Final State Interactions in 3-body decay: challenges and future

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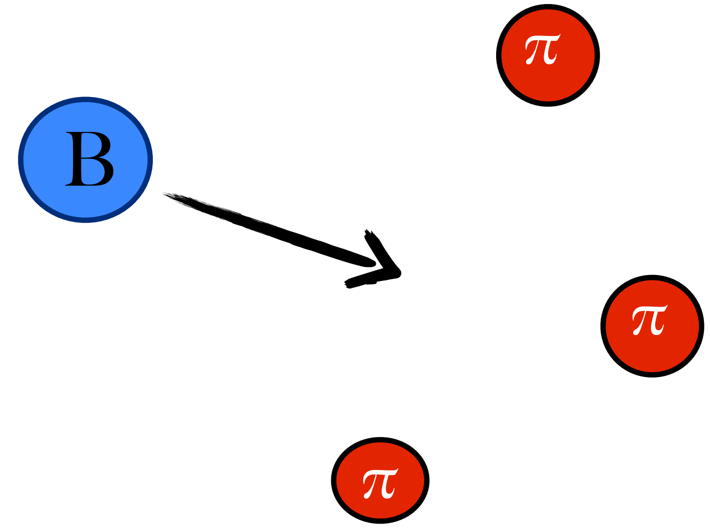
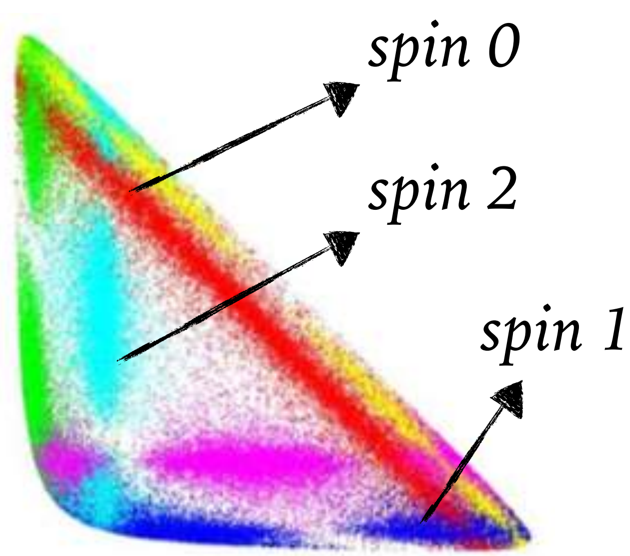
XV International Workshop on Hadron Physics - 13/09/2021

- Multi-body hadronic decays of B and D mesons

  ↪ are sensitive to strong phases



- signature of two-body resonances on data
  - spectroscopy



→ light scalars in (2001/2002) σ $[f_0(500)]$ and κ $[K_0^*(700)]$

→ exotics, tetra-quarks, pentaquark,…

- new high data sample from LHCb ⟶ more to come from LHCb, BelleII, BESIII

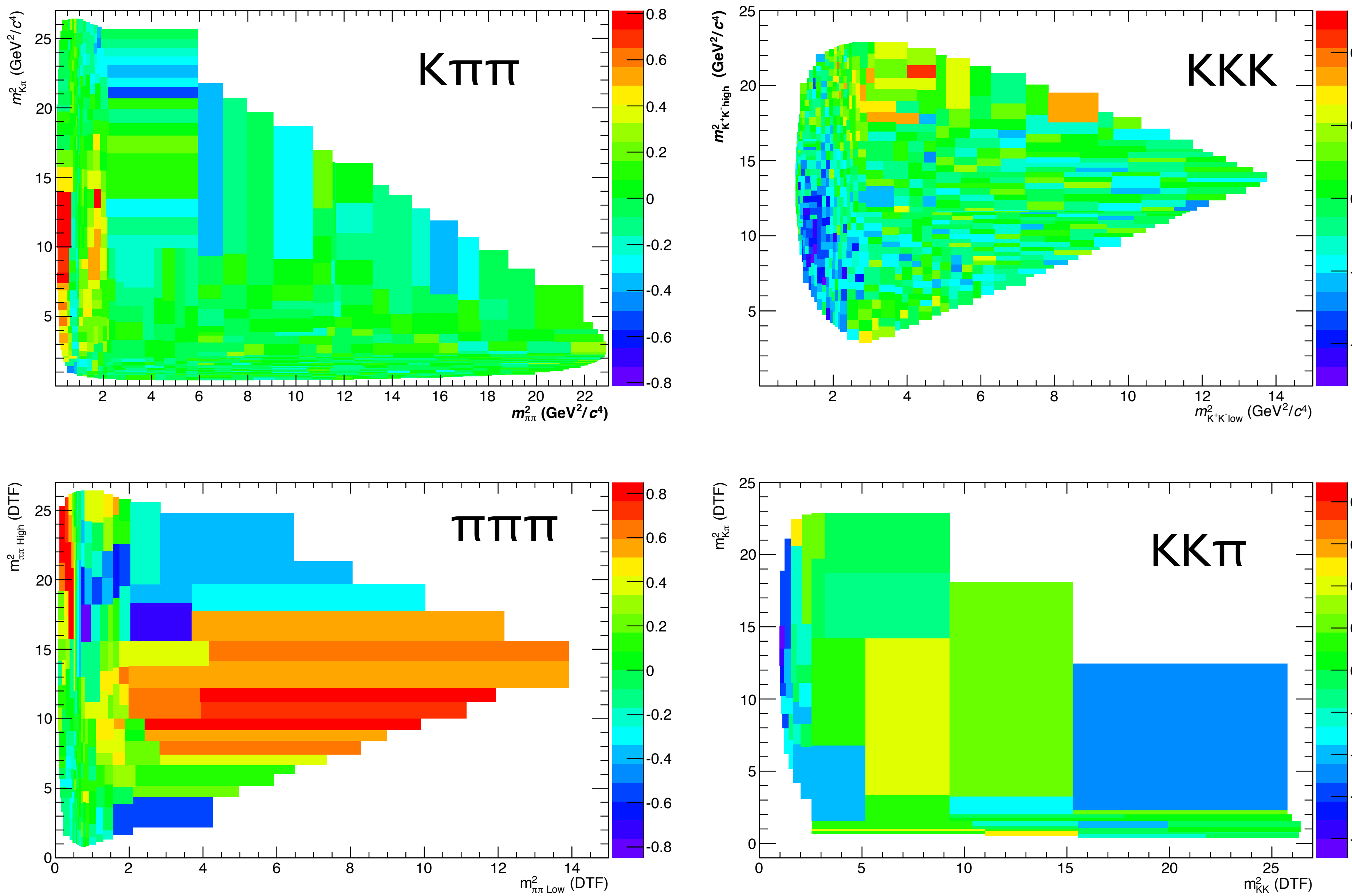
  ↪ simple models (only focus on two-body resonances) are not enough to explain data anymore

theoretical challenge !

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

LHCb PRD90 (2014) 112004
new one coming soon

- suggest dynamic effect
- middle looks "empty" $\downarrow$ CPV

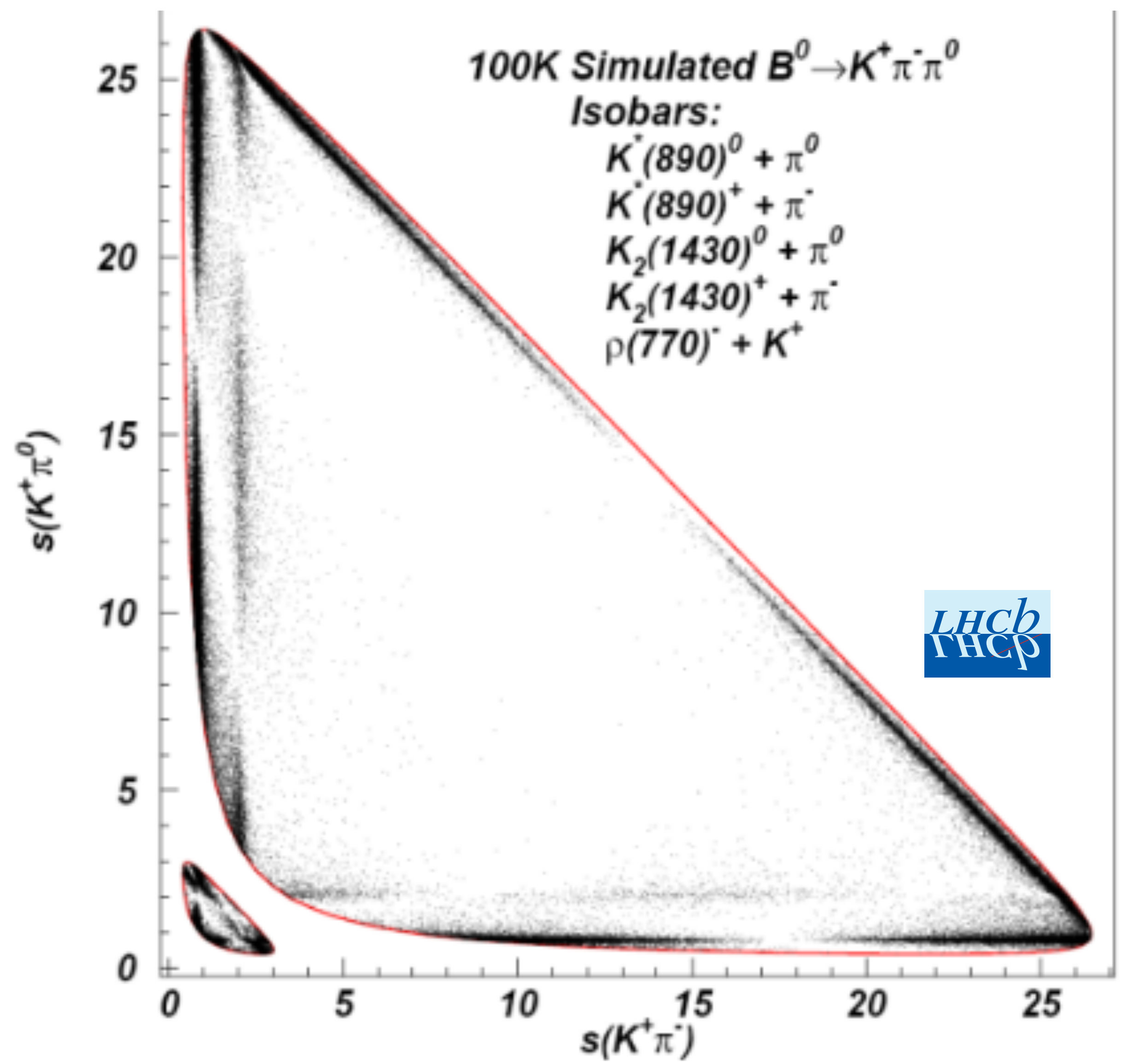


- 1st observation in charm LHCb 2019 $A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$

$\rightarrow$ CPV on charm three-body? can lead to new physics

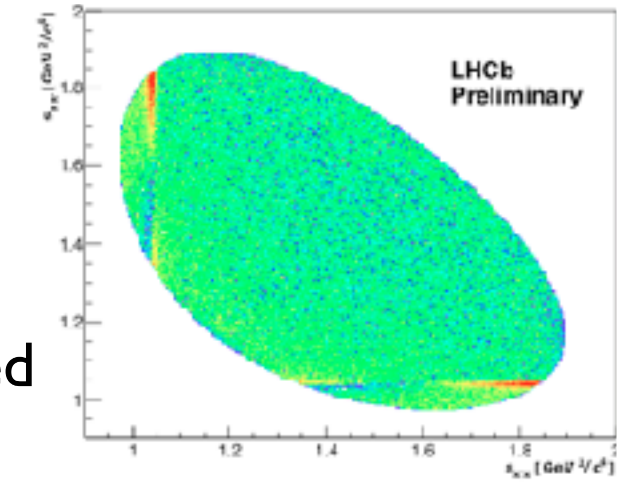
phase-space in D and B decays

- ≠ scales!!! → still similar FSI
- 3-body effects expected to be smaller in B
- B phase-space → + FSI possibilities

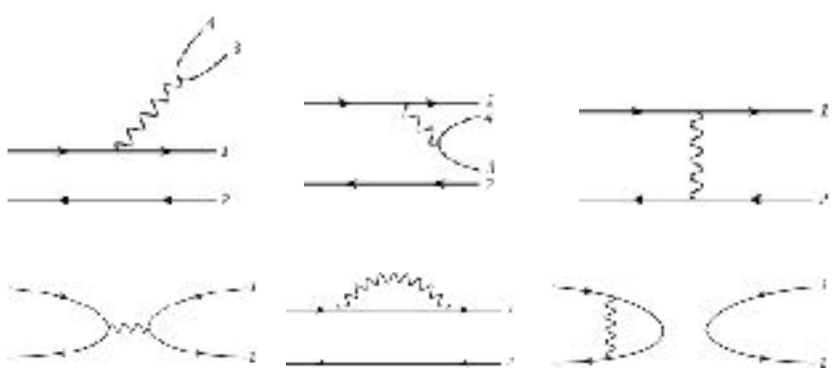


Three-body heavy meson decay Dynamics

- ex: $D^+ \to K^- K^+ K^-$

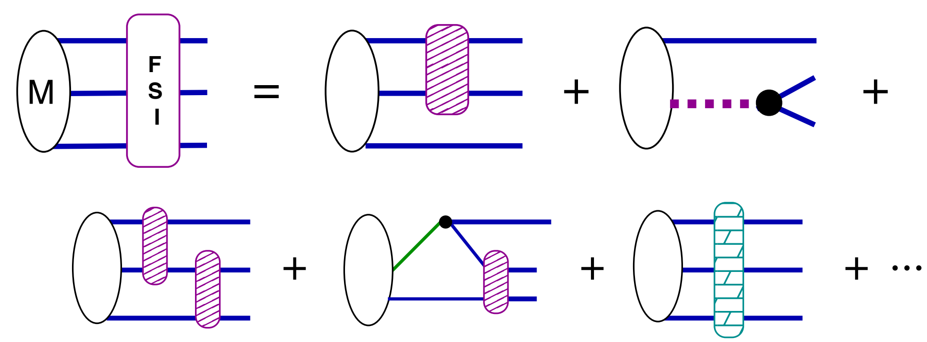


primary vertex
- weak -



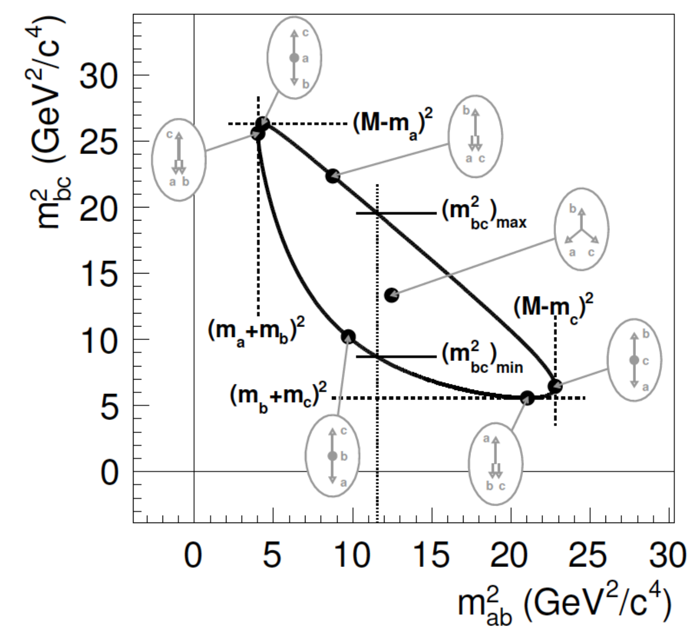
QCD, CKM coupling and phase

Final State Interactions
- strong -



(2+1) + 3-body interactions

Dalitz plot



- To extract information from data we need an amplitude MODEL

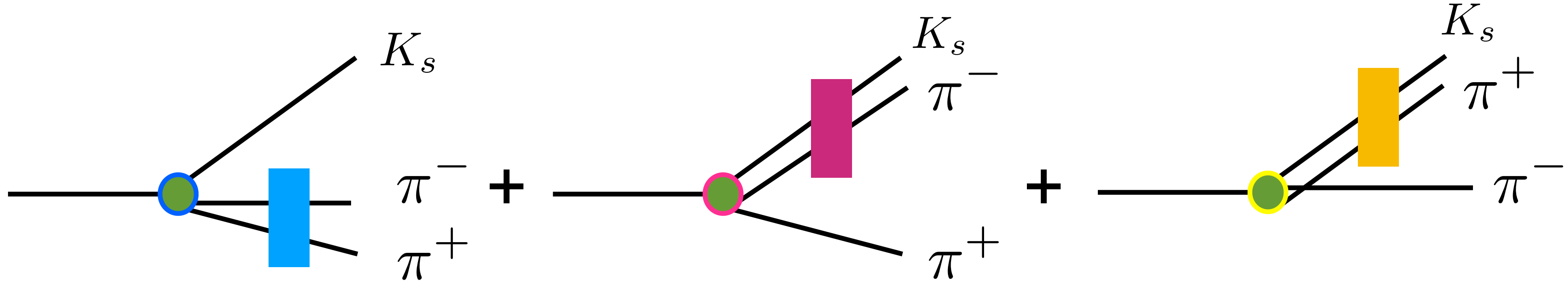
$$\frac{d\Gamma}{ds_{12}ds_{23}} = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|\mathcal{A}(s_{12},s_{23})|^2$$

dynamics

- common cartoon to described 3-body decay

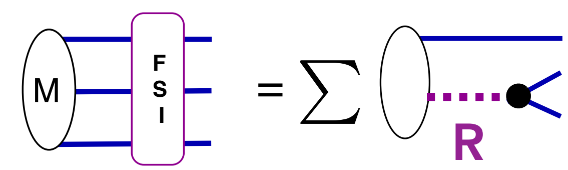
$D^0 \to K_s \pi^- \pi^+$

$\mathcal{A}(s_{12}, s_{23})$ =



- isobar model widely used by experimentalists:
  - (2+1) approximation → ignore the interaction with 3rd particle (bachelor)
  - $A = \sum c_k A_k$; + NR coherent sum of amplitude's in different parcial waves

! Warning: when A_k are single resonances



!

