CP violation in B decays

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Introduction

- CPV observed in K, B and D meson decays, well consistent with SM prediction
- But still too small to explain the absence of antimatter in the universe
- More searches for CPV are needed:

search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays **arXiv:1912.10741**

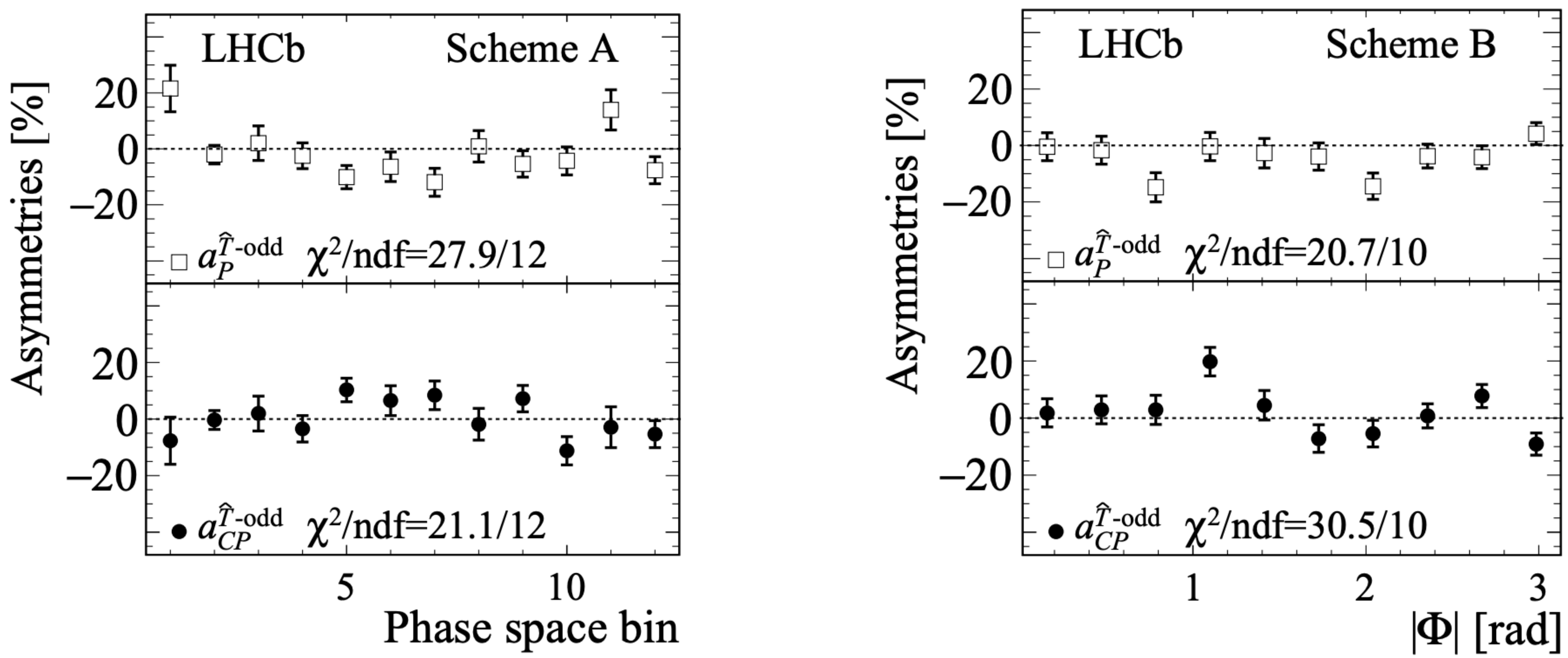
search for CPV in $B^+ \to \pi^+\pi^+\pi^-$ decays **PRL 124 (2020) 031801** **PRD 101 (2020) 012006**

- Unitary triangles measurements, please see talk from Mark Whitehead

Previous measurement in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

Nature Phys. 13 (2017) 391-396

- Previous results 3.3σ for CPV, using triple product asymmetries (TPA)
- Update with more data set



$3fb^{-1}$
@LHCb

Binning on resonances:
$\Delta^{++}, \rho(770), N*$

Binning angle between planes:
$\pi^+\pi^-_{\text{slow}}$ and $p\pi^-_{\text{fast}}$

New measurement

arXiv:1912.10741

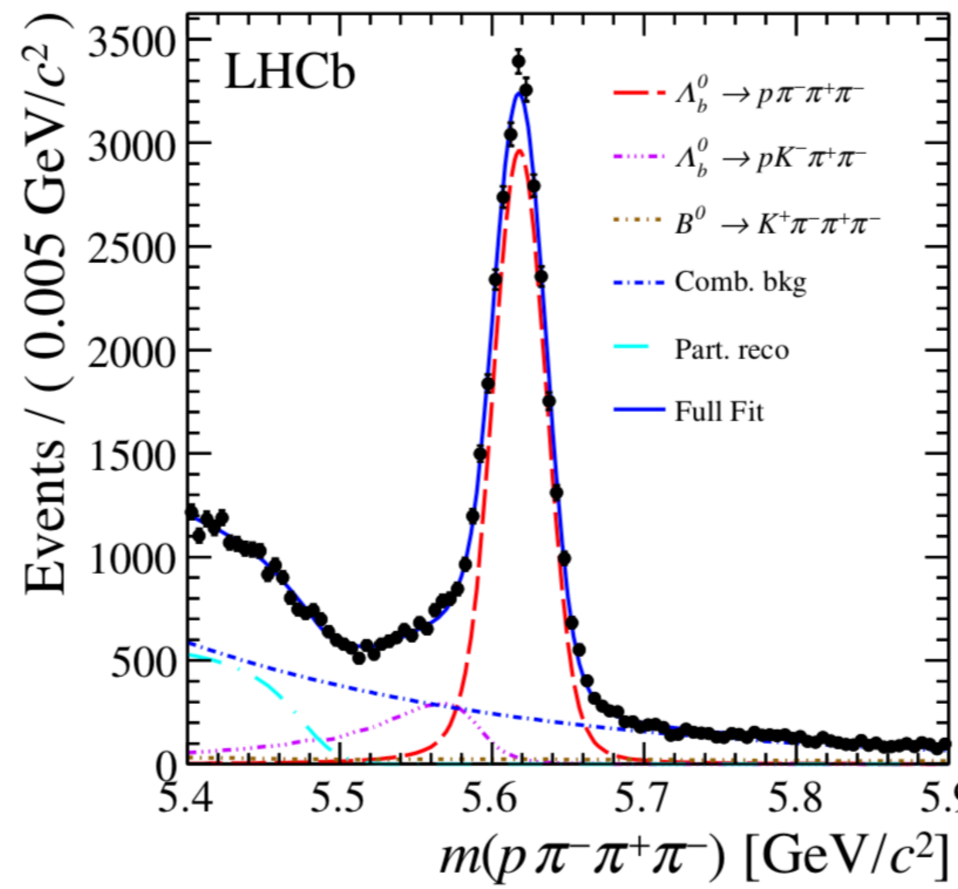
- New analysis of $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays with $6.6fb^{-1}$

  yields: 27600 ± 200, ~4 times previous

- Two approaches:

