A.1 Flavor symmetries and final-state interactions in hadronic decays

PLs: Feng-Kun Guo, Bastian Kubis, Stephan Paul

A.5 Quark mass dependence of hadronic observables

PLs: Feng-Kun Guo, Ulf-G. Meißner

The 7th Symposium on Symmetries and the Emergence of Structure in QCD

19-22 July, 2023, Rizhao

Accomplishments of the projects

Chinese side + collaborating with German nodes

- A.1
  - Three-body decays
    - $D\pi$ FSI from $B \to D\pi\pi$
    - Probing structure of $D_{s1}(2460)$ using $D_{s1} \to D_s\pi^+\pi^-$
  - Triangle singularities
    - estimate of the $X(3872)\gamma$ production rates via the TS mechanism
    - analysis of updated BESIII data for the reactions involving $Z_c(3900)$ with TS contributions
  - Threshold cusps
    - extraction of S-wave ND scattering lengths from $\Lambda_b \to \pi^- p\, D^0$
    - mechanism of $J/\psi p$ photoproduction
  - …
- A.5
  - Quark mass dependence
    - Analyzing $D\pi$-$D\eta$-$D_s\bar{K}$ finite volume energy levels from HadSpec at unphysical quark mass
  - θ-dependence ⇒ QCD axion properties
    - Δ contribution to the axioproduction of pion $aN \to \pi N$
  - …

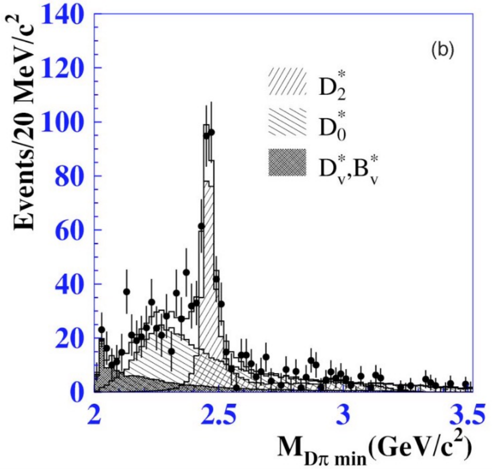
$D\pi$ FSI in $B \to D\pi\pi$

M.-L. Du, FKG, C. Hanhart, B. Kubis, U.-G. Meißner, PRL 126 (2021) 192001

- Lightest D_0^*: $D_0^*(2300)$ in PDG since 2004
  - Resonance parameters from fitting to $D\pi$ spectrum using BW

PDG2023

$D_0^*(2300)$ MASS	2343 ± 10 MeV
$D_0^*(2300)$ WIDTH	229 ± 16 MeV

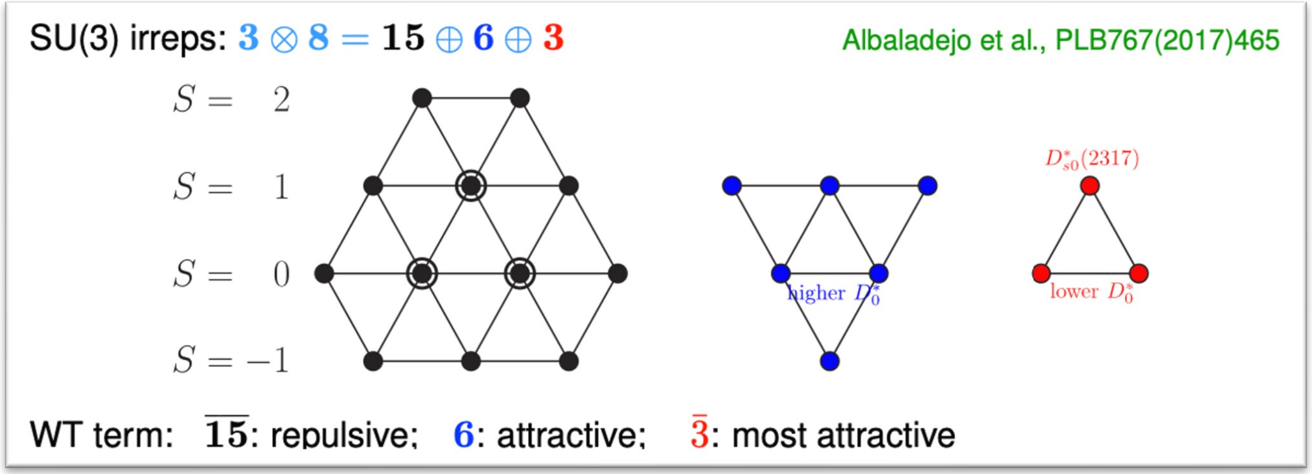


Belle, PRD 69 (2004) 112002

- Two poles in unitarized CHPT

$(M, \Gamma/2)$	Lower (MeV)	Higher (MeV)
D_0^*	$(2105^{+6}_{-8}, 102^{+10}_{-11})$	$(2451^{+36}_{-26}, 134^{+7}_{-8})$
D_1	$(2247^{+5}_{-6}, 107^{+11}_{-10})$	$(2555^{+47}_{-30}, 203^{+8}_{-9})$