↳ defined as Breit-Wigner $\mathrm{BW}(s_{12}) = \dfrac{1}{m_R^2 - s_{12} - i m_R \Gamma(s_{12})}$,

- sum of BW violates two-body unitarity (close Rs in the same channel - scalars)
- resonance's mass and width are processes dependent

Models available

- movement to use better 2-body (unitarity) inputs in data analysis

  - "K-matrix" : ππ S-wave 5 coupled-channel modulated by a production amplitude

    ↳ used by Babar, LHCb, BES III — Anisovich PLB 653(2007)

  - rescattering $\pi\pi \to KK$ contribution in LHCb $\begin{cases} B^\pm \to \pi^+\pi^-\pi^\pm & \text{PRD101 (2020) 012006; PRL 124 (2020) 031801} \\ B^\pm \to K^-K^+\pi^\pm & \text{PRL 123 (2019) 231802} \end{cases}$

    Pelaez, Yndurain PRD71(2005) 074016

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

→ still not enough to fully described data

- from theory: list of scalar and vector form factors

$< \pi\pi|0 >$ Moussallam EPJ C 14, 111 (2000); Daub, Hanhart, and B. Kubis JHEP 02 (2016) 009. Hanhart, PL B715, 170 (2012). Dumm and Roig EPJ C 73, 2528 (2013).

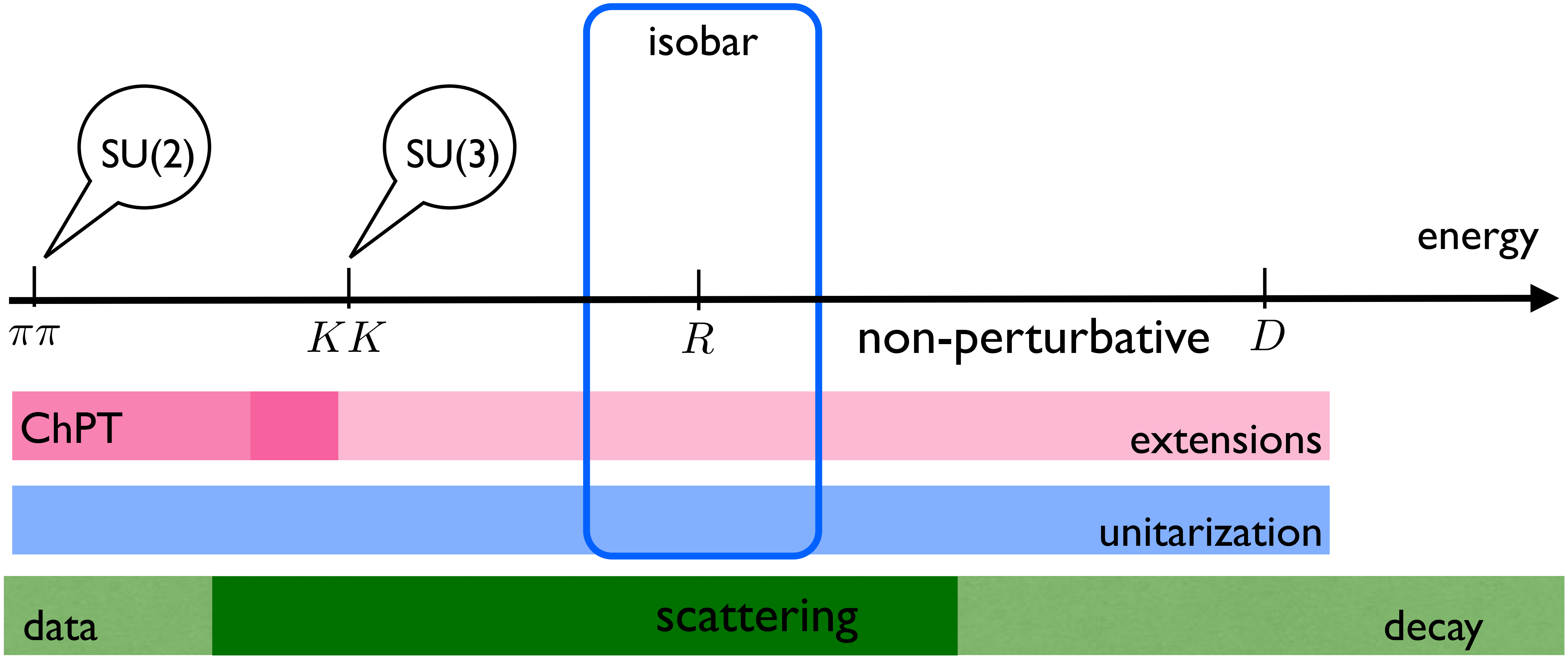
$< K\pi|0 >$ Moussallam EPJ C 53, 401 (2008) Jamin, Oller and Pich, PRD 74, 074009 (2006) Boito, Escribano, and Jamin EPJ C 59, 821 (2009).

$< KK|0 >$ Fit from 3-body data PCM, Robilotta + LHCb JHEP 1904 (2019) 063

no data — extrapolate from unitarity model Albaladejo and Moussallam EPJ C 75, 488 (2015).

quark model with isospin symmetry Bruch, Khodjamirian, and Kühn , EPJ C 39, 41 (2005)

scale issue



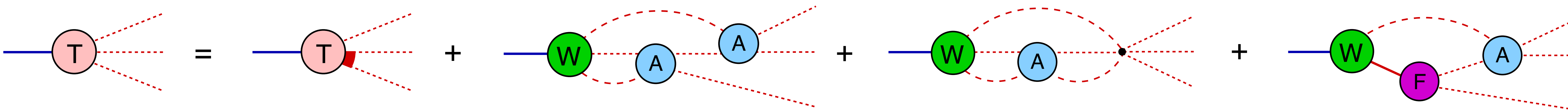
- we need non-perturbative meson-meson interactions up to…. 3 GeV
- extend 2-body amplitude theory validity

Ropertz, Kubis, Hanhart
EPJ Web Conf. 202 (2019) 06002

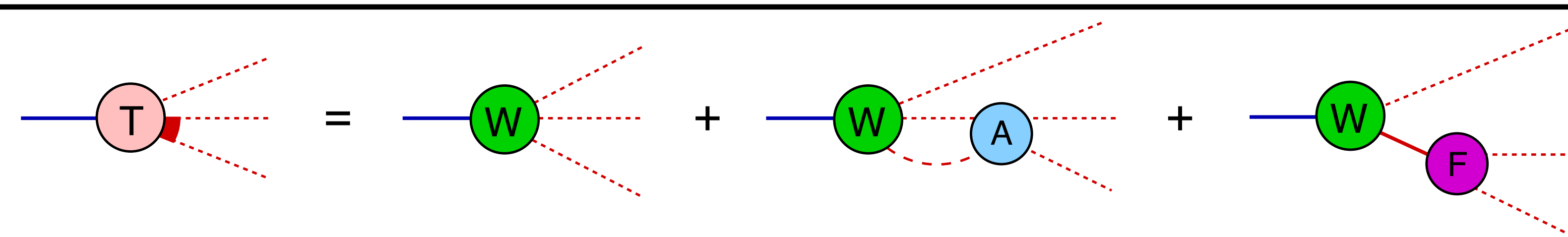
PCM, A.dos Reis, Robilotta
PRD 102, 076012 (2020)

MAGALHAES, A.dos Reis, Robilotta
PRD 102, 076012 (2020)

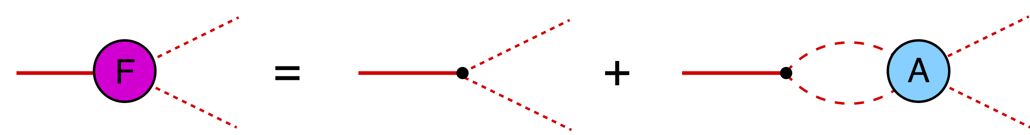
- Any 3-body decay amplitude



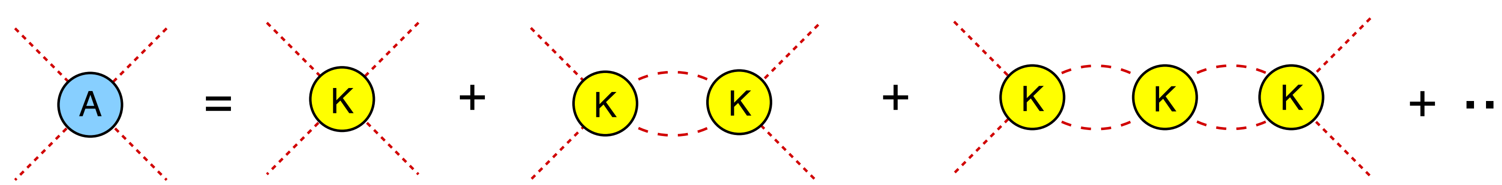
(2+1) approach

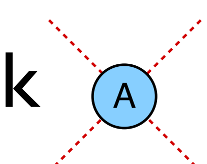


Form factor



meson-meson



↳ provide the building block 

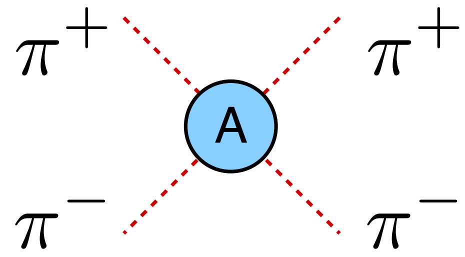
- includes multiple resonances in the same channel (as many as wanted)
- free parameter (massas and couplings) to be fitted to data.

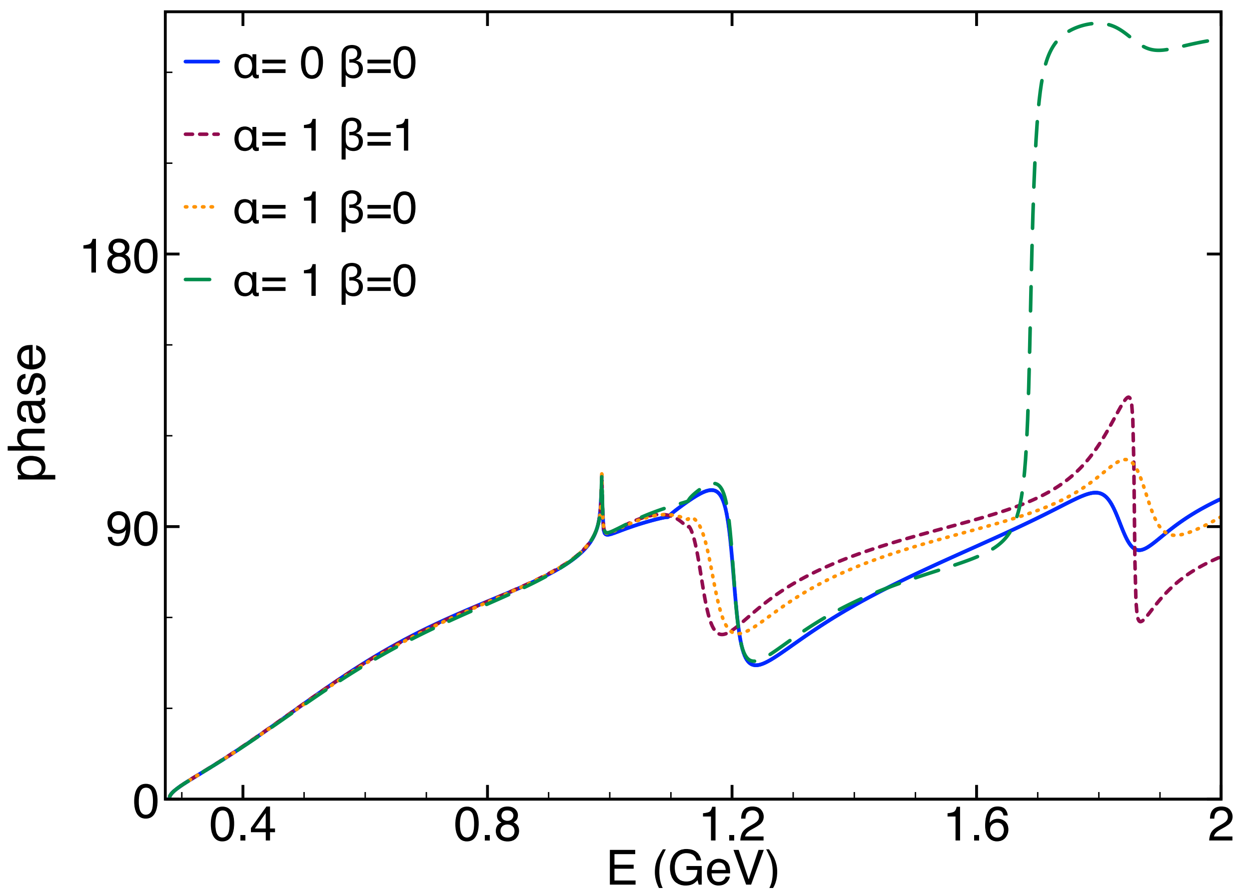
⟶ Available to be implement in data analysis!!

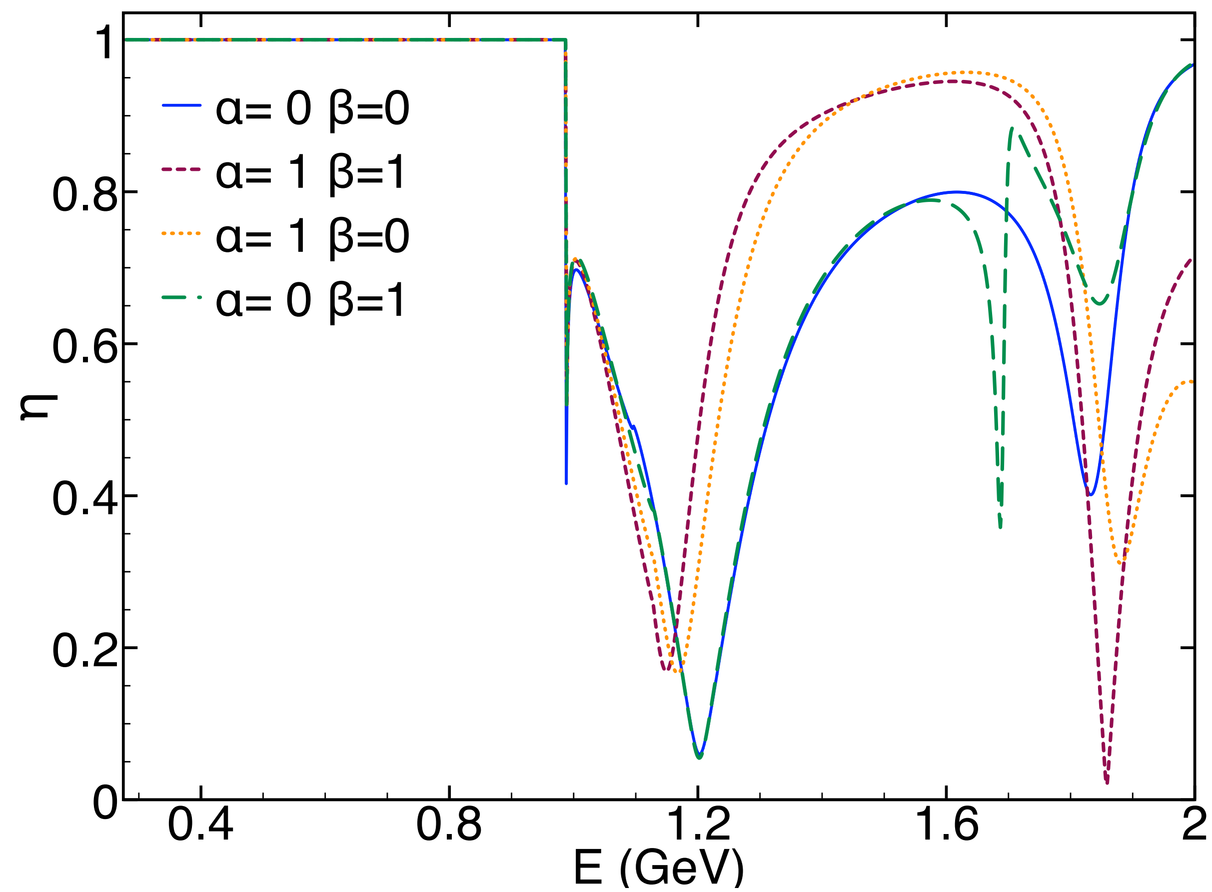
full ππ 3 coupled-channel amplitude

- 3 resonances: mx=0.98, my=1.37, mz=1.7 GeV

α and β are couplings of Rz





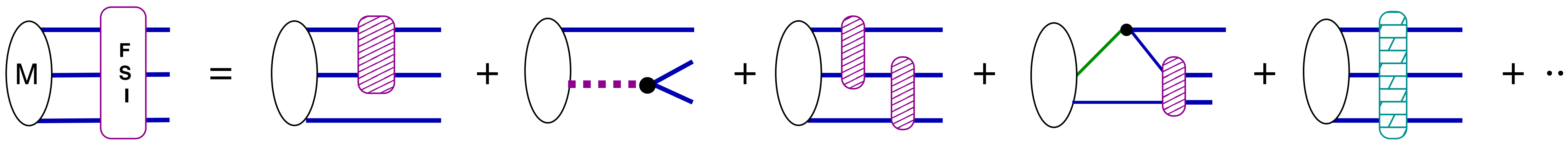


→ Extra res do not disturb the low-energy!

