Enhanced charm CP asymmetries from Final State Interactions

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Collaborators:

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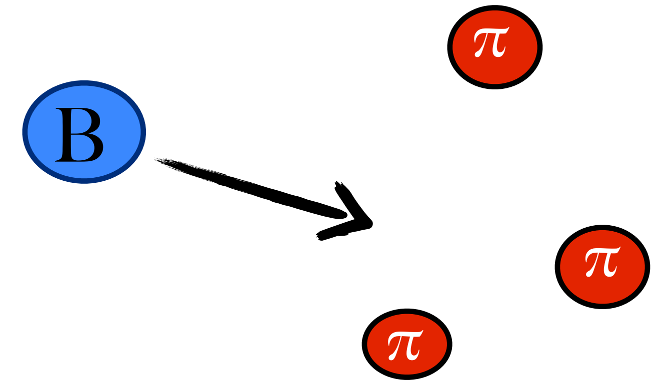
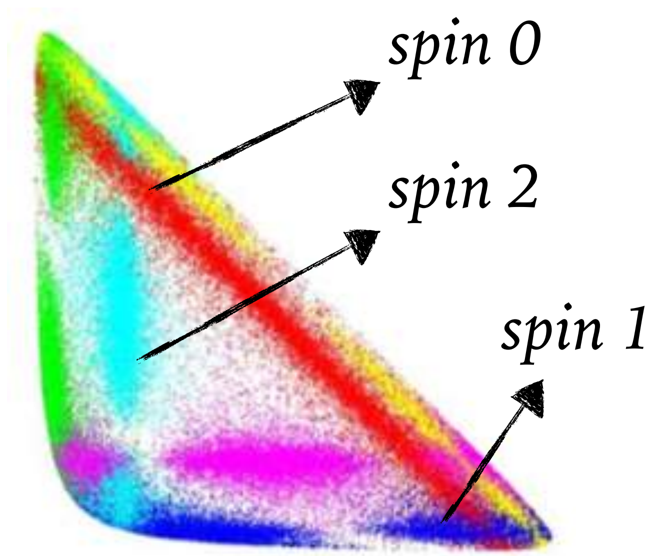
José Ramon Pelaez - UCM (Madrid)

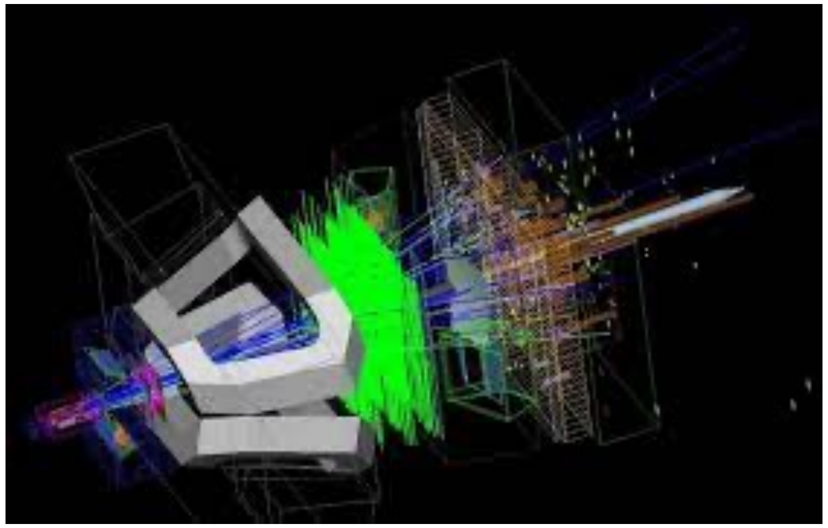
- Multi-body hadronic decays of B and D mesons
  - ↳ are sensitive to strong phases



- signature of resonances on data
- spectroscopy → exotics, tetra-quarks, pentaquark,…
- study CP violation



- high data sample from LHCb run II
  - ⟶ more to come from LHCb, BelleII, BESIII
  - ⟶ better models are needed (challenge)



CP asymmetry measurements

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Parity violation
T.D. Lee, C.N. Yang, C.S. Wu et al.

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LHCb

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LHCb

2022
1st obs of CPV in $D^0 \to \pi\pi$
LHCb

today

context

detector

- CPV in $B^\pm \to h^\pm h^- h^+$

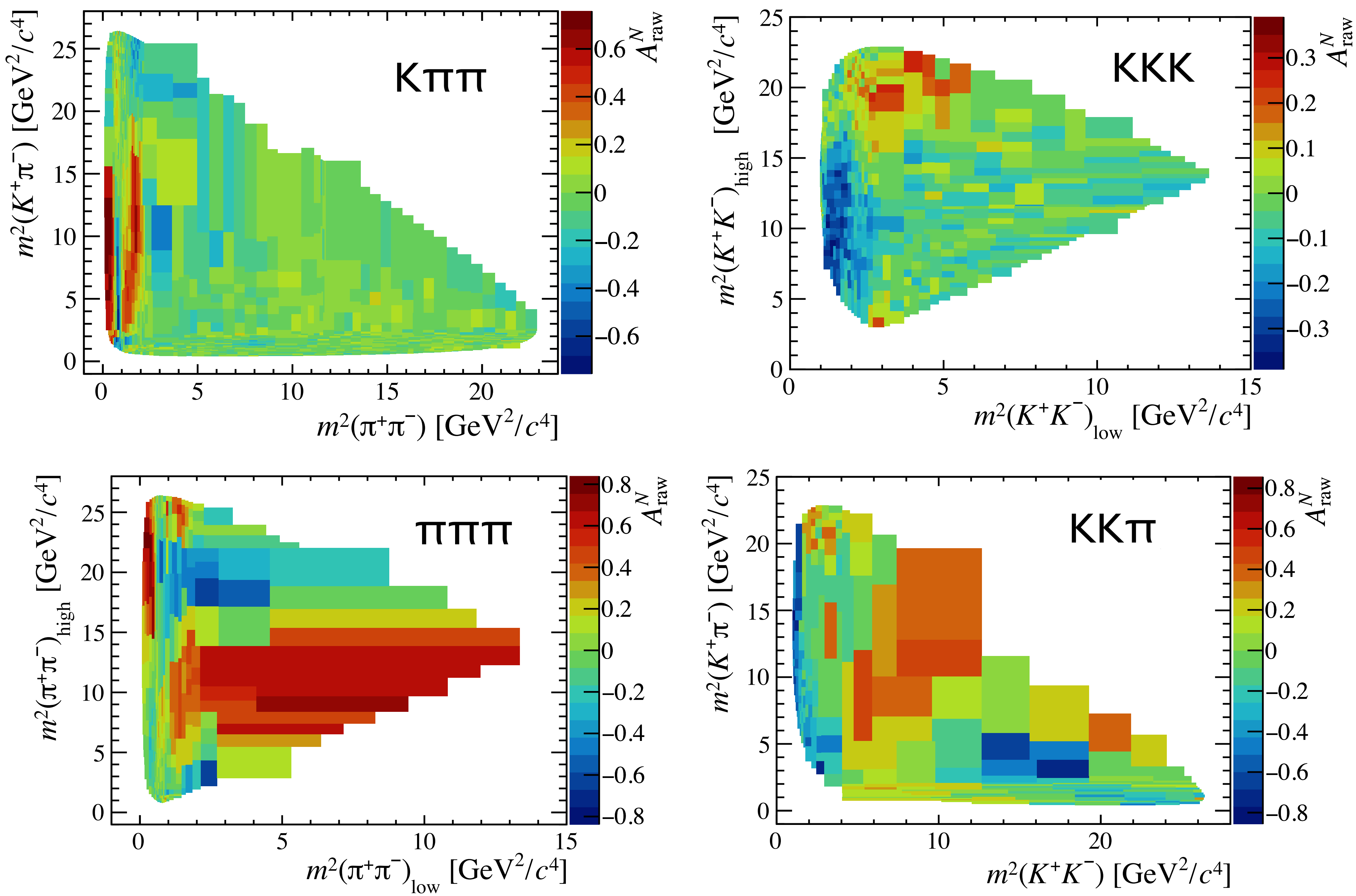
LHCb **Run II** 5.9 fb^{-1}

PRD D **108** 012008 (2023)

- integrated

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

- giant CPV



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

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

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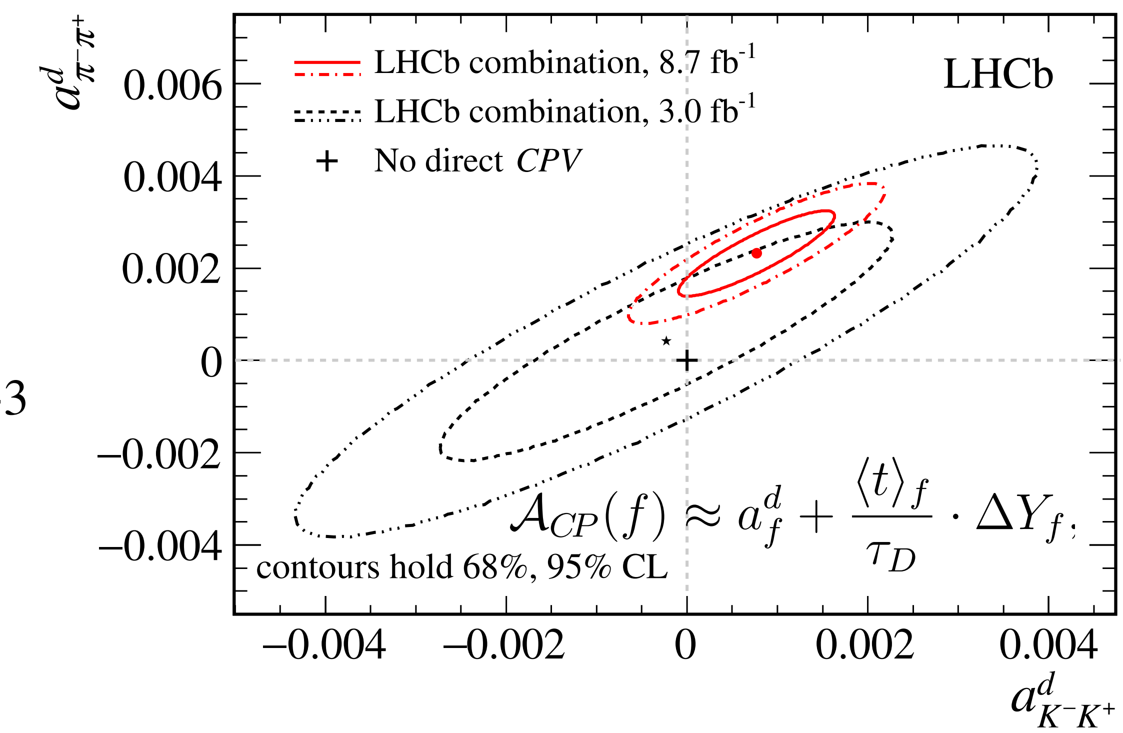
Phys. Rev. Lett.122, 211803 (2019)

➔ direct CP asymmetry observation

- $A_{CP}^{LHCb}(KK) = (0.77 \pm 0.57) \times 10^{-3}$

↳ $A_{CP}^{LHCb}(\pi\pi) = (2.32 \pm 0.61) \times 10^{-3}$

arXiv:2209.03179



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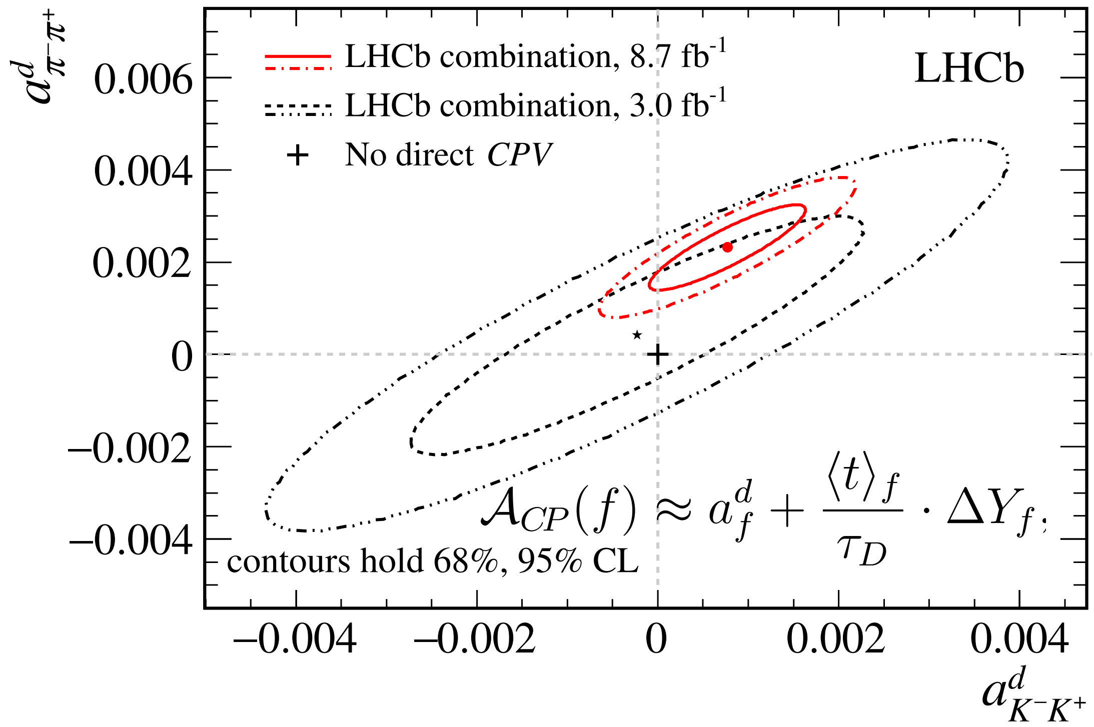

- QCD → LCSR predictions $A_{CP} \approx 10^{-4}$ (1 order magnitude bellow)

↳ new physics? nonperturbative effects?!

Khodjamirian, Petrov, Phys. Lett. B 774, 235 (2017)

CPV data

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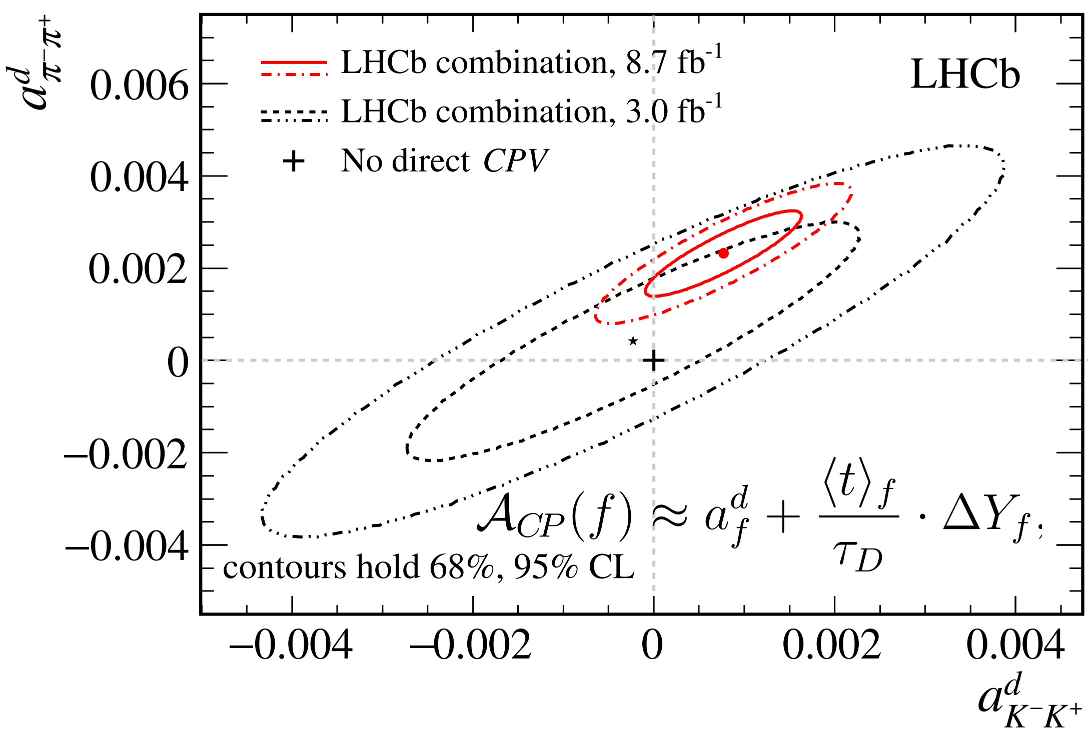

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→ what about CPV on $D \to hhh$?

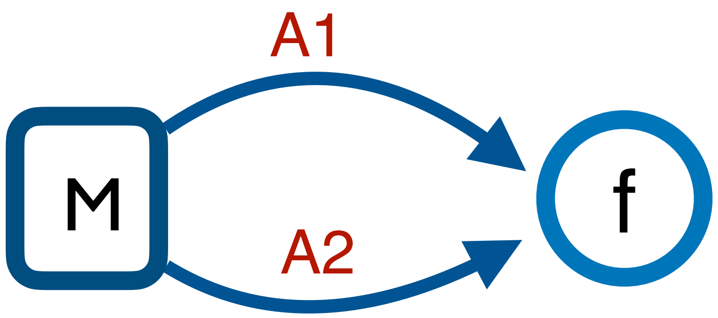
→ searches in many process at LHCb, BESIII, BelleII

↳ is expected soon with LHCb run II

direct CP violation

- Interference effect

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



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

CP

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

direct CP violation

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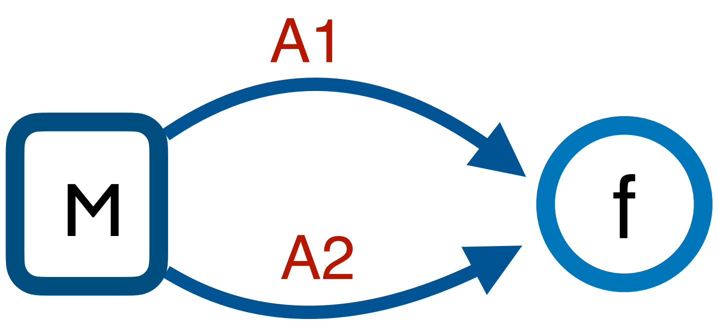

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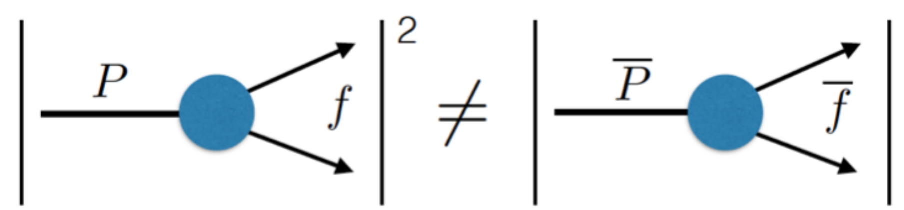
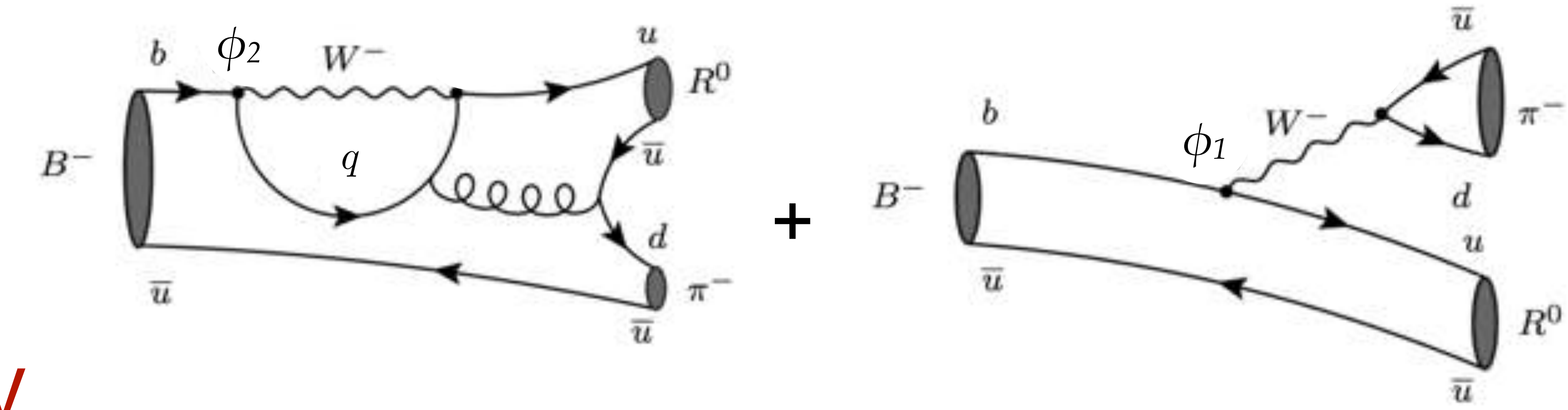
- $$A_{CP} = \frac{\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\bar{M} \to \bar{f})}$$ $\rightarrow$



