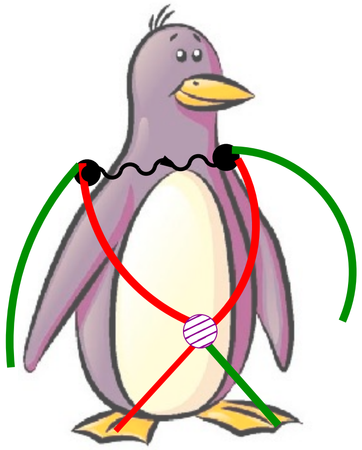
FSI in hadronic B decay



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Technical University of Munich - TUM

workshop on Multibody, hadronic, charmless B-hadron decays - Paris 6,7 June 2018

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discussion topics

- 3-body "pure light hadronic" heavy meson decay
    - dynamics, issues,…

- Importance of the FSI in low and high mass

- How to use informations from D meson decay?

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

- How to improve the B amplitude analysis ?

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

- what's next?

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- D and B three-body HADRONIC decays are dominated by resonances
  - spectroscopy
  - information of MM interactions ⟶ no $K\bar{K}$ data available
  - study of CP-Violation (strong phase needed) ⟶ can lead to new physics

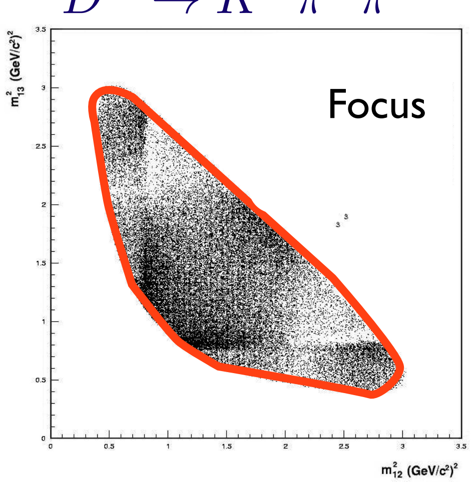
- new high data sample from LHCb ⟶ more to came from LHCb and Belle II

⟶ deserve better models

> isobar model ⚠
> - violates two-body unitarity (2 res in the same channel);
> - do NOT include rescattering and coupled-channels;
> - free parameters are not connected with theory !

- can we learn something from D decays?

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



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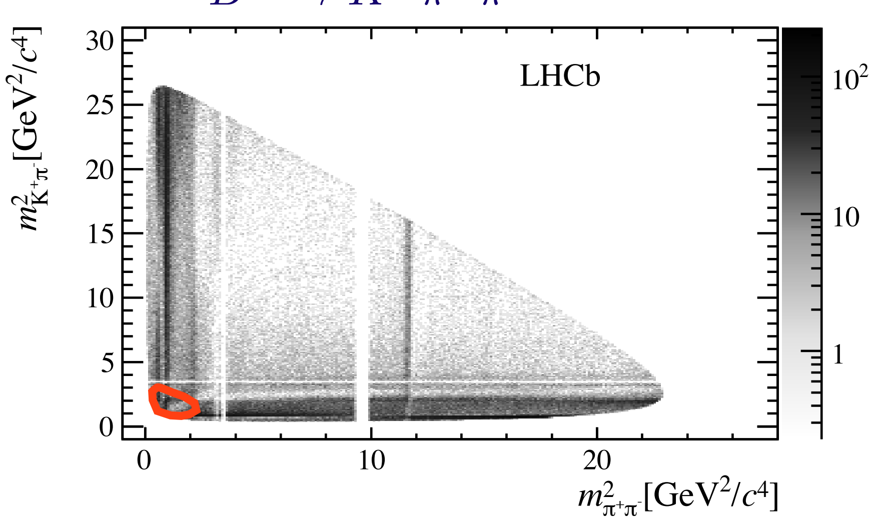
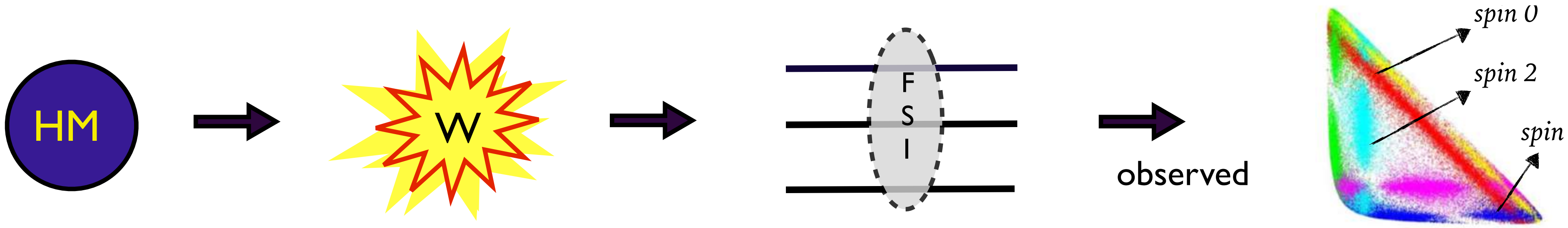
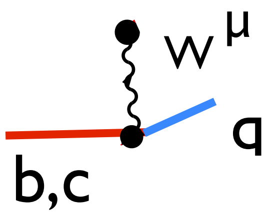


- ≠ scales!!! ⟶ similar FSI
- 2-body theories "works" up to mD
- B phase-space ⟶ + FSI possibilities charm-penguins, ….

- dynamics

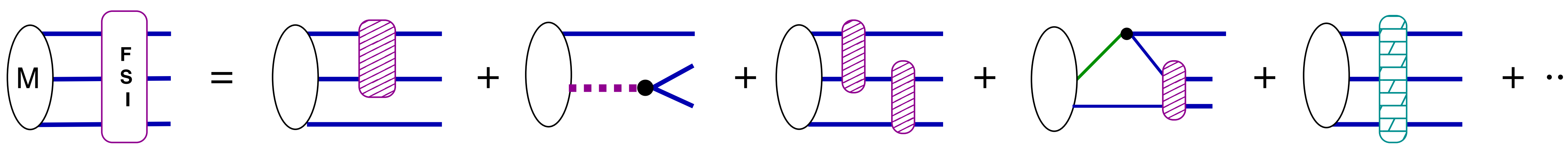


- weak primary vertex (W)



quark → hadron

- Final State Interactions (FSI)



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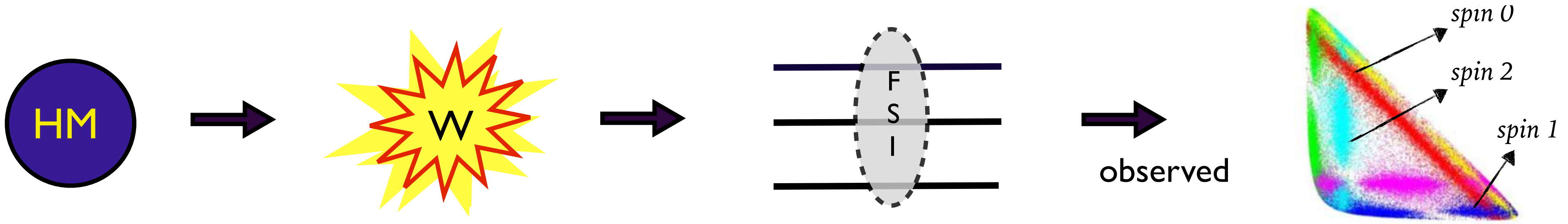
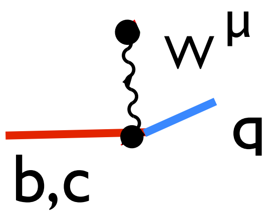


to extract information from data we need an amplitude MODEL

- weak primary vertex (W)



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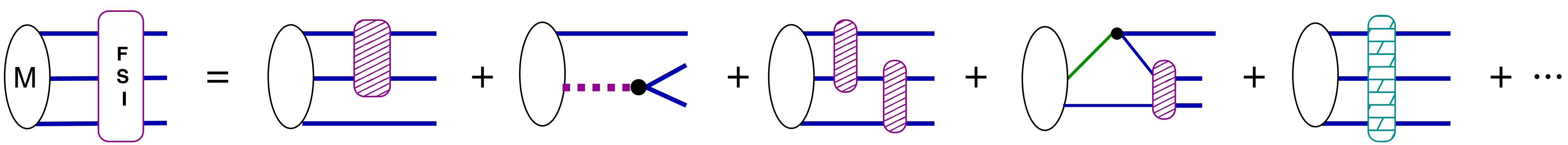

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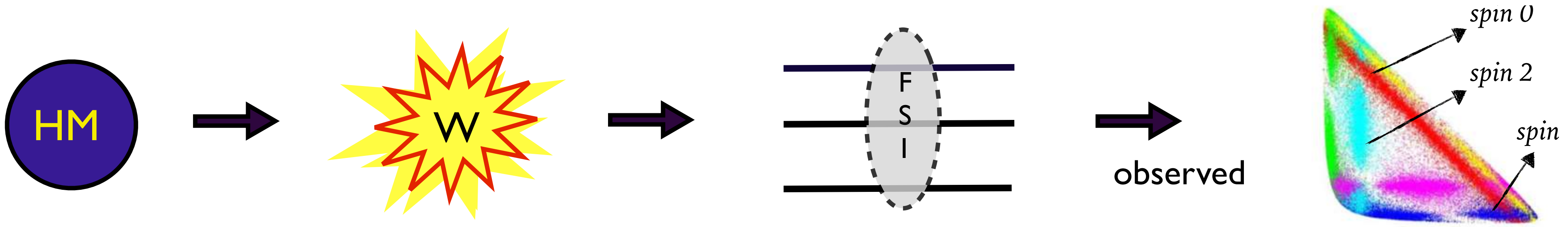
heavy meson decay

- dynamics



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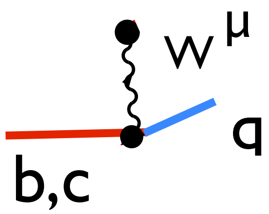

quark → hadron

- QCD factorization approach

→ not precise for 3-body

not allow all kinds of FSI and 3-body NR

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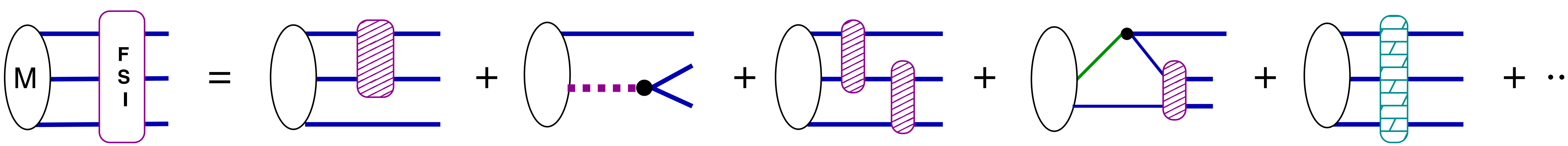

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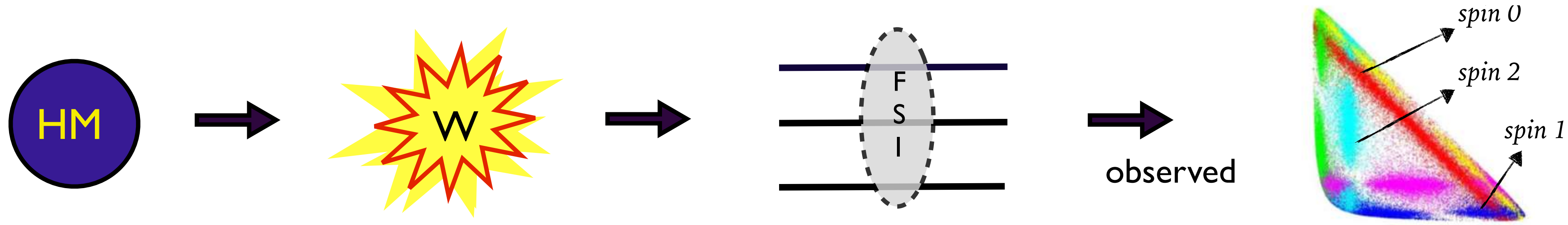

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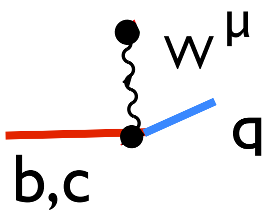

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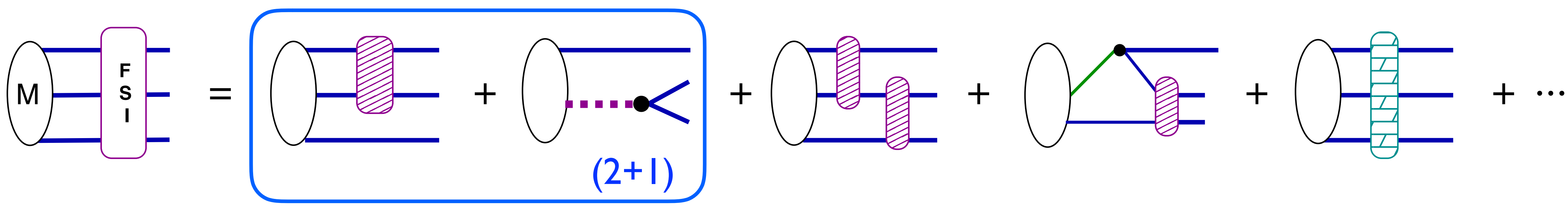

- 2-body is crucial
- full unitarity: Faddeev, Khury-Trieman, triangles

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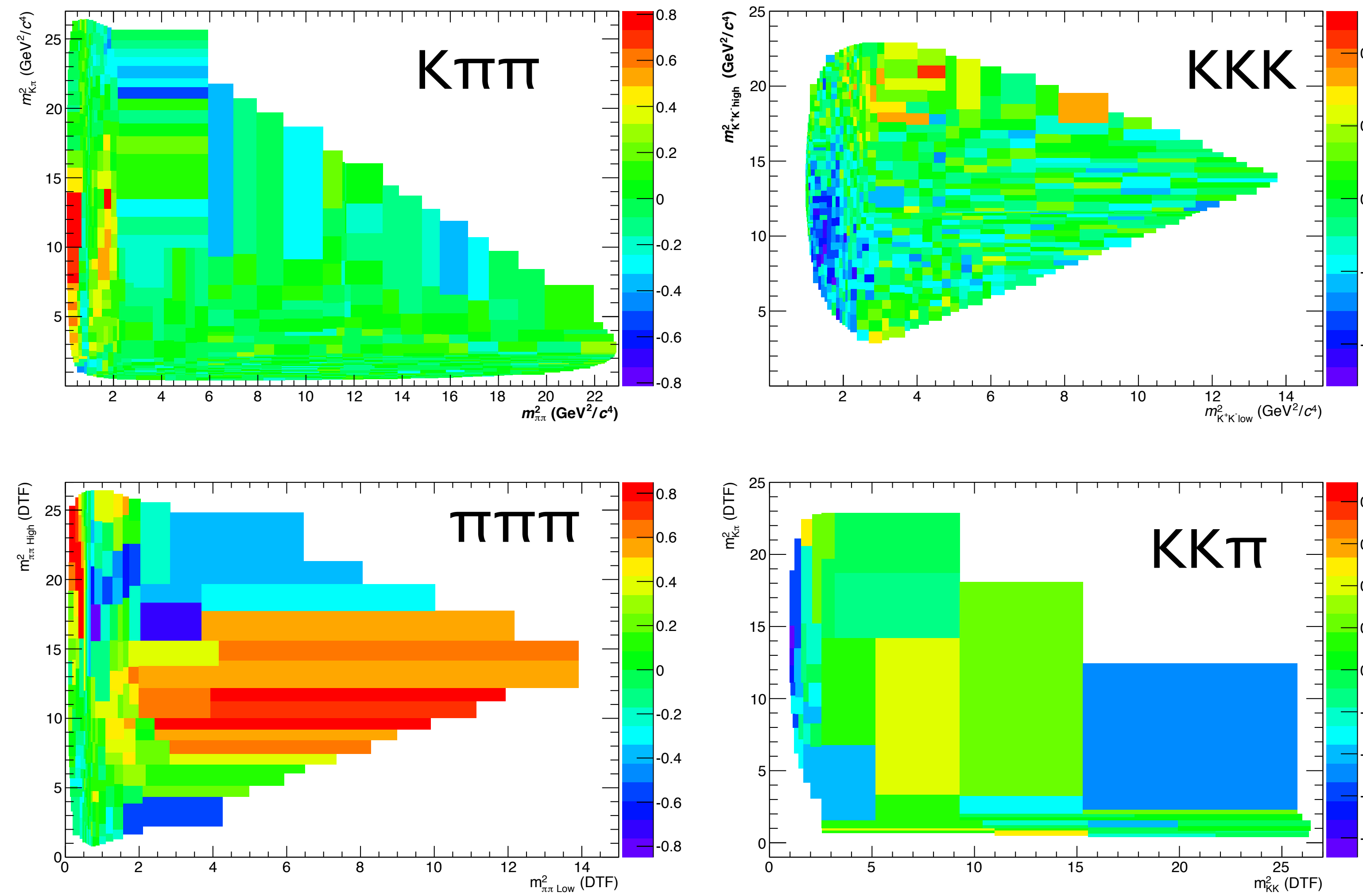
B - decays

- massive localized Acp

$B^{\pm} \to hhh$ LHCb



LHCb PRD90 (2014) 112004

- Charge Parity Violation (CPV):

$$A_{M\to f} = A_1\, e^{i(\delta_1-\phi_1)} + A_2\, e^{i(\delta_2-\phi_2)}$$

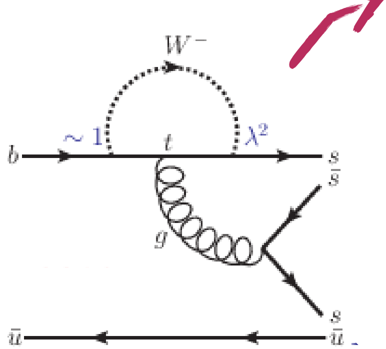
$$|A_{M\to f}|^2 - |A_{\bar{M}\to \bar{f}}|^2 = -4A_1A_2\, sin(\delta_1-\delta_2)\, \sin(\phi_1-\phi_2) \neq 0$$

↳ two ≠weak and strong phases

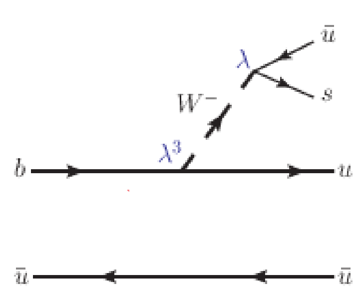
- BSS model 

Bander Silverman & Soni PRL 43 (1979) 242

not enough !!!



↗ strong phase



↗ weak phase: CKM

- factorization techniques
  - describes well two-body Br;
  - do not describe Acp data;

- FSI → strong phase

Wolfenstein PRD43 (1991) 151

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how to improve ANA in B decays?

- FSI
  - low energy MM rescattering, coupled-channels and resonances
  - 3-body + NR effects

two-body theoretical models (unitary & analicity) → dispersion relations and ChPT
limited to ~1 - 2 GeV

→ how far we really need 2-body amplitude?! all B phase-space ?

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how to improve ANA in B decays?

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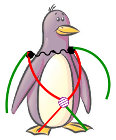
- what do we have in the marked ?

  L. Benoit talk

  - (2+1) parametrization with QCDF + scalar and vector meson-meson FF ; Boito et al [Paris,Kracov, SP]
  - 3- FSI at low energy: with triangle loops PCM et. al. [Brazil effort] or Khuri-Treiman Kubis et. al [Bonn] ↳ limited to very low E
  - 3-b FSI high energy: charm penguins  Bediaga, Fredrico & PCM
  - K-matrix: 2-b pole + polynomial with free parameter modulated by a production; ↳ (2+1) difficult to extract informations Anisovich, Babar, LHCb
  - GLASS, LASS use directly 2-body phases for 3-body process ⚠ ↳ (2+1)

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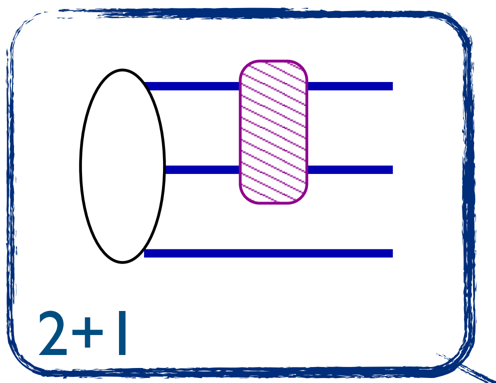
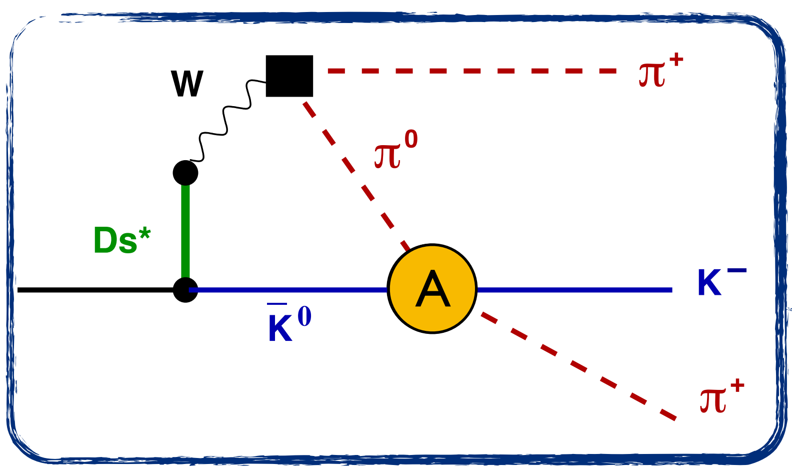
2-body x 3-body phases

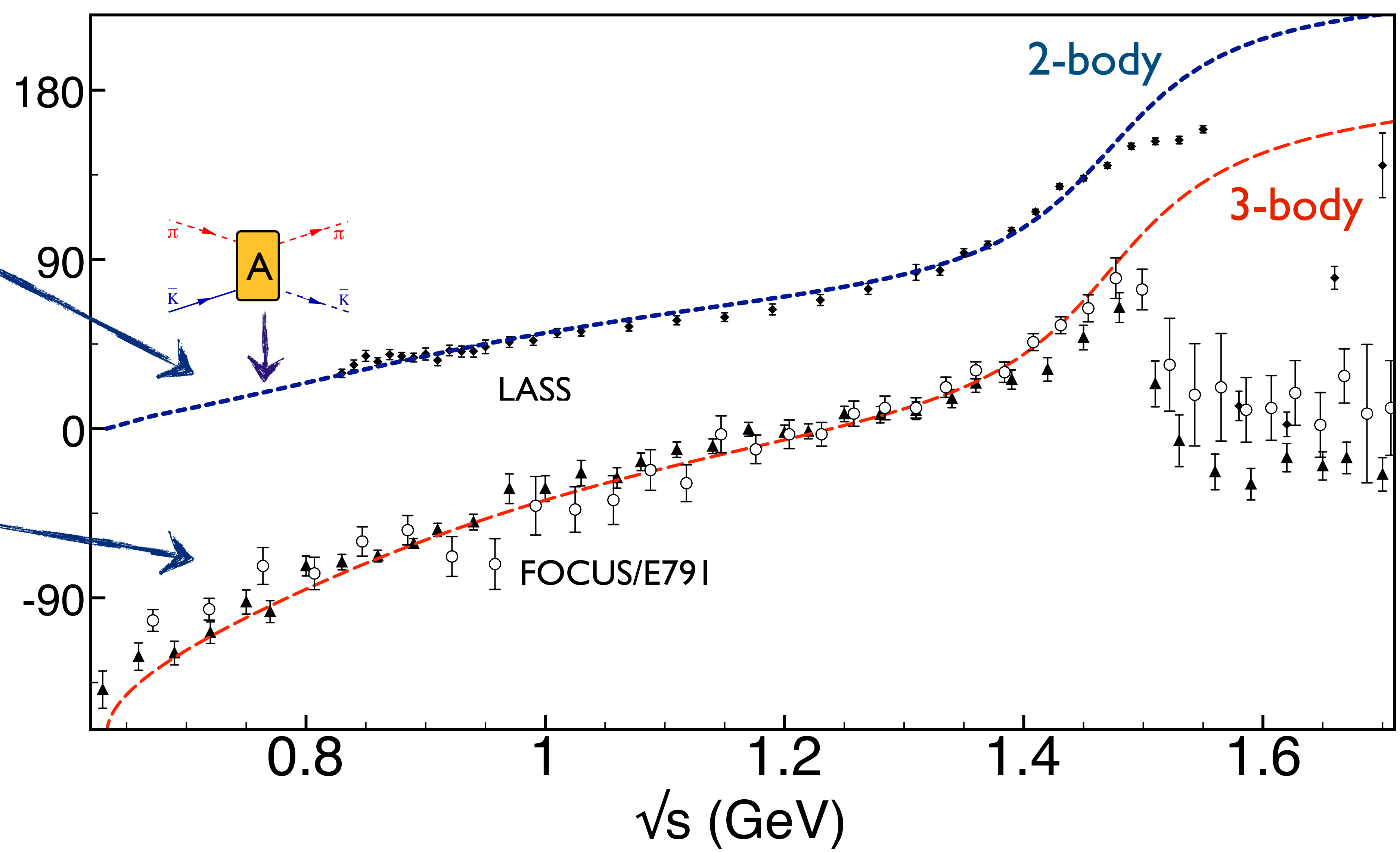
- Can we extract two-body information from 3-body data? Not directly!
- $D^+ \to K^-\pi^+\pi^+$ → different S- wave phase from $K^-\pi^+$





different dynamic!

PC Magalhães et.al: PRD84 094001 (2011), PRD92 094005 (2015)



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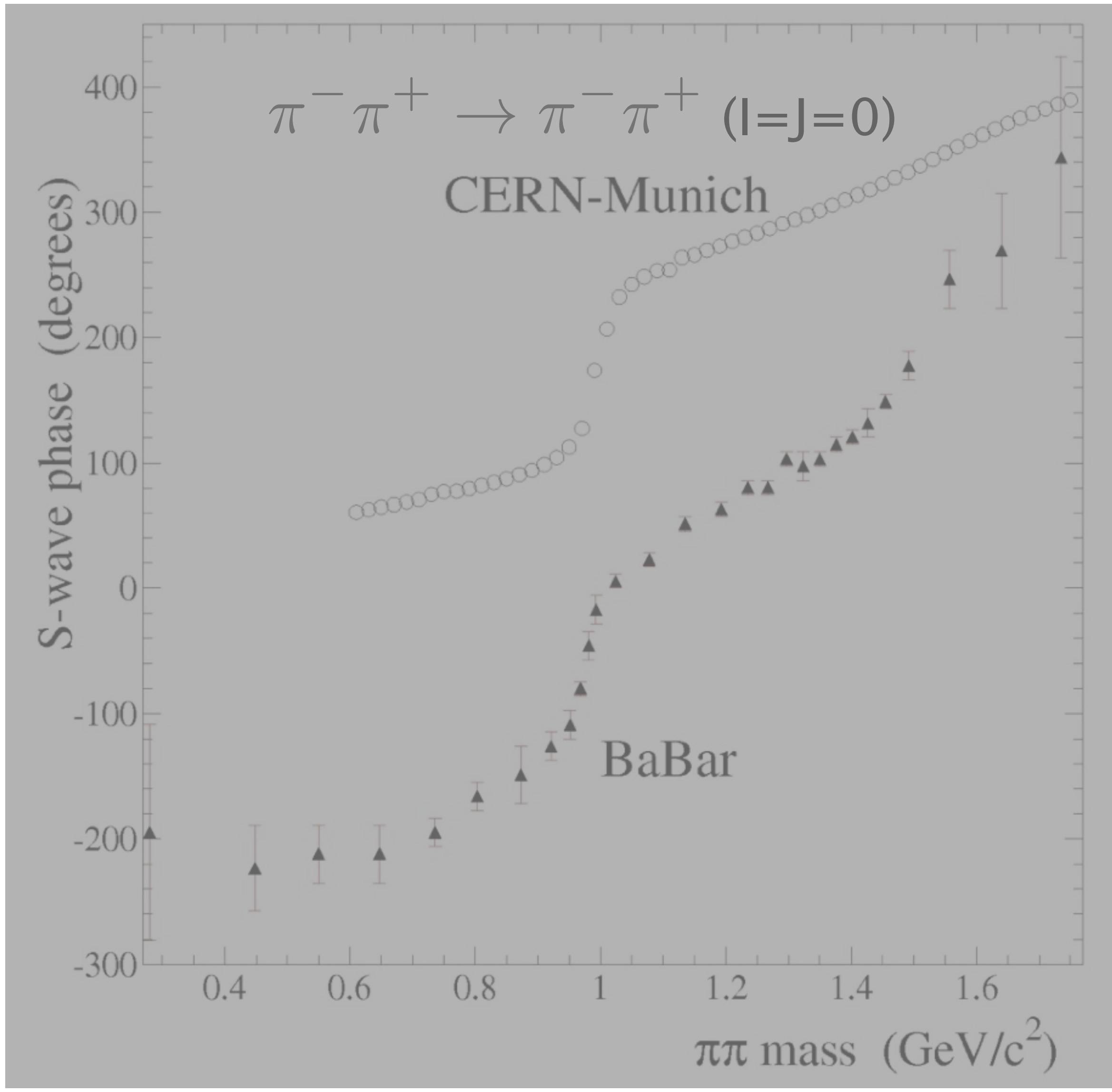
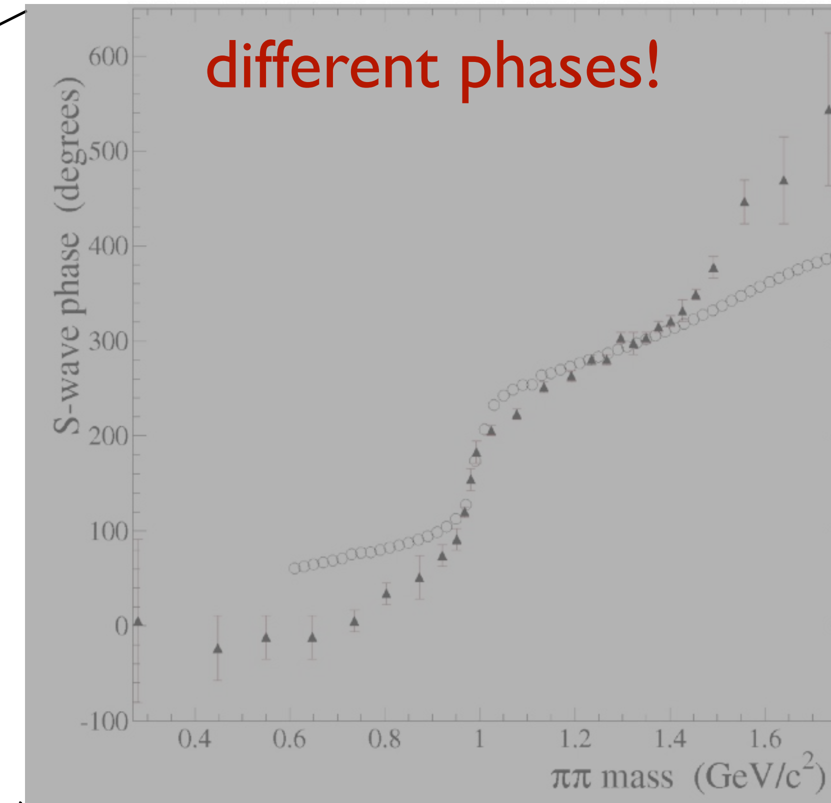
2-body x 3-body phases

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





Phys.Rev. D 79 (2009) 032003

- 2-body amplitude: spin and isospin well defined!
- 3-body data: only spin! & $\neq$ dynamics (weak vertex, FSI, 3rd particle, ...)