Albaladejo et al., PLB 767 (2017) 465;
M.-L. Du et al., PRD 98 (2018) 094018



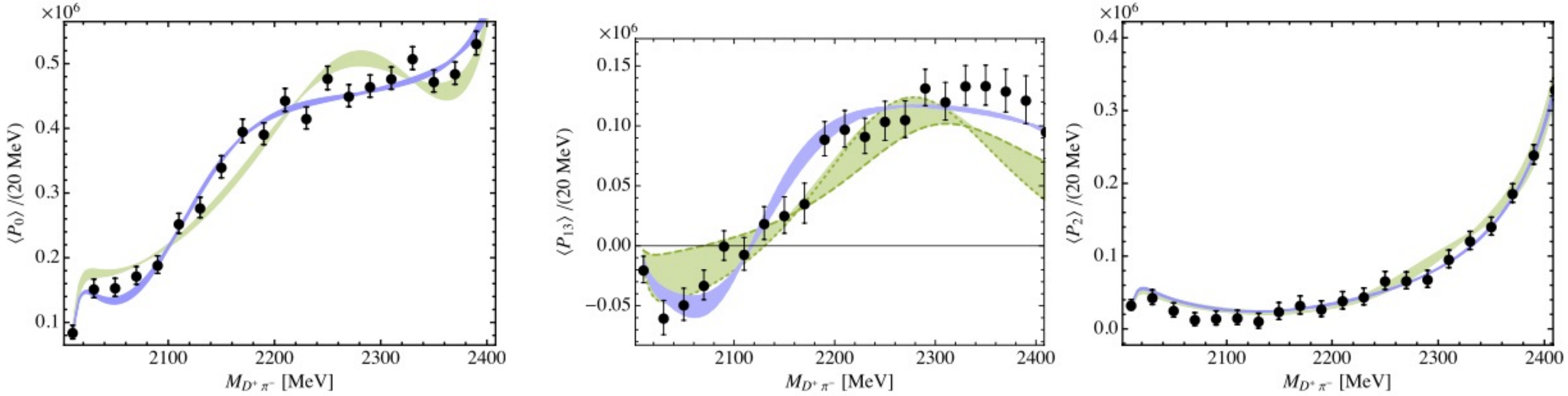
- Question
  - What can be learned from precise LHCb data of $B^- \to D^+\pi^-\pi^-$?

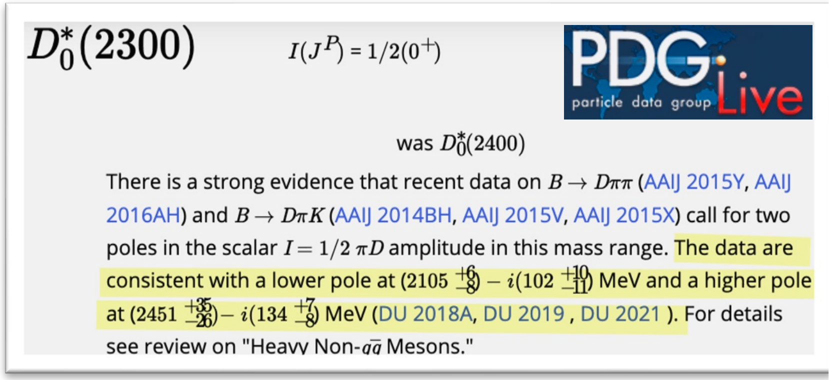
$D\pi$ FSI in $B \to D\pi\pi$

M.-L. Du, FKG, C. Hanhart, B. Kubis, U.-G. Meißner, PRL 126 (2021) 192001

- Fits of the $B^- \to D^+\pi^-\pi^-$ data with KT equation considering 3-body unitarity: using S-wave $D\pi$ scattering phase from UCHPT ($\chi^2/\text{d.o.f.} = 1.2$) and from BW ($\chi^2/\text{d.o.f.} = 2.0$)

Data: LHCb, PRD94(2016)072001




$D_0^*(2300)$ $I(J^P) = 1/2(0^+)$

PDG Live particle data group

was $D_0^*(2400)$

There is a strong evidence that recent data on $B \to D\pi\pi$ (AAIJ 2015Y, AAIJ 2016AH) and $B \to D\pi K$ (AAIJ 2014BH, AAIJ 2015V, AAIJ 2015X) call for two poles in the scalar $I = 1/2$ πD amplitude in this mass range. The data are consistent with a lower pole at $(2105\ ^{+6}_{-8}) - i(102\ ^{+10}_{-11})$ MeV and a higher pole at $(2451\ ^{+35}_{-26}) - i(134\ ^{+7}_{-8})$ MeV (DU 2018A, DU 2019 , DU 2021). For details see review on "Heavy Non-$q\bar{q}$ Mesons."

Independent analyses of data from other groups are called for to change the PDG entry!!

- The LHCb data are well described with UCHPT amplitude with two D_0^* states; the lowest has a mass about 2.1 GeV
- Support from recent lattice results:

L. Gayer et al. [HadSpec], JHEP07(2021)123

D_0^* with $M \approx 2.2$ GeV and $\Gamma \approx 0.4$ GeV obtained using $M_\pi \approx 239$ MeV

$D_{s1} \to D_s\pi^+\pi^-$

M.-N. Tang, Y.-H. Lin, FKG, C. Hanhart, U.-G. Meißner, CTP 75 (2023) 055203

- Experimental measurement:

$$\frac{\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right)}{\Gamma\left(D_{s1}(2460)^+ \to D_s^{*+}\pi^0\right)} = \begin{cases} 0.14 \pm 0.04 \pm 0.02 & \text{Belle, PRL 92(2004)012002} \\ 0.09 \pm 0.02 & \text{PDG fit} \end{cases}$$

