Theory of Hadron Resonances

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

supported by DFG, SFB/TR-110

by CAS, PIFI

by VolkswagenStftung

CONTENTS

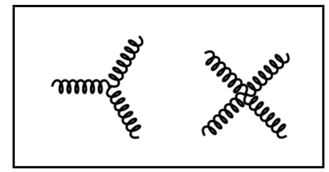
- **Intro: QCD and excited states**
- **Lesson 1: What is a resonance?**
- **Lesson 2: Well separated resonances**
- **Lesson 3: Coupled channels/thresholds**
- **Lesson 4: Hadronic molecules**
- **Lesson 5: The width of baryon resonances from EFT**
- **Short summary & outlook**

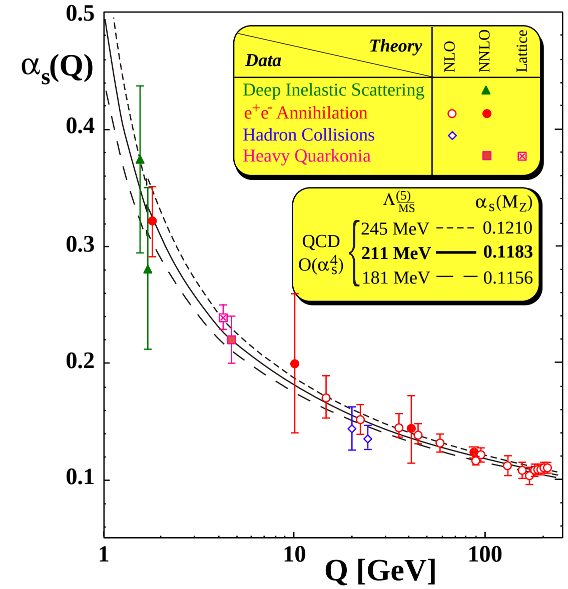
Introduction

QCD LAGRANGIAN

- $$\mathcal{L}_{\rm QCD} = -\frac{1}{4}\, G^a_{\mu\nu} G^{\mu\nu,a} + \sum_f \bar{q}_f (i \not{D} - \mathcal{M}) q_f + \ldots$$

$$D_\mu = \partial_\mu - i g A^a_\mu \lambda^a/2$$
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g[A^b_\mu, A^c_\nu]$$
$$f = (u, d, s, c, b, t)$$





- running of $\alpha_s = \dfrac{g^2}{4\pi} \Rightarrow \Lambda_{\rm QCD} = 210 \pm 14\,{\rm MeV} \quad (N_f = 5, \overline{MS}, \mu = 2\,{\rm GeV})$

- light (u,d,s) and heavy (c,b,t) quark flavors:

$$m_{\rm light} \ll \Lambda_{\rm QCD} \qquad m_{\rm heavy} \gg \Lambda_{\rm QCD}$$

$$m_u = 2.2^{+0.5}_{-0.3}\,{\rm MeV} \qquad m_c = 1.27 \pm 0.02\,{\rm GeV}$$
$$m_d = 4.7^{+0.5}_{-0.2}\,{\rm MeV} \qquad m_b = 4.18^{+0.03}_{-0.02}\,{\rm GeV}$$
$$m_s = 93^{+11}_{-5}\,{\rm MeV} \qquad m_t = 173.1 \pm 0.9\,{\rm GeV}$$

LIMITS of QCD

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

WHY EXCITED STATES?

- The spectrum of QCD is its **least** understood feature
  - $\rightarrow$ why only qqq and $\bar{q}q$ states? XYZ states? "exotics"? glueballs?
  - $\rightarrow$ important players: **hadronic molecules** $\leftrightarrow$ nuclear physics
  - $\rightarrow$ the quark model is much too simple ...
  - $\rightarrow$ need insight from EFTs $\leftrightarrow$ symmetries!

- Many recent high-precision data (utilizing e.g. double polarization exp's)
  - $\rightarrow$ ELSA at Bonn, CEBAF at Jefferson Lab, LHCb at CERN, BESIII at BEPCII, ..., PANDA at FAIR, GlueX at JLab12, ...

- Lattice QCD can get ground-states at almost physical pion masses
  - $\rightarrow$ most distinctive feature of excited states: *decays*
  - $\rightarrow$ only captured for very few states in lattice QCD
  - $\rightarrow$ must explore this (almost complete) *terra incognita*

Lesson 1
What is a resonance?

WHAT is a RESONANCE?

- *“Not every bump is a resonance and not every resonance is a bump”*

Moorhouse 1960ties

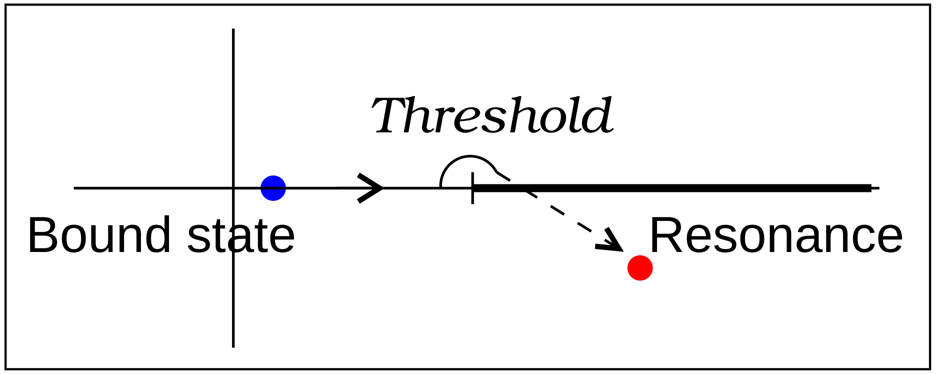
- Resonances have **complex** properties (mass & width, photo-couplings, . . .)

↪ these intrinsic properties do not depend on the experiment or theory (model)

- Resonances correspond to S-matrix poles on unphysical Riemann sheets

↪ only model-independent definition !

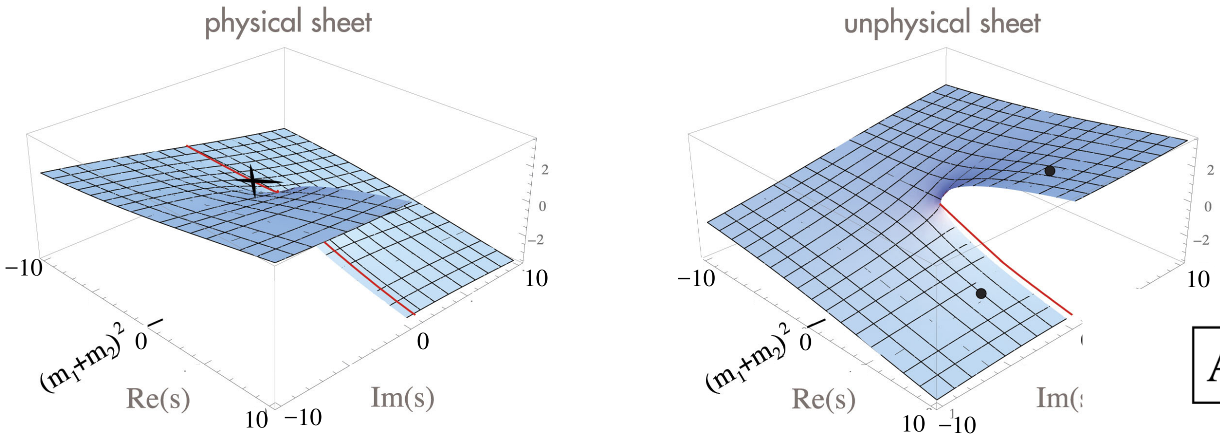
↪ matrix-elements from analytic cont. to the resonance pole p_R ↪ pics next slide



- That’s all nice in the continuum, but . . .

PICTURES of RESONANCES

- Resonances as complex poles on unphsyical sheets:

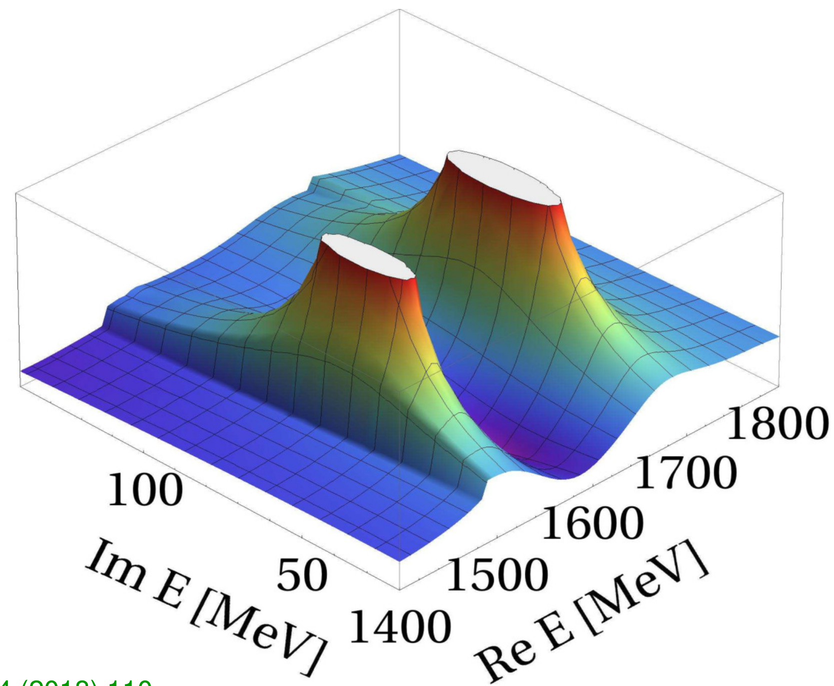


- A view of the two close-by baryon resonances:

  the two lowest nucleon excitations in the

  S_{11} partial wave of $\pi N \to \pi N$

  JüBo approach, D. Rönchen et al.



