CPV in heavy meson decays from FSI

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CP asymmetry measurements in Charm

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

Observation in charm
(Singly Cabibbo Suppressed)

Phys. Rev. Lett. 122, 211803 (2019)

$$\Delta A_{CP}^{\mathrm{LHCb}} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+) = -(1.54 \pm 0.29) \times 10^{-3}$$

➔ direct CP asymmetry observation: new physics?

➔ 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 basics

→ condition to CPV:

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

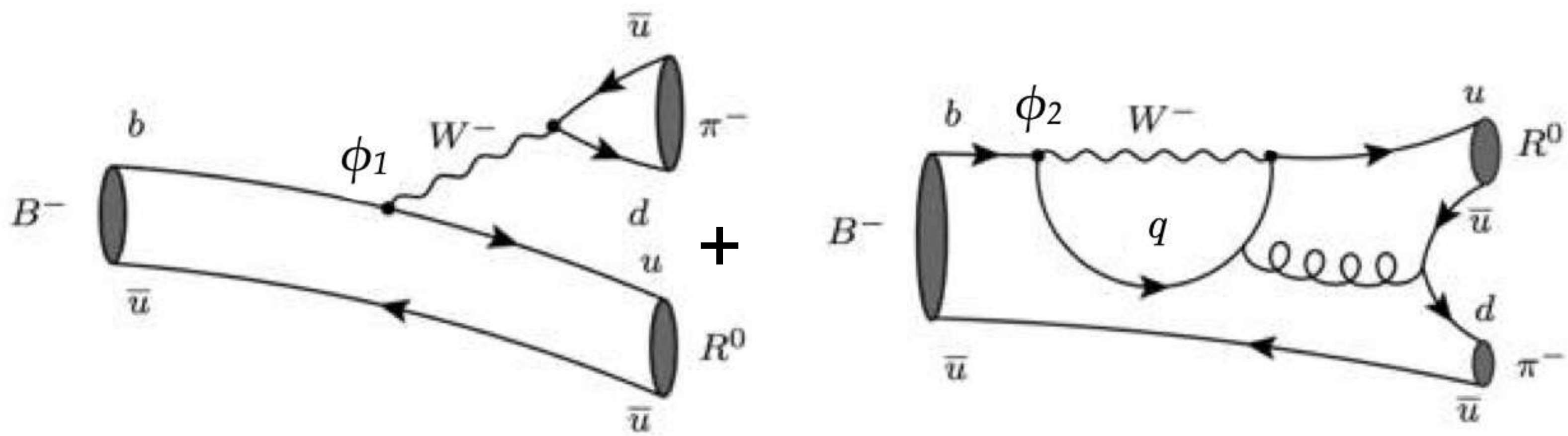
$$\langle f\,|\,T\,|\,M\rangle = A_1\,e^{i(\delta_1+\phi_1)} + A_2\,e^{i(\delta_2+\phi_2)}$$
$$\langle \bar f\,|\,T\,|\,\bar M\rangle = A_1\,e^{i(\delta_1-\phi_1)} + A_2\,e^{i(\delta_2-\phi_2)}$$

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

- weak phase → CKM   strong phase → QCD

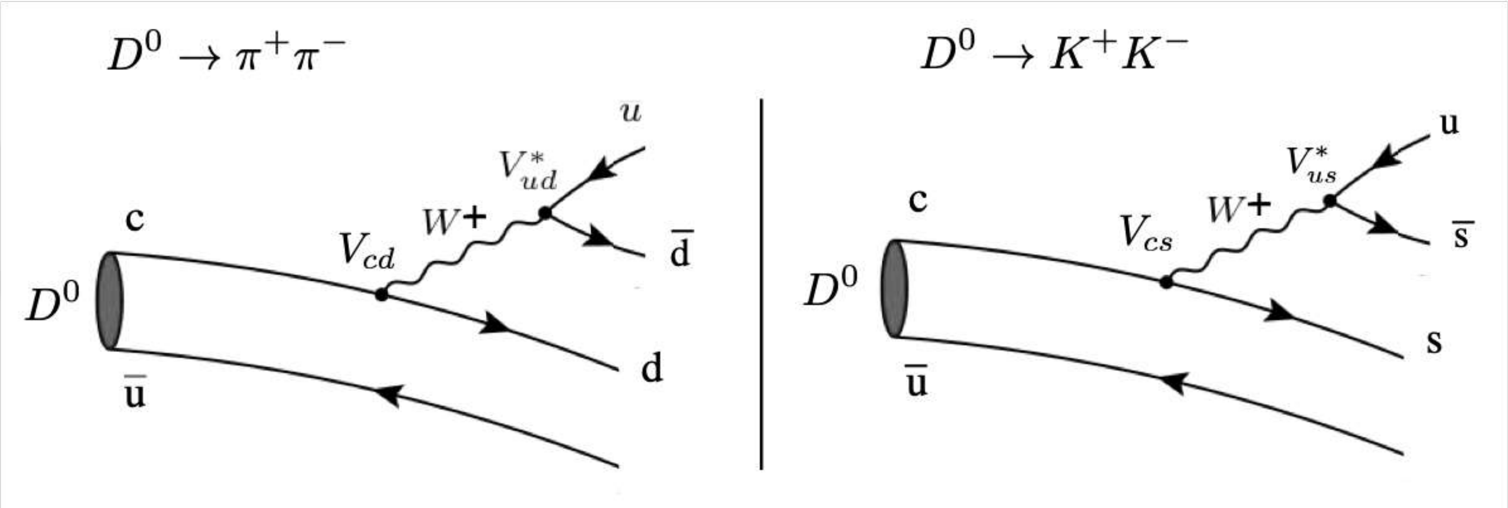
- CPV at quark level: BSS model Bander Silverman & Soni PRL 43 (1979) 242

- good for $B\to hh$



→ hadronic FSI interactions also can be a source of strong phase!

Theory approaches for CPV in D^0



- QCDF: how to calculate penguin contributions? cannot account for rescattering effects

- LCSR: QCD, model independent, predictions are one order magnitude below.
  Khodjamirian & Petrov, Phys. Lett. B 774, 235 (2017).

→ Long distance effects: topological approaches

- ❖ with/without SU(3) constraint Alexey Petrov, Bhubanjyoti Bhattacharya
- ❖ with SU(3) breaking through FSI (prediction agrees) H.-Y. Cheng and C.-W. Chiang, PRD 100, 093002 (2019). F. Buccella, A. Paul and P. Santorelli, PRD 99, 113001 (2019)
- ❖ with resonances (fit agrees) Schacht and A. Soni, Phys. Lett. B 825, 136855 (2022). Y. Grossman and S. Schacht, JHEP 07, 20 (2019)

Theories approaches for CPV in D^0

Annual Review of Nuclear and Particle Science

Mixing and *CP* Violation in the Charm System

Annu. Rev. Nucl. Part. Sci. 2021. 71:59–85

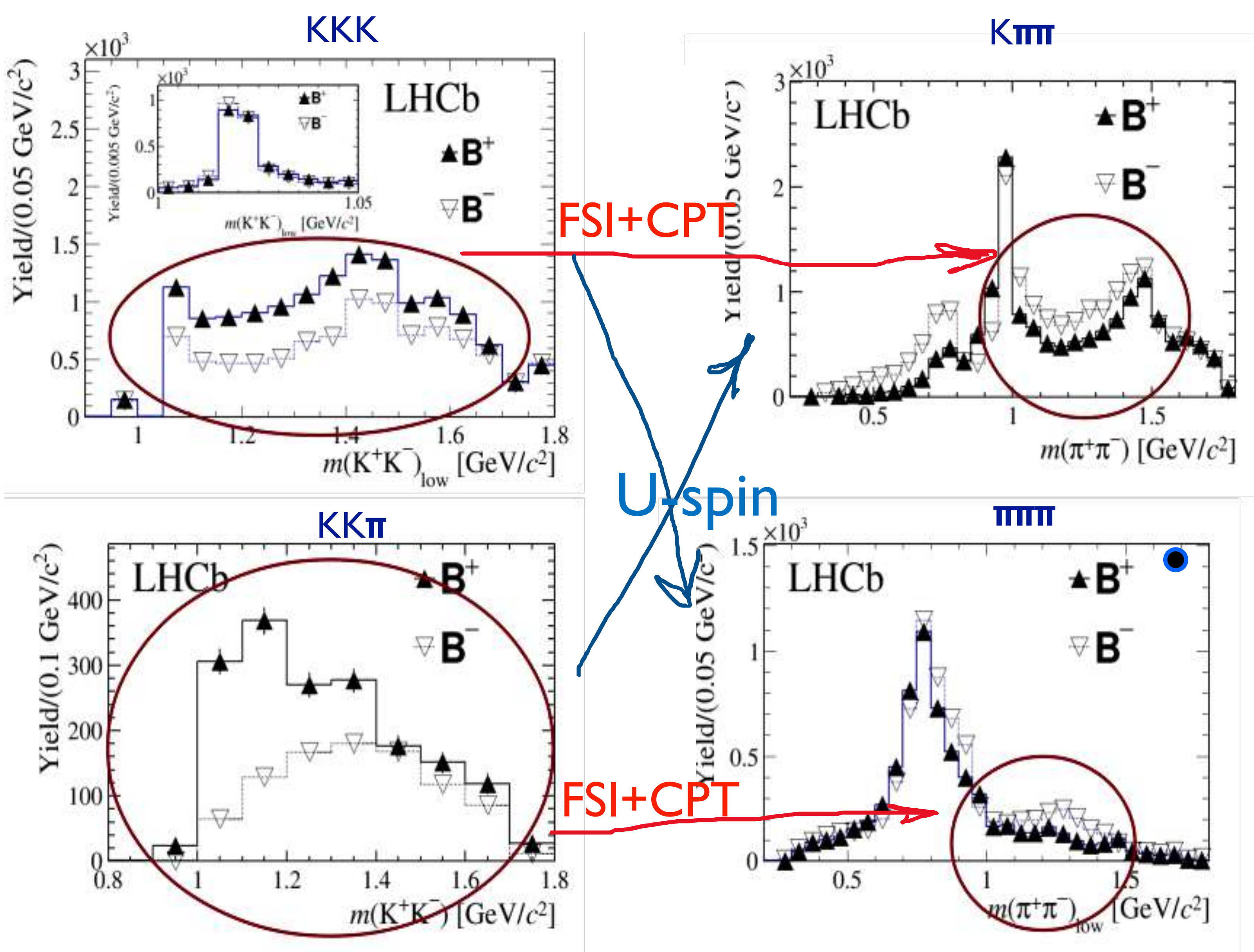
Alexander Lenz[1] and Guy Wilkinson[2]

