

TETRAQUARKS: SUCCESSES, CHALLENGES AND NEW AVENUES

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Double charm tetraquark and other exotics, Lyon 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 $X(3872)$
- Tetraquarks un UPC
- Conclusions

BRIEF REVIEW

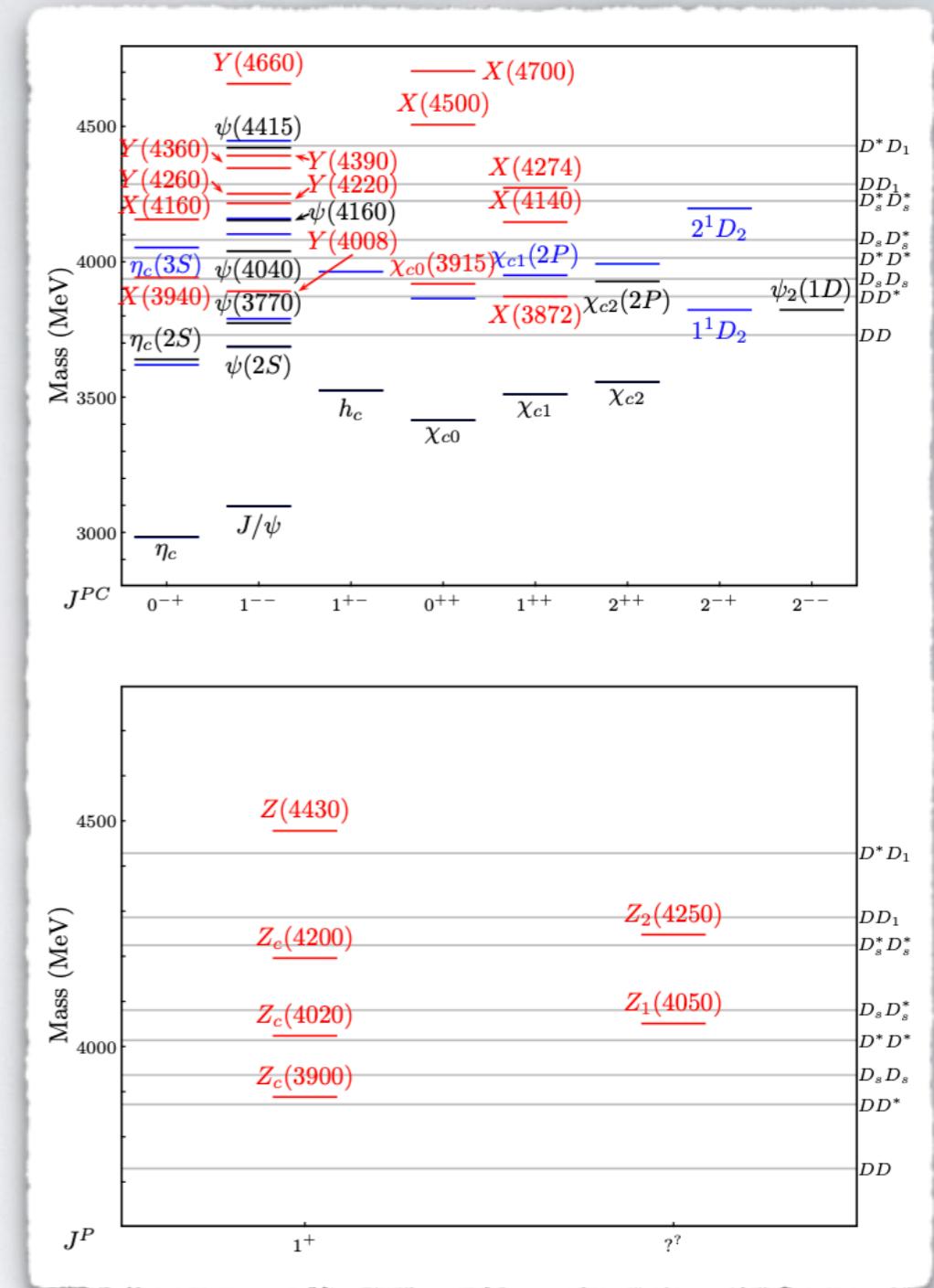
Exotic hadron spectrum

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

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

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

Does not have the same quantum numbers as the vacuum

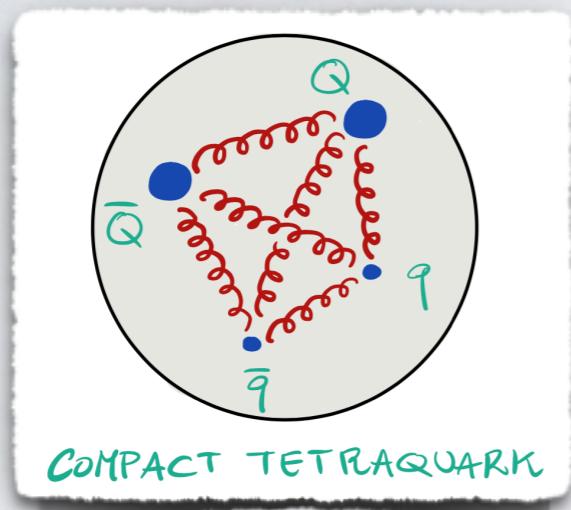


[AE, Pilloni, Polosa – Phys.Rept. (2017), 1611.07920]

EXOTIC MESONS

Possible interpretations

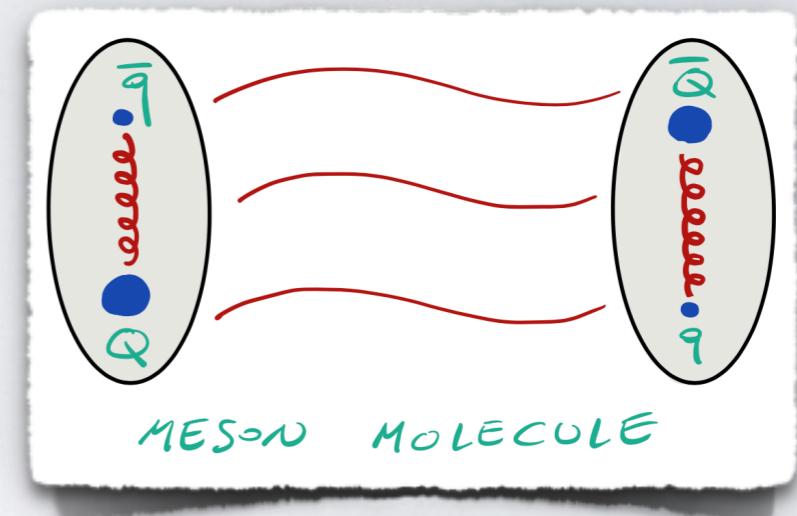
- Two competing interpretations



COMPACT TETRAQUARK

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

