Two-pole structures in QCD

Ulf-G. Meißner, Univ. Bonn & FZ Jülich

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- The story of the $\Lambda(1405)$
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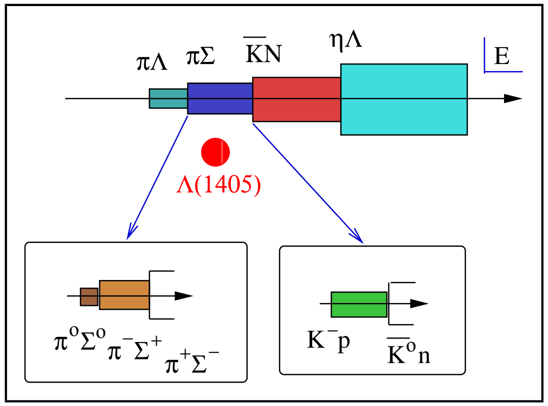
- Amplitude analysis of $B \to D\pi\pi$
- Summary & outlook

Details in: UGM, *Symmetry* **12** (2020) 981 [2005.06909 [hep-ph]]

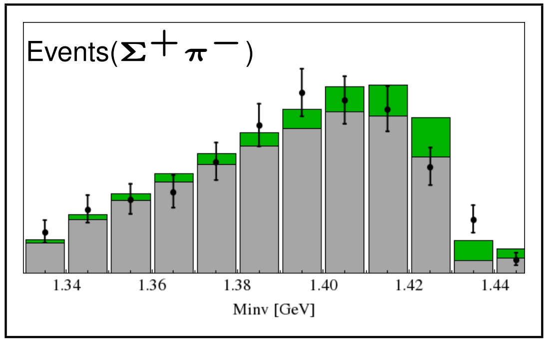
The story of the $\mathbf{\Lambda(1405)}$

BASICS of the $\Lambda(1405)$



- Quark model: uds excitation with $J^P = \frac{1}{2}^-$, a few hundred MeV above the $\Lambda(1116)$
  $m = 1405.1^{+1.3}_{-1.0}\,\mathrm{MeV}\,,\ \Gamma = 50.5 \pm 2.0\,\mathrm{MeV}$ [PDG 2019]

- Prediction as early as 1959 by Dalitz and Tuan:
  Resonance between the coupled $\pi\Sigma$ and $\bar{K}N$ channels
  Dalitz, Tuan, Phys. Rev. Lett. **2** (1959) 425; J.K. Kim, PRL **14** (1965) 29



- Clearly seen in $K^-p \to \Sigma 3\pi$ reactions at 4.2 GeV at CERN
  Hemingway, Nucl.Phys. B **253** (1985) 742

- An enigma: Too low in mass for the quark model,
  but well described in models (hadron exchanges, cloudy bags, ...)
  many authors

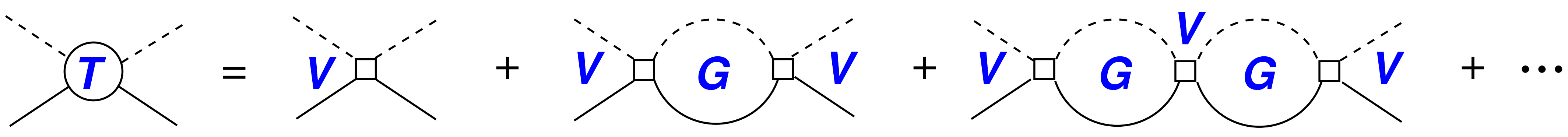
- Problems:

  ⋆ models are uncontrolled (theory like experiment **must** have errors!)

  ⋆ connections to QCD?

ENTERS CHIRAL DYNAMICS

- Great idea:
  Combine (leading-order) chiral SU(3) Lagrangian with coupled-channel dynamics
  Kaiser, Siegel, Weise, Nucl. Phys. A **594** (1995) 325



$\hookrightarrow$ Dominance of the Weinberg-Tomozawa term, excellent description of K^-p data and $\pi\Sigma$ mass distribution, also inclusion of NLO terms with constrained fits

$\hookrightarrow$ The $\Lambda(1405)$ appears as a **dynamically generated state** (MB molecule)

$\hookrightarrow$ Highly cited follow-ups from TUM group plus other groups, esp. “Spanish Mafia”
Oset, Ramos, Nucl. Phys. A **635** (1998) 99, . . .

- But: unpleasant regulator dependence (Yukawa-type, momentum cut-off)
  gauge invariance in photo-reactions?

CHIRAL SU(3) DYNAMICS: A NEW TWIST

- Re-analysis of coupled-channel $K^- p$ scattering and the $\Lambda(1405)$

  Oller, UGM Phys. Lett. B **500** (2001) 263

- Technical improvements:
  - Subtracted meson-baryon loop with dim reg $\hookrightarrow$ **standard method**
  - Coupled-channel approach to the $\pi\Sigma$ mass distribution
  - Matching formulas to any order in chiral perturbation theory established

- Most significant finding:

> "Note that the $\Lambda(1405)$ resonance is described by **two poles** on sheets II and III with rather different imaginary parts indicating a clear departure from the Breit-Wigner situation..."

[pole 1: (1379.2 -i 27.6) MeV, pole 2: (1433.7 -i 11.0) MeV on RS II]

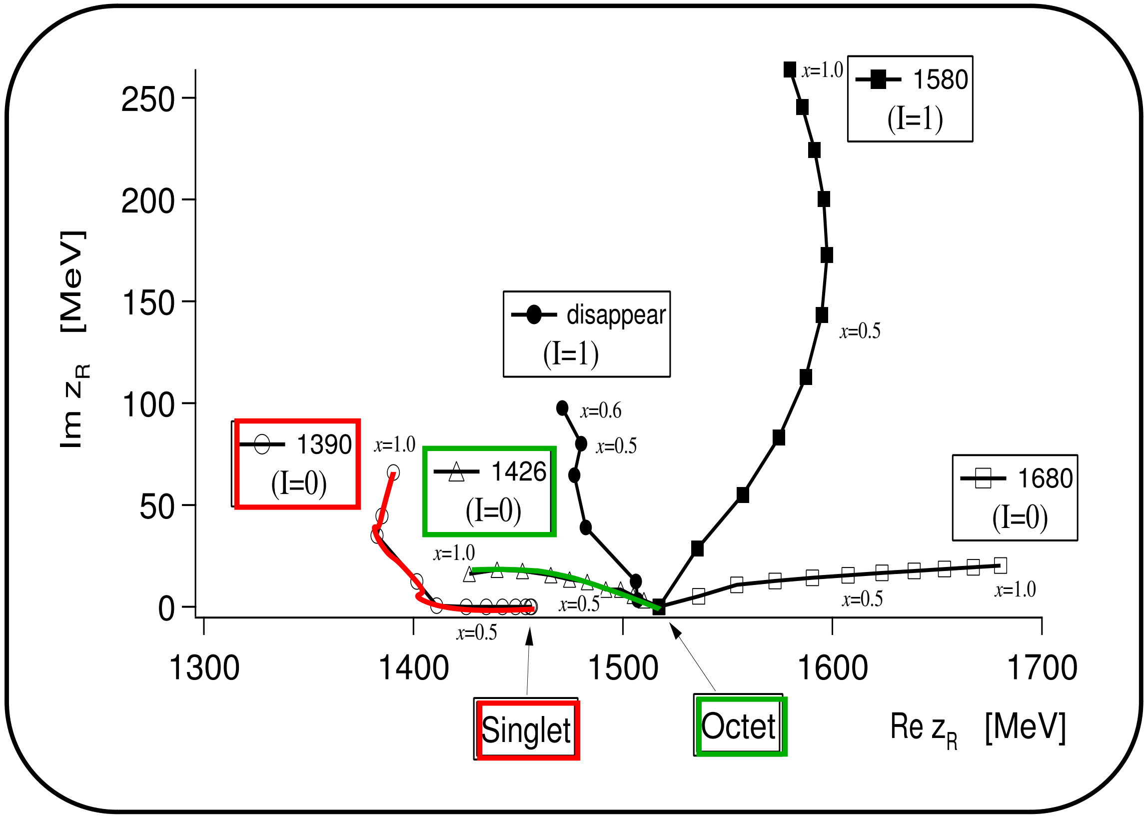
- Scrutinized through further calculations & group theory arguments 2 years later

  Jido, Oller, Oset, Ramos, UGM, Nucl. Phys. A **725** (2003) 181

SU(3) SYMMETRY CONSIDERATIONS

- Group theory: $\mathbf{8} \otimes \mathbf{8} = \underbrace{\mathbf{1} \oplus \mathbf{8}_s \oplus \mathbf{8}_a}_{\text{binding at LO}} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}$

- Follow the pole movement from the SU(3) limit to the physical masses:



INCLUDING KAONIC ATOM DATA

- Improved calculation with all NLO terms and constraints from kaonic hydrogen using precise theory for kaonic atoms based on NREFT

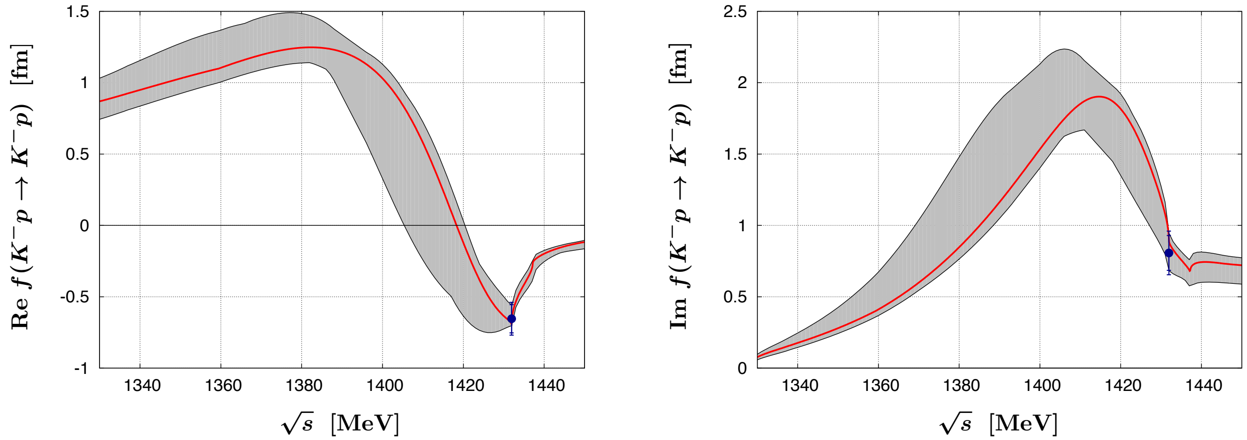
  Ikeda, Hyodo, Weise, Nucl. Phys. A **881** (2012) 98

  UGM, Raha, Rusetsky, Eur. Phys. J. C **35** (2004) 349

$\rightarrow$ Precise proton amplitudes

$\rightarrow$ Predictions for neutron amps.