There is no direct connection between phases of the 3-body decay amplitudes and two-body scattering amplitudes

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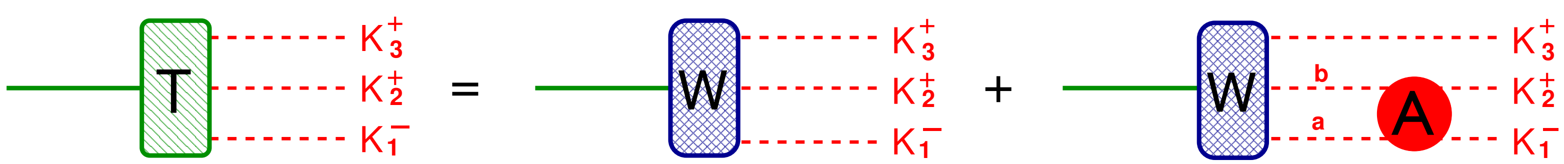
information from D decays

- 2-body is a crucial ingredient
  - ↗ limited from theory to low E
  - ↘ limited scattering data

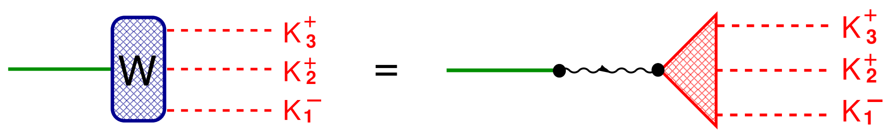
→ no KK scattering data and no theoretical model! just extensions

- use 3-body data to obtain information from two-body!

ex: a model for $D^+ \to K^- K^+ K^-$ that can predict the KK scattering



- alternative to isobar model in amplitude analysis arXiv: 1805.11764
- hypotheses that annihilation is dominant



- everything can be described by ChPT Lagrangian
  - A^{JI}_{ab} ⟶ unitary scattering amplitude for $ab \to K^+K^-$

→ parameters have physical meaning: masses and coupling constants

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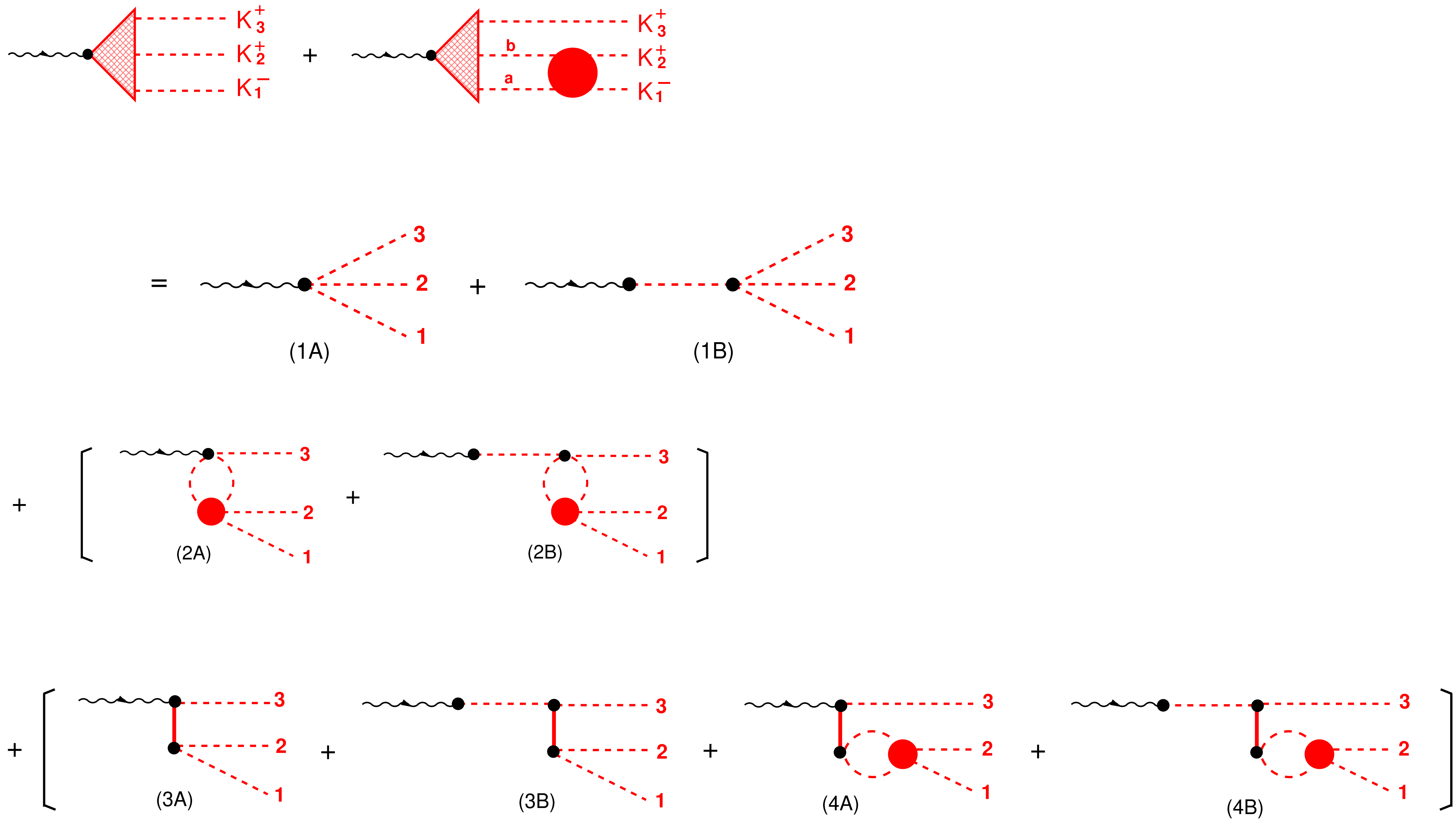
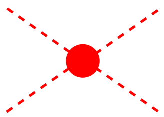
Triple - M





$K\bar{K}$ scattering amplitude

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

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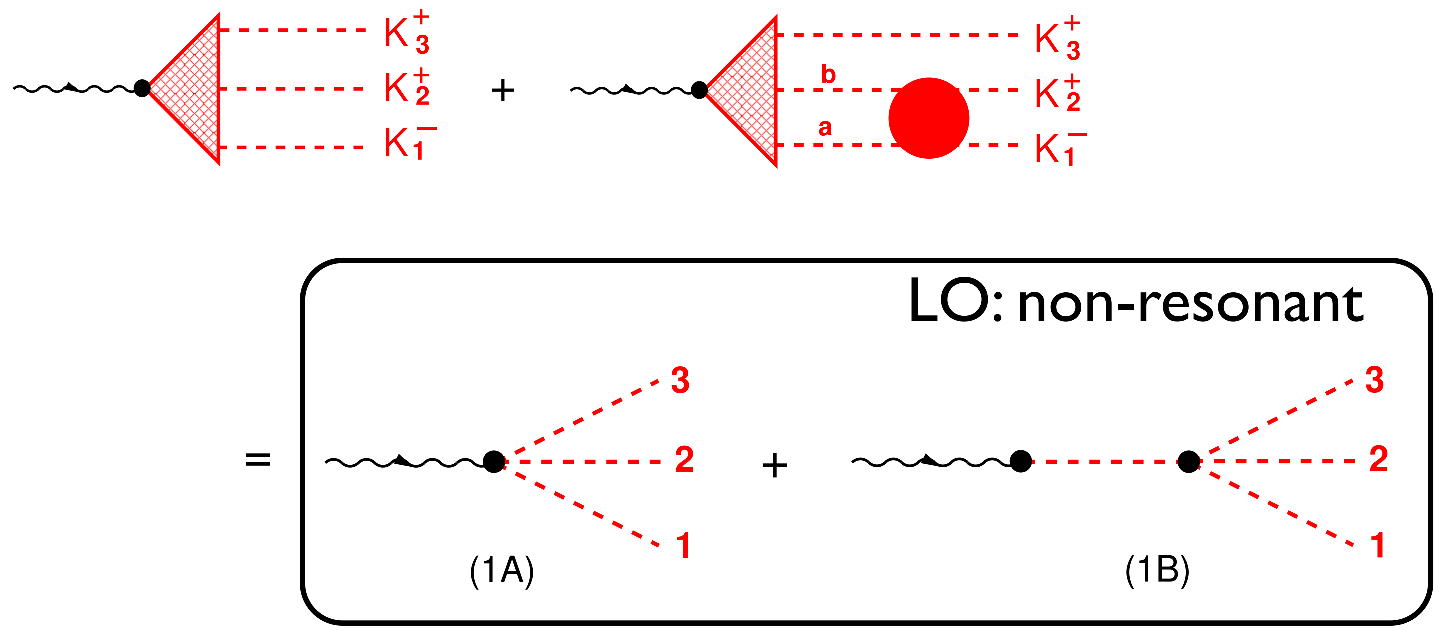
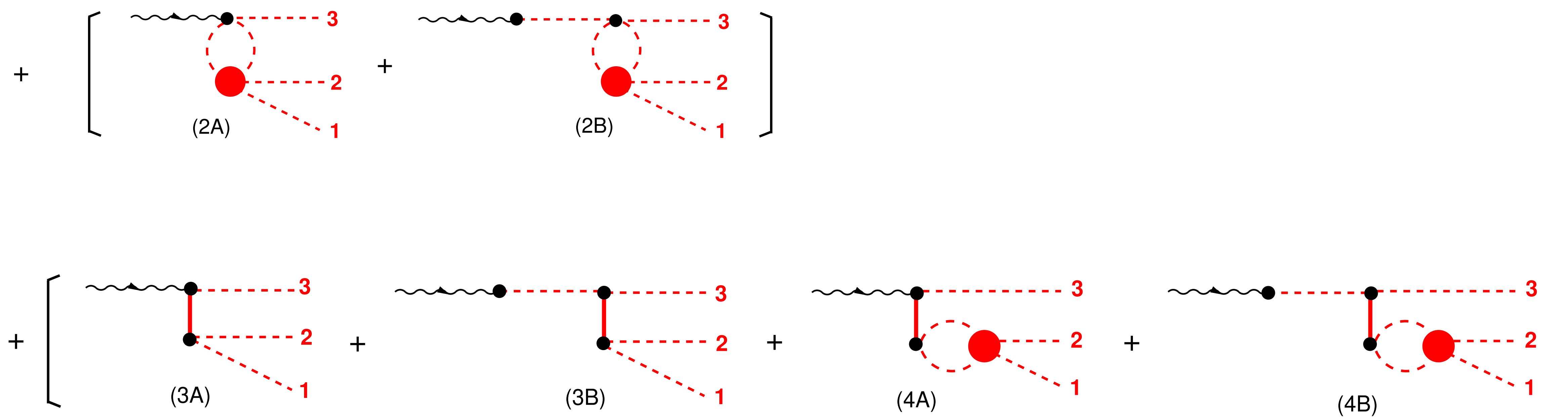
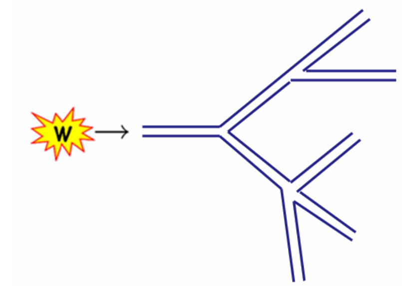
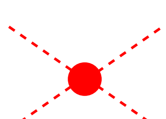






Chiral symmetry



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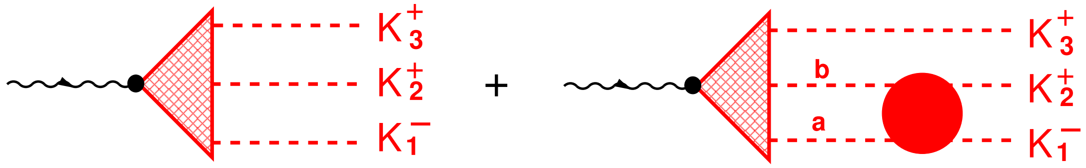
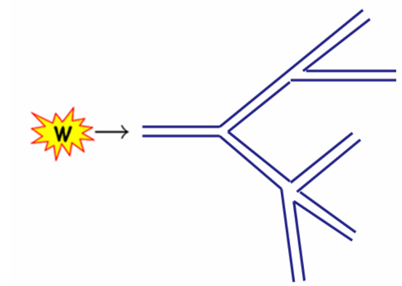
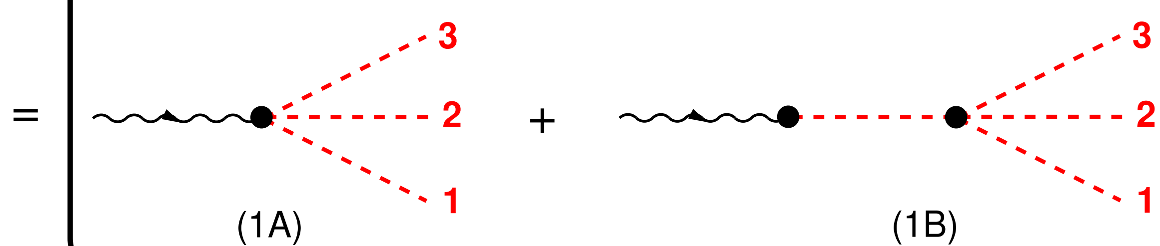




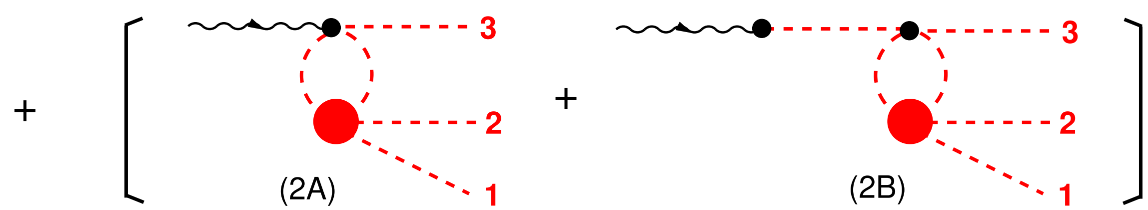
Chiral symmetry

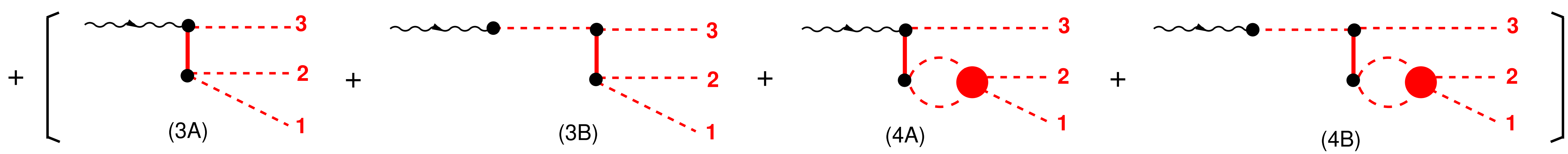
LO: non-resonant

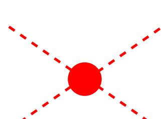


NLO

a_0, f_0, ρ, ϕ







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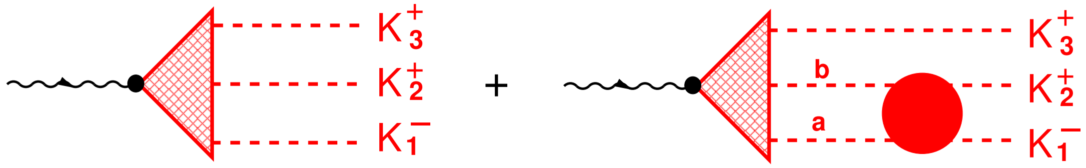

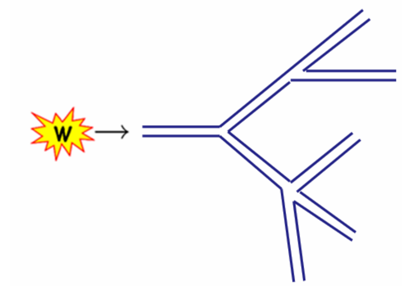

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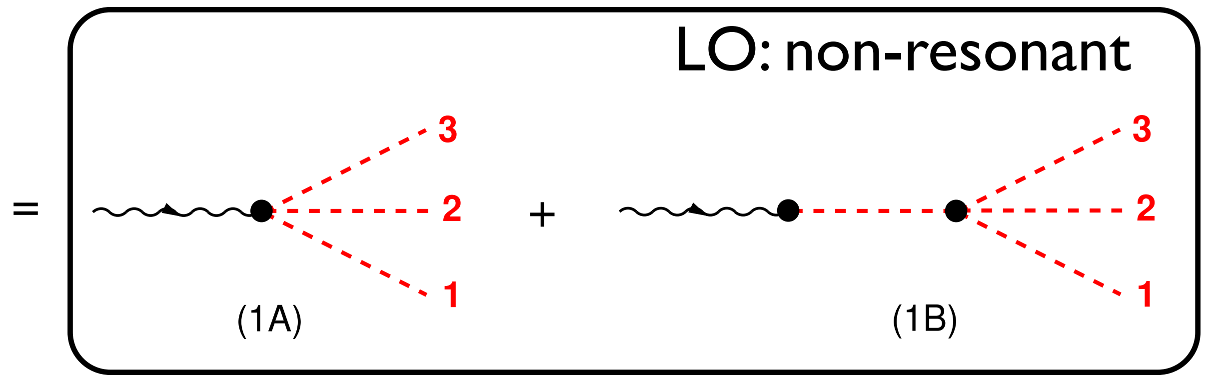
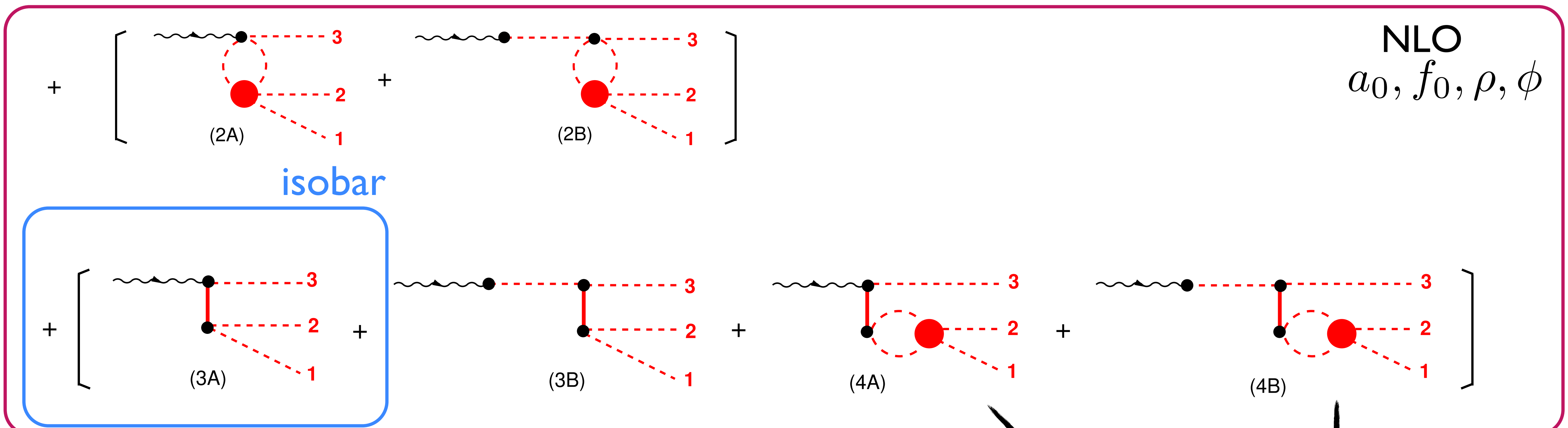
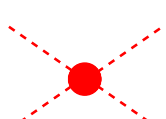




dynamical width



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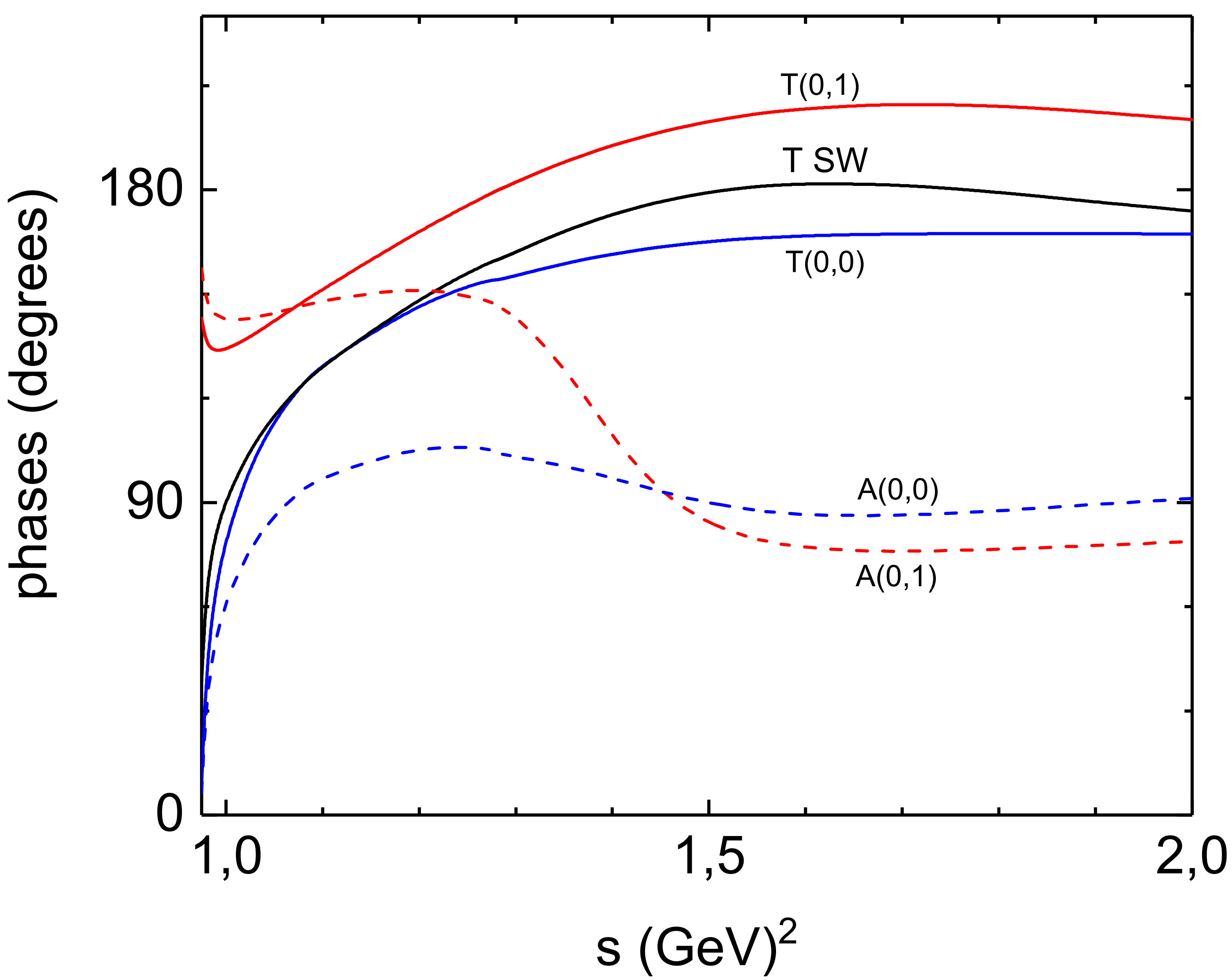
Triple - M - activement

- non-resonant: beyond (2+1) is a 3-body amplitude
- FSI: coupled-channel meson-meson from ChPTR Lagrangian
- intensity of each component is predict by theory → ≠ isobar model
- Toy studies



→ parameters with physical meaning (ChPT)

→ can disentangle a_0 and f_0

→ couple channel structure: cannot be ignored

arXiv: 1805.11764

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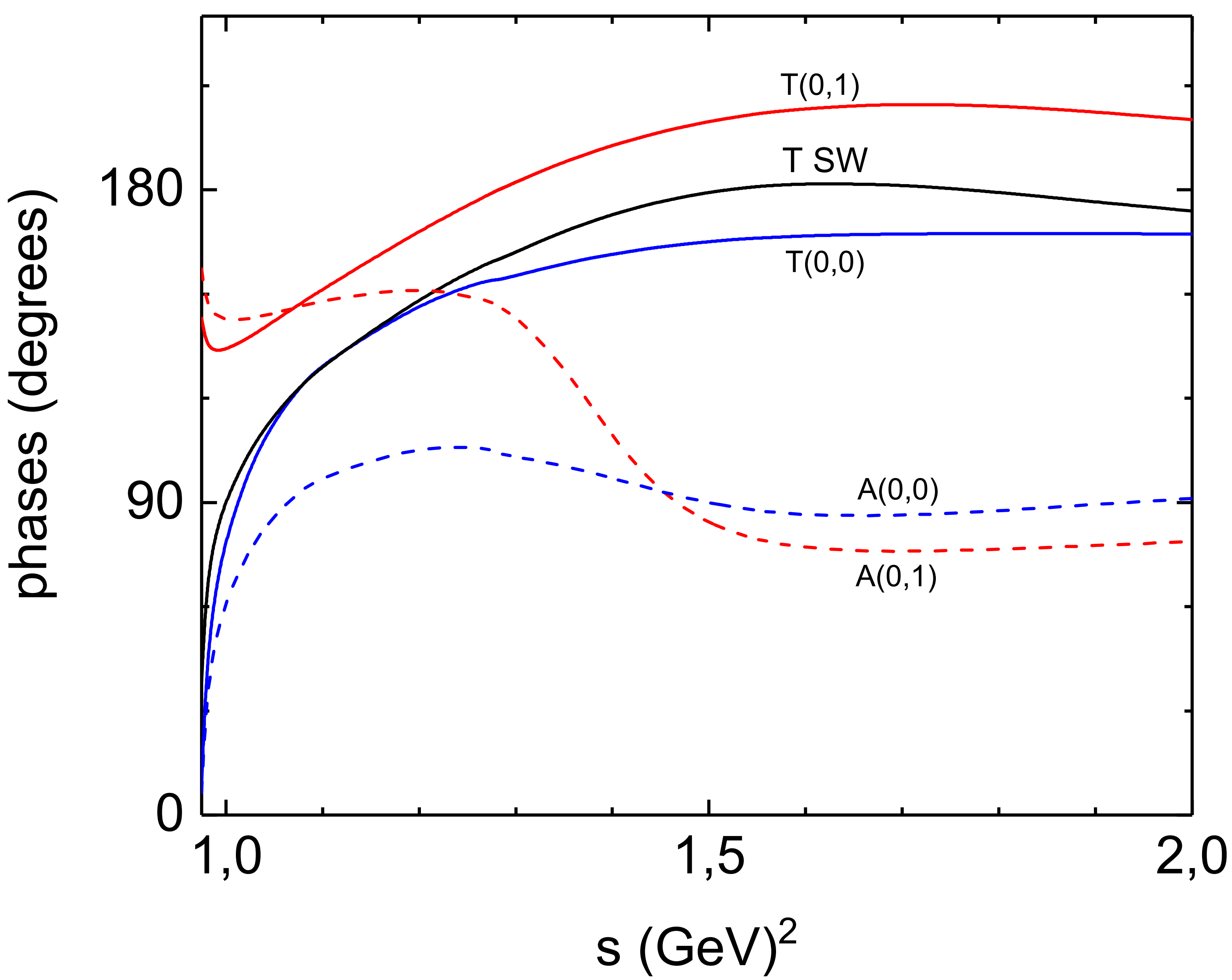

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Fitting data we can predict KK scattering phase

arXiv: 1805.11764

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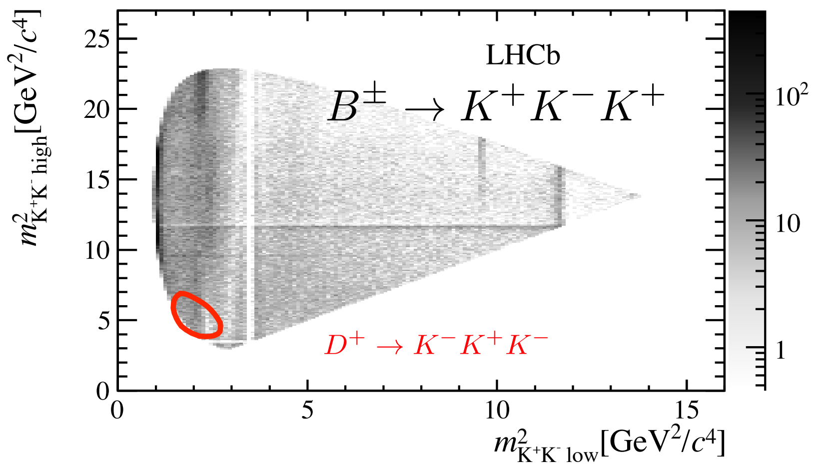
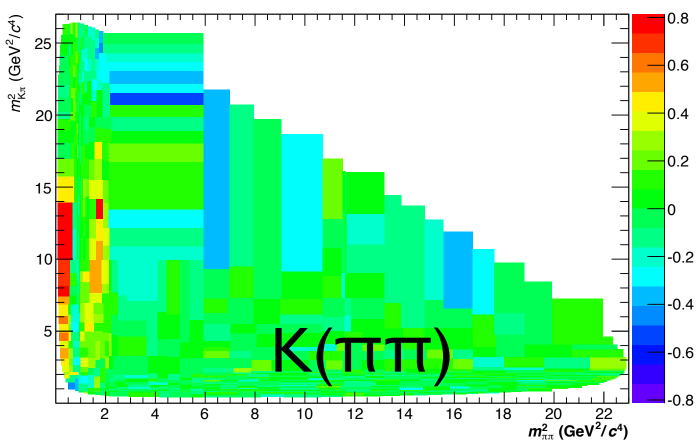
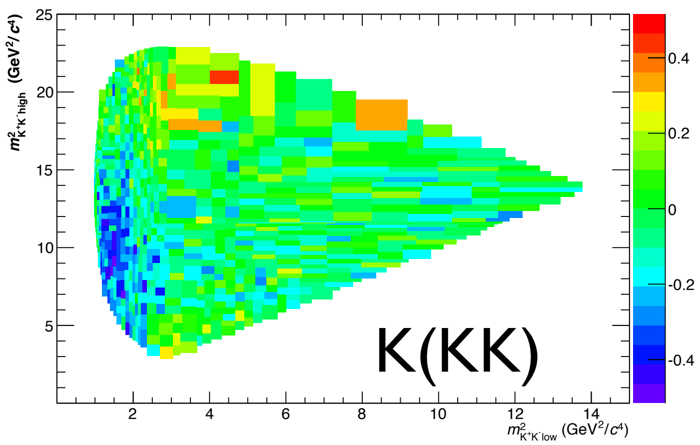
B decays



- huge phase-space
  - FSI at low and high energy → room for producing all sorts of particles
- localised CPV
  - low mass
    Bediaga, Frederico, & Lourenço PRD89(2014)094013
  - high mass?





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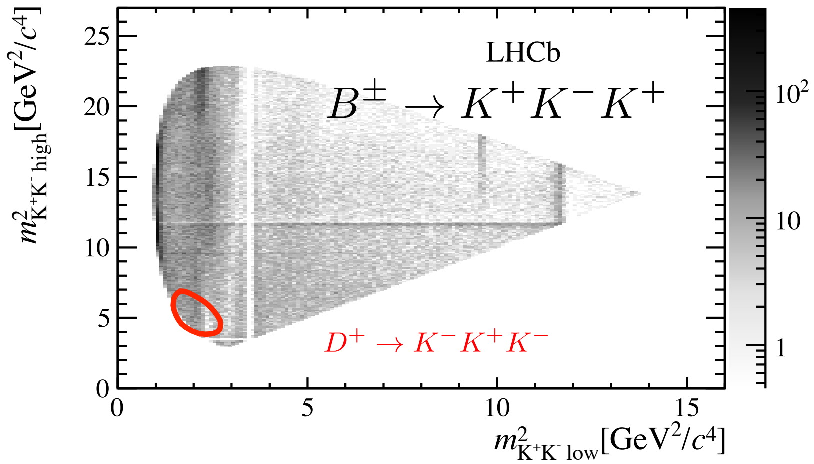
B decays



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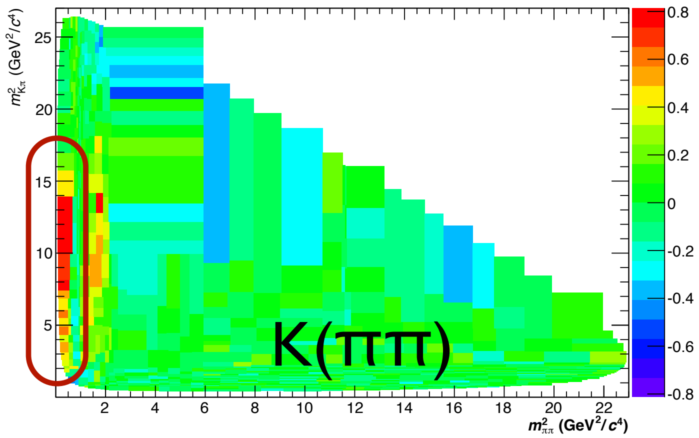

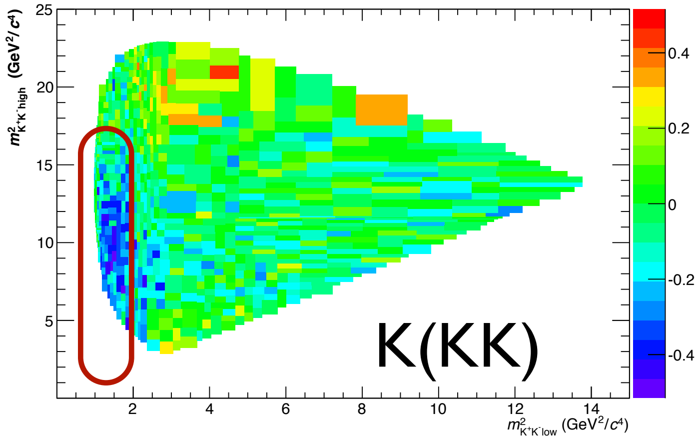

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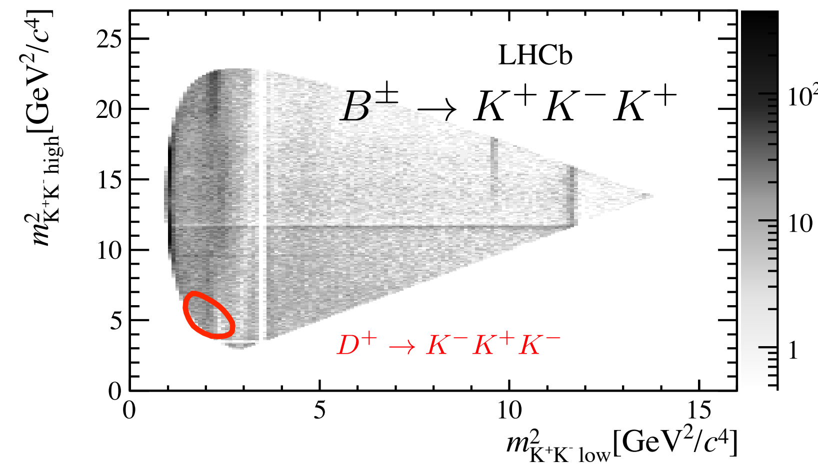
B decays



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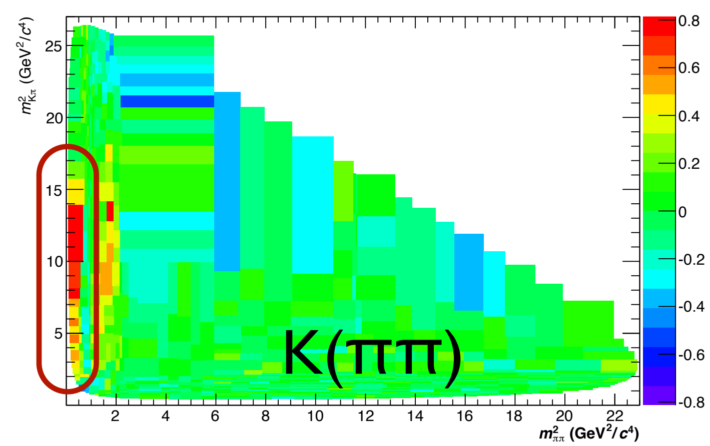
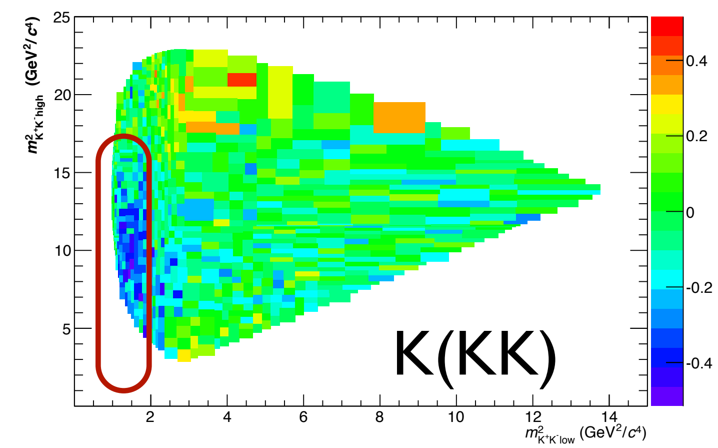
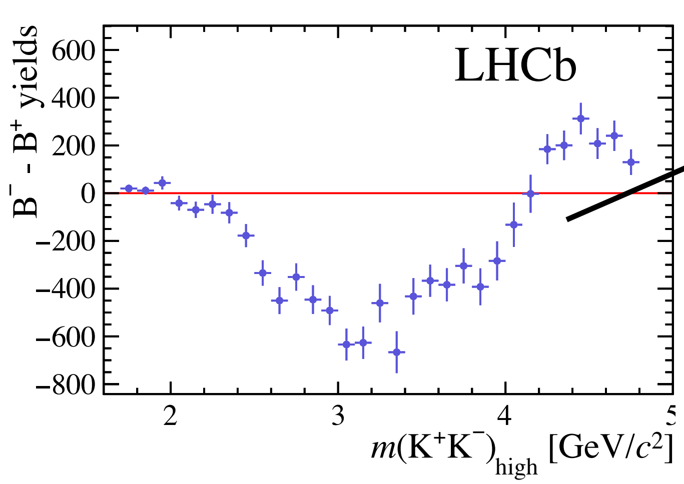
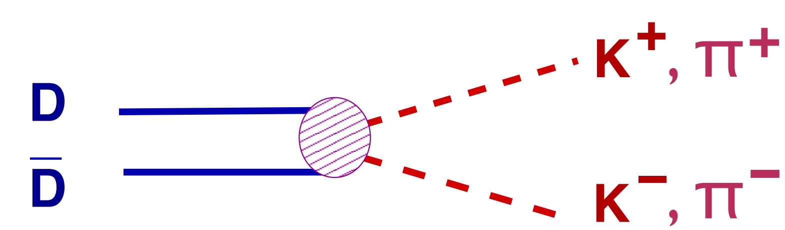




  - high mass?



