Towards a New Paradigm in Hadron Spectroscopy

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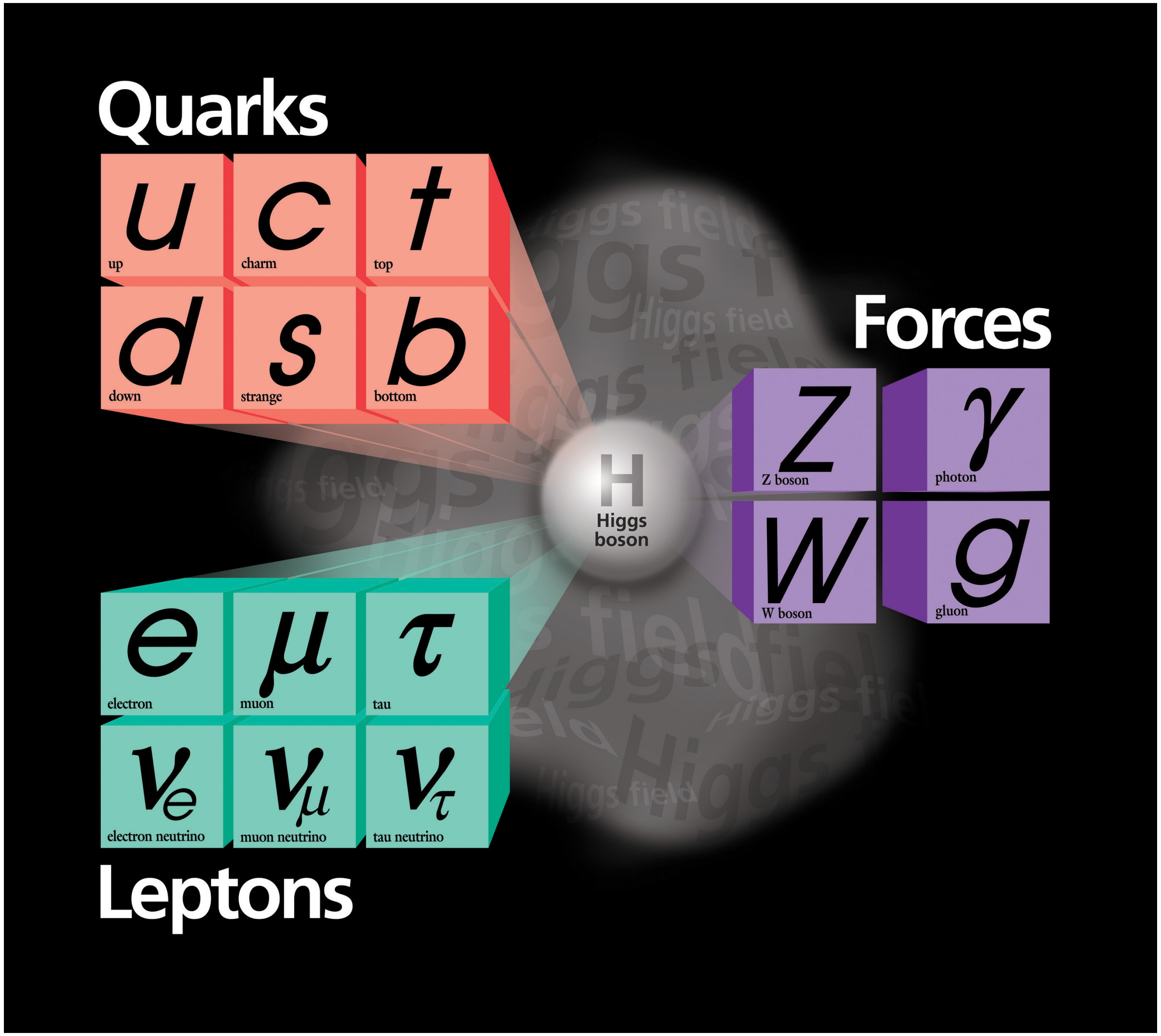
Mysteries of the strong interactions

THE STANDARD MODEL

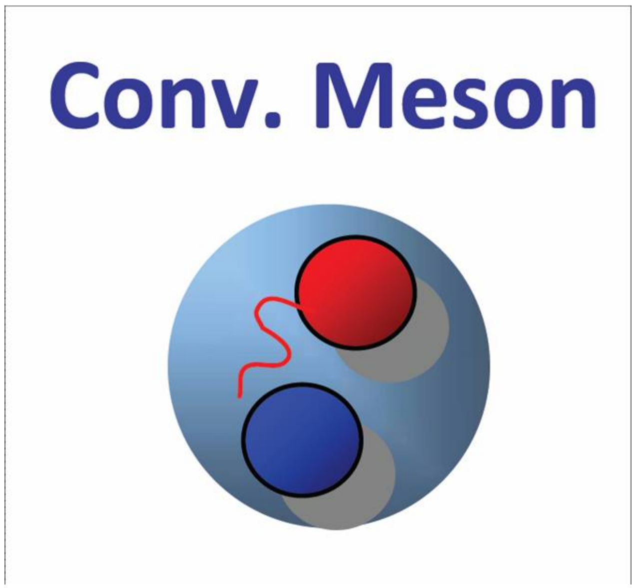


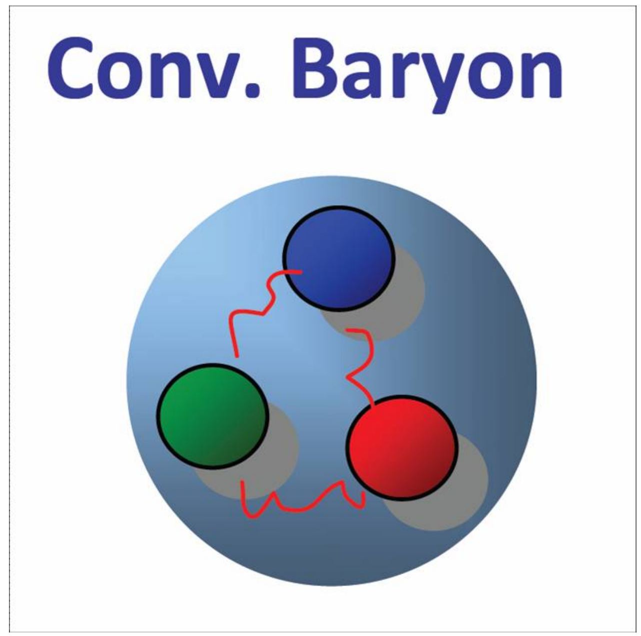
quarks make up the matter surrounding us

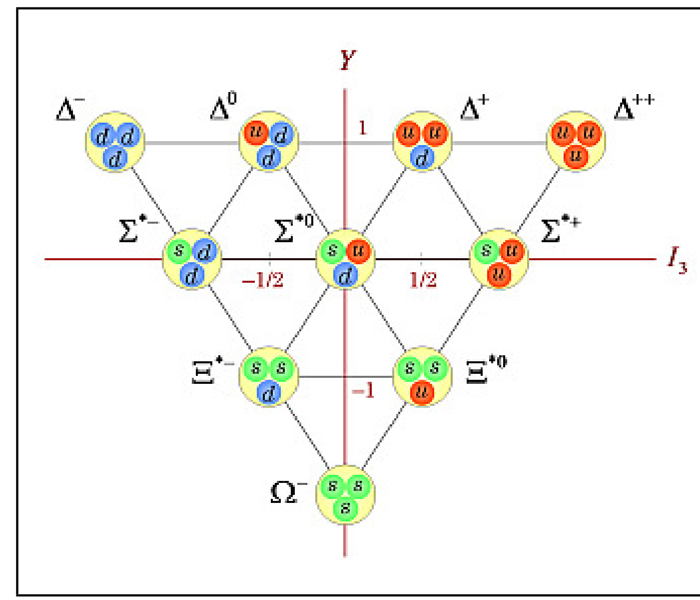
gluons mediate the forces between quarks

CONVENTIONAL HADRONS

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

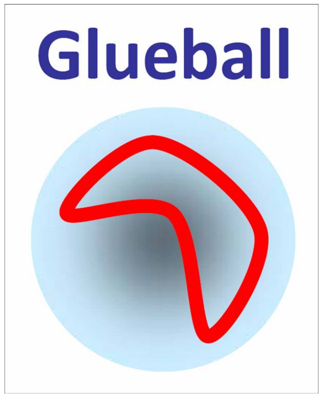


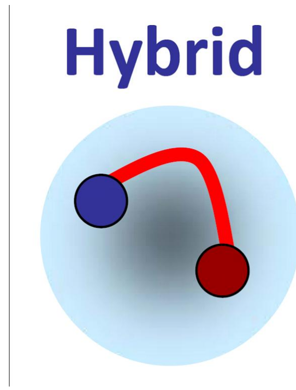


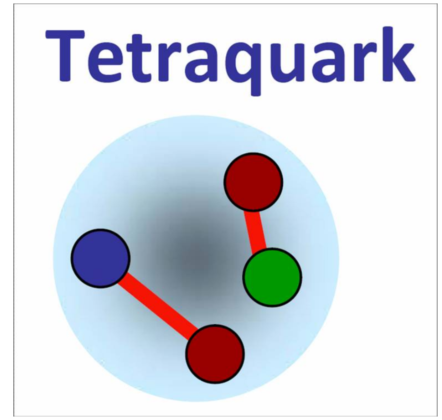


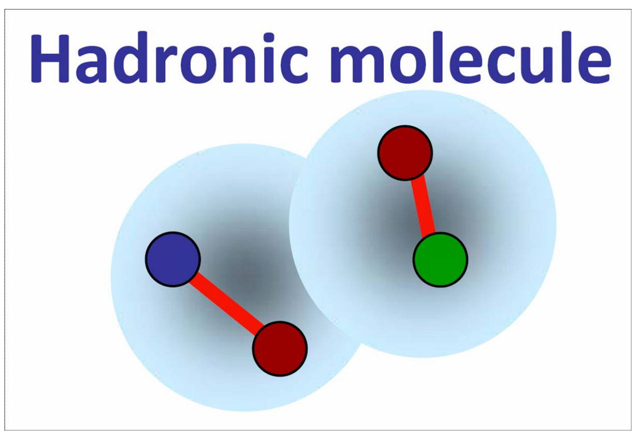
highly successfull picture – but why should it work?