TPA with improved binning schemes

Unbinned energy test method

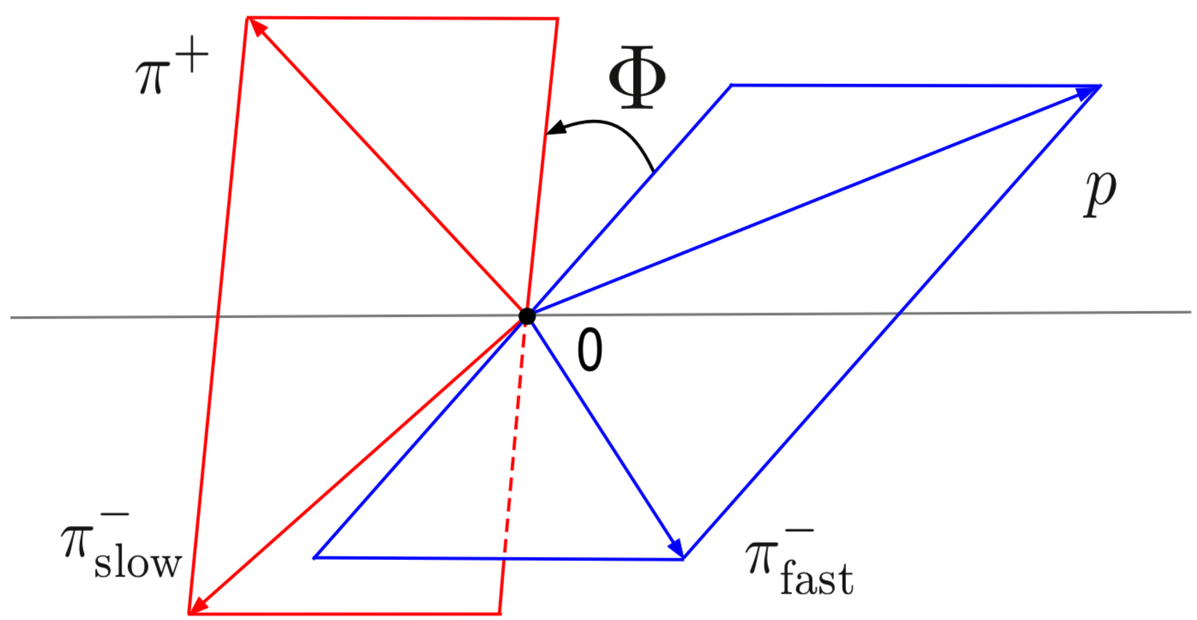


TPA approach

- Triple products in Λ_b^0 rest frame:

$$\Lambda_b^0:\ C_{\hat{T}} \equiv \overrightarrow{p}_p \cdot (\overrightarrow{p}_{\pi_{\text{fast}}} \times \overrightarrow{p}_{\pi^+}) \propto \sin\Phi$$

$$\bar{\Lambda}_b^0:\ \bar{C}_{\hat{T}} \equiv \overrightarrow{p}_{\bar{p}} \cdot (\overrightarrow{p}_{\pi_{\text{fast}}} \times \overrightarrow{p}_{\pi^-}) \propto \sin\bar{\Phi}$$



- P-odd asymmetries:

$$\Lambda_b^0:\quad A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)},$$

$$\bar{\Lambda}_b^0:\quad \overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}$$

- CP-violating observable:

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

- P-violating observable:

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

Improvement of binning schemes

arXiv:1912.10741

- Maximise the sensitivity of CPV with amplitude models

  G.Durieux, JHEP 10 (2016) 005

  G.Durieux, PRD 92 (2015) 076013

- S and P wave could interfere, and introduce P-odd CPV

$$\Lambda_b^0 \to N^{*+}/\Delta^{*+}\pi^- \qquad N^{*+}/\Delta^{*+} \to \Delta^{++}(\to p\pi^-)\pi^-$$

e.g. $\Lambda_b^0 \to N^{*+}(1/2)\pi^-$ $\qquad$ $\Lambda_b^0 \to N^{*+}(3/2)\pi^-$

S + ~~P~~ $\qquad$ P + ~~D~~

neglect higher partial wave P, D

$N(1440)\ 1/2^+$	$\Delta(1232)\ 3/2^+$
$N(1520)\ 3/2^-$	$\Delta(1600)\ 3/2^+$
$N(1535)\ 1/2^-$	$\Delta(1620)\ 1/2^-$
$N(1650)\ 1/2^-$	$\Delta(1700)\ 3/2^-$
$N(1675)\ 5/2^-$	$\Delta(1750)\ 1/2^+$
$N(1680)\ 5/2^+$	$\Delta(1900)\ 1/2^-$
$N(1700)\ 3/2^-$	$\Delta(1905)\ 5/2^+$
$N(1710)\ 1/2^+$	$\Delta(1910)\ 1/2^+$
$N(1720)\ 3/2^+$	$\Delta(1920)\ 3/2^+$
$N(1860)\ 5/2^+$	$\Delta(1930)\ 5/2^-$
$N(1875)\ 3/2^-$	$\Delta(1940)\ 3/2^-$
$N(1880)\ 1/2^+$	$\Delta(1950)\ 7/2^+$
$N(1895)\ 1/2^-$	$\Delta(2000)\ 5/2^+$
$N(1900)\ 3/2^+$	
$N(1990)\ 7/2^+$	
$N(2000)\ 5/2^+$	