“Thus, we are in the unfortunate situation that perturbative and sum-rule estimates are at least one order of magnitude below the experimental value, while symmetry-based approaches suggest that the SM is in perfect agreement with data. To identify the true origin of direct *CP* violation in the charm sector, greater theoretical understanding is necessary.”

FSI & CPT - CPV enhancement - Bediaga, Frederico PCM arxiv 2203.04056

Evidence of FSI&CPT from B→ hhh decays

B decays: 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

FSI+CPT+U-spin

FSI & CPT in CPV B→hhh

- Final State Interactions → strong phase

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

→ CPT invariance

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 relates channels with same quantum numbers

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

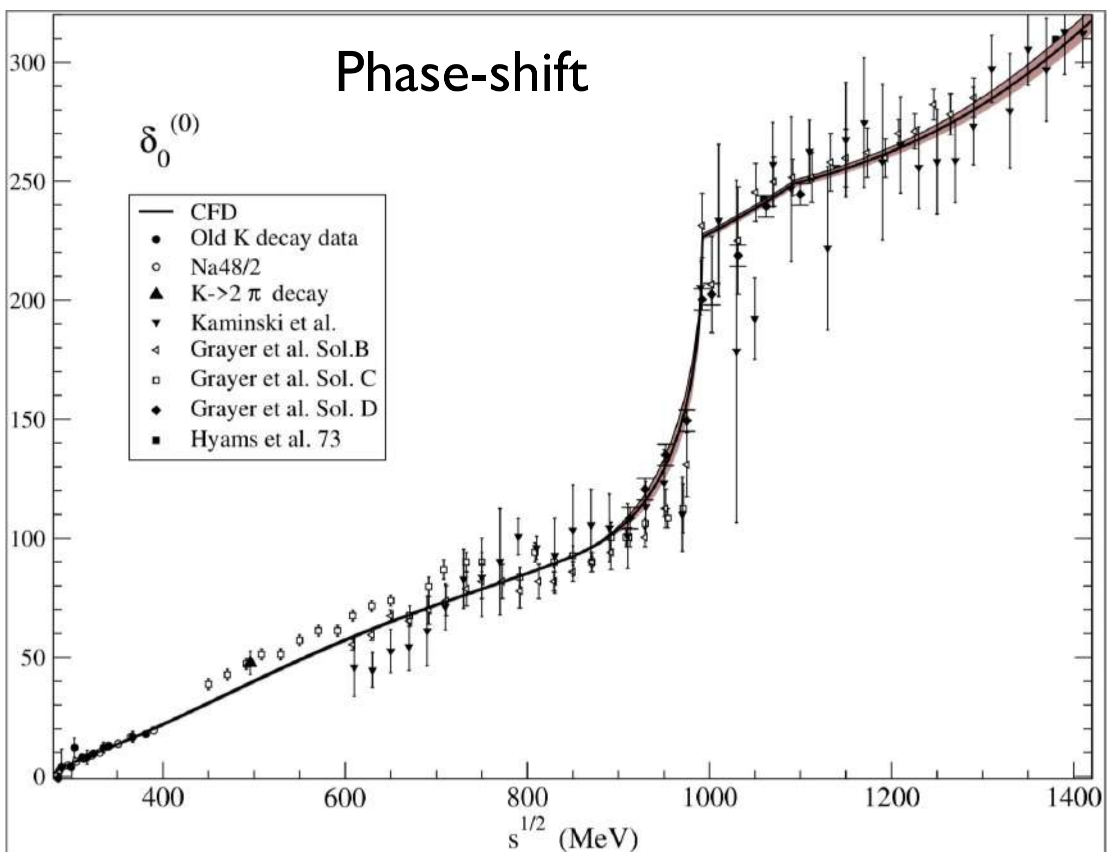
at low-energy [1 -1.6] GeV

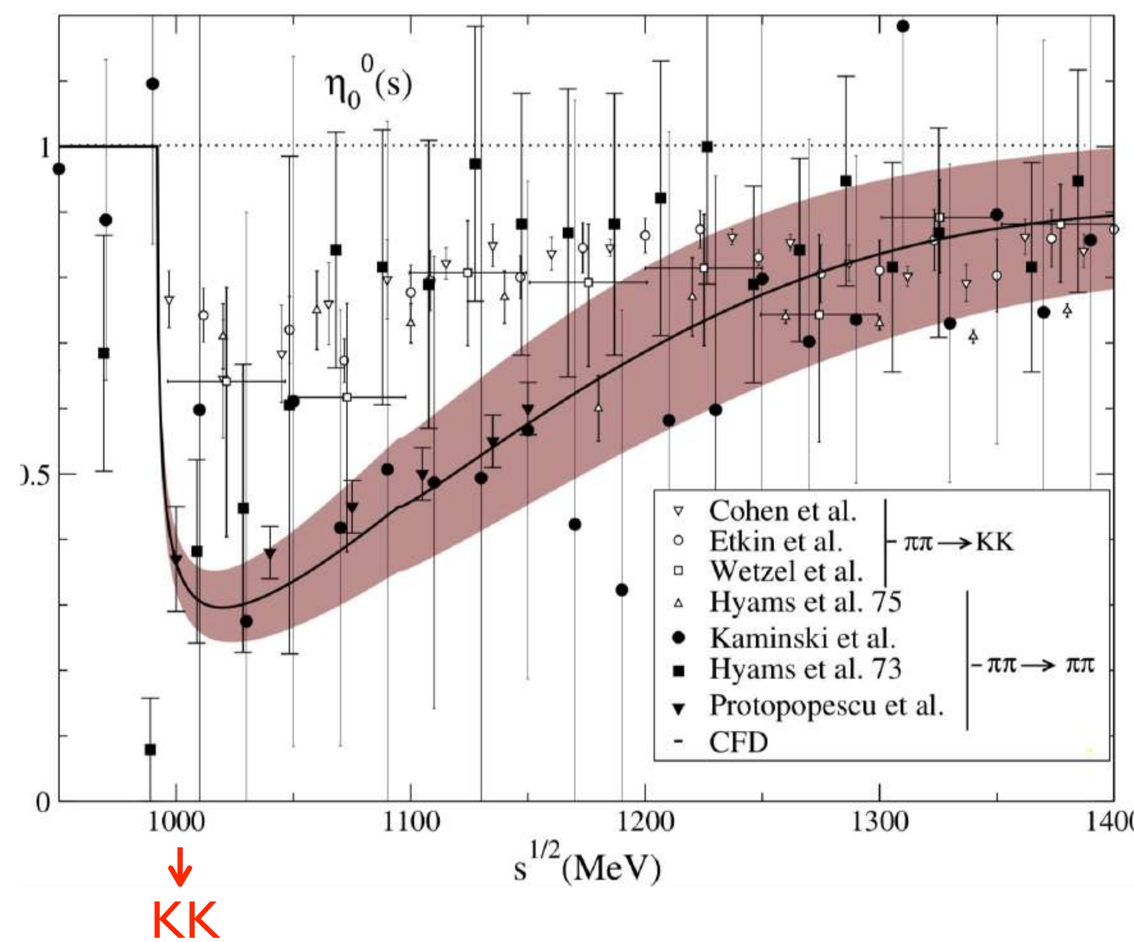
Rescattering π π→K K

s-wave Pelaez, Yndurain PRD71(2005) 074016

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

π π→K K





new parametrisation Pelaez, Rodas, Elvira EPJ C 79 (2019) 1008

FSI & CPV at low –mass region

Bediaga, Frederico, Lourenço PRD89(2014)094013

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

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

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

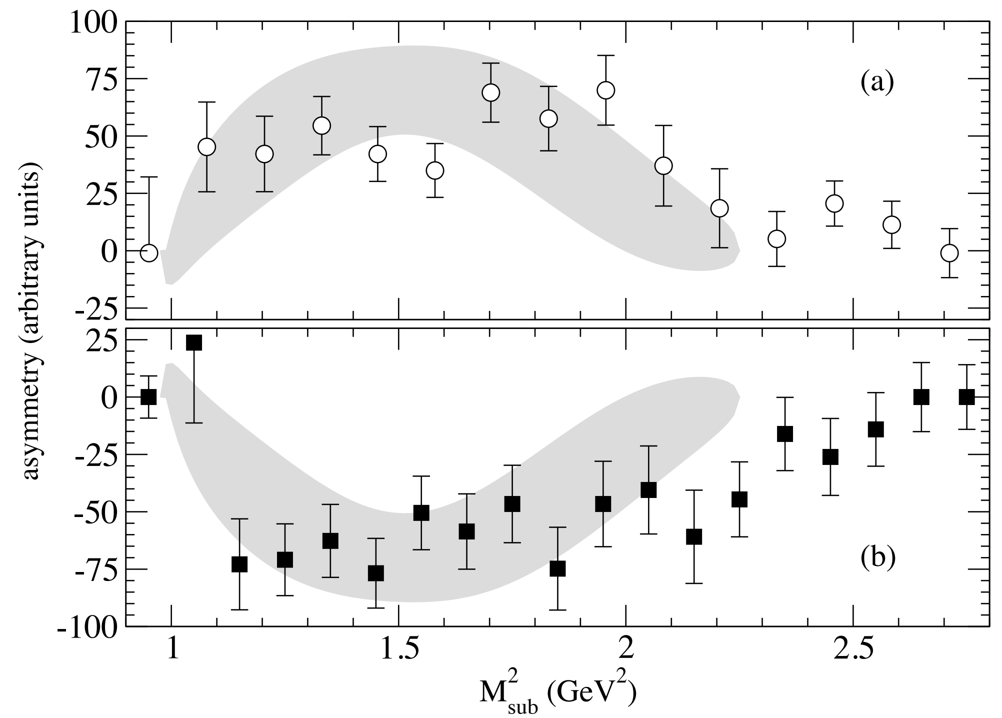


FIG. 1: Estimate (grey band) of Eq. (15) as a function of the subsystem mass compared to experimental data of (a) the asymmetry of $B^\pm \to K^\pm\pi^+\pi^-$ decay (circles), and of (b) the asymmetry of $B^\pm \to K^\pm K^+ K^-$ decay (squares). Data extracted from Ref. [5].

LHCb PRL111, 101801 (2013)

Alvarenga Nogueira etal PRD 92 (2015) 054010

FSI & Resonances $\rho(770)$ & $f_0(980)$

LHCb PRD 90, 112004 (2014)

$$\mathcal{A}^{\pm}_{LO} = \sum_{J\,R}\left(a^R_{0\lambda} + e^{\pm i\gamma} b^R_0\right) F^{BW}_{R\lambda} P_J(\cos\theta)$$