~ $D\bar{D}$ open channel →



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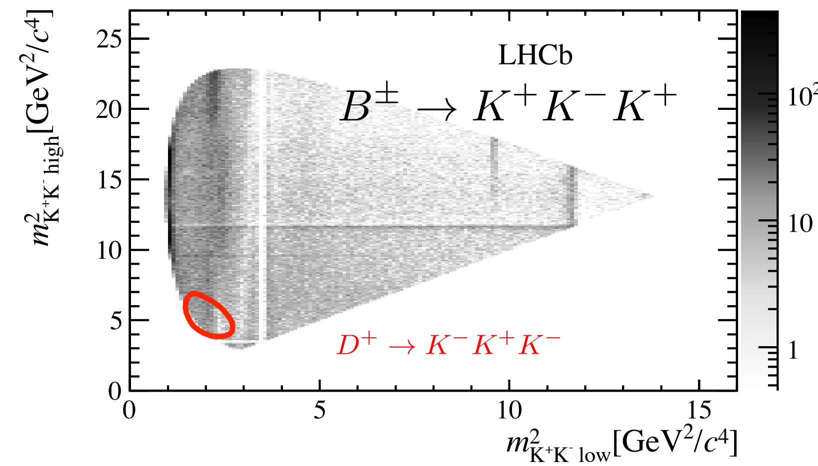
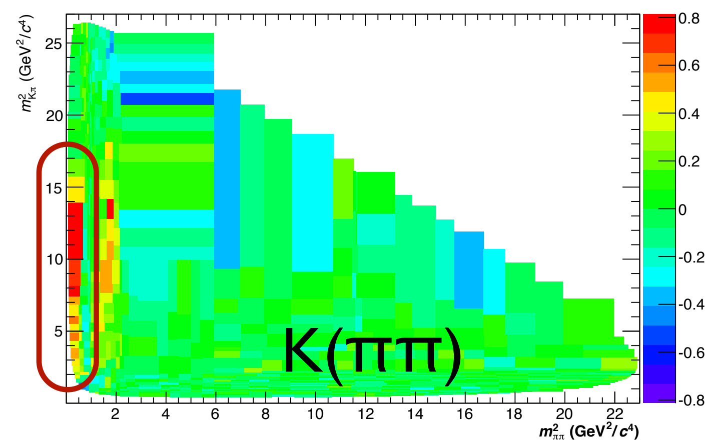
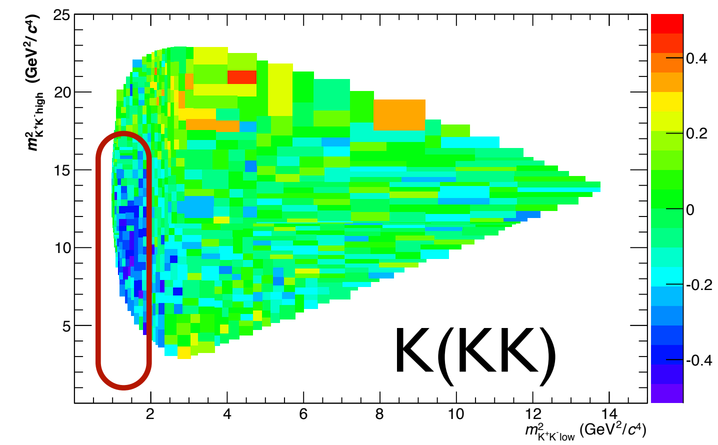
B decays

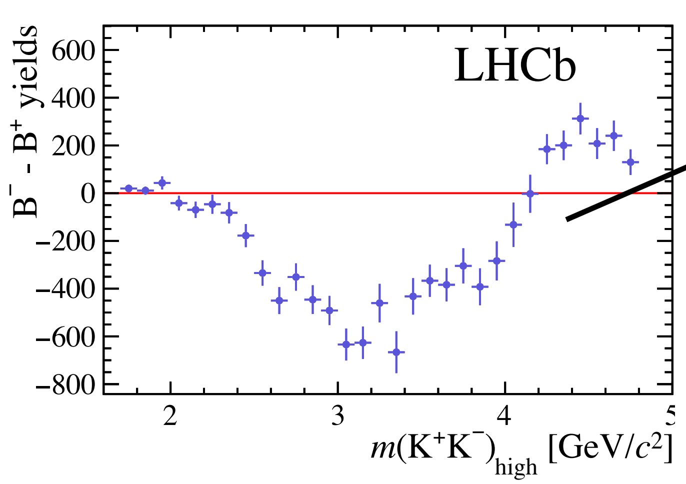


- huge phase-space
  - FSI at low and high energy → room for producing all sorts of particles
- localised CPV
  - low mass $\pi\pi \to KK$

    Bediaga, Frederico, & Lourenço
    PRD89(2014)094013
  - high mass?







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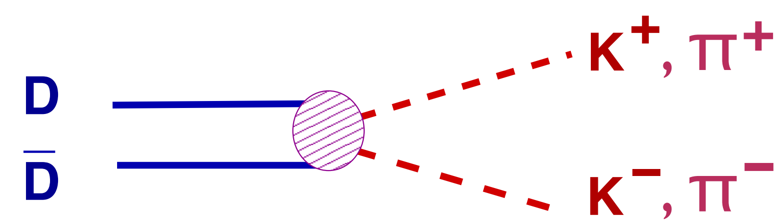

charm loops as source of strong phase

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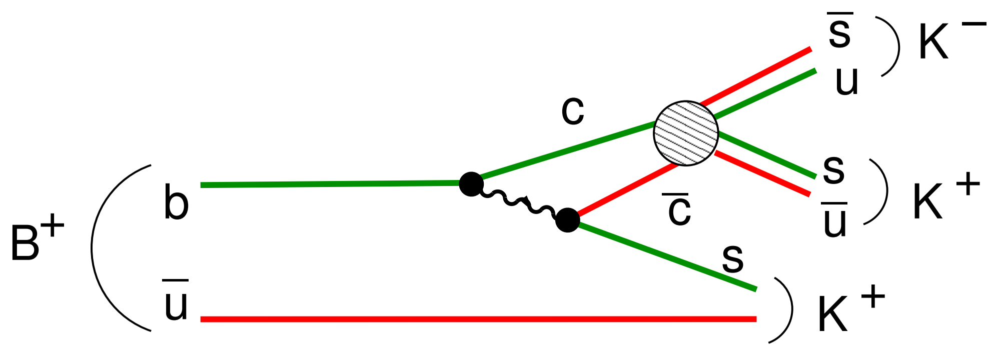
- charm FSI: $B \to 3h$, $B_c \to 3h$, $B \to K^* \mu\mu$, ...

investigate the charm penguin contribution to $B^{\pm} \to K^+K^-K^+$



PLB 780 (2018) 357

Cabibbo favoured V_{bc}

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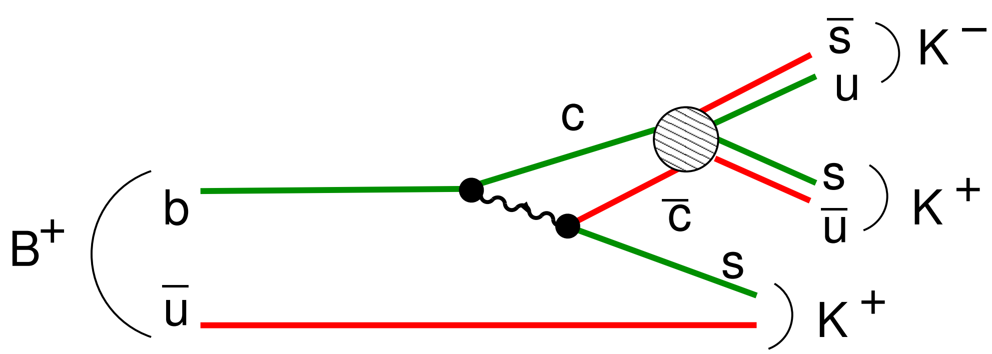
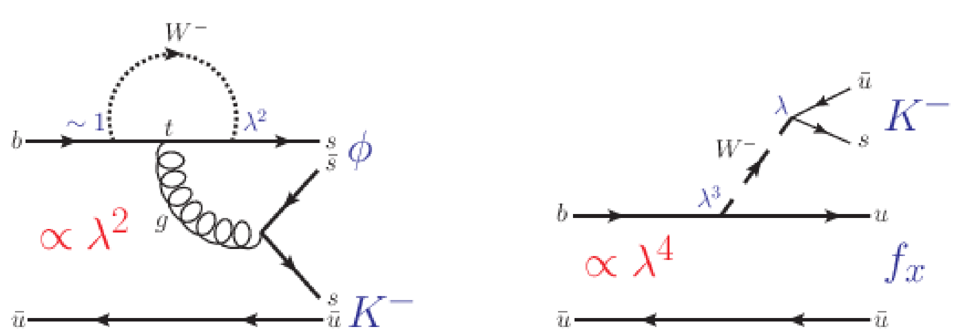
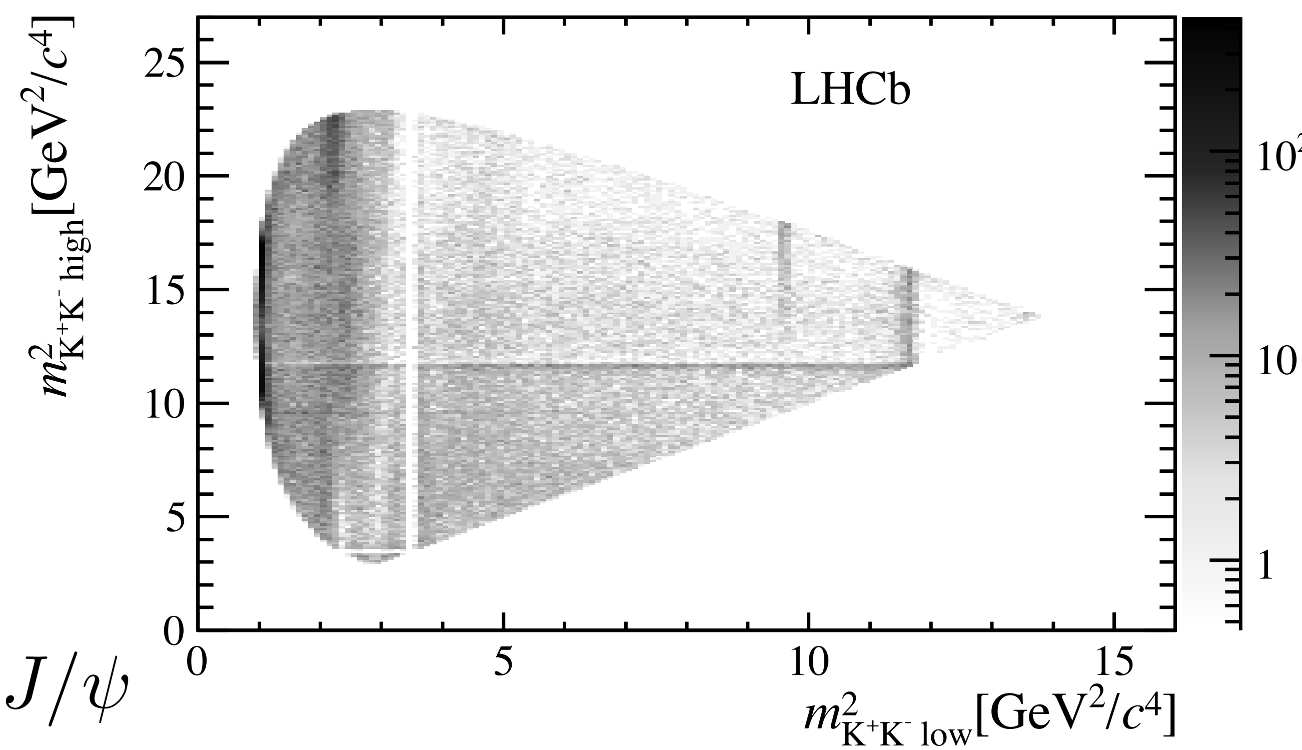


PLB 780 (2018) 357

Cabibbo favoured V_{bc}

- $B^{\pm} \to hhh$ highest statistic 109k
- nonresonant → all phase-space
- dominated by penguin





- presence of charm resonances: χ_{c0} J/ψ

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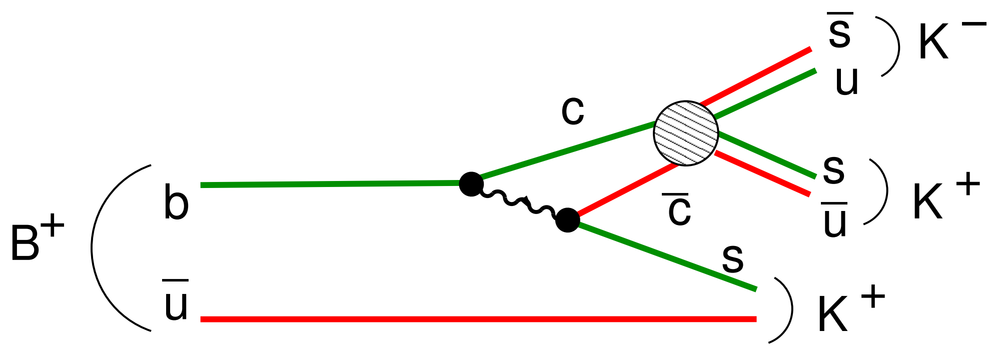

PLB 780 (2018) 357

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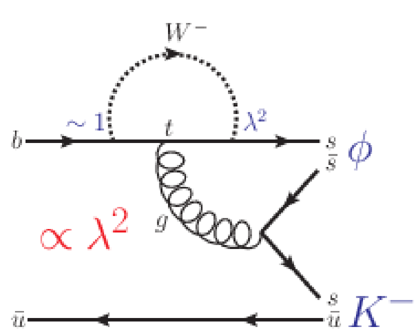
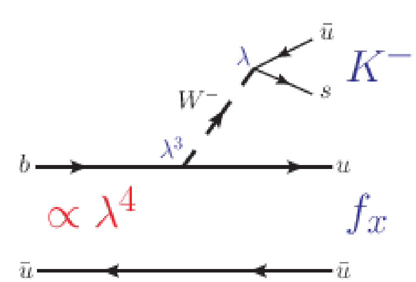
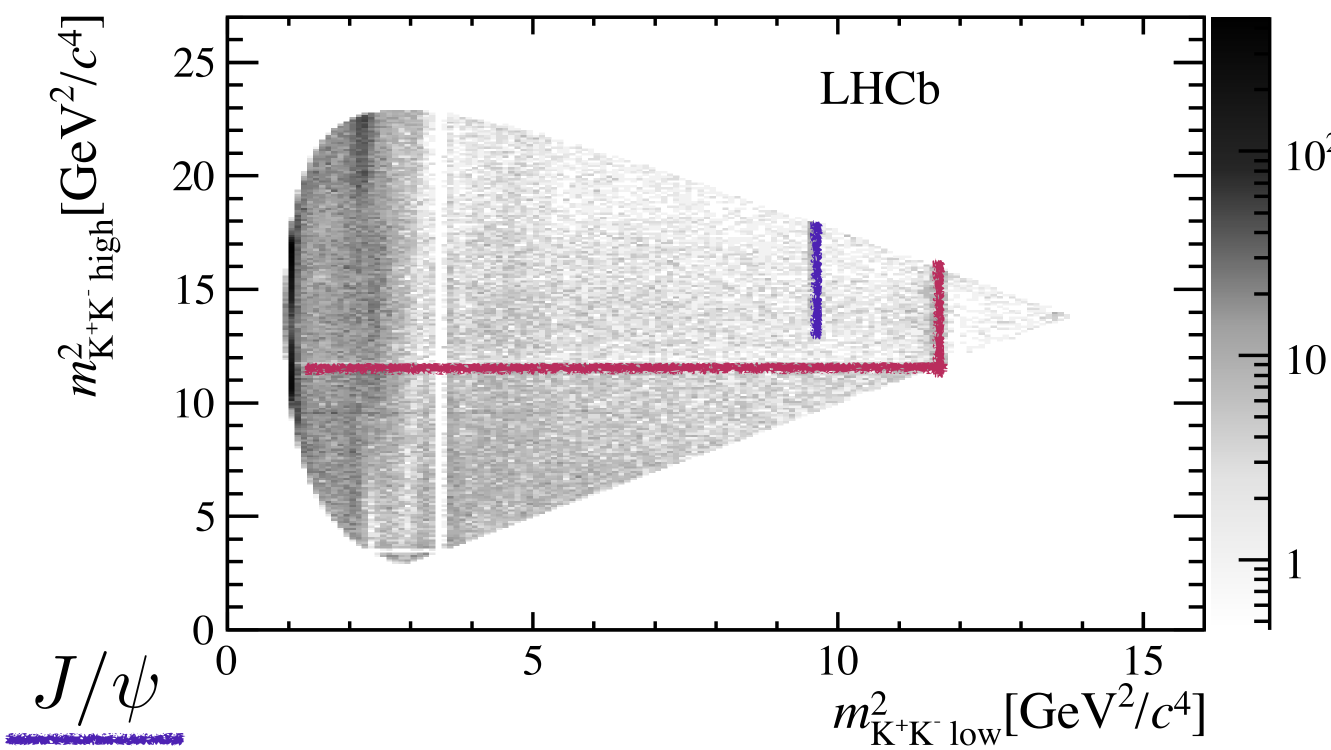




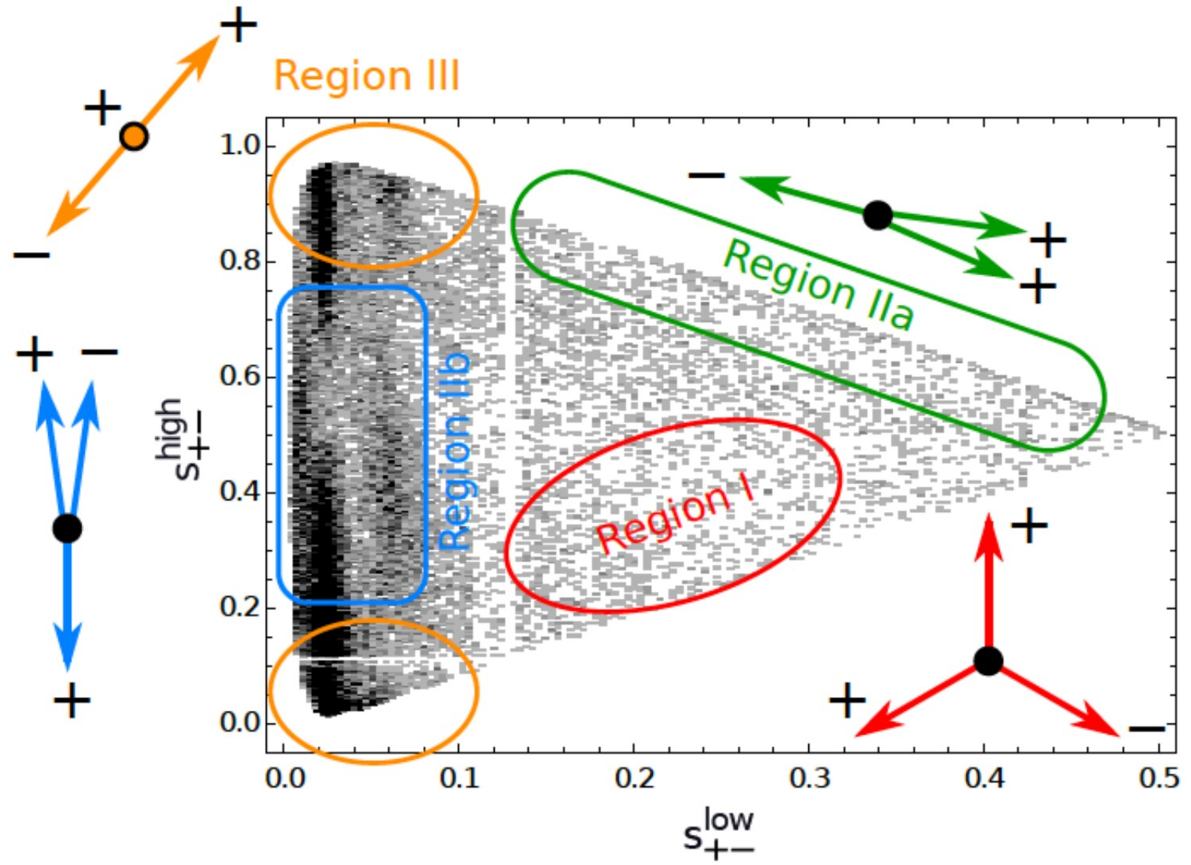


- presence of charm resonances: χ_{c0} J/ψ

- different QCD regimes in DP

Krünkl, Mannel & Virto, NPB 899 (2015) 247

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



Charm penguin in B decay

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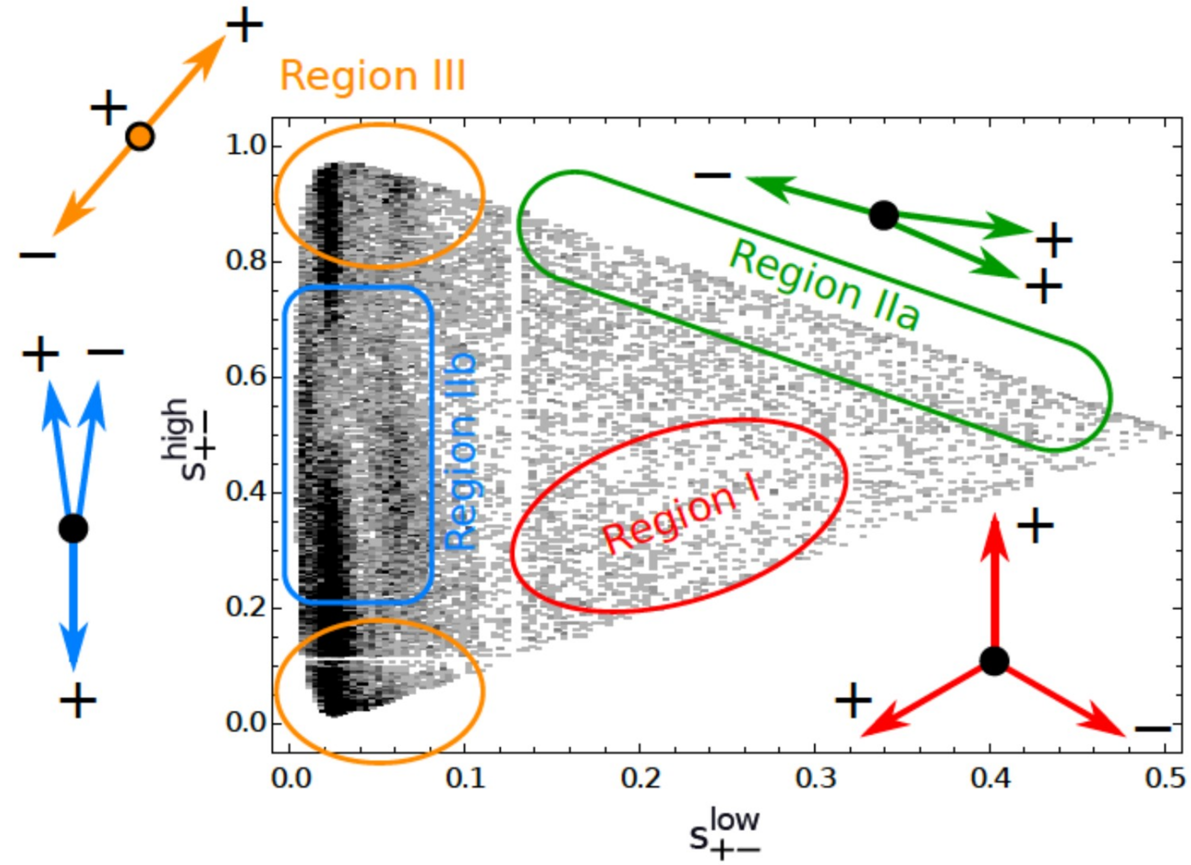
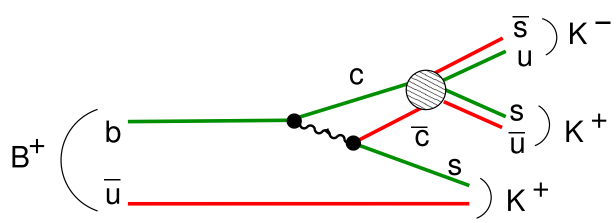
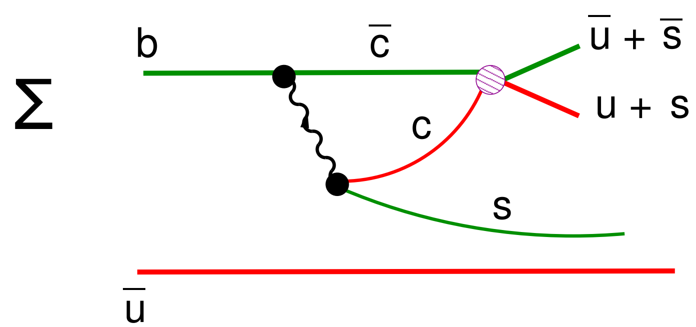


- 

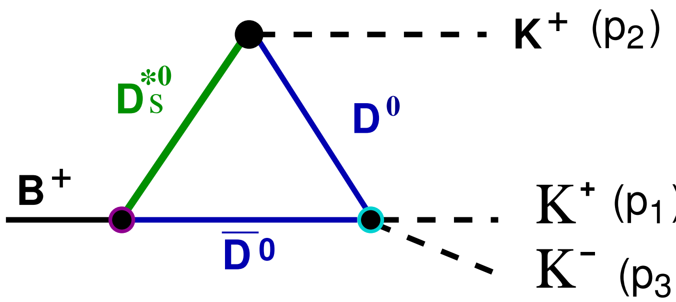
  2 QCD regimes

- perturbative: region I



duality principle

- nonperturbative: region II



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Charm penguin in B decay

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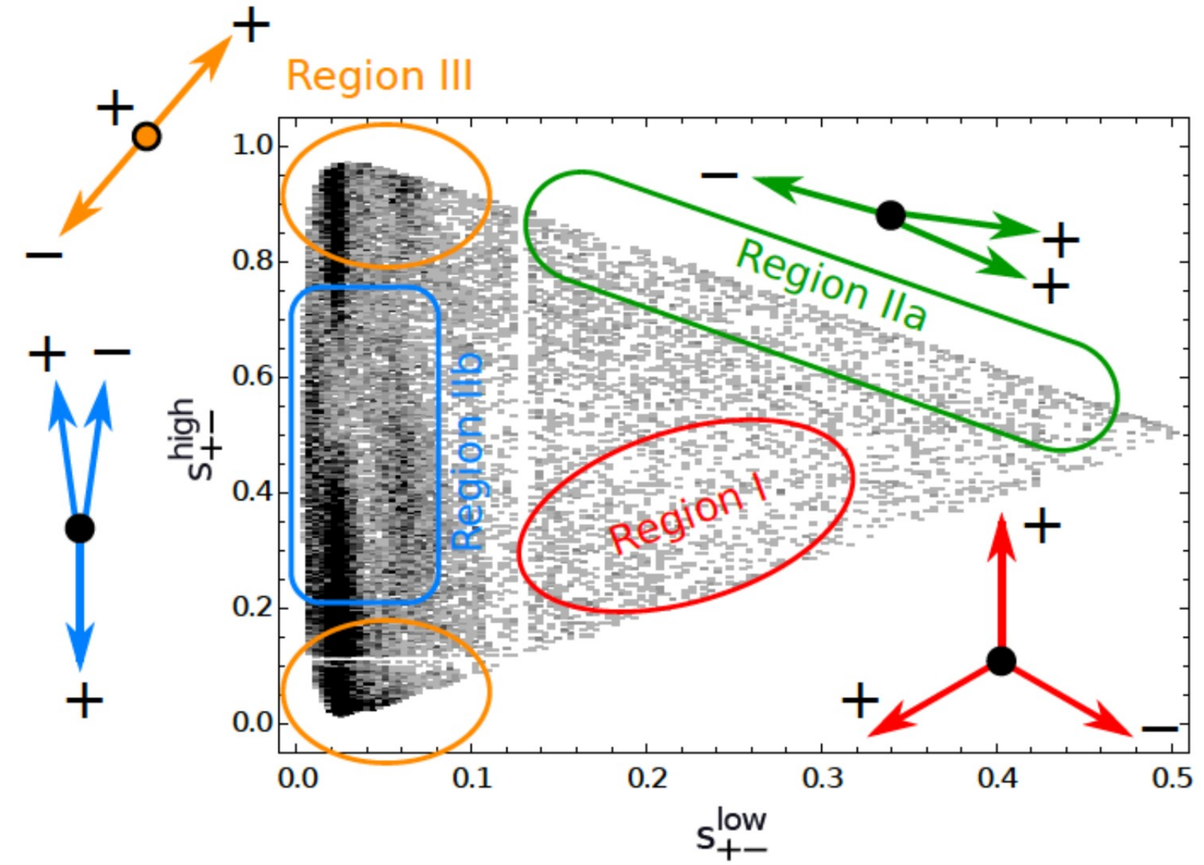
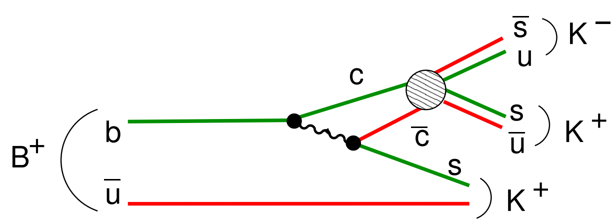
  Krünkl, Mannel & Virto, NPB 899 (2015) 247

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



- 

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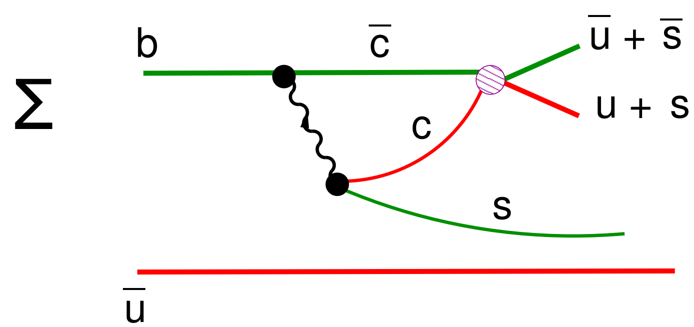

