QCD and hadrons in the era of future accelerators

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

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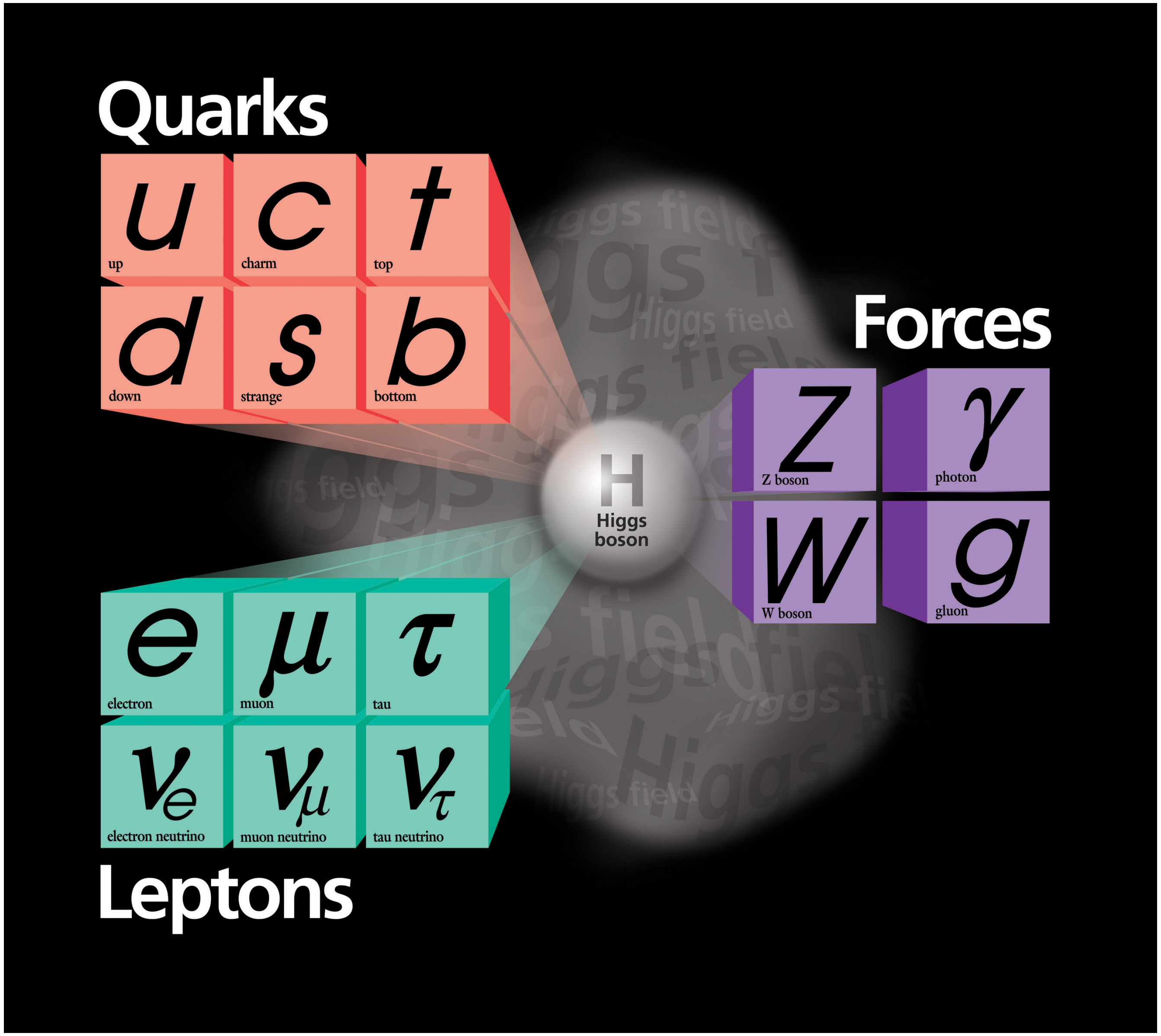


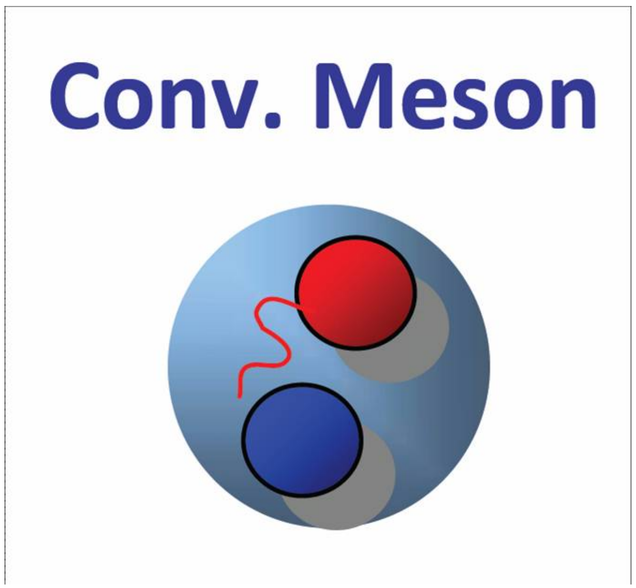
quarks make up the matter surrounding us

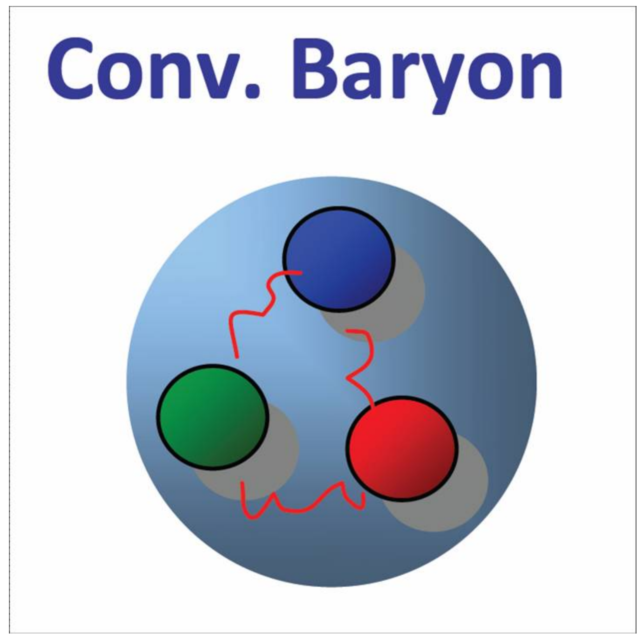
gluons mediate the forces between quarks

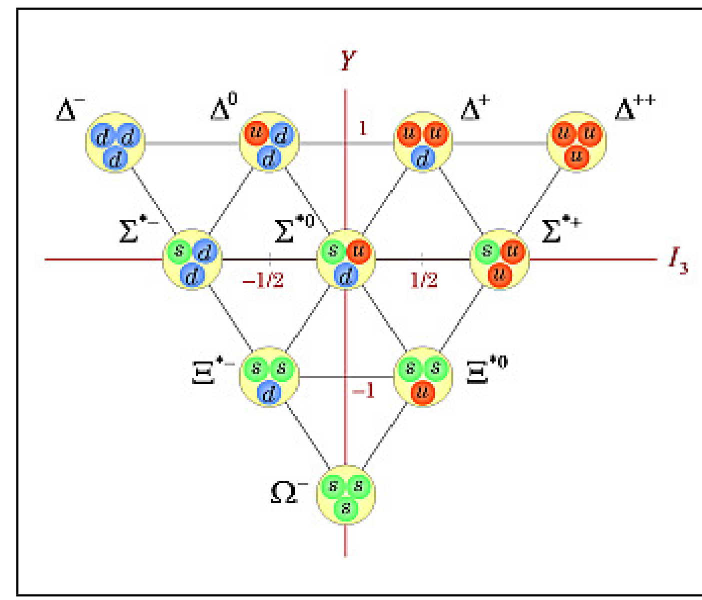
$\rightarrow$ confinement hadrons & nuclei

Conventional hadrons

- hundreds of hadrons (“the particle zoo”) can be described as $q\bar{q}$ and qqq states

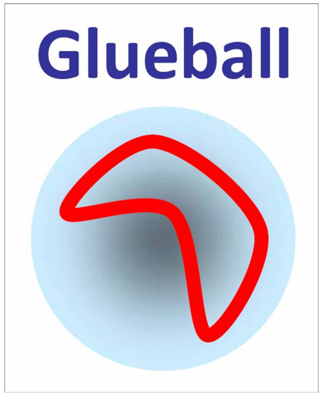


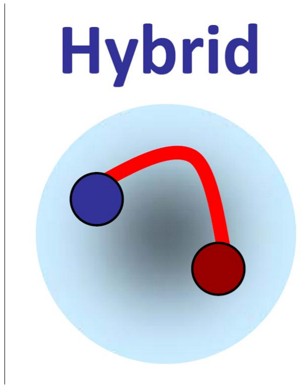


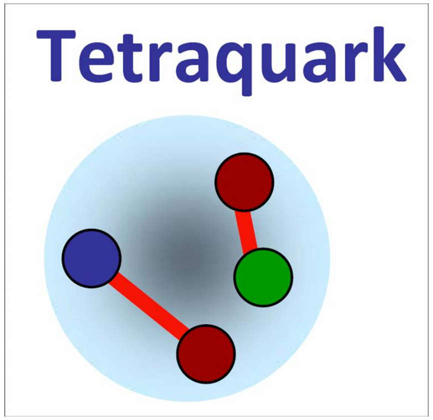


fairly successful picture – but why should it work?

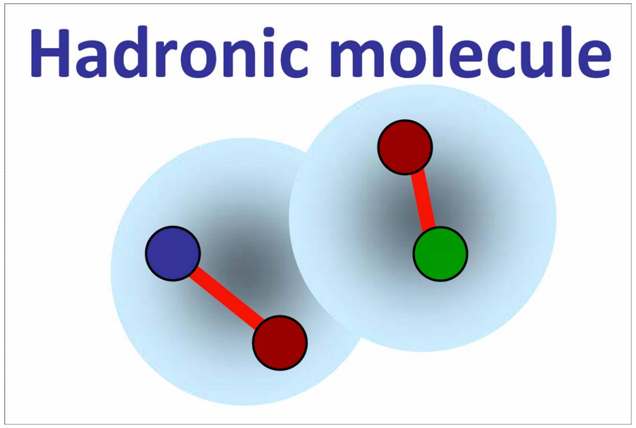
Multi-faces of QCD: “Exotic” hadrons

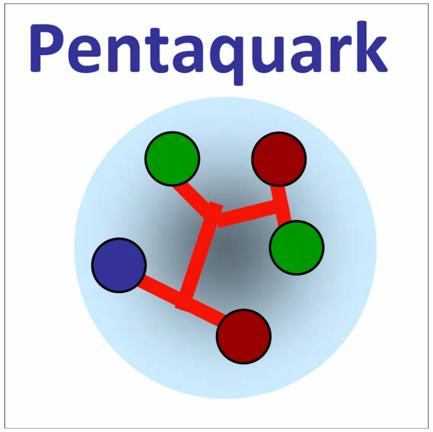






Exotic w.r.t. the quark model!





States with glue: QCD
$\to$ truely exotic!

Multi-Quark states: Gell-Mann, Phys.Lett. **8** (1964) 214

really: **dynamically generated states**

the experimental and theoretical study of such states is a key to understand QCD

Dynamically generated states / hadronic molecules

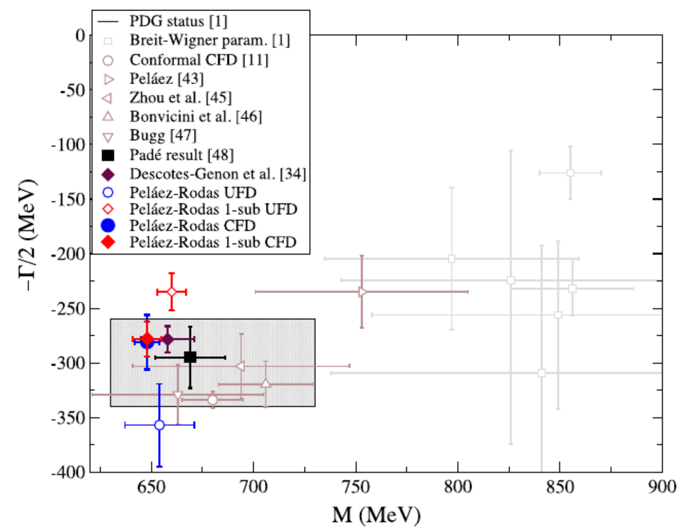
- Hadron-hadron (or three-hadron) interactions can dynamically generate resonances
- Hadronic molecules: a subclass of these (shallow binding, close to the real axis)
- Prime example: The light scalar mesons $\underbrace{f_0(500)}_{\sigma}, \underbrace{K_0^\star(700)}_{\kappa}, f_0(980)$

$$M_{f_0(500)} = 441^{+16}_{-8}\ \text{MeV}$$
$$\Gamma_{f_0(500)} = 544^{+18}_{-25}\ \text{MeV}$$

Caprini, Colangelo, Leutwyler (2005)

$$M_{K_0^\star(700)} = 648 \pm 7\ \text{MeV}$$
$$\Gamma_{K_0^\star(700)} = 280 \pm 16\ \text{MeV}$$

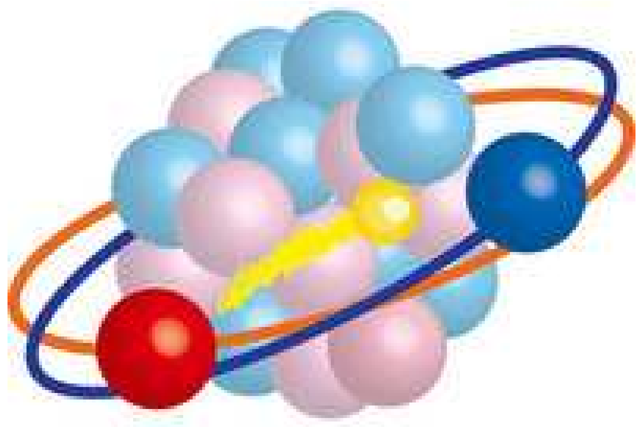
Pelaez, Rodas (2020)

