TETRAQUARKS: SUCCESSES, CHALLENGES AND NEW AVENUES

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PWA / ATHOS 2021

For a review on exotics see e.g.:
AE, Pilloni, Polosa — Phys.Rept. (2017), 1611.07920
Lebed, Mitchell, Swanson — Prog.Part.Nucl.Phys. (2017), 1610.04528
Guo, Hanhart, Meißner, Wang, Zhao — Rev.Mod.Phys. (2018), 1705.00141

OUTLINE

- Brief review on XYZ and the tetraquark model
  1. Successes: spectrum, isospin violation, …
  2. Challenges: missing states

- An emerging pattern for compact tetraquarks
  1. Spectroscopy: $X(6900)$, T_{cc}^{+} , Z_{cs}
  2. Lineshape of the $X(3872)$

- Conclusion

BRIEF REVIEW

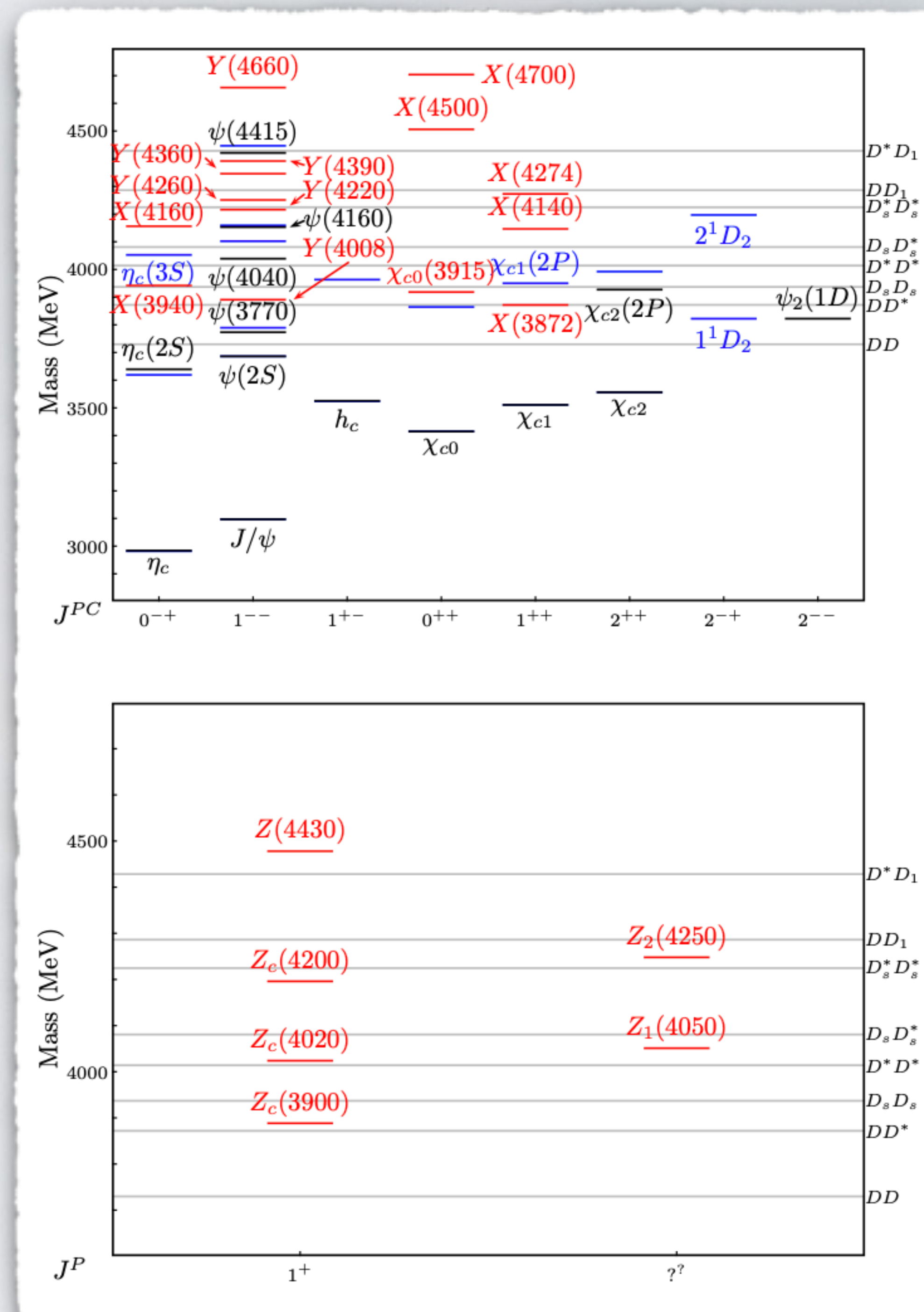
Exotic hadron spectrum

- Several new states in the quarkonium sector
- Their properties do not match standard quarkonia predictions
  1. Mass and quantum numbers
  2. Isospin violation
  3. Anomalously narrow
- The charged ones are manifestly 4-quark states:

$$Z_c^+(3900) \to J/\psi\, \pi^+$$

$c\bar{c}$ pair too heavy to be produced from the vacuum

Does not have the same quantum numbers as the vacuum

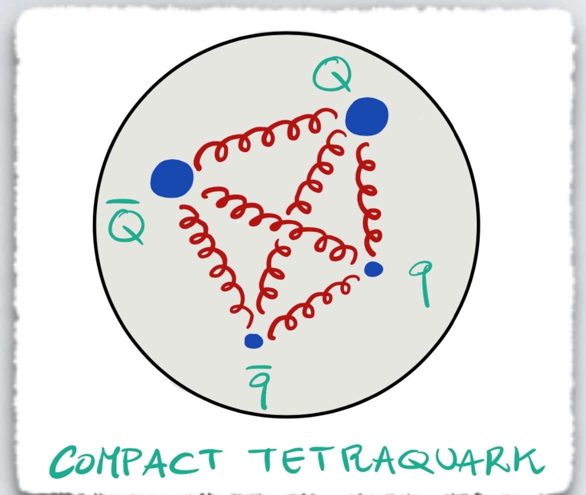


[AE, Pilloni, Polosa — Phys.Rept. (2017), 1611.07920]

EXOTIC MESONS

Possible interpretations

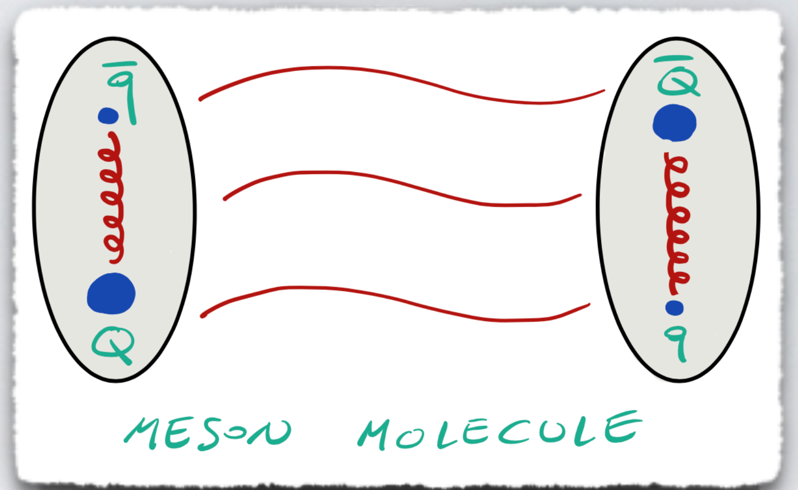
- Two competing interpretations



[see e.g. Maiani et al. — PRD (2014), 1405.1551]

1. Comprehensive description of the spectrum
2. Explains isospin violation
3. Slightly larger than an ordinary hadron ($d_{tetra} \simeq 1.3$ fm)

but… overpopulated



[see e.g. Guo et al. — Rev.Mod.Phys. (2018), 1705.00141]

1. Naturally explains closeness to threshold
2. Explains isospin violation
3. Very large state ($d_{mol} \simeq 10$ fm)

but… less systematic, cannot explain the prompt production and the effective range of the X

TETRAQUARKS

Main features

- Exotic mesons could be close analogues of the usual mesons and baryons
- Their spectrum is well reproduced by a diquarkonium model

diquark $\in \bar{\mathbf{3}}_c$

antidiquark $\in \mathbf{3}_c$

$$T(x) \sim \left[\epsilon_{ijk} Q^j(x) q^k(x)\right] \left[\epsilon^{imn} \bar{Q}_m(x) \bar{q}_n(x)\right]$$

$$H = \sum_{diq} m_{diq} - 2\kappa_{qQ} \left(\mathbf{S}_q \cdot \mathbf{S}_Q + \mathbf{S}_{\bar{q}} \cdot \mathbf{S}_{\bar{Q}}\right)$$

effective diquark mass

chromomagnetic coupling (e.g. $\kappa_{cq} \simeq 67$ MeV)

[Maiani, Polosa, Riquer — PRD (2014), 1405.1551; for pentaquarks: Maiani, Polosa, Riquer — PLB (2015), 1507.04980]

TETRAQUARKS

Main features

- Mass eigenstates ≠ isospin eigenstates: $X_u = [cu][\bar{c}\bar{u}]\,, \quad X_d = [cd][\bar{c}\bar{d}]$

