac{\int_{\mathrm{PhSp}} |A_j|^2 + |\overline{A}_j|^2 d\mathrm{PhSp}}{\int_{\mathrm{PhSp}} |\sum_j A_j|^2 + |\sum_j \overline{A}_j|^2 d\mathrm{PhSp}}$$

CP asymmetries

$$A^j_{\mathrm{CP}} = \frac{|\overline{A}_j|^2 - |A_j|^2}{|\overline{A}_j|^2 + |A_j|^2}$$

CP conserving fit fractions

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.4 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.01 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.7 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.2 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.3$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.5 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

Direct CP asymmetries

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 0.6 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 1.3 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 1.5 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 3.6 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 7.8 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 1.0 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

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

- Dominant contributions are $\pi\pi$ s-wave, $\rho^0(770), \mathrm{f}_2(1270), \rho - \omega\ mixing$
- The three methods give a similar representation of the data.

Full Charmless Fit Projection

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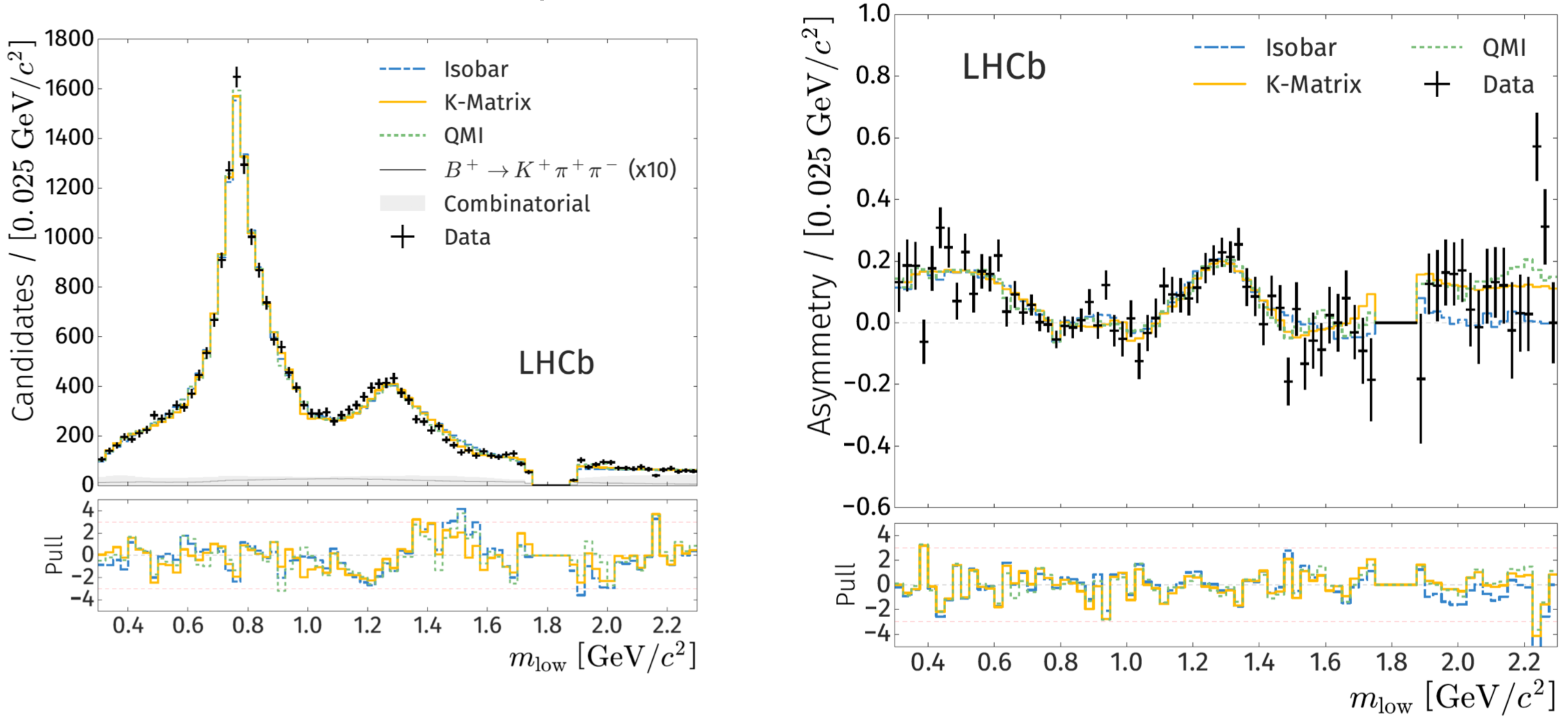

