FSI and CPV in B->hhh decays

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arXiv:2109.01625 [hep-ph]

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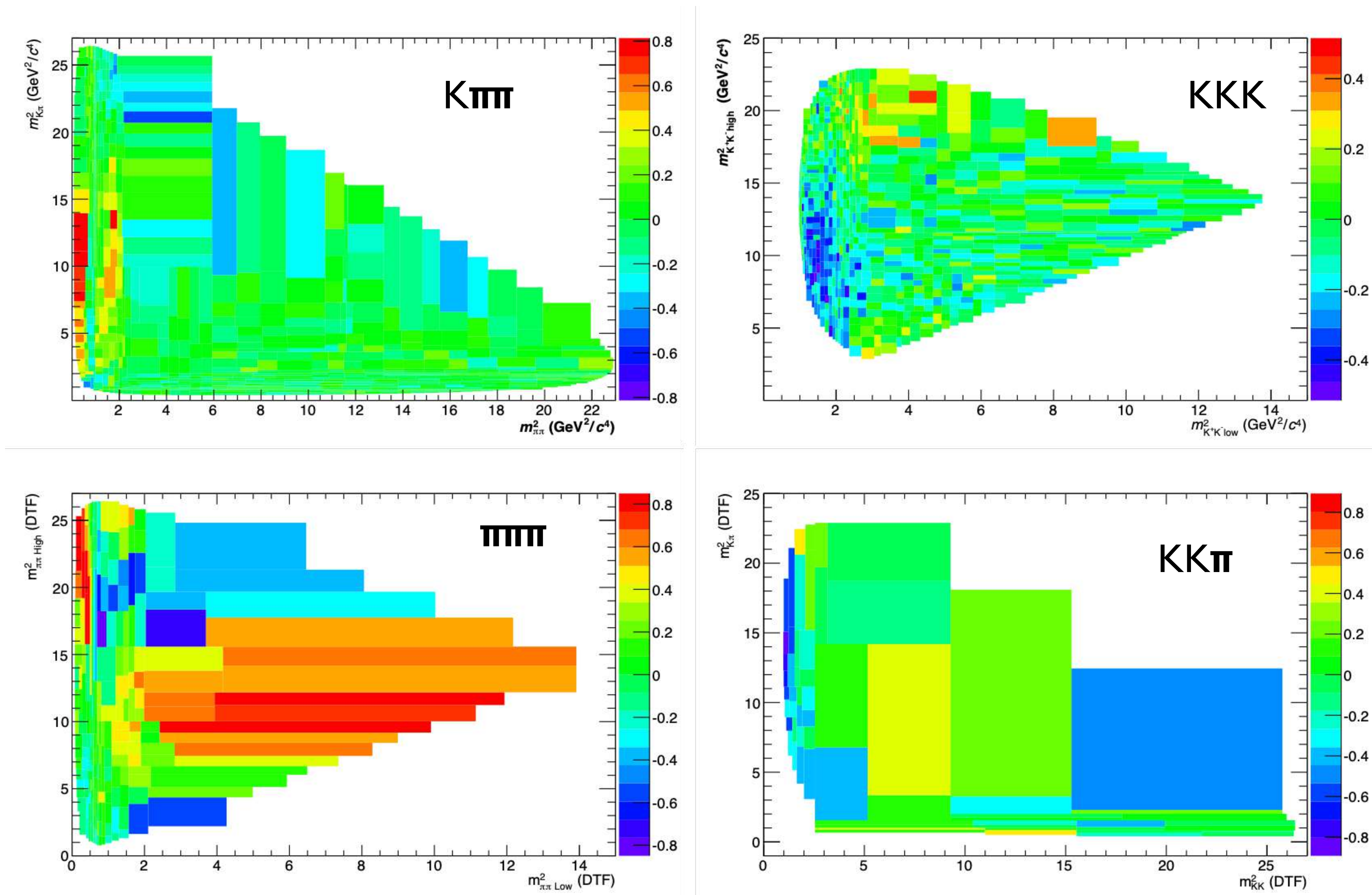
CPV Dalitz plot data: CP Asymmetry

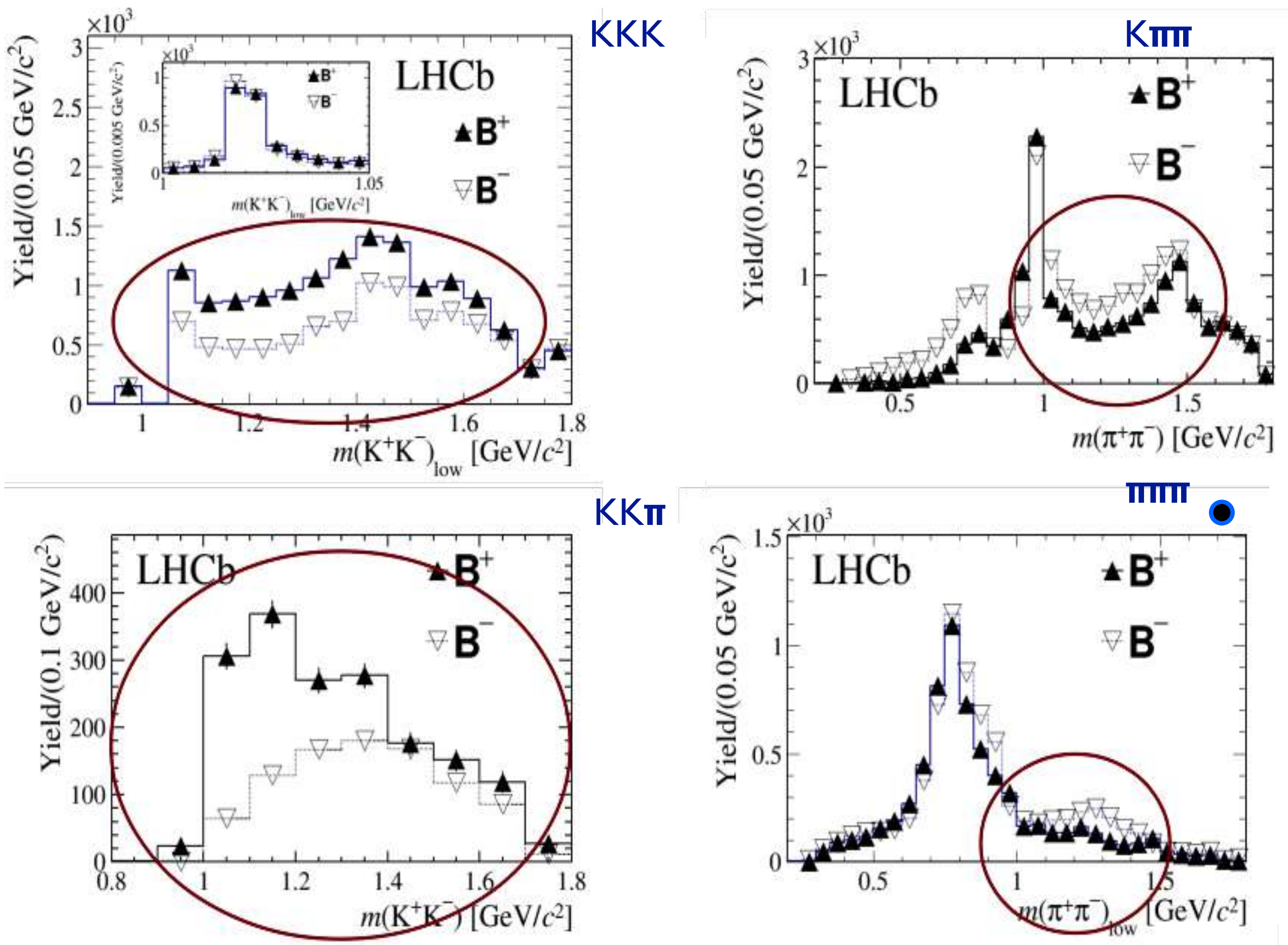
- $B^{\pm} \rightarrow h^{\pm}h^{-}h^{+}$

$$A_{CP} = \frac{\Gamma(M \rightarrow f) - \Gamma(\bar{M} \rightarrow \bar{f})}{\Gamma(M \rightarrow f) + \Gamma(\bar{M} \rightarrow \bar{f})}$$

LHCb PRD90 (2014) 112004



CPV in integrated yields



LHCb PRD90 (2014) 112004

K K K < 0 --- K π π >0

π π π >0 --- K K K < 0

Region: 1-1.5 GeV

(π π→K K)

$\pi \leftrightarrow K$

U-spin symm.