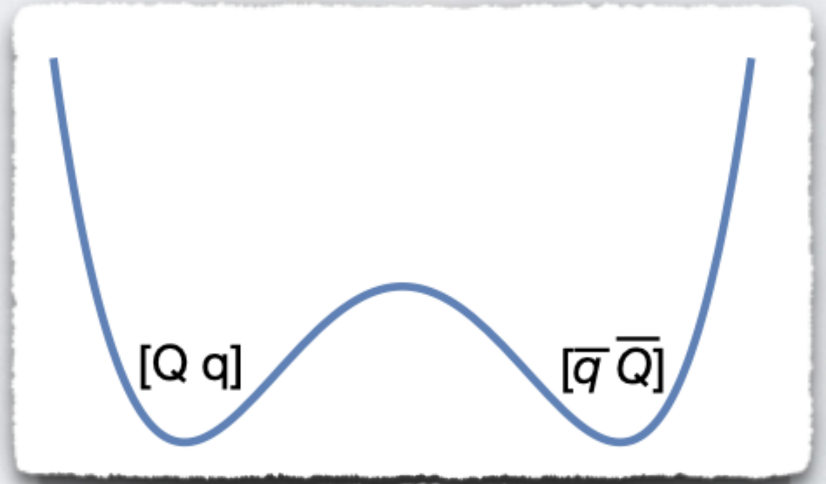
- Since $\alpha_s(2m_c)$ is small ⟶ mixing between X_u and X_d is suppressed

[Rossi, Veneziano — PLB (2004), hep-ph/0404262; Maiani, Piccinini, Polosa, Riquer — PRD (2005), hep-ph/0412098]

- Possible diquark-antidiquark repulsion at short distance

[Selem, Wilczek — hep-ph/0602128; Maiani, Polosa, Riquer — PLB (2018) 1712.05296; AE, Polosa — EPJC (2018), 1807.06040]

- $\Gamma\left(D\bar{D}^*\right) > \Gamma\left(J/\psi\right)$ because of tunneling suppression (never made fully quantitative…)

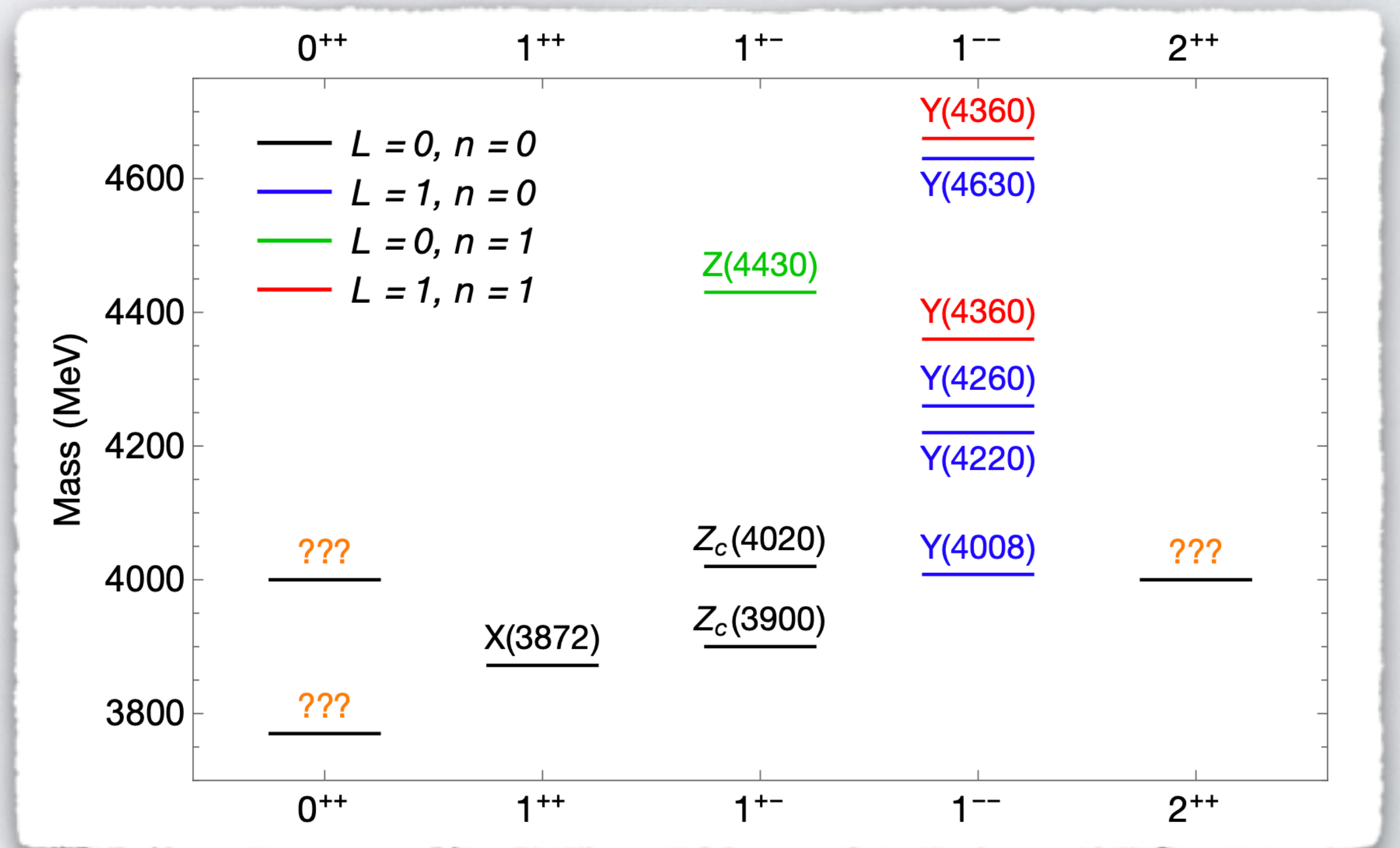


TETRAQUARKS

Challenges

- The simplest tetraquark model leaves some open issues
- In absence of further selection rules, its spectrum is overpopulated