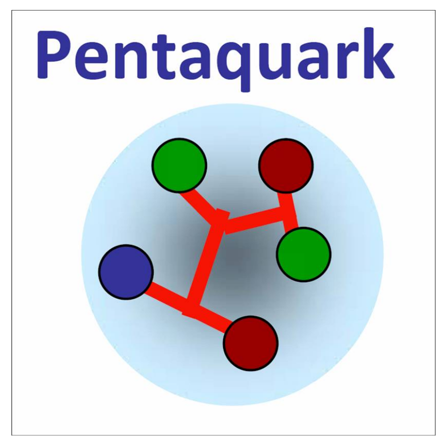
MULTI-FACES of QCD: EXOTIC HADRONS









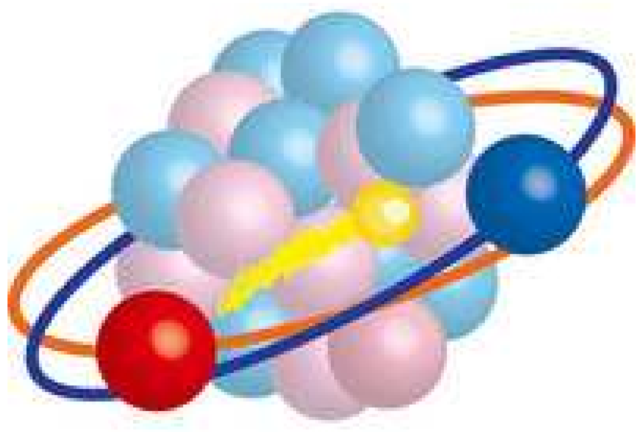


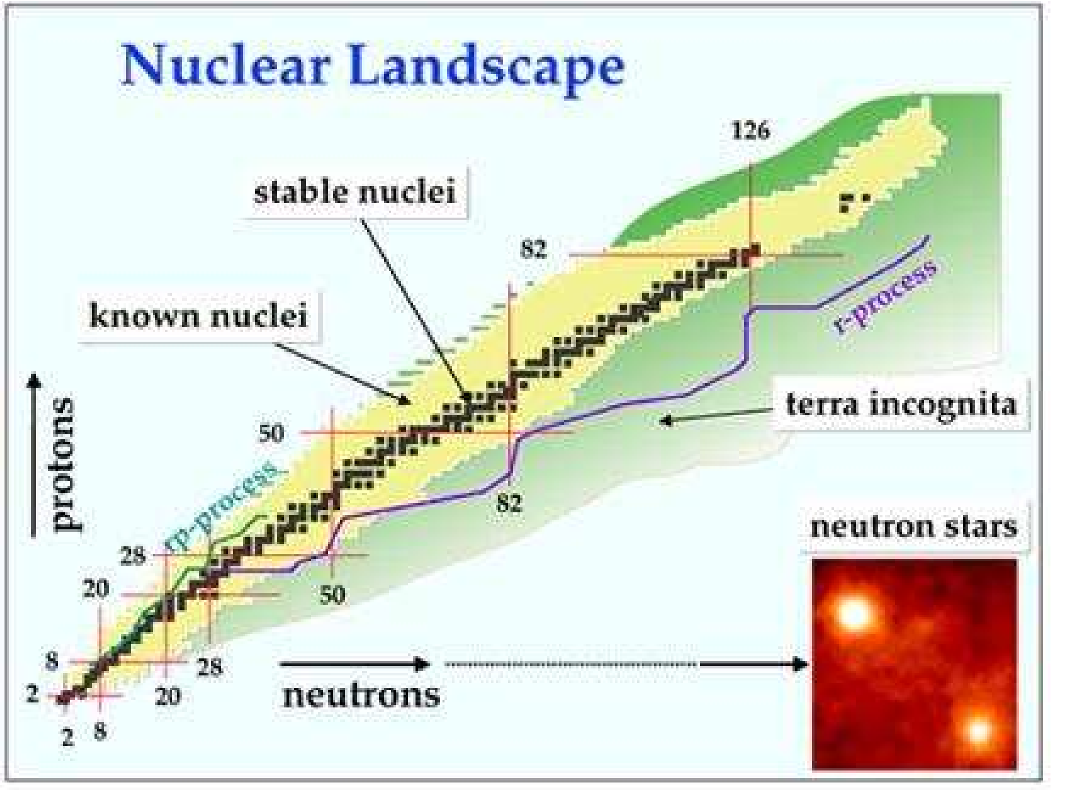
States with glue: QCD

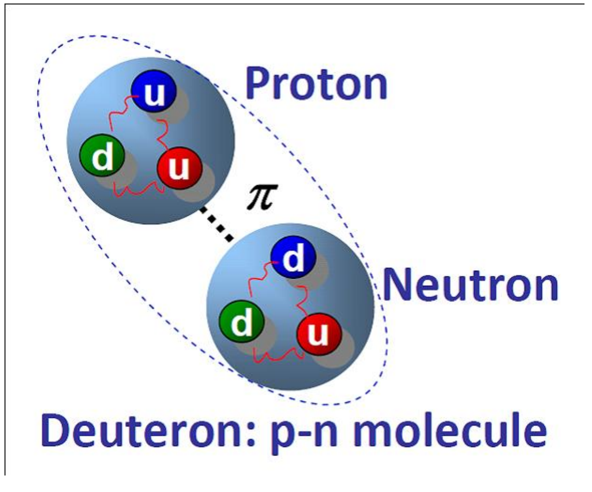
Multi-Quark states: Gell-Mann, Phys.Lett. **8** (1964) 214

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

STILL MORE STRUCTURE: ATOMIC NUCLEI

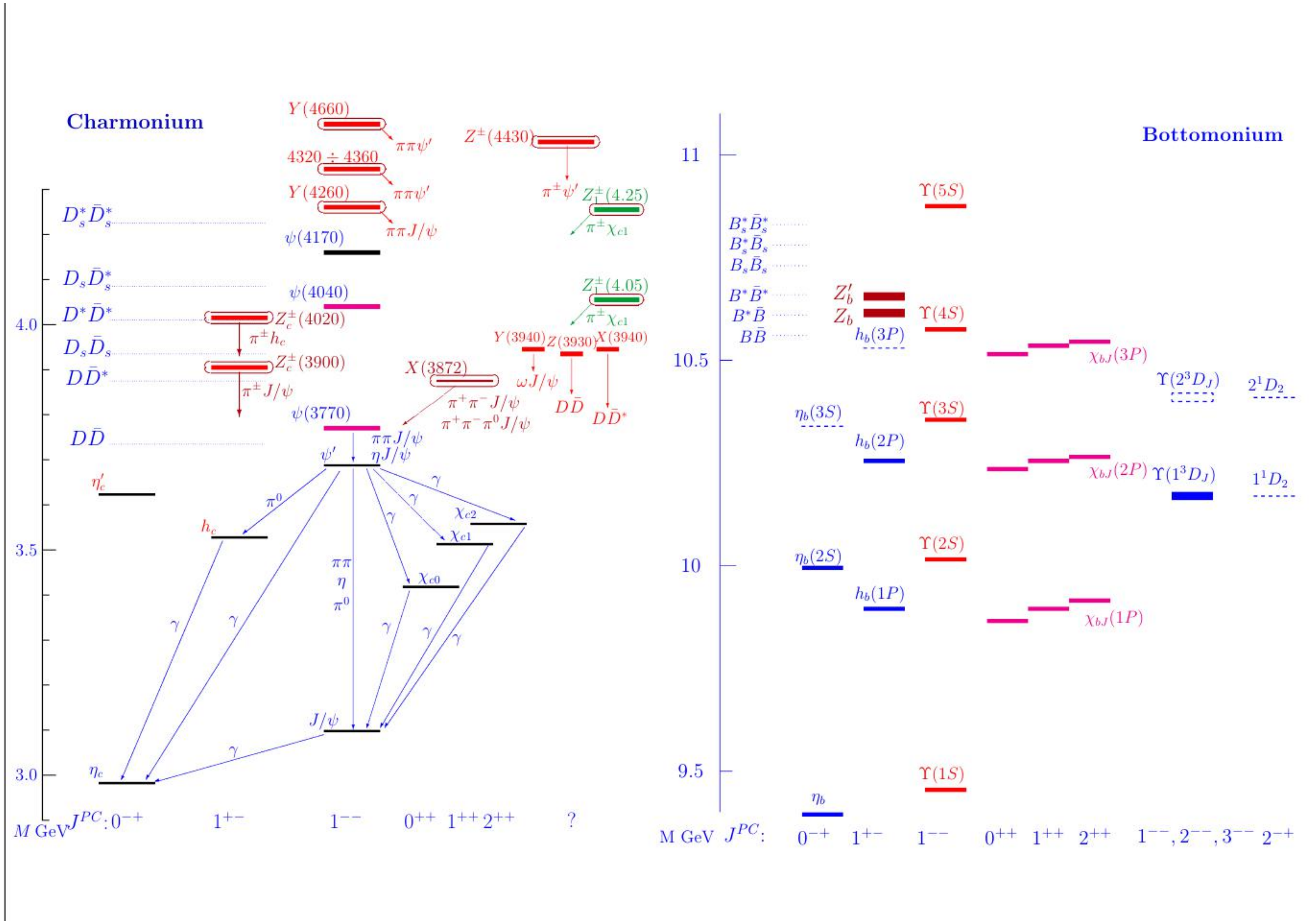






exploring the residual color force
$\rightarrow$ ab initio calculations possible

MYSTERIES in the QUARKONIUM SPECTRUM



- many of these close to thresholds $\hookrightarrow$ hadronic molecules
- some are charged $\hookrightarrow$ these must be exotic

MORE MYSTERIES in the CHARMONIUM REGION

• Open charm $c\bar{s}$ mesons: first indication of the quark model breakdown

⋆ $D^\star_{s0}(2317) : J^P = 0^+$ BaBar (2003)

