Molecular structures in hadron & nuclear physics

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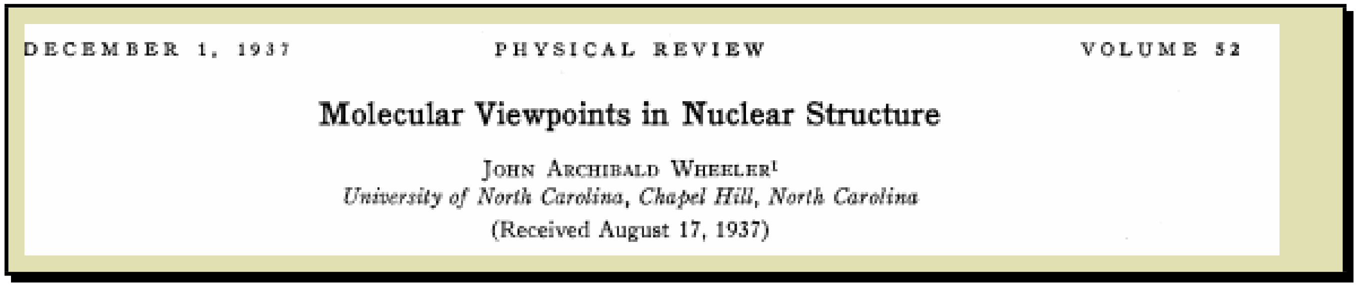
A bit of history

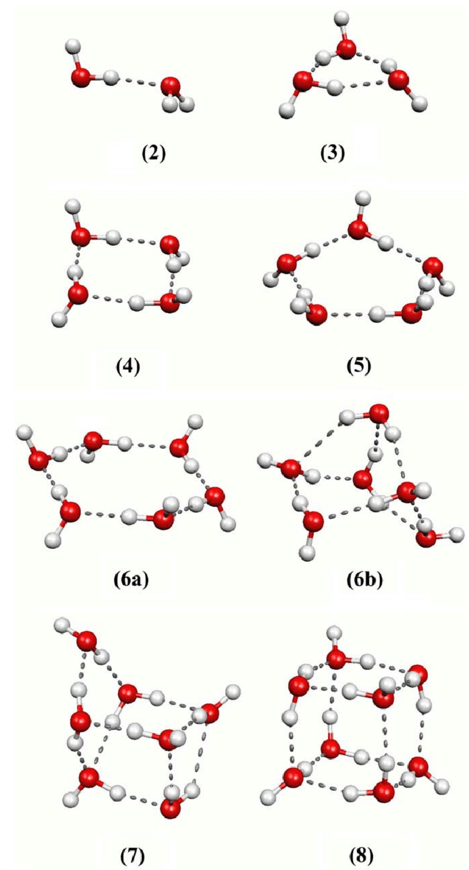
Molecular viewpoints in nuclear structure ?

- John Wheeler asked almost a century ago:


DECEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

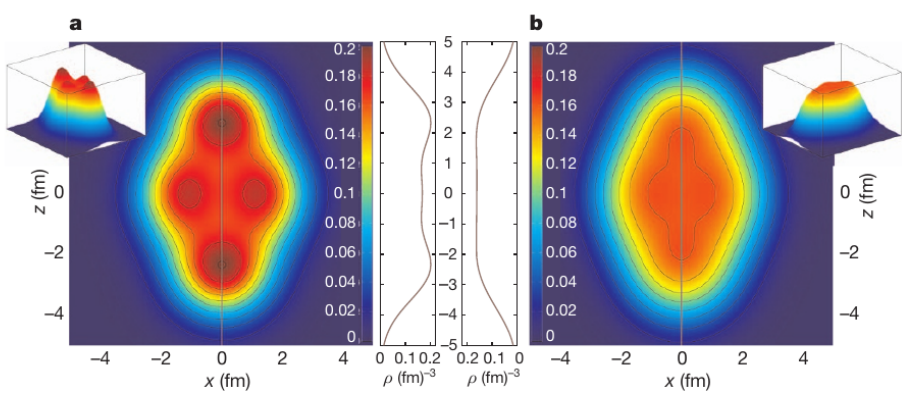
Molecular Viewpoints in Nuclear Structure

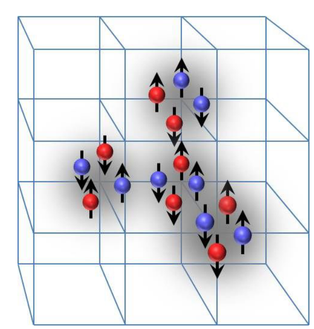
John Archibald Wheeler[1]
University of North Carolina, Chapel Hill, North Carolina
(Received August 17, 1937)



$\Rightarrow$ Birth of clustering in nuclei

$\Rightarrow$ A much studied phenomenon





Ebran, Khan, Niksic, Vretenar, Nature **487** (2012) 341
Epelbaum, Krebs, Lähde, Lee, UGM, Phys. Rev. Lett. **112** (2014) 102501
Freer, Horiuchi, Kanada-En'yo, Lee, UGM, Rev. Mod. Phys. **90** (2018) 035004

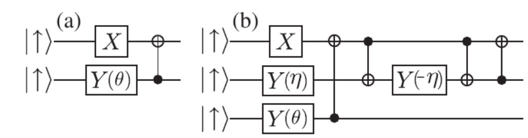
Molecular structures in hadron physics ?

- Are there hadronic states similar to the deuteron in nuclear physics?

$$H_N = \sum_{n,n'=0}^{N-1} \langle n'|(T+V)|n\rangle a^\dagger_{n'} a_n .$$

$$a^\dagger_n \to \frac{1}{2}\left[\prod_{j=0}^{n-1} -Z_j\right](X_n - iY_n),$$

$$a_n \to \frac{1}{2}\left[\prod_{j=0}^{n-1} -Z_j\right](X_n + iY_n).$$



$\hookrightarrow$ $\boldsymbol{B_d = 2.28(3)}$ MeV

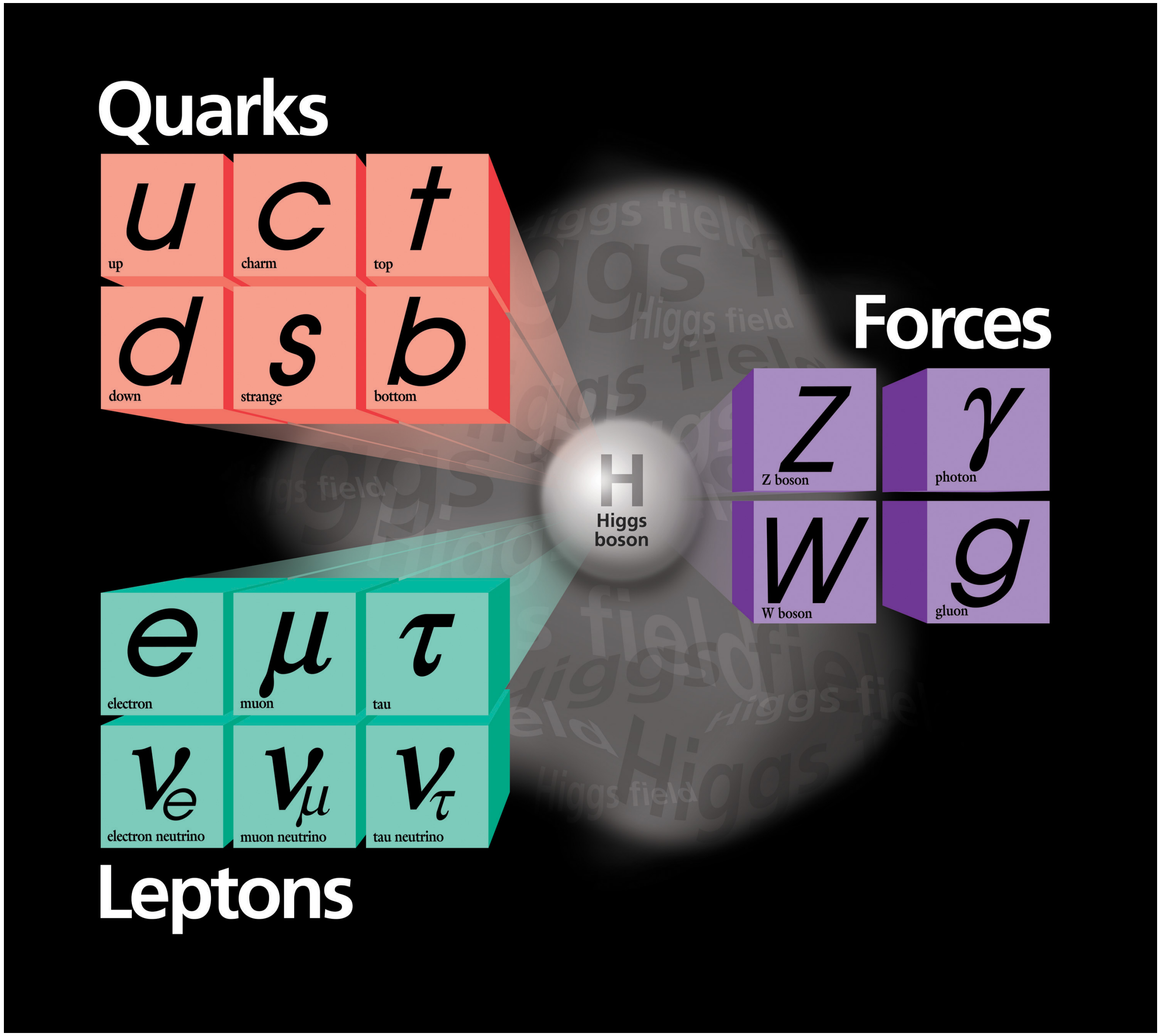
© Andy Sproles, ORNL

“Cloud quantum computing of an atomic nucleus”

