Dalitz Plot analysis of $D \to hhh$ @LHCb

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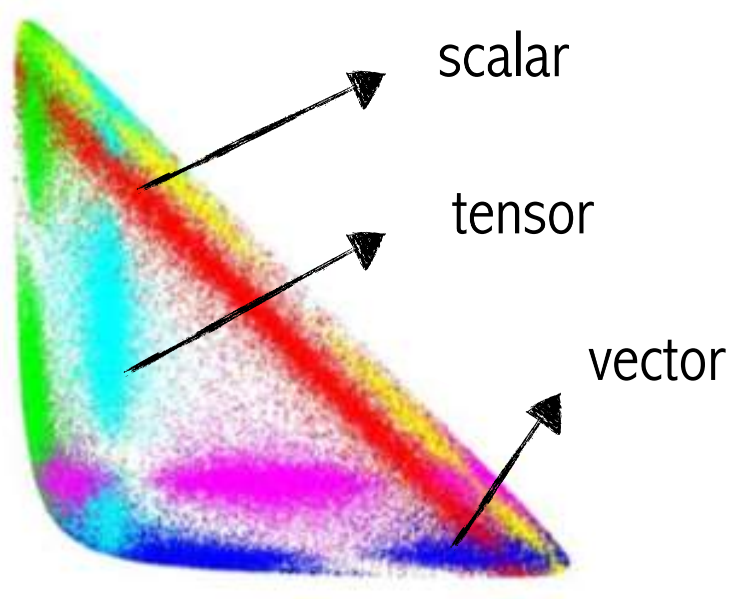
1st June 2021

Charm 2020 - Mexico City

what can we learn from $D \to hhh$?

- D three-body HADRONIC decay are dominated by resonances



→ spectroscopy low energy resonances

→ underlying strong force behave

↪ meson-meson interactions and resonance structures

- CP-Violation
  - $B^\pm \to h^\pm h^- h^+$ massive localized direct CP asymmetry
  - 1st observation in charm LHCb $A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$

    Angelo and Lorenzo talks

→ CPV on $D \to hhh$?

→ searches in many process

→ can lead to new physics

$D \rightarrow hhh$ @LHCb

- full description of the underling structures (amplitude analysis):
  - $D^+ \rightarrow K^+K^-K^+$ (DCS) JHEP 04 (2019) 063 will discuss
  - $D^0 \rightarrow K_sK^{\pm}\pi^{\mp}$ (SCS) PRD 93 (2016) 052018
  - $D^+ \rightarrow \pi^-\pi^+\pi^+$ and $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ - on going

- $D^0 \rightarrow K_sh^+h^-$ $(h = K, \pi)$ good sensitivity to measure mixing
  - input for γ determination in $B \rightarrow DK$ JHEP 08 (2018) 176
  - measurement of the mass difference $(D^0, \bar{D}^0)$ in $D^0 \rightarrow K_s\pi^+\pi^-$ PRL 122 (2019) 231802 Angelo's talk

    ↳ model dependent - on going

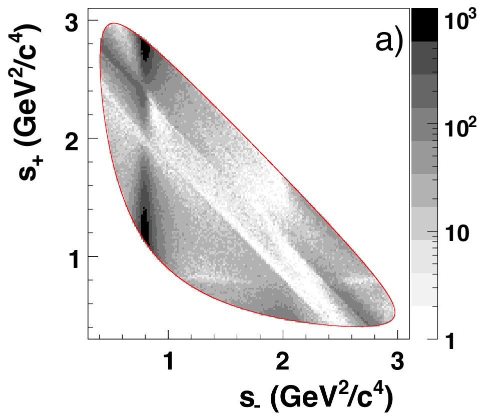
- LHCb data for each $D \rightarrow hhh$ decays include ~ 10^6 - 10^7 events

  → extremely challenging ↘ claim for precise theoretical models

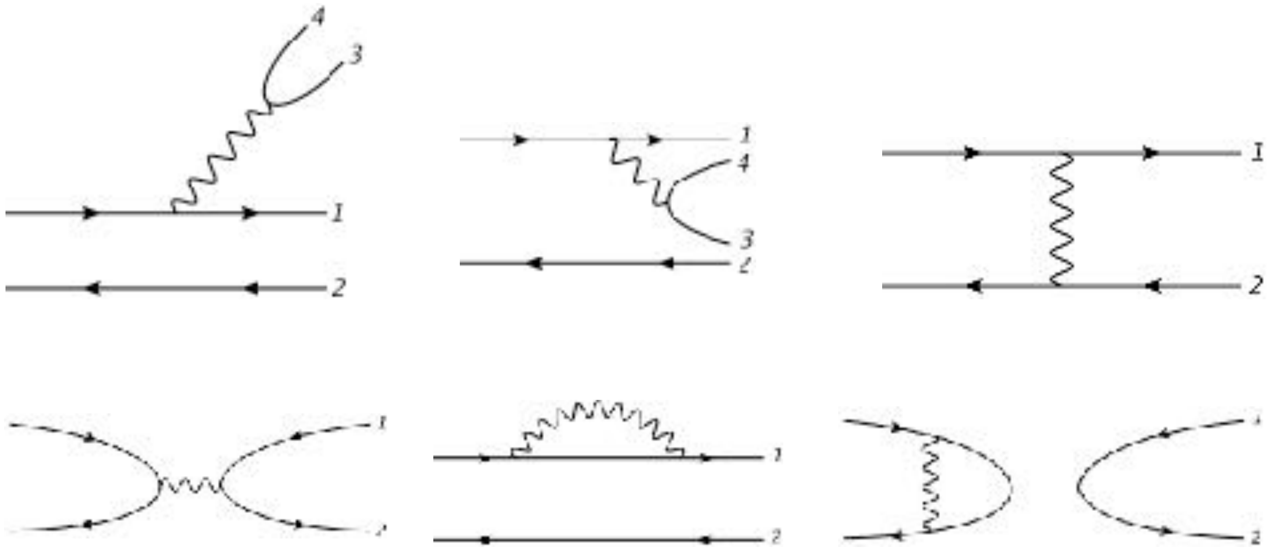
Three-body heavy meson decay Dynamics

hadronize

observed

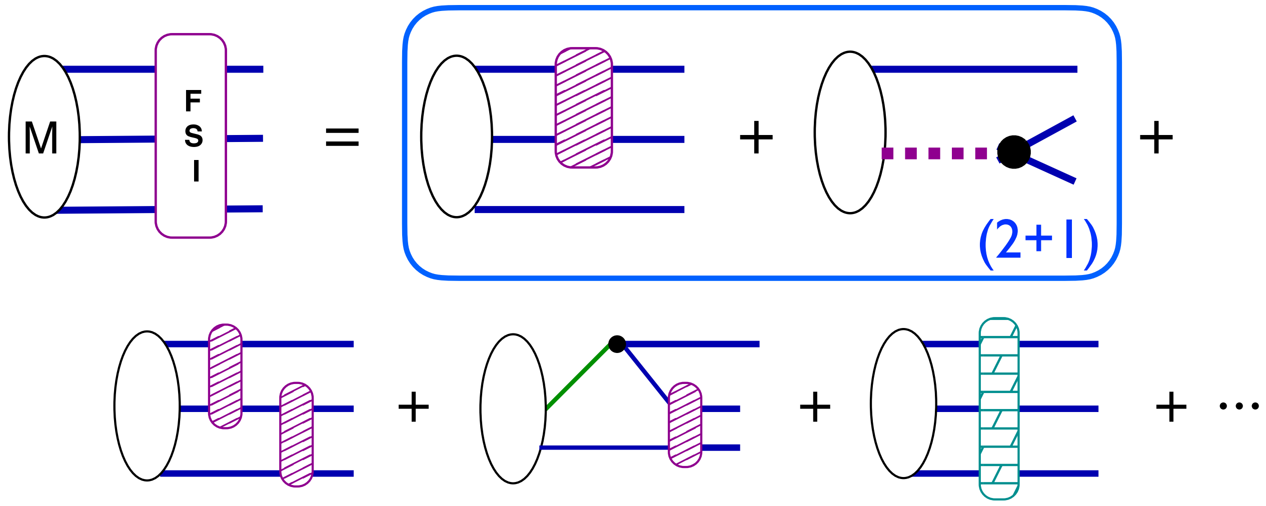


weak transition



QCD, CKM coupling and phase

Final State Interactions - strong -



- To extract information from data we need an amplitude **MODEL**

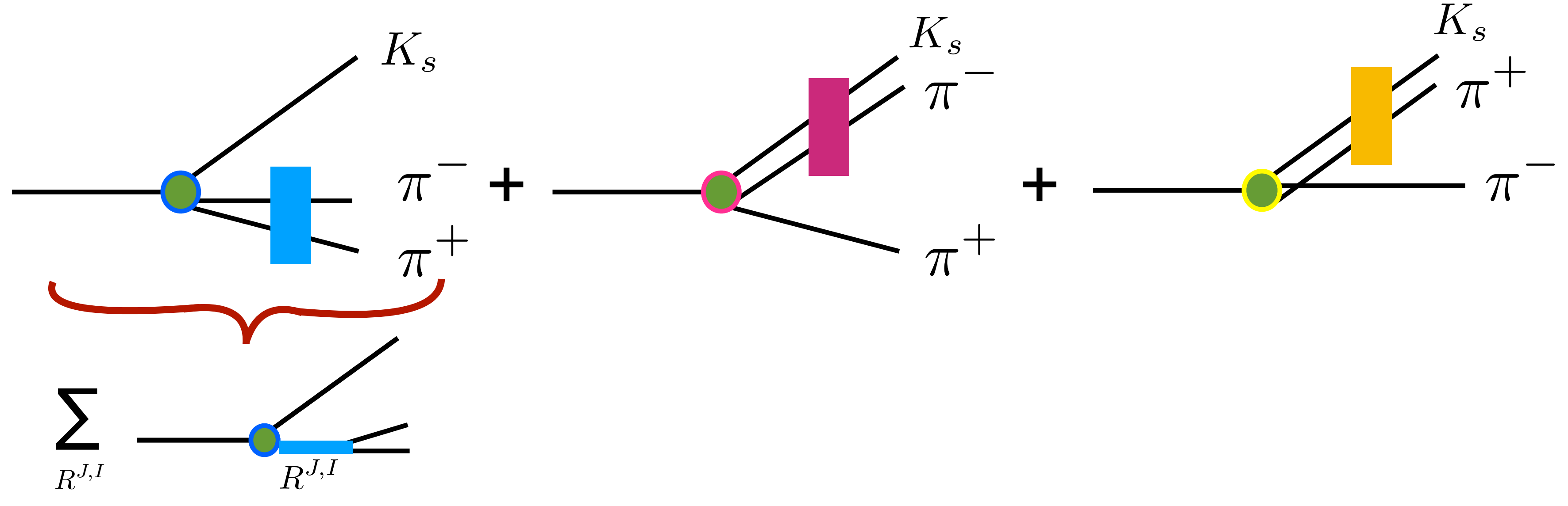
$$\frac{d\Gamma}{ds_{12}ds_{23}} = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|\mathcal{A}(s_{12},s_{23})|^2$$

standard approach

- common cartoon to described 3-body decay

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

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



- Standard isobar model widely used by experimentalists:
  - 3= (2+1) → ignore the interaction with 3rd particle (bachelor)

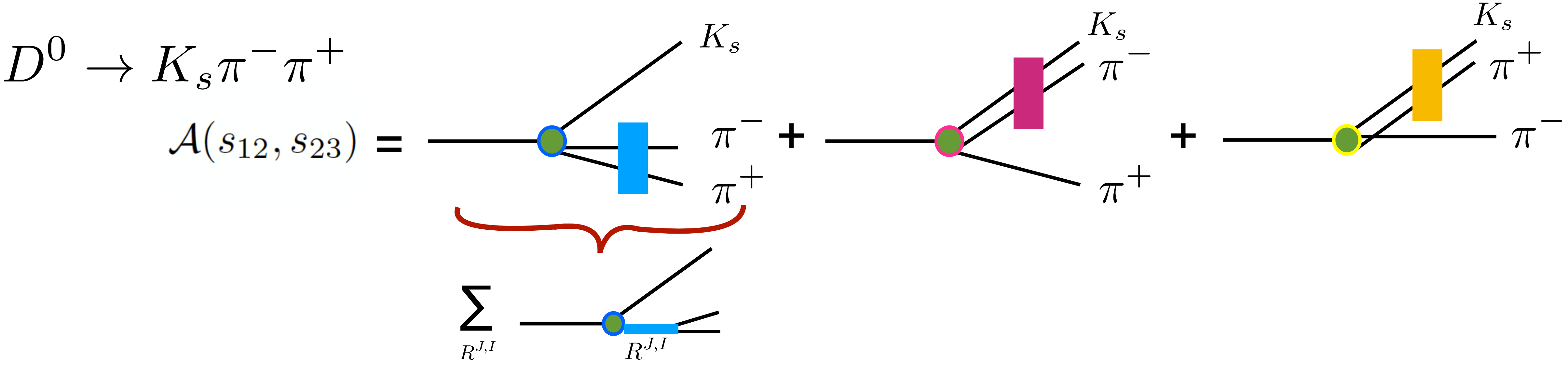
$A = \sum c_k \, A_k$ + NR $\left\{ \begin{array}{l} \text{non-resonant as constant or exponential!} \\ \text{each resonance as Breit-Wigner} \quad \mathrm{BW}(s_{12}) = \dfrac{1}{m_R^2 - s_{12} - i m_R \Gamma(s_{12})}, \end{array} \right.$

- always good to remember why we don't like this approach:
  - sum of BW violates two-body unitarity (2 res in the same channel);
  - do NOT include rescattering and coupled-channels;
  - free parameters are not connected with theory !