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

- weak phase ϕ → CKM
- strong phase δ → QCD

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



  - not enough for CPV

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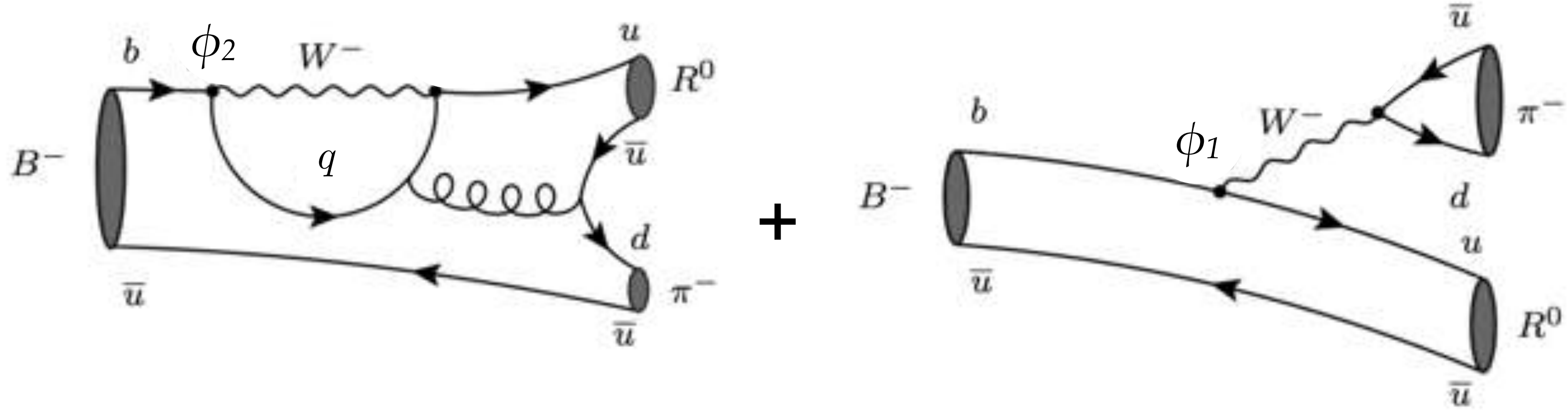

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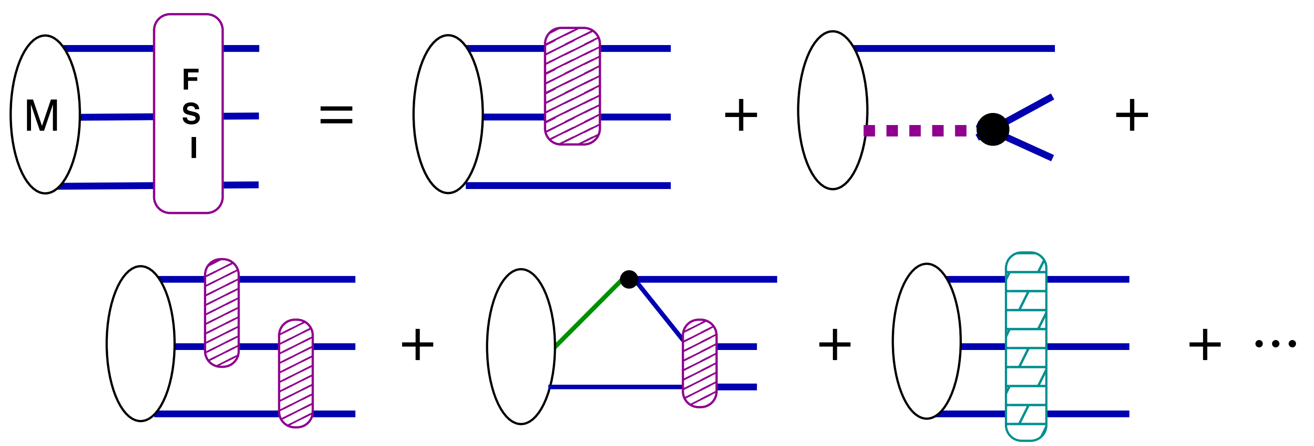
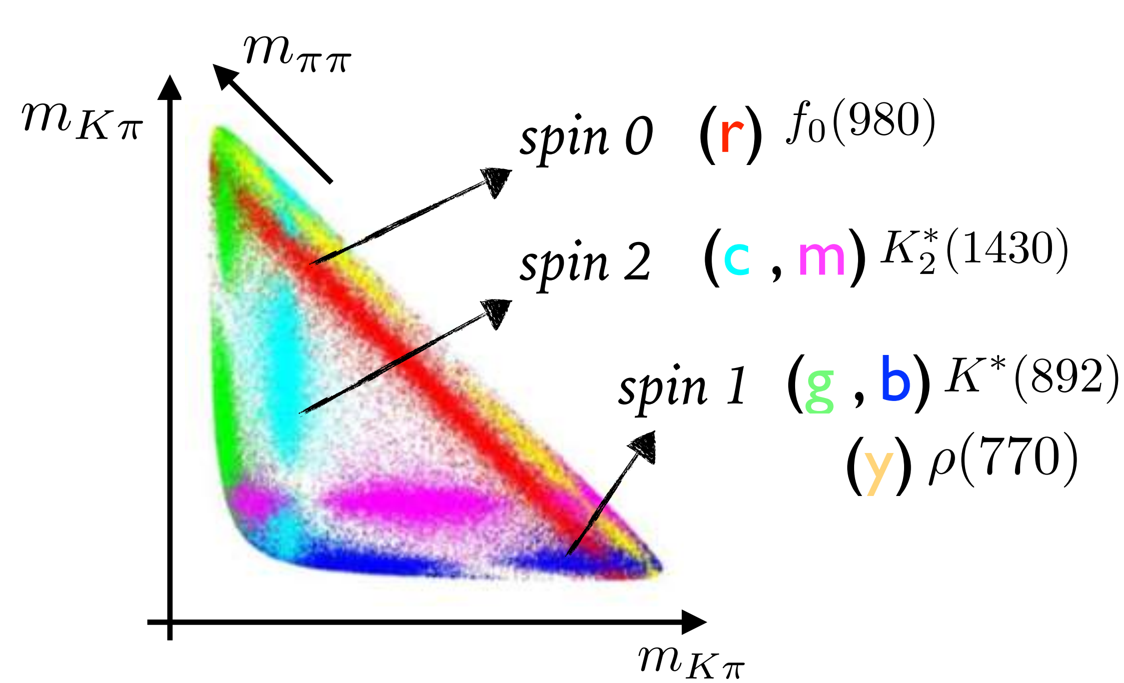
- **hadronic (not quark) interactions are natural sources of strong phase**



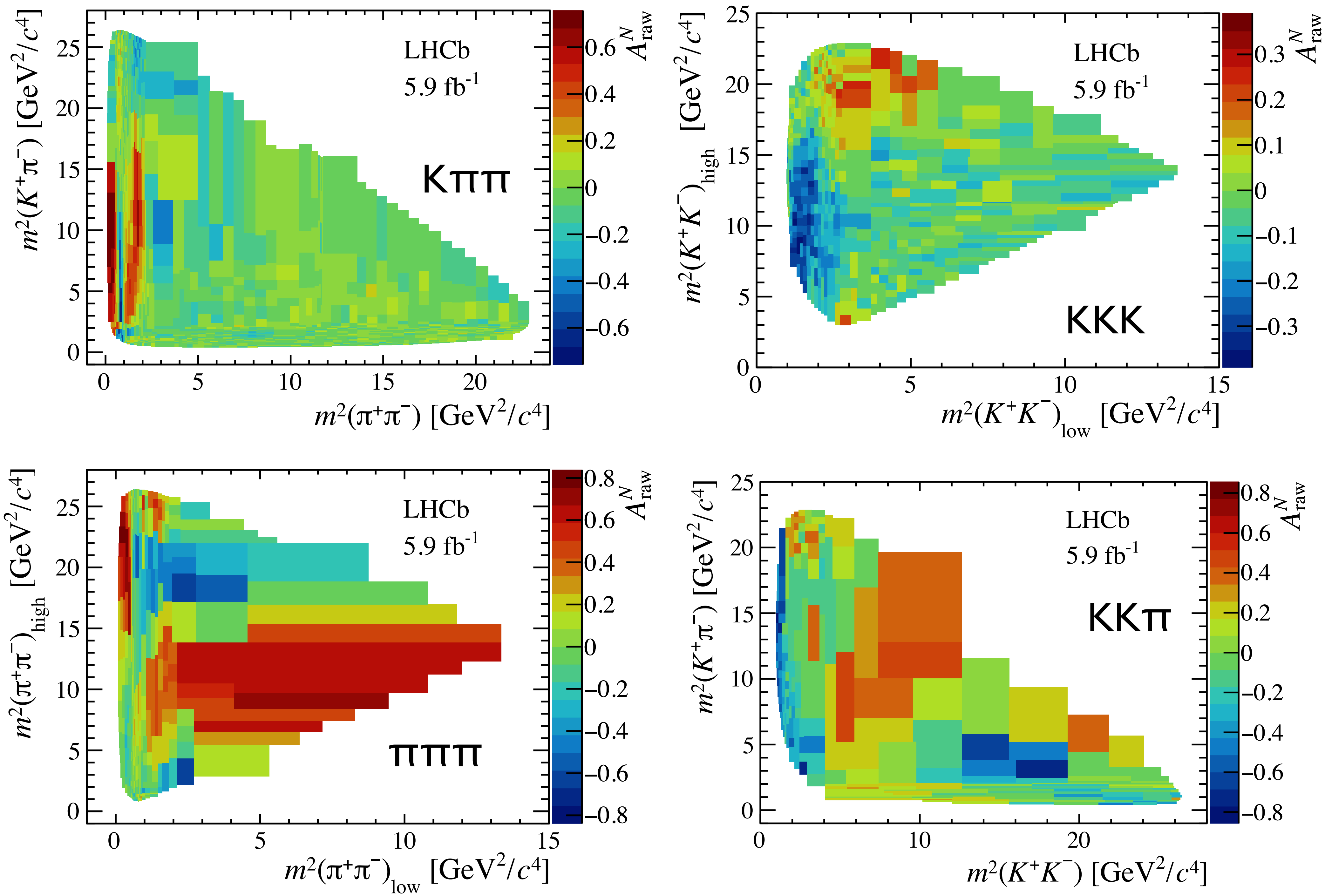
- exemplo: $D^0 \to K_s \pi^- \pi^+$



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

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

- suggest dynamic effect



$$\Delta\Gamma_f = \Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f}) = |\langle f\,|\,T\,|\,M\rangle|^2 - |\langle \bar{f}\,|\,T\,|\,\bar{M}\rangle|^2$$

- CPT must be preserved

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

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

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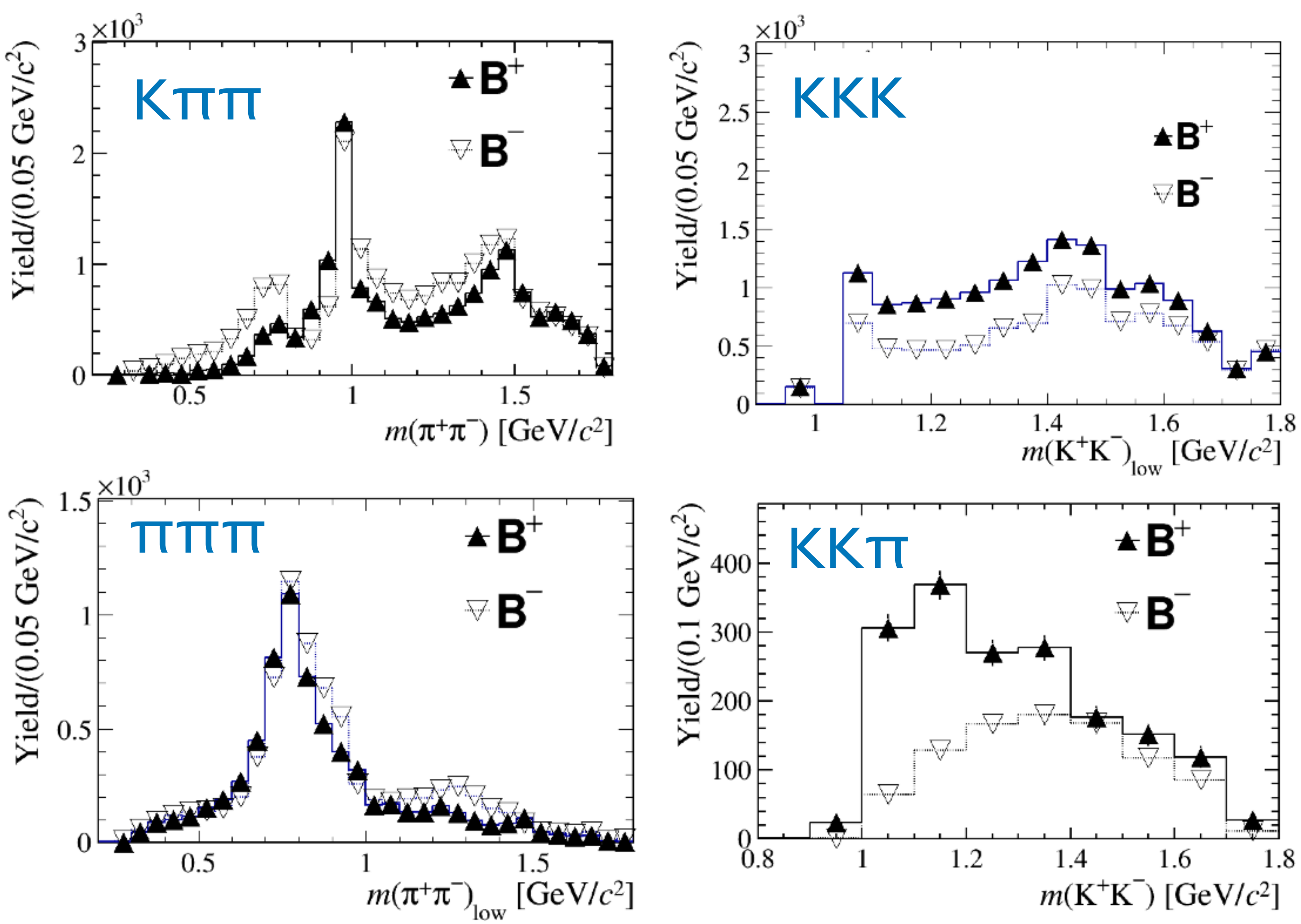
→ $$\sum \Delta\Gamma_{CP} = 0$$

CPV in one channel should be compensated by another, same quantum #, with opposite sign

- LHCb run 1 projections



rescattering as a CPV mechanism

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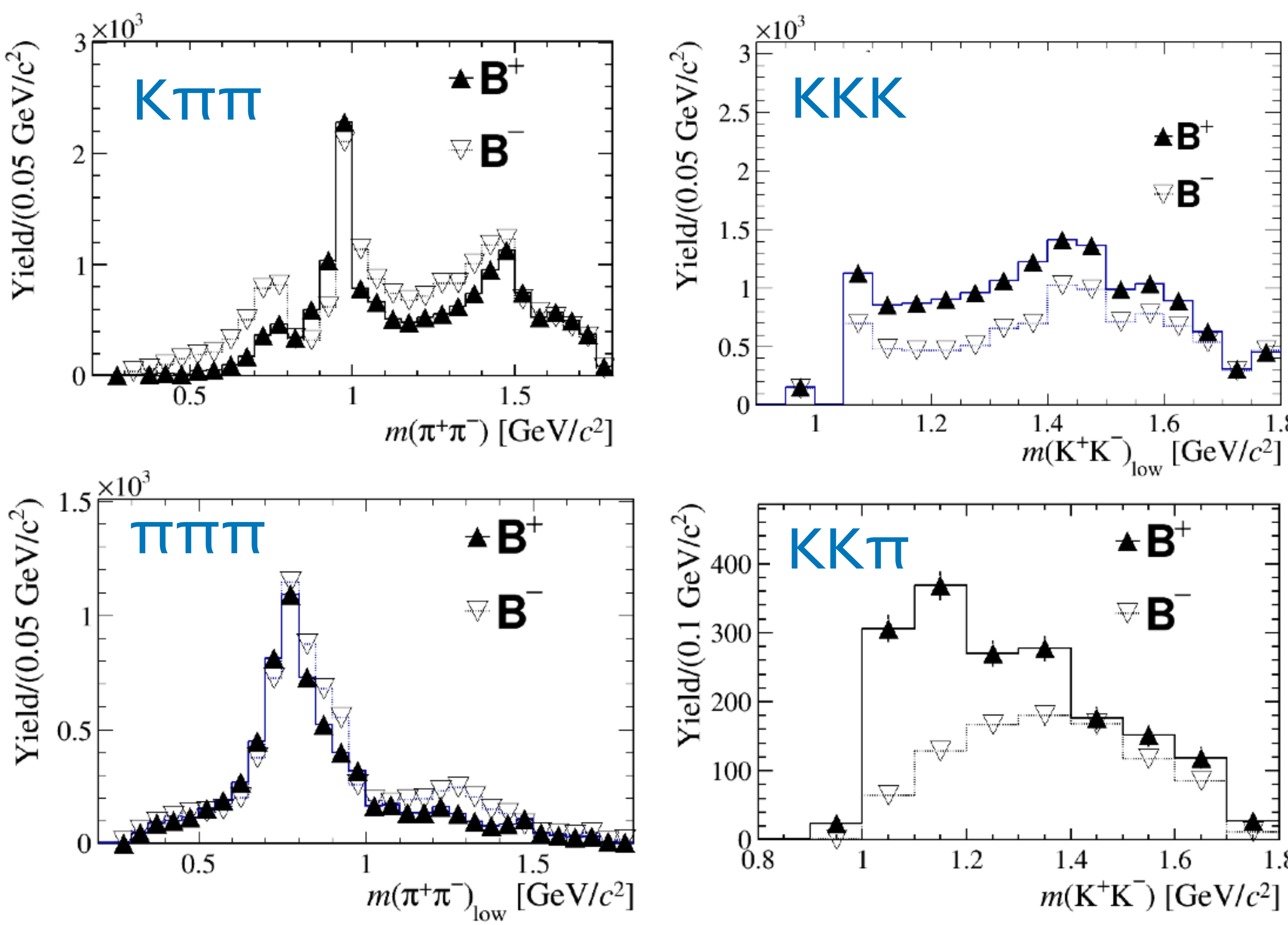

- rescattering $\pi\pi \to KK$

↳ CPV at [1 -1.6] GeV

Frederico, Bediaga, Lourenço PRD89(2014)094013

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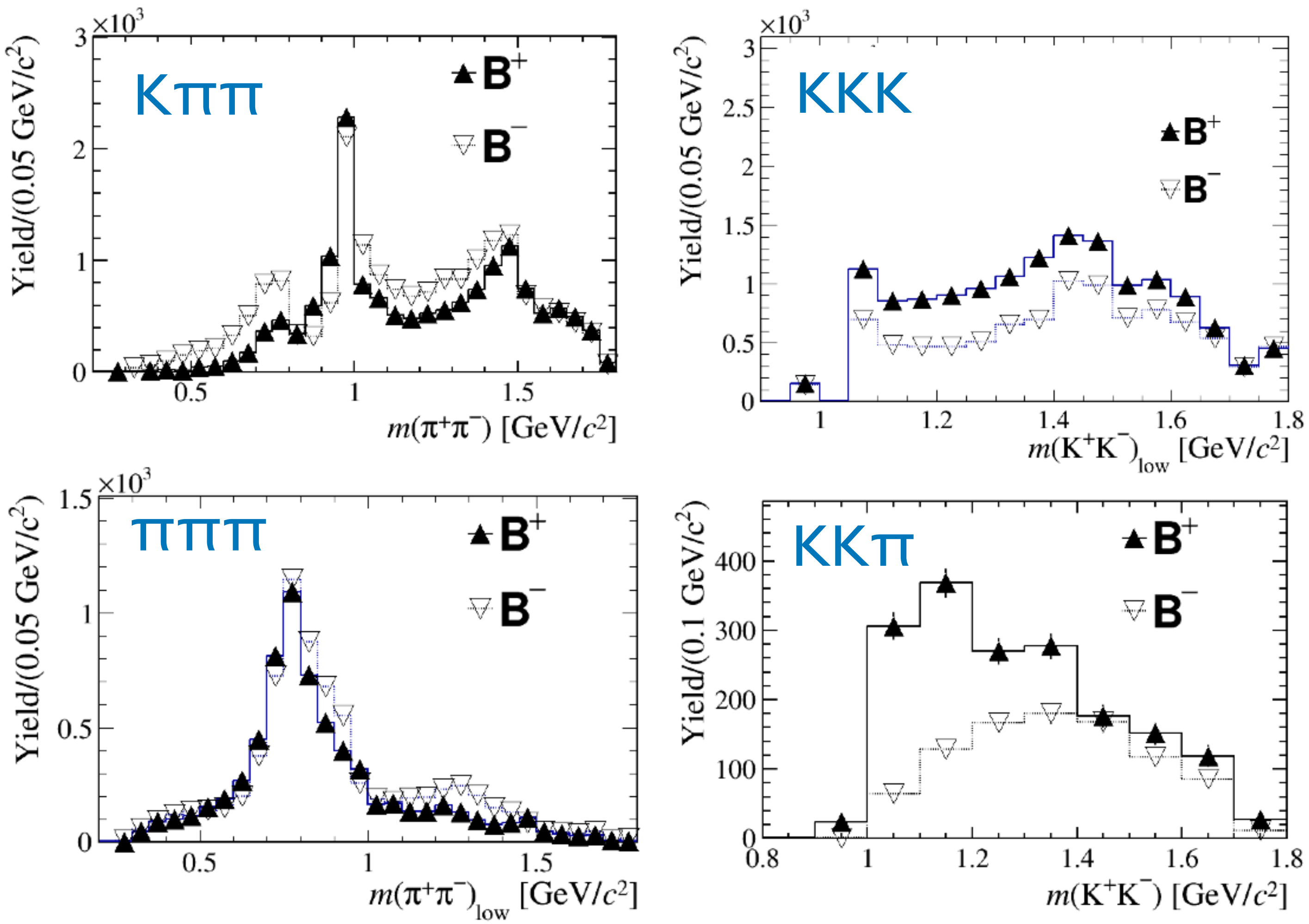