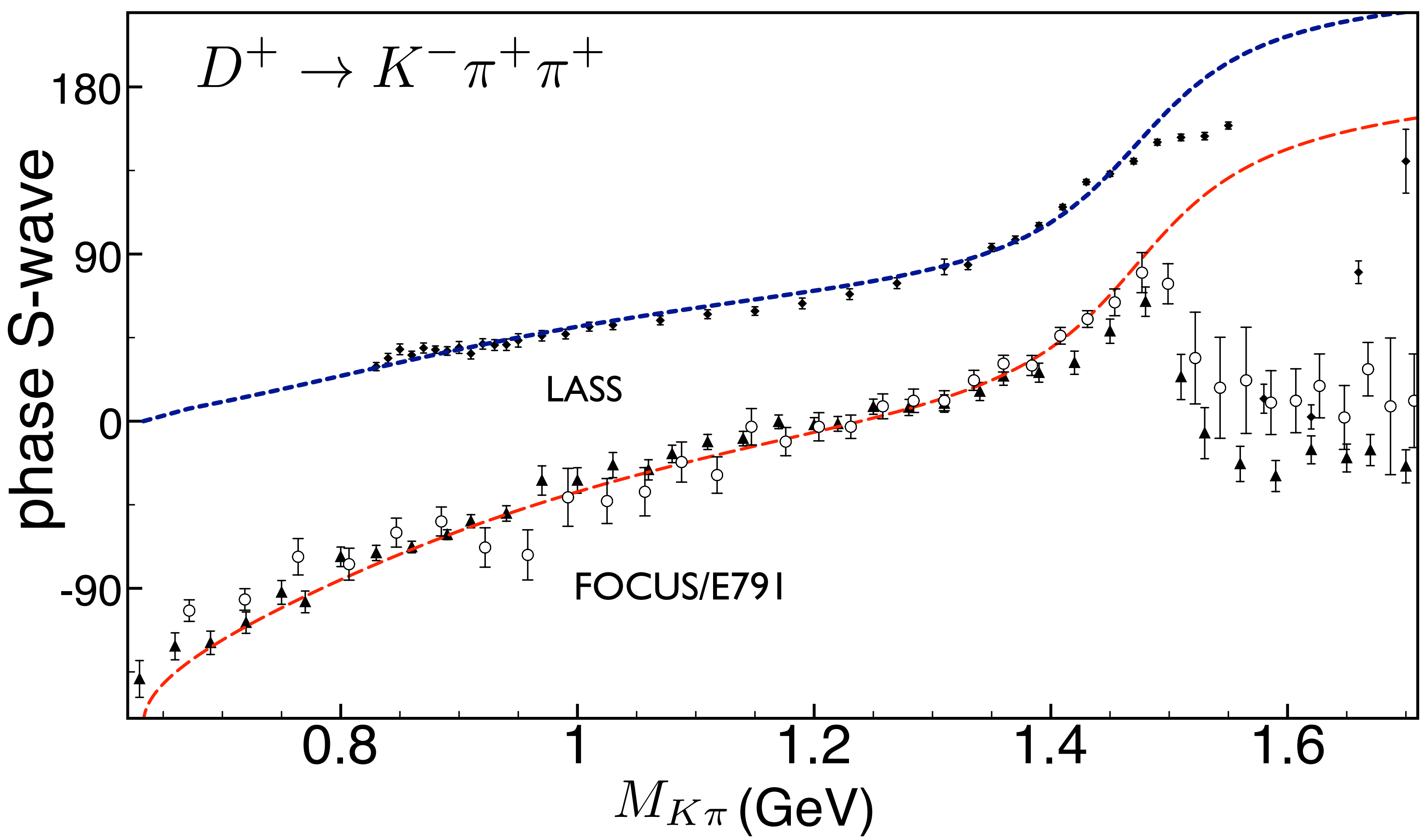
→ parameter should be fixed by data

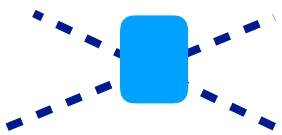
Three-body Models

- Three-body FSI (beyond 2+1)

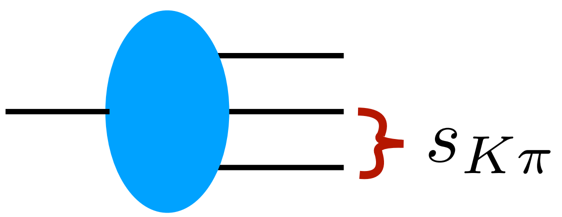


- shown to be relevant on charm sector

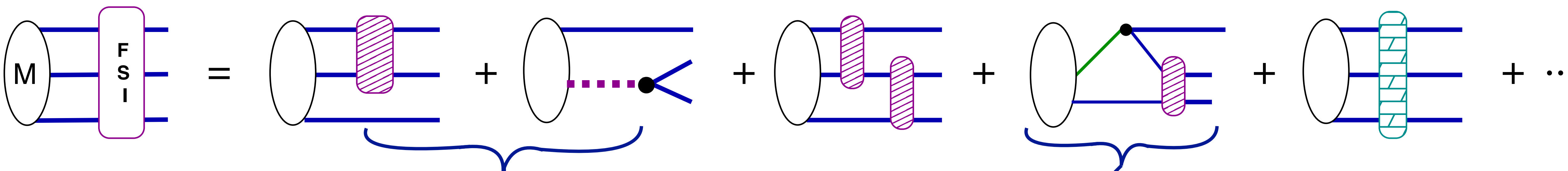




Decay projected in one pair mass

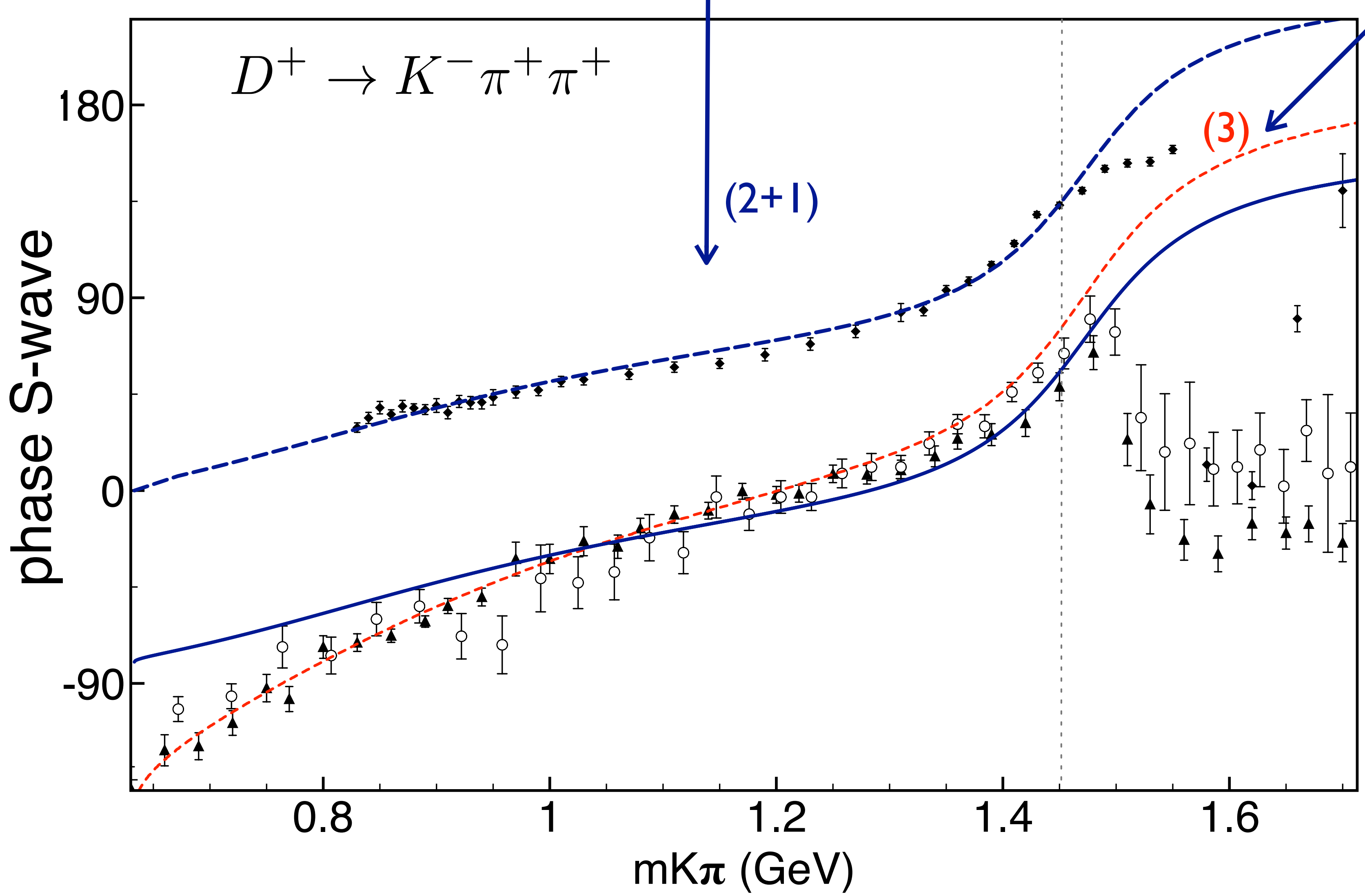


- Three-body FSI (beyond 2+1)

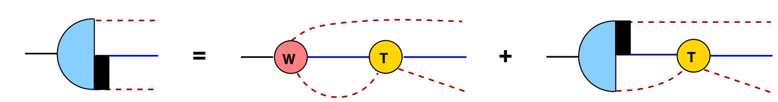


PRD92 094005 (2015)

- shown to be relevant on charm sector

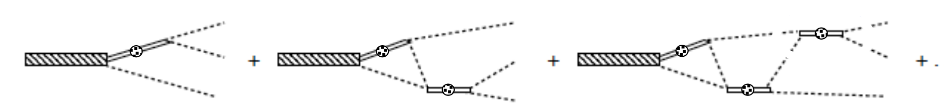


- Faddeev USP-ITA-CBPF collaboration



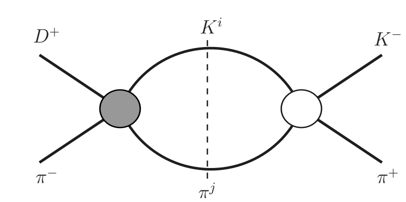
PCM et.al: PRD84 094001 (2011),

- triangle loops



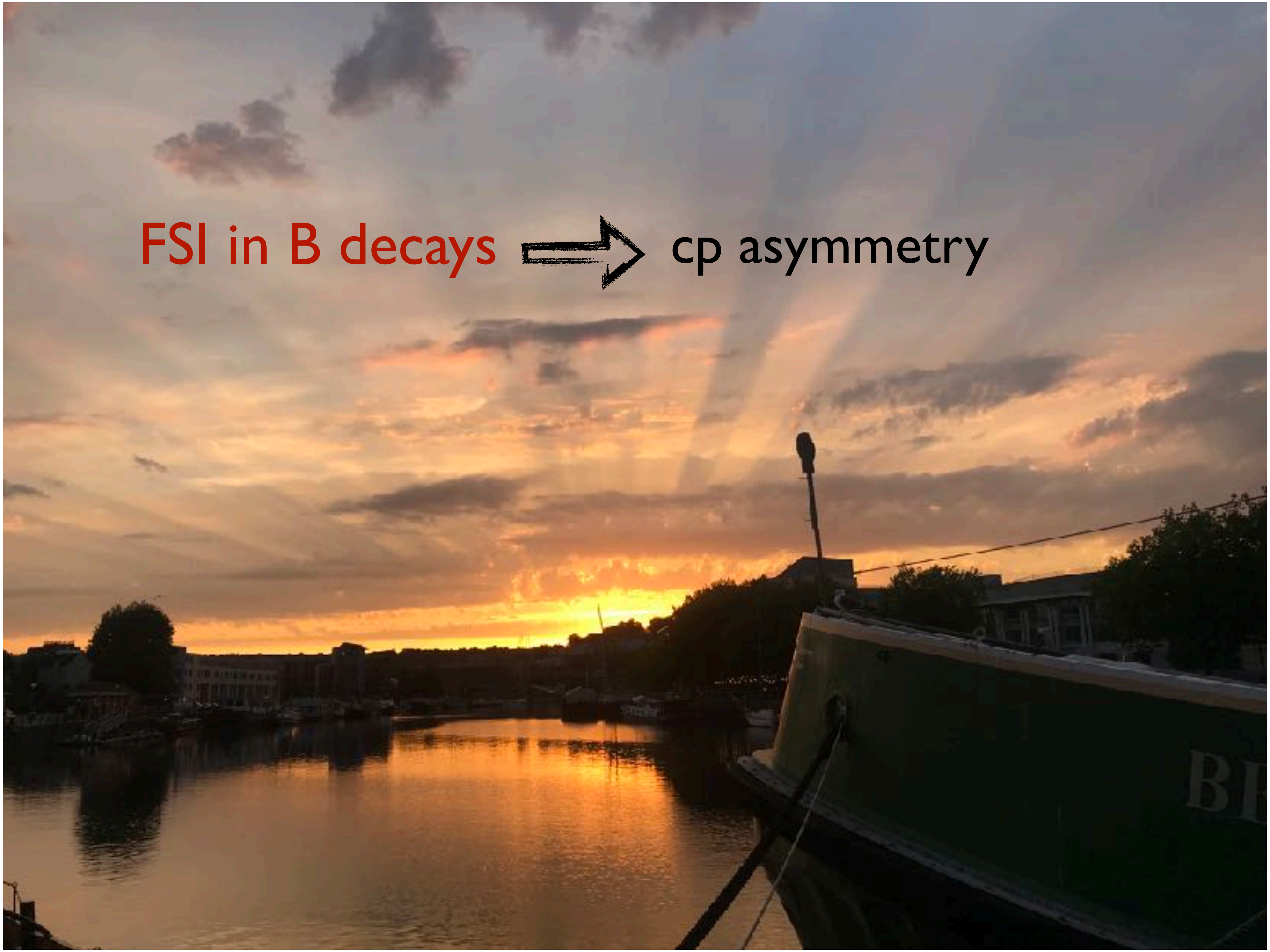
S.Nakamura PRD93 014005 (2016)

- Khuri-Treiman



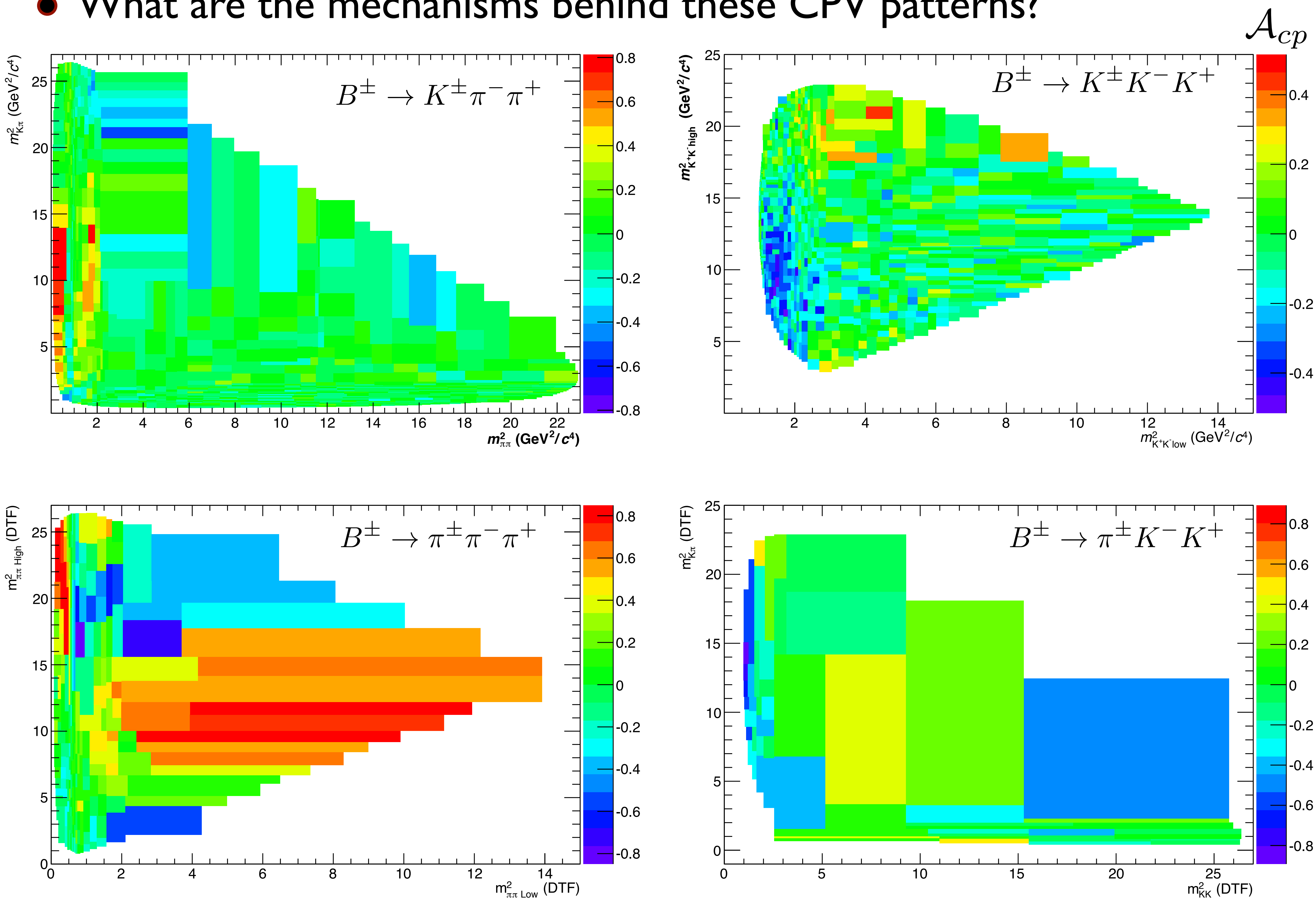
Niecknig, Kubis, JHEP10 142 (2015)

→ will be important for precision

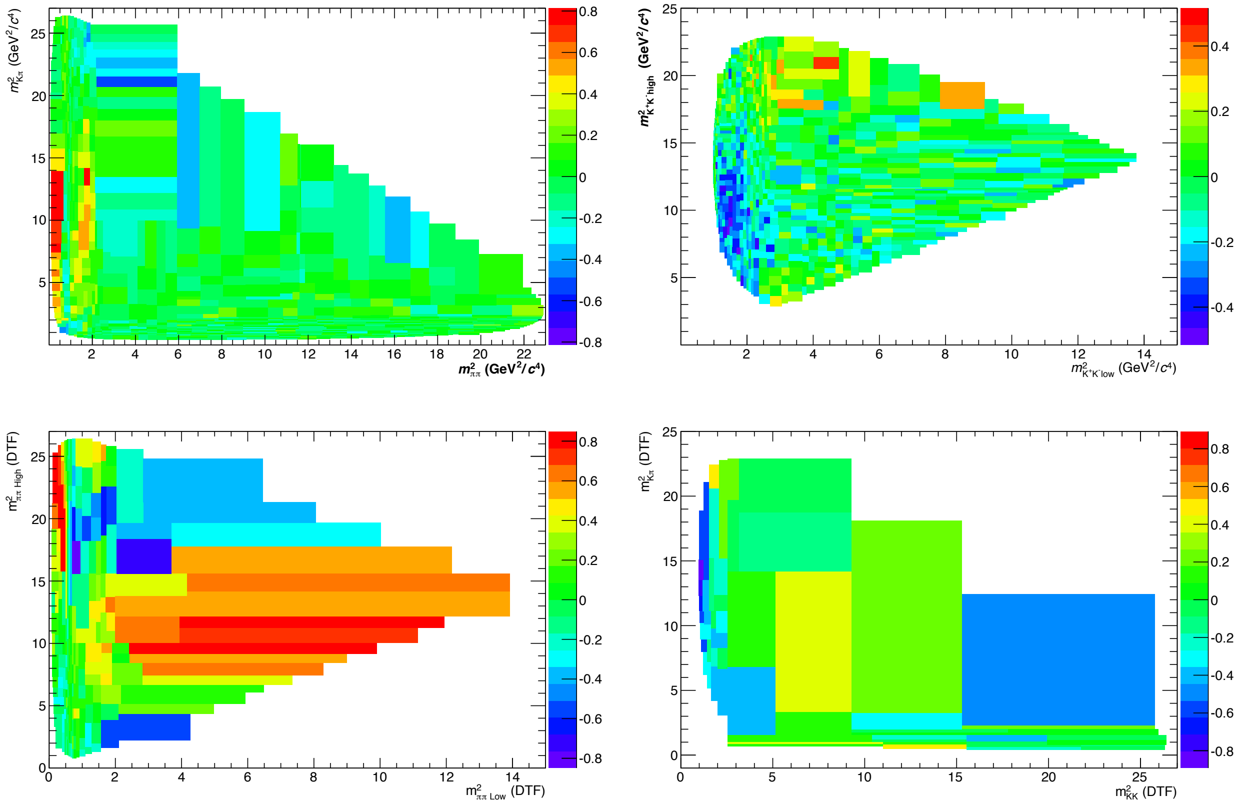

FSI in B decays ⟹ cp asymmetry
BI

CPV at low and high mass

- What are the mechanisms behind these CPV patterns?