- I. Generated by short distance QCD \longrightarrow present in the spectrum at $r \sim 1$ fm
2. Comprehensive and symmetry-based
but... overpopulated



MESON MOLECULE

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

- I. Generated by long distance QCD \longrightarrow due to physics at $r \gg 1$ fm
2. Naturally explains closeness to threshold and decay into open-flavor
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**

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

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

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

↑
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

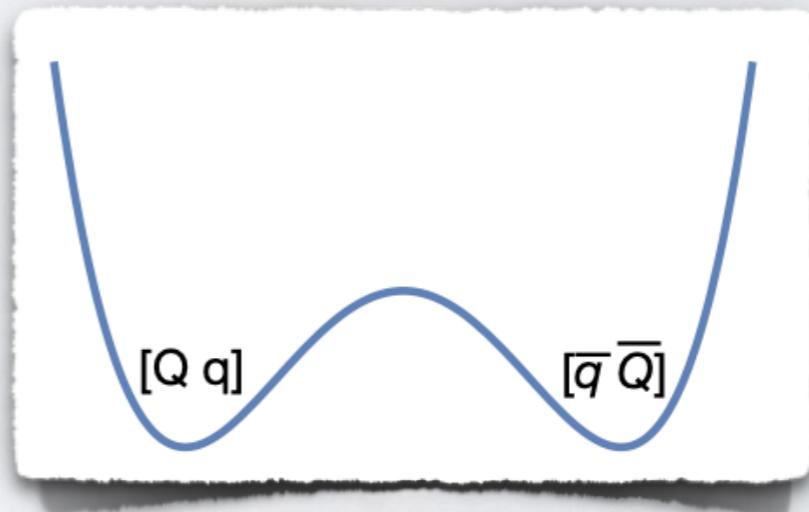
- Mass eigenstates \neq isospin eigenstates: $X_u = [cu][\bar{c}\bar{u}]$, $X_d = [cd][\bar{c}\bar{d}]$
- Since $\alpha_s(2m_c)$ is small \rightarrow mixing between X_u and X_d is suppressed