$$+ \sum_J \left(A^J_{0\lambda NR} + e^{\pm i\gamma} B^J_{0\lambda NR}\right)$$
$$+ i \sum_{\lambda',J} t^J_{\lambda',\lambda}\left(A^J_{0\lambda' NR} + e^{\pm i\gamma} B^J_{0\lambda' NR}\right)$$

Watson Theorem

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]

Global CPV

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

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

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

$$\boxed{\begin{aligned}\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-) &= -\Delta\Gamma_{CP}(\pi^\pm K^+K^-)\,,\\ \Delta\Gamma_{CP}(\pi^\pm\pi^+\pi^-) &= -\Delta\Gamma_{CP}(K^\pm K^+K^-)\,.\end{aligned}}$$

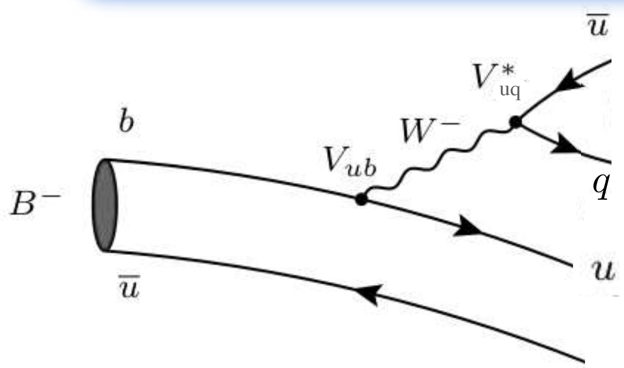
U-spin & FSI ? $$\frac{\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-)}{\Delta\Gamma_{CP}(\pi^\pm\pi^+\pi^-)} = 1.59 \pm 0.62 \text{ and } \frac{\Delta\Gamma_{CP}(K^\pm K^+K^-)}{\Delta\Gamma_{CP}(\pi^\pm K^+K^-)} = 1.77 \pm 0.55$$

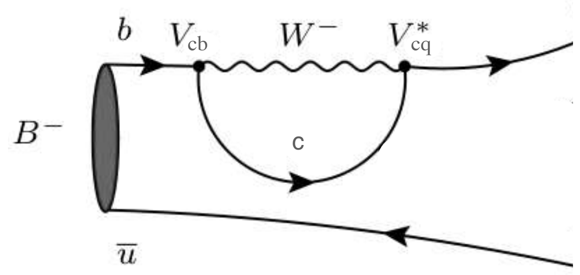
Global CPV, U-spin and FSI

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

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

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.

Application to the two channel model ππ –KK

Global CPV, U-spin and FSI in two-channel model

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

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

q= d or s

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

$\Delta\Gamma(q_{\pi\pi}) = -\Delta\Gamma(q_{KK})$ change in sign pion-pion → KK

U-spin symm:

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

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

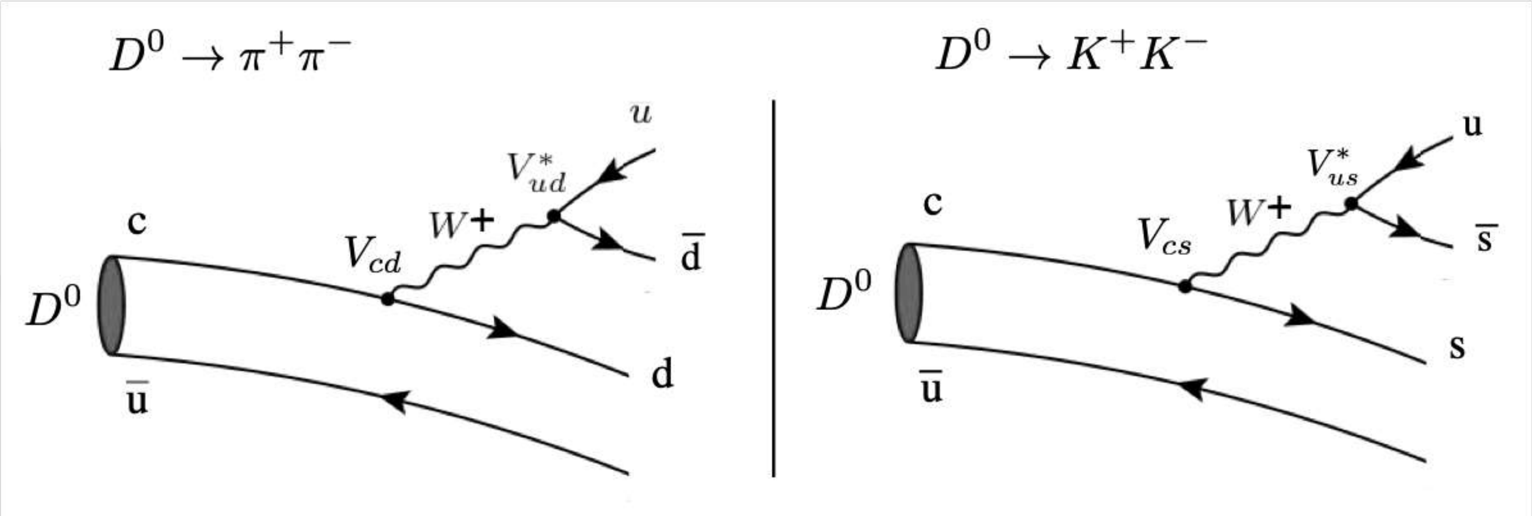
$$\frac{\Delta\Gamma_{CP}(\pi^\pm K^+K^-)}{\Delta\Gamma_{CP}(K^\pm\pi^+\pi^-)} \sim -1 \quad \text{and} \quad \frac{\Delta\Gamma_{CP}(\pi^\pm \pi^+\pi^-)}{\Delta\Gamma_{CP}(K^\pm K^+K^-)} \sim -1\,.$$