LHCb PRD90 (2014) 112004



- massive phase-space localized Asymmetry

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

- condition to CPV:

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

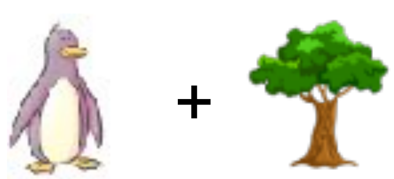
$$\langle f \,|\, T \,|\, M \rangle = A_1\, e^{i(\delta_1 + \phi_1)} + A_2\, e^{i(\delta_2 + \phi_2)}$$

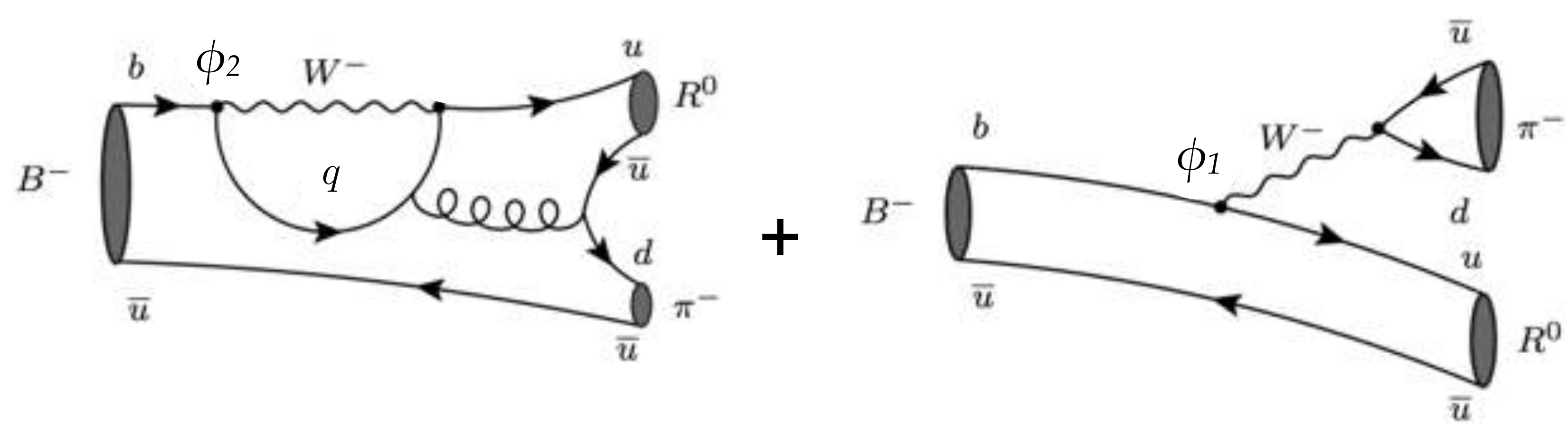
$$\langle \bar{f} \,|\, T \,|\, \bar{M} \rangle = A_1\, e^{i(\delta_1 - \phi_1)} + A_2\, e^{i(\delta_2 - \phi_2)}$$

$$\boxed{\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f}) = |\langle f \,|\, T \,|\, M \rangle|^2 - |\langle \bar{f} \,|\, T \,|\, \bar{M} \rangle|^2 = -4 A_1 A_2 \sin(\delta_1 - \delta_2)\, \sin(\phi_1 - \phi_2)}$$

- CPV at quark level: BSS model

Bander Silverman & Soni PRL 43 (1979) 242





  - not enough

→ hadronic interactions as source of strong phase

rescattering as a CPV mechanism

- CPT must be preserved

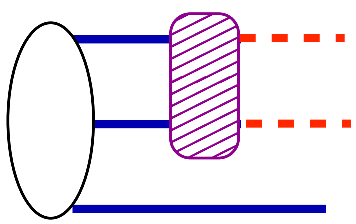
Lifetime $\tau = 1 / \Gamma_{total} = 1 / \overline{\Gamma}_{total}$

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

$\overline{\Gamma}_{total} = \overline{\Gamma}_1 + \overline{\Gamma}_2 + \overline{\Gamma}_3 + \overline{\Gamma}_4 + \overline{\Gamma}_5 + \overline{\Gamma}_6 + \dots$

→ CPV in one channel should be compensated by another one with opposite sign

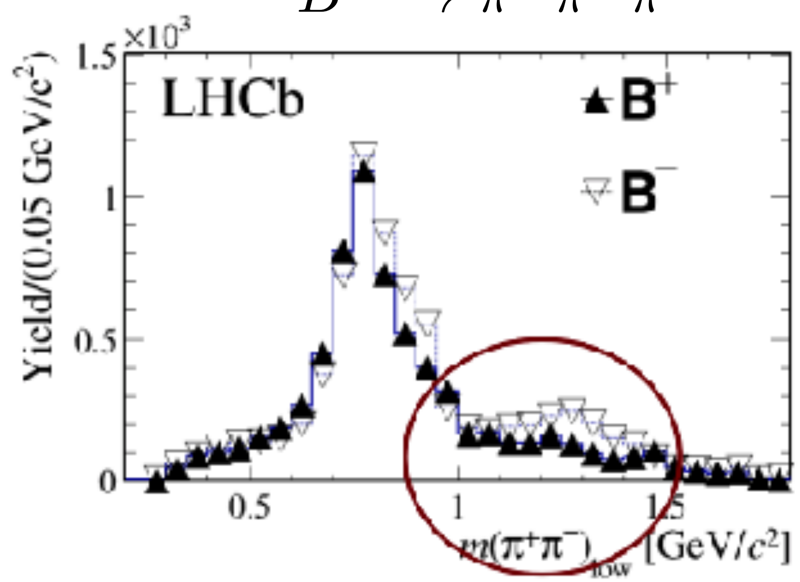
- rescattering $\boxed{\pi\pi \to KK}$



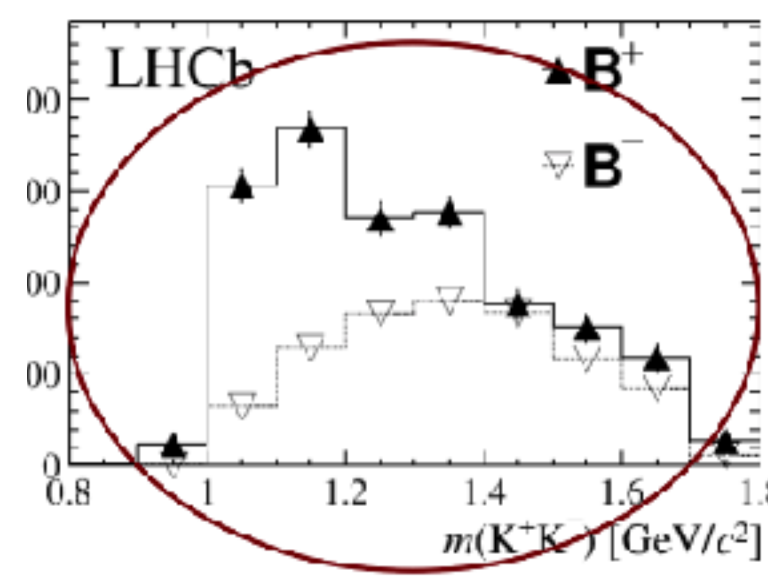
↳ explain CPV at [1 -1.6] GeV

Frederico, Bediaga, Lourenço PRD89(2014)094013

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



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

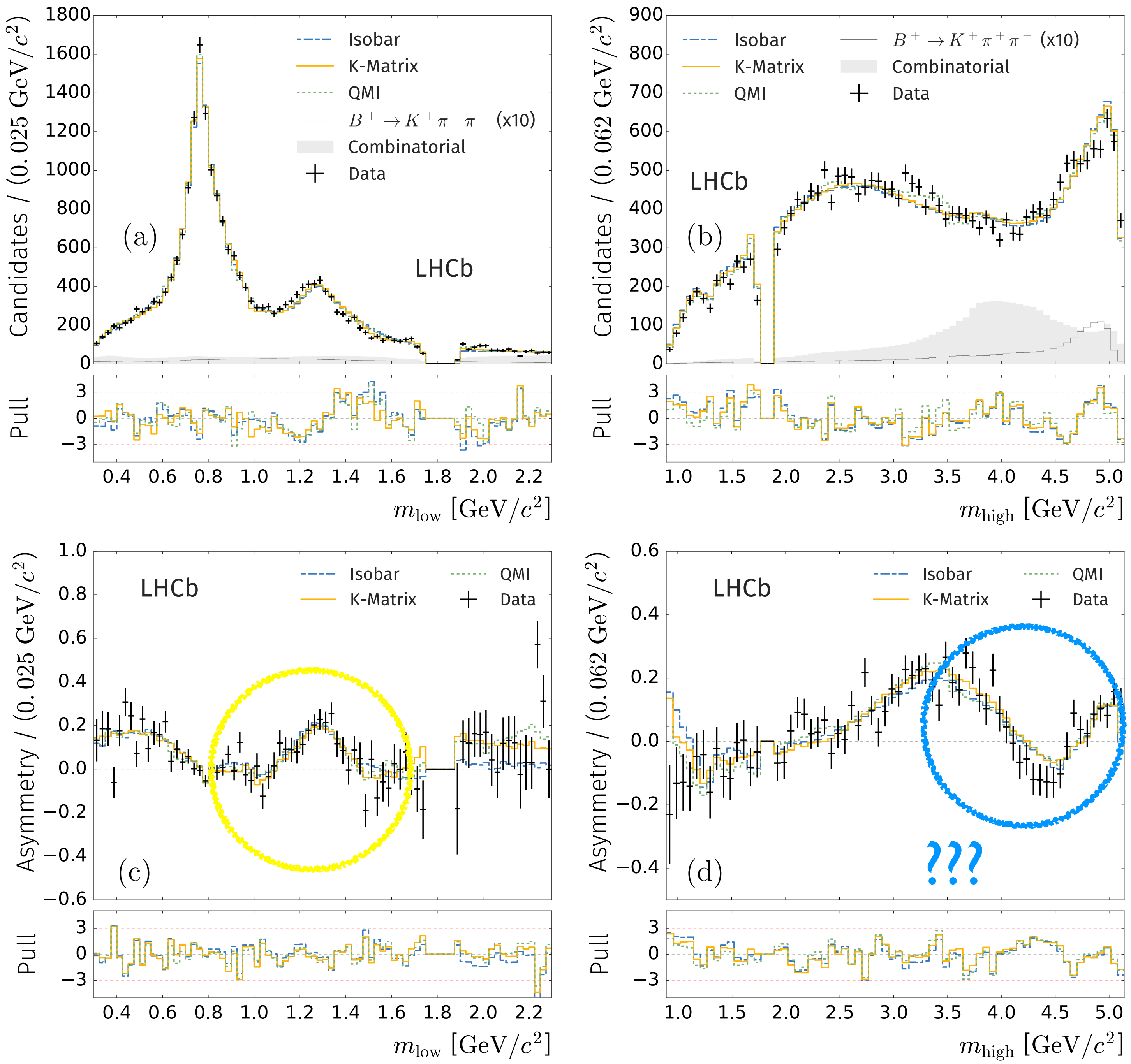


- confirmed by LHCb Amplitude Analysis $B^\pm \to \pi^-\pi^+\pi^\pm$ and $B^\pm \to \pi^\pm K^- K^+$

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[°] (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	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$	$1.91 \pm 0.09 \pm 0.06$	$-56 \pm 12 \pm 18$
			$0.86 \pm 0.07 \pm 0.04$	$-81 \pm 14 \pm 15$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$	$0.20 \pm 0.07 \pm 0.02$	$-52 \pm 23 \pm 32$
			$0.22 \pm 0.06 \pm 0.04$	$107 \pm 33 \pm 41$

Bediaga, Frederico, PCM, Torres Machado
ArXiv:2109.01625

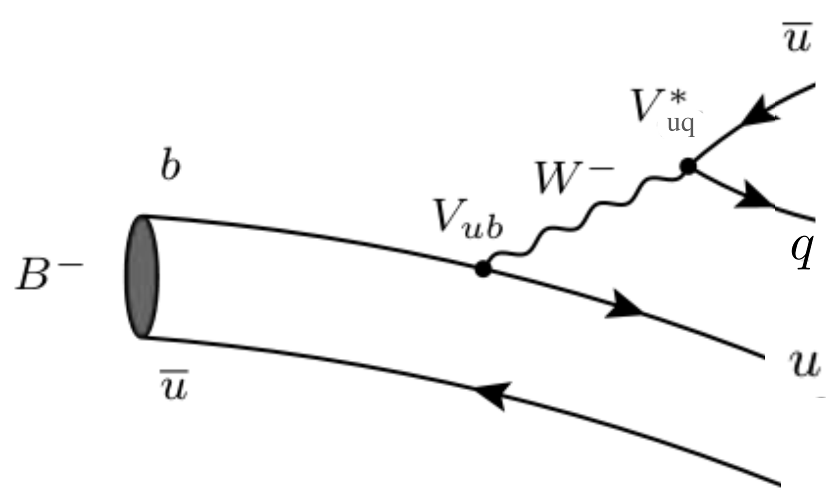
- understand global asymmetries in LHCb data

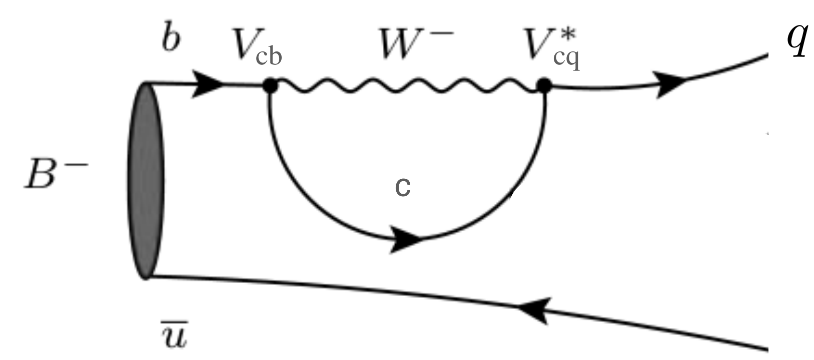
Decay channel	$\Delta\Gamma_{CP}(10^6\,\mathrm{s}^{-1})$
$B^\pm \to K^\pm\pi^+\pi^-$	$+0.84 \pm 0.25$
$B^\pm \to K^\pm K^+ K^-$	-0.68 ± 0.17
$B^\pm \to \pi^\pm\pi^+\pi^-$	$+0.53 \pm 0.13$
$B^\pm \to \pi^\pm K^+ K^-$	-0.39 ± 0.07

$$\sum \Delta\Gamma_{CP} \overset{\text{CPT}}{=} 0$$

$$\begin{aligned}\Delta\Gamma_{CP}(h_1^\pm h_2^+ h_3^-) &= \Gamma(B^- \to h_1^- h_2^+ h_3^-) - \Gamma(B^+ \to h_1^+ h_2^- h_3^+) \\ &= A_{CP}(B^\pm \to h_1^\pm h_2^+ h_3^-)\mathcal{B}(B^+ \to h_1^+ h_2^+ h_3^-)/\tau(B^+) \\ &= 4\,\mathrm{Im}[V_{ub}^* V_{uq} V_{cb} V_{cq}^*] \sum_{j,k} \mathrm{Im}\left[S_{j,i} S_{k,i}^* \mathcal{U}_{q_j}^* \mathcal{C}_{q_k}\right]\end{aligned}$$

$q = d, s$





U-spin symmetry and FSI with CPT

NEW!

Bediaga, Frederico, PCM, Torres Machado
ArXiv:2109.01625

- understand global asymmetries in LHCb data

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

CPT

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

$$\Delta\Gamma_{CP}(h_1^\pm h_2^\pm h_3^\mp) = \Gamma(B^- \to h_1^- h_2^+ h_3^-) - \Gamma(B^+ \to h_1^+ h_2^- h_3^+)$$
$$= A_{CP}(B^\pm \to h_1^\pm h_2^\pm h_3^-)\mathcal{B}(B^+ \to h_1^+ h_2^+ h_3^-)/\tau(B^+)$$
$$= 4\,\mathrm{Im}[V_{ub}^* V_{uq} V_{cb} V_{cq}^*] \sum_{j,k} \mathrm{Im}\left[S_{j,i} S_{k,i}^* \mathcal{U}_{q_j}^* \mathcal{C}_{q_k}\right]$$

- U-Spin symmetry: quark (s, d) form a dublet

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

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

CKM unitarity

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

  - $d \leftrightarrow s$ everywhere

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

  - $d \leftrightarrow s$ weak-vertex

$$\frac{\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-)}{\Delta\Gamma_{CP}(\pi^\pm\pi^+\pi^-)} = 1.59 \pm 0.62 \text{ and } \frac{\Delta\Gamma_{CP}(K^\pm K^+K^-)}{\Delta\Gamma_{CP}(\pi^\pm K^+K^-)} = 1.77 \pm 0.55,$$

contradiction

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

  CPT on strong interaction

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

U-spin symmetry and FSI with CPT

NEW!