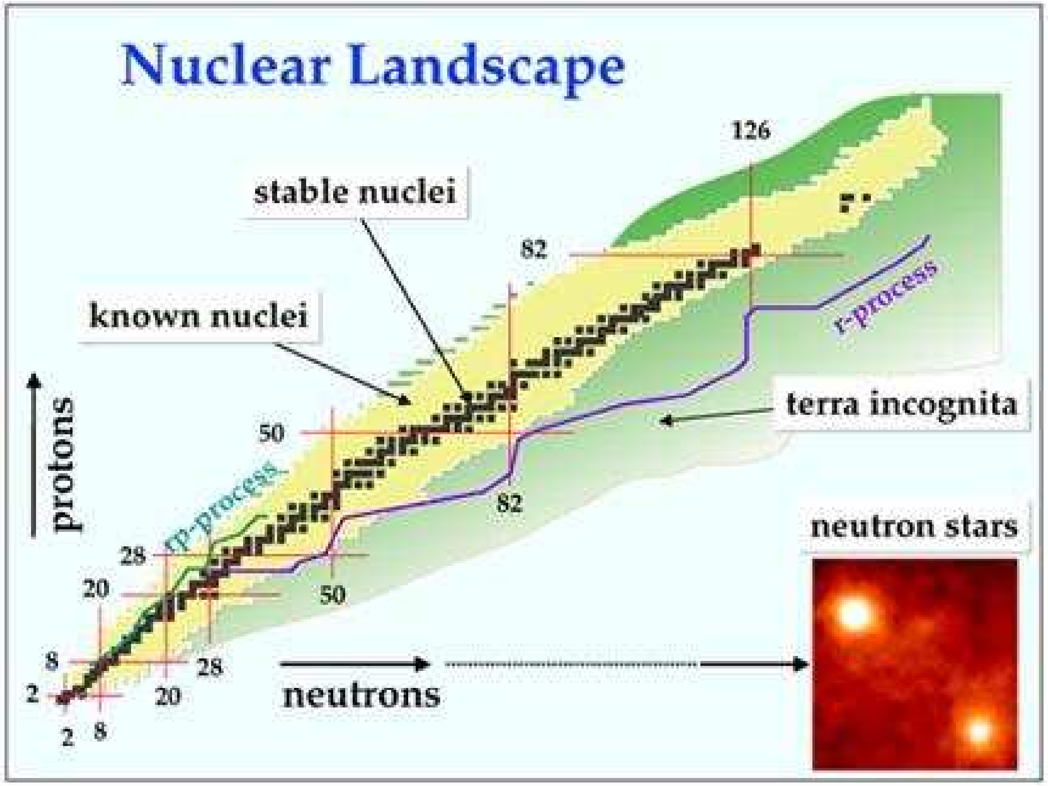


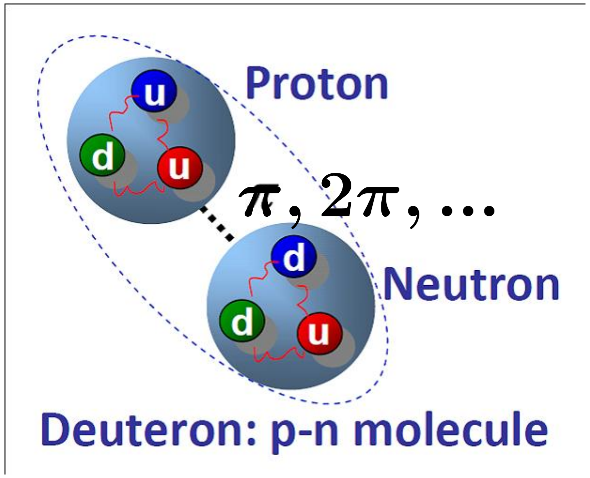
$$\left.\begin{aligned} M_{f_0(980)} &= 990 \pm 20\ \text{MeV} \\ \Gamma_{f_0(980)} &= 10 - 100\ \text{MeV} \end{aligned}\right\}$$ in between the K^+K^- and $K^0\bar{K}^0$ thresholds

$\hookrightarrow$ it is a molecule!

Still more structure: Atomic nuclei







exploring the residual color force
$\rightarrow$ ab initio calculations possible

Renaissance of hadron spectroscopy

- Charm-strange mesons observed 2003 by BaBar & CLEO

↪ do not fit quark model expectations

- even more “exotica” in the quarkonium ($\bar{c}c, \bar{b}b$) spectrum

↪ started in 2003 with the X(3872) found by Belle

↪ some are charged ⟶ at least 4 quarks

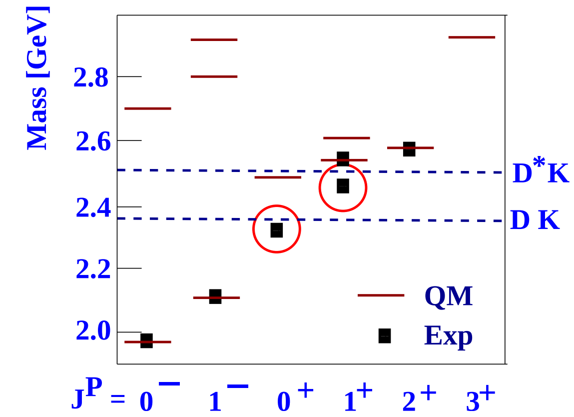
- most of these states close to two-particle thresholds

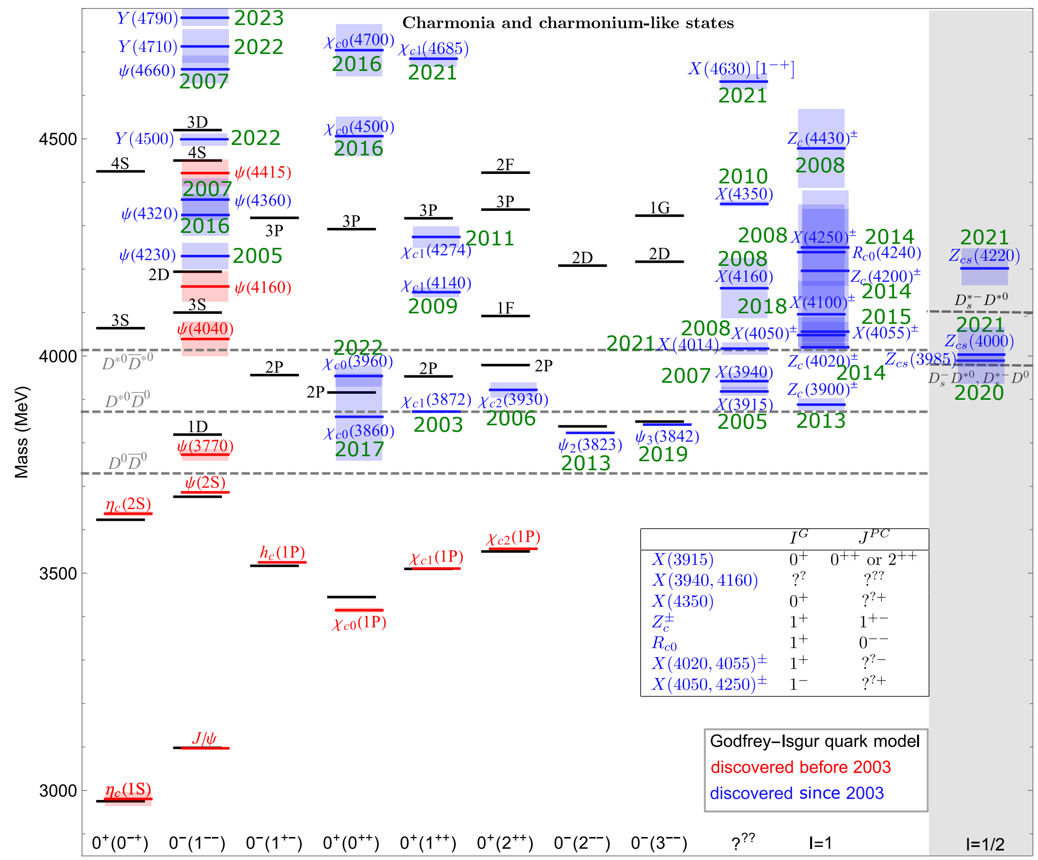
↪ molecular nature very natural!

- still more states being found

↪ like the T_{cc} (double charm 4q state)

- also experiments were not designed for hadron spectroscopy, the most quoted papers are from this field (Belle, LHCb,...)





Salient features of QCD

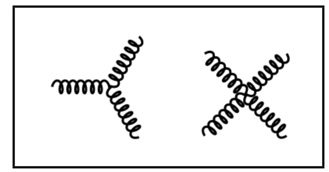
QCD Lagrangian

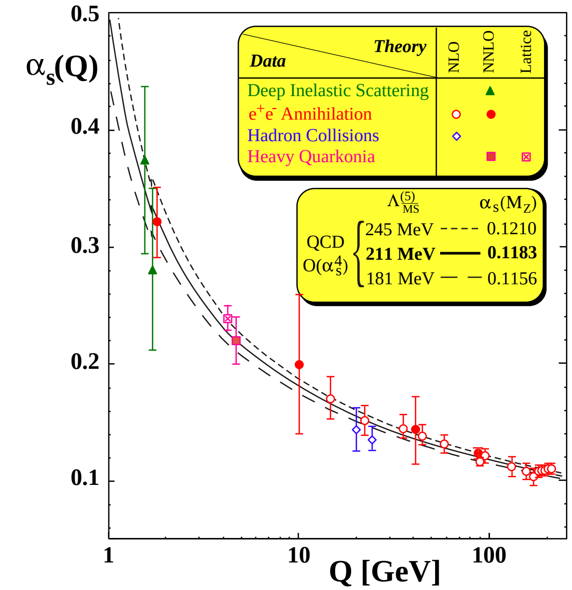
- $$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} + \sum_f \bar{q}_f (i \not{D} - \mathcal{M}) q_f + \ldots$$

$$D_\mu = \partial_\mu - i g A^a_\mu \lambda^a/2$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g[A^b_\mu, A^c_\nu]$$

$$f = (u, d, s, c, b, t)$$





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

- light (u,d,s) and heavy (c,b,t) quark flavors [two different worlds]:

$m_{\rm light} \ll \Lambda_{\rm QCD}$	$m_{\rm heavy} \gg \Lambda_{\rm QCD}$
$m_u = 2.2^{+0.6}_{-0.4}$ MeV	$m_c = 1.28 \pm 0.03$ GeV
$m_d = 4.7^{+0.5}_{-0.4}$ MeV	$m_b = 4.18^{+0.04}_{-0.03}$ GeV
$m_s = 96^{+8}_{-4}$ MeV	$m_t = 173.1 \pm 0.6$ GeV

Limits of QCD

- **light quarks:** $\mathcal{L}_{\rm QCD} = \bar{q}_L\, i\not{D} q_L + \bar{q}_R\, i\not{D} q_R + \mathcal{O}(m_f/\Lambda_{\rm QCD})$ $\quad q = (u, d, s)$

  – 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:** $\mathcal{L}_{\rm QCD} = \bar{Q}\, iv \cdot D\, Q + \mathcal{O}(\Lambda_{\rm QCD}/m_f)$ $\quad Q = (c, b)$

  – 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

More on EFTs

- Much more details on EFTs in light quark physics:

Effective Field Theories

AUTHORS:

Ulf-G Meißner, Rheinische Friedrich-Wilhelms-Universität Bonn and Forschungszentrum Jülich

Akaki Rusetsky, Rheinische Friedrich-Wilhelms-Universität Bonn

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Theory & phenomenology of hadronic molecules

What are hadronic molecules ?

- 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 $R \sim 1/\sqrt{2\mu E_B}$ [μ = red. mass]

- the classical example:

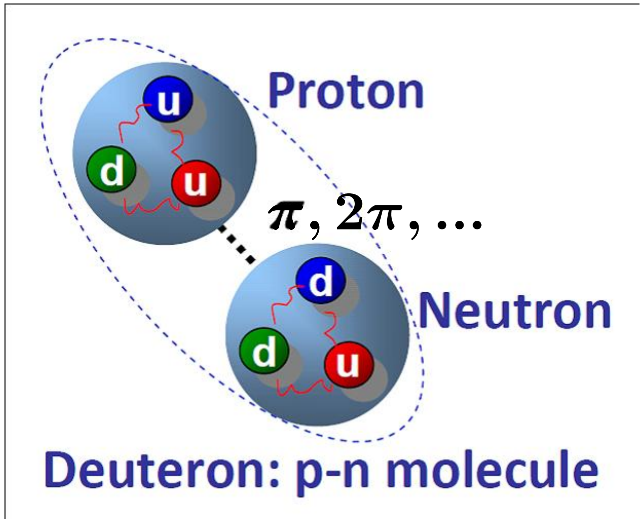
  $\star$ the deuteron

  $m_p + m_n = 938.27 + 939.57$ MeV,

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

  $B_d/m_d \simeq 1/1000$

  $r_d = 2.14$ 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 ?

More on hadronic molecules

- Energy distribution within a hadron

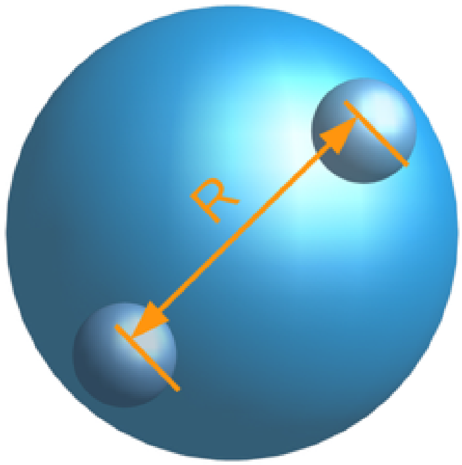
$\hookrightarrow$ different confinement realizations

$\hookrightarrow$ large size systems instead of compact color-singlet clusters

- Crucial quantity: Compositeness $1 - Z$

$\hookrightarrow$ well-defined for loosely bound S-wave states

$\hookrightarrow$ can be related to low-energy observables



$Z = 0$

$Z = 1$

$$a \simeq -\frac{2(1-Z)}{(2-Z)\sqrt{2\mu E_B}}$$

- Ex: deuteron as pn molecule: $E_B = 2.2$ MeV, $a(^3S_1) = -5.4$ fm

$$a(Z=1) = 0 \text{ fm}\,, \qquad a(Z=0) = (4.3 \pm 1.4) \text{ fm}$$

Weinberg (1965), Baru et al. (2004), Hyodo et al. (2012), ..., Li et al (2022),...

