EXOTIC HADRONS

(Esposito, Germani, Maiani, Polosa)

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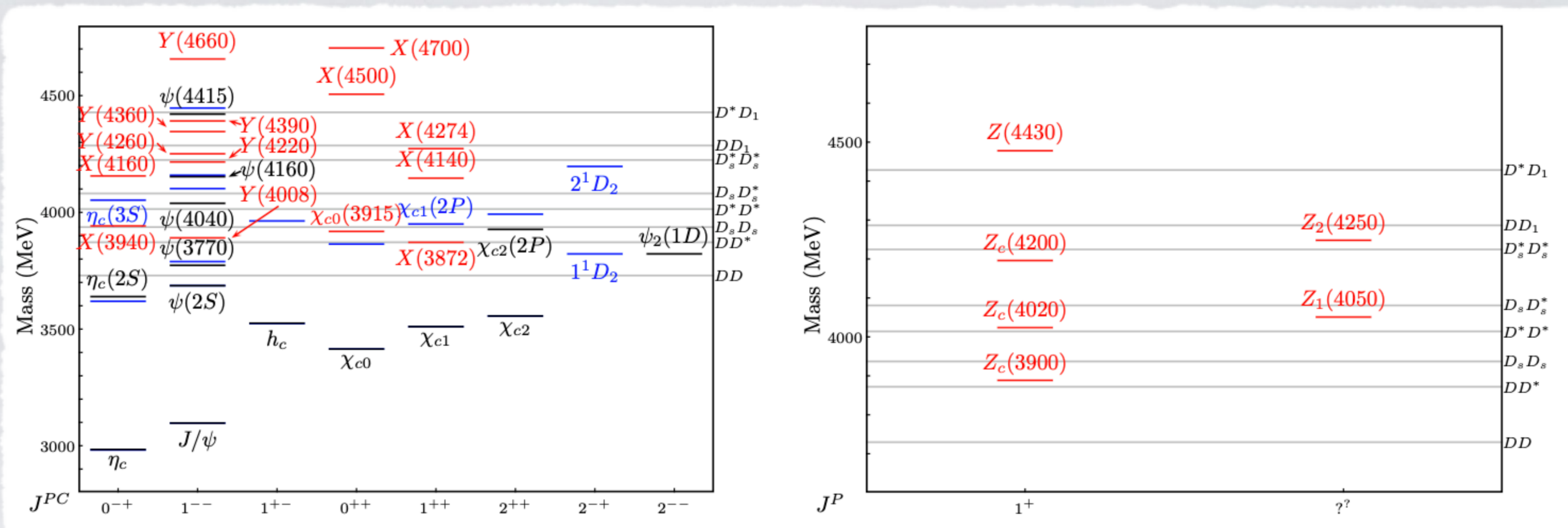
4-QUARK STATES

- Since 2003, ~ 20 resonances that cannot be described as heavy $Q\bar{Q}$

Unexpected masses and quantum numbers, anomalously narrow, electrically charged, …



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

- $X(3872)$:

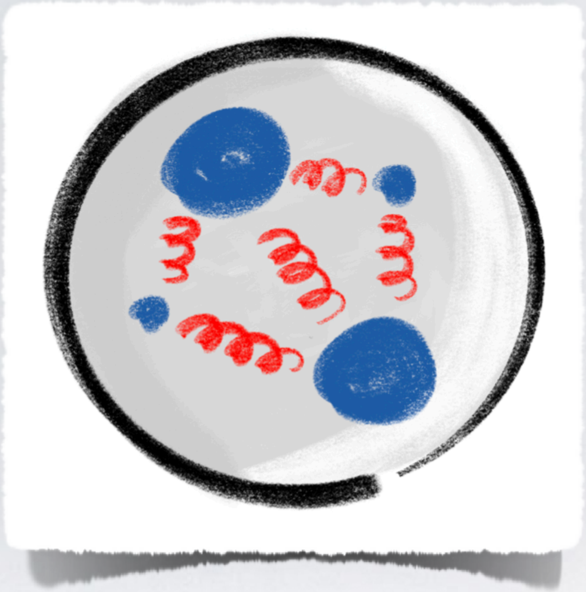
$$m_X \simeq m_{D^0} + m_{\bar{D}^{*0}}$$

$$\Gamma_X \simeq 200 \text{ keV}, \quad \Gamma(X \to J/\psi\rho) \simeq \Gamma(X \to J/\psi\omega)$$