Dumitrescu et al., Phys. Rev. Lett. **120** (2018) 210501

Mysteries of the strong interactions

The Standard Model

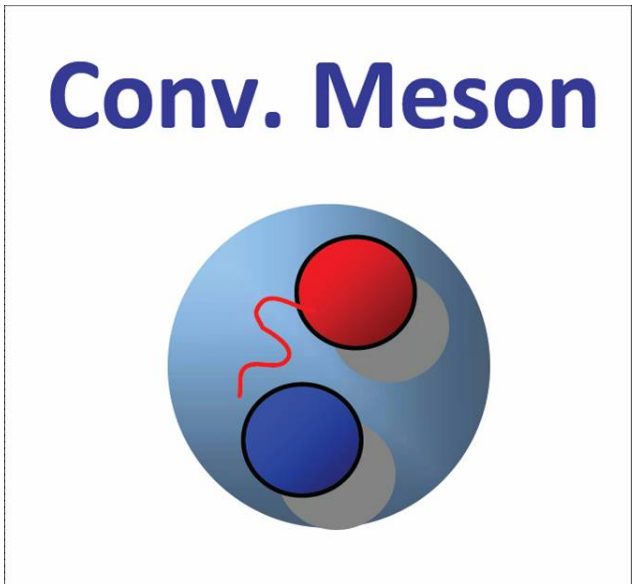


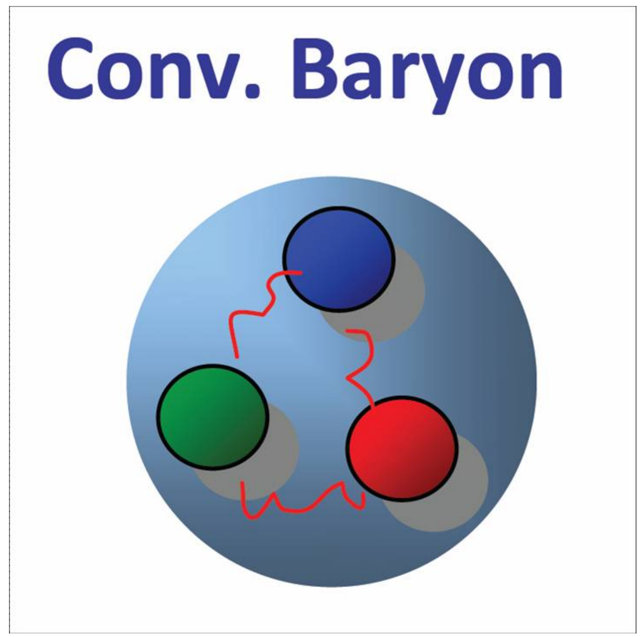
quarks make up the matter surrounding us

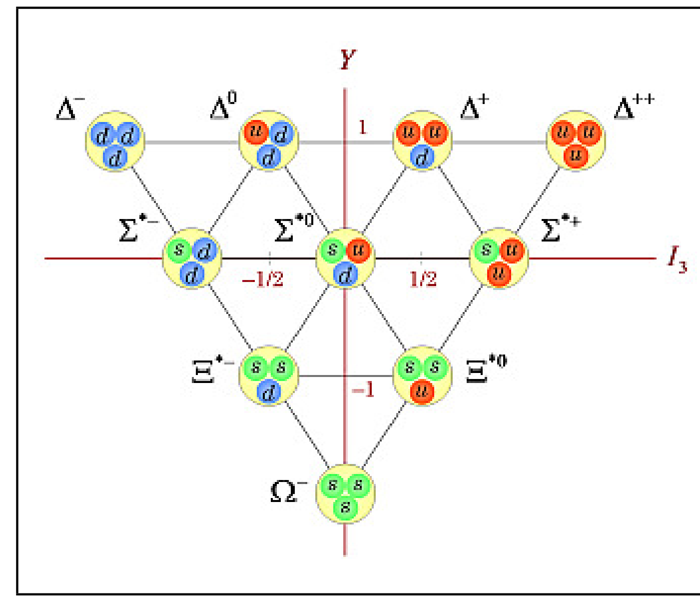
gluons mediate the forces between quarks

Conventional hadrons

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

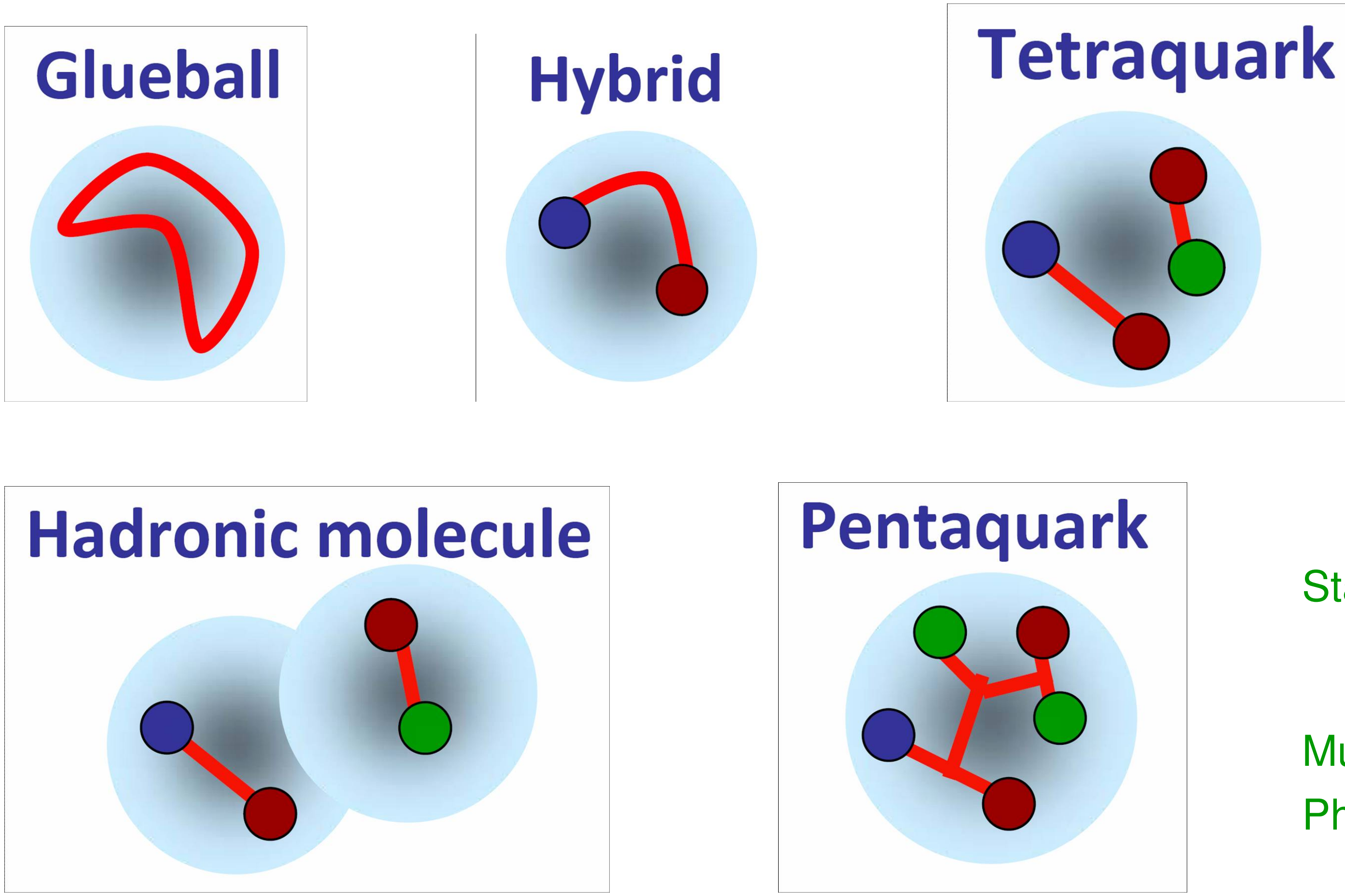






fairly successful picture – but why should it work?

Multi-faces of QCD: “Exotic” hadrons



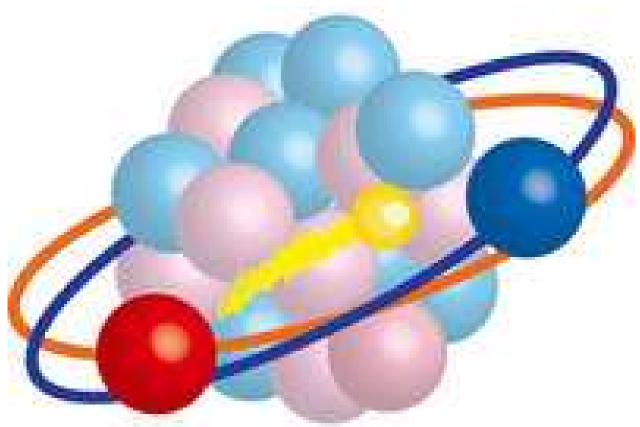
Exotic w.r.t. the quark model!

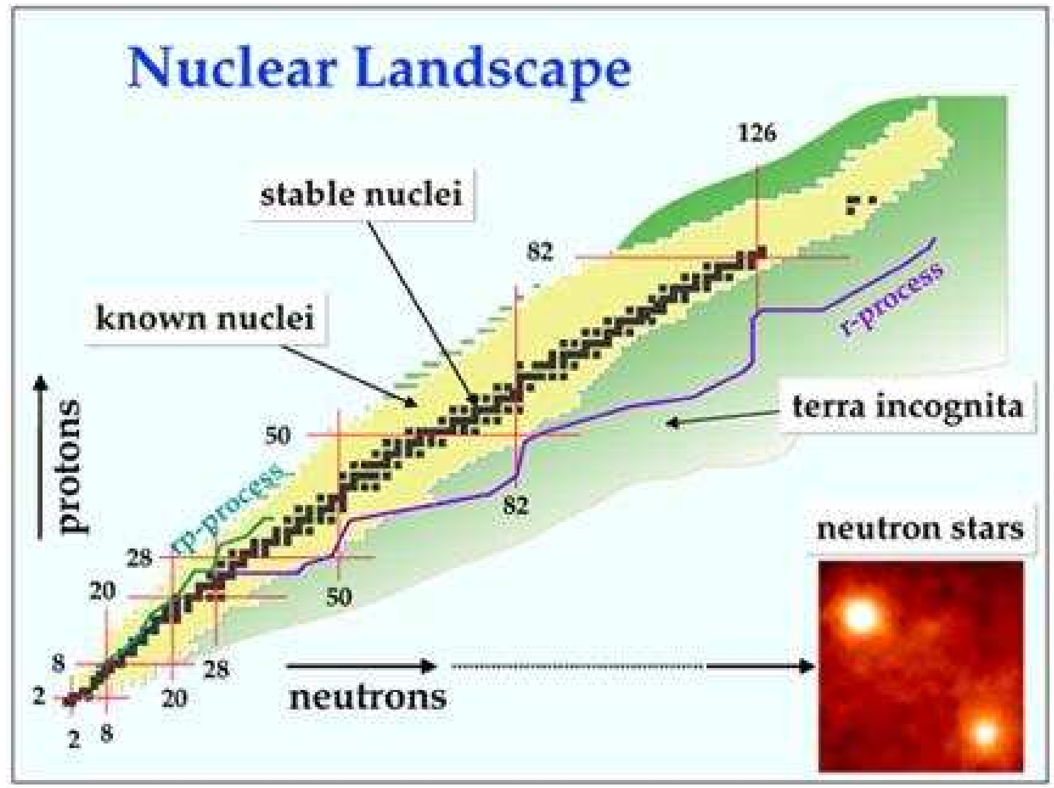
States with glue: QCD
$\to$ truely exotic!

