Recent CPV measurements at LHCb

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第十九届重味物理和CP破坏研讨会
2022年12月9-11日

Outline

- Introduction
- CPV in charmless B decays
- Measurements of γ angle (backup) 张舒楠的报告
- CPV in charm

CP violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM mixing matrix

- **Origin of CPV in SM: nonzero CKM weak phase** ($\eta \neq 0$ in Wolfenstein parameterization)

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \boxed{A\lambda^3(\rho - i\eta)} \\ \boxed{-\lambda - iA^2\lambda^5\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \boxed{A\lambda^3(1-\hat{\rho}-i\hat{\eta})} & \boxed{-A\lambda^2 - iA\lambda^4\eta} & 1 \end{pmatrix}$$

CPV in charm

$|V_{td}|e^{-i\beta}$
CPV in B^0

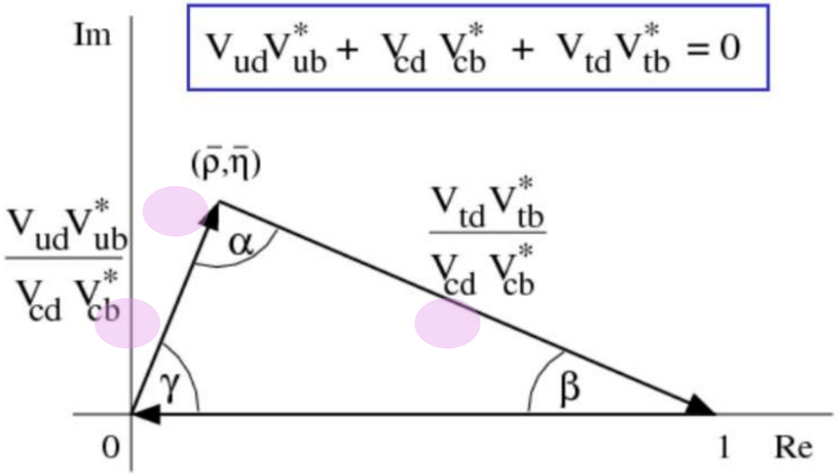
$-|V_{ts}|e^{i\beta_s}$
CPV in B_s^0

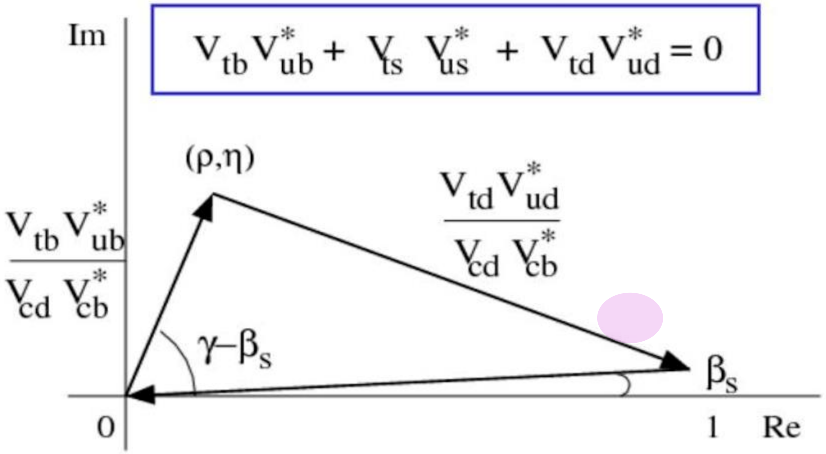
$|V_{ub}|e^{-i\gamma}$
CPV in $B \to DK$

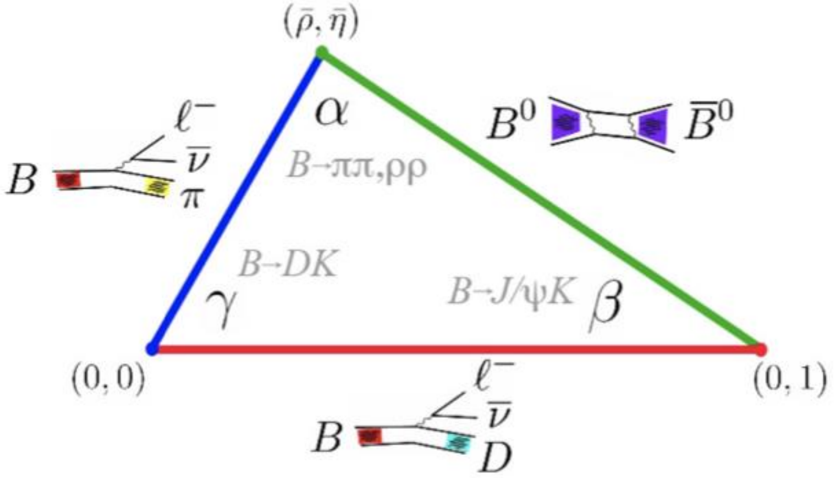
- **CPV provided by the SM is short by 10^{10} to explain the Baryon Asymmetry in the Universe**

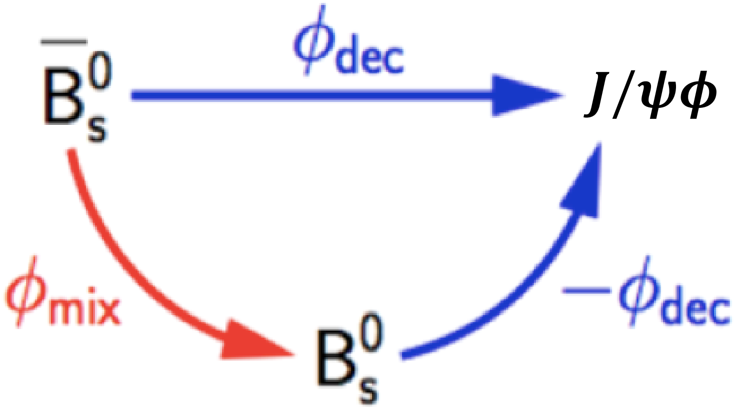
Unitarity triangles

- **Test unitarity by measuring sides (rates, B_q^0 mixing) and angles (CP asymmetries)**



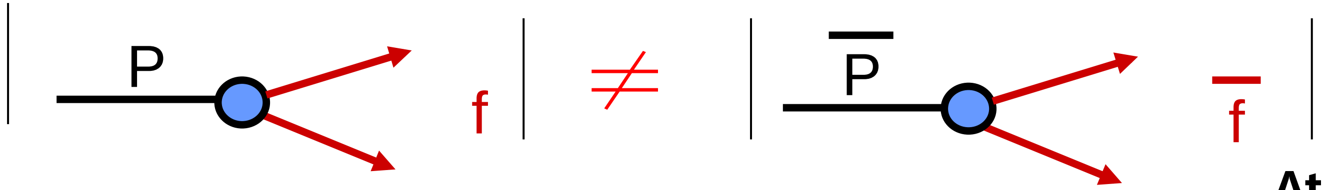






Three types of CPV

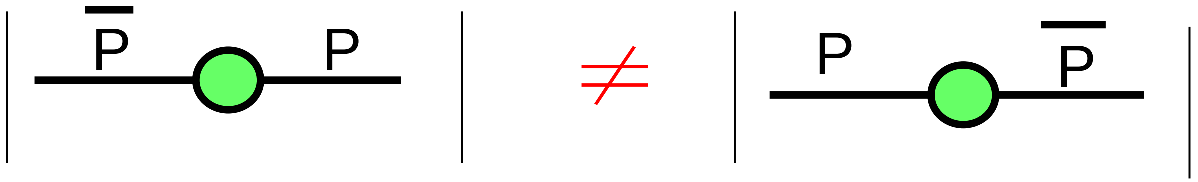
~~CP~~ in decay



$$\left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| = \left|\frac{\sum_i A_i e^{i\varphi_i} e^{i\delta_i}}{\sum_i A_i e^{-i\varphi_i} e^{i\delta_i}}\right| \neq 1$$

At least two interfering amplitudes with different strong and different weak phases

~~CP~~ in mixing (“indirect ~~CP~~”)

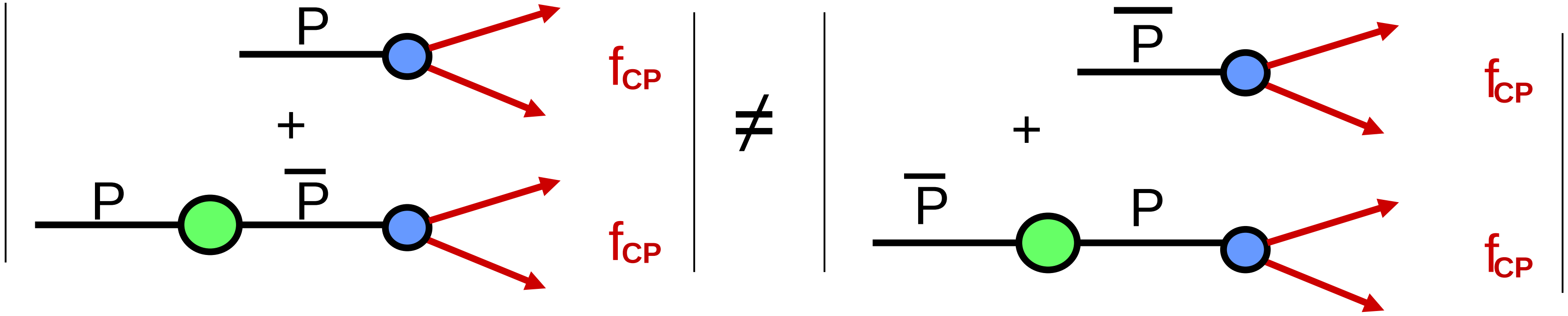


$$|P_1\rangle = p|P^o\rangle + q|\bar{P}^o\rangle$$

$$|P_2\rangle = p|P^o\rangle - q|\bar{P}^o\rangle$$

$|q/p|2$
$\neq 1$

~~CP~~ in interference between mixing and decay (“Mixing induced ~~CP~~”)



