Interação de estado final em decaimentos hadronicos de 3 corpos no LHCb: mecanismos para entender a *Violação de CP* em decaimentos de mésons B e D

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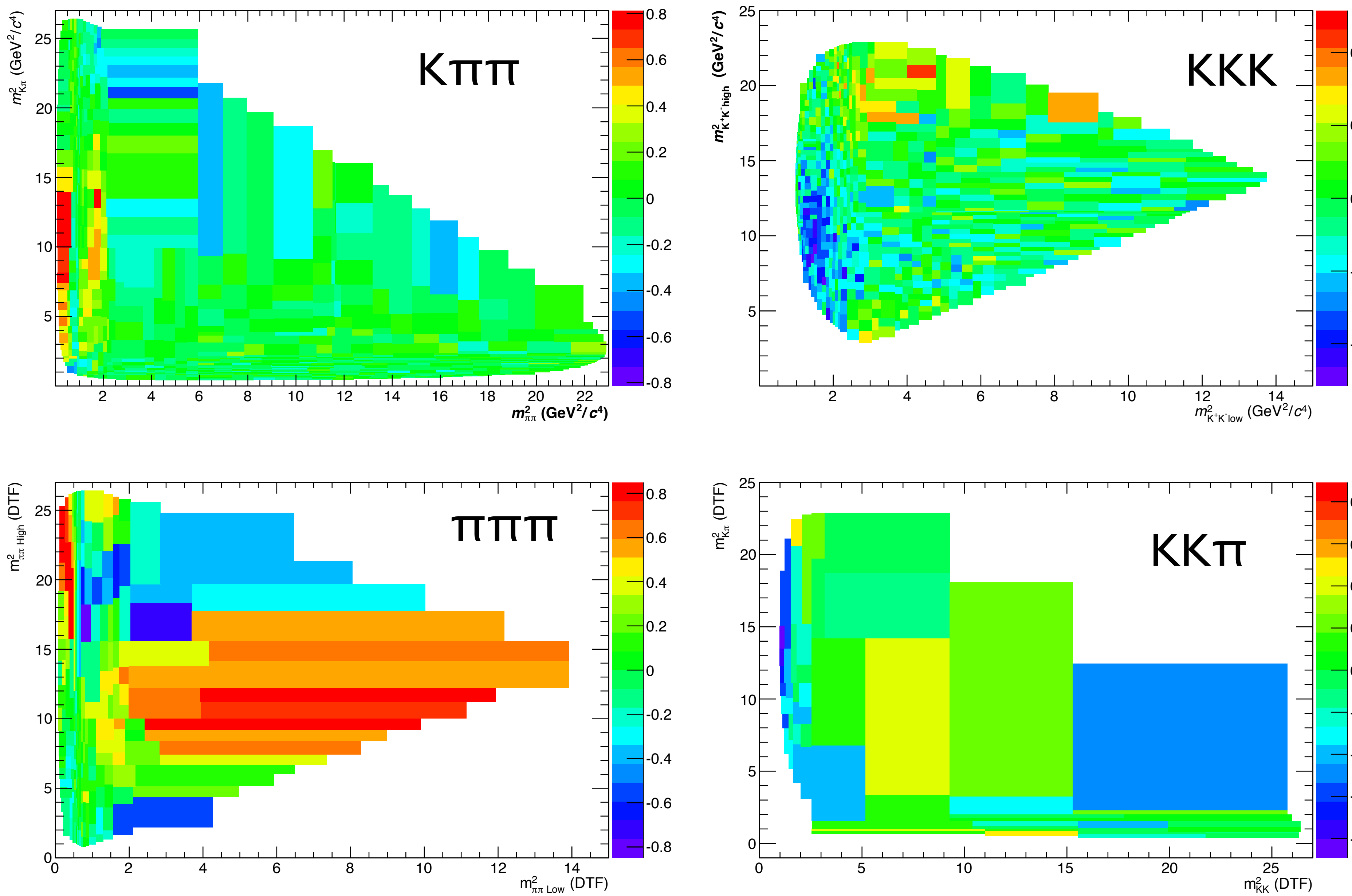
Motivation

- $B^\pm \to h^\pm h^- h^+$ massive localized Acp

LHCb PRD90 (2014) 112004

- suggest dynamic effect

- middle looks "empty" ↓ CPV

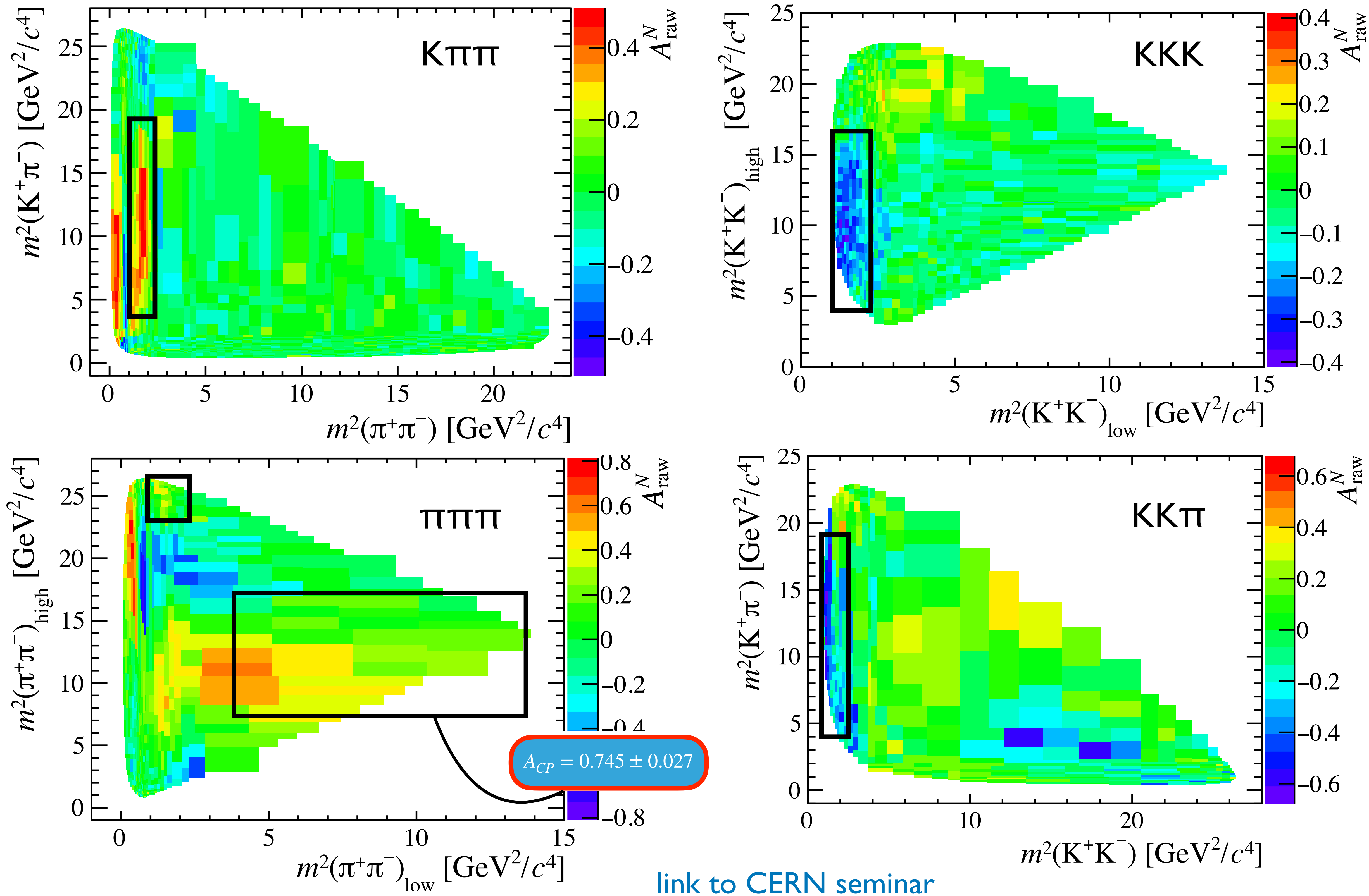


new one CERN conference

FSI as source of CP asymmetry in B decays

- $B^{\pm} \to h^{\pm} h^{-} h^{+}$ LHCb new one

still massive localized Acp



link to CERN seminar

CP asymmetry measurements

- 1st observation in charm LHCb 2019 $A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

→ direct CP asymmetry observation

- $A_{CP}(K^-K^+) = (0.04 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (syst)})\%$ LHCb Phys.Lett.B 767 (2017) 177

  ↳ $A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14 \text{ (stat)} \pm 0.11 \text{ (syst)})\%$

→ CPV on $D \to hhh$?

→ searches in many process at LHCb, BESIII, BelelI

→ can lead to new physics (DCS for ex)

→ understand the mechanism in two-body is crucial to three-body studies

CPV on data: Puzzle!

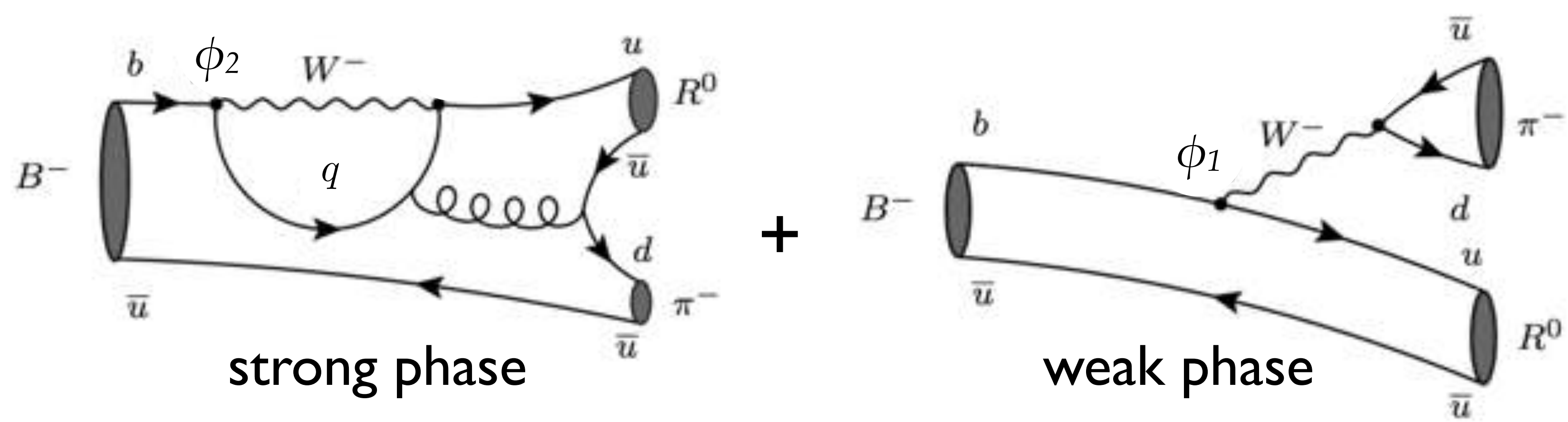
- condition to CPV

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

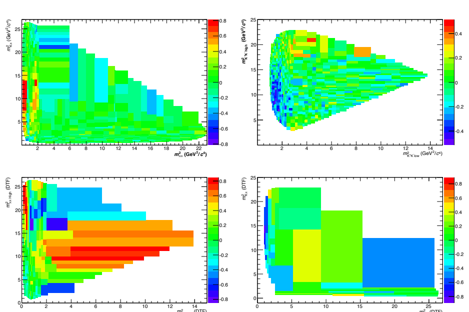
  - $2 \neq$ amplitudes, SAME final state with $\neq$ strong (δ_i) and weak (ϕ_i) phase