M. Bazzi *et al.* [SIDDHARTA Collaboration], Phys. Lett. B **704** (2011) 113

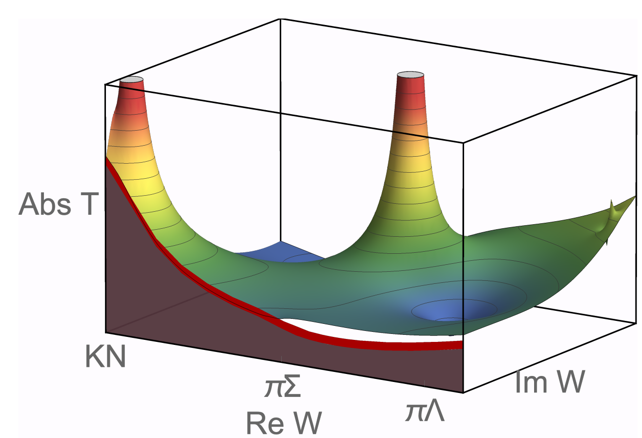


- Similar developments by the Bonn & Murcia groups

  Mai, UGM, Nucl. Phys. A **900** (2013) 51

  Oller, Guo, Phys. Rev. C **87** (2013) 035202

$\hookrightarrow$ Confirms two-pole structure



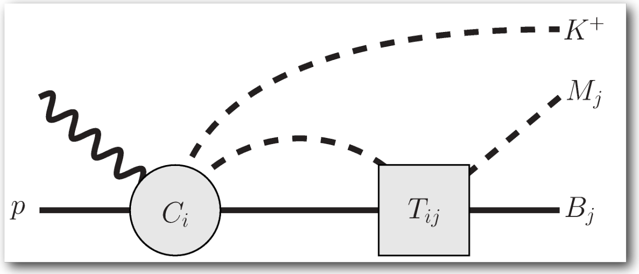
INCLUDING PHOTOPRODUCTION DATA

Mai and UGM, EPJ A **51** (2015) 30

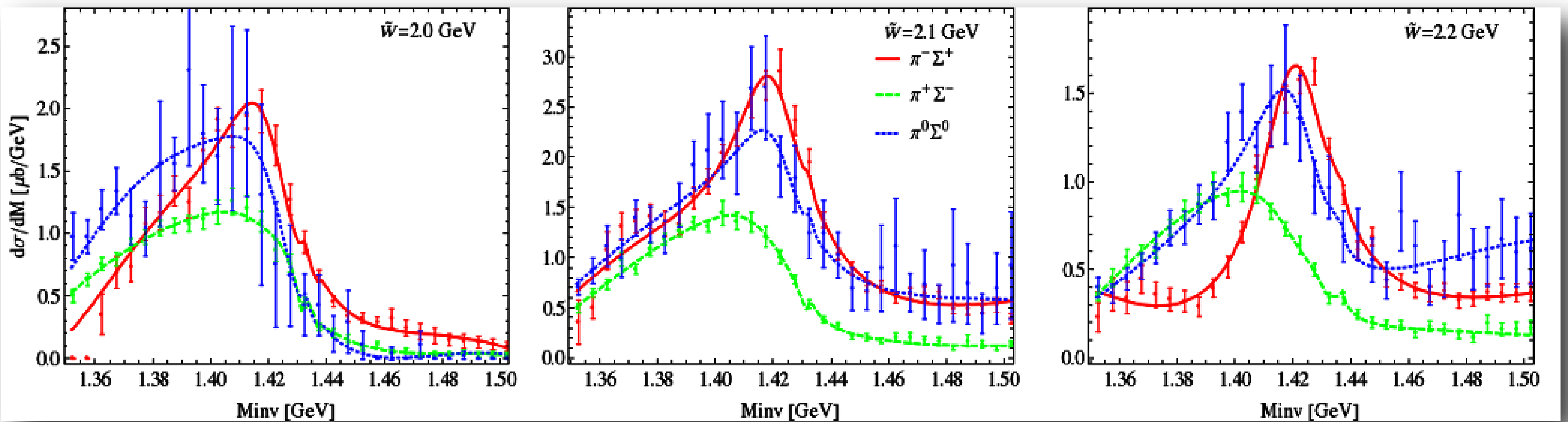
- Simple model for $\gamma p \to K^+\Sigma\pi \to$ CLAS data

  CLAS, Phys. Rev. C **87**, 035206 (2013)

  Roca, Oset, Phys. Rev. C **87**, 055201 (2013)

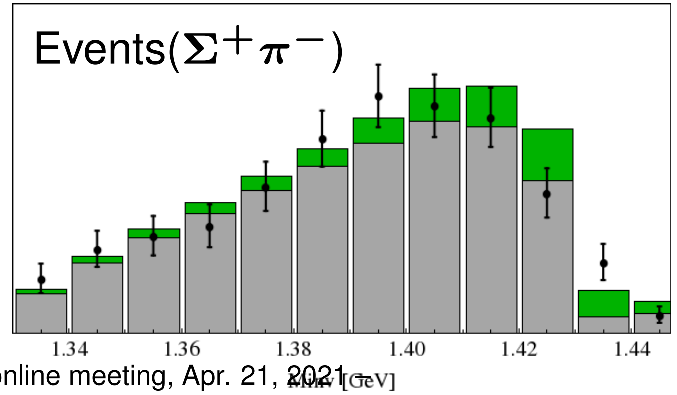


- CLAS data prefer solution 4



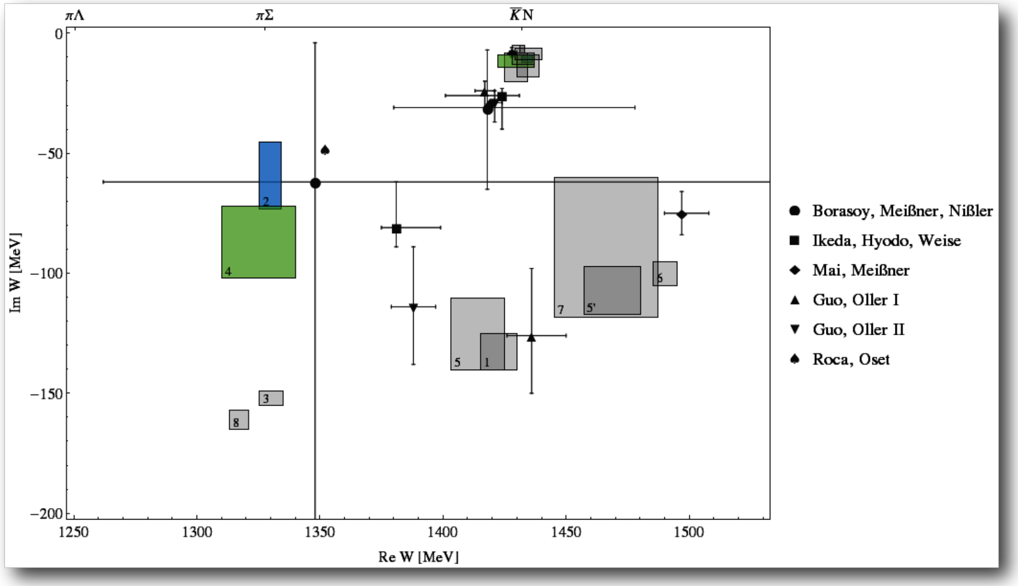
- also good description of $\Sigma^+\pi^-$ distribution from $K^-p \to \Sigma^+\pi^-\pi^+\pi^-$ (not fitted)

- solution 2 also acceptable



STATUS of the TWO-POLE SCENARIO

- Two poles from scattering plus CLAS data:



→ PDG 2016: **http://pdg.lbl.gov/2015/reviews/rpp2015-rev-lam-1405-pole-struct.pdf**

POLE STRUCTURE OF THE $\Lambda(1405)$ REGION Written November 2015 by Ulf-G. Meißner and Tetsuo Hyodo – constantly updated –

→ **return to the RPP in the summary!**

OPEN ENDS

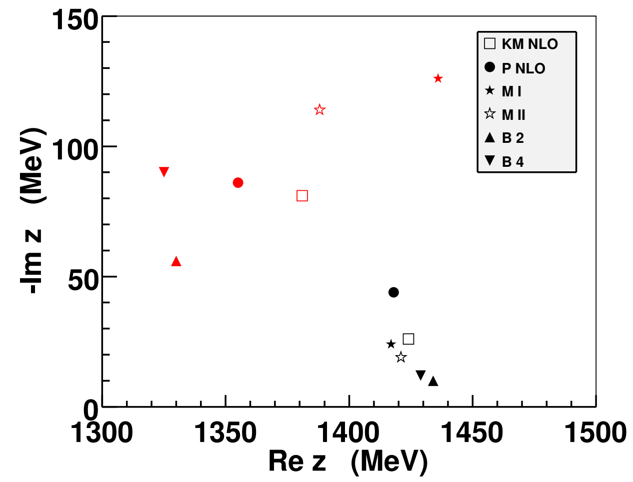
- The story is not yet told to the end:

  Consider various NLO approaches

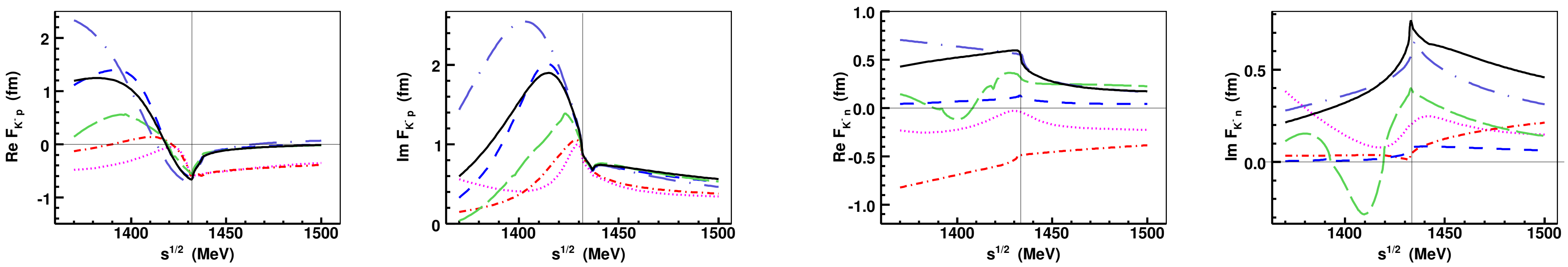
  ⋆ precise location of the heavier pole

  ⋆ subthreshold amp's not yet well determined

  Cieply, Mai, UGM, Smejkal, Nucl. Phys. A **954** (2016) 17



ReF_{K^-p} ImF_{K^-p} ReF_{K^-n} ImF_{K^-n}

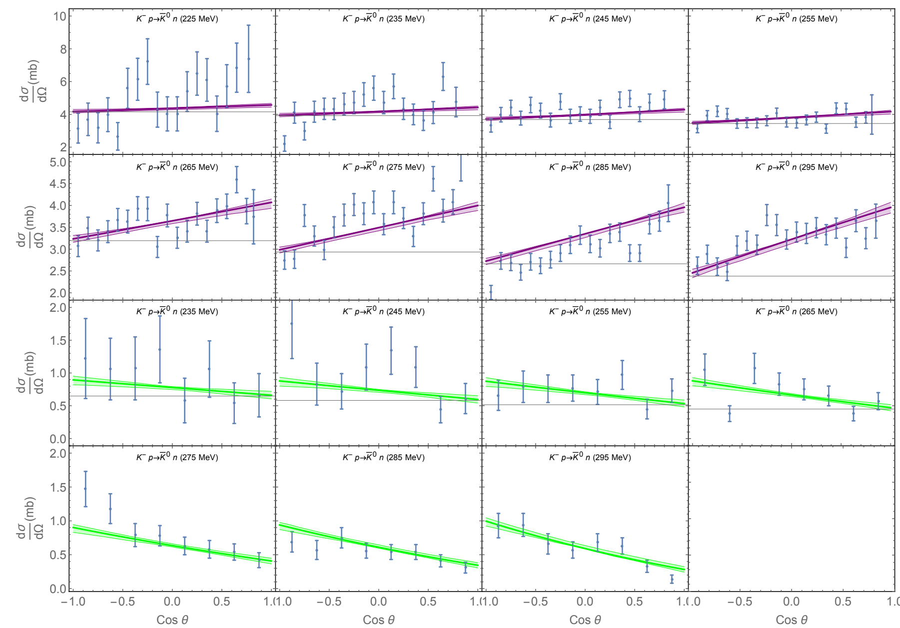


Kyoto-Munich Bonn 2 Bonn 4 Murcia 1 Murcia 2 — · — Prague

Prague: Cieply, Smejkal, Nucl. Phys. A **881** (2012) 115

INCLUDING P-WAVES

- First UCHPT calc. with S- and P-waves & fitting to differential XS data



- Various tests of the scattering amp:

$\hookrightarrow$ $\pi\Sigma$ inv. mass. distribution $\surd$

$\hookrightarrow$ CLAS photoproduction data $\surd$

$\hookrightarrow$ multiple fits w/ constraints on the LECs

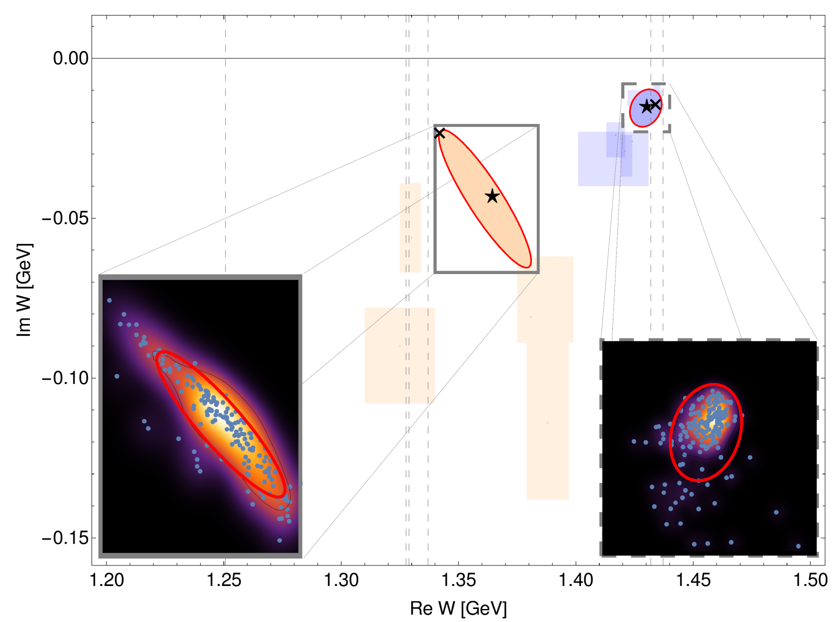
- Two-pole scenario again validated

pole I: $(1430(5) - i15(4))$ MeV
pole II: $(1360(13) - i43(14))$ MeV

Sadavasian, Mai, Döring, Phys. Lett. B**789** (2019) 329

- Update of the two-pole plot available

Mai, arXiv:2010.00056 [nucl-th]



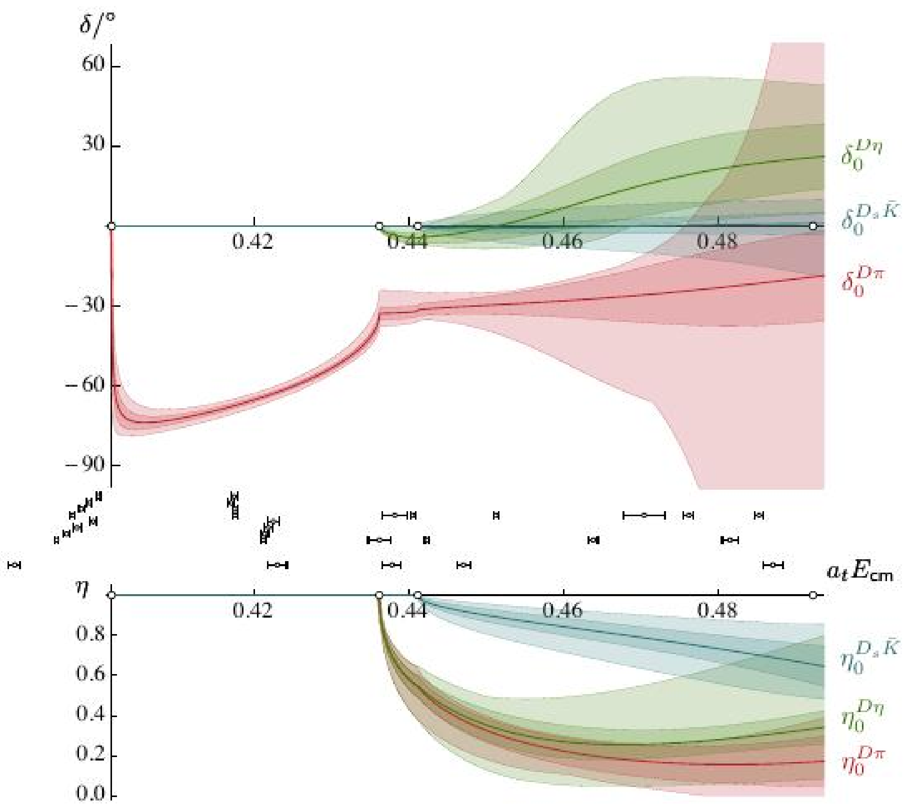
Two-pole structures in the meson sector

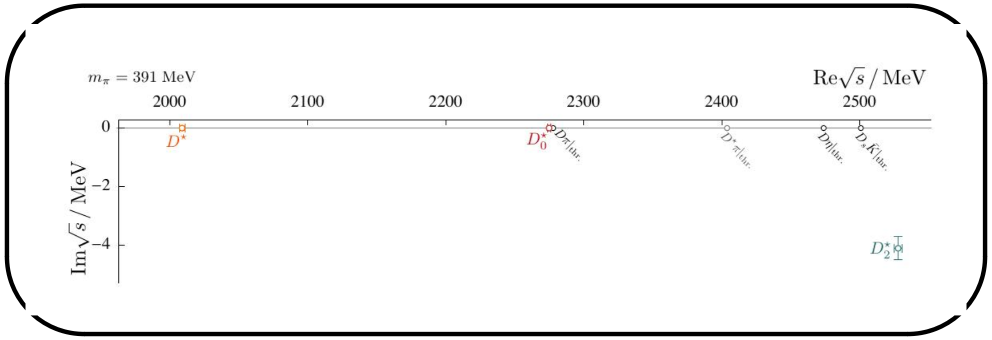
COUPLED CHANNEL SCATTERING on the LATTICE