Different weak phases in mixing and decay

CPV in charmless B decays

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \boxed{A\lambda^3(\rho - i\eta)} \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \boxed{A\lambda^3(1-\hat{\rho}-i\hat{\eta})} & \boxed{-A\lambda^2 - iA\lambda^4\eta} & 1 \end{pmatrix}$$

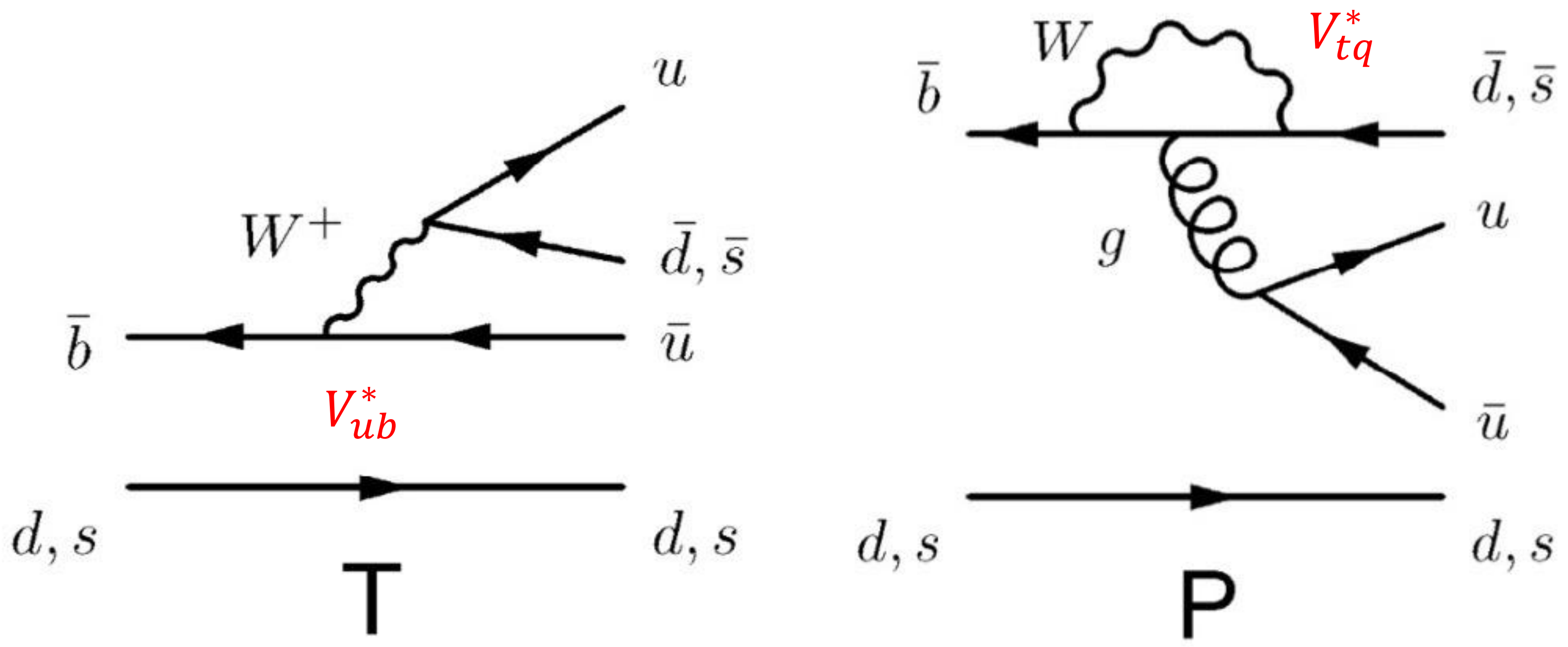
$|V_{ub}|e^{-i\gamma}$

$|V_{td}|e^{-i\beta}$

$-|V_{ts}|e^{i\beta_s}$

Charmless B decays

- Mediated by $b \to u$ tree and $b \to d(s)$ penguin diagrams with **comparable magnitude** and **large weak phases**
- Expecting direct CPV



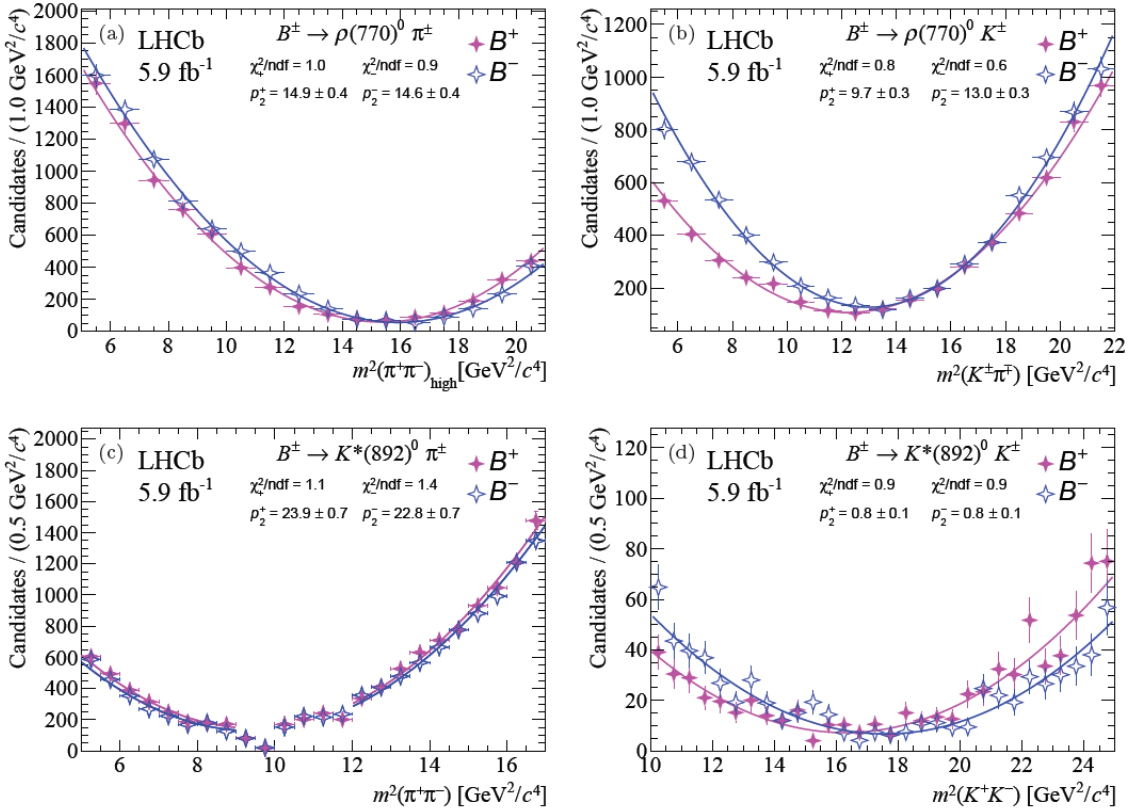
$B \to PV$ decays with Run 2 data

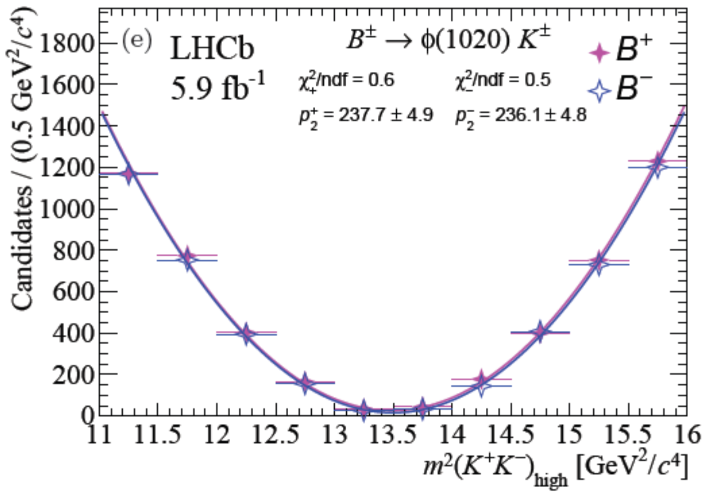
- **Quasi-two-body $B \to PV$ decays: $B^{\pm} \to R(\to h_1^- h_2^+) h_3^{\pm}$**