!

Two-body resonances signature in DP

- common cartoon to described 3-body decay



- one expect to see all 3 channels res:

→ But in reality…….
not all of them are clearly present

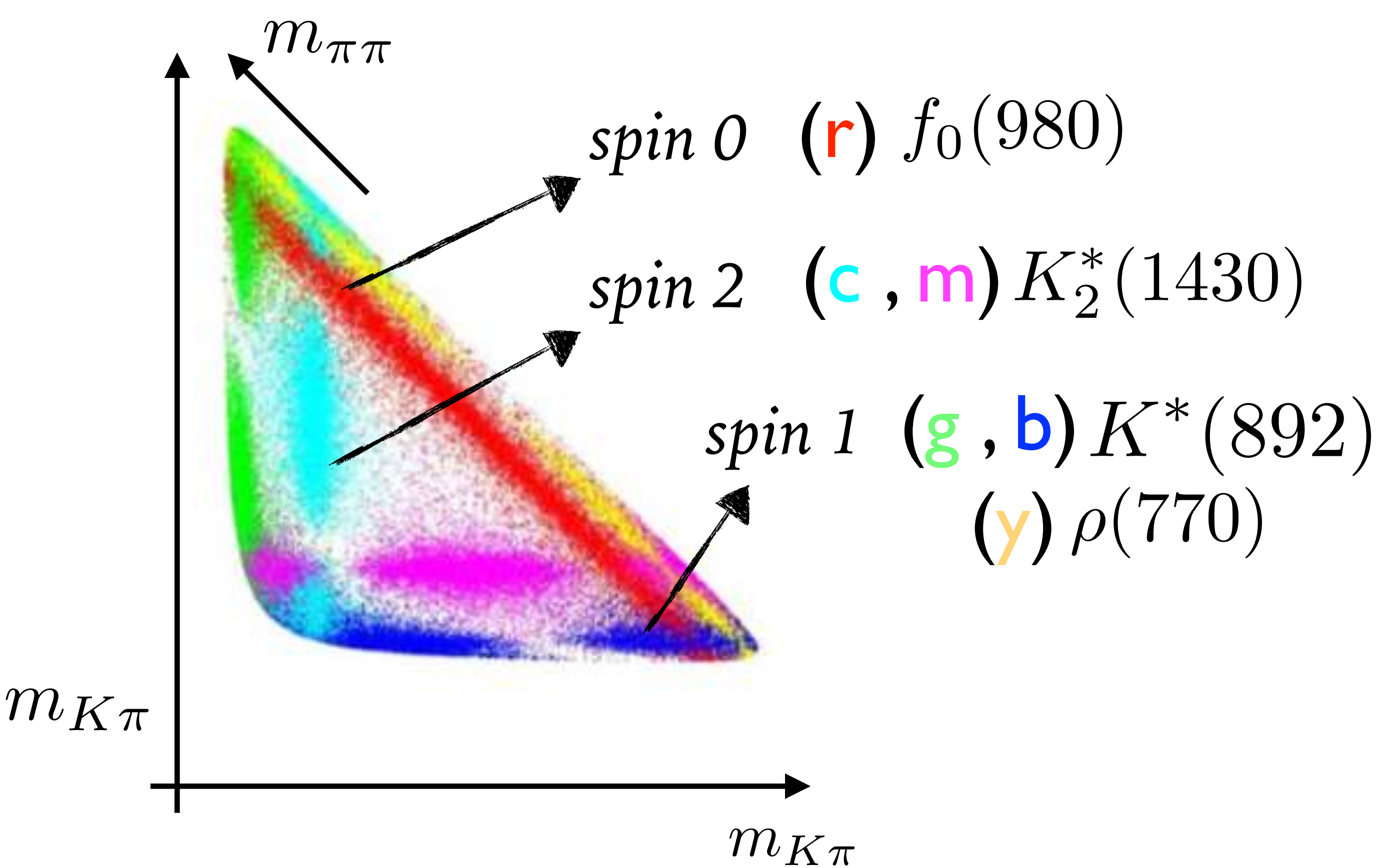
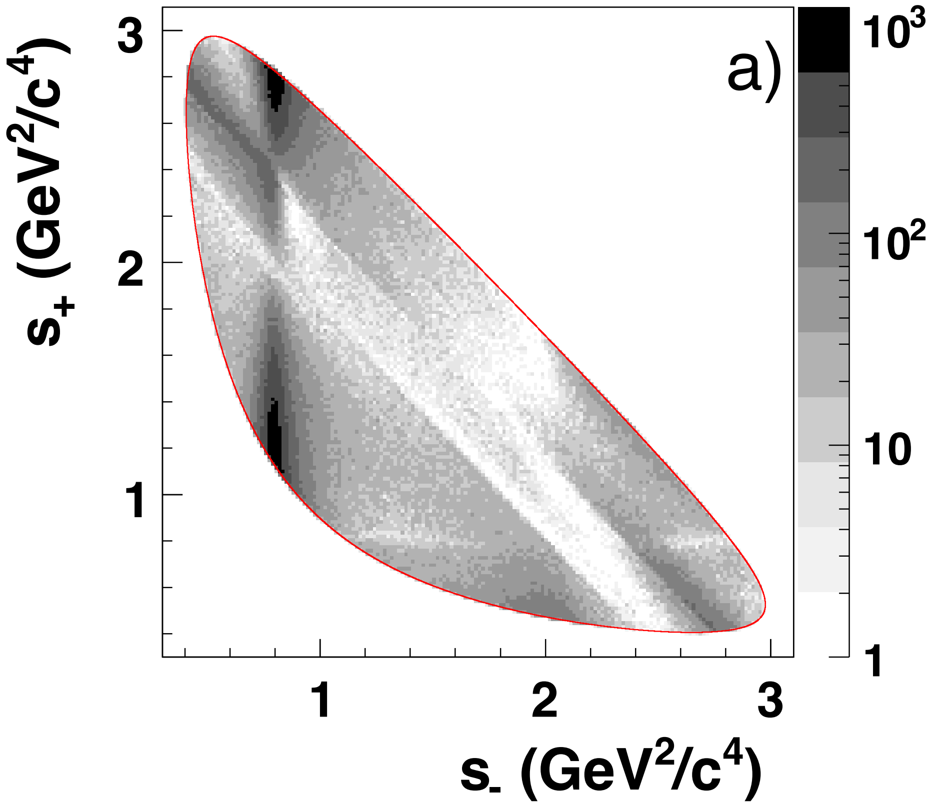