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:

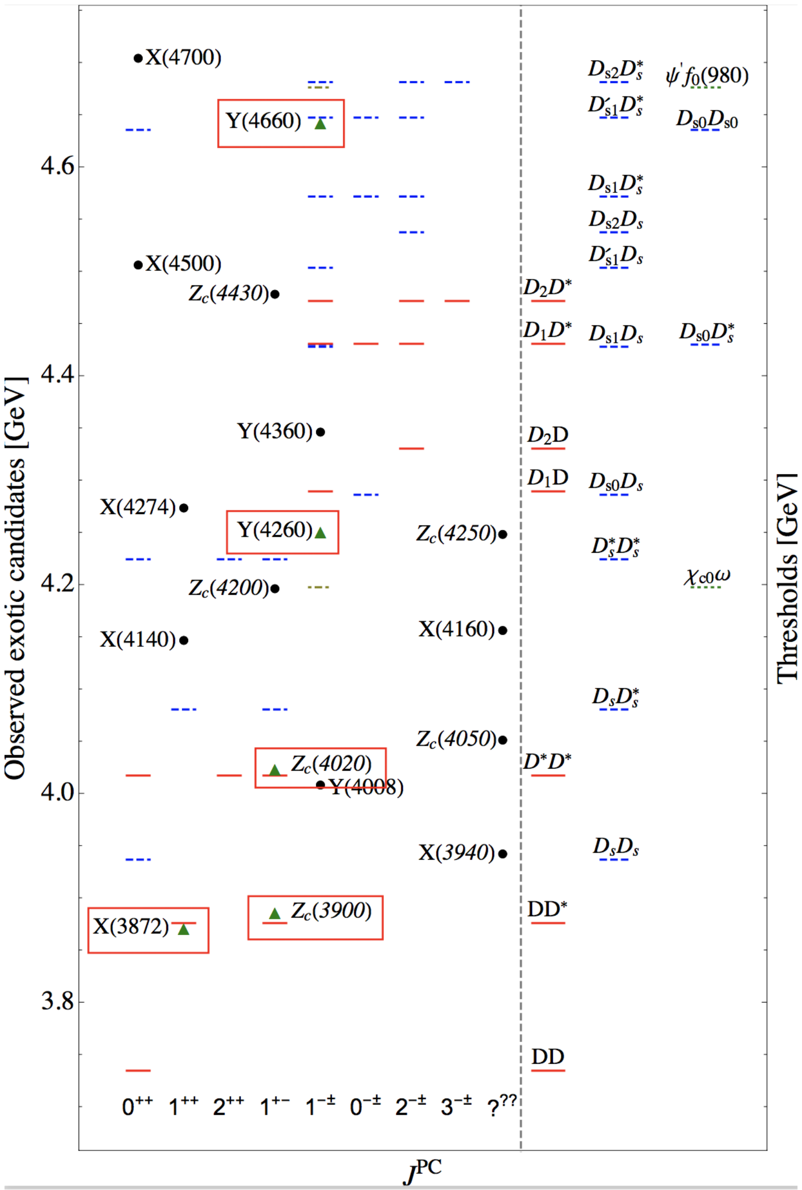
  $D^\star_{s0}(2317)$, $D_{s1}(2460)$, $D^\star_{s1}(2860)$, ...

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

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

- and some examples of heavy baryons:

  $\Lambda_c(2595)$, $\Lambda_c(2940)$, $P_c(4312)$, $P_c(4440)$, ...



Details in: Guo, Hanhart, UGM, Wang, Zhao, Zou, Rev. Mod. Phys. **90** (2018) 015004

General remarks

- Consider an hadronic molecule with w.f. Ψ, made of two hadrons h_1, h_2, located close to the threshold $E_{\rm thr} = m(h_1) + m(h_2)$

$\Rightarrow$ long-distance scale $\gamma = \sqrt{2\mu E_B} \ll \beta$ [$1/\beta$ = range of forces]

- **Two classes** of decay and production processes:

  - **long-distance processes**, in which the momenta of all particles in the c.m. frame of $h_1 h_2$ are of $\mathcal{O}(\gamma)$ [$X(3872)$ in e^+e^- collisions]

  - **short-distance processes**, which involve particles with a momentum $\gtrsim \beta$ in the c.m. frame of $h_1 h_2$ [hadroproduction of the $X(3872)$]

$\Rightarrow$ only the former class of processes is entirely sensitive to the molecular component e.g. enhanced production through the triangle singularity

$\Rightarrow$ for the second class, one requires knowledge about short-distance physics and thus can often only make estimates (discuss two pitfalls often encountered)

The X(3872) [aka $\chi_{c1}(3872)$]

- seen at B-factories (Belle, BaBar) and colliders (D0, CDF, LHCb, . . .)

- extremely close to the $D^0\bar{D}^{*0}$ threshold: $\boxed{E_B(X) = 0.07 \pm 0.12 \text{ MeV}}$

$\rightarrow$ tremendously large scattering length

$\rightarrow$ universality $\quad E_B = 1/(\mu a^2)$

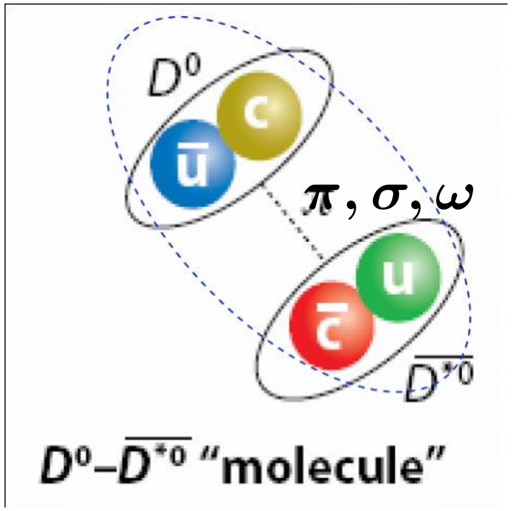
- maximal isospin violation:

$$\Gamma(X \to J/\psi\pi\pi) \simeq \Gamma(X \to J/\psi\pi\pi\pi)$$

- quantum numbers: $J^{PC} = 1^{++}$ (LHCb 2013)

- a prime candidate for a hadronic molecule:

$$|X\rangle = \frac{1}{\sqrt{2}}\left(|D^0\bar{D}^{0*}\rangle + |\bar{D}^0 D^{0*}\rangle\right)$$

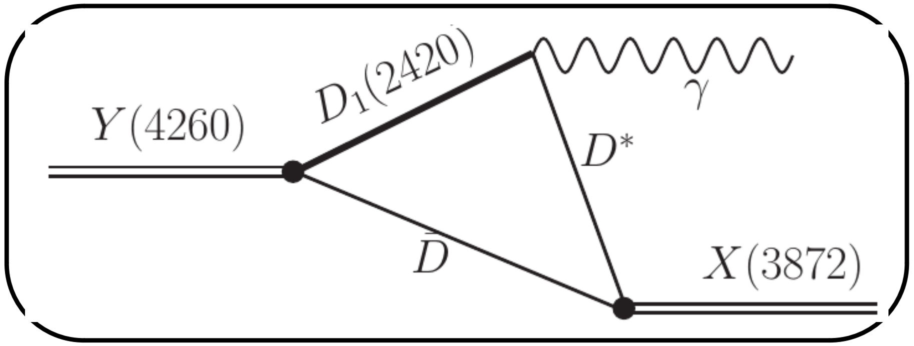


Voloshin, Okun (1976)

X(3872) Production in e^+e^- collisions

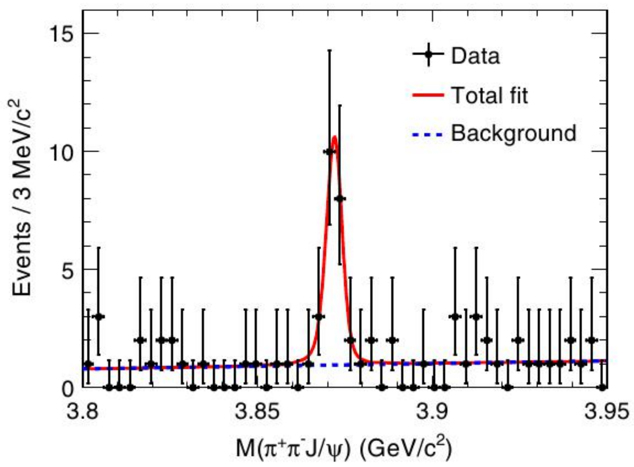
Guo, Hanhart, UGM, Wang, Zhao, Phys. Lett. B **725** (2013) 127

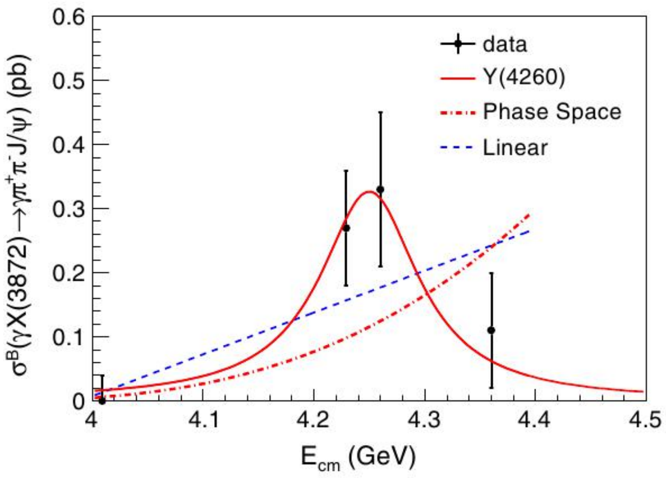
- Prediction of a long-distance process:
  If the X(3872) is a $D\bar{D}^\star$ molecule and
  the Y(4260) is a $D\bar{D}_1$ molecule,
  there will be a strong radiative transition
  $\boldsymbol{Y(4260) \to X(3872)\gamma}$ in e^+e^- collisions



- Data from BESIII

PRL 112 (2014) 092001





$\star$ Clear evidence of the X(3872)

$\star$ Data hint that it proceeds through a Y state $\to$ more data needed

Hadroproduction of the X(3872)

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

- Nice example of a process involving short-distance physics

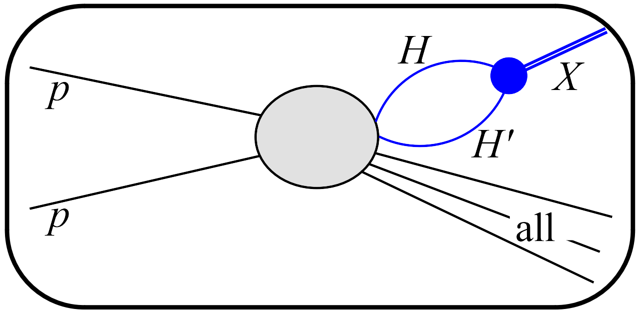
↪ still, factorization is at work, best seen using EFT

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 or HERWIG):

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

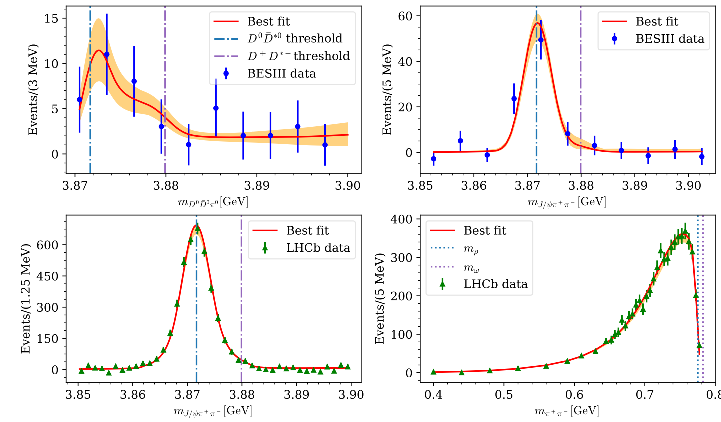
⇒ not very precise, but perfectly consistent with the data!

Precise determination of the properties of the X(3872)

Ji, Dong, Guo, Hanhart, UGM, [arXiv:2502.04458 [hep-ph]]

- $D^0\bar{D}^{*0}$-D^+D^{*-} coupled-channel analysis in EFT
  w/ $J/\psi\rho, J/\psi\omega$ channels as inelasticities

- Fit to the BESIII and LHCb data in a narrow energy range



↪ the $X(3872)$ is a quasi-bound state below $D^0\bar{D}^{*0}$ thr.