Improvement of binning schemes

arXiv:1912.10741

- Maximise the sensitivity of CPV with amplitude models

  G.Durieux, JHEP 10 (2016) 005

  G.Durieux, PRD 92 (2015) 076013

- Scheme A (new improved scheme)

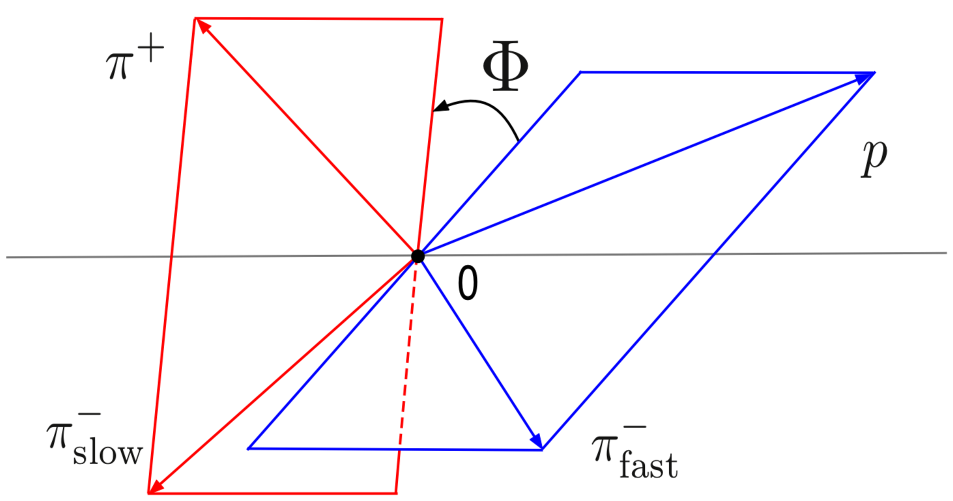
  16 bins

  in polar and azimuthal angles of proton(Δ^{++}) in the Δ^{++}(N^{*+}) rest frame

- Scheme B, as previous measurement

  10 bins

  in $|\Phi|$ angle between decay planes $\pi^+\pi^-_{\text{slow}}$ and $p\pi^-_{\text{fast}}$



TPA results

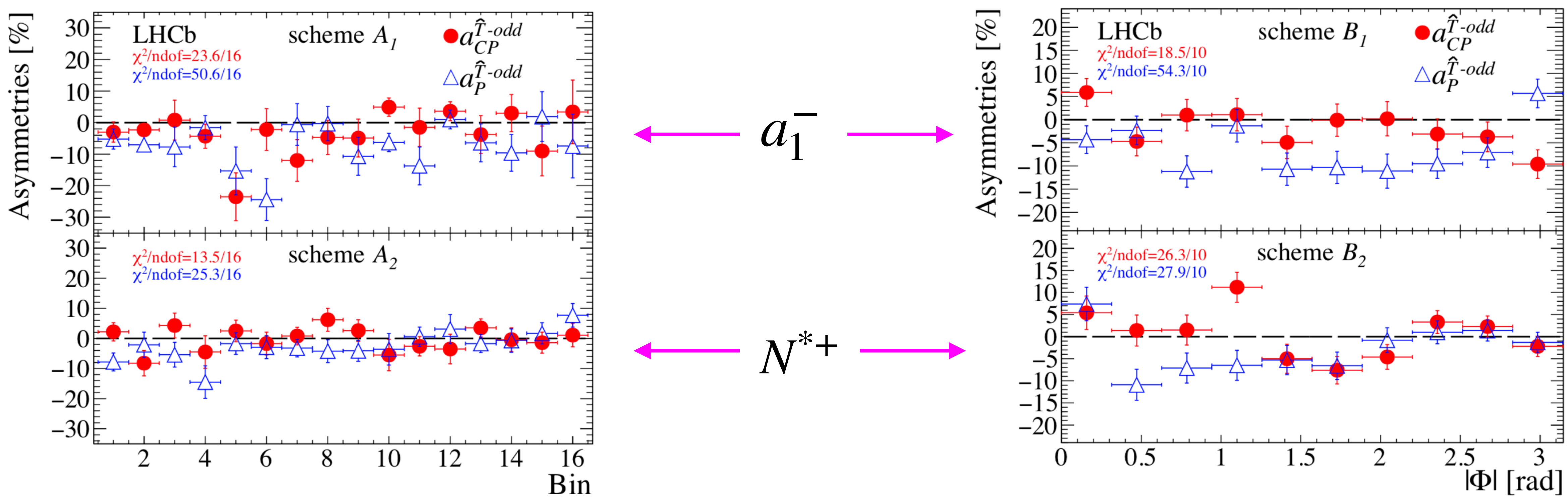
arXiv:1912.10741

- PHSP integrated measurement:

$a_{CP}^{\hat{T}\text{-odd}} = (-0.7 \pm 0.7 \pm 0.2)\,\%$ — consistent with CP symmetry

$a_{P}^{\hat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\,\%$ — 5.5σ deviation from P symmetry