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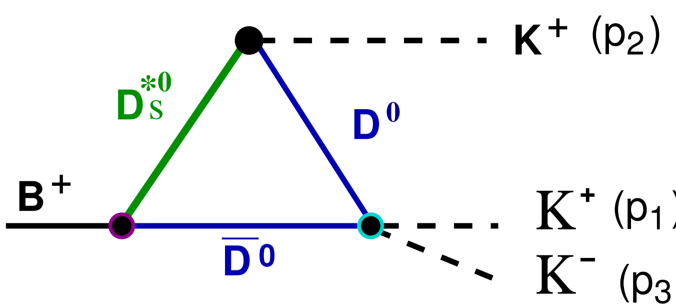

identify their signatures to amplitude analyses with LHCb data

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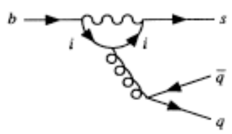
partonic loop

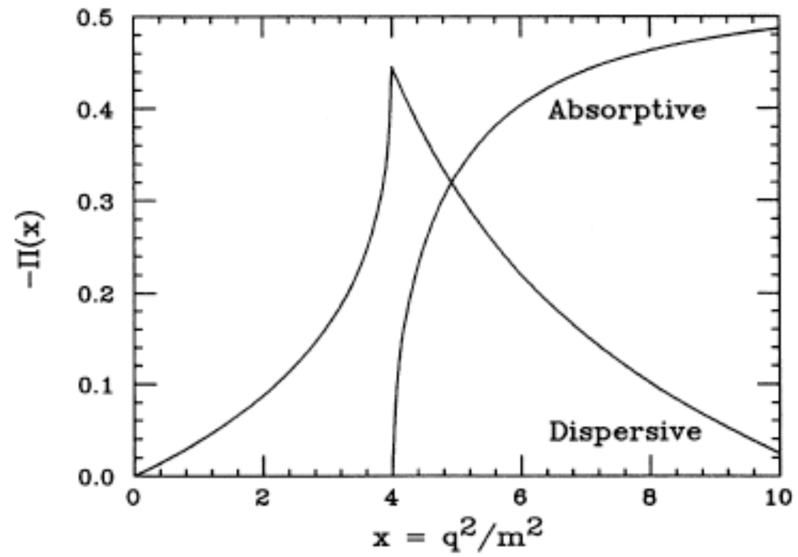
- loop

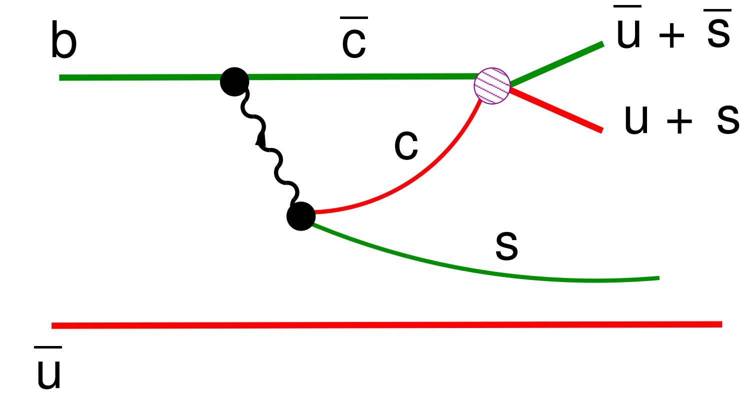


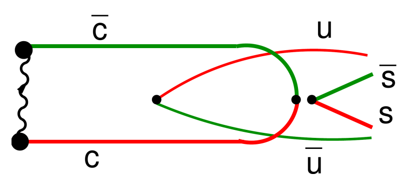
$$Re\Pi(x) = -\frac{1}{6}\left\{\frac{5}{3} + \frac{4}{x} - \left(1+\frac{2}{x}\right)\left[\sqrt{1-\frac{4}{x}}\,\ln\left(\frac{1+\sqrt{1-4/x}}{1-\sqrt{1-4/x}}\right)\Theta\left[1-\frac{4}{x}\right] + 2\sqrt{\frac{4}{x}-1}\,arcot\left[\sqrt{\frac{4}{x}-1}\right]\Theta\left[\frac{4}{x}-1\right]\right]\right\}$$

$$Im\Pi(x) = -\frac{\pi}{6}\left(1+\frac{2}{x}\right)\sqrt{1-\frac{4}{x}}\,\Theta\left[1-\frac{4}{x}\right]$$

Gerard& Hou PRD43 (1991) 2909





- 

many possible excitations → average of charm mass

$$A_{parton} = \int_{mc_{min}}^{mc_{max}} \Pi(s)\,\frac{1}{2\,\pi\,\Gamma^2}\,e^{\frac{(m-m_{c0})^2}{2\,\Gamma^2}}$$

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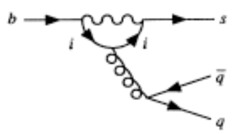
partonic loop

- loop



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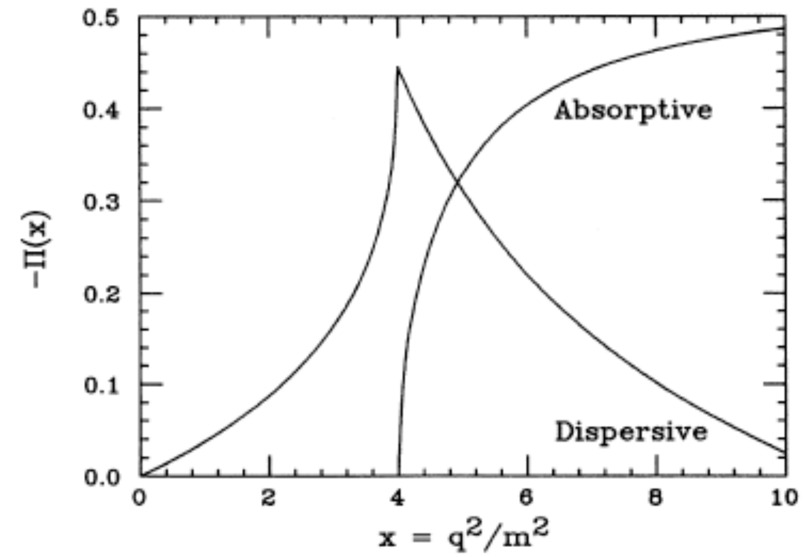
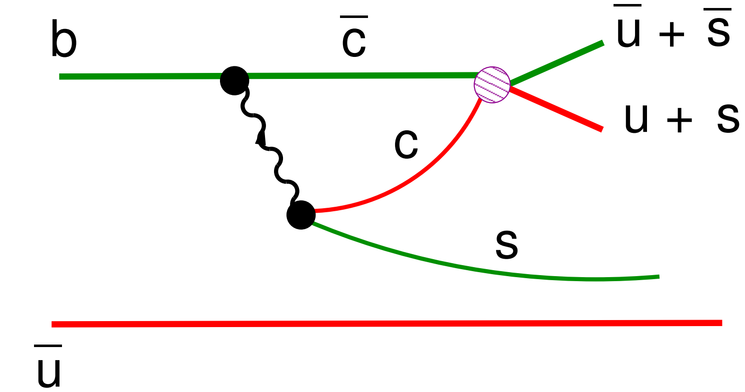
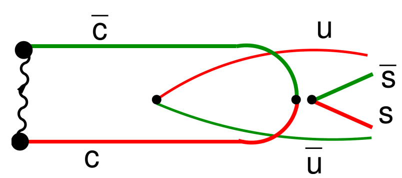
Gerard& Hou PRD43 (1991) 2909





- 

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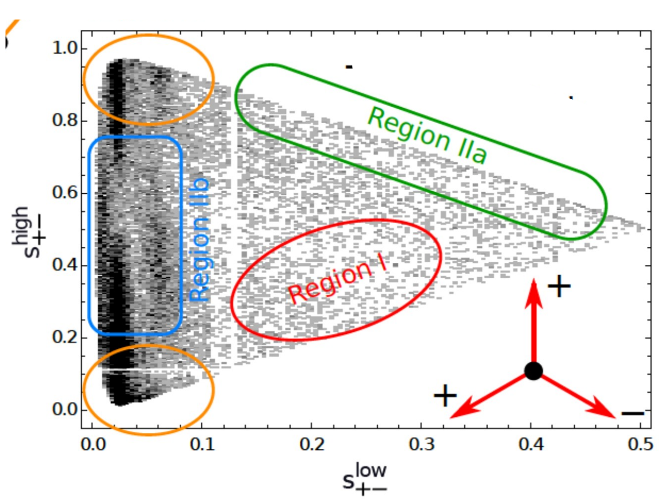
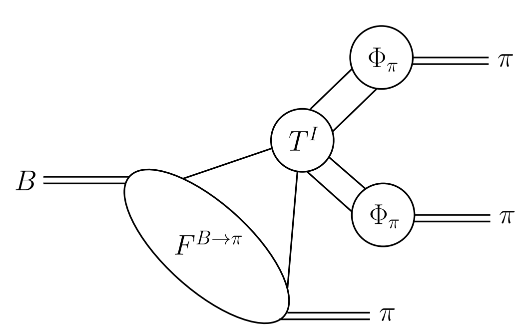
- Amplitude in region 1 $B \to 3\pi$

from Mannel et al



$$A_p(s) = T(s)(M_B^2 - s)f_+(s)$$



- Kernel of interaction

$$T(s) \equiv A_{parton}$$

- $f_+(s) = \dfrac{1}{1 - s/M_{Bs}^{*2}}$ → $B \to K$

vector form factor

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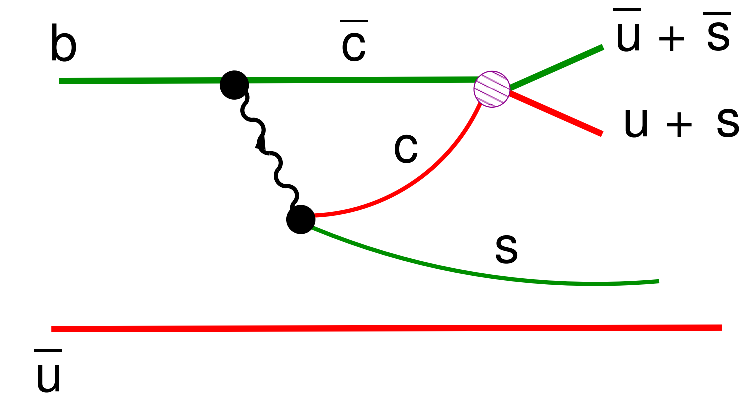
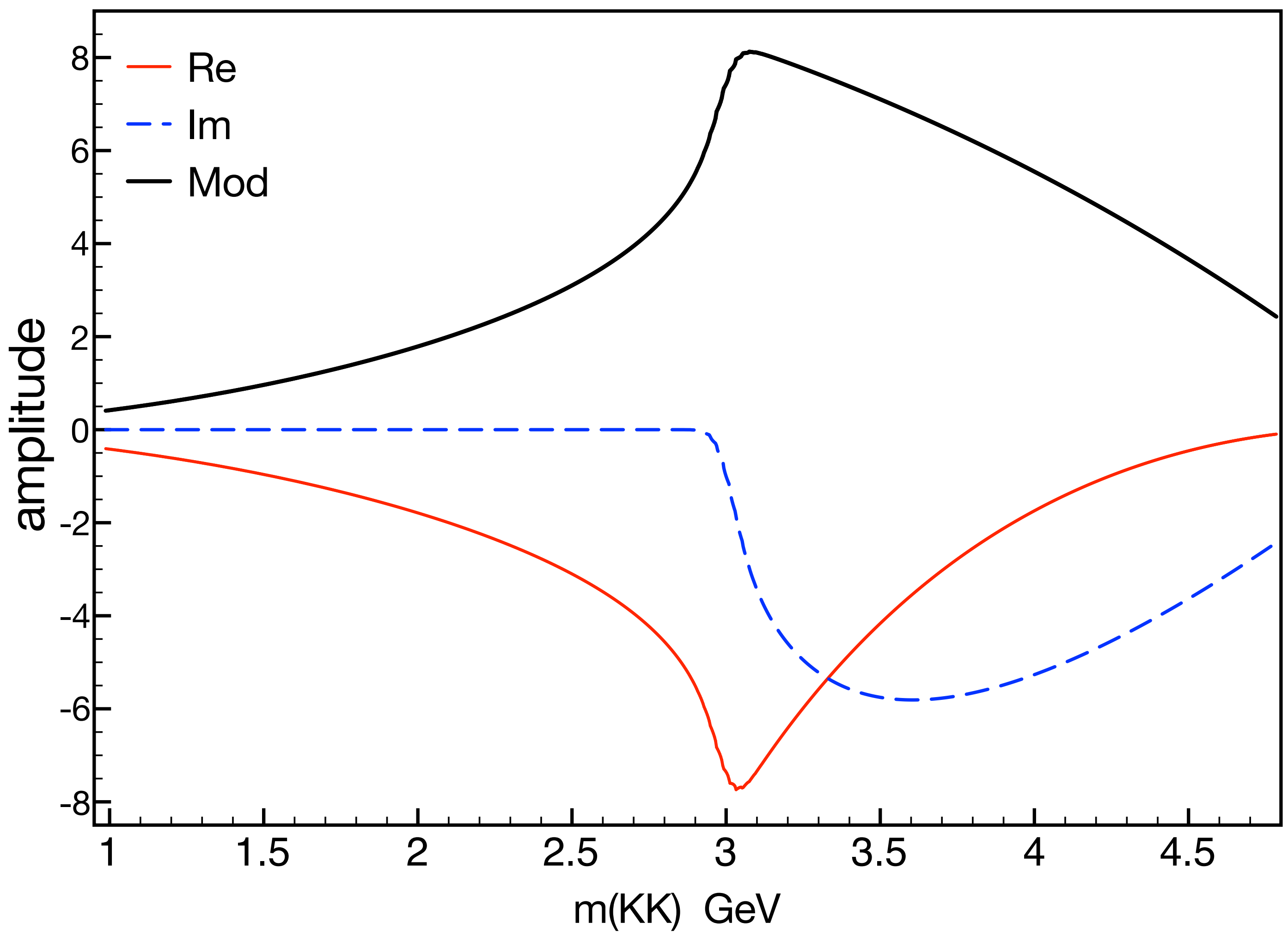
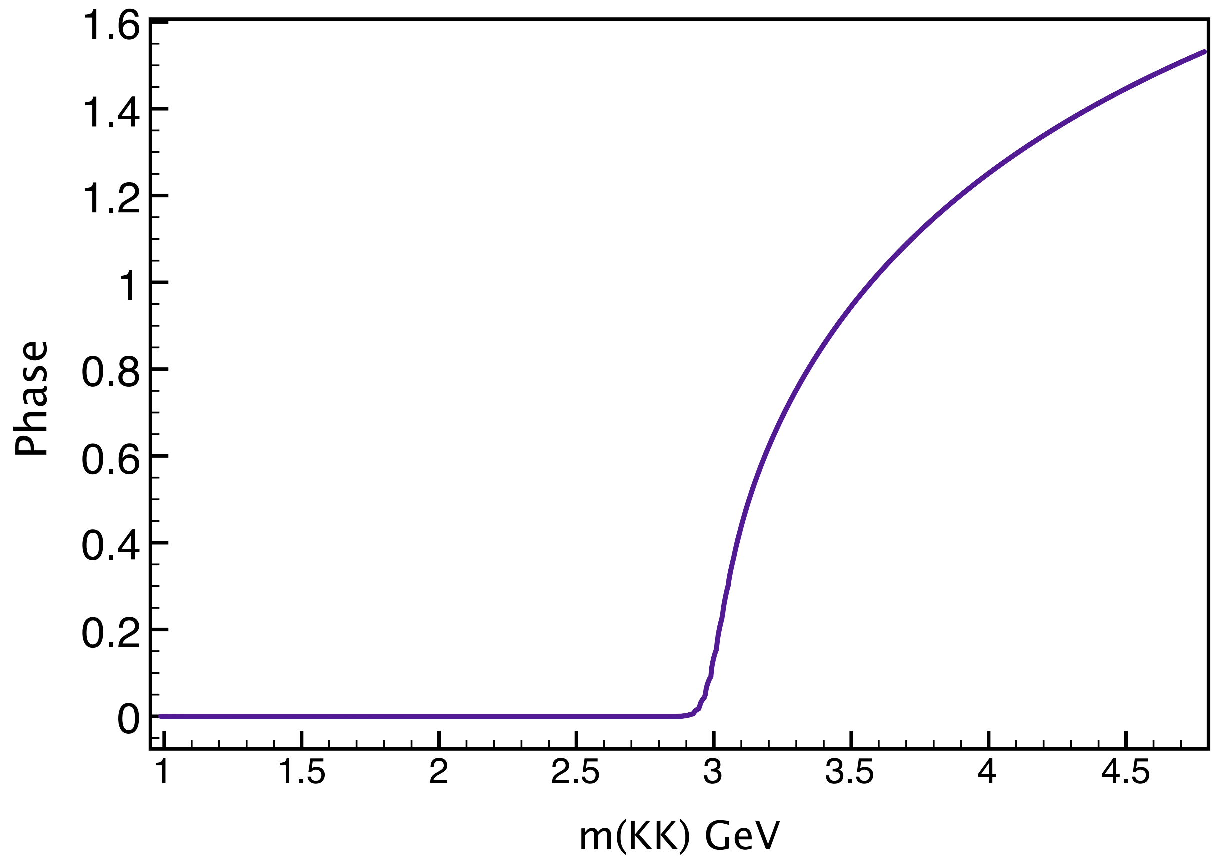
- gaussian parameters should be fitted to data

$$\frac{1}{2\,\pi\,\Gamma^2}\,e^{\frac{(m-m_{c0})^2}{2\,\Gamma^2}} \rightarrow \begin{array}{r}\Gamma = 0.02\,GeV\\ m_{c0} = 1.5\,GeV\end{array}$$







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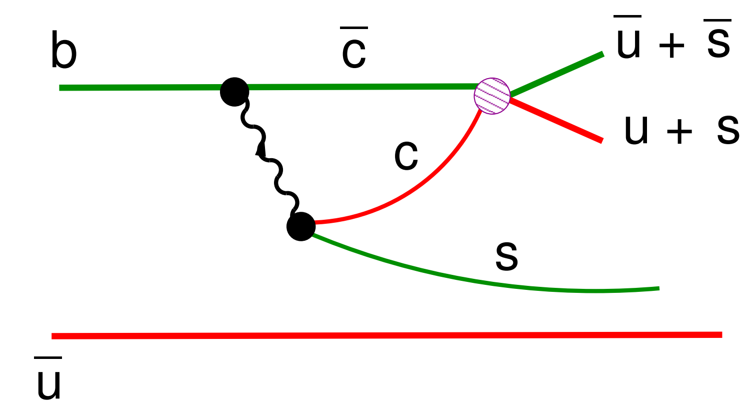
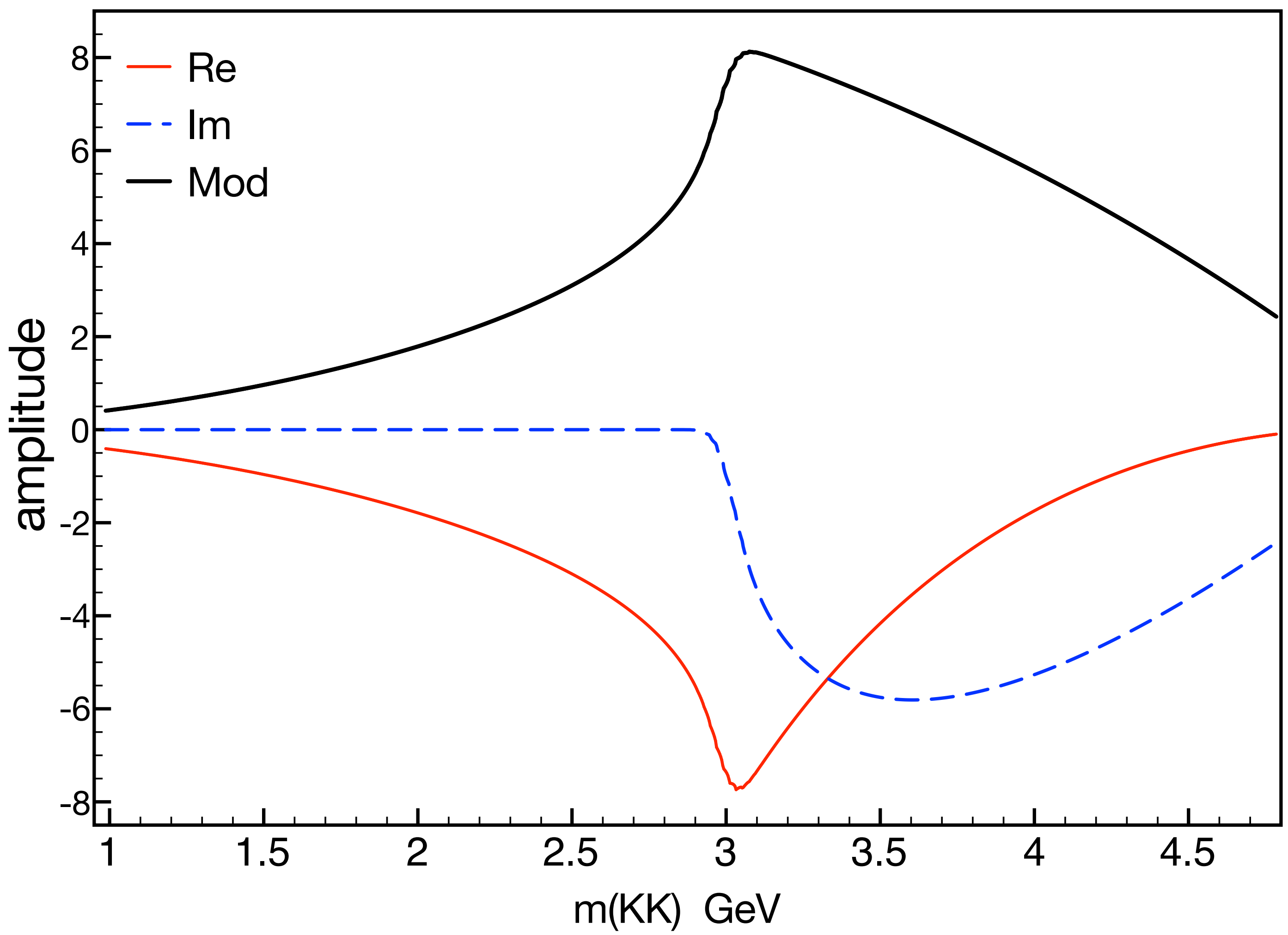
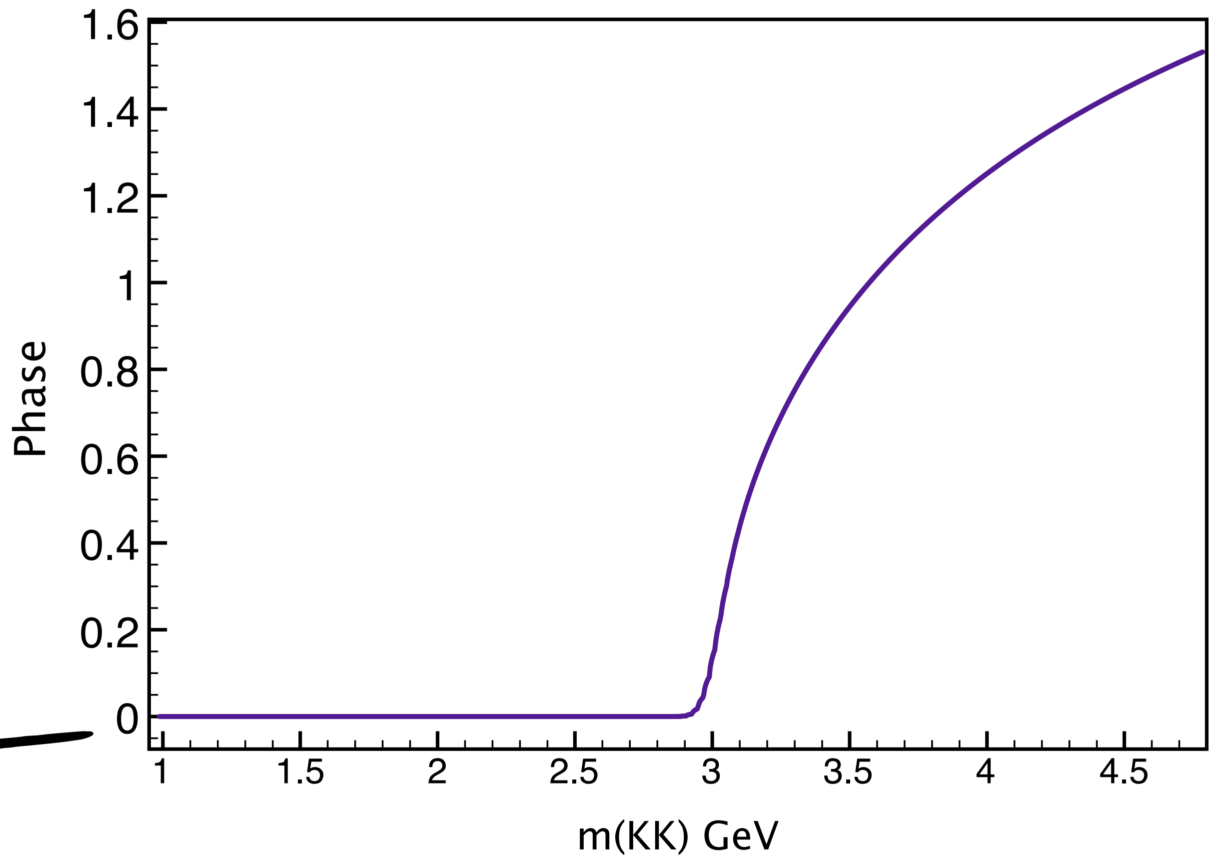




max at ~ 3 GeV



zero bellow threshold

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- gaussian parameters should be fitted to data

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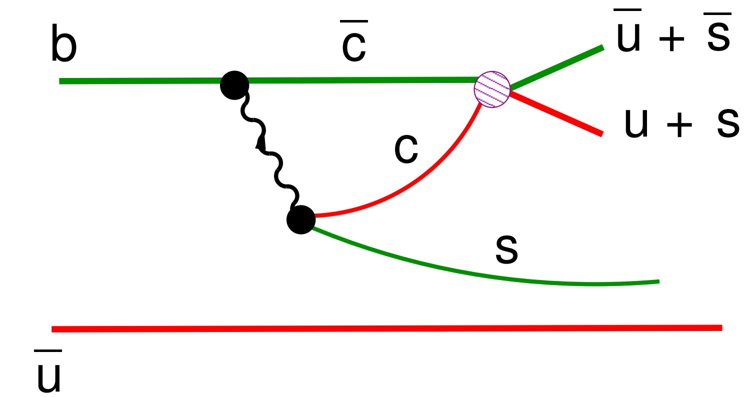
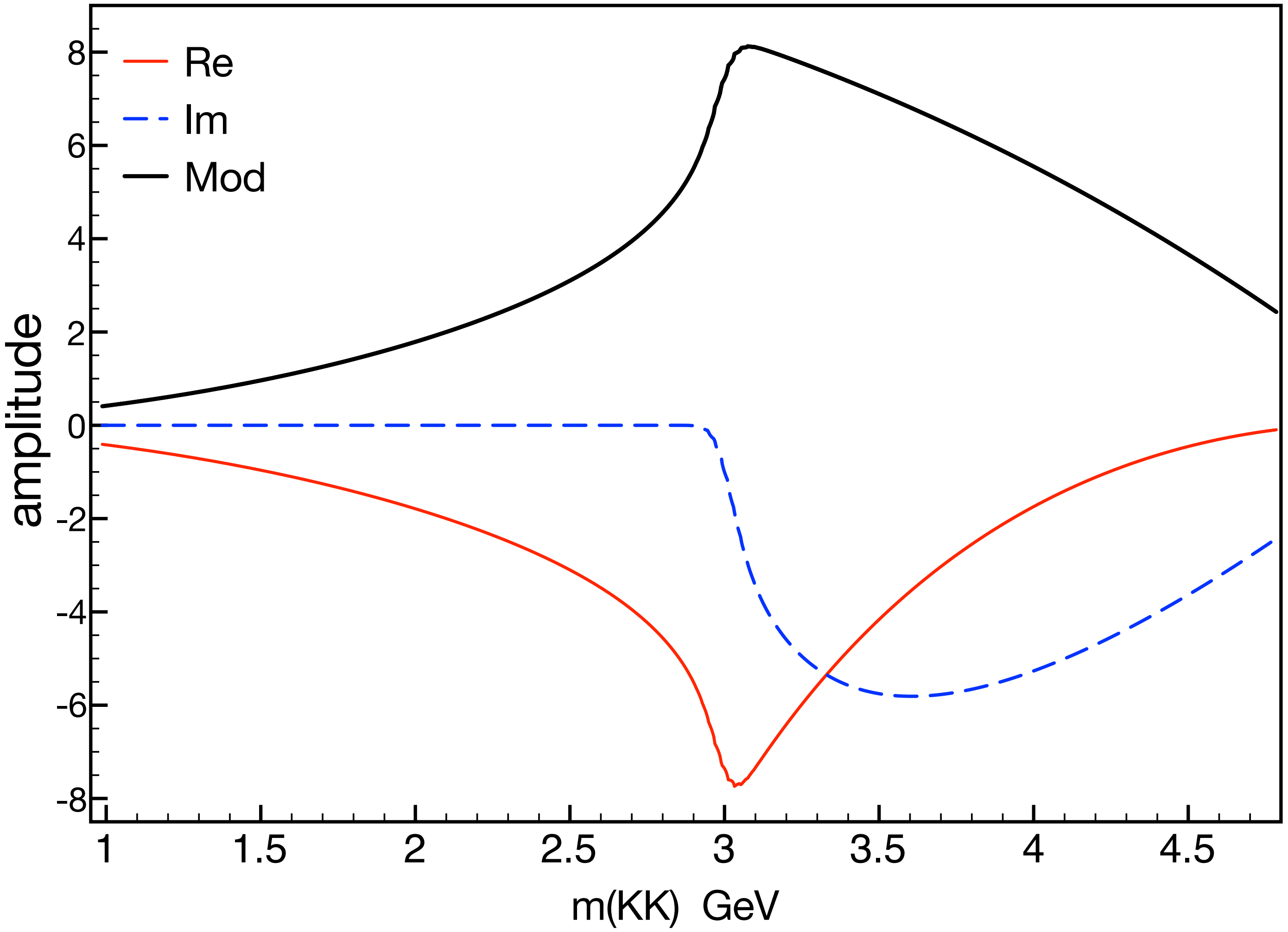
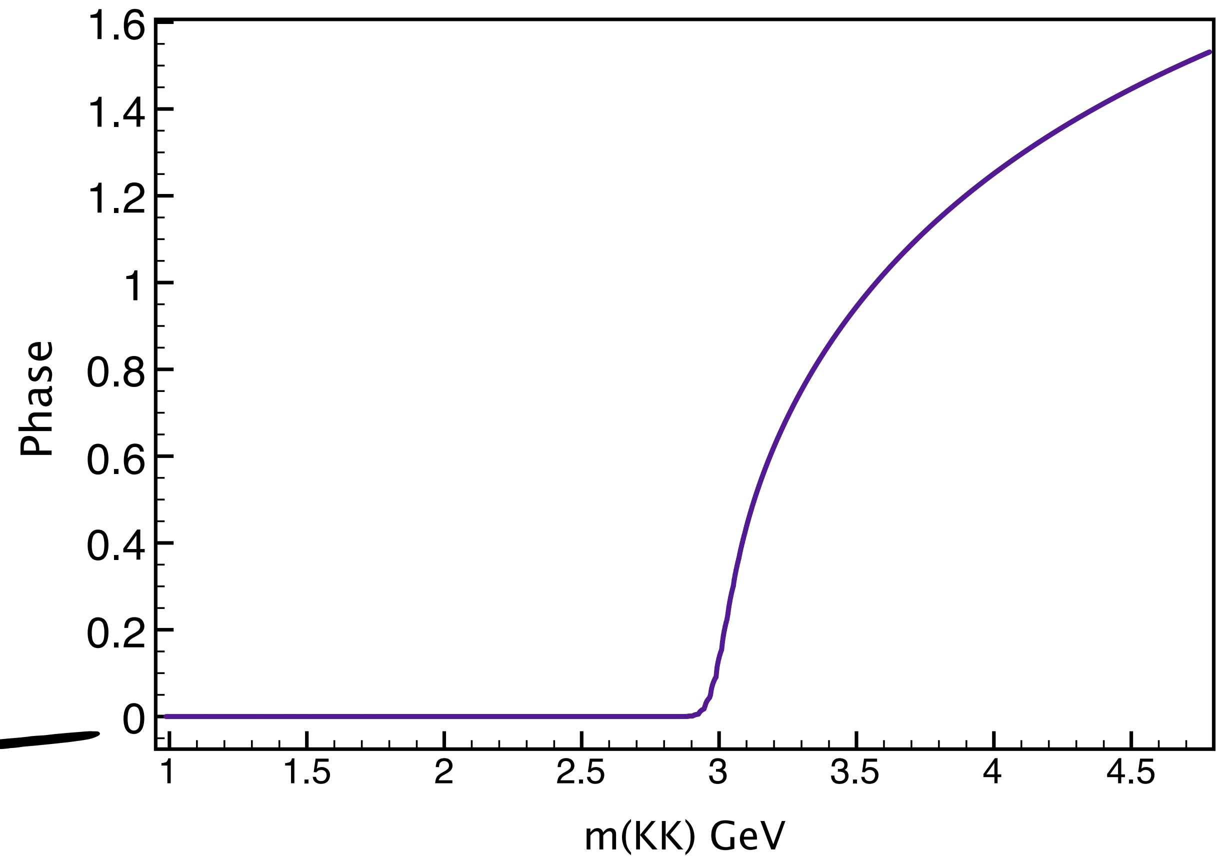




max at ~ 3 GeV

can change the inference pattern



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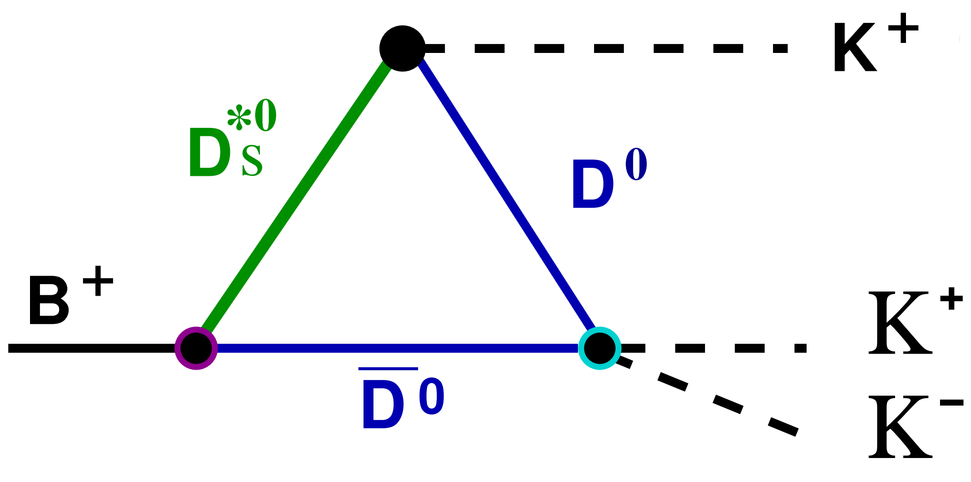
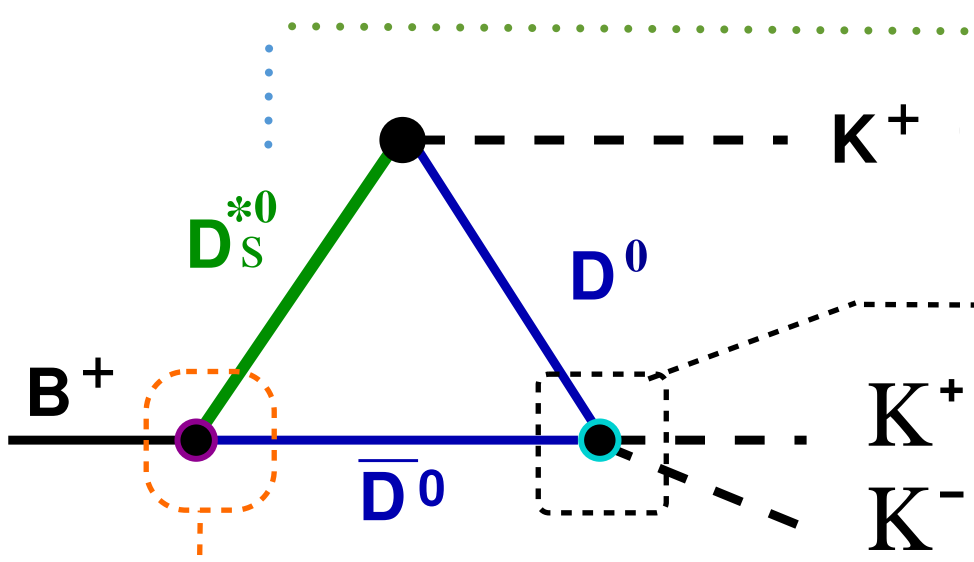