NP A829 (2009) 170; A851 (2011) 58; EPJ A49 (2013) 44; A50 (2014) 101; A51 (2015) 70; A54 (2018) 110

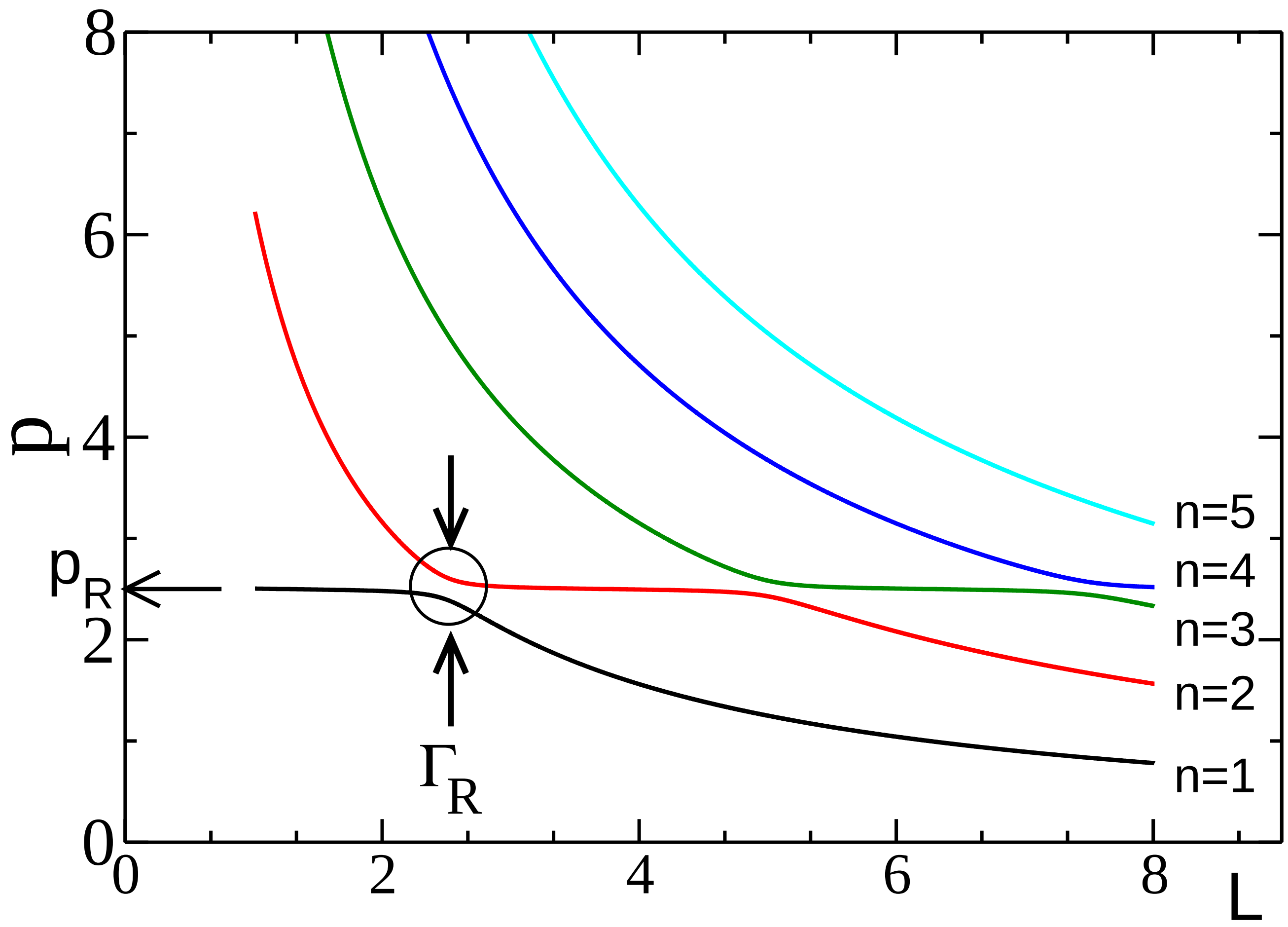
RESONANCES IN A BOX

- Resonances in a box: not eigenstates of the Hamiltonian

  $\Rightarrow$ volume dependence of the energy spectrum

Lüscher, Wiese, . . .

- consider a narrow resonance $\rightarrow$ *avoided level crossing*



Lesson 2
Well separated resonances

ISOLATED RESONANCES in a BOX

- Two identical particles of mass m in a box, no interaction:

$$E = 2\sqrt{m^2 + |\vec{p}\,|^2}\,, \qquad p_i = \frac{2\pi}{L} n_i\,, \quad n_i \in \mathbb{Z}$$

- turn on interaction $\to$ scattering phase $\to$ Lüscher formula: Lüscher 1985

$$\delta(p) = -\phi(q) \bmod \pi\,, \quad q = \frac{pL}{2\pi}$$

$$\phi(q) = -\frac{\pi^{3/2} q}{\mathcal{Z}_{00}(1;q^2)}\,, \quad \mathcal{Z}_{00}(1;q^2) = \frac{1}{\sqrt{4\pi}} \sum_{\vec{n}\in\mathbb{Z}^3} \frac{1}{\vec{n}^{\,2} - q^2}$$

- assume resonance with mass $m_R > 2m$ $\to$ effective range expansion (Breit-Wigner shape):

$$\tan\left(\delta - \frac{\pi}{2}\right) = \frac{E^2 - m_R^2}{m_R \Gamma_R} \qquad \text{[not general!]}$$

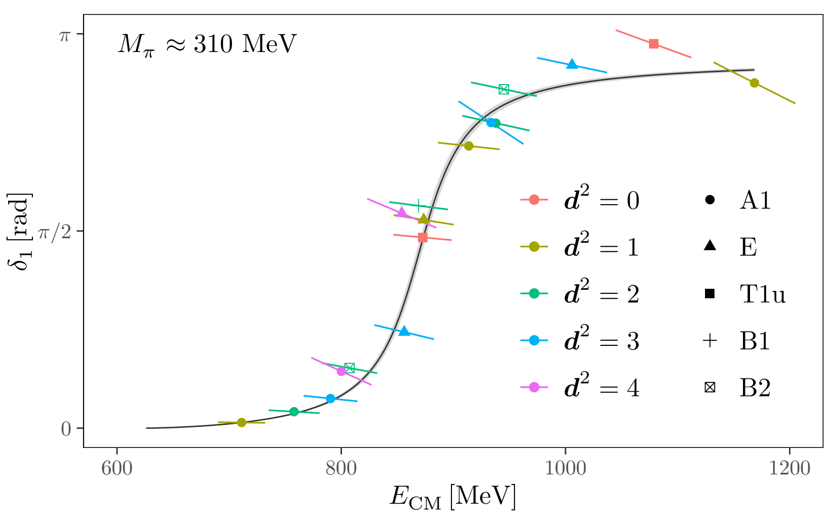
$\Rightarrow$ measure the phase shift in the resonance region and fit m_R, Γ_R
& extension to moving frames Rummukainen, Gottlieb (1995) + . . .

RESULTS for the $\rho(770)$-MESON

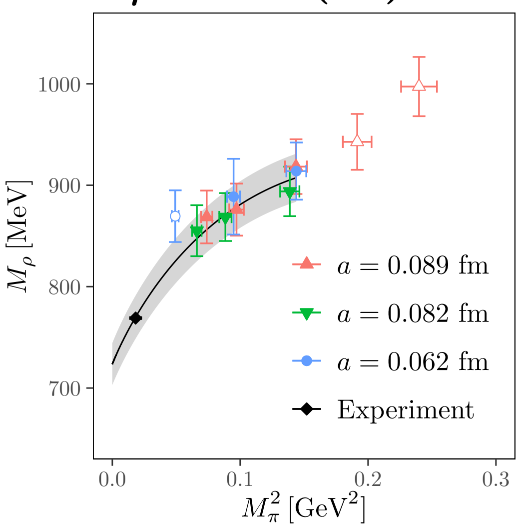
- The $\rho(770)$ is a well separated meson resonance in the $\pi\pi$ system
- P-wave $\pi\pi$ scattering, $M_\pi = 280 - 500$ MeV, three different a, three different L, boosts $\vec{d} = 0, 1, 2, 3, 4$, all irreps

Werner et al. [ETMC] 1907.01237 [hep-lat]

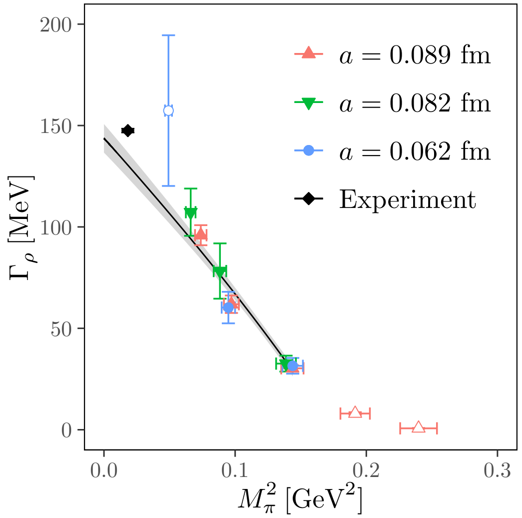
- Phase shift



- Mass $M_\rho = 770(19)$ MeV



- Width $\Gamma_\rho = 130(7)$ MeV

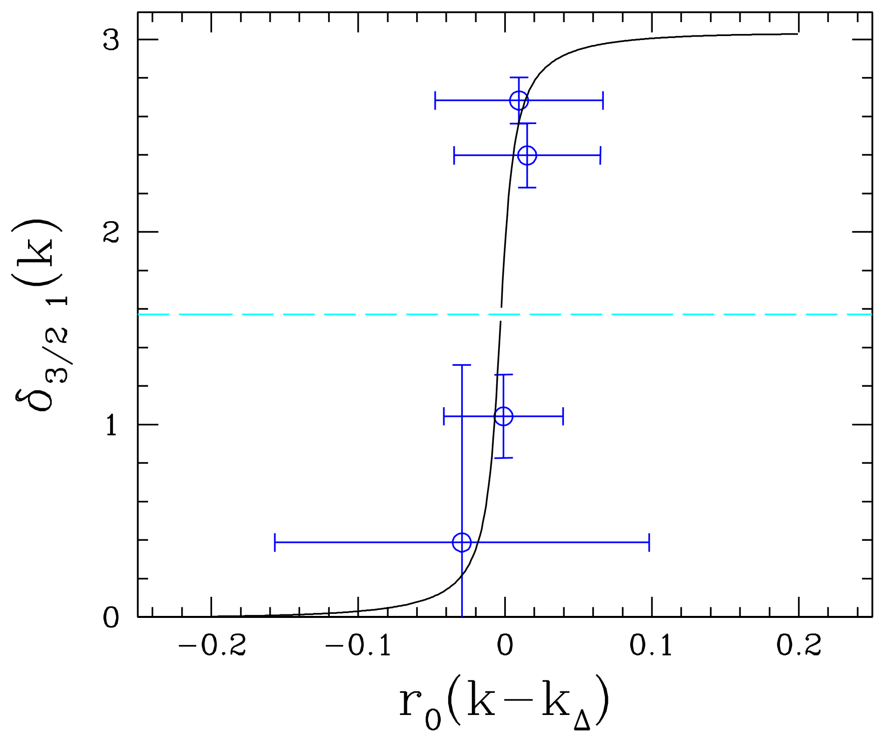


- consistent with other collaborations world-wide
- pioneered in: Feng, Jansen, Renner (2011)

RESULTS for the $\Delta(1232)$

QCDSF-Bonn-Jülich coll., see UGM, J. Phys. Conf. Ser. **295** (2011) 012001

- The $\Delta(1232)$ is a well separated baryon resonance in the πN system
- $l = 1, I = 3/2$ πN phase shift



- M_π = 160 - 390 MeV, large volumes
- consistent with the experimental width
- precision determination of $g_{\pi N\Delta}$
  requires more precise data
  around $\delta = \pi/2$

→ for new quantitative results, see
Alexandrou et al., Phys.Rev. D88 (2013) 031501
Alexandrou et al., Phys.Rev. D93 (2016) 114515
Andersen et al., Phys.Rev. D97 (2018) 014506

Lesson 3: Coupled channels / thresholds

EXTENSION to COUPLED CHANNELS

- Isolated (well-separated) resonances are the exception
- Coupled channel effects, close-by thresholds: $f_0(980), a_0(980), \Lambda(1405), \ldots$
- various extensions of Lüscher's approach:

  ⋆ purely quantum mechanical treatment

  Feng, He, Liu, Li, . . .