Tobias's seminar last week

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

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

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:

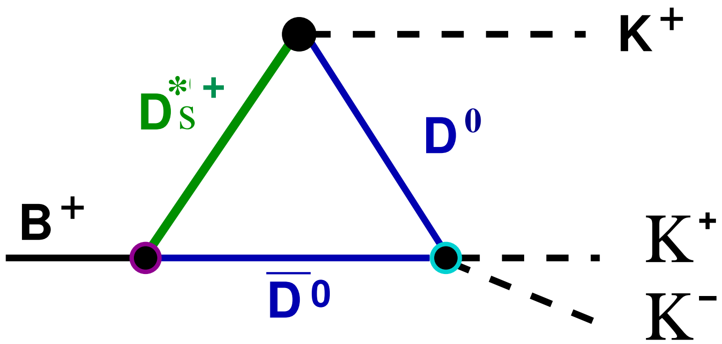
$$\frac{\Delta\Gamma_{CP}(\pi^{\pm}K^{+}K^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}K^{0}\bar{K}^{0})} \sim 1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(\pi^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma_{CP}(\pi^{\pm}\pi^{0}\pi^{0})} \sim 1$$

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

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

Bediaga, Frederico, MAGALHAES, PLB 780 (2018) 357

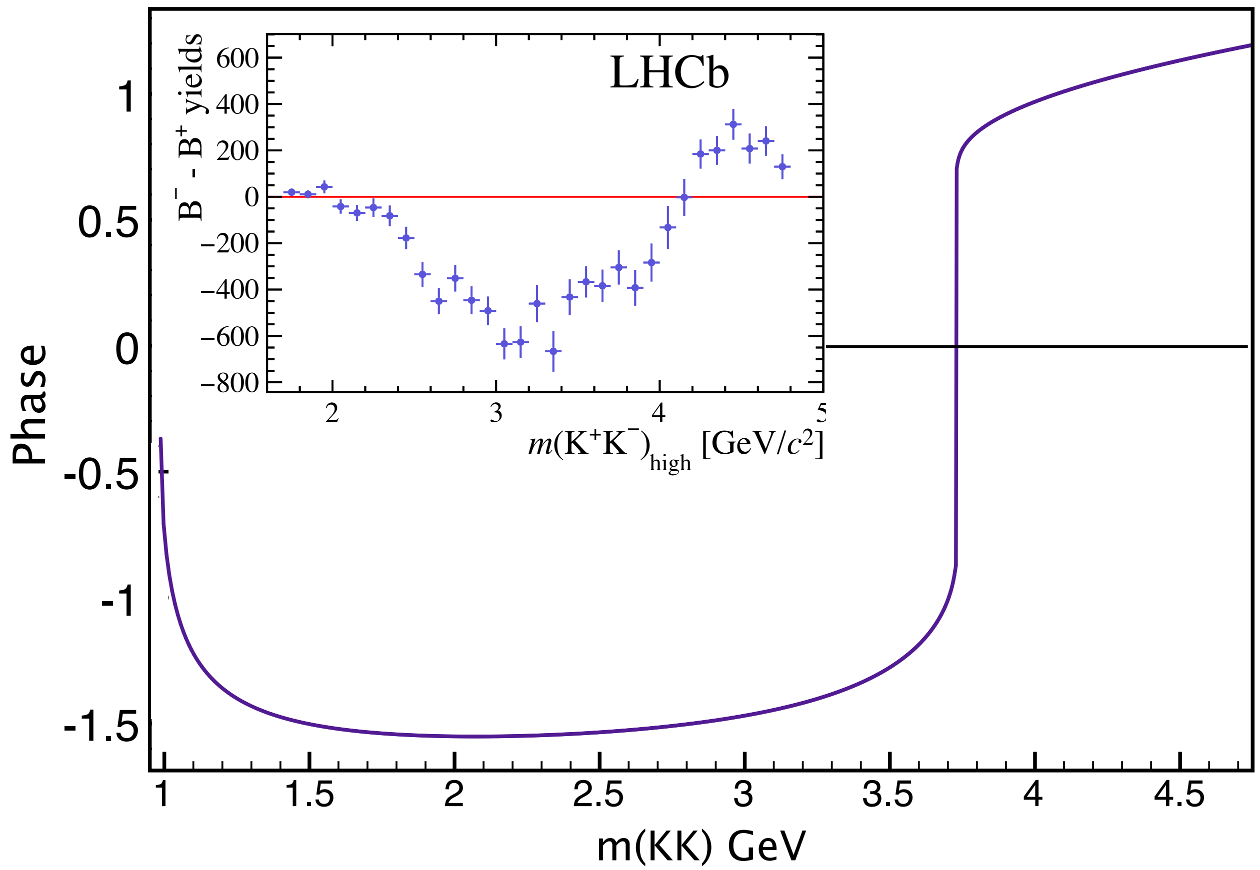
- $B^+ \to K^- K^+ K^+$
  - analogue of $\pi\pi \leftrightarrow KK$ but with $D\bar{D} \to K^+K^-(\pi^+\pi^-)$
  - charm triangle



$Br\left[B \to DD_s^*\right]$ ~1%

→ 1000 x $Br\left[B \to KKK\right]$

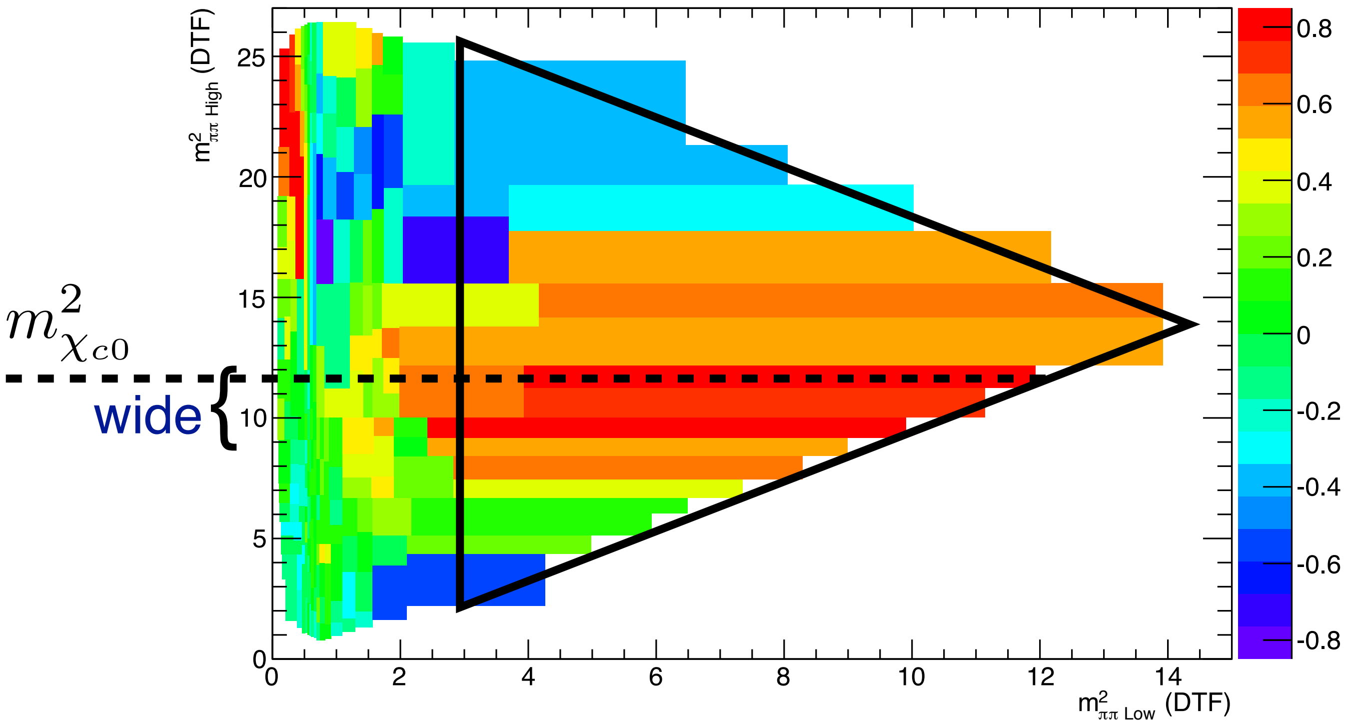
  - change sign ~ $D\bar{D}$ open channel



→ how the change in sign leads to CPV?

Bediaga, Frederico, MAGALHAES - PLB 806 (2020) 135490

- 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)



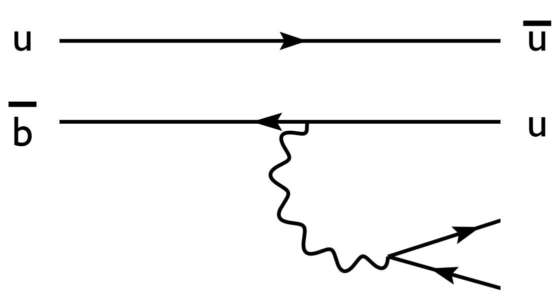
- Important data features
  - data shows a huge CP asymmetry around $m^2_{\chi_{c0}} = 11.65\,GeV^2$
  - wide CP asymmetry: same source for a nonresonant amplitude and χ_{c0}
    ↳ charm loop and χ_{c0}

Amplitude model

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

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

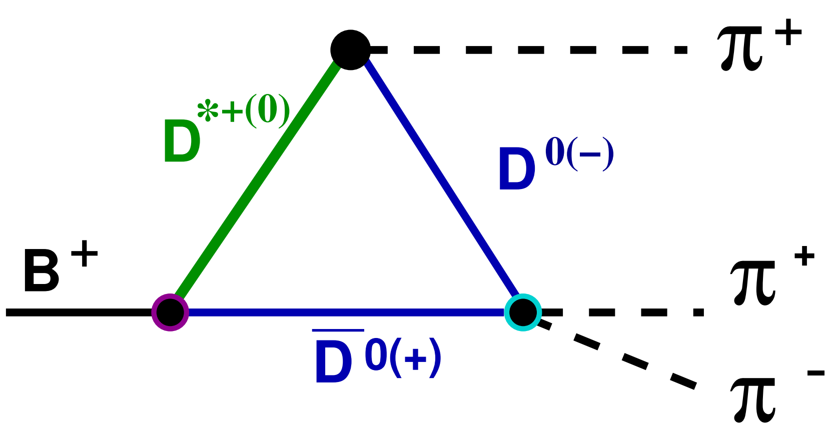
  - $A^{\pm}_{tree} = a_0\, e^{\pm i\gamma}$: weak phase γ from the dominant $b \to u$ tree diagram



→ Nonresonant (only resonances tails)

→ a_0 is complex (strong phase)

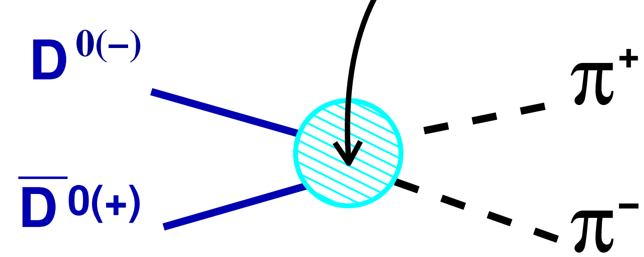
  - $A_{D\bar{D}}$ charm rescattering with χ_{c0} : source of strong phase variation



→ similar triangle loop

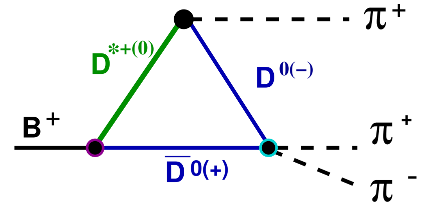
→

χ_{c0} is a pole bellow threshold



(more math)

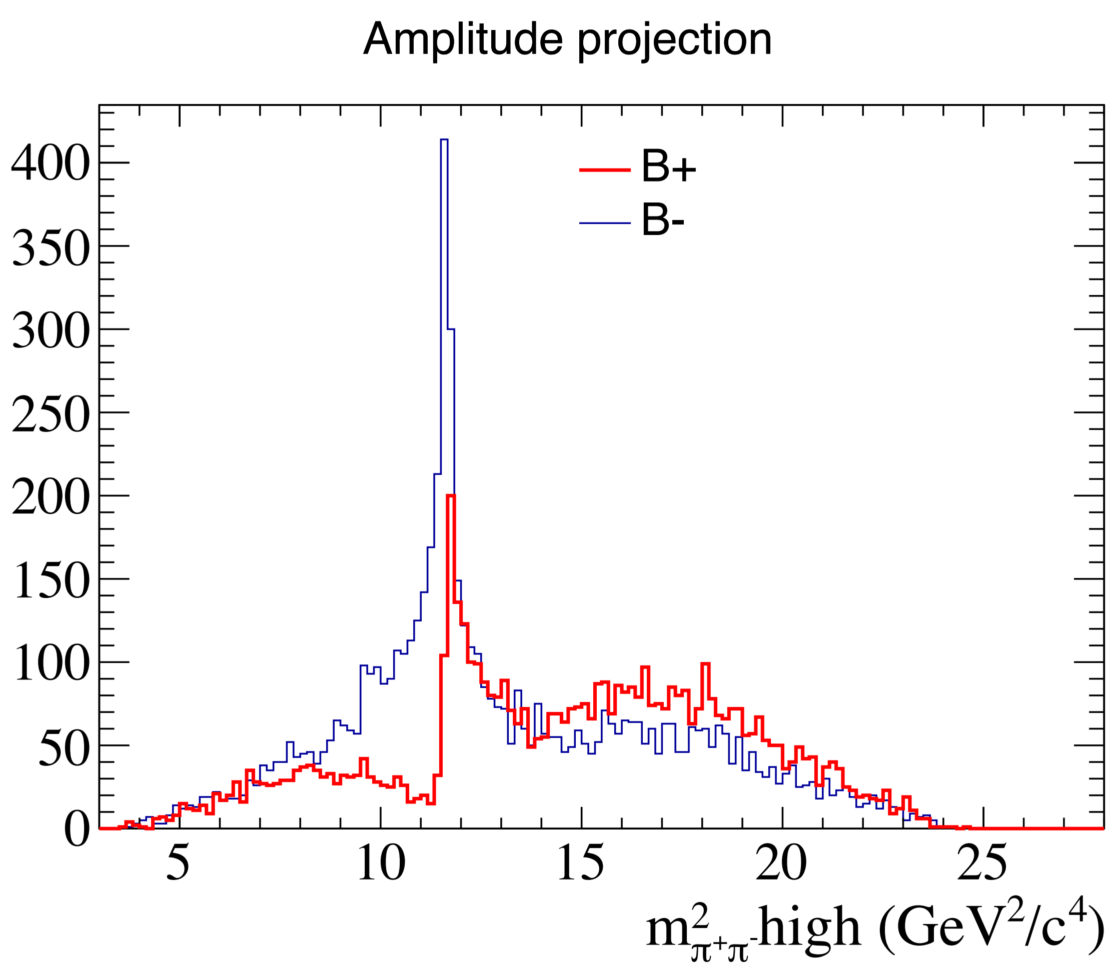
Results

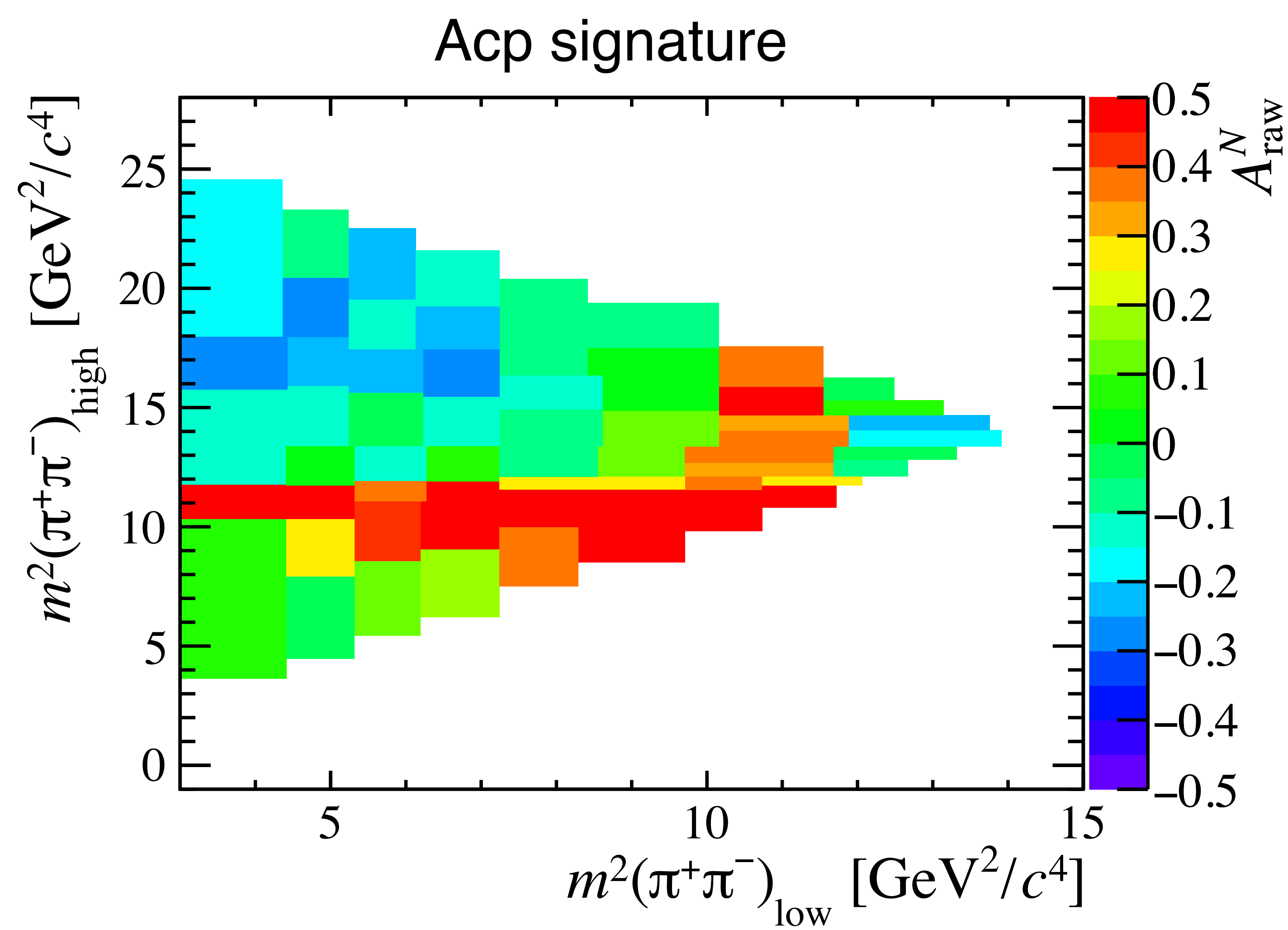
- $A_{B^\pm\to\pi^-\pi^+\pi^\pm}(s_{12}, s_{23}) =$ 