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

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



  - **Not enough to explain**



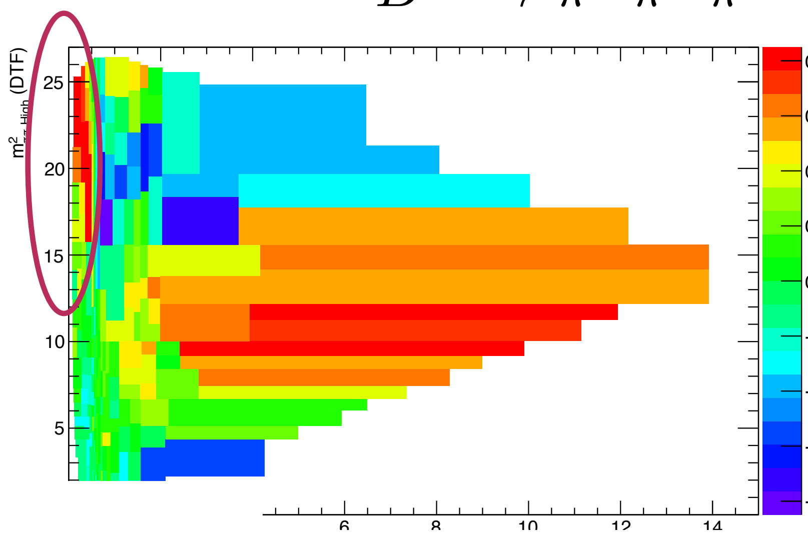
hadronic interactions as source of strong phase

rescattering as a CPV mechanism

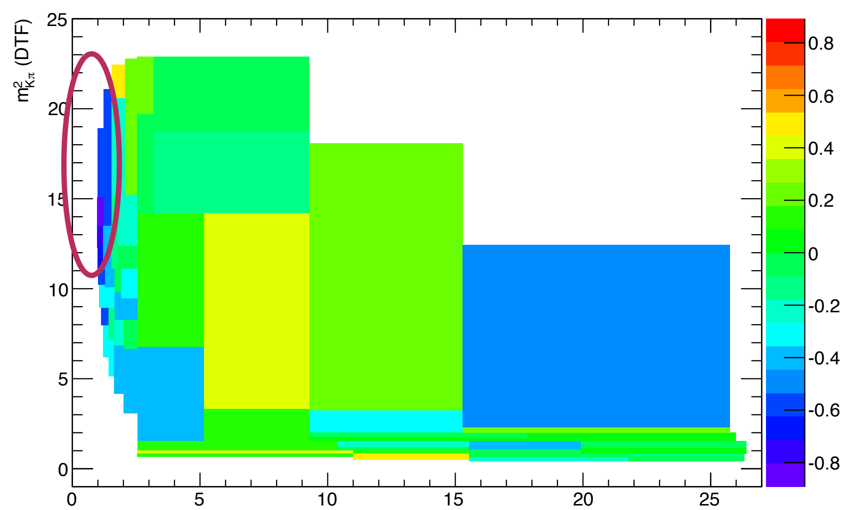
- CPT must be preserved

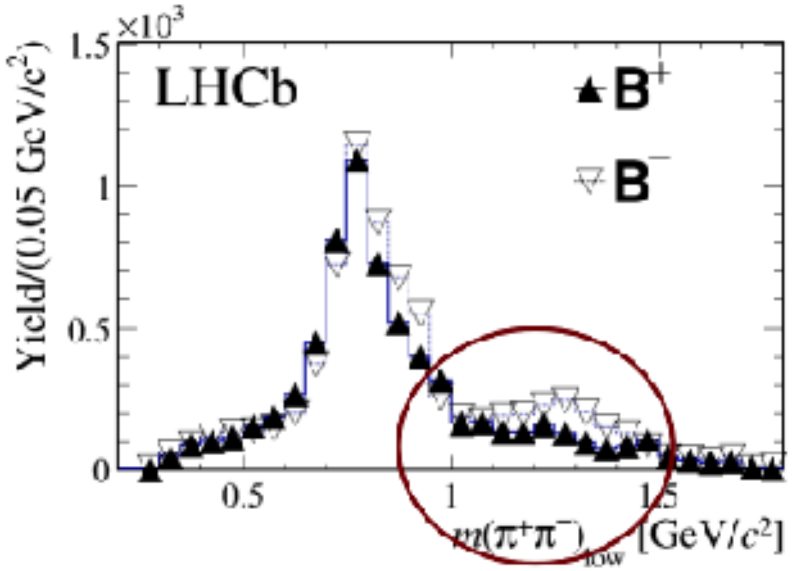
$$\sum \Delta\Gamma_{CP} = 0$$ → CPV in one channel should be compensated by another, same quantum #, with opposite sign

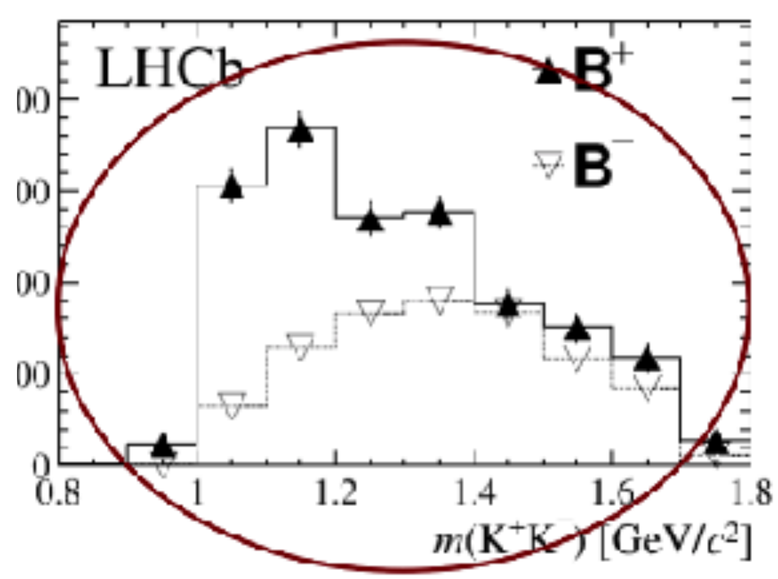
$B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$



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







rescattering $\pi\pi \to KK$

→ CPV at [1 -1.6] GeV

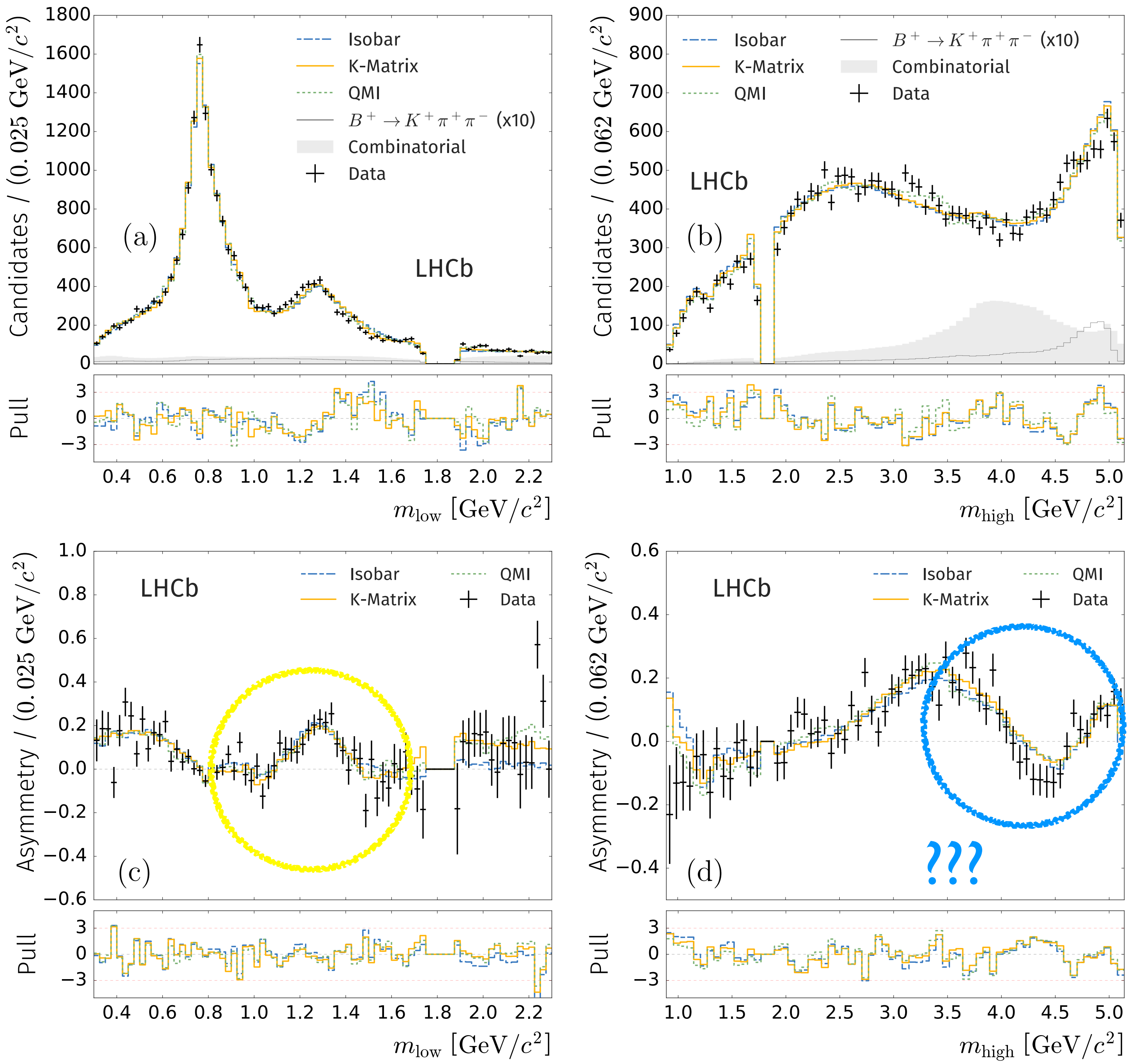
Frederico, Bediaga, Lourenço PRD89(2014)094013

- confirmed by LHCb Amplitude Analysis $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ and $B^{\pm} \to \pi^{\pm}K^{-}K^{+}$

PRD101 (2020) 012006; PRL 124 (2020) 031801 PRL 123 (2019) 231802

CPV: amplitude analysis $B^{\pm} \to \pi^- \pi^+ \pi^{\pm}$

- recent Amplitude analysis $B^{\pm} \to \pi^- \pi^+ \pi^{\pm}$ PRD101 (2020) 012006; PRL 124 (2020) 031801
  - $(\pi^- \pi^+)_{S-Wave}$ 3 different model:
    - ↪ σ as BW (!) + rescattering;
    - ↪ P-vector K-Matrix;
    - ↪ binned freed lineshape (QMI);



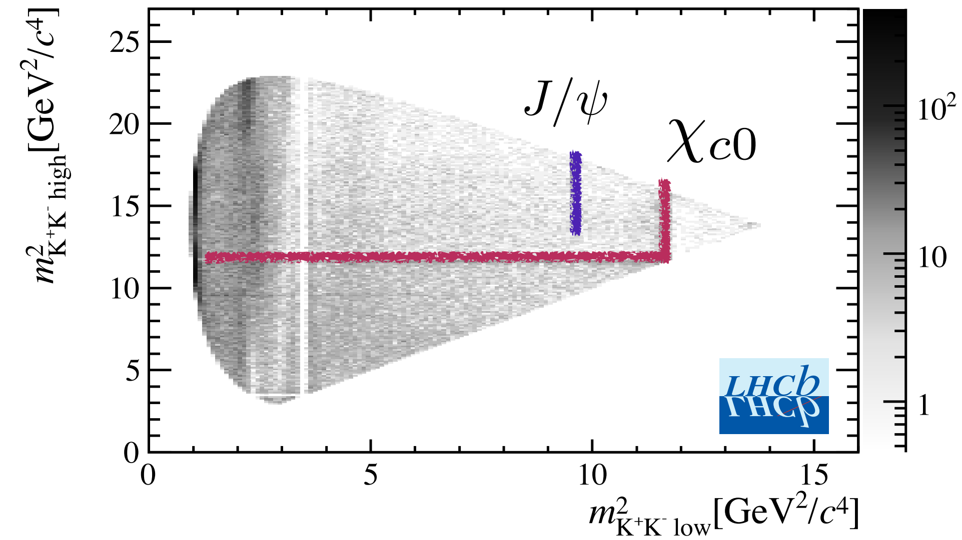
Contribution	Fit fraction (10^{-2})	A_{CP} (10^{-2})	B^+ phase (°)	B^- phase (°)
Isobar model				
$\rho(770)^0$	$55.5 \pm 0.6 \pm 2.5$	$+0.7 \pm 1.1 \pm 1.6$	—	—
$\omega(782)$	$0.50 \pm 0.03 \pm 0.05$	$-4.8 \pm 6.5 \pm 3.8$	$-19 \pm 6 \pm 1$	$+8 \pm 6 \pm 1$
$f_2(1270)$	$9.0 \pm 0.3 \pm 1.5$	$+46.8 \pm 6.1 \pm 4.7$	$+5 \pm 3 \pm 12$	$+53 \pm 2 \pm 12$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 1.9$	$-12.9 \pm 3.3 \pm 35.9$	$+127 \pm 4 \pm 21$	$+154 \pm 4 \pm 6$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.3$	$-80.1 \pm 11.4 \pm 25.3$	$-26 \pm 7 \pm 14$	$-47 \pm 18 \pm 25$
S-wave	$25.4 \pm 0.5 \pm 3.6$	$+14.4 \pm 1.8 \pm 2.1$	—	—
Rescattering	$1.4 \pm 0.1 \pm 0.5$	$+44.7 \pm 8.6 \pm 17.3$	$-35 \pm 6 \pm 10$	$-4 \pm 4 \pm 25$
σ	$25.2 \pm 0.5 \pm 5.0$	$+16.0 \pm 1.7 \pm 2.2$	$+115 \pm 2 \pm 14$	$+179 \pm 1 \pm 95$
K-matrix				
$\rho(770)^0$	$56.5 \pm 0.7 \pm 3.4$	$+4.2 \pm 1.5 \pm 6.4$	—	—
$\omega(782)$	$0.47 \pm 0.04 \pm 0.03$	$-6.2 \pm 8.4 \pm 9.8$	$-15 \pm 6 \pm 4$	$+8 \pm 7 \pm 4$
$f_2(1270)$	$9.3 \pm 0.4 \pm 2.5$	$+42.8 \pm 4.1 \pm 9.1$	$+19 \pm 4 \pm 18$	$+80 \pm 3 \pm 17$
$\rho(1450)^0$	$10.5 \pm 0.7 \pm 4.6$	$+9.0 \pm 6.0 \pm 47.0$	$+155 \pm 5 \pm 29$	$-166 \pm 4 \pm 51$
$\rho_3(1690)^0$	$1.5 \pm 0.1 \pm 0.4$	$-35.7 \pm 10.8 \pm 36.9$	$+19 \pm 8 \pm 34$	$+5 \pm 8 \pm 46$
S-wave	$25.7 \pm 0.6 \pm 3.0$	$+15.8 \pm 2.6 \pm 7.2$	—	—
QMI				
$\rho(770)^0$	$54.8 \pm 1.0 \pm 2.2$	$+4.4 \pm 1.7 \pm 2.8$	—	—
$\omega(782)$	$0.57 \pm 0.10 \pm 0.17$	$-7.9 \pm 16.5 \pm 15.8$	$-25 \pm 6 \pm 27$	$-2 \pm 7 \pm 11$
$f_2(1270)$	$9.6 \pm 0.4 \pm 4.0$	$+37.6 \pm 4.4 \pm 8.0$	$+13 \pm 5 \pm 21$	$+68 \pm 3 \pm 66$
$\rho(1450)^0$	$7.4 \pm 0.5 \pm 4.0$	$-15.5 \pm 7.3 \pm 35.2$	$+147 \pm 7 \pm 152$	$-175 \pm 5 \pm 171$
$\rho_3(1690)^0$	$1.0 \pm 0.1 \pm 0.5$	$-93.2 \pm 6.8 \pm 38.9$	$+8 \pm 10 \pm 24$	$+36 \pm 26 \pm 46$
S-wave	$26.8 \pm 0.7 \pm 2.2$	$+15.0 \pm 2.7 \pm 8.1$	—	—