Phys. Rev. D94 (2016) 054028

- **A new method: resonances with masses below or around 1 GeV/c^2**

	$B^{\pm} \to K^{\pm}\pi^+\pi^-$	$B^{\pm} \to K^{\pm}K^+K^-$	$B^{\pm} \to \pi^{\pm}\pi^+\pi^-$	$B^{\pm} \to \pi^{\pm}K^+K^-$
B^-	243 960	159 673	51 977	17 161
B^+	240 884	176 345	44 389	21 178
Purity	0.91	0.96	0.88	0.76





arXiv:2206.02038

$B \to PV$ decays with Run 2 data

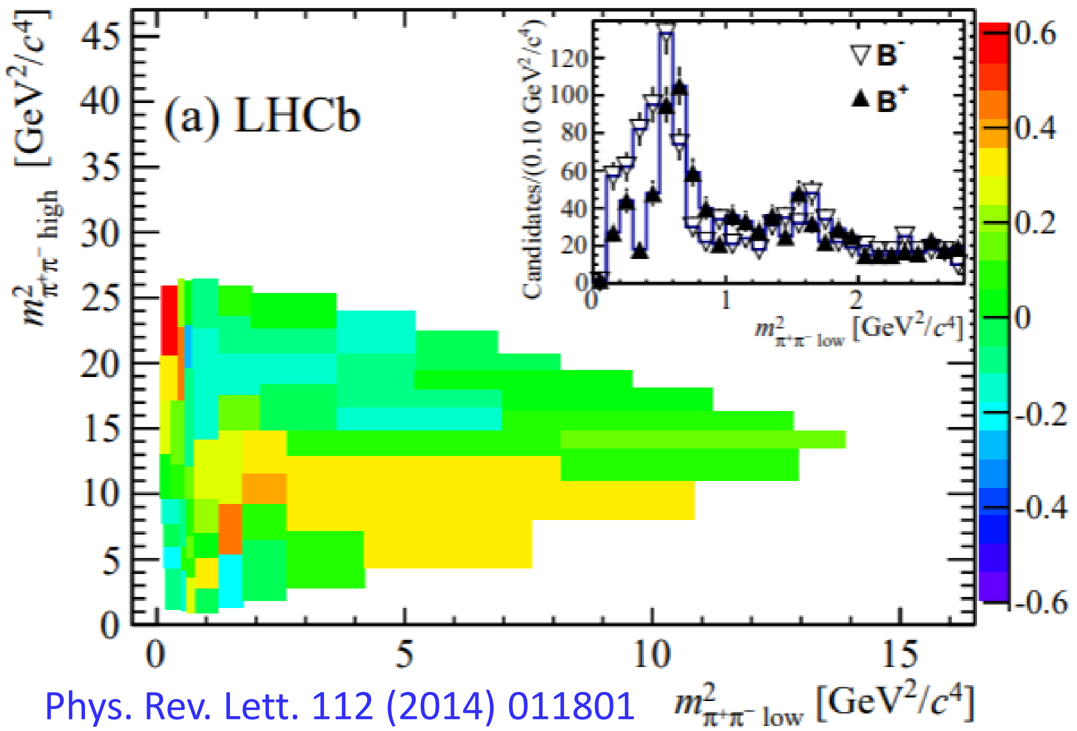
Decay channel	This work	Previous measurements
$B^\pm \to (\rho(770)^0 \to \pi^+\pi^-)\pi^\pm$	$-0.004 \pm 0.017 \pm 0.009$	$+0.007 \pm 0.011 \pm 0.016$ (LHCb [20, 21])
$B^\pm \to (\rho(770)^0 \to \pi^+\pi^-)K^\pm$	$+0.150 \pm 0.019 \pm 0.011$	$+0.44 \pm 0.10 \pm 0.04$ (BaBar [28]) $+0.30 \pm 0.11 \pm 0.02$ (Belle [22])
$B^\pm \to (\overset{(-)}{K}{}^*(892)^0 \to K^\pm\pi^\mp)\pi^\pm$	$-0.015 \pm 0.021 \pm 0.012$	$+0.032 \pm 0.052 \pm 0.011$ (BaBar [28]) $-0.149 \pm 0.064 \pm 0.020$ (Belle [22])
$B^\pm \to (\overset{(-)}{K}{}^*(892)^0 \to K^\pm\pi^\mp)K^\pm$	$+0.007 \pm 0.054 \pm 0.032$	$+0.123 \pm 0.087 \pm 0.045$ (LHCb [19])
$B^\pm \to (\phi(1020) \to K^+K^-)K^\pm$	$+0.004 \pm 0.014 \pm 0.007$	$+0.128 \pm 0.044 \pm 0.013$ (BaBar [26])

arXiv:2206.02038

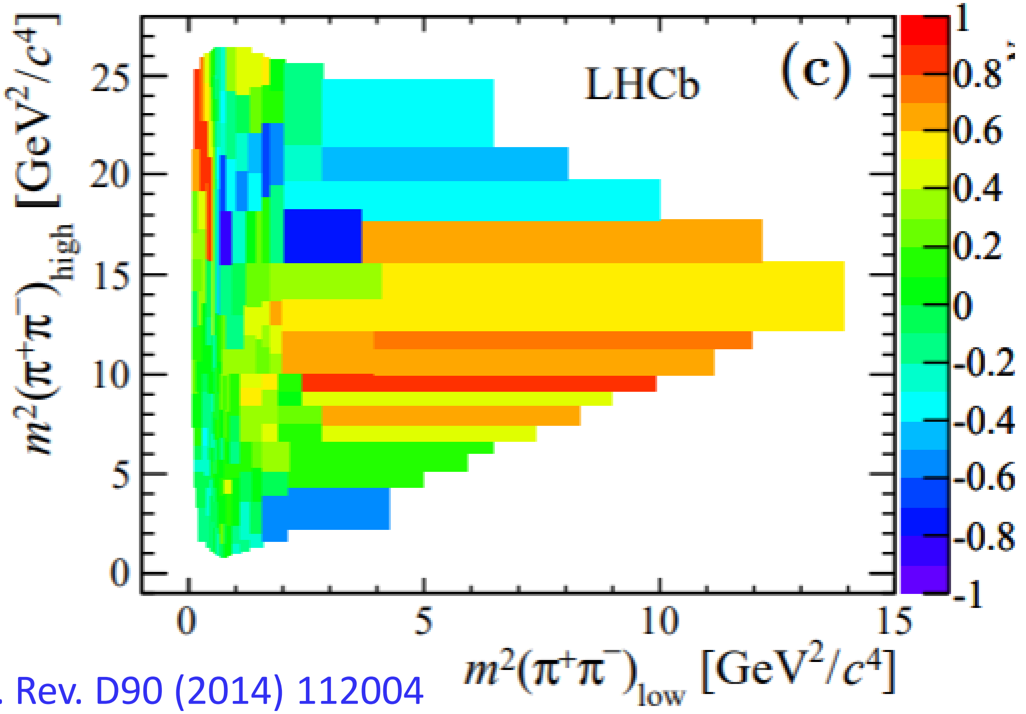
- **A new method, without the need for amplitude analyses**
- **For $B^\pm \to \rho(770)K^\pm$: 6.8σ differs from 0**
- **For the other channels, $A_{CP} \approx 0$ (CPT symmetry)**
- **More precise than the previous results**