  ⋆ non-relativistic EFT (NREFT)

  Beane, Savage, Bernard, Lage, UGM, Rusetsky, Briceno. Davoudi, Luu, . . .

  ⋆ finite-volume unitarized CHPT

  Döring, UGM, Rusetsky, Oset, . . .

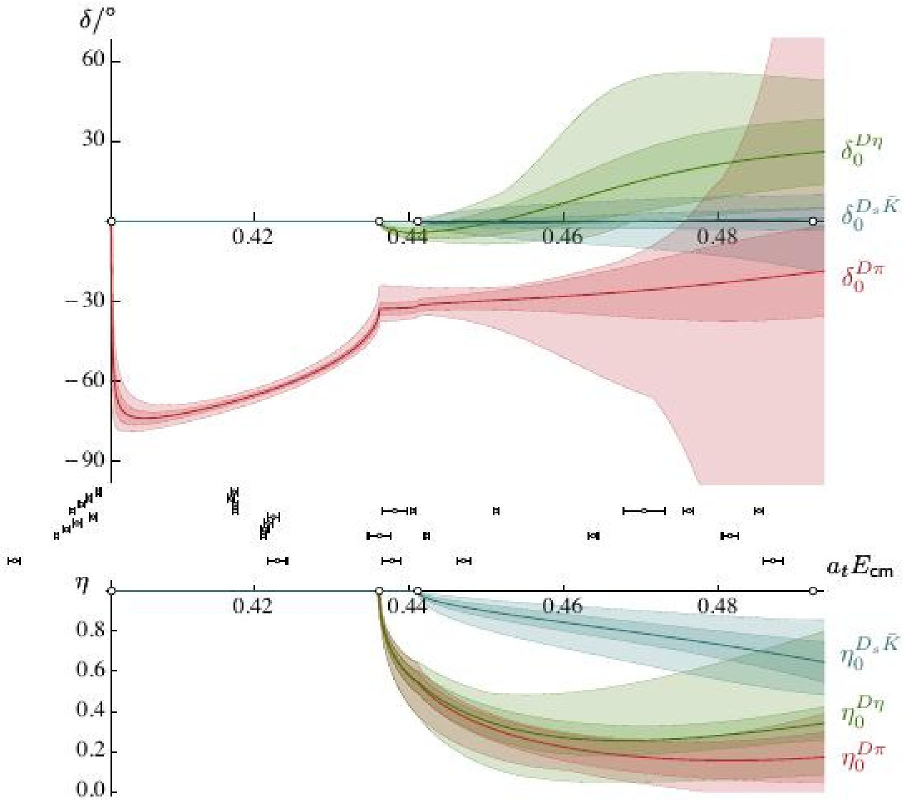
- Mostly done in the meson sector, very little for baryons
- Be aware of methods that can mislead you (K-matrix and alike)

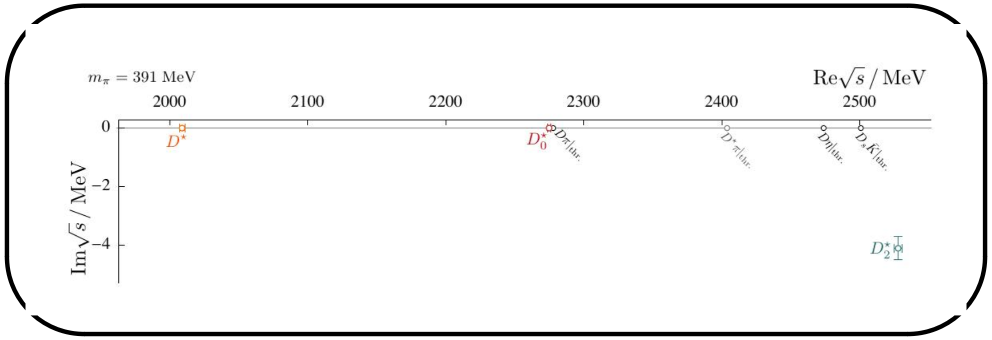
COUPLED CHANNEL SCATTERING

G. Moir, M. Peardon, S. Ryan, C. E. Thomas, D. J. 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

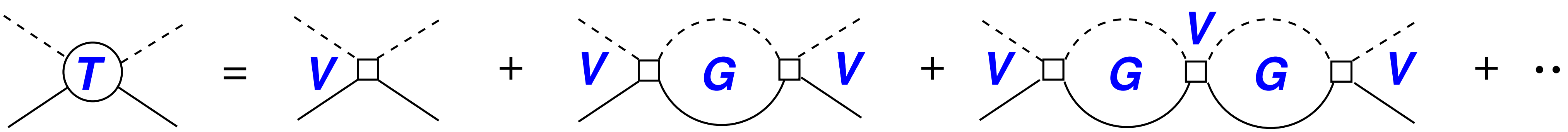
- consistent w/ $D_0^\star(2300)$ of PDG

- BUT: chiral symmtery 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. B666 (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

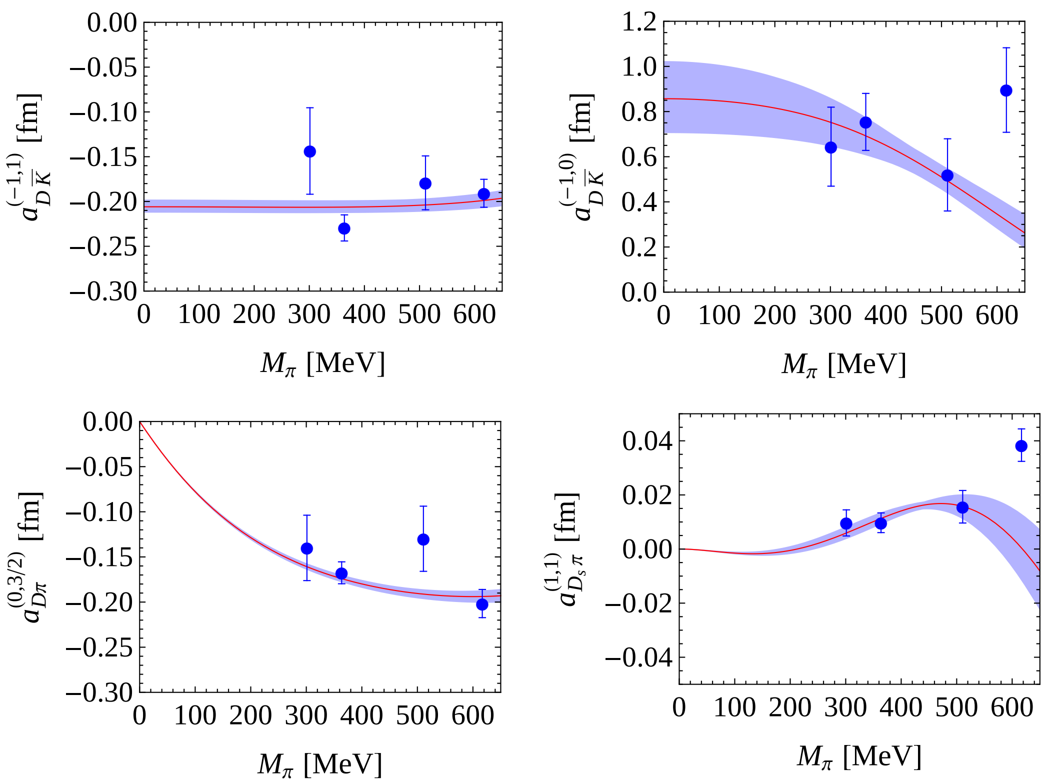
$\hookrightarrow$ $h_{2,3,4,5}$ from a fit to lattice data ($D\pi \to D\pi, D\bar{K} \to D\bar{K}, \ldots$)

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

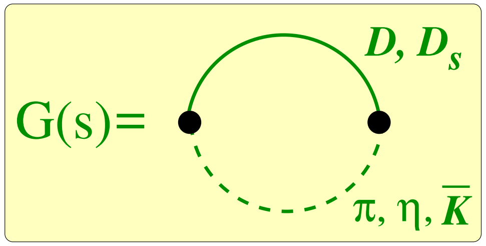
Experiment: $M_{D^\star_{s0}(2317)} = (2317.7 \pm 0.6)$ MeV PDG2016

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 $D_0^\star(2400)$

- 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: $\int d^3\vec{q} \to \frac{1}{L^3}\sum_{\vec{q}}$