??????

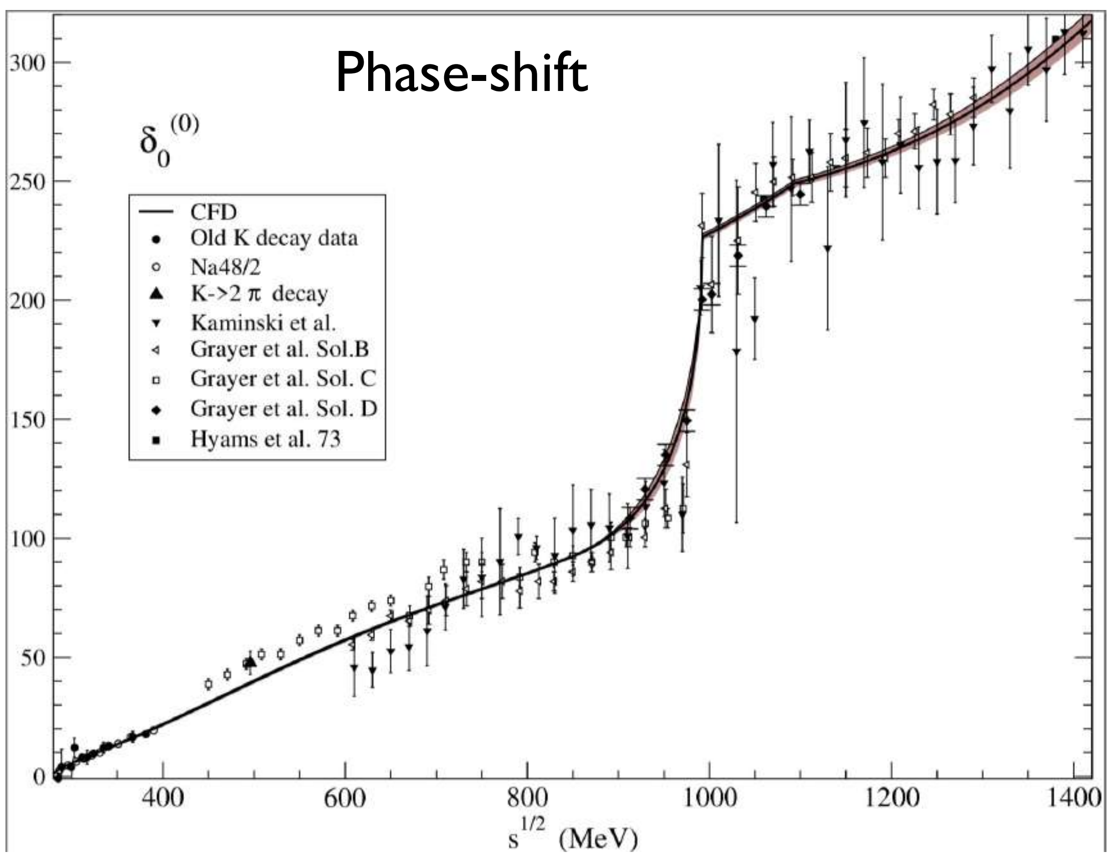
Bhattacharya, Gronau, Rosner, PLB 726 (2013) 337

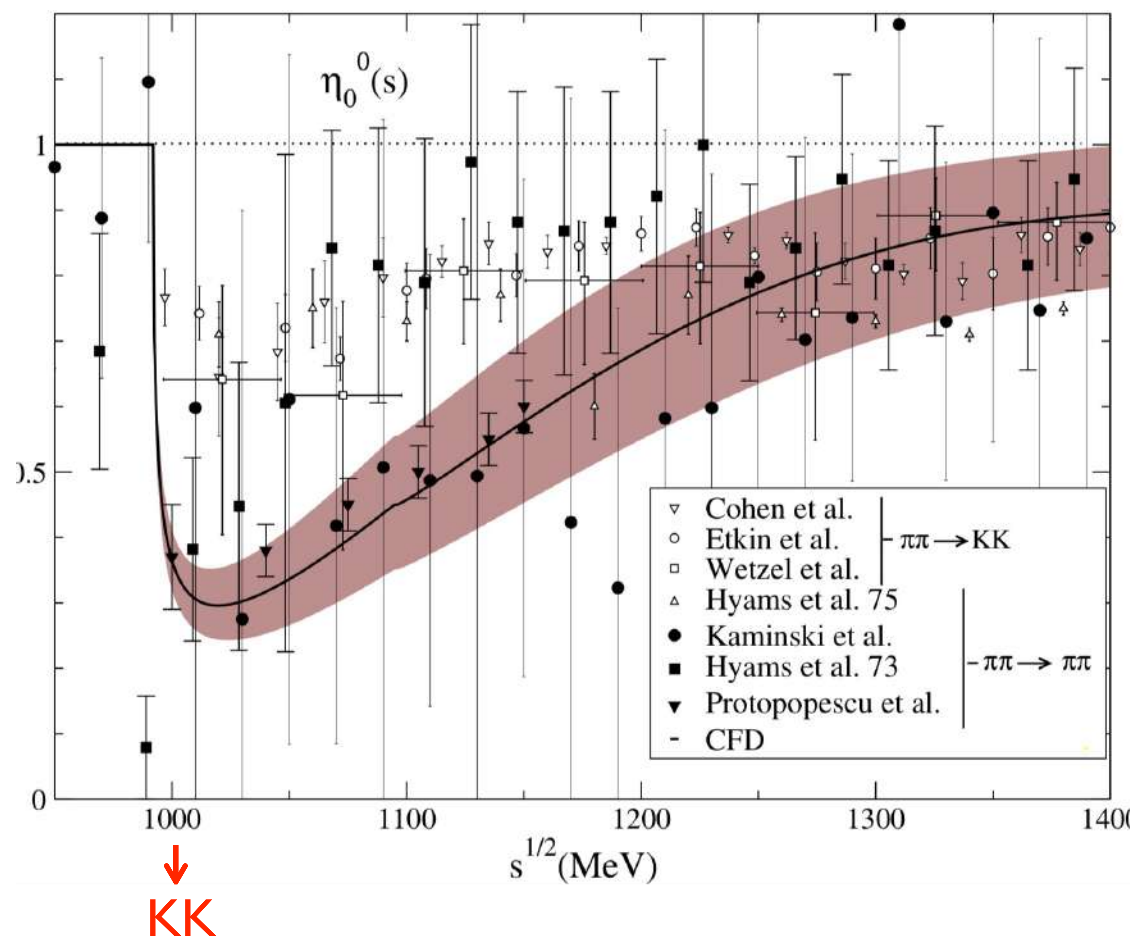
Rescattering π π→K K

s-wave Pelaez, Yndurain PRD71(2005) 074016

- $\hat{f}_l(s) = \left[\frac{\eta_l e^{2i\delta_l} - 1}{2i}\right]$ $\qquad \sigma_l^{\text{el}} = \frac{1}{2}\left\{\frac{1+\eta_l^2}{2} - \eta\cos 2\delta_l\right\},$