[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]

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



TETRAQUARKS

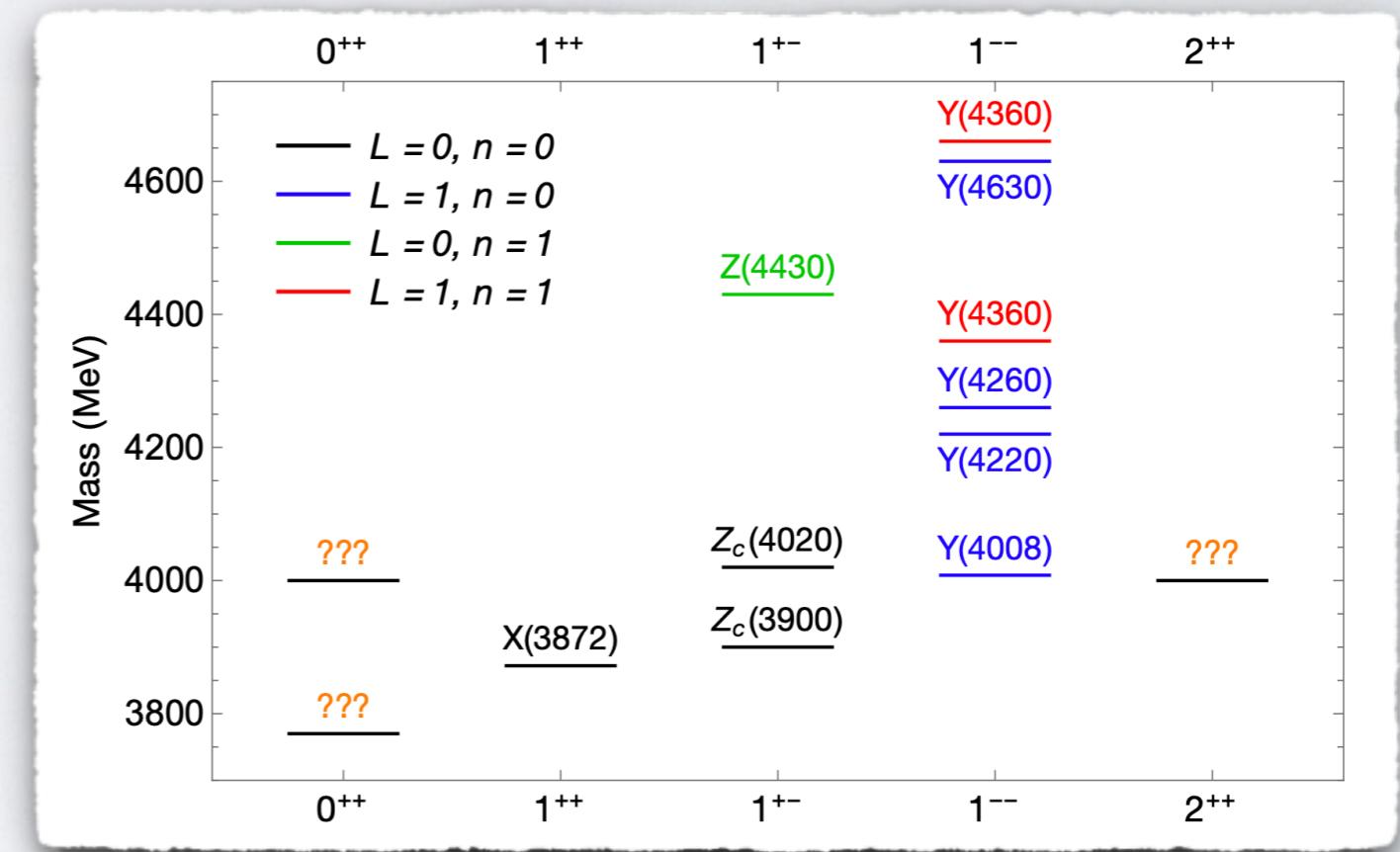