1. Charged partners of the $X(3872)$?
2. Spin-0 and spin-2 states?
3. Analogue of the $X^{0,\pm}$ in the beauty sector?



AN EMERGING PATTERN

Fully charmed

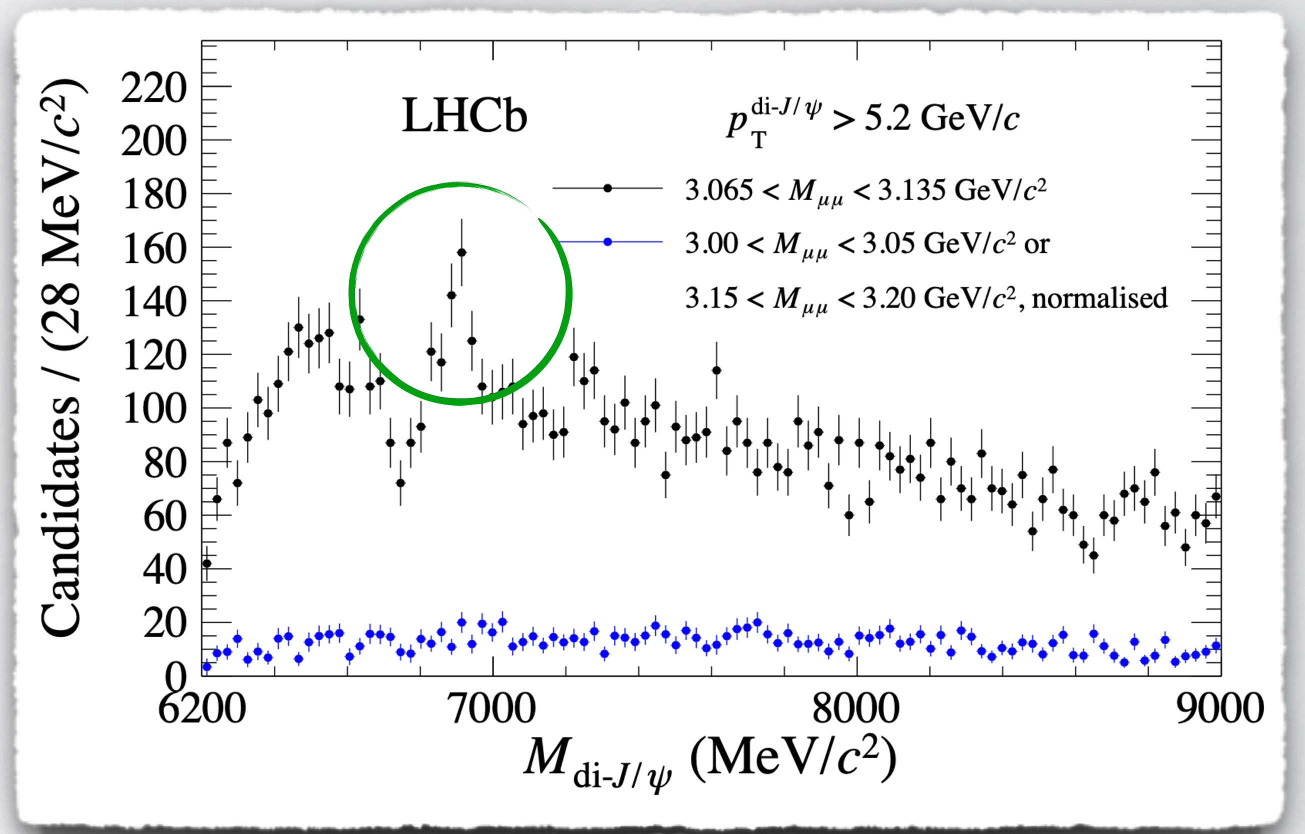
- A number of states predicted by the tetraquark model have been recently observed

- Most striking is the $X(6900) \sim cc\bar{c}\bar{c}$

$$X(6900) \to J/\psi J/\psi$$

- Breit-Wigner mass and width

$$M = 6905 \pm 18 \text{ MeV}$$
$$\Gamma = 80 \pm 52 \text{ MeV}$$



[LHCb — Sci.Bull. (2020), 2006.16957]

- No single light hadron can create loosely bound molecules out of charmonia ⟶ most likely a tetraquark

[Maiani — Sci. Bull. (2020), 2008.01637; see also Dong et al. — 2107.03946]