- rescattering $\pi\pi \to KK$
  - CPV at [1 -1.6] GeV
  - Frederico, Bediaga, Lourenço PRD89(2014)094013
- implemented in LHCb amplitude analysis:
  - $B^\pm \to \pi^-\pi^+\pi^\pm$ PRD101 (2020) 012006; PRL 124 (2020) 031801
  - $B^\pm \to \pi^\pm K^- K^+$ PRL 123 (2019) 231802

- $B \to K\pi\pi$ - LHCb full run1 data

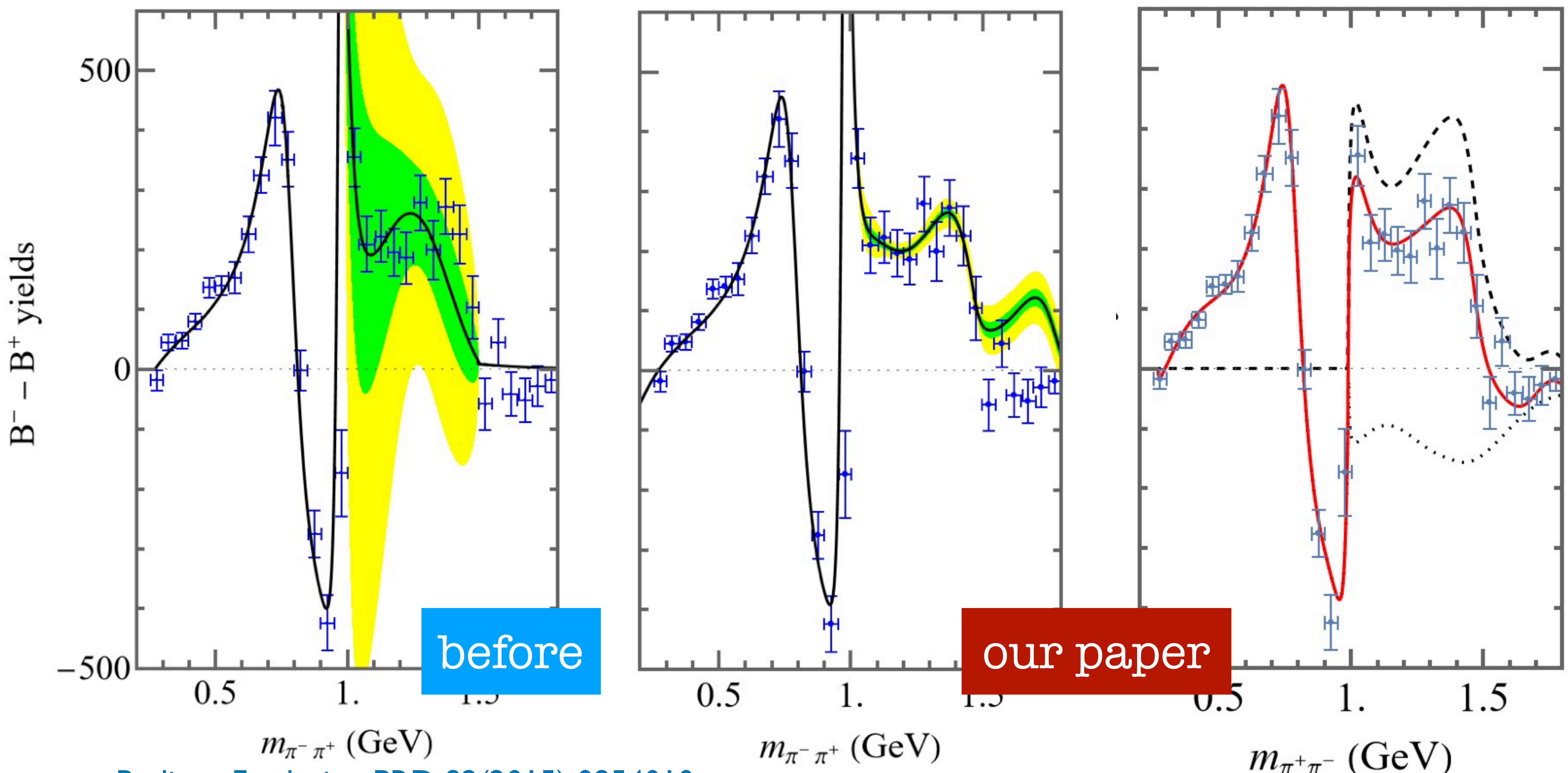
PCM,Pelaez PRL130 201901 2023

→ revisit previous work, improving FSI amplitudes

$\delta_{\pi\pi KK} = 2\delta_{\pi\pi}$ and $|S_{\pi\pi KK}| \to \sqrt{1-\eta^2}$

CFD $\pi\pi \to K\bar{K}$ dispersive analysis

$KK \to \pi\pi$ and $\pi\pi \to \pi\pi$ dispersive analysis



Alvarenga, Bediaga, Frederico PRD 92(2015) 0954010

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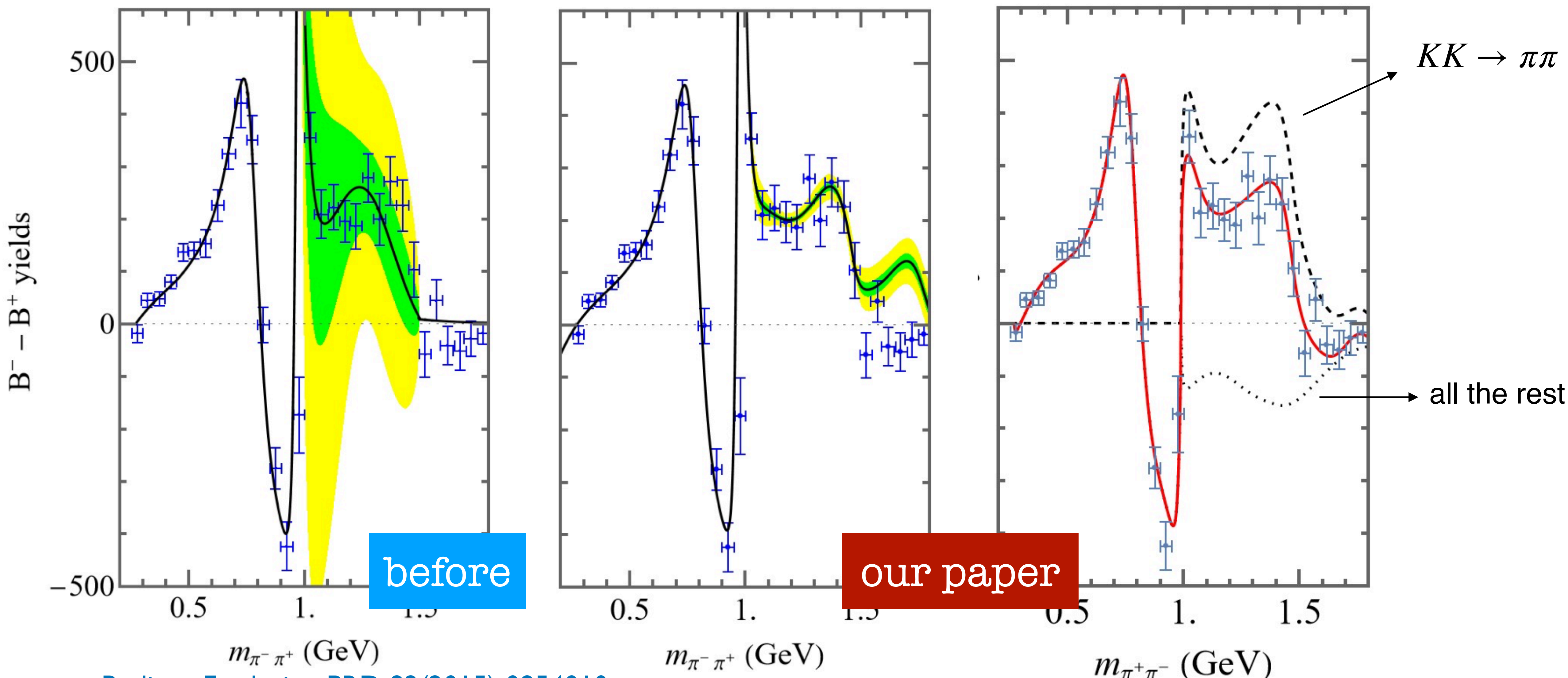
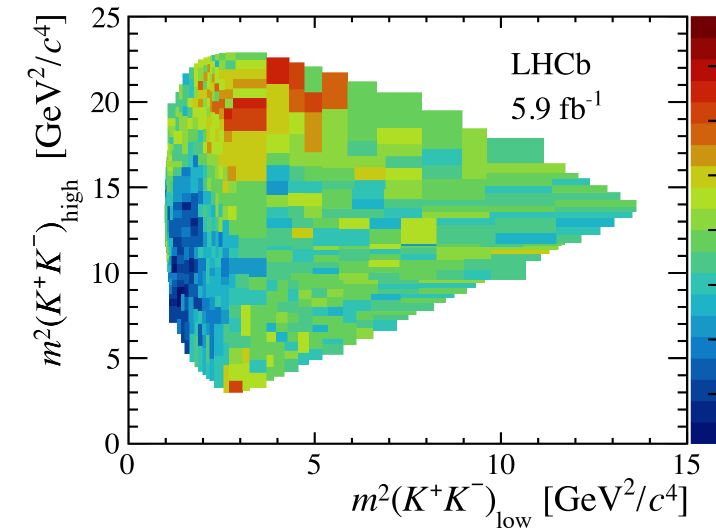


Alvarenga, Bediaga, Frederico PRD 92(2015) 0954010

↳ conclusion remains the same: $KK \to \pi\pi$ dominates between 1-1.5 GeV

- $B^+ \to K^- K^+ K^+$ Bediaga, Frederico, MAGALHAES, PLB 780 (2018) 357



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

CPV at high energy

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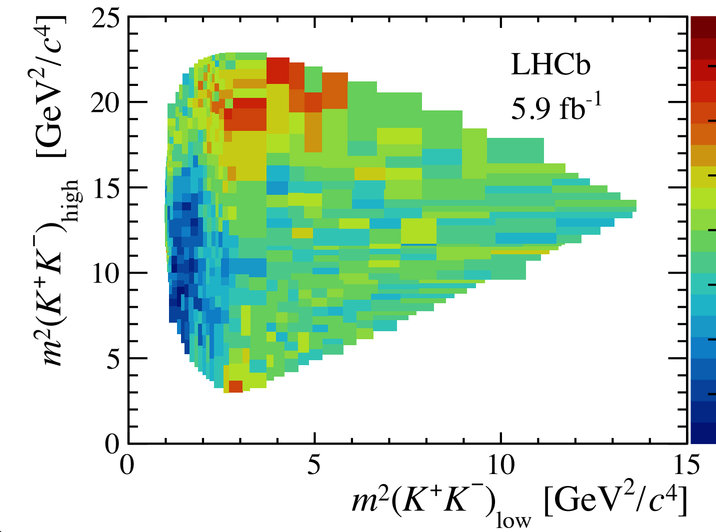

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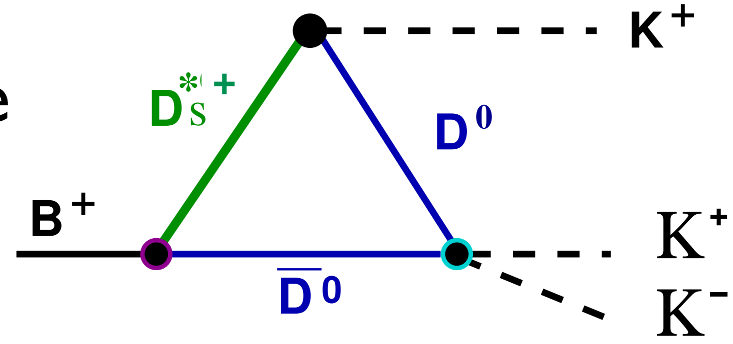
- charm triangle



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

→ 1000 x $Br\,[B \to KKK]$

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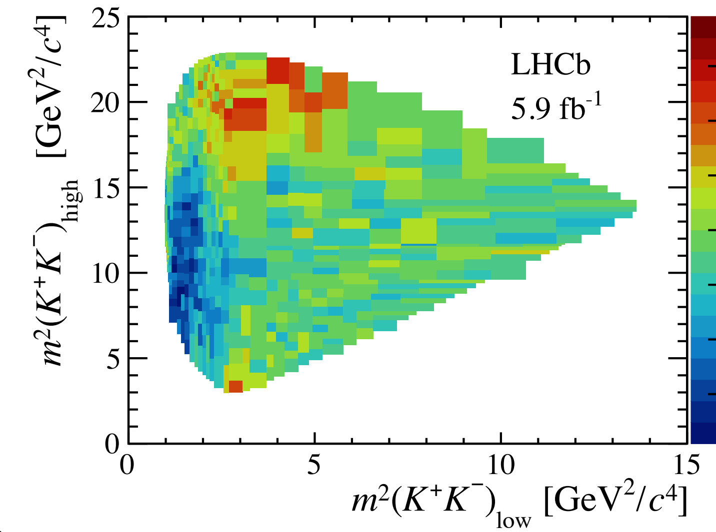

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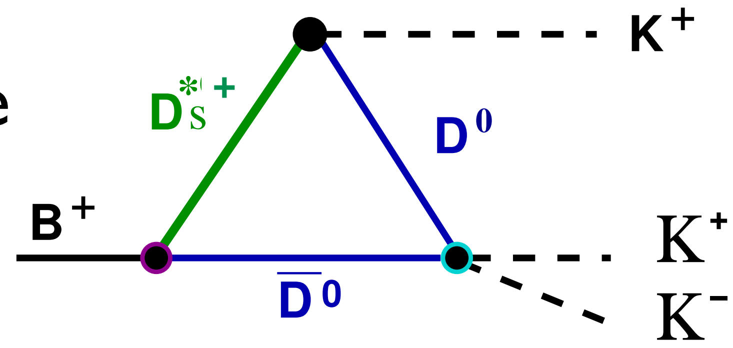

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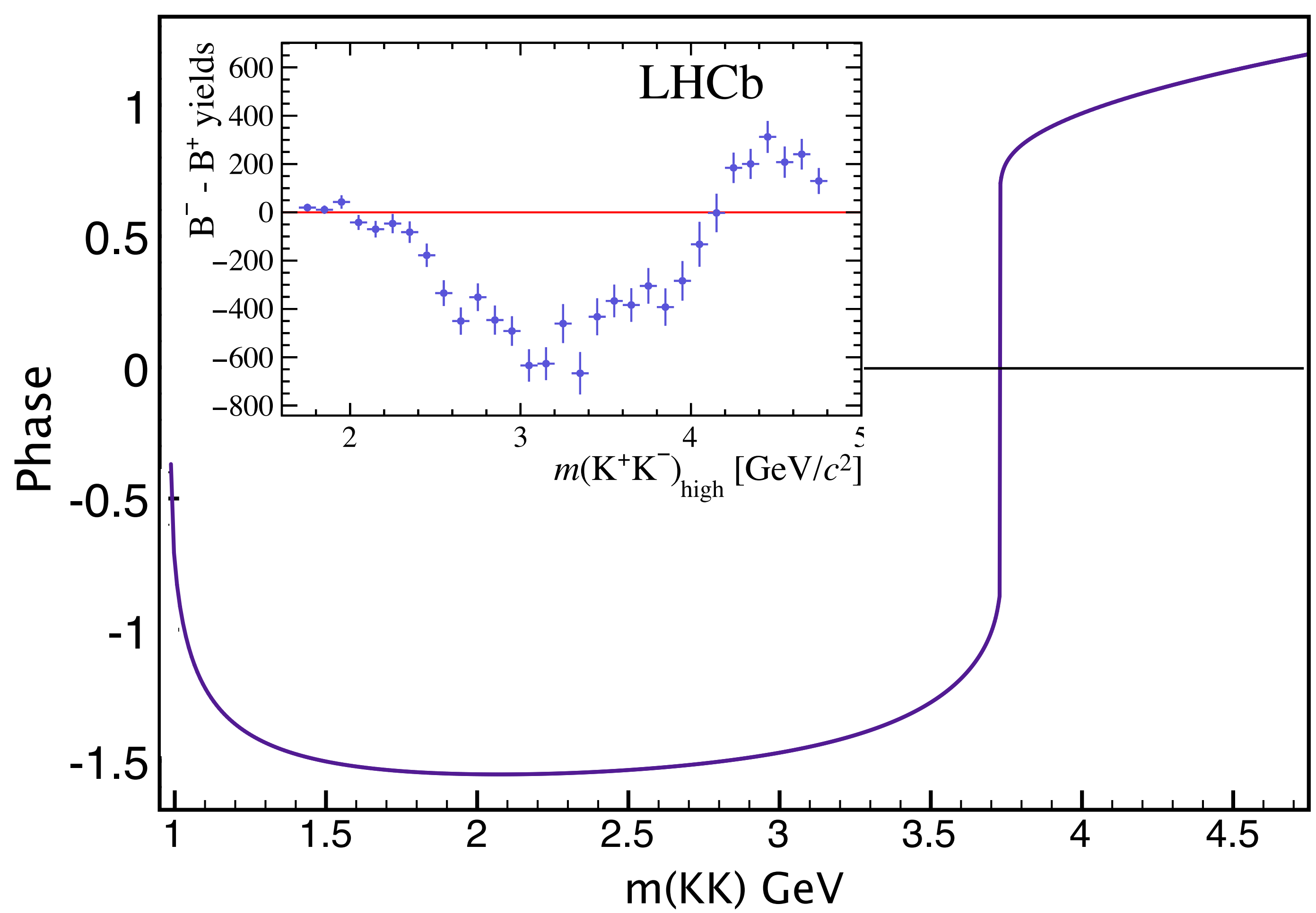
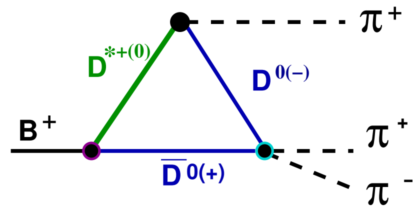
→ 1000 x $Br\,[B \to KKK]$

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



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

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

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

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

  - charm rescattering as a source of strong phase

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

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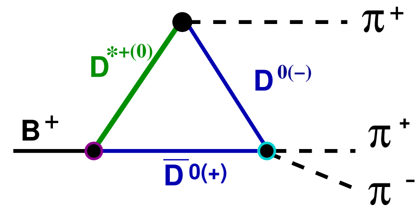