$M = (2317.7 \pm 0.6)$ MeV

$\Gamma < 3.8$ MeV

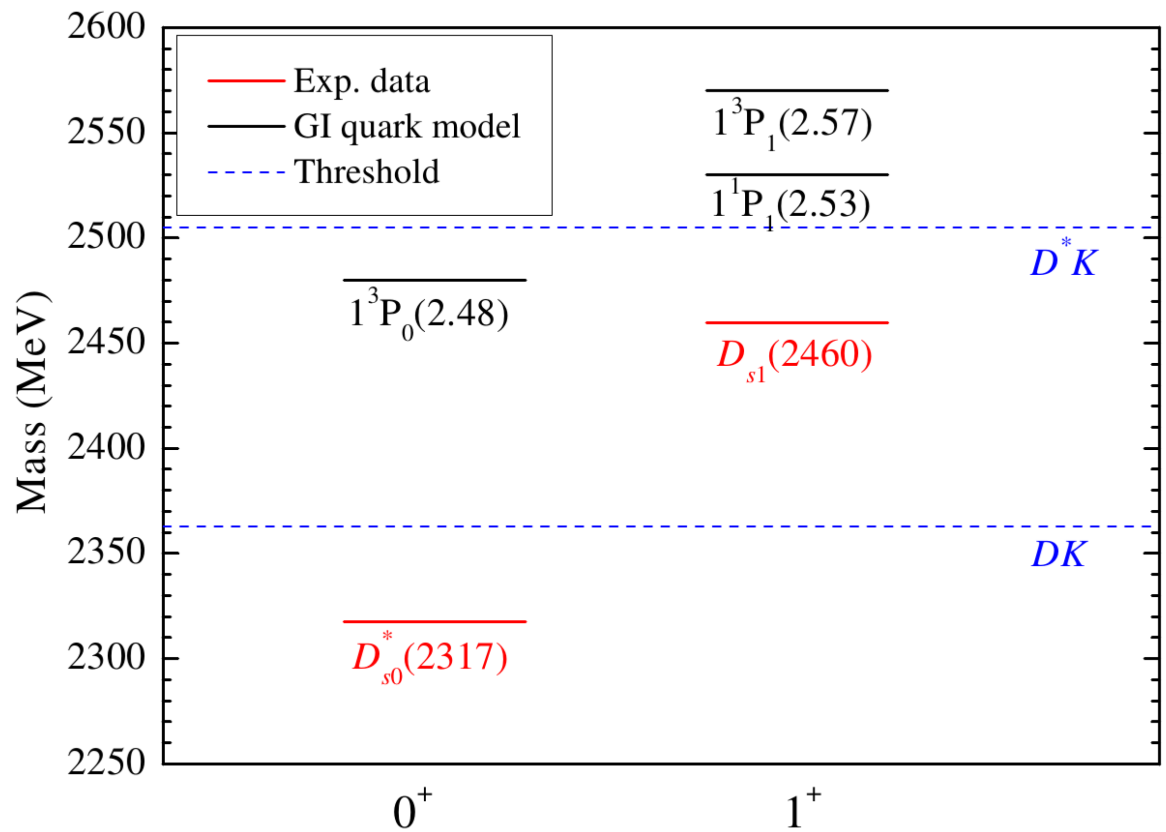
only hadronic decay: $D_s\pi$

$\hookrightarrow$ isospin-violating

⋆ $D_{s1}(2460) : J^P = 1^+$ CLEO (2003)

$M = (2459.5 \pm 0.6)$ MeV

$\Gamma < 3.5$ MeV



⋆ no isospin partners observed $\Rightarrow I = 0$

tiny widths

GI: Godfrey, Isgur, Phys. Rev. D **32** (1985) 189

MORE MYSTERIES in the CHARMONIUM REGION

- $D_0^\star(2400)$ Belle (2004)

  $M = (2318 \pm 29)$ MeV , $\Gamma = (247 \pm 67)$ MeV , $J^P = 0^+$ PDG2016

- New measurements by LHCb: $M = (2360 \pm 15)$ MeV LHCb (2015)

- In all experiments, a Breit-Wigner resonance from was assumed!

  [often very dangerous!]

- Puzzles to be answered:

> ⋆ why are the masses of the $D_{s0}^\star(2317)$ and the $D_{s1}(2460)$ much lower than the quark model predictions for $c\bar{s}$ mesons?
>
> ⋆ why $M_{D_{s1}(2460)} - M_{D_{s0}^\star(2317)} \simeq M_{D^\star} - M_D$? (within 1 MeV)
>
> ⋆ why $M_{D_0^\star(2400)} \gtrsim M_{D_{s0}^\star(2317)}$ and $M_{D_1(2430)} \simeq M_{D_{s1}(2460)}$?

Salient features of QCD

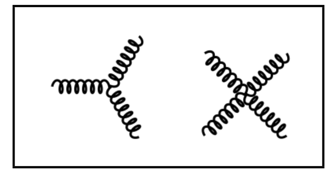
QCD LAGRANGIAN

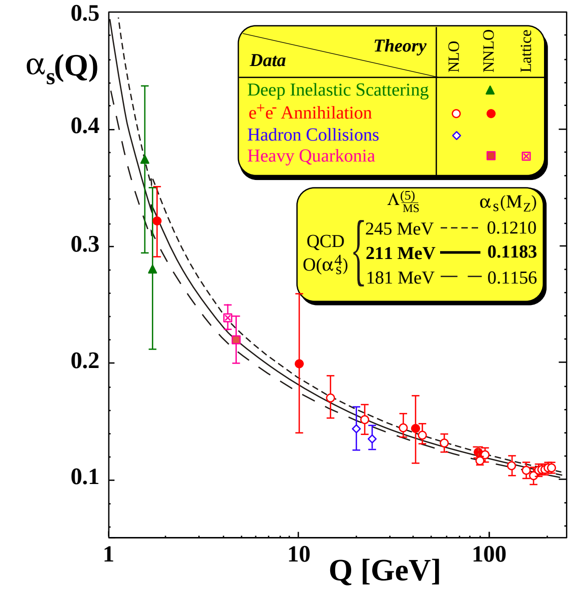
- $$\mathcal{L}_{\rm QCD} = -\frac{1}{4}\, G^a_{\mu\nu} G^{\mu\nu,a} + \sum_f \bar{q}_f (i\not{D} - \mathcal{M}) q_f + \ldots$$

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

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

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





- 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:

$m_{\rm light} \ll \Lambda_{\rm QCD}$	$m_{\rm heavy} \gg \Lambda_{\rm QCD}$
$m_u = 2.2^{+0.6}_{-0.4}$ 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:** $\mathcal{L}_{\rm QCD} = \bar{q}_L\, i\not{D} q_L + \bar{q}_R\, i\not{D} q_R + \mathcal{O}(m_f/\Lambda_{\rm QCD})$
  - 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

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

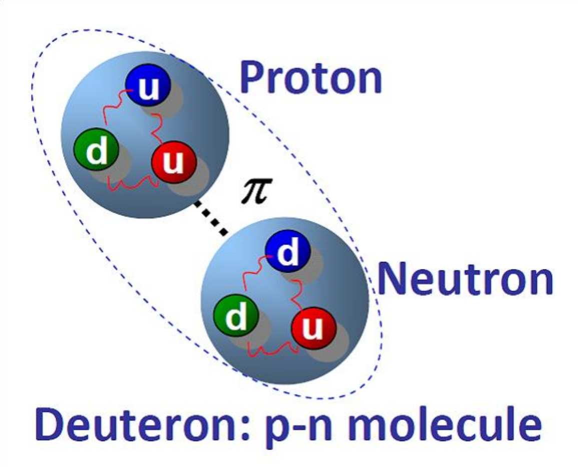
- the classical example:

  $\star$ the deuteron

  $m_p + m_n = 938.27 + 939.57$ MeV,

  $m_d = m_p + m_n - \varepsilon \to \varepsilon = 2.22$ 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 (1963), Morgan (1991), Tornquist (1995), Baru et al. (2003), . . .

- Consider S-wave scattering of two hadrons, forming a bound state:

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

a = scattering length, γ/E_B = binding momentum/energy,
μ = reduced mass of the two-particle system, β = range of forces

$\Rightarrow$ pure molecule ($Z = 0$): maximal scattering length $a = -1/\gamma$

$\Rightarrow$ compact state ($Z = 1$): the scattering length is $a = -\mathcal{O}(1/\beta)$

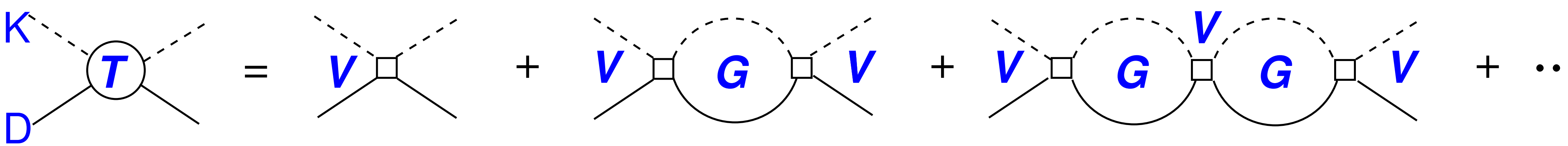
- The deuteron: $E_B = 2.22$ MeV $\to \gamma = 45.7$ MeV
  with the range of forces: $1/\beta \sim 1/M_\pi \simeq 1.4$ fm
  leads with $Z = 0$ to: $a_{\rm mol} = -(4.3 \pm 1.4)$ fm
  consistent with the data: $a = -5.419(7)$ fm , $r = 1.764(8)$ fm

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

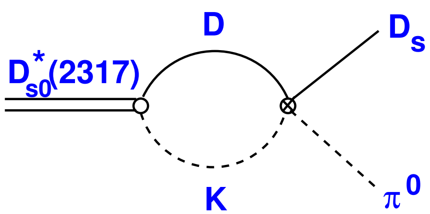
$D^\star_{s0}(2317)$ and $D_{s1}(2460)$ as HADRONIC MOLECULES

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

- $D^{(\star)}K$ bound states: Poles of the c.c. T-matrix (potential from CHPT & unitarization)



- large coupling to DK $\Rightarrow$ **large** isospin-breaking width from $[D^+K^0] - [D^0K^+]$



$$\boxed{\Gamma(D^\star_{s0}(2317) \to D_s\pi) = \mathcal{O}(100\ \text{keV})}$$

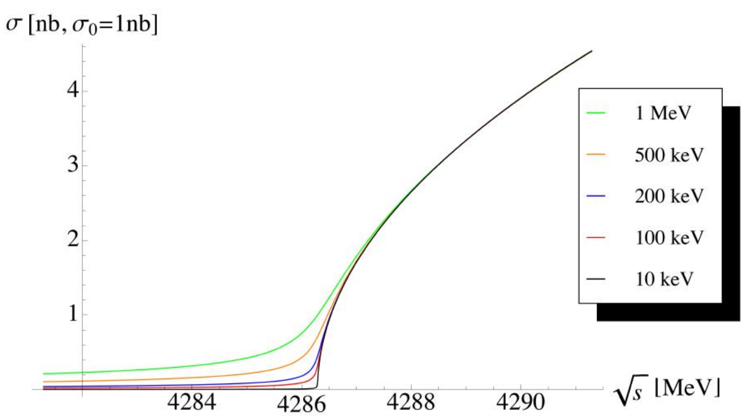
Faessler et al (2006), Lutz, Soyeur (2008), Guo et al (2008), Liu et al (2013), ...