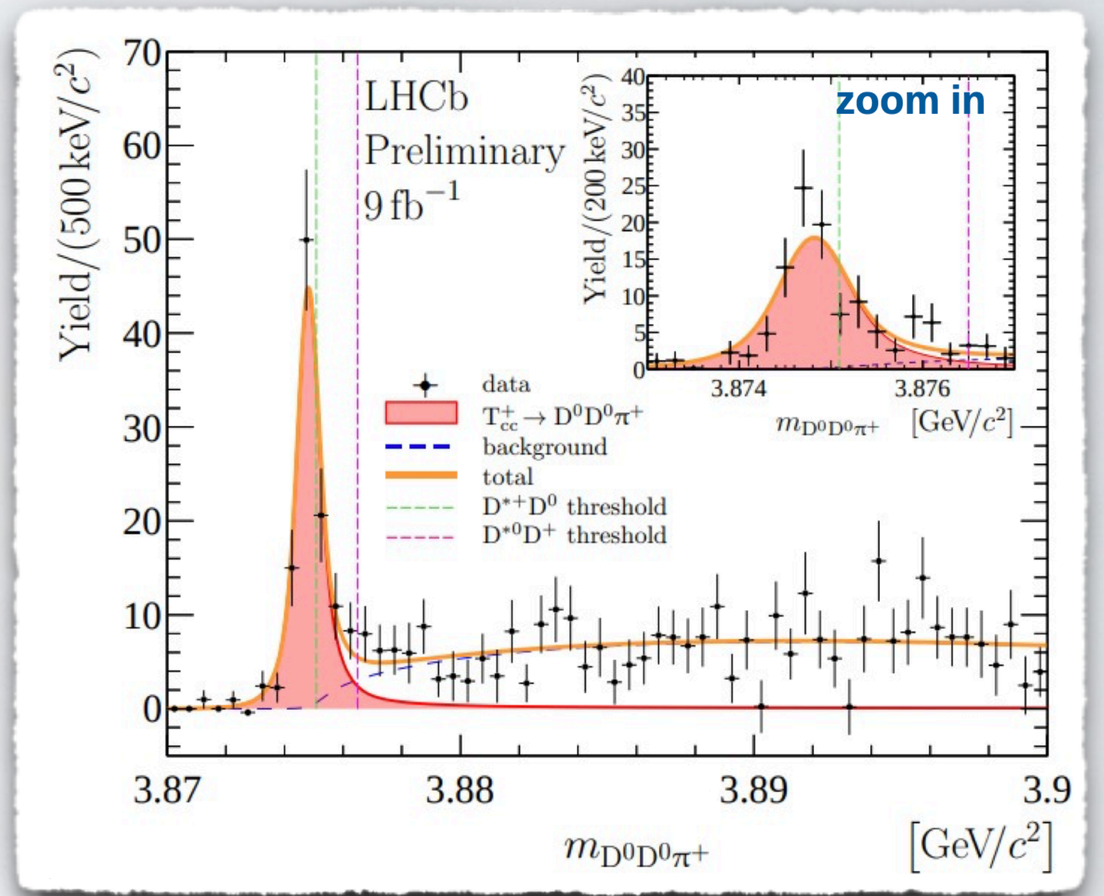
AN EMERGING PATTERN

Doubly charmed

- LHCb observed the first doubly charmed tetraquark $T_{cc}^{+}(cc\bar{u}\bar{d}) \to D^0 D^0 \pi^+$

- These states have been predicted/studied in several works

  [see e.g. del Fabbro et al. — PRD (2005), hep-ph/0408258; Carames et al. — PLB (2011); Hyodo et al. — PLB (2013), 1209.6207; AE et al. — PRD (2013), 1307.2873]



[LHCb preliminary — talk presented at EPS-HEP 2021]

- Important for two reasons:

  1. Should be paired with a T_{bb} state far away from threshold

  2. $SU(3)$ multiplet contains doubly-charged states ⟶ cannot be meson molecules because of Coulomb repulsion