Moir, Peardon, Ryan, Thomas, Wilson, JHEP **1610** (2016) 011

- $D\pi$, $D\eta$, $D_s\bar{K}$ scattering with $I = 1/2$:

- 3 volumes, one a_s, one a_t, $M_\pi \simeq 390$ MeV, various K-matrix type extrapolations





- S-wave pole at (2275.9 ± 0.9) MeV

- close to the $D\pi$ threshold

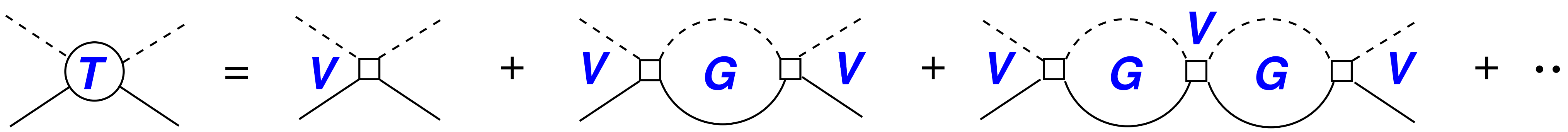
- consistent w/ $D_0^\star(2300)$ of PDG

- BUT: chiral symmetry ignored... :-(

COUPLED CHANNEL DYNAMICS

Kaiser, Weise, Siegel (1995), Oset, Ramos (1998), Oller, UGM (2001), Kolomeitsev, Lutz (2002),Jido et al. (2003), Guo et al. (2006), . . .

- $D\phi$ bound states: Poles of the T-matrix (potential from CHPT and unitarization)



- Unitarized CHPT as a non-perturbative tool:

$$T^{-1}(s) = V^{-1}(s) - G(s)$$

- $V(s)$: derived from the SU(3) chiral Lagrangian, 6 LECs up to NLO $\longrightarrow$ next slide
- $G(s)$: 2-point scalar loop function, regularized w/ a subtraction constant $a(\mu)$
- T, V, G: all these are matrices, channel indices suppressed

COUPLED CHANNEL DYNAMICS cont'd

Barnes et al. (2003), van Beveren, Rupp (2003), Kolomeitsev, Lutz (2004), Guo et al. (2006), . . .

- NLO effective chiral Lagrangian for coupled channel dynamics

Guo, Hanhart, Krewald, UGM, Phys. Lett. B **666** (2008) 251

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(1)} + \mathcal{L}^{(2)}$$

$$\mathcal{L}^{(1)} = \mathcal{D}_\mu D \mathcal{D}^\mu D^\dagger - M_D^2 D D^\dagger\ , \quad D = (D^0, D^+, D_s^+)$$

$$\mathcal{L}^{(2)} = D\left[-h_0\langle\chi_+\rangle - h_1\chi_+ + h_2\langle u_\mu u^\mu\rangle - h_3 u_\mu u^\mu\right] D$$

$$+\mathcal{D}_\mu D\left[h_4\langle u^\mu u^\nu\rangle - h_5\{u^\mu, u^\nu\}\right]\mathcal{D}_\nu D$$

with $u_\mu \sim \partial_\mu \phi\ , \ \ \chi_+ \sim \mathcal{M}_{\rm quark}\ , \ \ldots$

- LECs:

$\hookrightarrow h_0$ absorbed in masses

$\hookrightarrow h_1 = 0.42$ from the D_s-D splitting

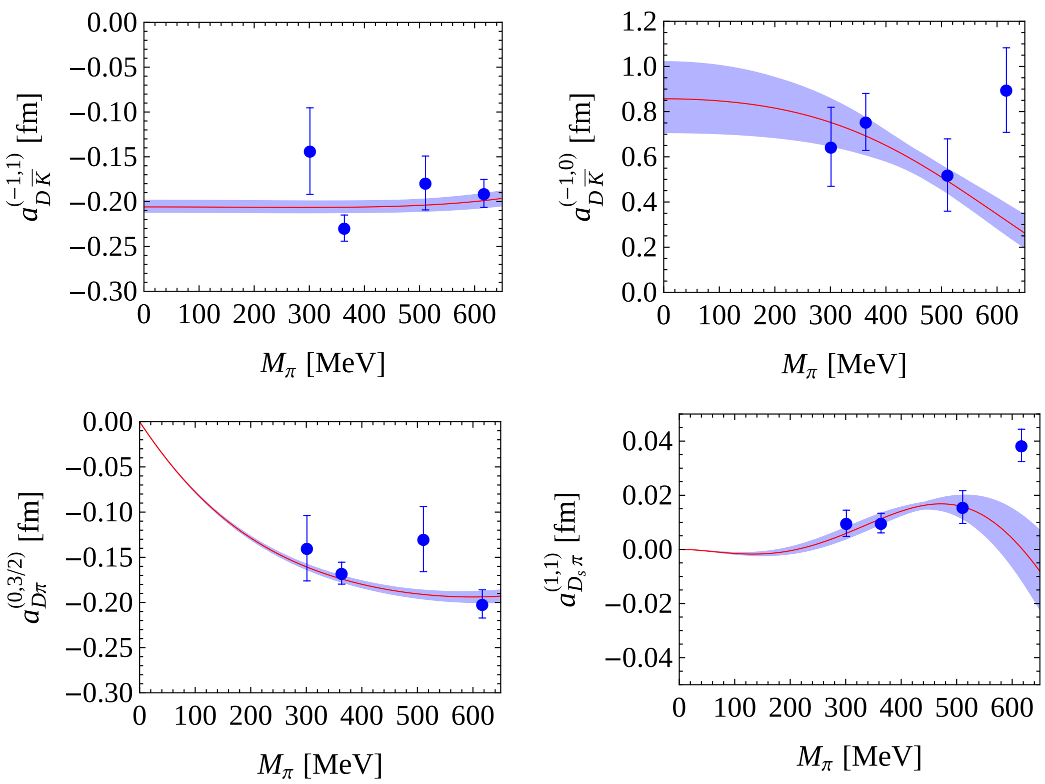
$\hookrightarrow h_{2,3,4,5}$ from a fit to lattice data ($D\pi \to D\pi, D\bar{K} \to D\bar{K}, \ldots$)

Liu, Orginos, Guo, Hanhart, UGM, Phys. Rev. D **87** (2013) 014508

FIT to LATTICE DATA

Liu, Orginos, Guo, Hanhart, UGM, PRD **87** (2013) 014508

- Fit to lattice data in 5 “simple” channels: no disconnected diagrams



[$M_\pi = 600$ MeV not fitted]

- Prediction: Pole in the $(S, I) = (1, 0)$ channel: 2315^{+18}_{-28} MeV

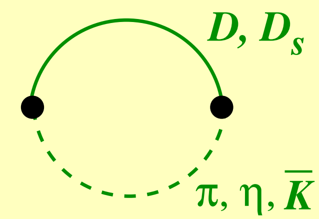
Experiment: $M_{D^\star_{s0}(2317)} = (2317.8 \pm 0.5)$ MeV PDG2019

FINITE VOLUME FORMALISM

- Goal: postdict the finite volume (FV) energy levels for $I = 1/2$ and compare with the recent LQCD results from Moir et al. using the already fixed LECs
  $\to$ parameter-free insights into the $D_0^\star(2300)$

- In a FV, momenta are quantized: $\vec{q} = \frac{2\pi}{L}\vec{n}\,, \quad \vec{n} \in \mathbb{Z}^3$

$\Rightarrow$ Loop function $G(s)$ gets modified: $\int d^3\vec{q} \to \frac{1}{L^3}\sum_{\vec{q}}$



$$\tilde{G}(s,L) = G(s) = \lim_{\Lambda\to\infty}\left[\frac{1}{L^3}\sum_{\vec{n}}^{|\vec{q}|<\Lambda} I(\vec{q}) - \int_0^\Lambda \frac{q^2dq}{2\pi^2} I(\vec{q})\right]$$