- Split two samples: 1, $a_1(1260)^-$ dominated; 2, multiple N^{*+} dominated



No evidence for CPV, highest significance 2.9σ in B2

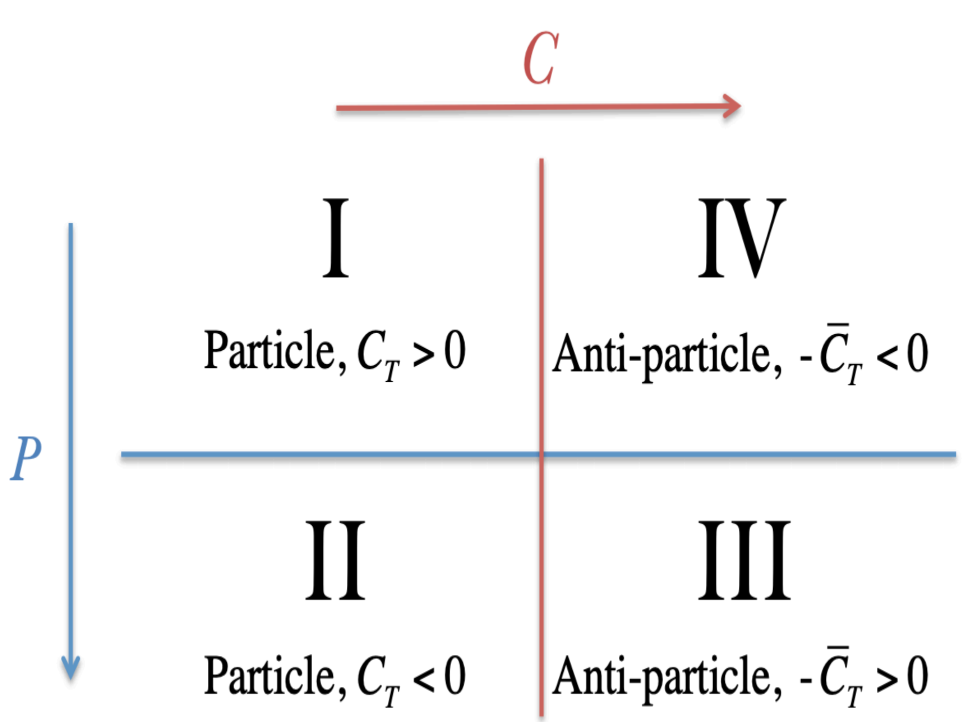
Energy test

- A model-independent unbinned test
- Sensitive to local differences between two samples

$$T \equiv \frac{1}{2n(n-1)}\sum_{i\neq j}^{n}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\sum_{i\neq j}^{\bar{n}}\psi_{ij} - \frac{1}{n\bar{n}}\sum_{i=1}^{n}\sum_{j=1}^{\bar{n}}\psi_{ij}$$

$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, d_{ij} distance between two candidates

δ distance scale



- CP test

P-odd: I+IV v.s. II + III

P-even: I+II v.s. III + IV

- P test

I+III v.s. II+IV

Energy test

arXiv:1912.10741

- A model-independent unbinned test
- Sensitive to local differences between two samples

$$T \equiv \frac{1}{2n(n-1)}\sum_{i\neq j}^{n}\psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)}\sum_{i\neq j}^{\overline{n}}\psi_{ij} - \frac{1}{n\overline{n}}\sum_{i=1}^{n}\sum_{j=1}^{\overline{n}}\psi_{ij}$$

$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, d_{ij} distance between two candidates

δ distance scale

Distance scale δ	$1.6\ \mathrm{GeV}^2/c^4$	$2.7\ \mathrm{GeV}^2/c^4$	$13\ \mathrm{GeV}^2/c^4$
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

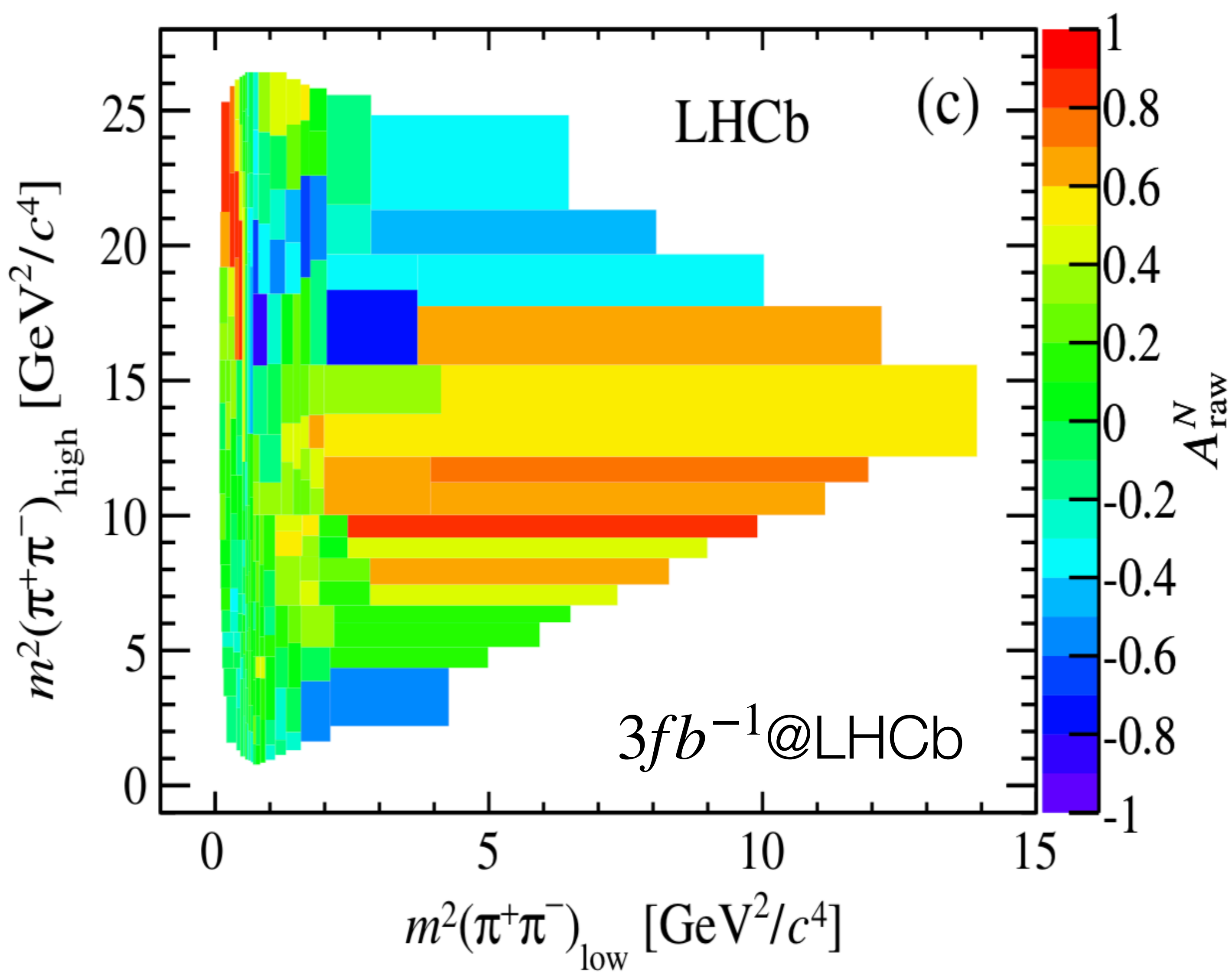
CP test: highest significance 3.0σ, combined P even $<3\sigma$