– only a few keV in the quark model

Godfrey (2003), Nielsen (2006), ...

– to be measured at $\overline{\mathrm{P}}\mathrm{ANDA}$

Mertens [PANDA Collaboration] (2013)



HEAVY QUARK SYMMETRY for $D^\star_{s0}(2317)$ and $D_{s1}(2460)$

Cleven, Guo, Hanhart, UGM (2011)

- A natural consequence of HQSS ($DK \to D^\star K$): similar binding energies

$$M_D + M_K - M_{D^\star_{s0}} \simeq 45\,\text{MeV}$$

$$\Rightarrow M_{D_{s1}(2460)} - M_{D^\star_{s0}(2317)} \simeq M_{D^\star} - M_D \text{ is understood!}$$

- Easy prediction for the bottom analogues from HQFS:

$$M_{B^\star_{s0}} \simeq M_B + M_K - 45\,\text{MeV} \simeq 5.730\,\text{GeV}$$

$$M_{B_{s1}} \simeq M_{B^\star} + M_K - 45\,\text{MeV} \simeq 5.776\,\text{GeV}$$

- Recent lattice QCD results: Lang et al (2015)

$$M^{\text{lat}}_{B^\star_{s0}} = (5.711 \pm 0.013 \pm 0.019)\,\text{GeV}$$

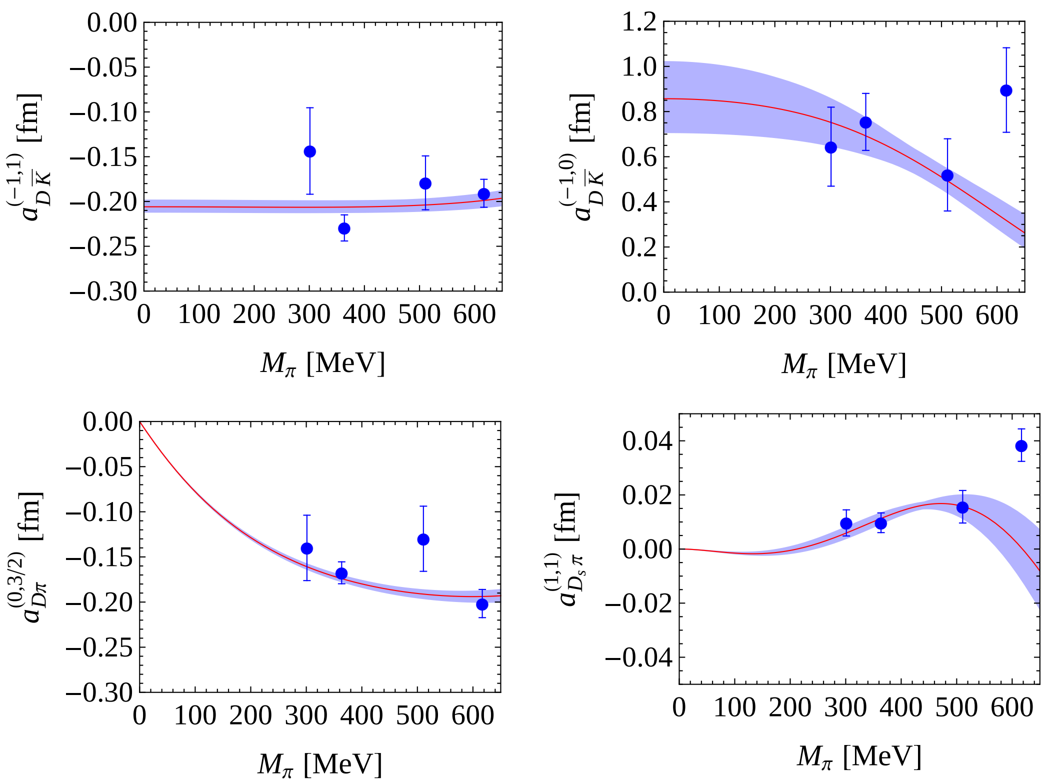
$$M^{\text{lat}}_{B_{s1}} = (5.750 \pm 0.017 \pm 0.019)\,\text{GeV}$$

Lattice results for charmed scalar mesons

FIT to LATTICE DATA

Liu, Orginos, Guo, Hanhart, UGM (2013)

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



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

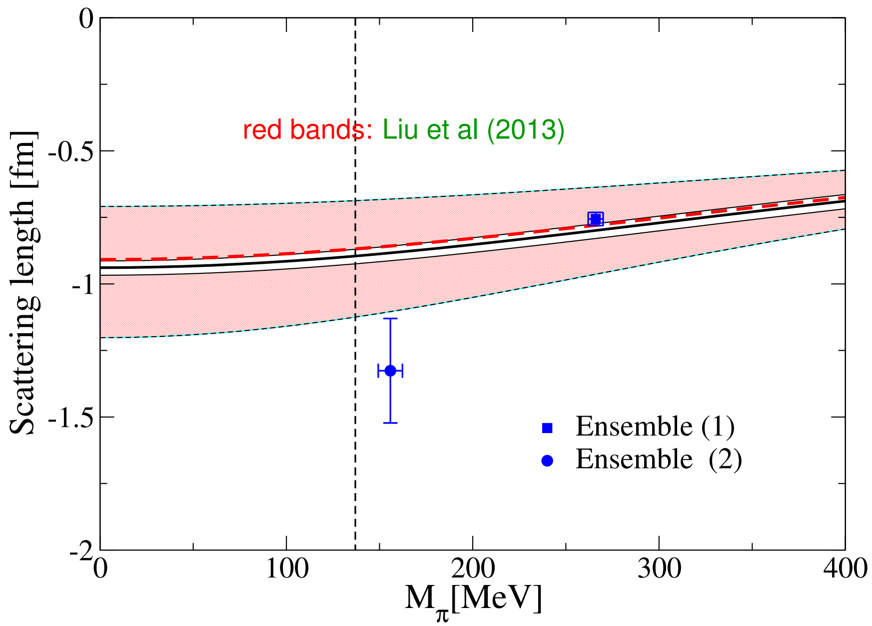
- Prediction: Pole in the $(S, I) = (1, 0)$ channel: 2315^{+18}_{-28} MeV

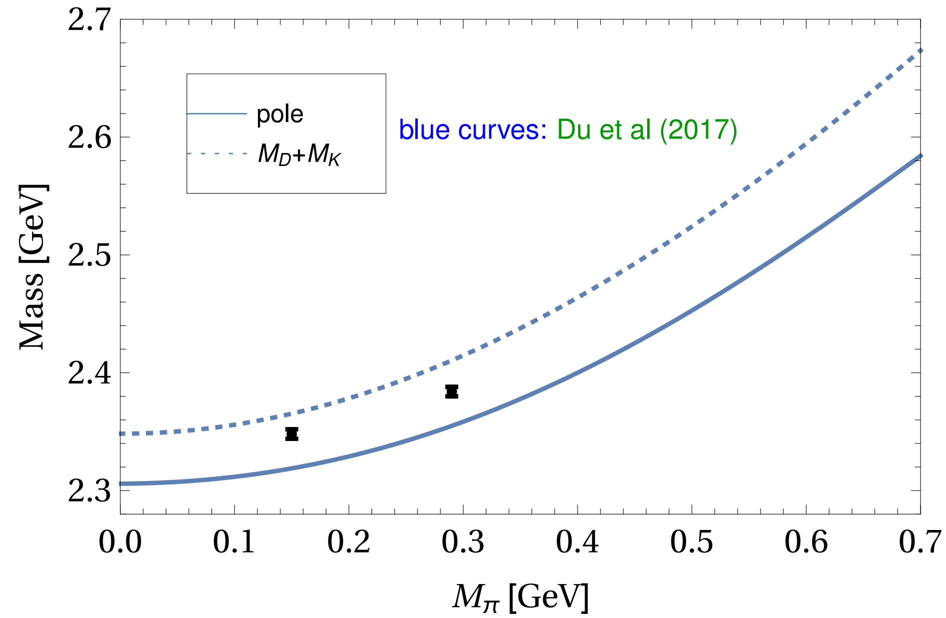
Experiment: $M_{D^\star_{s0}(2317)} = (2317.7 \pm 0.6)$ MeV PDG2016

DIRECT CALCULATION of the $D^\star_{s0}(2317)$

Mohler et al. (2013), Bali et al. (2017)

- Calculations with $c\bar{s} + DK$ interpolators and relatively light pions:





- Scattering length consistent with the molecular picture:

$$a_0 = -1.33(20)\ \text{fm}$$

$$a_0^{\rm mol} = -\frac{2}{\sqrt{\mu_{DK}\epsilon}} \simeq -1\ \text{fm}$$

- Chiral extrapolation consistent with the molecular picture:

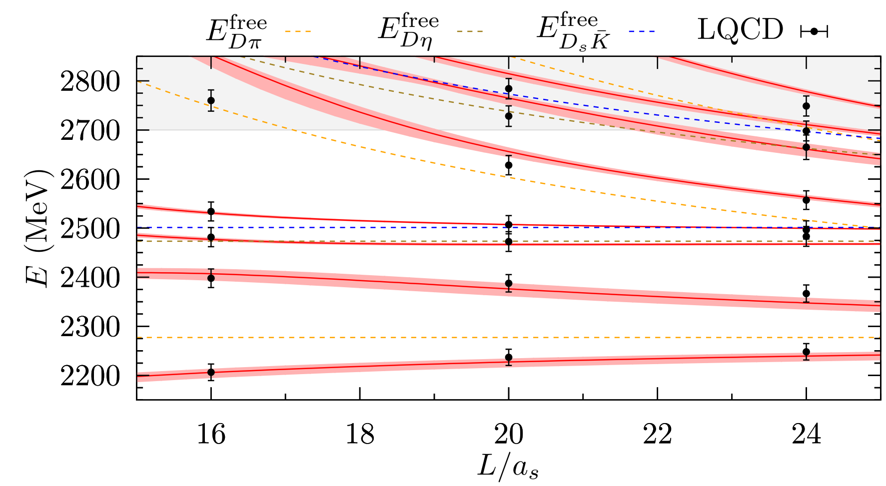
$$1 - Z = 1.04(0.08)(0.30)$$

WHAT ABOUT the $D_0^\star(2400)$?