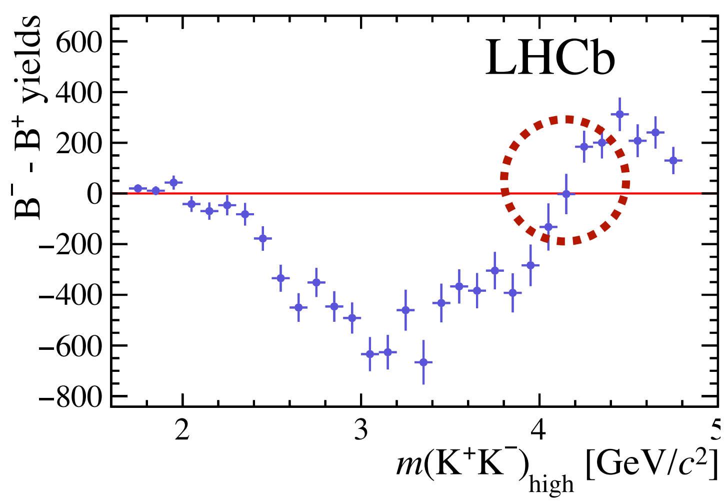
- ANA for $B^{\pm} \to \pi^{\pm} K^- K^+$ PRL 123 (2019) 231802

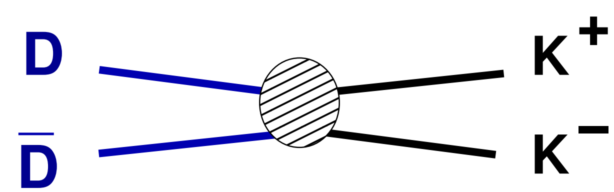
Contribution	Fit Fraction(%)	A_{CP}(%)	Magnitude (B^+/B^-)	Phase[^{o}] (B^+/B^-)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$	$0.94 \pm 0.04 \pm 0.02$	0 (fixed)
			$1.06 \pm 0.04 \pm 0.02$	0 (fixed)
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$	$0.74 \pm 0.09 \pm 0.09$	$-176 \pm 10 \pm 16$
			$0.82 \pm 0.09 \pm 0.10$	$136 \pm 11 \pm 21$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$	$2.19 \pm 0.13 \pm 0.17$	$-138 \pm 7 \pm 5$
			$1.97 \pm 0.12 \pm 0.20$	$166 \pm 6 \pm 5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$	$2.14 \pm 0.11 \pm 0.07$	$-175 \pm 10 \pm 15$
			$1.92 \pm 0.10 \pm 0.07$	$140 \pm 13 \pm 20$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$	$0.86 \pm 0.09 \pm 0.07$	$-106 \pm 11 \pm 10$
			$1.13 \pm 0.08 \pm 0.05$	$-128 \pm 11 \pm 14$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$	$1.91 \pm 0.09 \pm 0.06$	$-56 \pm 12 \pm 18$
			$0.86 \pm 0.07 \pm 0.04$	$-81 \pm 14 \pm 15$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$	$0.20 \pm 0.07 \pm 0.02$	$-52 \pm 23 \pm 32$
			$0.22 \pm 0.06 \pm 0.04$	$107 \pm 33 \pm 41$

CPV high energy

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

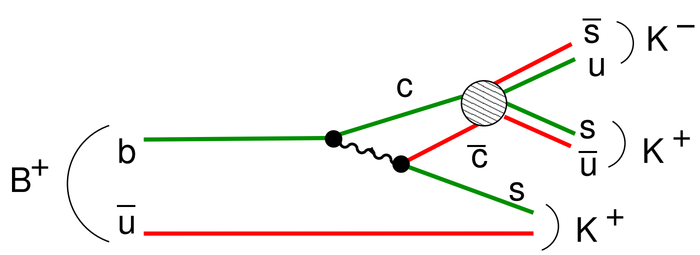


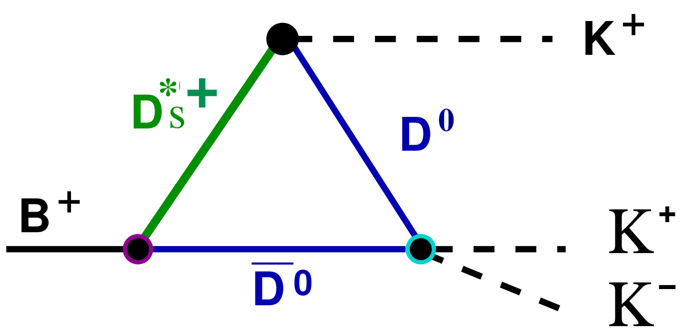




  - charm intermediate processes as source of strong phase

I. Bediaga, PCM, T Frederico
PLB 780 (2018) 357





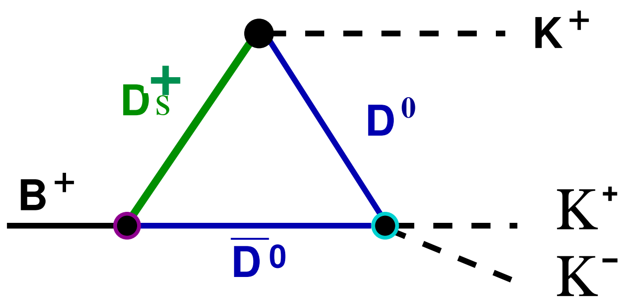
  - even dynamically suppressed $Br[B \to D D_s^*]$ ~1% → 1000 x $Br[B \to KKK]$

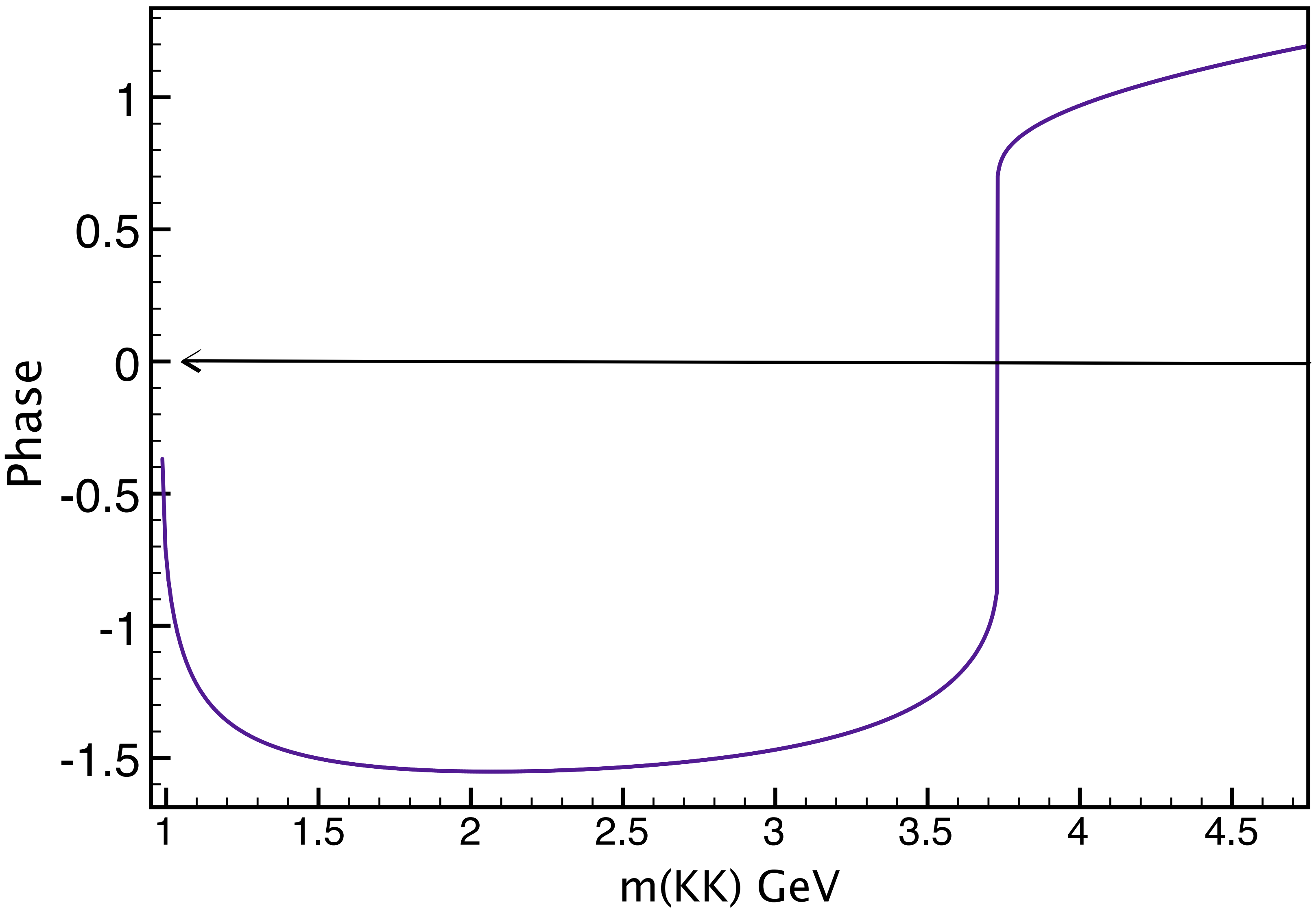
- hadronic loop technique $D^+ \to \pi^+ K^- \pi^+$

PCM & M Robilotta PRD 92 094005 (2015)
PCM et al PRD 84 094001 (2011)

hadronic loop results for $B^{\pm} \to K^{\pm} K^{-} K^{+}$

- Triangle hadronic loop with charm rescattering can generate a phase that change signal near DD threshold





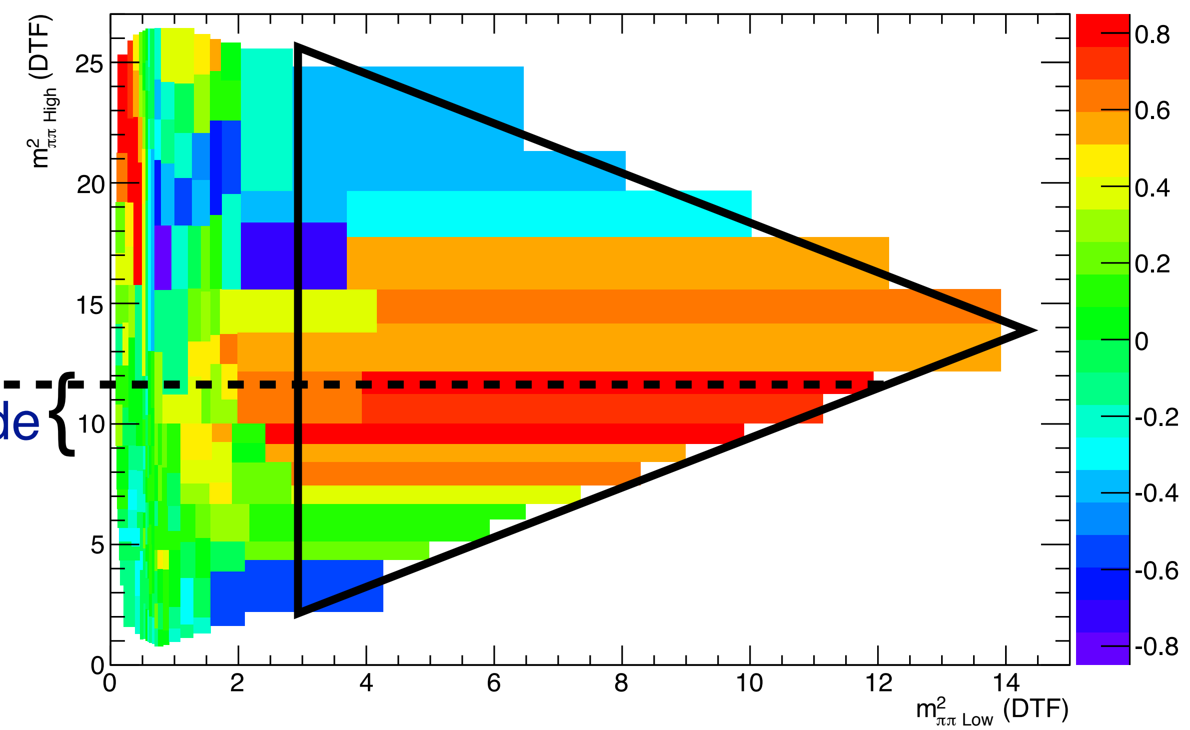
- how this can be translated to the observable CPV?

we need inference with weak-phase!