P test: combined 5.3σ

Previous measurement in $B^+ \to \pi^+\pi^+\pi^-$ decays

PRD 90 (2014) 112004

- Raw asymmetries localised in regions of Dalitz plot were observed



asymmetries may come from:

low mass s-wave contribution and $\rho(770)^0$ interference

$\rho(770)^0$ and $\omega(782)$ mixing

$\pi\pi \leftrightarrow KK$ rescattering

- Amplitude analysis is needed

Amplitude analysis for CPV

PRL 124 (2020) 031801
PRD 101 (2020) 012006

- Amplitude with CPV

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

$c_j^\pm = (x_j \pm \Delta x_j) + i(y_j \pm \Delta y_j)$: complex coefficients. CP violating

F_j: strong dynamics. CP conserving

Three different methods to describe S-wave: Isobar model, K-matrix, quasi model independent approach (QMI)

- Observables

$$\mathcal{A}_{CP}^j = \frac{|c_j^-|^2 - |c_j^+|^2}{|c_j^-|^2 + |c_j^+|^2} \qquad \mathcal{F}_j = \frac{\int_{\mathrm{DP}} (|A_j^+(m_{13}^2, m_{23}^2)|^2 + |A_j^-(m_{13}^2, m_{23}^2)|^2) \mathrm{d}m_{13}^2 \mathrm{d}m_{23}^2}{\int_{\mathrm{DP}} (|A^+(m_{13}^2, m_{23}^2)|^2 + |A^-(m_{13}^2, m_{23}^2)|^2) \mathrm{d}m_{13}^2 \mathrm{d}m_{23}^2}$$

Dalitz plots

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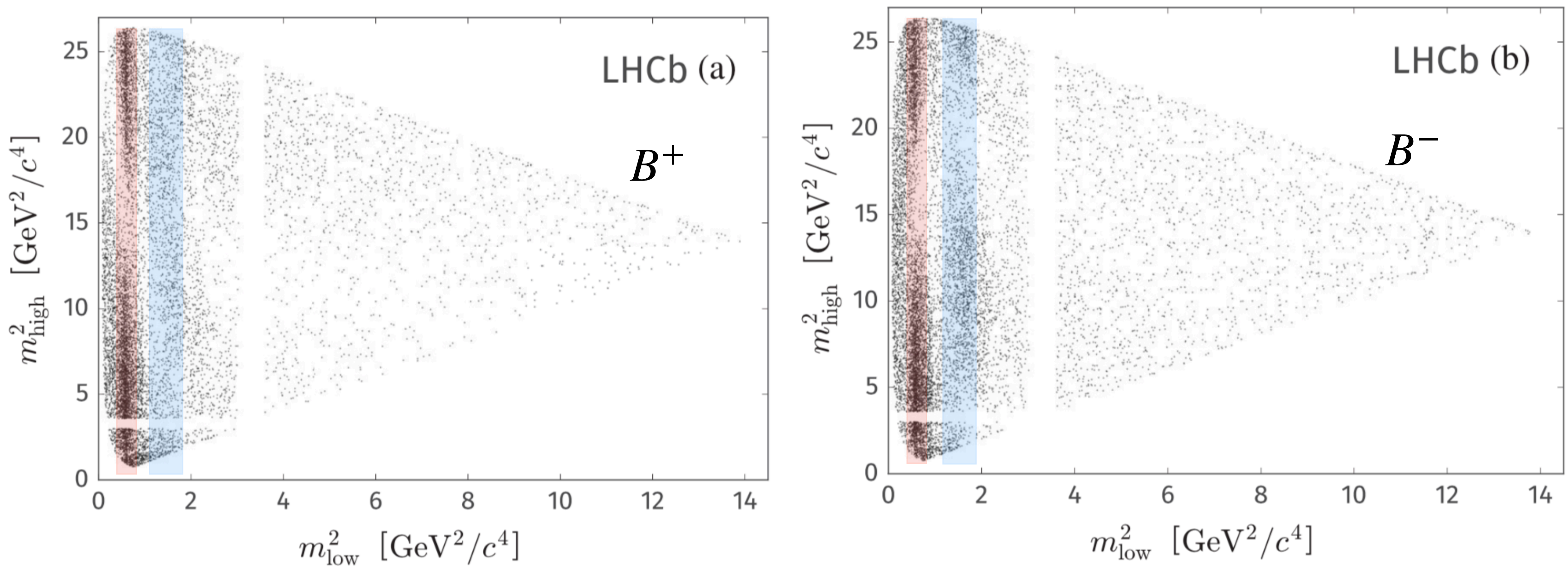
- Signal yields 20600 ± 1600 with $3fb^{-1}$



- Rich phase space structures

$f_0(500)$ $\rho(770)^0$, $f_2(1270)$

$\pi\pi \leftrightarrow KK$ rescattering in $1.0 < m_{\pi\pi} < 1.5GeV$

Numerical results

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- $\mathcal{F}_j$ in %: dominant contributions from $\rho(770)^0$ and S-wave

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	$25.4 \pm 0.5 \pm 0.5 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

- $\mathcal{A}_{CP}^j$ in %: large CPV from $f_2(1270)$ and S-wave, but no asymmetries from $\rho(770)^0$

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	$+14.4 \pm 1.8 \pm 1.0 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