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

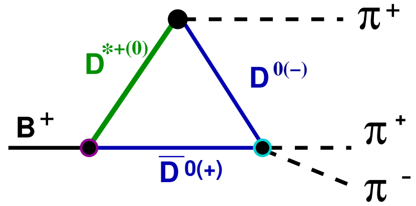
$$\boxed{\begin{aligned} \gamma &= 70^o \\ a_0 &= 2\, e^{i(\delta_s = 45^o)} \end{aligned}}$$

- the goal was to reproduce the main observed CPV characteristics



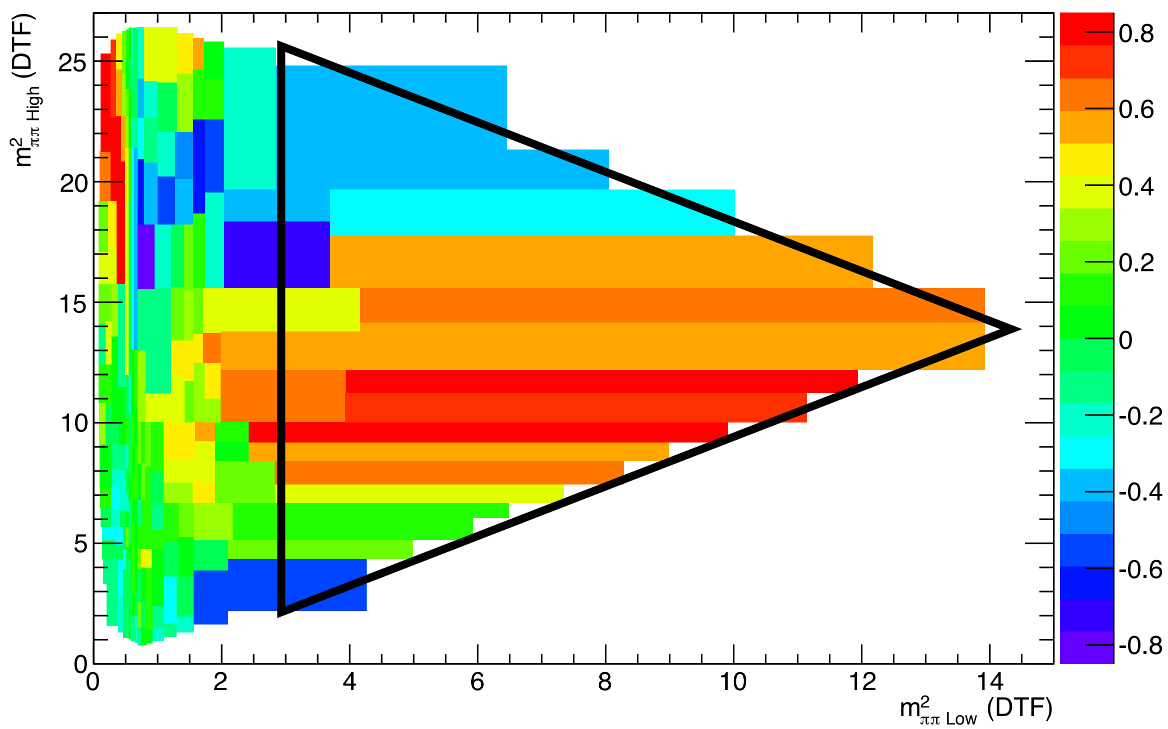


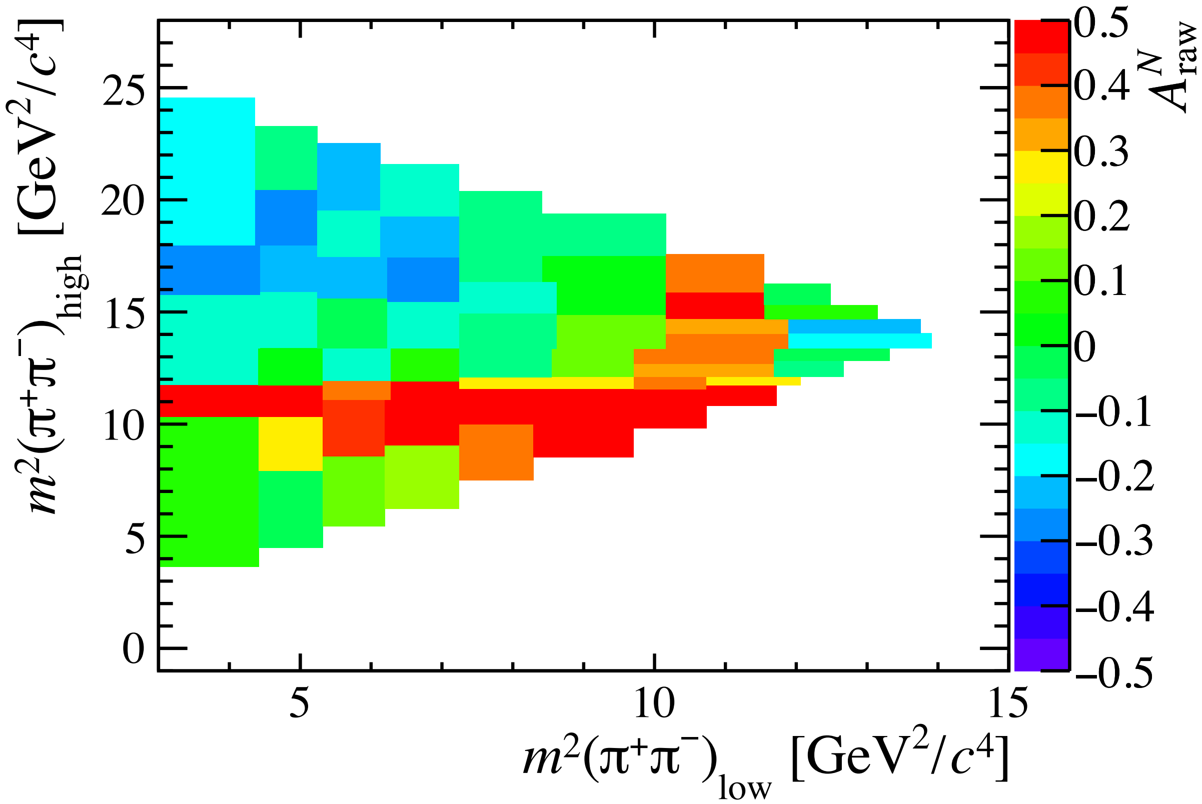
Results

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

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

- LHCb Run I
- our model





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

→ parameters have to be fitted to data

→ will be included in amplitude analysis of Run II data

- FSI play an important role in B and D hadronic decays
  - D decays: three-body effects are important for describe/understand data
    - ↳ extract 2-body information from data
    - ↳ important for precision and CPV searches
  - 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

- two-body coupled-channel description is crucial!!!
  - tool kit for amplitude analysis with theoretically sound models to ANA

→ need to extend the energy range of meson-meson. Include the open charm

- Where phenomenology have to improve?
  - models need to connect the weak and strong description

    → QCDF and FSI
  - models have to merge low and high FSI

obrigada!!

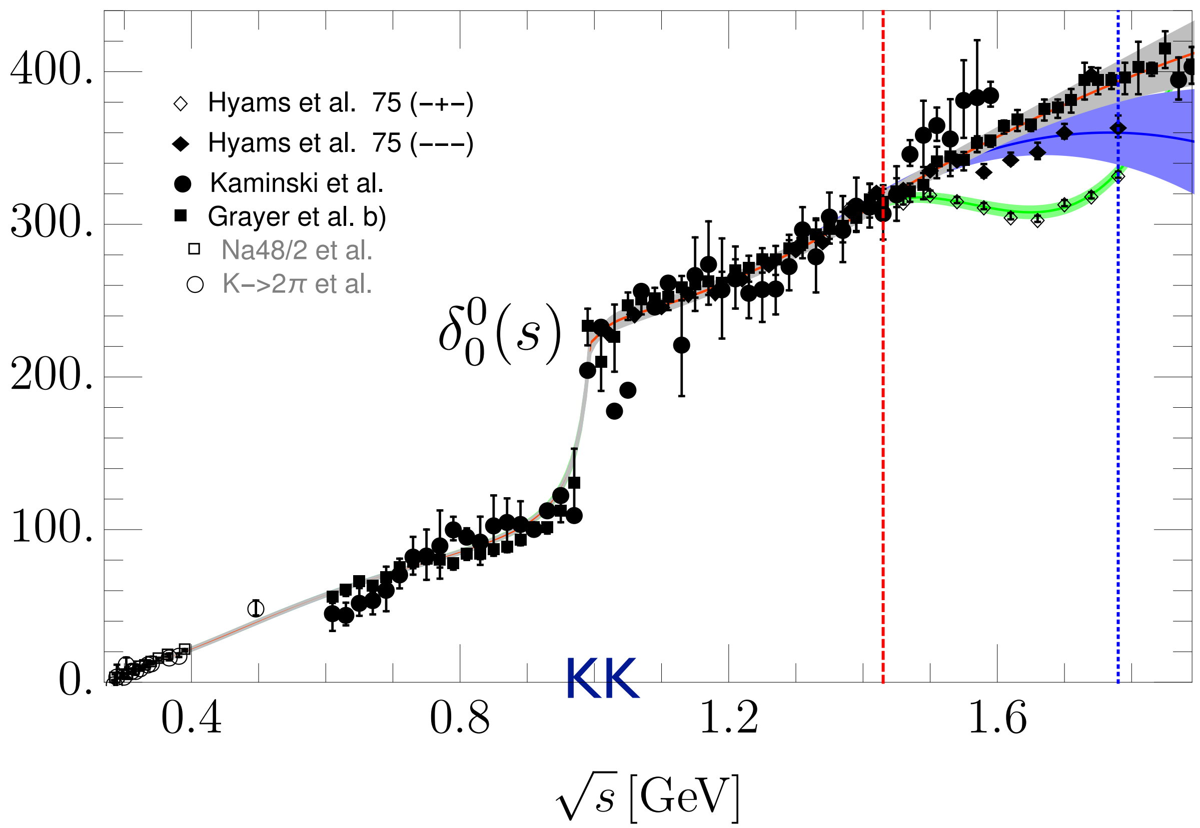
#staysafe

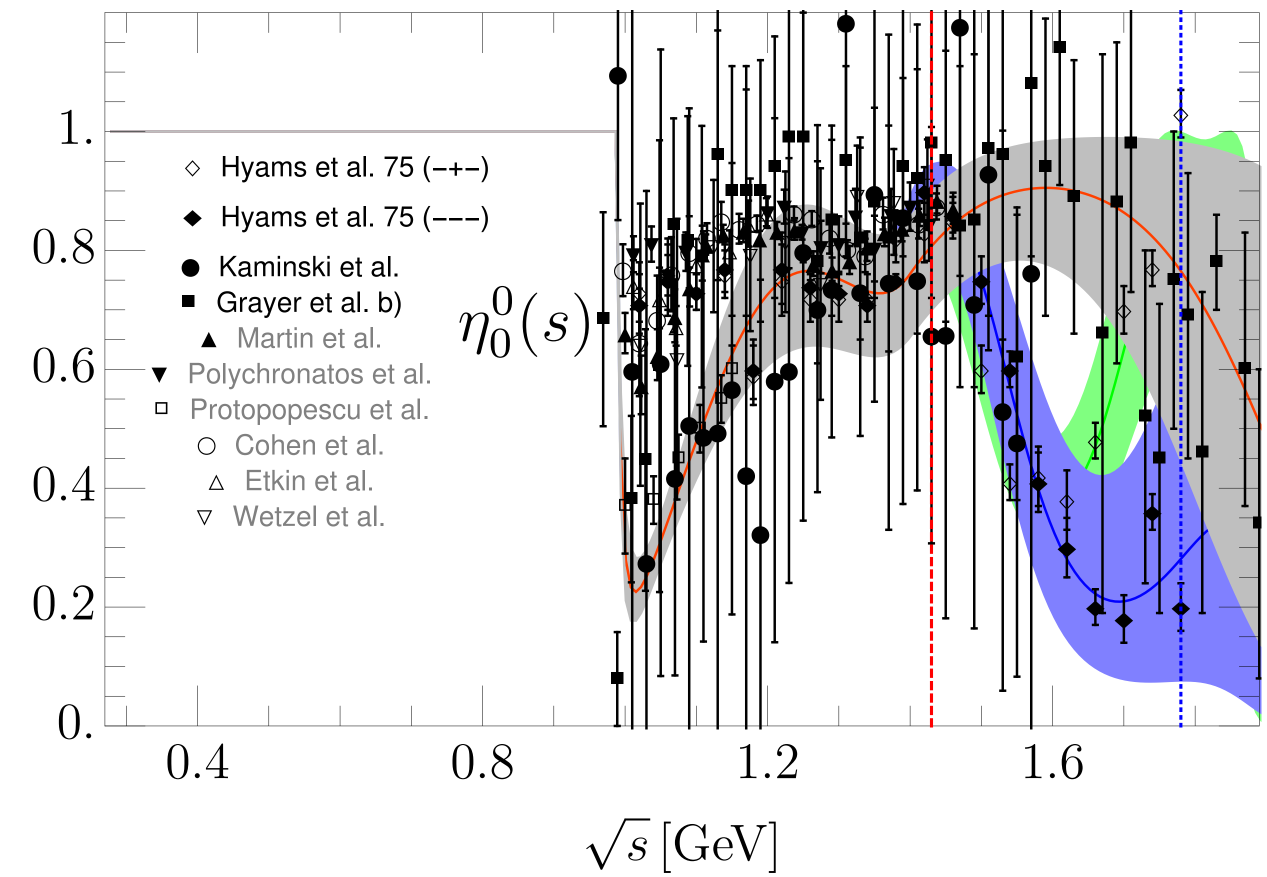
Backup slides

- $\pi\pi$ scattering data S-Wave

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

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

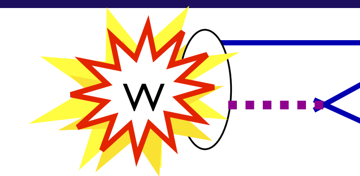




$$\sigma_l^{\rm el} = \frac{1}{2}\left\{\frac{1+\eta_l^2}{2} - \eta\cos 2\delta_l\right\},$$

Inelasticity: one minus the probability of losing signal (1=>elastic)

decay models available - weak sector



(2+1)

- QCD factorization approach → factorize the quark currents

$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pq}^* V_{pb} \left[C_1(\mu) O_1^p(\mu) + C_2(\mu) O_2^p(\mu) + \sum_{i=3}^{10} C_i(\mu) O_i(\mu) + C_{7\gamma}(\mu) O_{7\gamma}(\mu) + C_{8g}(\mu) O_{8g}(\mu) \right] + \text{ h.c. },$$

challenging for 3-body
not all FSI and 3-body NR
scale issue with charm
!

→ ex: $B^+ \to \pi^+\pi^-\pi^+$

how to describe it?

$$\text{A} \sim \langle \underbrace{[\pi^+(p_2)\pi^-(p_3)]}_{\text{R}} \; |(\bar{u}b)_{V-A}|B^-\rangle \; \langle \pi^-(p_1)|(\bar{d}u)_{V-A}|0\rangle + \langle \pi^-(p_1)|(\bar{d}b)_{sc-ps}|B^-\rangle \; \langle \underbrace{[\pi^+(p_2)\pi^-(p_3)] \; |(\bar{d}d)_{sc+ps}|0\rangle}_{\text{FF}}$$

- naive factorization
  - intermediate by a resonance R;
  - FSI with scalar and vector form factors FF

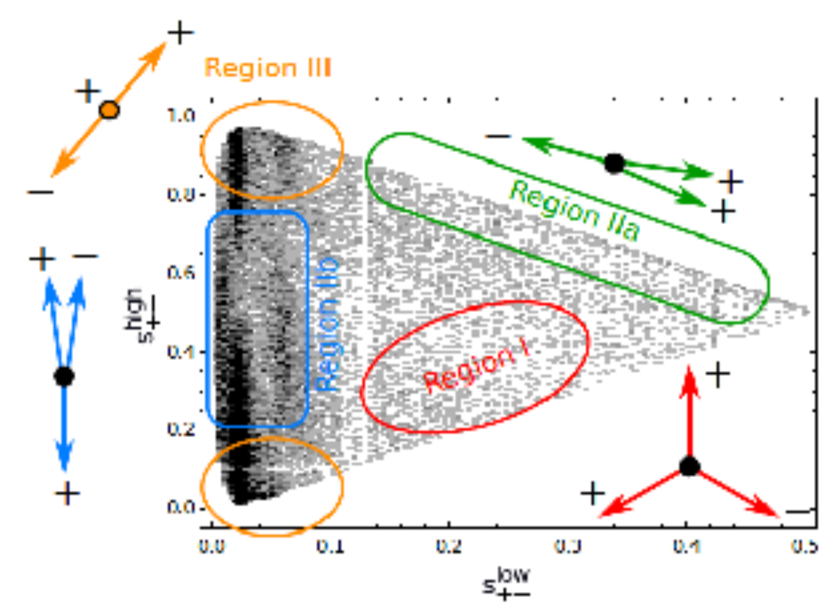
↳ parametrizations for B and D→3h Boito et al. PRD96 113003 (2017)

- modern QDC factorization: different in each region

↳ improvement over (2+1)

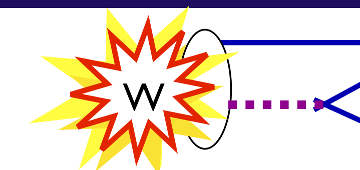
→ introduce new non-perturbative strong phase

Klein, Mannel, Virto, Keri Vos JHEP10 117 (2017)



- QCDF predictions

Not enough



(2+1)

Branching Fraction (tree dominated decays)