Döring, UGM, Rusetsky, Oset, Eur. Phys. J. A**47** (2011) 139

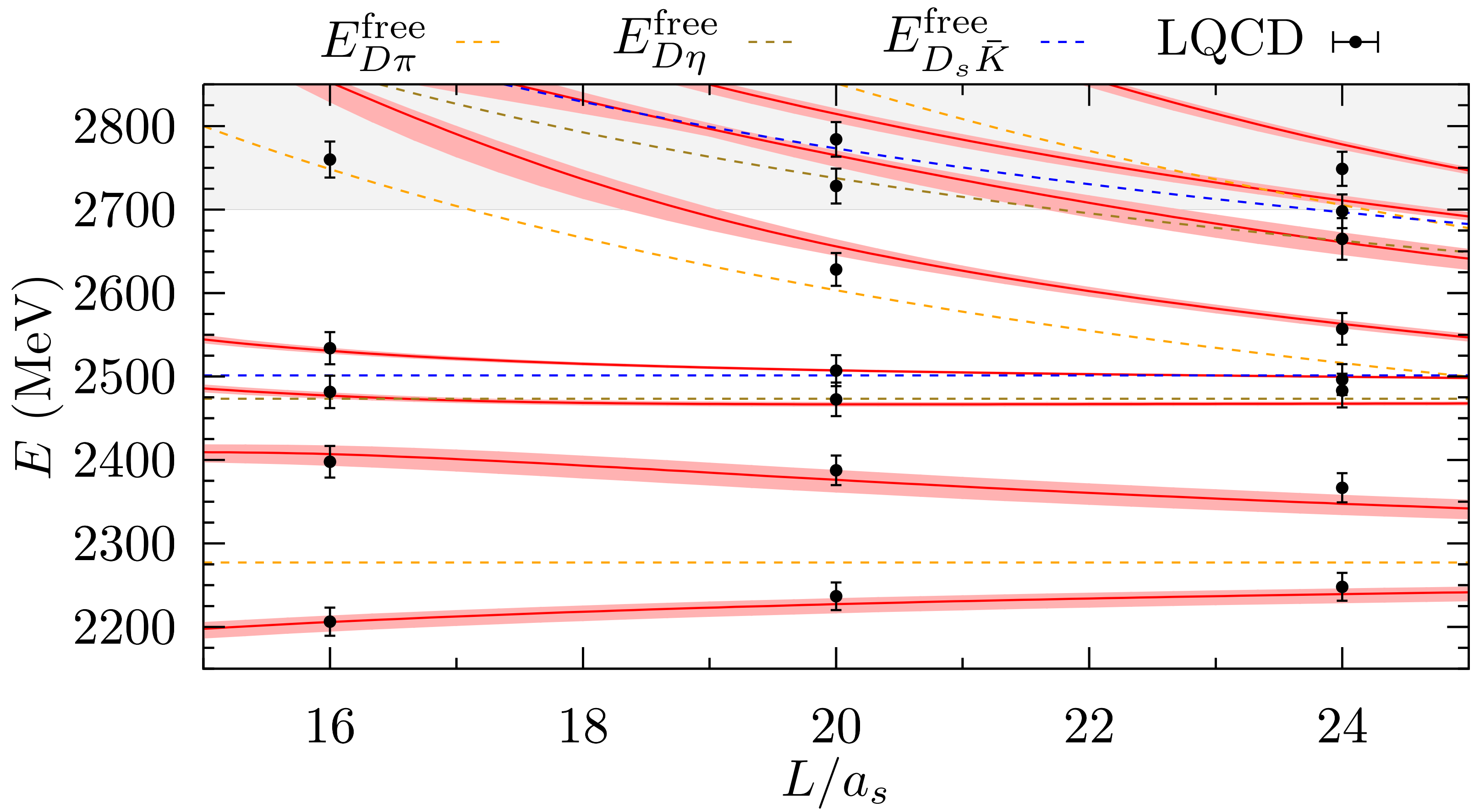
- FV energy levels from the poles of $\tilde{T}(s,L)$:

$$\tilde{T}^{-1}(s,L) = V^{-1}(s) - \tilde{G}(s,L)$$

WHAT ABOUT the $D_0^\star(2300)$?

- Results for $I = 1/2$ $D\phi$ scattering

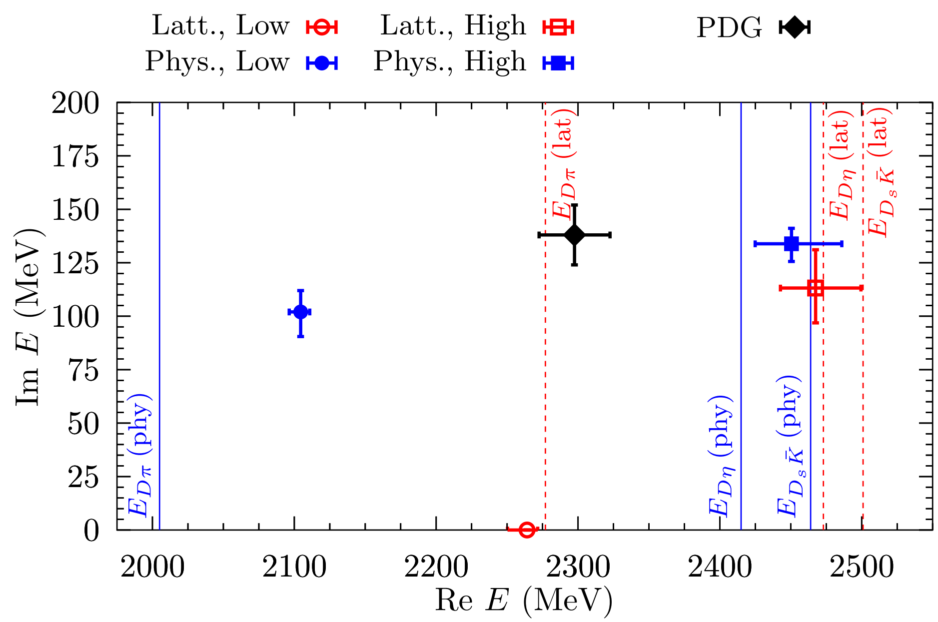
Albaladejo, Fernandez-Soler, Guo, Nieves, Phys. Lett. B **767** (2017) 465



- this is NOT a fit!
- all LECs taken from the earlier study of Liu et al. (discussed before)

WHAT ABOUT the $D_0^\star(2300)$?

Albaladejo, Fernandez-Soler, Guo, Nieves (2017)



- reveals a two-pole scenario! [cf. $\Lambda(1405)$]

- understood from group theory

$$\bar{\mathbf{3}} \otimes \mathbf{8} = \underbrace{\bar{\mathbf{3}} \oplus \mathbf{6}}_{\text{attractive}} \oplus \overline{\mathbf{15}}$$

- this was seen earlier in various calc's

  Kolomeitsev, Lutz (2004), F. Guo, Shen, Chiang, Ping, Zou (2006),
  F. Guo, Hanhart, UGM (2009), Z. Guo, UGM, Yao (2009)

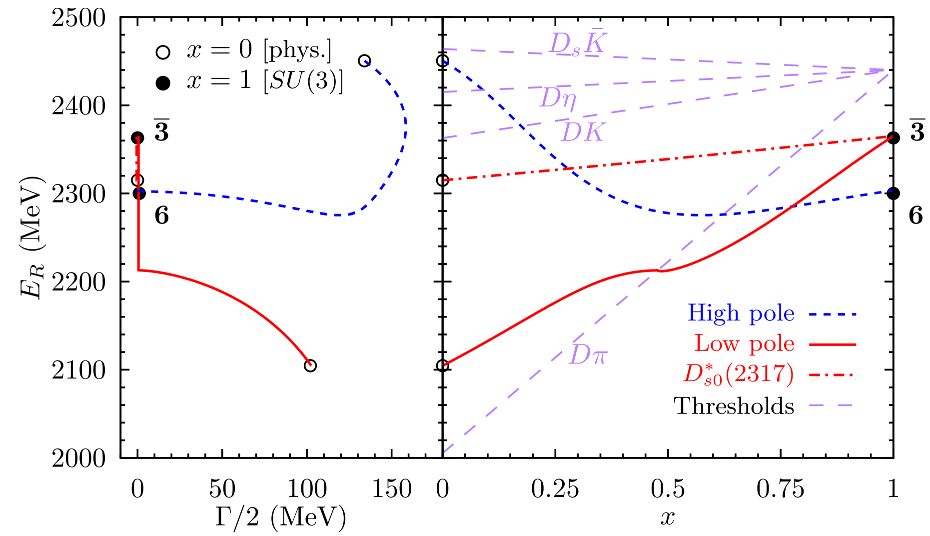
- Again: important role of **chiral symmetry**

- Easy lattice QCD test:

  sextet pole becomes a bound state

  for $M_\phi > 575$ MeV in the SU(3) limit

  Du et al., Phys.Rev. D **98** (2018) 094018



TWO-POLE SCENARIO in the HEAVY-LIGHT SECTOR

- Two states in various $I = 1/2$ states in the heavy meson sector $(M, \Gamma/2)$

	Lower [MeV]	Higher [MeV]	PDG [MeV]
$D_0^\star$	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+36}_{-26}, 134^{+7}_{-8}\right)$	$(2318 \pm 29, 134 \pm 20)$
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$	$\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$(2427 \pm 40, 192^{+65}_{-55})$
$B_0^\star$	$\left(5535^{+9}_{-11}, 113^{+15}_{-17}\right)$	$\left(5852^{+16}_{-19}, 36 \pm 5\right)$	—
B_1	$\left(5584^{+9}_{-11}, 119^{+14}_{-17}\right)$	$\left(5912^{+15}_{-18}, 42^{+5}_{-4}\right)$	—

Lattice QCD: $M_{B^\star_{s0}} = 5711(13)(19)$ MeV , $M_{B_{s1}} = 5750(17)(19)$ MeV

Lang et al., Phys.Lett. B **750** (2015) 17

$\longrightarrow$ but is there further experimental support for this?