New CPV pattern $\rho(770)^0$

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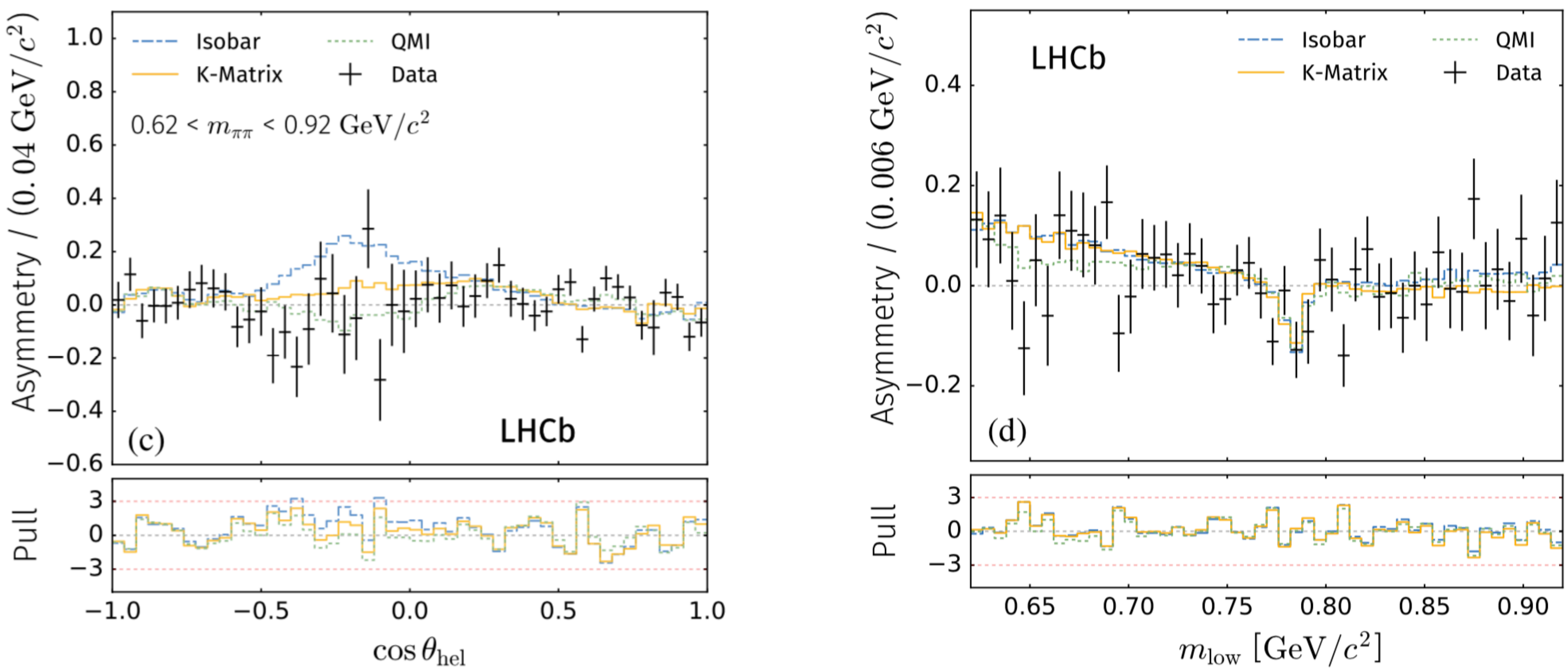
- Very small asymmetries in mass and helicity angle distributions



New CPV pattern $\rho(770)^0$

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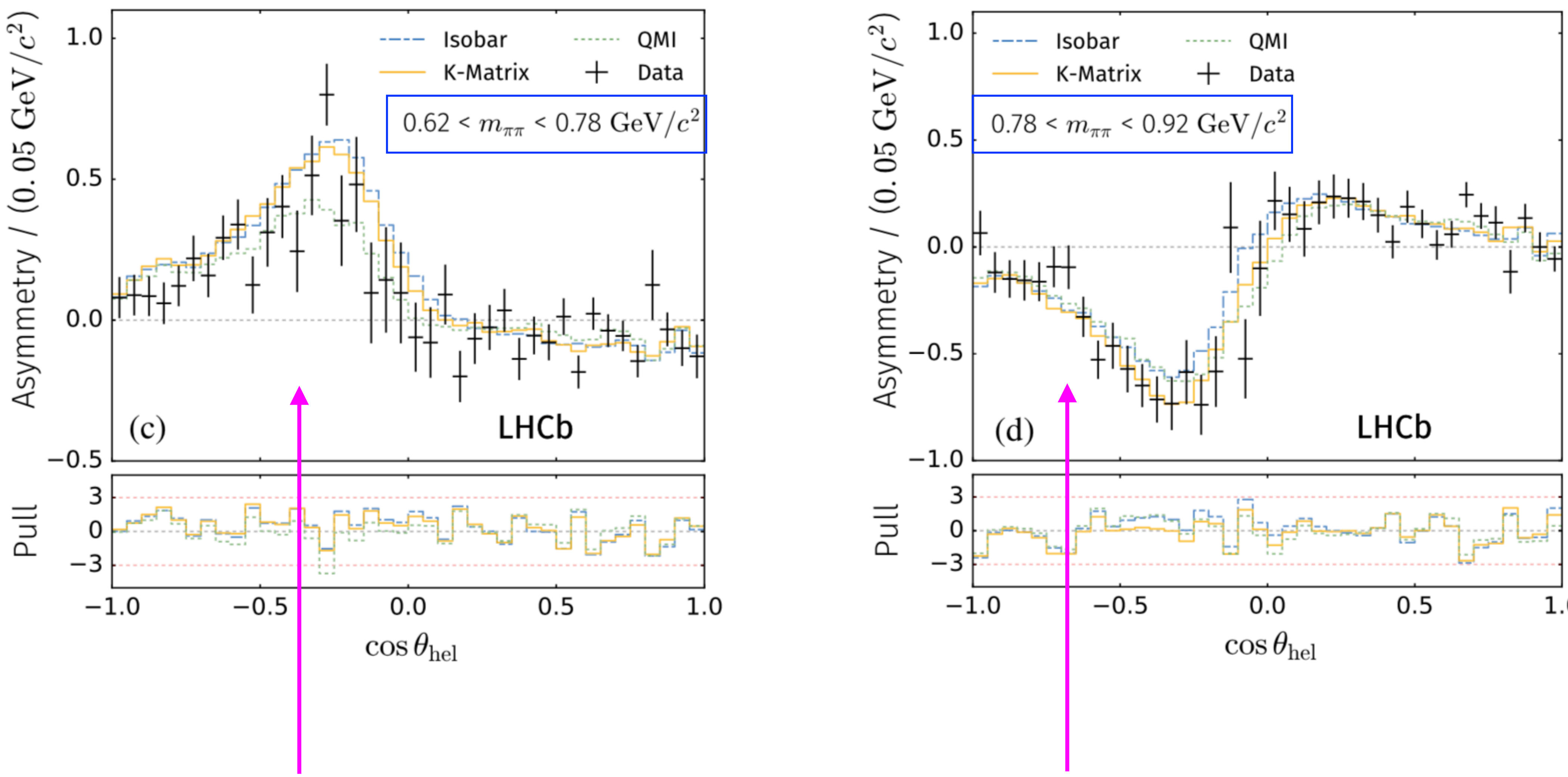
- But large asymmetries below and above $\rho(770)^0$ mass