	Theory I		Theory II		Experiment
$B^- \to \pi^- \pi^0$	$5.43\,^{+0.06\,+1.45}_{-0.06\,-0.84}$	$(\star)$	$5.82\,^{+0.07\,+1.42}_{-0.06\,-1.35}$	$(\star)$	$5.59^{+0.41}_{-0.40}$
$\bar{B}^0_d \to \pi^+ \pi^-$	$7.37\,^{+0.86\,+1.22}_{-0.69\,-0.97}$	$(\star)$	$5.70\,^{+0.70\,+1.16}_{-0.55\,-0.97}$	$(\star)$	5.16 ± 0.22
$\bar{B}^0_d \to \pi^0 \pi^0$	$0.33\,^{+0.11\,+0.42}_{-0.08\,-0.17}$		$0.63\,^{+0.12\,+0.64}_{-0.10\,-0.42}$		1.55 ± 0.19
			BELLE CKM 14:		0.90 ± 0.16
$B^- \to \pi^- \rho^0$	$8.68\,^{+0.42\,+2.71}_{-0.41\,-1.56}$	$(\star\star)$	$9.84\,^{+0.41\,+2.54}_{-0.40\,-2.52}$	$(\star\star)$	$8.3^{+1.2}_{-1.3}$
$B^- \to \pi^0 \rho^-$	$12.38\,^{+0.90\,+2.18}_{-0.77\,-1.41}$	$(\star)$	$12.13\,^{+0.85\,+2.23}_{-0.73\,-2.17}$	$(\star)$	$10.9^{+1.4}_{-1.5}$
$\bar{B}^0 \to \pi^+ \rho^-$	$17.80\,^{+0.62\,+1.76}_{-0.56\,-2.10}$	$(\star)$	$13.76\,^{+0.49\,+1.77}_{-0.44\,-2.18}$	$(\star)$	15.7 ± 1.8
$\bar{B}^0 \to \pi^- \rho^+$	$10.28\,^{+0.39\,+1.37}_{-0.39\,-1.42}$	$(\star\star)$	$8.14\,^{+0.34\,+1.35}_{-0.33\,-1.49}$	$(\star\star)$	7.3 ± 1.2
$\bar{B}^0 \to \pi^\pm \rho^\mp$	$28.08\,^{+0.27\,+3.82}_{-0.19\,-3.50}$	$(\dagger)$	$21.90\,^{+0.20\,+3.06}_{-0.12\,-3.55}$	$(\dagger)$	23.0 ± 2.3
$\bar{B}^0 \to \pi^0 \rho^0$	$0.52\,^{+0.04\,+1.11}_{-0.03\,-0.43}$		$1.49\,^{+0.07\,+1.77}_{-0.07\,-1.29}$		2.0 ± 0.5
$B^- \to \rho^-_L \rho^0_L$	$18.42^{+0.23\,+3.92}_{-0.21\,-2.55}$	$(\star\star)$	$19.06^{+0.24\,+4.59}_{-0.22\,-4.22}$	$(\star\star)$	$22.8^{+1.8}_{-1.9}$
$\bar{B}^0_d \to \rho^+_L \rho^-_L$	$25.98^{+0.85\,+2.93}_{-0.77\,-3.43}$	$(\star\star)$	$20.66^{+0.68\,+2.99}_{-0.62\,-3.75}$	$(\star\star)$	$23.7^{+3.1}_{-3.2}$
$\bar{B}^0_d \to \rho^0_L \rho^0_L$	$0.39^{+0.03\,+0.83}_{-0.03\,-0.36}$		$1.05^{+0.05\,+1.62}_{-0.04\,-1.04}$		$0.55^{+0.22}_{-0.24}$

Theory I: $f_+^{B\pi}(0) = 0.25 \pm 0.05$, $A_0^{B\rho}(0) = 0.30 \pm 0.05$, $\lambda_B(1\,\mathrm{GeV}) = 0.35 \pm 0.15\,\mathrm{GeV}$

Theory II: $f_+^{B\pi}(0) = 0.23 \pm 0.03$, $A_0^{B\rho}(0) = 0.28 \pm 0.03$, $\lambda_B(1\,\mathrm{GeV}) = 0.20^{+0.05}_{-0.00}\,\mathrm{GeV}$

→ good agreement for Br

Acp (penguin dominante decays)

f	NLO	NNLO	NNLO + LD	Exp
$\pi^- \bar{K}^{*0}$	$1.36\,^{+0.25\,+0.60}_{-0.26\,-0.47}$	$1.49\,^{+0.27\,+0.69}_{-0.29\,-0.56}$	$0.27\,^{+0.05\,+3.18}_{-0.05\,-0.67}$	-3.8 ± 4.2
$\pi^0 K^{*-}$	$13.85\,^{+2.40\,+5.84}_{-2.70\,-5.86}$	$18.16\,^{+3.11\,+7.79}_{-3.52\,-10.57}$	$-15.81\,^{+3.01\,+69.35}_{-2.83\,-15.39}$	-6 ± 24
$\pi^+ K^{*-}$	$11.18\,^{+2.00\,+9.75}_{-2.15\,-10.62}$	$19.70\,^{+3.37\,+10.54}_{-3.80\,-11.42}$	$-23.07\,^{+4.35\,+86.20}_{-4.05\,-20.64}$	-23 ± 6
$\pi^0 \bar{K}^{*0}$	$-17.23\,^{+3.33\,+7.59}_{-3.00\,-12.57}$	$-15.11\,^{+2.93\,+12.34}_{-2.65\,-10.64}$	$2.16\,^{+0.39\,+17.53}_{-0.42\,-36.80}$	-15 ± 13
$\delta(\pi \bar{K}^*)$	$2.68\,^{+0.72\,+5.44}_{-0.67\,-4.30}$	$-1.54\,^{+0.45\,+4.60}_{-0.58\,-9.19}$	$7.26\,^{+1.21\,+12.78}_{-1.34\,-20.65}$	17 ± 25
$\Delta(\pi \bar{K}^*)$	$-7.18\,^{+1.38\,+3.38}_{-1.28\,-5.35}$	$-3.45\,^{+0.67\,+9.48}_{-0.59\,-4.95}$	$-1.02\,^{+0.19\,+4.32}_{-0.18\,-7.86}$	-5 ± 45
$\rho^- \bar{K}^0$	$0.38\,^{+0.07\,+0.16}_{-0.07\,-0.27}$	$0.22\,^{+0.04\,+0.19}_{-0.04\,-0.17}$	$0.30\,^{+0.06\,+2.28}_{-0.06\,-2.39}$	-12 ± 17
$\rho^0 K^-$	$-19.31\,^{+3.42\,+13.95}_{-3.61\,-8.96}$	$-4.17\,^{+0.75\,+19.26}_{-0.80\,-19.52}$	$43.73\,^{+7.07\,+44.00}_{-7.62\,-137.77}$	37 ± 11
$\rho^+ K^-$	$-5.13\,^{+0.95\,+6.38}_{-0.97\,-4.02}$	$1.50\,^{+0.29\,+8.69}_{-0.27\,-10.36}$	$25.93\,^{+4.43\,+25.40}_{-4.90\,-75.63}$	20 ± 11
$\rho^0 \bar{K}^0$	$8.63\,^{+1.59\,+2.31}_{-1.65\,-1.69}$	$8.99\,^{+1.66\,+3.60}_{-1.71\,-7.44}$	$-0.42\,^{+0.08\,+19.49}_{-0.08\,-8.78}$	6 ± 20
$\delta(\rho \bar{K})$	$-14.17\,^{+2.80\,+7.98}_{-2.96\,-5.39}$	$-5.67\,^{+0.96\,+10.86}_{-1.01\,-9.79}$	$17.80\,^{+3.15\,+19.51}_{-3.01\,-62.44}$	17 ± 16
$\Delta(\rho \bar{K})$	$-8.75\,^{+1.62\,+4.78}_{-1.66\,-6.48}$	$-10.84\,^{+1.98\,+11.67}_{-2.09\,-9.09}$	$-2.43\,^{+0.46\,+4.60}_{-0.42\,-19.43}$	-37 ± 37

not good agreement for Acp ←

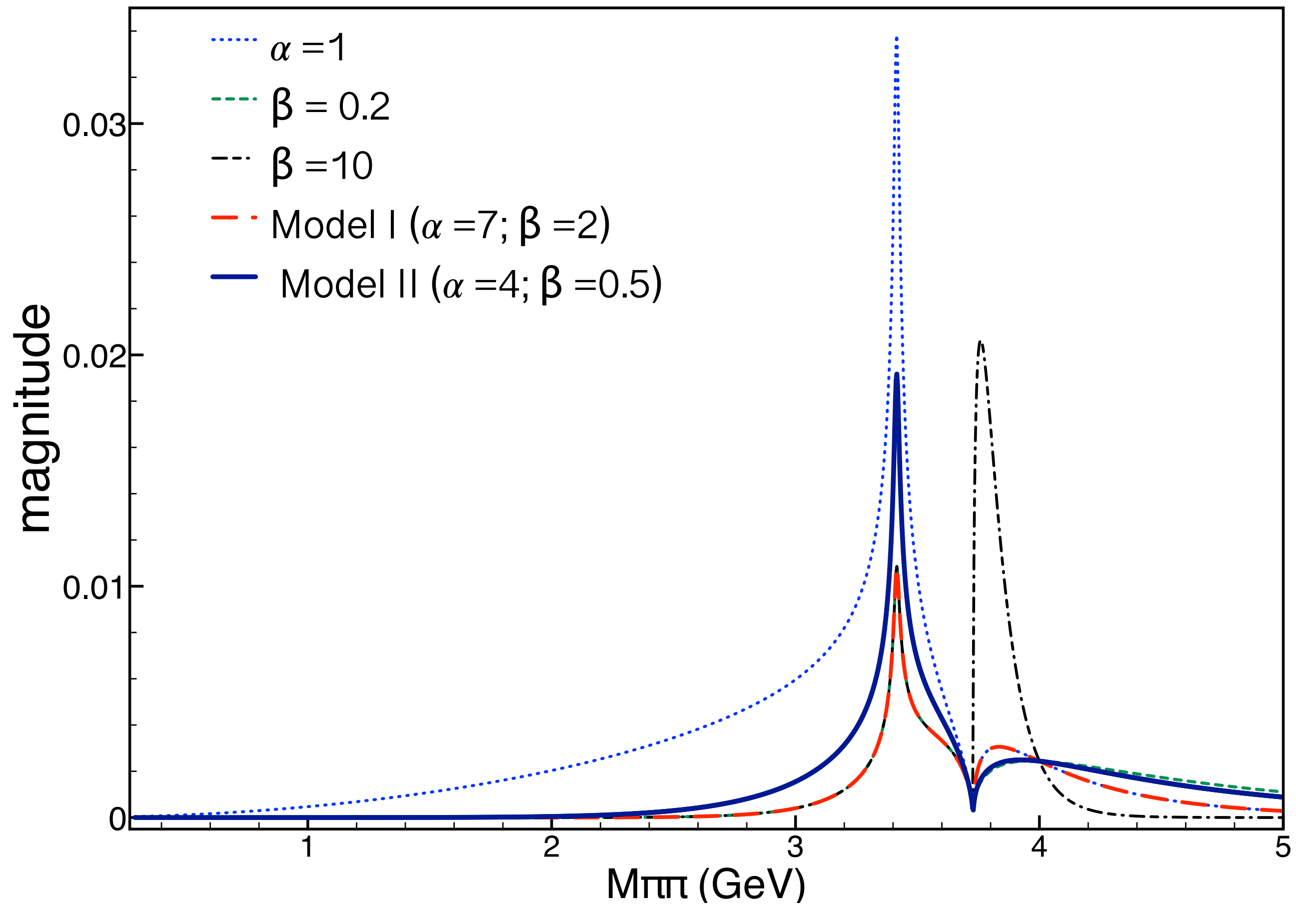
Beneke Seminar at "Future Challenges in Non-Leptonic B Decays", Bad Honnef, 2016

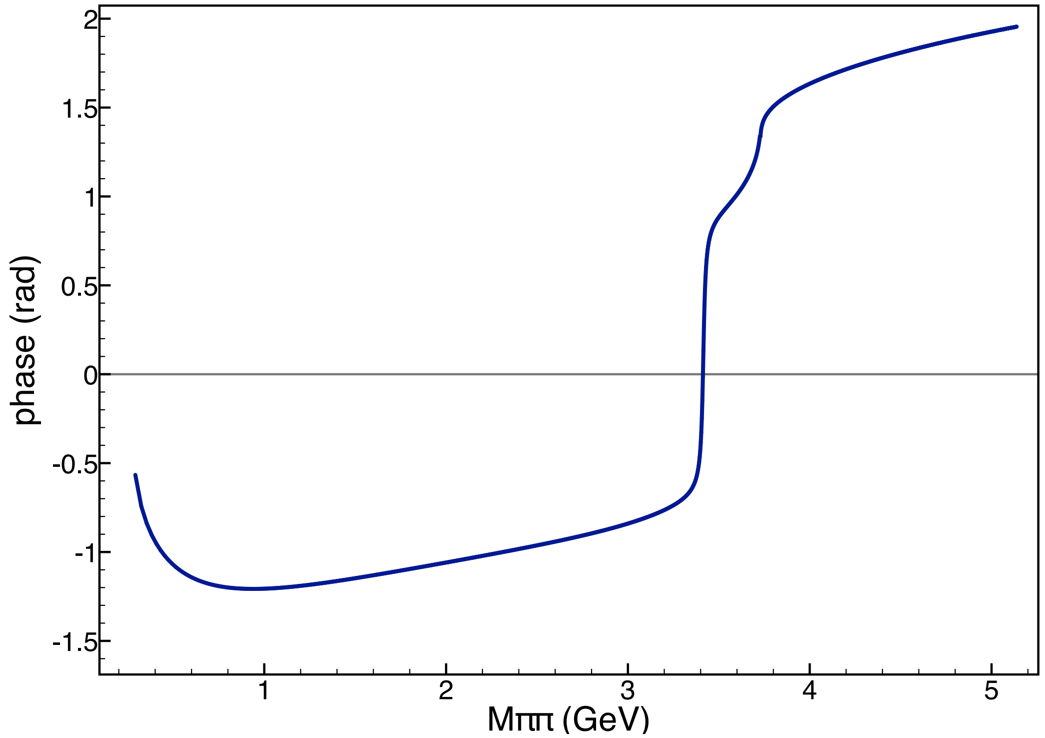
phenomenological $D\bar{D} \to \pi^+\pi^-$ amplitude

- unitary coupled-channel S-matrix $= \begin{pmatrix} \eta\, e^{2i\delta_1} & \boxed{i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)}} \\ i\sqrt{1-\eta^2}\, e^{i(\delta_1+\delta_2)} & \eta\, e^{2i\delta_2} \end{pmatrix}$

  → χ_{c0} (3414) : a pole bellow $D\bar{D}$ threshold in δ_2

- amplitude features:
  - χ_{c0} peak superposed to a wide bump below threshold;
  - zero at $D\bar{D}$ threshold
  - phase jump at $D\bar{D}$ threshold