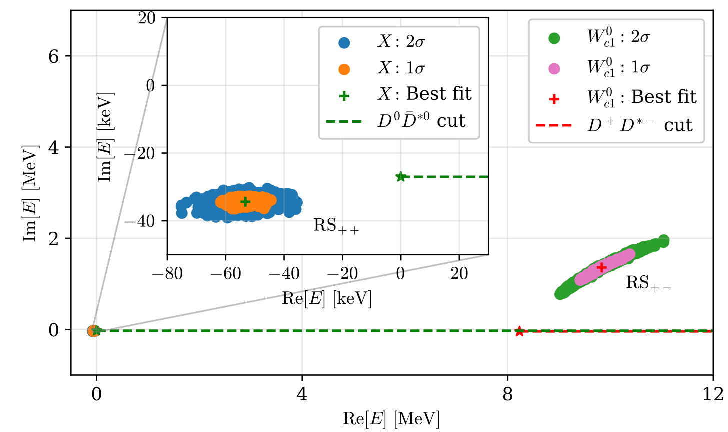
$$E_X = \left(-53^{+\,9+4}_{-24-8} - i\,34^{+\,2+0}_{-12-0}\right)\,\mathrm{keV}$$

↪ and its isospin-breaking ratio R_X is

$$R_X = \frac{\mathrm{Br}(X(3872)\to J/\psi 3\pi)}{\mathrm{Br}(X(3872)\to J/\psi 2\pi)} = 2.4(6)$$

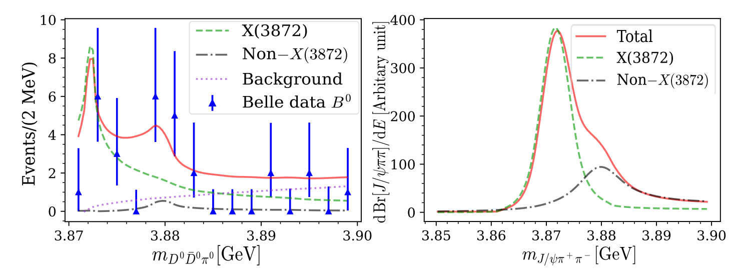
↪ and it has an isovector partner W^0_{c1} on sheet RS$_{+-}$

$$E_W = \left(1.6^{+0.7}_{-0.9} + i\,1.4^{+0.3}_{-0.6}\right)\ \mathrm{MeV}$$



⇒ Predictions for LHCb & Belle II (such as $B^0 \to K^0 D\bar{D}^*$)

⇒ An SU(3)$_f$ multiplet structure for hidden-charm
hadronic molecules is emerging (poles, cusps)
[like the NN system]



Two-pole structures

Two-pole structures

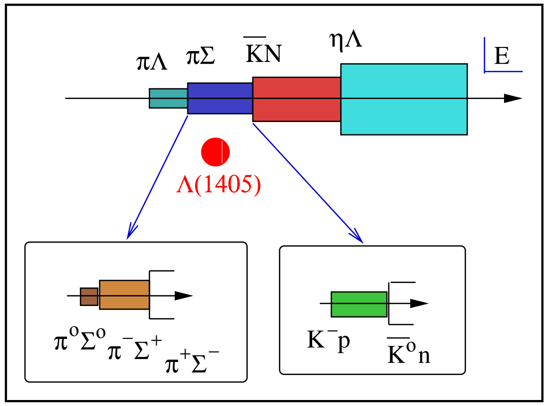
- What is a two-pole structure ?

> The term two-pole structure refers to the fact that particular single states in the hadron spectrum as listed in the PDG tables are indeed two states.

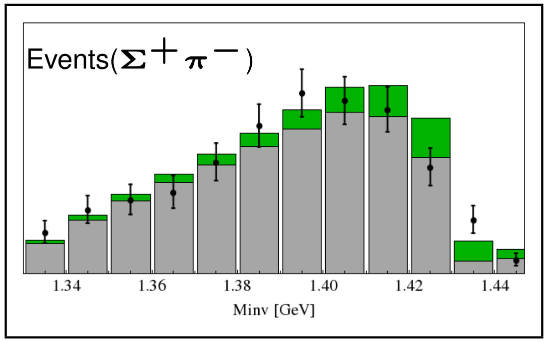
- Basic ingredients:
  - coupled channels
  - molecular states / dynamically generated states

The first exotic – the story of the two $\Lambda(1405)$

- Quark model: uds excitation with $J^P = \frac{1}{2}^-$ CLAS (2014)
  a few hundred MeV above the $\Lambda(1116)$
  $m = 1405.1^{+1.3}_{-1.0}\,\text{MeV}\,,\ \Gamma = 50.5 \pm 2.0\,\text{MeV}$ [PDG 2015]

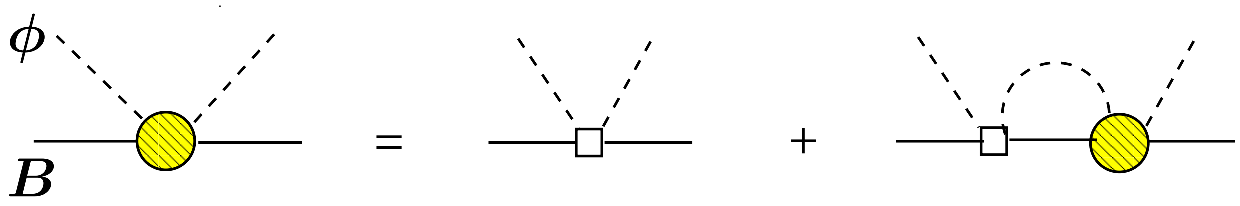


- Prediction as early as 1959 by Dalitz and Tuan:
  Resonance between the coupled $\pi\Sigma$ and $\bar{K}N$ channels
  Dalitz, Tuan, Phys. Rev. Lett. **2** (1959) 425; J.K. Kim, PRL **14** (1965) 29



- 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 unitarized chiral perturbation theory: $\phi B \to \phi B$



Kaiser, Siegel, Weise, Ramos, Oset, Oller, UGM, Lutz, ...

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]

$\hookrightarrow$ Chiral dynamics generates **two** poles, but: how?

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

The two-pole scenario explained

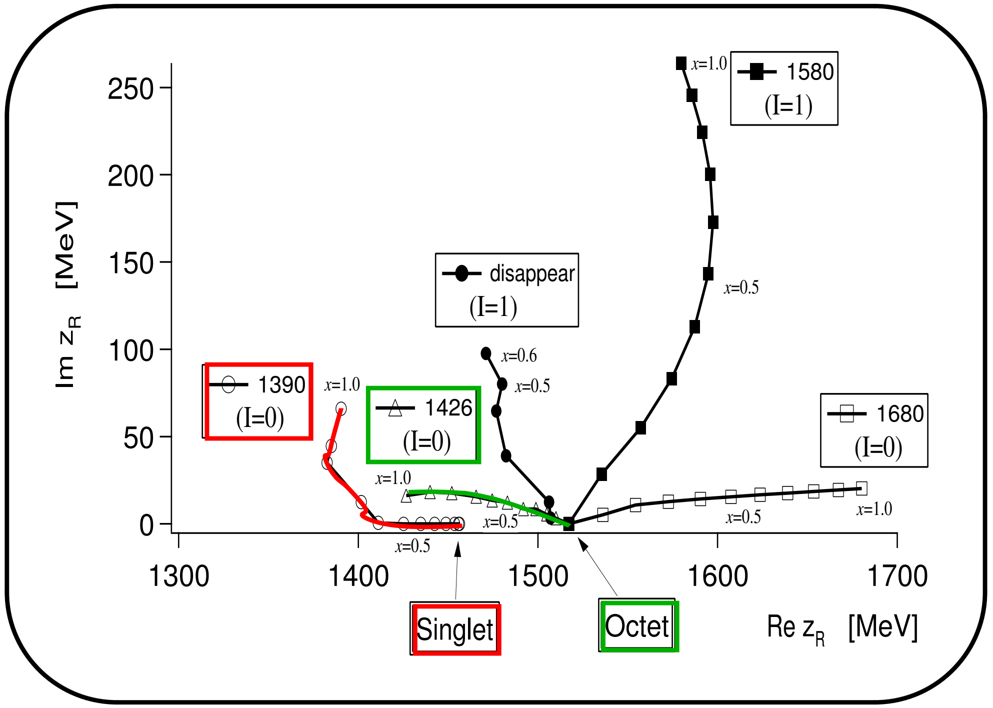
- Detailed analysis found **two** poles in the complex energy plane

$\hookrightarrow$ generated by chiral dynamics, but can we understand this in more detail?

- Group theory:

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

- Follow the pole movement from the SU(3) limit to the physical masses:
  Jido, Oller, Oset, Ramos, UGM,
  Nucl. Phys. A **725** (2003) 181



- Verified by various groups world-wide

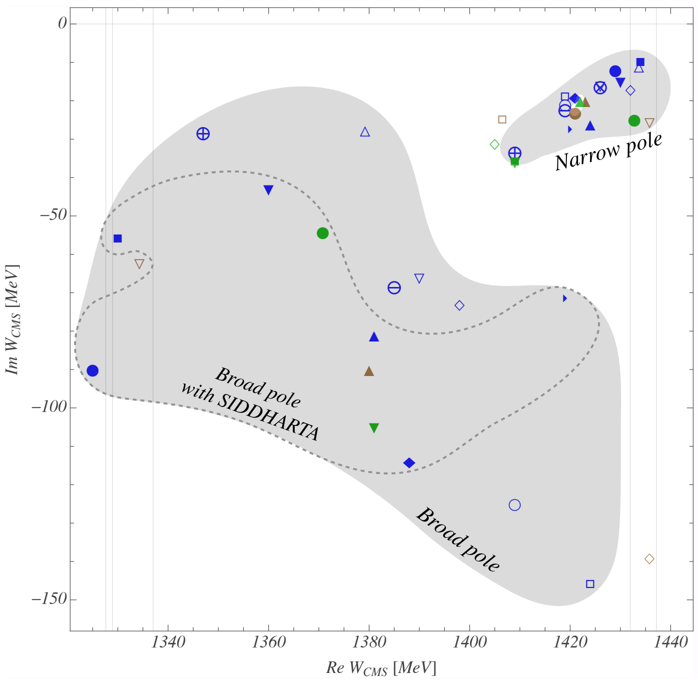
- However: scattering and kaonic atom data alone do not lead to a unique solution (two poles, but spread in the complex plane)

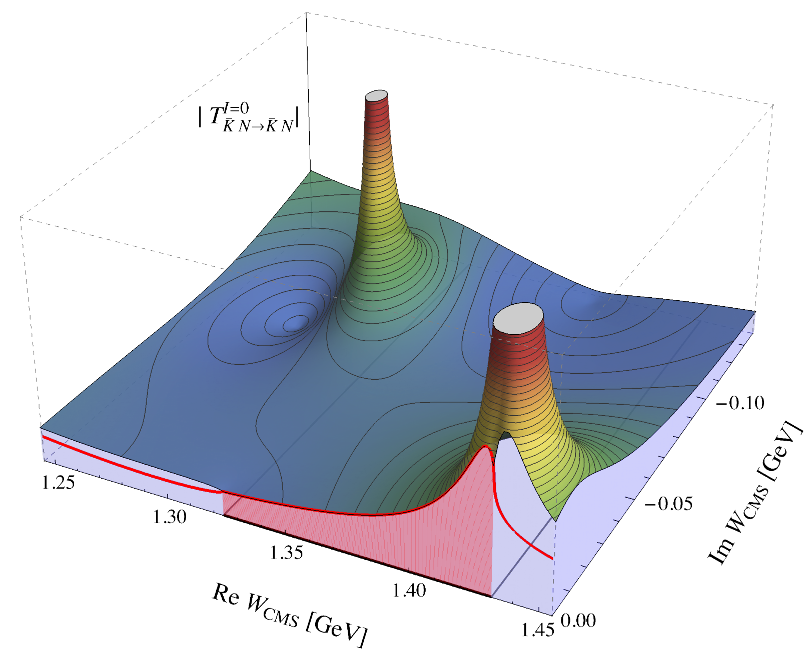
- Photoproduction to the rescue: $\gamma p \to K^+ \Sigma \pi$ CLAS, Phys. Rev. C **87**, 035206 (2013)

Present status of the two-pole scenario

- Two poles from scattering + SIDDHARTA data (one well, the other not-so-well fixed):

for details, see Mai, Eur. Phys. J. ST **230** (2021) 1593 [arXiv:2010.00056 [nucl-th]]





Figures courtesy Maxim Mai

Resonances are poles in the complex plane!

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

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

Status in the Review of Particle Physics

- Two excited Λ states listed in the 2020 RPP 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

Hyodo, UGM

- a new two-star resonance at 1380 MeV
- still not in the summary table
- there are more such two-pole states!
- this is a fascinating phenomenon
  intimately tied to molecular structures
- Two Λ's: recenty confirmed by lattice QCD Bulava et al., PRL **132** (2024) 051901
  $\hookrightarrow$ nature of the lower pole not really pinned down
- for a review, see UGM, *Symmetry* **12** (2020) 981

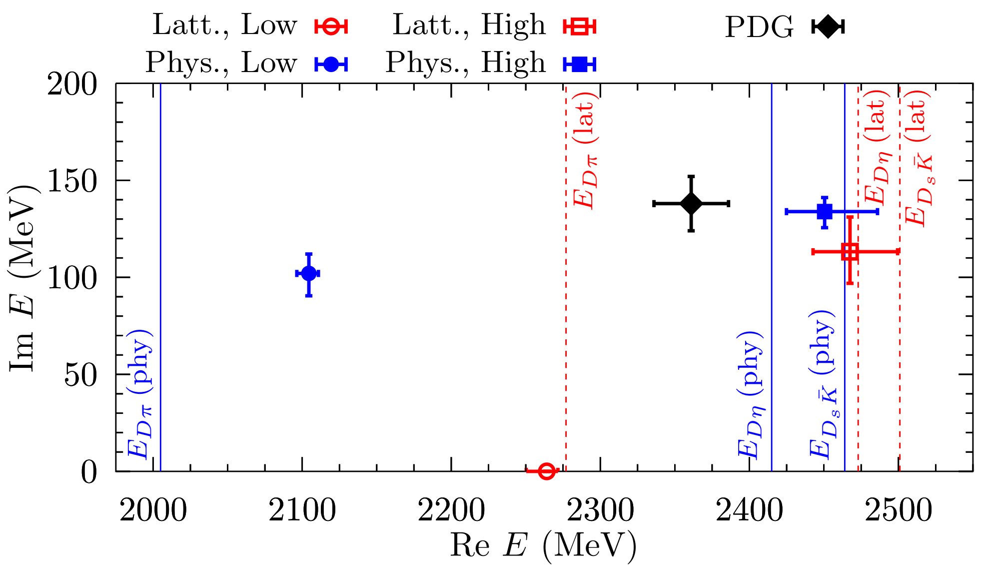
Two-pole structure of the $D_0^\star(2300)$