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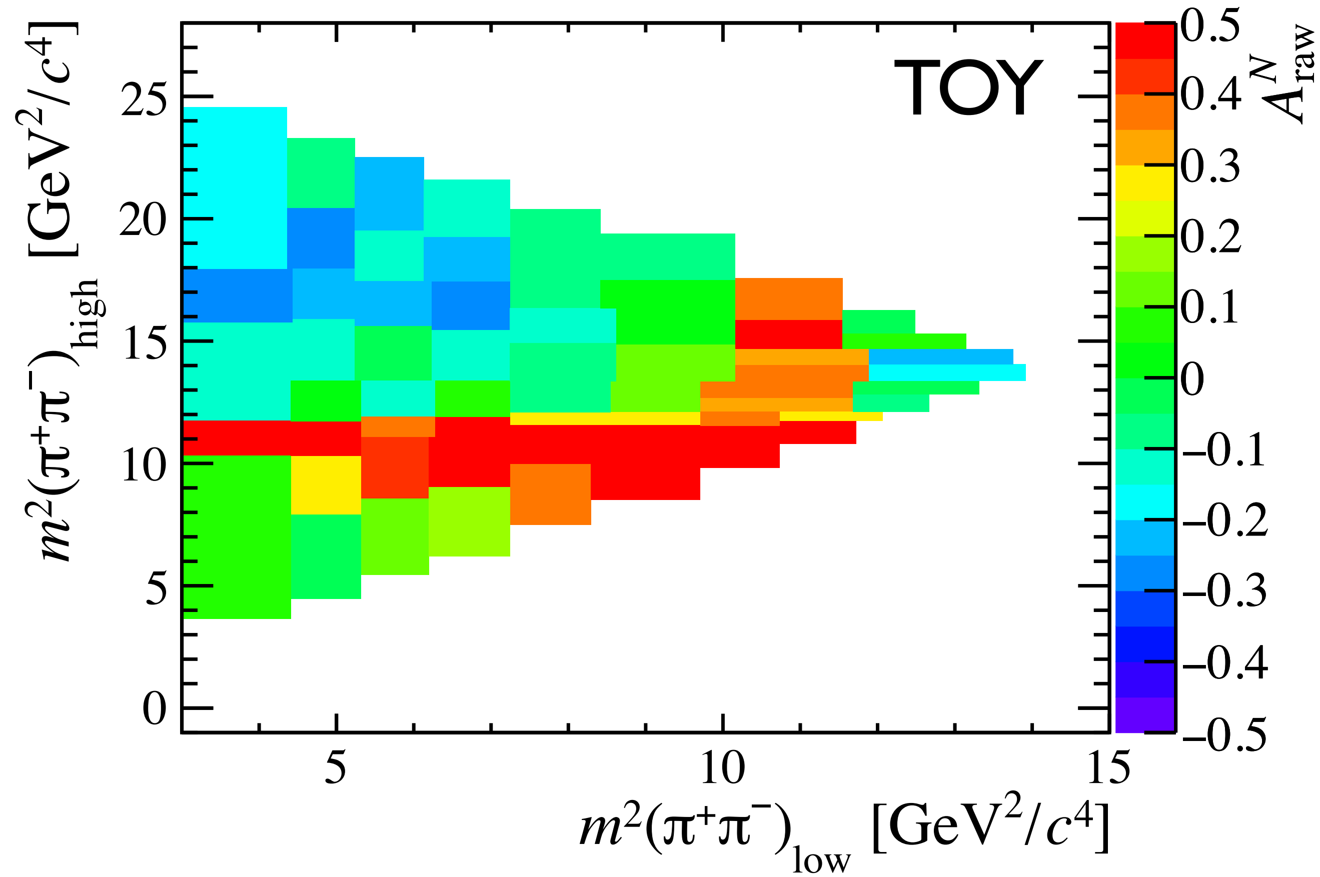
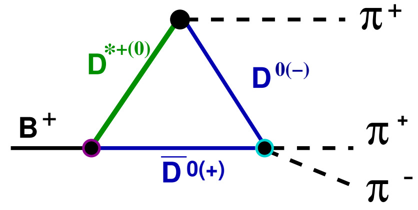
Acp signature



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

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

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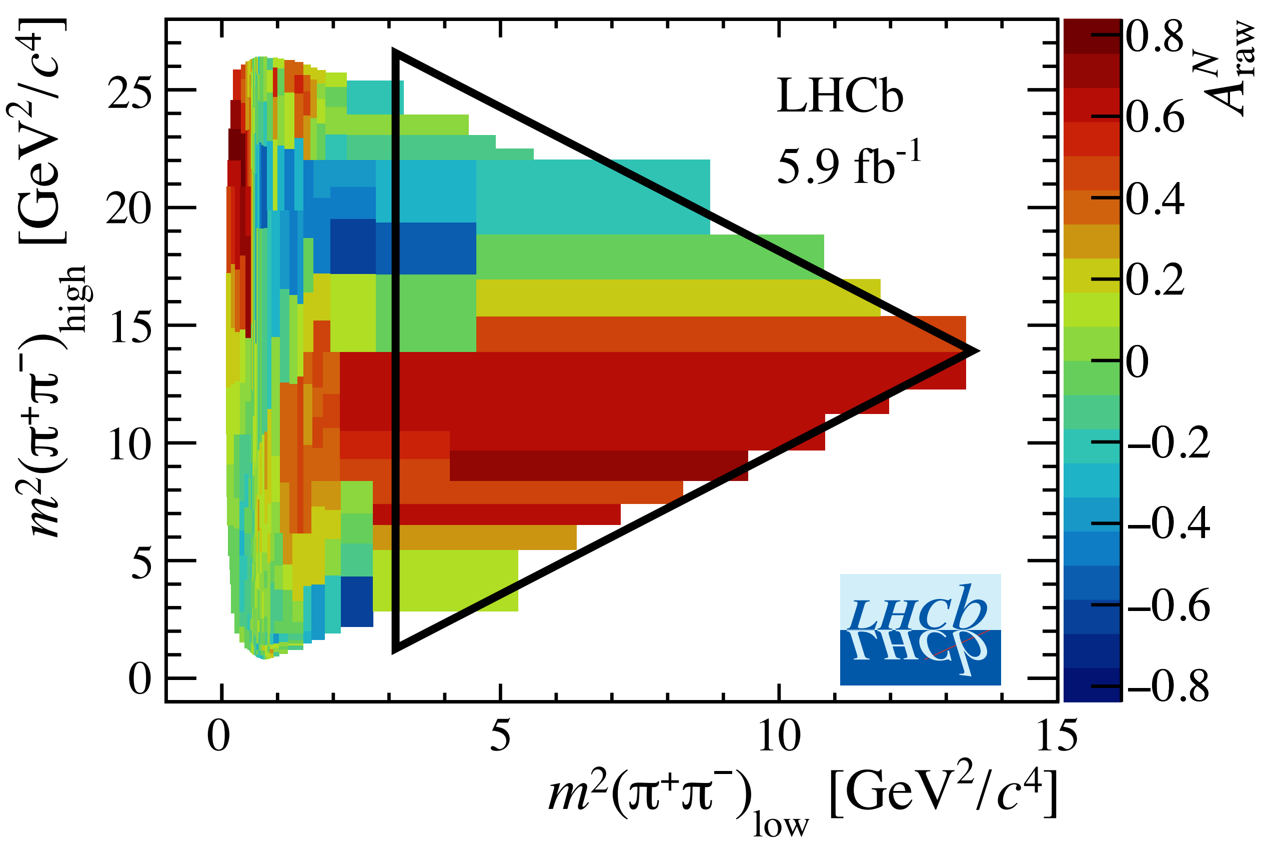

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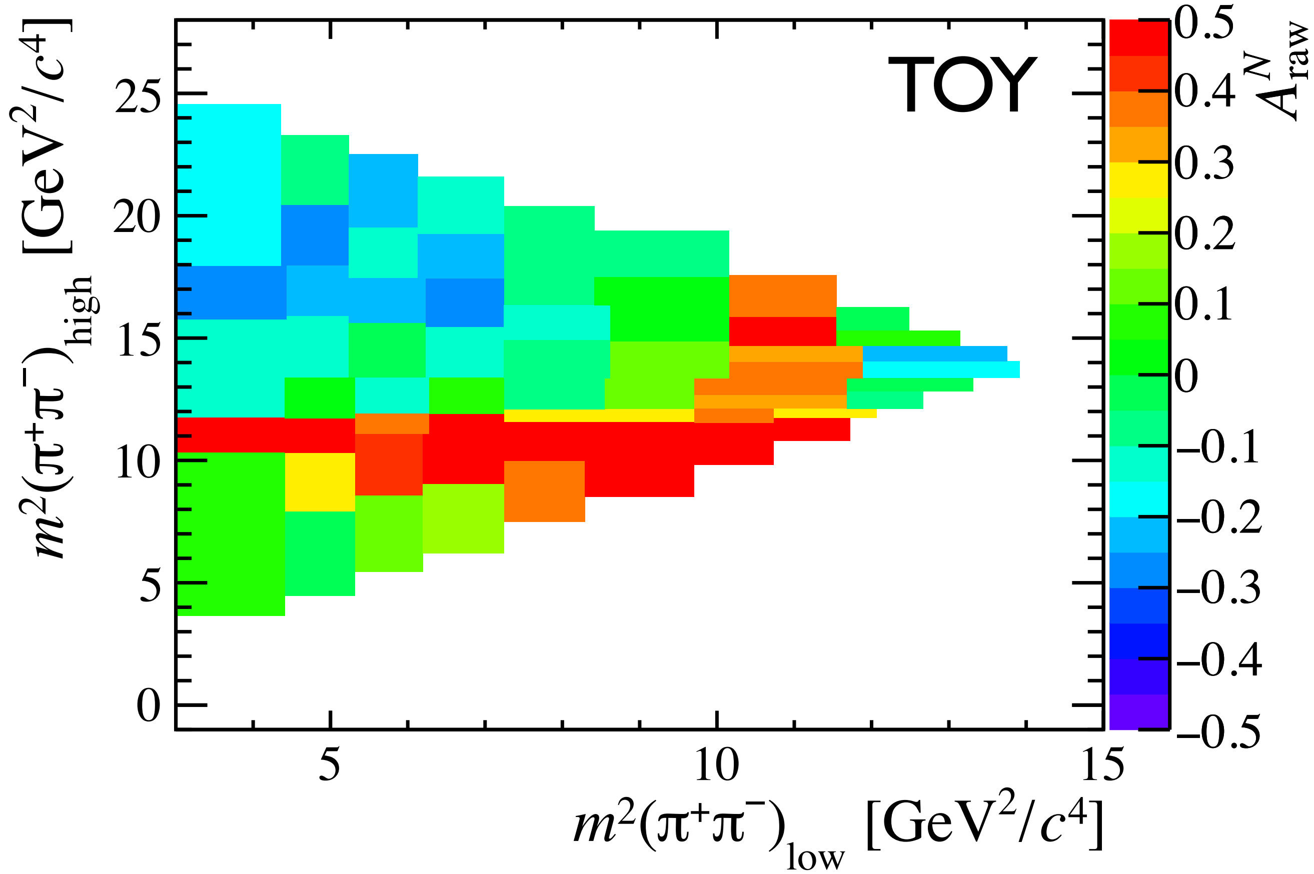

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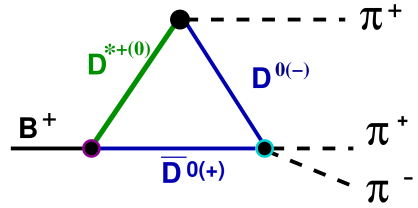
- $A_{B^\pm \to \pi^-\pi^+\pi^\pm}(s_{12}, s_{23}) =$ 

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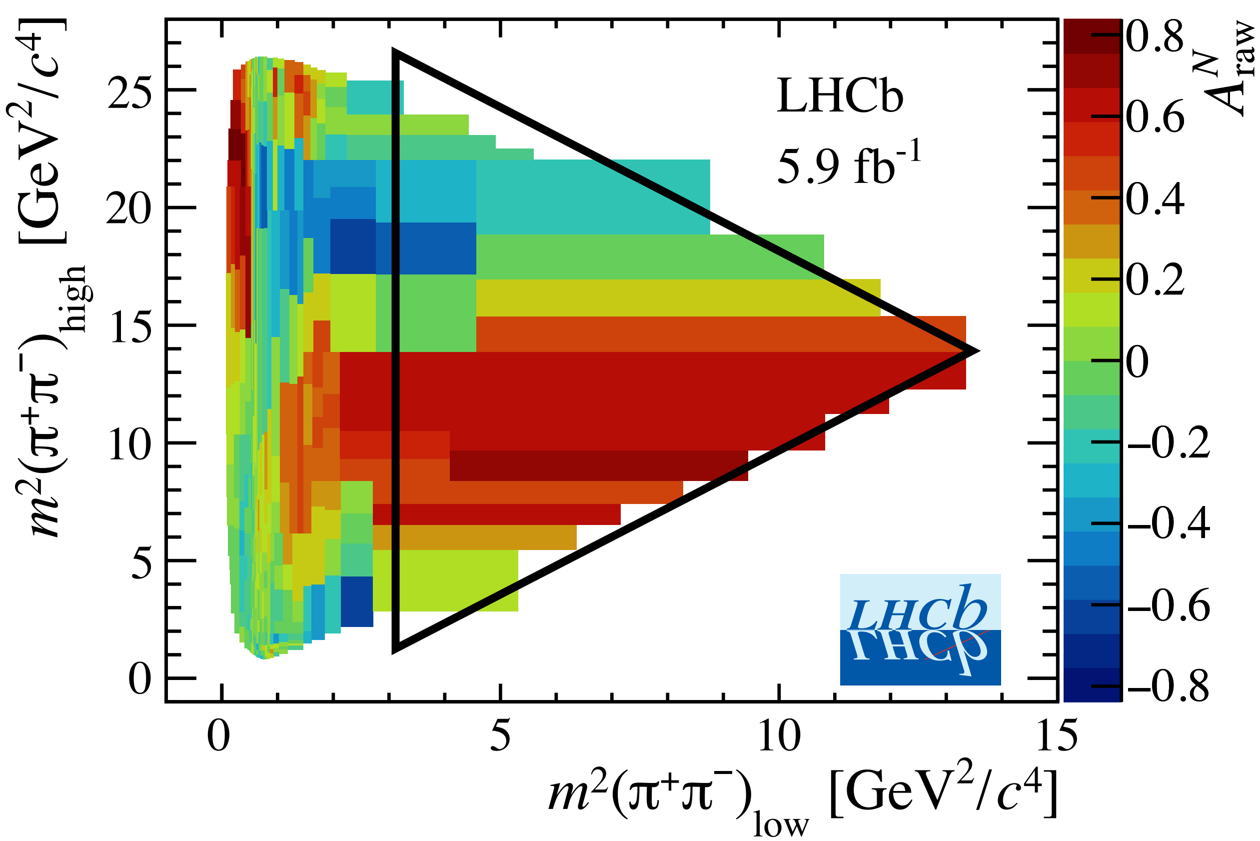

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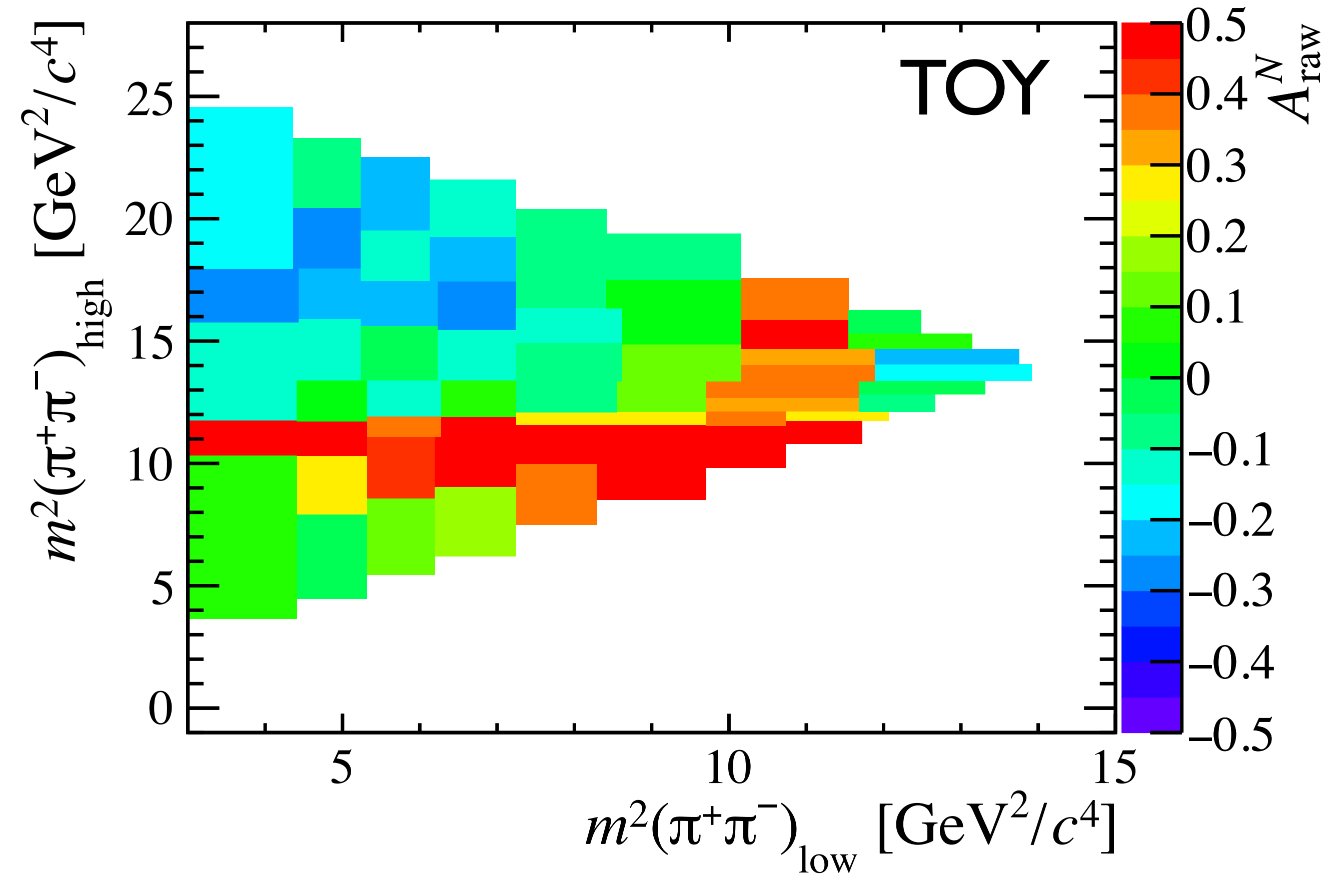

→ mimic CPV pattern at high mass

→ New mechanism of CPV!

→ to be tested on data!

- how to explain the CPV in charm?

LHCb

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

- how to explain the CPV in charm?

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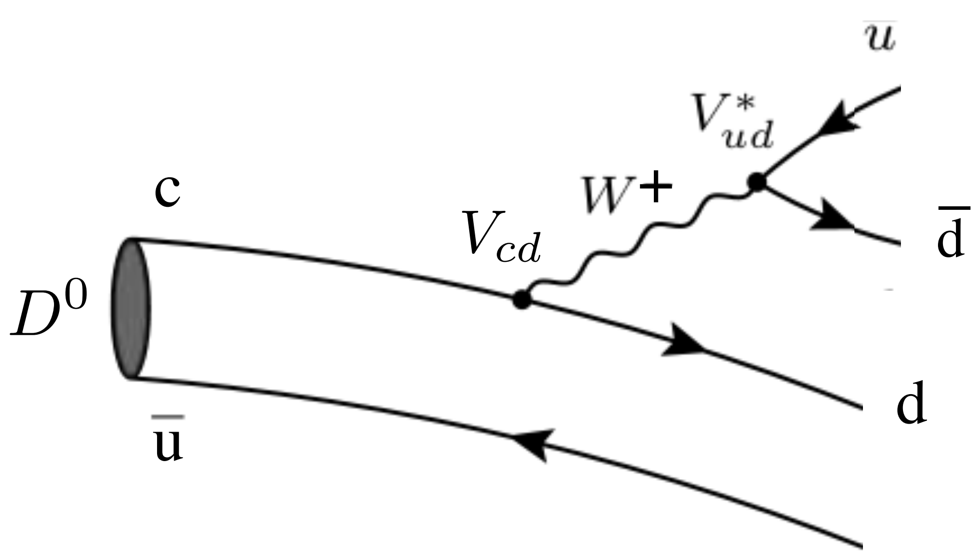
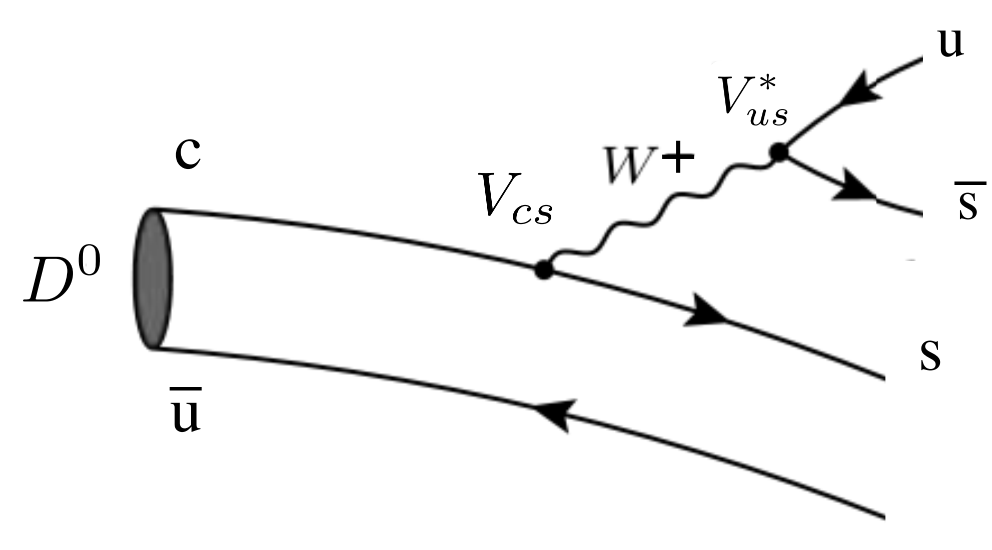
  - single cabibbo suppressed decays

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



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

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



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

  - weak phase in KK is 20 times smaller

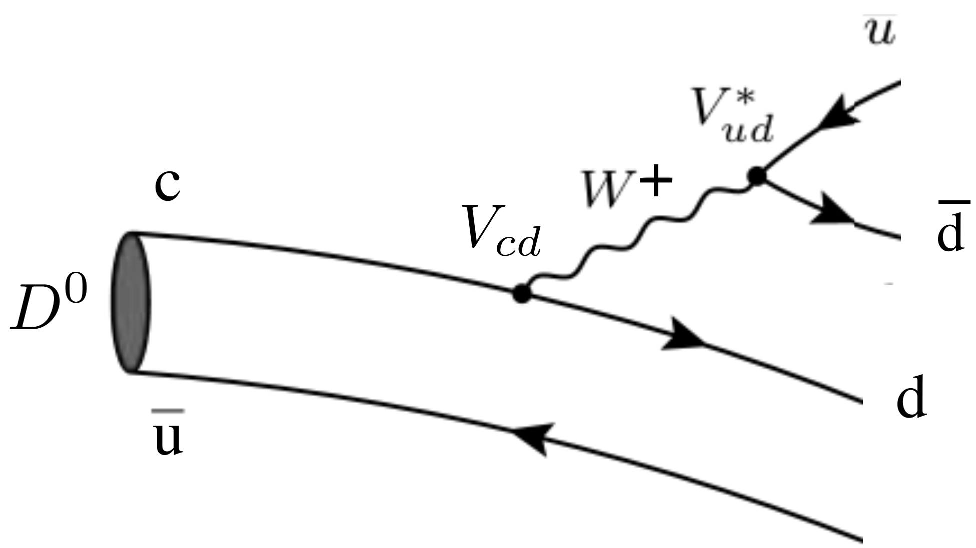
Lenz ,Wilkinson, Annu. Rev. Nucl. Part. Sci. 71, 59 (2021)

- how to explain the CPV in charm?