- Isospin breaking $D_{s1} \to D_s^*\pi^0$: (111 ± 15) keV — H.-L. Fu et al., EPJA58(2022)70
- How about $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$?
  - CHPT result from — S. Fajfer, A. Prapotnik Brdnik, PRD92(2015)074047

$$\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right) = 0.25(4)(7)\left({}^{+2}_{-4}\right)\,\mathrm{keV}$$

  Both D_s and D_{s1} were treated statically, P-wave happens between π^+ and π^- $\Rightarrow I(\pi^+\pi^-) = 1$, isospin breaking

  - But isospin is conserved (!!) for P-wave between D_s and isoscalar $\pi^+\pi^-$

M.-N. Tang, Y.-H. Lin, FKG, C. Hanhart, U.-G. Meißner, CTP 75 (2023) 055203

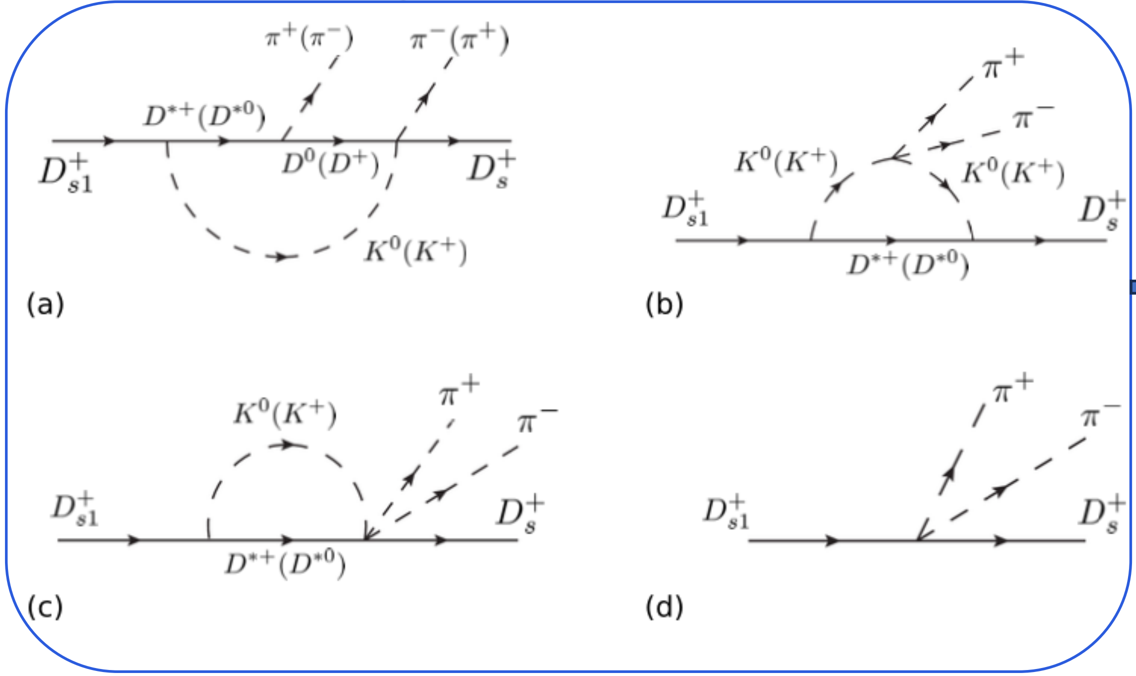
- Hadronic molecule v.s. other (compact) components

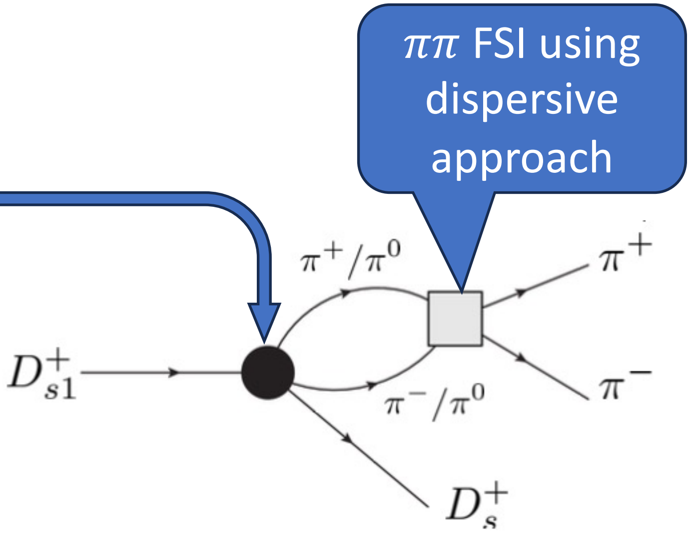
  Effective coupling contains crucial information   S. Weinberg, PR137(1965)B672

$$g^2 \propto (1 - Z)\sqrt{2\mu E_B}$$

  is maximized for a pure molecular state

- Diagrams for $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$: (a,b,c): leading for molecular state