π π→K K





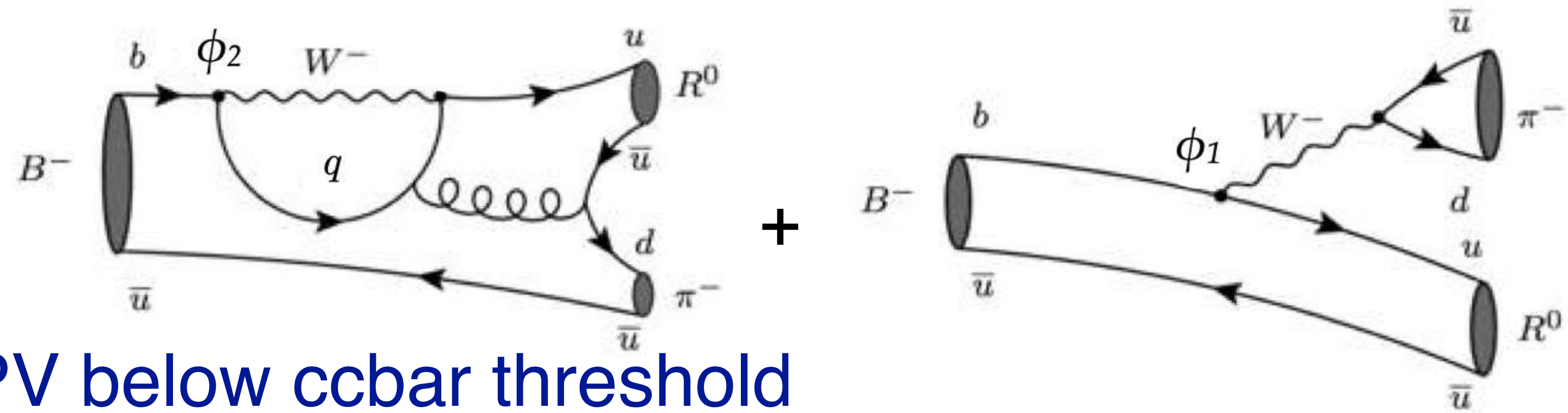
→ there is a new parametrisation Pelaez, Rodas, Elvira *EPJ C* 79 (2019)12, 1008

Theory CPV B→hhh

$$\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f}) = |\langle f\,|\,T\,|\,M\rangle|^2 - |\langle \bar{f}\,|\,T\,|\,\bar{M}\rangle|^2 = -4A_1A_2\sin(\delta_1-\delta_2)\,\sin(\phi_1-\phi_2)$$

- condition for CPV: 2 $\neq$ amplitudes, SAME final state with $\neq$ strong (δ_i) and weak (ϕ_i) phase

- CPV at quark level: BSS model Bander Silverman & Soni PRL 43 (1979) 242



Not enough to explain CPV below ccbar threshold

hadronic interactions as source of strong phase?

Theory CPV B→hhh

- Final State Interactions → strong phase

  Wolfenstein PRD43 (1991) 151 — Frederico, Bediaga, Lourenço PRD89(2014)094013

$$\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f}) = |\langle f\,|\,T\,|\,M\rangle|^2 - |\langle \bar{f}\,|\,T\,|\,\bar{M}\rangle|^2 = -4A_1A_2 \sin(\delta_1 - \delta_2)\,\sin(\phi_1 - \phi_2)$$

Lifetime $\tau = 1/\Gamma_{total} = 1/\bar{\Gamma}_{total}$

$$\Gamma_{total} = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4 + \Gamma_5 + \Gamma_6 + \ldots$$

$$\bar{\Gamma}_{total} = \bar{\Gamma}_1 + \bar{\Gamma}_2 + \bar{\Gamma}_3 + \bar{\Gamma}_4 + \bar{\Gamma}_5 + \bar{\Gamma}_6 + \ldots$$

- CPT: CPV in one channel should be compensated by another one with opposite sign

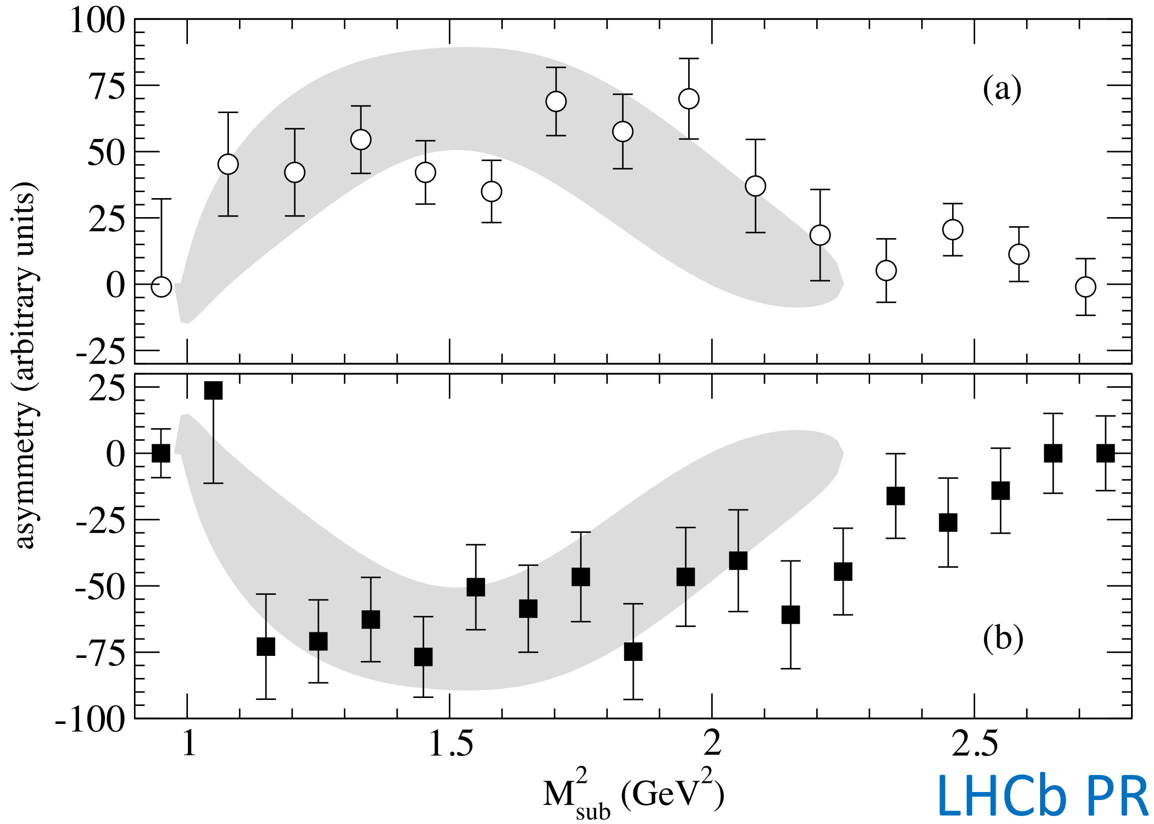
- $\pi\pi \to KK$ can explain CPV pattern

  ↳ $B^\pm \to h^\pm\pi^-\pi^+$ and $B^\pm \to h^\pm K^-K^+$

  at low-energy [1 -1.6] GeV

FSI & CPV at low –mass region

Bediaga, Frederico, Lourenço PRD89(2014)094013



LHCb PRL111, 101801 (2013)

FIG. 1: Estimate (grey band) of Eq. (15) as a function of the subsystem mass compared to experimental data of (a) the asymmetry of $B^\pm \to K^\pm \pi^+ \pi^-$ decay (circles), and of (b) the asymmetry of $B^\pm \to K^\pm K^+ K^-$ decay (squares). Data extracted from Ref. [5].

$$\Delta\Gamma^{comp}_{KK} = -\Delta\Gamma^{comp}_{\pi\pi}$$

$$\Delta\Gamma^{comp}_{KK} \approx \mathcal{C}\sqrt{1-\eta^2}\,\cos\left(\delta_{KK} + \delta_{\pi\pi} + \Phi_{KK}\right) F(M^2_{KK})$$

$$\mathcal{C} = 4|K|\,(\sin\gamma)$$

FSI & CPV at low –mass region inclusion of ressonances

Alvarenga Nogueira etal PRD 92 (2015) 054010

LHCb PRD 90, 112004 (2014)

$$\mathcal{A}^{\pm}_{LO} = \sum_{J\,R} \left(a^{R}_{0\lambda} + e^{\pm i\gamma} b^{R}_{0}\right) F^{BW}_{R\lambda} P_J(\cos\theta) + \sum_{J} \left(A^{J}_{0\lambda NR} + e^{\pm i\gamma} B^{J}_{0\lambda NR}\right) + i \sum_{\lambda',J} t^{J}_{\lambda',\lambda} \left(A^{J}_{0\lambda' NR} + e^{\pm i\gamma} B^{J}_{0\lambda' NR}\right)$$

$$\rho(770) \;\; \& \;\; f_0(980)$$

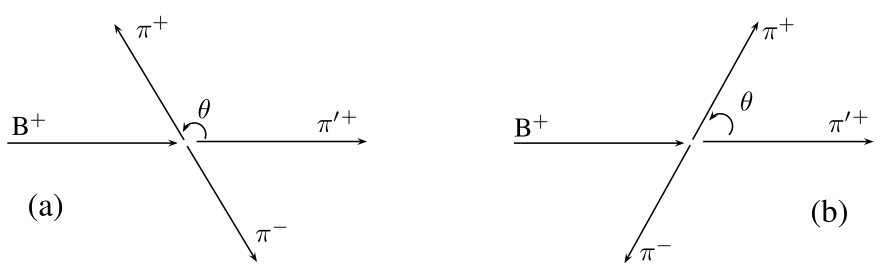


FIG. 1. $B^+ \to \pi^+\pi^+\pi^-$ decay with π'^+ being the bachelor particle. (a): $\cos\theta < 0$ ($\theta > \frac{\pi}{2}$). (b): $\cos\theta > 0$ ($\theta < \frac{\pi}{2}$).