Three-body charmless B decay

- Localised A_{CP} in $B \to 3\pi,\ 3K, KK\pi, K\pi\pi$



Phys. Rev. Lett. 112 (2014) 011801

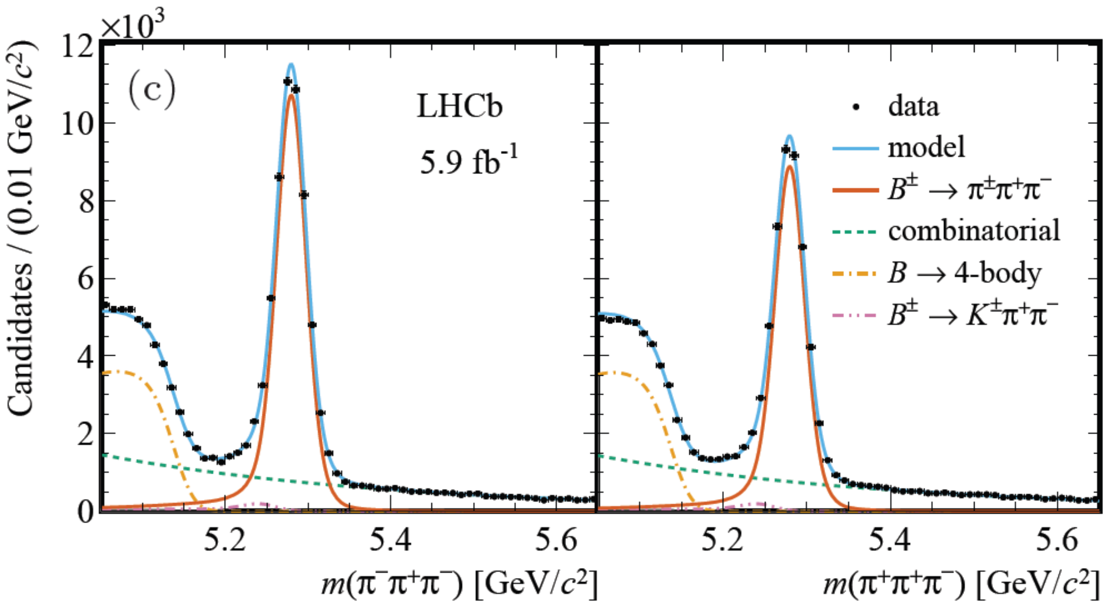


Phys. Rev. D90 (2014) 112004

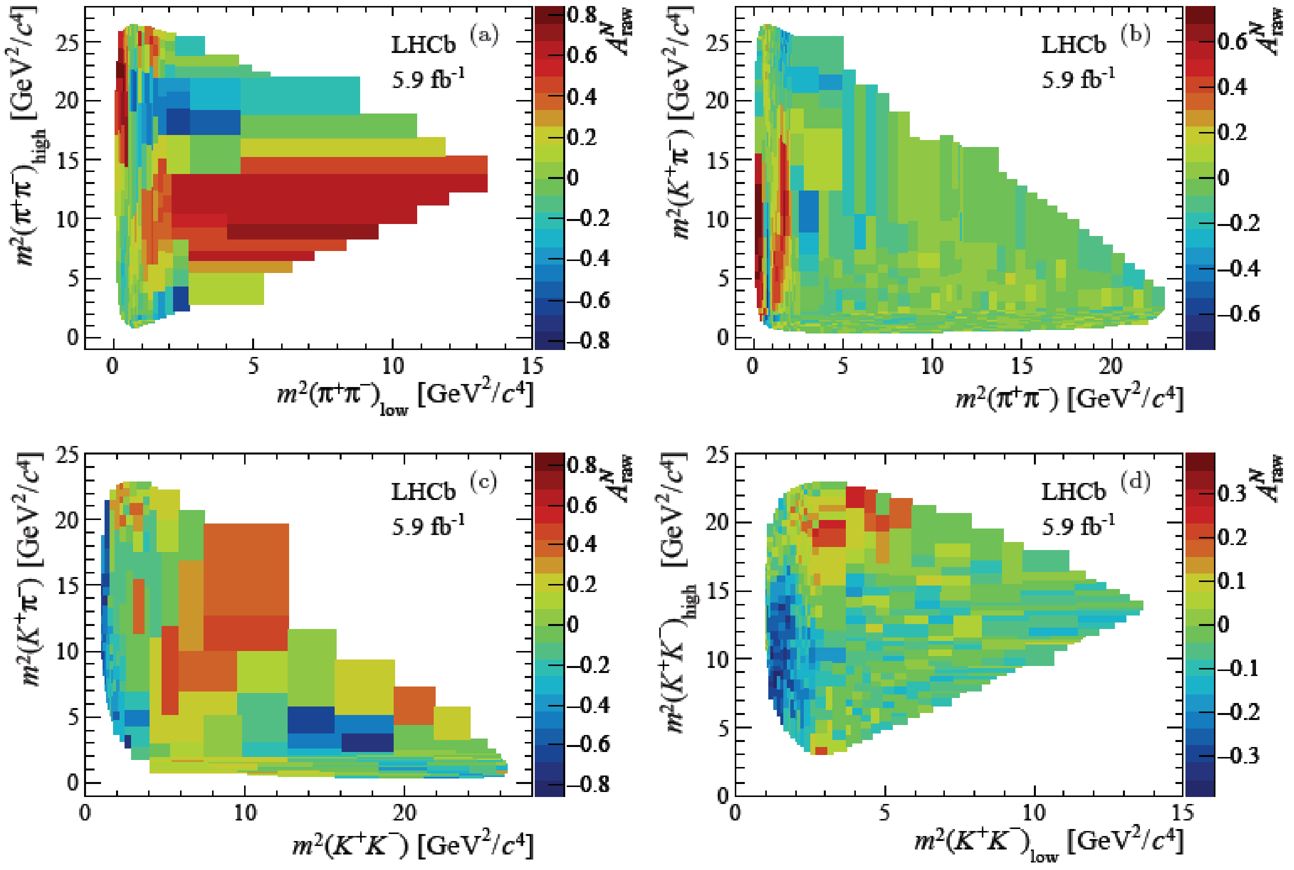
Prog. Part. Nucl. Phys. 114 (2020) 103808

- Originating from long-distance hadronic interactions
  - ☐ $f_0(500) - \rho(770)$ arXiv:2209.02348 Phys. Rev. D 105, 093007(2022)
  - ☐ $\pi\pi - KK$

Three-body charmless B decay with Run 2 data



$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003,$$
$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003,$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003,$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003,$$



- **Significant A_{CP}: $B \to 3\pi,\ 3K$ for the first time**

arXiv:2206.07622

- **Confirmed high localised A_{CP}**

Search for CPV using TPA

- Triple products in Λ_b rest frame
  $\hat{T}$ = motion reversal operator

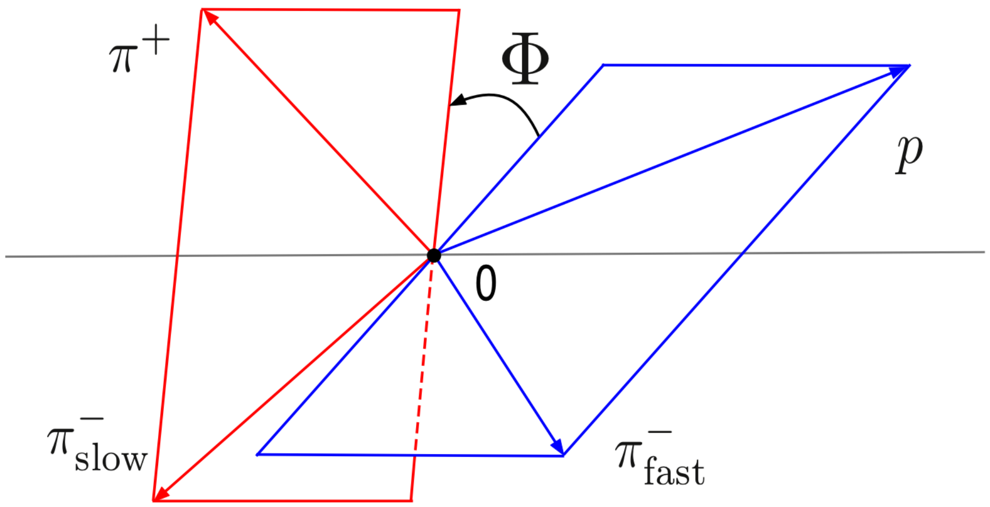
$$C_{\widehat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \quad \propto \sin\Phi$$

$$\overline{C}_{\widehat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \quad \propto \sin\overline{\Phi}$$

- $\hat{T}$ – odd asymmetries:

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

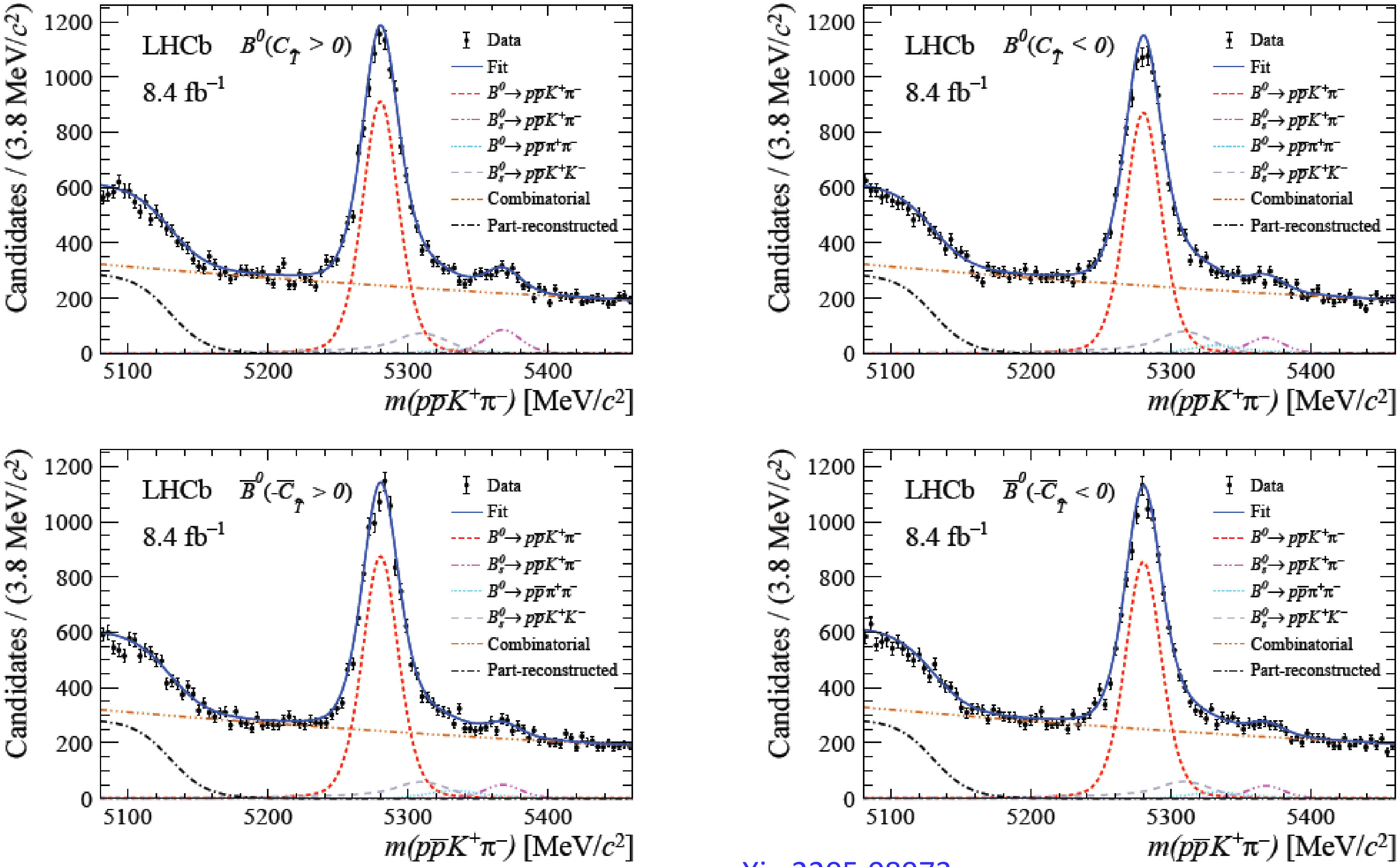
$$\overline{A}_{\widehat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\widehat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\widehat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\widehat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\widehat{T}} < 0)}$$