AN EMERGING PATTERN

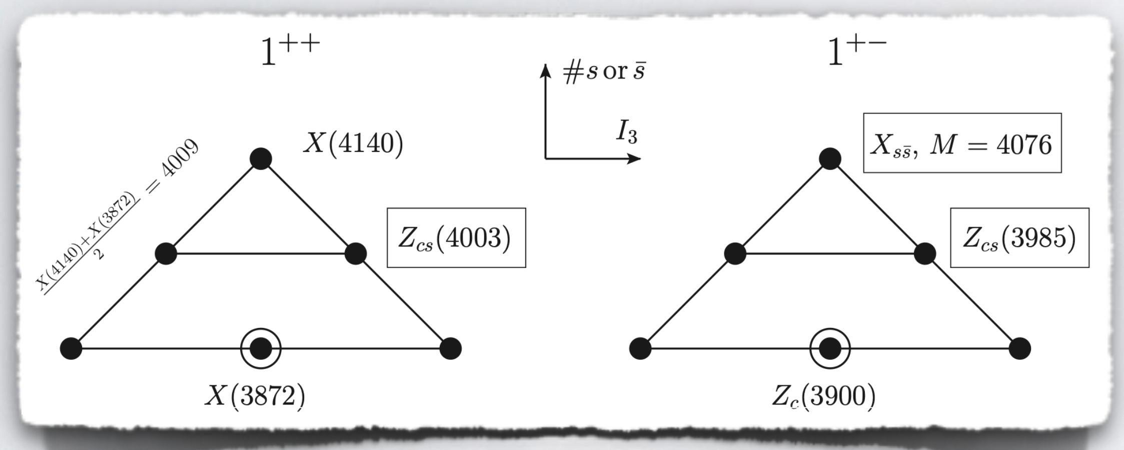
Hidden charm-strange

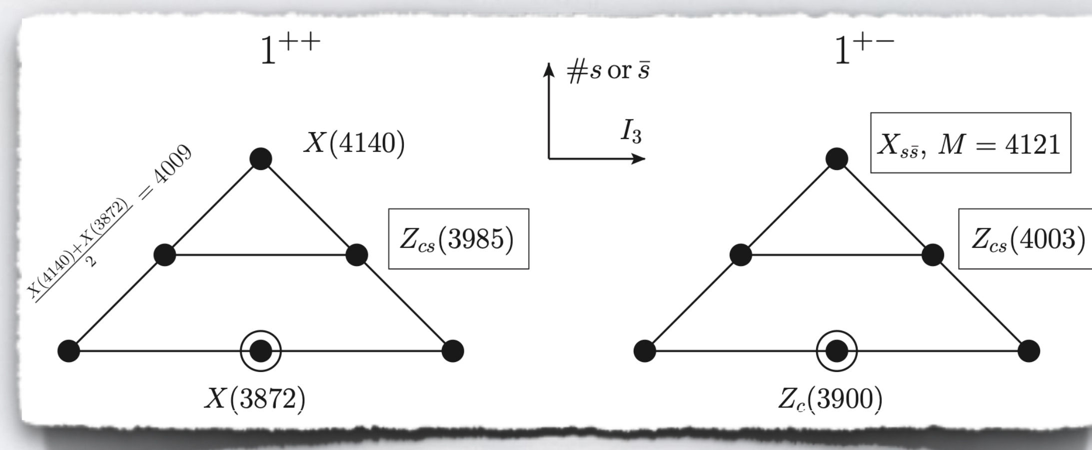
- BESIII and LHCb recently observed hidden charm-strange states

$$Z_{cs}^-(3985) \to D_s^- D^{*0} \qquad \text{and} \qquad Z_{cs}^+(4003) \to J/\psi K^+$$

[BESIII – PRL (2021), 2011.07855; LHCb – PRL (2021), 2103.01803]

- Nicely fit in the $SU(3)$ multiplets of the $X(3872)$ and $Z_c(3900)$





[Maiani, Polosa, Riquer – Sci.Bull. (2021), 2103.08331]

- π-exchange forces are very different from η, ϕ-exchange $\longrightarrow$ meson molecules should not fall into $SU(3)$ multiplets