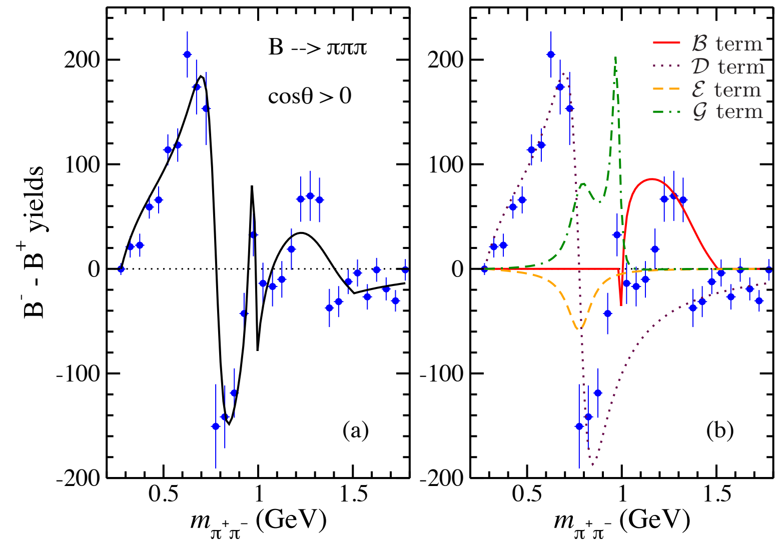


FIG. 8. (Color online) CP asymmetry of the $B^\pm \to \pi^\pm\pi^+\pi^-$ decay, integrated Eq. (44), compared with the experimental values (blue points) taken from Ref. [9]. Results for $\cos\theta > 0$ for (a) total and (b) individual contributions.

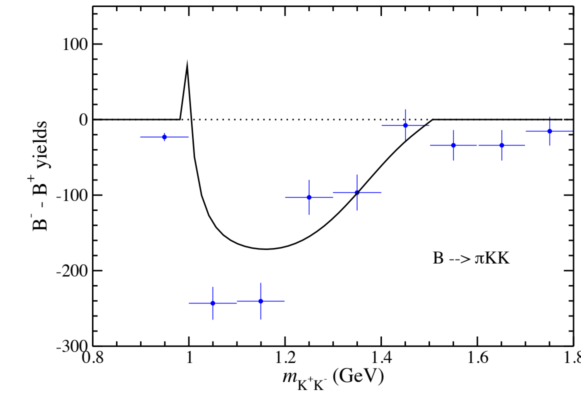


FIG. 10. (Color online) CP asymmetry of the $B^\pm \to \pi^\pm K^+K^-$ decay, Eq. (60), compared with experimental data (blue points) taken from Fig. 7b of Ref. [9].

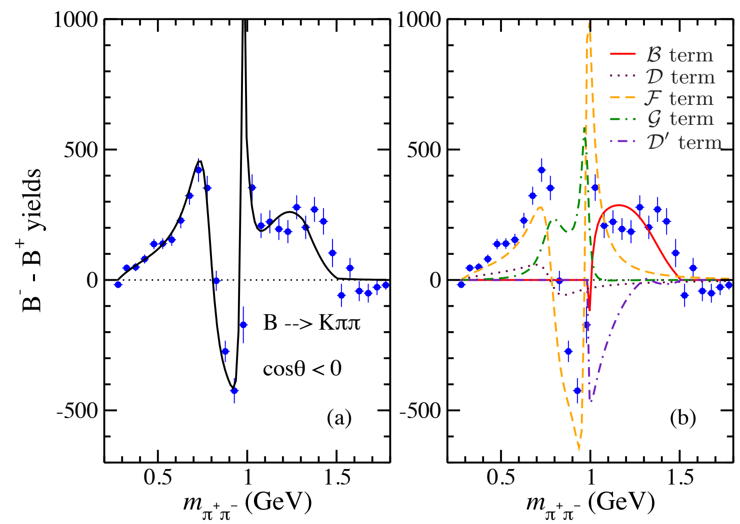


FIG. 11. (Color online) CP asymmetry of the $B^\pm \to K^\pm\pi^+\pi^-$ decay, integrated Eq. (44), compared with the experimental values (blue points) taken from Fig. 5c of Ref. [9]. Results for $\cos\theta < 0$ for (a) total and (b) individual contributions.

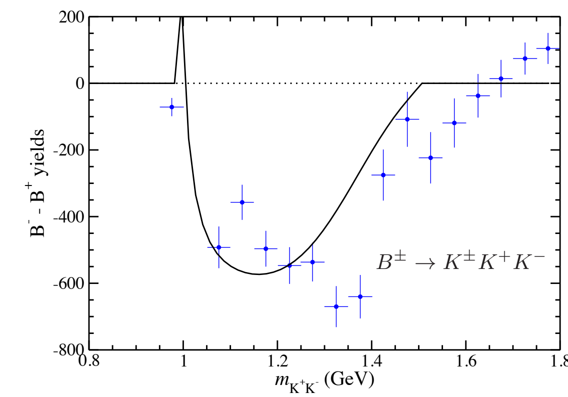


FIG. 12. CP asymmetry of the $B^\pm \to K^\pm K^+K^-$ decay compared with experimental values (blue points) taken from the sum of Figs. 6c and 6d of Ref. [9].

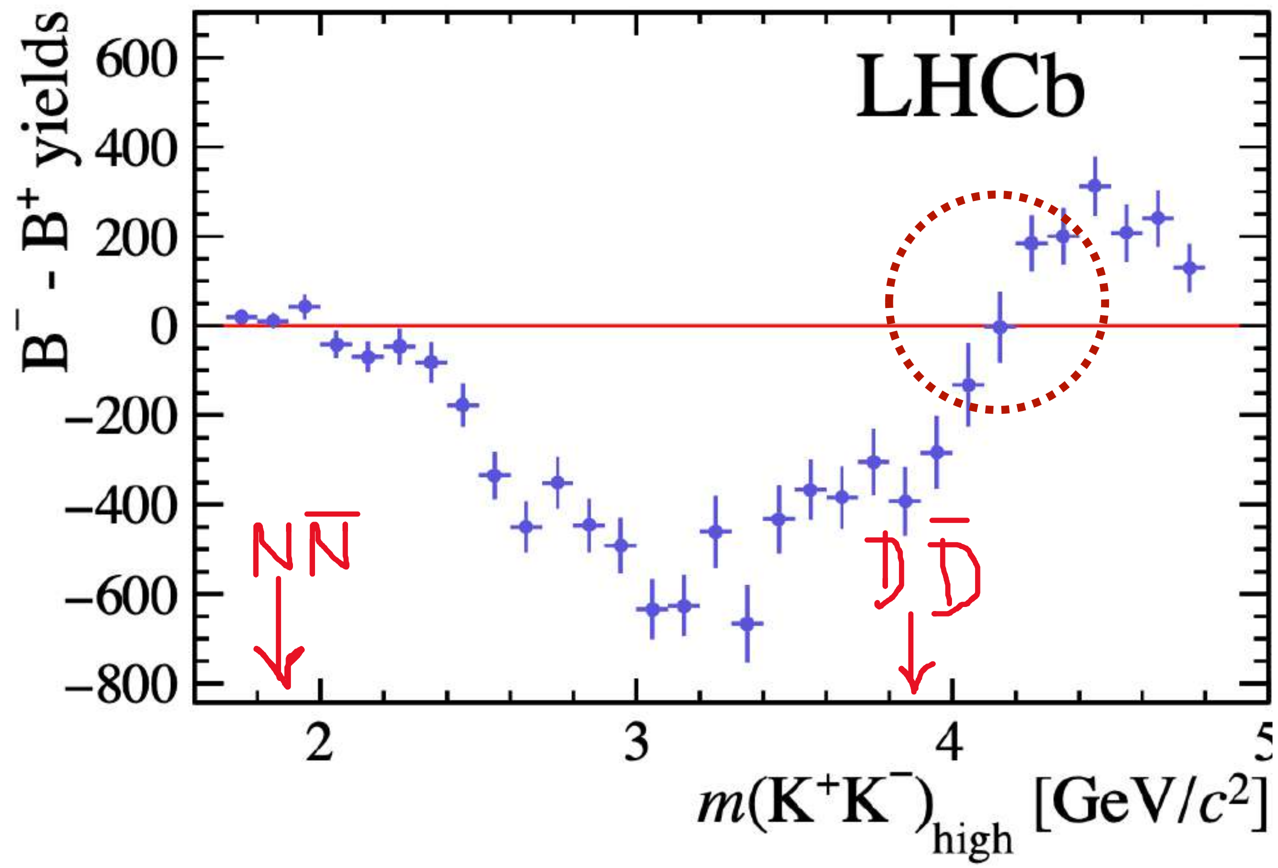
- confirmed in Amp Analysis
- rescattering $\pi\pi \to KK$ contribution in LHCb $\begin{cases} B^\pm \to \pi^+\pi^-\pi^\pm \\ B^\pm \to K^-K^+\pi^\pm \end{cases}$

