Exotic Spectroscopy

‘Old’ problems and New solutions

A. Esposito, A. Glioti, D. G., A. D. Polosa arXiv:2502.02505 [hep-ph]

Overview

Introduction

- **Exotic hadrons**
- **Exotic spectroscopy**

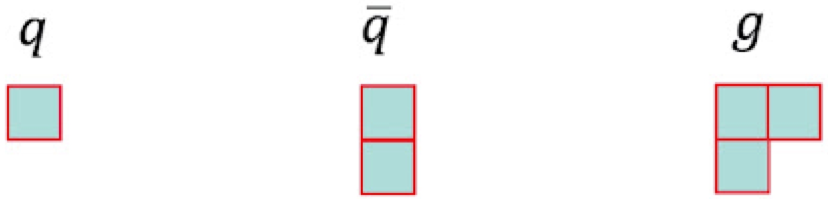
X(3872): compact vs molucule

- **X(3872) natura from NREFT**
- **Future prospects**

Exotic Hadrons

Exotic hadrons are subatomic particles composed of quarks and gluons, but which consist of more than three valence quarks or have an explicit valence gluon content.

R. Jaffe, **Phys. Rev. D 15, 267 (1977)** DOI: 10.1103/PhysRevD.15.267; H. Fritzsch and M. Gell-Mann, **Proceedings of the XVI International Conference on High Energy Physics**, Chicago-Batavia (**1972**).



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- $\mathbf{SU(3)_C}$ **rule:** every combination is allowed **as long as** it respects **confinement i.e. boxes forms columns of three elements**

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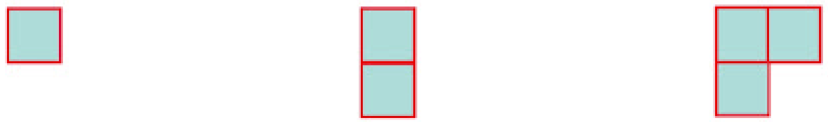

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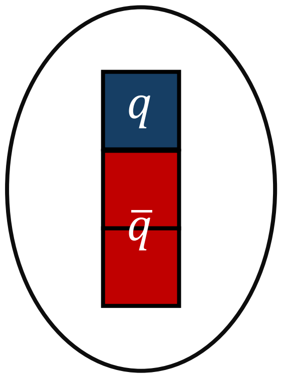

Meson

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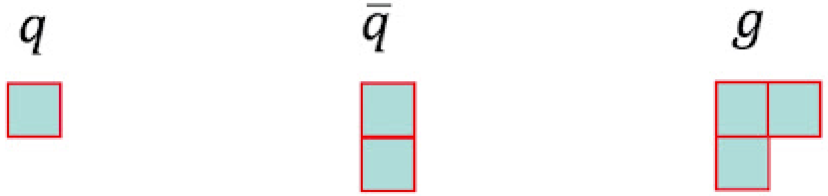

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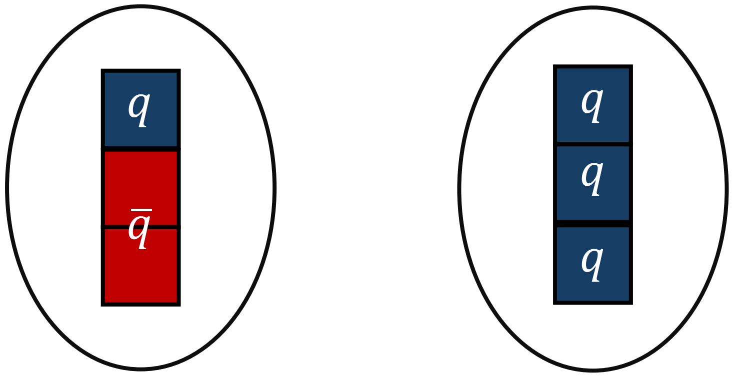

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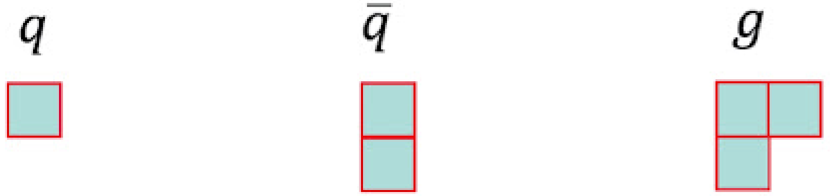

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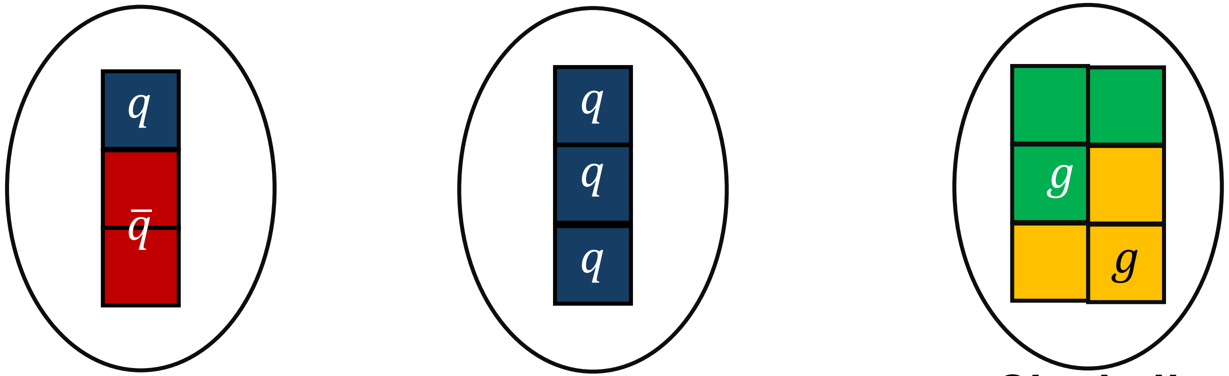

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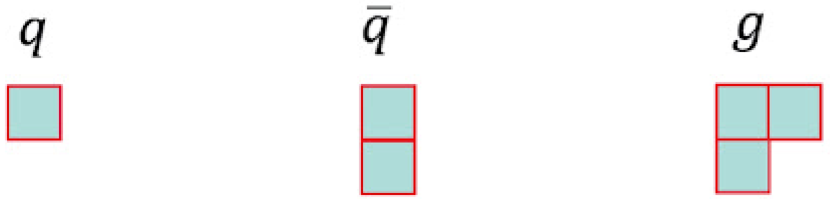

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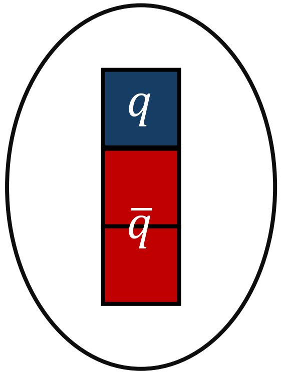

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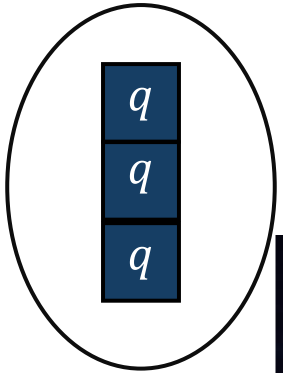

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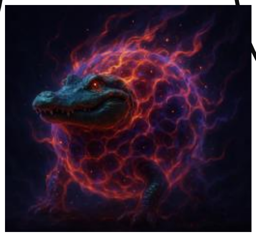
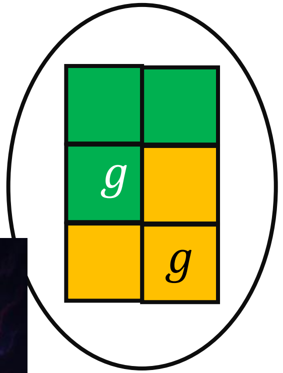