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

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

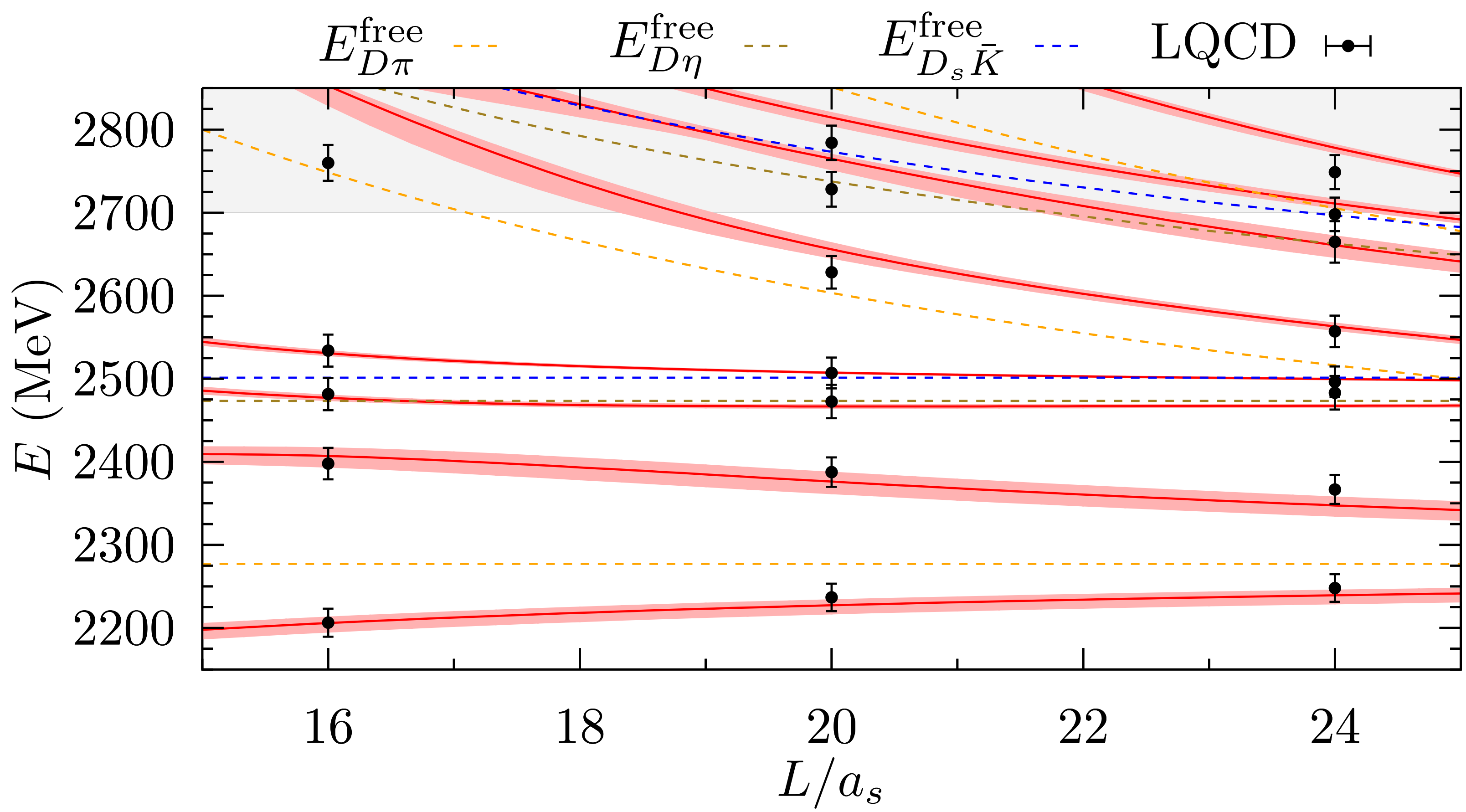
- FV energy levels from the poles of $\tilde{T}(s,L)$:

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

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

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

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

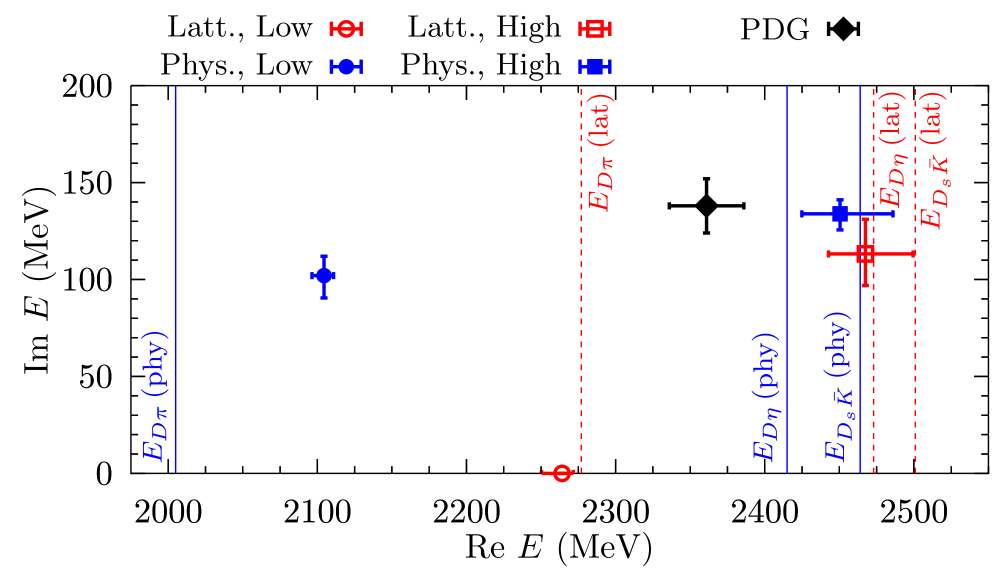


- this is NOT a fit!
- all LECs taken from the earlier study of Liu et al. (discussed before)

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)

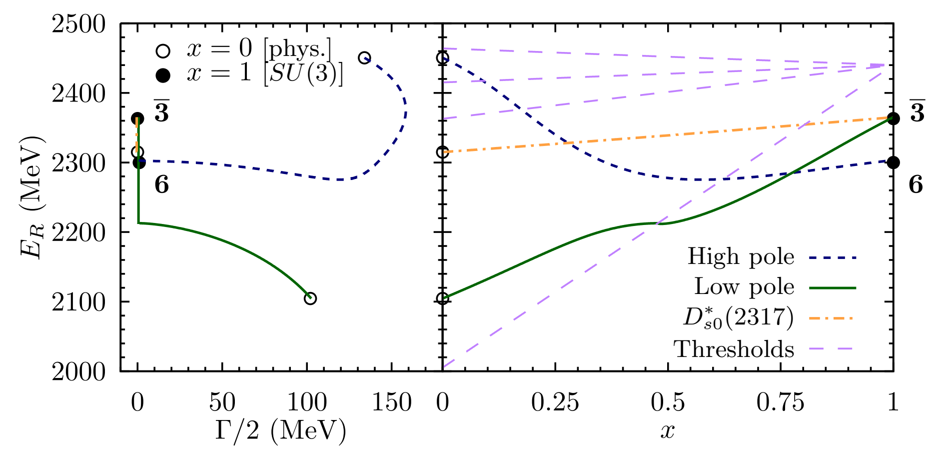
- Again: important role of **chiral symmetry**

- Easy lattice QCD test:

  sextet pole becomes a bound state

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

  Du et al. (2018)



TWO-POLE SCENARIO in the HEAVY-LIGHT SECTOR

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

http://pdg.lbl.gov/

	Lower [MeV]	Higher [MeV]	PDG [MeV]
$D_0^\star$	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+36}_{-26}, 134^{+7}_{-8}\right)$	$(2300 \pm 19, 137 \pm 20)$
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	$\left(5584^{+9}_{-11}, 119^{+14}_{-17}\right)$	$\left(5912^{+15}_{-18}, 42^{+5}_{-4}\right)$	—

$\rightarrow$ but is their experimental support for this? YES, but this is another talk...
($B \rightarrow D\pi\pi$ from LHCb)

Lesson 4: Hadronic molecules

What are HADRONIC MOLECULES ?

- QCD offers yet another set of bound states, first seen in **nuclear physics**
  $\hookrightarrow$ **hadronic molecules** (made of 2 or 3 hadrons)

- Bound states of two hadrons in an S-wave very close a 2-particle threshold or between two close-by thresholds $\Rightarrow$ particular decay patterns

- weak binding entails a large spatial extension

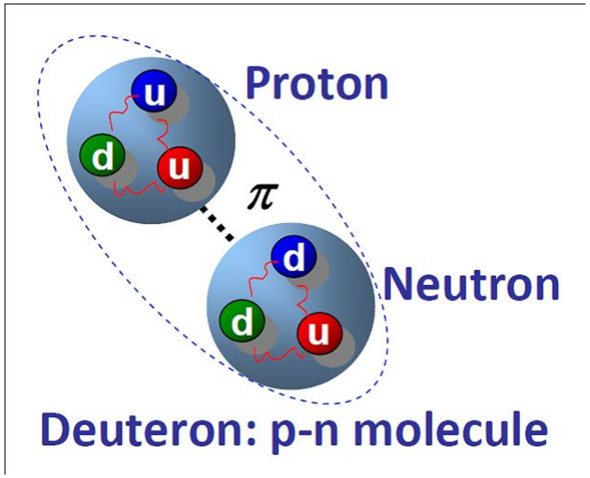
- the classical example:

  $\star$ the deuteron

  $m_p + m_n = 938.27 + 939.57$ MeV,

  $m_d = m_p + m_n - E_B \to E_B = 2.22$ MeV

  $r_d = 2.14$ fm $[r_p = 0.85$ fm]



- other examples: $\Lambda(1405)$, $f_0(980)$, $X(3872)$, ...

$\Rightarrow$ how to distinguish these from compact multi-quark states ?

COMPOSITENESS CRITERION

Weinberg (1965), Morgan (1991), Tornquist (1995), Baru et al. (2003), Sekihara et al. (2013), . . .

- Wave fct. of a bound state with a compact & a two-hadron component in S-wave:

$$|\Psi\rangle = \begin{pmatrix} \sqrt{Z}|\psi_0\rangle \\ \chi(\vec{k})|h_1 h_2\rangle \end{pmatrix}$$

compact comp. w/ probability $\sqrt{Z}$

two-hadron comp. w/ relative w.f. $\chi(\vec{k})$

- consider the scattering amplitude and compare with the ERE:

$$a = -2\frac{1-Z}{2-Z}\left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)\ ,\ r = -\frac{Z}{1-Z}\left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right) \qquad \gamma = \sqrt{2\mu E_B}$$

a = scattering length, γ/E_B = binding momentum/energy (**shallow** b.s.)

μ = reduced mass of the two-particle system, β = range of forces

$\Rightarrow$ pure molecule ($Z = 0$): maximal scattering length $a = -1/\gamma$
natural effective range $r = \mathcal{O}(1/\beta)$

$\Rightarrow$ compact state ($Z = 1$): the scattering length is $a = -\mathcal{O}(1/\beta)$
effective range diverges, $r \to -\infty$

The DEUTERON

Weinberg, Phys. Rev. **137** (1965) B672

- The deuteron: shallow neutron-proton bound state ($E_B \ll m_d$):

$$E_B = 2.22\,\text{MeV} \to \gamma = 45.7\,\text{MeV} \; = 0.23\,\text{fm}^{-1}$$

- range of forces set by the one-pion-exchange:

$$1/\beta \sim 1/M_\pi \simeq 1.4\,\text{fm}$$

- set $Z = 0$ in the Weinberg formula:

$$a_{\rm mol} = -(4.3 \pm 1.4)\,\text{fm}$$

- this is consistent with the data:

$$a = -5.419(7)\,\text{fm}\;, \;\; r = 1.764(8)\,\text{fm}$$

> One begins to suspect that Nature is doing her best to keep us from learning whether the "elementary" particles deserve that title. (Weinberg, 1965)

EXTENSION to RESONANCES

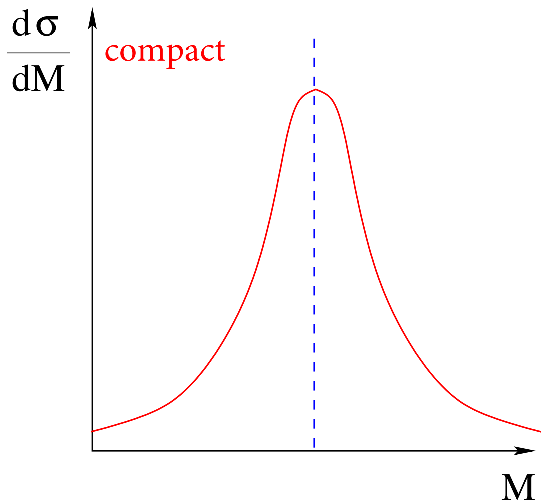
Baru et al. (2003), Braaten, Lu (2007), Aceti, Oset (2012), Hyodo et al. (2012), Guo, Oller (2016), . . .