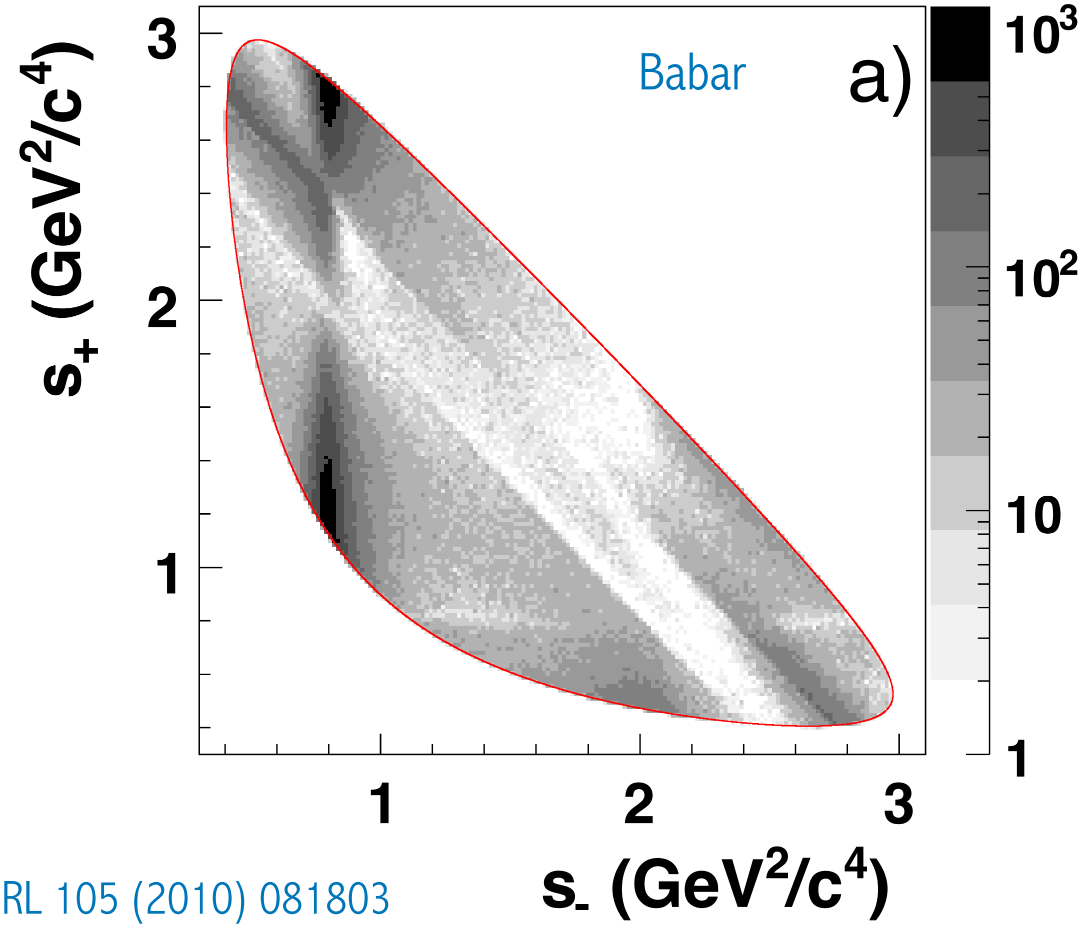
image credit:Tom Latham



BABAR PRL 105 (2010) 081803

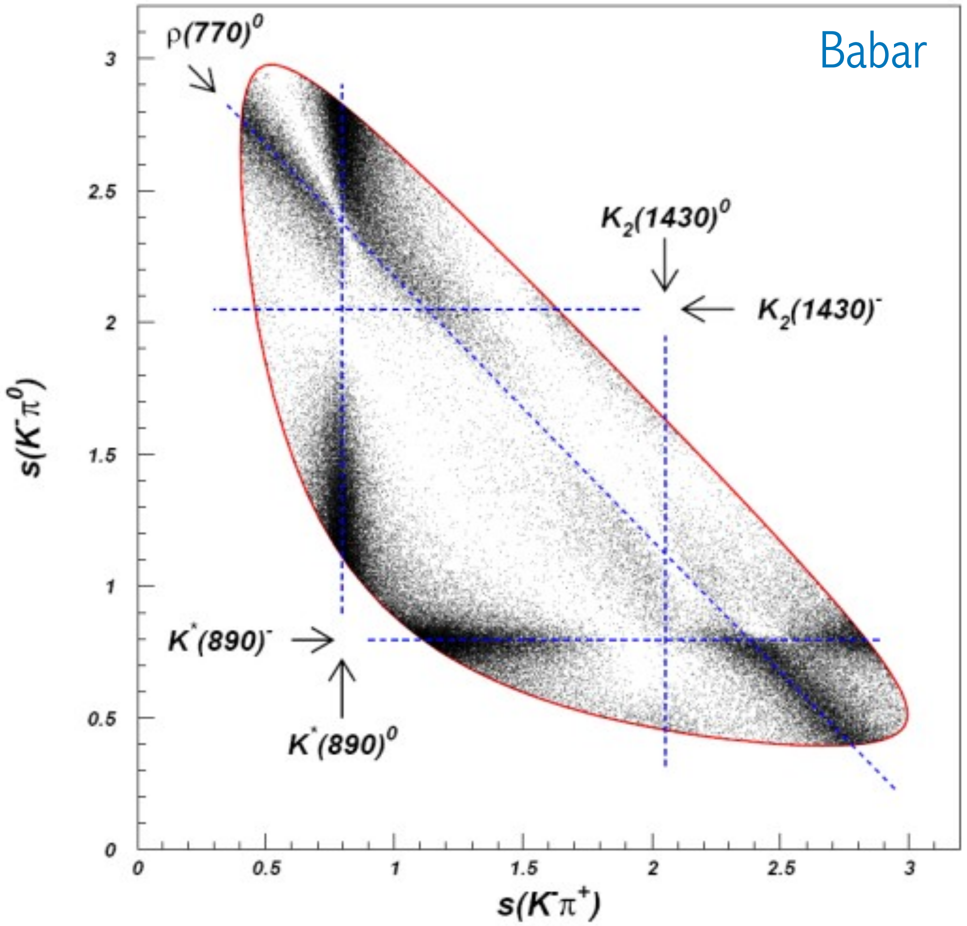
similar final state different signatures

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



PRL 105 (2010) 081803

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



PRL 103 (2009) 103211801

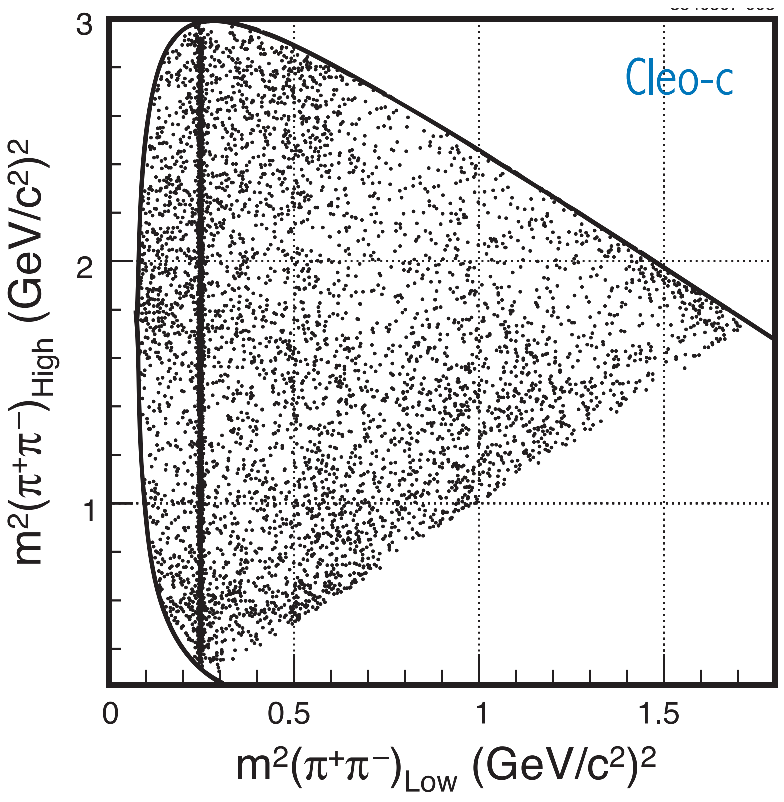
⟶ Similar final state but different interference pattern