ChatGPT



~~Glueball~~
Gluballo

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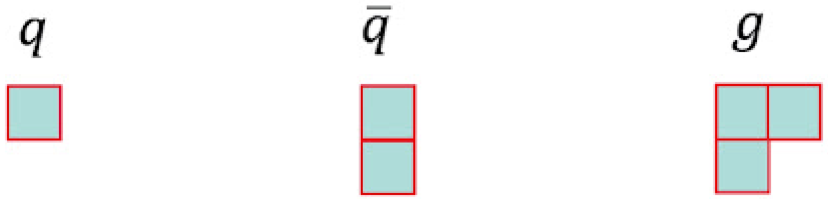

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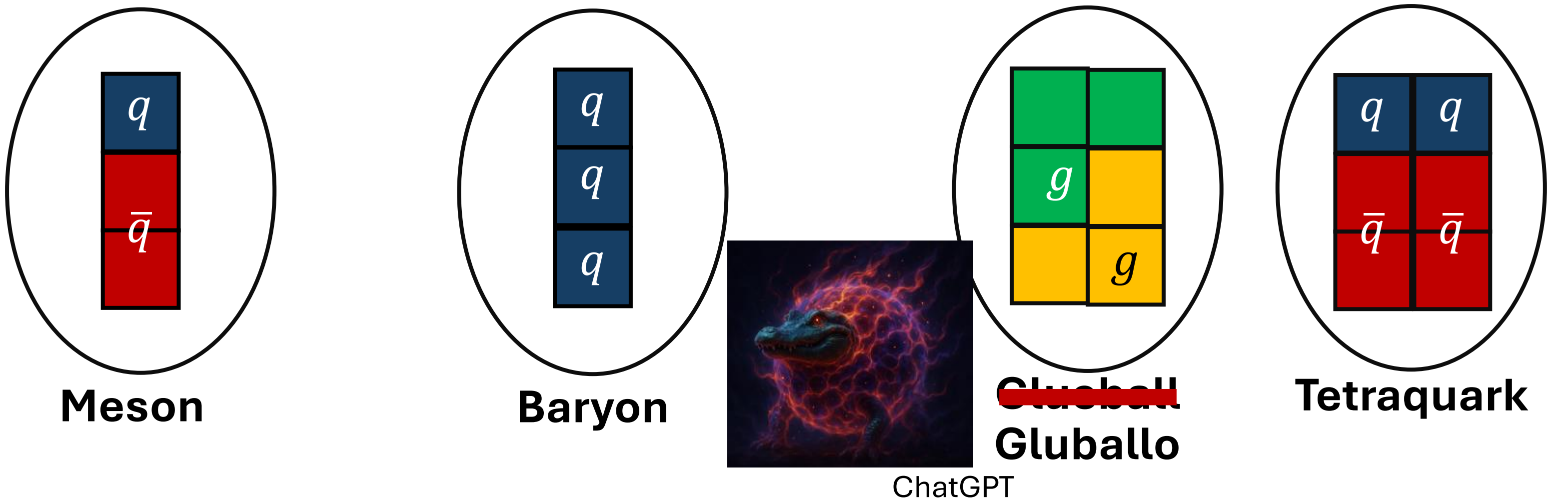

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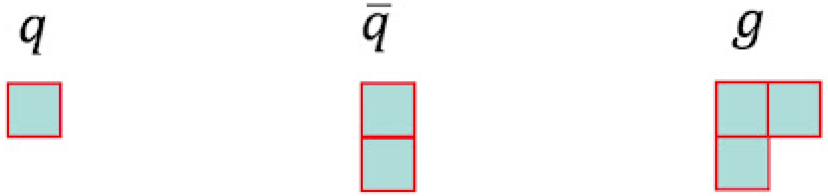

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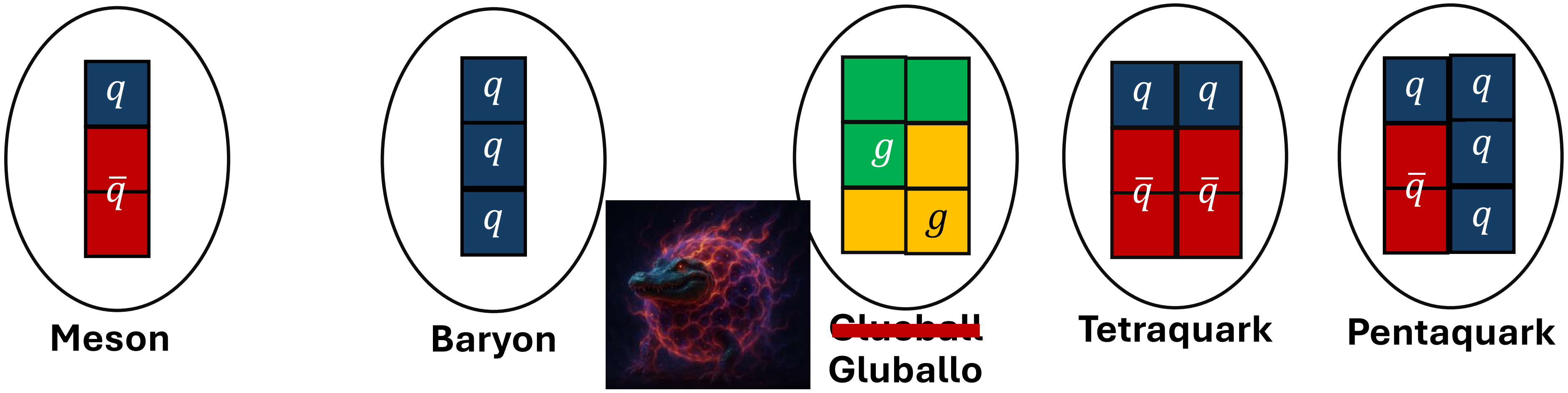

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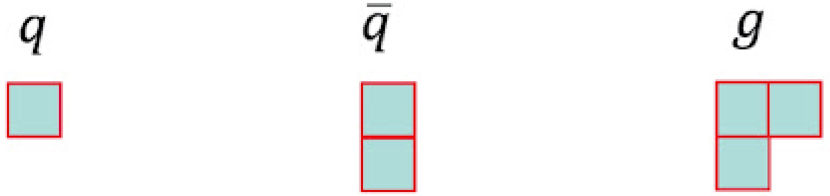

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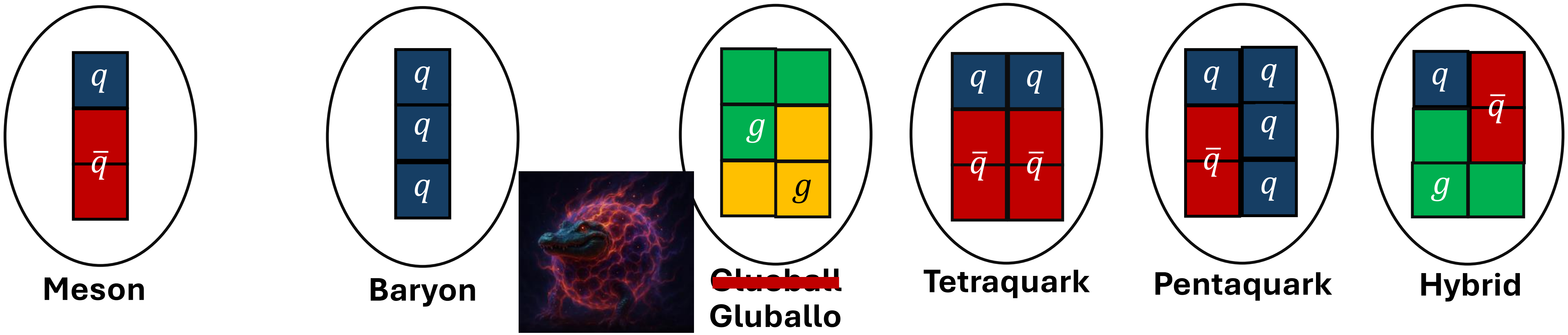

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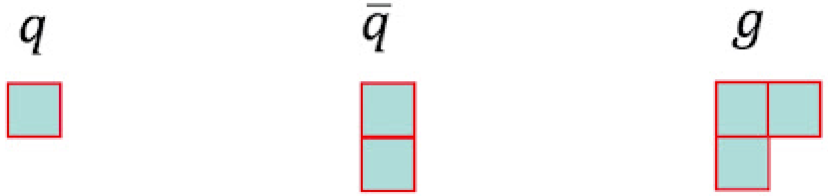