CP-violation observed in S-wave at low $m_{\pi\pi}$, S - P interference around the $\rho(770)$ pole and $f_2(1270)$

$\rho(770)^0$ region

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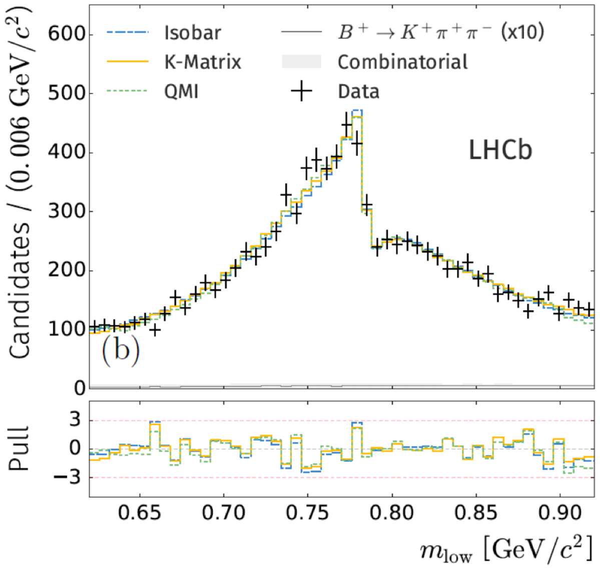
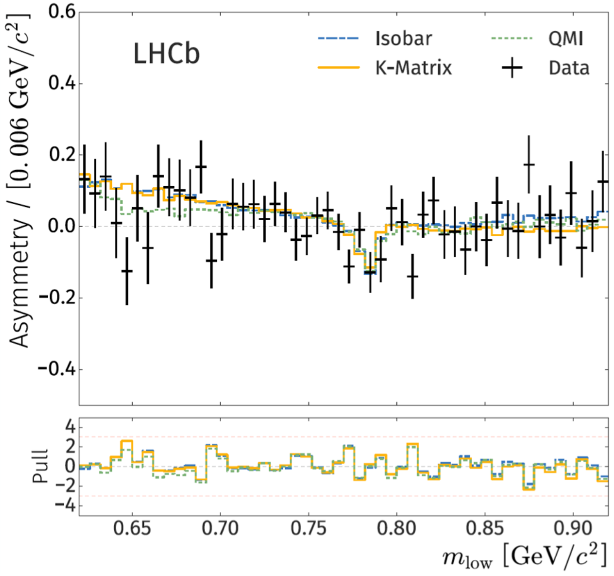
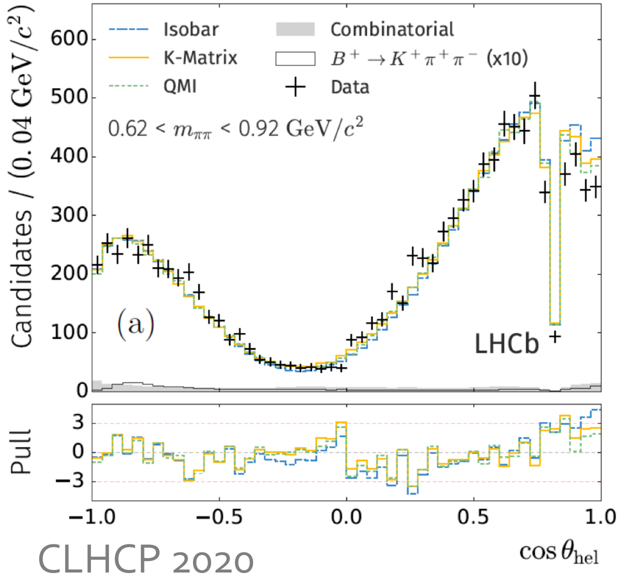
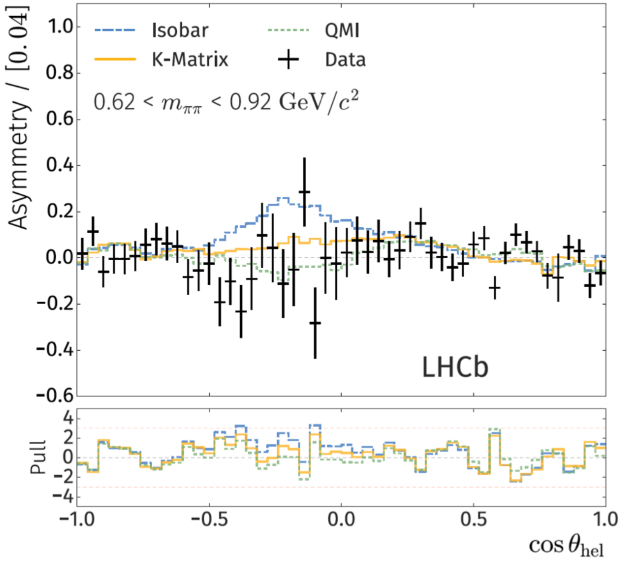
- Very little asymmetry in this region as a function of mass:





- Also very little asymmetry as a function of helicity





$\rho(770)^0$ region

- Below and above the $\rho(770)^0$ mass:

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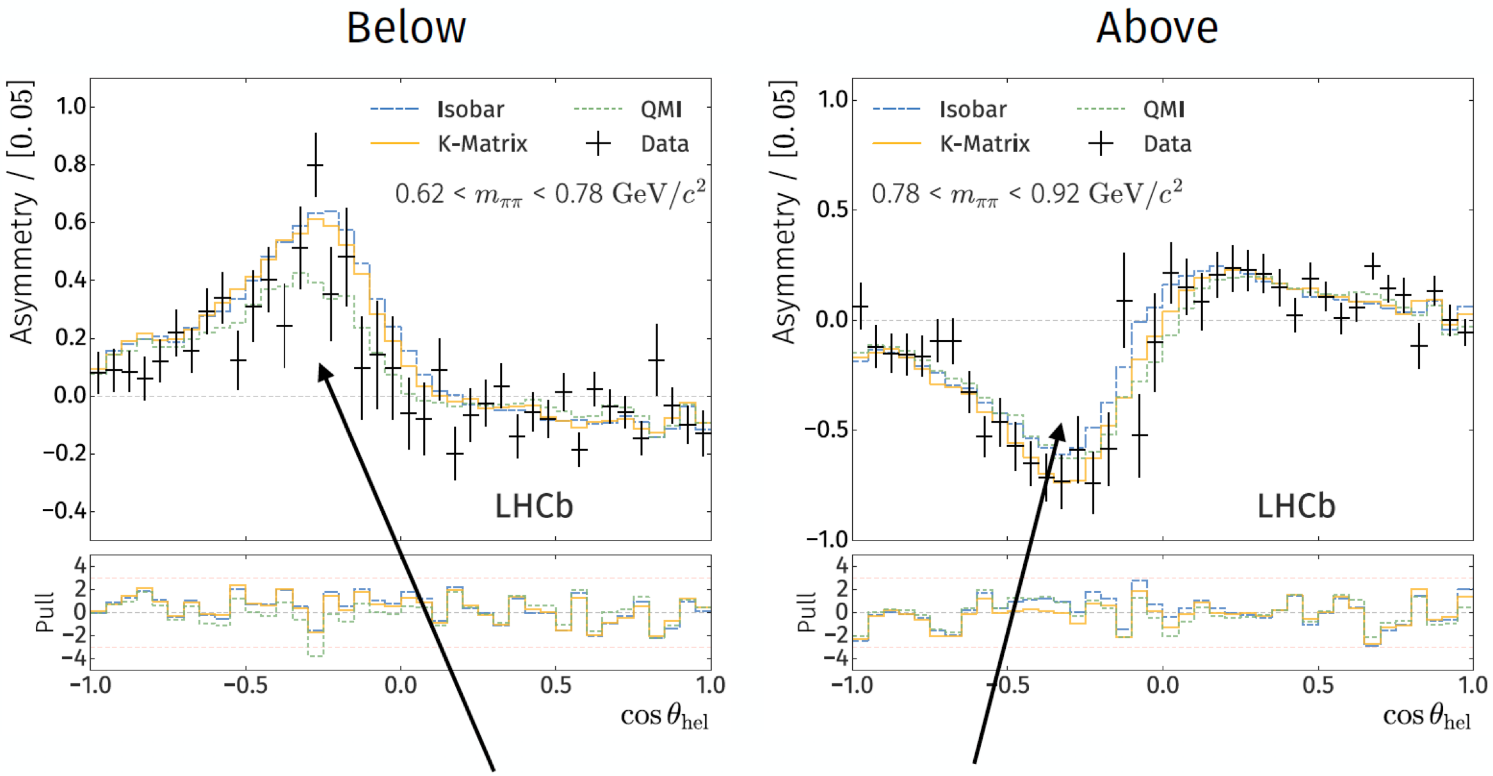

Almost perfect cancellation!