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

  - single cabibbo suppressed decays

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



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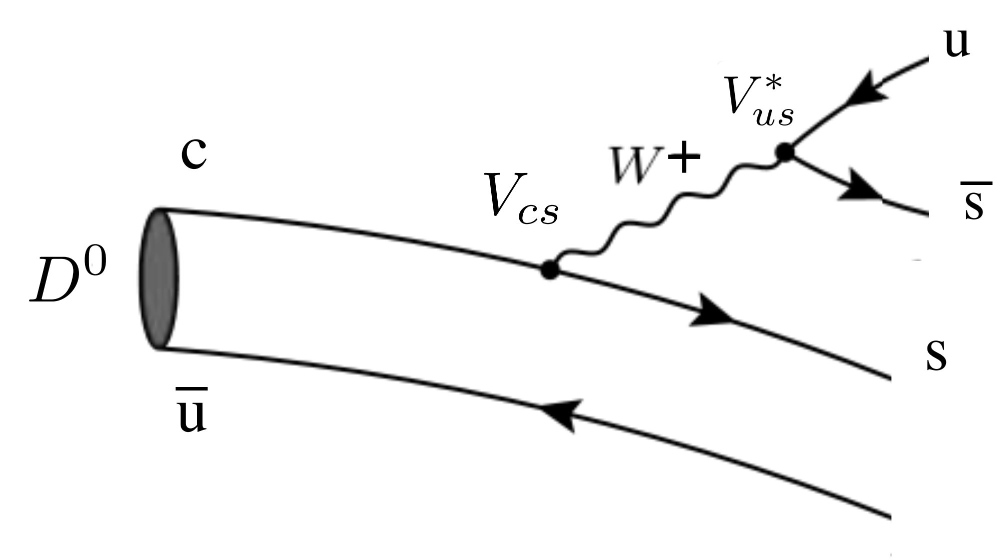


$V_{cs}V^*_{us} \approx \lambda(1 - \lambda^2)$

  - weak phase in KK is 20 times smaller Lenz ,Wilkinson, Annu. Rev. Nucl. Part. Sci. 71, 59 (2021)

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

Bediaga, Frederico, PCM PRL 131 051802 (2023) ;Grossman, Schacht JHEP07 20 (2019); Schacht, Soni PLB825 136855 (2022).

Theoretical approaches to CPV on charm

QCD short-distance

- QCDF → how to calculate penguin contributions? call BSM effects

Pich, Solomonidi, Silva arXiv:2305.11951

Chala, Lenz, Rusov, Scholtz, JHEP 07, 161 (2019).

- LCSR → QCD, model independent but predictions are 1 order magnitude bellow

Khodjamirian, Petrov, Phys. Lett. B 774, 235 (2017)

long distance effect:

- topological and group symmetry approach
  - with SU(3) breaking through FSI (fit agrees)

    H.-Y. Cheng and C.-W. Chiang, PRD 100, 093002 (2019).
    F. Buccella, A. Paul and P. Santorelli, PRD 99, 113001 (2019)
    Franco, Mishima, Silvestrini JHEP05, 140 (2012)

  - with resonances (fit agrees)

    Schacht and A. Soni, Phys. Lett. B 825, 136855 (2022).
    Y. Grossman and S. Schacht, JHEP 07, 20 (2019)

- FSI with CPT (prediction agrees)

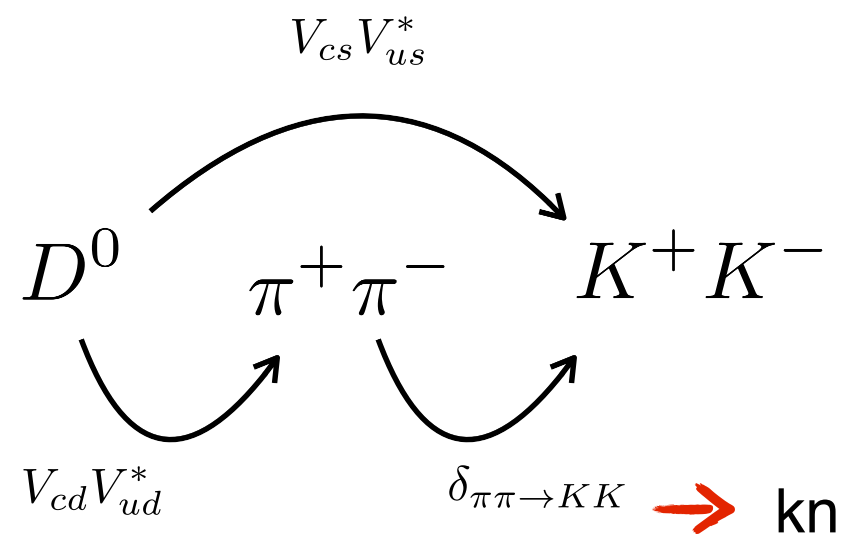
Bediaga,Frederico,Magalhaes PRL131, 051802 (2023)

arxiv 2203.04056v2

FSI as the source of CPV

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

Bediaga, Frederico, PCM
PRL131, 051802 (2023)
arxiv 2203.04056v3



→ known from 80's experiment

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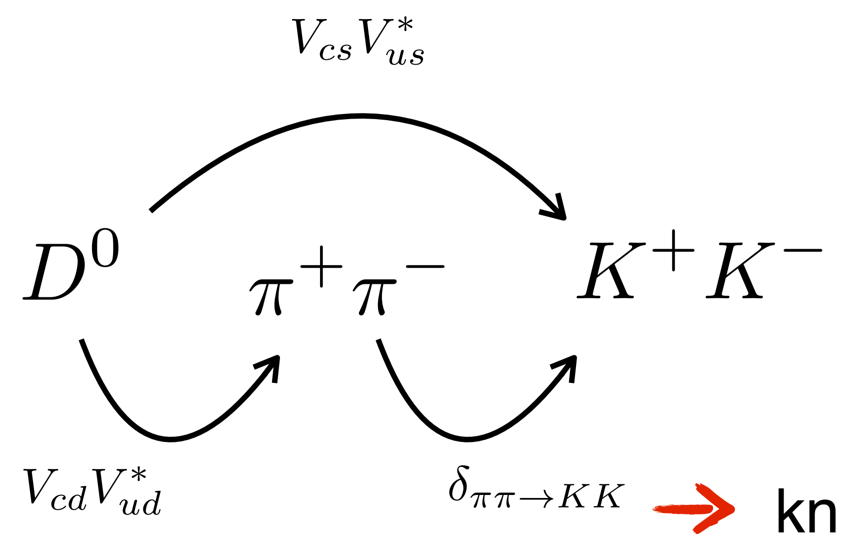


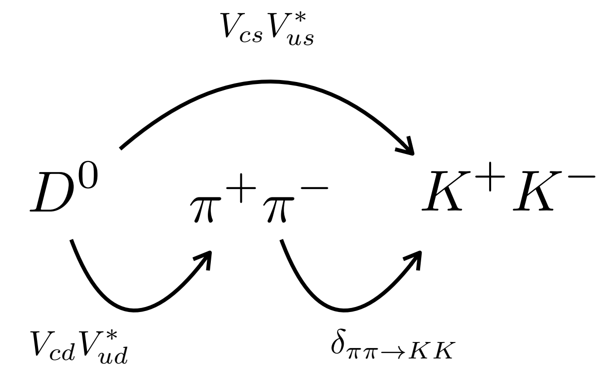
→ known from 80's experiment

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

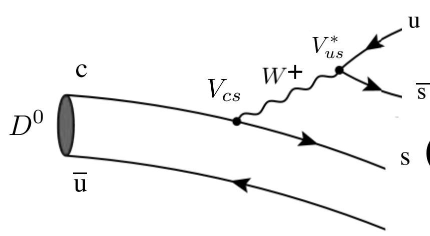
    → $$\sum \Delta\Gamma_{CP} = 0$$

  - Watson theorem relates the strong phase from the rescattering process to the decay amplitudes
  - the unitarity of the strong S-matrix - assume only 2 channels ie the dominant ones $\pi\pi, K\bar{K}$

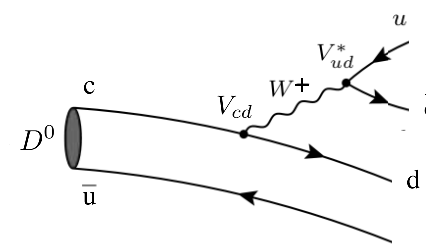
- dressing the weak tree topology with FSI
  - → penguin are suppressed



- $D^0 \to KK$



$\otimes$ $KK \to KK$ +



$\otimes$ $\pi\pi \to KK$

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

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

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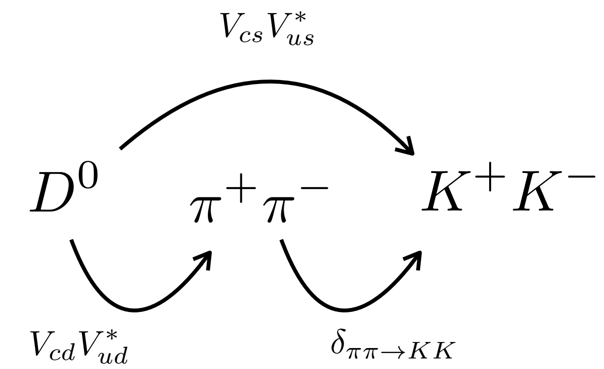

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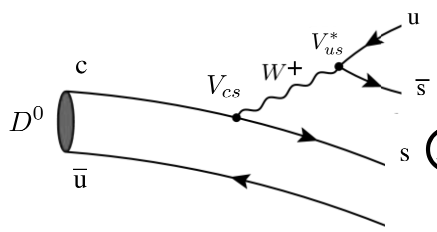

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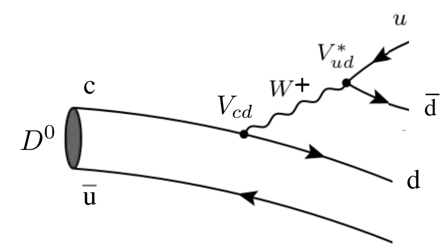

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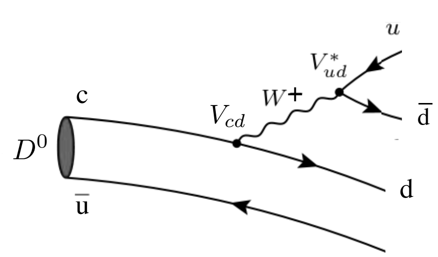

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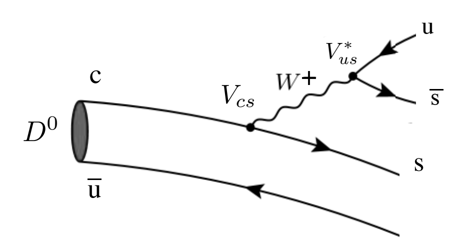

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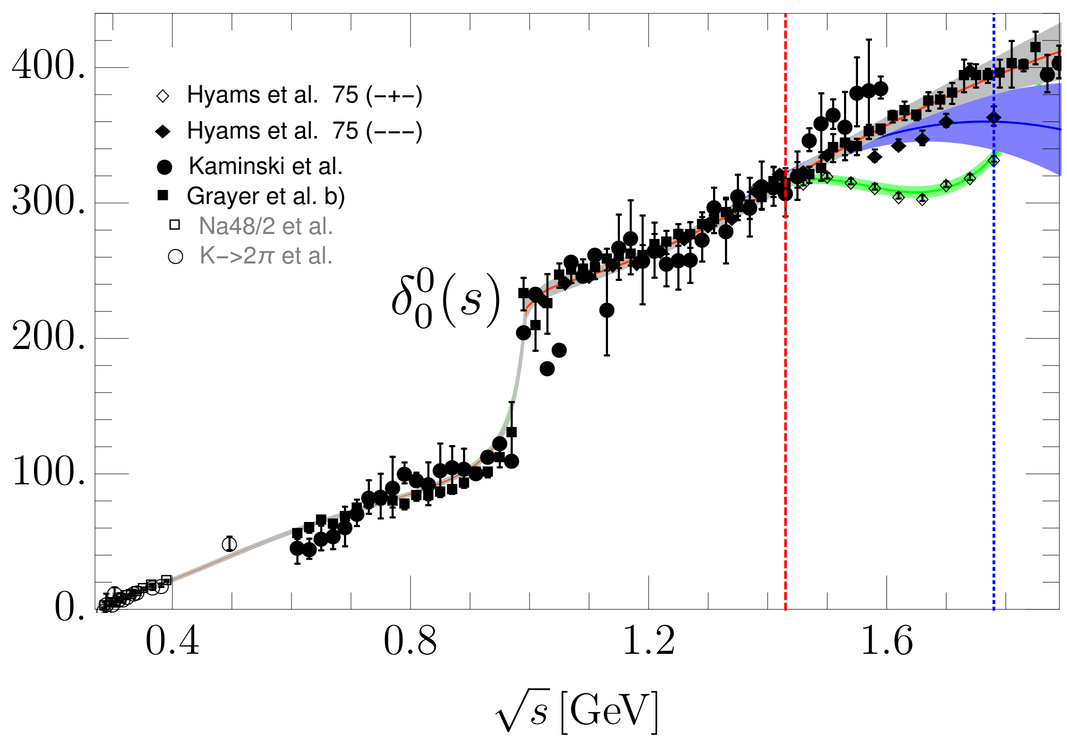
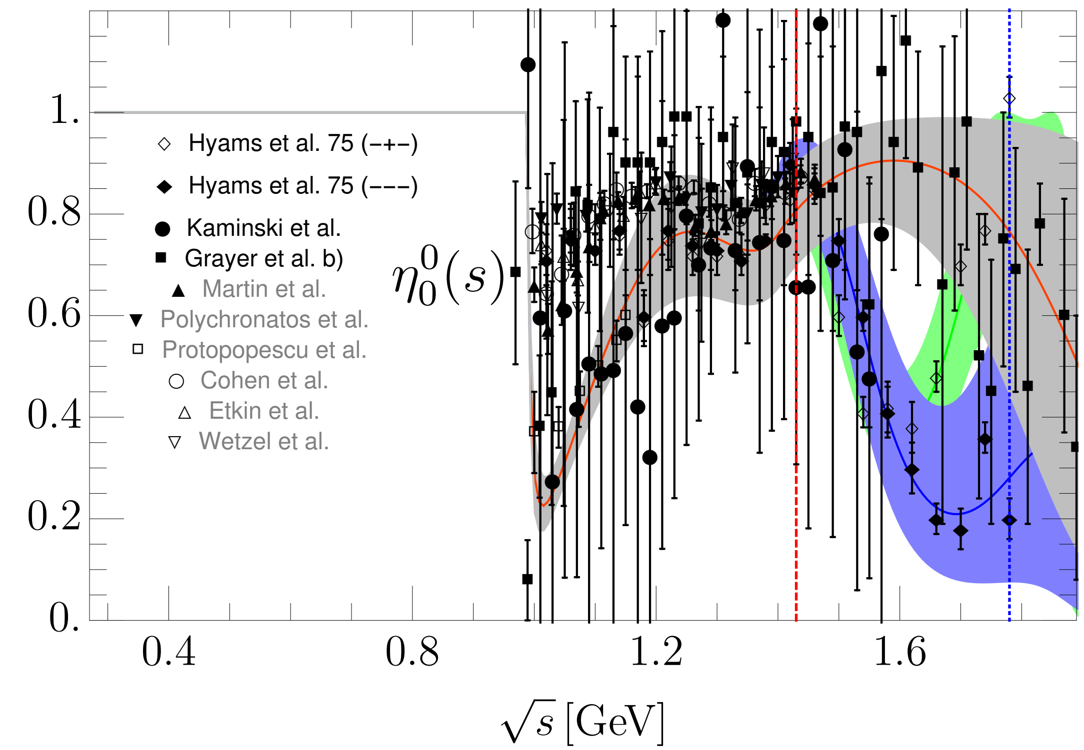
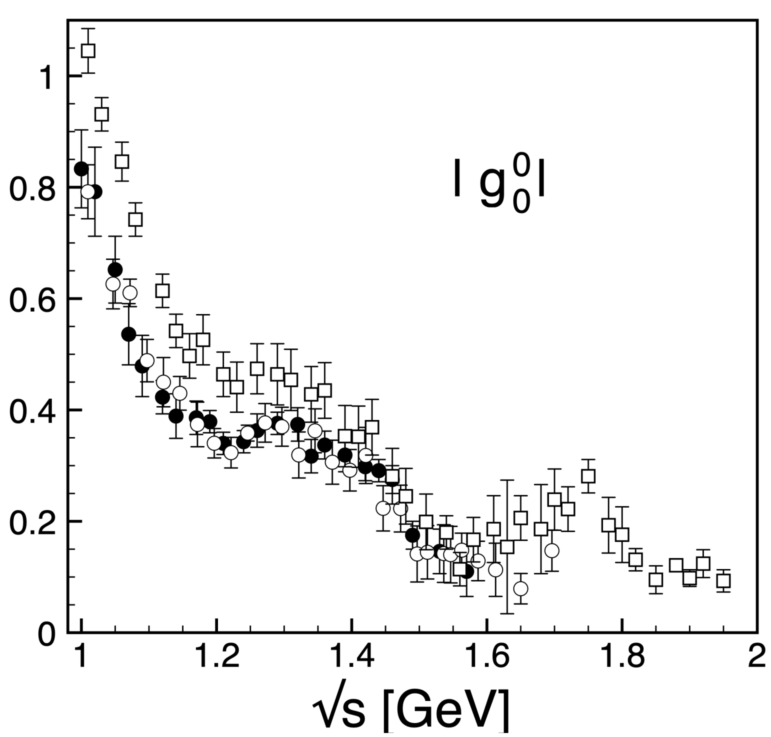
- a_{KK} and $a_{\pi\pi}$ do not carry any strong phases (real)

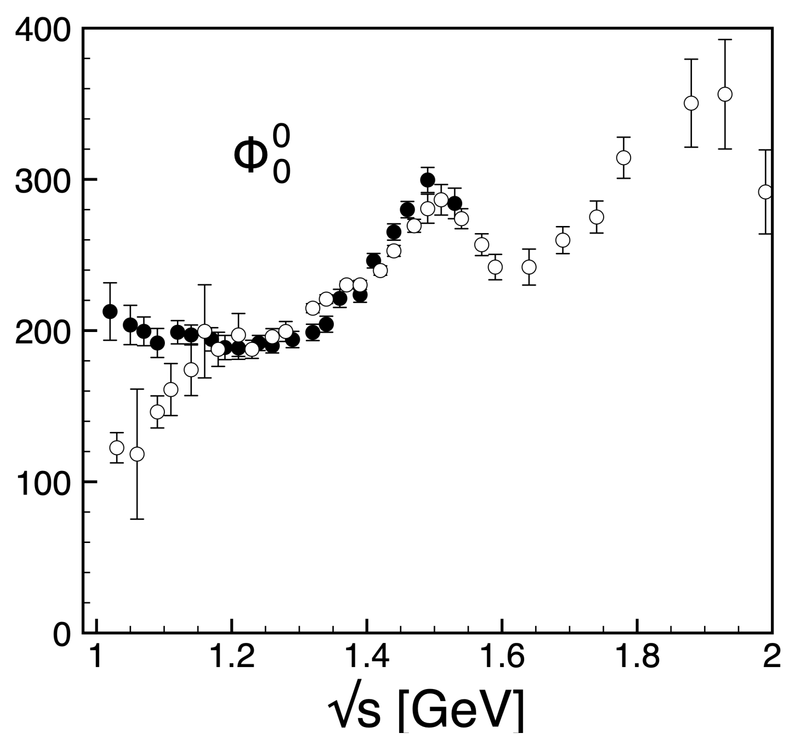
- $\pi\pi \to \pi\pi$ Pelaez, Rodas, Elvira *Eur.Phys.J.C* 79 (2019) 12, 1008





- $\pi\pi \to KK$ Pelaez and Rodas, Eur. Phys. J. C 78, 897 (2018)





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

$$= i\,4\sqrt{\frac{q_\pi q_K}{s}}\,|g_0^0(s)|\, e^{i\phi_0^0(s)}\,\Theta(s-4m_K^2)$$

$$|g_0^0(M_D^2)| \approx 0.125 \pm 0.025$$

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

$$\eta \approx 0.973$$

Partial decay widths

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

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

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→ $\Delta\Gamma_{\pi\pi} = -\Delta\Gamma_{KK} = 4\,\mathrm{Im}[V_{cs} V_{us}^* V_{cd}^* V_{ud}]\, a_{\pi\pi}\, a_{KK}\, \eta\sqrt{1-\eta^2}\cos\phi$

  - $\phi = \delta_{KK} - \delta_{\pi\pi}$
  - the sign of $\Delta\Gamma_f$ is determined by the CKM elements and the S-wave phase-shifts

Partial decay widths

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  - the sign of $\Delta\Gamma_f$ is determined by the CKM elements and the S-wave phase-shifts
  - need to quantify $a_{\pi\pi}$ and a_{KK}:

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

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

we can use experimental input

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

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- $A_{CP}(f) = \dfrac{\Gamma\left(D^0 \to f\right) - \Gamma(\bar{D}^0 \to f)}{\Gamma\left(D^0 \to f\right) + \Gamma(\bar{D}^0 \to f)}$ = $\Delta\Gamma_f / 2\Gamma_f$

Final values for A_{CP}

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

  $+$ $\pi\pi$
  $-$ KK

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

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

  - $\cos\phi$: $\phi = \delta_{KK} - \delta_{\pi\pi} = (\delta_{KK} + \delta_{\pi\pi}) - 2\delta_{\pi\pi}$

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    ϕ_0^0

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    $(\delta_{KK} + \delta_{\pi\pi}) \to \phi_0^0$

from $\pi\pi$ and $\pi\pi \to KK$ data: $\cos\phi = 0.99 \pm 0.18$.