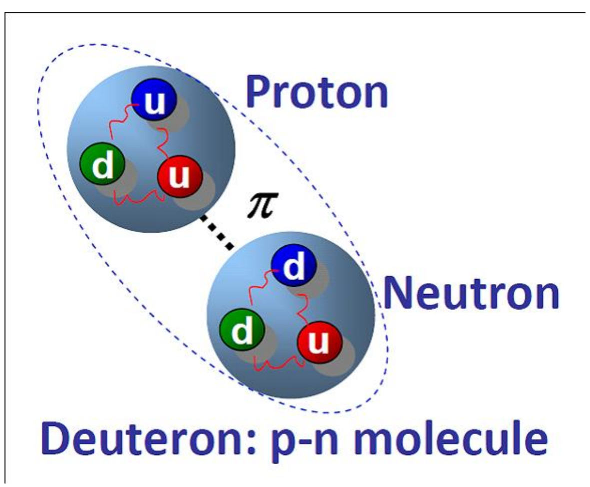
Multi-Quark states: Gell-Mann, Phys.Lett. **8** (1964) 214

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

Still more structure: Atomic nuclei

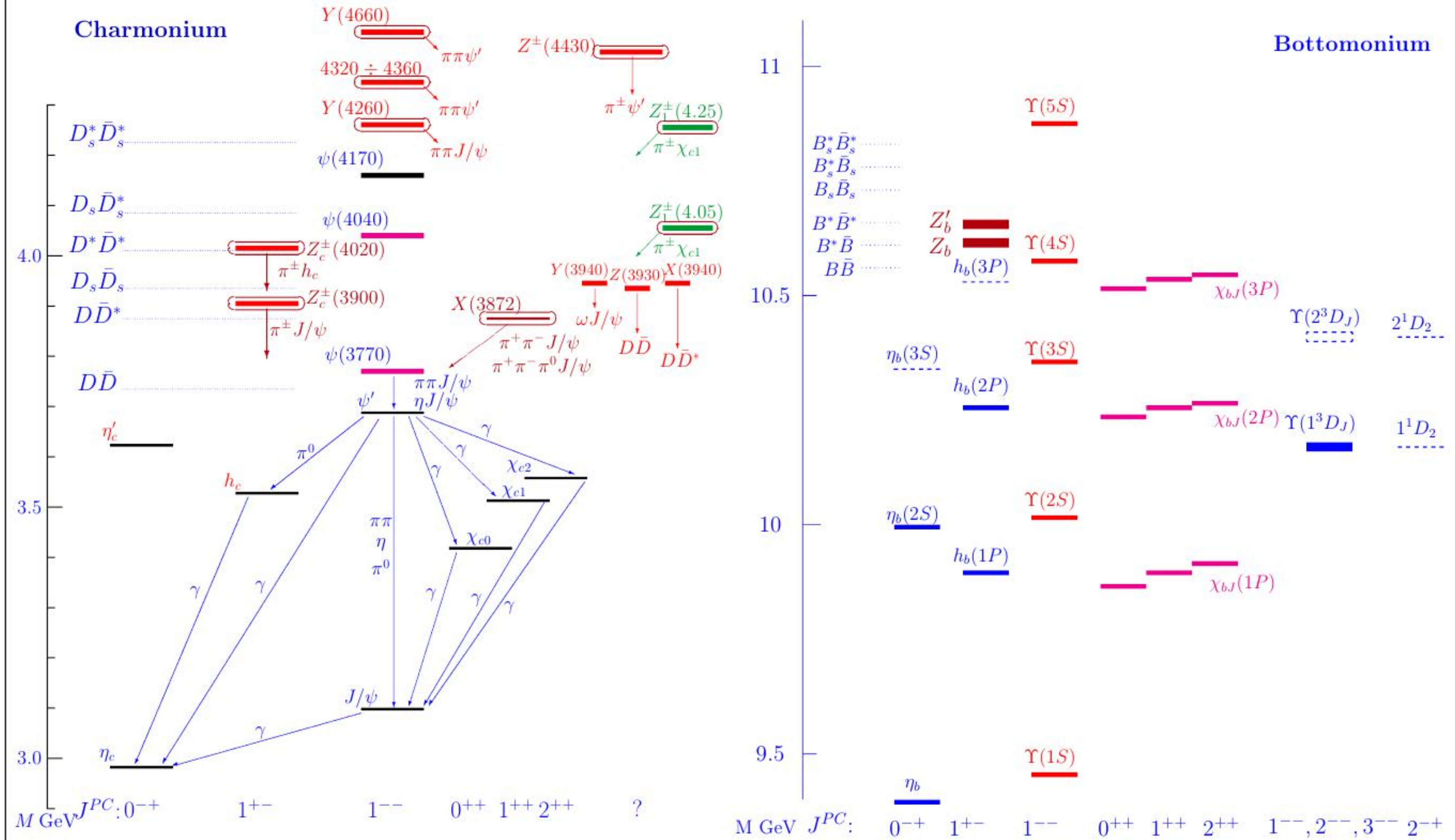






exploring the residual color force
→ ab initio calculations possible

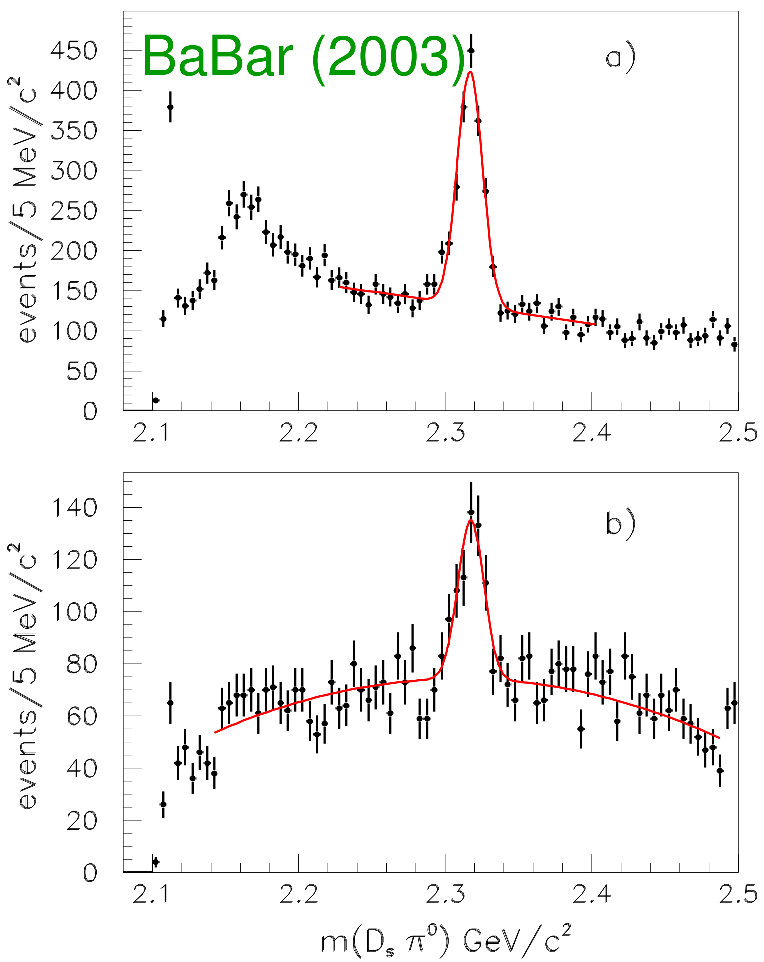
Mysteries in the quarkonium spectrum

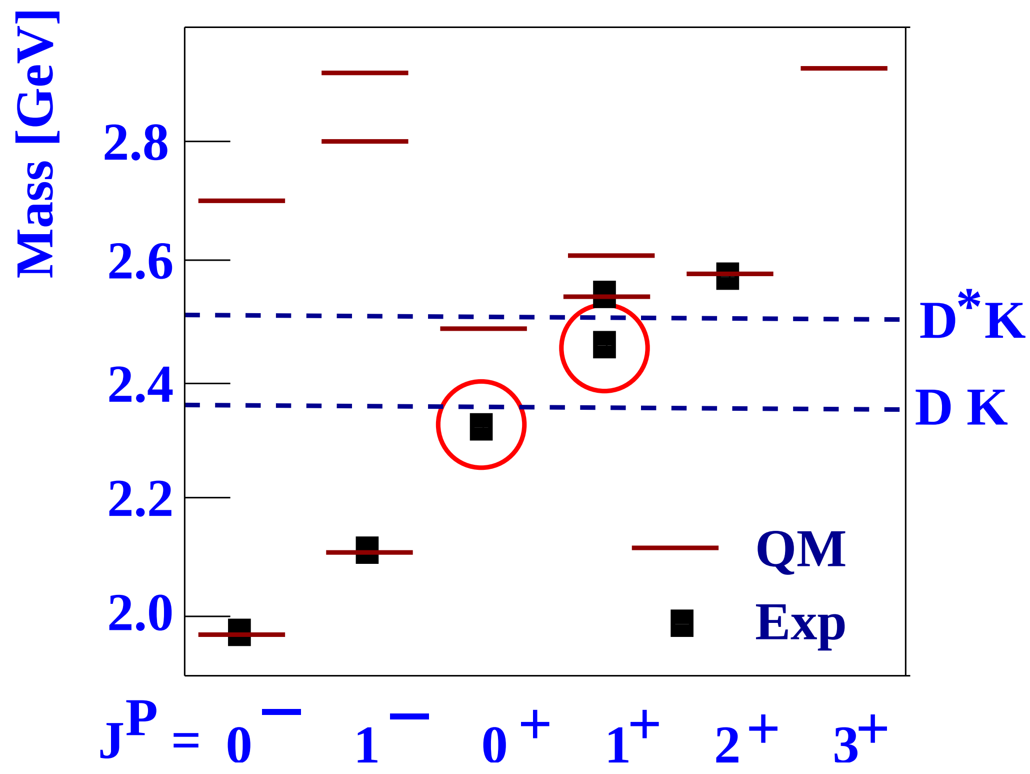


- many of these close to two-particle thresholds $\hookrightarrow$ hadronic molecules
- some are charged $\hookrightarrow$ these must be exotic (at least four quarks)

More mysteries: Charm-strange mesons

- observed 2003 by BaBar & CLEO, isospin-violating strong decays
- mass much lower than in quark models, just below the KD/KD^* threshold





⇒ moleculare nature?
⇒ yes, but no time...