Challenges

- 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?

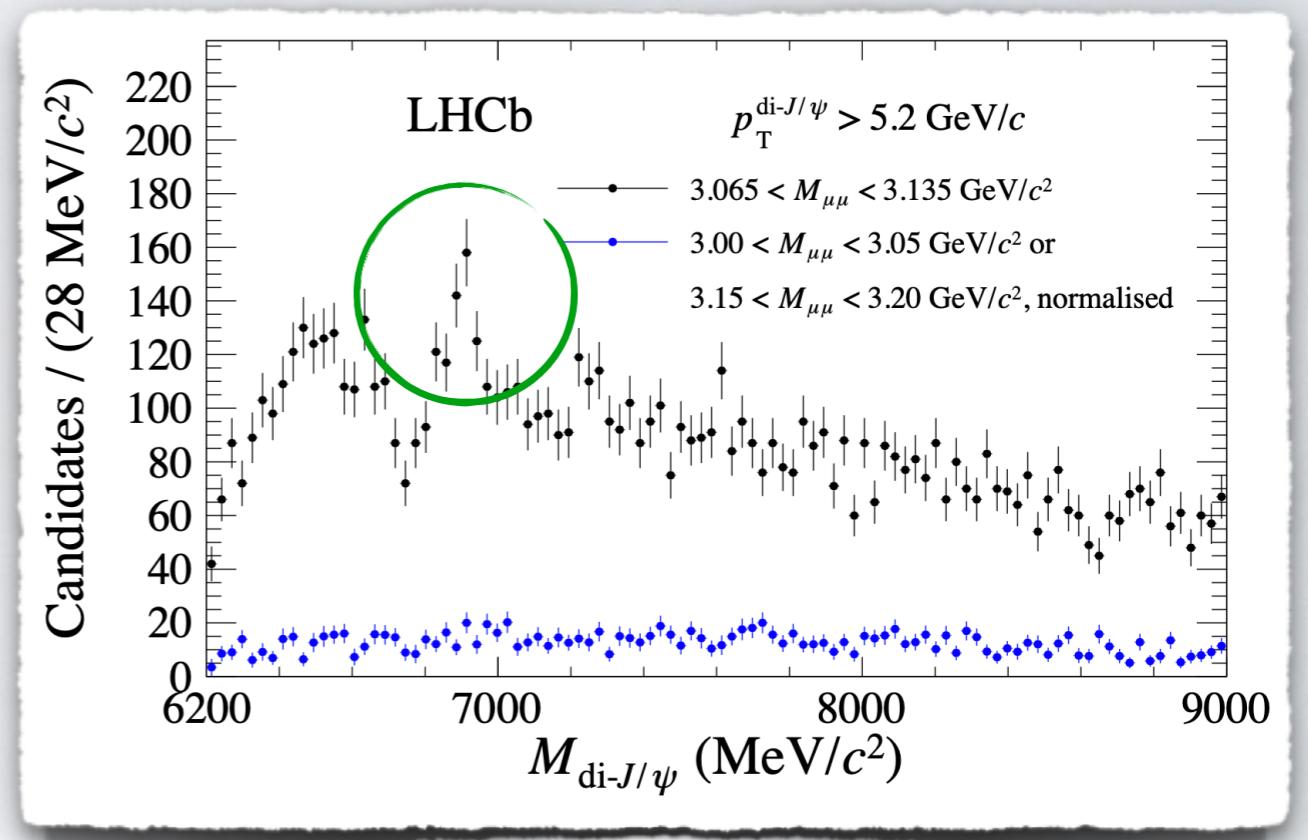
3. Analogue of the $X^{0,\pm}$
in the beauty sector?