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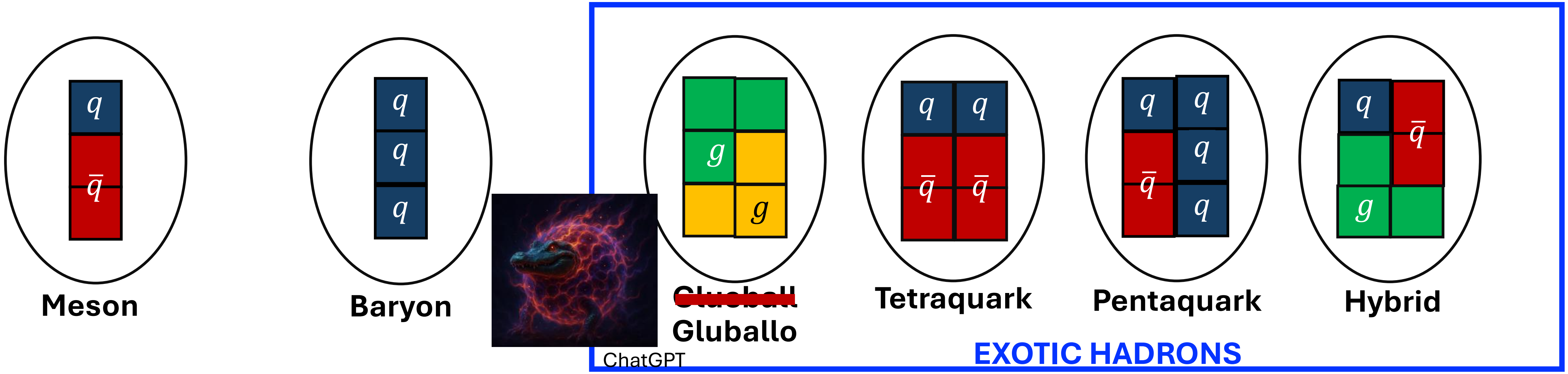
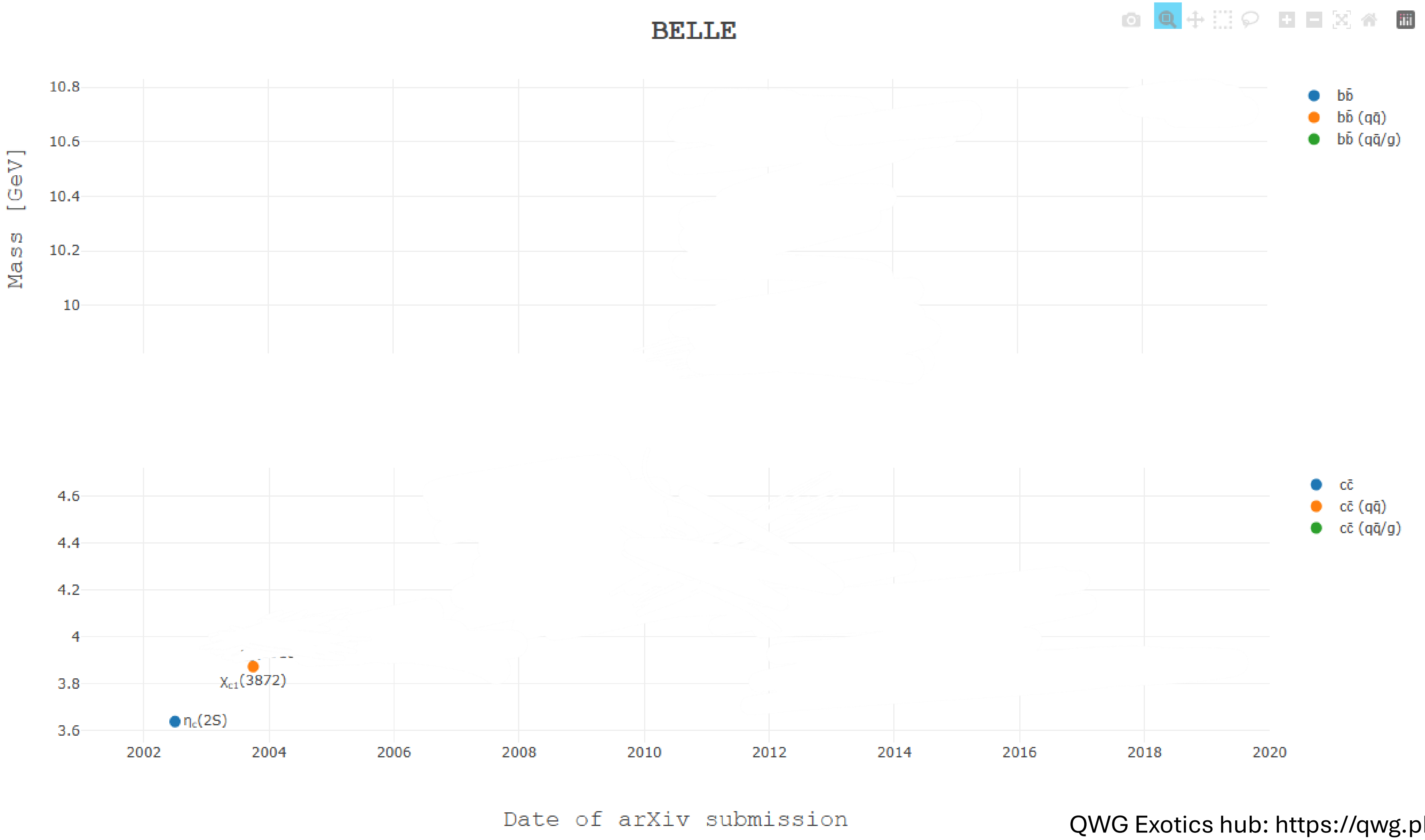


Exotic Hadrons

Although the existence of exotic states had already been theorized in the 1970s, the first exotic particle was discovered in 2003: the ***X(3872)***.