K+
D*0 S
D0
B+
K+
D̄0
K−

form factor for $W^+ \to D^0 K^+$



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

phenomenological:
S- matrix unitarity + Regge theory

weak transition $B^+ \to W^+ \bar{D}^0$ → $C_0 \times$ form factor to regulate

- $Br\left[B \to D D_s^*\right]$ ~1% → 1000 x $Br\left[B \to KKK\right]$

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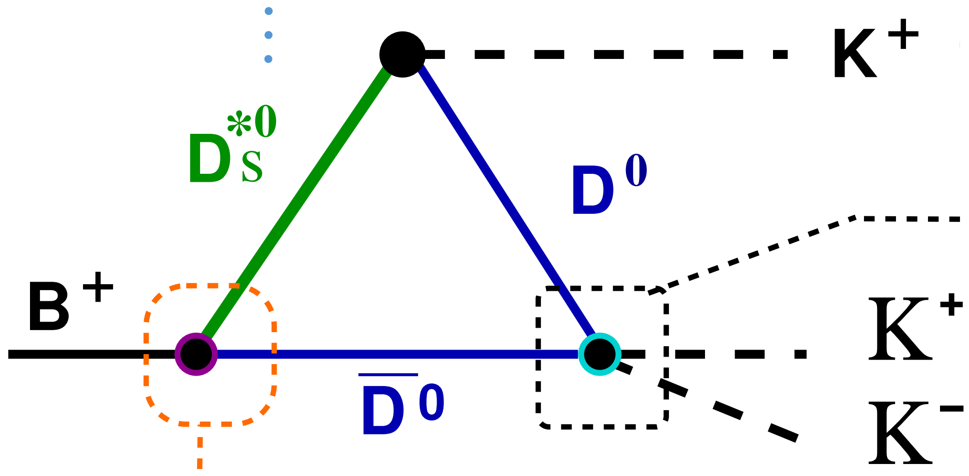
hadronic loop



form factor for $W^+ \to D^0 K^+$

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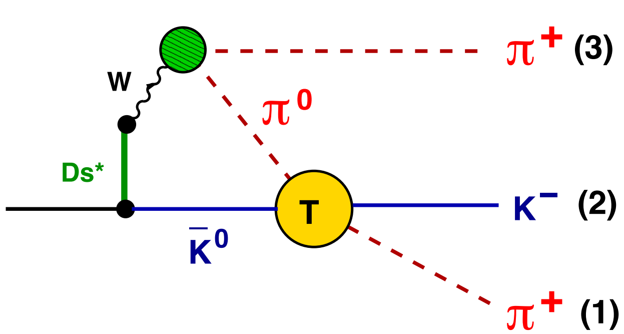
- hadronic loop → three-body FSI - introduce new complex structures

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

PCM & I Bediaga
arXiv:1512.09284

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



PCM & M Robilotta
PRD 92 094005 (2015) [arXiv:1504.06346]
PCM et al
PRD 84 094001 (2011) [arXiv:1105.5120]

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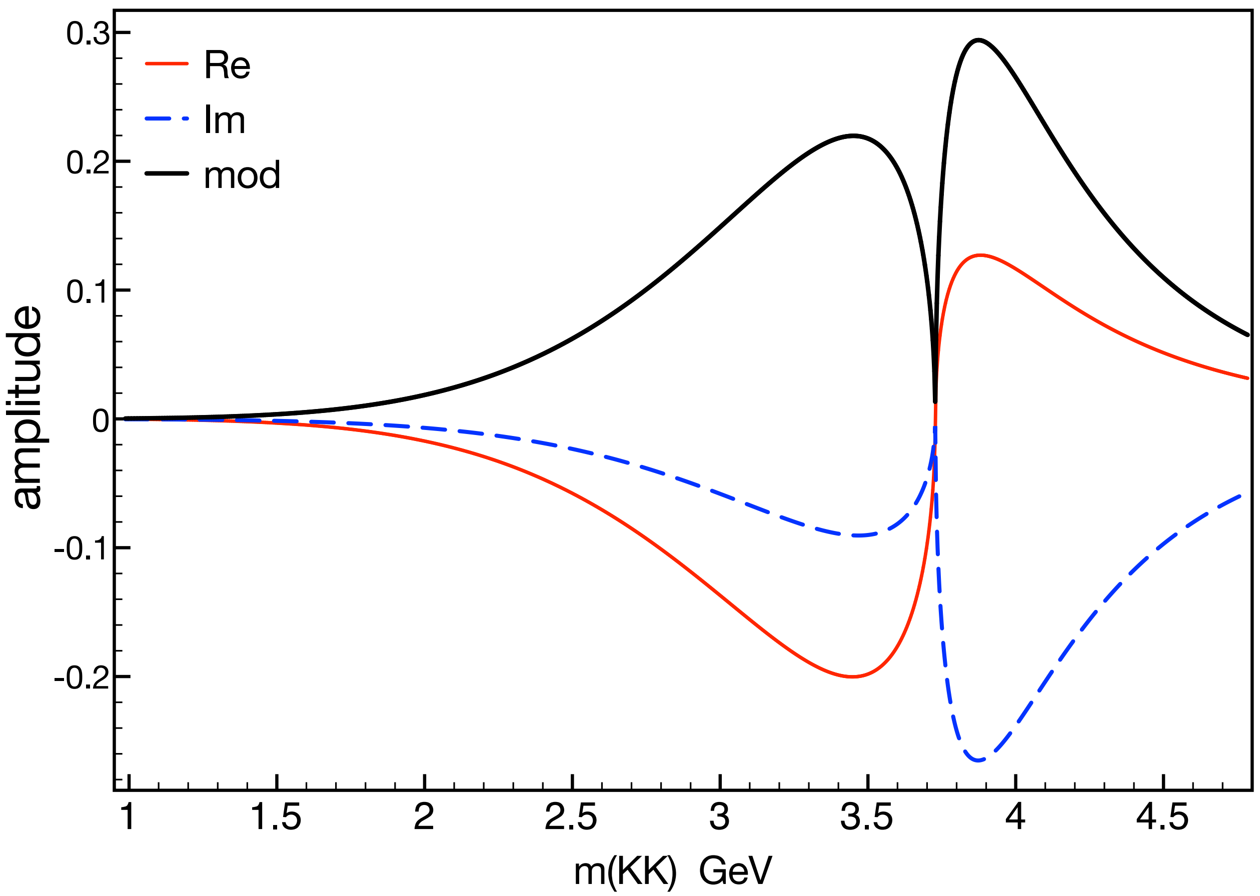
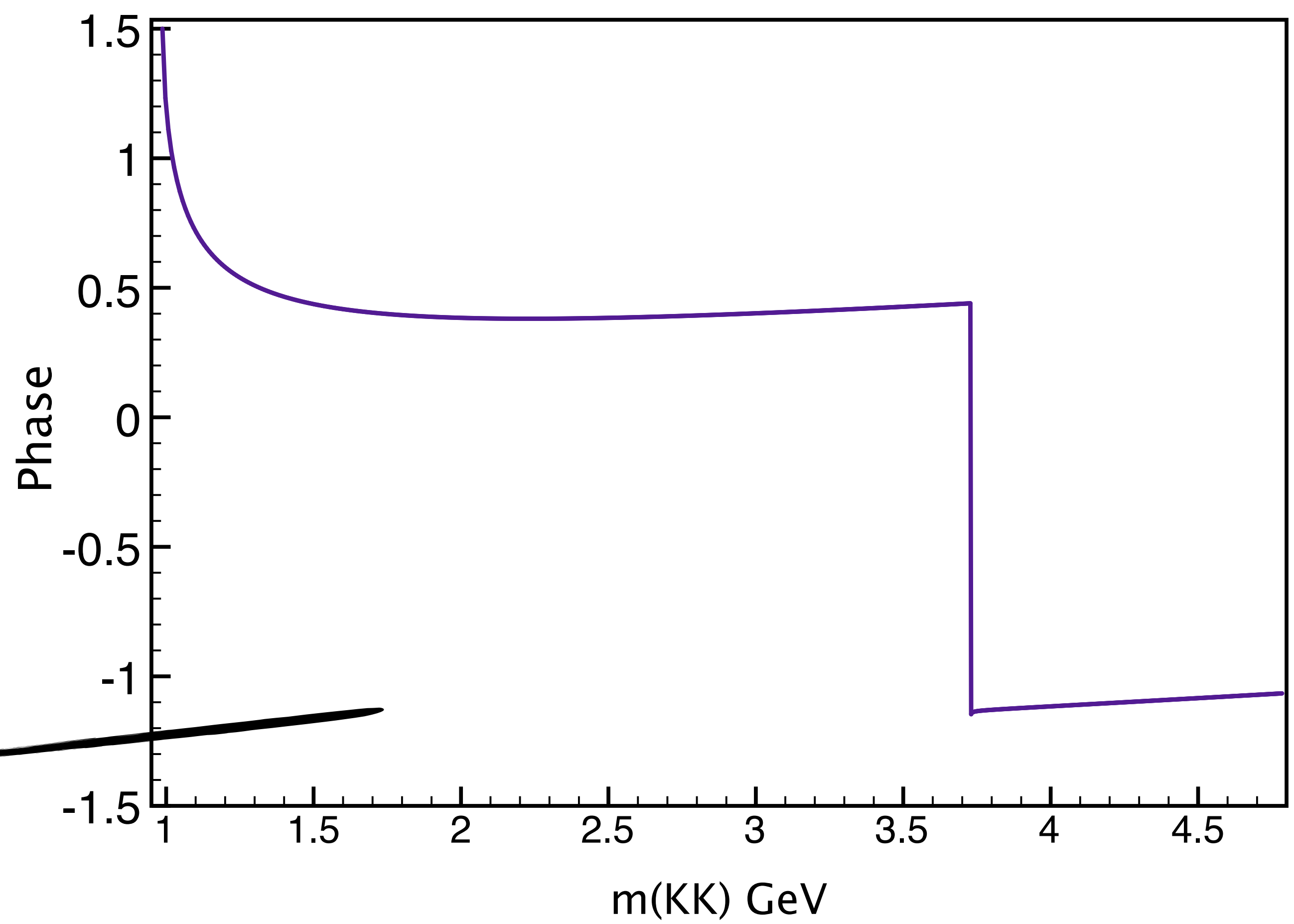
$D^0\bar{D}^0 \to K^+K^-$ scattering amplitude

- freedom to chose $D^0\bar{D}^0 \to K^+K^-$ parameters → fix by data!



→ zero at threshold



discontinuity at threshold ←

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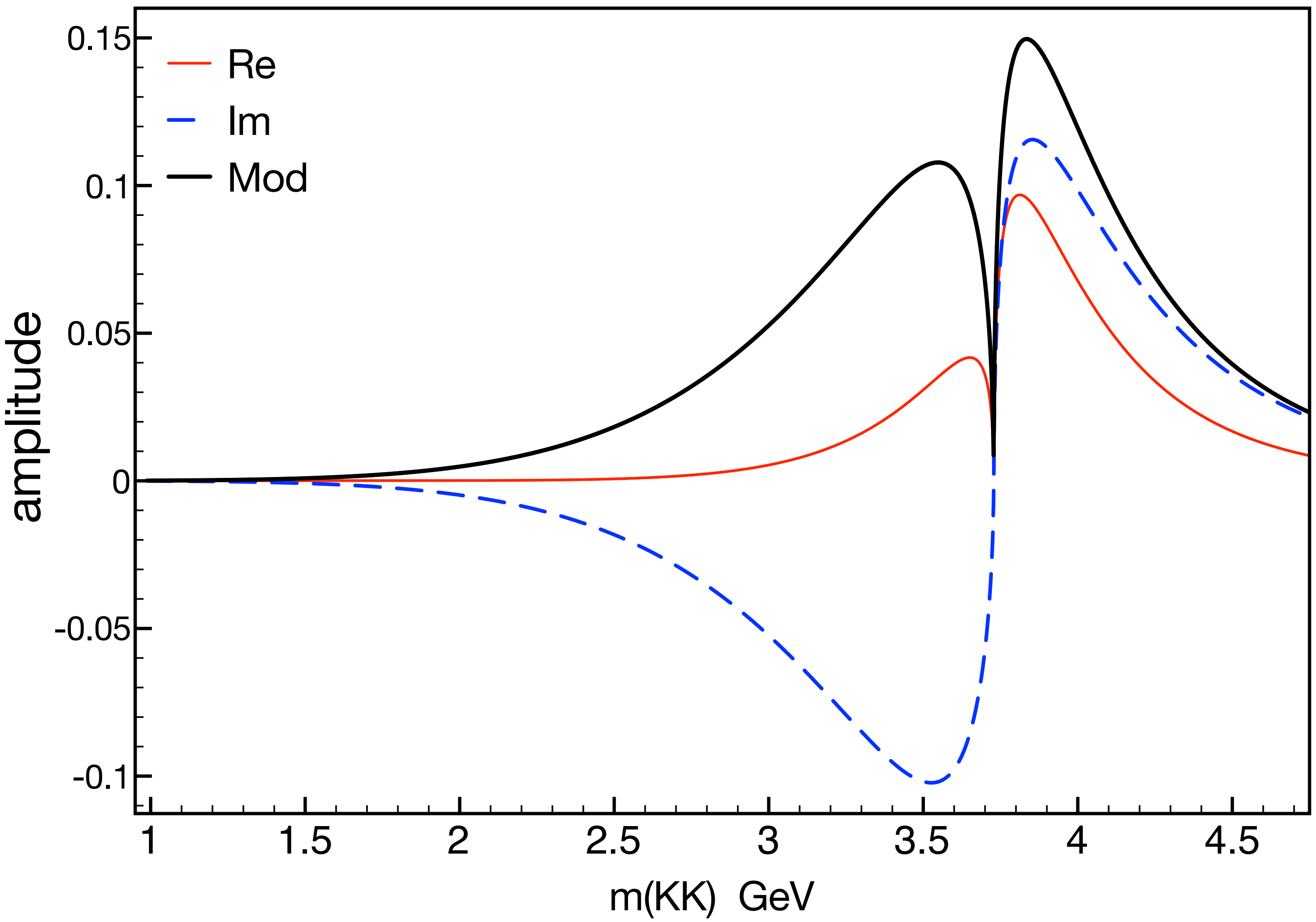
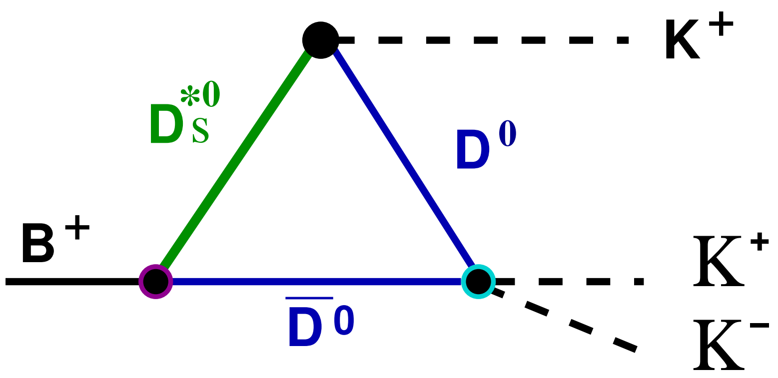
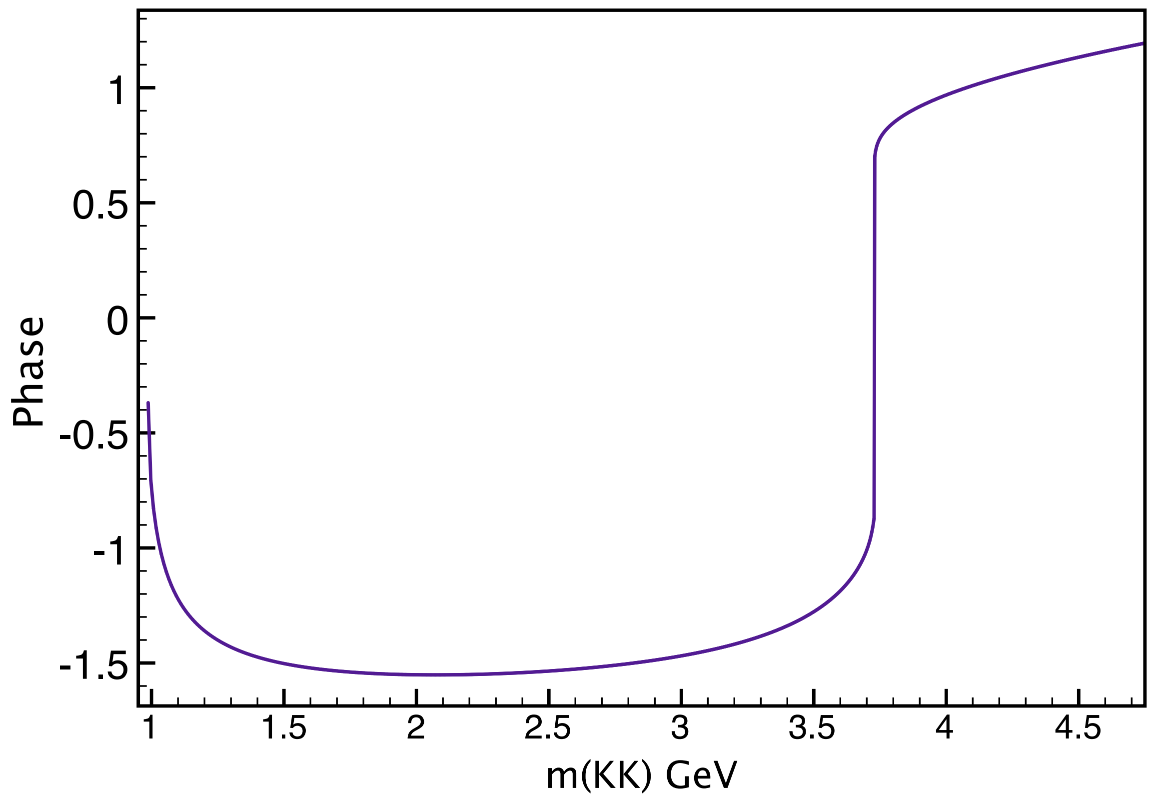
hadronic loop

- total amplitude $A = i\, C_O\, T_{DD\to KK}\, A_P^h$







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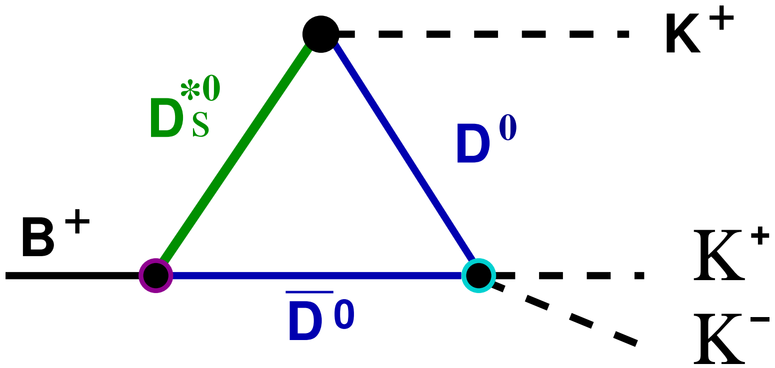
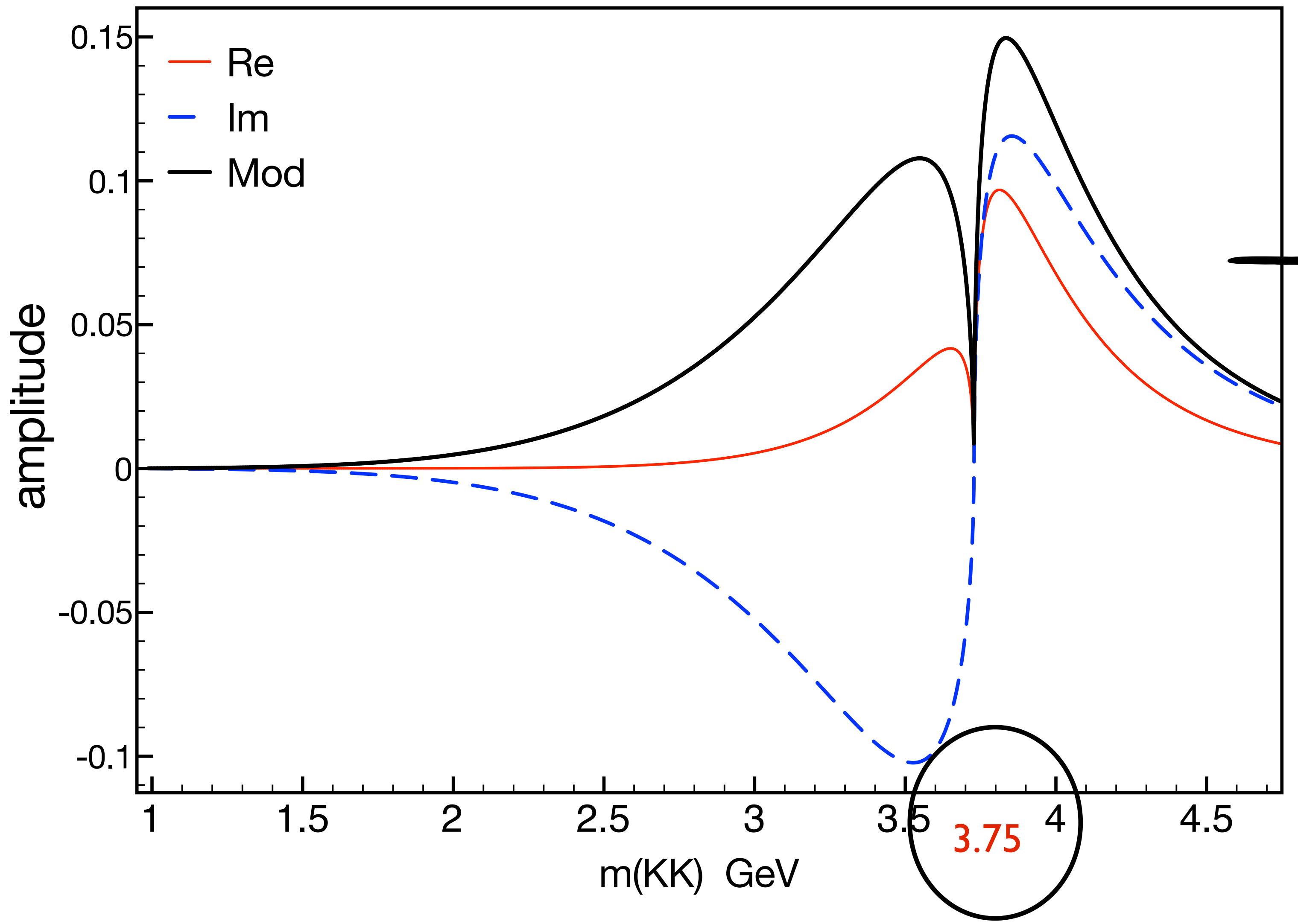
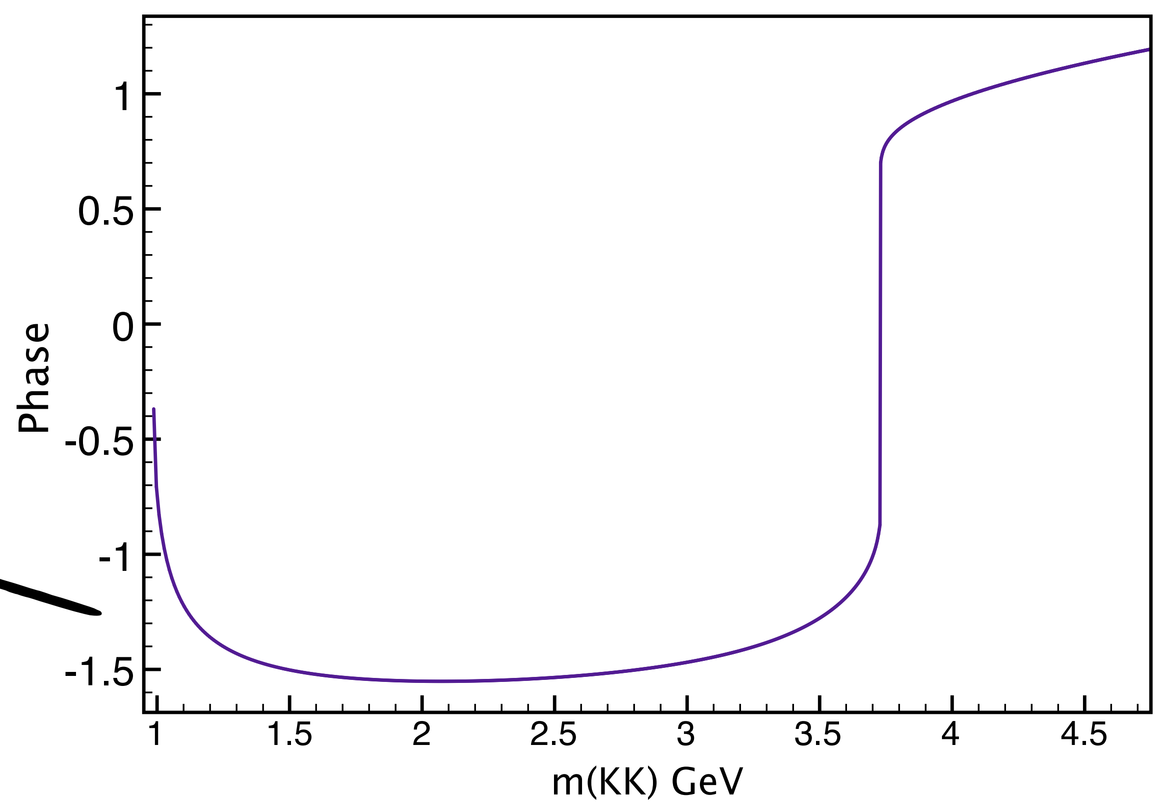




zero in between two bumps

non zero bellow threshold



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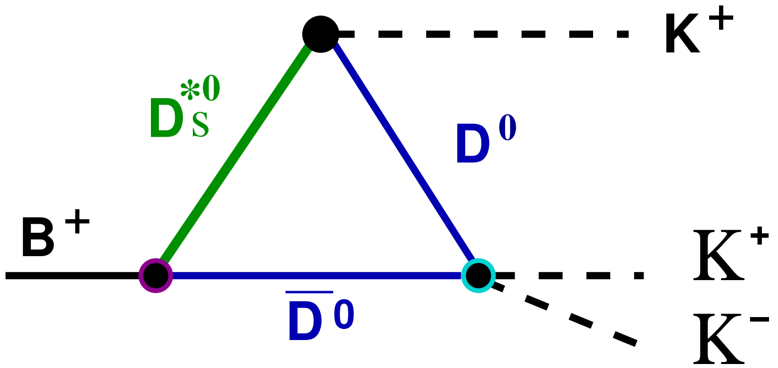
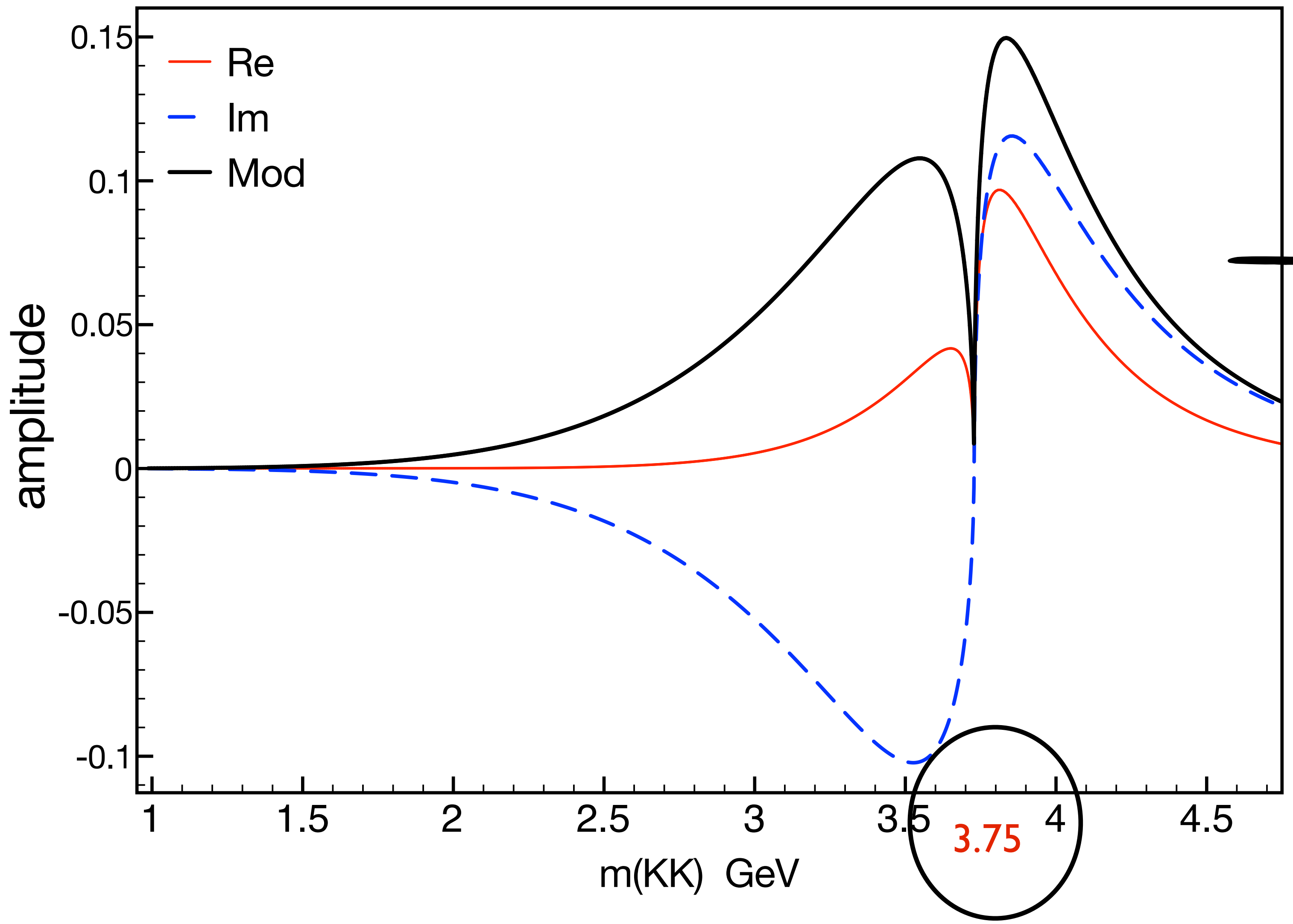
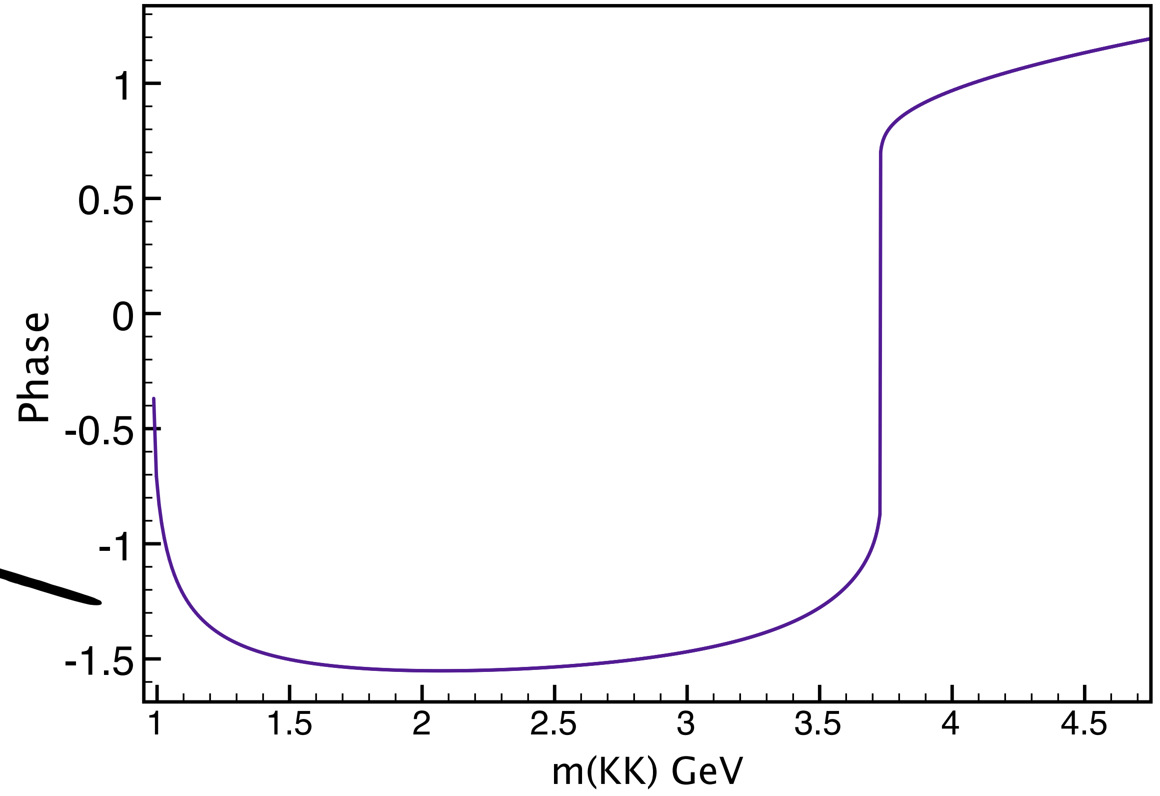
- total amplitude $A = i\, C_O\, T_{DD\to KK}\, A_P^h$





zero in between two bumps

can change CPV signal in DP!!!



non zero bellow threshold

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

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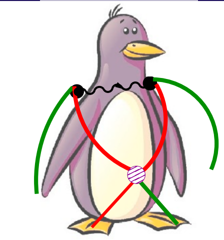
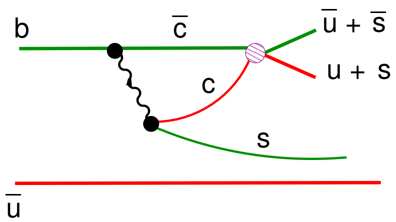
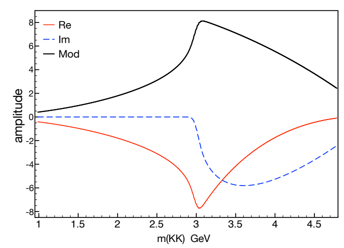


$B \to KKK$ charm penguins

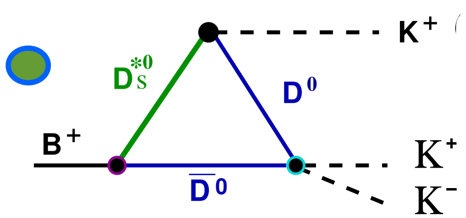


(partonic)

- wide amplitude spread in the center of the Dalitz plane



→ NR population observed!