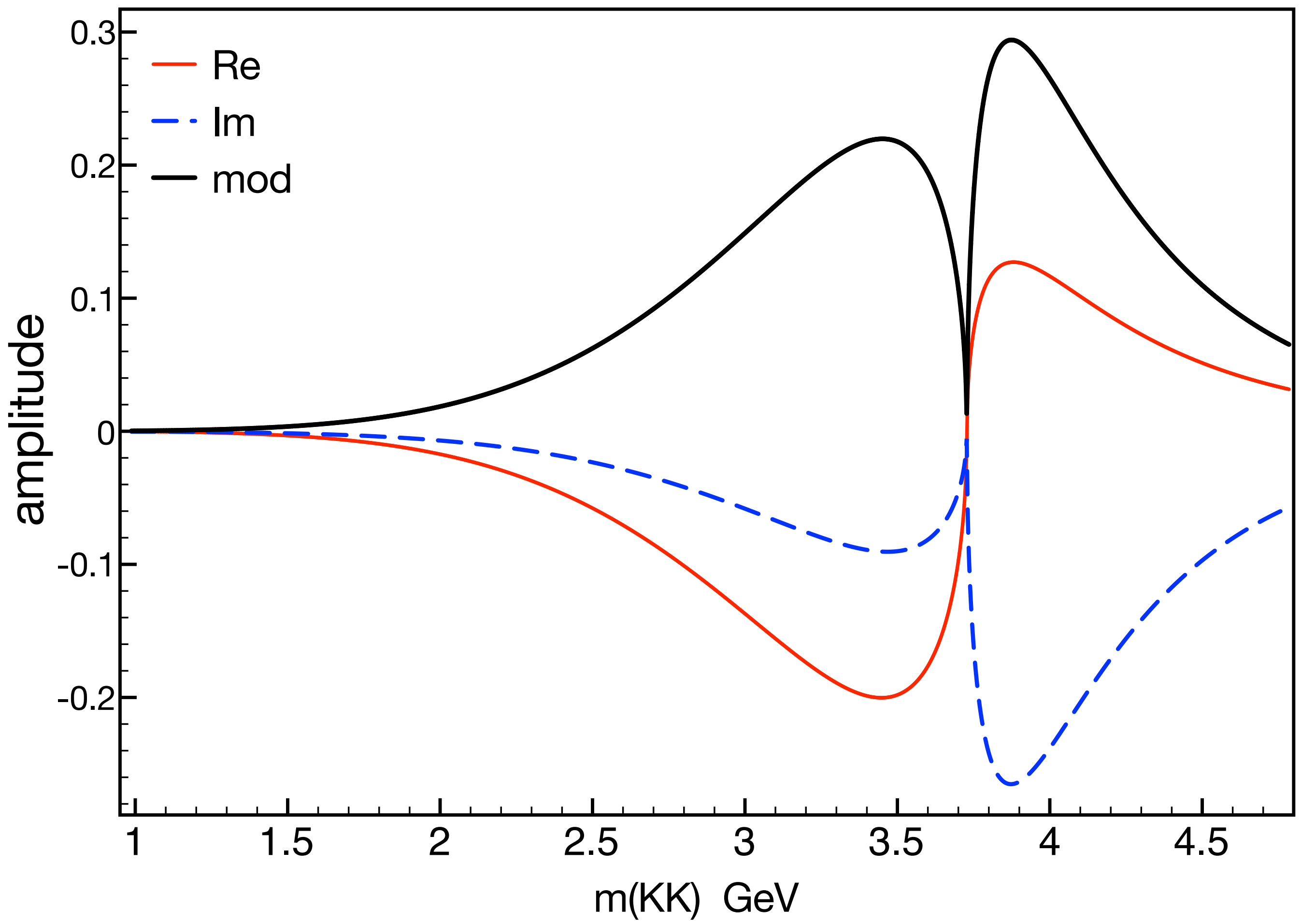


→ parameters should should be fitted

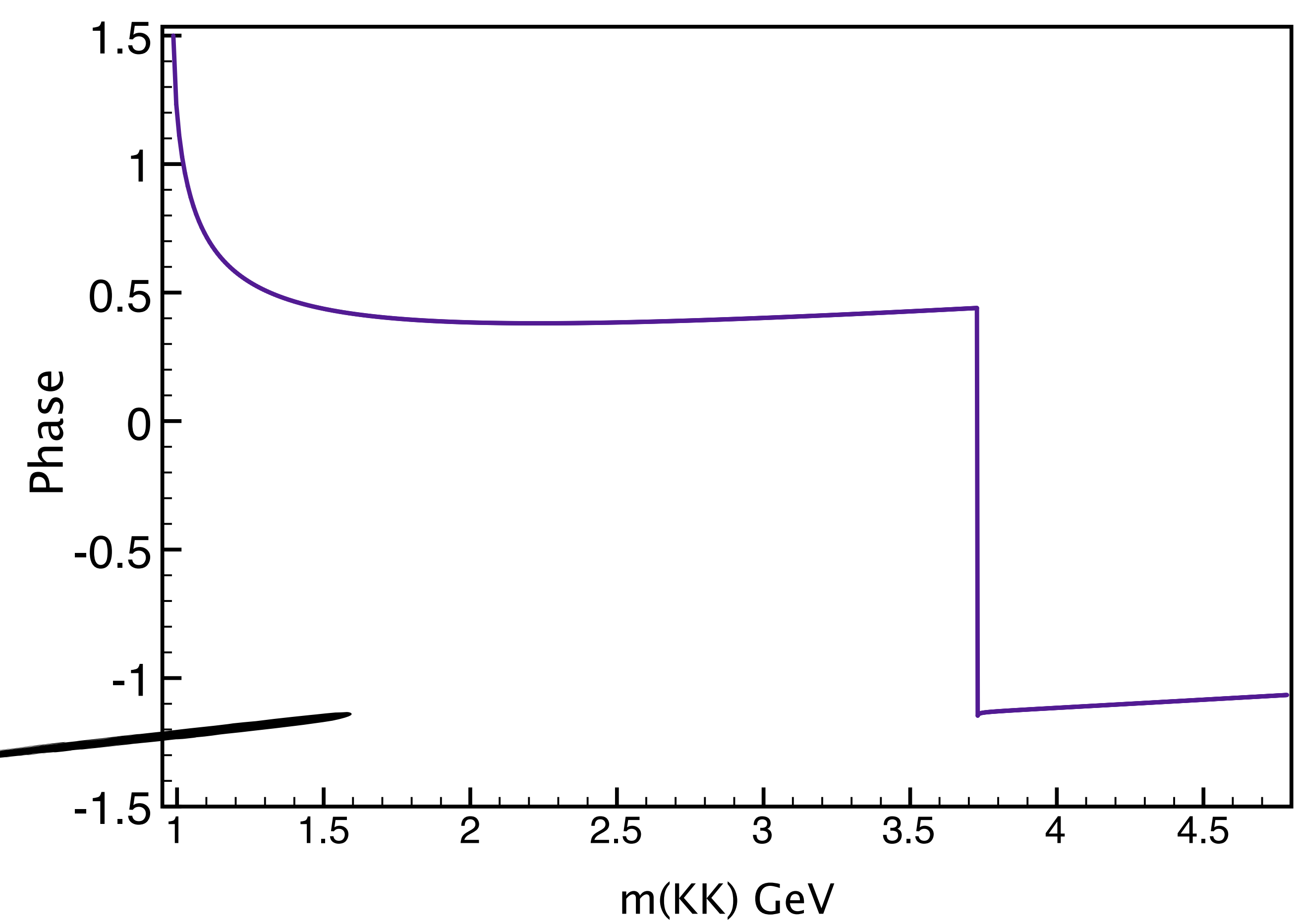
$D^0\bar{D}^0 \to K^+K^-$ scattering amplitude

- $$T_{\bar{D}^0 D^0 \to KK}(s) = \frac{s^\alpha}{s^\alpha_{th\,D\bar{D}}} \frac{2\kappa_2}{\sqrt{s_{th\,D\bar{D}}}} \left(\frac{s_{th\,D\bar{D}}}{s + s_{QCD}}\right)^{\xi+\alpha} \left[\left(\frac{c + bk_1^2 - ik_1}{c + bk_1^2 + ik_1}\right) \left(\frac{\frac{1}{a} + \kappa_2}{\frac{1}{a} - \kappa_2}\right)\right]^{\frac{1}{2}}, \; s < s_{th\,D\bar{D}}$$
  $$= -i \frac{2\,k_2}{\sqrt{s_{th\,D\bar{D}}}} \left(\frac{s_{th\,D\bar{D}}}{s + s_{QCD}}\right)^{\xi} \left(\frac{m_0}{s - m_0}\right)^{\beta} \left[\left(\frac{c + bk_1^2 - ik_1}{c + bk_1^2 + ik_1}\right) \left(\frac{\frac{1}{a} - ik_2}{\frac{1}{a} + ik_2}\right)\right]^{\frac{1}{2}}, s \geq s_{th\,D\bar{D}}$$

parameters fix by data!



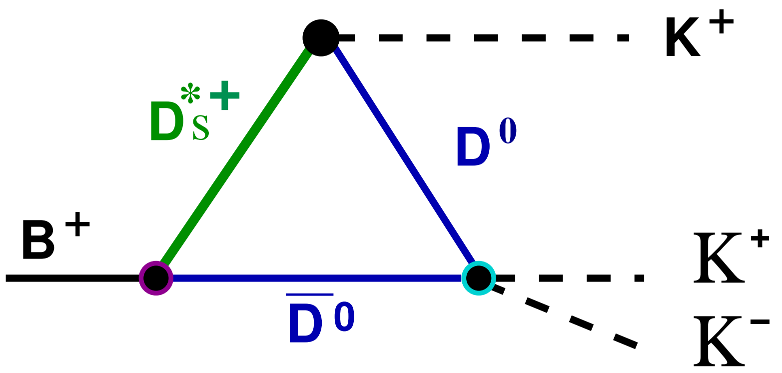
zero at threshold

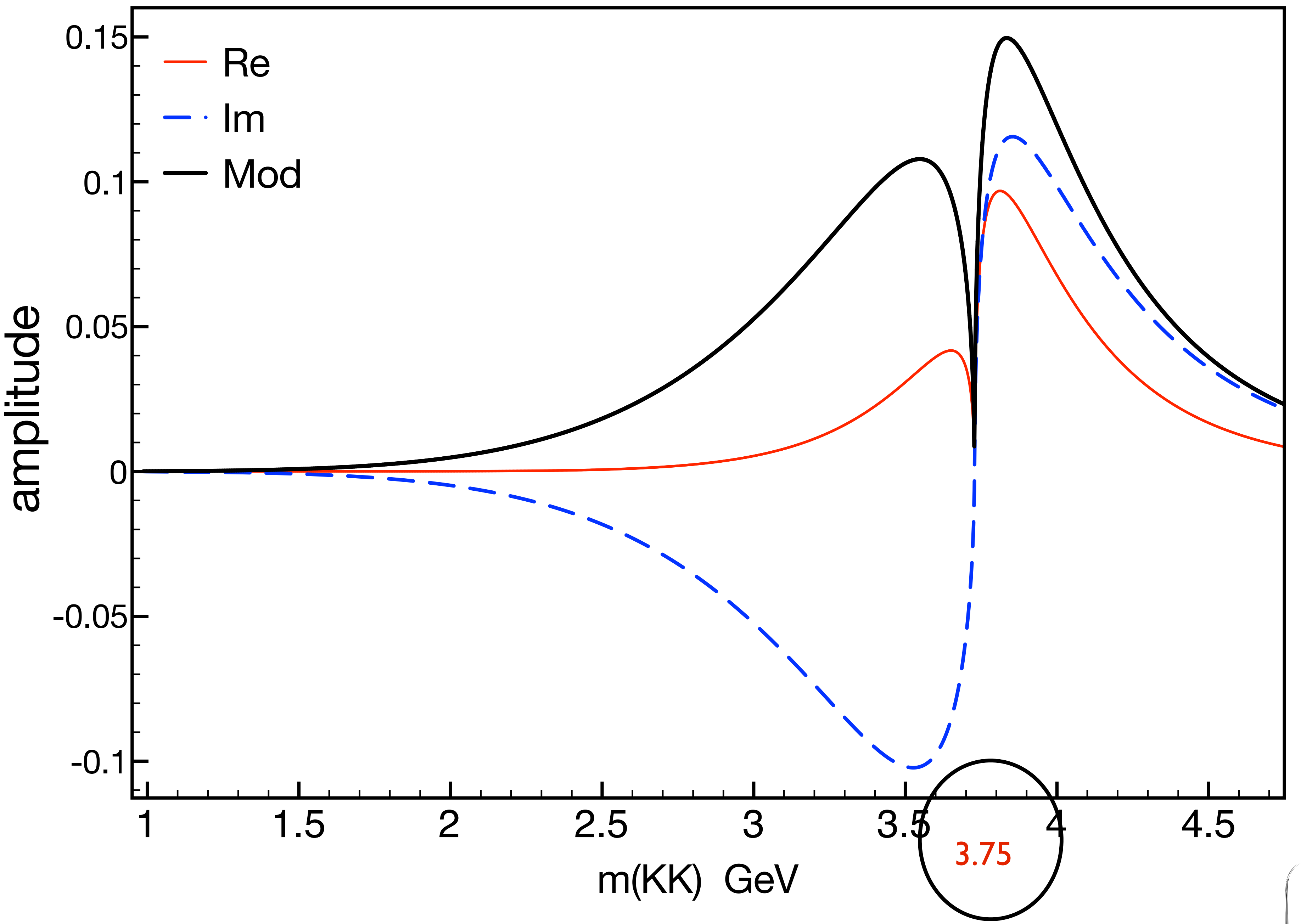


discontinuity at threshold

Final Amplitude

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

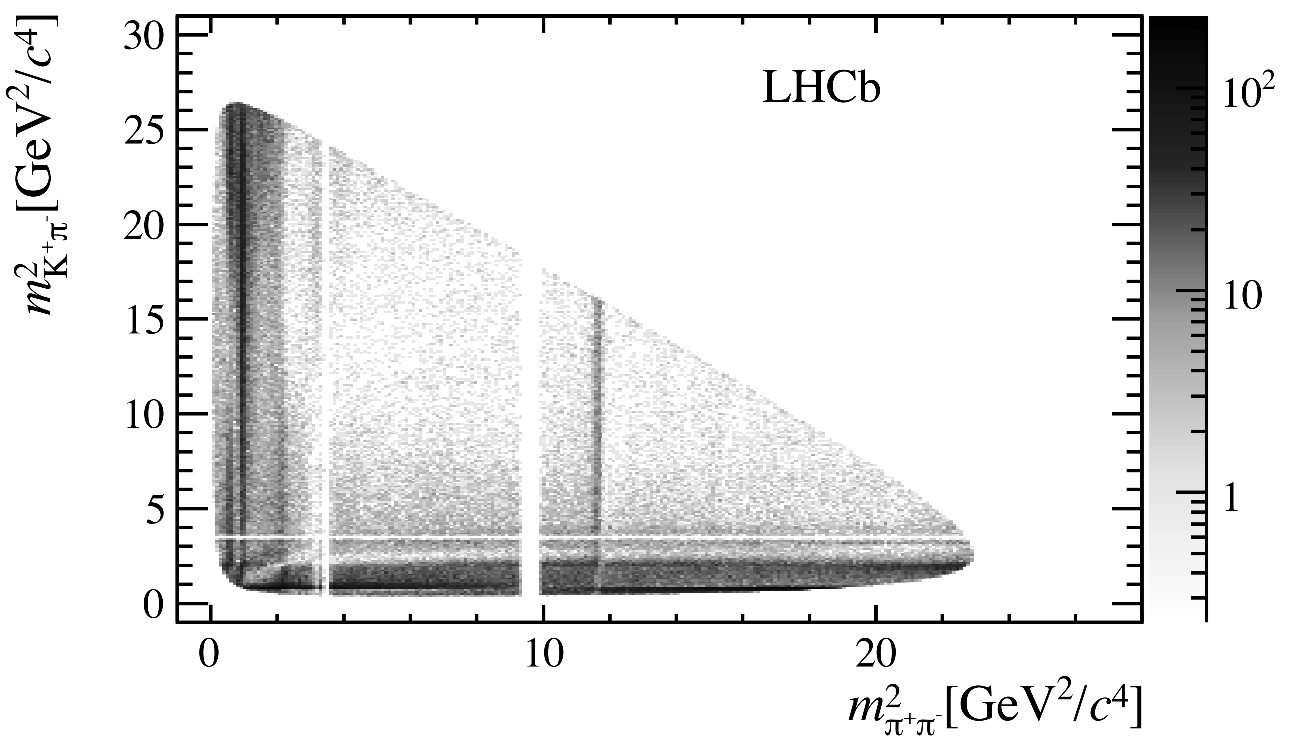




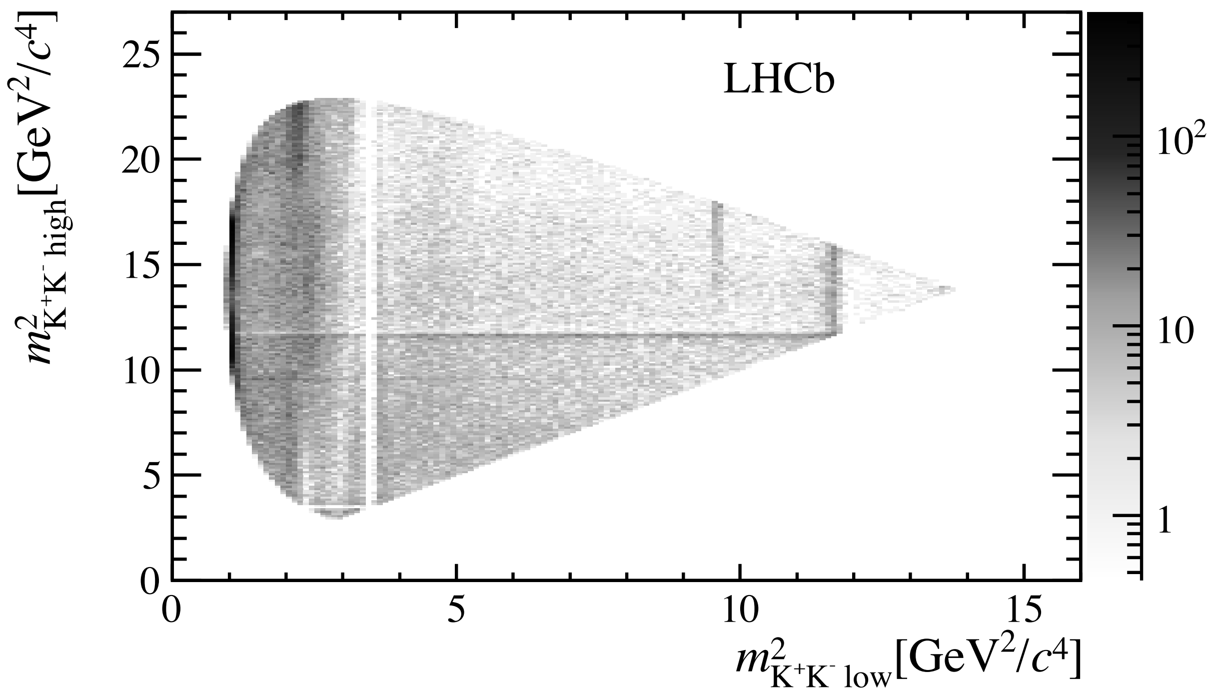
→ zero in between two bumps

rescattering $D^0\bar{D}^0 \to K^+K^-$ play a major role

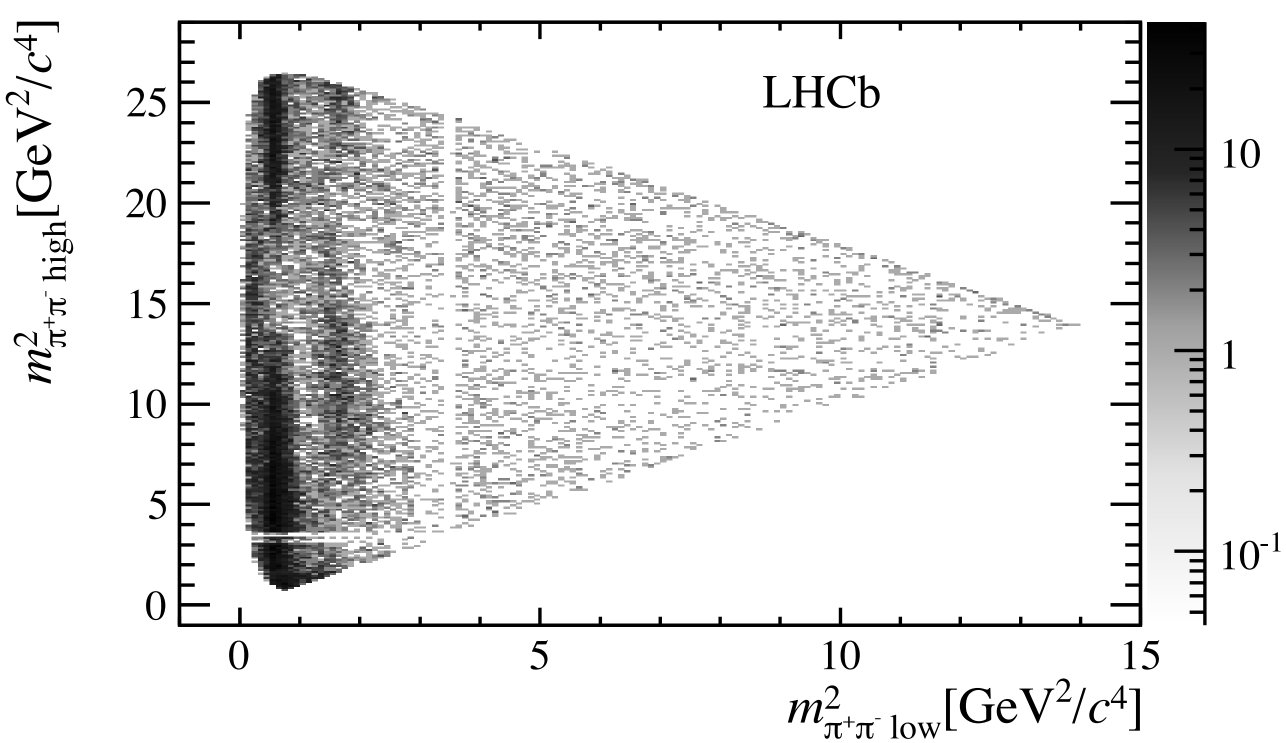
Kpp



KKK



PPP



KKp