QWG Exotics hub: https://qwg.ph.nat.tum.de/exoticshub/

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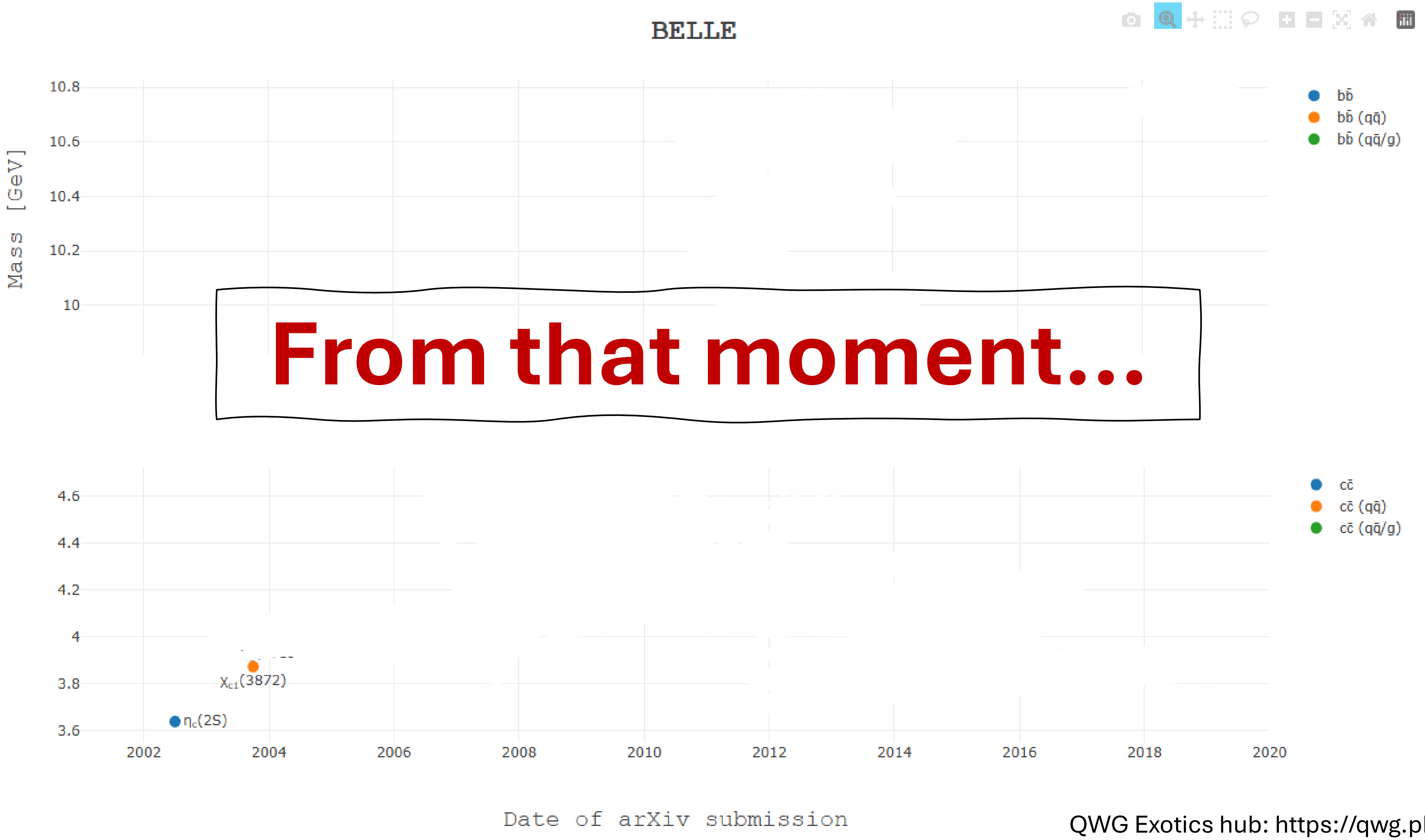

From that moment…

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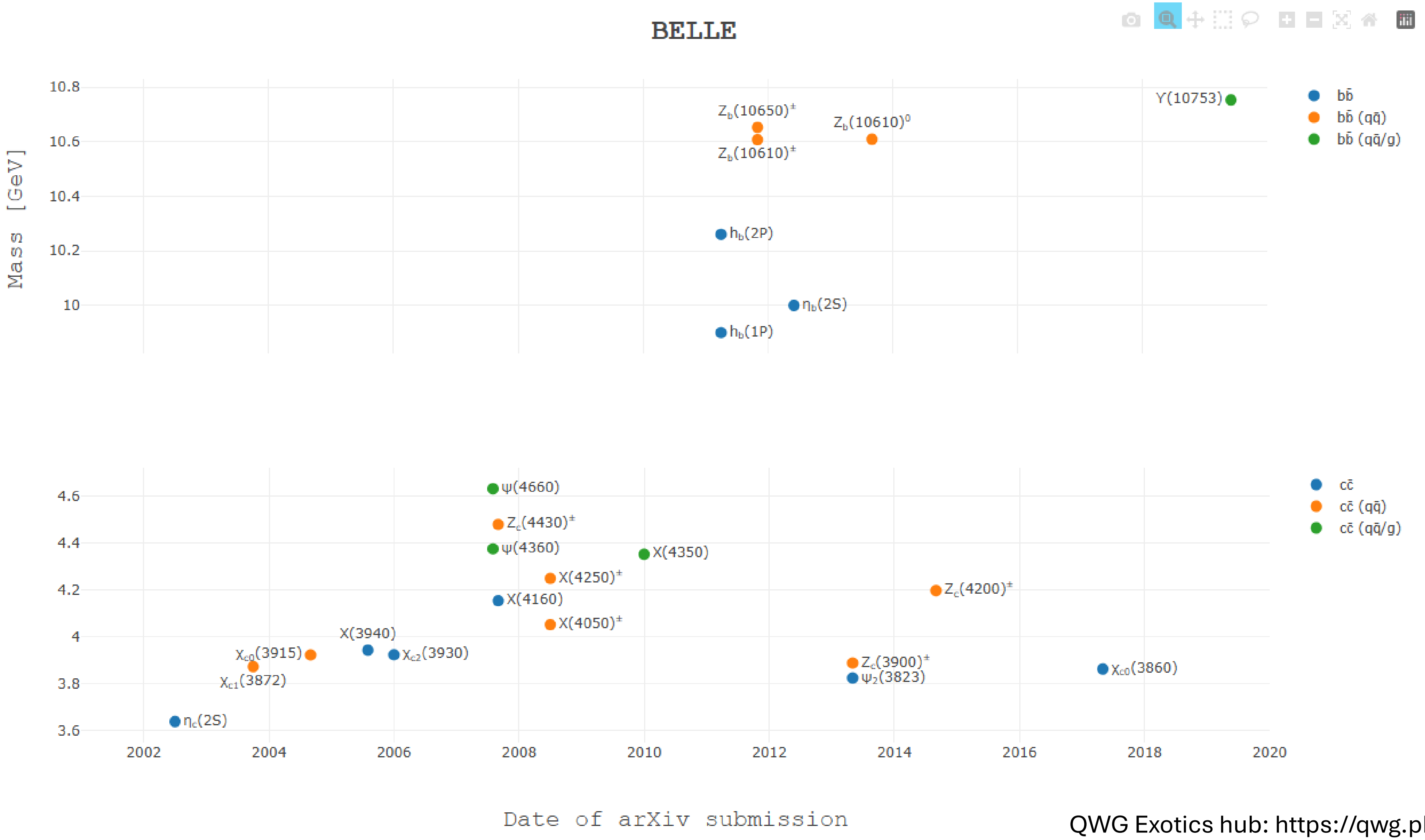

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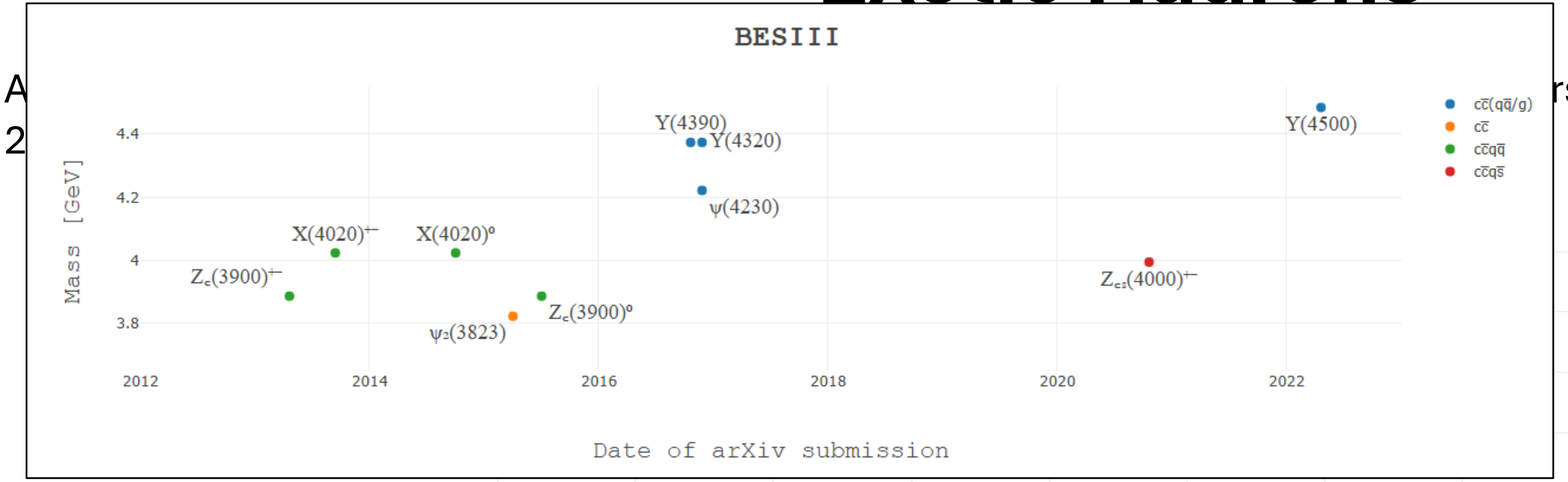