(hadronic)

- amplitude: two narrow peaks in between a zero (threshold)
  → superposition of triangles

- phase: change sign in a region close where data shows a CP asymmetry change in sign!

→ **FSI mechanism to produce CP asymmetry at high mass**

- interference between: triangles & partonic & other NR sources & resonances
  → can shift the position of the CP asymmetry sign change

→ should be tested in data ANA!

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final remarks

- FSI → superposition of resonant and non-resonant at low and high energy
- different weak vertices topologies for same FS → how to add them?
    - need to know about short distance!
- to improve ANA and learn from data we need:

→ good analytic and unitary 2-body coupled-channels;

- with LASS/GLASS and Matriz K we don't learn much…

→ B-decays must include the diff QCD regime dynamics;

- NR charm penguins!!

→ NR 2 and 3-body effects;

- at least a way to parametrize this different from 2-body without adding phases

How to do that? … → …

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TRR110 Workshop - Amplitudes for Three-Body Final States

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Patricia Magalhães
Bastian Kubis
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Meson-Meson scattering

Jacobo Ruiz de Elvira (Bern)
Dispersive analysis for πK

Bachir Moussallam (Paris)
Dispersive analysis of ππ, πK and πη

Miguel Albaladejo (Murcia)
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Thank you!!!

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Extra slides

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FSI in three-body decay :

references

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Suzuki,Wolfenstein, Phys. Rev. D 60 (1999)074019;
Falk et al. Phys. Rev. D 57,4290(1998);
Blok, Gronau, Rosner, *Phys. Rev Letters* 78, 3999 (1997).

many more ...

Charm Penguin

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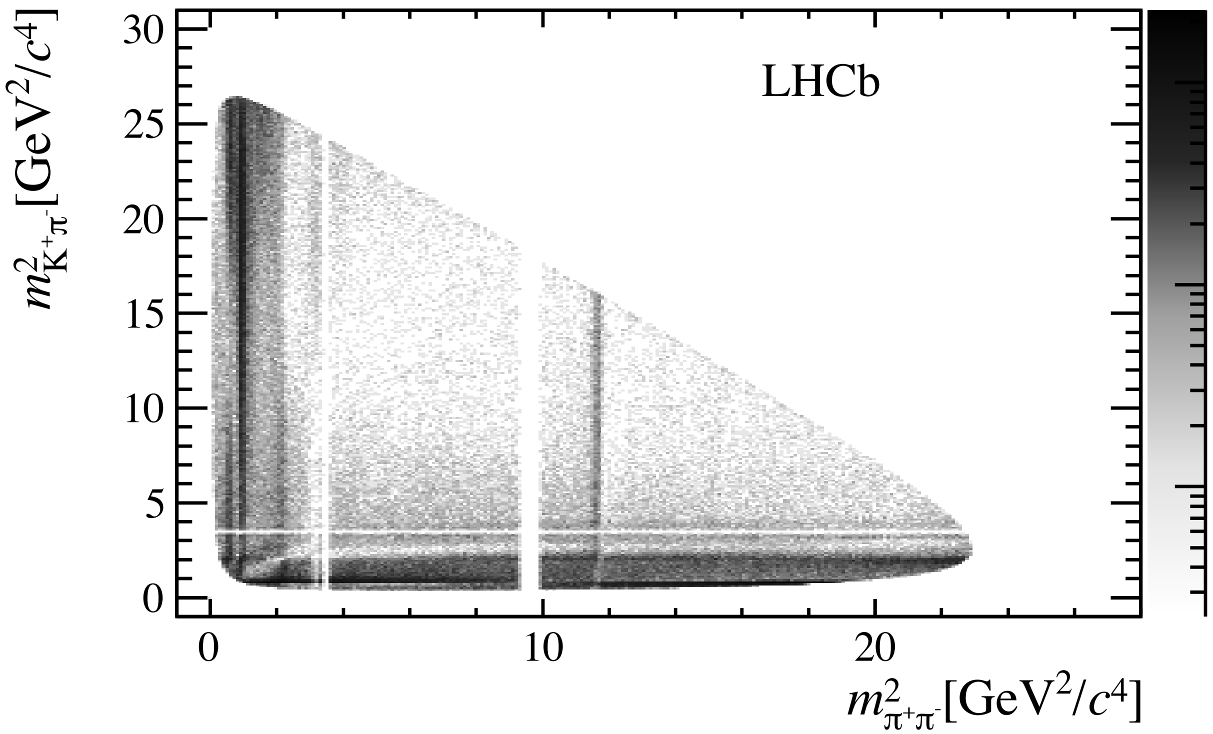
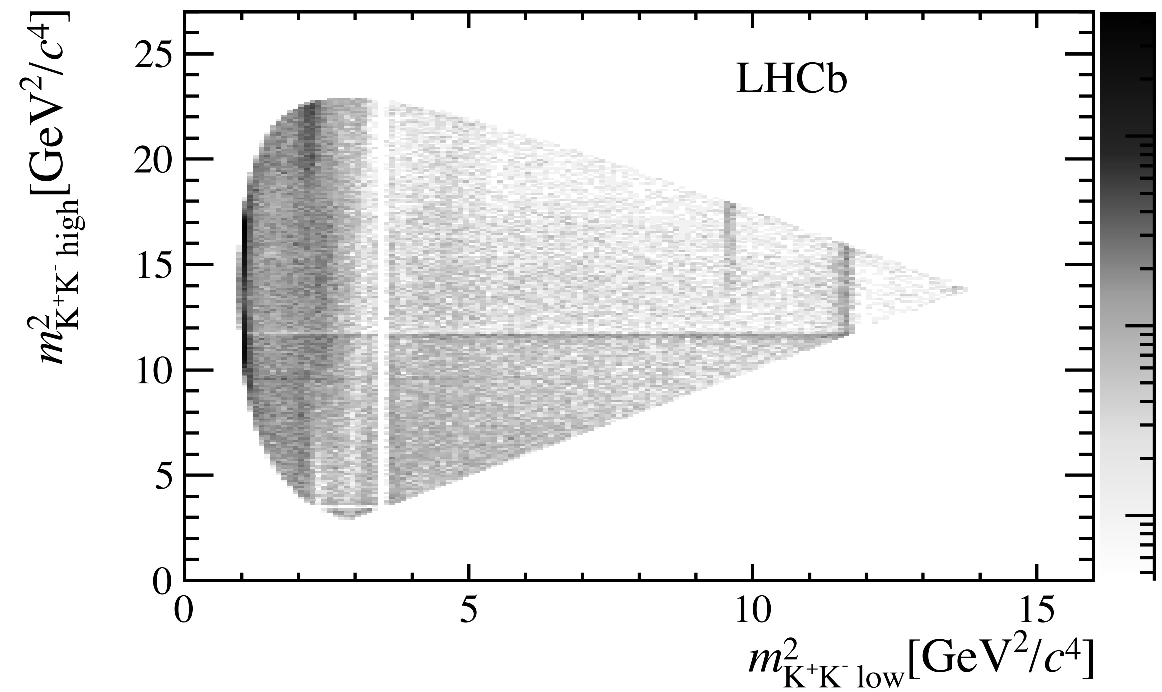
if needed

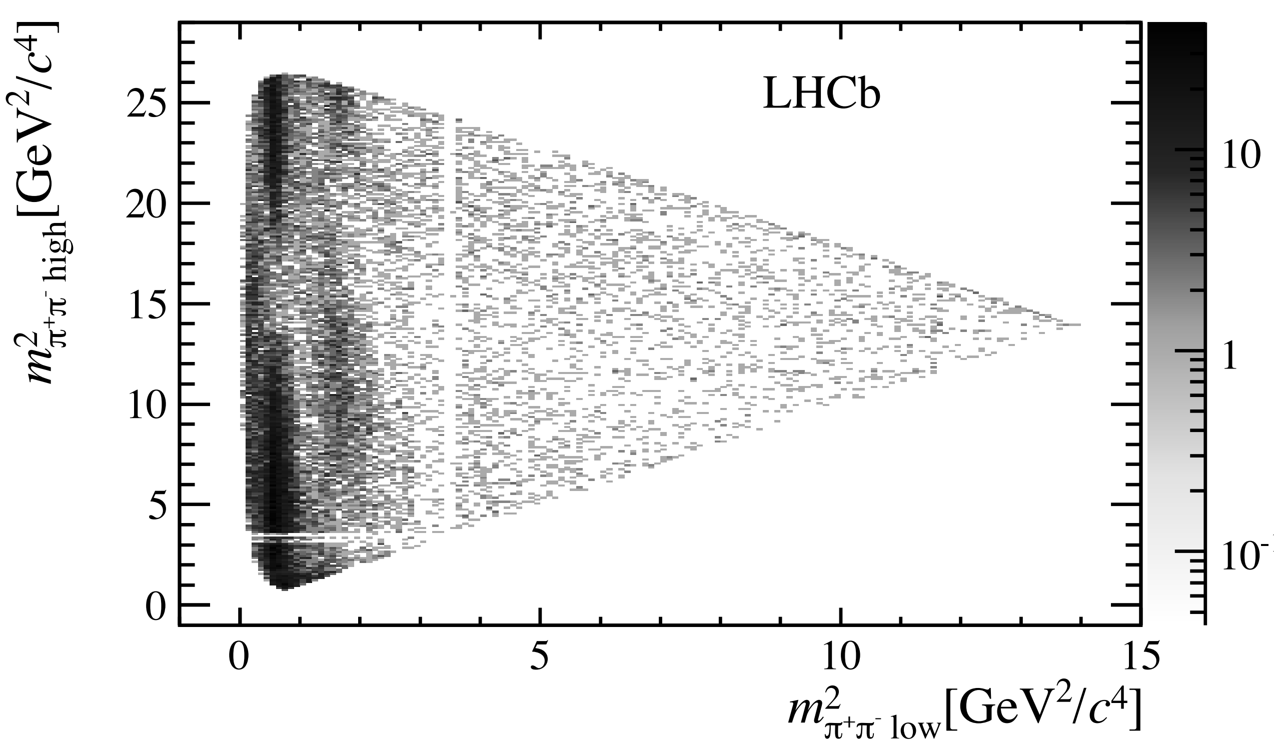
Kpp



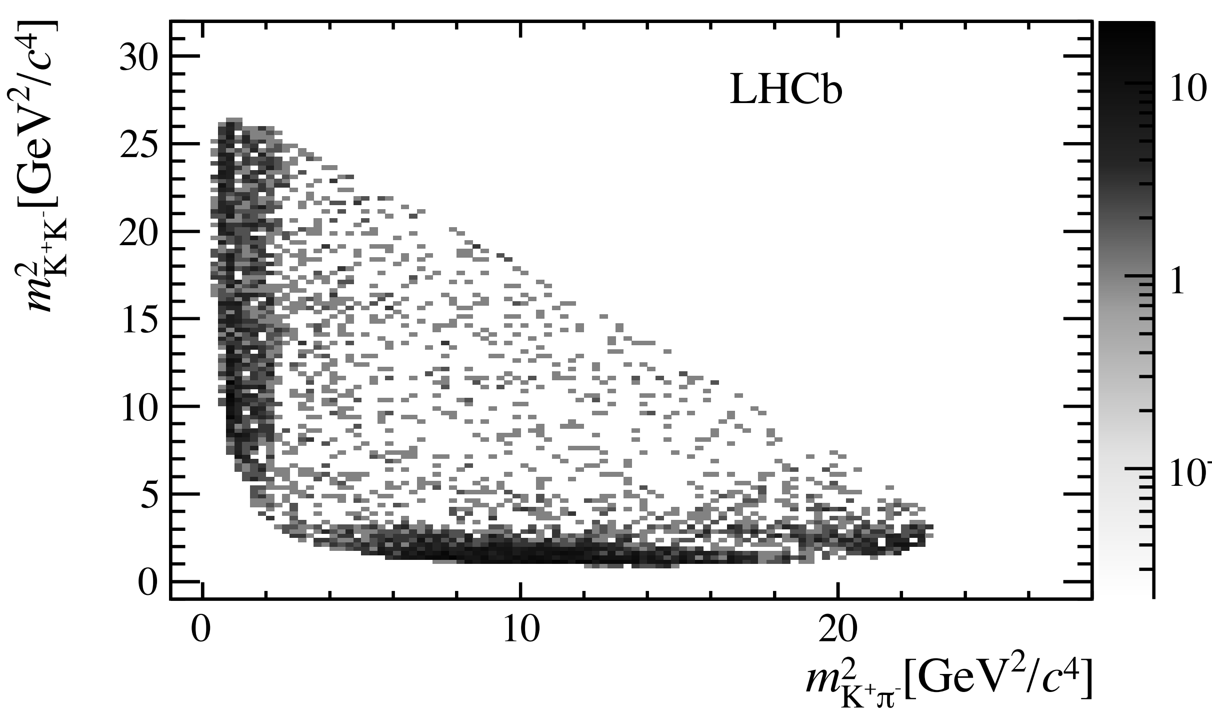
KKK



ppp

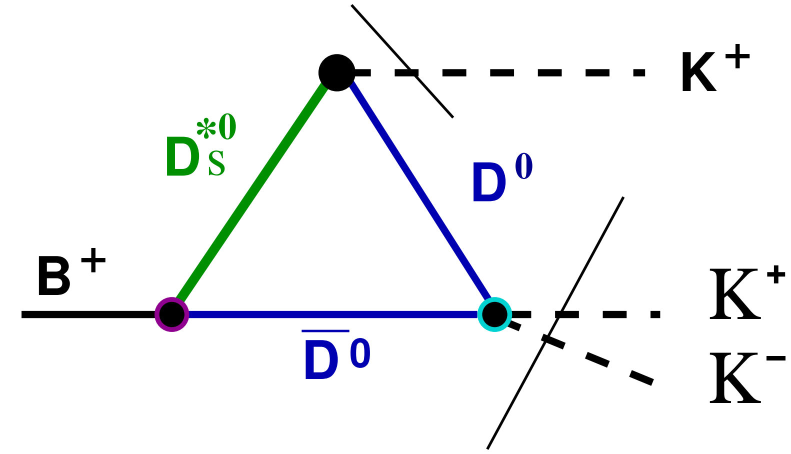


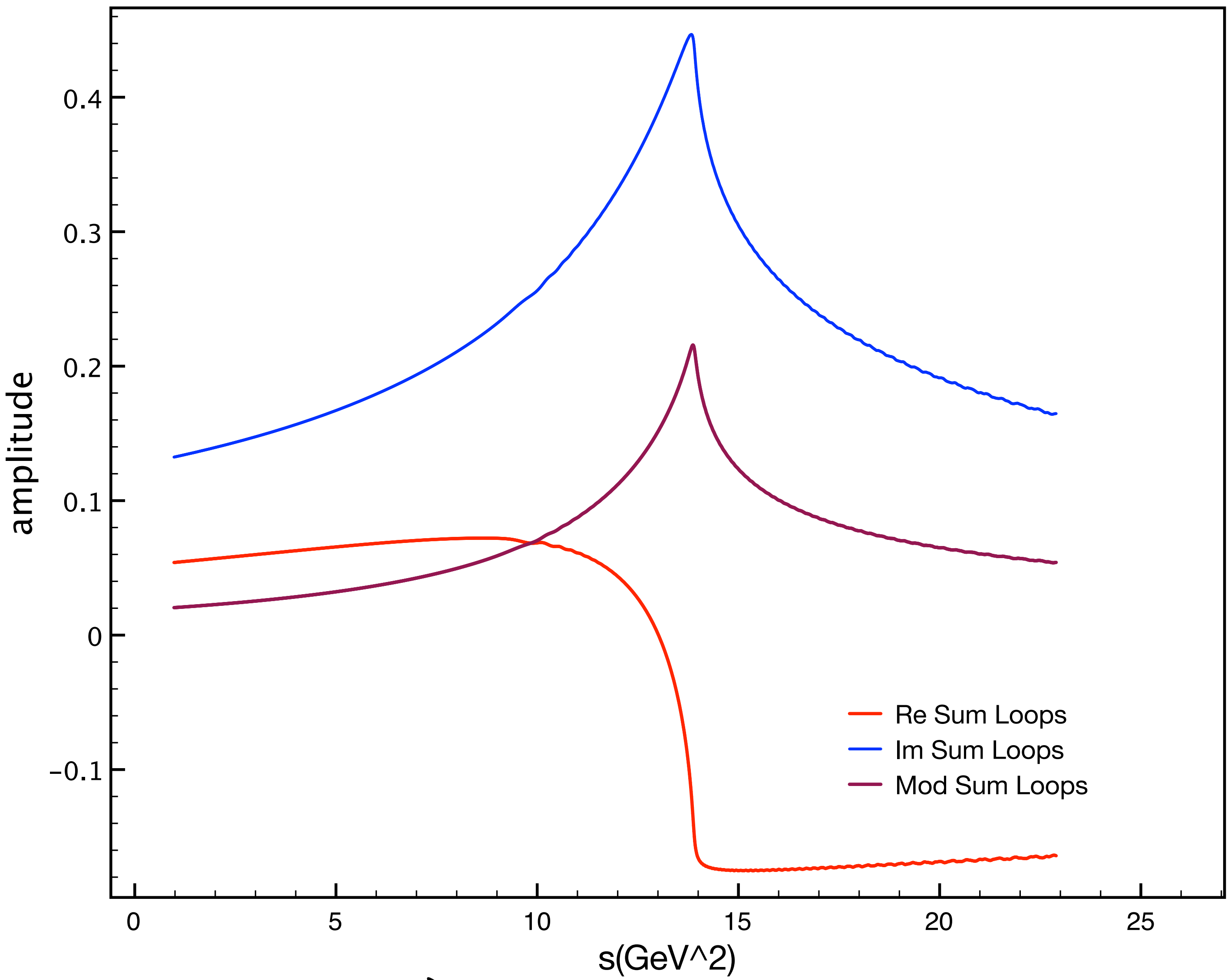
KKp



- loop contribution

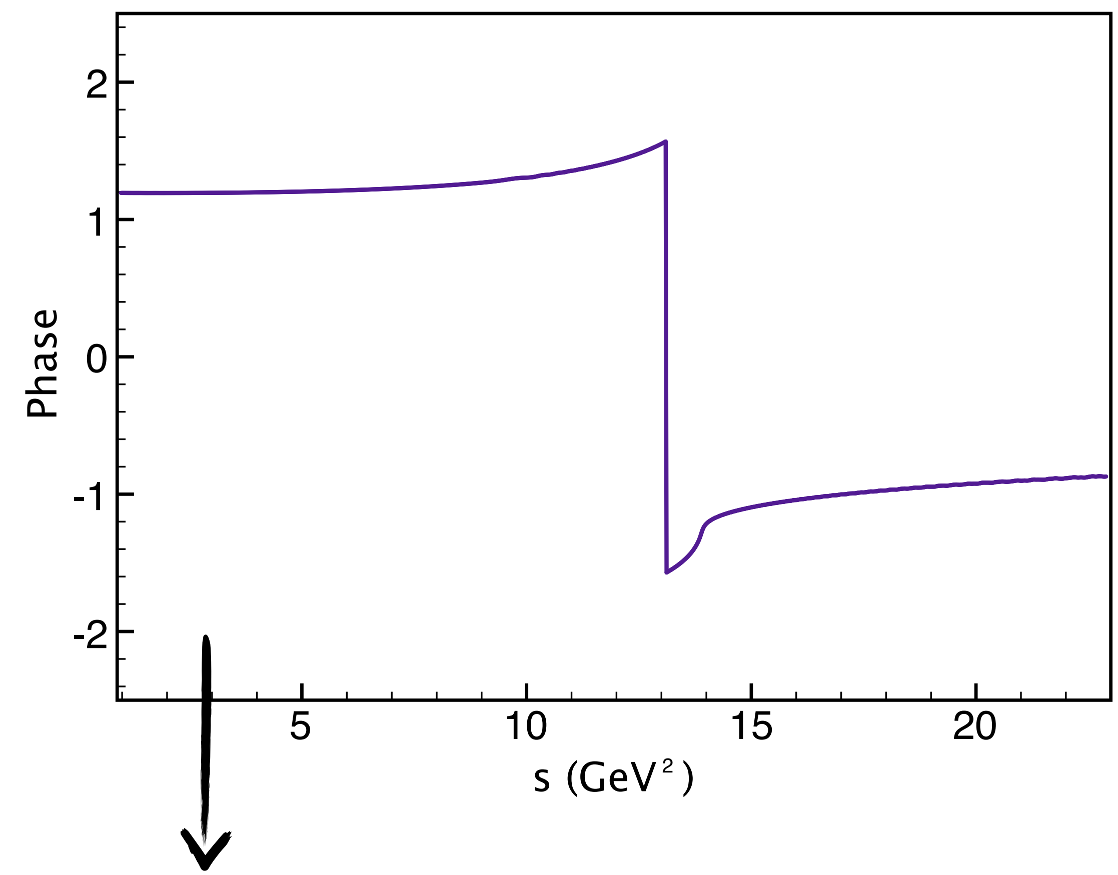
$$A_P^h = i\int \frac{d^4\ell}{(2\pi)^4}\,\frac{\Delta_{D^0}+2\,\Delta_{\bar{D}^0}-2\,s_{23}+3\,M_K^2+M_B^2-l^2}{\Delta_{D^0}\,\Delta_{\bar{D}^0}\,\Delta_{D*}\,[l^2-m_{B^*}]}$$





off shell effect

- two threshold effect



discontinuity at threshold

allow CPV below threshold

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

- not well understand on literature

Donoghue *et al.*, *PRL* 77(1996)2178;
Suzuki, Wolfenstein, PRD 60 (1999)074019;
Falk et al. PRD 57,4290(1998);
Blok, Gronau, Rosner, PRL 78, 3999 (1997).

- important as FSI in B two-body decays

- phenomenological amplitude

Antunes, Bediaga, Frederico, PCM
ICHEP2016 - proceedings

  - unitarity of the S-matrix $S = \begin{pmatrix} \eta\, e^{2i\alpha} & \sqrt{1-\eta^2}\, e^{i(\alpha+\beta)} \\ -\sqrt{1-\eta^2}\, e^{i(\alpha+\beta)} & \eta\, e^{2i\beta} \end{pmatrix}$

  - inspired in the damping factor of the S matrix i.e. $\pi\pi \to KK$

$$\eta = \mathcal{N}\sqrt{s/s_{th} - 1}/(s/s_{th})^{2.5}$$

KK: $e^{2i\alpha} = 1 - \frac{2ik_1}{\frac{c}{1-k_1/k_0} + ik_1}$, DD: $e^{2i\beta} = 1 - \frac{2ik}{\frac{1}{a} + ik}$

$$S_{\beta,\alpha} = \delta_{\beta,\alpha} + it_{\beta,\alpha}$$

$$t_{\beta,\alpha} = \sqrt{1-\eta^2} e^{i(\alpha+\beta)}$$

$k = \sqrt{\frac{s-s_{th}}{4}}$, $k_1 = \sqrt{\frac{s-s_{th1}}{4}}$ and $k_0 = \sqrt{\frac{s_0-s_{th}}{4}}$

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D—>KKK

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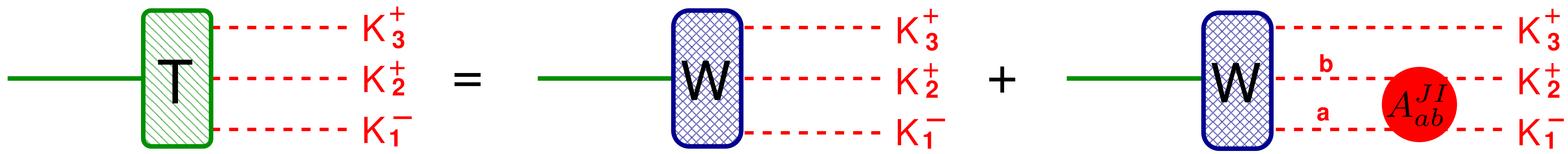
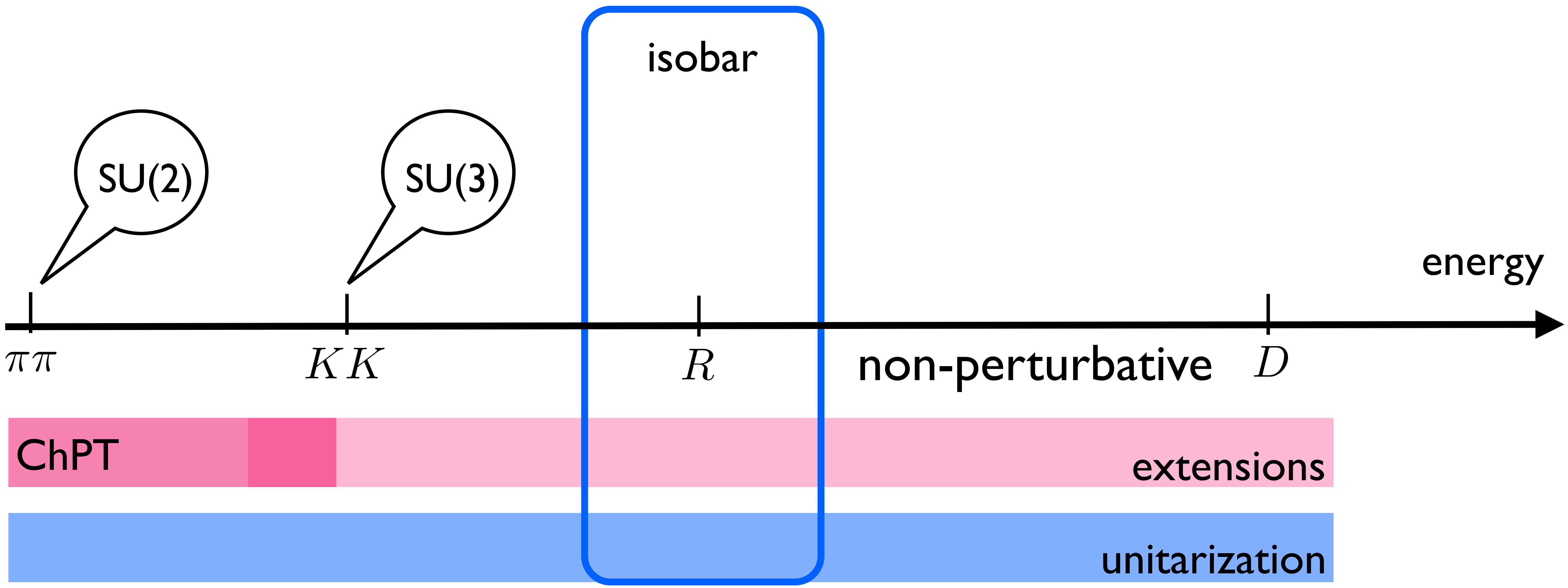
theory - $D^+ \to K^- K^+ K^+$





- A_{ab}^{JI} : unitary coupled-channel amplitude for $[J, I = (0,1), (0,1)]$

  $\longrightarrow ab = \pi\pi,\ K\overline{K},\ \eta\pi,\ \rho\pi,\ \eta\eta$

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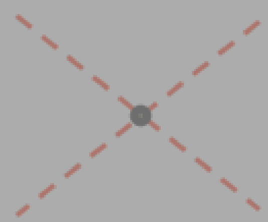
ChPT

- solid theory to describe MM interactions at low energy

- 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

$$\mathcal{L}_S^{(2)} = \frac{2\,\tilde{c}_d}{F^2} R_0\, \partial_\mu\phi_i\, \partial^\mu\phi_i - \frac{4\,\tilde{c}_m}{F^2} B\, R_0\left(\sigma_0\,\delta_{ij}+\sigma_8\,d_{8ij}\right)\phi_i\,\phi_j$$

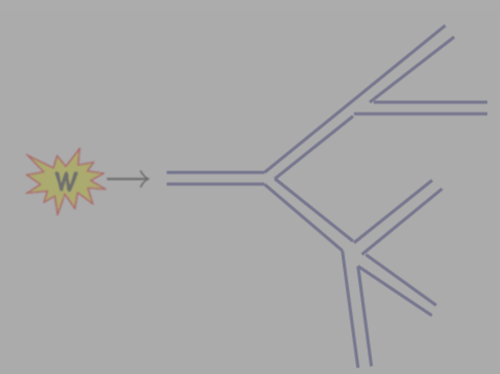
$$+ \frac{2\,c_d}{\sqrt{2}F^2} d_{ijk}\, R_k\, \partial_\mu\phi_i\, \partial^\mu\phi_i - \frac{4Bc_m}{\sqrt{2}F^2}\left[\sigma_0\,d_{ijk}+\sigma_8\left(\frac{2}{3}\delta_{ik}\,\delta_{j8}+d_{i8s}\,d_{jsk}\right)\right]\phi_i\,\phi_j R_k$$

vectors

$$\mathcal{L}_V^{(2)} = \frac{iG_V}{\sqrt{2}}\langle V_{\mu\nu}u^\mu u^\nu\rangle$$

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

- hadronization of Weak current



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

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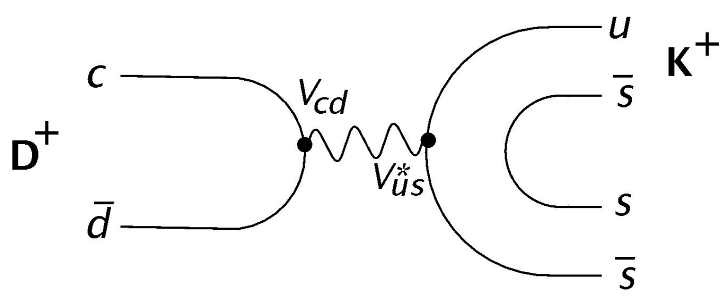
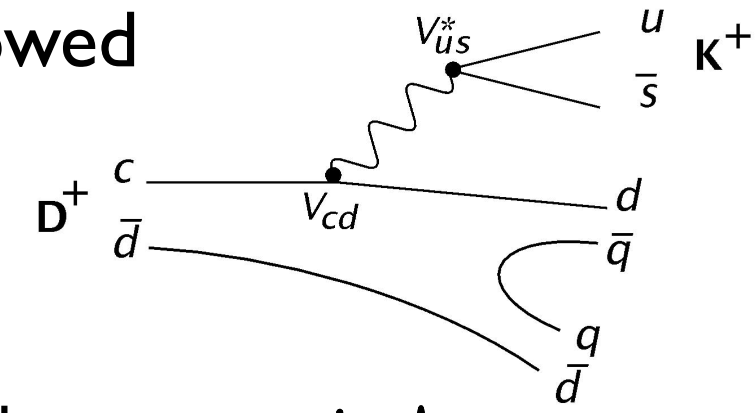
Chau [Phys. Rep. 95,1(1983)]

- tree level

annihilation

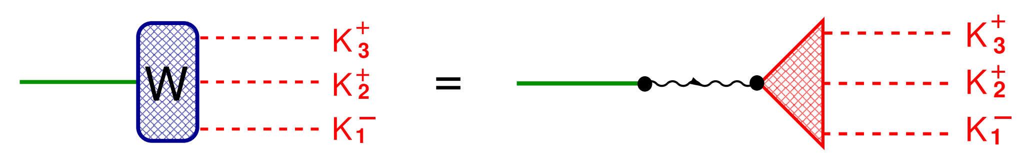


color allowed



- need a rescattering!