asymmetries change sign cross $\rho(770)^0$ mass

perfect cancellation

New CPV pattern $\rho(770)^0$

PRL 124 (2020) 031801
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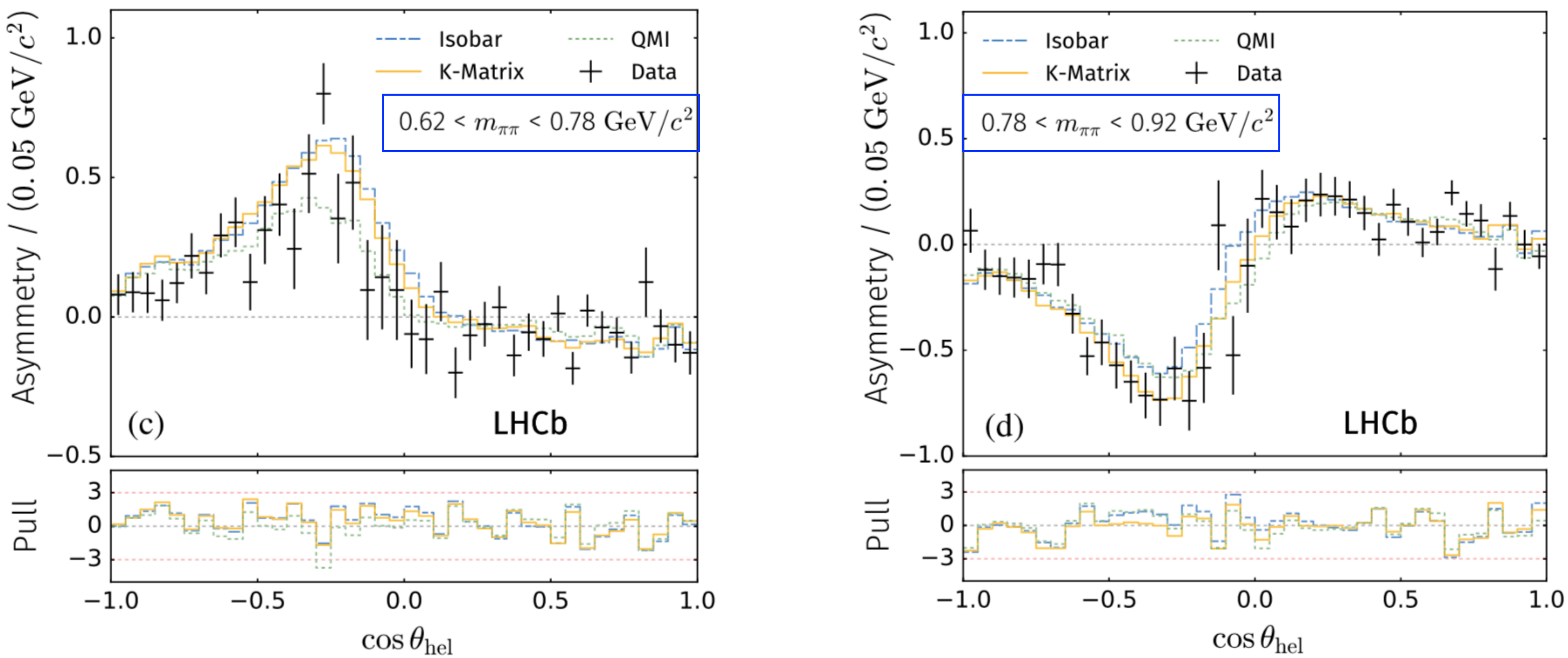
- But large asymmetries below and above $\rho(770)^0$ mass

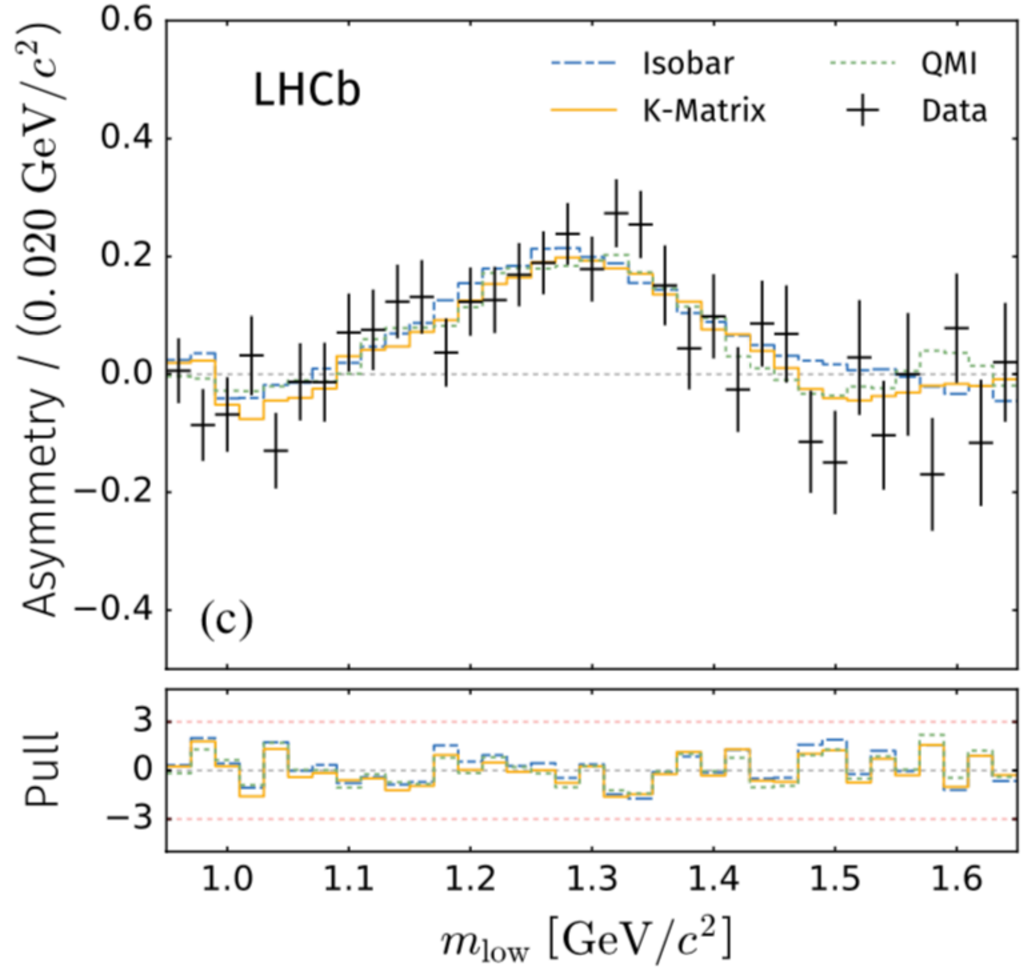


- Characteristic pattern due to S- and P- wave interference
- Interference term proportional to $\cos\theta_{hel}$