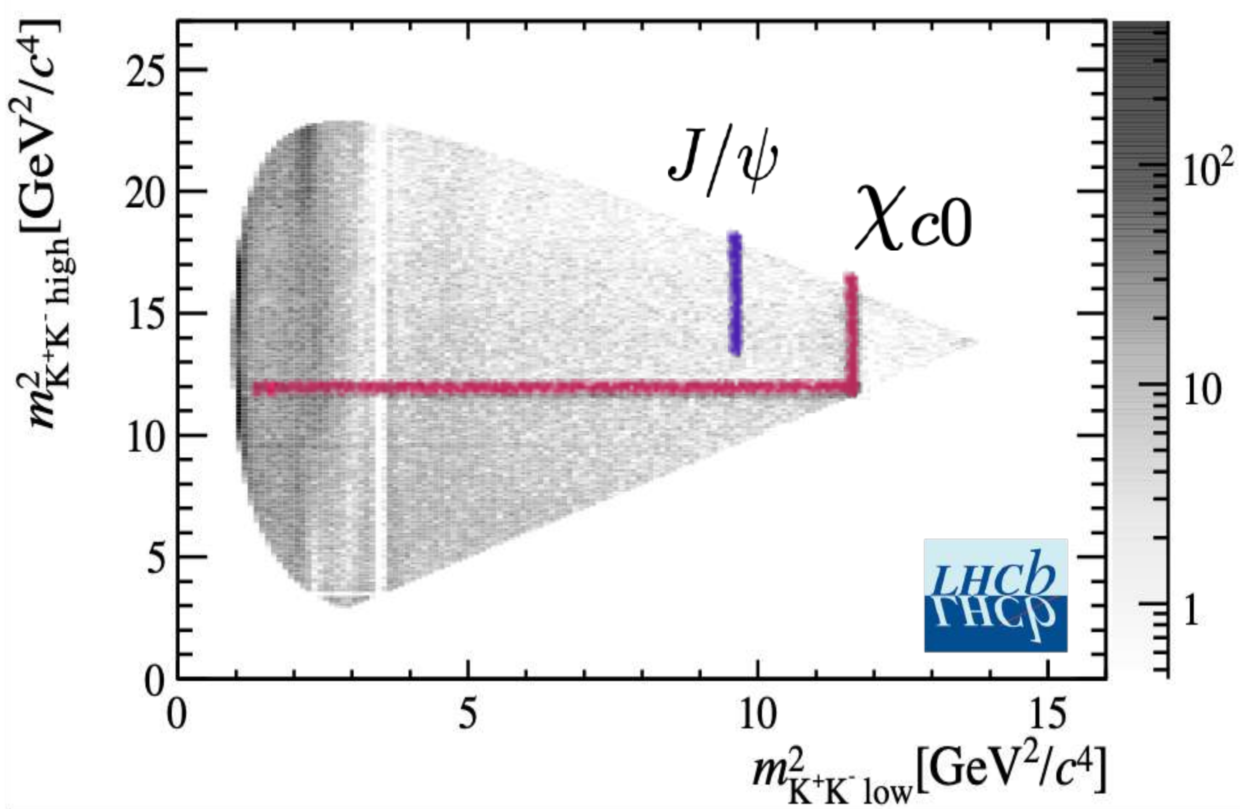
PRL [arXiv:1909.05211]
PRD [arXiv:1909.05212]
PRL [arXiv:1905.09244]

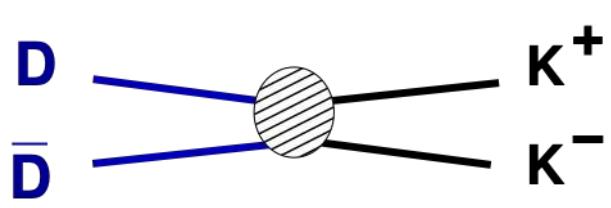
CPV high-mass

- $B^+ \to K^- K^+ K^+$
  - $\mathcal{A}_{cp}$ change sign ~ $D\bar{D}$ open channel

LHCb PRD90 (2014) 112004
https://cds.cern.ch/record/1751517/files/.







I. Bediaga, P.Magalhães, TF. PLB 780 (2018) 357

Global CPV

Bediaga, TF, PCM, Torres Machado arXiv:2109.01625 [hep-ph]

$$\Delta\Gamma_{CP}(h_1^{\pm}h_2^{+}h_3^{-}) = \Gamma(B^- \to h_1^- h_2^+ h_3^-) - \Gamma(B^+ \to h_1^+ h_2^- h_3^+)$$
$$= A_{CP}(B^{\pm} \to h_1^{\pm}h_2^{+}h_3^{-})\mathcal{B}(B^+ \to h_1^+ h_2^+ h_3^-)/\tau(B^+)$$

PDG Prog. Theor. Exp. Phys. 2020 (2020) 083C01

Decay channel	$\Delta\Gamma_{CP}(10^6\,\mathrm{s}^{-1})$
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	$+0.84 \pm 0.25$
$B^{\pm} \to K^{\pm}K^{+}K^{-}$	-0.68 ± 0.17
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	$+0.53 \pm 0.13$
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	-0.39 ± 0.07

Table 2: Total charge asymmetries A_{CP}^{all} and partial ones A_{CP}^{Par} in the re-scattering region $\pi\pi \to KK$ from 1.0 up to 1.5 GeV/c^2. Uncertainties are only statistical [1].