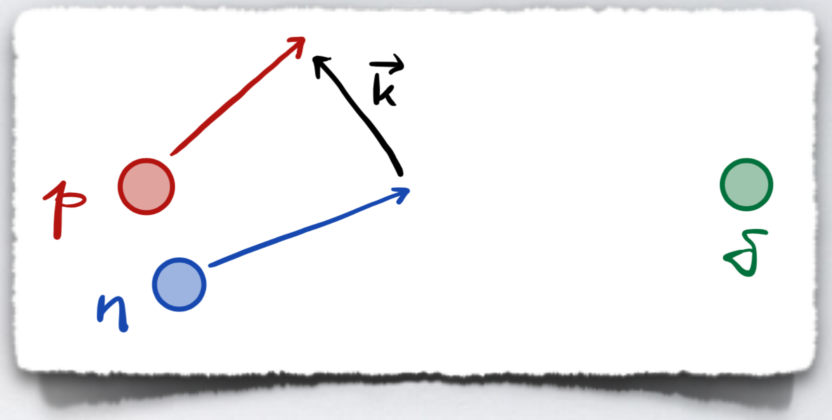
LINESHAPE OF THE $X(3872)$

Weinberg's compositeness criterion

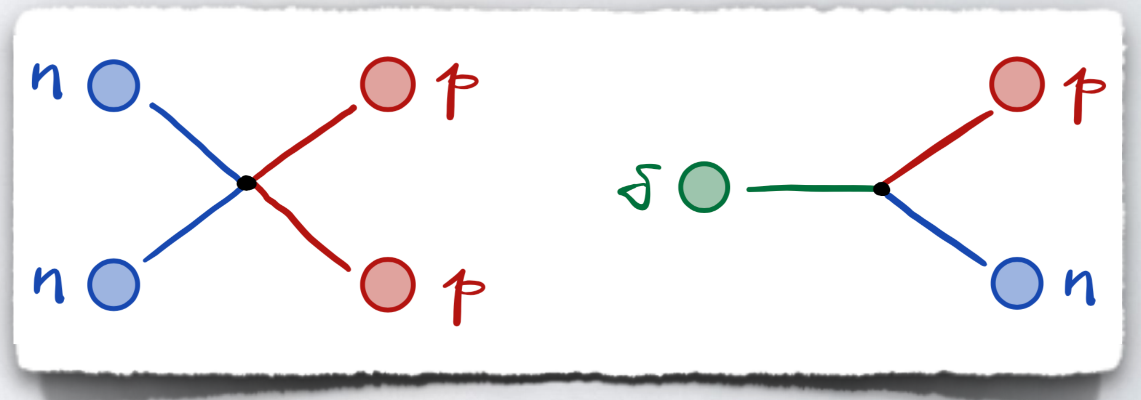
- Analogue question: is the deuteron composite or elementary?

[Weinberg — Phys. Rev. (1965)]

- Free Hamiltonian H_0 contains:
  1. Free proton-neutron pairs, $|pn(\mathbf{k})\rangle$
  2. **Possibly** an elementary deuteron, $|\mathfrak{d}\rangle$



- Interaction potential V in general contains:
  1. Quartic $pn - pn$ interaction
  2. Cubic $\mathfrak{d} - pn$ interaction



LINESHAPE OF THE $X(3872)$

Weinberg's compositeness criterion

- The physical interacting deuteron will in general by

$$|d\rangle = \sqrt{Z}\,|\mathfrak{d}\rangle + \int \frac{d^3k}{(2\pi)^3} C(\mathbf{k})\,|pn(\mathbf{k})\rangle$$

- Three qualitatively different instances:
  A. Deuteron is a composite state $(Z = 0)$ ⟶ no $\mathfrak{d}$ in the theory ⟶ deuteron is generated by $pn - pn$ interactions
  B. Deuteron is elementary and free $(Z = 1)$ ⟶ physical deuteron is just $\mathfrak{d}$
  C. Deuteron is elementary and interacting $(0 < Z < 1)$ ⟶ the state overlaps with free pn pairs (not a molecule!)

- *"An elementary deuteron would have* $0 < Z < 1$*"* [Weinberg — Phys. Rev. (1965)]

LINESHAPE OF THE $X(3872)$

Weinberg's compositeness criterion

- Using old fashioned perturbation theory and/or EFTs one derives

$$a = 2\frac{1-Z}{2-Z}\frac{1}{\sqrt{2\mu B}} + O\left(m_\pi^{-1}\right), \qquad r_0 = -\frac{Z}{1-Z}\frac{1}{\sqrt{2\mu B}} + O\left(m_\pi^{-1}\right)$$

A. Composite deuteron $(Z=0)$ $\longrightarrow$ $r_0 = O\left(m_\pi^{-1}\right)$

B. Elementary deuteron $(Z>0)$ $\longrightarrow$ $r_0 < 0$ and $|r_0| \gtrsim m_\pi^{-1}$

- The deuteron is indeed composite: $r_0^{exp} \simeq +1.7\text{ fm} \simeq m_\pi^{-1}$

- *"The true token that the deuteron is composite is an effective range r_0 small and positive rather than large and negative"* [Weinberg — Phys. Rev. (1965)]

LINESHAPE OF THE $X(3872)$

Smorodinsky's theorem for molecules

- A theorem by Smorodinsky also fixes the sign of the $O\left(m_\pi^{-1}\right)$ terms

- Starting from the Schrodinger's equation for an attractive potential one finds the following exact expression for the effective range

solution to the free equation for $k = 0$

solution to the full equation for $k = 0$

$$r_0 = 2\int_0^\infty dr\left(\psi_0^2 - u_0^2\right) > 0$$

- What happens to the deuteron is indeed a theorem:

For ground state molecules we always have $r_0 > 0$

[Smorodinsky — Dokl.Akad.Nauk (1948)]