CPT symm:

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

-0.73 ± 0.22 and -0.81 ± 0.31

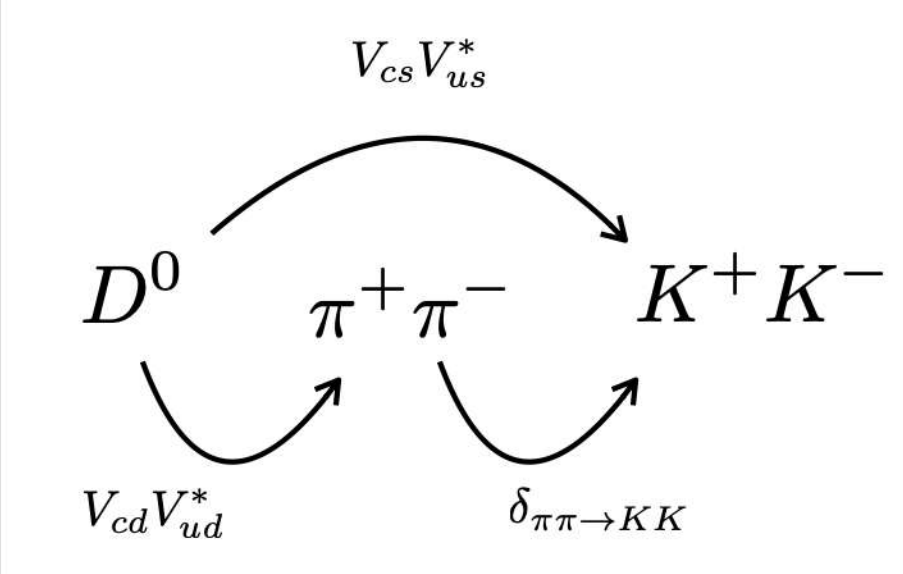
Singly Cabibbo suppressed decays: tree level



weak phase in s to $\pi\pi$ is 20 times KK one

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

→ strong phases: hadronic FSI



known from 80's experiment

CPT in SCS D decays: S-matrix

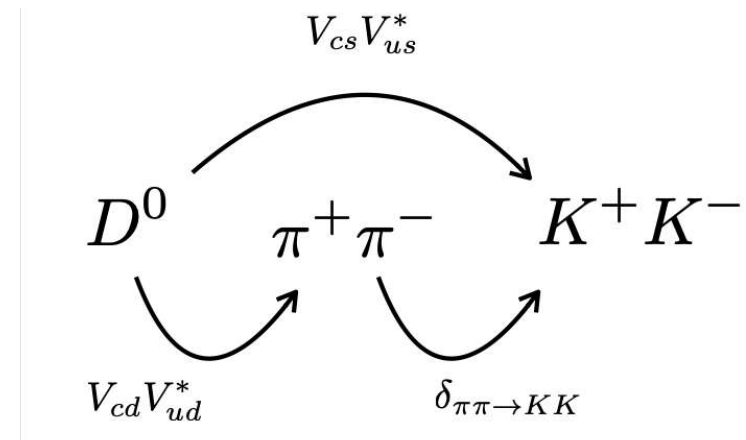
- In principle FSI in D, $\overline{D}$ can include multiple mesons
  - general S-matrix can mix this FSI states $$S = \begin{pmatrix} S_{2M,2M} & S_{2M,3M} & S_{2M,4M} & \cdots \\ S_{3M,2M} & S_{3M,3M} & S_{3M,4M} & \cdots \\ S_{4M,2M} & S_{4M,3M} & S_{4M,4M} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}$$
- $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$

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

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

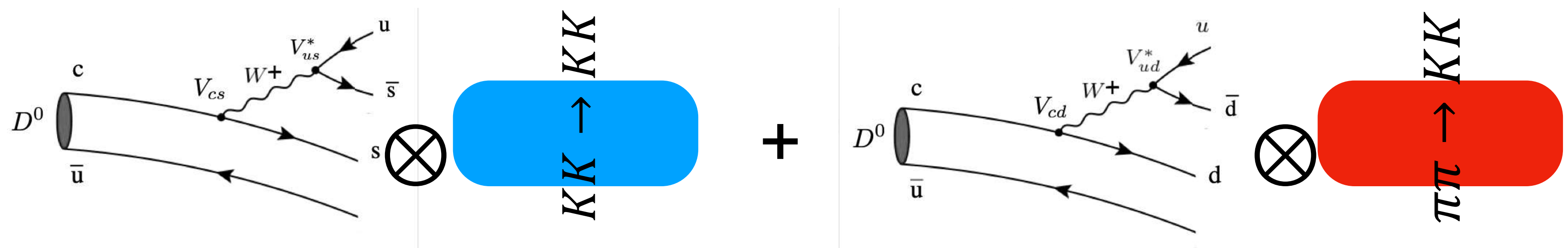
$$\boxed{\begin{aligned} S_{\pi\pi,\pi\pi} &= \eta\, e^{2i\delta_{\pi\pi}} \quad S_{KK,KK} = \eta\, e^{2i\delta_{KK}} \\ S_{\pi\pi,KK} &= S_{KK,\pi\pi} = \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_{\pi\pi}+\delta_{KK})} \end{aligned}}$$

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



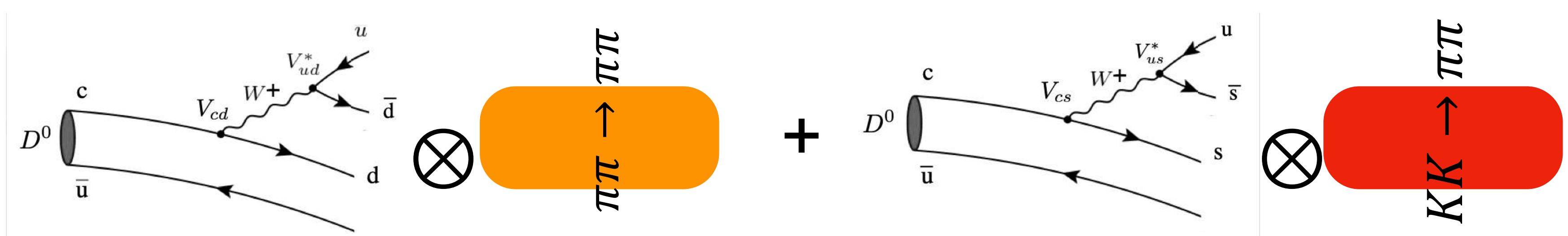
- **Dressing the weak tree topology with FSI**
- $D^0 \to KK$

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



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

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



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

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

CPT constraint is valid: $\sum_{f=(\pi\pi,KK)} \left(|\mathcal{A}_{D^0\to f}|^2 - |\mathcal{A}_{\bar{D}^0\to f}|^2\right) = 0$

Partial decay widths D^0 decays

- $\Delta\Gamma_f = \Gamma\left(D^0 \to f\right) - \Gamma(\bar{D}^0 \to f)$

$\overline{A}_f^2$

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

- $\boxed{\Delta\Gamma_{\pi\pi} = -4\,\mathrm{Im}[V_{cs}^* V_{us} V_{cd} V_{ud}^*]\, a_{\pi\pi}\, a_{KK}\, \eta\sqrt{1-\eta^2}\cos\phi}$
    - $\phi = \delta_{KK} - \delta_{\pi\pi}$
    - the sign of $\Delta\Gamma_f$ is determined by the CKM matrix elements and the S-wave phase-shifts
    - need to quantify $a_{\pi\pi}$ and a_{KK}:

at D^0 mass $\sqrt{1-\eta^2} << 1$ $\rightarrow$ $\Gamma_{\pi\pi} \approx \eta^2 |V_{cd}^* V_{ud}|^2\, a_{\pi\pi}^2$, $\Gamma_{KK} \approx \eta^2 |V_{cs}^* V_{us}|^2 a_{KK}^2$

$Br[D \to f] = \Gamma_f / \Gamma_{total}$

A_{CP}

- $$A_{CP}(\pi\pi) = \Delta\Gamma_{\pi\pi}/2\Gamma_{\pi\pi} = \frac{-2\,\mathrm{Im}[V_{cs}^* V_{us} V_{cd} V_{ud}^*]}{\eta |V_{cd}^* V_{ud}|^2} \frac{a_{KK}}{a_{\pi\pi}} \sqrt{1-\eta^2} \cos\phi$$