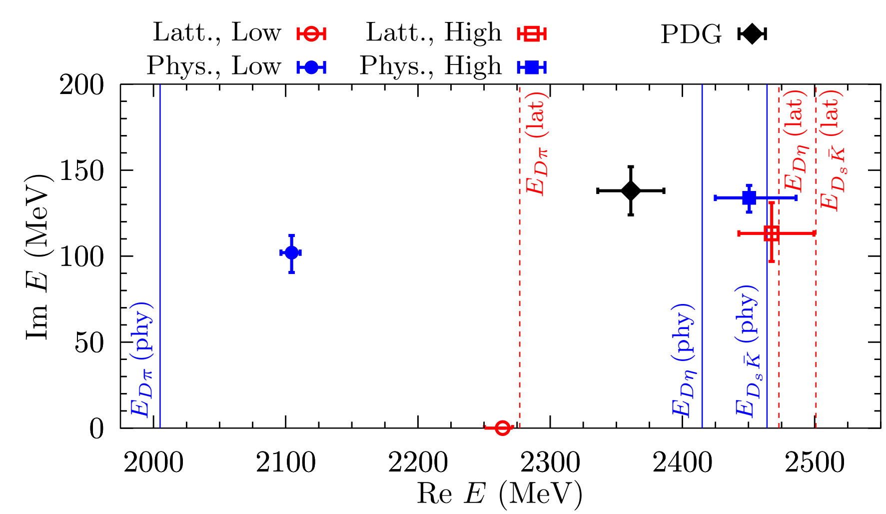
- Recent results from the *Hadron Spectrum Coll.* for $I = 1/2$ finding one pole corresponding to the $D_0^\star(2400)$

Moir et al., JHEP 1610 (2016) 011

- Postdict finite volume energy levels based on Liu et al. (2013)
  $\to$ this is NOT a fit!
  Albaladejo, Fernandez-Soler, Guo, Nieves (2017)



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



- similar for $D_1, B_0^\star, B_1$

$\to$ but is their experimental support for this?

TWO-POLE SCENARIO in the HEAVY-LIGHT SECTOR

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

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

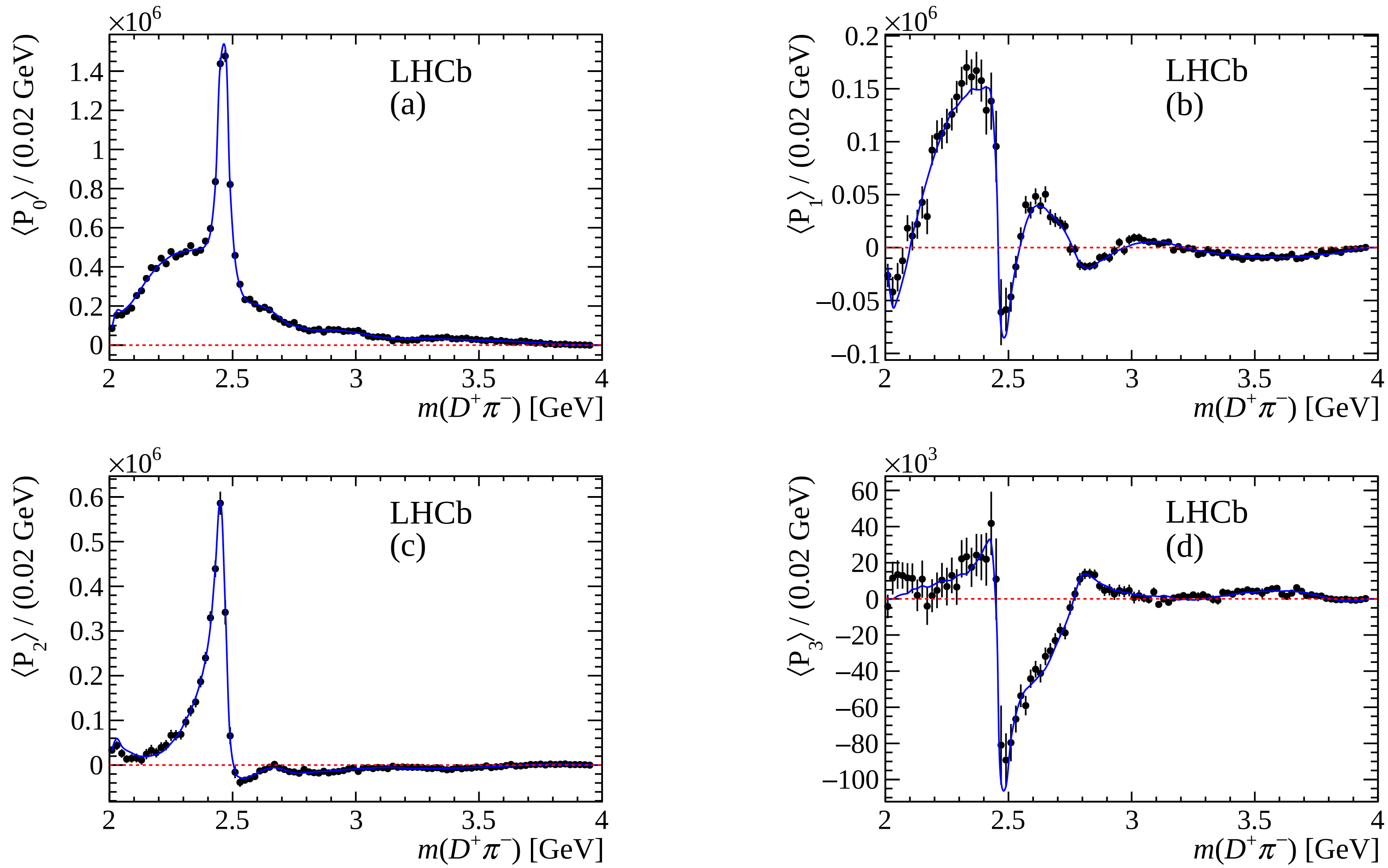
Amplitude Analysis of $B \to D\pi\pi$

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

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

Aaji et al. [LHCb], PRD94(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, Yao [1712.07957]

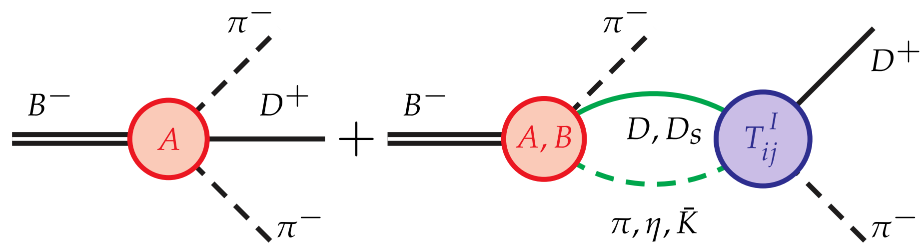
- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI

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

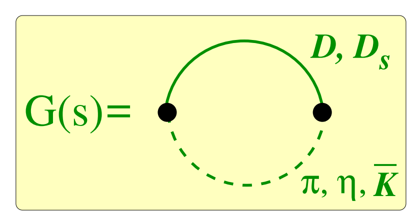
  $\to$ P-wave: $D^\star$, $D^\star(2860)$; D-wave: $D_2(2460)$ as by LHCb

  $\to$ 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 LECs C and one subtraction constant in the G_{ij})



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



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

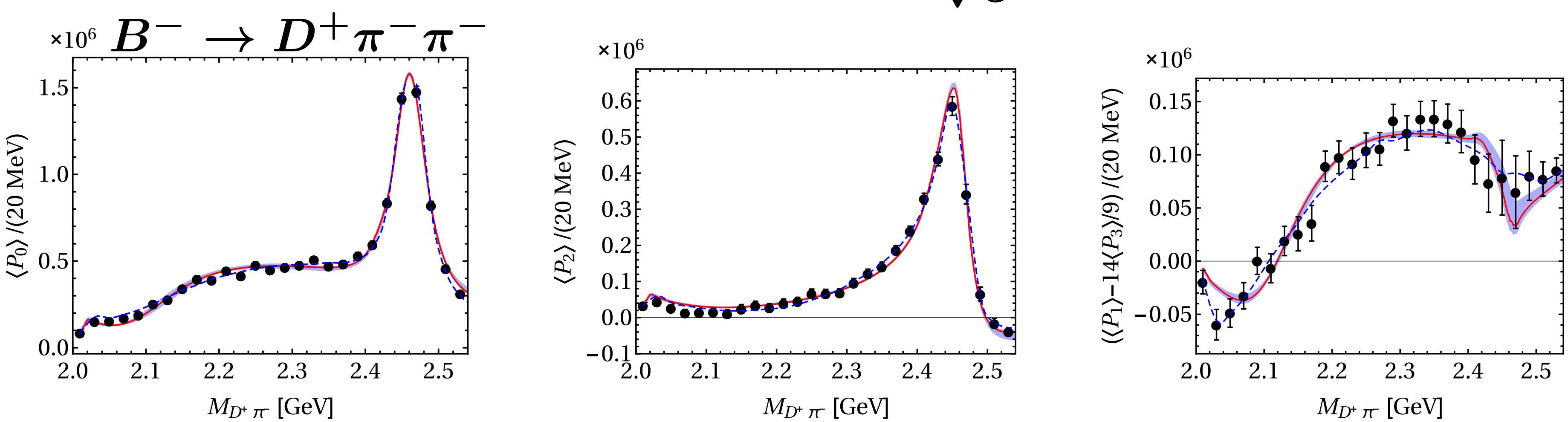
Du, Albadajedo, Fernandez-Soler, Guo, Hanhart, UGM, Nieves, Yao [1712.07957]

- 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

SUMMARY and OUTLOOK

- All **three puzzles** related to the positive-parity charm mesons are **resolved**:

  Q: Why are the masses of the $D^\star_{s0}(2317)$ and the $D_{s1}(2460)$ much lower than the quark model predictions for $c\bar{s}$ mesons?