Final values for A_{CP}

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  - $\cos\phi$: $\phi = \delta_{KK} - \delta_{\pi\pi} = (\delta_{KK}+\delta_{\pi\pi}) - 2\delta_{\pi\pi}$ (with $\delta_{KK}+\delta_{\pi\pi} \to \phi_0^0$)

  from $\pi\pi$ and $\pi\pi\to KK$ data: $\cos\phi = 0.99\pm0.18$

- $$A_{CP}(\pi\pi) = (1.99\pm0.37)\times10^{-3}\sqrt{\eta^{-2}-1}$$
  $$A_{CP}(KK) = -(0.71\pm0.13)\times10^{-3}\sqrt{\eta^{-2}-1}$$

as a function of inelasticity

Predictions for ΔA_{CP}

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

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

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  - from $\pi\pi \rightarrow KK$ data (only one set) → $\eta \approx 0.973 \pm 0.011$

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

3σ

→ largest theoretical prediction within SM without relying on fitting parameters

→ systematic uncertainties are unknown in η → error is underestimated

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

→ largest theoretical prediction within SM without relying on fitting parameters

→ systematic uncertainties are unknown in η → error is underestimated

- Alternatively one can assume all inelasticity in $\pi\pi \to \pi\pi$ is due to KK

→ more precise data (Grayer) → $\eta = 0.78 \pm 0.08$ *

$$\Delta A_{CP}^{th} = -(1.31 \pm 0.20) \times 10^{-3}$$ 1σ

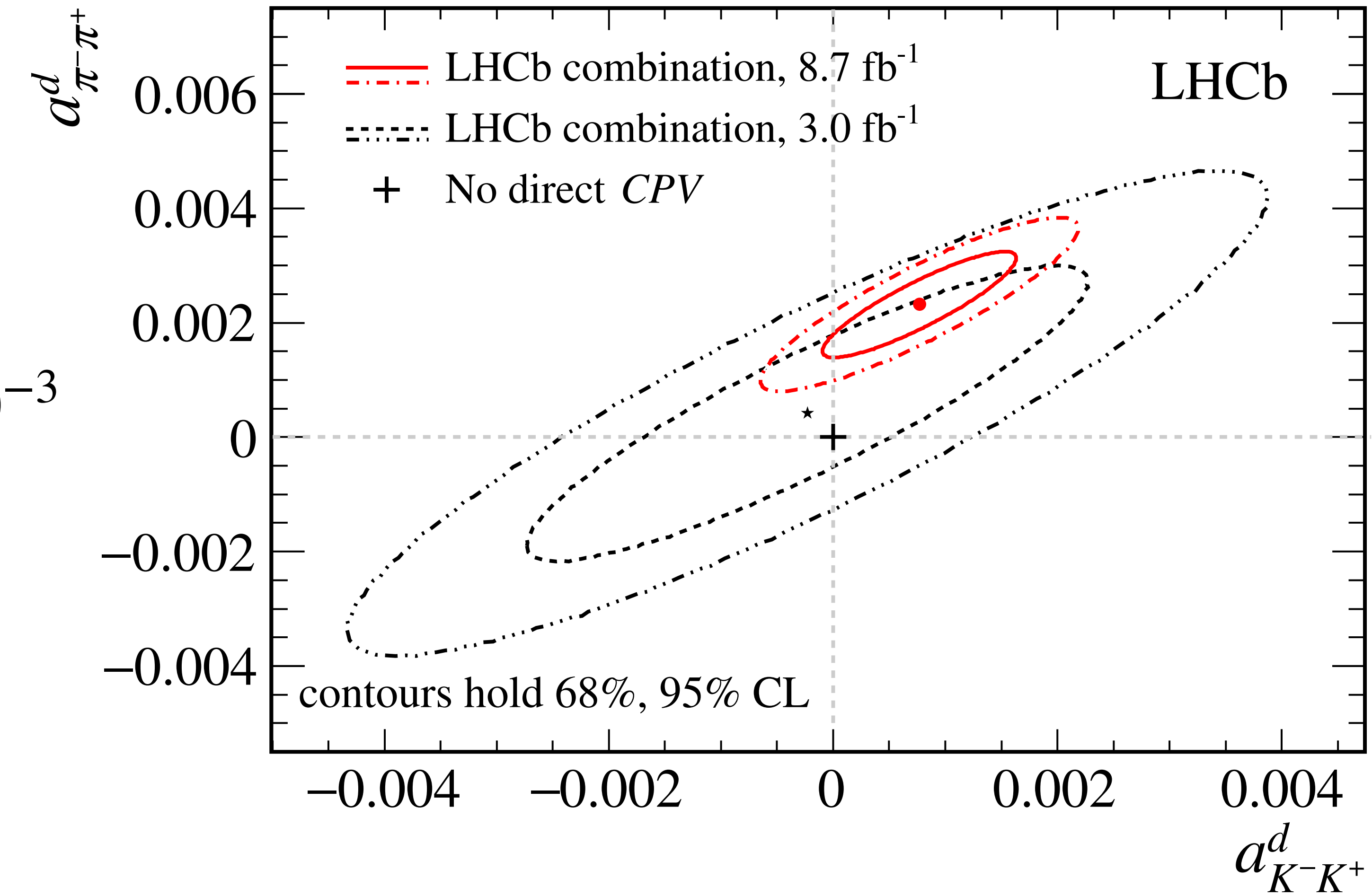
* $\sqrt{1 - \eta^2} \approx 1$ not valid

- direct CP asymmetry observation

$$A_{CP}^{LHCb}(KK) = (0.77 \pm 0.57) \times 10^{-3}$$

$$\hookrightarrow A_{CP}^{LHCb}(\pi\pi) = (2.32 \pm 0.61) \times 10^{-3}$$

arXiv:2209.03179



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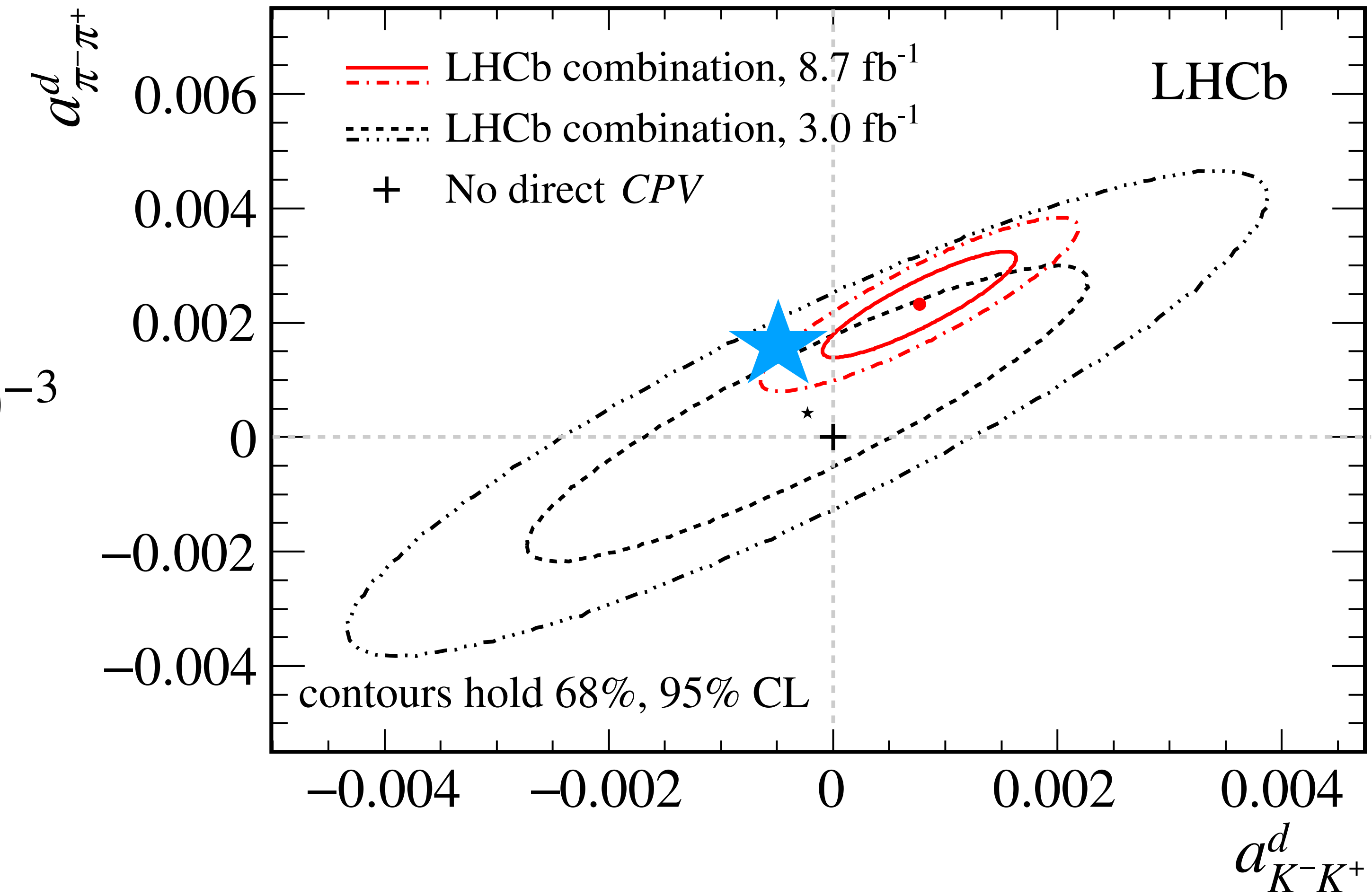

- with $\eta = 0.78 \pm 0.08$

$$A_{CP}(KK) = -(0.34 \pm 0.15) \times 10^{-3}$$

$$A_{CP}(\pi\pi) = (0.97 \pm 0.05) \times 10^{-3}$$

2σ

- direct CP asymmetry observation

$$A_{CP}^{LHCb}(KK) = (0.77 \pm 0.57) \times 10^{-3}$$

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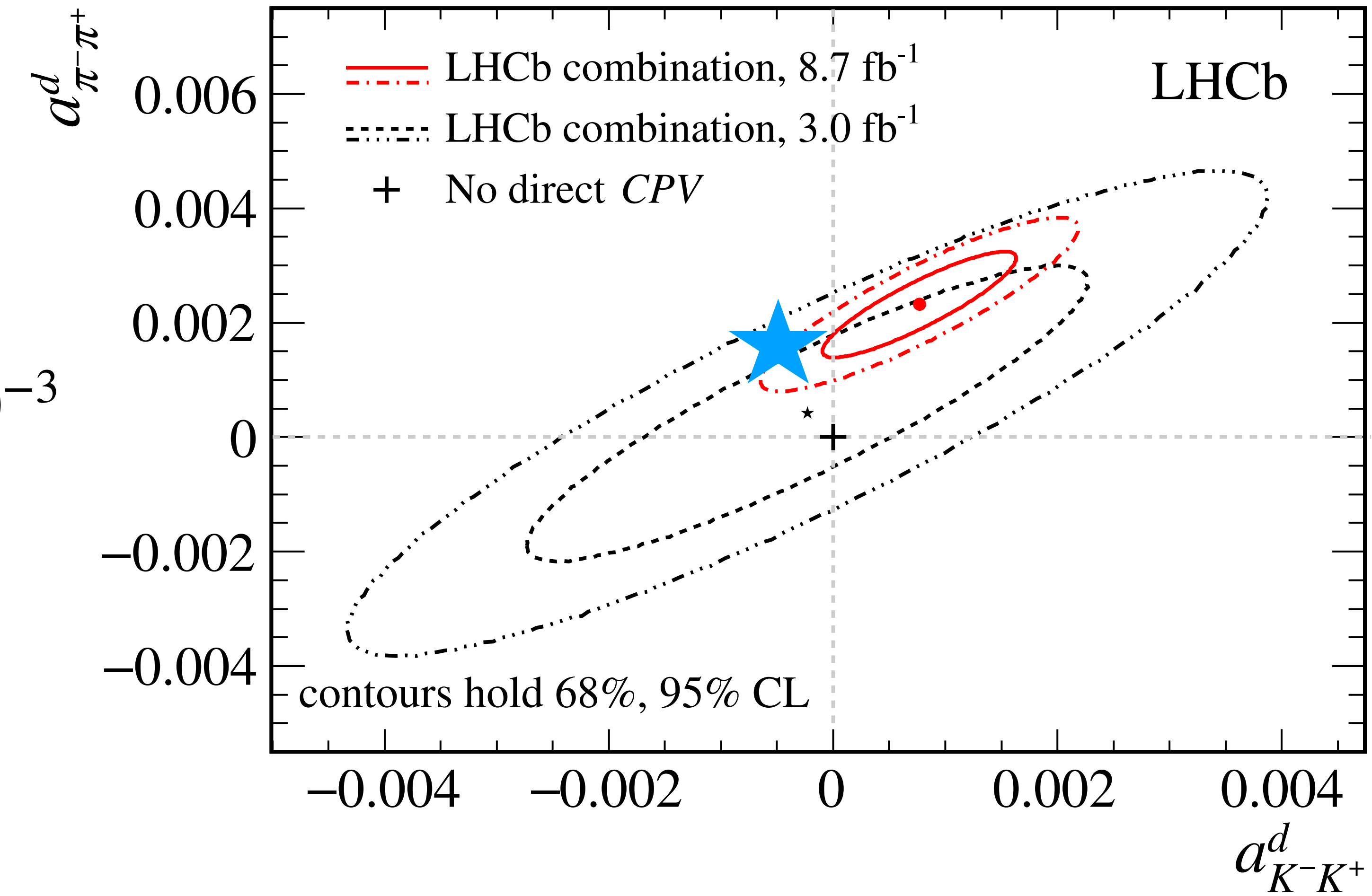

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$$A_{CP}(KK) = -(0.34 \pm 0.15) \times 10^{-3}$$

$$A_{CP}(\pi\pi) = (0.97 \pm 0.05) \times 10^{-3}$$

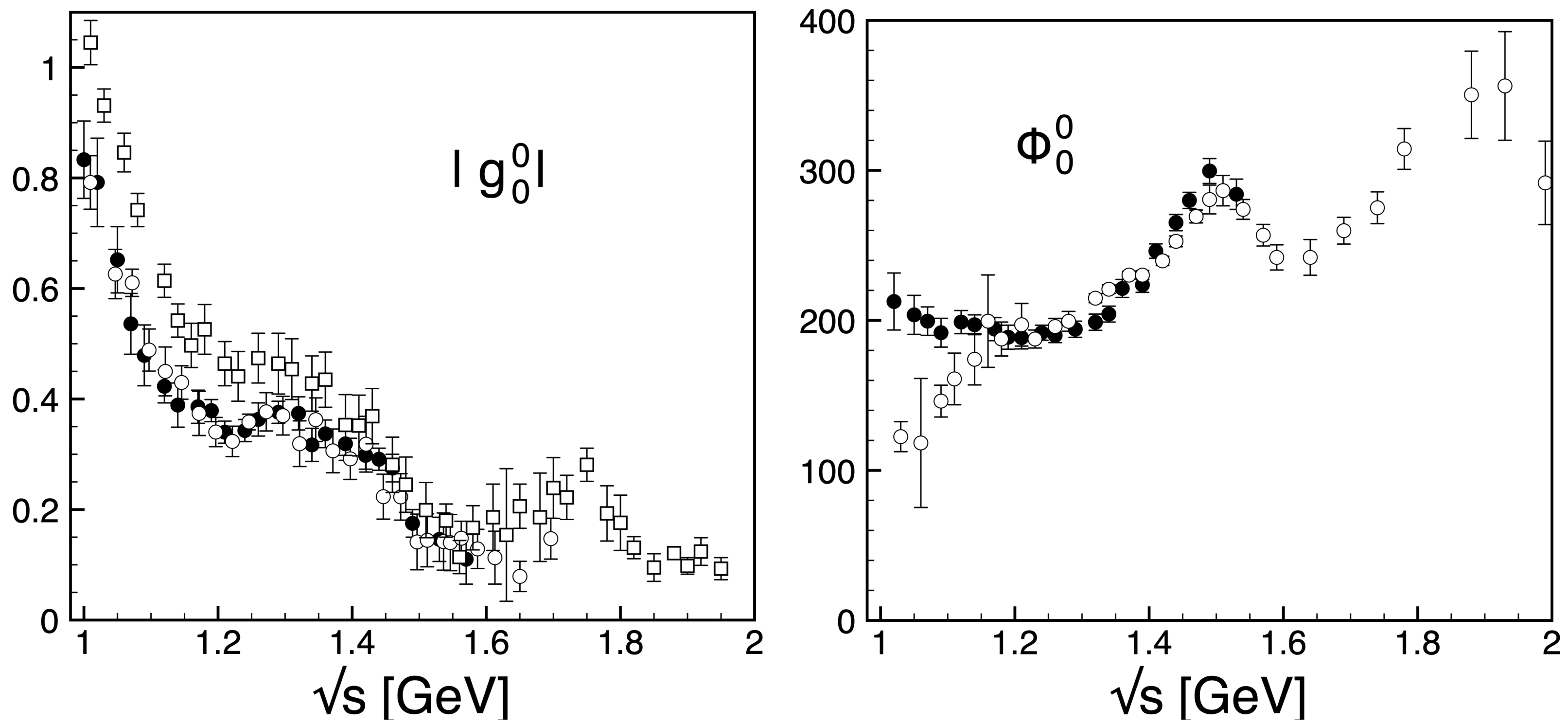
2σ

↳ we still need more data to fully understood it

What's next?

- In 3-body decays this effect will be bigger and phase-space distributed
  - ↪ $D^+ \to \pi^+\pi^-\pi^+$ and $D^+ \to \pi^+K^-K^+$ have exactly the same Weak vertex
- expected CPV in run II analysis

50 million events…



Final remarks

- hadronic FSI (and their strong phases) are crucial to explain CP violation in B and D decays at low and high mass regions

  - by including the FSI $\pi\pi \to KK$ we are able to identify:
    - one of the GIANT source of CPV observed in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$
    - explain the large CPV observed in $D^0(\bar{D}^0) \to \pi\pi$ and $K\bar{K}$

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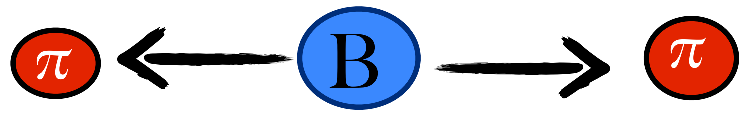
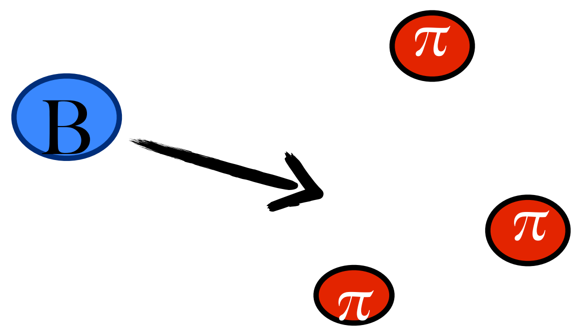
thank you!