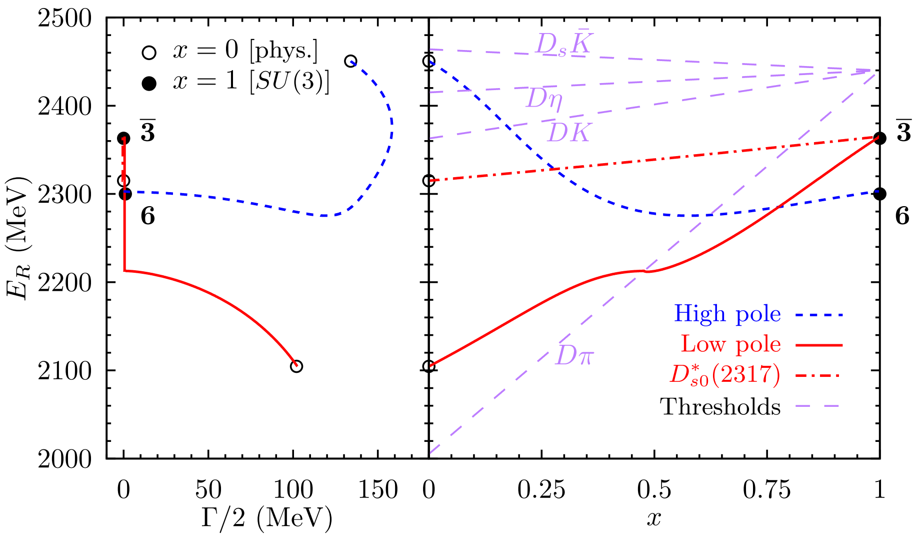
Albaladejo, Fernandez-Soler, Guo, Nieves, Phys. Lett. B **767** (2017) 465

- Re-analysis of LQCD data on $D\pi, D\eta, D_s\bar{K}$ scattering ($I = 1/2$) reveals a two-pole scenario!
  Moir et al. [HadSpec] JHEP **10** (2016) 011
- understood from group theory

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

- Again: important role of symmetries → next slide
- Lattice QCD test: sextet pole becomes a b.s. for $M_\phi > 575$ MeV in the SU(3) limit
  Du et al., Phys.Rev. D **98** (2018) 094018
- FZJ LQCD finds a b.s. for $M_\pi = 600$ MeV
  Gregory et al., 2106.15391 [hep-ph]
- HadSpec finds a virtual state ($M_\pi = 700$ MeV)
  Yeo et al., JHEP **07** (2024) 012





Two-pole structure consistent with the lattice data?

Ashokan, Tang, Guo, Hanhart, Kamiya, UGM, EPJ **C 83** (2023) 850

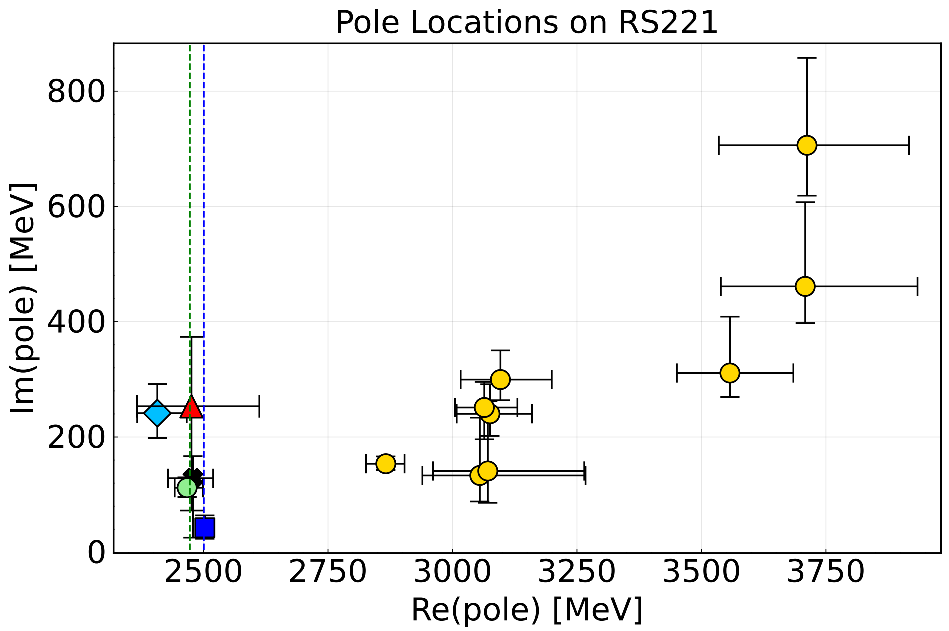
- Can we understand why HadSpec only reported one pole?
- Impose SU(3) symmetry on the K-matrix to fit the FV energy levels $\longrightarrow$ less parameters!

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

- perform various fits
  (switch off various terms)

$\hookrightarrow$ Poles are consistent w/ UChPT !

$\hookrightarrow$ never ignore symmetries!



Two-pole scenario in the heavy-light sector

- Invoke HQSS and HQFS:

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

	Lower [MeV]	Higher [MeV]	PDG2024 [MeV]
$D_0^\star$	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+36}_{-26}, 134^{+7}_{-8}\right)$	$(2343 \pm 10, 115 \pm 8)$
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$	$\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$(2412 \pm 9, 157 \pm 15)$
$B_0^\star$	$\left(5535^{+9}_{-11}, 113^{+15}_{-17}\right)$	$\left(5852^{+16}_{-19}, 36 \pm 5\right)$	—
B_1	$\left(5584^{+9}_{-11}, 119^{+14}_{-17}\right)$	$\left(5912^{+15}_{-18}, 42^{+5}_{-4}\right)$	—

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

$\rightarrow$ YES! LHCb data on $B \to D\pi\pi$ and $B \to DK\pi$ decays

Du et al., PRD **98** (2108) 094018; PRD **99** (2019) 114002; PRL **126** (2021) 192001

PDG update

- The PDG group is like a heavy tanker, still there is motion:

$D_0^*(2300)$ $I(J^P) = \frac{1}{2}(0^+)$

was $D_0^*(2400)$

There is a strong evidence that recent data on $B \to D\pi\pi$ (AAIJ 15Y, AAIJ 16AH) and $B \to D\pi K$ (AAIJ 14BH, AAIJ 15V, AAIJ 15X) 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 18A, DU 19, DU 21). For details see review on "Heavy Non-$q\bar{q}$ Mesons."

$D_0^*(2300)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
2343±10 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				

- RPP 2024: 79. Heavy Non-$q\bar{q}$ Mesons, Hanhart, Gutsche, Mitchell

↪ stay tuned on further developments!

↪ many more such two-poles structures found

→ a new type of player in the hadron spectrum

Misconceptions

Case 1: Misconcptions 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 $\rightarrow$ **this is wrong!**

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

$$\sigma(\bar{p}p \to X) \sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

$$\leq \int_{\mathcal{R}} d^3\mathbf{k} \, \left| \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

- The result depends crucially on the value of $\mathcal{R}$ which specifies the region where the bound state wave function "$\Psi(\mathbf{k})$ is significantly different from zero"
- Assumption by Bignamini et al: $\mathcal{R} \simeq 35$ MeV of the order of γ [$\simeq 0$ now]

  $\hookrightarrow$ $\sigma(\bar{p}p \to X) \simeq 0.07[0.0]$ nb way smaller than experiment

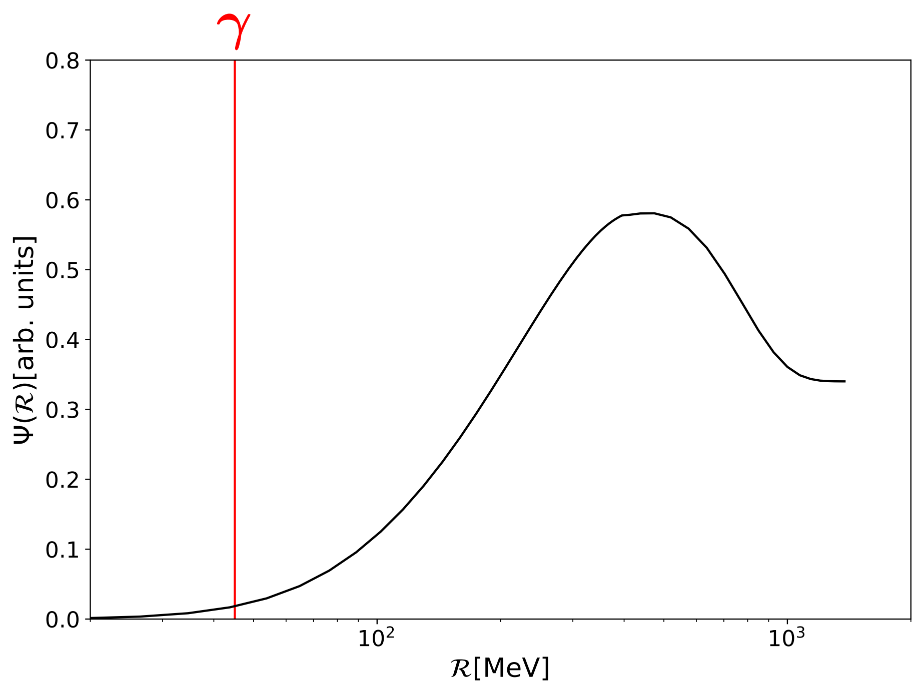
  $\hookrightarrow$ the X(3872) can not be a molecule

  $\hookrightarrow$ so what goes wrong?

Misconceptions on hadroproduction continued

- 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

Case 2: Misconcptions on femtoscopy

Epelbaum, Heihoff, UGM, Tscherwon, arXiv:2504.08631 [nucl-t

- Femtoscopy is claimed as precision tool to analyze hadron interactions & the spectrum

PHYSICAL REVIEW LETTERS **124,** 092301 (2020)

Scattering Studies with Low-Energy Kaon-Proton Femtoscopy in Proton-Proton Collisions at the LHC

S. Acharya *et al.**
(A Large Ion Collider Experiment Collaboration)

(Received 18 July 2019; revised manuscript received 3 December 2019; accepted 11 February 2020; published 6 March 2020)

The study of the strength and behavior of the antikaon-nucleon ($\bar{K}N$) interaction constitutes one of the key focuses of the strangeness sector in low-energy quantum chromodynamics (QCD). In this Letter a unique high-precision measurement of the strong interaction between kaons and protons, close and above the kinematic threshold, is presented. The femtoscopic measurements of the correlation function at low pair-frame relative momentum of $(K^+p \oplus K^-\bar{p})$ and $(K^-p \oplus K^+\bar{p})$ pairs measured in pp collisions at $\sqrt{s} = 5, 7$, and 13 TeV are reported. A structure observed around a relative momentum of 58 MeV/c in the measured correlation function of $(K^-p \oplus K^+\bar{p})$ with a significance of 4.4σ constitutes the first experimental evidence for the opening of the $(\bar{K}^0 n \oplus K^0\bar{n})$ isospin breaking channel due to the mass difference between charged and neutral kaons. The measured correlation functions have been compared to Jülich and Kyoto models in addition to the Coulomb potential. The high-precision data at low relative momenta presented in this work prove femtoscopy to be a powerful complementary tool to scattering experiments and provide new constraints above the $\bar{K}N$ threshold for low-energy QCD chiral models.

Physics Letters B 797 (2019) 134822

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Study of the Λ–Λ interaction with femtoscopy correlations in pp and p–Pb collisions at the LHC

ALICE Collaboration

ARTICLE INFO

Article history:
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Editor: L. Rolandi

ABSTRACT

This work presents new constraints on the existence and the binding energy of a possible Λ–Λ bound state, the H-dibaryon, derived from Λ–Λ femtoscopic measurements by the ALICE collaboration. The results are obtained from a new measurement using the femtoscopy technique in pp collisions at $\sqrt{s} =$ 13 TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, combined with previously published results from pp collisions at $\sqrt{s} = 7$ TeV. The Λ–Λ scattering parameter space, spanned by the inverse scattering length f_0^{-1} and the effective range d_0, is constrained by comparing the measured Λ–Λ correlation function with calculations obtained within the Lednický model. The data are compatible with hypernuclei results and lattice computations, both predicting a shallow attractive interaction, and permit to test different theoretical approaches describing the Λ–Λ interaction. The region in the (f_0^{-1}, d_0) plane which would accommodate a Λ–Λ bound state is substantially restricted compared to previous studies. The binding energy of the possible Λ–Λ bound state is estimated within an effective-range expansion approach and is found to be $B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\text{stat})^{+1.8}_{-1.0}(\text{syst})$ MeV.

Article

Unveiling the strong interaction among hadrons at the LHC

https://doi.org/10.1038/s41586-020-3001-6
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Accepted: 20 October 2020
Published online: 9 December 2020
Open access
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ALICE Collaboration*

One of the key challenges for nuclear physics today is to understand from first principles the effective interaction between hadrons with different quark content. First successes have been achieved using techniques that solve the dynamics of quarks and gluons on discrete space-time lattices[1,2]. Experimentally, the dynamics of the strong interaction have been studied by scattering hadrons off each other. Such scattering experiments are difficult or impossible for unstable hadrons[3–6] and so high-quality measurements exist only for hadrons containing up and down quarks[7]. Here we demonstrate that measuring correlations in the momentum space between hadron pairs[8–12] produced in ultrarelativistic proton–proton collisions at the CERN Large Hadron Collider (LHC) provides a precise method with which to obtain the missing information on the interaction dynamics between any pair of unstable hadrons. Specifically, we discuss the case of the interaction of baryons containing strange quarks (hyperons). We demonstrate how, using precision measurements of proton–omega baryon correlations, the effect of the strong interaction for this hadron–hadron pair can be studied with precision similar to, and compared with, predictions from lattice calculations[13,14]. The large number of hyperons identified in proton–proton collisions at the LHC, together with accurate modelling[15] of the small (approximately one femtometre) inter-particle distance and exact predictions for the correlation functions, enables a detailed determination of the short-range part of the nucleon-hyperon interaction.