  A: They are dominantly DK and $D^\star K$ molecular states, respectively

  Q: Why $M_{D_{s1}(2460)} - M_{D^\star_{s0}(2317)} \simeq M_{D^\star} - M_D$ within 1 MeV?

  A: Consequence of HQSS for dominantly DK and $D^\star K$ molecules

  Q: Why $M_{D^\star_0(2400)} \gtrsim M_{D^\star_{s0}(2317)}$ and $M_{D_1(2430)} \simeq M_{D_{s1}(2460)}$?

  A: There are two $D^\star_0$ and two D_1, and the lower ones have smaller masses

$\Rightarrow$ Strong support from remarkable agreememt with lattice and exp. data!

$\Rightarrow$ The same pattern should occur in the bottom sector $\to$ exp. tests!

$\Rightarrow$ Immediate tests: strong variation in $\langle P_{13}\rangle$ around the $D\eta$ and $D_s\bar{K}$ thresholds

SUMMARY and OUTLOOK continued

- A new **paradigm** in open-flavor heavy meson spectroscopy:

So far: All ground states should be $c\bar{q}$ or $b\bar{q}$ quark model states

But: Going up in mass, more and more two-particle thresholds open
$\hookrightarrow$ quark model less and less reliable

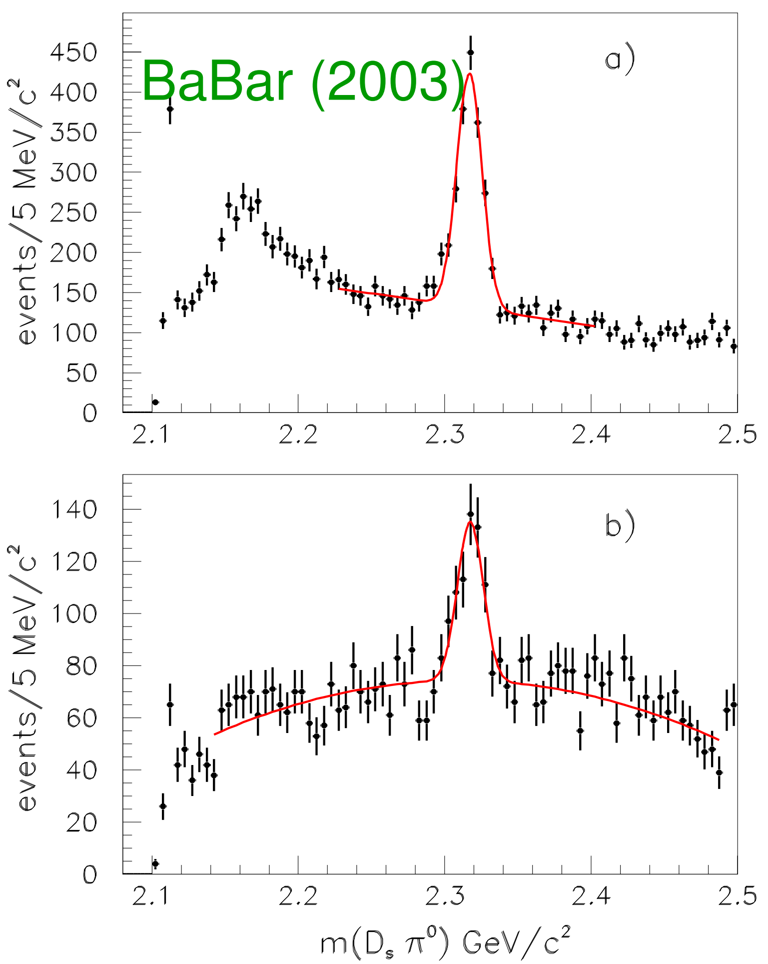
$\Rightarrow$ the hadron spectrum must be viewed as more than a collection of quark model states, but rather as a manifestation of a more complex dynamics that leads to an intricate pattern of various types of states that can only be understood by an interplay of theory and experiment (cf. the light scalar mesons)

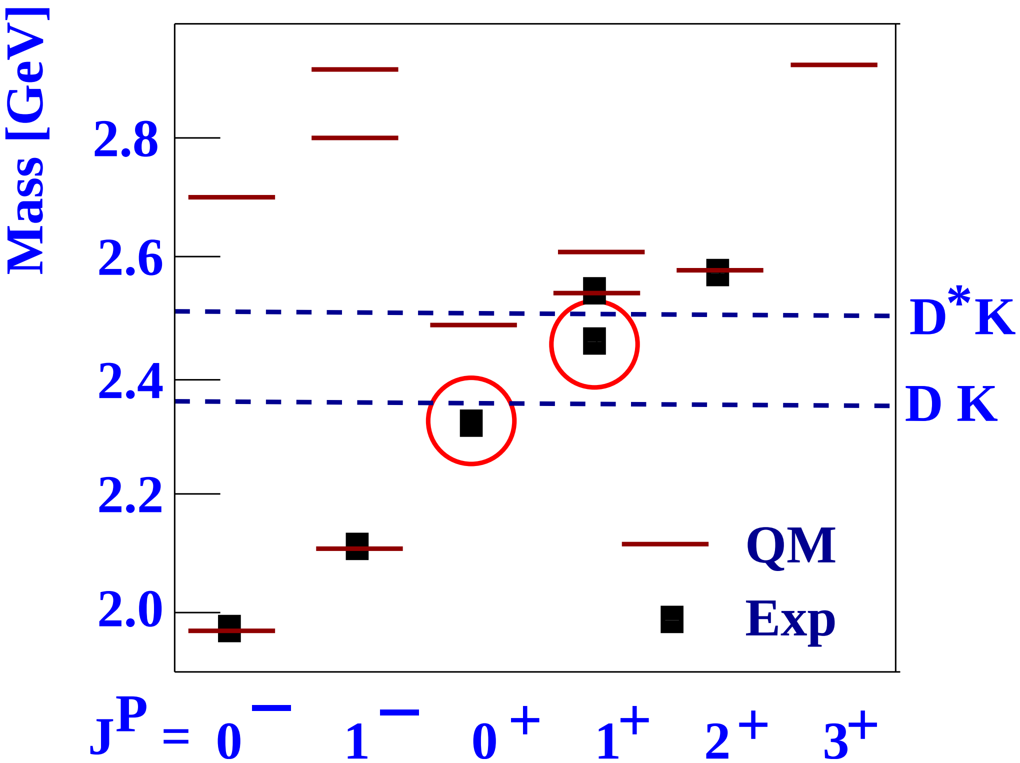
$\Rightarrow$ A bright future for FAIR
& for HADRON PHYSICS

SPARES

OBSERVATION of CHARM-STRANGE MESONS

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



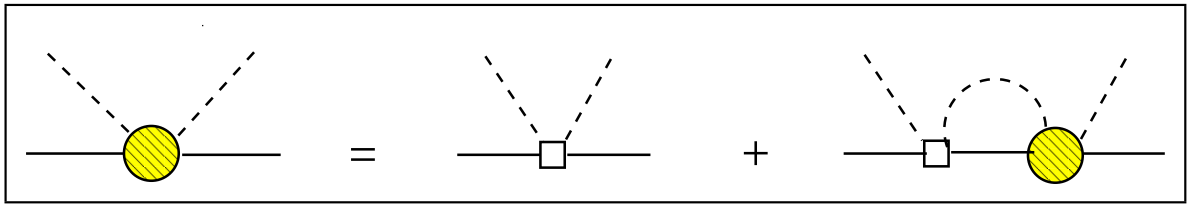


$\Rightarrow$ moleculare nature?

MOLECULAR PICTURE of the charm-strange MESONS

- Goldstone boson octet (π, K, η) scatters off D-meson triplet (D^0, D^+, D_s^+)
- multi-scale/multi-faceted problem:
  - light particles, chiral symmetry $\to$ chiral expansion in (p, m_q)
  - heavy particles, heavy quark symmetry $\to$ expansion in $1/m_c$
  - unitarization of the amplitude $\to$ dynamical generation of poles (tower)

Guo, UGM (2011)



- at next-to-leading order, only two parameters
- fix one parameter from the mass of the $D_s(2317)$, vary the other

$\Rightarrow$ make predictions

PREDICTIONS

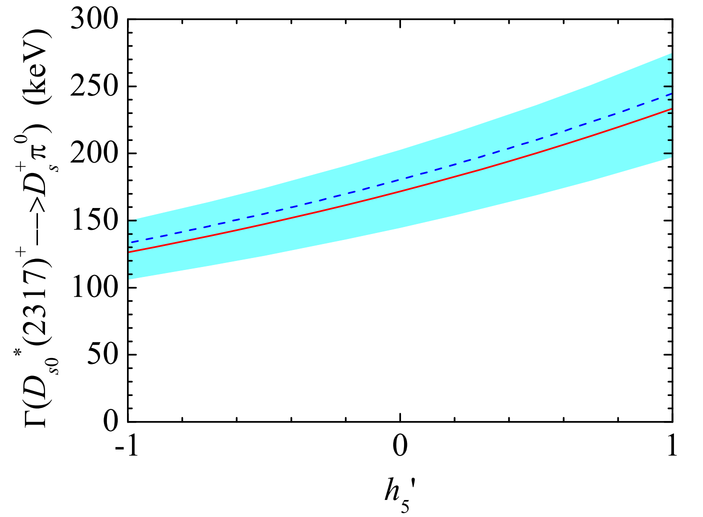
Guo, Hanhart, UGM; Lutz, Soyeur; Gutsche, . . .