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



- separate the different energy scales:

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

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

→ know how to calculate everything

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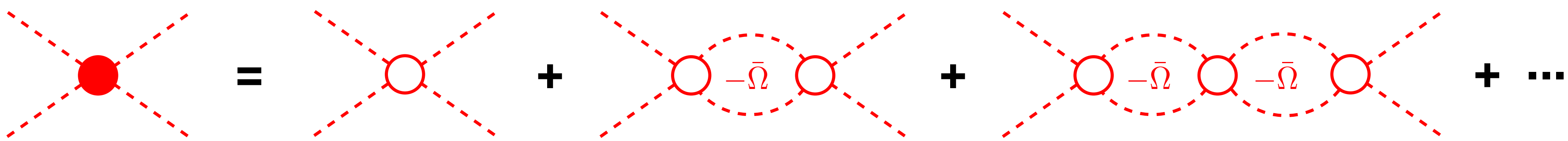
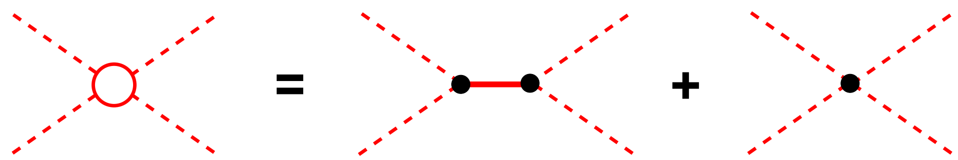
unitarized amplitude $P^a P^b \to P^c P^d$

- unitarize amplitude by Bethe-Salpeter eq. [Oller and Oset PRD 60 (1999)]



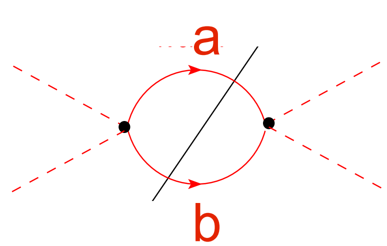
$$\mathcal{A}_{ab}^{JI} = \frac{\mathcal{K}^{(JI)}_{ab\to cd}}{1+\bar\Omega_{ab}\,\mathcal{K}^{(JI)}_{ab\to cd}}$$

- kernel $\mathcal{K}^{(J,I)}_{ab\to cd}$



resonance (NLO) + contact (LO)

- loops → K-matrix approximation: only on-shell



$$\{I_{ab};\, I^{\mu\nu}_{ab}\} = \int \frac{d^4\ell}{(2\pi)^4}\frac{\{1;\, \ell^\mu\,\ell^\nu\}}{D_a\,D_b}$$

$$D_a = (\ell+p/2)^2 - M_a^2 \qquad D_b = (\ell-p/2)^2 - M_b^2$$

→

$$\bar\Omega^S_{ab} = -\frac{i}{8\pi}\frac{Q_{ab}}{\sqrt{s}}\,\theta(s-(M_a+M_b)^2)$$

$$\bar\Omega^P_{aa} = -\frac{i}{6\pi}\frac{Q^3_{aa}}{\sqrt{s}}\,\theta(s-4\,M_a^2)$$

$$Q_{ab} = \frac{1}{2}\sqrt{s-2\,(M_a^2+M_b^2)+(M_a^2-M_b^2)^2/s}$$

- parameters from ChPT lagrangians → $\neq$ meaning !

- masses:

  $m_\rho\,,\, m_{a_0}\,,\, m_{s0}\,,\, m_{s1}$ — $SU(3)$ singlet and octet

  → physical f_0 states are linear combination of $m_{s0}\,,\, m_{s1}$

- coupling constants:

  $g_\rho\,,\, g_\phi$ — vector

  $c_d\,,\, c_m\,,\, \tilde{c}_d\,,\, \tilde{c}_m$ — scalar

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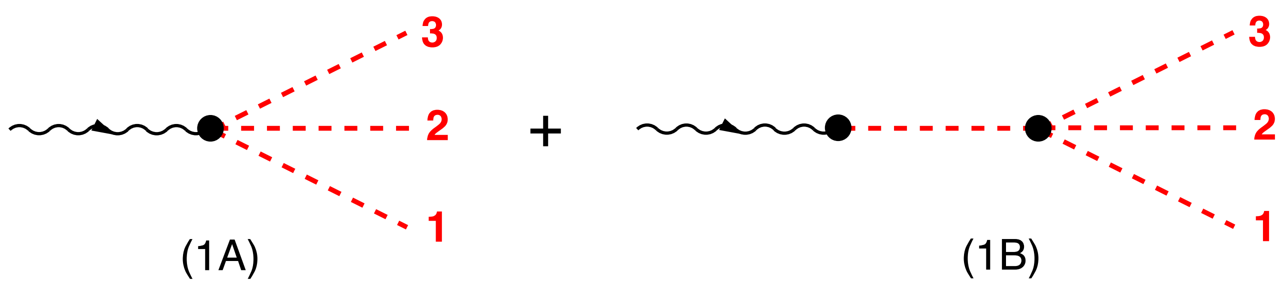
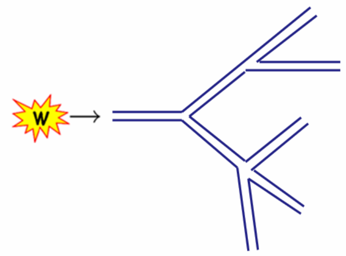




Chiral symmetry

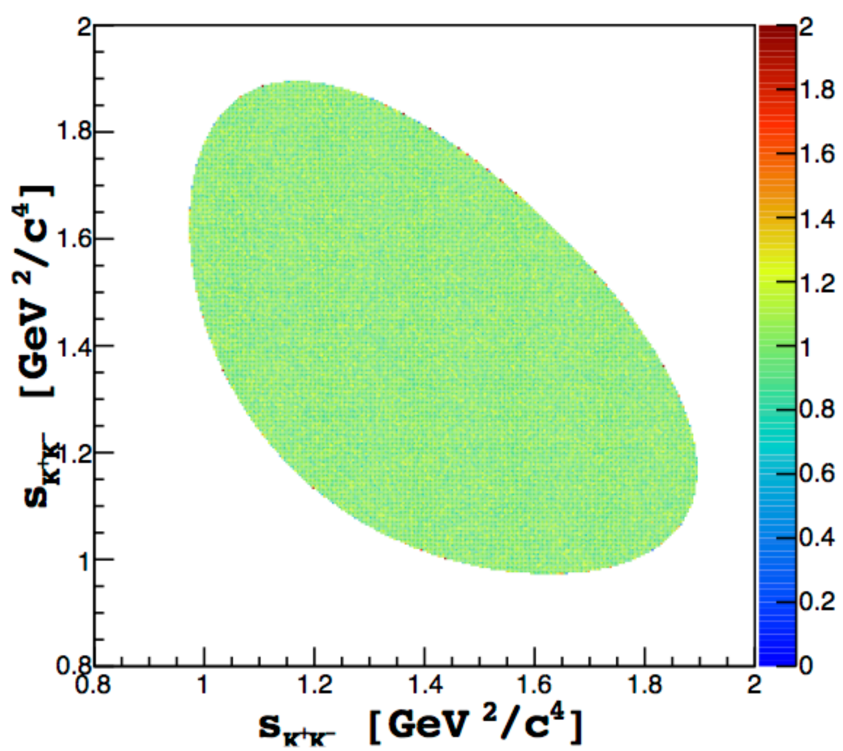
$$T_{NR} = \left[\frac{C}{4}\left(M^2 - M_K^2 + m_{12}^2\right) + \frac{C}{4}\left(m_{13}^2 - m_{23}^2\right) + (2 \leftrightarrow 3)\right]$$

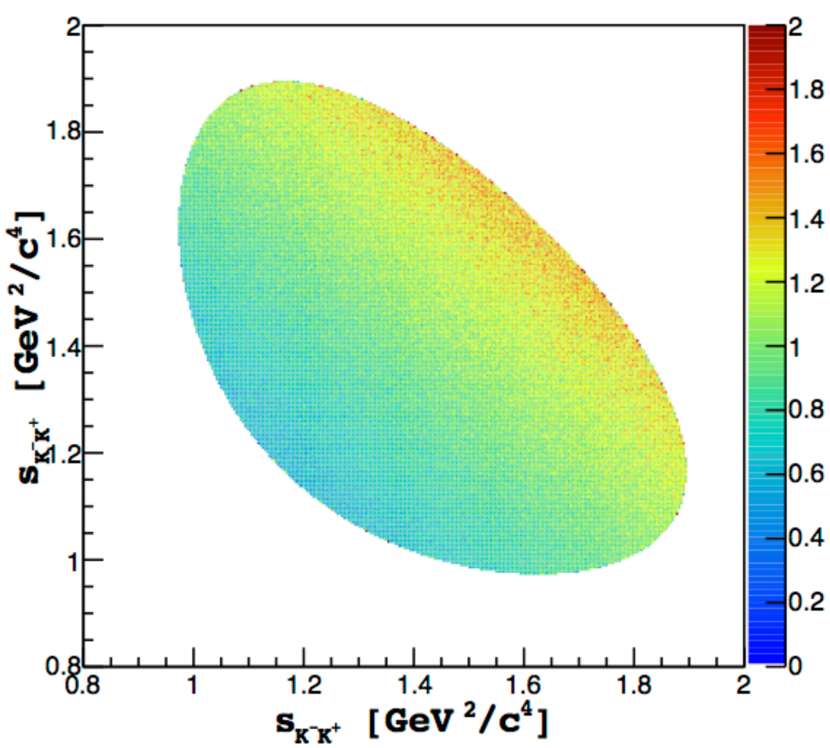
$$C = \left\{\left[\frac{G_F}{\sqrt{2}}\sin^2\theta_C\right]\frac{2F_D}{F}\frac{M_K^2}{M_D^2 - M_K^2}\right\}$$

project into S- and P- wave

3-body effect predicted by Chiral symmetry

- comparing with isobar (constant)





real polynomial

no possible free parameter

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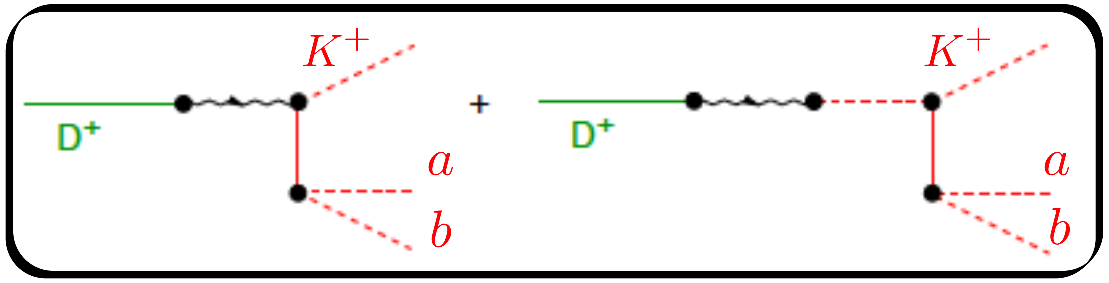
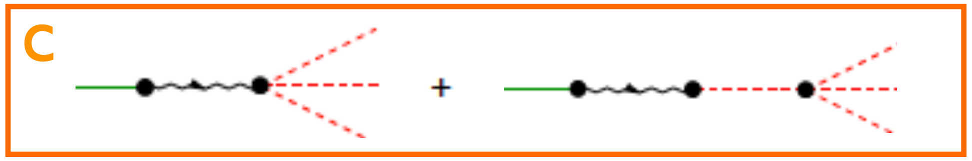
a_0 example

$[J, I = 0,1] \rightarrow \eta\pi,\ KK$

- tree $D \to a\, b\, K^+$

$$\langle U_3 (K^+) \,|\, T^{(0,1)}_{(0)} \,|\, D \rangle = \left\{ \Gamma^{(0,1)}_{(0)\,\pi 8} \langle U_3^{\pi 8}| + \Gamma^{(0,1)}_{(0)\,KK} \langle U_3^{KK}| \right\}$$



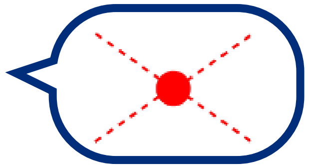


to avoid double counting!

$$\Gamma^{(0,1)}_{(0)\,\pi 8} = C \left\{ \left[\frac{2\sqrt{2}}{\sqrt{3}\,F^2} \right] \frac{[-c_d\, P\cdot p_3 + c_m\, M_D^2]}{m_{12}^2 - m_{a_0}^2} \left[c_d\, (m_{12}^2 - M_\pi^2 - M_8^2) + 2\, c_m\, M_\pi^2 \right] + \left[-\frac{\sqrt{3}}{\sqrt{2}} \left[M_D^2/3 - P\cdot p_3 \right] \right]_c^{C} \right\}$$

$$\Gamma^{(0,1)}_{(0)\,KK} = C \left\{ \left[\frac{2}{F^2} \right] \frac{[-c_d\, P\cdot p_3 + c_m\, M_D^2]}{m_{12}^2 - m_{a_0}^2} \left[c_d\, (m_{12}^2 - 2M_K^2) + 2\, c_m\, M_K^2 \right] + \left[-\frac{1}{2} \left[M_D^2 - P\cdot p_3 \right] \right]_c^{C} \right\}$$

- FSI



one interaction

$$\Gamma^{(0,1)}_{(1)\,\pi 8} = -\mathcal{K}^{(0,1)}_{\pi 8|\pi 8} \left[\bar{\Omega}^S_{\pi 8} \right] \Gamma^{(0,1)}_{(0)\,\pi 8} - \mathcal{K}^{(0,1)}_{\pi 8|KK} \left[\frac{1}{2}\, \bar{\Omega}^S_{KK} \right] \Gamma^{(0,1)}_{(0)\,KK}$$

$$\Gamma^{(0,1)}_{(1)\,KK} = -\mathcal{K}^{(0,1)}_{\pi 8|KK} \left[\bar{\Omega}^S_{\pi 8} \right] \Gamma^{(0,1)}_{(0)\,\pi 8} - \mathcal{K}^{(0,1)}_{KK|KK} \left[\frac{1}{2}\, \bar{\Omega}^S_{KK} \right] \Gamma^{(0,1)}_{(0)\,KK}$$

$$\Gamma^{(0,1)}_{(1)} = \begin{bmatrix} \Gamma^{(0,1)}_{(1)\,\pi 8} \\ \Gamma^{(0,1)}_{(1)\,KK} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} \Gamma^{(0,1)}_{(0)\,\pi 8} \\ \Gamma^{(0,1)}_{(0)\,KK} \end{bmatrix} = M^{(0,1)}\, \Gamma^{(0,1)}_{(0)}$$

infinity interactions

$$\Gamma^{(0,1)} = \left\{ 1 + M^{(0,1)} + [M^{(0,1)}]^2 + \cdots \right\} \Gamma^{(0,1)}_{(0)} \;\rightarrow\; \Gamma^{(0,1)} = \left[1 - M^{(0,1)} \right]^{-1} \Gamma^{(0,1)}_{(0)}$$

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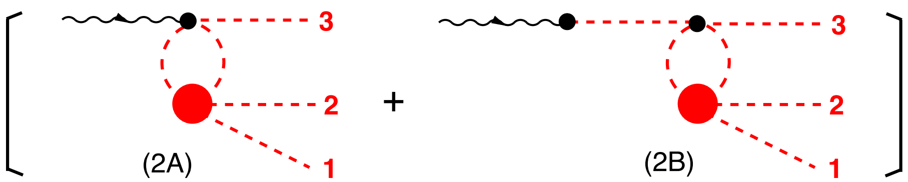
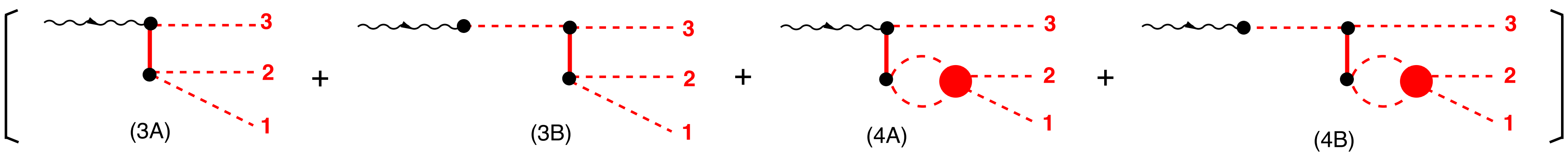
- full FSI!





a_0 example

$[J, I = 0, 1] \rightarrow \eta\pi,\ KK$

- $$T^{(0,1)} = -\frac{1}{2}\left[\bar{\Gamma}^{(0,1)}_{KK} - \Gamma^{(0,1)}_{c|KK}\right]$$

$$\rightarrow \quad \bar{\Gamma}^{(0,1)}_{KK} = \frac{(m_{12}^2 - m_{a_0}^2)}{D_{a_0}(m_{12}^2)}\left[M_{21}\,\Gamma^{(0,1)}_{(0)\,\pi 8} + (1 - M_{11})\,\Gamma^{(0,1)}_{(0)\,KK}\right]$$

$$D_{a_0} = (m_{12}^2 - m_{a_0}^2)\,\left[(1 - M_{11})\,(1 - M_{22}) - M_{12}\,M_{21}\right]$$

$$M_{11} = -\mathcal{K}^{(0,1)}_{\pi 8|\pi 8}\,[\bar{\Omega}^S_{\pi 8}]$$

$$M_{12} = -\mathcal{K}^{(0,1)}_{\pi 8|KK}\,[(1/2)\,\bar{\Omega}^S_{KK}]$$

$$M_{21} = -\mathcal{K}^{(0,1)}_{\pi 8|KK}\,[\bar{\Omega}^S_{\pi 8}]$$

$$M_{22} = -\mathcal{K}^{(0,1)}_{KK|KK}\,[(1/2)\,\bar{\Omega}^S_{KK}]$$

- only resonance

$$\bar{\Gamma}^{(0,1)}_{KK} = \frac{(m_{12}^2 - m_{a_0}^2)}{D_{a_0}(m_{12}^2)}\,\Gamma^{(0,1)}_{(0)\,KK}$$

Flatté

$$D_{a_0}(s) = (s - m_{a_0}^2) + i\, m_{a_0}\,\Gamma_{a_0}(s)$$

$$m_{a_0}\Gamma_{a_0}(s) = \frac{1}{8\pi\sqrt{s}}\left\{\left[\frac{4}{3\,F^4}\right]\left[c_d\,(s - M_\pi^2 - M_8^2) + 2\,c_m\,M_\pi^2\right]^2 Q_{\pi 8} + \left[\frac{1}{F^4}\right]\left[c_d\,(s - 2\,M_K^2) + 2\,c_m\,M_K^2\right]^2 Q_{KK}\right\}$$

$\rightarrow$ parameter: $c_d,\ c_m\ m_{a_0}$

access two-body dynamics !

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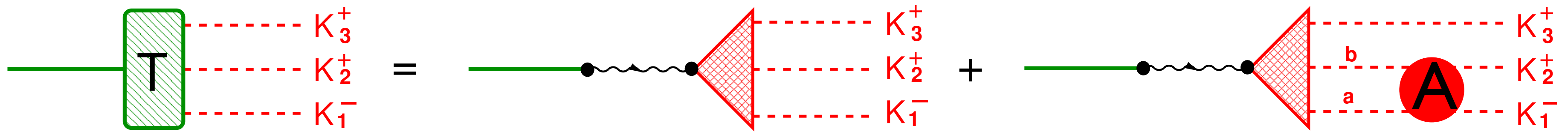

- $T = \left[T^S + T^P + (2 \leftrightarrow 3)\right]$

$$T^S = \left[\frac{C}{4}\left(M_D^2 - M_K^2 + m_{12}^2\right) + T^{(0,1)} + T^{(0,0)}\right]$$

$$T^P = \left[\frac{C}{4}\left(m_{13}^2 - m_{23}^2\right) + T^{(1,1)} + T^{(1,0)}\right] .$$

- A^{IJ} → prediction by Triple-M
  - extend ChPT to non perturbative region → parameter have different meaning $m_{S1} = m_{So}$
- parameter for Toy studies :

masses from PDG (GeV)

$m_\rho = 0.776,\ m_\phi = 1.019,$
$m_{a0} = 0.960,\ m_{So} = 0.980$

→ $m_{S1} = 1.370\, GeV$

low energy couplings (GeV)

$[F, G_V] = [0.093, 0.067]$ vectors
$[c_d, c_m] = [0.032, 0.042]$ scalar octet
$[\tilde{c_d}, \tilde{c_m}] = [0.018, 0.025]$ scalar singlet

additional PDG

$\Gamma_{\phi \to K\bar{K}} \sim 3.54\, MeV$
$\sin\theta = 0.605\ (\phi - \omega)$ mixing

→ all (13) could be free in a fit to data

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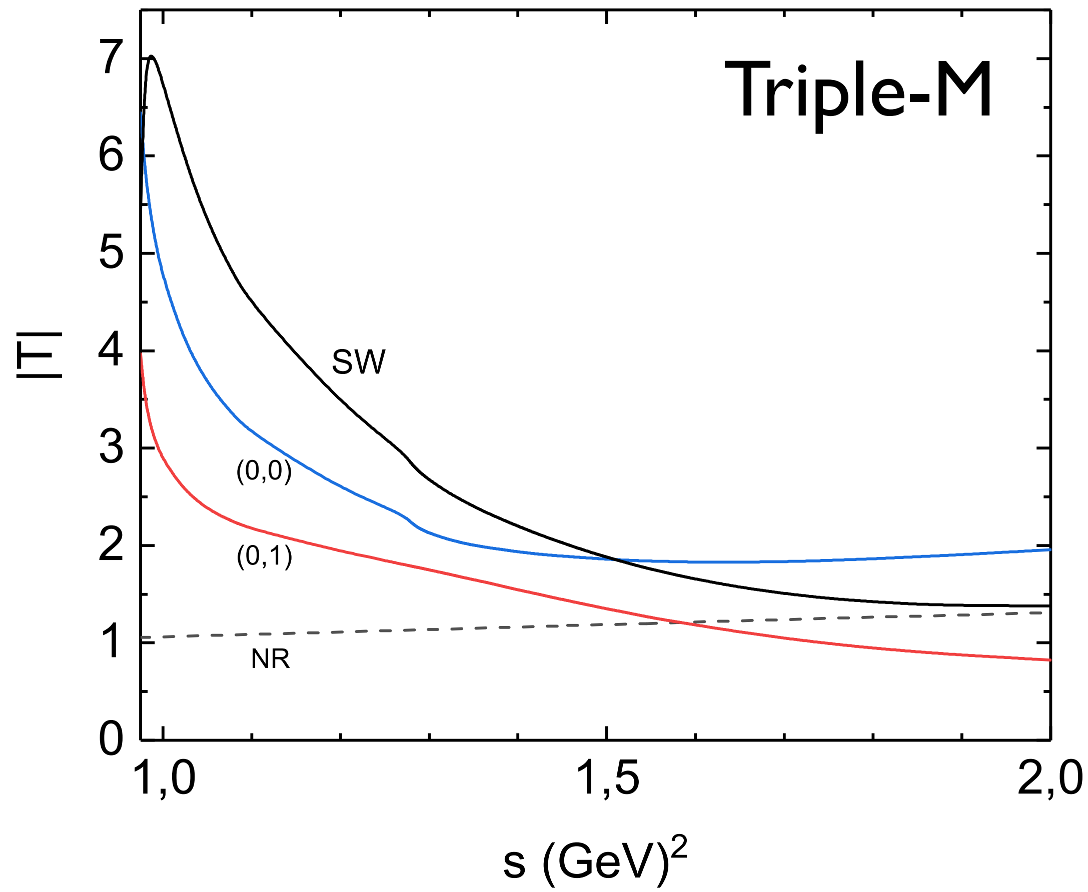
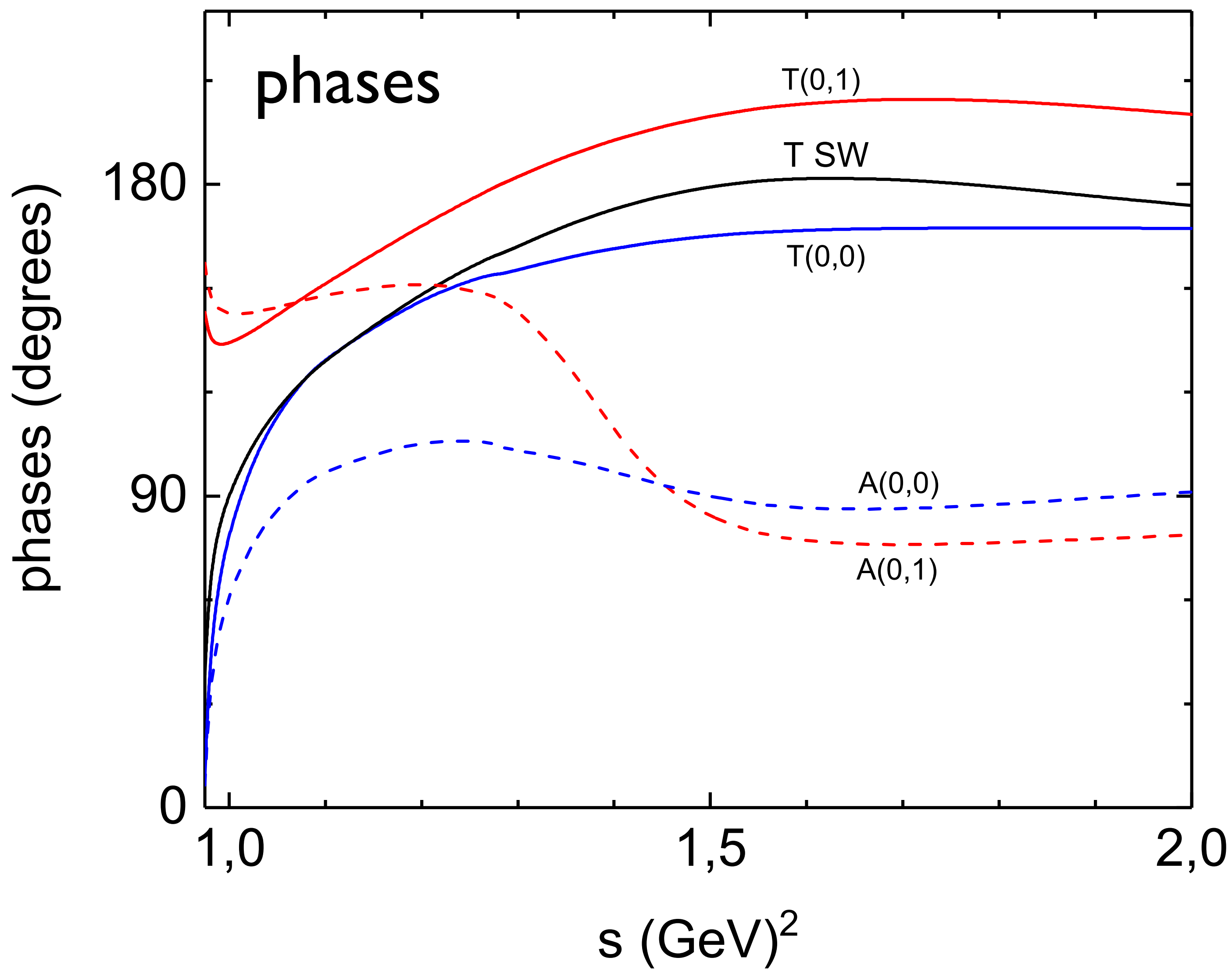
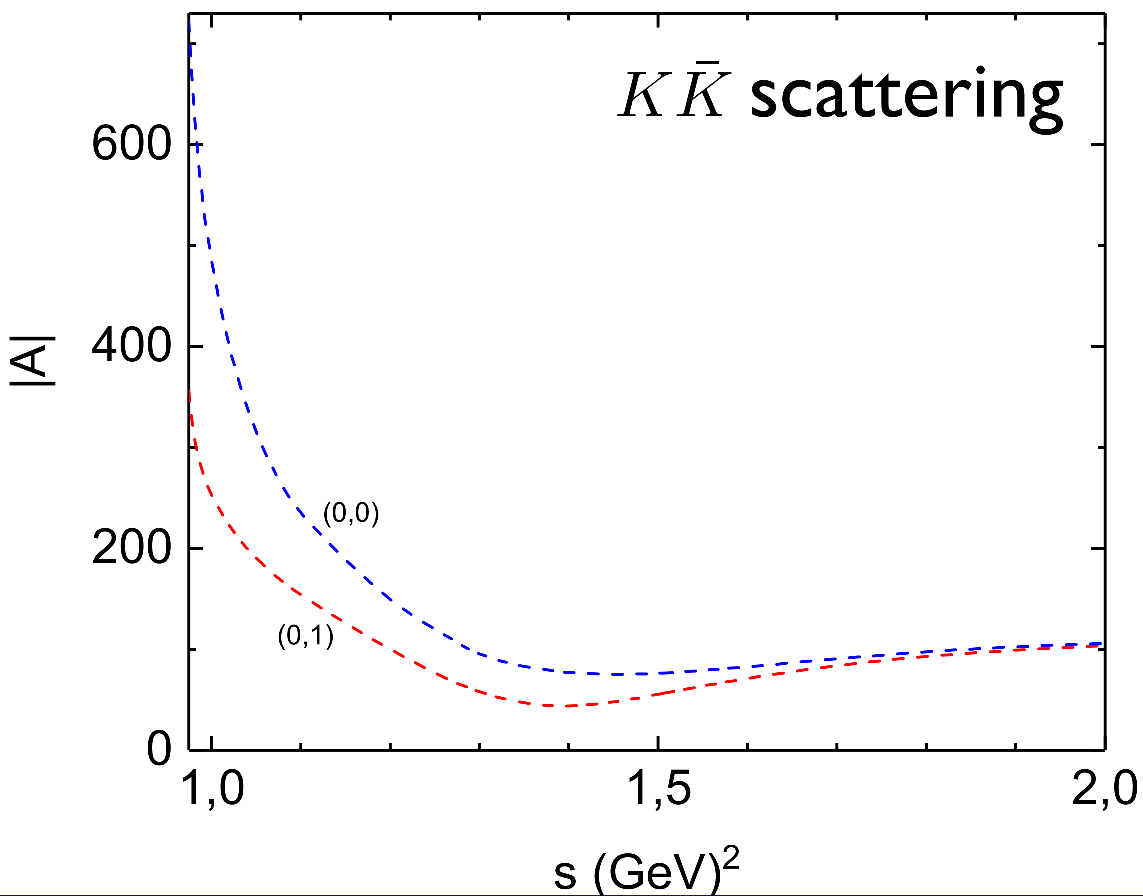
Toy results S-wave







- amplitude with similar behave $\neq$ phase
- not possible to extract A(J,I) from data
- Triple-M disentangle $\neq$ isospins in data