AN EMERGING PATTERN

Fully charmed

- A number of states predicted by the tetraquark model have been recently observed
- Most striking is the $X(6900) \sim c\bar{c}c\bar{c}$
$$X(6900) \rightarrow J/\psi J/\psi$$
- Breit-Wigner mass and width
$$M = 6905 \pm 18 \text{ MeV}$$
$$\Gamma = 80 \pm 52 \text{ MeV}$$
- No single light hadron can create loosely bound molecules out of charmonia



[LHCb – Sci.Bull. (2020), 2006.16957]

→ most likely a tetraquark

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

AN EMERGING PATTERN

Doubly charmed

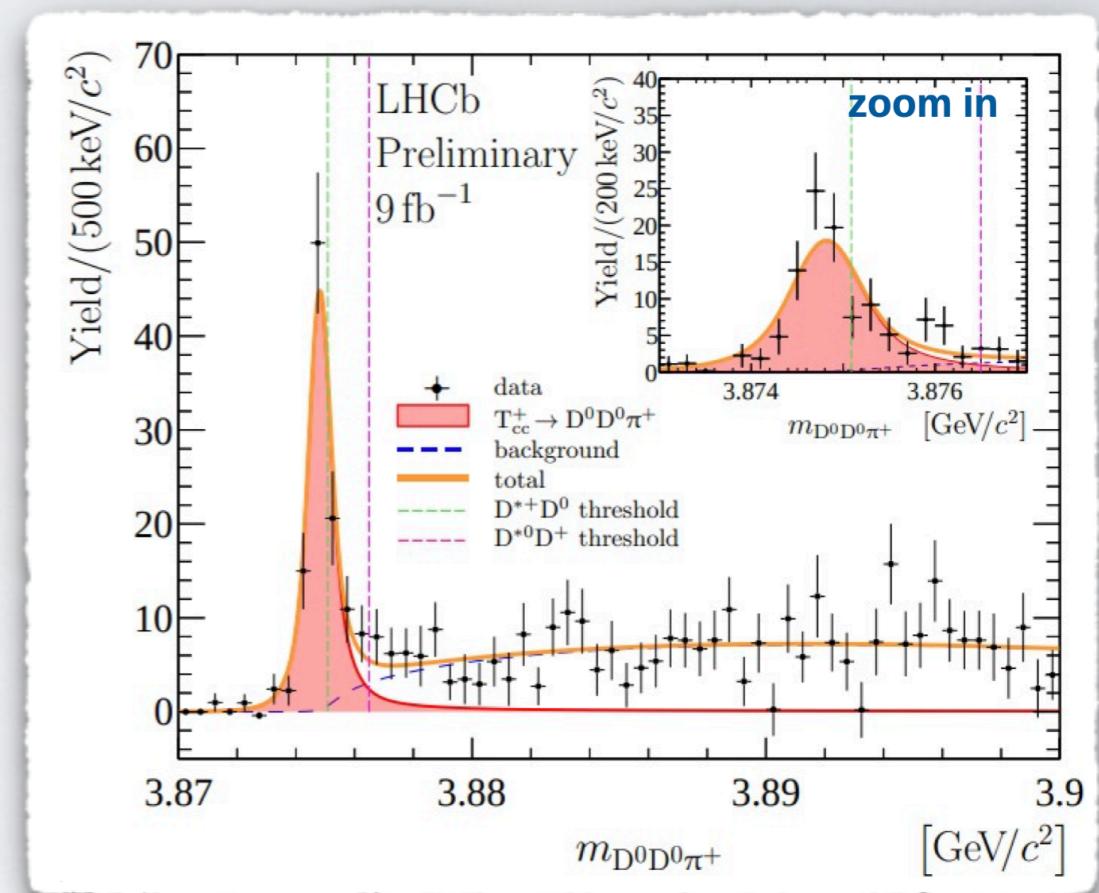
- LHCb observed the first **doubly charmed tetraquark**

$$T_{cc}^+ (cc\bar{u}\bar{d}) \rightarrow D^0 D^0 \pi^+$$

- 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]