↳ different dynamics to be understood

⟶ to disentangle the interference we need amplitude analysis

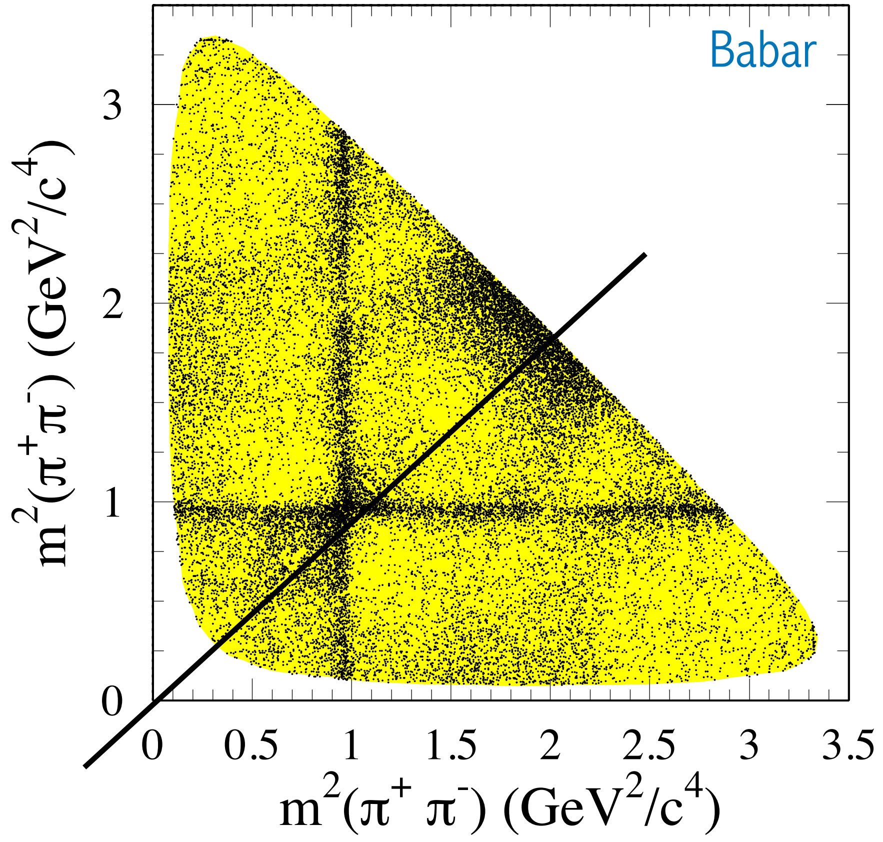
same final state different signatures

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



PRD 76 (2007)012001

- $D_s^+ \to \pi^+\pi^-\pi^+$

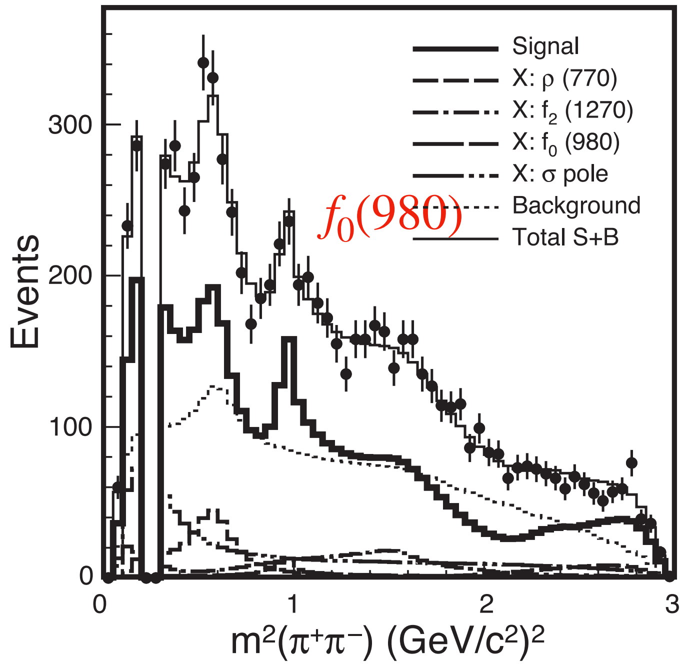


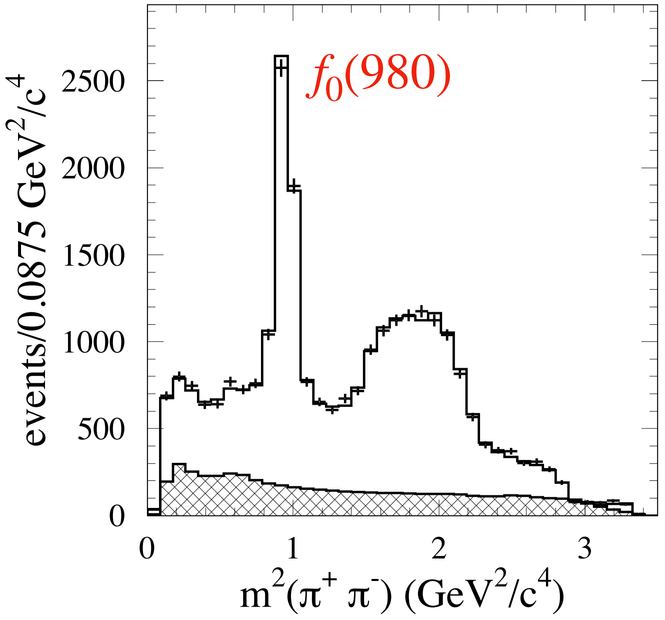
PRD 79 (2009)032003

→ different resonance signature

→ projection highlight that S-wave is very different

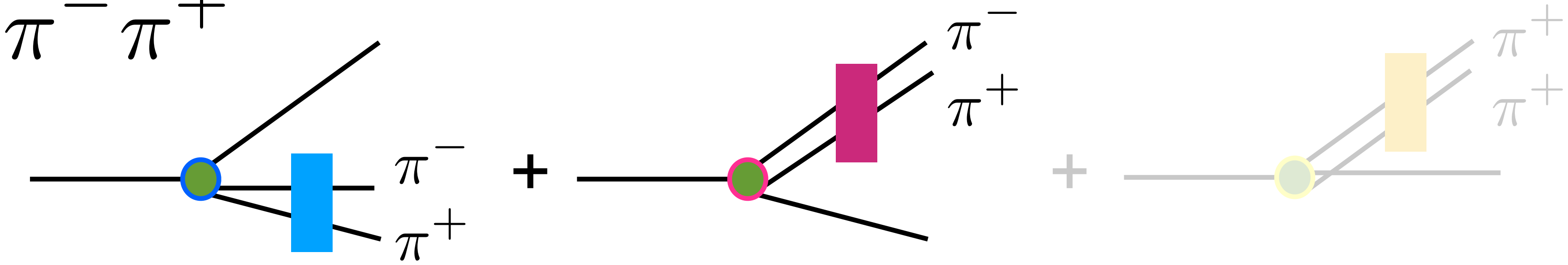
→ production environment matters





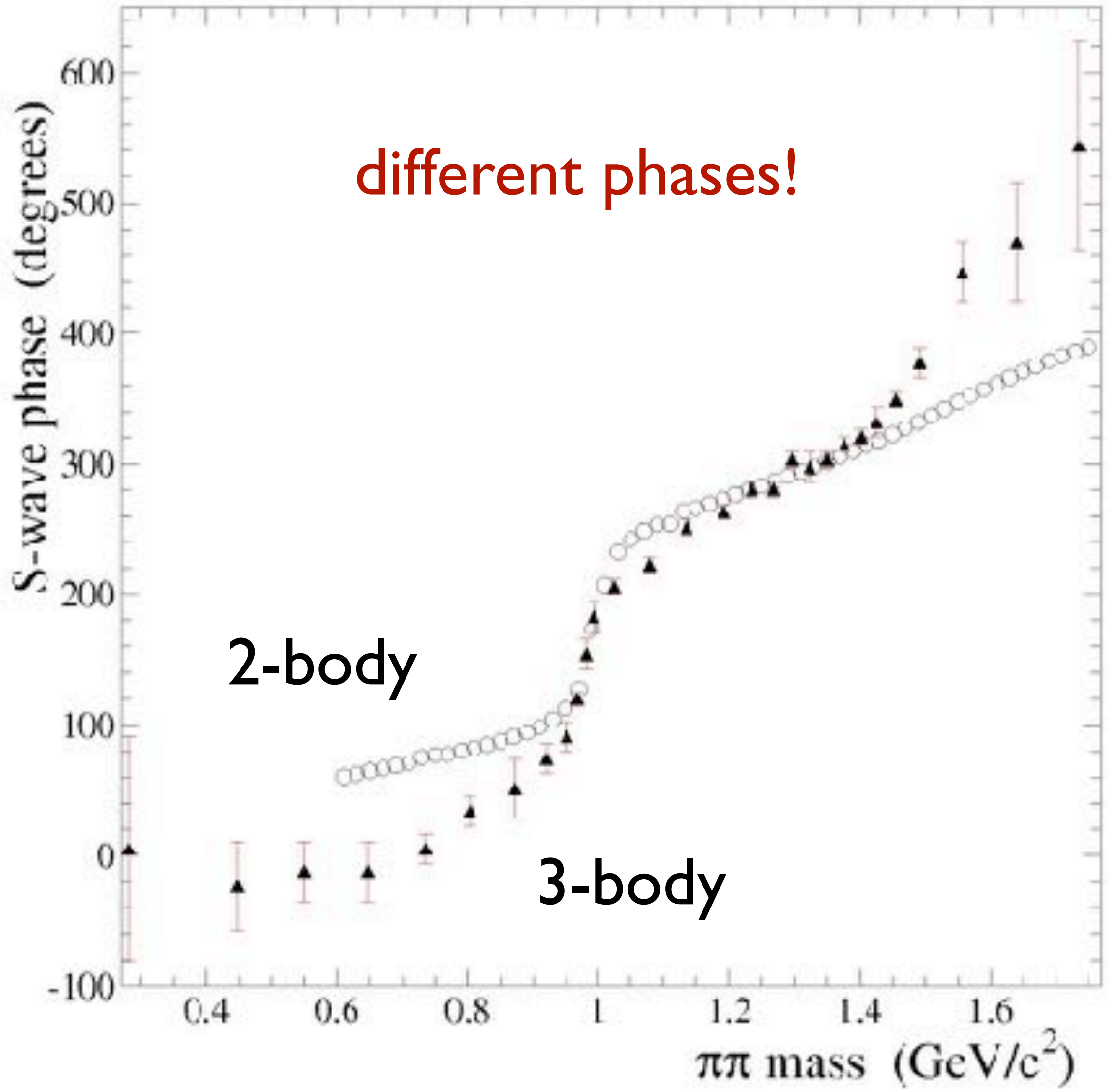
2-body x 3-body phases

- $D_s^+ \to \pi^+\pi^-\pi^+$



  - If this is the "nature" picture → decay phase should be the same as 2-body

    ↳ Watson's Theorem



different phases!

2-body

3-body

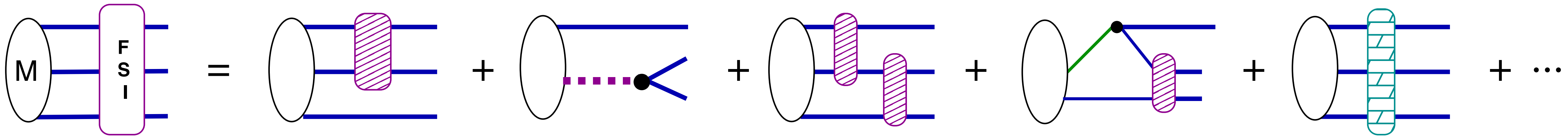
PRD 79 (2009) 032003

- Quantum numbers:
  - 2-body amplitude: spin and isospin well defined!
  - 3-body data: only spin! and $\neq$ dynamics

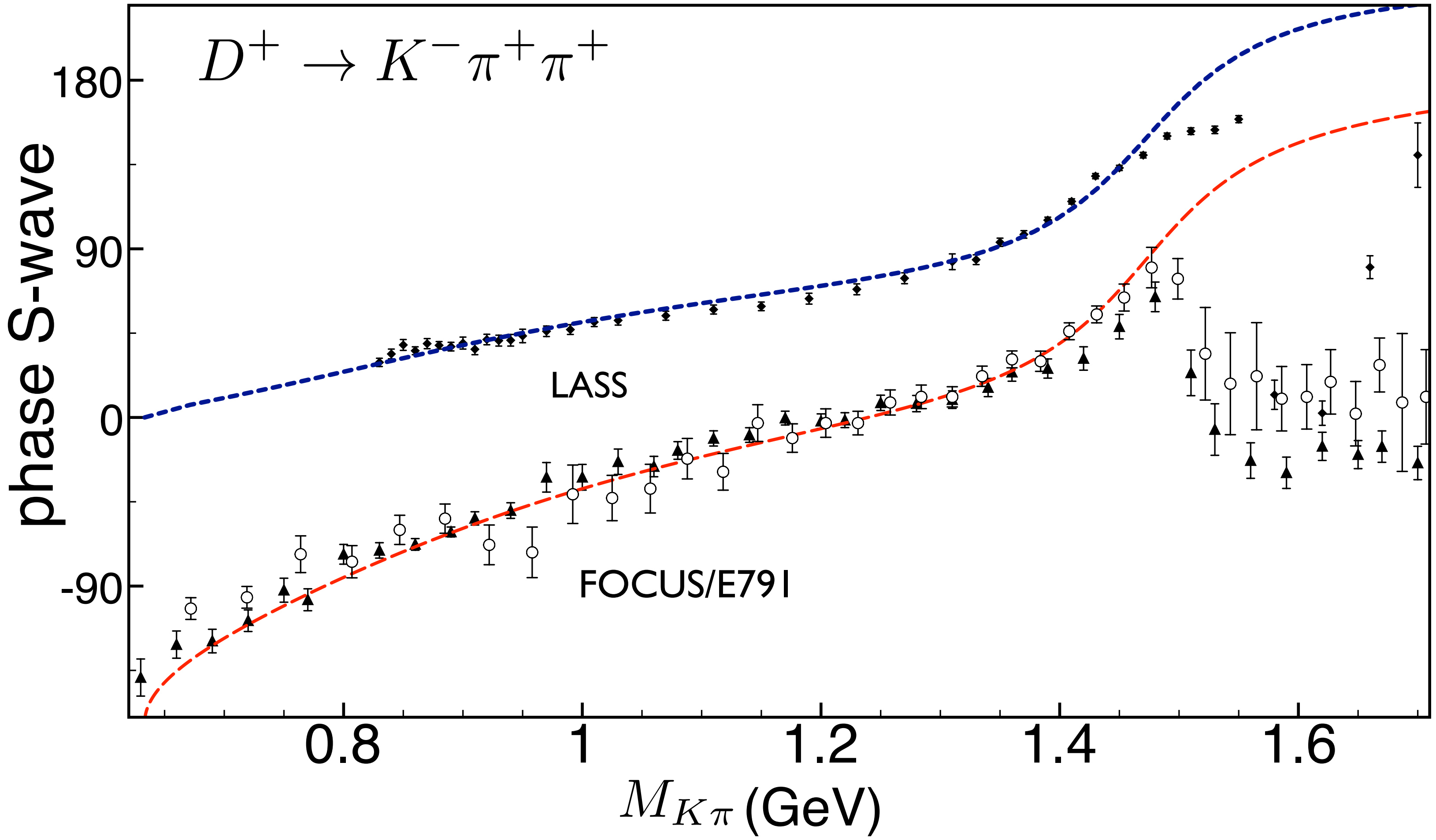
There is more than only 2-body

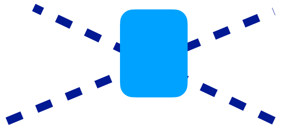
Three-body Models

- Three-body FSI (beyond 2+1)



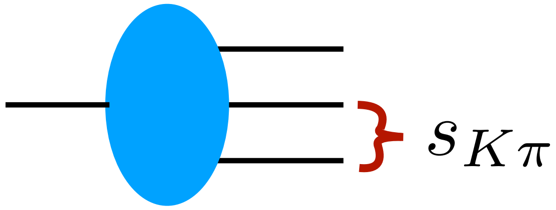
  - shown to be relevant on charm sector





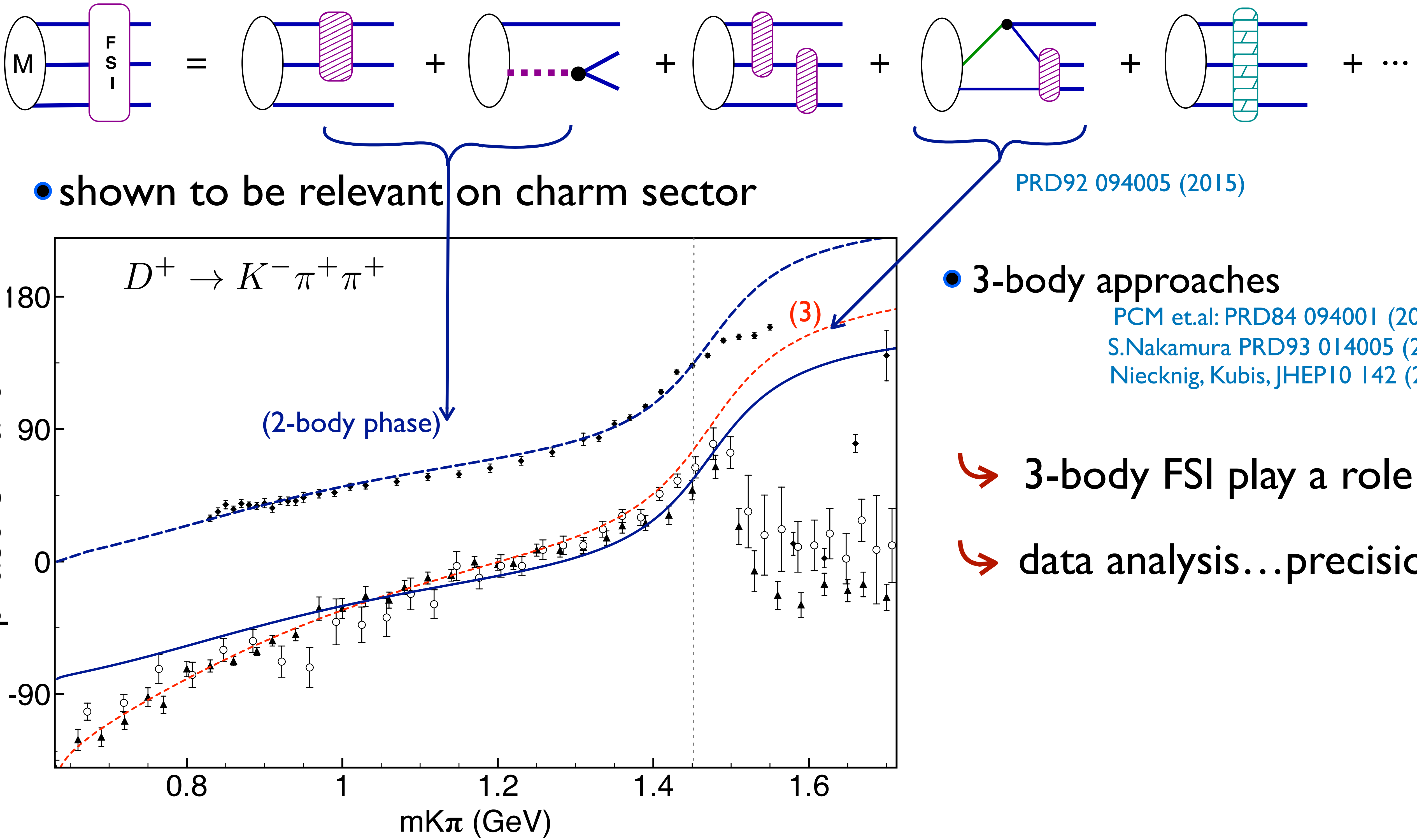
Scattering

Decay projected in one pair mass



Models available

- Three-body FSI (beyond 2+1)