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

- CPT constraint for the model: $\Delta\Gamma_{\pi\pi} = -\Delta\Gamma_{KK}$

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

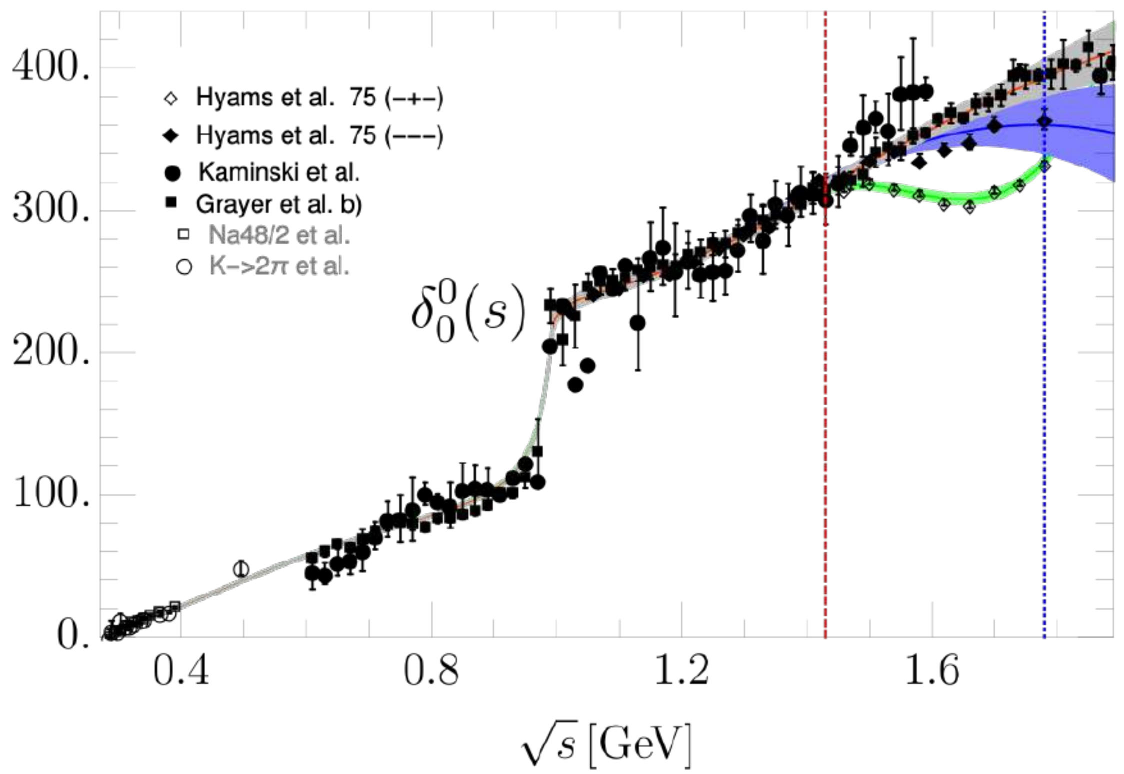
Phase and inelasticity in $\pi\pi \to \pi\pi$ scattering

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

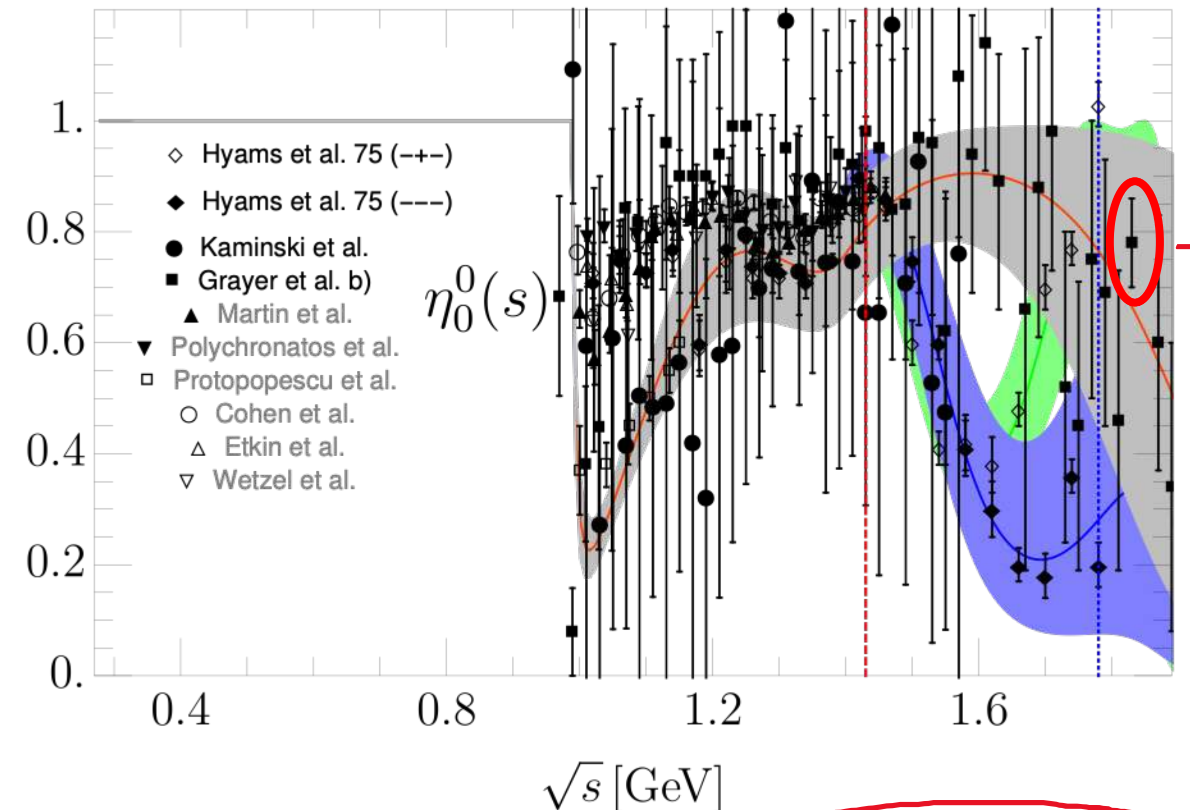
→ CERN-Munich data from 80's

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

Grayer et al. Nucl. Phys. B 75, 189 (1974).
Hyams et al., Nucl. Phys. B 100, 205 (1975)
Longacre et al., Phys. Lett. B 177, 223 (1986).
Ochs, J. Phys. G 40, 043001 (2013)