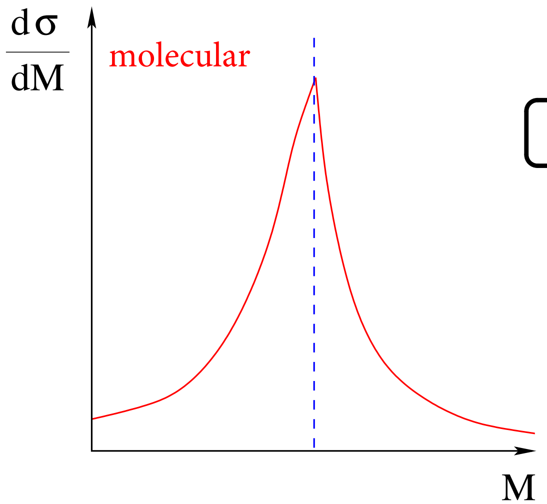
- Still assume closeness to a two-particle threshold:

$$T(E) = \frac{g^2/2}{E - E_r + (g^2/2)(ik + \gamma) + i\Gamma_0/2}$$

with $E = k^2/(2\mu)$, Γ_0 accounts for the inelasticities of other channels

- leads to very different **line shapes** for compact and molecular states:





$$\boxed{M = m_1 + m_2 + E}$$

k^2 term dominates $\rightarrow$ symmetric $\qquad$ g^2 term dominates $\rightarrow$ asymmetric/cusp

- extension to instable particles/additional poles have also been worked out

SOME CANDIDATES

- Prominent examples in the light quark sector:

  $f_0(980)$, $a_0(980)$, the two $\Lambda(1405)$, ...

- Prominent examples in the $c\bar{c}$ spectrum:

  $X(3872)$, $Z_c(3900)$, $Y(4260)$, $Y(4660)$, ...

- Prominent examples of heavy-light mesons:

  $D^\star_{s0}(2317)$, $D_{s1}(2460)$, $D^\star_{s1}(2860)$, ...

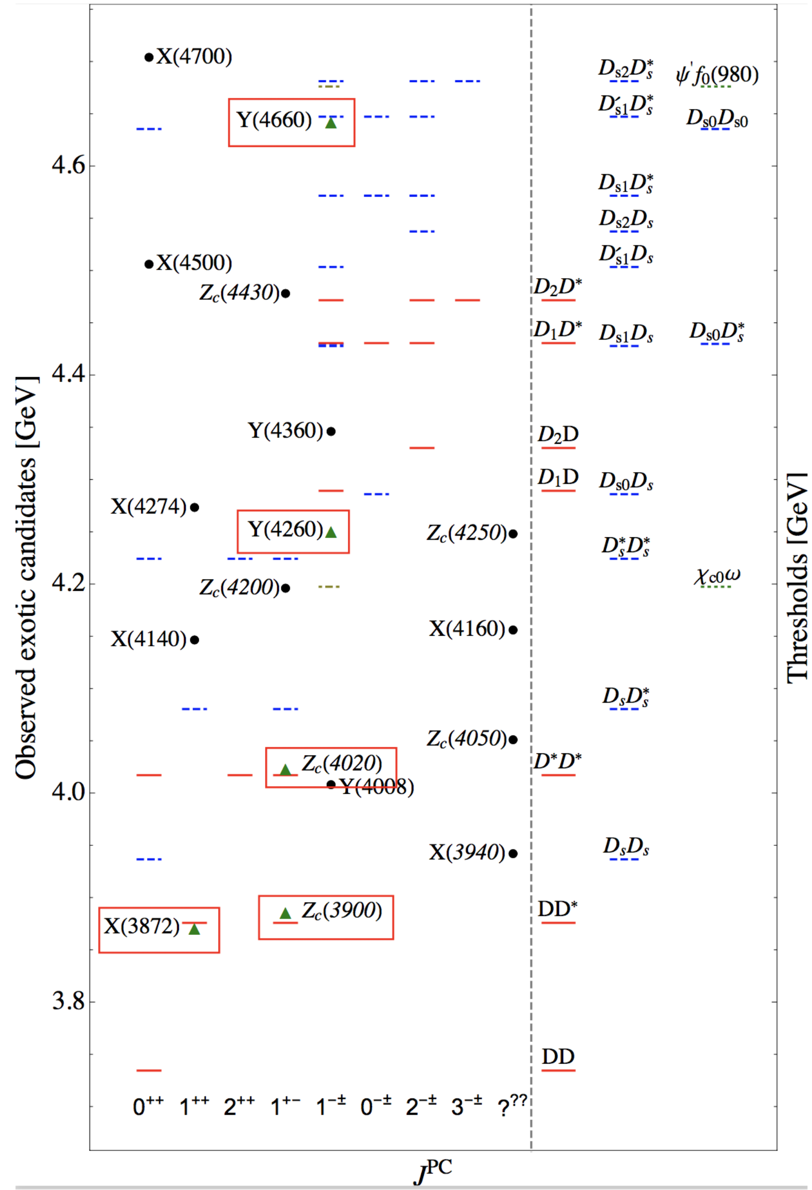
- Prominent examples in the $b\bar{b}$ spectrum:

  $Z_b(10610)$, $Z_b(10650)$

- and some examples of heavy baryons:

  $\Lambda_c(2595)$, $\Lambda_c(2940)$, $P_c(4312)$, $P_c(4557)$, ...

- suitable EFTs: UCHPT, NREFT$_1$, NREFT$_2$, CMS, ...



- Details in the review: Guo et al., Rev. Mod. Phys. **90** (2018) 015004

MISCONCEPTIONS on HADROPRODUCTION

Albaladejo, Guo, Hanhart, UGM, Nieves, Nogga, Yang, Chin.Phys. C **41** (2017) 121001

- It is often claimed that molecules due to their large spatial extent can not be produced in high-energy collisions, say at the LHC $\to$ **this is wrong!**

Bignamini, Grinstein, Piccinini, Polosa, Sabelli, Phys. Rev. Lett. **103** (2009) 162001

$$
\begin{aligned}
\sigma(\bar{p}p \to X) &\sim \left|\int d^3\mathrm{k} \langle X|D^0\bar{D}^{*0}(\mathrm{k})\rangle\langle D^0\bar{D}^{*0}(\mathrm{k})|\bar{p}p\rangle\right|^2 \\
&\simeq \left|\int_{\mathcal{R}} d^3\mathrm{k} \langle X|D^0\bar{D}^{*0}(\mathrm{k})\rangle\langle D^0\bar{D}^{*0}(\mathrm{k})|\bar{p}p\rangle\right|^2 \\
&\leq \int_{\mathcal{R}} d^3\mathrm{k}\, |\Psi(\mathrm{k})|^2 \int_{\mathcal{R}} d^3\mathrm{k} \left|\langle D^0\bar{D}^{*0}(\mathrm{k})|\bar{p}p\rangle\right|^2 \\
&\leq \int_{\mathcal{R}} d^3\mathrm{k} \left|\langle D^0\bar{D}^{*0}(\mathrm{k})|\bar{p}p\rangle\right|^2
\end{aligned}
$$

- The result depends crucially on the value of $\mathcal{R}$ which specifies the region where the bound state wave function "$\Psi(\mathrm{k})$ is significantly different from zero"

- assumption by Bignamini et al: $\mathcal{R} \simeq 35$ MeV of the order of γ

  $\hookrightarrow$ $\sigma(\bar{p}p \to X) \simeq 0.07$ nb way smaller than experiment

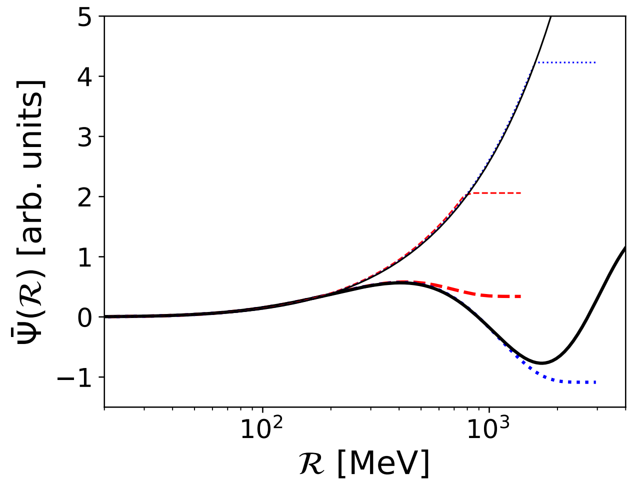
  $\hookrightarrow$ the X(3872) can not be a molecule

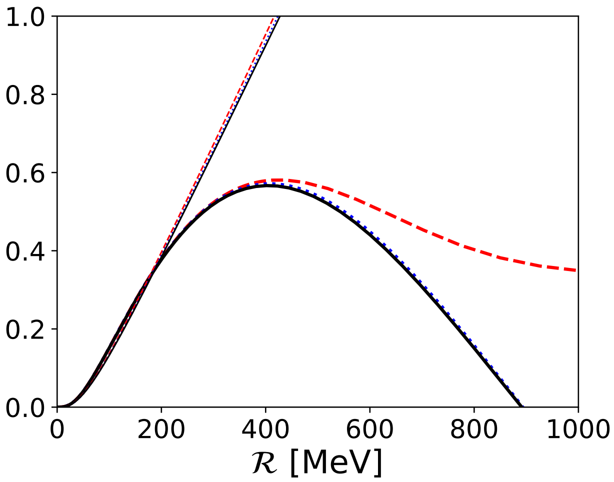
  $\hookrightarrow$ so what goes wrong?