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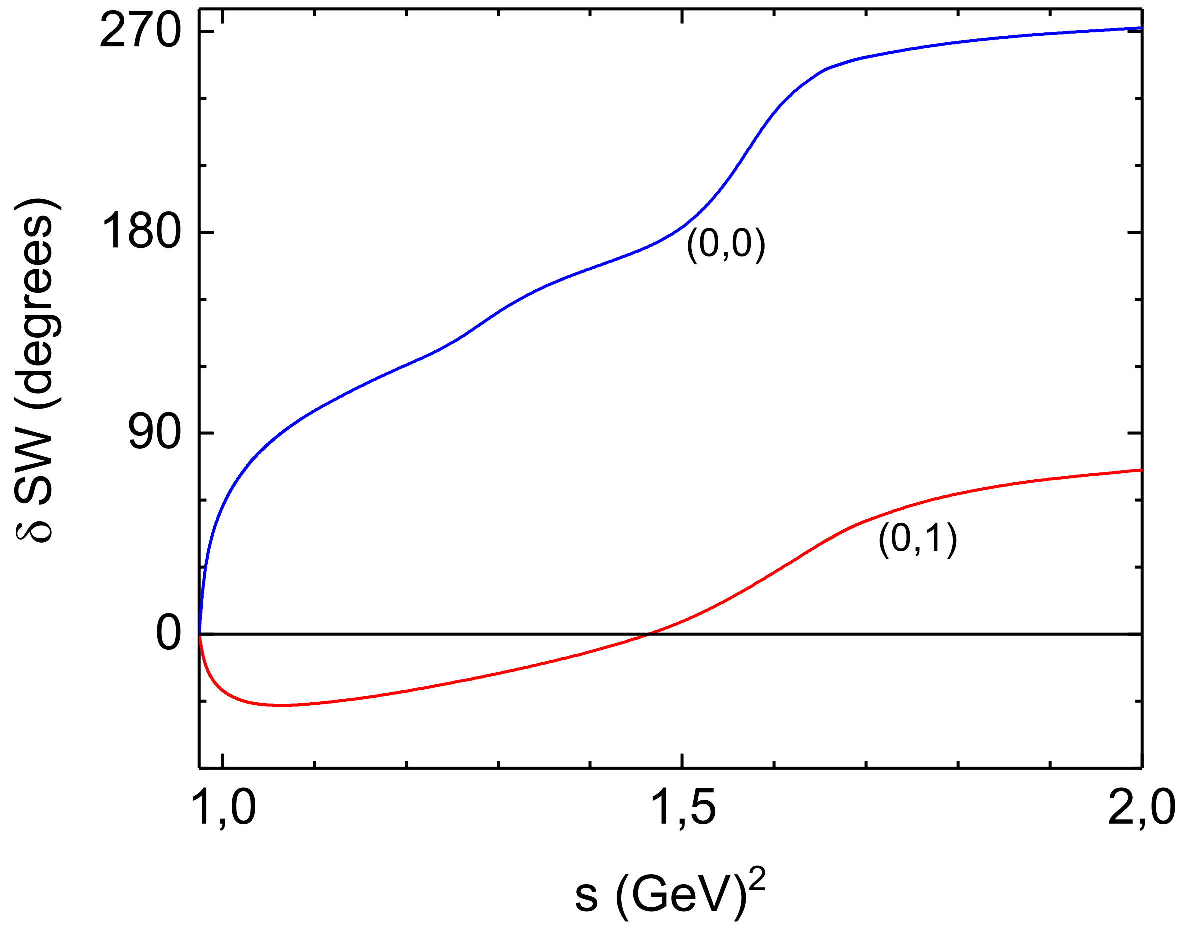
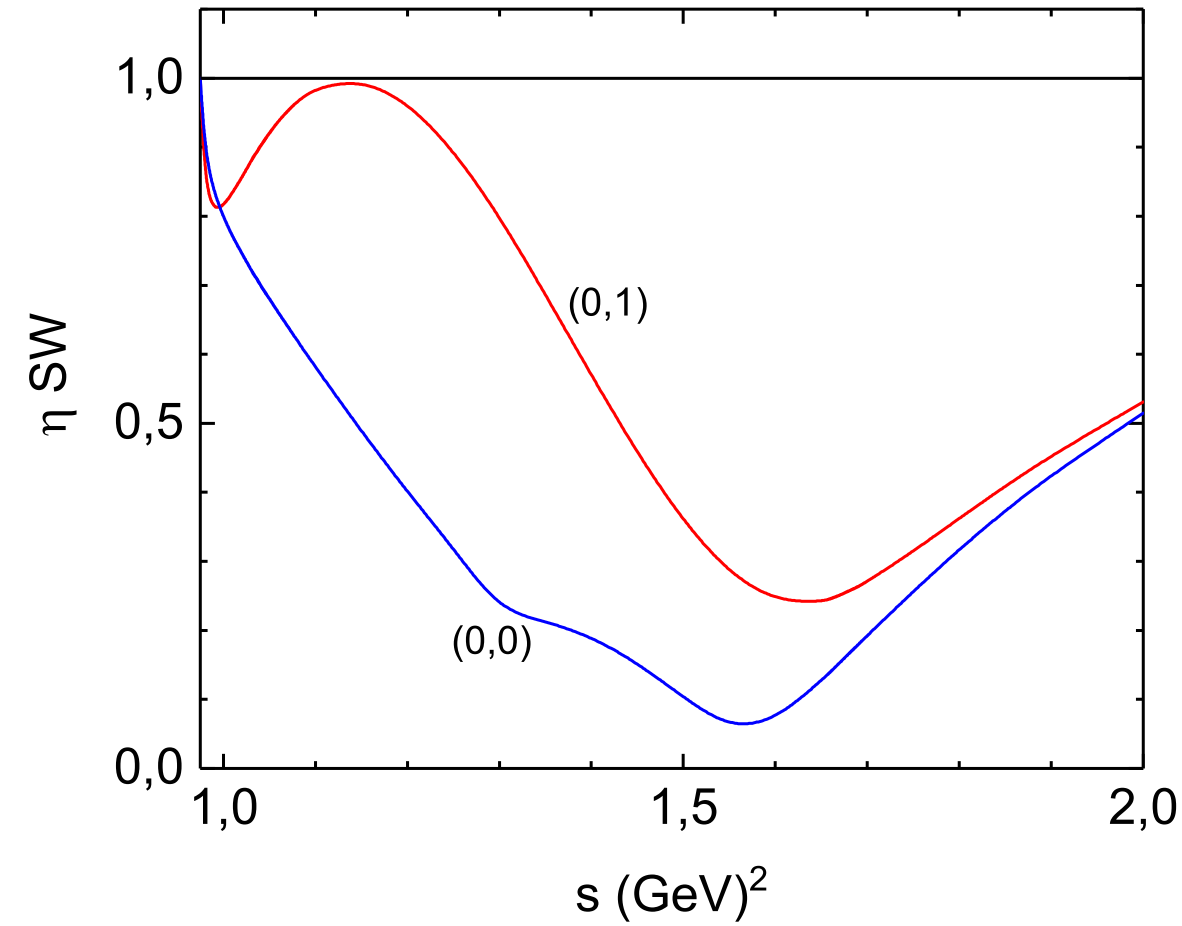
- Triple-M predictions for A
  - phase

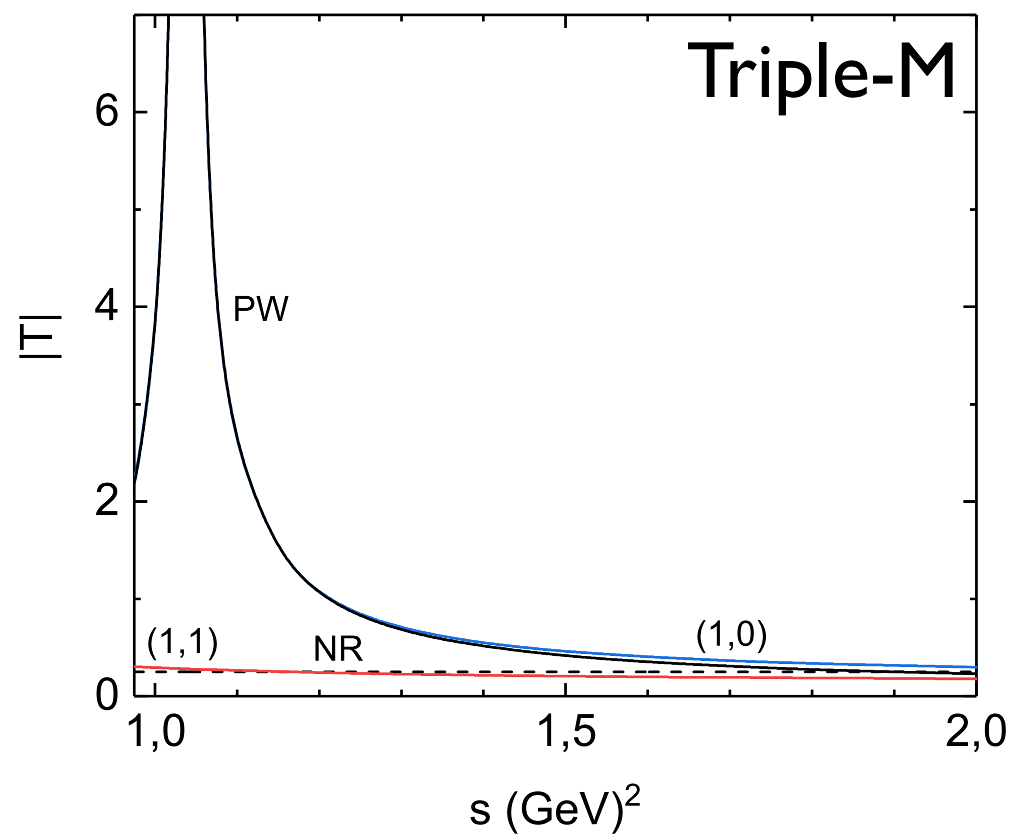


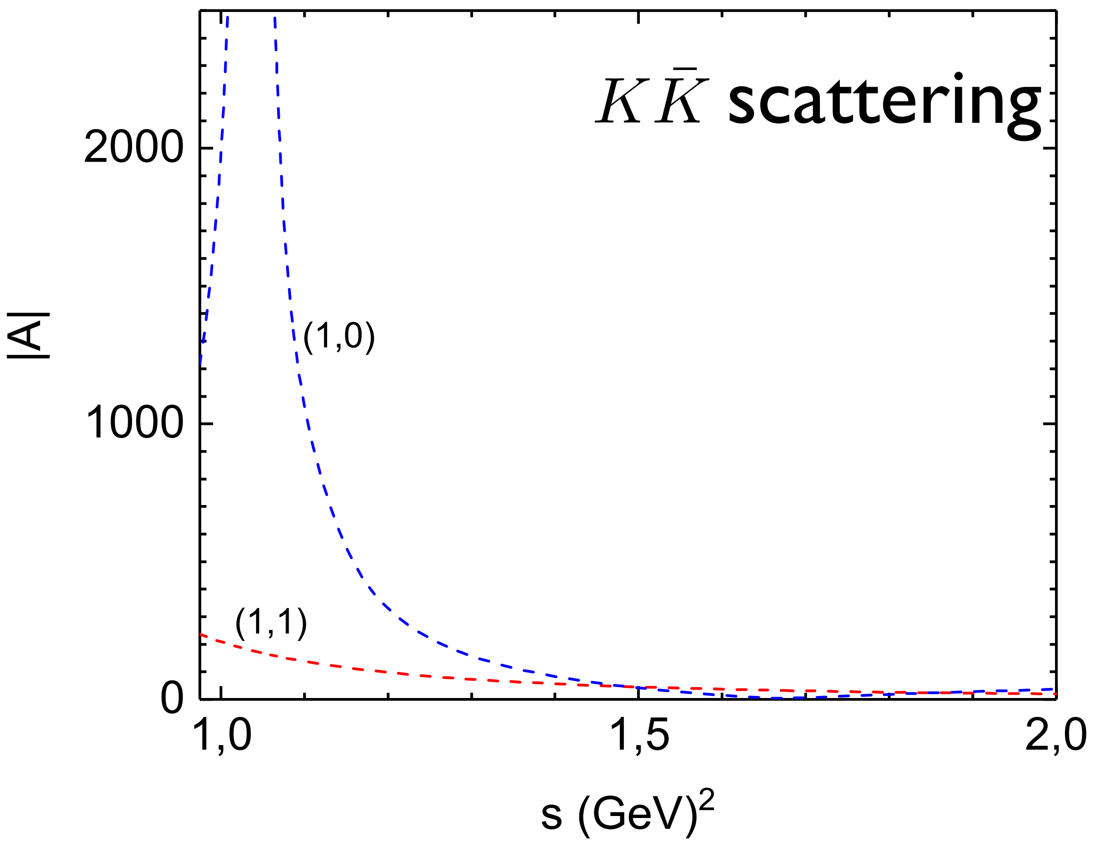
  - inelasticity

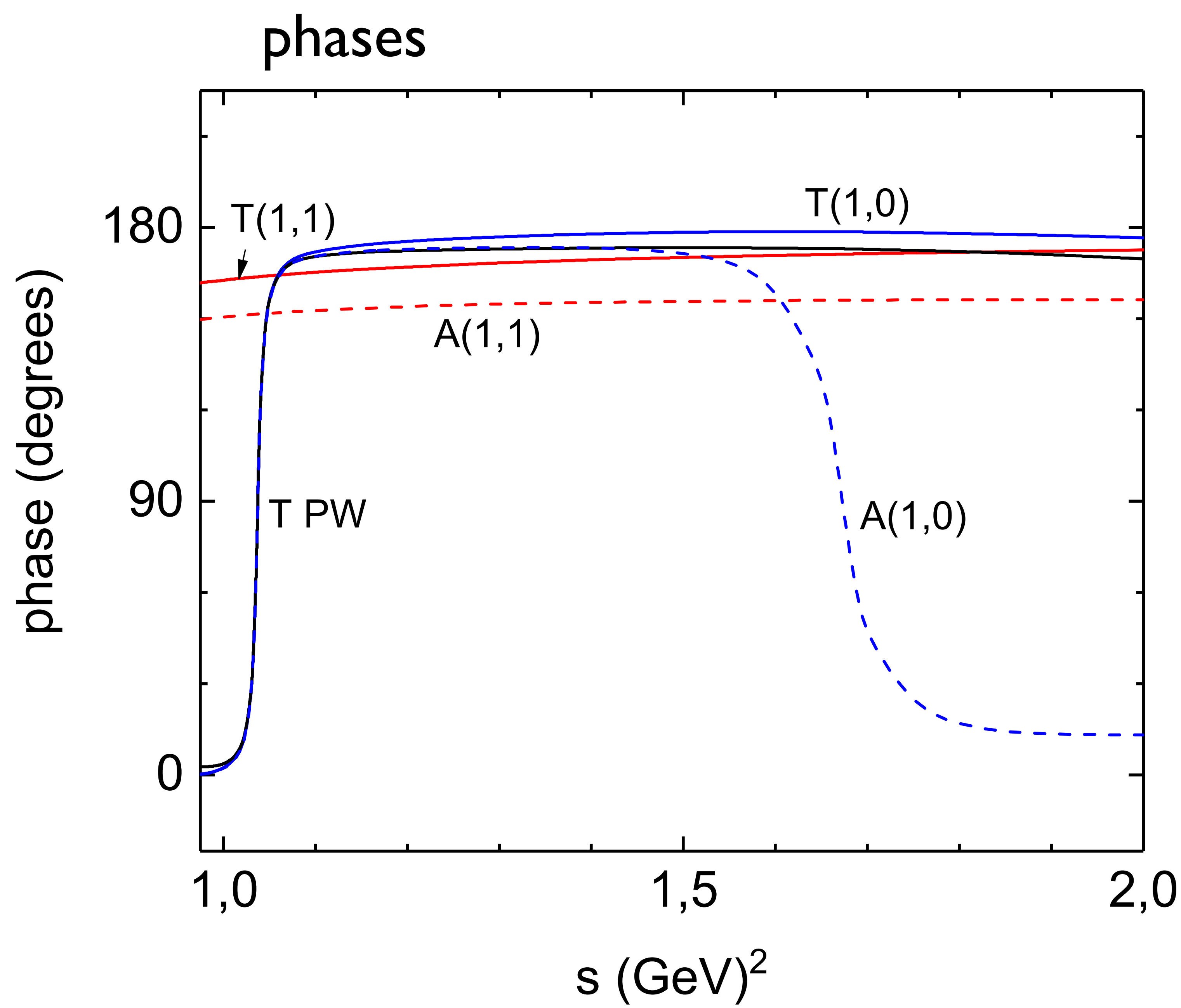


- importance of coupled-channels

- two resonances in the (J = 0, I = 0) channel, preserving unitarity







- ρ and NR contributions are tiny in TM $\longrightarrow$ small in KK
- ϕ phases are $\neq$ for $s > 1.5$

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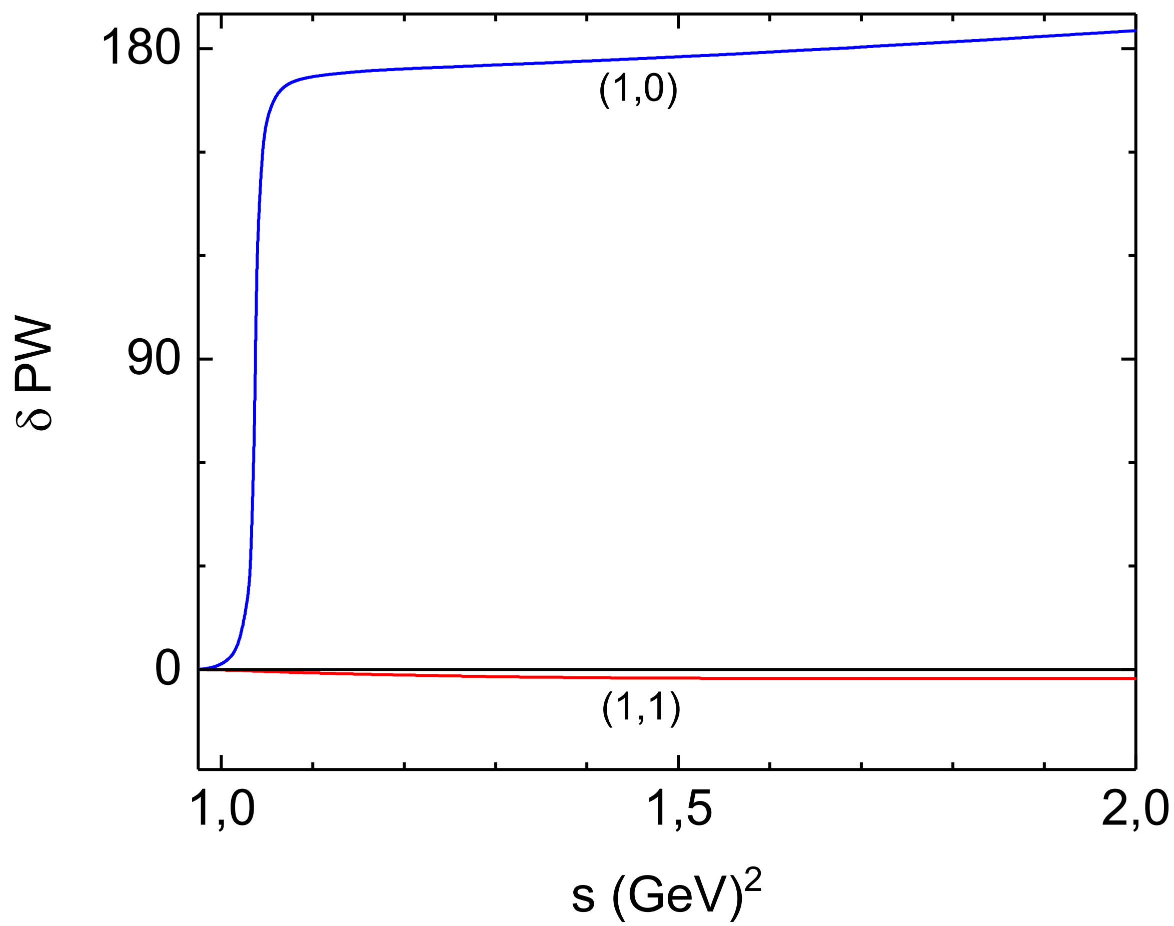
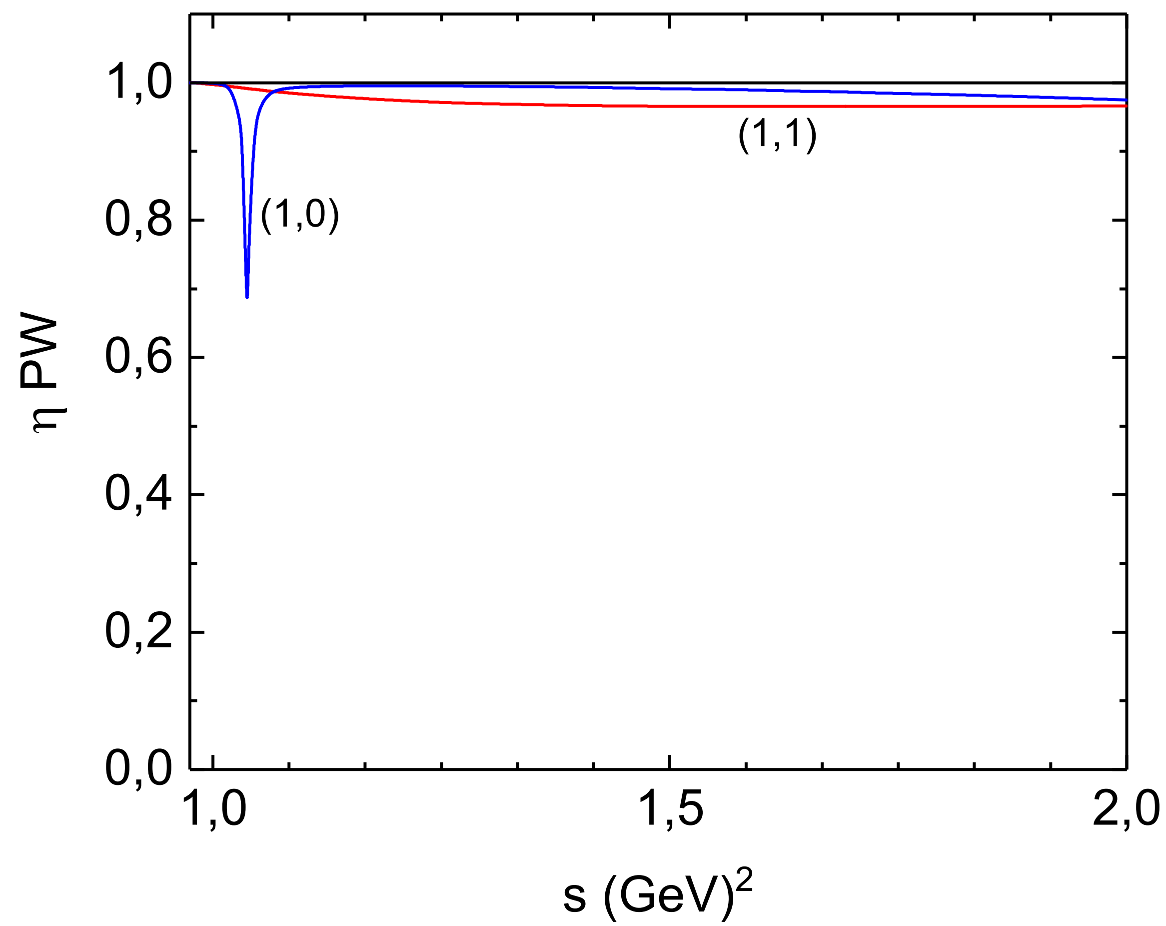
Toy results P-wave

- Triple-M predictions for A
  - phase
  - inelasticity





- ϕ is the dominant channel
- $\phi \to \rho\pi$ inelasticity → 15% of the life-time
- $\rho \to \pi\pi$ → constant inelasticity

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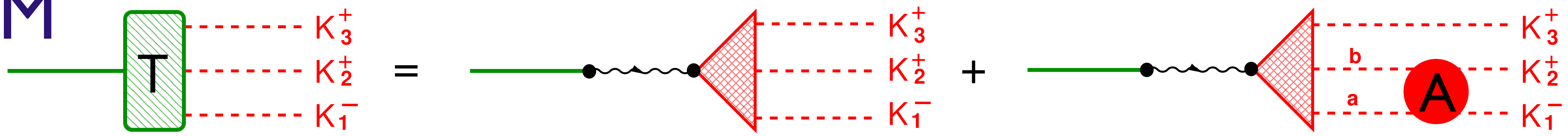
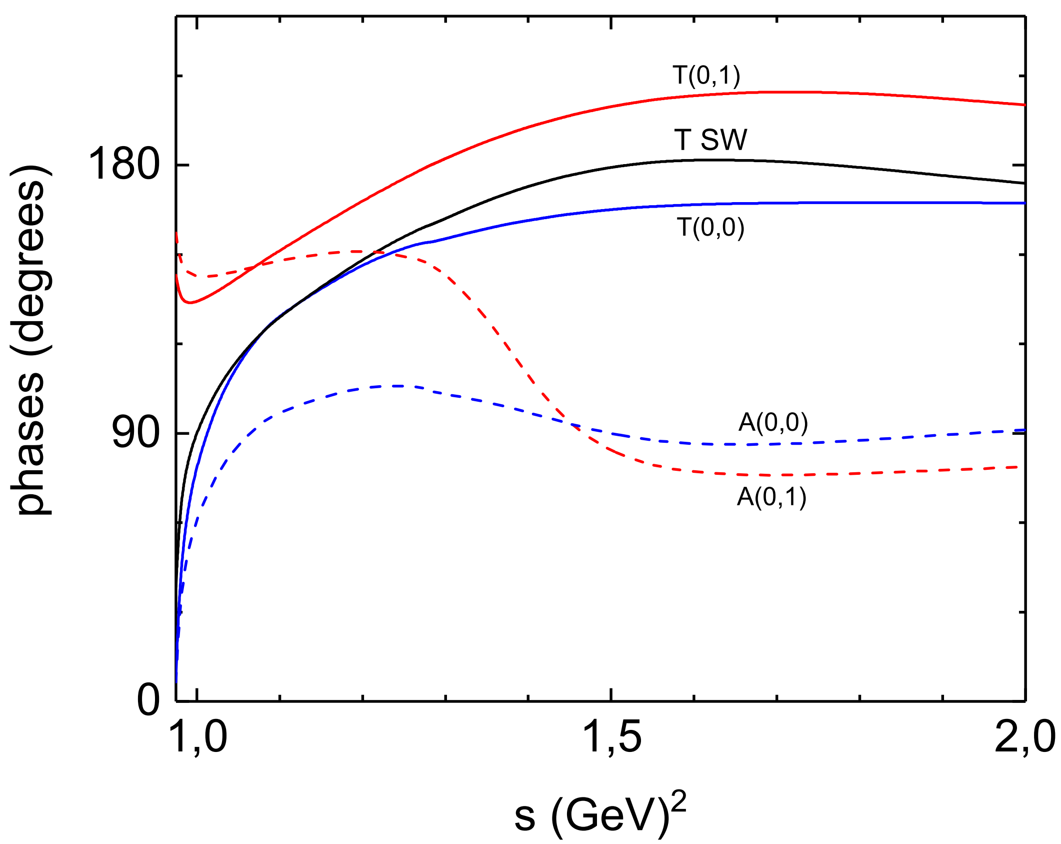
Triple-M



- annihilation weak topology dominance → ChPT multi-meson description
  - non-resonant: beyond (2+1) is a 3-body amplitude
- FSI: coupled-channel meson-meson from ChPTR Lagrangian
- intensity of each component is predict by theory → $\neq$ isobar model
- Toy studies



→ parameters have physical meaning from ChPT
masses and coupling const. fix by fitting data

→ can disentangle a_0 and f_0

→ couple channel structure: cannot be ignored

although $\neq$ is possible to extract 2-body phase from 3-body data with TM

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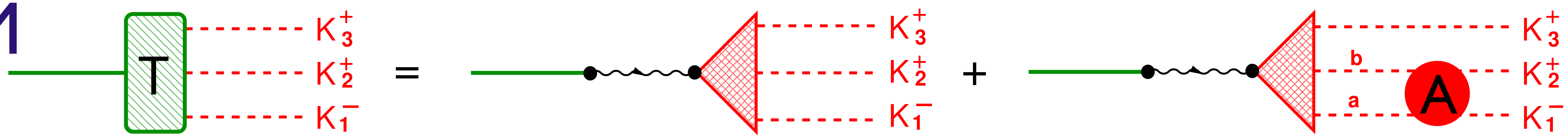
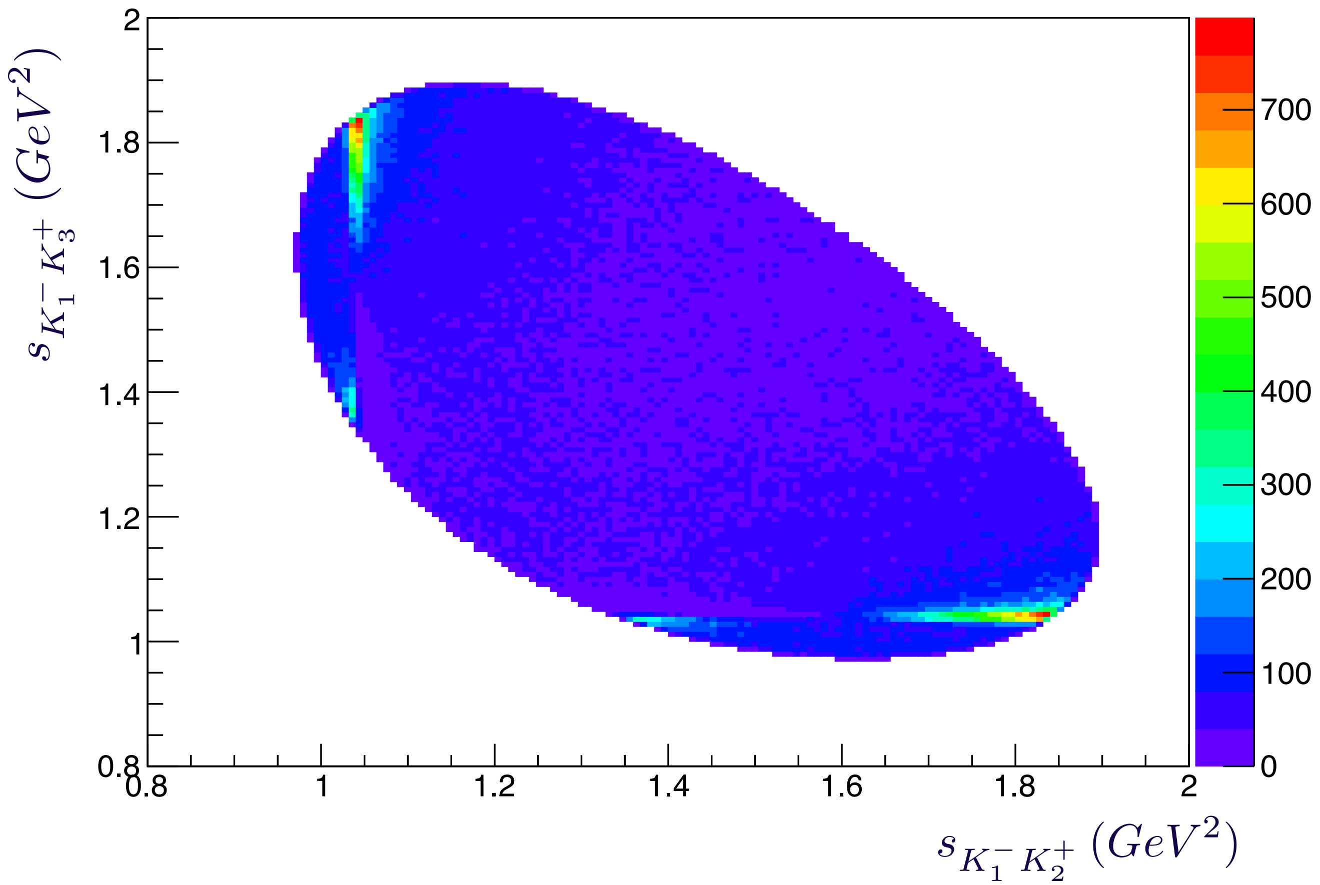
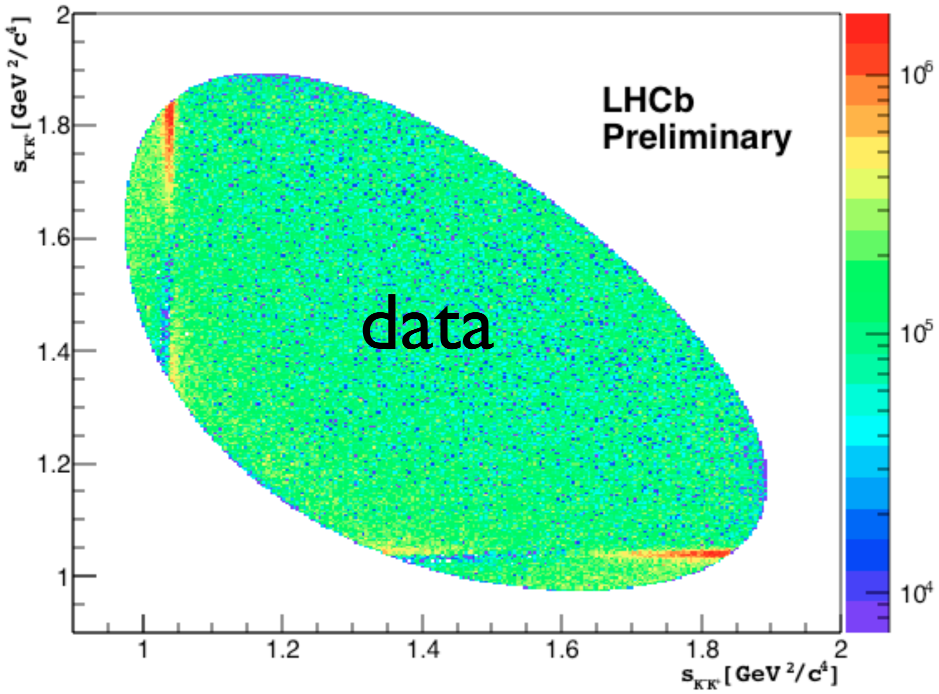
- Triple-M



Triple-M Toy Dalitz plot



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



→ Fit data with Triple-M

→ powerful tool to extract KK scattering S-wave