- Prediction for the width of the $D^*_{s0}(2317)$

$$\boxed{\Gamma(D^*_{s0}(2317)^+ \to D_s^+\pi^0) = (180 \pm 110)\,\mathrm{keV}}$$

testable prediction

note: much smaller in quark models (a few keV)



- expectation for the scattering length for $DK(I=0)$ in the molecular picture:

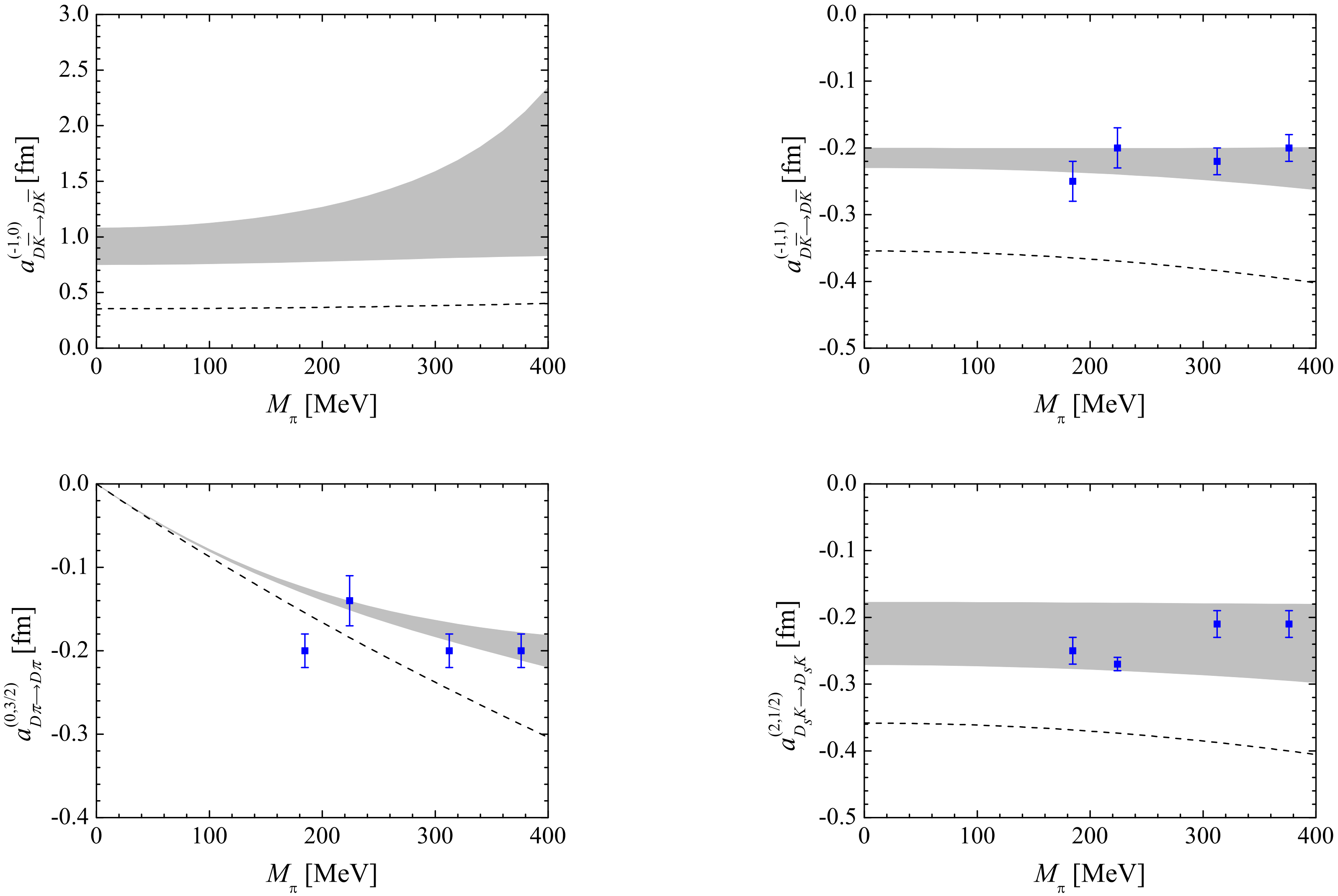
$$a_{DK}^{I=0} = -g_{\rm eff}^2 \Delta_{DK} = -\frac{1}{2\sqrt{\mu_{DK}\varepsilon}} \simeq 1\,\mathrm{fm}$$

- no data, but first lattice investigations at varying quark masses

Liu, Lin, Orginos, arXiv:0810.5412 [hep-lat]

QUARK MASS DEPENDENCE

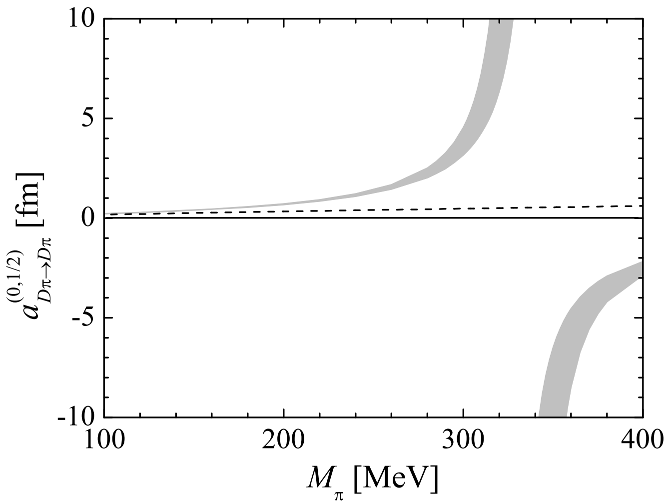
- *predictions:* channels with no poles



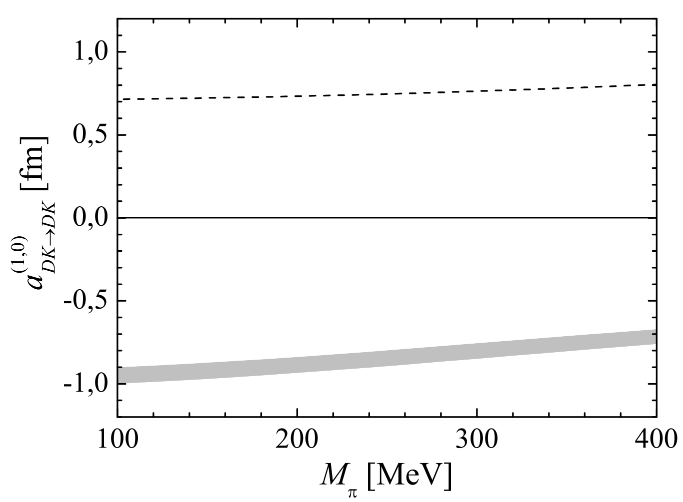
QUARK MASS DEPENDENCE cont'd

- *predictions:* channels with poles $\rightarrow$ resonances or molecular states

$D\pi \rightarrow D\pi\ (0, 1/2)$



$DK \rightarrow DK\ (1, 0)$



a pair of poles above thr.

$$a^{(0,1/2)}_{D\pi} = 0.35(1)\ \text{fm}$$

a bound states below thr. $D^*_{s0}(2317)$

$$a^{(1,0)}_{DK} = -0.93(5)\ \text{fm}$$

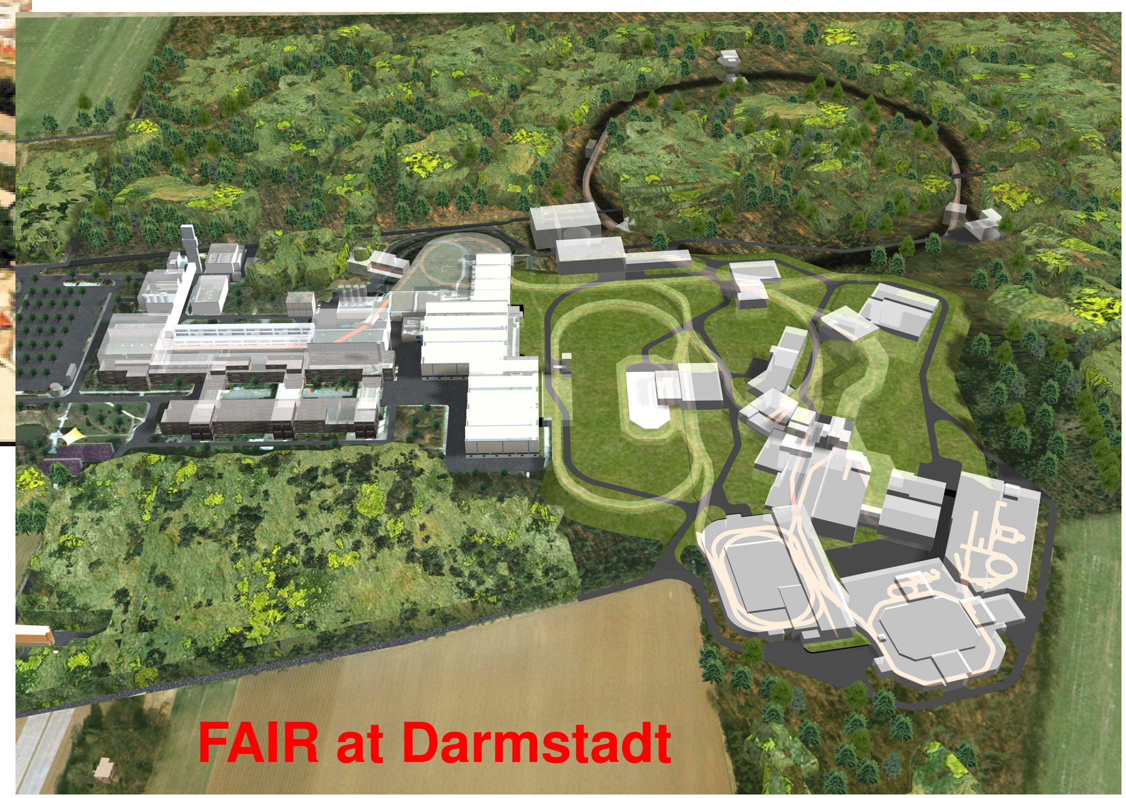
$\Rightarrow$ lattice test of the molecular nature

Prospects and summary

HADRON PHYSICS COMPLEXES

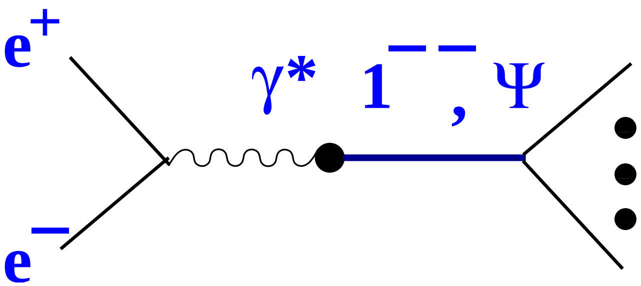
- present and future HPC = Hadron Physics Complexes → BEPC-II, FAIR