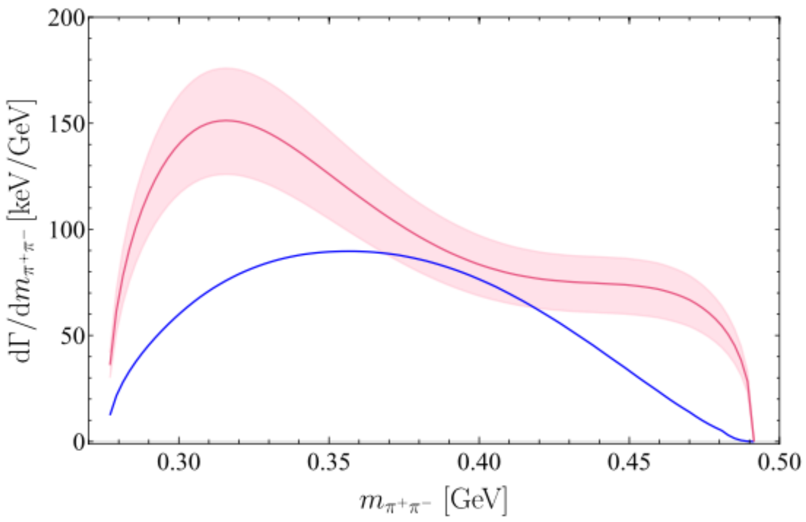


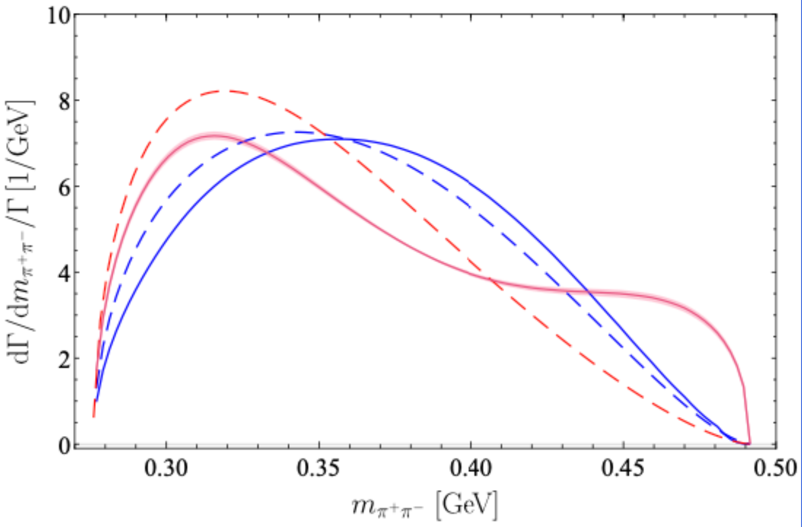


$D_{s1} \to D_s\pi^+\pi^-$

M.-N. Tang, Y.-H. Lin, FKG, C. Hanhart, U.-G. Meißner, CTP 75 (2023) 055203

- Double bump structure in the $\pi\pi$ invariant mass distribution as a feature of the hadronic molecular picture
  - ⋆ Red: molecular, assuming the $D_{s1}D_s\pi\pi$ contact term to vanish
  - ⋆ Blue: compact, without D^*K loops



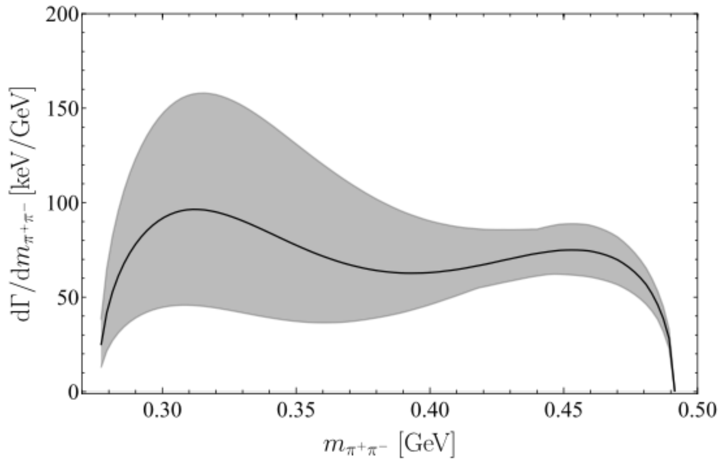


Dashed: without $\pi\pi$ FSI

- agree with Belle measurement $0.14 \pm 0.04 \pm 0.02$:

$$\left.\frac{\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right)}{\Gamma\left(D_{s1}(2460)^+ \to D_s^{*+}\pi^0\right)}\right|_{\text{mol.}} = 0.19^{+0.07}_{-0.05}$$

- With contact term (consistent with zero) fixed from the Belle measurement



- Prediction for the bottom analogue:

$$\Gamma\left(B_{s1}^0 \to B_s^0\pi^+\pi^-\right) = (3 \pm 1)\,\text{keV}$$

Threshold cusps: ND scattering length

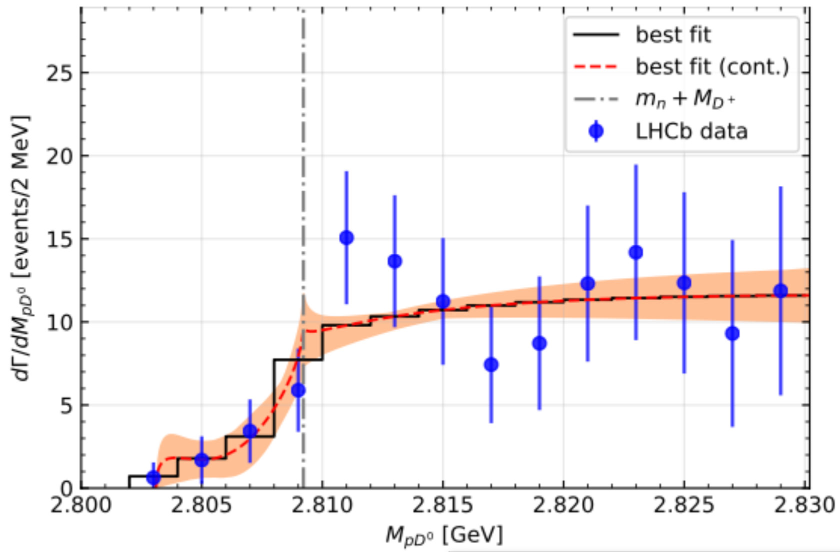
S. Sakai, FKG, B. Kubis, PLB 808 (2020) 135623

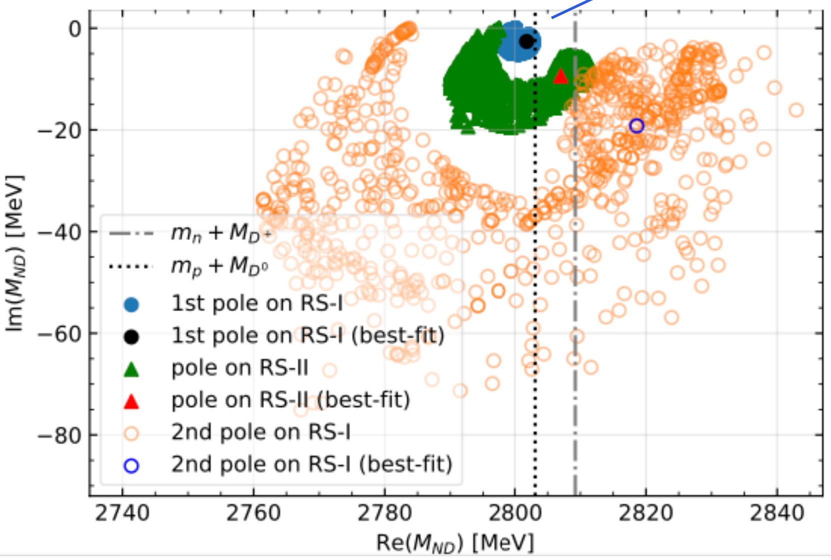
- ND near-threshold interaction is relevant for understanding charmed baryons around 2.8 GeV, e.g. $\Sigma_c(2800)$ ($J^P = ?^?$)
- The LHCb data on $\Lambda_b \to \pi^- p D^0$ show peculiar behavior around nD^+ threshold

  LHCb, JHEP05(2017)030

- Analysis with nonrelativistic EFT with two channels: pD^0 and nD^+.

Could be $\Sigma_c(2800)$
$\Rightarrow J^P = 1/2^-$





- Scattering lengths:

a_{ND} [fm]	Our result	SU(4) [10]	SU(4) [11]	SU(8) [12]	Meson-exchange model [15]
$I=0$	$-0.79^{+0.66}_{-0.61}$	-0.43	$-0.57+i\,0.001$	$0.004+i\,0.002$	$-0.41+i\,0.04$
$I=1$	$-3.8^{+1.4}_{-2.0}+i\,2.7^{+1.6}_{-2.7}$	-0.41	$-1.47+i\,0.65$	$0.33+i\,0.05$	$-2.07+i\,0.57$

Lutz et al. (2006) Mizutani et al. (2006) García-Recio et al. (2009) Haidenbauer et al. (2011)