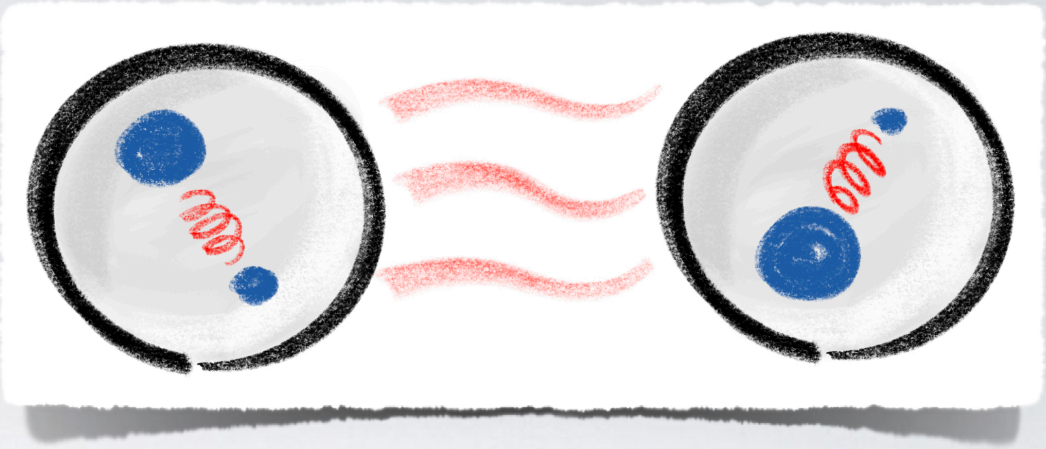
$Q\bar{Q}q_1\bar{q}_2$ **states!**

4-QUARK STATES

- How are the constituents organized?



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



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

Tetraquark

Generated by short distance QCD

Hadronic size $(r \sim 1 \text{ fm})$

Analogue to mesons and baryons

Meson molecule

Vanishing binding energy $(B \simeq 0)$

Generated by long distance QCD

Very large $(r \gg 1 \text{ fm})$

Analogue to deuteron

EFFECTIVE RANGE

- A way to discriminate between the two instances is by looking at low energy meson-meson scattering:

$$f(k) = \frac{1}{-1/a - ik + \frac{1}{2} r_0 k^2 + \ldots}$$

- Weinberg's compositness criterion: [Weinberg — Phys. Rev. 1965]

$$|r_0| \lesssim 1/\Lambda \quad \Rightarrow \quad \text{molecule}$$
$$r_0 < 0 \text{ and } |r_0| \gg 1/\Lambda \quad \Rightarrow \quad \text{compact}$$

- Model independent → very promising!

EFFECTIVE RANGE

- The application of Weinberg's criterion to high-statistics LHCb data results in

$$X(3872): \quad r_0 \in [-5.3, -1.6]\ \text{fm} \quad \Rightarrow \quad |r_0| \gtrsim 1/m_\pi$$
$$T_{cc}^+(3875): \quad r_0 \in [-16.2, -4.3]\ \text{fm} \quad \Rightarrow \quad |r_0| \gg 1/m_\pi$$

[**AE**, Maiani, Pilloni, Polosa, Riquer — PRD 2022, 2108.11413; Mikhasenko — 2203.04622]

- In both instances this points to a compact nature… however:

A. application of Weinberg's criterion has been critisized

[Baru et al. — PLB 2022, 2110.07484]

B. are we sure that $\Lambda \sim m_\pi$ is correct?

EFFECTIVE RANGE

- It is possible to explicitly include effect of the pion on the scattering amplitude → very interesting non-unitary behavior

$$D^* \to D\pi \quad \Rightarrow \quad V_\pi(r) \sim \frac{e^{-i\mu r}}{r}$$

- Contribution of the pion to the effective range can be computed, but is completely negligible:

$$\text{Re}\, r_0 \in [-0.20, -0.16]\ \text{fm}\,, \qquad \text{Im}\, r_0 \in [0, 0.17]\ \text{fm}$$

[**AE**, Germani, Glioti, Polosa, Rattazzi, Tarquini — PLB 2023, 2307.11400]

- No news here… are the $X(3872)$ and the $T_{cc}^+(3875)$ truly compact?