MISCONCEPTIONS on HADROPRODUCTION

Albaladejo, Guo, Hanhart, UGM, Nieves, Nogga, Yang, Chin.Phys. C **41** (2017) 121001

- Consider the relevant integral for the deuteron: $\bar{\Psi}_\lambda(\mathcal{R}) \equiv \int_\mathcal{R} d^3\mathbf{k}\, \Psi_\lambda(\mathbf{k})$
- the binding momentum is $\gamma \simeq 45$ MeV, use that for the support $\mathcal{R}$:





$\hookrightarrow$ the integral is by far not saturated for $\mathcal{R} = \gamma$, need $\mathcal{R} \simeq 2M_\pi \simeq 300$ MeV

- Similar misconception: Molecules can not be produced at large p_T

$\hookrightarrow$ true for nuclei but not quarkonia and alike (q versus $\bar{q}$)

HADROPRODUCTION of the X(3872)

- Nice example of a process involving short-distance physics

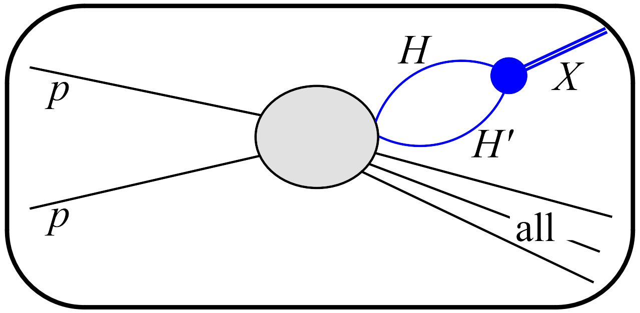
↪ still, factorization is at work, best seen using EFT

Artoisenet, Braaten, Phys. Rev. D **81** (2010) 114018

↪ consider production at the Tevatron and at LHC

$$\sigma[X] = \frac{1}{4m_H m_{H'}} g^2 |G|^2 \left(\frac{d\sigma[HH'(k)]}{dk}\right)_{\rm MC} \frac{4\pi^2\mu}{k^2}$$

$$G(E,\Lambda) = -\frac{\mu}{\pi^2}\left[\sqrt{2\pi}\,\frac{\Lambda}{4} + \sqrt{\pi}\,\gamma D\left(\frac{\sqrt{2}\gamma}{\Lambda}\right) - \frac{\pi}{2}\,\gamma\, e^{2\gamma^2/\Lambda^2}\right]$$



- typical results (using PYTHIA/HERWIG):

Guo, UGM, Wang, Yang, Eur. Phys. J. C **74** (2014) 3063

$\sigma(pp/\bar{p} \to X(3872))$	$\Lambda = 0.5 - 1.0$ GeV	Exp.
Tevatron	5 - 29 [nb]	37 - 115 [nb]
LHC7	4 - 55 [nb]	13 - 39 [nb]

⇒ not very precise, but perfectly consistent with the data!

⇒ also predictions for the charm-strange mesons

Guo, UGM, Wang, Yang, JHEP **1405** (2014) 138

Lesson 5: The width of baryon resonances from EFT

EFT including the Δ-RESONANCE

- Task: calculate the width of the Δ at two-loop order [one-loop too simple]

Gegelia, UGM, Siemens, Yao, Phys. Lett. B763 (2016) 1

- Consider the effective chiral Lagrangian of pions, nucleons and deltas:

$$\mathcal{L}^{(1)}_{\pi N} = \bar{\Psi}_N \left\{ i\not{D} - m + \frac{1}{2} g \not{u} \gamma^5 \right\} \Psi_N$$

$$\begin{aligned}\mathcal{L}^{(1)}_{\pi\Delta} = & -\bar{\Psi}^i_\mu \xi^{\frac{3}{2}}_{ij} \Big\{ \left(i\not{D}^{jk} - m_\Delta \delta^{jk} \right) g^{\mu\nu} - i \left(\gamma^\mu D^{\nu,jk} + \gamma^\nu D^{\mu,jk} \right) + i\gamma^\mu \not{D}^{jk} \gamma^\nu \\ & + m_\Delta \delta^{jk} \gamma^\mu \gamma^\nu + g_1 \frac{1}{2} \not{u}^{jk} \gamma_5 g^{\mu\nu} + g_2 \frac{1}{2} (\gamma^\mu u^{\nu,jk} + u^{\nu,jk} \gamma^\mu) \gamma_5 \\ & + g_3 \frac{1}{2} \gamma^\mu \not{u}^{jk} \gamma_5 \gamma^\nu \Big\} \xi^{\frac{3}{2}}_{kl} \Psi^l_\nu\end{aligned}$$

$$\mathcal{L}^{(1)}_{\pi N\Delta} = h \, \bar{\Psi}^i_\mu \xi^{\frac{3}{2}}_{ij} \Theta^{\mu\alpha}(z_1) \, \omega^j_\alpha \Psi_N + \text{h.c.}$$

$$\mathcal{L}^{(2)}_{\pi N\Delta} = \bar{\Psi}^i_\mu \xi^{\frac{3}{2}}_{ij} \Theta^{\mu\alpha}(z_2) \left[i \, b_3 \omega^j_{\alpha\beta} \gamma^\beta + i \, b_8 \frac{1}{m} \omega^j_{\alpha\beta} i \, D^\beta \right] \Psi_N + \text{h.c.} + \ldots$$

$$\begin{aligned}\mathcal{L}^{(3)}_{\pi N\Delta} = & \bar{\Psi}^i_\mu \xi^{\frac{3}{2}}_{ij} \Theta^{\mu\nu}(z_3) \Big[f_1 \frac{1}{m} [D_\nu, \omega^j_{\alpha\beta}] \gamma^\alpha i \, D^\beta - f_2 \frac{1}{2m^2} [D_\nu, \omega^j_{\alpha\beta}] \{D^\alpha, D^\beta\} + f_4 \omega^j_\nu \langle \chi_+ \rangle \\ & + f_5 [D_\nu, i\chi^j_-] \Big] \Psi_N + \text{h.c.} + \ldots\end{aligned}$$

- Power counting rests on $m_\Delta - m_N$ being a small quantity

- So many LECs, how can one possibly make a prediction?

COMPLEX-MASS RENORMALIZATION

- Method originally introduced for W, Z-physics, later transported to chiral EFT

  Stuart (1990), Denner, Dittmaier et al. (1999), Actis, Passarino (2007)

  Djukanovic, Gegelia, Keller, Scherer, Phys. Lett. B680 (2009) 235

- Evaluate the Δ self-energy on the complex pole:

$$z - m_\Delta^0 - \Sigma_1(z^2) - z\,\Sigma_6(z^2) \equiv z - m_\Delta^0 - \Sigma(z) = 0 \text{ with } \boxed{z = m_\Delta - i\,\frac{\Gamma_\Delta}{2}}$$

- Self-energy diagrams:

→ one-loop easy

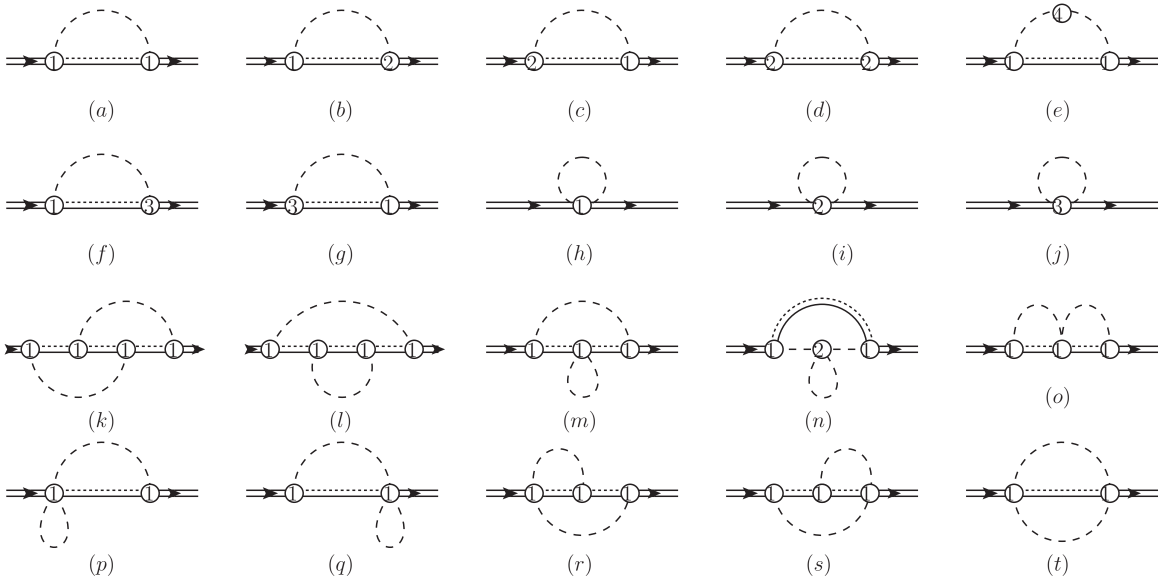
→ two-loops:

use Cutkovsky rules for

instable particles

→ width $\sim |A(\Delta \to N\pi)|^2$

Veltman, Physica 29 (1963) 186



CALCULATION of the WIDTH

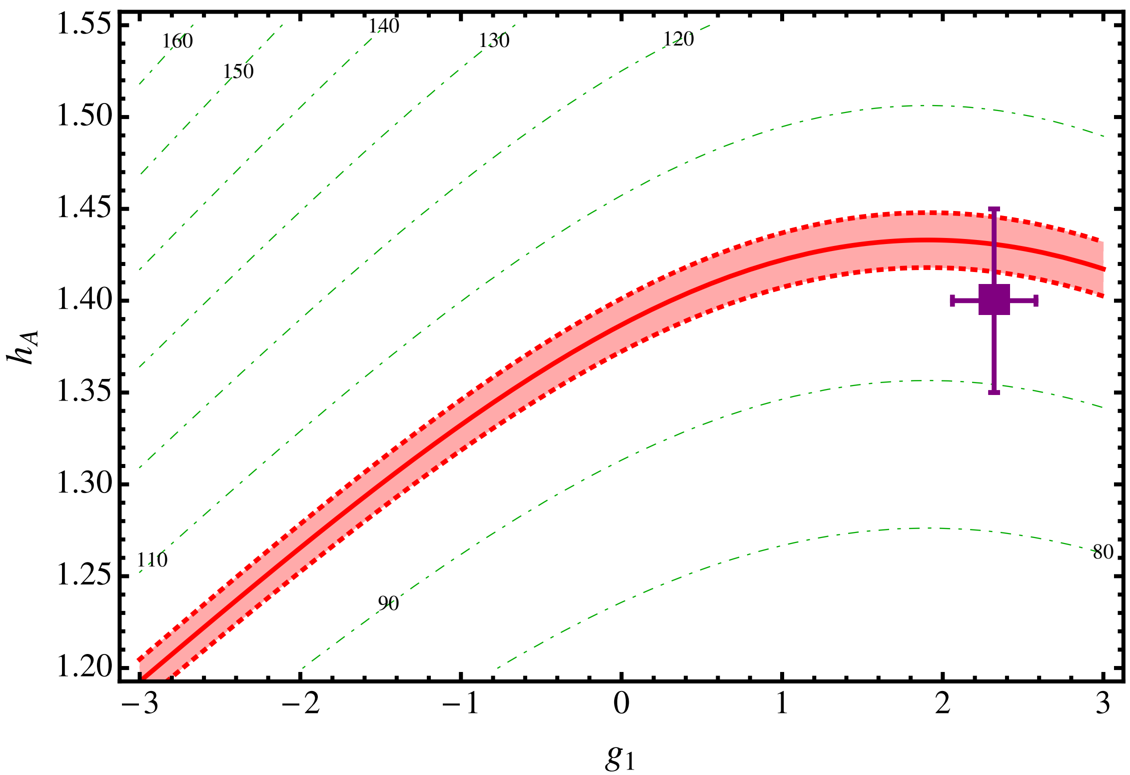
- Remarkable reduction of parameters: $\Delta_{23} = m_N - m_\Delta$, $\Delta_{123} = (M_\pi^2 + m_N^2 - m_\Delta^2)/(2m_N)$

$$h_A = h - (b_3\Delta_{23} + b_8\,\Delta_{123}) - (f_1\Delta_{23} + f_2\,\Delta_{123})\,\Delta_{123} + 2(2f_4 - f_5)M_\pi^2$$

- Very simple formula for the decay width $\Delta \to N\pi$:

$$\Gamma(\Delta \to N\pi) = (53.91\,h_A^2 + 0.87 g_1^2 h_A^2 - 3.31 g_1 h_A^2 - 0.99\,h_A^4)\ \mathrm{MeV}$$

- Correlation:



■ large N$_C$ w/ unc.