Phys. Lett. B 856 (2024) 138915

Contents lists available at ScienceDirect

Physics Letters B

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Letter

Investigating the composition of the $K_0^*(700)$ state with $\pi^\pm K_S^0$ correlations at the LHC

ALICE Collaboration *

ARTICLE INFO

Editor: M. Doser

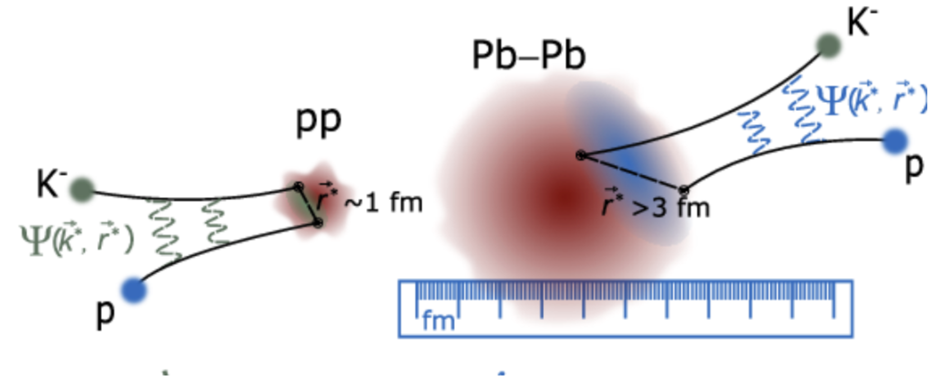
Dataset link: https://www.hepdata.net/record/ins2739149

ABSTRACT

The first measurements of femtoscopic correlations with the particle pair combinations $\pi^\pm K_S^0$ in pp collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider (LHC) are reported by the ALICE experiment. Using the femtoscopic approach, it is shown that it is possible to study the elusive $K_0^*(700)$ particle that has been considered a tetraquark candidate for over forty years. Source and final-state interaction parameters are extracted by fitting a model assuming a Gaussian source to the experimentally measured two-particle correlation functions. The final-state interaction in the $\pi^\pm K_S^0$ system is modeled through a resonant scattering amplitude, defined in terms of a mass and a coupling parameter, The extracted mass and Breit–Wigner width, derived from the coupling parameter, of the final-state interaction are found to be consistent with previous measurements of the $K_0^*(700)$. The small value and increase of the correlation strength with increasing source size support the hypothesis that the $K_0^*(700)$ is a four-quark state, i.e. a tetraquark state of the form $(q_1, \overline{q_2}, q_3, \overline{q_3})$ in which q_1, q_2 and q_3 indicate the flavor of the valence quarks of the π and K_S^0. This latter trend is also confirmed via a simple geometric model that assumes a tetraquark structure of the $K_0^*(700)$ resonance.

Case 2: Misconcptions on femtoscopy continued

Epelbaum, Heihoff, UGM, Tscherwon, arXiv:2504.08631 [nucl-th]



- Koonin-Pratt (KP) formula for the correlation function $C(\mathbf{k})$ in the CMS:

$$C(\mathbf{k}) = \int d\mathbf{r}\, S_{12}(\mathbf{r}) \left|\Psi(\mathbf{r},\, \mathbf{k})\right|^2$$

$\mathbf{k}$ = the relative momentum, $S_{12}(\mathbf{r})$ = the source function

$\Psi(\mathbf{r},\, \mathbf{k})$ = relative wf of the outgoing two-body state (solution of the scattering problem)

Koonin, Phys. Lett. **70B** (1977) 1219, Pratt, Phys. Rev. Lett. **53** (1984) 1219

- From experiment to interpretation:

  Step 1: measure the correlation functions $C(\mathbf{k})$

  Step 2: modeling of the source function $S_{12}(\mathbf{r})$ which is deemed to be **universal**
  assume Gaussian form, extract r_0 from one reaction (pp) assuming some interaction model

  Step 3: Once $S_{12}(\mathbf{r})$ is fixed, use the KP formula to analyze hadronic interactions

- Note many refinements for coupled channels etc, but let us keep it simple

Femtoscopy revisited

Epelbaum, Heihoff, UGM, Tscherwon, arXiv:2504.08631 [nucl-th]

- Fundamental flaw of the KP formula:

  Combined with the universality assumption for the source function $S_{12}(\mathbf{r})$,
  it implies the measurability of hadronic wave functions
  and thus also of the corresponding interaction potentials

- But: hadronic potentials are **not** observable (scheme-dependent) [as is well known]

- Consider non-relativistic systems:

$$C(\mathbf{k}) = \langle \Psi^{(+)}_{-\mathbf{k}} | \hat{S}_{12} | \Psi^{(+)}_{-\mathbf{k}} \rangle \quad \text{for} \quad \langle \mathbf{r}' | \hat{S}_{12} | \mathbf{r} \rangle = \delta(\mathbf{r}' - \mathbf{r}) S_{12}(\mathbf{r}) \quad \text{(local)}$$

- Consider unitary transformations ($\hat{U}^\dagger \hat{U} = \hat{U}\hat{U}^\dagger = 1$)

$$C(\mathbf{k}) = \left(\langle \Psi^{(+)}_{-\mathbf{k}} | \hat{U}^\dagger \right) \left(\hat{U} \hat{S}_{12} \hat{U}^\dagger \right) \left(\hat{U} | \Psi^{(+)}_{-\mathbf{k}} \rangle \right) = \langle \Psi'^{(+)}_{-\mathbf{k}} | \hat{S}'_{12} | \Psi'^{(+)}_{-\mathbf{k}} \rangle$$

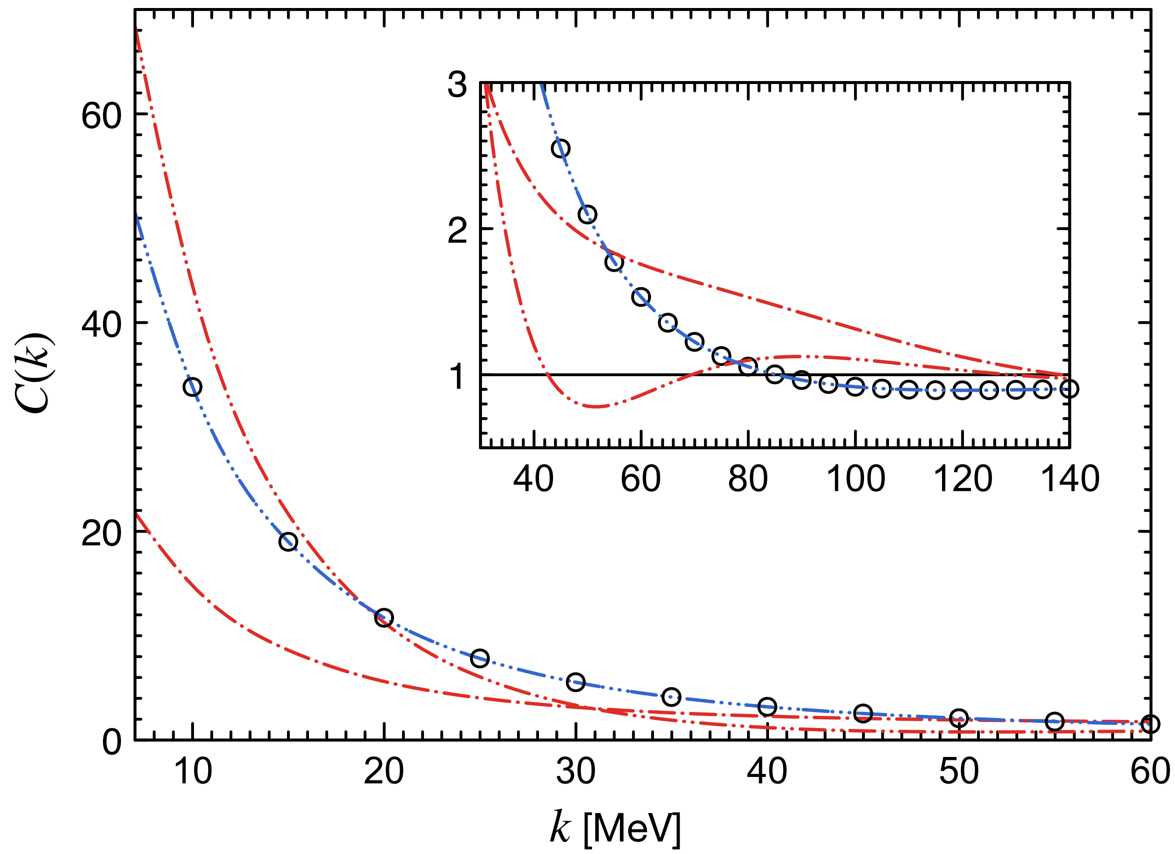
- Universality of the source term means $\hat{S}'_{12} = \hat{S}_{12}$

  $\hookrightarrow$ model dependence of the calculated correlation functions

Femtoscopy revisited continued

Epelbaum, Heihoff, UGM, Tscherwon, arXiv:2504.08631 [nucl-th]

- Perform unitary transformations that leave the scattering matrix (phase shifts) invariant



↪ inherent scheme dependence not accounted for! systematic error!

↪ particularly bad in the three-hadron system!

Case 3: Misconceptions on resonances

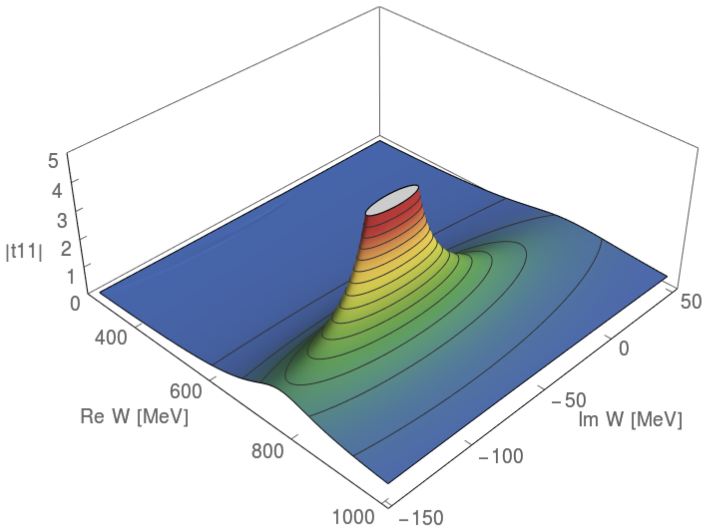
- Bump hunting: "Not every bump is a resonance, not every resonance is a bump"

  Moorhouse (1960ties)

- Resonances are poles in the complex energy-plane

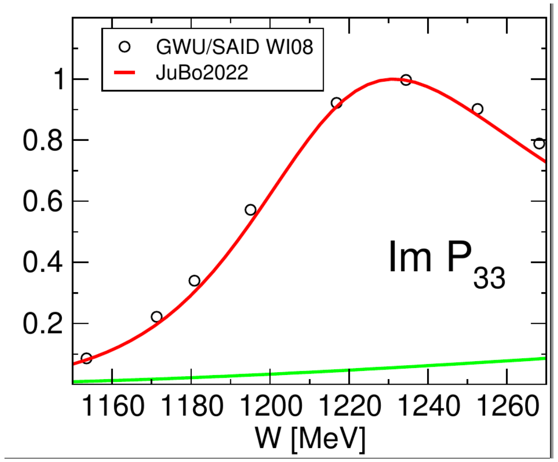
$\hookrightarrow$ must determine the scattering amplitude
(often coupled channels!)

$\hookrightarrow$ pole searches, Argand diagrams, speed plots



- Often (<u>mis</u>)used: Breit-Wigner (BW) parameterization
  (here given in its non-relativistic form)

$$\mathbf{BW}(E) \sim \frac{1}{(E - E_R)^2 + \Gamma_R^2/4}$$



$\hookrightarrow$ valid for isolated resonances with mass E_R and width Γ_R
on a mildly varying background (in energy)

- A few examples: $\rho(770), \omega(782), \Delta(1232)$

  $\hookrightarrow$ these are **exceptions!** rather than the rule

Case 3: Misconceptions on resonances cont'd

- Still, many collaborations use the BW parameterization tho' it is **not** applicable

nature physics

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Letter | Open access | Published: 16 June 2022

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration

Nature Physics **18**, 751–754 (2022) | Cite this article

RAPID COMMUNICATION | OPEN ACCESS | ACCESS BY FORSCHUNGSZENTRUM JUELICH GMBH

Study of $\eta(1475)$ and $X(1835)$ in radiative J/ψ decays to $\gamma\phi$

M. Ablikim[1], M. N. Achasov[9,e], S. Ahmed[14], O. Albayrak[5], M. Albrecht[4], M. Alekseev[51a,51c], D. J. Ambrose[46], A. Amoroso[51a,51c], F. F. An[1] *et al.* (BESIII Collaboration)

Show more ⌄

Phys. Rev. D **97**, 051101(R) – **Published 6 March, 2018**

DOI: https://doi.org/10.1103/PhysRevD.97.051101

- Such papers should never have passed any referee / should never be published

- Amplitude analysis is required – "Experimental data should only be analyzed by theorists"

Gerhard Höhler (1990ties)

- If ampliude analysis is not available, use at least the Flatté parameterization

$$T(s) = \frac{\sqrt{\rho_{\rm fin}}}{\mathcal{M}^2 - s - i\sum_k g_k^2 \rho_k}$$

$\rho_{\rm fin}$ = p.s. of the final state, ρ_k = p.s. of the channel k

$\mathcal{M}^2$ = parameter [mass]^2, g_k = coupling to channel k

$\hookrightarrow$ and no excuses, please!