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

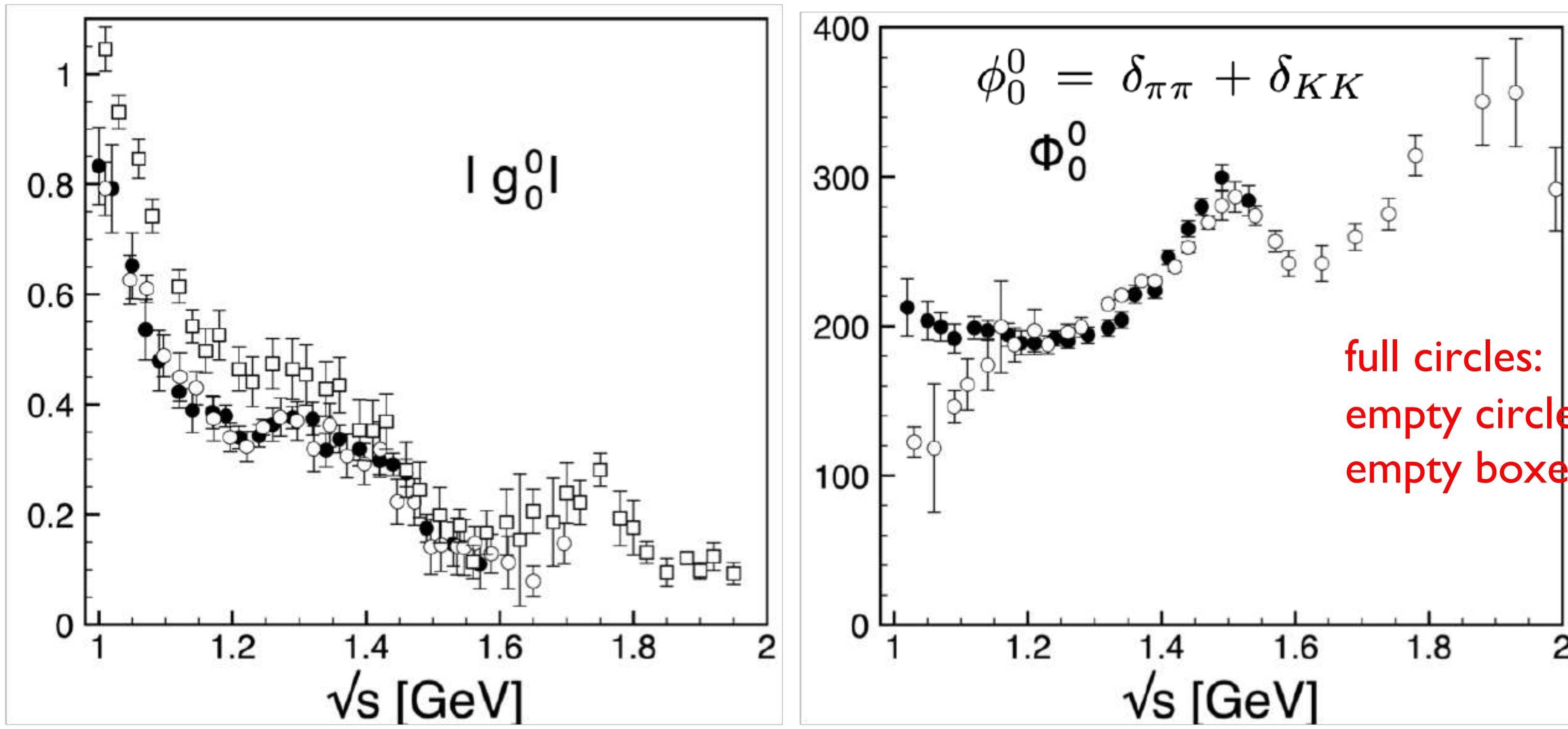


$\eta = 0.78 \pm 0.08$

Grayer et al. Nucl. Phys. B 75, 189 (1974)

Off-diagonal S-matrix $\pi\pi \to KK$

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



full circles: Cohen et al., Phys. Rev. D 22, 259 (1980)
empty circles: Etkin et al., Phys. Rev. D 25, 1786 (1982)
empty boxes: Longacre et al., Phys. Lett. B 177, 223 (1986).

Parametrization @ M_D^2: Pelaez and Rodas, Eur. Phys. J. C 78, 897 (2018)

$$|g_0^0(M_D^2)| \approx 0.125 \pm 0.025 \qquad \sqrt{1-\eta^2} = 0.229 \pm 0.046 \rightarrow \eta = 0.973 \pm 0.003$$

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

$cos\phi$

- No experimental data for KK scattering !
  - Use $\pi\pi$ and $KK \to \pi\pi$ data: $\delta_{KK} - \delta_{\pi\pi} = \phi_0^0 - 2\delta_{\pi\pi} = (\delta_{KK} + \delta_{\pi\pi}) - 2\delta_{\pi\pi}$
  - CERN-Munich data (revised Ochs)

$\sqrt{s}$ [GeV]	$\cos\phi$
1.58	0.989 ± 0.149
1.62	0.994 ± 0.105
1.66	0.999 ± 0.040
1.70	0.987 ± 0.160
1.74	0.999 ± 0.048
1.78	0.999 ± 0.037
$m_D^2 \rightarrow$ 1.846	0.987 ± 0.175

$\rightarrow \cos(\delta_{KK} - \delta_{\pi\pi}) \lesssim 1$

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

A_{CP} Formula

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

$+\pi\pi$

$-KK$

How good is the experimental determination ?

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

$$\frac{\mathrm{Im}[V_{cs}V_{us}^* V_{cd}^* V_{ud}]}{|V_{cs}V_{us}^* V_{cd}^* V_{ud}|} = (6.02 \pm 0.32) \times 10^{-4}$$

$$A_{CP}(\pi\pi) = (1.99 \pm 0.37) \times 10^{-3} \sqrt{\eta^{-2} - 1}\,,$$
$$A_{CP}(KK) = -(0.71 \pm 0.13) \times 10^{-3} \sqrt{\eta^{-2} - 1}$$

$$\Delta_{CP}^{th} = -(2.70 \pm 0.50) \times 10^{-3} \sqrt{\eta^{-2} - 1}$$

SM prediction!

$$\Delta A_{CP}^{\mathrm{LHCb}} = -(1.54 \pm 0.29) \times 10^{-3} \qquad \Delta A_{CP}^{\mathrm{av}} = -(1.61 \pm 0.28) \times 10^{-3}$$

Values for A_{CP} : SM predictions

$\eta = 0.973 \pm 0.003$ Pelaez and Rodas, Eur. Phys. J. C 78, 897 (2018)

$$A_{CP}(\pi\pi) = (0.47 \pm 0.13) \times 10^{-3}$$
$$A_{CP}(KK) = -(0.17 \pm 0.05) \times 10^{-3}$$

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

$\eta = 0.78 \pm 0.08$ Grayer et al. Nucl. Phys. B 75, 189 (1974)

$$\rightarrow \Delta A_{CP}^{th} = -(2.17 \pm 0.70) \times 10^{-3}$$

$$\Delta A_{CP}^{\mathrm{LHCb}} = -(1.54 \pm 0.29) \times 10^{-3} \qquad \Delta A_{CP}^{\mathrm{av}} = -(1.61 \pm 0.28) \times 10^{-3}$$

CPT in two channels exact

- $$\sum_{f=(\pi\pi,KK)} \left(|\mathcal{A}_{D^0\to f}|^2 - |\mathcal{A}_{\bar{D}^0\to f}|^2\right) = 0$$

→ $$A_{CP}(\pi\pi) = -\frac{\Delta A_{CP}\,\mathrm{Br}(D^0\to K^+K^-)}{\mathrm{Br}(D^0\to K^+K^-)+\mathrm{Br}(D^0\to\pi^+\pi^-)}$$

→ $$A_{CP}(KK) = \frac{\Delta A_{CP}\,\mathrm{Br}(D^0\to \pi^+\pi^-)}{\mathrm{Br}(D^0\to K^+K^-)+\mathrm{Br}(D^0\to\pi^+\pi^-)}$$

All quantities given by data

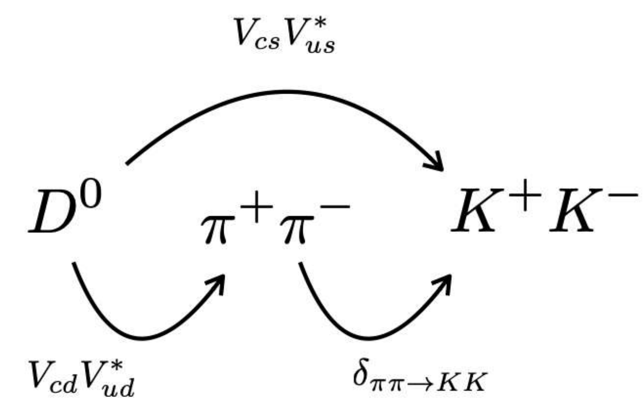
$$\boxed{\begin{aligned} A_{CP}(\pi\pi) &= \quad(1.135\pm0.021)\times10^{-3} \\ A_{CP}(KK) &= -(0.405\pm0.077)\times10^{-3} \end{aligned}}$$

by construction this gives:

$$\boxed{\frac{A_{CP}(D^0\to\pi^-\pi^+)}{A_{CP}(D^0\to K^-K^+)} = -\frac{\mathrm{Br}(D^0\to K^-K^+)}{\mathrm{Br}(D^0\to\pi^-\pi^+)} = -2.8\pm0.06}$$

Summary

- ΔA_{CP} with FSI approach is compatible with LHCb data
  - coupling between $\pi\pi$ and $K\overline{K}$ channels as source of strong phase in a CPT invariant framework