Bediaga, Frederico, PCM - PLBX (2020)[arXiv:2003.10019]

- high mass CPV study in $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$
  - Focus on $m^2_{\pi\pi} > 3\, GeV^2$
    - ↳ avoid low energy resonances
  - include χ_{c0} (expected in Run II)

Run I

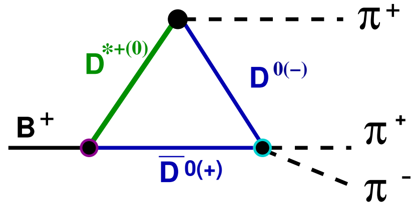


$m^2_{\chi_{c0}}$

wide

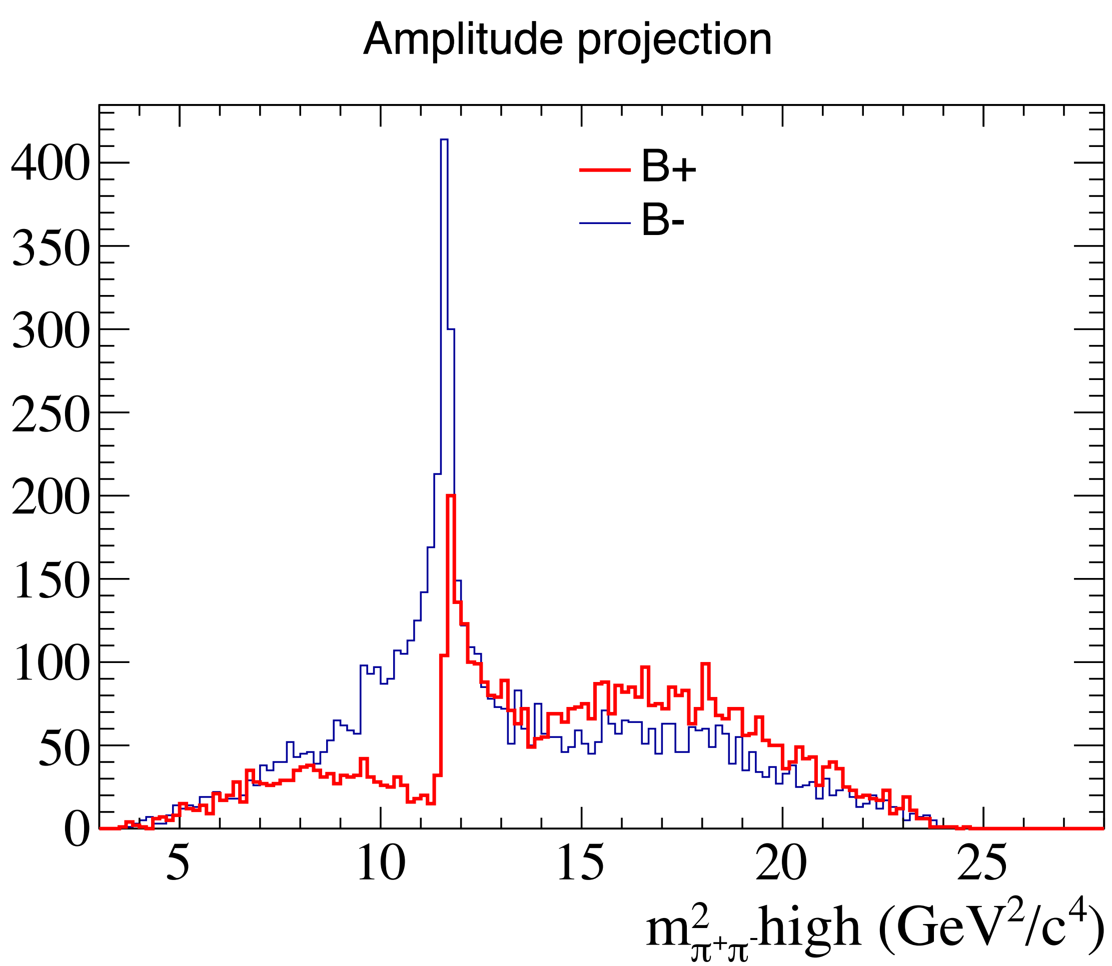
- Important data features
  - data shows a huge CP asymmetry around $m^2_{\chi_{c0}} = 11.65\, GeV^2$
  - wide CP asymmetry: same source for a nonresonant amplitude and χ_{c0}
    - ↳ charm loop and χ_{c0}

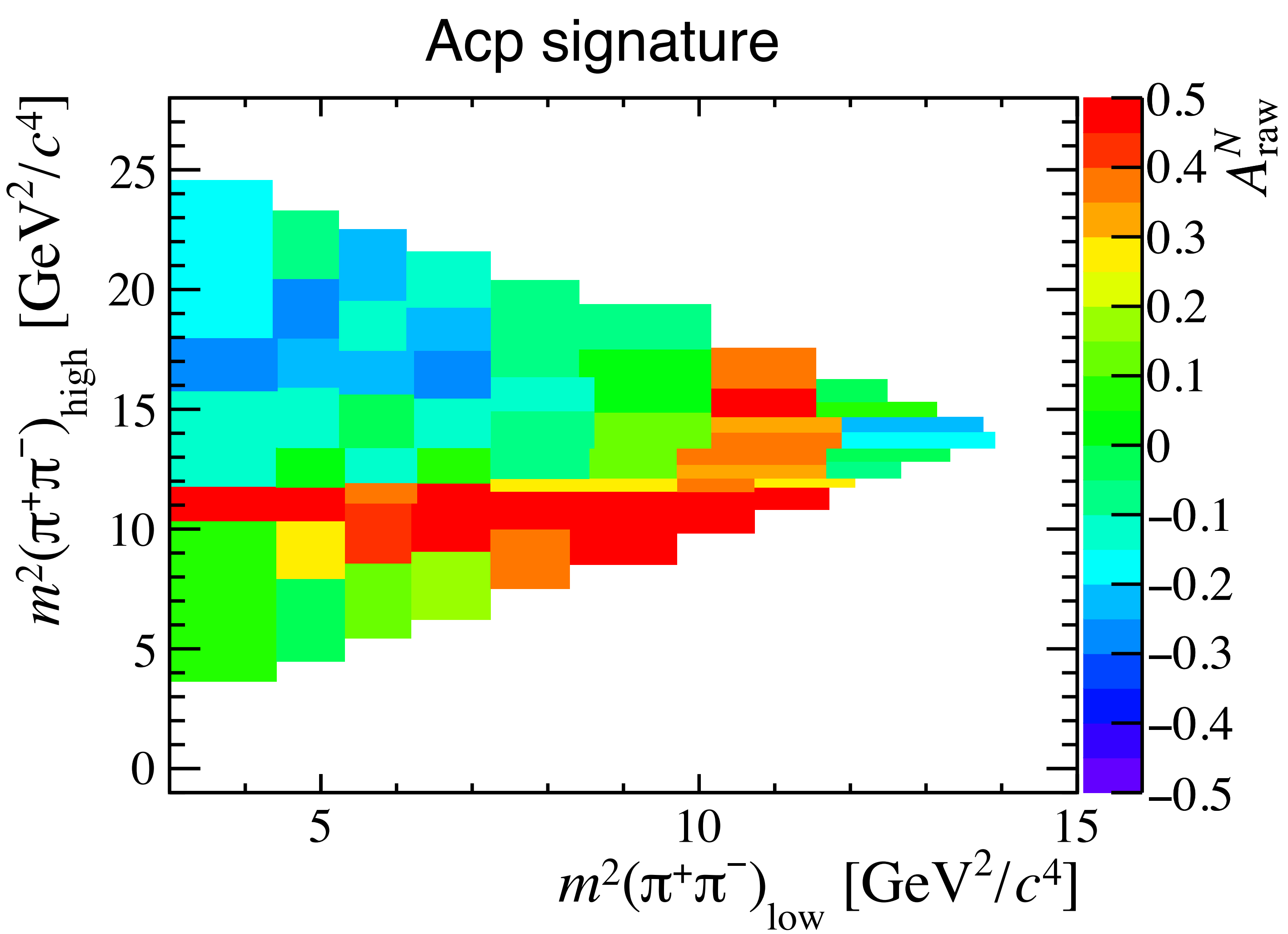
charm rescattering in $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$

- $A_{B^{\pm}\to\pi^{-}\pi^{+}\pi^{\pm}}(s_{12}, s_{23}) =$  $+ \quad a_0\, e^{\pm i\gamma}$

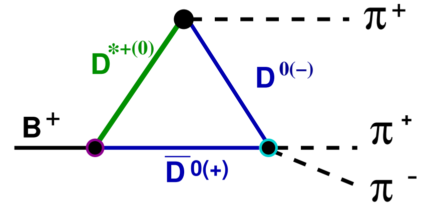
$$\gamma = 70^o$$
$$a_0 = 2\, e^{i(\delta_s = 45^o)}$$

- the goal was to reproduce the main observed CPV characteristics





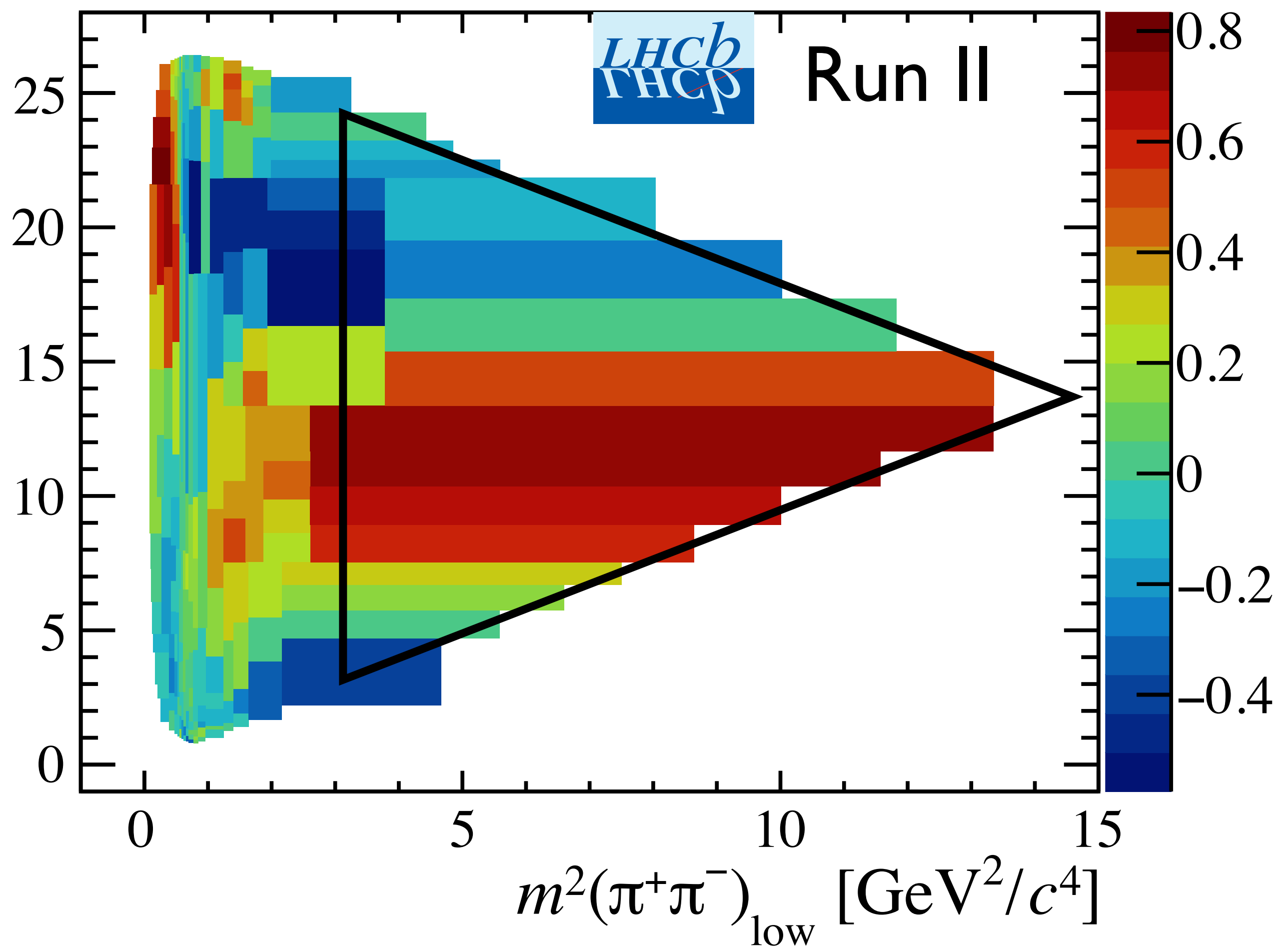
charm rescattering in $B^\pm \to \pi^\pm\pi^-\pi^+$