$\rho(770)^0$ region

- But why?
  - This region is dominated by slowly varying spin 0, and the rapidly varying spin-1 $\rho(770)^0$
  - Interference term between these is $\sim\cos\theta_{hel}$, when projecting on mass (integrating over $\cos\theta_{hel}$) this term vanishes!

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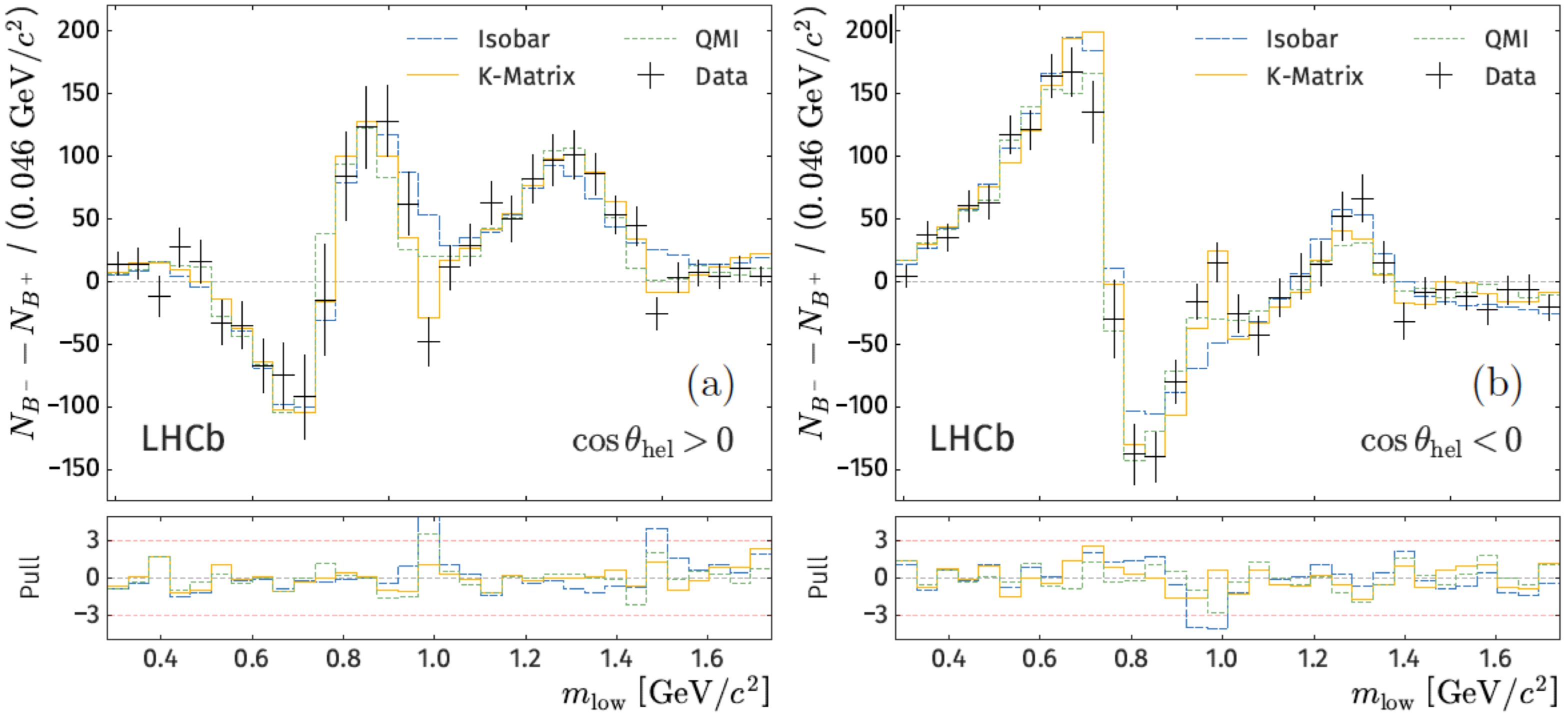