Salient features of QCD

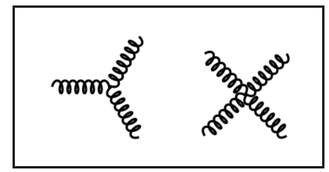
QCD Lagrangian

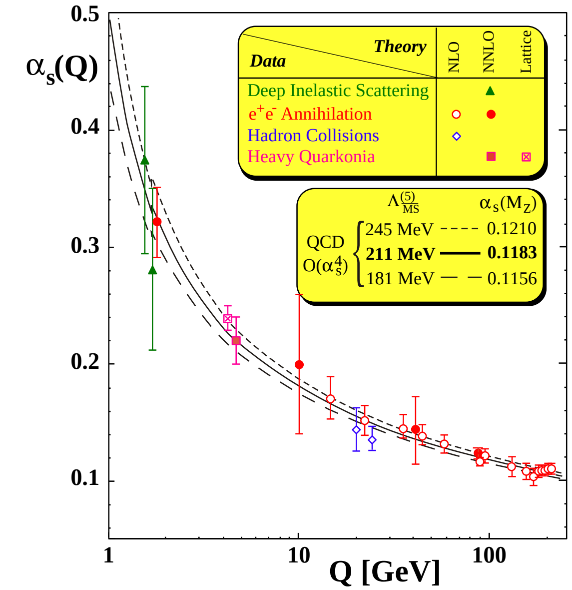
- $$\mathcal{L}_{\rm QCD} = -\frac{1}{4}\, G^a_{\mu\nu} G^{\mu\nu,a} + \sum_f \bar{q}_f (i\not{D} - \mathcal{M}) q_f + \ldots$$

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

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

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





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

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

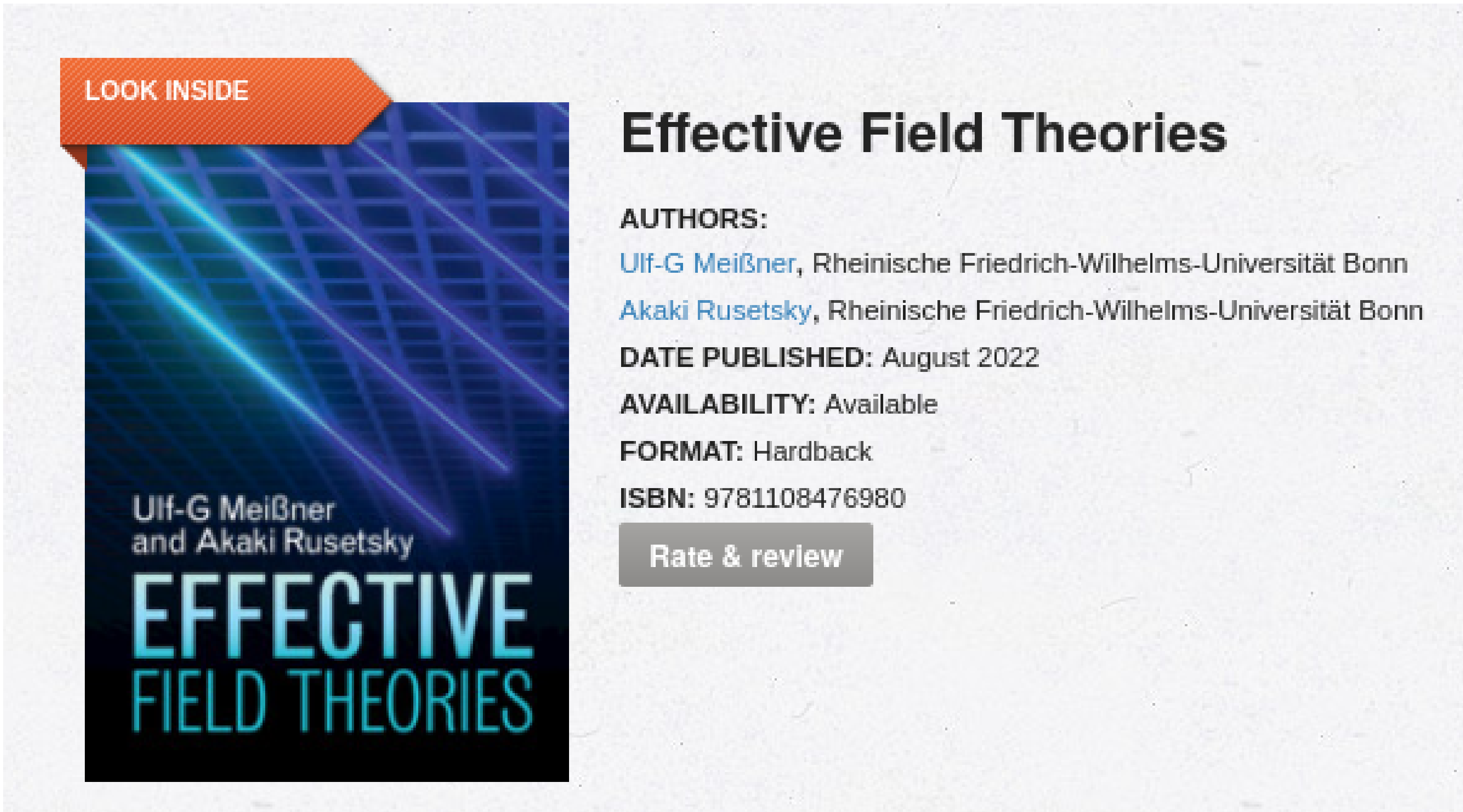
$m_{\rm light} \ll \Lambda_{\rm QCD}$	$m_{\rm heavy} \gg \Lambda_{\rm QCD}$
$m_u = 2.2^{+0.6}_{-0.4}$ MeV	$m_c = 1.28 \pm 0.03$ GeV
$m_d = 4.7^{+0.5}_{-0.4}$ MeV	$m_b = 4.18^{+0.04}_{-0.03}$ GeV
$m_s = 96^{+8}_{-4}$ MeV	$m_t = 173.1 \pm 0.6$ GeV

Limits of QCD

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



https://www.cambridge.org/de/academic/subjects/physics/theoretical-physics-and-mathematical-physics/effective-field-theories

Theory 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

- the classical example:

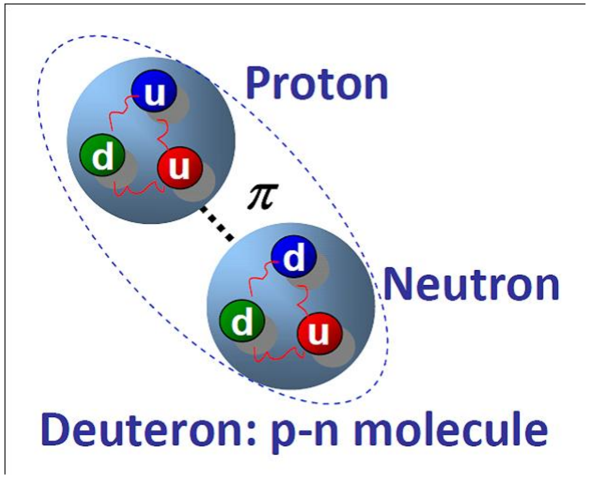
  $\star$ the deuteron

  $m_p + m_n = 938.27 + 939.57$ 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 ?

Reminder of scattering theory

- Consider non-relativistic (NR) $2 \to 2$ scattering at energy E [$\hbar = c = 1$]:

$$T_{\rm NR}(E) = -\frac{2\pi}{\mu}\frac{1}{k\cot\delta(k) - ik}\,, \quad k = \sqrt{2\mu E}\,, \quad \mu = \frac{m_1 m_2}{m_1 + m_2}$$

with $\delta(k)$ = scattering phase shift

k = two-hadron relative momentum

μ = reduced mass of the two-hadron system

- Effective range expansion (ERE):

$$k\cot\delta(k) = \frac{1}{a} + \frac{1}{2}rk^2 + \mathcal{O}(k^4)$$

with a = scattering length

r = effective range

} fundamental paramaters of low-energy scattering

Compositeness criterion

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

- 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:

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

$$\gamma = \sqrt{2\mu B}$$

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

μ = reduced mass of the two-particle system, $1/\beta$ = 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 (1965)

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

$$B_d = 2.225\,\text{MeV} \to \gamma = 45.7\,\text{MeV} \;= 0.23\,\text{fm}^{-1}$$

- 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:

$$a_{\rm mol} = -(4.3 \pm 1.4)\,\text{fm}\;, \quad r_{\rm mol} = \mathcal{O}(1.4\,\text{fm})$$

- this is consistent with the data in the $^3S_1$ channel:

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

> 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

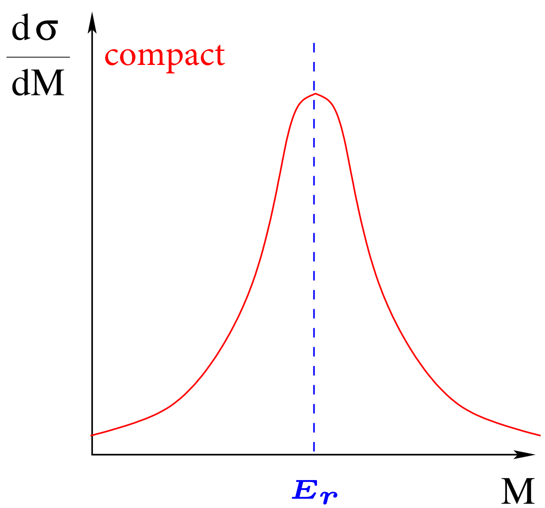
Baru et al. (2003), Braaten, Lu (2007), Aceti, Oset (2012), Guo, Oller (2016), . . .