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

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

CPV in $B^0 \to p\bar{p}K^+\pi^-$ with Run 1&2

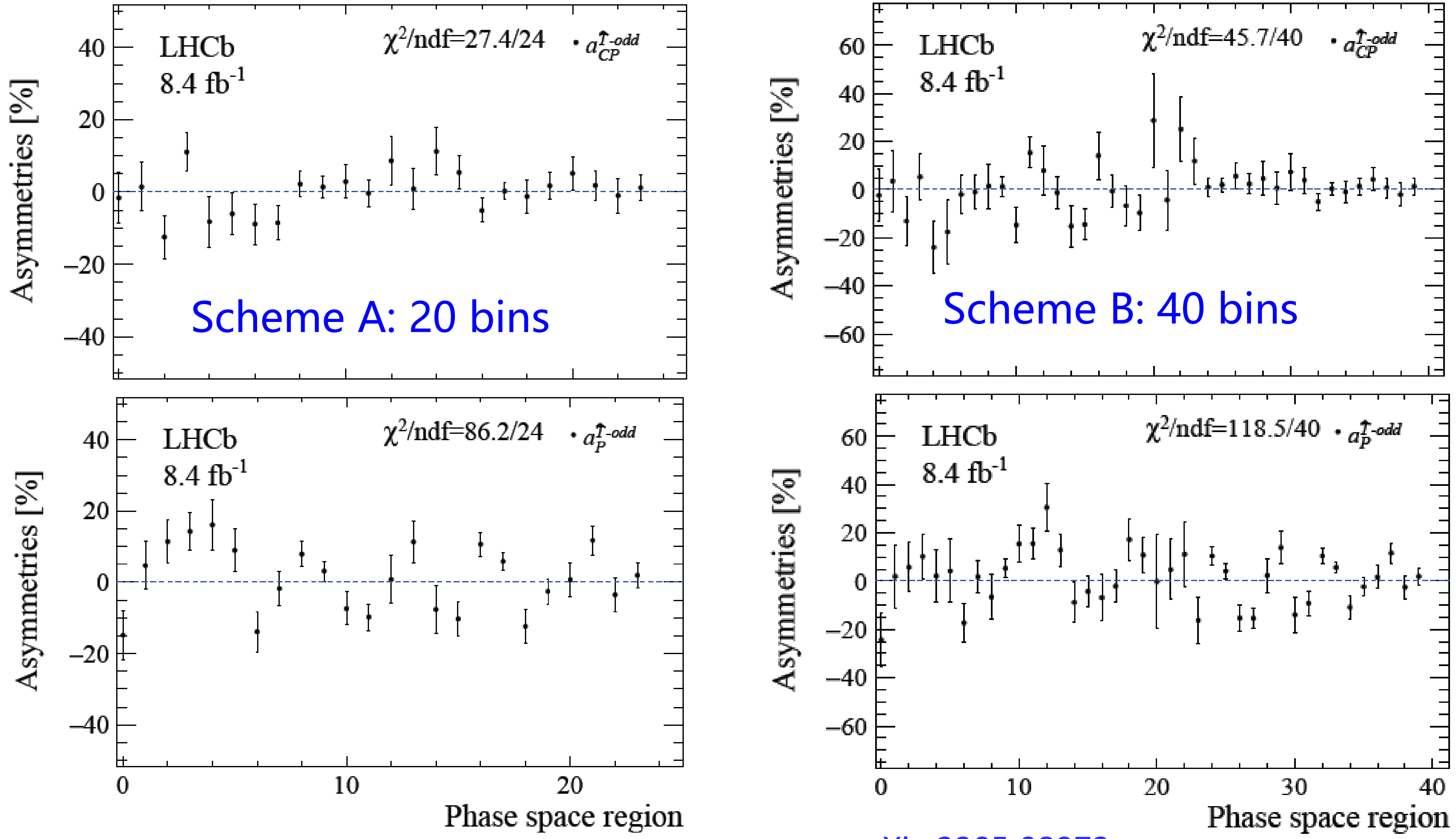


$$a_P^{\hat{T}\text{-odd}} = (1.49 \pm 0.85 \pm 0.08)\%,$$
$$a_{CP}^{\hat{T}\text{-odd}} = (0.51 \pm 0.85 \pm 0.08)\%,$$

arXiv:2205.08973

Measurement asymmetries in phase space regions

➢ **Two different schemes to avoid possible biases**



arXiv:2205.08973

➢ **No CP and P-violation**

CPV in charm

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(\rho - i\eta\right) \\ \boxed{-\lambda - iA^2\lambda^5\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3\left(1-\hat{\rho}-i\hat{\eta}\right) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

CPV in charm decays, # events we need?

CPV in SM is small：			# events
B meson :	O(1)	discovered (2001)	10^3
K meson :	$O(10^{-3})$	discovered (1964)	10^6
D meson :	$O(10^{-4})$	discovered(2019)	10^8

- **First observation of CP violation in charm decays in 2019**

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4},$$ Phys. Rev. Lett. 122 (2019) 211803

- **Search new sources of CP violation beyond the SM in charm sector**

The time-integrated A_{CP} in $D^0 \to K^+K^-$ with Run 2 data

- The time-integrated A_{CP}

$$\mathcal{A}_{CP}(f) \equiv \frac{\int \mathrm{d}t\, \epsilon(t)\left[\Gamma(D^0 \to f)(t) - \Gamma(\overline{D}^0 \to f)(t)\right]}{\int \mathrm{d}t\, \epsilon(t)\left[\Gamma(D^0 \to f)(t) + \Gamma(\overline{D}^0 \to f)(t)\right]},$$

- D^0 from $D^{*+} \to D^0\pi^+$
- "tagging" pion to identify the flavor of the D^0

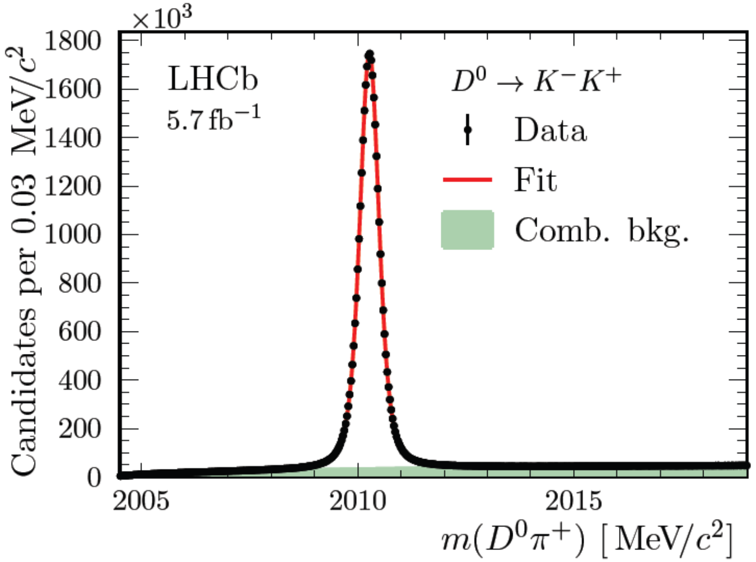
$$A(K^-K^+) \equiv \frac{N\left(D^{*+} \to D^0\pi^+\right) - N\left(D^{*-} \to \overline{D}^0\pi^-\right)}{N\left(D^{*+} \to D^0\pi^+\right) + N\left(D^{*-} \to \overline{D}^0\pi^-\right)},$$