$f_2(1270)$ region

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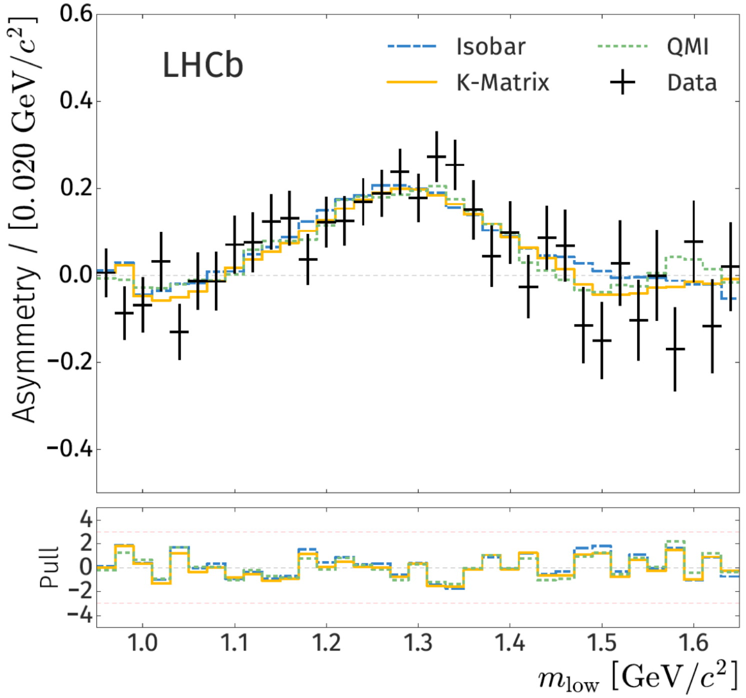
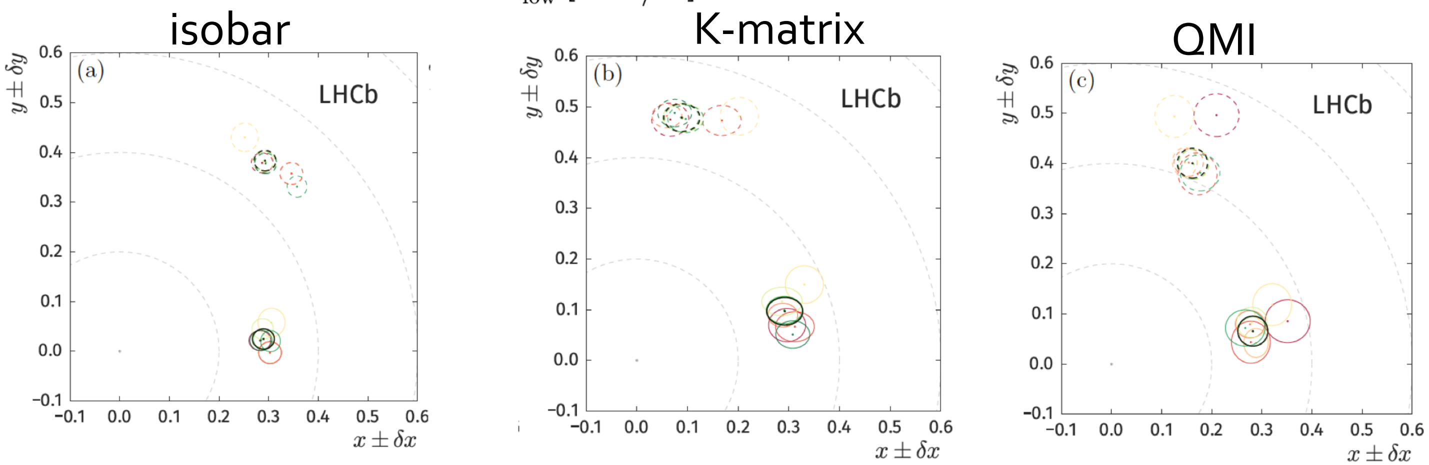


1. Very large asymmetry in this region, associated with the $f_2(1270)$, component, An A_{CP} of around 40% in all models
2. One of the largest CP asymmetries ever observed!