- Two nice features:
 - Should be paired with a T_{bb} state far away from threshold
 - $SU(3)$ multiplet contains **doubly-charged** states → cannot be meson molecules because of Coulomb repulsion



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

AN EMERGING PATTERN

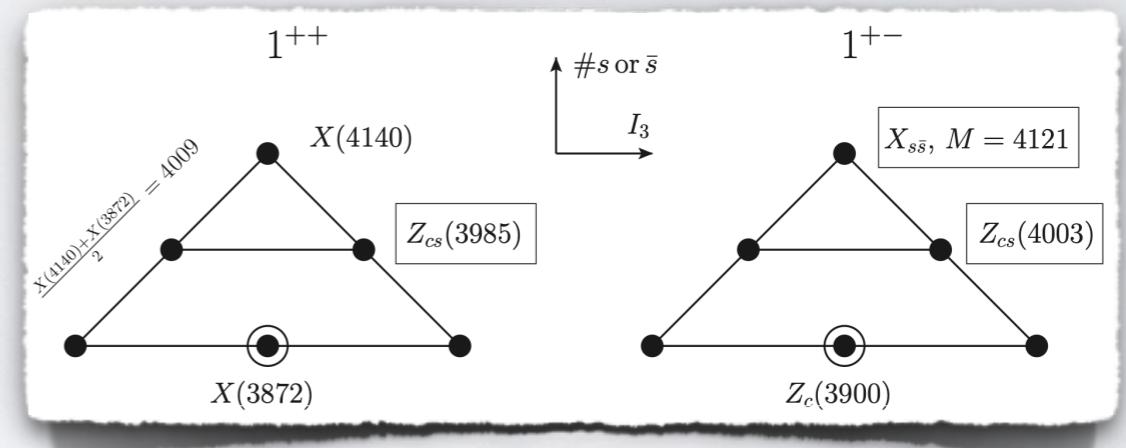
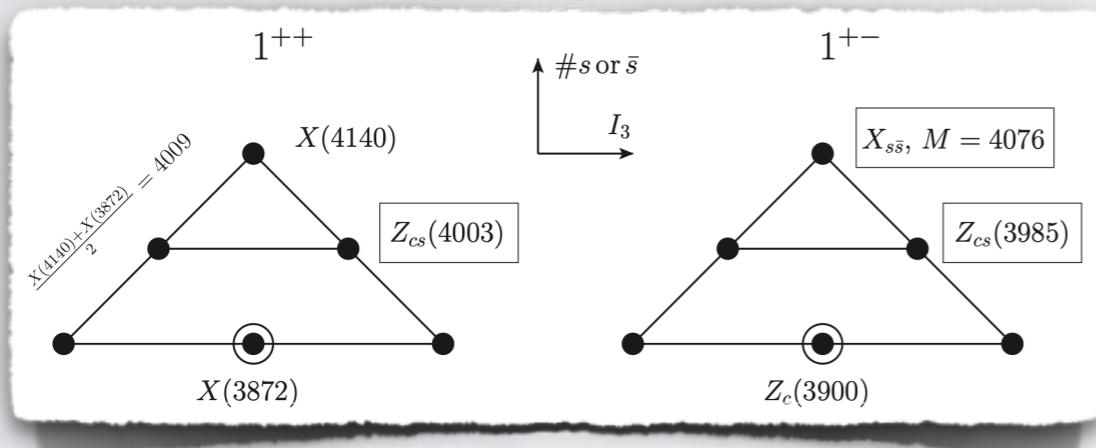
Hidden charm-strange

- BESIII and LHCb recently observed hidden charm-strange states

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

[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 → meson molecules
should not fall into $SU(3)$ multiplets