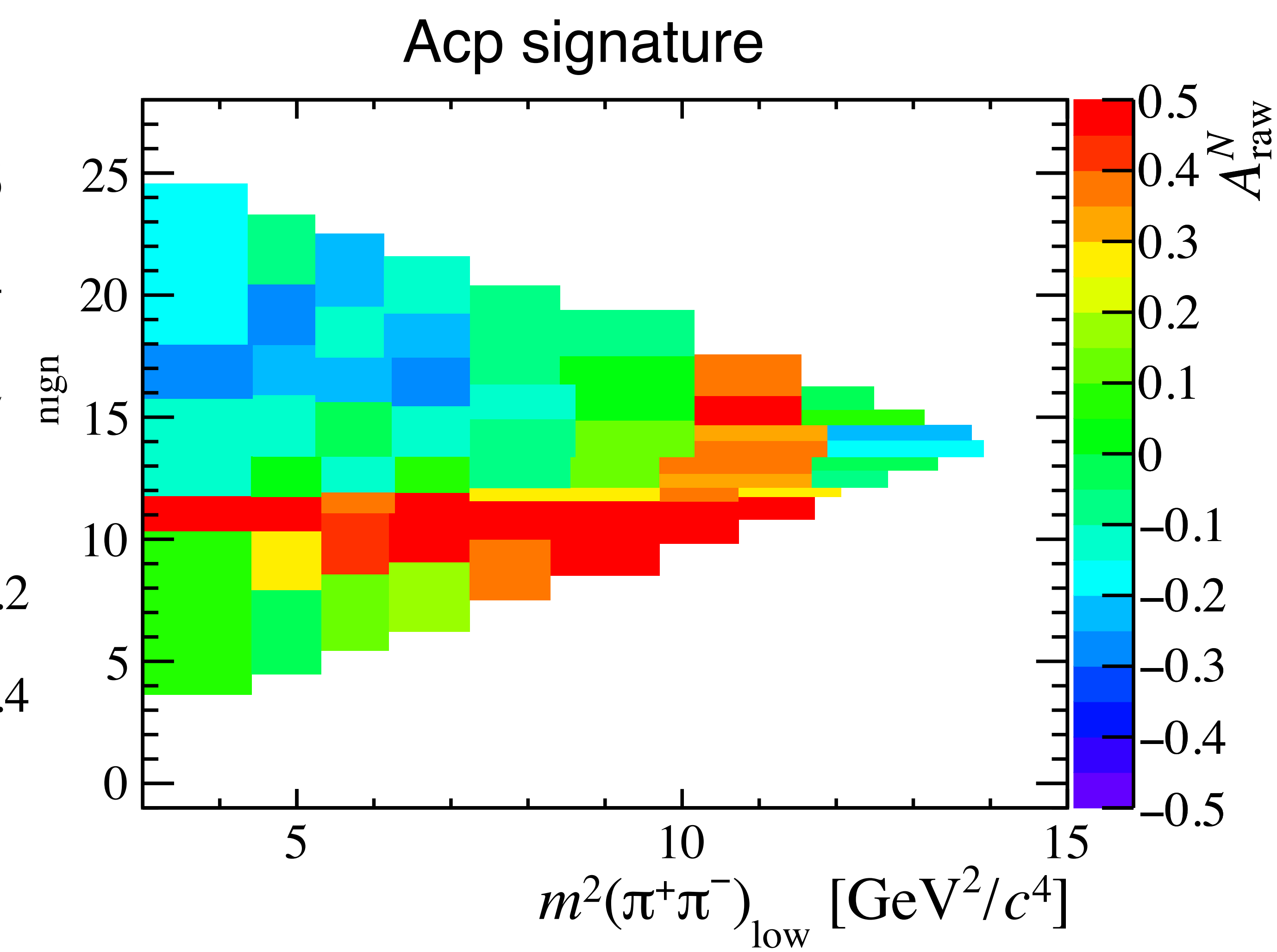
- $A_{B^\pm\to\pi^-\pi^+\pi^\pm}(s_{12},s_{23}) =$ 

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

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

- the goal was to reproduce the main observed CPV characteristics



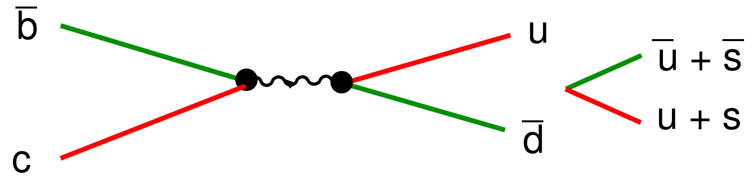


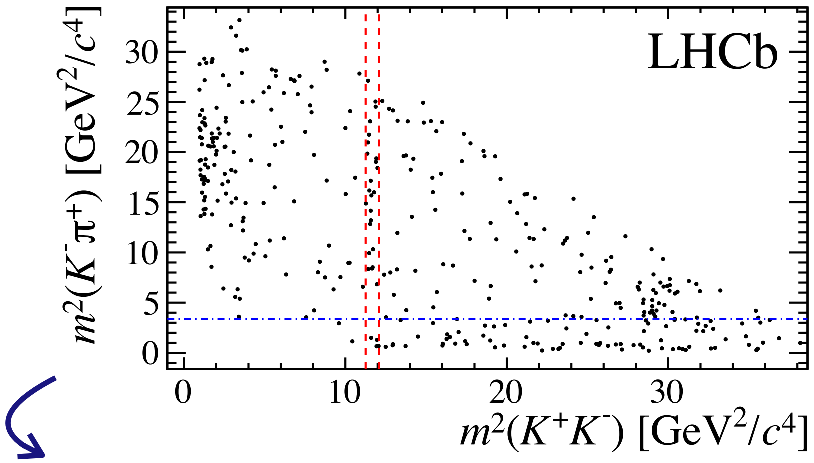
→ mimic some of the CPV pattern at high mass

→ implementing this in RunII amplitude analysis!

charm rescattering in $B_C^+ \to K^+K^-\pi^+$

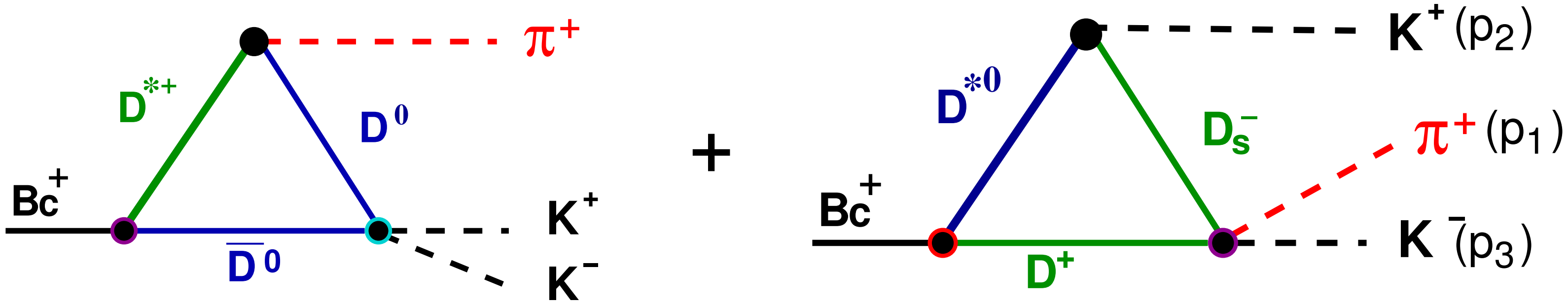
- $B_c^+ \to K^+K^-\pi^+$
  - very suppressed direct production (annihilation)





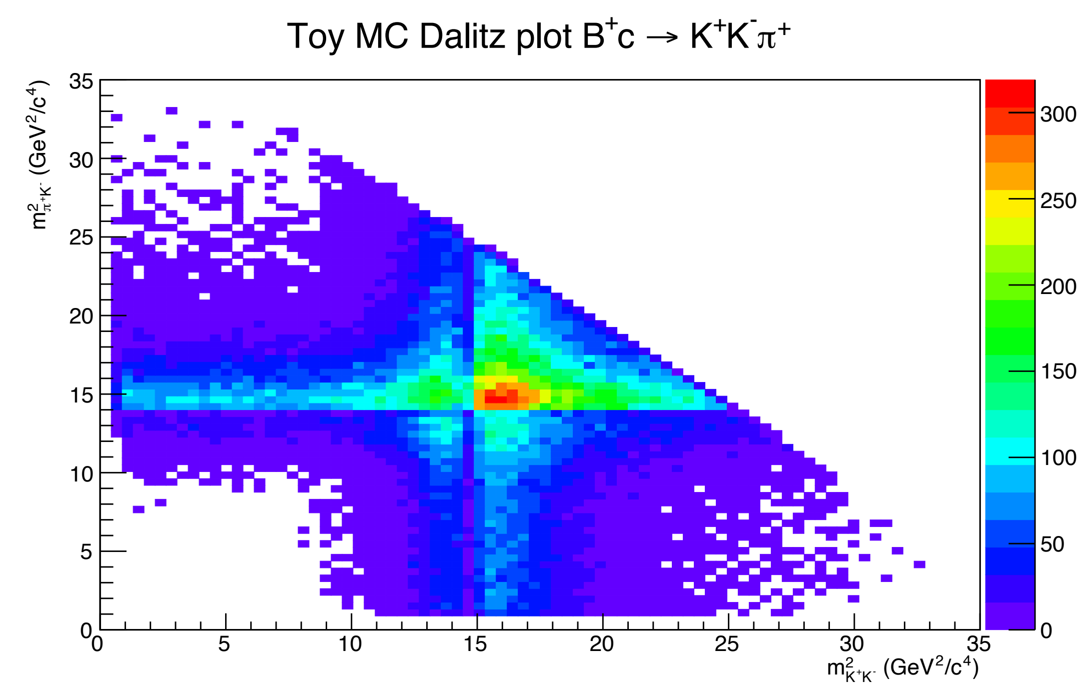
more events than expected

- Charm rescattering can be the dominant mechanism to generate $KK\pi$



I. Bediaga, PCM, T Frederico
PLB 785 (2018) 581

  - same favored weak vertex
  - leave a signature in the middle of the Dalitz plot
  - new data can test it !



$B^{\pm} \to h^{\pm}(V \to h^- h^+)$ CP Violation directly from data

Bediaga, Frederico, PCM
PRD 94 (2016) 054028

- Proposed a method to extract the type of CPV in particular regions of the phase-space directly from data

- Amplitudes contain only one vector resonance and NR background

$$\mathcal{M}_+ = a_+^V e^{i\delta_+^V} F_V^{\rm BW} \cos\theta(s_\perp, s_\parallel) + a_+^{\rm NR} e^{i\delta_+^{\rm NR}} F^{\rm NR}$$
$$\mathcal{M}_- = a_-^V e^{i\delta_-^V} F_V^{\rm BW} \cos\theta(s_\perp, s_\parallel) + a_-^{\rm NR} e^{i\delta_-^{\rm NR}} F^{\rm NR}$$

$S_{||} \equiv (p_{h^+} + p_{h^-})^2$
$S_\perp \equiv (p_{h_b} + p_{h^\pm})^2$
$\theta \equiv$ helicity angle

- Asymmetry ∝ to square modulus of amplitude difference:

$$|\mathcal{M}_+|^2 \mp |\mathcal{M}_-|^2 = \left[\left(a_+^V\right)^2 \mp \left(a_-^V\right)^2\right] \left|F_V^{\rm BW}\right|^2 \cos^2\theta\left(s_\perp, s_\parallel\right) + \left[\left(a_+^{\rm NR}\right)^2 \mp \left(a_-^{\rm NR}\right)^2\right] \left|F^{\rm NR}\right|^2$$
$$+ 2\cos\theta\left(s_\perp, s_\parallel\right) \left|F_V^{\rm BW}\right|^2 \left|F^{\rm NR}\right|^2 \times$$
$$\left\{\left(m_V^2 - s_\parallel\right)\left[a_+^V a_+^{\rm NR} \cos\left(\delta_+^V - \delta_+^{\rm NR}\right) \mp a_-^V a_-^{\rm NR} \cos\left(\delta_-^V - \delta_-^{\rm NR}\right)\right]\right.$$
$$\left. - m_V \Gamma_V \left[a_+^V a_+^{\rm NR} \sin\left(\delta_+^V - \delta_+^{\rm NR}\right) \mp a_-^V a_-^{\rm NR} \sin\left(\delta_-^V - \delta_-^{\rm NR}\right)\right]\right\}$$

direct vector A_{CP} | direct NR A_{CP} | NR and vector interference

$B^\pm \to h^\pm(V \to h^- h^+)$ CP Violation directly from data

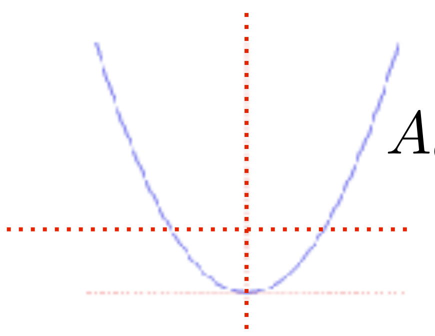
Bediaga, Frederico, PCM
PRD 94 (2016) 054028

- we select a small region around the resonance in $s_\parallel$ and look for the distribution $\Delta|\mathcal{M}^2|$ on $s_\perp$
  - $s_\parallel \approx m_V^2$ → cosθ ($s_\perp$)
  - can parametrize $$\Delta|\mathcal{M}|^2 = a(x - c_0)^2 + b(x - c_0) + c$$ for $\cos\theta = x - c_0$

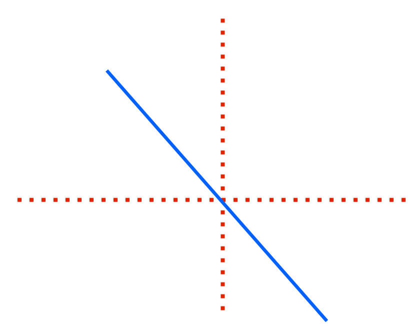
a ⇒ direct vector A_{CP}

b ⇒ interference

c ⇒ direct NR A_{CP}



$$A_{CP} = \frac{a^+ - a^-}{a^+ + a^-}$$



constant

- Applied to LHCb runII data !