Decay	A_{CP}^{all}	A_{CP}^{par}
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	$+0.025 \pm 0.004$	$+0.123 \pm 0.012$
$B^{\pm} \to K^{\pm}K^{+}K^{-}$	-0.036 ± 0.004	-0.209 ± 0.011
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	$+0.058 \pm 0.008$	$+0.173 \pm 0.021$
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	-0.123 ± 0.017	-0.326 ± 0.028

U-spin: $$\frac{\Delta\Gamma_{CP}(\pi^{\pm}K^{+}K^{-})}{\Delta\Gamma_{CP}(K^{\pm}\pi^{+}\pi^{-})} = -0.46 \pm 0.16 \text{ and } \frac{\Delta\Gamma_{CP}(\pi^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma_{CP}(K^{\pm}K^{+}K^{-})} = -0.77 \pm 0.27$$

U-spin symmetry: Bhattacharya, Gronau, Rosner, PLB 726 (2013) 337

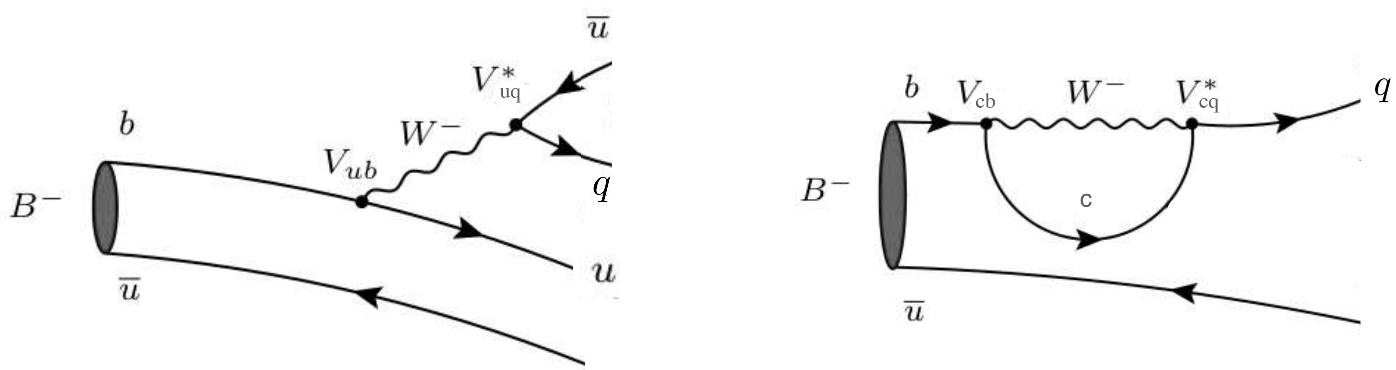
U-spin & FSI ? $$\frac{\Delta\Gamma_{CP}(K^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}\pi^{+}\pi^{-})} = 1.59 \pm 0.62 \text{ and } \frac{\Delta\Gamma_{CP}(K^{\pm}K^{+}K^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}K^{+}K^{-})} = 1.77 \pm 0.55$$

Global CPV, U-spin and FSI

strong phase from FSI Wolfenstein PRD43 (1991) 151

$$A(B^u \to f^q) = \langle f^q_{out}|\mathcal{H}_{\rm w}|B^u\rangle = V_{ub}V^*_{uq}\langle f^q_{out}|U^q|B^u\rangle + V_{cb}V^*_{cq}\langle f^q_{out}|C^q|B^u\rangle$$

$$A(\bar{B}^u \to \bar{f}^q) = \langle \bar{f}^q_{out}|\mathcal{H}_{\rm w}|\bar{B}^u\rangle = V^*_{ub}V_{uq}\langle \bar{f}^q_{out}|\bar{U}^q|\bar{B}^u\rangle + V^*_{cb}V_{cq}\langle \bar{f}^q_{out}|\bar{C}^q|\bar{B}^u\rangle$$



$$\mathcal{U}_{f^q} = \langle f^q_{out}|U^q|B^u\rangle \quad \text{and} \quad \mathcal{C}_{f^q} = \langle f^q_{out}|C^q|B^u\rangle$$

$$\Delta\Gamma_{CP}(q_i) = 4\,\mathrm{Im}[V^*_{ub}V_{uq}V_{cb}V^*_{cq}]\sum_{j,k}\mathrm{Im}\Big[S_{j,i}S^*_{k,i}\,\mathcal{U}^*_{q_j}\mathcal{C}_{q_k}\Big]$$

q= d or s

S-matrix unitarity and CPT invariance of the weak and strong Hamiltonians

Global CPV, U-spin and FSI

$q = d$ or s

$$\Delta\Gamma_{CP}(f^q) = |A(B^u \to f^q)|^2 - |A(\bar{B}^u \to \bar{f}^q)|^2$$
$$= 4\,\mathrm{Im}[V_{ub}^* V_{uq} V_{cb} V_{cq}^*]\,\mathrm{Im}\left[\mathcal{U}_{f^q}\mathcal{C}_{f^q}^*\right],$$
$$= 4\,\mathrm{Im}[V_{ub}^* V_{uq} V_{cb} V_{cq}^*]\sum_{j,k}\mathrm{Im}\left[S_{j,i}S_{k,i}^*\,\mathcal{U}_{q_j}^*\mathcal{C}_{q_k}\right]$$

CPT symm:

$$\sum_{f^q}\Delta\Gamma_{CP}(f^q) = 4\,\mathrm{Im}[V_{ub}^* V_{uq} V_{cb} V_{cq}^*]\sum_{f^q}\mathrm{Im}\left[\mathcal{U}_{f_q}\,\mathcal{C}_{f_q}^*\right] = 0$$

G.C. Branco, L. Lavoura, J.P. Silva, CP Violation, Oxford University Press, 1999.
I.I. Bigi, A.I. Sanda, CP Violation, second ed., Cambridge University Press, 2009.

$$\mathcal{U}_{f^q} = \langle f_{out}^q | U^q | B^u\rangle \quad \text{and} \quad \mathcal{C}_{f^q} = \langle f_{out}^q | C^q | B^u\rangle$$

U-spin symm:

$$\langle f_{out}^s | U^s | B^u\rangle = \langle f_{out}^d | U^d | B^u\rangle \quad \text{and} \quad \langle f_{out}^s | C^s | B^u\rangle = \langle f_{out}^d | C^d | B^u\rangle$$

CKM unitarity:

$$\mathrm{Im}(V_{ub}^* V_{us} V_{cb} V_{cs}^*) = -\,\mathrm{Im}(V_{ub}^* V_{ud} V_{cb} V_{cd}^*)$$

Bhattacharya, Gronau, Rosner, PLB 726 (2013) 337

$$\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-) = -\Delta\Gamma_{CP}(\pi^\pm K^+K^-),$$
$$\Delta\Gamma_{CP}(\pi^\pm\pi^+\pi^-) = -\Delta\Gamma_{CP}(K^\pm K^+K^-).$$

Coupled $\pi\pi$ and KK channels in $B^\pm$ three-body decays

S-wave $$\begin{pmatrix} S_{\pi\pi,\pi\pi} & S_{\pi\pi,K\bar{K}} \\ S_{K\bar{K},\pi\pi} & S_{K\bar{K},K\bar{K}} \end{pmatrix} = \begin{pmatrix} \eta\, e^{2\imath\delta_{\pi\pi}} & \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_{\pi\pi}+\delta_{KK})} \\ \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_{\pi\pi}+\delta_{KK})} & \eta\, e^{2\imath\delta_{KK}} \end{pmatrix}$$

$$\Delta\Gamma_{CP}^{(\mathrm{LO})}(q_{\pi\pi}) = w_q \ \mathrm{Re}\left[e^{\imath(\delta_{\pi\pi}-\delta_{KK})}\, \mathcal{U}^*_{0q_{\pi\pi}} \mathcal{C}_{0q_{KK}} - e^{-\imath(\delta_{\pi\pi}-\delta_{KK})}\, \mathcal{U}^*_{0q_{KK}} \mathcal{C}_{0q_{\pi\pi}} \right]$$

q= d or s

$$w_q = 4\eta\sqrt{1-\eta^2}\ \mathrm{Im}[V^*_{ub}V_{uq}V_{cb}V^*_{cq}]$$

U-spin symm:

$$\mathcal{U}_{0d_{\pi\pi}} = \mathcal{U}_{0s_{KK}} \quad \text{and} \quad \mathcal{U}_{0d_{KK}} = \mathcal{U}_{0s_{\pi\pi}}\,,$$
$$\mathcal{C}_{0d_{\pi\pi}} = \mathcal{C}_{0s_{KK}} \quad \text{and} \quad \mathcal{C}_{0d_{KK}} = \mathcal{C}_{0s_{\pi\pi}}\,.$$

$$\frac{\Delta\Gamma_{CP}(\pi^\pm K^+K^-)}{\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-)} \sim -1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(\pi^\pm\pi^+\pi^-)}{\Delta\Gamma_{CP}(K^\pm K^+K^-)} \sim -1\,.$$

CPT symm:

$$\Delta\Gamma(q_{\pi\pi}) = -\Delta\Gamma(q_{KK})$$

$$\frac{\Delta\Gamma_{CP}(\pi^\pm K^+K^-)}{\Delta\Gamma_{CP}(\pi^\pm\pi^+\pi^-)} = -1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(K^\pm K^+K^-)}{\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-)} = -1$$