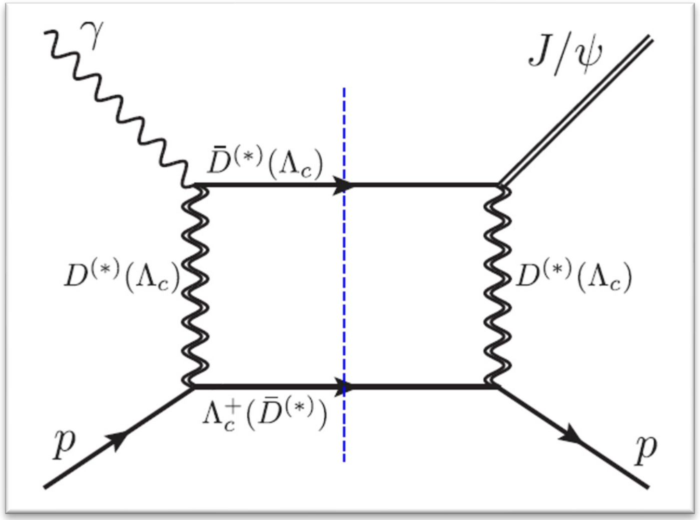
Mechanism of $J/\psi p$ photoproduction

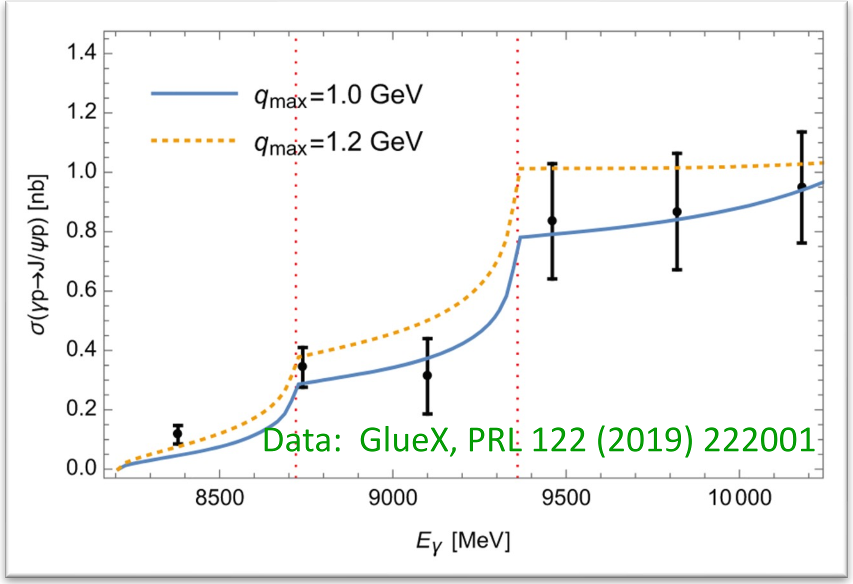
M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, A. Nefediev, I. Strakovsky, EPJC 80 (2020) 1053

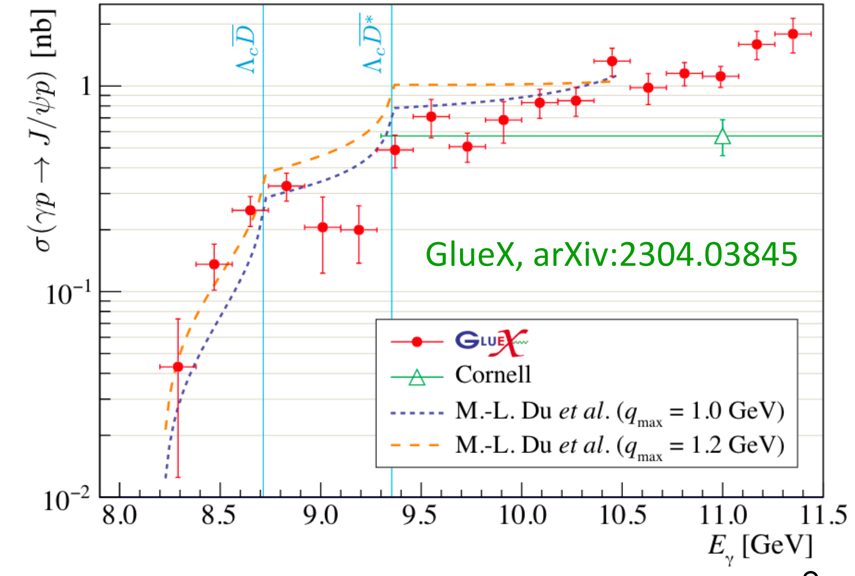
- Open-charm channels easier to be produced than $J/\psi p$; thresholds nearby

Unitarity: $J/\psi p \to J/\psi p$ enters w/o VMD, but cannot be singled out

$\Lambda_c^+ + D^-$: 2286 + 1865 = 4151 MeV
$J/\psi + p$: 3097 + 938 = 4035 MeV







- Unique feature: cusps at $\Lambda_c\bar{D}^{(*)}$ thresholds

- The same mechanism for $J/\psi p \to J/\psi p$ leads to small scattering length; need to compare with the scattering length from gluon exchanges (ongoing):

$$\left|a^{J=1/2}\right| = 0.2\ldots3.1\ \text{mfm}, \quad \left|a^{J=3/2}\right| = 0.2\ldots3.0\ \text{mfm},$$

$D\pi$ energy levels in finite volume

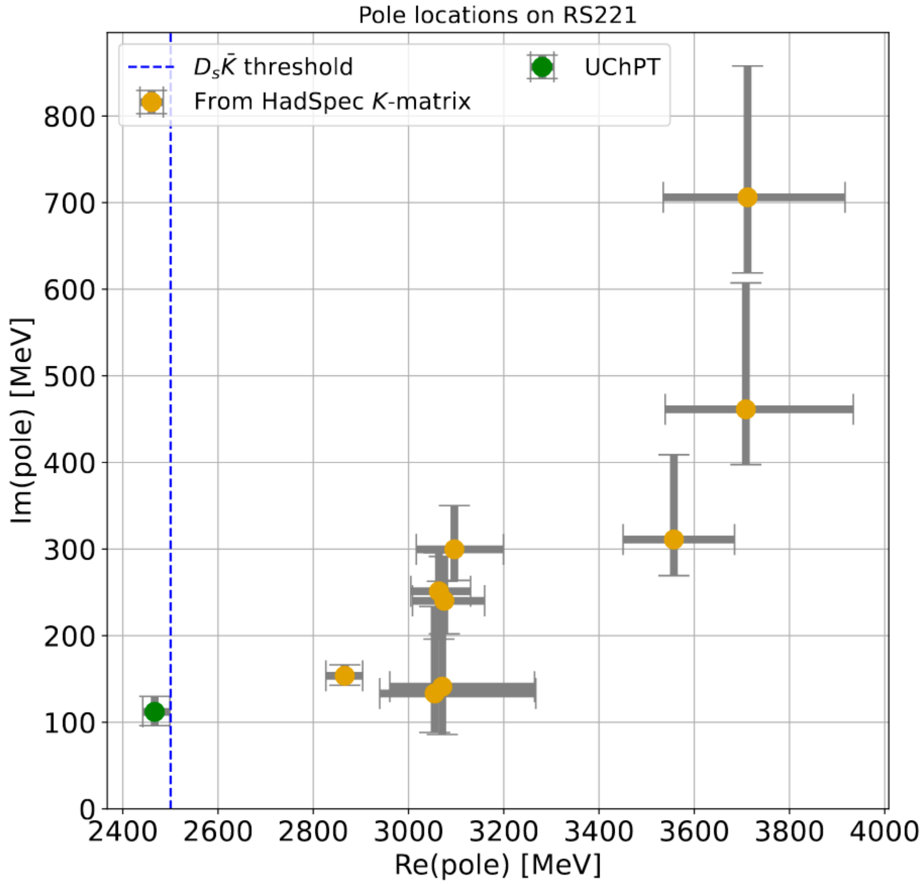
A. Asokan, M.-N. Tang, FKG, C. Hanhart, Y. Kamiya, U.-G. Meißner, arXiv:2212.07856