Decay channel	Vector Resonance	$\mathcal{A}_{CP}^V \pm\sigma_{\text{stat}} \pm \sigma_{\text{syst}}$	
$B^\pm \to \pi^\pm\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	-0.004 ± 0.017 ± 0.007	(0.2σ)
$B^\pm \to K^\pm\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	+0.150 ± 0.019 ± 0.008	(7.2σ)
	$K^*(892)^0 \to K^\pm\pi^\mp$	-0.015 ± 0.021 ± 0.007	(0.7σ)
$B^\pm \to \pi^\pm K^+K^-$	$K^*(892)^0 \to K^\pm\pi^\mp$	+0.007 ± 0.054 ± 0.028	(0.1σ)
$B^\pm \to K^\pm K^+K^-$	$\phi(1020) \to K^+K^-$	+0.004 ± 0.010 ± 0.006	(0.2σ)

Global CP Violation

Bediaga, Frederico, PCM, Torres Machado
PLB 824 (2022) 136824

- understand global asymmetries in LHCb data

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

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

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

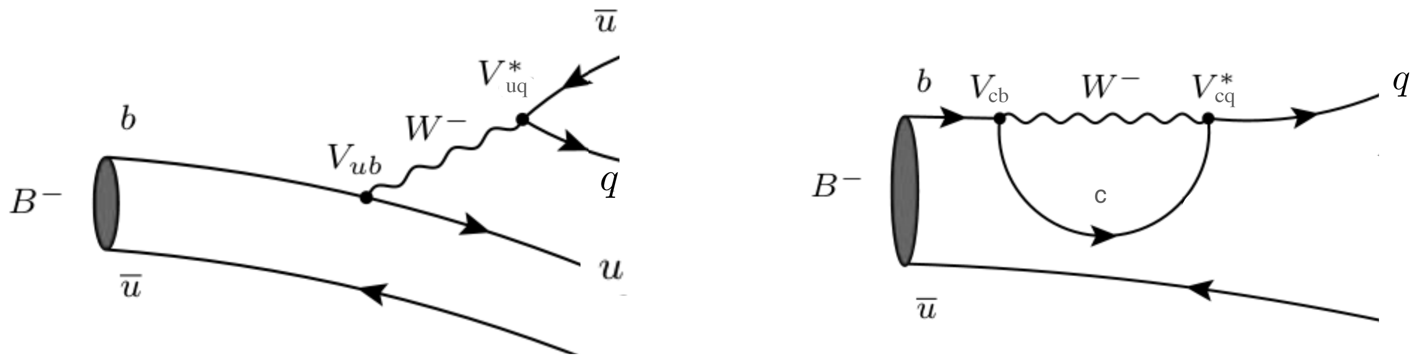
U-spin & FSI ? $$\frac{\Delta\Gamma_{CP}(K^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}\pi^{+}\pi^{-})} = 1.59 \pm 0.62 \text{ and } \frac{\Delta\Gamma_{CP}(K^{\pm}K^{+}K^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}K^{+}K^{-})} = 1.77 \pm 0.55$$

only U-spin don't work

Global CP Violation

Bediaga, Frederico, PCM, Torres Machado
PLB 824 (2022) 136824

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



$q = d, s$

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

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

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

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

- S-matrix unitarity and CPT invariance applied to 2-coupled-channel $\pi\pi \leftrightarrow KK$

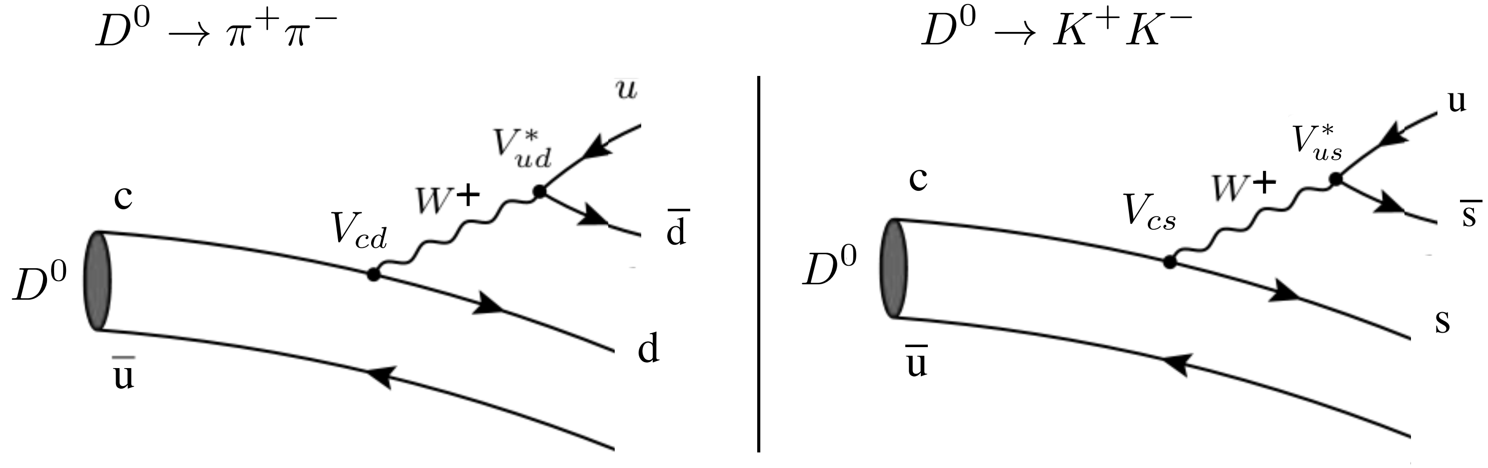
  ↪ $\sum \Delta\Gamma_{CP} = 0 \rightarrow \Delta\Gamma(q_{\pi\pi}) = -\Delta\Gamma(q_{KK})$

- $$\frac{\Delta\Gamma_{CP}(\pi^{\pm}K^{+}K^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}\pi^{+}\pi^{-})} = -0.73 \pm 0.23 \qquad \frac{\Delta\Gamma_{CP}(K^{\pm}K^{+}K^{-})}{\Delta\Gamma_{CP}(K^{\pm}\pi^{+}\pi^{-})} = -0.81 \pm 0.32$$

FSI as the source of CPV in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

- 1st observation in charm LHCb 2019 $A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$

- single cabibbo suppressed decays



$V_{cd}V^*_{ud} \approx \lambda(1 - \lambda^4\, e^{i\delta})$

$V_{cs}V^*_{us} \approx \lambda(1 - \lambda^2)$

- weak phase in KK is 20 times smaller

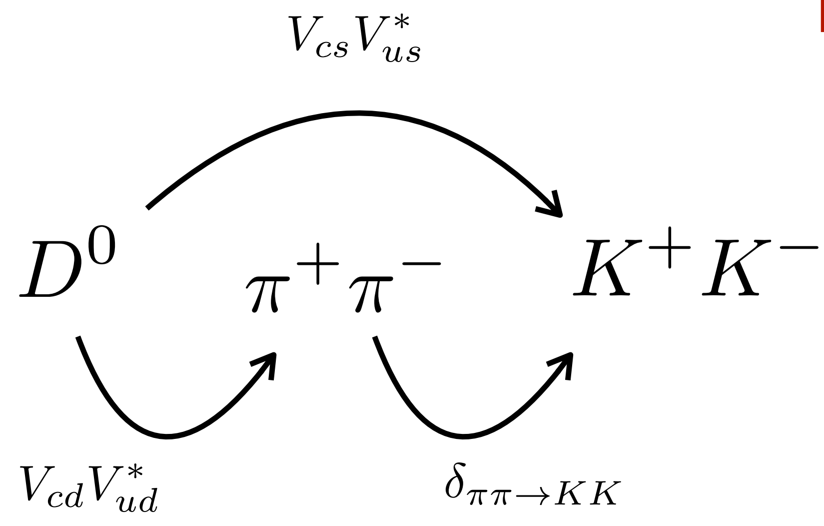
Lenz and Wilkinson, Annu. Rev. Nucl. Part. Sci. 71, 59 (2021)

→ what about strong phases if not from penguin? hadronic FSI

FSI as the source of CPV

Bediaga, Frederico, PCM
arXiv:2203.04056v2

- D and $\bar{D}$ can decay to $\pi\pi$ and KK



↘ known from 80's experiment

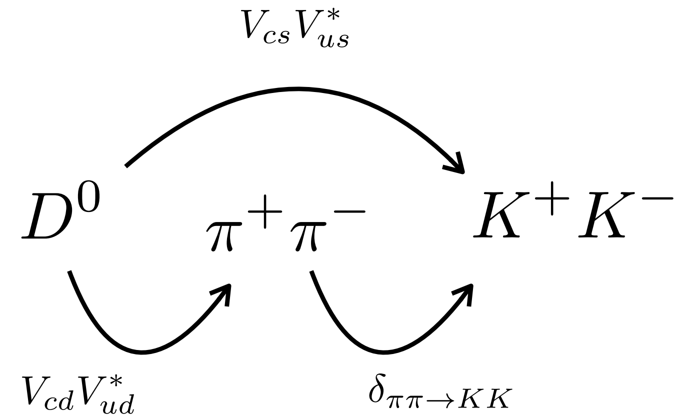
- Describe amplitudes decays implying three constraints:
  - CPT invariance relates channels with same quantum numbers

$$\rightarrow \sum \Delta\Gamma_{CP} = 0$$

  - Watson theorem relates the strong phase from the rescattering process to the decay amplitudes
  - the unitarity of the strong S-matrix.

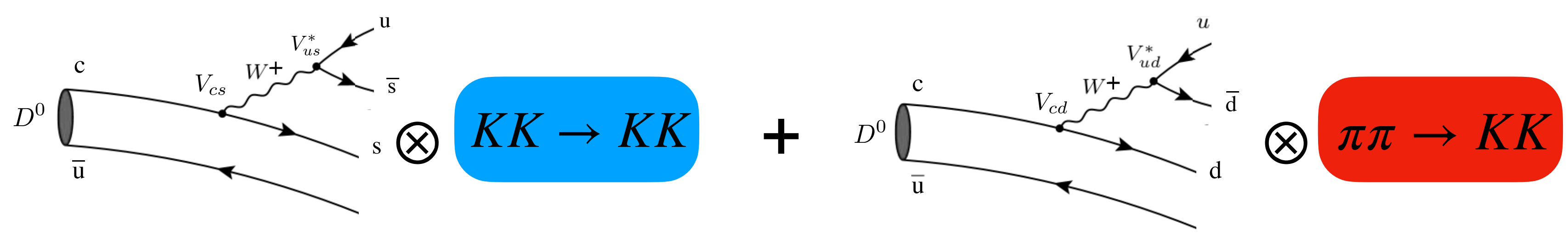
Decay amplitudes

- dressing the weak tree topology with FSI



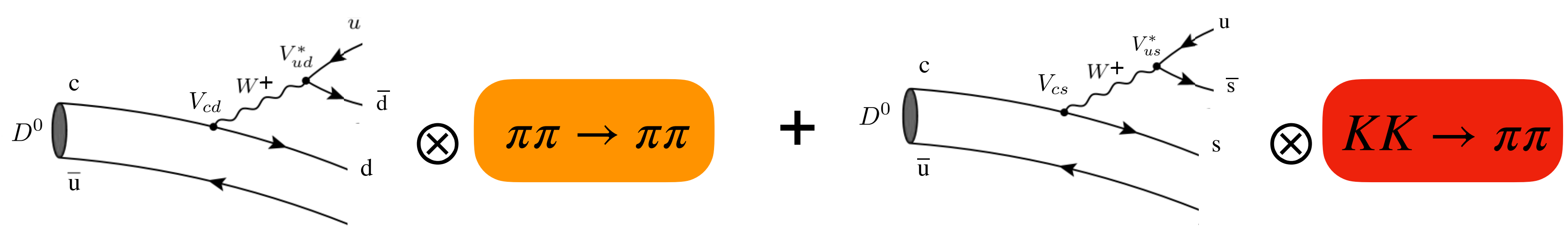
- $D^0 \to KK$

➔ $$\mathcal{A}_{D^0\to KK} = \eta\, \mathrm{e}^{2i\delta_{KK}}\, V_{cs}^* V_{us}\, a_{KK} + i\sqrt{1-\eta^2}\, \mathrm{e}^{i(\delta_{\pi\pi}+\delta_{KK})}\, V_{cd}^* V_{ud}\, a_{\pi\pi}$$



➔ $\mathcal{A}_{\bar{D}^0\to f}$ same with CKM cc.