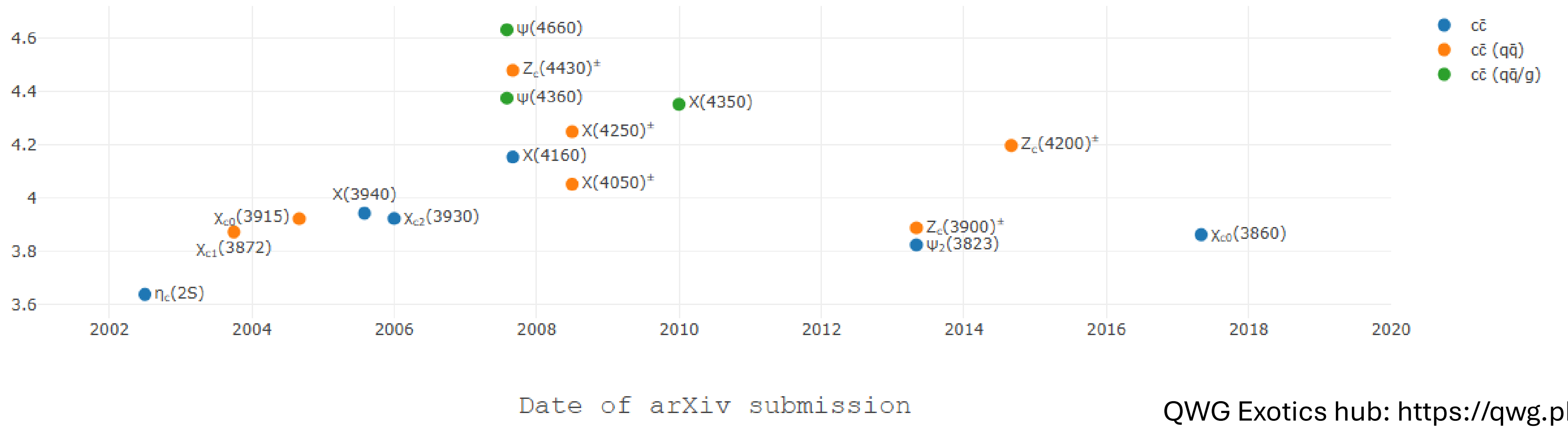

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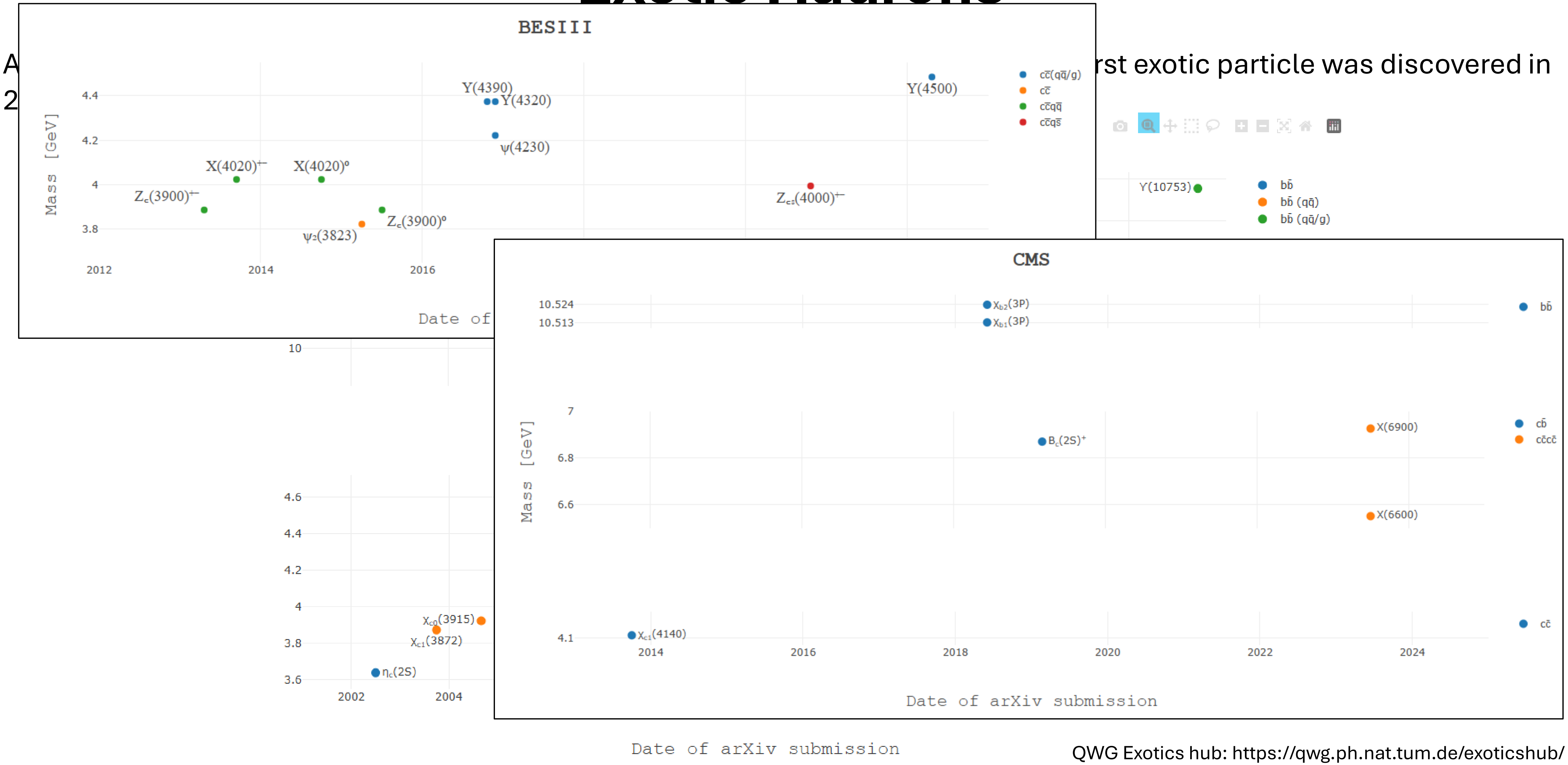