CPV in $f_2(1270)$

PRL 124 (2020) 031801
PRD 101 (2020) 012006

- First observation for CPV in process involving a tensor
- A very large CP asymmetry of ~40%
- Robust to systematic effects



S-wave results

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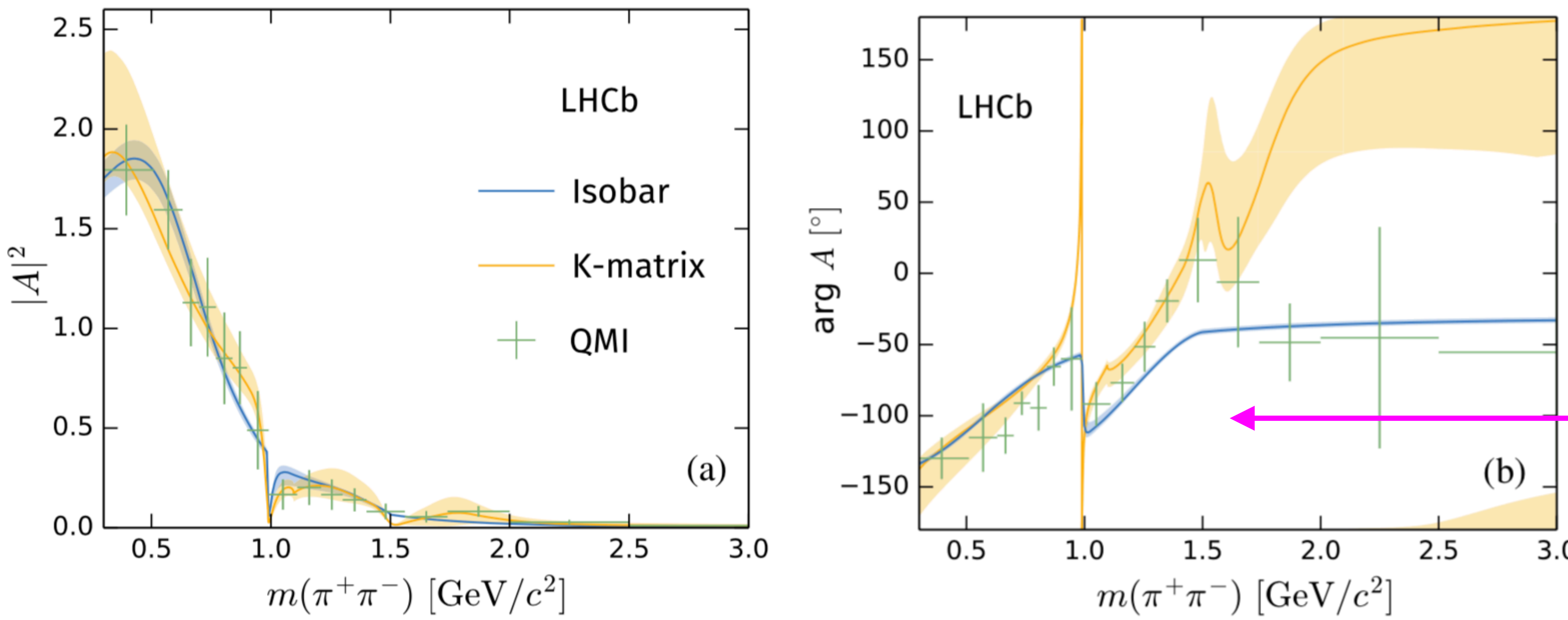
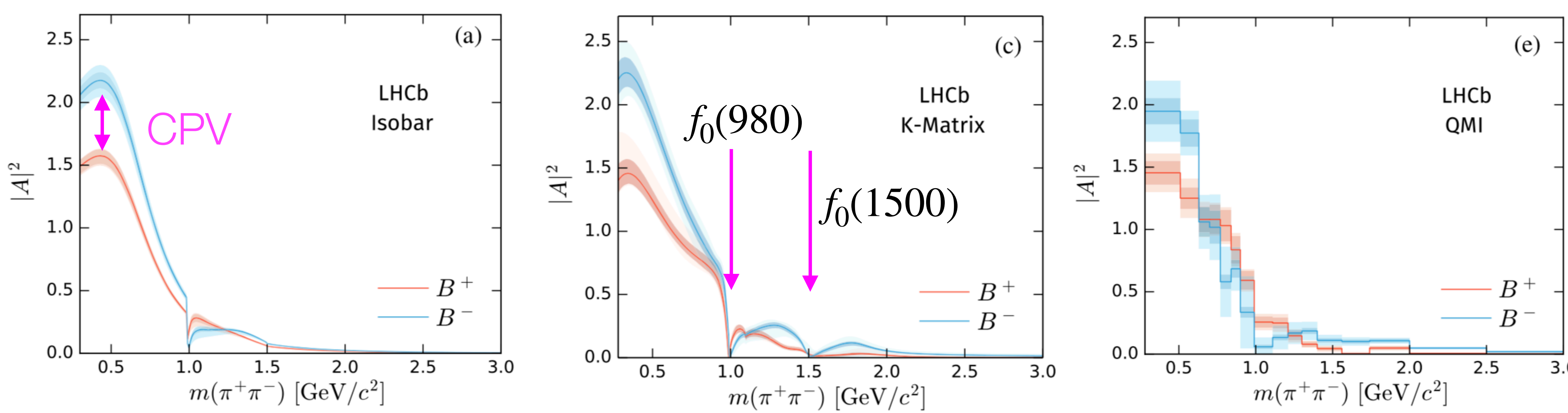
- Good agreement between three approaches



no $f_0(1500)$ in isobar model

- Similar CPV pattern for the three approaches



Summary

- Multibody decays are an interesting place to search for CPV

  rich phase space structures would improve sensitivity

- Parity violation observed in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays, but no evidence for CPV

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

  new CPV pattern of $\rho(770)^0$

  CPV in process with $f_2(1270)$

  CPV in S-wave in low mass region

Thank you!

BACK UP