- $D^0 \to \pi\pi$



➔ $$\mathcal{A}_{D^0\to \pi\pi} = \eta\, \mathrm{e}^{2i\delta_{\pi\pi}}\, V_{cd}^* V_{ud}\, a_{\pi\pi} + i\sqrt{1-\eta^2}\, \mathrm{e}^{i(\delta_{\pi\pi}+\delta_{KK})}\, V_{cs}^* V_{us}\, a_{KK}$$

- a_{KK} and $a_{\pi\pi}$ do not carry any or strong phases ➔ production

Final values for A_{CP}

- $$A_{CP}(f) \approx \pm 2 \frac{-\mathrm{Im}[V_{cs}^* V_{us} V_{cd} V_{ud}^*]}{|V_{cs}^* V_{us} V_{cd} V_{ud}^*|} \, \eta^{-1} \sqrt{1-\eta^2} \, \cos\phi \left[\frac{\mathrm{Br}(D^0 \to K^+K^-)}{\mathrm{Br}(D^0 \to \pi^+\pi^-)} \right]^{\pm\frac{1}{2}}$$

  - $\mathrm{Br}(D^0 \to \pi^+\pi^-) = (1.455 \pm 0.024) \times 10^{-3}$
    $\mathrm{Br}(D^0 \to K^+K^-) = (4.08 \pm 0.06) \times 10^{-3}$

    + $\pi\pi$
    − KK

  - $\eta \approx 0.973$ (from Pelaez Parametrization)

→ $A_{CP}(\pi\pi) = (0.47 \pm 0.13) \times 10^{-3}$

→ $A_{CP}(KK) = -(0.17 \pm 0.19) \times 10^{-3}$

$$\Delta A_{CP}^{th} = -(0.64 \pm 0.18) \times 10^{-3}$$

SM like!

$$\Delta A_{CP}^{\mathrm{LHCb}} = -(1.54 \pm 0.29) \times 10^{-3}$$

- In three-body this effect will be bigger and phase-space distributed
  - ↳ SCS $D^+ \to \pi^+\pi^-\pi^+$ and $D^+ \to \pi^+K^-K^+$ have exactly the same WV

Final remarks

- Crucial and profit theoretical x experimental Colaboration (Bediaga-CBPF/LHCb, Frederico-ITA, PCM-ITA/UOB/LHCb)

  We investigate the FSI role in B and D hadronic decays

  ↳ our phenomenological models have been implemented to LHCb data

- B decays: understand of CPV at low and high mass regions

  ↳ $\pi\pi \to KK$ rescattering dominates the global A_{CP} in $B \to hhh$

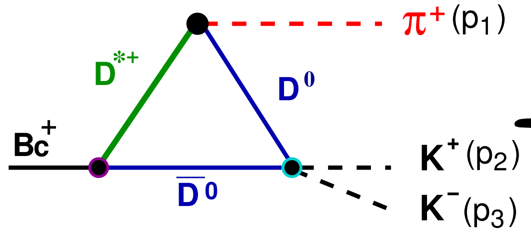
  ↳ make predictions to neutron modes!

  ↳ Charm rescattering triangles is an important mechanism

  ↳ interference produce similar CPV data signature

  ↳ developed a technique to identify the type of CPV directly from data

- Bc decays:

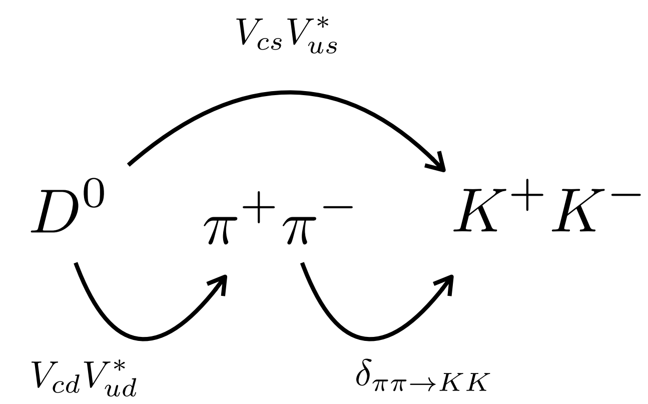


→ main mechanism to produce this final state

Final remarks

- D decays: we predicted ΔA_{CP} with FSI approach compatible with LHCb

  - the key ingredient is the coupling between $\pi\pi$ and $K\bar{K}$ channels as source of strong phase in a CPT invariant framework



↳ new measurement from LHCb will put a straight constraint

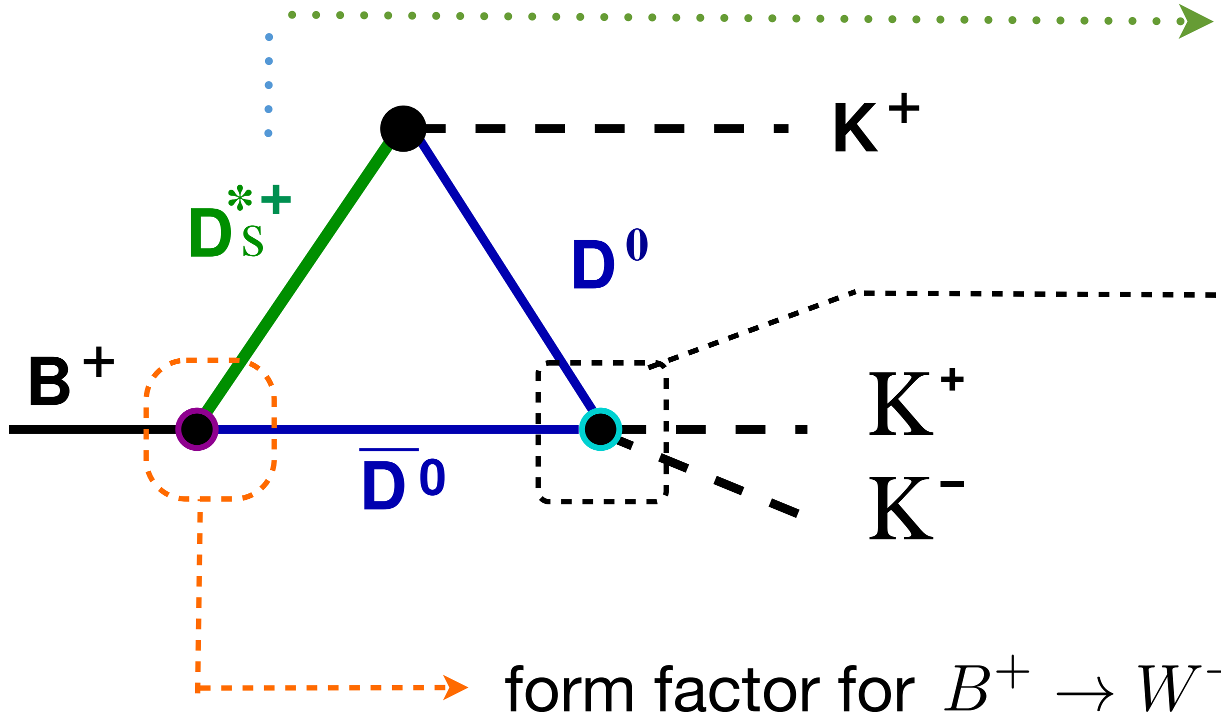
- much more to came!

obrigada!!

#staysafe

Banksy

Backup slides



$W^+ \to D_s^{+*} \to D^0 K^+$

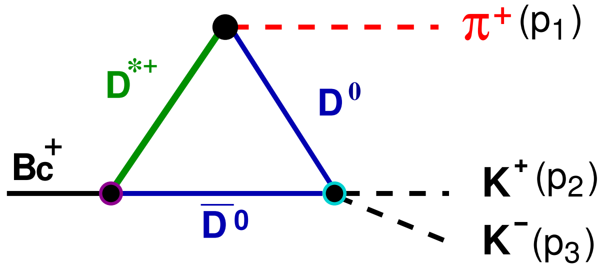
$D^0 \bar{D}^0 \to K^+ K^-$

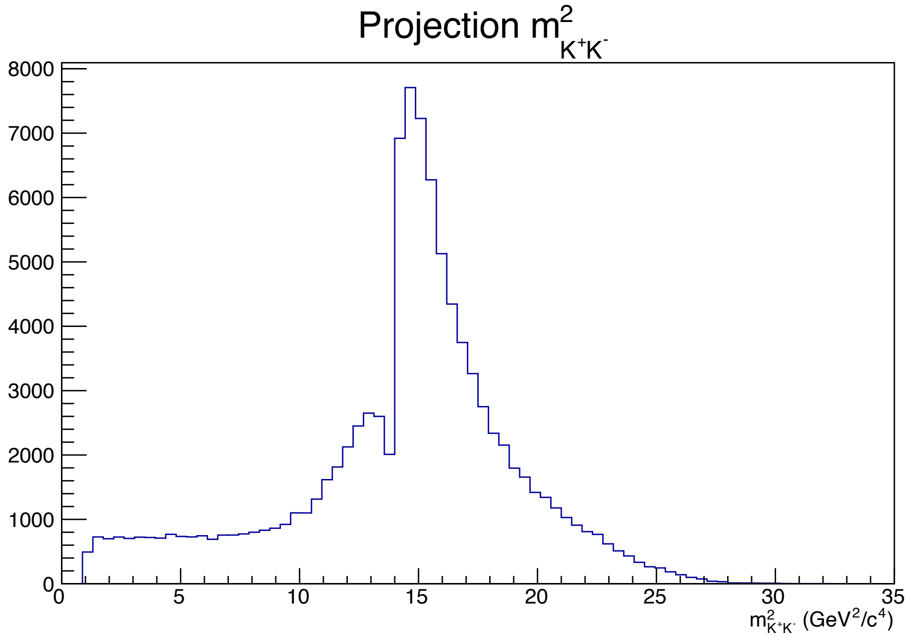
form factor for $B^+ \to W^+ \bar{D}^0$ (single pole B^*)

- $$A = iC\ m_a^2 \int \frac{d^4\ell}{(2\pi)^4} \frac{T_{\bar{D}^0 D^0 \to KK}(s_{23})\,[-2\,p_3' \cdot (p_2' - p_1)]}{\Delta_{D^{+*}}\,\Delta_{D^0}\,\Delta_{\bar{D}^0}\,\Delta_a}\,, \quad \to \quad \Delta_{D^{+*}} = s - m_{D^{*+}}^2$$
- $$A = iC\ m_a^2\ T_{\bar{D}^0 D^0 \to KK}(s_{23}) \int \frac{d^4\ell}{(2\pi)^4} \frac{\Delta_{D^0} + 2\,\Delta_{\bar{D}^0} - 2\,s_{23} + 3\,M_K^2 + M_B^2 - l^2}{\Delta_{D^0}\,\Delta_{\bar{D}^0}\,\Delta_{D^*}\,[l^2 - m_{B^*}]}$$

→ solved by Feynman technique

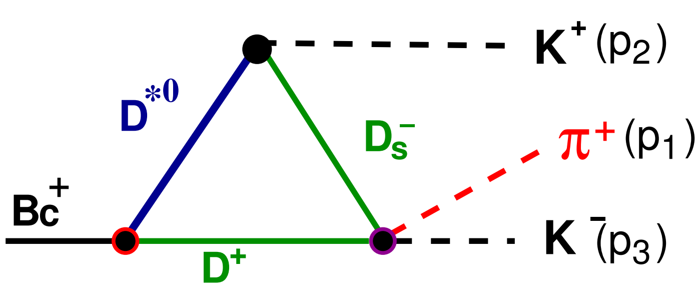
- Amplitudes projections

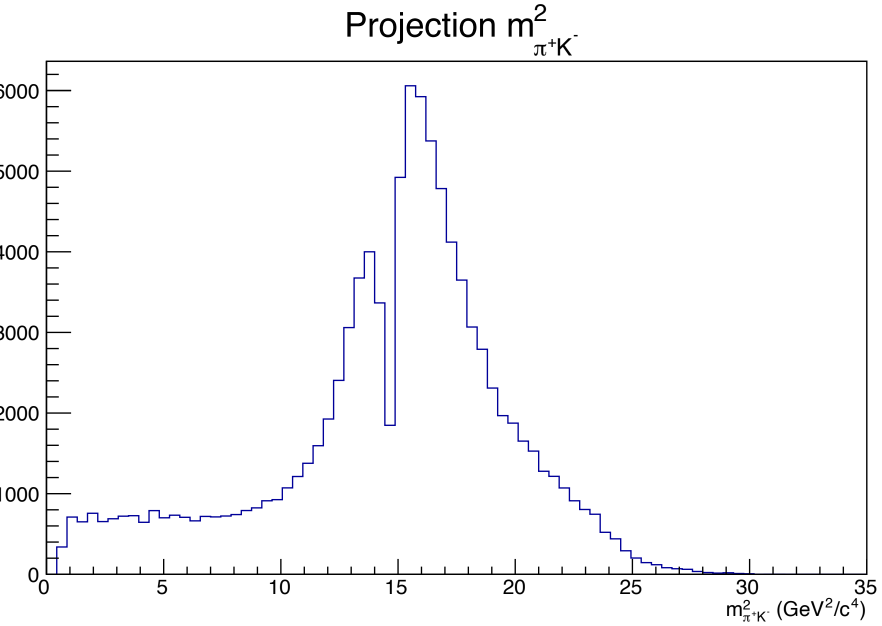




⟶ minima in different positions (≠ thresholds)

⟶ ≠ mass parameters inside triangle and rescattering amplitudes are relevant





CPT in SCS D decays

- In principle FSI in D, $\bar{D}$ can include multiple mesons
  - general S-matrix can mix this FSI states

$$S = \begin{pmatrix} S_{2M,2M} & S_{2M,3M} & S_{2M,4M} & \cdots \\ S_{3M,2M} & S_{3M,3M} & S_{3M,4M} & \cdots \\ S_{4M,2M} & S_{4M,3M} & S_{4M,4M} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}$$

- $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$

assume only 2 couple-channels will contribute to FSI, ie the dominant one $K\bar{K}$

$$\rightarrow \quad S_{2M,2M} = \begin{pmatrix} S_{\pi\pi,\pi\pi} & S_{\pi\pi,KK} \\ S_{KK,\pi\pi} & S_{KK,KK} \end{pmatrix}$$

$$S_{\pi\pi,\pi\pi} = \eta\, e^{2i\delta_{\pi\pi}} \quad S_{KK,KK} = \eta\, e^{2i\delta_{KK}}$$
$$S_{\pi\pi,KK} = S_{KK,\pi\pi} = \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_{\pi\pi}+\delta_{KK})}$$

- two pions cannot go to three pions due to G-parity
- ignore four pion coupling to the 2M channel based on 1/Nc counting
- ignore $\eta\eta$ channel once their coupling to the $\pi\pi$ channel are suppressed with respect to $K\bar{K}$.