Siemens et al.,
Phys. Lett. B 770 (2017) 27

EFT including the ROPER-RESONANCE

- Task: calculate the width of the Roper $N^*(1440)$ at two-loop order

Gegelia, UGM, Yao, Phys. Lett. B760 (2016) 736

- Remarkable feature: $\Gamma(R \to N\pi) \simeq \Gamma(R \to N\pi\pi)$

- Consider the effective chiral Lagrangian of pions, nucleons and deltas:

Borasoy et al., Phys. Lett. B641 (2006) 294, Djukanovic et al., Phys. Lett. B690 (2010) 123

Long, van Kolck, Nucl. Phys. A870-871 (2011) 72

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{\pi\Delta} + \mathcal{L}_{\pi R} + \mathcal{L}_{\pi N\Delta} + \mathcal{L}_{\pi NR} + \mathcal{L}_{\pi\Delta R}$$

$$\mathcal{L}_{\pi R}^{(1)} = \bar{\Psi}_R \left\{ i\not{D} - m_R + \frac{1}{2} g_R \not{u} \gamma^5 \right\} \Psi_R$$

$$\mathcal{L}_{\pi R}^{(2)} = \bar{\Psi}_R \left\{ c_1^R \langle \chi_+ \rangle \right\} \Psi_R + \ldots$$

$$\mathcal{L}_{\pi NR}^{(1)} = \bar{\Psi}_R \left\{ \frac{1}{2} g_{\pi NR} \gamma^\mu \gamma_5 u_\mu \right\} \Psi_N + \text{h.c.}$$

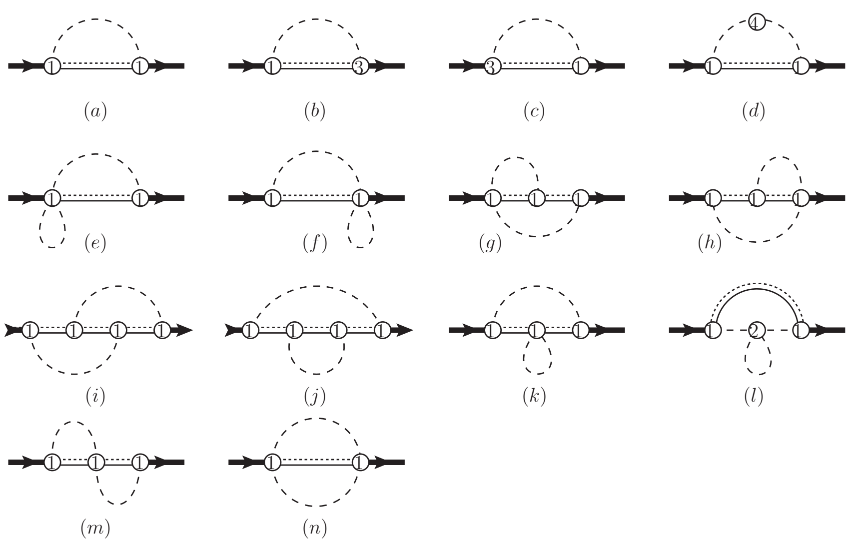
$$\mathcal{L}_{\pi\Delta R}^{(1)} = h_R \, \bar{\Psi}_\mu^i \xi_{ij}^{\frac{3}{2}} \Theta^{\mu\alpha}(\tilde{z}) \, \omega_\alpha^j \Psi_R + \text{h.c.}$$

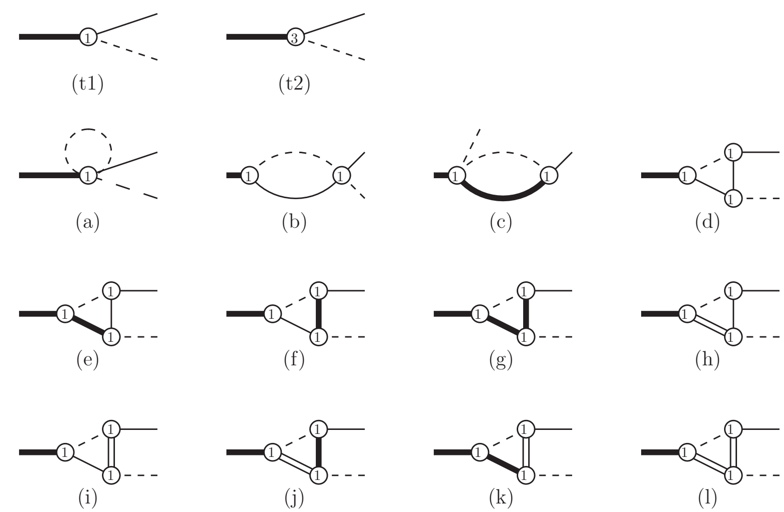
EFT including the ROPER-RESONANCE continued

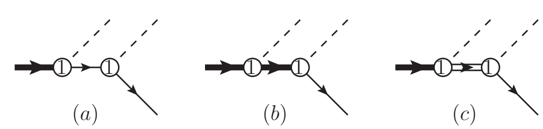
- The power counting is complicated, but can be set up around the complex pole:

$$m_R - m_N \sim \varepsilon\,,\quad m_R - m_\Delta \sim \varepsilon^2\,,\quad m_\Delta - m_N \sim \varepsilon^2\,,\quad M_\pi \sim \varepsilon^2$$

- Calculate the two-loop self-energy and the corresponding decay amplitudes







CALCULATION of the WIDTH

- A lengthy calculation leads to:

$$\Gamma(R \to N\pi) = 550(58)\, g_{\pi NR}^2 \,\text{MeV}$$

$$\begin{aligned}\Gamma(R \to N\pi\pi) = \Big(&1.49(0.58)\, g_A^2\, g_{\pi NR}^2 - 2.76(1.07)\, g_A\, g_{\pi NR}^2\, g_R \\ &+ 1.48(0.58)\, g_{\pi NR}^2\, g_R^2 + 2.96(0.94)\, g_A\, g_{\pi NR}\, h h_R \\ &- 3.79(1.37)\, g_{\pi NR}\, g_R\, h h_R + 9.93(5.45)\, h^2 h_R^2\Big)\,\text{MeV}\end{aligned}$$

- Fix $g_{\pi NR}$ from the PDG value: $g_{\pi NR} = \pm(0.47 \pm 0.05)$ PDG 2016

- Maximal mixing assumption: $g_R = g_A\,,\quad h_R = h$

Beane, van Kolck, J. Phys. G31 (2005) 921

↪ can make a prediction for the two-pion decay width of the Roper

$$\boxed{\Gamma(R \to N\pi\pi) = (41 \pm 22_{\text{LECs}} \pm 17_{\text{h.o.}})\,\text{MeV}}$$

- consistent with the PDG value of (67 ± 10) MeV
- need an improved determination of the LECs g_R and h_R

Summary & Outlook

SUMMARY & OUTLOOK

- Lessons learned / take home:

The QCD spectrum is more than a collection of quark model states

Structure formation in QCD ties nuclear and hadron physics together

Lattice QCD is making progress in addressing complex resonance properties (must respect chiral symmetry)

EFTs are of utmost importance in pushing this program forward

SPARES

LATTICE QCD

- In principle ab initio calcs of non–pert. QCD on a discretized space–time

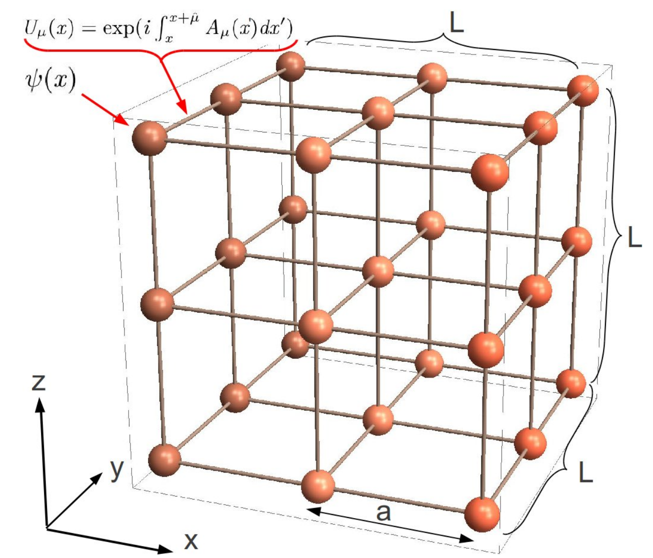
  $\hookrightarrow$ already some successes *but only now entering the chiral regime*

- Extrapolations neccessary:

  $\star$ finite volume $V = L^3 \times L_t \to \infty$

  $\star$ finite lattice spacing $a \to 0$

  $\star$ chiral extrapolation $m_q \to m_q^{\rm phys}$



- All these effects can be treated in suitably tailored EFTs

- how are resonances defined in such a finite space-time?