Summary and outlook

- The hadron spectrum is the last direct frontier of the Standard Model
- Hadronic molecules are a particular manifestation of non-conventional states

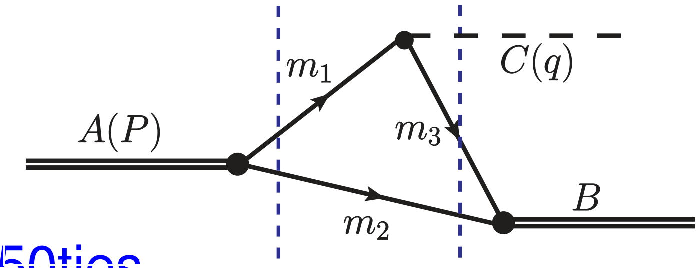
  $\hookrightarrow$ they appear in nuclear and hadronic physics (also 3-body states)
- New players emerge: Two-pole structures

  $\hookrightarrow$ more to be discovered
- A number of misconceptions are flourishing :-(

$\Longrightarrow$ Through an interplay of experiment, theory and lattice simulations, we are experiencing a paradigm shift: The QCD spectrum is much more than a collection of quark model states!

SPARES

SUITABLE NREFTs



- Most exotic candidates found through decays

$\rightarrow$ triangle diagram: **anomalous triangle singularity**

$\rightarrow$ already studied by Landau, Nambu and other in the 1950ties

- **NREFT$_1$**: all intermediate particles close to their mass shell

  $\hookrightarrow$ expand in powers of the average velocity and external (small) momenta

  $\hookrightarrow$ applied systematically to a number of charmonium transitions $\surd$

  Guo, Hanhart, UGM, Zhao (2009,2010,2011), Guo, UGM (2012), . . .

- **NREFT$_2$**: one intermediate particle further off its mass shell

  $\hookrightarrow$ integrate out this particle, then proceed as before

  $\hookrightarrow$ was originally invented as XEFT for the study of the X(3872)

  $\hookrightarrow$ XEFT resembles much the pionless EFT of nuclear physics

  $\hookrightarrow$ systematic studies of processes involving the X(3872) and Z_b states

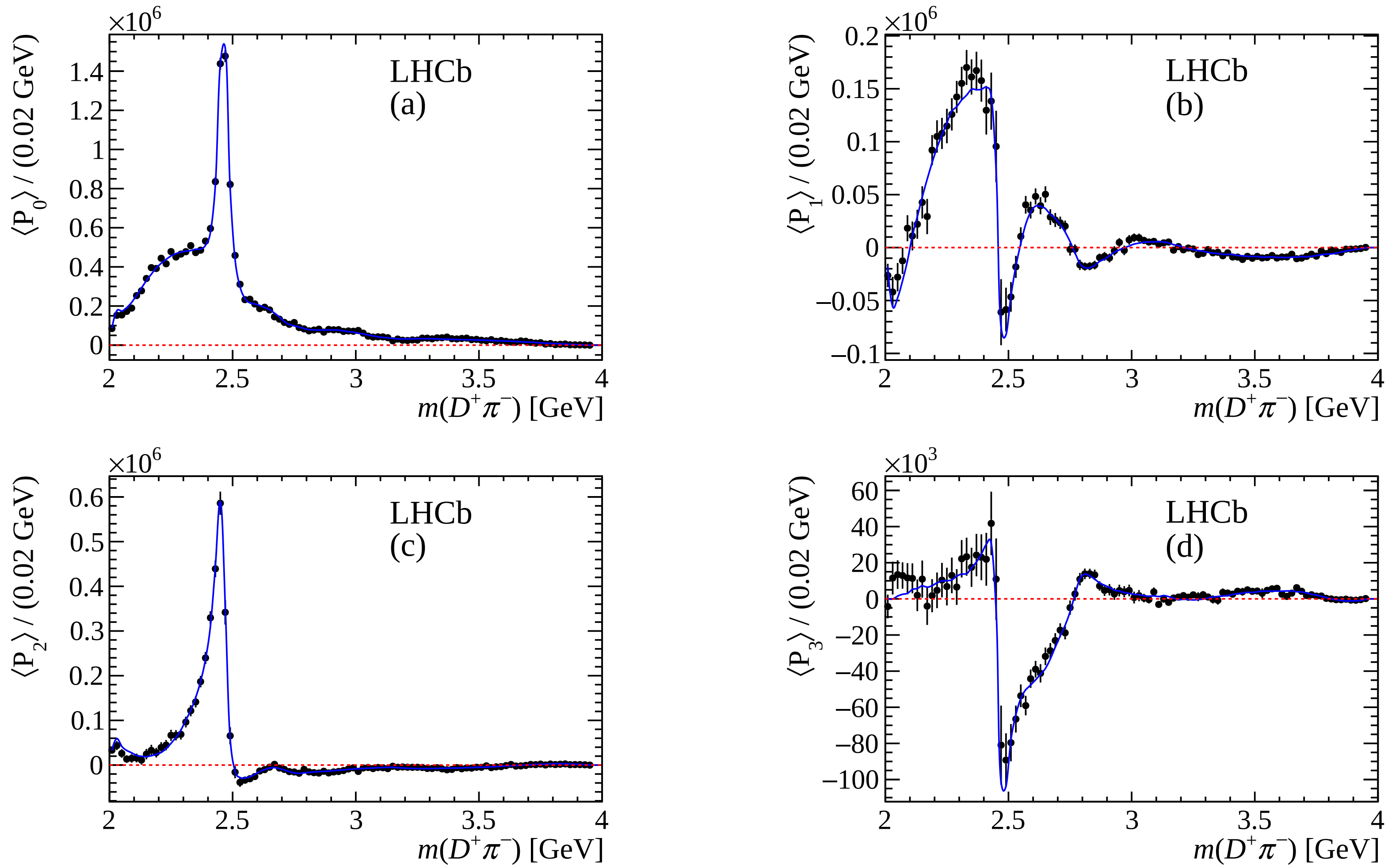
  Fleming et al. (2007), Braaten, Hammer, Mehen (2010), Mehen, Powell (2011), . . .

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):



Theory of $B \to D\pi\pi$

Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Phys. Rev. D **98** (2018) 094018

- Effective Lagrangian for $B \to D$ transitions w/ one fast & one slow pseudoscalar
  Savage, Wise, Phys. Rev. D **39** (1989) 3346

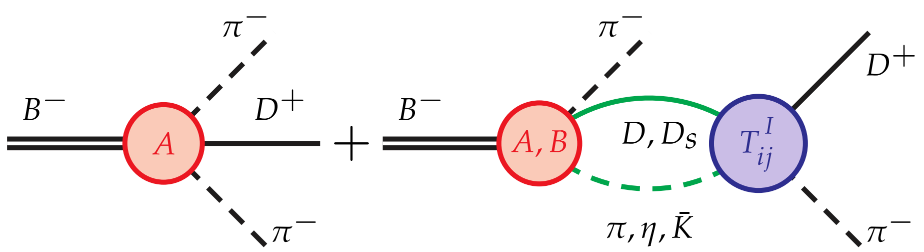
- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI

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

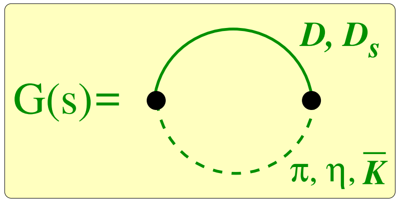
  $\to$ P-wave: $D^\star$, $D^\star(2680)$; D-wave: $D_2(2460)$ as by LHCb

  $\to$ 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})



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



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

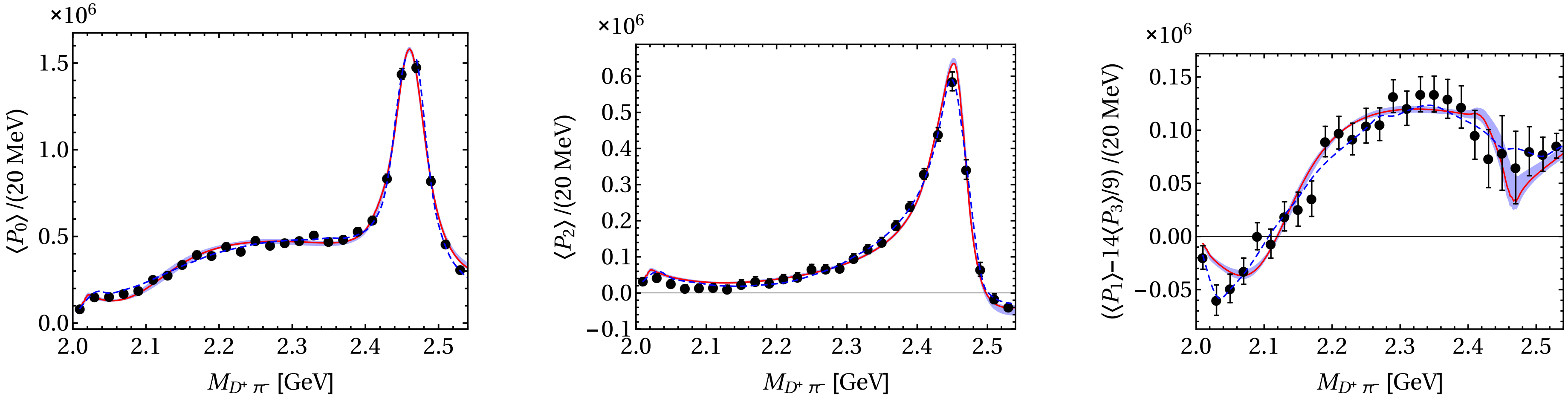
Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Yao, Phys. Rev. D **98** (2018) 094018

- More appropriate combinations of the angular moments:

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

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

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

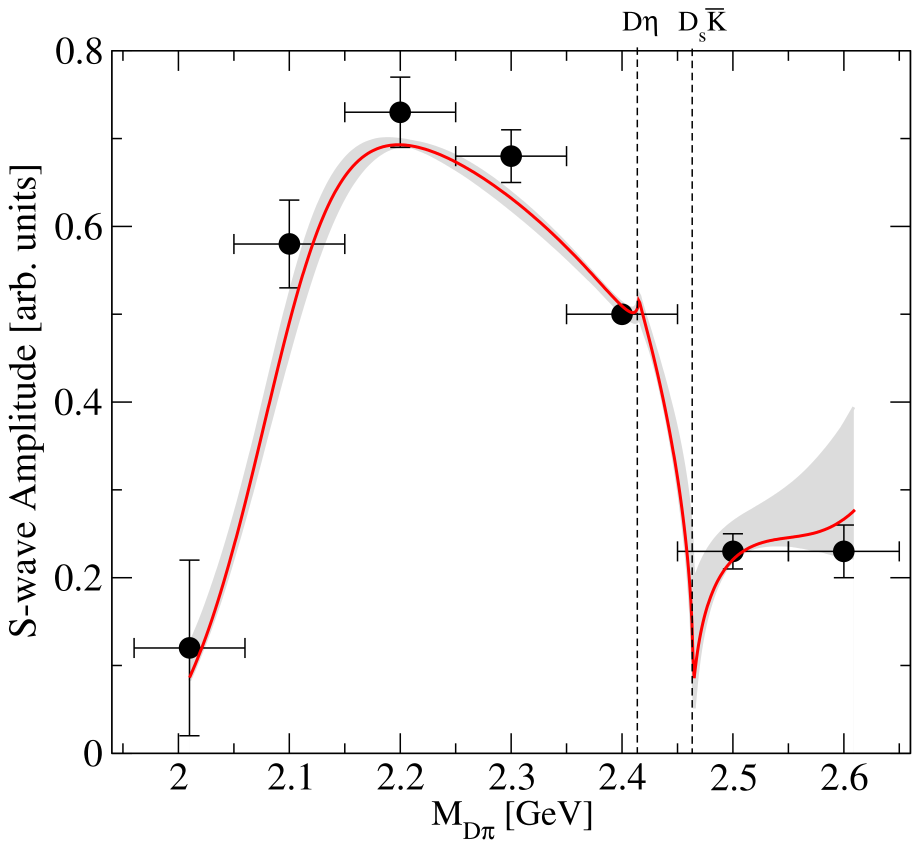


- The **S-wave** $D\pi$ can be very well described using pre-fixed amplitudes
- Fast variation in [2.4,2.5] GeV in $\langle P_{13} \rangle$: cusps at the $D\eta$ and $D_s\bar{K}$ thresholds

$\hookrightarrow$ 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

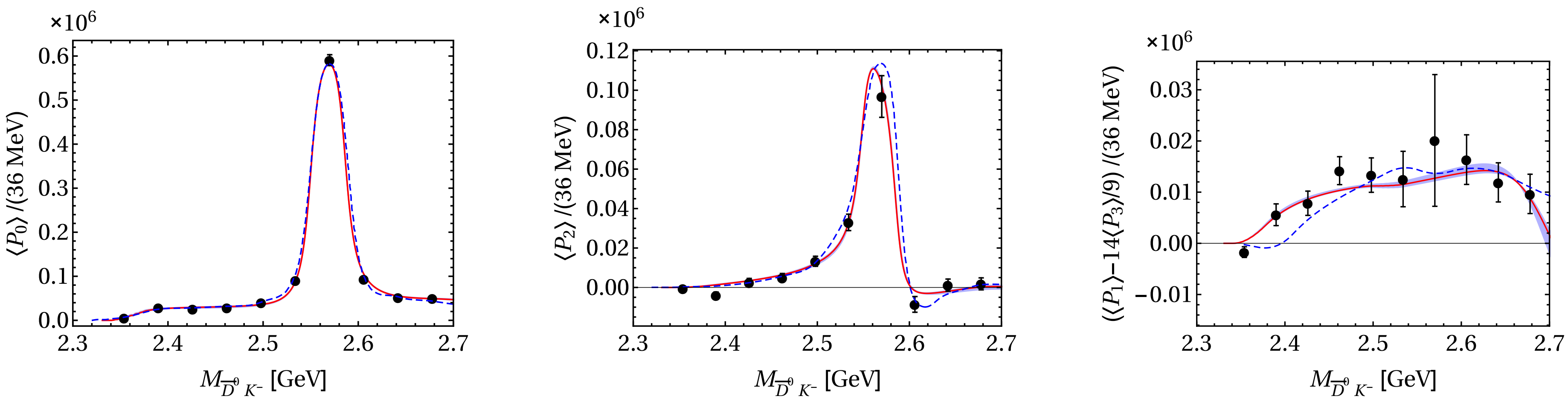


- Higher mass pole at 2.46 GeV clearly amplifies the cusps predicted in our amplitude

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

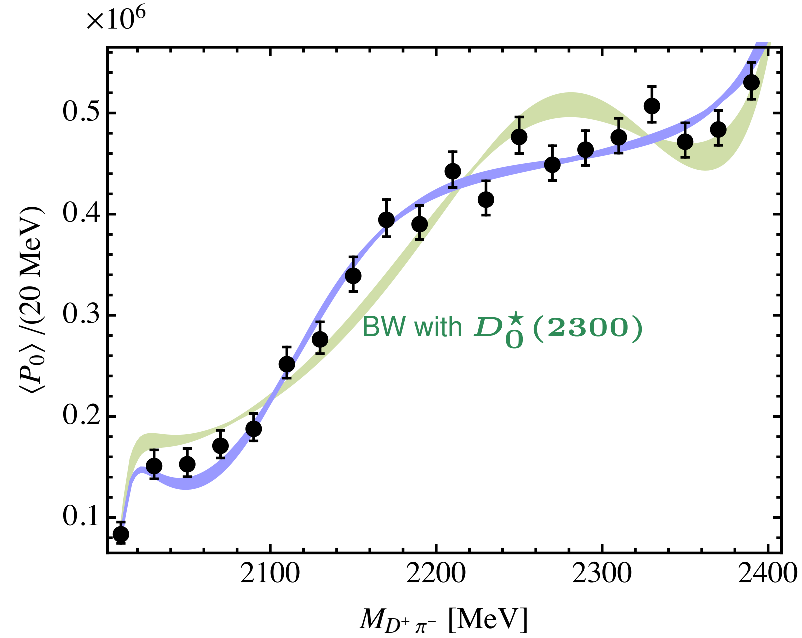
$\Rightarrow$ better data for $\langle P_{13} \rangle$ would be welcome

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

Where is the lowest charm-strange meson?