- shown to be relevant on charm sector

PRD92 094005 (2015)

- 3-body approaches

PCM et.al: PRD84 094001 (2011),
S.Nakamura PRD93 014005 (2016)
Niecknig, Kubis, JHEP10 142 (2015)

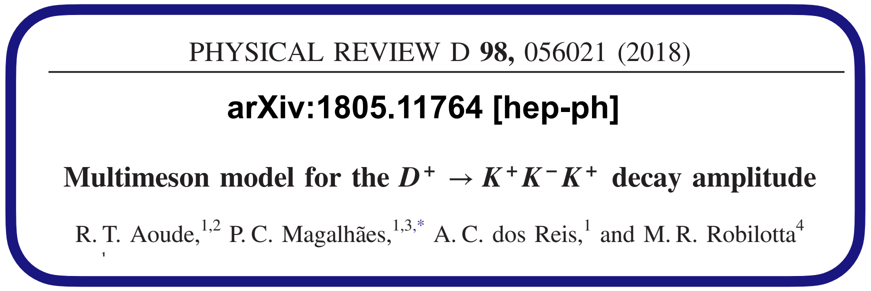
↳ 3-body FSI play a role

↳ data analysis…precision

amplitude analysis @LHCb

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

Theoretical model



PHYSICAL REVIEW D **98,** 056021 (2018)

arXiv:1805.11764 [hep-ph]

Multimeson model for the $D^+ \to K^+K^-K^+$ decay amplitude

R. T. Aoude,[1,2] P. C. Magalhães,[1,3,*] A. C. dos Reis,[1] and M. R. Robilotta[4]

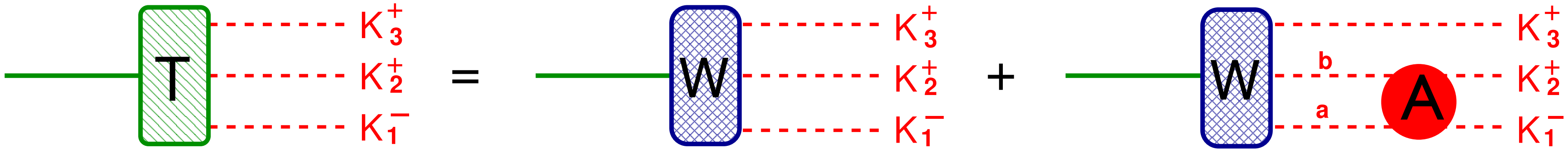
fitted to LHCb data

JHEP 1904 (2019) 063

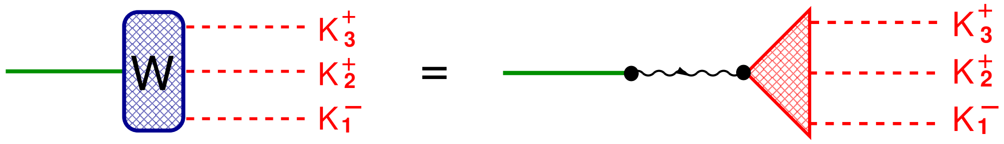
KK scattering amplitude

multi meson model - $D^+ \to K^- K^+ K^+$

Triple-M



- hypothesis that annihilation is dominant

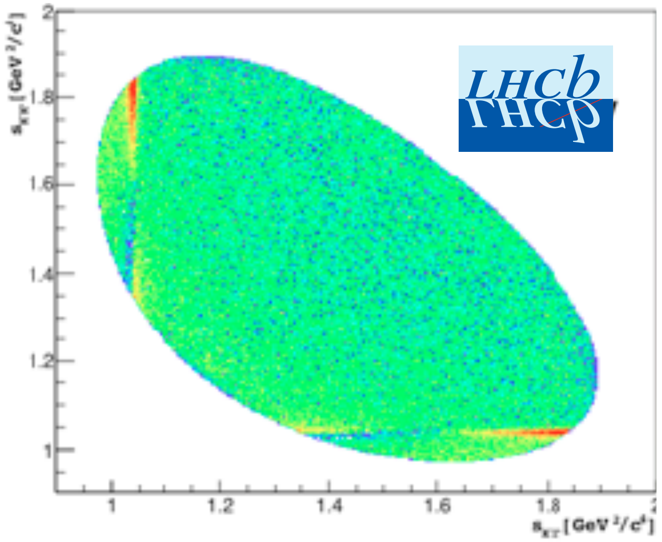


- depart from a fundamental theory → ChPT Lagrangian
  - track the ingredients we include in our model!
  - $A_{ab}^{JI} \longrightarrow$ unitary scattering amplitude for $ab \to K^+ K^-$

- fit the model to LHCb data

  run I (8 TeV CM) $2fb^{-1}$

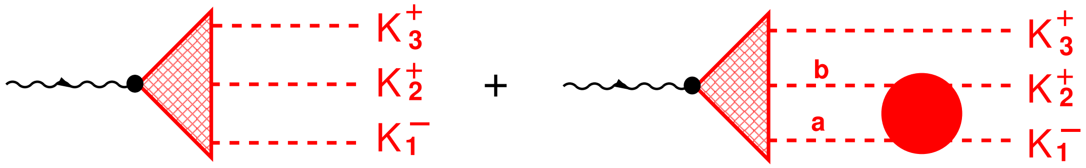
  JHEP 1904 (2019) 063

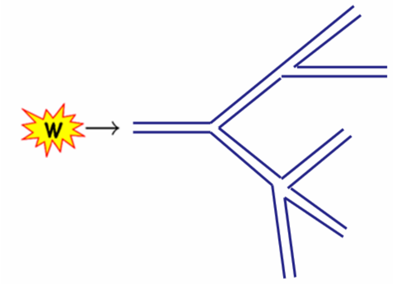


→ predict KK scattering amplitude

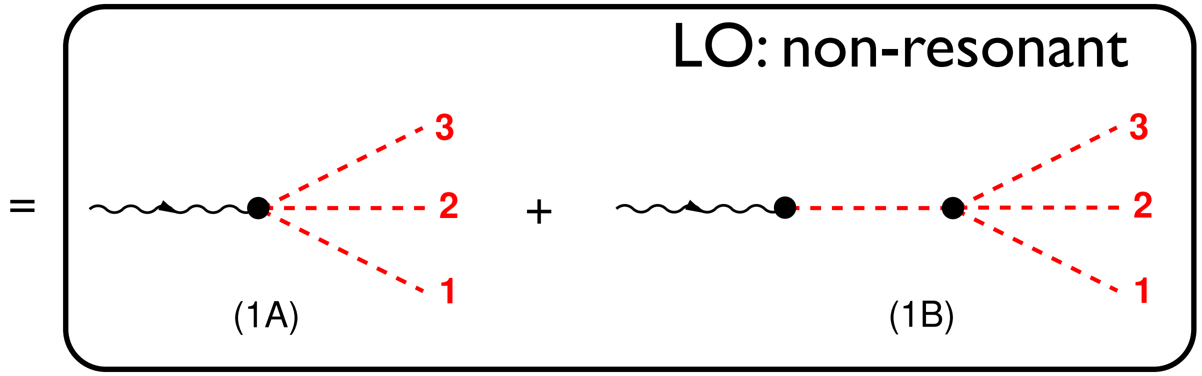
→ parameters have physical meaning: resonance masses and coupling constants

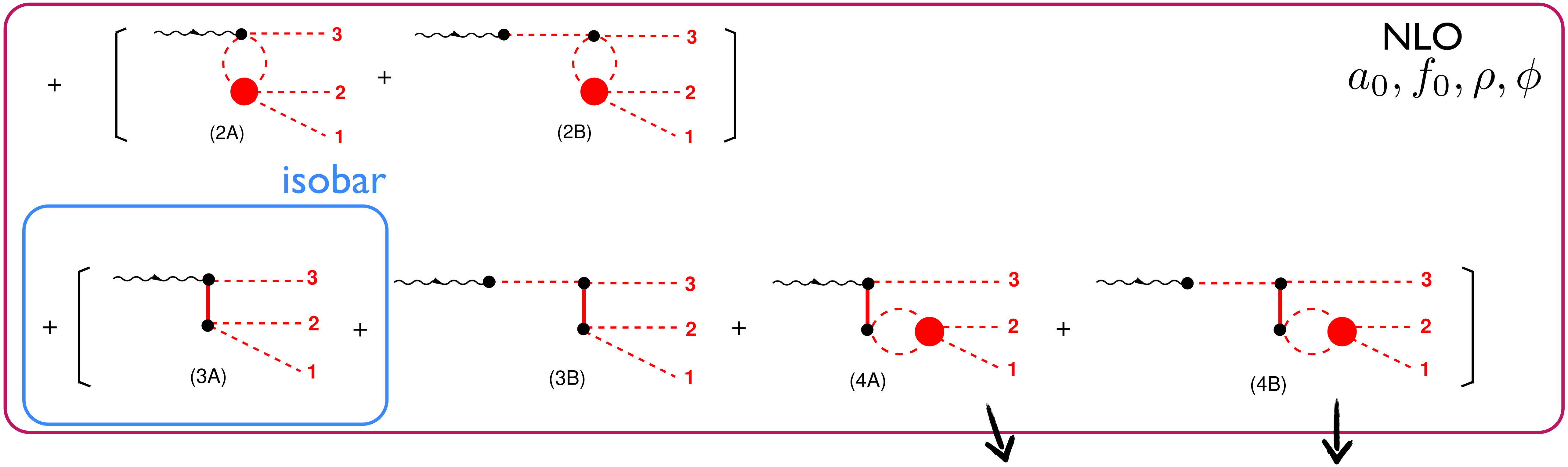
Triple - M



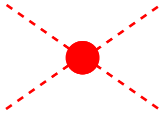


Chiral symmetry





width obtained through dynamics



$K\bar{K}$ coupled-channel unitary amplitude

$\pi\pi,\ \eta\eta,\ \pi\eta,\ \rho\pi$

- isospin decomposition $[J, I = (0,1), (0,1)]$

$$\langle K^- K^+| = (i/2)\,\langle V_3^{KK} + V_8^{KK}| - (1/2)\,\langle U_3^{KK} + S^{KK}|$$