  - there is room from improvement: go beyond two-coupled channels

So far the SM is enough→ new physics has to wait…

- New measurement from LHCb

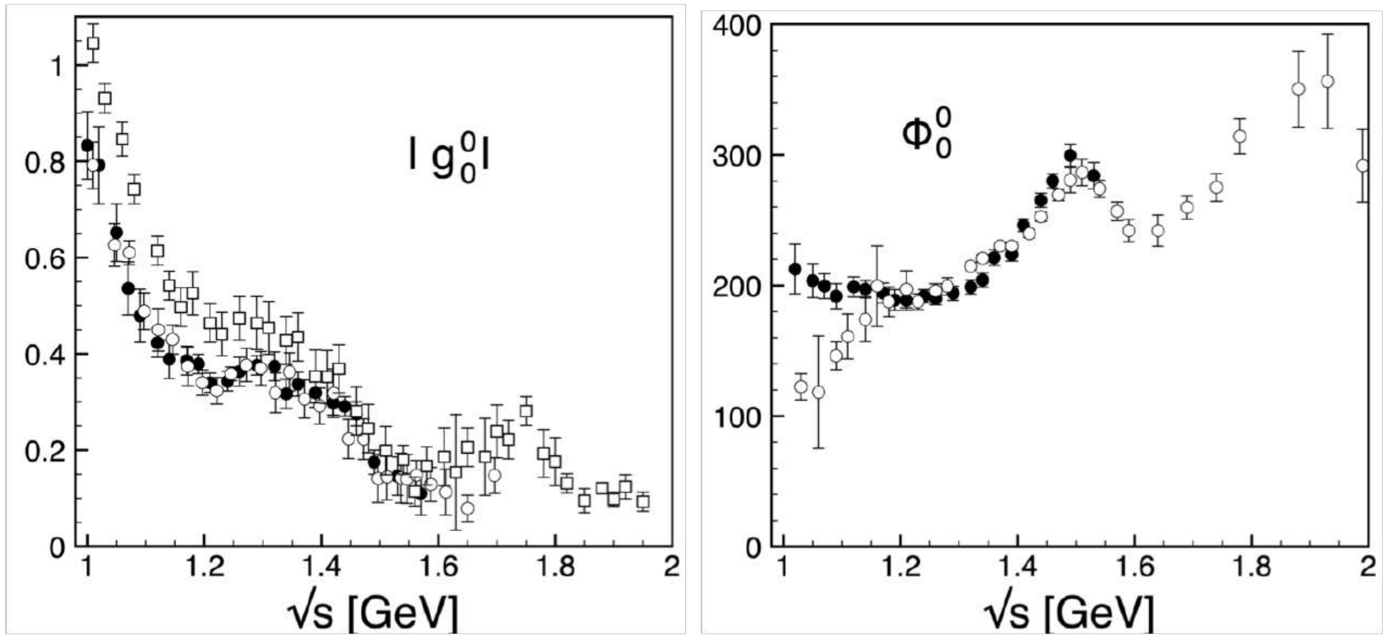
↳ check the CPT condition for only these two channels:

$$\frac{A_{CP}(D^0 \to \pi^-\pi^+)}{A_{CP}(D^0 \to K^-K^+)} = -\frac{\mathrm{Br}(D^0 \to K^-K^+)}{\mathrm{Br}(D^0 \to \pi^-\pi^+)} = -2.8 \pm 0.06$$

↳ constraint to phase difference and inelasticities of $\pi\pi$ and $K\overline{K}$ at D^0 mass

Prospect

- In three-body this effect will be bigger and phase-space distributed
  - SCS $D^+ \to \pi^+\pi^-\pi^+$ and $D^+ \to \pi^+K^-K^+$



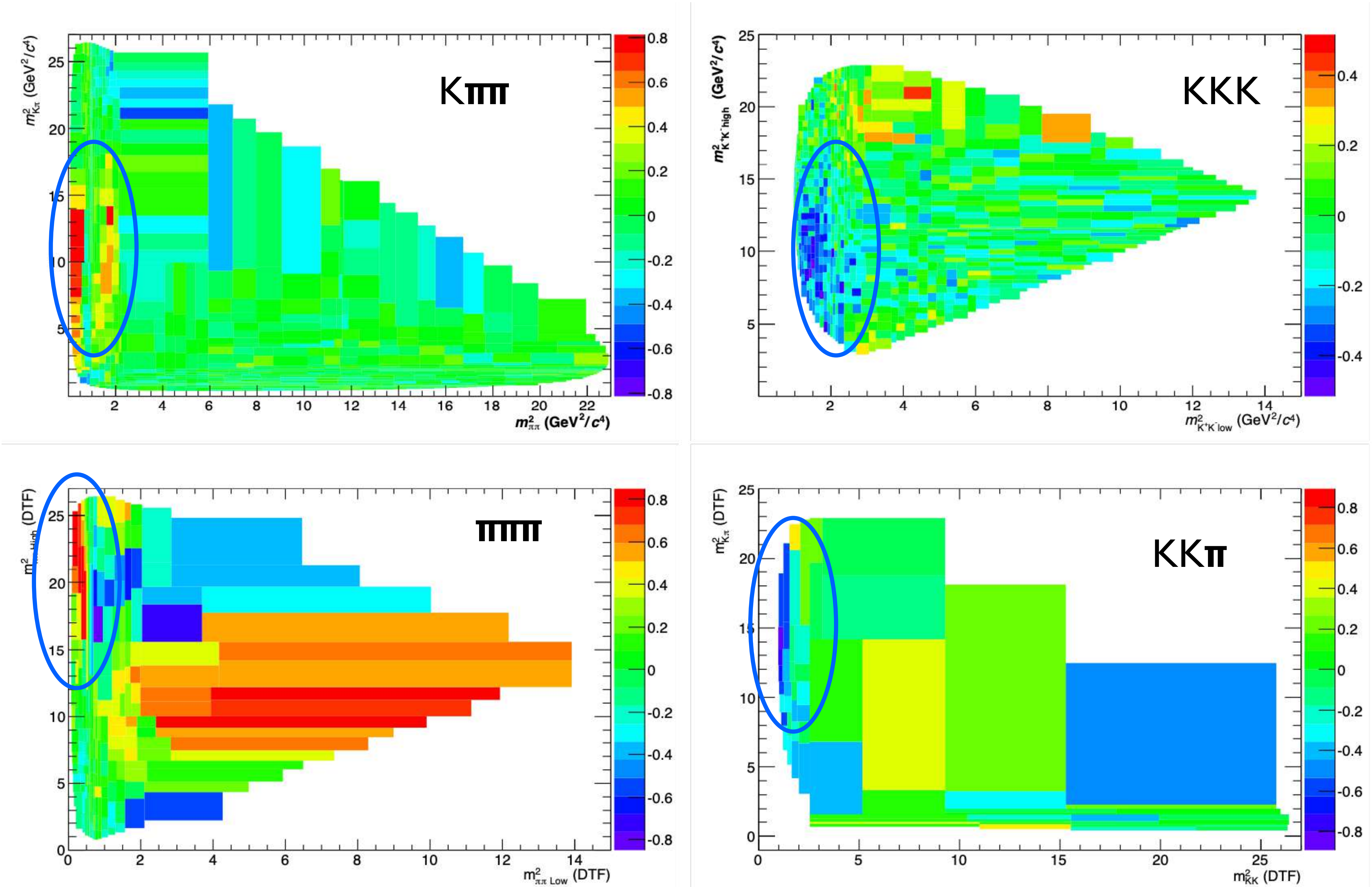
Thank you!

Backup slides

Dalitz plot: CP Asymmetry in B decays

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

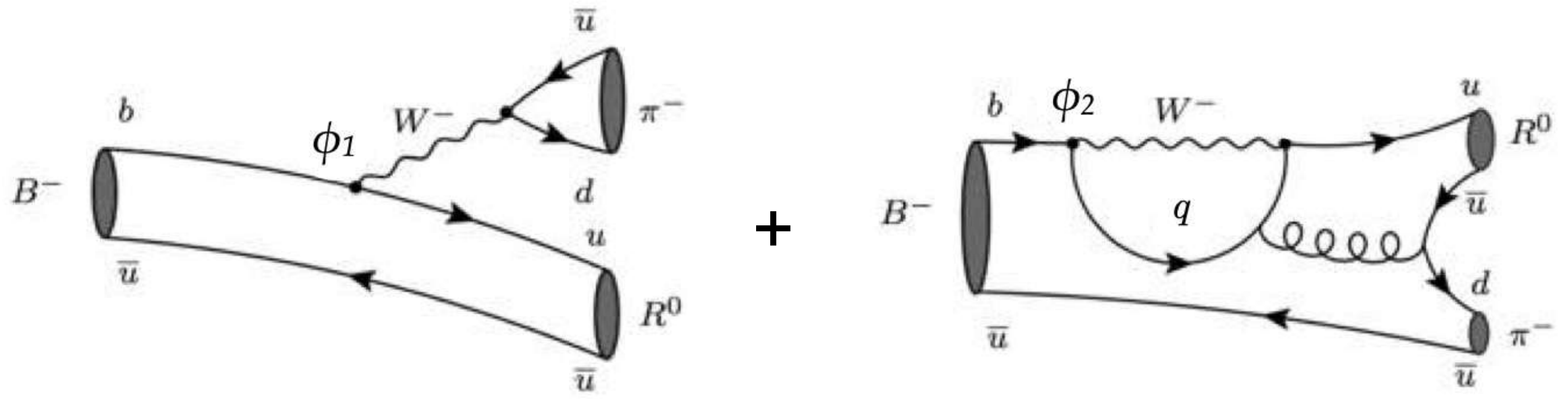
LHCb PRD90 (2014) 112004



CPV in low mass region ~ 1-1.5 GeV

BSS model CPV B→hhh

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



Not enough to explain CPV below ccbar threshold

Hadronic FSI interactions as source of strong phase

FSI & CPV at low –mass region inclusion of resonances

Alvarenga Nogueira etal PRD 92 (2015) 054010

$$\mathcal{A}^{\pm}_{LO} = \sum_{J\,R} \left(a^R_{0\lambda} + e^{\pm i\gamma} b^R_0\right) F^{BW}_{R\lambda} P_J(\cos\theta)$$
$$+ \sum_{J} \left(A^J_{0\lambda NR} + e^{\pm i\gamma} B^J_{0\lambda NR}\right)$$
$$+ i \sum_{\lambda', J} t^J_{\lambda',\lambda} \left(A^J_{0\lambda' NR} + e^{\pm i\gamma} B^J_{0\lambda' NR}\right)$$