Remarks

$$\Delta S = 0, \quad B^\pm \to \pi^\pm K^+ K^-, \ \pi^\pm K^0 \bar{K}^0, \ K^\pm \bar{K}^0 \pi^0, \ \pi^\pm \pi^+ \pi^-, \ \pi^\pm \pi^0 \pi^0.$$

$$\Delta S = 1 \quad B^\pm \to K^\pm \pi^+ \pi^-, \ \pi^\pm K^0 \pi^0, K^\pm \pi^0 \pi^0, \ K^\pm K^0 \bar{K}^0, \ K^\pm K^+ K^-$$

three-body re-scattering is expect to be small

Alvarenga Nogueira, TF, Lourenço, Few-Body Syst. 58 (2017) 98

CPT constraint for decay channels coupled by the strong interaction

$$\Delta\Gamma_{CP}(\pi^\pm K^+ K^-) + \Delta\Gamma_{CP}(\pi^\pm K^0 \bar{K}^0) + \Delta\Gamma_{CP}(\pi^\pm \pi^+ \pi^-) + \Delta\Gamma_{CP}(\pi^\pm \pi^0 \pi^0) = 0$$

$$\Delta\Gamma_{CP}(K^\pm \pi^+ \pi^-) + \Delta\Gamma_{CP}(K^\pm \pi^0 \pi^0) + \Delta\Gamma_{CP}(K^\pm K^+ K^-) + \Delta\Gamma_{CP}(K^\pm K^0 \bar{K}^0) = 0$$

assuming:

$$\frac{\Delta\Gamma_{CP}(\pi^\pm K^+ K^-)}{\Delta\Gamma_{CP}(\pi^\pm K^0 \bar{K}^0)} \sim 1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(\pi^\pm \pi^+ \pi^-)}{\Delta\Gamma_{CP}(\pi^\pm \pi^0 \pi^0)} \sim 1$$

$$\frac{\Delta\Gamma_{CP}(K^\pm \pi^+ \pi^-)}{\Delta\Gamma_{CP}(K^\pm \pi^0 \pi^0)} \sim 1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(K^\pm K^+ K^-)}{\Delta\Gamma_{CP}(K^\pm K^0 \bar{K}^0)} \sim 1$$

$$\frac{\Delta\Gamma_{CP}(\pi^\pm K^0 \bar{K}^0)}{\Delta\Gamma_{CP}(\pi^\pm \pi^0 \pi^0)} \sim -1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(K^\pm K^0 \bar{K}^0)}{\Delta\Gamma_{CP}(K^\pm \pi^0 \pi^0)} \sim -1$$

charm rescattering in $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$

Bediaga, Frederico, PCM - PLB 806 (2020) 135490 [arXiv:2003.10019]

- high mass CPV

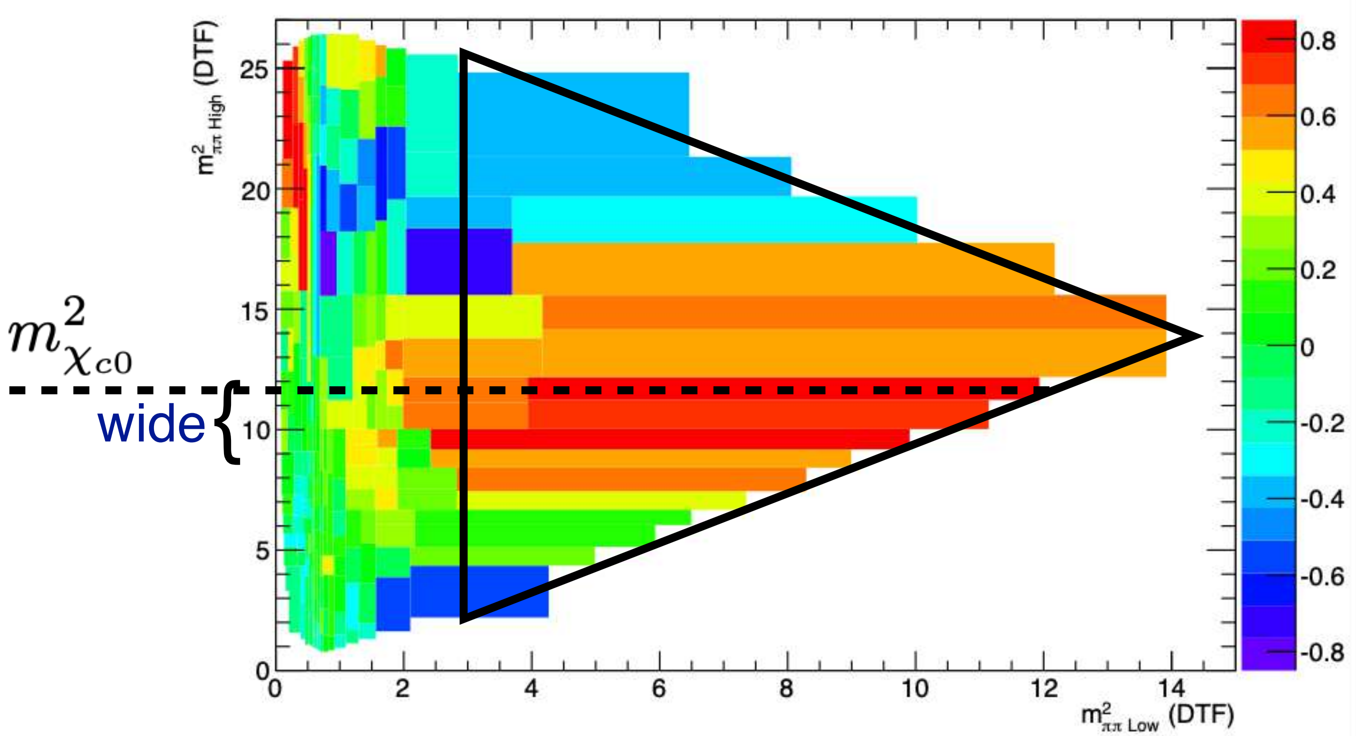
- $m^2_{\pi\pi} > 3\,GeV^2$

  avoid low energy resonances

- include χ_{c0} (expected in Run II)

  $m^2_{\chi_{c0}} = 11.65\,GeV^2$

  charm loop



→ QCDF approach: excited χ_{c0}(3680) Mannel, Olschewsky, Vos JHEP 06 (2020) 073 [arXiv:2003.12053]

thanks to P. C. Magalhães

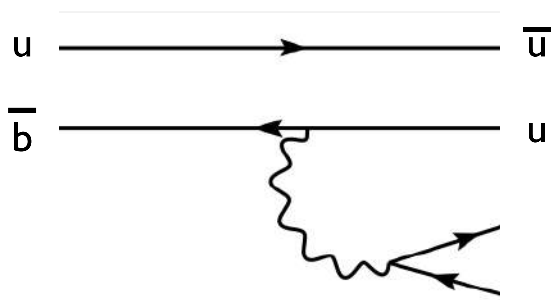
Amplitude model

NEW!

- Amplitude Model for $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ high mass $m^2_{\pi\pi} > 3\,GeV^2$

$$A_{B^{\pm}\to\pi^{-}\pi^{+}\pi^{\pm}}(s_{12}, s_{23}) = A^{\pm}_{tree}(s_{12}, s_{23}) + A_{D\bar{D}}(s_{12}, s_{23})$$

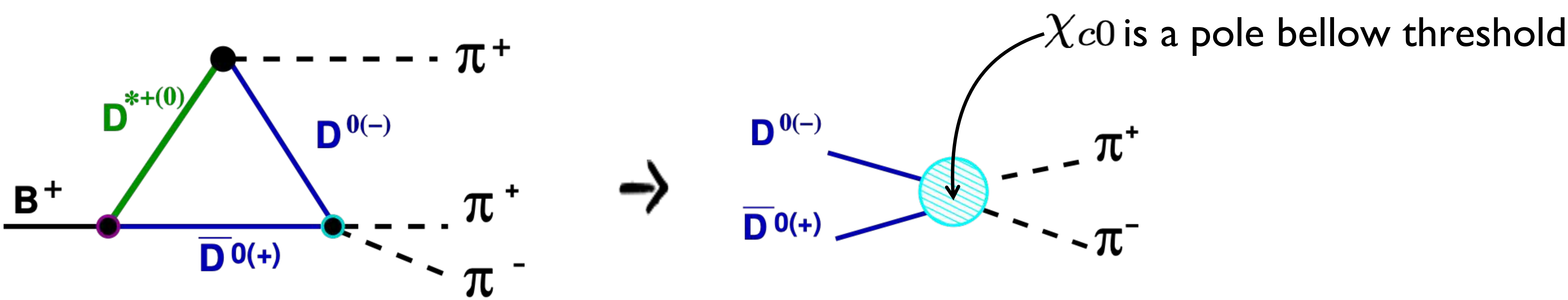
- $A^{\pm}_{tree} = a_0\, e^{\pm i\gamma}$: weak phase γ from the dominant $b \to u$ tree diagram