Triple M   LHCb fit

- Theoretical sound model

$$T^S = T^S_{NR} + T^{00} + T^{01}$$

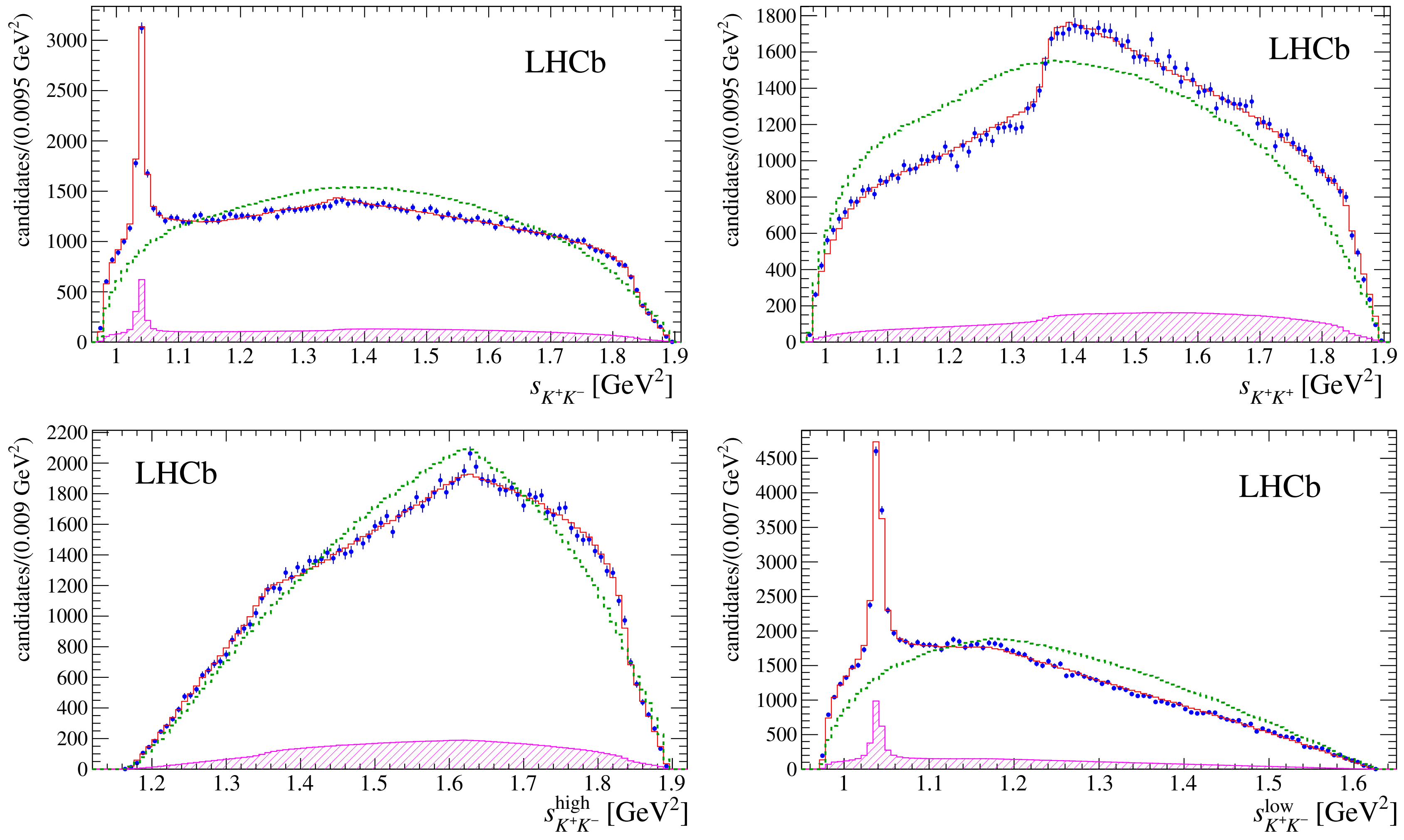
$$T^P = T^P_{NR} + T^{11} + T^{10}$$

- free parameters

parameter	value
F	$94.3^{+2.8}_{-1.7} \pm 1.5\,\mathrm{MeV}$
m_{a_0}	$947.7^{+5.5}_{-5.0} \pm 6.6\,\mathrm{MeV}$
m_{S_o}	$992.0^{+8.5}_{-7.5} \pm 8.6\,\mathrm{MeV}$
m_{S_1}	$1330.2^{+5.9}_{-6.5} \pm 5.1\,\mathrm{MeV}$
m_ϕ	$1019.54^{+0.10}_{-0.10} \pm 0.51\,\mathrm{MeV}$
G_ϕ	$0.464^{+0.013}_{-0.009} \pm 0.007$
c_d	$-78.9^{+4.2}_{-2.7} \pm 1.9\,\mathrm{MeV}$
c_m	$106.0^{+7.7}_{-4.6} \pm 3.3\,\mathrm{MeV}$
$\tilde{c}_d$	$-6.15^{+0.55}_{-0.54} \pm 0.19\,\mathrm{MeV}$
$\tilde{c}_m$	$-10.8^{+2.0}_{-1.5} \pm 0.4\,\mathrm{MeV}$

$\mathrm{FF_{NR}}$	FF^{00}	FF^{01}	FF^{10}	FF^{11}	$\mathrm{FF_{S-wave}}$
14 ± 1	29 ± 1	131 ± 2	7.1 ± 0.9	0.26 ± 0.01	94 ± 1

χ^2/ndof = 1.12 (Isobar 1.14-1.6)



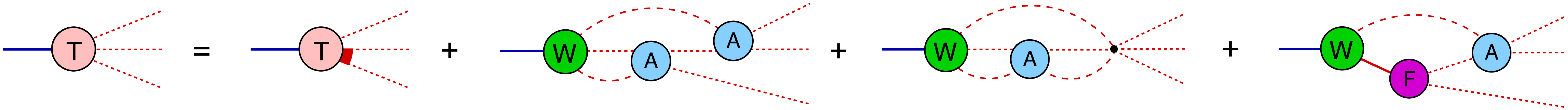
JHEP 1904 (2019) 063

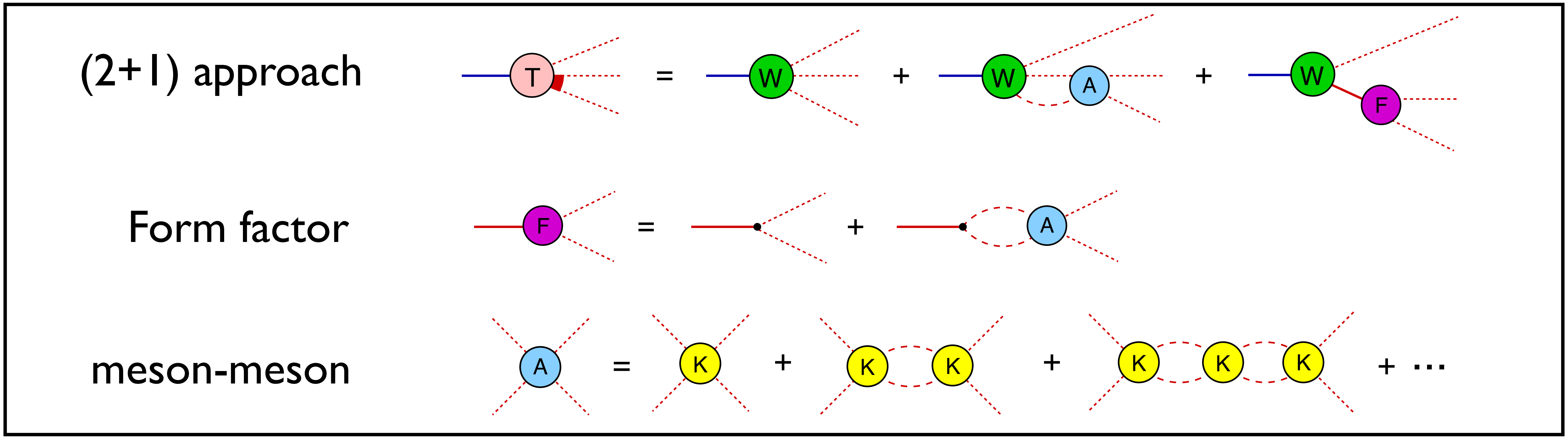
→ good fit with fewer parameters than the isobar

Tool kit for meson-meson interactions in 3-body decay

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

- Any 3-body decay amplitude

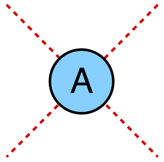




(2+1) approach

Form factor

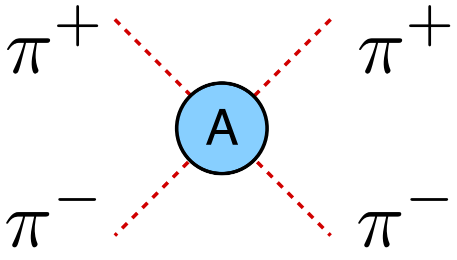
meson-meson

↳ provide the building block  in SU(3)

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

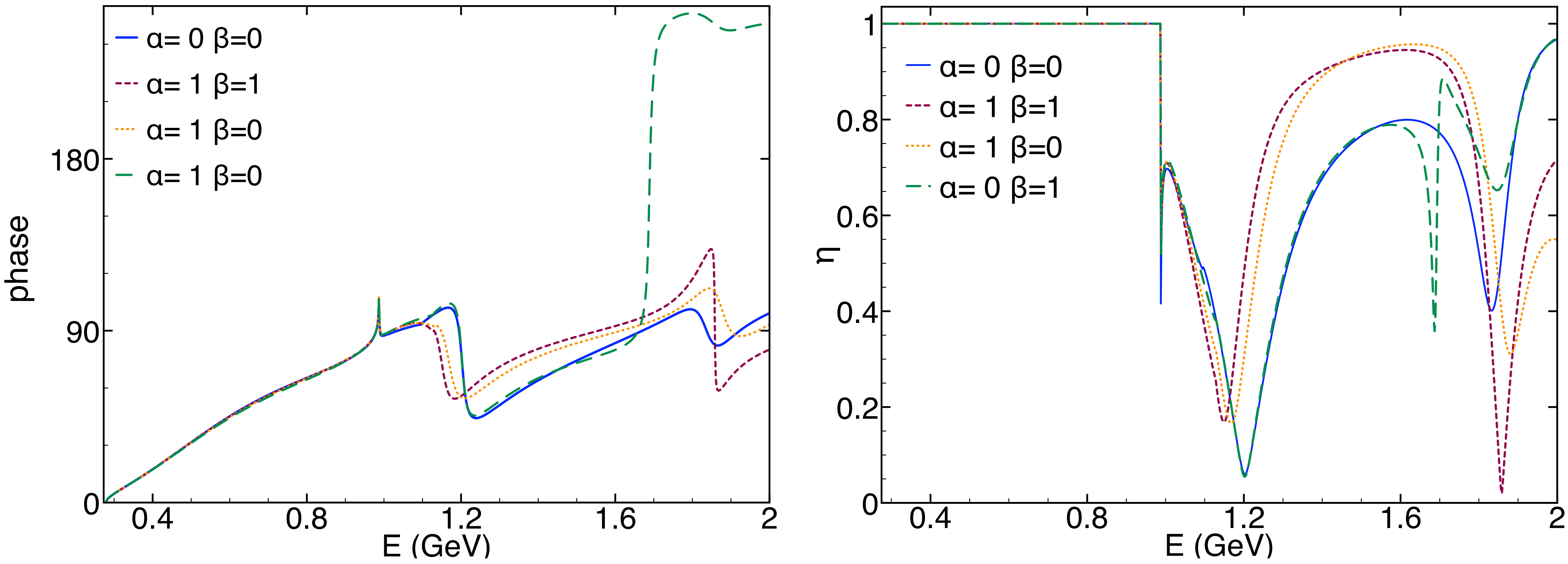
⟶ Available to be implement in data analysis!!

ex: ππ amplitude



- coupled-channels: $\pi\pi$, KK and $\eta\eta$
  - 3 resonances: mx=0.98, my=1.37, mz=1.7 GeV

    ↳ α and β are couplings from mz



→ extra res do not disturb the low-energy!