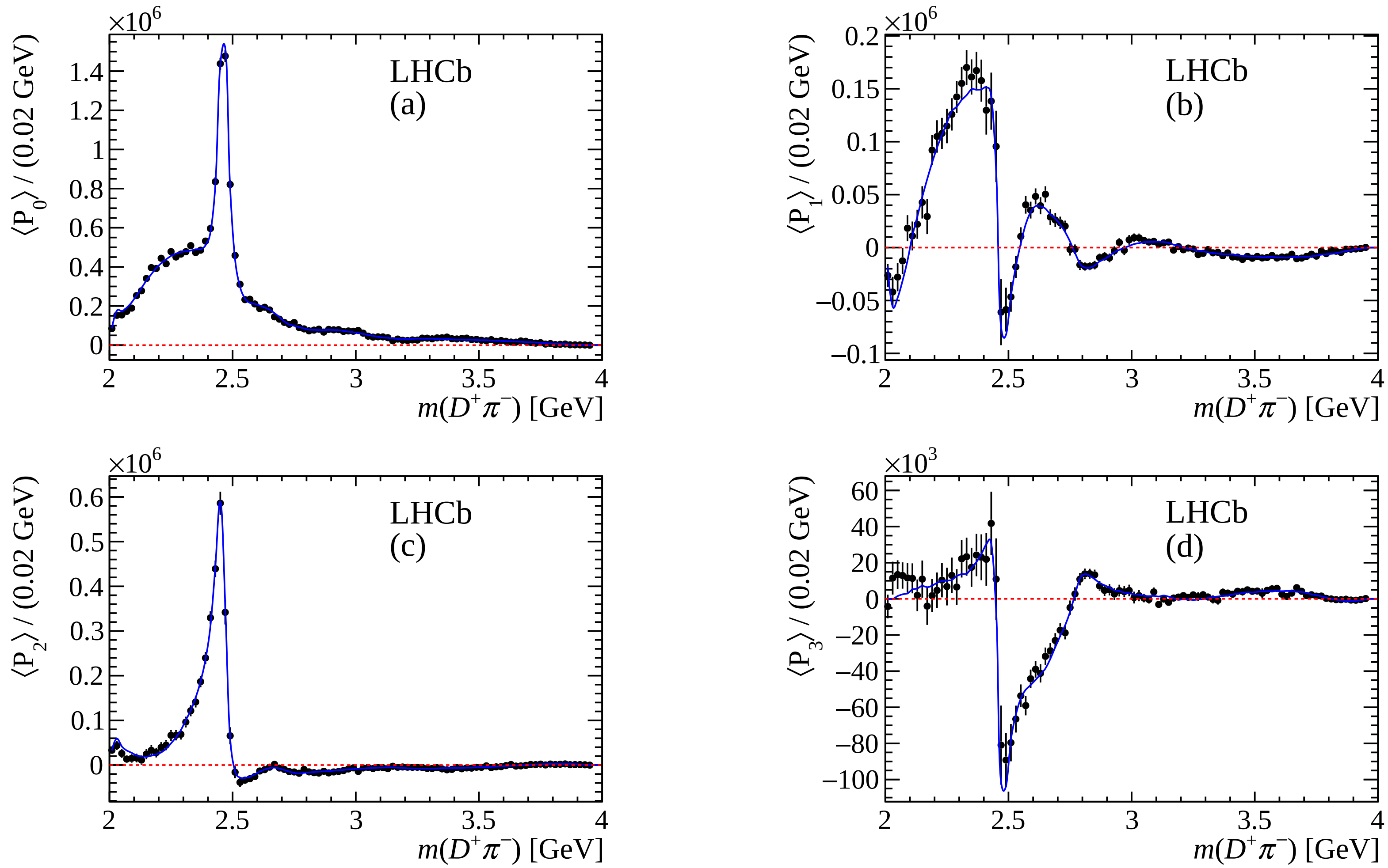
Amplitude Analysis of $B \to D\pi\pi$

DATA for $B \to D\pi\pi$

- Recent high precision results for $B \to D\pi\pi$ from LHCb

Aaji et al. [LHCb], Phys. Rev. D **94** (2016) 072001

- Spectroscopic information in the angular moments ($D\pi$ FSI):



CHIRAL LAGRANGIAN for $B \to D$ TRANSITIONS

Savage, Wise, Phys. Rev. D39 (1989) 3346

- Consider $\bar{B} \to D$ transition with the emission of two light pseudoscalars (pions)

  $\hookrightarrow$ chiral symmetry puts constraints on one of the two pions

  $\hookrightarrow$ the other pion moves fast and does not participate in the final-state interactions

- Chiral effective Lagrangian:

$$\begin{aligned}\mathcal{L}_{\rm eff} = \bar{B}\big[&c_1\,(u_\mu t M + M t u_\mu) + c_2\,(u_\mu M + M u_\mu)\,t \\ &+ c_3\,t\,(u_\mu M + M u_\mu) + c_4\,(u_\mu \langle M t\rangle + M\langle u_\mu t\rangle) \\ &+ c_5\,t\langle M u_\mu\rangle + c_6\langle (M u_\mu + u_\mu M)\,t\rangle\big]\partial^\mu D^\dagger\end{aligned}$$

with

$\bar{B} = (B^-, \bar{B}^0, \bar{B}^0_s)\,, \quad D = (D^0, D^+, D^+_s)$

M is the matter field for the fast-moving pion

$t = uHu$ is a spurion field for Cabbibo-allowed decays

$\to$ only some combinations of the LECs c_i appear

$$H = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

THEORY of $B \to D\pi\pi$

Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Phys. Rev. **D98** (2018) 094018

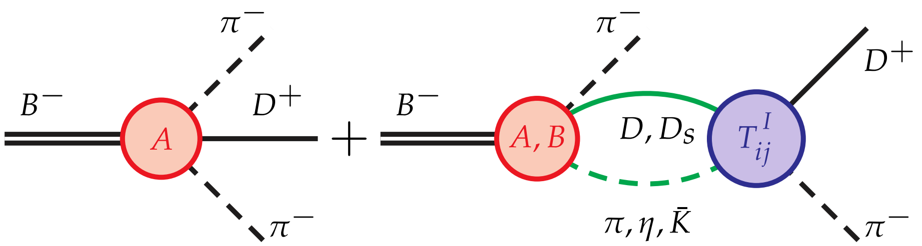
- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI

- consider S, P, D waves: $\mathcal{A}(B^- \to D^+\pi^-\pi^-) = \mathcal{A}_0(s) + \mathcal{A}_1(s) + \mathcal{A}_2(s)$

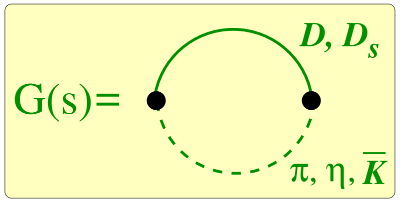
  $\to$ P-wave: $D^\star$, $D^\star(2680)$; D-wave: $D_2(2460)$ as by LHCb

  $\to$ S-wave: use coupled channel ($D\pi$, $D\eta$, $D_s\bar{K}$) amplitudes with all parameters fixed before

  $\to$ only two parameters in the S-wave (one combination of the LECs c_i and one subtraction constant in the G_{ij})



$$\mathcal{A}_0(s) \propto E_\pi \left[2 + G_{D\pi}(s)\left(\tfrac{5}{3}T_{11}^{1/2}(s) + \tfrac{1}{3}T_{11}^{3/2}(s)\right)\right] + \tfrac{1}{3}E_\eta G_{D\eta}(s)T_{21}^{1/2}(s) + \sqrt{\tfrac{2}{3}}E_{\bar{K}}G_{D_s\bar{K}}(s)T_{31}^{1/2}(s) + C\,E_\eta G_{D\eta}(s)T_{21}^{1/2}(s)$$



THEORY of $B \to D\pi\pi$ continued

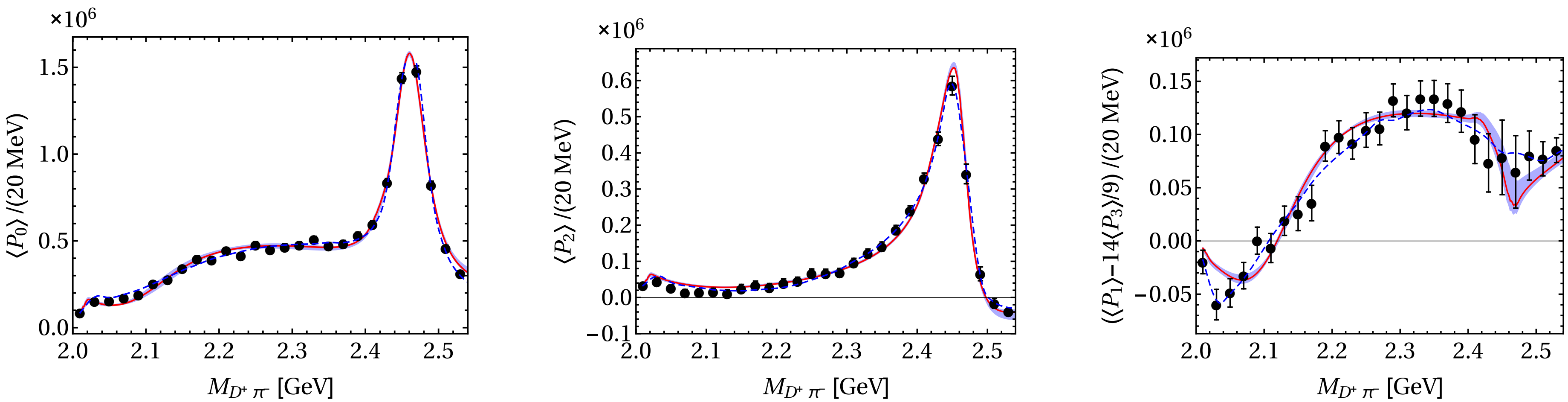
Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Yao, Phys. Rev. **D98** (2018) 094018

- More appropriate combinations of the angular moments:

$$\langle P_0 \rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2$$

$$\langle P_2 \rangle \propto \tfrac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_2 - \delta_0)$$