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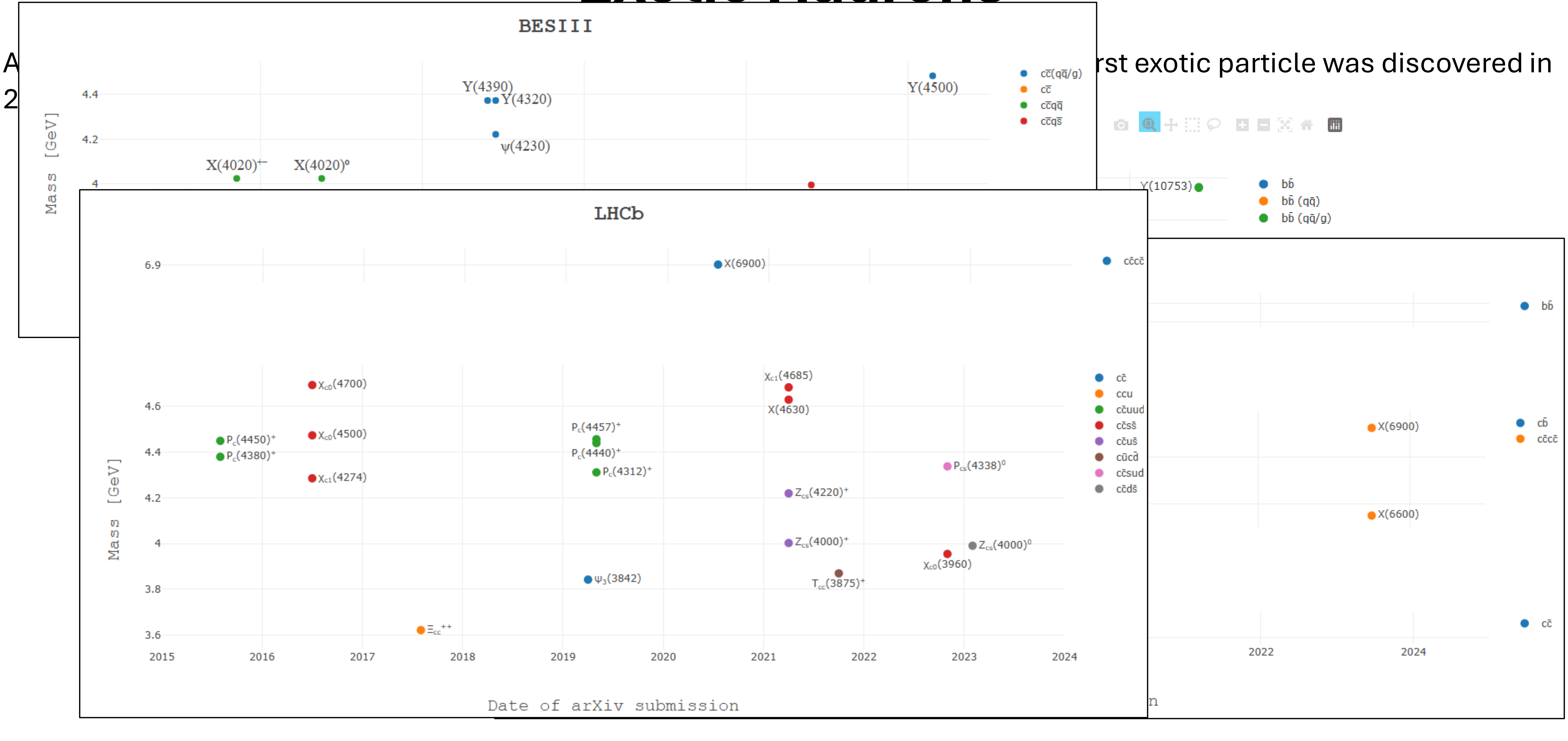

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Exotic spectroscopy

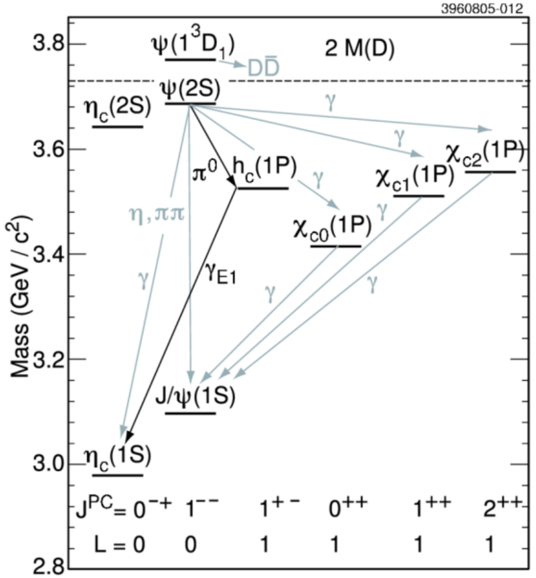
Around **50 exotic hadrons** with at least one heavy (c or b) quark are reported.

N. Hüsken, E. Spadaro Norella, I. Polyakov **arXiv:2410.06923 [hep-ph]**

Exotic spectroscopy is a branch of particle physics that focuses on studying the properties of exotic hadrons.

- Provide a theoretical explanation of the experimentally observed properties, grounded as much as possible in first principles (QCD).
- Make predictions about the masses and quantum numbers of exotic hadrons to test hypotheses on the non-confining dynamics of QCD.

Idea



[CLEO Collaboration], **Phys. Rev. D 72**, 092004 (2005)

Reality

Figure from E. Braaten talk: **Charm 2020 conference**

Who is the *X(3872)*?

$$I(J^{PC}) = 0(1^{++})$$

↓

Isosinglet

DISTINGUISHING FEATURES:

Threshold distance:

$$(m_D + m_{D^*}) - m_X \sim O(\text{keV})$$

Main decay channel:

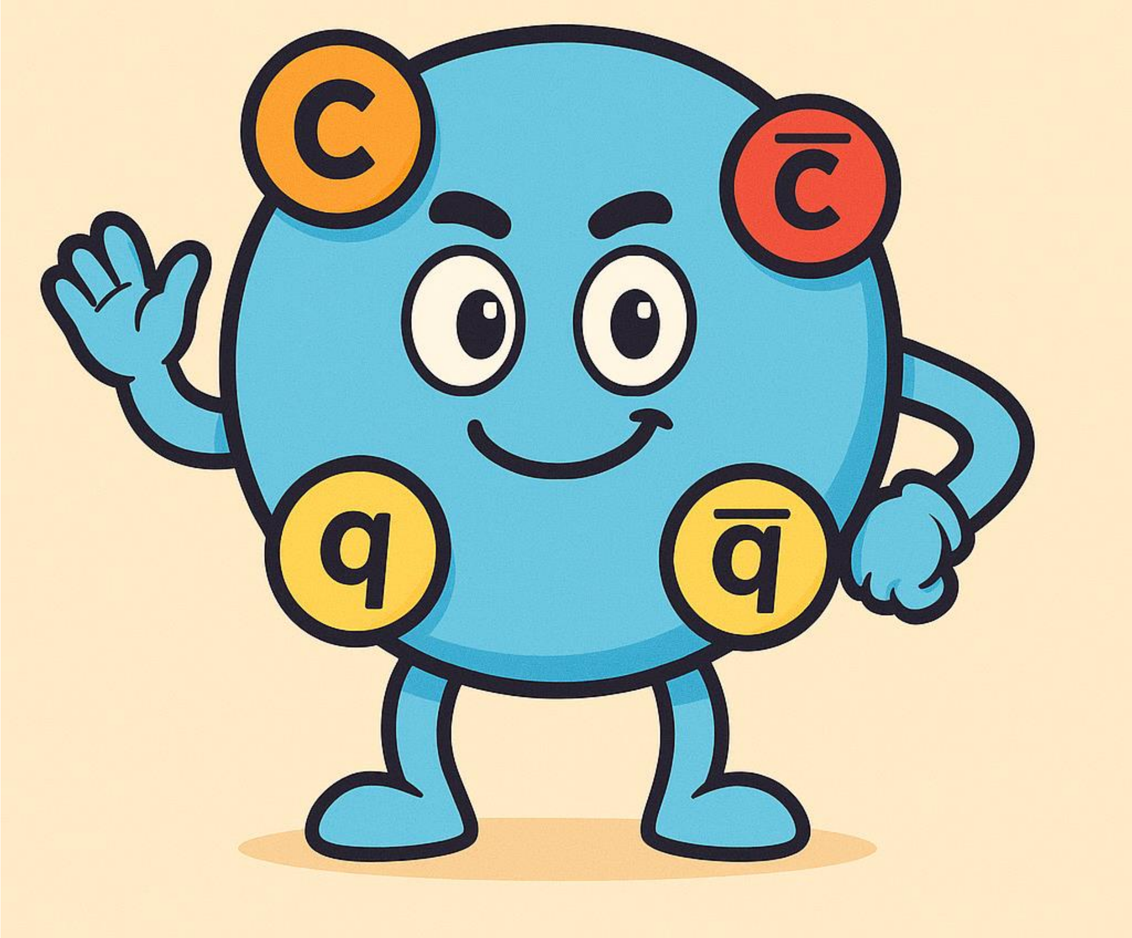
$$X(3872) \longrightarrow D^0\bar{D}^{0*} \longrightarrow D^0\bar{D}^0\pi^0 \quad (\mathbf{55 \pm 28})\%$$

Isospin violating decay:

$$\frac{\mathcal{B}\left(X \to J/\psi\,\omega\right)}{\mathcal{B}\left(X \to J/\psi\,\rho\right)} \simeq 1$$