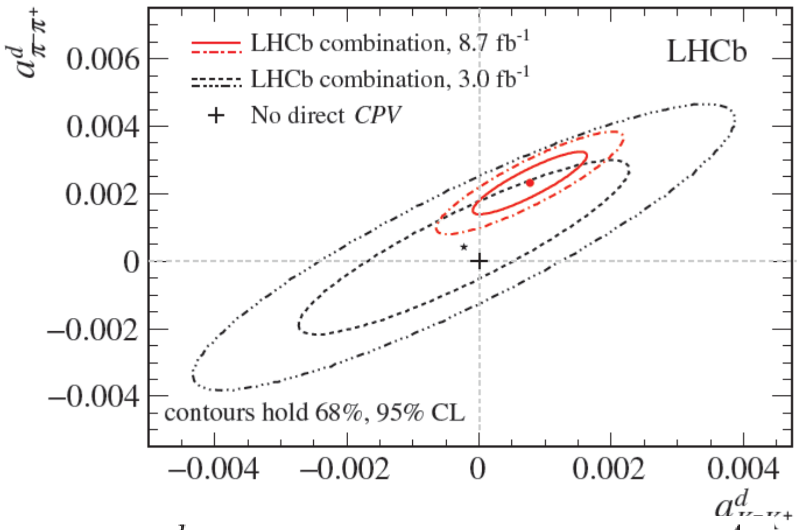
$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_{\mathrm{P}}(D^{*+}) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}}),$$

- D^+ and D_s^+ to get $A_P(D^{*+}) \to \mathcal{O}(10^{-6})$

$$\mathrm{C}_{D^+}: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0),$$
$$\mathrm{C}_{D_s^+}: \mathcal{A}_{CP}(K^-K^+) = A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0).$$

The time-integrated A_{CP} in $D^0 \to K^+K^-$ with Run 2 data

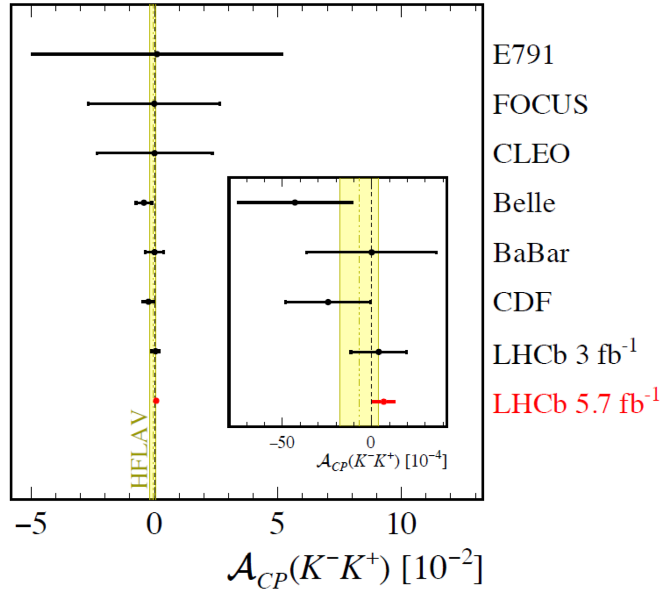




arXiv:2209.03179

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$

$$\mathrm{C}_{D^+}: \ \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4},$$
$$\mathrm{C}_{D_s^+}: \ \mathcal{A}_{CP}(K^-K^+) = [\ 2.8 \pm 6.7\,(\text{stat}) \pm 2.0\,(\text{syst})] \times 10^{-4},$$
$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4},$$



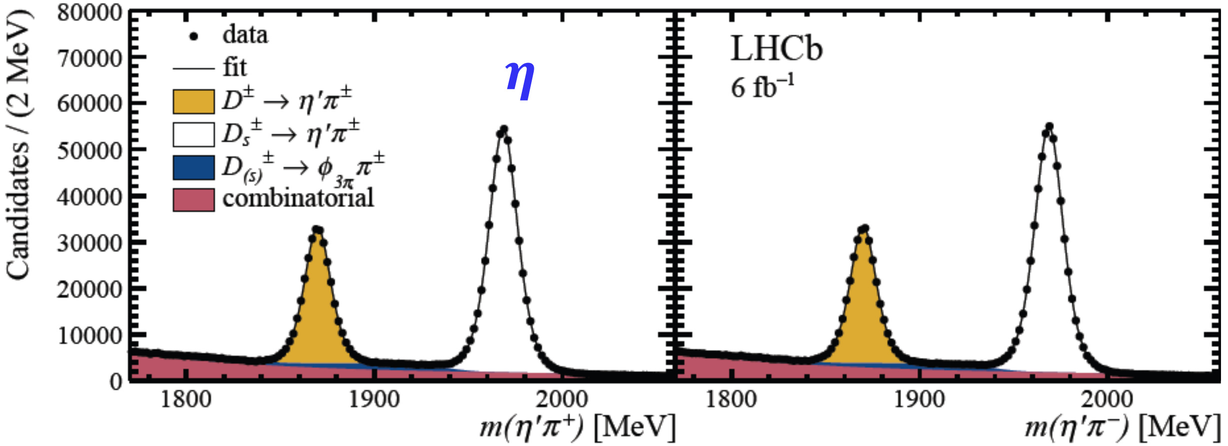
- **1.4σ for $D^0 \to K^+K^-$ and 3.8σ for $D^0 \to \pi^+\pi^-$**
- **The first evidence for direct CPV in a specific D^0 decay.**

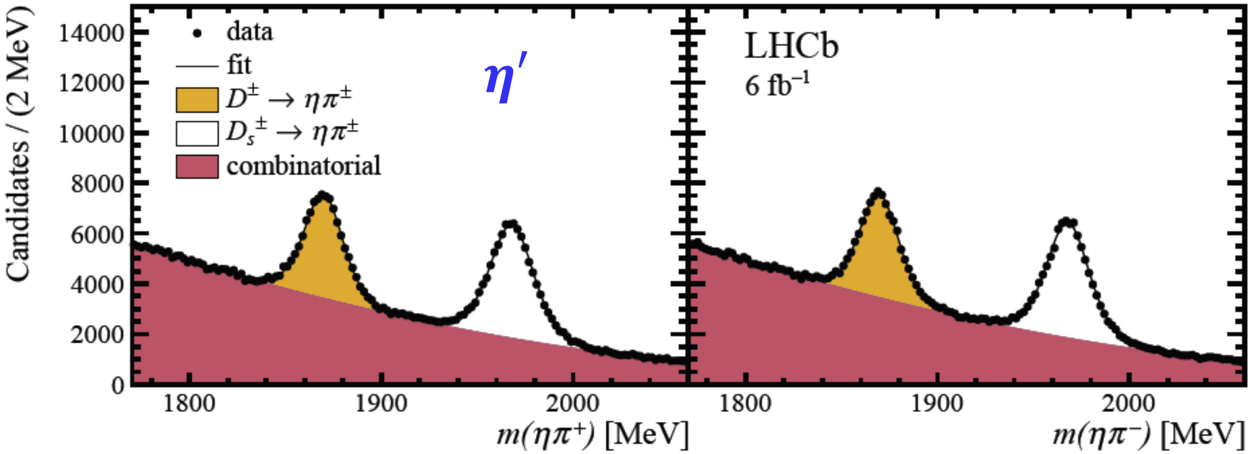
Measurement of A_{CP} in $D^+_{(s)} \to \eta(\eta')\pi^+$ with Run 2 data

$$\mathcal{A}^{\rm raw}(D^+_{(s)} \to f^+) \equiv \frac{N(D^+_{(s)} \to f^+) - N(D^-_{(s)} \to f^-)}{N(D^+_{(s)} \to f^+) + N(D^-_{(s)} \to f^-)}. \qquad \mathcal{A}^{\rm raw}(D^+_{(s)} \to f^+) \approx \mathcal{A}^{CP}(D^+_{(s)} \to f^+) + \mathcal{A}^{\rm prod}(D^+_{(s)}) + \mathcal{A}^{\rm det}(f^+),$$

- $D^+_{(s)} \to \phi\pi^+$ **to get** $A_P(D^+_{(s)})$

arXiv:2204.12228





$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%,$$

- **Consistent with the absence of CPV**
- **The most precise to date for these decays**

Summary and prospects

- **There is no sign of CP violation beyond the SM source yet**
  - Charmless B decays: two-body, three-body and four-body decay
  - Search CPV in charm: $D^0 \to K^+K^-$, $D^+_{(s)} \to \eta(\eta')\pi^+$
- **Opportunities with Run 3&4 (50 fb^{-1})**
  - Higher precision in benchmark measurements: $\gamma, \beta, \phi_s, \mathrm{A}_{\mathrm{CP}}$, ...
  - Wider scope for exploitation: CPV in baryon decays, CPV in rare decays,...