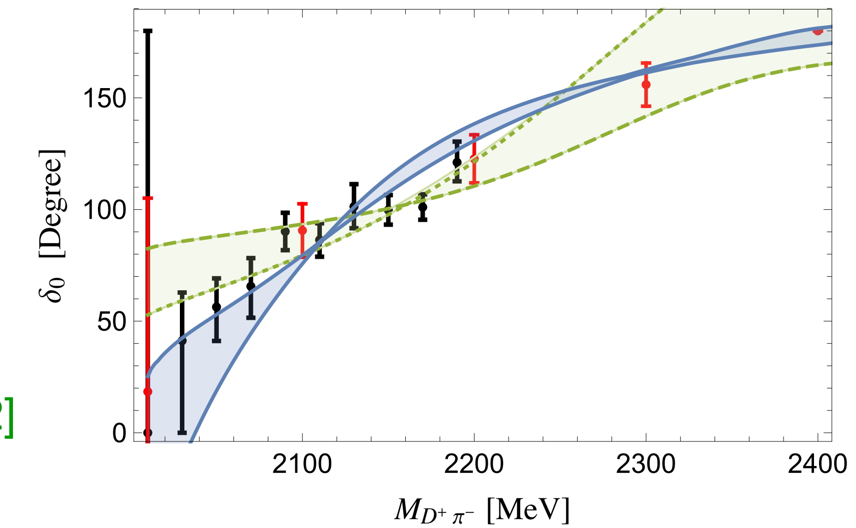
Du, Guo, Hanhart, Kubis, UGM, Phys. Rev. Lett. **126** (2021) 192001 [2012.04599]

- 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:

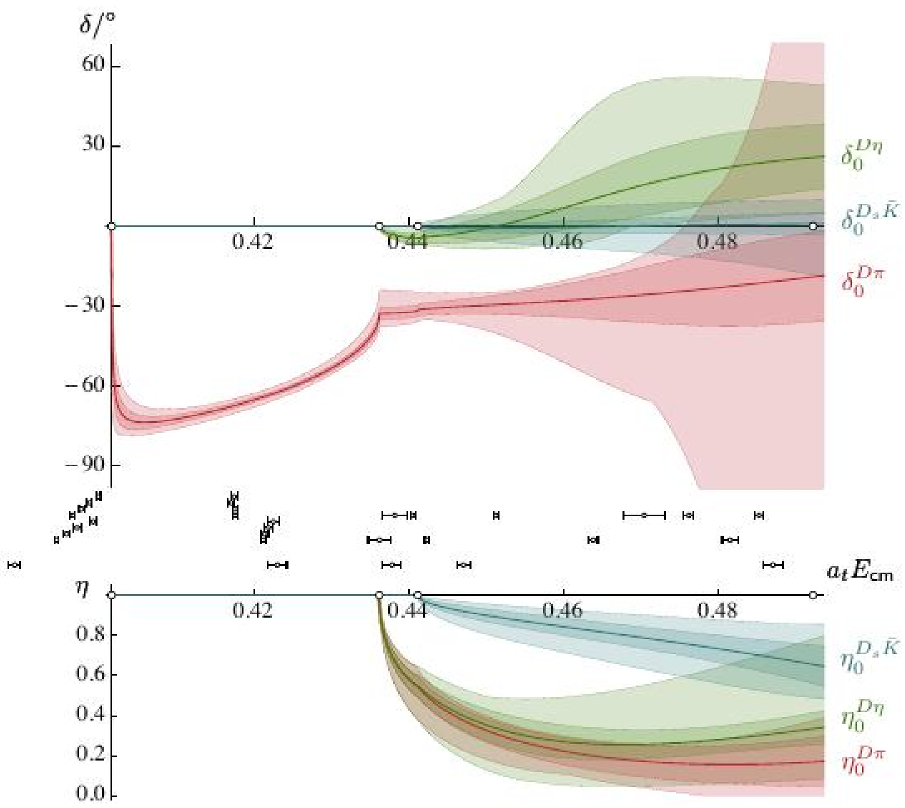
$$\left(2105^{+6}_{-8} - i\,102^{+10}_{-11}\right)\ \text{MeV}$$

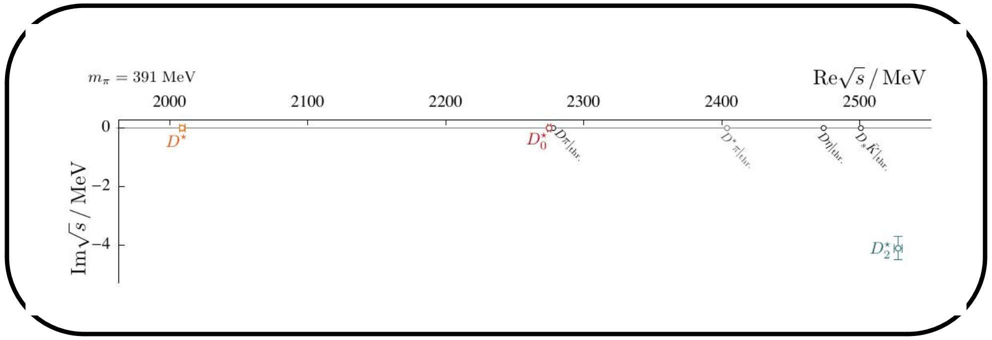
- Recently confirmed by Lattice QCD!
  Cheung et al. [HadSpec], JHEP **02** (2021) 100 [2008.06432]

Coupled channel scattering on the lattice

Moir, Peardon, Ryan, Thomas, Wilson [HadSpec], 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



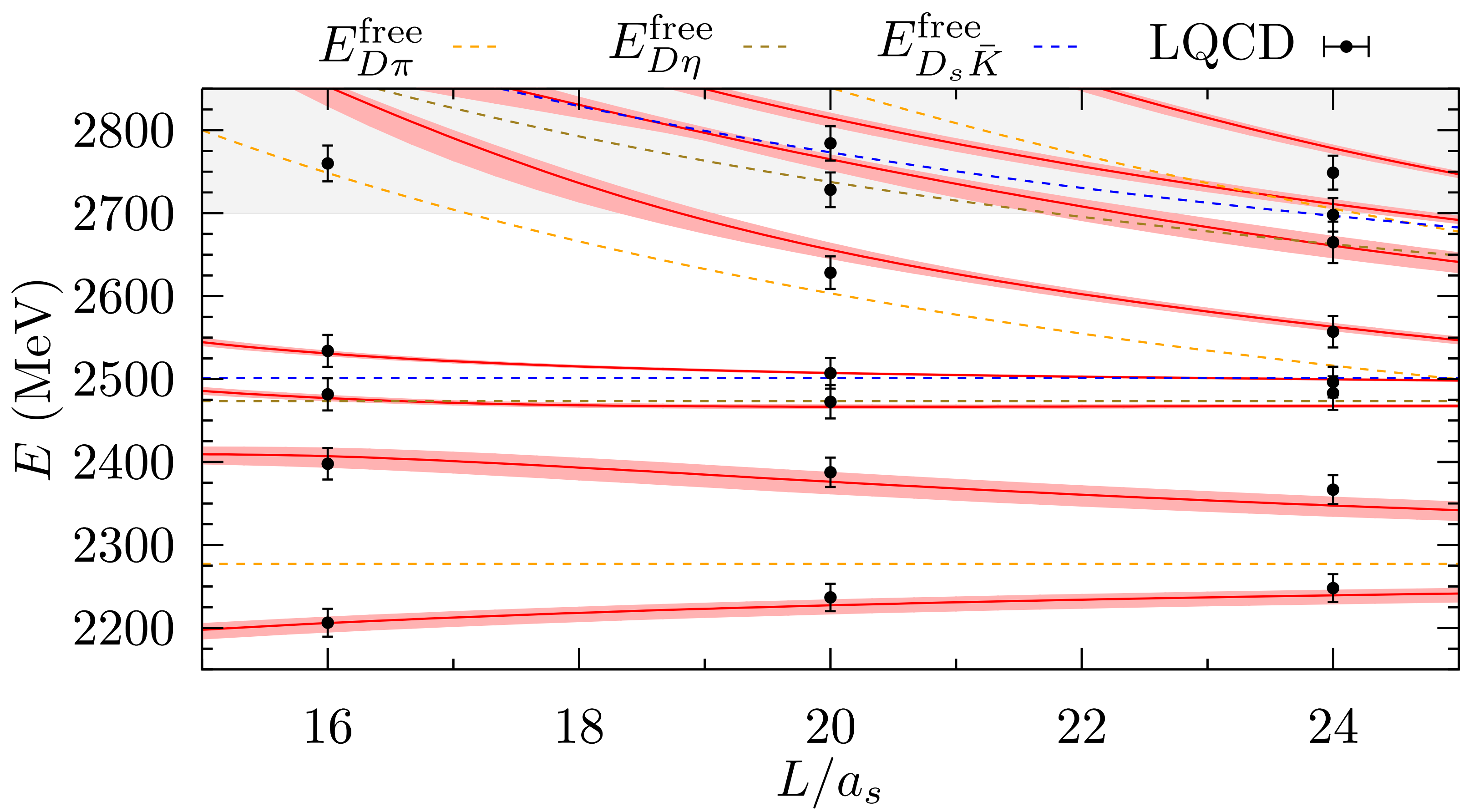


- S-wave pole at (2275.9 ± 0.9) MeV
- close to the $D\pi$ threshold
- consistent w/ $D_0^\star(2300)$ of PDG
- BUT: symmetries ignored... :-(

What about the $D_0^\star(2300)$?

- Calculate the finite volume energy levels for $I = 1/2$ in unitarized cc approach

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

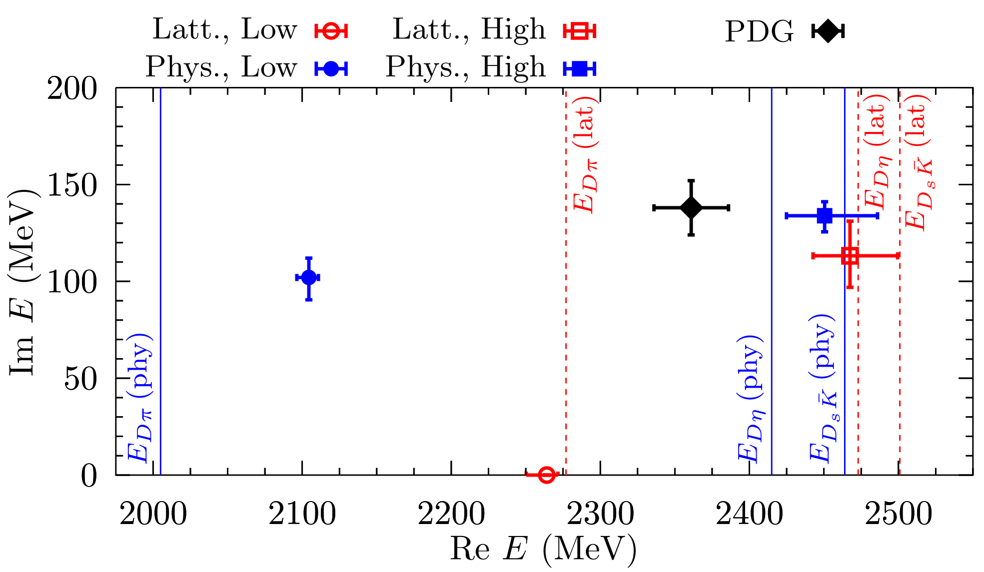


↪ this is NOT a fit!

↪ all LECs taken from the earlier study Liu, Orginos, Guo, Hanhart, UGM, PRD **87** (2013) 014508

What about the $D_0^\star(2300)$? – cont'd

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



- reveals a two-pole scenario! [cf. $\mathbf{\Lambda(1405)}$]
- 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 symmetries $\longrightarrow$ next slide
- Lattice QCD test: sextet pole becomes a b.s.

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

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

- FZJ LQCD finds a b.s. for $M_\pi = 600$ MeV

  Gregory et al., 2106.15391 [hep-ph]

- HadSpec finds a virtual state ($M_\pi = 700$ MeV)

  Yeo et al., JHEP **07** (2024) 012