  $\Rightarrow$ consider finite volume effects for **low-lying hadron resonances**

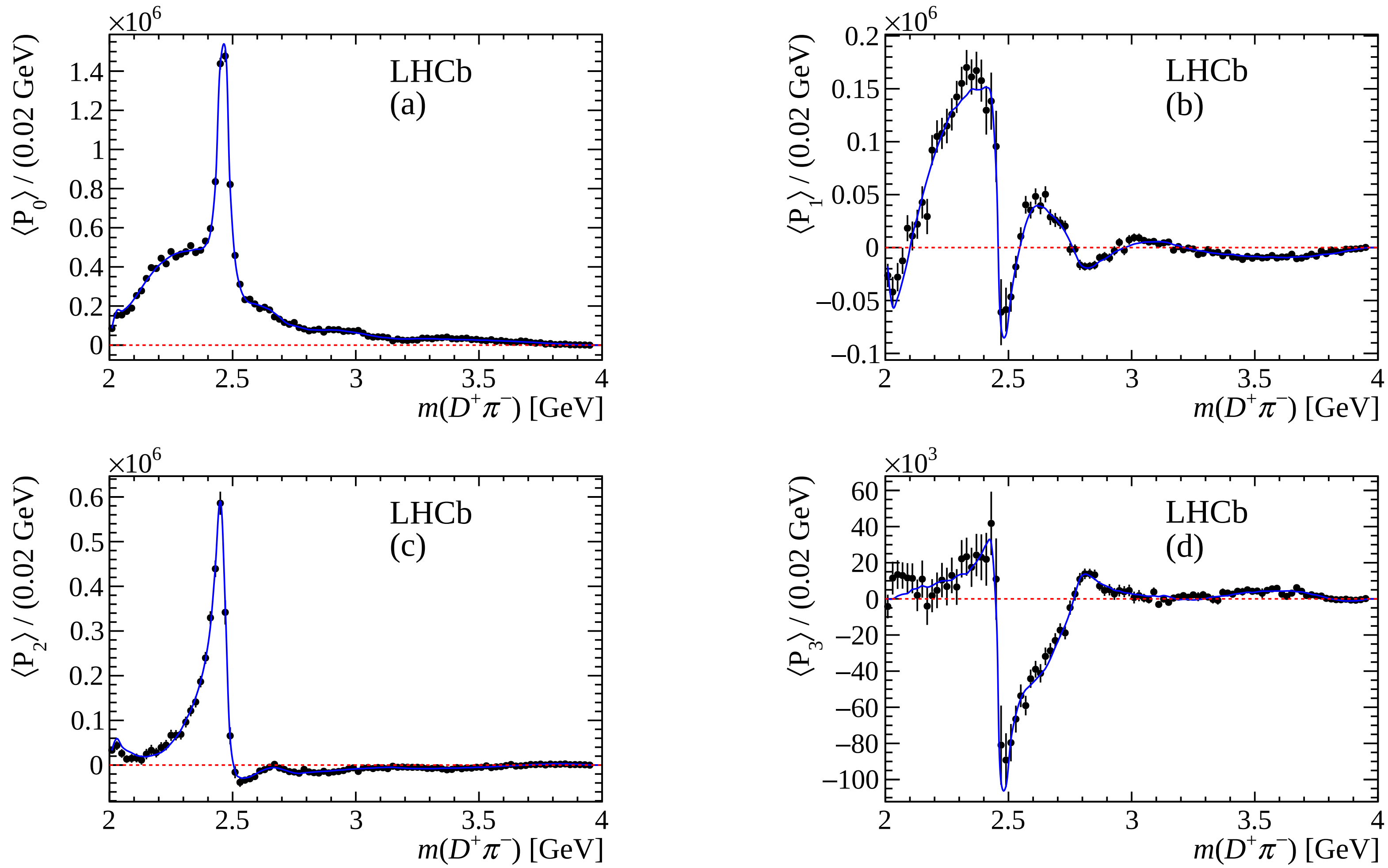
Amplitude Analysis of $B \to D\pi\pi$

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:

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

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

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

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

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

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

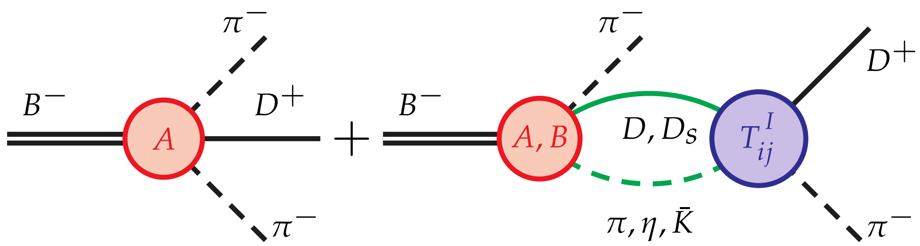
- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI

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

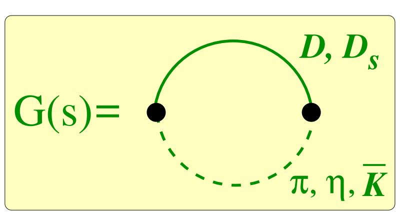
  $\to$ P-wave: $D^\star$, $D^\star(2860)$; D-wave: $D_2(2460)$ as by LHCb

  $\to$ 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

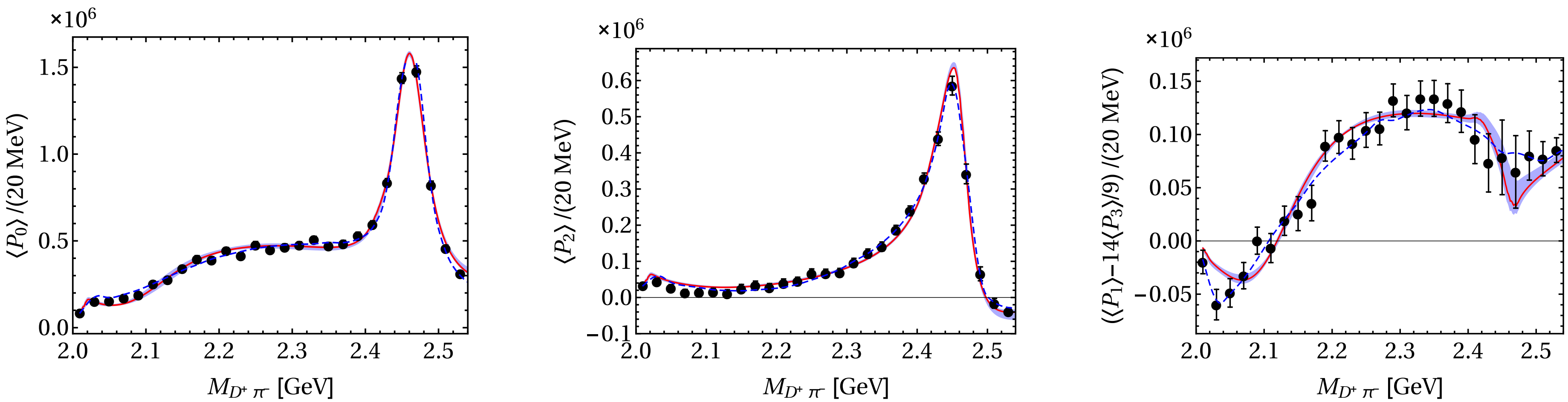
Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Yao, Phys. Rev. **D98** (2018) 094018

- More appropriate combinations of the angular moments:

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

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

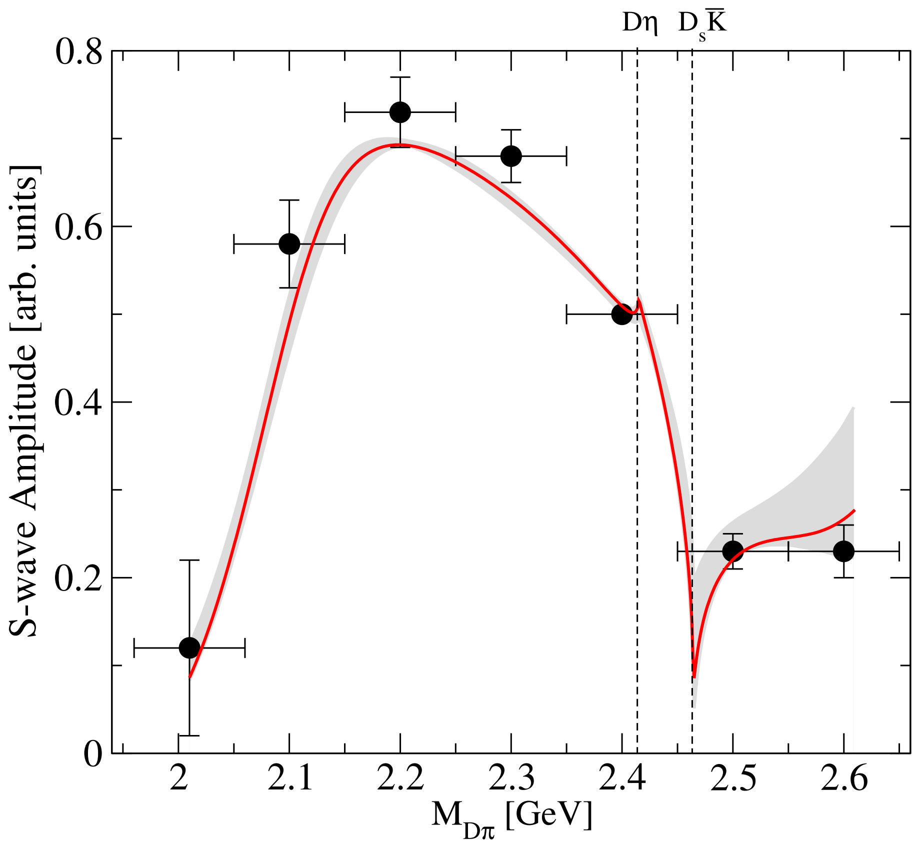
$$\langle P_{13} \rangle = \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1| \cos(\delta_1 - \delta_0)$$



- 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

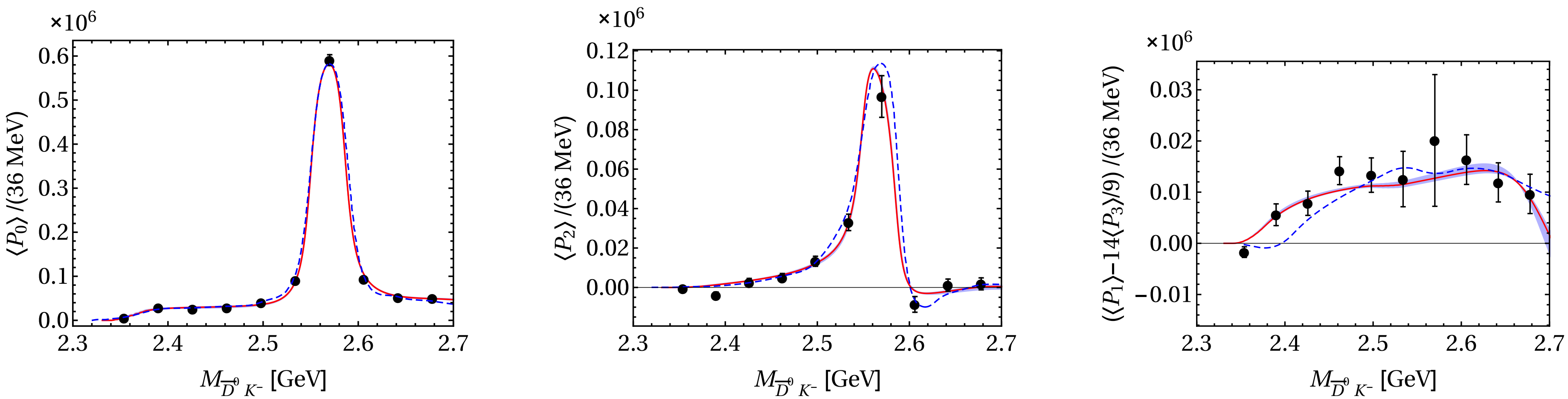


- Higher mass pole at 2.46 GeV clearly amplifies the cusps predicted in our amplitude

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 ↪ one parameter fit!



⇒ these data are also well described

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

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