Backup

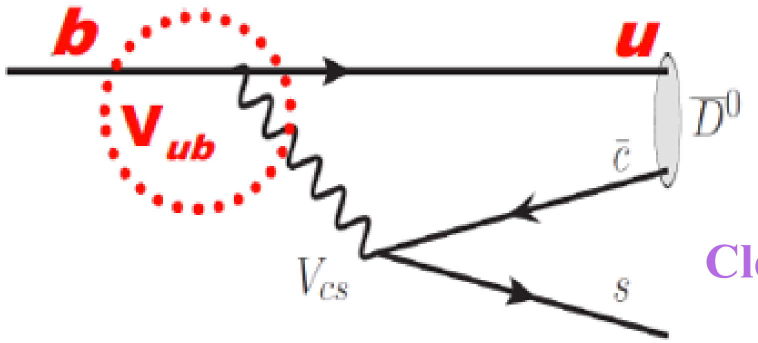
Measurements of γ angle

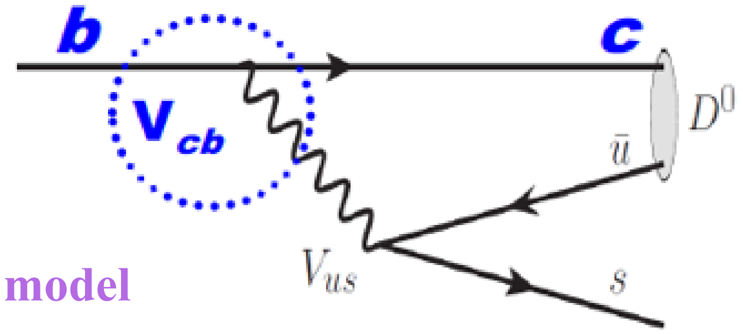
$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \boxed{A\lambda^3(\rho - i\eta)} \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

$|V_{ub}|e^{-i\gamma}$

How to measure γ angle

➢ **The least known CKM variable; Access via b→u and b→c interference**





Clean test of standard model

$$A(b \to u)/A(b \to c) = r_B e^{i\delta_B \pm \gamma}$$

➢ **Sensitive channels with small BFs: need to combine many channels**

GLW: D = CP eigenstates, e.g. KK, ππ

M. Gronau and D. Wyler, Phys. Lett. B 253 (1991) 483
M.Gronau and D. London, Phys. Lett. B 265 (1991) 172

ADS: D = quasi-flavour-specific states e.g. Kπ

D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. 78 (1997) 3257

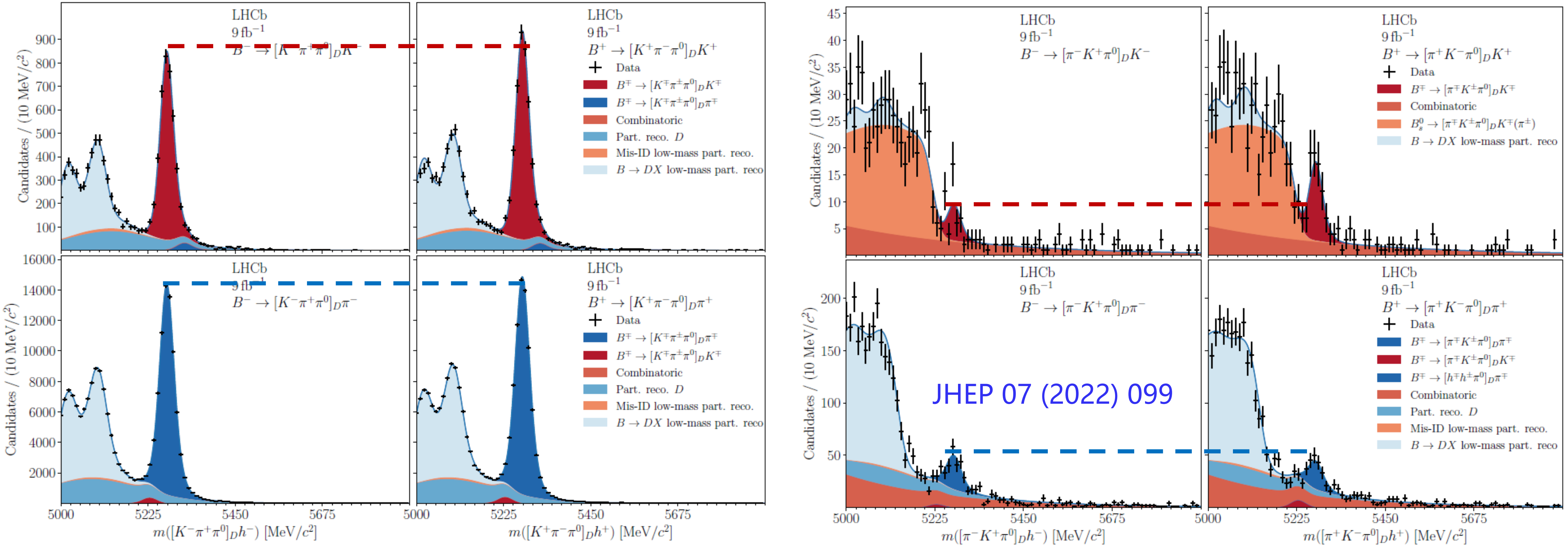
GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$

A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D68 (2003) 054018

GLS: ADS variant with singly Cabbibo-suppresed decay D→K_sKπ

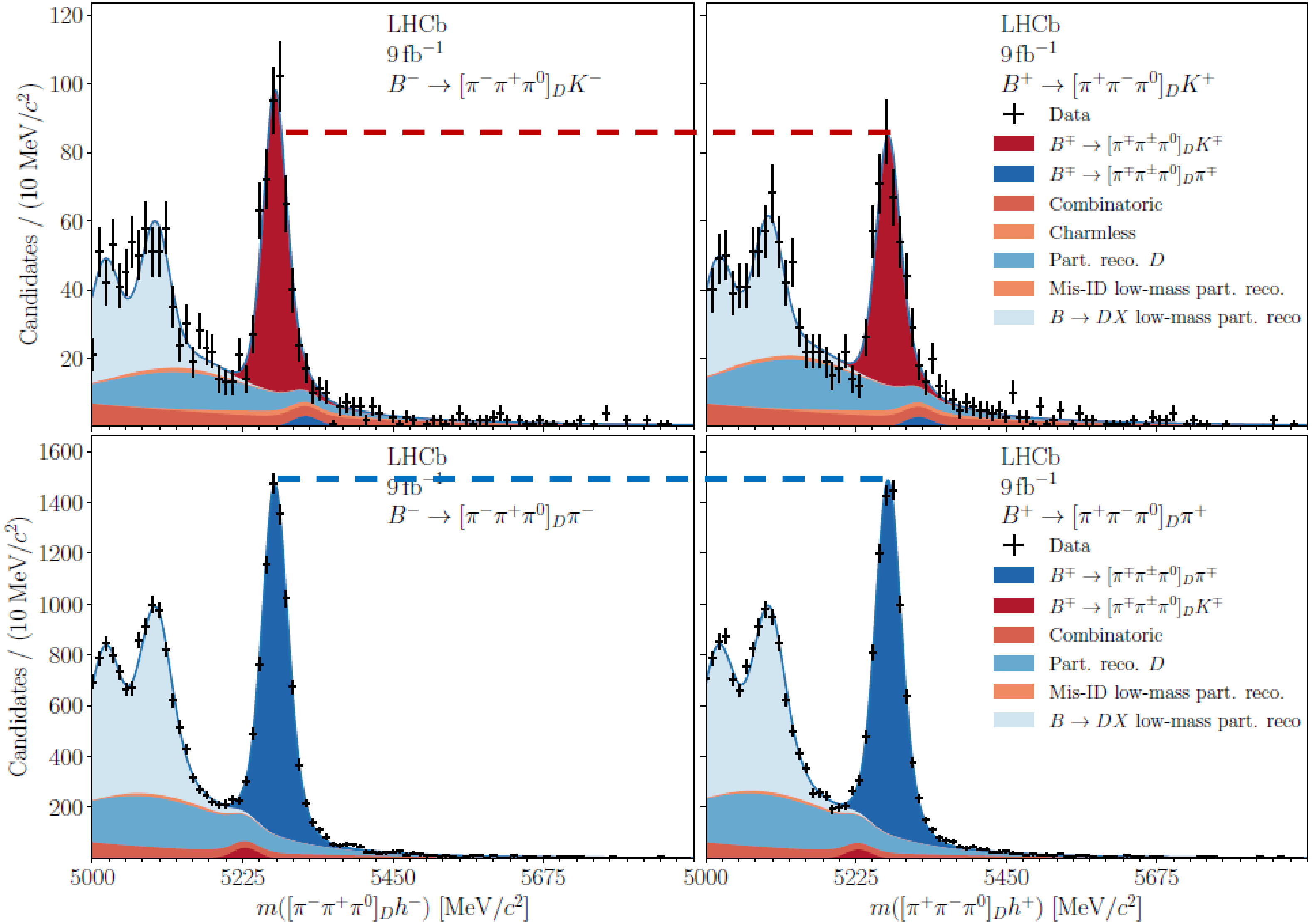
Y. Grossman, Z. Ligeti and A. Soffer. Phys. Rev. D67 (2003) 071301

Three-body D decays $B^{\pm} \to Dh^{\pm}$ with Run 1&2 data



- $B^{\pm} \to D(\to K^+\pi^-\pi^0)h^{\pm}$ and $B^{\pm} \to D(\to \pi^+K^-\pi^0)h^{\pm}$
- Partially reconstructed $B^{\pm} \to D^*h^{\pm}$
- $A^K_{K\pi\pi^0} = -0.024 \pm 0.013 \pm 0.002$