S. Navas et al. (Particle Data Group), **Phys. Rev. D 110**, 030001 (2024)

Exotic Meson $[Q\bar{Q}q\bar{q}]$



Mass: $\mathbf{3871.65 \pm 0.06}$ MeV

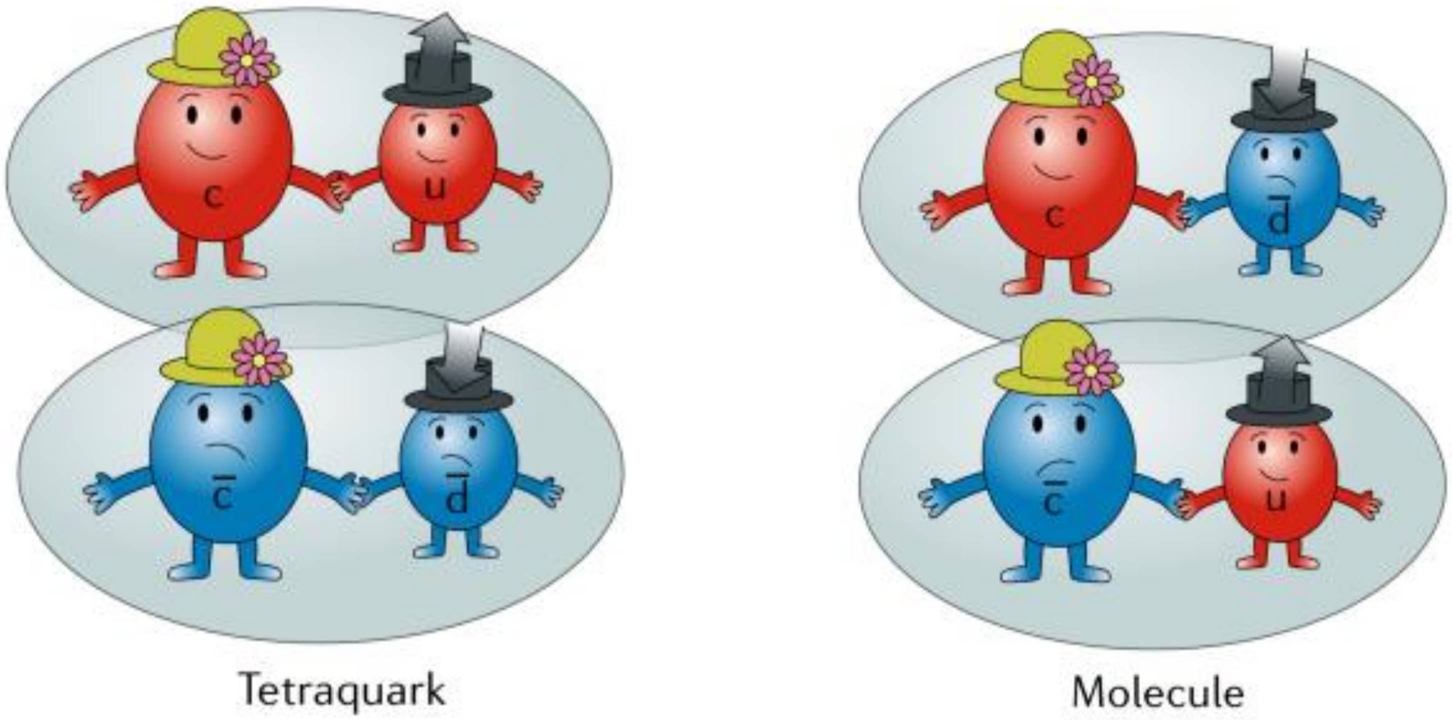
Who is the *X(3872)*?

Fine Tuning

$$B \ll \Lambda_{QCD} \longrightarrow \frac{1}{10^3}$$

Compact objects vs Molecules

The X(3872)'s closeness to the $D^0 D^{*0}$ threshold makes it challenging to clearly determine whether the state is molecular or compact.



C. Z. Yuan and S. L. Olsen **Nat Rev Phys 1**, 480-494 (2019)

Non-relativistic EFT: Effective range & Nature of Poles

At low energies, the scattering amplitude depends on two parameters.

Limit $k \to 0$:

$$f(\theta) \simeq f_0 = \frac{1}{k\cot\delta_0 - ik}$$

$$k\cot\delta_0 = -\frac{1}{a_s} + \frac{1}{2}r_0 k^2 + \mathcal{O}(k^4)$$

The sign of r_0 is related to whether the particle is a molecule or a compact state (Weinberg 1965).

Weinberg Phys. Rev. 137, B672 (1965)

- $a_s > 0$: the pole is related to a **real particle;**
- $a_s < 0$: the pole is related to a **virtual particle.**

- $r_0 \geq 0$: The particle is a **bound state**;
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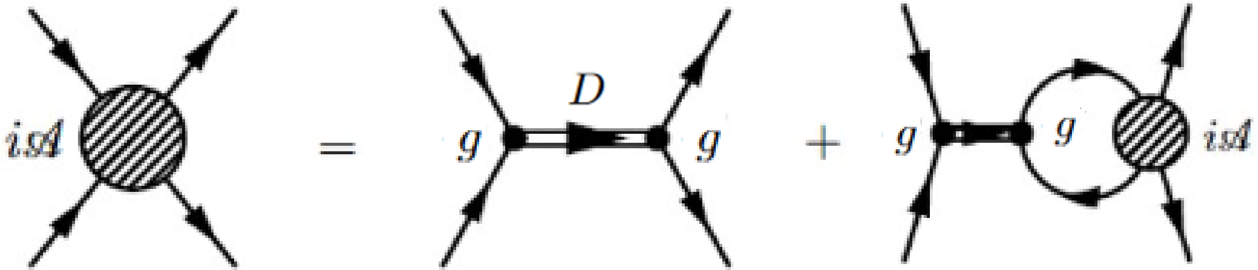
Proton – Neutron: the dibarion field (aka deuteron)

$$\mathscr{L} = N^\dagger \left(i\partial_t + \frac{\nabla^2}{2M} \right) N + \sigma\, D^\dagger \left(i\partial_t + \frac{\nabla^2}{4M} - \mu \right) D - g\, D^\dagger (NN) + h.c.$$

D. B. Kaplan, **Nucl. Phys. B 494(1997)**, 471–484, nucl-th/9610052.

Dibarion field

The dibarion's kinetic term is defined up to a sign $\sigma = \pm 1$



$$f = -\frac{M}{4\pi} \frac{\sigma\, g^2}{E - \mu + i\,\sigma g^2 \frac{M}{4\pi} k}$$

D. B. Kaplan, **Nucl. Phys. B 494(1997)**, 471–484, nucl-th/9610052.

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$$\frac{1}{a_s} = -\sigma \frac{4\pi}{Mg^2}\mu$$

$$r_0 = -\sigma \frac{8\pi}{g^2 M^2}$$

- $\sigma = +1$: 'Classical' kinetic term and $r_0 < 0$. The field represents a **compact particle** if $\mu < 0$.
- $\sigma = -1$: 'Inverted' kinetic term and $r_0 > 0$. The field represents a **bound state** if $\mu > 0$.