→ parameter should be fixed by data

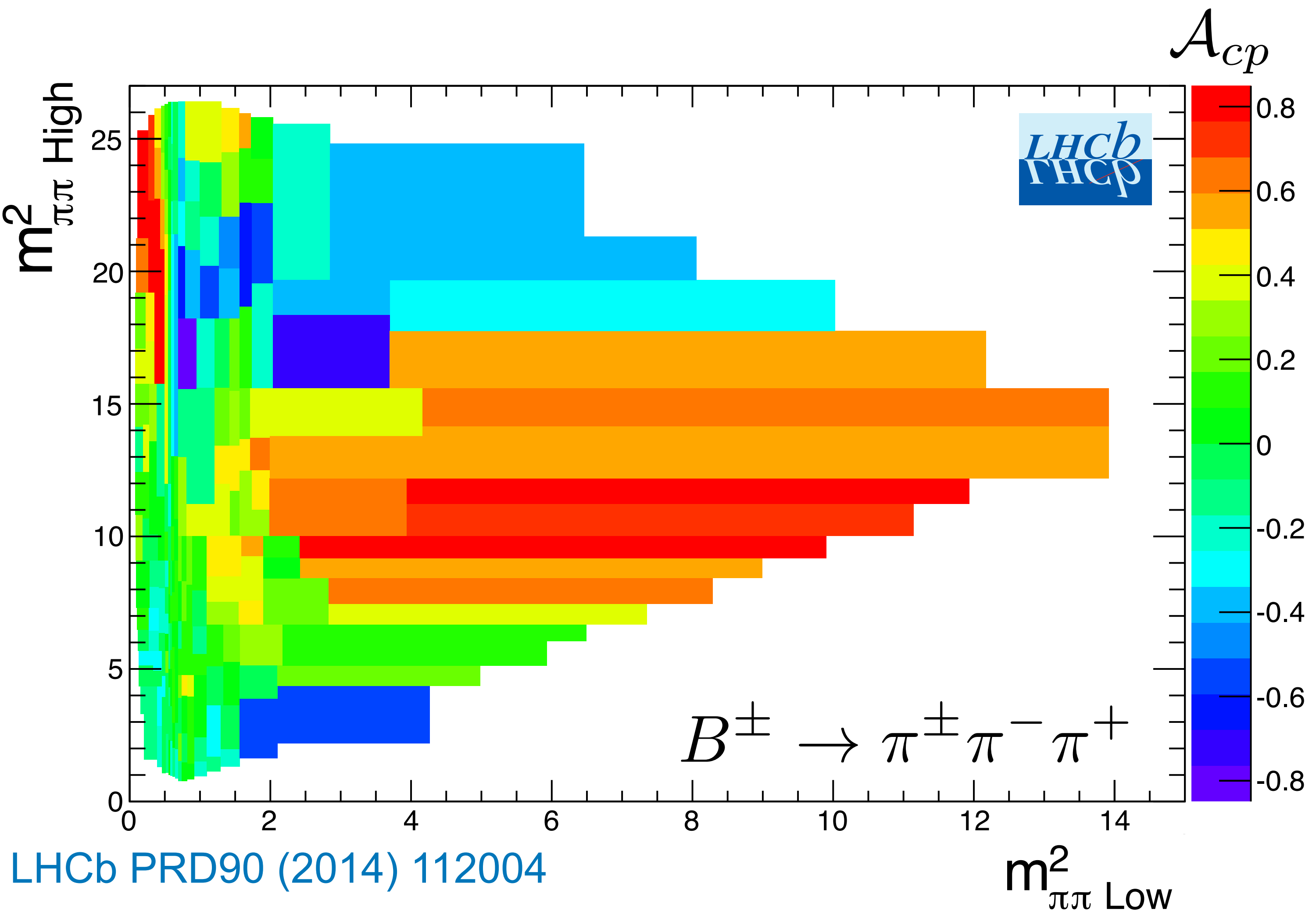
→ will apply this methodology in other $D \to hhh$

CP violation in charm

Dalitz plot analysis

What we learn from CPV in B decays?

- CP-Violation directly from Dalitz plot



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

$$\boxed{\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f}) \ = -4A_1A_2 \sin(\delta_1 - \delta_2)\,\sin(\phi_1 - \phi_2)}$$

- hadronic Final State Interactions are important sources to generate CPV

- to disentangle CPV mechanisms in data we need amplitude analysis!
  - recent LHCb work on $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ PRD101 (2020) 012006; PRL 124 (2020) 031801

↳ CPV on $f_2(1270)$ and rescattering $\pi\pi \to KK$ in S-wave

CPV in $D \to hhh$

- New results on CPV on charm can hint for new searches procedures

↳ $A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$ PRL 122 (2019) 211803

↳ run I + run II

- we expect to see CPV in $D \to hhh$: similar weak vertices are present !

- To extract CPV from Dalitz plot (as in B decay) we need:

I - model independent procedure to show localized CP asymmetry

↳ Mirandizing

2 - Amplitude analysis with a theoretical sound model to describe FSI properly

- on going in LHCb for $D_{(s)} \to \pi\pi\pi$

Final remarks

- A consistent treatment of FSI is crucial to reach precision in $D \rightarrow hhh$ ANA

  → two-body coupled-channels description in mandatory

  → learn much more about the underling dynamics

  → relevant for CPV search

- New LHCb $D^+ \rightarrow h^+h^-h^+$ amplitude analysis are expected soon (SCS, CF)

  ↳ huge data samples claim accurate models

- $D^+ \rightarrow KKK$: exemple of theory/experimental join work

  → tool kit for amplitude analysis with theoretically sound models

obrigada!!

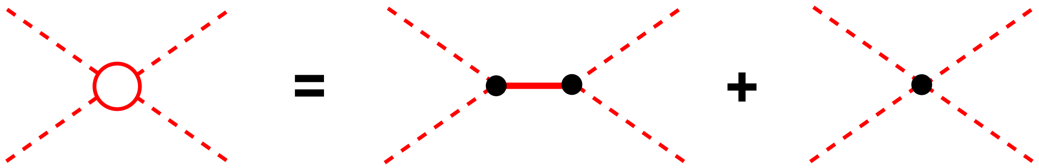
#staysafe

p.magalhaes@cern.ch

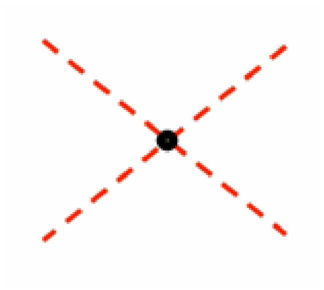
Backup slides !

meson-meson interactions at low E

- solid theory to describe MM interactions at low energy == ChPT



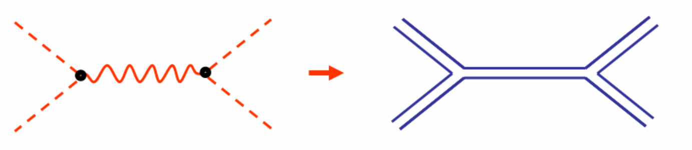
- LO:



$$\mathcal{L}_M^{(2)} = -\frac{1}{6F^2} f_{ijs}\, f_{kls}\, \phi_i\, \partial_\mu \phi_j\, \phi_k\, \partial^\mu \phi_l + \frac{B}{24F^2}\left[\sigma_0\left(\frac{4}{3}\delta_{ij}\,\delta_{kl} + 2\, d_{ijs}\, d_{kls}\right) + \sigma_8\left(\frac{4}{3}\delta_{ij}\, d_{kl8} + \frac{4}{3} d_{ij8}\,\delta_{kl} + 2\, d_{ijm}\, d_{kln}\, d_{8mn}\right)\right]\phi_i\,\phi_j\,\phi_k\,\phi_l$$

Gasser & Leutwyler
[Nucl. Phys. B250(1985)]

- NLO: include resonances as a field



Ecker, Gasser, Pich and De Rafael
[Nucl. Phys. B321(1989)]

scalars

$$\mathcal{L}_S^{(2)} = \frac{2\,\tilde{c}_d}{F^2} R_0\, \partial_\mu \phi_i\, \partial^\mu \phi_i - \frac{4\,\tilde{c}_m}{F^2} B\; R_0\,(\sigma_0\,\delta_{ij} + \sigma_8\, d_{8ij})\;\phi_i\,\phi_j$$
$$+ \frac{2\,c_d}{\sqrt{2}F^2} d_{ijk}\; R_k\, \partial_\mu \phi_i\, \partial^\mu \phi_i - \frac{4Bc_m}{\sqrt{2}F^2}\left[\sigma_0\, d_{ijk} + \sigma_8\left(\frac{2}{3}\delta_{ik}\,\delta_{j8} + d_{i8s}\, d_{jsk}\right)\right]\;\phi_i\,\phi_j R_k$$

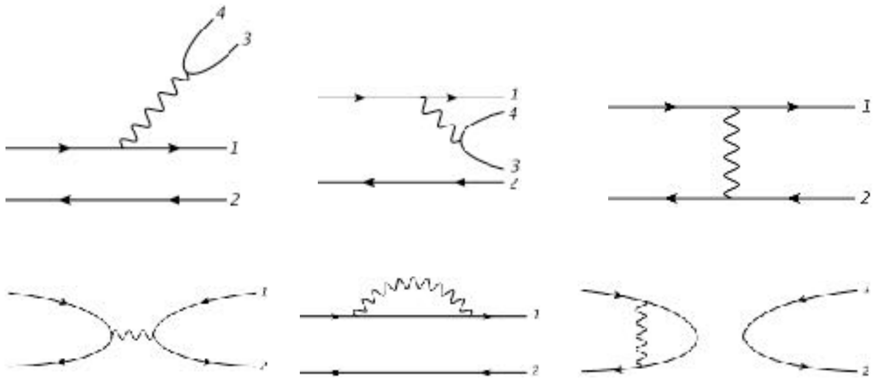
vectors

$$\mathcal{L}_V^{(2)} = \frac{iG_V}{\sqrt{2}}\langle V_{\mu\nu} u^\mu u^\nu\rangle$$
$$\langle V_{\mu\nu} u^\mu u^\nu\rangle = \frac{1}{F^2} V_a^{\mu\nu}\, \partial_\mu \phi_i\; \partial_\nu \phi_j\; (if_{aij} + d_{aij})$$

⟶ because we want to extend this to high E the parameters change meaning and can be free to fit!

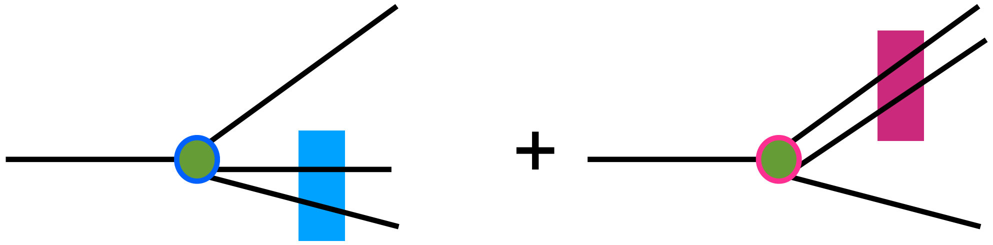
QCDF

- QCD factorization approach → factorize the quark currents



Chau [Phys. Rep. 95,1(1983)]

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



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

→ ex: $B^+ \to \pi^+\pi^-\pi^+$

how to describe it?

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

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

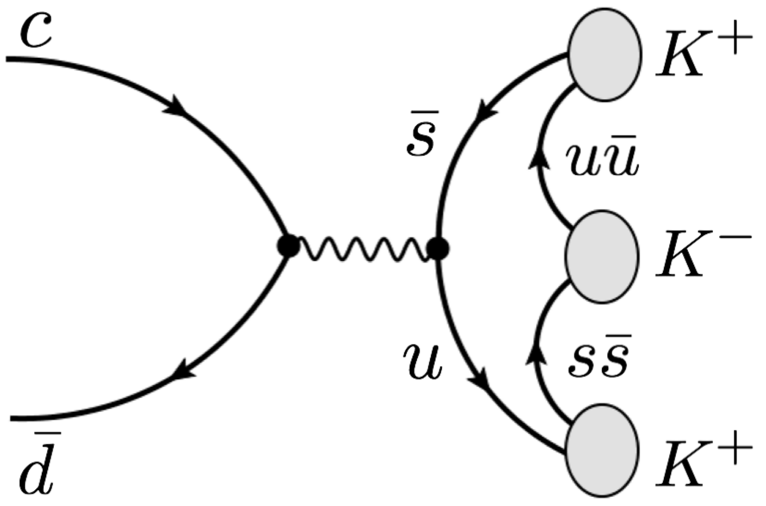
↳ parametrizations for B and D→3h   Boito et al. PRD96 113003 (2017)

- modern QDC factorization: improvement to include "long distance"

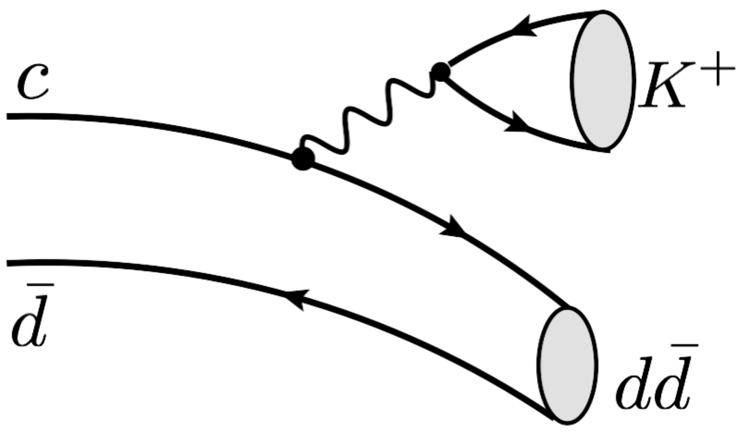
Klein, Mannel, Virto, Keri Vos JHEP10 117 (2017)

annihilation hypothesis

- annihilation

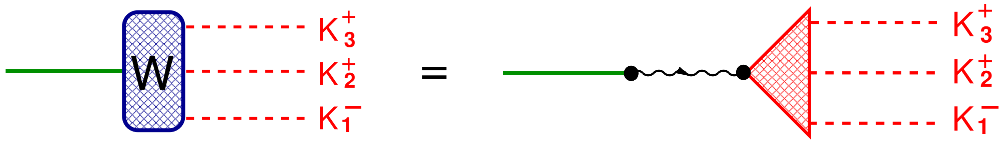


- color allowed



↪ need a rescattering!