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

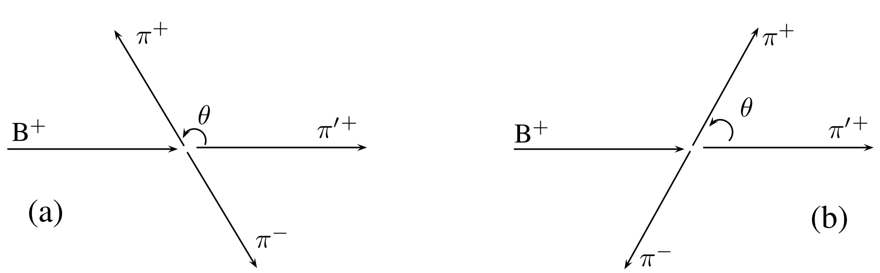


FIG. 1. $B^+ \to \pi^+\pi^+\pi^-$ decay with π'^+ being the bachelor particle. (a): $\cos\theta < 0$ ($\theta > \frac{\pi}{2}$). (b): $\cos\theta > 0$ ($\theta < \frac{\pi}{2}$).

LHCb PRD 90, 112004 (2014)

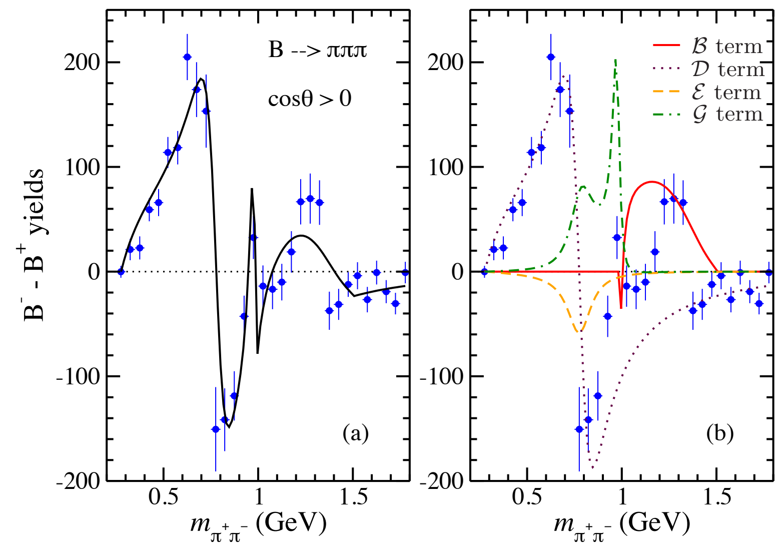


FIG. 8. (Color online) CP asymmetry of the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay, integrated Eq. (44), compared with the experimental values (blue points) taken from Ref. [9]. Results for $\cos\theta > 0$ for (a) total and (b) individual contributions.

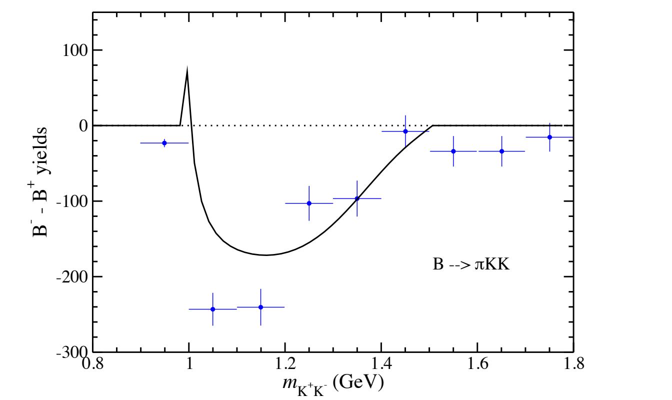


FIG. 10. (Color online) CP asymmetry of the $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decay, Eq. (60), compared with experimental data (blue points) taken from Fig. 7b of Ref. [9].

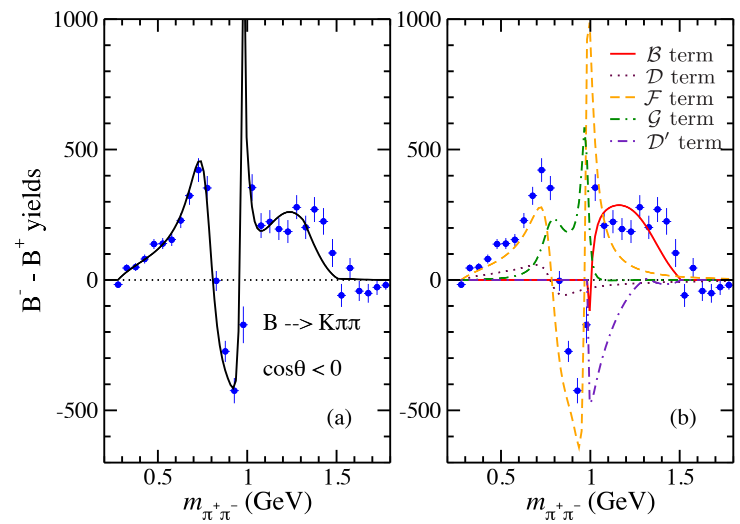


FIG. 11. (Color online) CP asymmetry of the $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ decay, integrated Eq. (44), compared with the experimental values (blue points) taken from Fig. 5c of Ref. [9]. Results for $\cos\theta < 0$ for (a) total and (b) individual contributions.

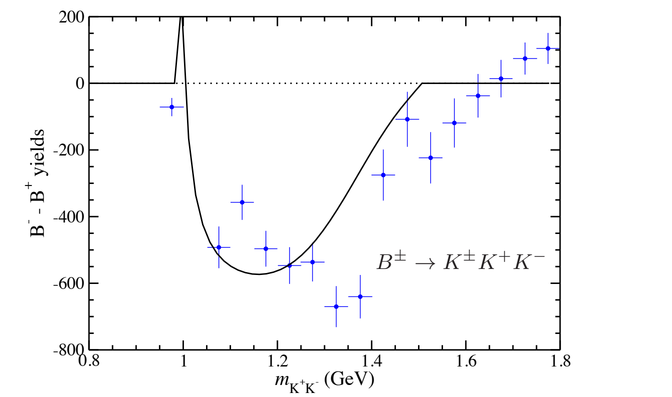


FIG. 12. CP asymmetry of the $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decay compared with experimental values (blue points) taken from the sum of Figs. 6c and 6d of Ref. [9].

- 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]

Global CPV, U-spin and FSI

$q = d$ or s

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

CPT symm:

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

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.

U-spin symm:

$$\boxed{\langle f^s_{out}|U^s|B^u\rangle = \langle f^d_{out}|U^d|B^u\rangle \quad \text{and} \quad \langle f^s_{out}|C^s|B^u\rangle = \langle f^d_{out}|C^d|B^u\rangle}$$

CKM unitarity:

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

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

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

Three-body channels

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

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

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:

$$\left.\begin{array}{l} \dfrac{\Delta\Gamma_{CP}(\pi^\pm K^+ K^-)}{\Delta\Gamma_{CP}(\pi^\pm K^0 \bar{K}^0)} \sim 1 \quad \text{and} \quad \dfrac{\Delta\Gamma_{CP}(\pi^\pm \pi^+ \pi^-)}{\Delta\Gamma_{CP}(\pi^\pm \pi^0 \pi^0)} \sim 1 \\[2ex] \dfrac{\Delta\Gamma_{CP}(K^\pm \pi^+ \pi^-)}{\Delta\Gamma_{CP}(K^\pm \pi^0 \pi^0)} \sim 1 \quad \text{and} \quad \dfrac{\Delta\Gamma_{CP}(K^\pm K^+ K^-)}{\Delta\Gamma_{CP}(K^\pm K^0 \bar{K}^0)} \sim 1 \end{array}\right\} \quad \dfrac{\Delta\Gamma_{CP}(\pi^\pm K^0 \bar{K}^0)}{\Delta\Gamma_{CP}(\pi^\pm \pi^0 \pi^0)} \sim -1 \quad \text{and} \quad \dfrac{\Delta\Gamma_{CP}(K^\pm K^0 \bar{K}^0)}{\Delta\Gamma_{CP}(K^\pm \pi^0 \pi^0)} \sim -1$$