→ Nonresonant (only resonances tails)

→ a_0 is complex (strong phase)

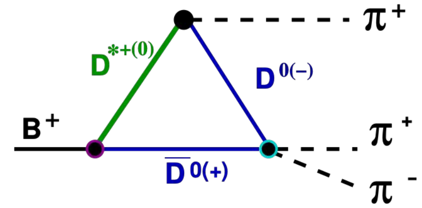
- $A_{D\bar{D}}$ charm rescattering with χ_{c0}: source of strong phase variation



→ χ_{c0} (3414) : a pole below $D\bar{D}$ threshold

thanks to P. C. Magalhães

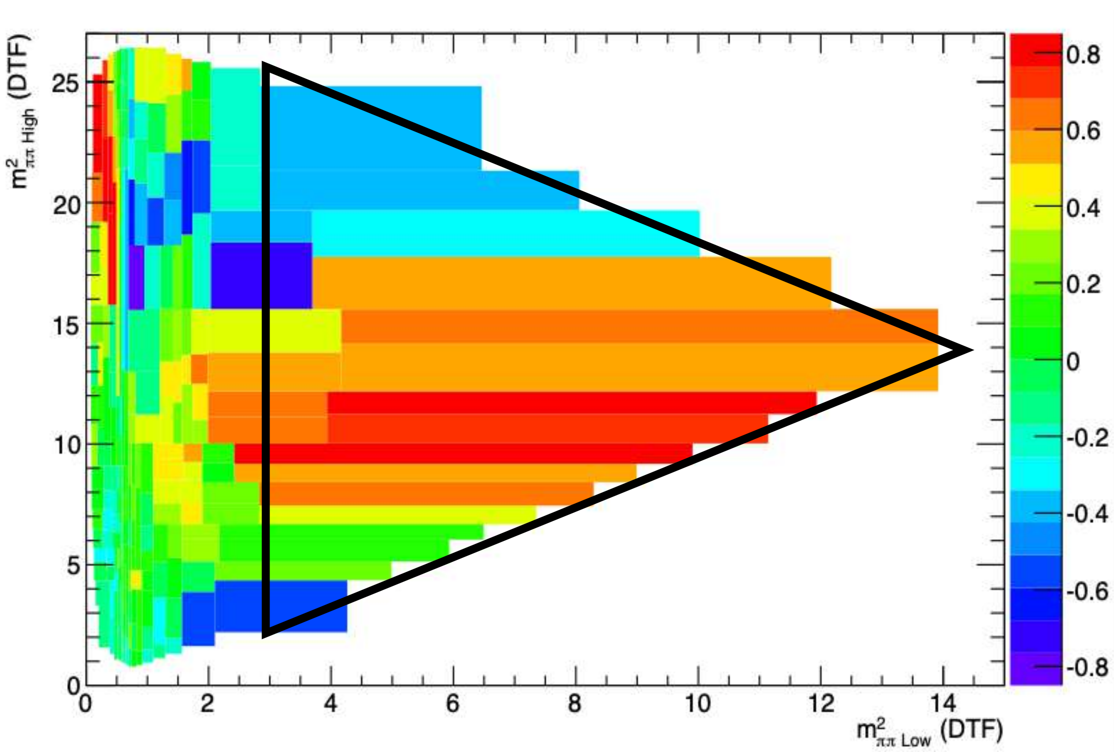
Results

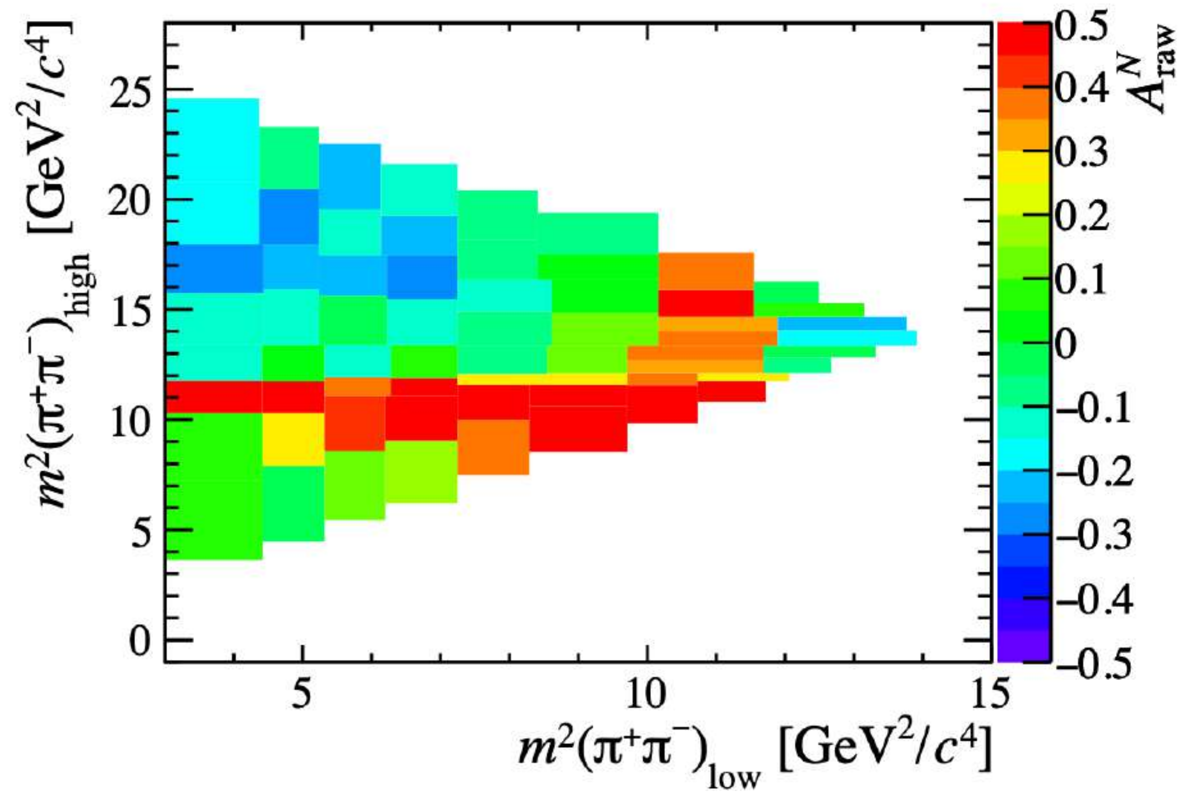
- $A_{B^{\pm}\to\pi^-\pi^+\pi^\pm}(s_{12}, s_{23}) =$ 

$+ \quad a_0\, e^{\pm i\gamma}$

$$\gamma = 70^o$$
$$a_0 = 2\, e^{(\delta_s = 45^o)}$$

- LHCb Run I
- our model





- not the same binning and scale
- mimic some of the CPV pattern at high mass
- superposition of triangles and excited states can enlarge de CPV signature

→ parameters from $D\bar{D} \to \pi^+\pi^-$ have to be fitted to data

thanks to P. C. Magalhães

Summary CPV

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

- Relevance of Hadronic FSI, CPT constraint and U-spin symmetry for CPV

→ two-body unitary and coupled-channels

- Understading of CPV– Global, region of low-mass resonance and for 1-1.5GeV (LHCb amplitude analysis)

- unified treatment low and high masses of the Dalitz with FSI

→ low-mass resonances, pion-pion→KK,
pion-pion(KK)→ nucleon-antinucleon,
pion-pion(KK)→ D-Dbar & high mass resonances

→ two-body unitary, coupled-channels, three-body unitarity?

Thank you!!