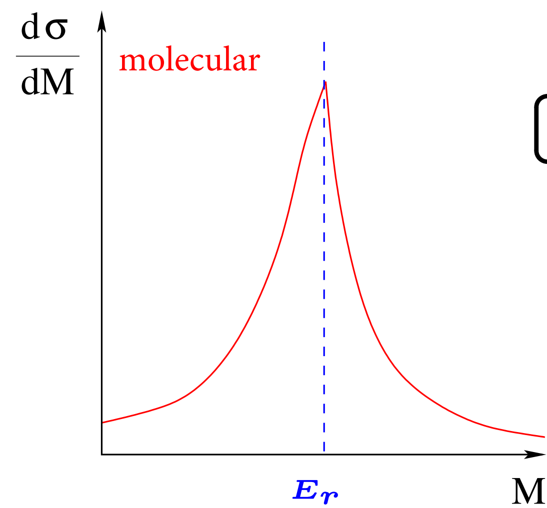
- Still assume closeness to a two-particle threshold:

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

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:





$M = m_1 + m_2 + E$

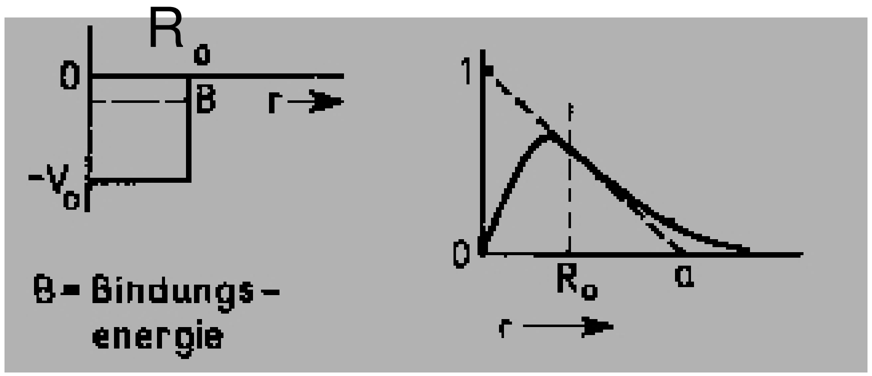
k^2 term dominates $\rightarrow$ symmetric

g^2 term dominates $\rightarrow$ asymmetric/cusp

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

Universality

Braaten, Hammer, Phys. Rept. **428** (2006) 259, . . .



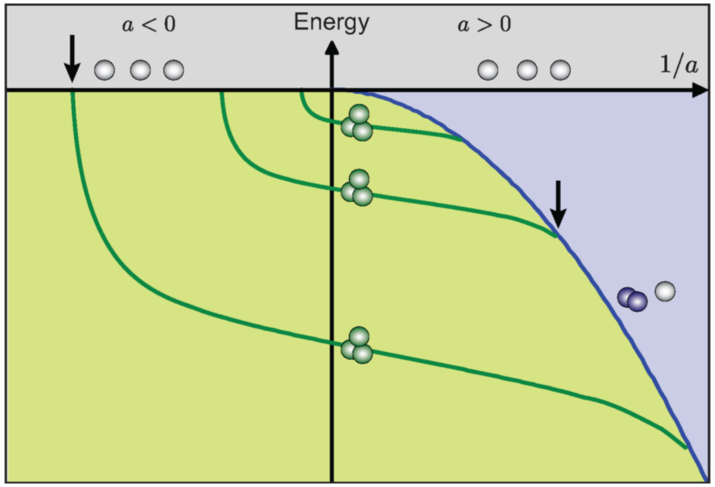
• Consider systems with the two-particle scattering length much, much bigger than the range of forces: $a \gg R_0 = 1/\beta$

⇒ physics is independent of the overall energy scale. Predictions:

⋆ Two-body binding energy: $B_2 = \dfrac{1}{\mu\, a^2}$

applies for energy scales from neV (cold atoms) to GeV (charmonium, bottomonium)

Deuteron: $B_2 = 1.86$ MeV (range corrections)



⋆ Three-body systems: Efimov effect

Efimov, Phys. Lett. B **33** (1970) 563

↪ another talk

Candidates for hadronic molecules

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:

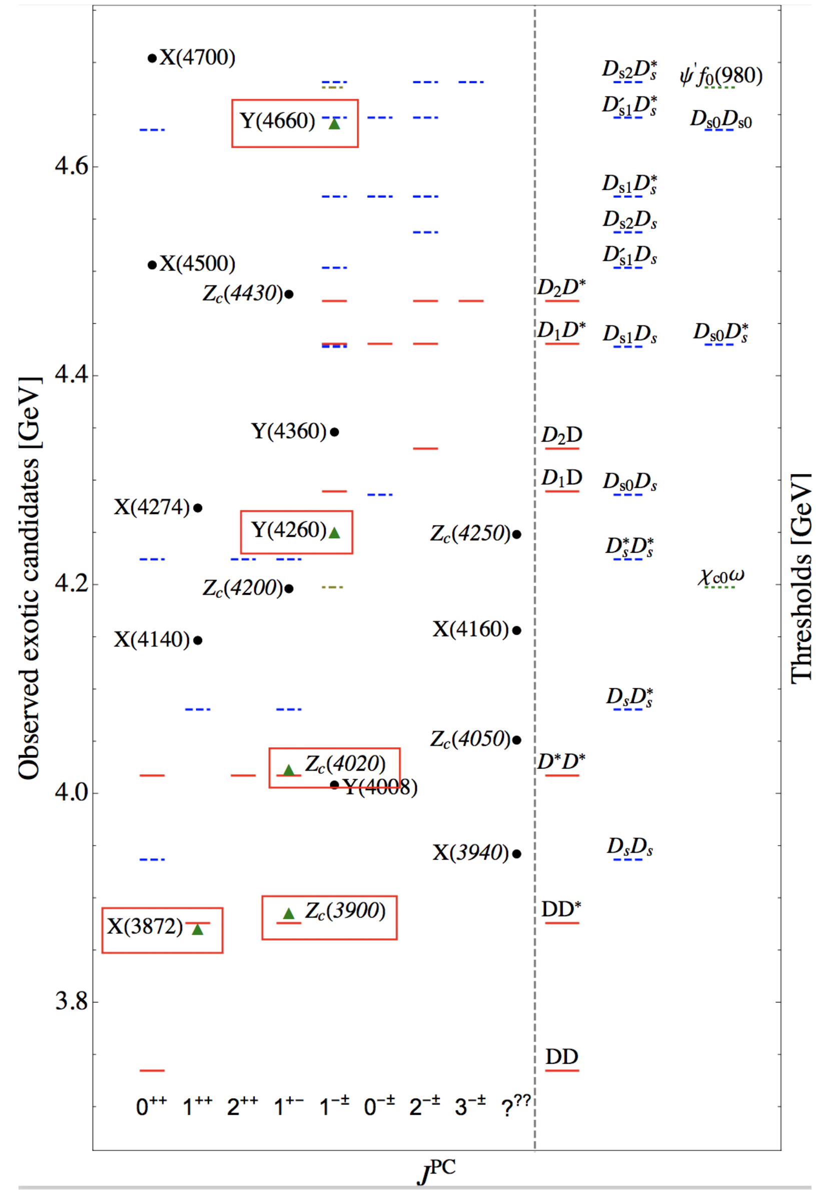
  $D^\star_{s0}(2317)$, $D_{s1}(2460)$, $D^\star_{s1}(2860)$, ...

- 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

Phenomenology of hadronic molecules

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 $\gamma = \sqrt{2\mu B} \ll \beta$ [$1/\beta$ = 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 $\mathcal{O}(\gamma)$

    - **short-distance processes**, which involve particles with a momentum $\gtrsim \beta$ in the c.m. frame of $h_1 h_2$

$\Rightarrow$ 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: $B_X = 0.07 \pm 0.12$ MeV

$\to$ tremendously large scattering length

$\to$ universality

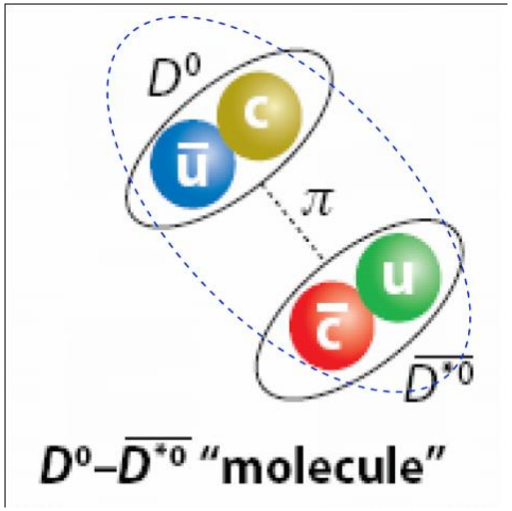
- maximal isospin violation:

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

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

- a prime candidate for a hadronic molecule:

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



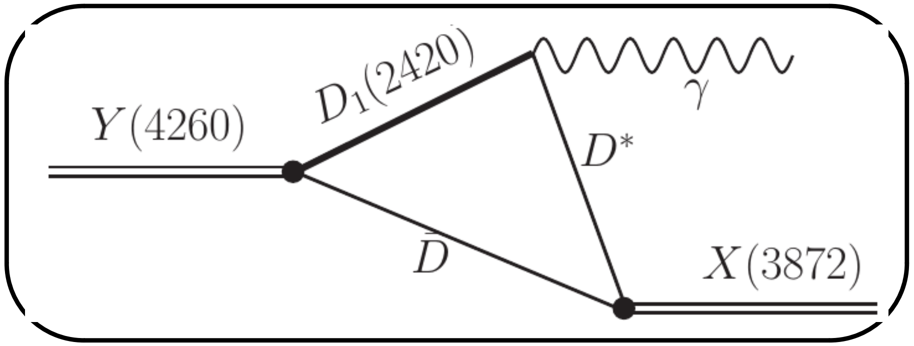
Voloshin, Okun (1976)

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

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

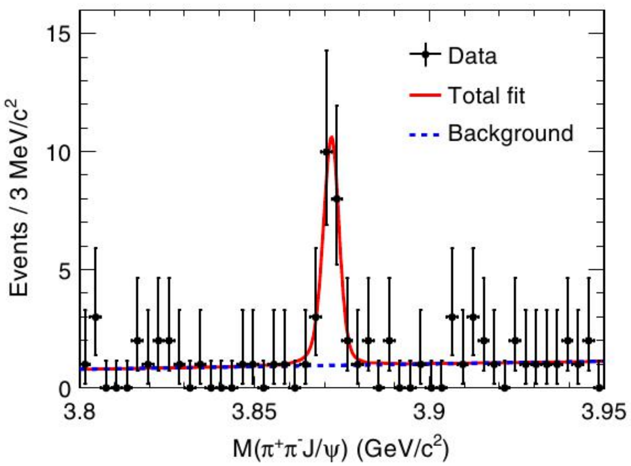
- Prediction of a long-distance process:

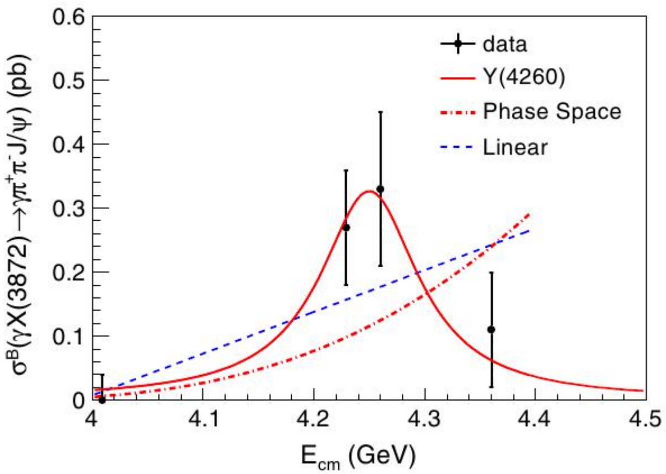
  If the X(3872) is a $D\bar{D}^\star$ molecule and the Y(4260) is a $D\bar{D}_1$ molecule, there will be a strong radiative transition $Y(4260) \to X(3872)\gamma$ in e^+e^- collisions



- Data from BESIII

PRL 112 (2014) 092001





⋆ Clear evidence of the X(3872)

⋆ Data hint that it proceeds through a Y state → 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

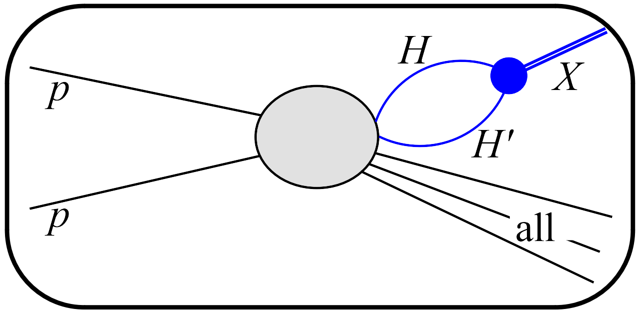
↪ still, factorization is at work, best seen using EFT

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

↪ consider production at the Tevatron and at LHC

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

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



- 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!

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

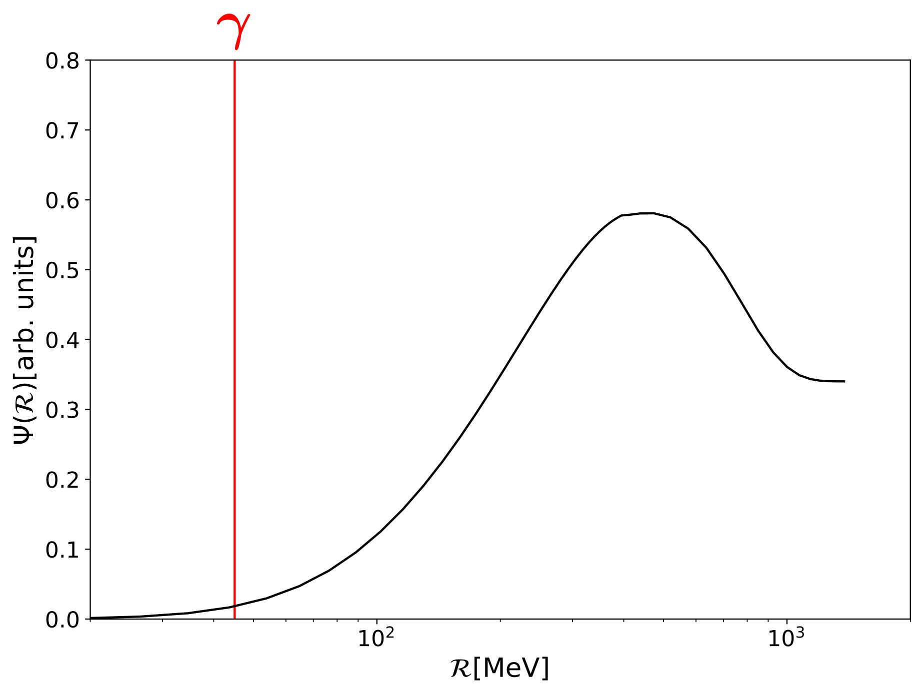
$\hookrightarrow$ the X(3872) can not be a molecule

$\hookrightarrow$ so what goes wrong?

Misconceptions on hadroproduction continued

- Consider the relevant integral for the deuteron: $\bar{\Psi}_{\lambda}(\mathcal{R}) \equiv \int_{\mathcal{R}} d^3\mathbf{k}\, \Psi_{\lambda}(\mathbf{k})$

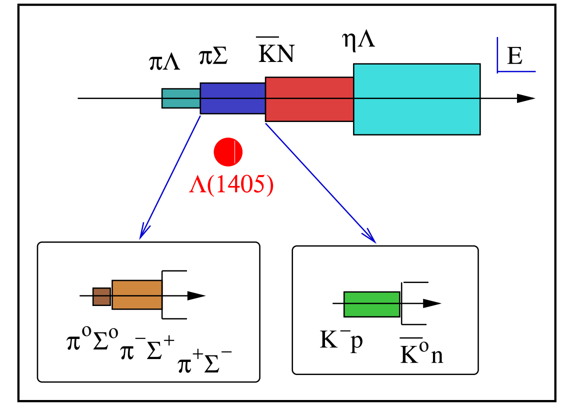
- The binding momentum is $\gamma \simeq 45$ MeV, use that for the support $\mathcal{R}$:



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

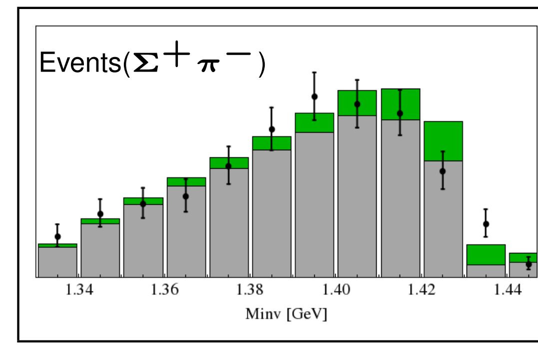
A short tale of the two Λ(1405) states

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



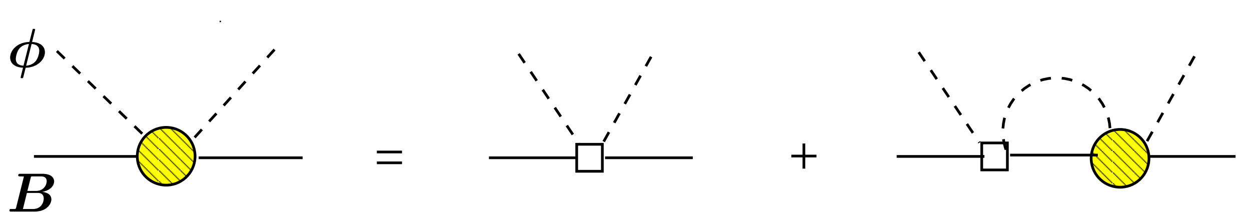
- Quark model: uds excitation with $J^P = \frac{1}{2}^-$ CLAS (2014)
  a few hundred MeV above the $\Lambda(1116)$
  $m = 1405.1^{+1.3}_{-1.0}\,\text{MeV}\,,\ \Gamma = 50.5 \pm 2.0\,\text{MeV}$ [PDG 2015]

- 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, ...

The two-pole scenario

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

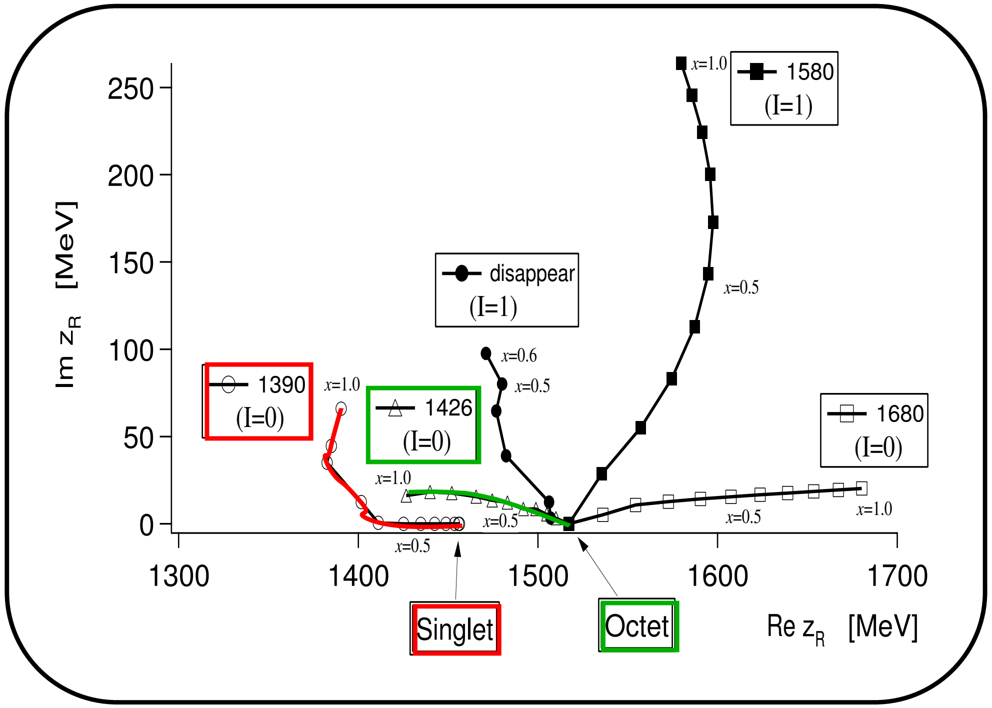
  Oller, UGM, Phys. Lett. B **500** (2001) 263

- 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:

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



- Verified by various groups world-wide

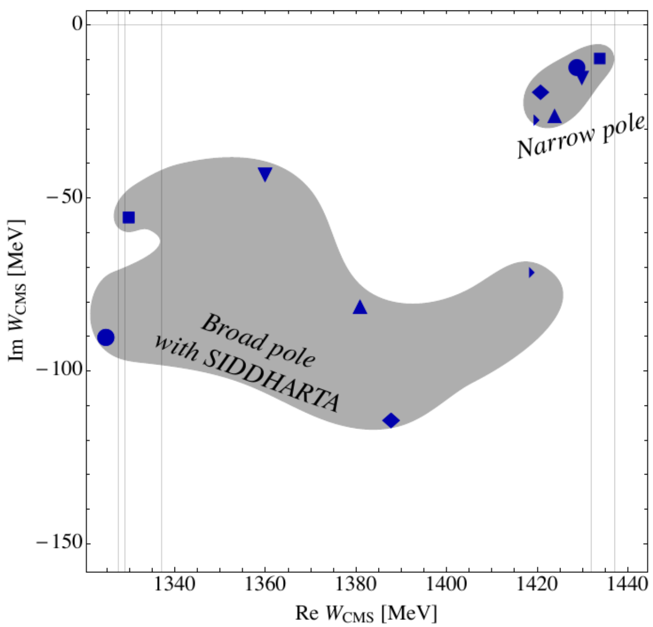
- However: scattering and kaonic atom data alone do not lead to a unique solution (two poles, but spread in the complex plane)

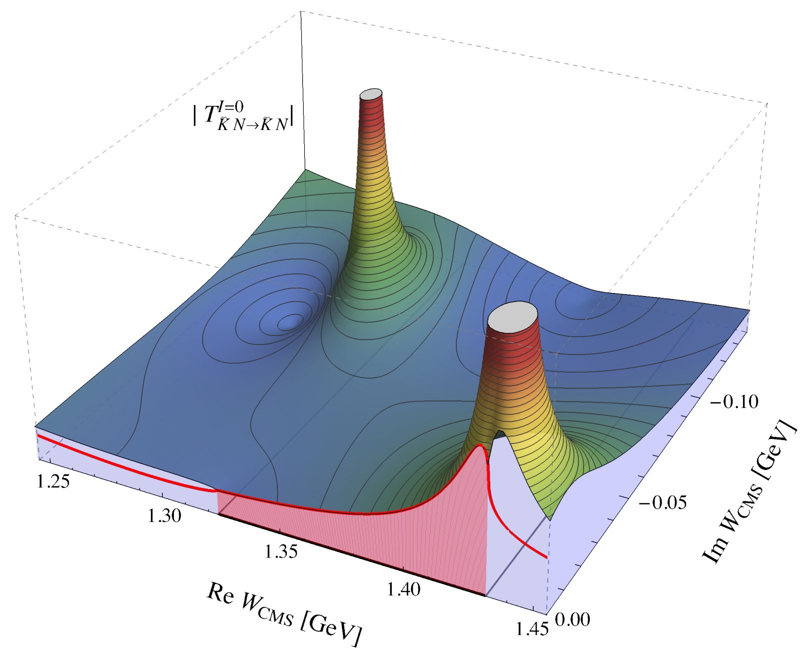
- Photoproduction to the rescue: $\gamma p \to K^+ \Sigma \pi$ CLAS, Phys. Rev. C **87**, 035206 (2013)

Present status of the two-pole scenario

- Two poles from scattering plus CLAS 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 $\mathbf{\Lambda(1405)}$ REGION
Written 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
- for a review, see UGM, *Symmetry* **12** (2020) 981

Summary and outlook

- Hadronic molecules are a particular manifestation of non-conventional states

  $\hookrightarrow$ they appear in nuclear and hadronic physics (also 3-body states)

- Closeness to two-particle thresholds allows to formulate suitable NREFTs

  $\hookrightarrow$ systematic access to production, decay and other processes

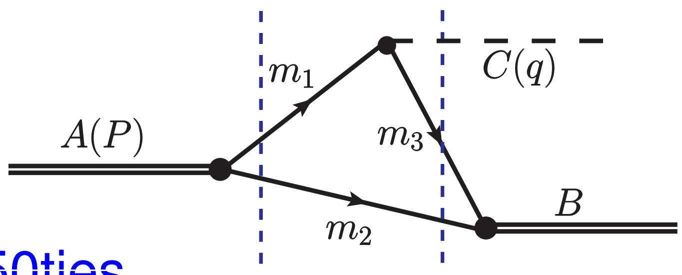
- Must differentiate between long-distance and short-distance processes

  $\hookrightarrow$ can lead to misconceptions about the dynamcis of such states

$\Longrightarrow$ More than 60 years after Weinberg's groundbreaking work on the compositeness of the deuteron, we are now in the position to identity and understand many more of such loosely bound states through an interplay of experiment, theory and lattice simulations. This leads to 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

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

$\to$ 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

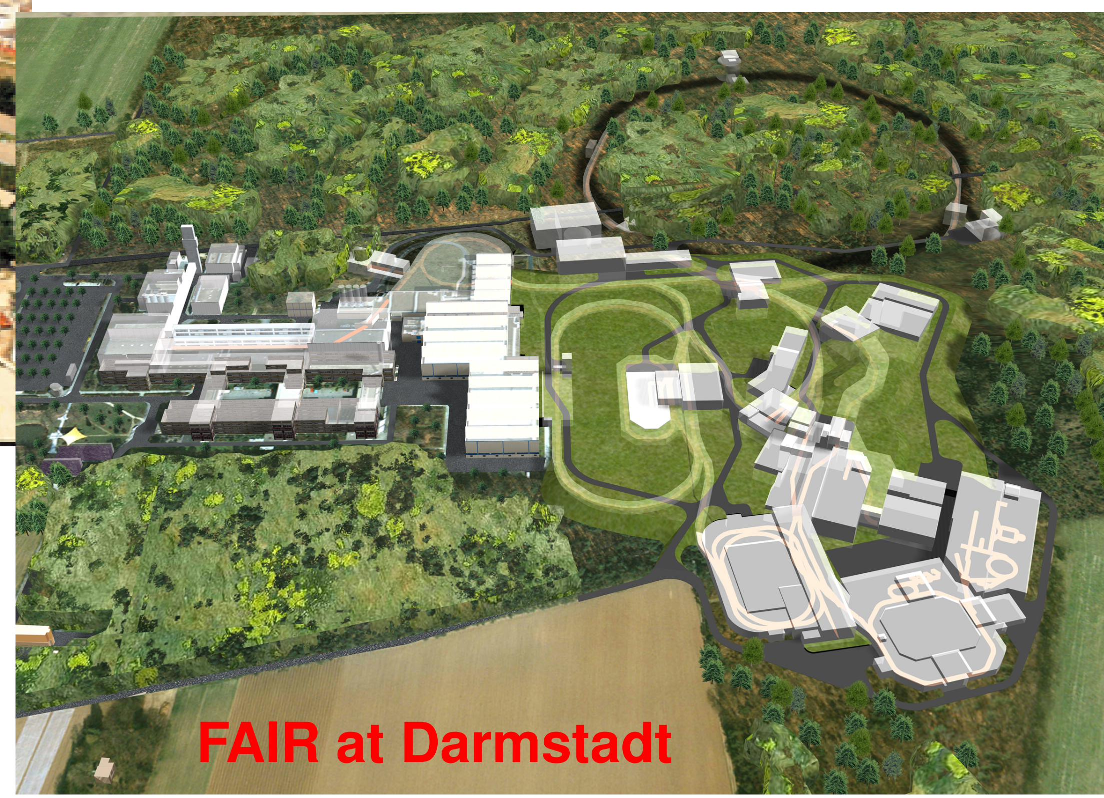
  Fleming et al. (2007), Braaten, Hammer, Mehen (2010), Mehen, Powell (2011), ...

Prospects and summary

HADRON PHYSICS COMPLEXES

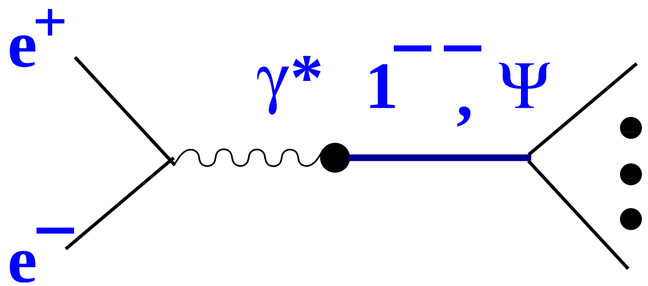
- present and future HPC = Hadron Physics Complexes → BEPC-II, FAIR

  (the contenders: B-factories and colliders)



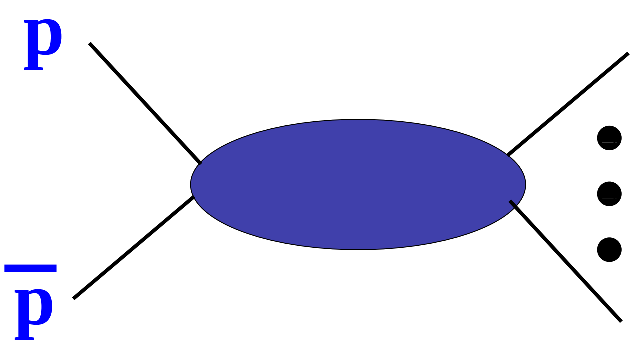
COMPLEMENTARITY

- BEPC-II e^+e^- collisions to generate numerous $J/\psi, \psi', \ldots$ particles



- relatively low luminosity
- clean background
- final states from J/ψ resonance decay

- FAIR fixed target $\bar{p}$ on p collisions



- high luminosity
- complicated background
- access to most quantum numbers directly

MEASURING LINE SHAPES

- Measuring line shapes $\to$ resolution defined by the beam momentum, not by the detector!