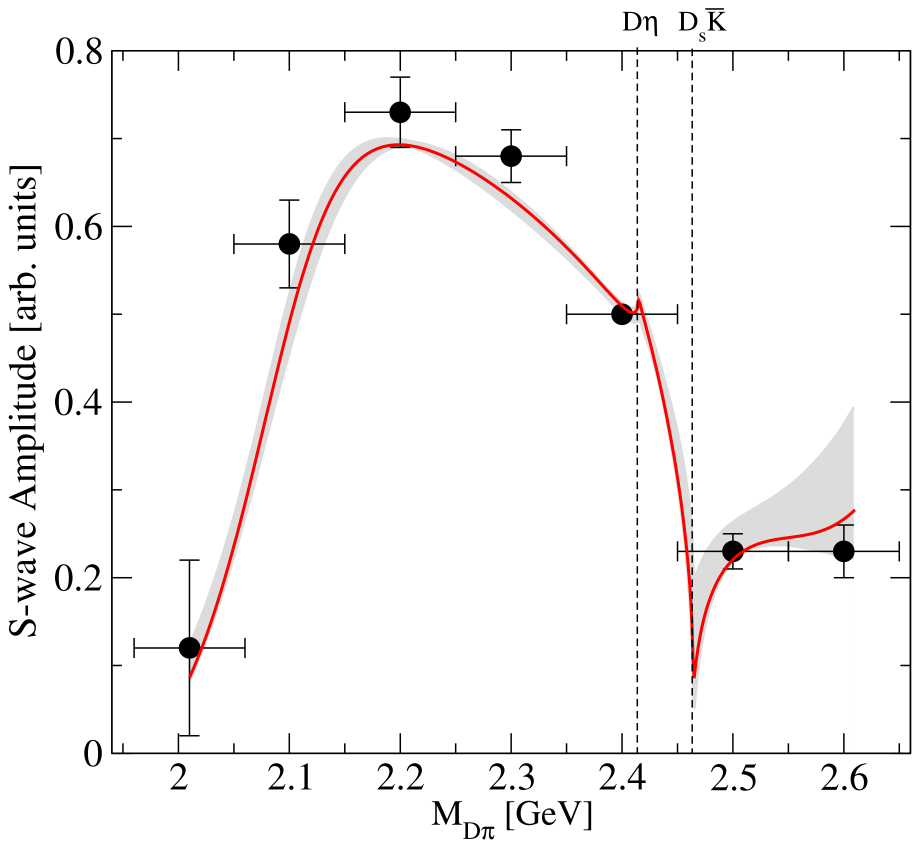
$$\langle P_{13} \rangle = \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1 - \delta_0)$$



- The **S-wave** $D\pi$ can be very well described using pre-fixed amplitudes
- Fast variation in [2.4,2.5] GeV in $\langle P_{13} \rangle$: cusps at the $D\eta$ and $D_s\bar{K}$ thresholds
  $\hookrightarrow$ should be tested experimentally

A CLOSER LOOK at the S–WAVE

- LHCb provides anchor points, where the strength and the phase of the S-wave were extracted from the data and connected by cubic spline

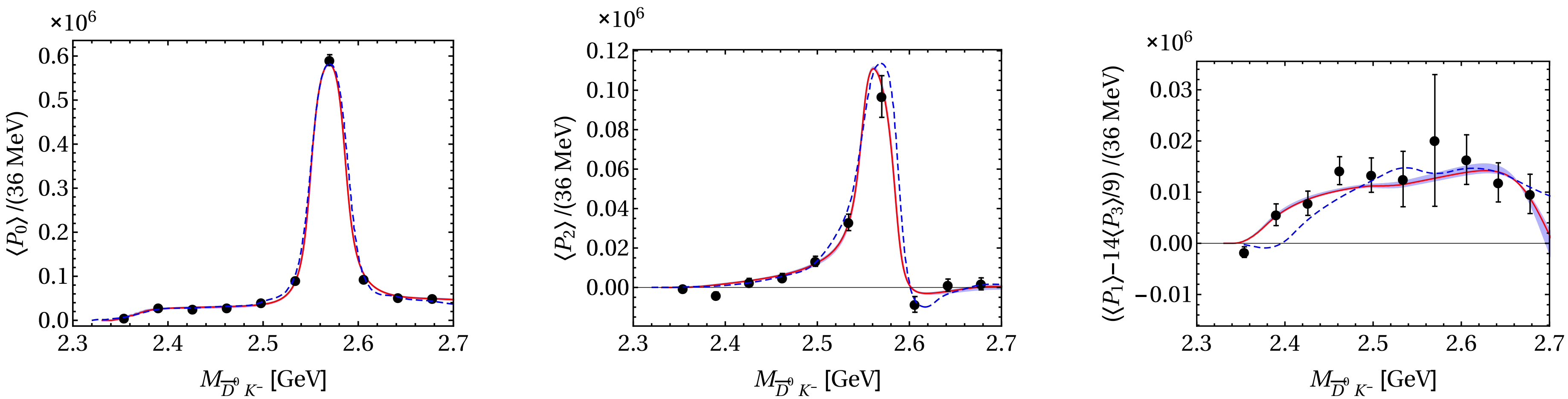


- Higher mass pole at 2.46 GeV clearly amplifies the cusps predicted in our amplitude

THEORY of $B_s^0 \to \bar{D}^0 K^- \pi^+$

Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Yao, Phys. Rev. **D98** (2018) 094018

- LHCb has also data on $B_s^0 \to \bar{D}^0 K^- \pi^+$, but less precise
- Same formalism as before, one different combination of the LECs c_i
- same resonances in the P- and D-wave as LHCb $\hookrightarrow$ one parameter fit!



$\Rightarrow$ these data are also well described

$\Rightarrow$ better data for $\langle P_{13} \rangle$ would be welcome

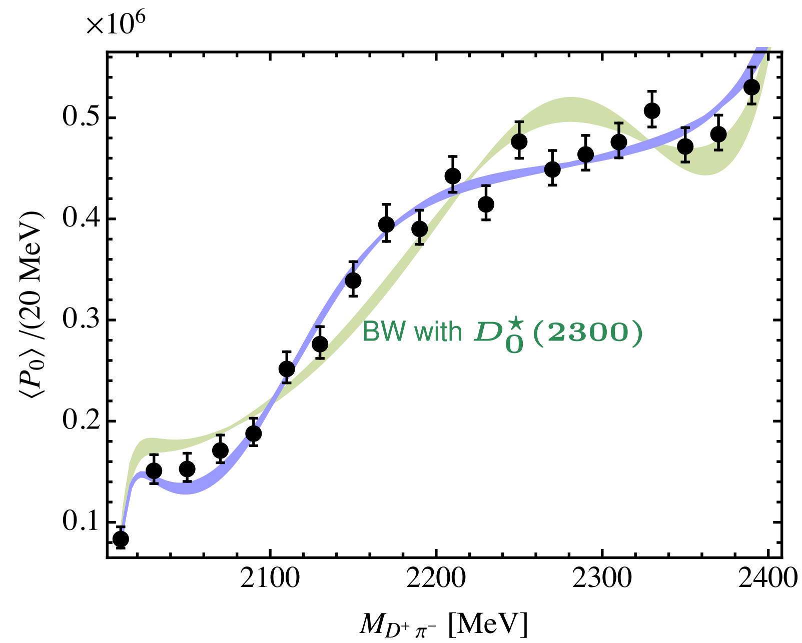
$\Rightarrow$ even more channels, see Du, Guo, UGM, Phys. Rev. D **99** (2019) 114002

Where is the lowest charm-strange meson?

Du, Guo, Hanhart, Kubis, UGM, Phys. Rev. Lett. (2021) in press [2012.04599]

- Precise analysis of the LHCb data on $B^- \to D^+\pi^-\pi^-$ using UChPT and Khuri-Treiman eq's (3-body unit.)
  Aaji et al. [LHCb], Phys. Rev. D **94** (2016) 072001

- Breit-Wigner description not appropriate for the S-wave but UChPT and the dispersive analysis are!

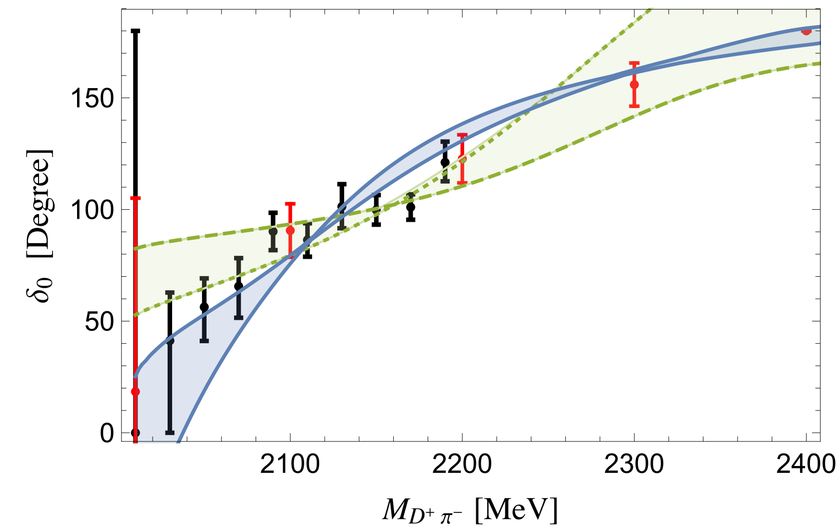


- First determination of the $D\pi$ phase shift

- The lowest charm-strange meson is located at:

$$\left(2105^{+6}_{-8} - i\,102^{+10}_{-11}\right) \text{MeV}$$

- Recently confirmed by Lattice QCD!
  Cheung et al. [HadSpec], JHEP 02 (2021) 100



SUMMARY & OUTLOOK

- It all started with the two-pole structure of the $\mathbf{\Lambda(1405)}$

  $\hookrightarrow$ well established fact!

  $\hookrightarrow$ lighter pole still needs better determination ↯

  $\hookrightarrow$ be aware of models that can not cope with this

- Clear candidates in the meson sector

  $\hookrightarrow$ some excited charm mesons are good candidates for molecules

  $\hookrightarrow$ esp. $\boldsymbol{D_0^\star(2300)}$, $\boldsymbol{D_{s0}^\star(2317)}$, $\boldsymbol{D_{s1}(2460)}, \ldots$

  $\hookrightarrow$ this solves various puzzles: masses, ordering, . . .