- CPT constraint restricted to the two-channels: $\sum_{f=(\pi\pi,KK)} (|\mathcal{A}_{D^0\to f}|^2 - |\mathcal{A}_{\bar{D}^0\to f}|^2) = 0$

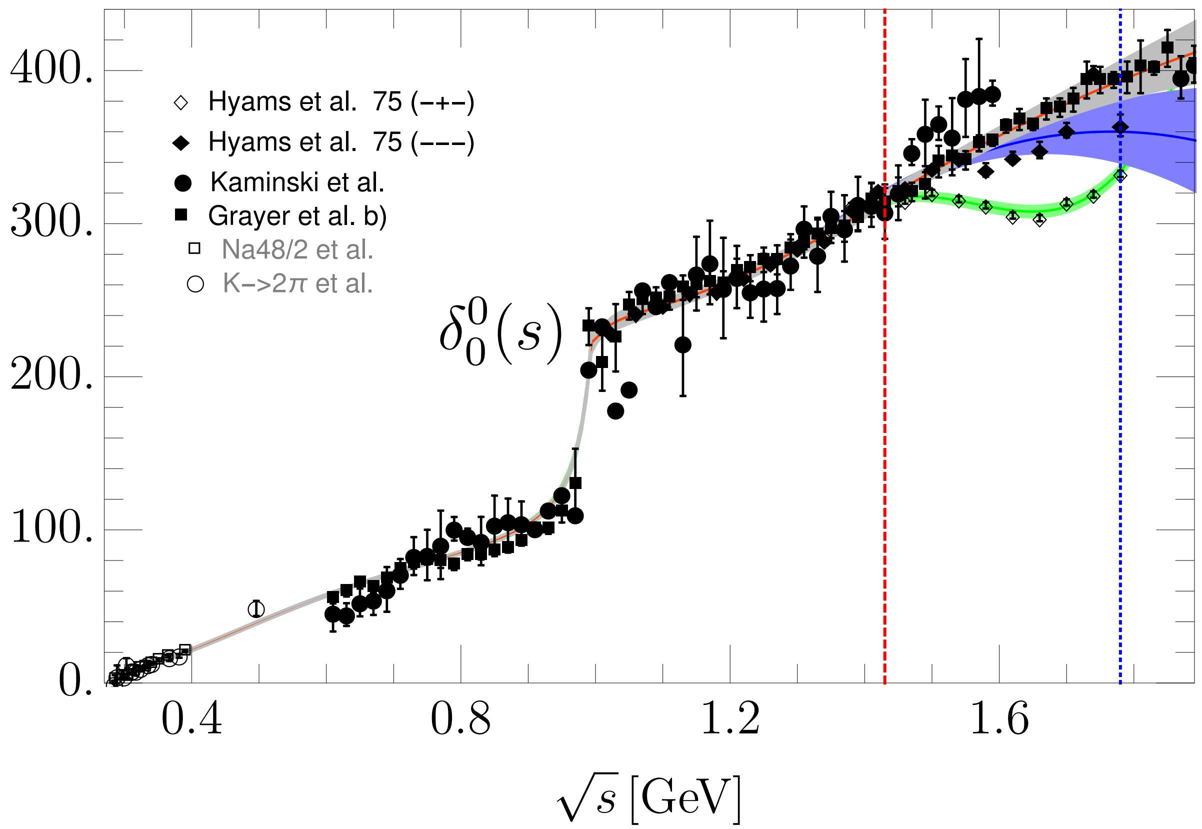
Watson theorem

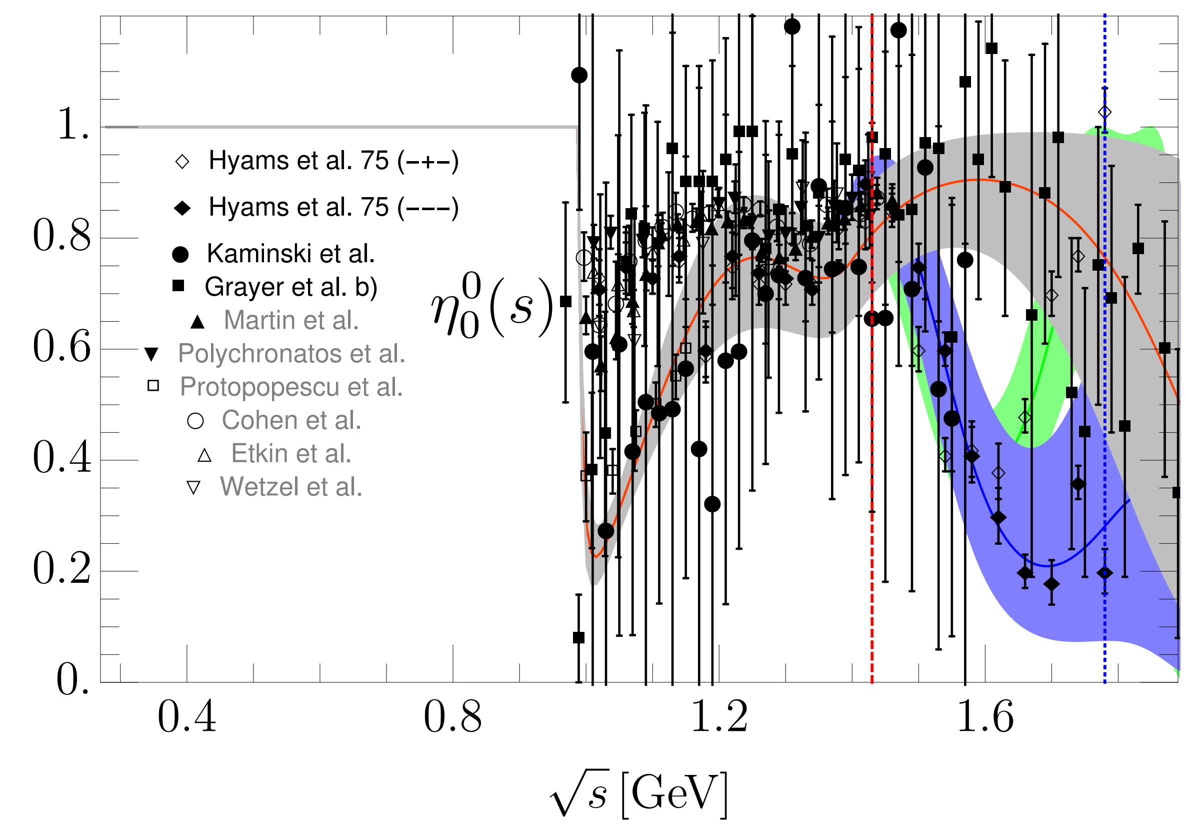
- strong phases $\delta_{\pi\pi}$, δ_{KK} and $\delta_{\pi\pi\to KK}$ are the same independent of the initial process

→ we can use CERN-Munich data from 80's

Longacre et al., Phys. Lett. B 177, 223 (1986)
Hyams et al., Nucl. Phys. B 100, 205 (1975)
Ochs, J. Phys. G 40, 043001 (2013)

- $\pi\pi \to \pi\pi$





Pelaez, Rodas, Elvira *Eur.Phys.J.C* 79 (2019) 12, 1008

amplitude $\hat{f}_l(s) = \left[\frac{\eta_l e^{2i\delta_l} - 1}{2i}\right].$

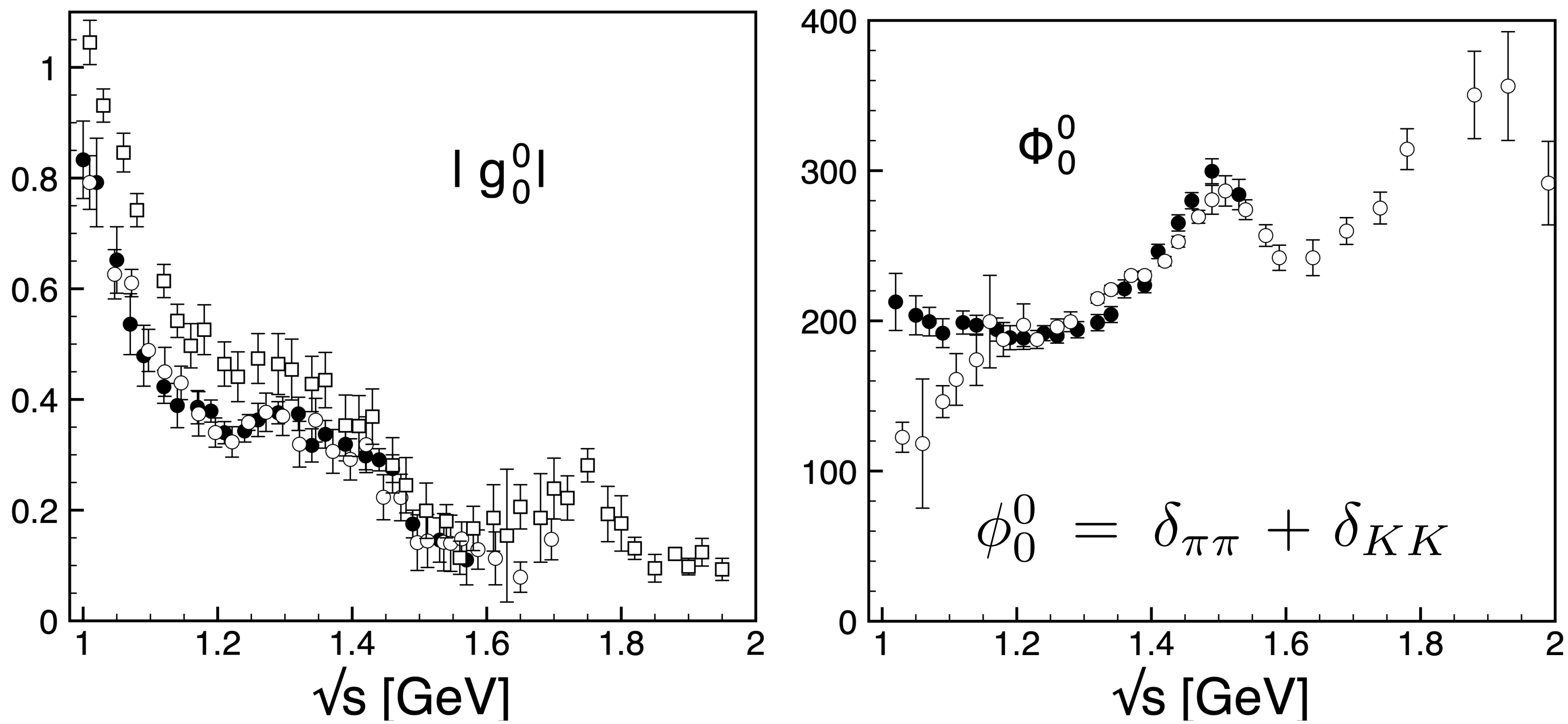
→ elasticity drops dramatically near $K\bar{K}$ → strongly couple

Watson theorem

- $\pi\pi \to KK$

$$S_{\pi\pi,KK}(s) = \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_{\pi\pi}+\delta_{KK})} = i\,4\sqrt{\frac{q_\pi q_K}{s}}|g_0^0(s)|\,e^{i\phi_0^0(s)}\,\Theta(s-4m_K^2)$$

Pelaez and Rodas, Eur. Phys. J. C 78, 897 (2018)



Cohen et al., Phys. Rev. D 22, 2595 (1980)
Etkin et al., Phys. Rev. D 25, 1786 (1982)

- Pelaez parametrization @ M_D^2:

$|g_0^0(M_D^2)| \approx 0.125 \pm 0.025$ → $\sqrt{1-\eta^2} \approx 0.229 \pm 0.046$ → $\eta \approx 0.973$

$\phi_0^0 = \delta_{\pi\pi} + \delta_{KK} \approx 343^o \pm 8^o$