- Example: observation of the χ_{c1} state

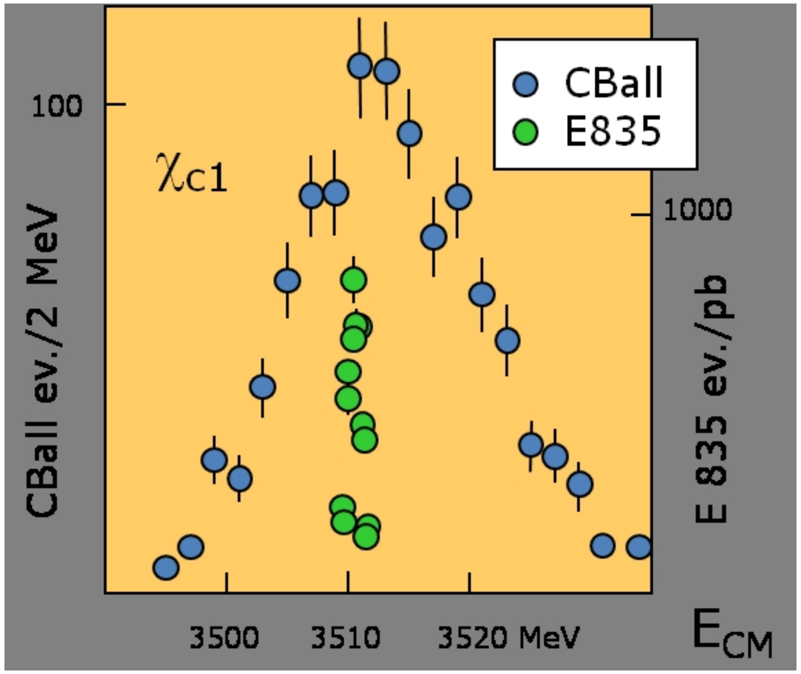
- $M(\chi_{c1}) = 3610$ MeV, $J^{PC} = 1^{++}$

e^+e^- annihilation:

$$e^+e^- \to \psi' \to \boxed{\gamma\chi_{c1}} \to \gamma\gamma J/\psi \to \gamma\gamma e^+e^-$$

$\bar{p}p$ annihilation:

$$\bar{p}p \to \boxed{\chi_{c1}} \to \gamma J/\psi \to \gamma e^+e^-$$



$\to$ eagerly waiting for PANDA at HESR

FACETS of STRONG QCD

- running coupling constant $\alpha_S(Q^2)$ in QCD

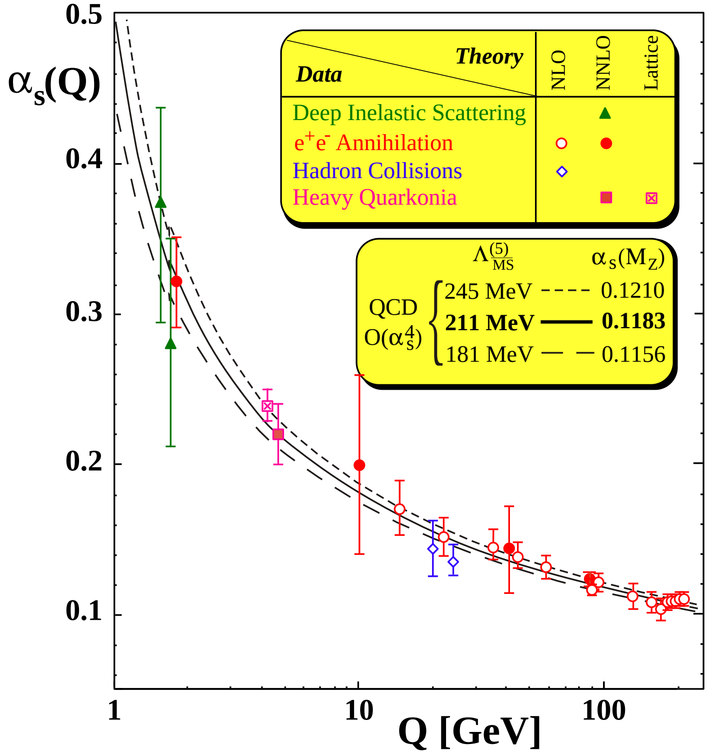
  $\Rightarrow$ two regimes: strong & perturbative

- quarks and gluons form hadrons

  $\Rightarrow$ exploring the strong color force

  $\Rightarrow$ which kind of states are formed?

  $\Rightarrow$ how are these states formed?



What are HADRONIC MOLECULES ?

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

- weak binding entails a large spatial extension

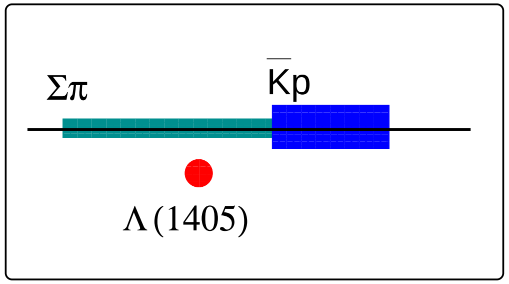
- classical examples:

$\star$ the deuteron $\quad m_p + m_n = 938.27 + 939.57$ MeV, $\varepsilon = 2.22$ MeV

$\star$ the $\Lambda(1405)$ Dalitz et al., (1960)

$$m_\Sigma + m_\pi = 1189.37 + 139.57 = 1328.94\,\text{MeV}$$

$$m_p + m_{\bar K} = 938.27 + 493.68 = 1431.96\,\text{MeV}$$



$\star$ the scalar mesons $f_0(980), \ldots$

$m_K + m_{\bar K} = 2 \times 493.68 = 987.35\,\text{MeV},\ m(f_0) = 976.8$ MeV [KLOE 2007]

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

NATURE of the $D_{s1}(2460)$

- Nature of the $D_{s1}(2460)$: $M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \simeq M_{D^*} - M_D$

$\Rightarrow$ most likely a $D^\star K$ molecule (if the $D^\star_{s0}(2317)$ is DK)

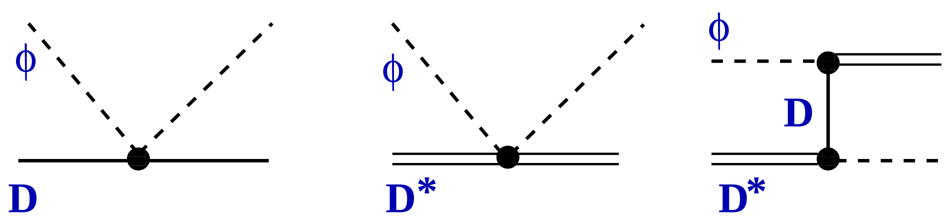
$\Rightarrow$ study Goldstone boson scattering off D- and $D^\star$-mesons

- Use heavy meson chiral perturbation theory   Wise, Falk et al., Casalbuoni et al., ...

$$H_v = \frac{1+\not{v}}{2}\left[\not{V}^*_v + iP_v\gamma_5\right]$$

$$P = (D^0, D^+, D^+_s)\,, \quad V^*_\mu = (D^{*0}_\mu, D^{*+}_\mu, D^{*+}_{s,\mu})$$

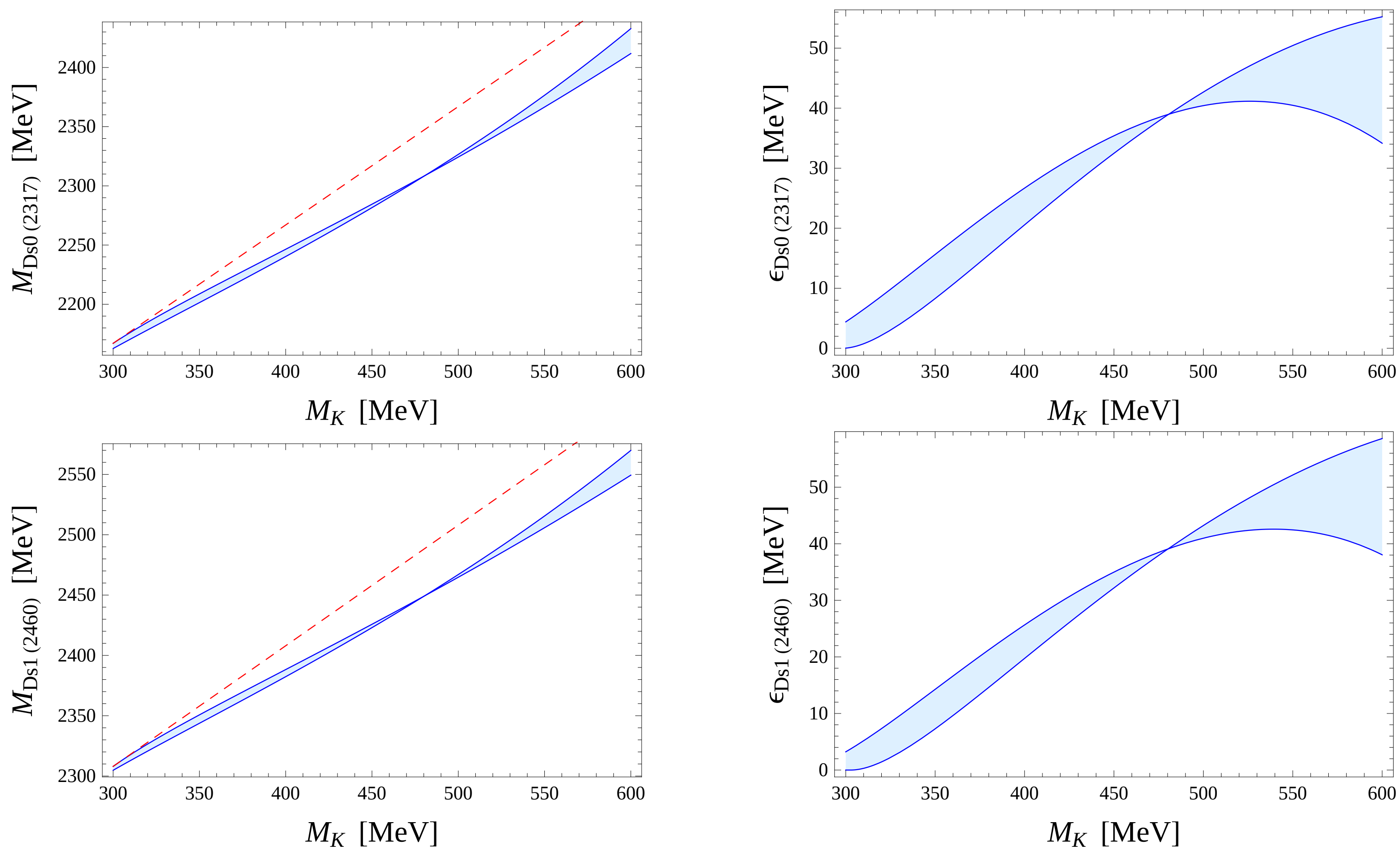
- T-matrix:



- Unitarization (as before) $\rightarrow$ find poles in the complex plane

KAON MASS DEPENDENCE

- Mass and binding energy: $M_{\rm mol} = M_K + M_H - \epsilon$



$\Rightarrow$ typical for a molecule $\rightarrow$ test in LQCD

COMPOSITENESS CRITERION

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

- 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. $\chi(\vec{k})$

- Calculate the hadron-hadron scattering amplitude with:

$$\mathcal{H}|\Psi\rangle = E|\Psi\rangle \ , \qquad \mathcal{H} = \begin{pmatrix} \mathcal{H}_c & \mathcal{V} \\ \mathcal{V} & \mathcal{H}_0^{hh} \end{pmatrix}$$