- D_0^* from lattice
  - one bound state pole just below $D\pi$ threshold with $M_\pi = 390$ MeV   HadSpec, JHEP 10 (2016) 011
  - evolving to a resonance with $M \approx 2.2$ GeV, $\Gamma \approx 0.4$ GeV when $M_\pi = 239$ MeV   HadSpec, JHEP 08 (2021) 123
- K-matrix parametrization of the T-matrix
  - the one used by HadSpec

$$T_{ij}^{-1}(s) = K_{ij}^{-1}(s) + I_{ij}(s)$$

$$K_{ij}(s) = \left(g_i^{(0)} + g_i^{(1)} s\right)\left(g_j^{(0)} + g_j^{(1)} s\right)\frac{1}{m^2 - s} + \gamma_{ij}^{(0)} + \gamma_{ij}^{(1)} s$$

the second pole present, but badly constrained



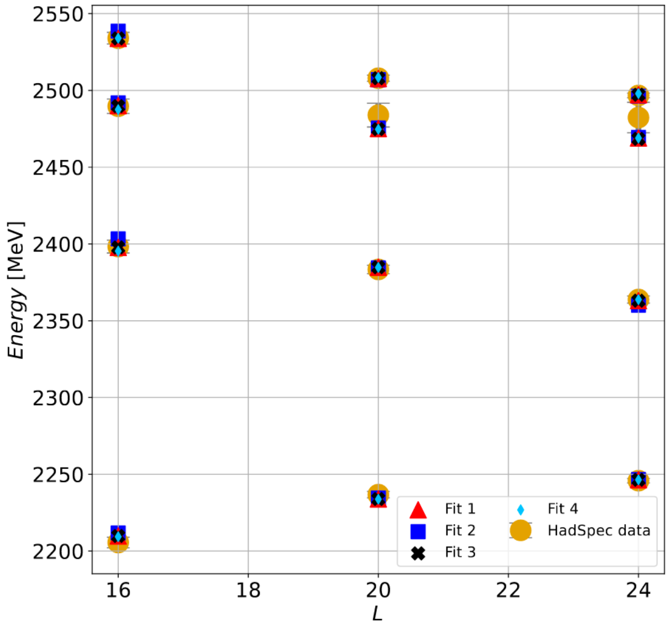
$D\pi$ energy levels in finite volume

A. Asokan, M.-N. Tang, FKG, C. Hanhart, Y. Kamiya, U.-G. Meißner, arXiv:2212.07856

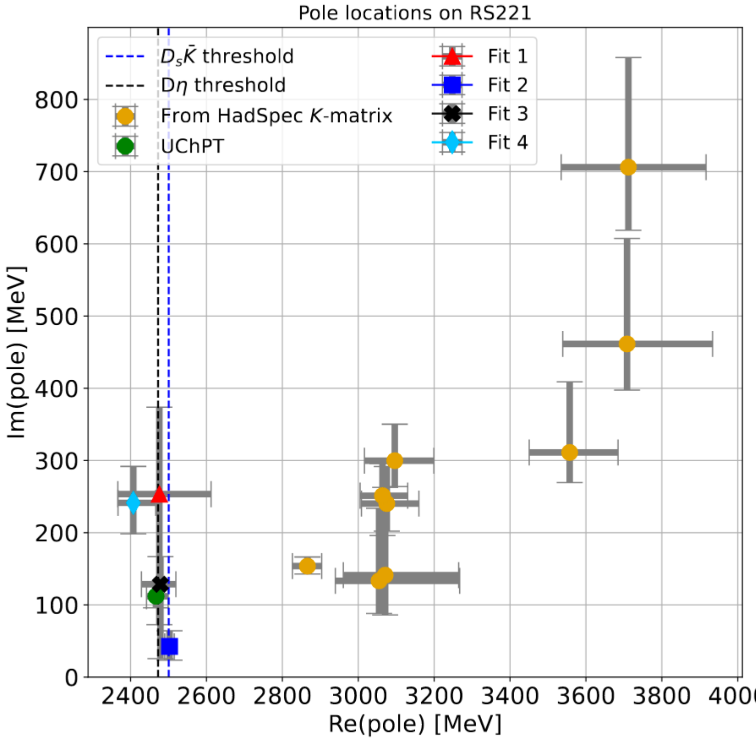
- SU(3) constrained K-matrix
  - contact terms in all three irreps
  - bare poles in $\bar{3}$ and 6

$$K = \left(\frac{g_{\bar{3}}^2}{m_{\bar{3}}^2 - s} + c_{\bar{3}}\right) C_{\bar{3}} + \left(\frac{g_6^2}{m_6^2 - s} + c_6\right) C_6 + c_{\overline{15}}\, C_{\overline{15}}.$$