Obrigada!

Backup slides

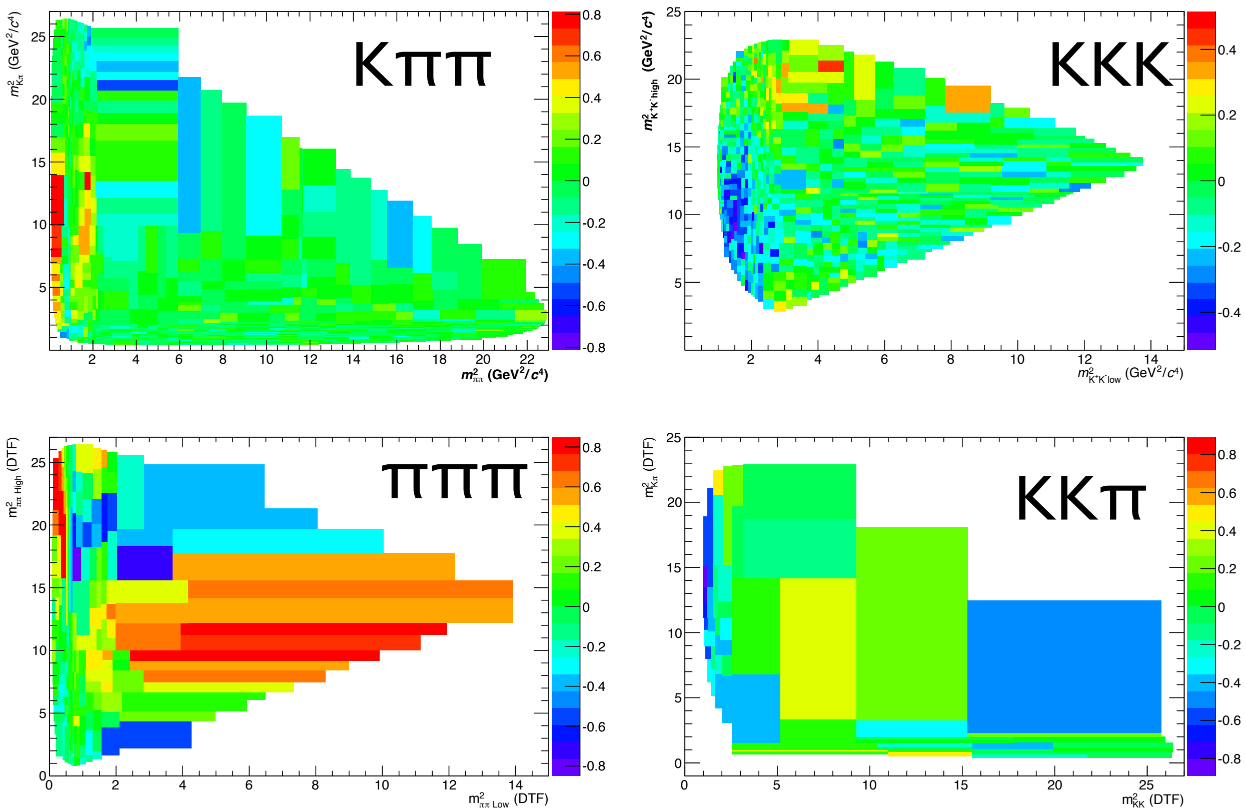
- 2-body decays: 

  - energy if fixed by the decay particle
  - FSI is relevant at the fix energy (ie is a number)
  - CPV is also a number

- 3-body decays: 

  - energy is distributed by particle momenta and $\sum p_i = M_B^2$
  - FSI is a function that depend on the invariant moment of each pair
  - the strong phase contributing to CPV will by a distribution in energy

→ FSI affects more drastically CPV in 3-body

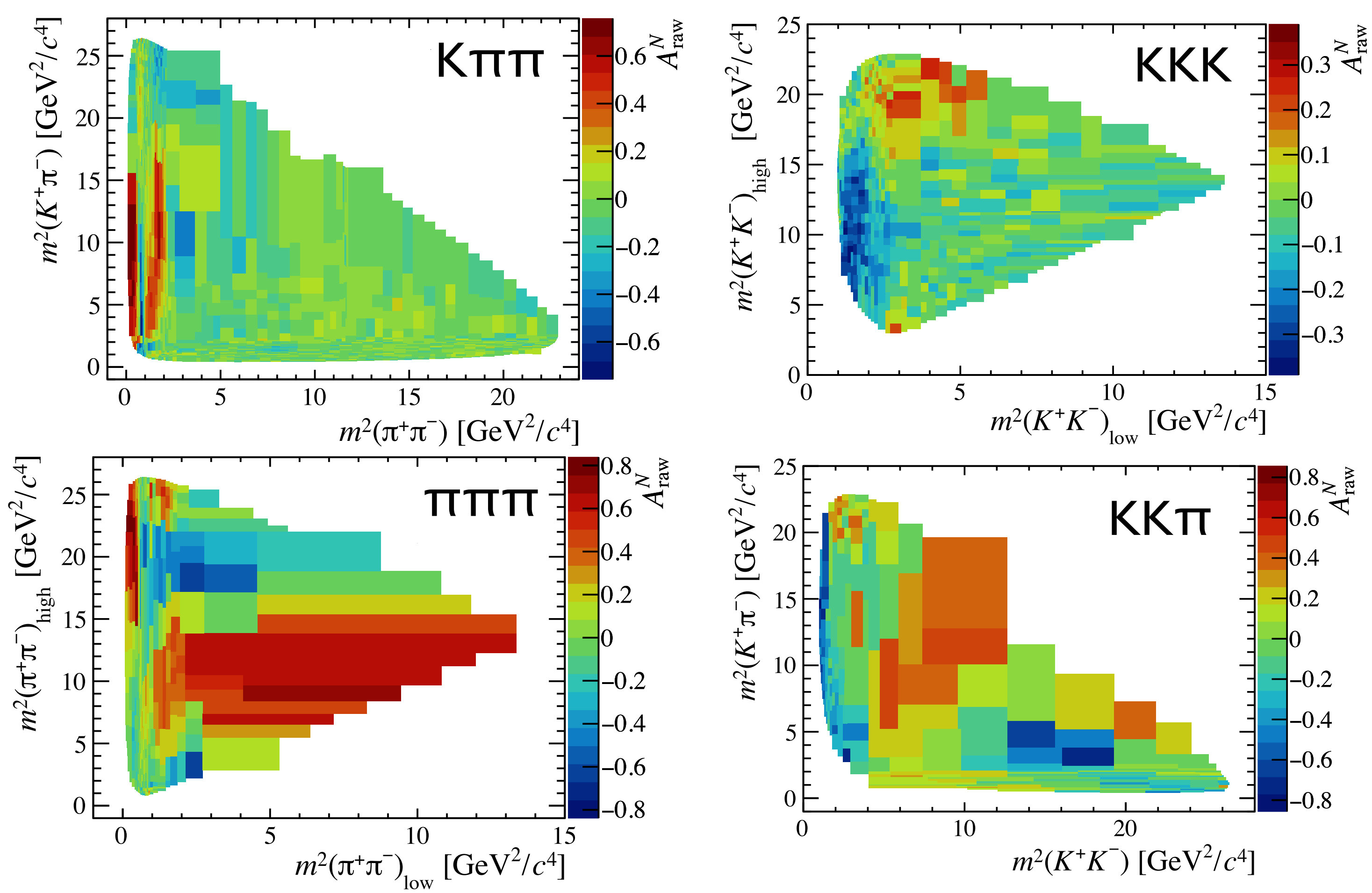


- run I ($3\,fb^{-1}$ luminosity)

  PRD90 (2014) 112004

- run II ($5.9\,fb^{-1}$ luminosity)

  arXiv:2206.07622 PRD accepted



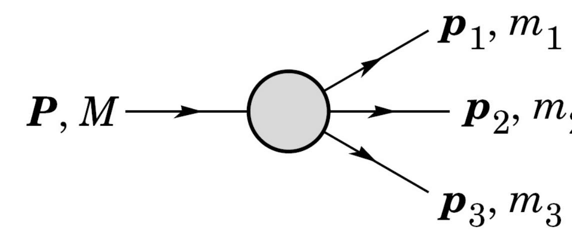
$K\pi\pi$: 2.8

KKK: 3.3

$\pi\pi\pi$: 4.1

$KK\pi$: 5.3

- In three-body decay phase-space is NOT one-dimension!
  ↳ bi-dimension phase-space information



- DALITZ PLOT : proposed by Richard Dalitz (1925-2006) in 1953

Mandelstam variables for 3-body

$$s_{12} = (p_1 + p_2)^2 = m_{12}^2$$

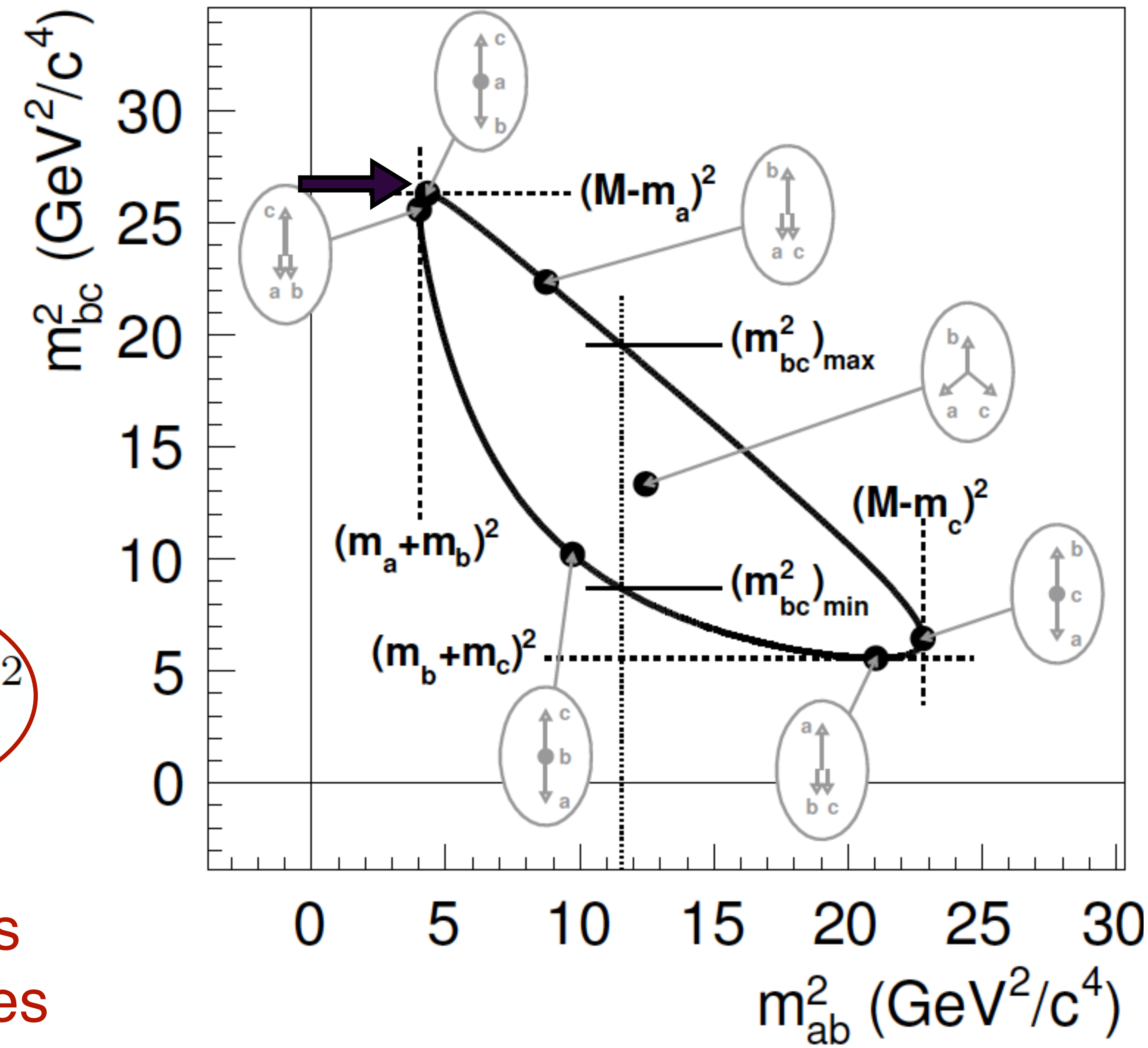
$$s_{13} = (p_1 + p_3)^2 = m_{13}^2$$

$$s_{23} = (p_2 + p_3)^2 = m_{23}^2$$

$$s_{12} + s_{13} + s_{12} = M^2 + m_1^2 + m_2^2 + m_3^2$$

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

dynamics
resonances



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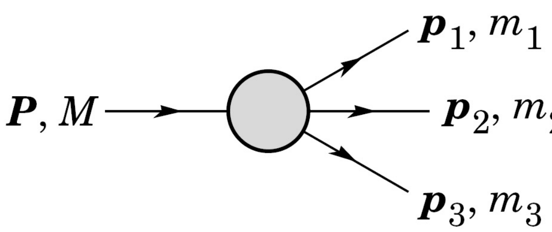

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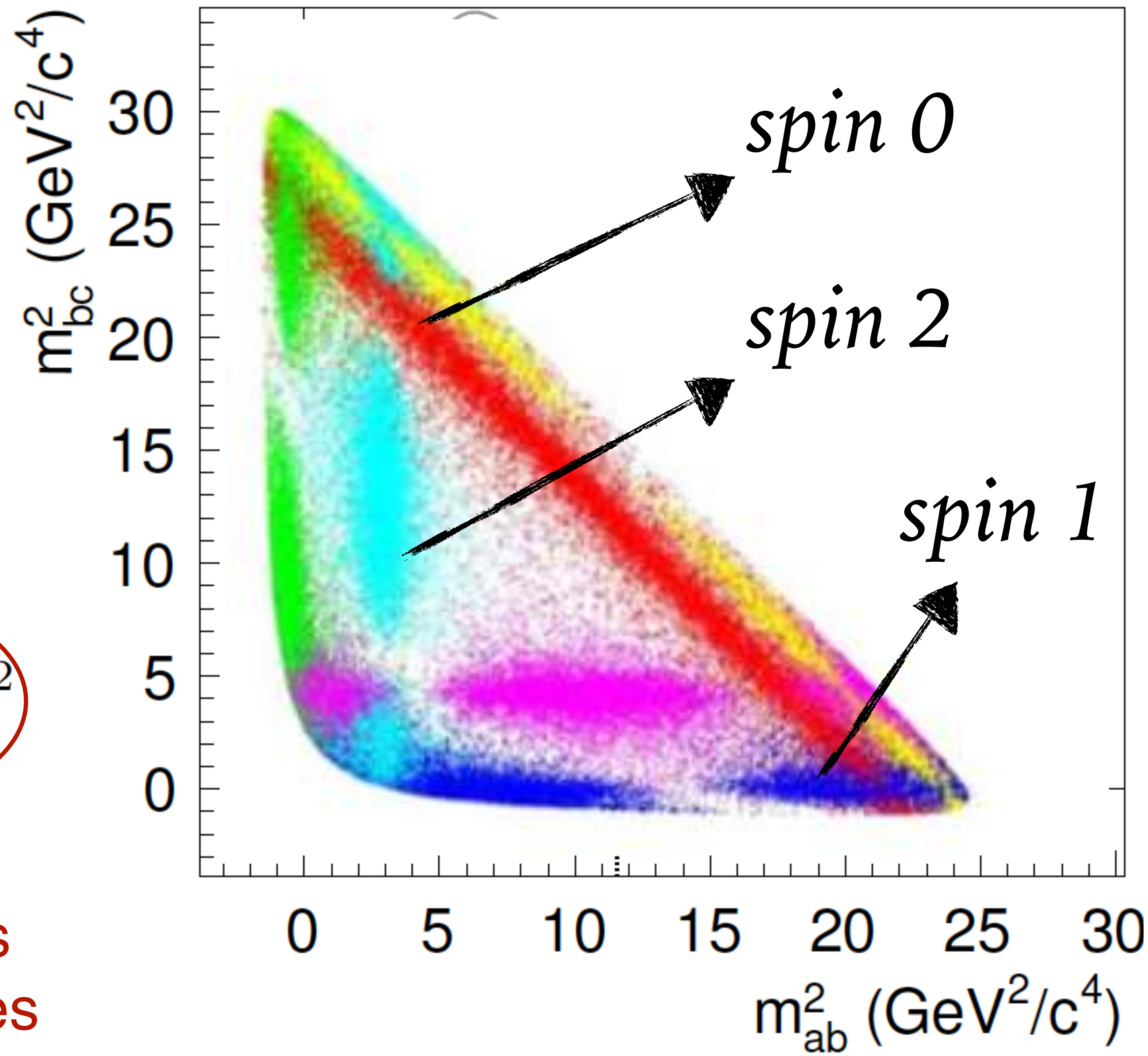
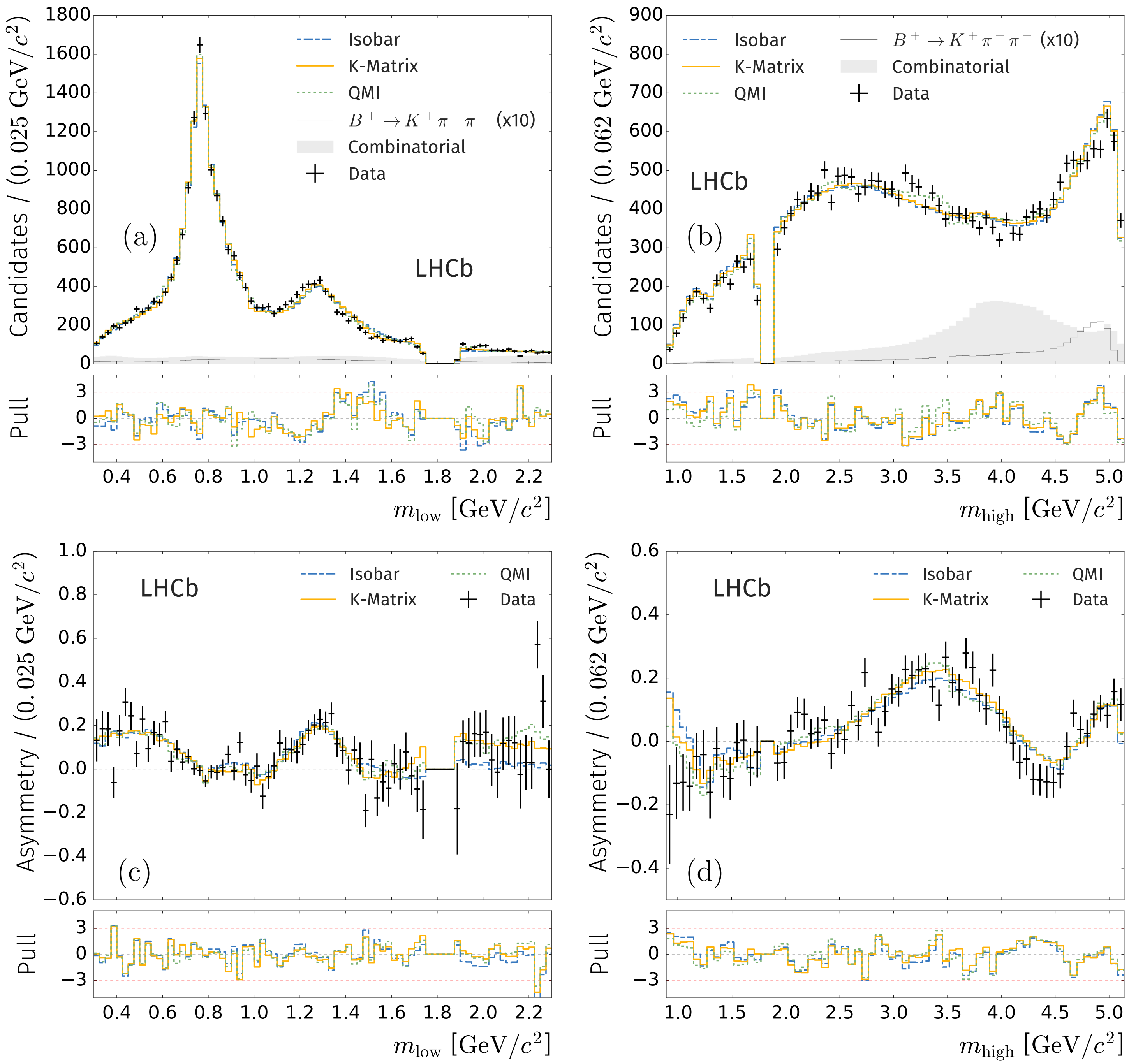