- both are doubly Cabibbo-suppressed
- hypotheses that annihilation is dominant



- separate the different energy scales:

$$\mathcal{T} = \langle (KKK)^+|T|D^+\rangle = \underbrace{\langle (KKK)^+|A_\mu|0\rangle}_{\text{ChPT}} \; \langle 0|A^\mu|D^+\rangle .$$

↪ $-i\,G_F\,\sin^2\theta_C\,F_D\,P^\mu$

⟶ know how to calculate everything

rescattering as a CPV mechanism

- CPT must be preserved

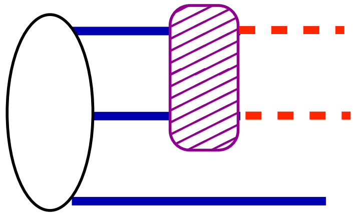
Lifetime $\tau = 1 / \Gamma_{total} = 1 / \overline{\Gamma}_{total}$

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

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

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

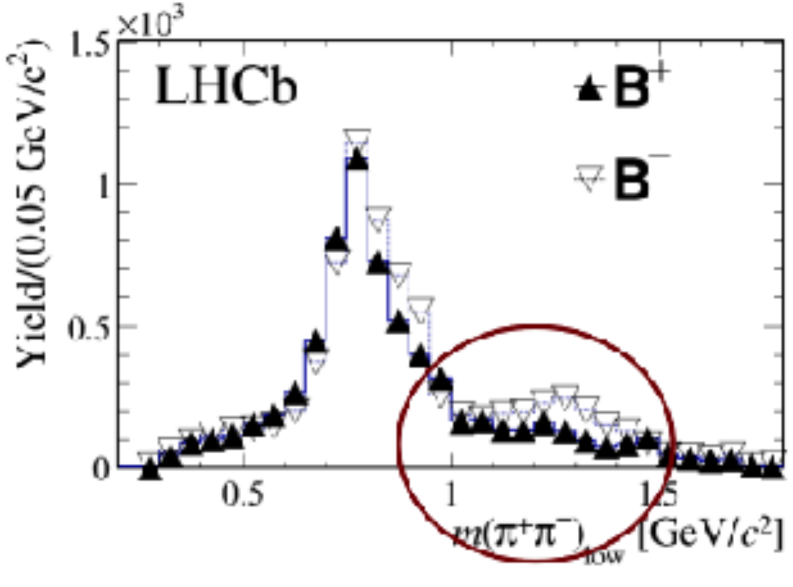
- rescattering $\boxed{\pi\pi \to KK}$



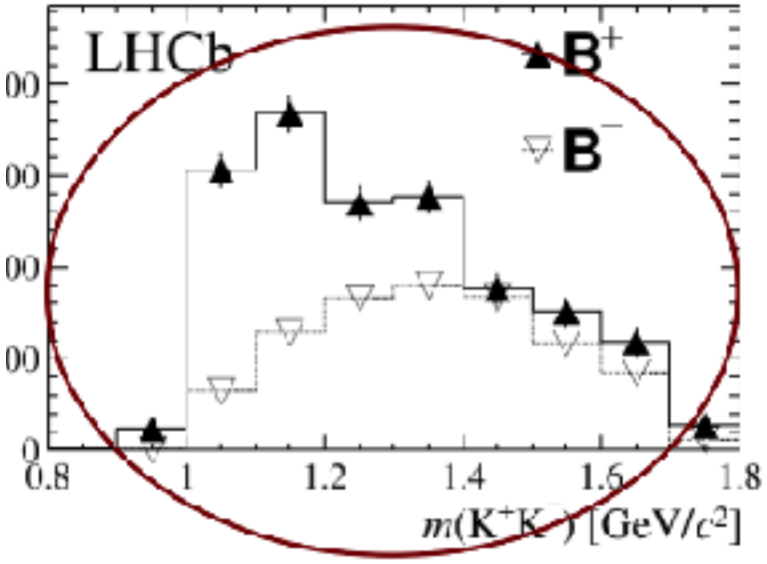
↳ explain CPV at [1 -1.6] GeV

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

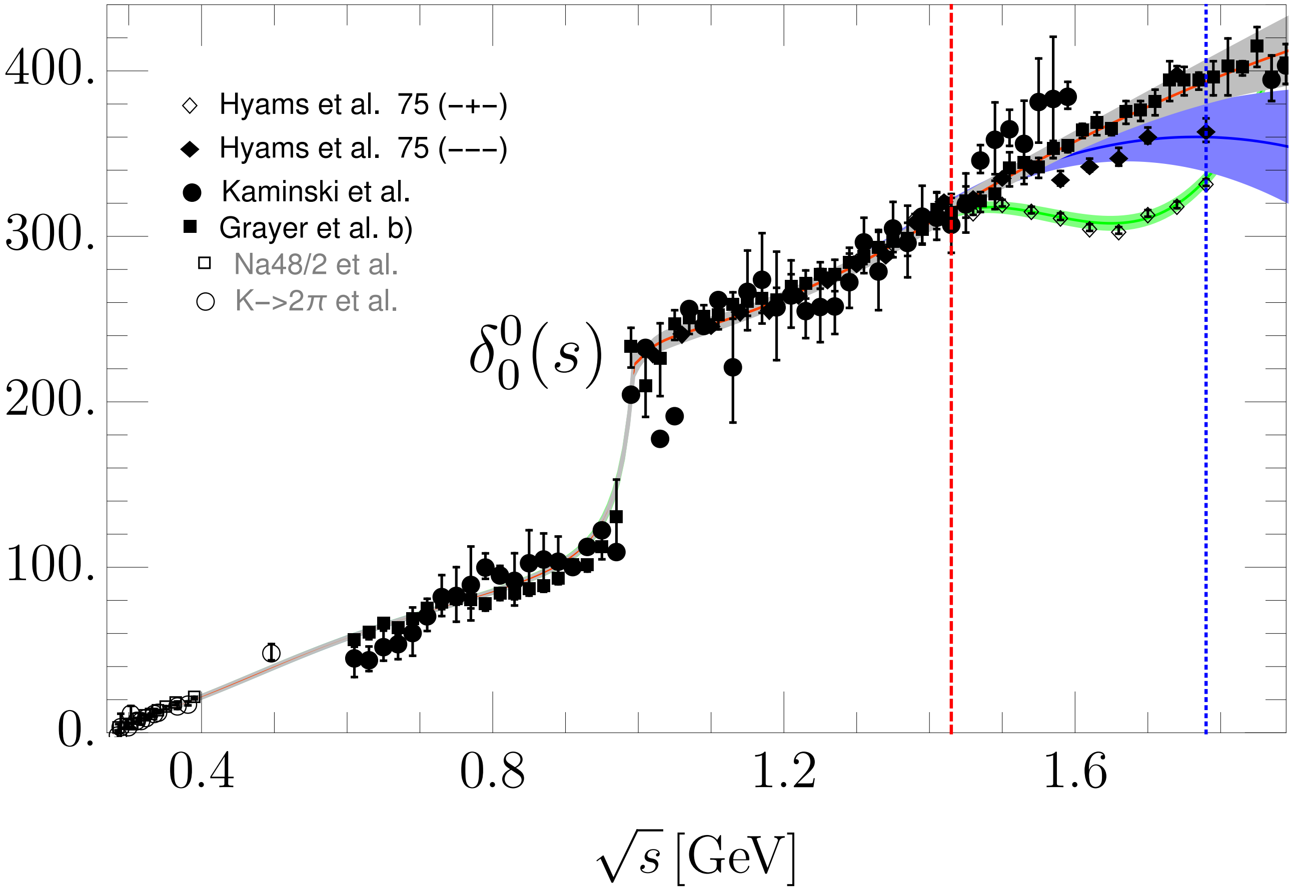
PRD101 (2020) 012006; PRL 124 (2020) 031801 PRL 123 (2019) 231802

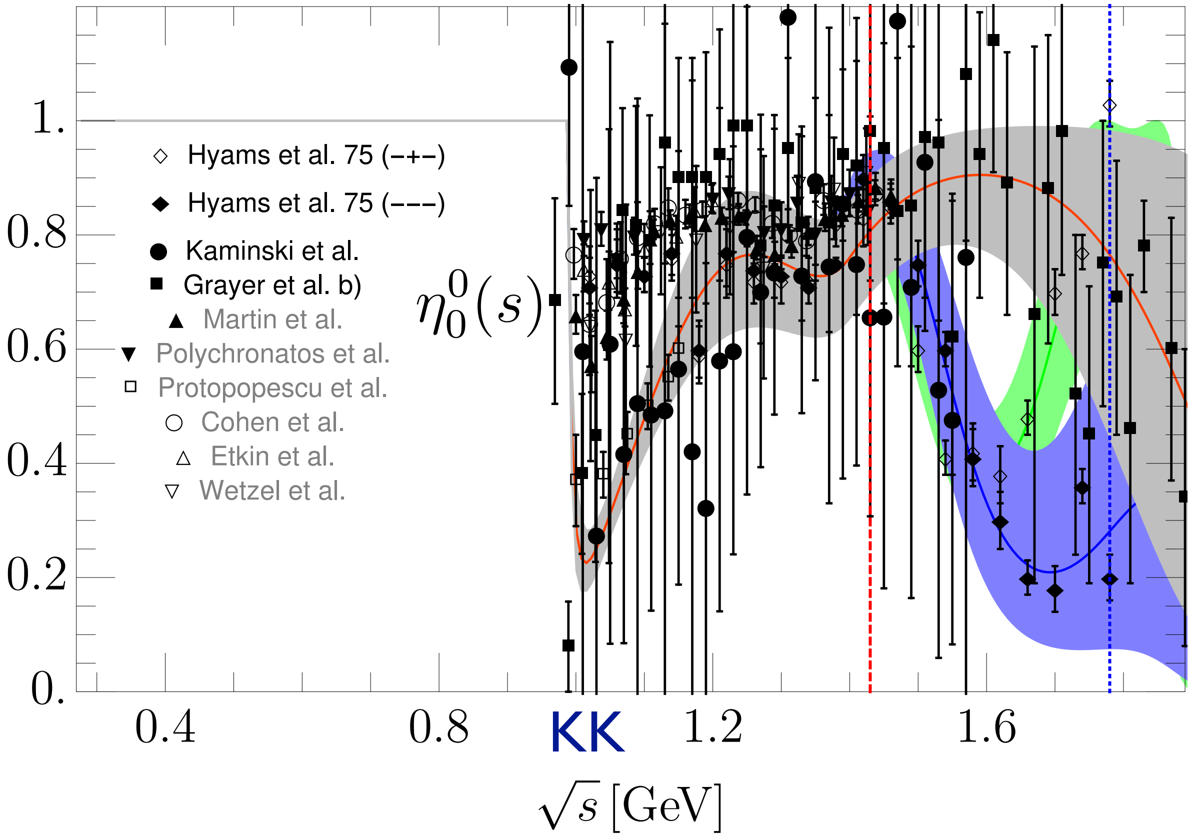
ππ parametrisation

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

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

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





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

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