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The XEFT

A. Esposito et al. arXiv:2502.02505 [hep-ph]

$$\mathscr{L}_{kin} = D^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_D} - \begin{pmatrix} \Delta_1 & 0 \\ 0 & 0 \end{pmatrix} \right) D + \bar{D}^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_D} - \begin{pmatrix} 0 & 0 \\ 0 & \Delta_1 \end{pmatrix} \right) \bar{D} +$$
$$+ \boldsymbol{D}^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_{D^*}} - \begin{pmatrix} \Delta_2 & 0 \\ 0 & 0 \end{pmatrix} \right) \boldsymbol{D} + \bar{\boldsymbol{D}}^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_{D^*}} - \begin{pmatrix} 0 & 0 \\ 0 & \Delta_2 \end{pmatrix} \right) \bar{\boldsymbol{D}} +$$
$$+ \boldsymbol{X}^\dagger \left(i\partial_t + \frac{\nabla^2}{2(m_D + m_{D^*})} - m_F \right) \boldsymbol{X} \,.$$

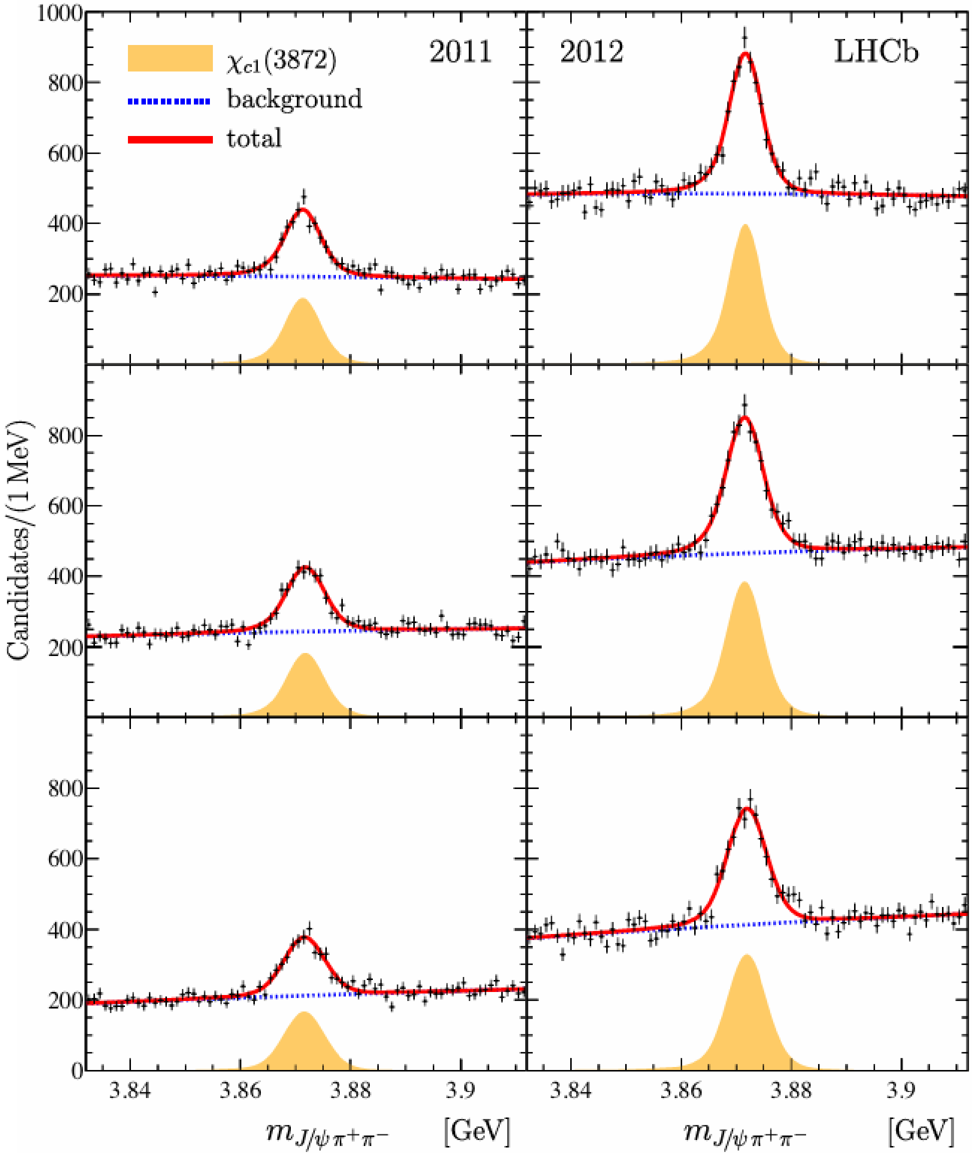
A lot of fields...

and interactions

$$\mathscr{L}_{\rm int} \supset -\frac{\lambda_S}{2} (\bar{D}\boldsymbol{D})_+^\dagger \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} (\bar{D}\boldsymbol{D})_+ - \frac{\lambda_T}{2} (\bar{D}\boldsymbol{D})_+^\dagger \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} (\bar{D}\boldsymbol{D})_+$$
$$- \frac{g}{\sqrt{2}} \boldsymbol{X}^\dagger (\bar{D}^0 \boldsymbol{D}^0)_+ + \frac{g}{\sqrt{2}} \boldsymbol{X}^\dagger (D^- \boldsymbol{D}^+)_+ \,.$$

The XEFT: what can we do?

R. Aaij, et al. [LHCb], Phys. Rev. D 102, 9 (2020),092005, 2005.13419.



$$\frac{dR(J/\psi\pi^+\pi^-)}{dE} \propto \frac{\Gamma_\rho(E)}{|D(E)|^2}$$

$$D(E) = E - E_f + \frac{i}{2}\left[g(k_1 + k_2) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right].$$

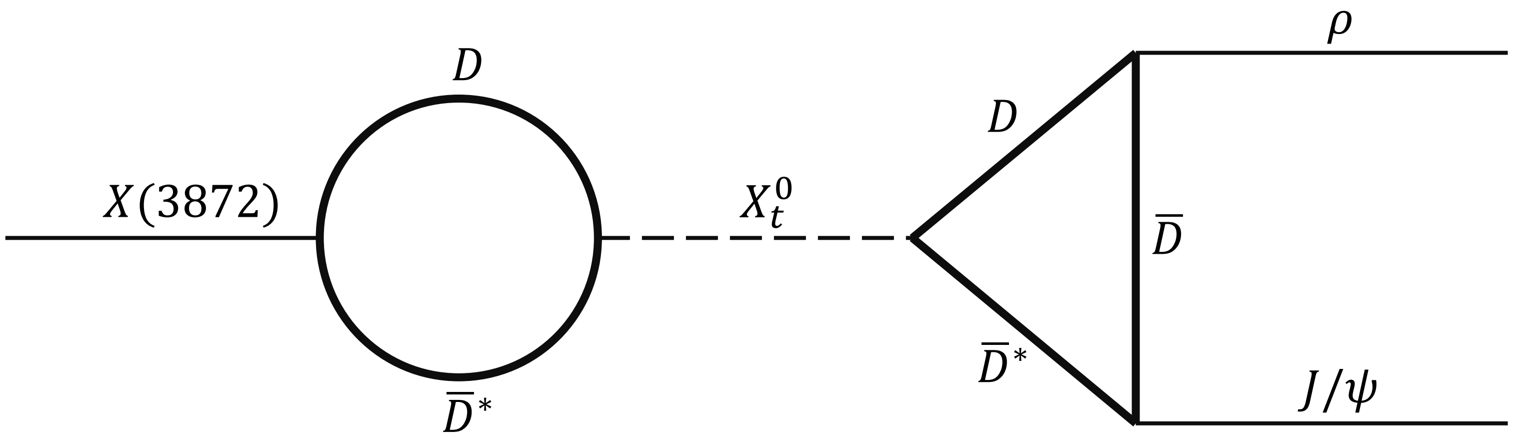
$$\frac{1}{a} = -\frac{2m_F}{g_{\text{LHCb}}} - \sqrt{2m_+\Delta} \simeq 6.92 \text{ MeV},$$

$$r_0 = -\frac{2}{m g_{\text{LHCb}}} - \sqrt{\frac{m_+}{2m^2\Delta}} \simeq -5.34 \text{ fm}.$$

A. Esposito et al. arXiv:2502.02505 [hep-ph]

The XEFT: what needs to be done

In the previous Lagrangian, it is also possible to add a field for the isospin triplet X_t, that we expect since SU(2) is a good symmetry of QCD. By doing so, we can generate loops that turn the isosinglet $X(3872)$ into its neutral isotriplet partner X_t^0.



The enhancement of the isospin violating decay could be due to mixing between the isosinglet and isotriplet, induced by D-meson loops.

Conclusions

Since 2003, the nature of the *X(3872)* has eluded our understanding. In a NREFT framework, we can infer the nature of the resonance by analyzing the kinetic term in the Lagrangian. So far, LHCb data suggest a compact nature for the resonance. By introducing the isospin triplet partners, the isospin-violating decay can be explained through the mixing induced by D and D^* mesons.