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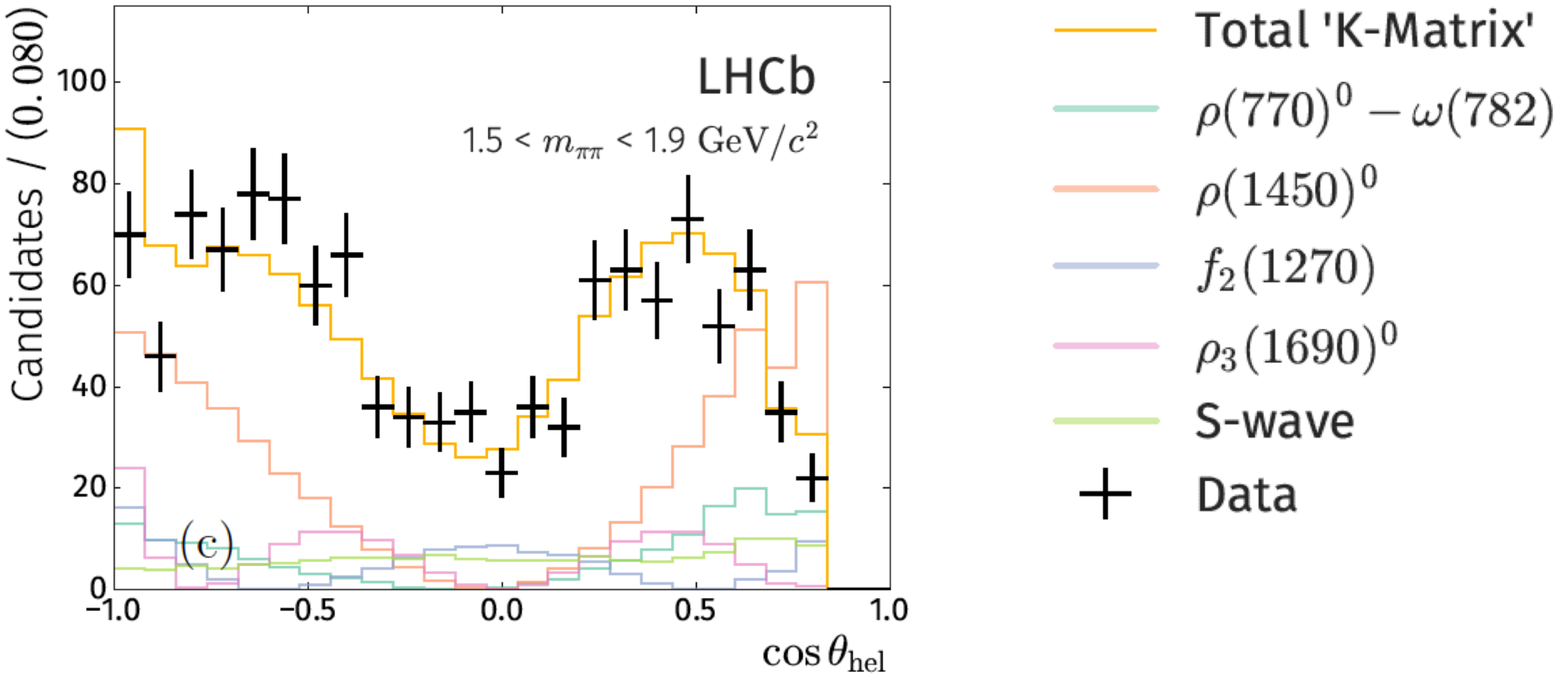
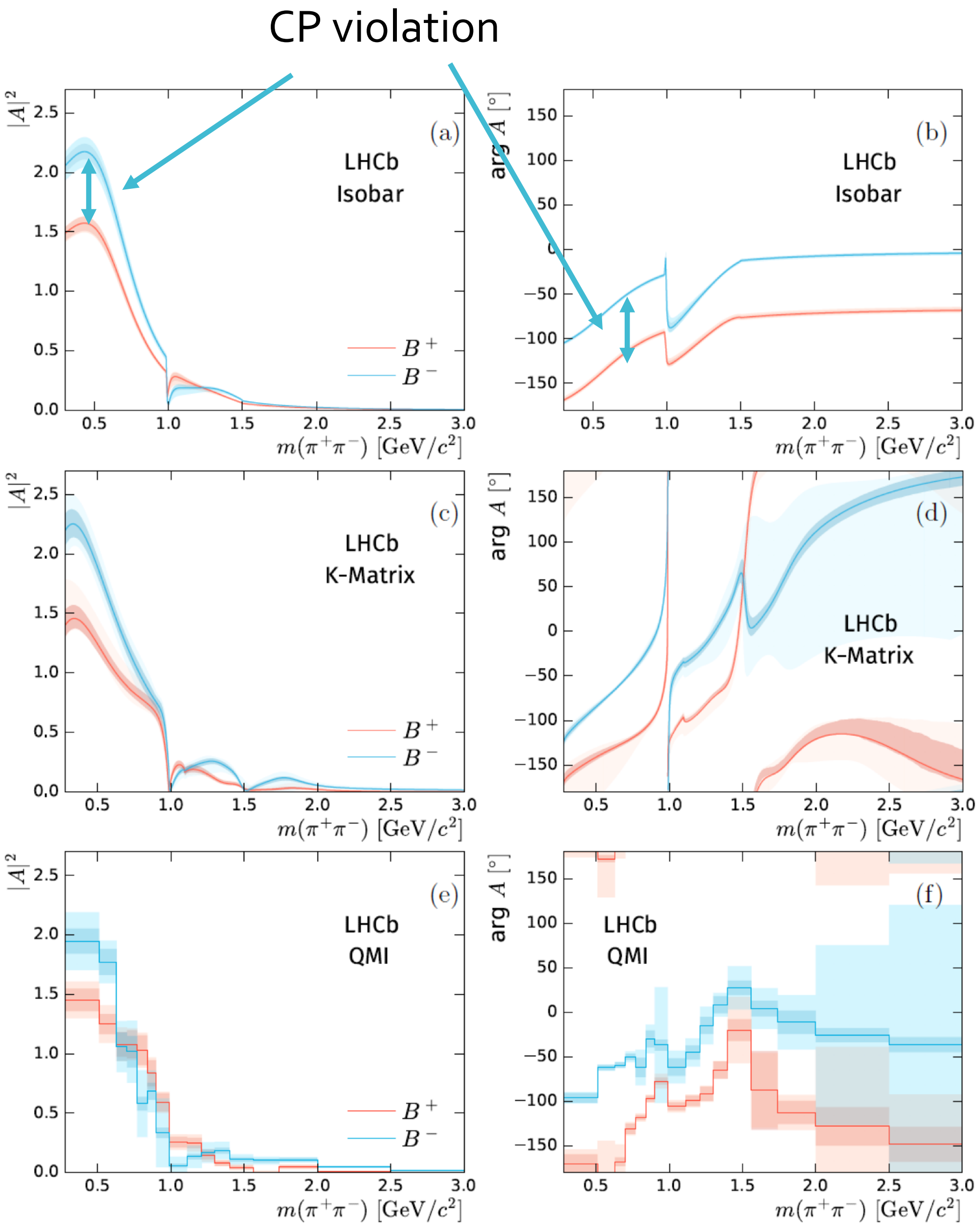
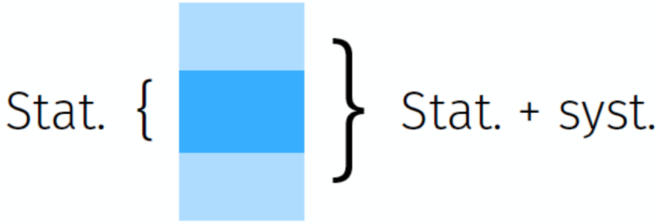
$\rho^3(1690)$ region



- K-matrix has the strongest $\rho_3(1690)^0$ contribution
- Peaking at $1.0, \pm 0.5$ in helicity
- Amplitude significant due to unique helicity structure around interference effects

S-wave model projections





- CP violation is pretty evident here

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Summary

- Observations of large CP violation, and the first observation of CP violation in the interference between resonances in the $B^+ \to \pi^+\pi^-\pi^+$ decay
- 3 different kinds of CP violation observed for the first time
  - In the S-wave at low $m_{\pi\pi}$
  - In S - P interference around the $\rho(770)$ pole
  - In the $f_2(1270)$
- The CP violation effect is now associated to resonances rather than to integrated or localized regions of the Dalitz plot.
- Paper can be found
  - Phys.Rev.D101(2020) 012006 (arXiv:1909.05212v3)
  - Phys.Rev.L 124(2020) 031801 (arXiv:1909.05211v2)

Thank you for your attention!

backup

Efficiencies and Backgrounds