  (the contenders: B-factories and colliders)



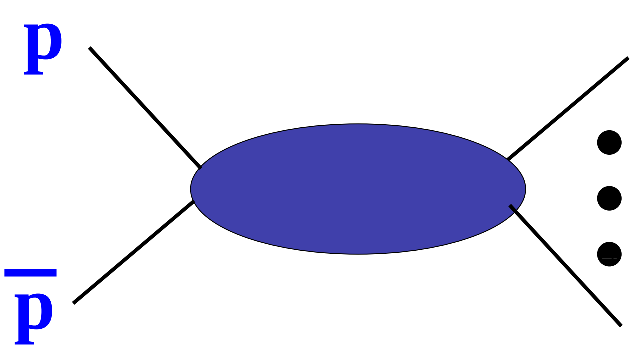
COMPLEMENTARITY

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



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

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



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

MEASURING LINE SHAPES

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

- Example: observation of the χ_{c1} state

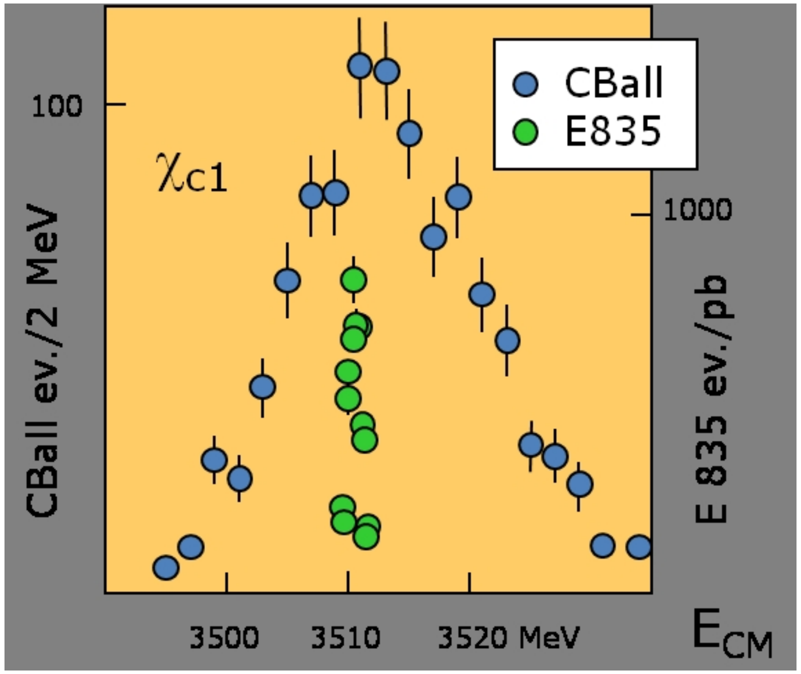
- $M(\chi_{c1}) = 3610$ MeV, $J^{PC} = 1^{++}$

e^+e^- annihilation:

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

$\bar{p}p$ annihilation:

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



$\rightarrow$ eagerly waiting for PANDA at HESR

FACETS of STRONG QCD

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

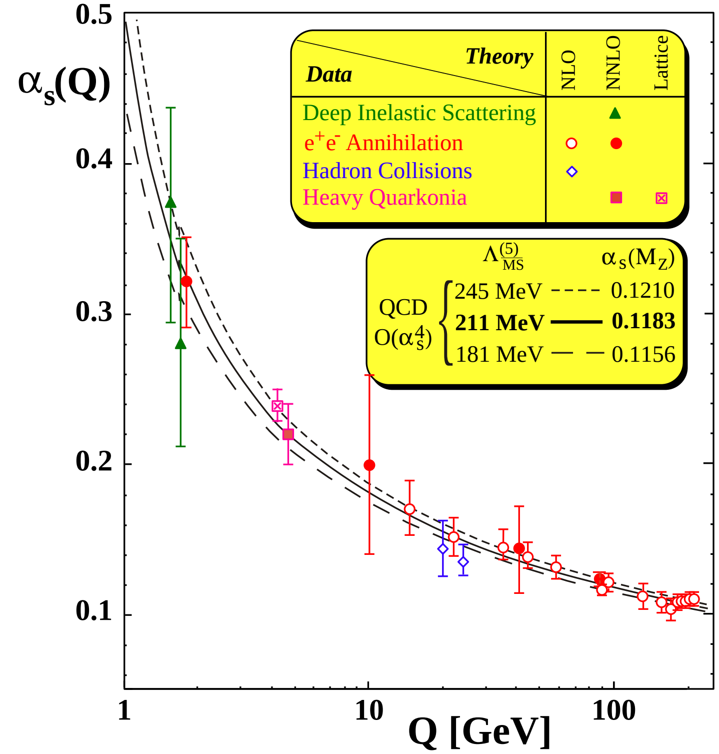
  $\Rightarrow$ two regimes: strong & perturbative

- 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

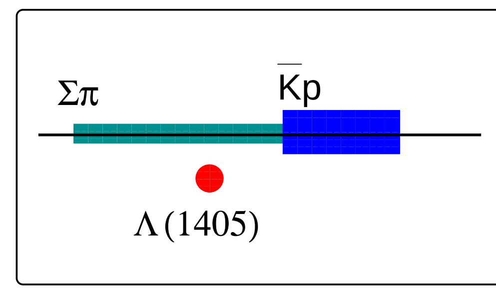
- classical examples:

$\star$ 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)

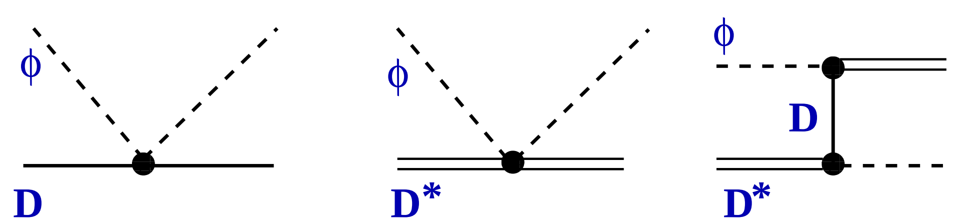
$\Rightarrow$ study Goldstone boson scattering off D- and $D^\star$-mesons

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

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

$$P = (D^0, D^+, D_s^+)\,, \quad V_\mu^* = (D_\mu^{*0}, D_\mu^{*+}, D_{s,\mu}^{*+})$$

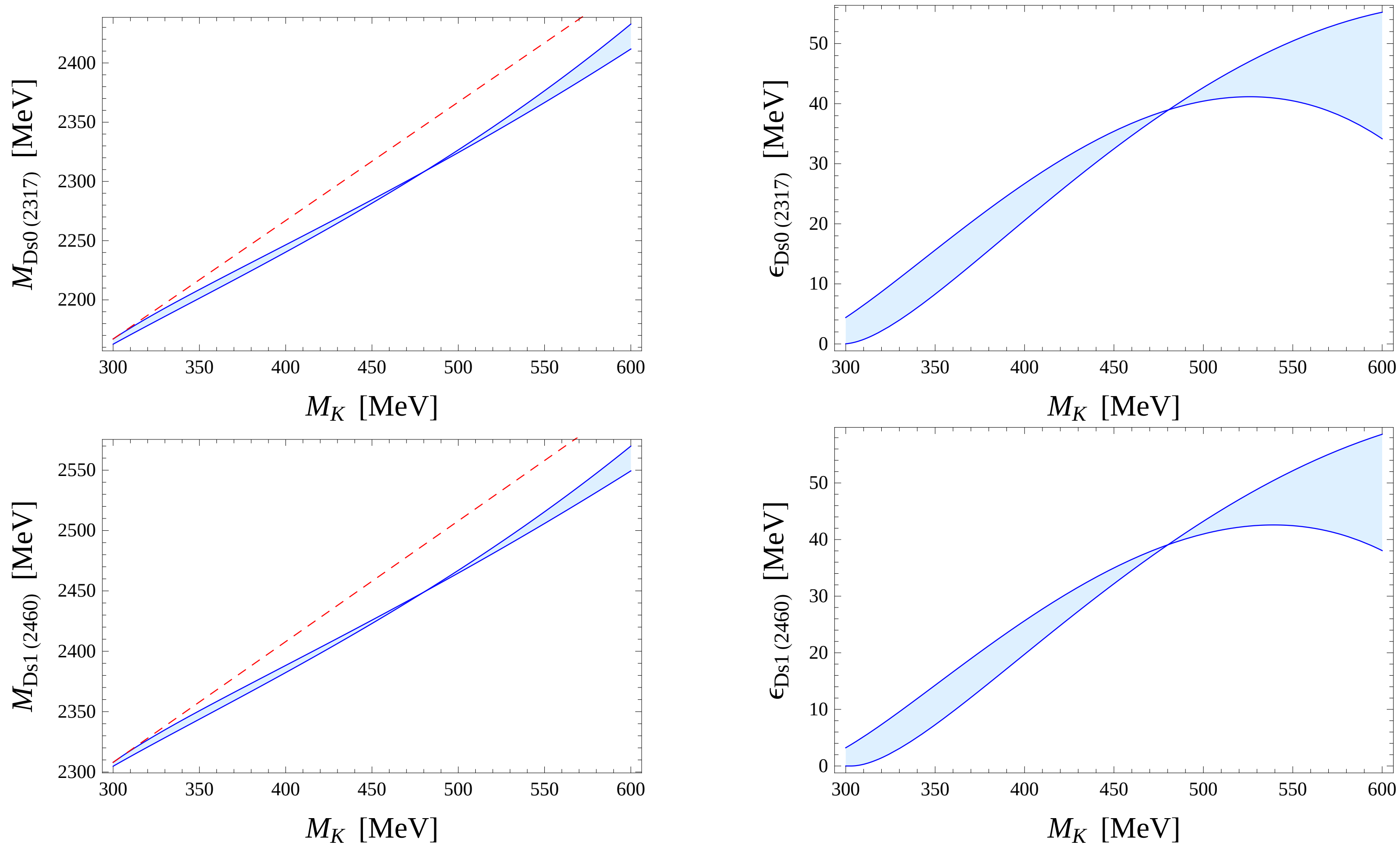
- T-matrix:



- Unitarization (as before) $\longrightarrow$ 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