LINESHAPE OF THE $X(3872)$

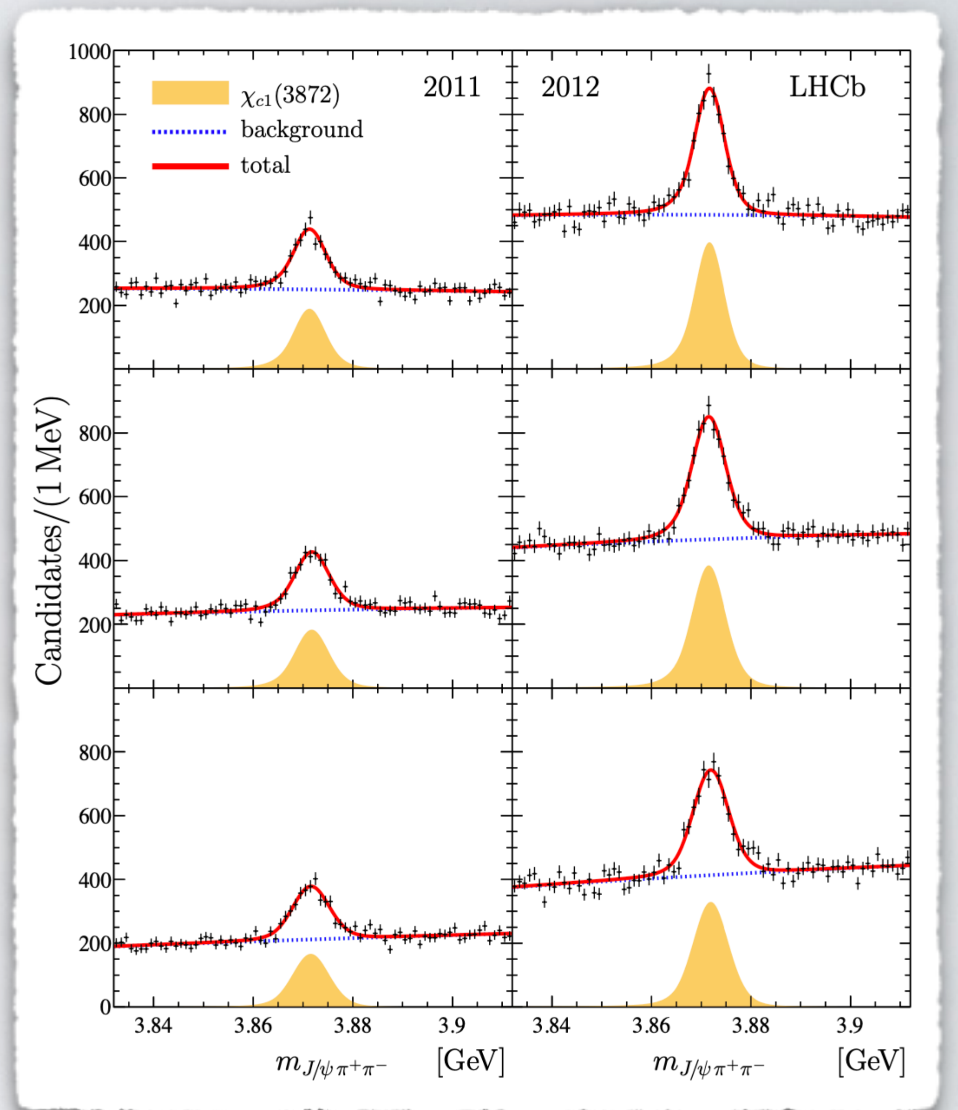
The LHCb data

- What does LHCb say about the $X(3872)$?

[LHCb — PRD (2020), 2005.13419]

- LHCb lineshape is:

$$f(X \to J/\psi \pi^+\pi^-) = -\frac{N}{E - m_X^0 + \frac{i}{2} g_{LHCb}\left(\sqrt{2\mu E} + \sqrt{2\mu_+(E-\delta)}\right) + \frac{i}{2}\left(\Gamma_\rho^0 + \Gamma_\omega^0 + \Gamma_0^0\right)}$$



- Fit to high statistics data returns

$$m_X^0 = -7.18 \text{ MeV} \quad (\text{fixed}), \qquad g_{LHCb} = 0.108 \pm 0.003$$

LINESHAPE OF THE $X(3872)$

The LHCb data

- To apply the composite criterion we must set $\Gamma^0_\rho = \Gamma^0_\omega = \Gamma^0_0 = 0$:

$$f\left(X \to J/\psi\pi^+\pi^-\right) \simeq -\frac{N\frac{2}{g_{LHCb}}}{\frac{2}{g_{LHCb}}\left(E - m_X^0\right) - \sqrt{2\mu_+\delta + E\sqrt{\frac{\mu_+}{2\delta}}} + ik}$$

- From here we extract

$$r_0 = -\frac{2}{\mu g_{LHCb}} - \sqrt{\frac{\mu_+}{2\mu^2\delta}} \simeq -5.34 \text{ fm}$$

[Esposito, Maiani, Pilloni, Polosa, Riquer — 2108.11413]

- The effective range is negative and well beyond m_π^{-1} ⟶ the dynamics can only be explained if the X is an elementary, interacting tetraquark

CONCLUSION

- Compact tetraquarks are a systematic, universal way of describing exotic mesons
- While the issue is still largely debated, recent data seem to fit very well within this description (new states, prompt production, …)
- If the LHCb analysis is confirmed, it is an unequivocal indication of the existence of a compact $X(3872)$ interacting with other mesons via short-distance QCD forces
- The completion of the tetraquark flavor-spin multiplet is crucial $\longrightarrow$ a promising avenue to look for scalar and tensor states is in ultra-peripheral heavy ion collisions (to appear soon w/ Manzari, Pilloni, Polosa)

Thank you for your attention!