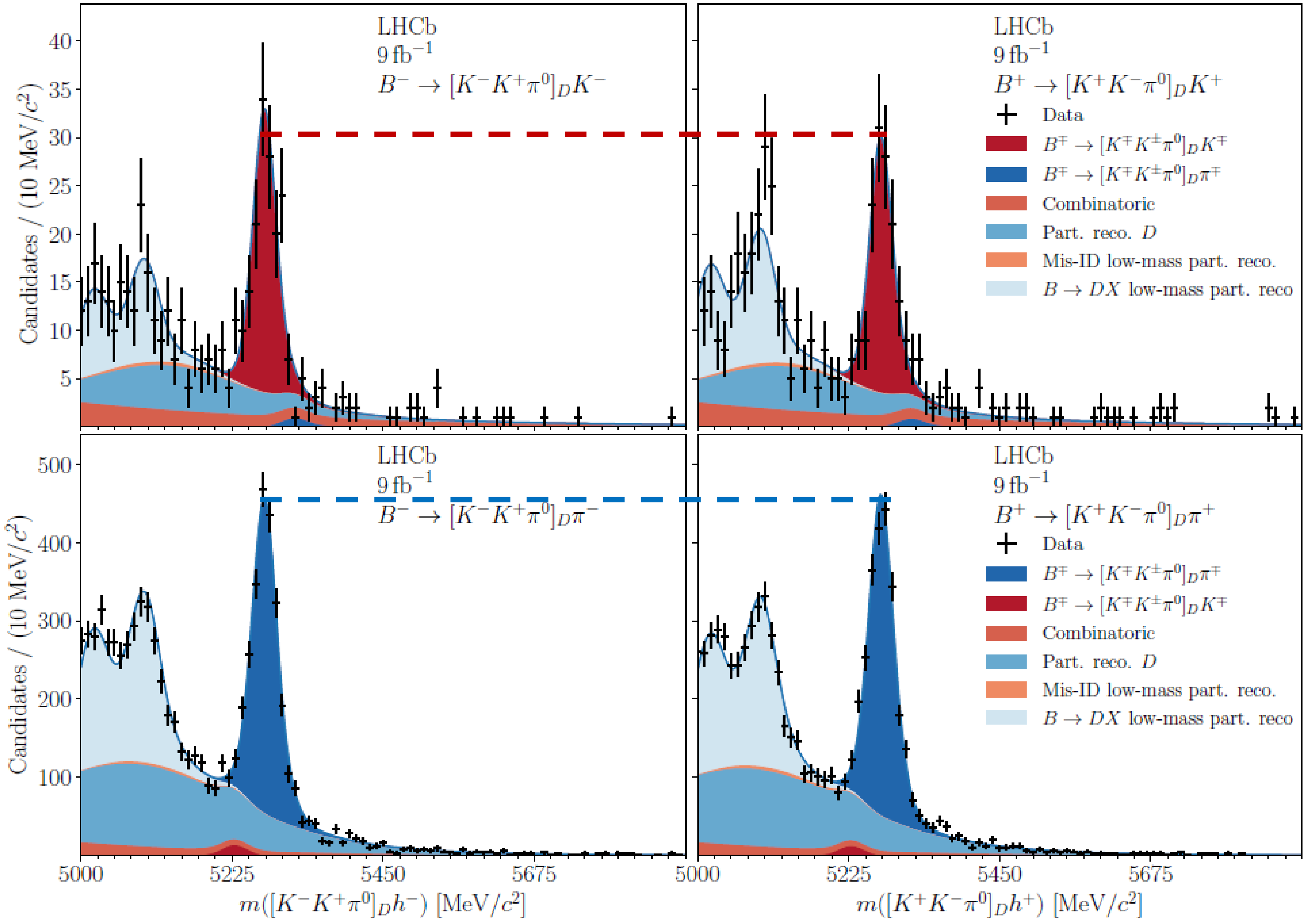
Three-body D decays $B^{\pm} \to Dh^{\pm}$ with Run 1&2 data



JHEP 07 (2022) 099

- $B^{\pm} \to D(\to \pi^+\pi^-\pi^0)h^{\pm}$
- Partially reconstructed $B^{\pm} \to D^* h^{\pm}$
- $A^K_{\pi^+\pi^-\pi^0} = -0.109 \pm 0.043 \pm 0.003$
- $A^{\pi}_{\pi^+\pi^-\pi^0} = 0.001 \pm 0.010 \pm 0.002$

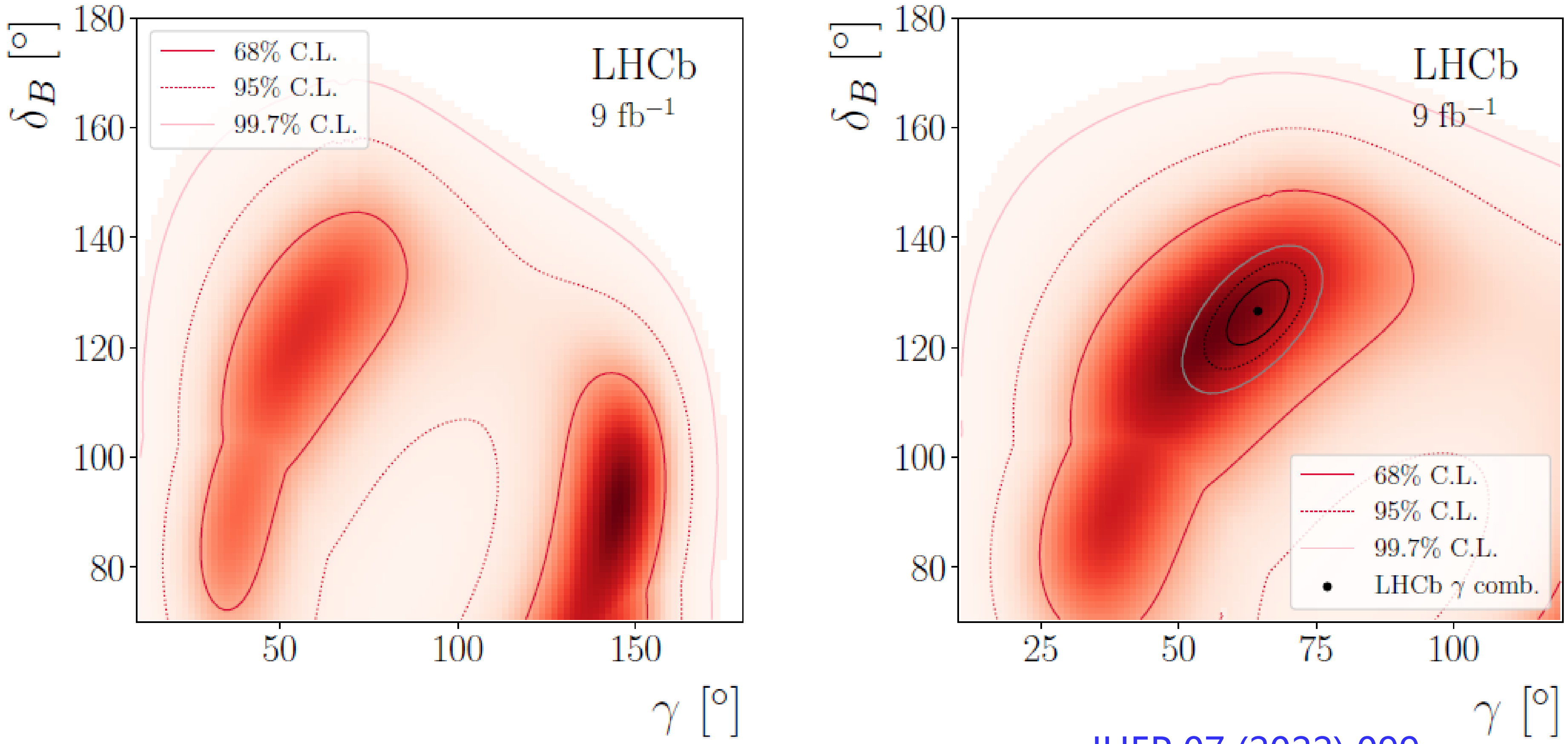
Three-body D decays $B^\pm \to Dh^\pm$ with Run 1&2 data



JHEP 07 (2022) 099

- $B^\pm \to D(\to K^+K^-\pi^0)h^\pm$
- Partially reconstructed $B^\pm \to D^* h^\pm$
- $A^K_{K^+K^-\pi^0} = -0.067 \pm 0.073 \pm 0.003$
- $A^\pi_{K^+K^-\pi^0} = -0.001 \pm 0.019 \pm 0.002$
- Conbine

Three-body D decays $B^{\pm} \to Dh^{\pm}$ with Run 1&2 data



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$$\begin{aligned} \gamma &= (56^{+24}_{-19})^{\circ}, \\ \delta_B &= (122^{+19}_{-23})^{\circ}, \\ r_B &= (9.3^{+1.0}_{-0.9}) \times 10^{-2}, \end{aligned}$$