  $\hookrightarrow$ testable predictions for various beauty mesons $\boldsymbol{B_0^\star, B_1}$

- All this is not properly reflected in the PDG tables

  $\hookrightarrow$ summary tables e.g. only lists one pole for the $\mathbf{\Lambda(1405)}$

  $\hookrightarrow$ many states analyzed using BW parametrization :-(

  $\hookrightarrow$ **PDG needs a more serious approach to the hadron spectrum!**

SUMMARY & OUTLOOK II

- but there is some hope, two excited Λ states listed now (2020 edition):

P. A. Zyla *et al.* [Particle Data Group], PTEP **2020** (2020) 083C01

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Lambda(1380)$ $1/2^-$ $J^P = \frac{1}{2}^-$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

See the related review on "Pole Structure of the $\Lambda(1405)$ Region."

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Lambda(1405)$ $1/2^-$ $I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the N-$\overline{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that this behavior "is characteristic of S-wave coupling; the other below threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its N-$\overline{K}$ coupling is P-wave. For $\Lambda(1405)$ this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

A recent measurement by the CLAS collaboration, MORIYA 14, definitively established the long-assumed $J^P = 1/2^-$ spin-parity assignment of the $\Lambda(1405)$. The experiment produced the $\Lambda(1405)$ spin-polarized in the photoproduction process $\gamma p \to K^+ \Lambda(1405)$ and measured the decay of the $\Lambda(1405)$(polarized) $\to \Sigma^+$(polarized)π^-. The observed isotropic decay of $\Lambda(1405)$ is consistent with spin $J = 1/2$. The polarization transfer to the Σ^+(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

See the related review(s):
Pole Structure of the $\Lambda(1405)$ Region

- a new two-star resonance at 1380 MeV
- still not in the summary table
- above/below the line dubious!

⇒ this general phenomenon must be accounted for!

SPARES

Short Introduction

LIMITS of QCD

- **light quarks:** $\mathcal{L}_{\rm QCD} = \bar{q}_L \, i\not{D} q_L + \bar{q}_R \, i\not{D} q_R + \mathcal{O}(m_f/\Lambda_{\rm QCD}) \quad [f = u, d, s]$
  - L and R quarks decouple ⇒ chiral symmetry
  - spontaneous chiral symmetry breaking ⇒ pseudo-Goldstone bosons
  - pertinent EFT ⇒ chiral perturbation theory (CHPT)
- **heavy quarks:** $\mathcal{L}_{\rm QCD} = \bar{Q}_f \, iv \cdot D \, Q_f + \mathcal{O}(\Lambda_{\rm QCD}/m_f) \quad [f = c, b]$
  - independent of quark spin and flavor
    ⇒ SU(2) spin and SU(2) flavor symmetries (HQSS and HQFS)
  - pertinent EFT ⇒ heavy quark effective field theory (HQEFT)
- **heavy-light systems:**
  - heavy quarks act as matter fields coupled to light pions
  - combine CHPT and HQEFT

CHIRAL DYNAMICS — UPDATE

- QCD with three light flavors: A theoretical paradise — Leutwyler

$$\boxed{\mathcal{L}_{\rm QCD} = \mathcal{L}^0_{\rm QCD} - \bar{q}\mathcal{M}q}\,,\quad q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}\,,\quad \mathcal{M} = \begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix}$$

⇒ Exhibits **spontaneuous** and **explicit** chiral symmetry breaking

⇒ Can be analyzed **systematically** & **precisely** using EFT = chiral perturbation theory

Weinberg (1979) Gasser, Leutwyler (1984,1985)

⇒ Many intriguing results, but:

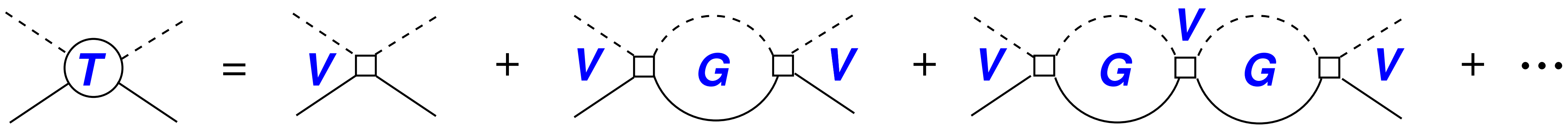
— often convergence problems in the presence of **strange** quarks

— limited by the appearance of **resonances** and **bound** states

- Discuss here such cases & methods that overcome these limitations w/ particular emphasis on WW’s contribution [baryon spectrum & interactions]

ENTERS CHIRAL DYNAMICS

- Great idea:
  Combine (leading-order) chiral SU(3) Lagrangian with coupled-channel dynamics
  Kaiser, Siegel, Weise, Nucl. Phys. A **594** (1995) 325



$\hookrightarrow$ Dominance of the Weinberg-Tomozawa term, excellent description of K^-p data and $\pi\Sigma$ mass distribution, also inclusion of NLO terms with constrained fits

$\hookrightarrow$ The $\Lambda(1405)$ appears as a **dynamically generated state** (MB molecule)

$\hookrightarrow$ Highly cited follow-ups from TUM group plus other groups, esp. “Spanish Mafia”
Oset, Ramos, Nucl. Phys. A **635** (1998) 99, ...

- But: unpleasant regulator dependence (Yukawa-type, momentum cut-off)
  gauge invariance in photo-reactions?

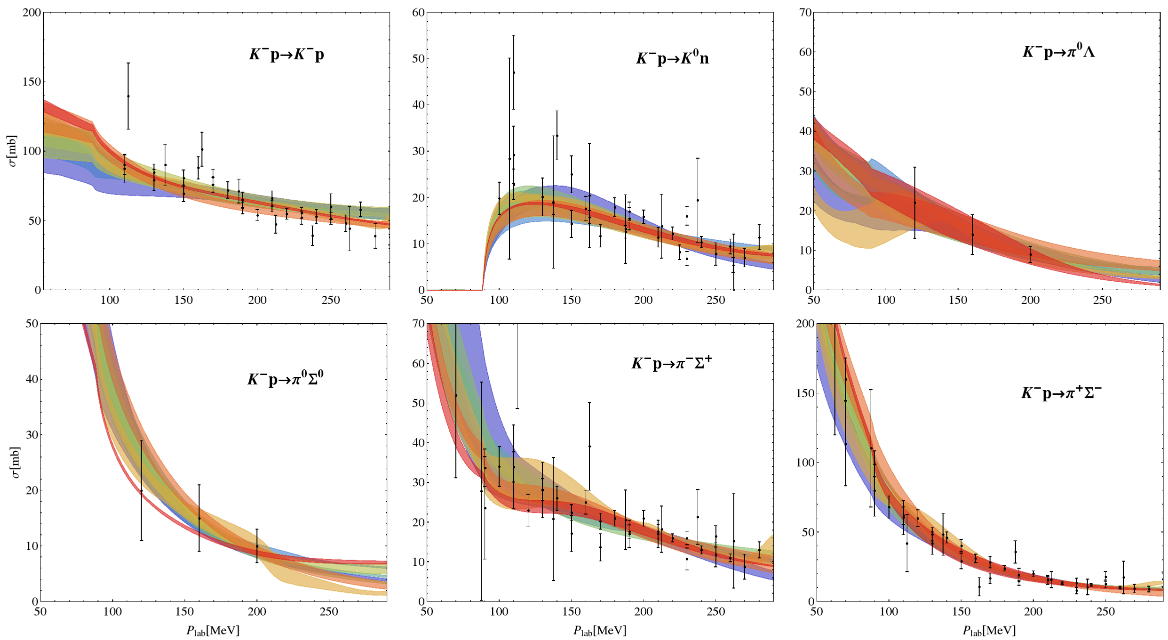
YET ANOTHER TWIST

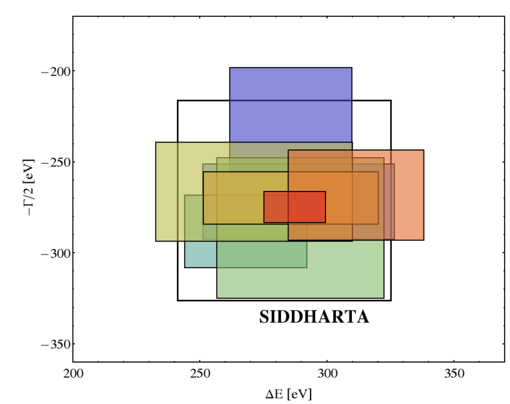
- Looking even more closely, yet another surprise:

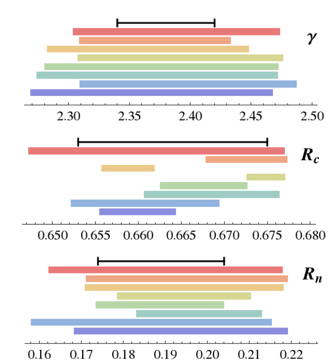
$\Rightarrow$ at least 8 solutions of similar quality w/ different pairs of poles for the $\mathbf{\Lambda(1405)}$

Mai and UGM, EPJ A **51** (2015) 30

- Scattering data
- Kaonic hydrogen
- Threshold ratios







SIDDHARTA: M. Bazzi et al., Phys. Lett. B **704**, 113 (2011)
Scatt. data: Ciborowski et al., J. Phys. G **8**, 13 (1982), Humphrey, Ross, Phys. Rev. **127**, 1305 (1962)
Sakitt et al., Phys. Rev. B **139**, 719 (1965), Watson et al., Phys.Rev. **131**, 2248 (1963)