CPV: amplitude analysis $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$

- LHCb 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				
$\rho(770)^0$	$54.8 \pm 1.0 \pm 2.2$	$+4.4 \pm 1.7 \pm 2.8$	—	—
$\omega(782)$	$0.57 \pm 0.10 \pm 0.17$	$-7.9 \pm 16.5 \pm 15.8$	$-25 \pm 6 \pm 27$	$-2 \pm 7 \pm 11$
$f_2(1270)$	$9.6 \pm 0.4 \pm 4.0$	$+37.6 \pm 4.4 \pm 8.0$	$+13 \pm 5 \pm 21$	$+68 \pm 3 \pm 66$
$\rho(1450)^0$	$7.4 \pm 0.5 \pm 4.0$	$-15.5 \pm 7.3 \pm 35.2$	$+147 \pm 7 \pm 152$	$-175 \pm 5 \pm 171$
$\rho_3(1690)^0$	$1.0 \pm 0.1 \pm 0.5$	$-93.2 \pm 6.8 \pm 38.9$	$+8 \pm 10 \pm 24$	$+36 \pm 26 \pm 46$
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- 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	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$	$1.91 \pm 0.09 \pm 0.06$	$-56 \pm 12 \pm 18$
			$0.86 \pm 0.07 \pm 0.04$	$-81 \pm 14 \pm 15$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$	$0.20 \pm 0.07 \pm 0.02$	$-52 \pm 23 \pm 32$
			$0.22 \pm 0.06 \pm 0.04$	$107 \pm 33 \pm 41$

- recent Amplitude analysis $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ PRD101 (2020) 012006; PRL 124 (2020) 031801
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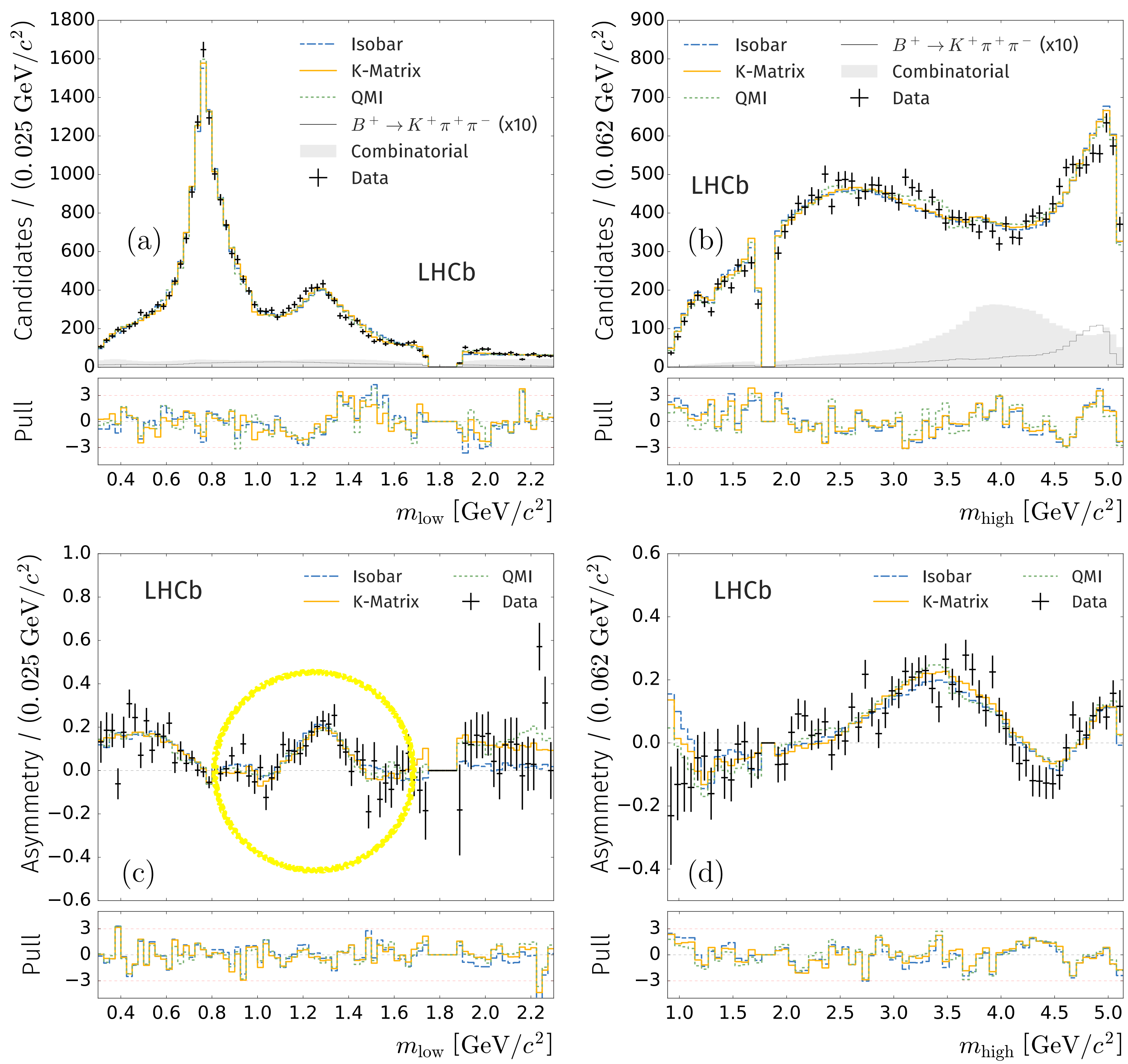

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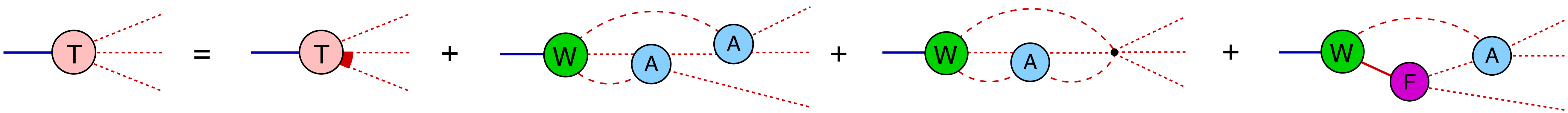
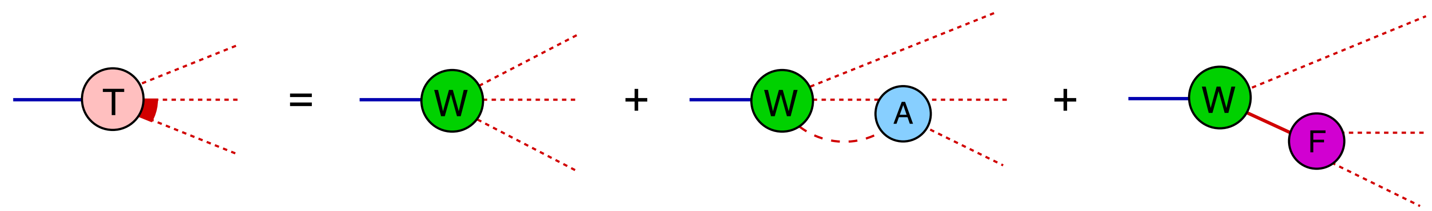
Full story in 3-body decay

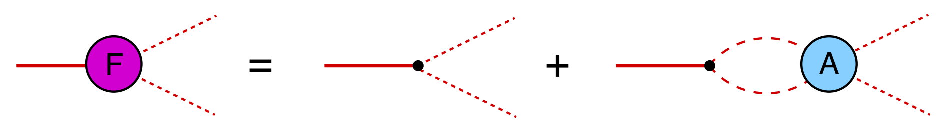
- Any 3-body decay amplitude



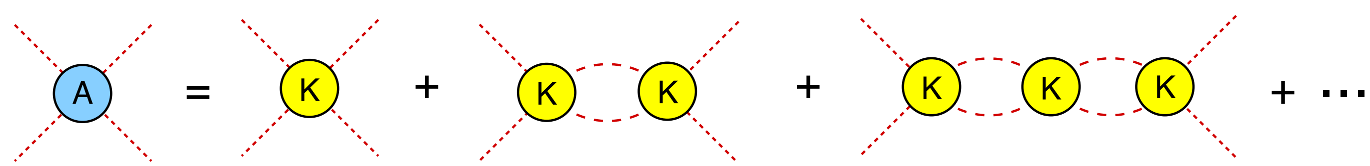
(2+1) approach



Form factor

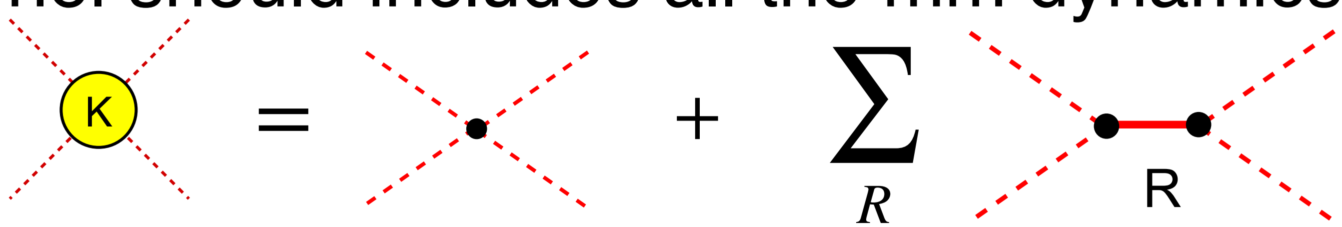


meson-meson

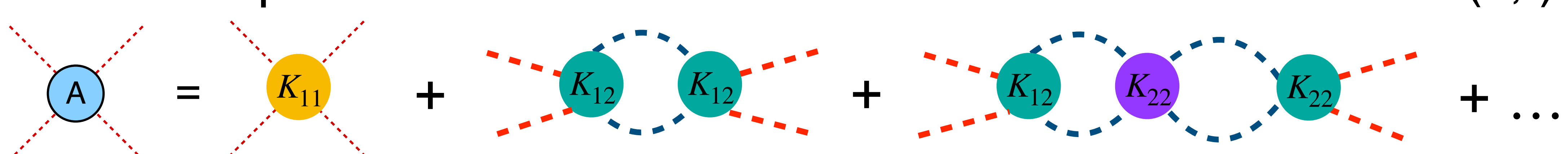


MAGALHAES, A.dos Reis, Robilotta
PRD 102, 076012 (2020)

- kernel should includes all the mm dynamics



- Unitarized amplitude should includes all channels with the same (J,I)



FSI and CPT in D decays

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

- assume only 2 couple-channels to FSI, ie the dominant ones $\pi\pi, K\bar{K}$

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

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

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

  - 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 $K\bar{K}$.

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

-

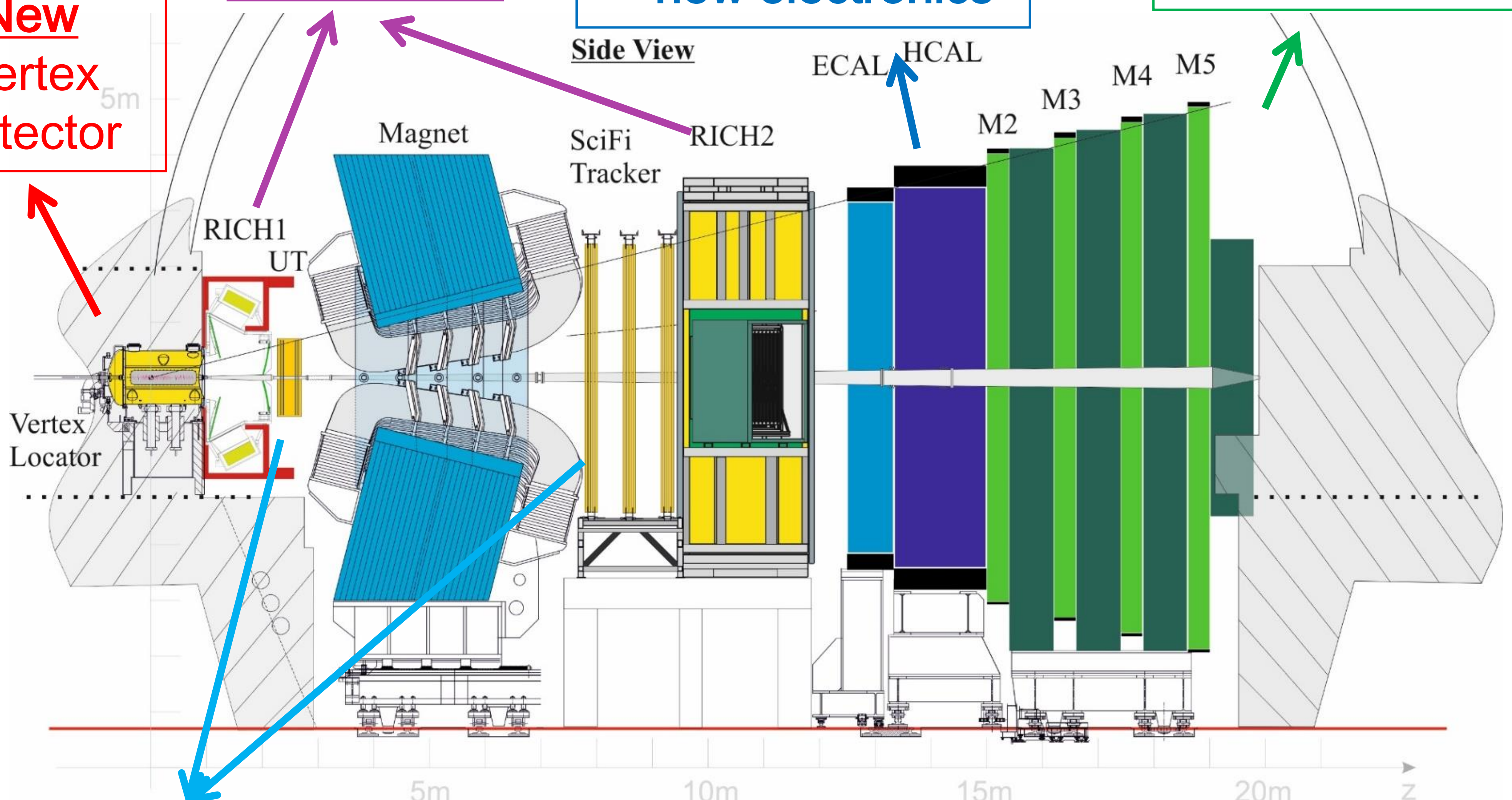
Phase-I upgraded LHCb detector

Particle ID
New detector + electronics

Calorimeters
Reduce PMT gain
+ **new electronics**

Muon
new electronics

New Vertex Detector



New Tracking stations

+ trigger-less readout & sw trigger on GPUs

back

ICHEP2020, 28 July – 6 August 2020 Federico Alessio, CERN 11

FSI as source of CP asymmetry before us

- R1, R2 make 2 approximations:

1. only 2-channel can interact $(S_{\lambda\lambda'}) = \begin{pmatrix} \eta e^{2i\delta_{11}} & i\sqrt{1-\eta^2}e^{i(\delta_{11}+\delta_{22})} \\ i\sqrt{1-\eta^2}e^{i(\delta_{11}+\delta_{22})} & \eta e^{2i\delta_{22}} \end{pmatrix}$

   ↳ $\delta_{\pi\pi KK} \simeq \delta_{\pi\pi\pi\pi} + \delta_{KKKK}$

   ↳ $|S_{\pi\pi KK}| \to \sqrt{1-\eta^2}$

2. crudely assume $\delta_{KKKK} \simeq \delta_{\pi\pi\pi\pi}$

   ↳ $\delta_{\pi\pi KK} \simeq 2\delta_{\pi\pi\pi\pi}$

- R1, R2 make 2 approximations:

1 only 2-channel can interact

$$(S_{\lambda\lambda'}) = \begin{pmatrix} \eta e^{2i\delta_{11}} & i\sqrt{1-\eta^2}e^{i(\delta_{11}+\delta_{22})} \\ i\sqrt{1-\eta^2}e^{i(\delta_{11}+\delta_{22})} & \eta e^{2i\delta_{22}} \end{pmatrix}$$

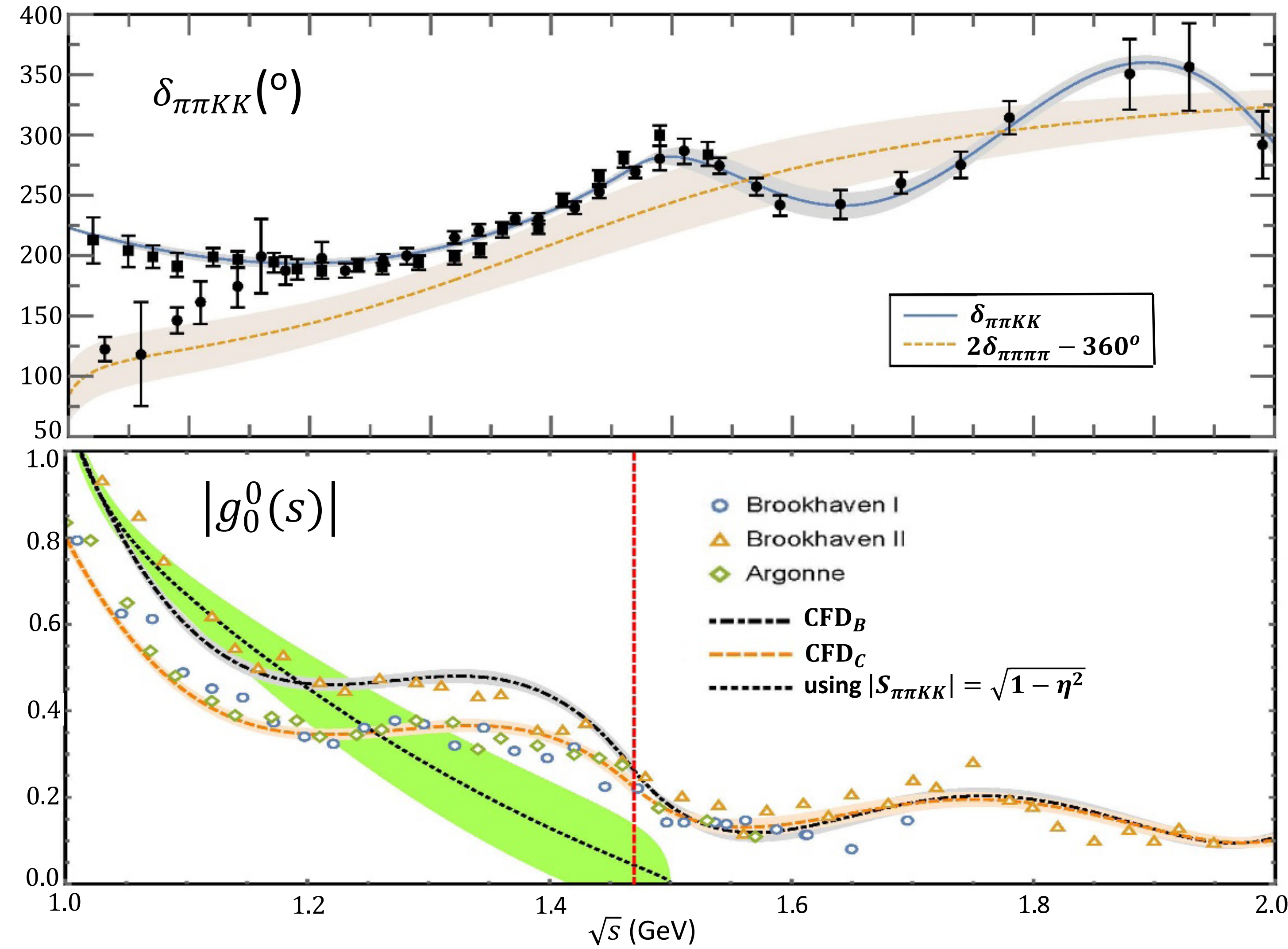
↳ $\delta_{\pi\pi KK} \simeq \delta_{\pi\pi\pi\pi} + \delta_{KKKK}$

↳ $|S_{\pi\pi KK}| \to \sqrt{1-\eta^2}$

2 crudely assume $\delta_{KKKK} \simeq \delta_{\pi\pi\pi\pi}$

↳ $\delta_{\pi\pi KK} \simeq 2\delta_{\pi\pi\pi\pi}$

- clearly a distortion from $\pi^+\pi^- \to K^+K^-$ phase and $|S_{\pi\pi KK}|$



FSI as source of CP asymmetry before us

- R1, R2 make 2 approximations:

  1. only 2-channel can interact $(S_{\lambda\lambda'}) = \begin{pmatrix} \eta e^{2i\delta_{11}} & i\sqrt{1-\eta^2}e^{i(\delta_{11}+\delta_{22})} \\ i\sqrt{1-\eta^2}e^{i(\delta_{11}+\delta_{22})} & \eta e^{2i\delta_{22}} \end{pmatrix}$
     - $\delta_{\pi\pi KK} \simeq \delta_{\pi\pi\pi\pi} + \delta_{KKKK}$
     - $|S_{\pi\pi KK}| \to \sqrt{1-\eta^2}$
  2. crudely assume $\delta_{KKKK} \simeq \delta_{\pi\pi\pi\pi}$
     - $\delta_{\pi\pi KK} \simeq 2\delta_{\pi\pi\pi\pi}$

- clearly a distortion from $\pi^+\pi^- \to K^+K^-$ phase and $|S_{\pi\pi KK}|$

- Are the conclusions still valid?

  We can do better!