- Fit to energy levels by HadSpec



- Existence of the second D_0^* pole
  - mass consistent with the one in UCHPT



	$g_{\bar{3}}$ [GeV]	$m_{\bar{3}}$ [MeV]	g_6 [GeV]	m_6 [MeV]	$c_{\bar{3}}$	c_6	$c_{\overline{15}}$	χ^2	χ^2/dof
Fit 1	2.92 ± 0.39	2275.1 ± 0.6	0.32 ± 0.32	2542 ± 50	4 ± 3	0.7 ± 0.4	−0.6 ± 0.2	7.1	1.4
Fit 2	2.31 ± 0.14	2274.5 ± 0.8	0.66 ± 0.17	2560 ± 37	-	-	−0.6 ± 0.2	14	1.9
Fit 3	2.91 ± 0.39	2275.1 ± 0.6	1.20 ± 0.62	2735 ± 266	4 ± 2	-	−0.6 ± 0.2	7.3	1.2
Fit 4	3.16 ± 0.38	2275.3 ± 0.6	-	-	5 ± 2	1.0 ± 0.2	−0.4 ± 0.2	8.2	1.2

Axioproduction of pion

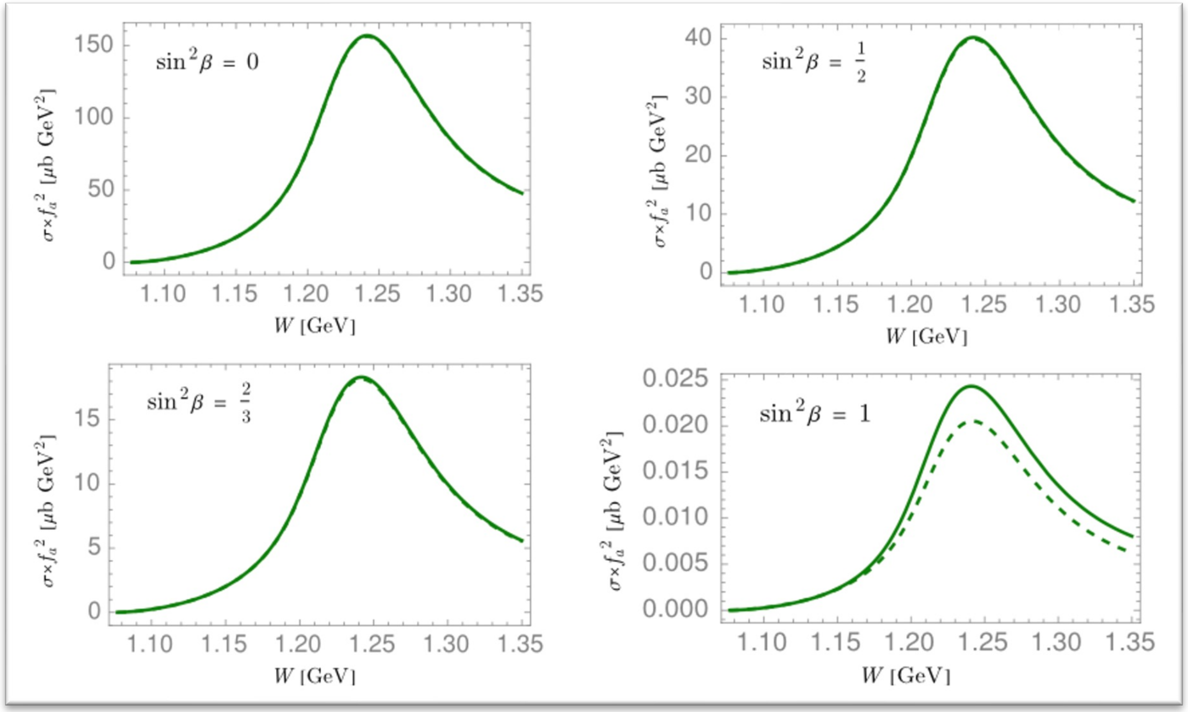
T. Vonk, F.-K. Guo and U.-G. Meißner, PRD 105 (2022) 054029

- The pion axioproduction $aN \to \pi N$ process was proposed to be employed to detect axions
  - with naive estimate around the Δ resonance

P. Carenza, B. Fore, M. Giannotti, A. Mirizzi, S. Reddy, PRL 126 (2021) 071102

$$\sigma_{aN\to\pi N} \approx \frac{F_\pi^2}{f_a^2}\sigma_{\pi N\to\pi N} = \mathcal{O}\left(\frac{1\text{mb}\,\text{GeV}^2}{f_a^2}\right)$$

- However, isospin breaking! The Δ contribution to the $aN \to \pi N$ using UCHPT
  - feature: isospin breaking in amplitude $\propto \frac{m_d-m_u}{m_d+m_u}$ v.s. normal isospin breaking $\propto \frac{m_d-m_u}{\Lambda_{\rm QCD}}$ or $\frac{m_d-m_u}{m_s}$



Summary

- Good progress has been made
- Intensive collaborations between the Chinese and German nodes

Thank you for your attention !