RADIATIVE DECAYS

- Another discriminant between tetraquarks and molecules could be the radiative decays of the $X(3872)$

- Experimentally one finds

$$\mathcal{R} = \frac{\mathcal{B}(X \to \psi'\gamma)}{\mathcal{B}(X \to \psi\gamma)} = 2.46 \pm 0.93$$

[LHCb — Nucl.Phys.B 2014, 1404.0275]

- Radiative decay can only happen via:

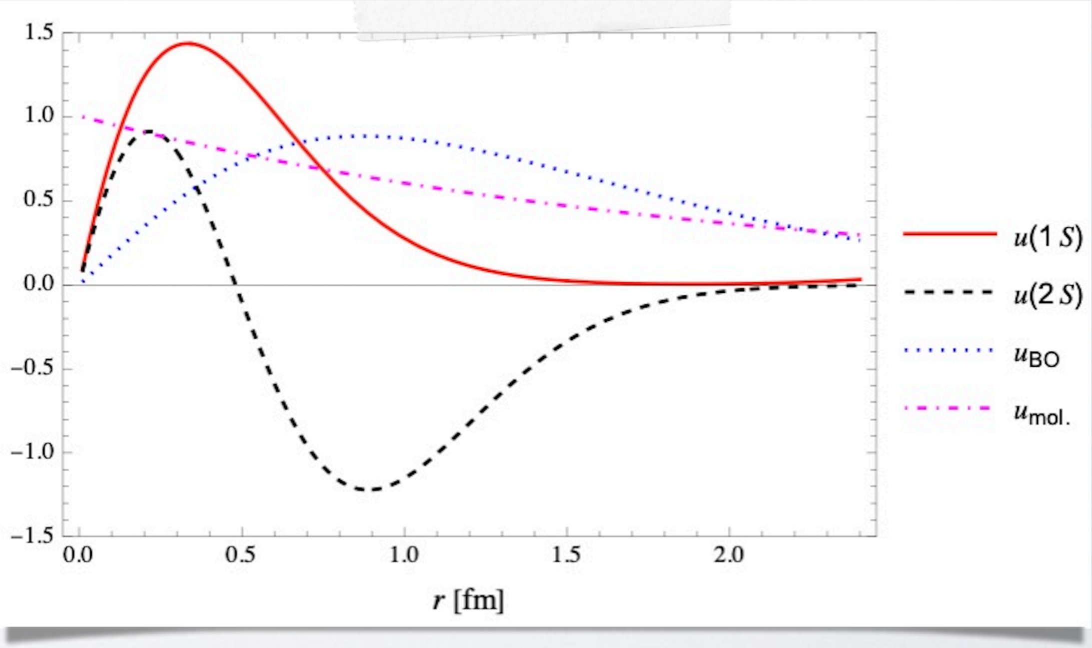
$$c\bar{c}q\bar{q} \to c\bar{c}(q\bar{q}) \to (c\bar{c})\gamma$$

- Decay rate essentially dictated by the size of the initial state vs the size of the final one

RADIATIVE DECAYS

- For the tetraquark, radiative decays can be computed within the Born-Oppenheimer approximation:

$$r_{tetra} \sim r_{c\bar{c}} \quad \Rightarrow \quad \mathscr{R}\,\big|_{tetra} \simeq 1 - 12$$



- The molecular wave function is instead fixed by universality:

$$\psi(r) \sim \frac{e^{-r/a}}{r} \quad \Rightarrow \quad r_{mol} \gg r_{c\bar{c}} \quad \Rightarrow \quad \mathscr{R}\,\big|_{mol} \simeq 0.04$$

- Universality forces the ratio for a meson molecule to be much smaller than what observed

[Grinstein, Maiani, Polosa — 2401.11623]

COMMENTS

- The question about the nature of the exotic hadron is a compelling open problem in low energy QCD

- Very active field, with constant interplay between theory and experiment

- Of utmost important to identify model independent observables able to discriminate between possibilities

Thank you for the attention!