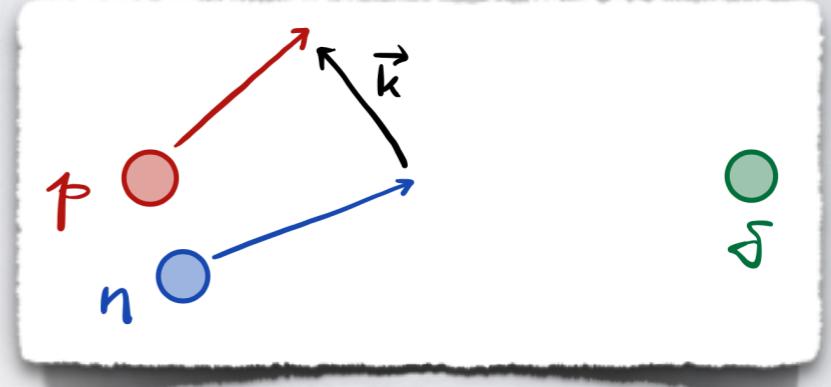
LINESHAPE OF THE $X(3872)$

Weinberg's compositeness criterion

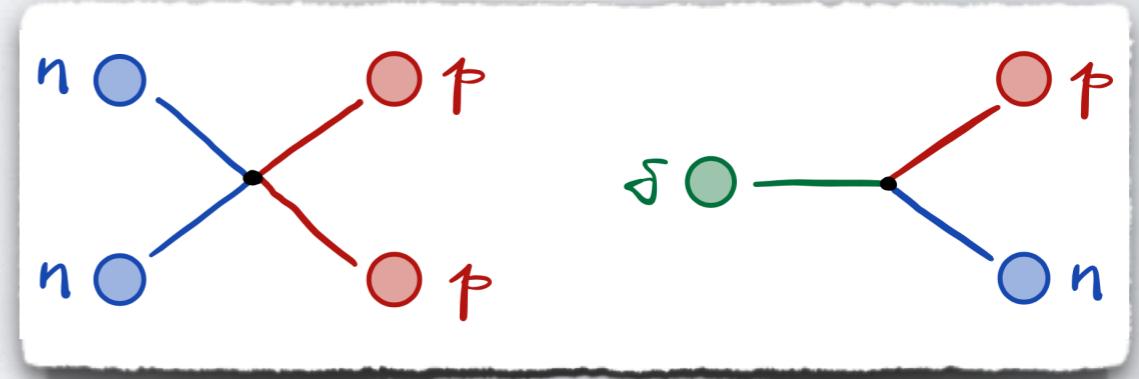
- Analogue question: is the deuteron composite or elementary?

[Weinberg – Phys. Rev. (1965)]

- Free Hamiltonian H_0 contains:
 - Free proton-neutron pairs, $|pn(\mathbf{k})\rangle$
 - Possibly an elementary deuteron, $|\delta\rangle$



- Interaction V in general contains:
 - Quartic $pn - pn$ interaction
 - Cubic $\delta - pn$ interaction



LINESHAPE OF THE $X(3872)$

Weinberg's compositeness criterion

- The physical interacting deuteron will in general be

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

- 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

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

- A. Composite deuteron ($Z = 0$) $\rightarrow r_0 = O(m_\pi^{-1})$
- B. Elementary deuteron ($Z > 0$) $\rightarrow r_0 < 0$ 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 $X(3872)$

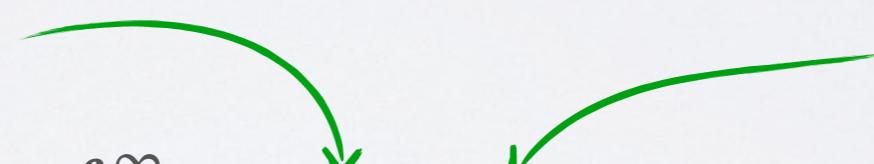
Smorodinsky's theorem for molecules

- A theorem by Smorodinsky also fixes the sign of the $O(m_\pi^{-1})$ terms
- Starting from the Schrodinger's equation for an attractive potential one finds the following exact expression for the effective range

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

solution to the free equation for $k = 0$

solution to the full equation for $k = 0$



- 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 $X(3872)$?

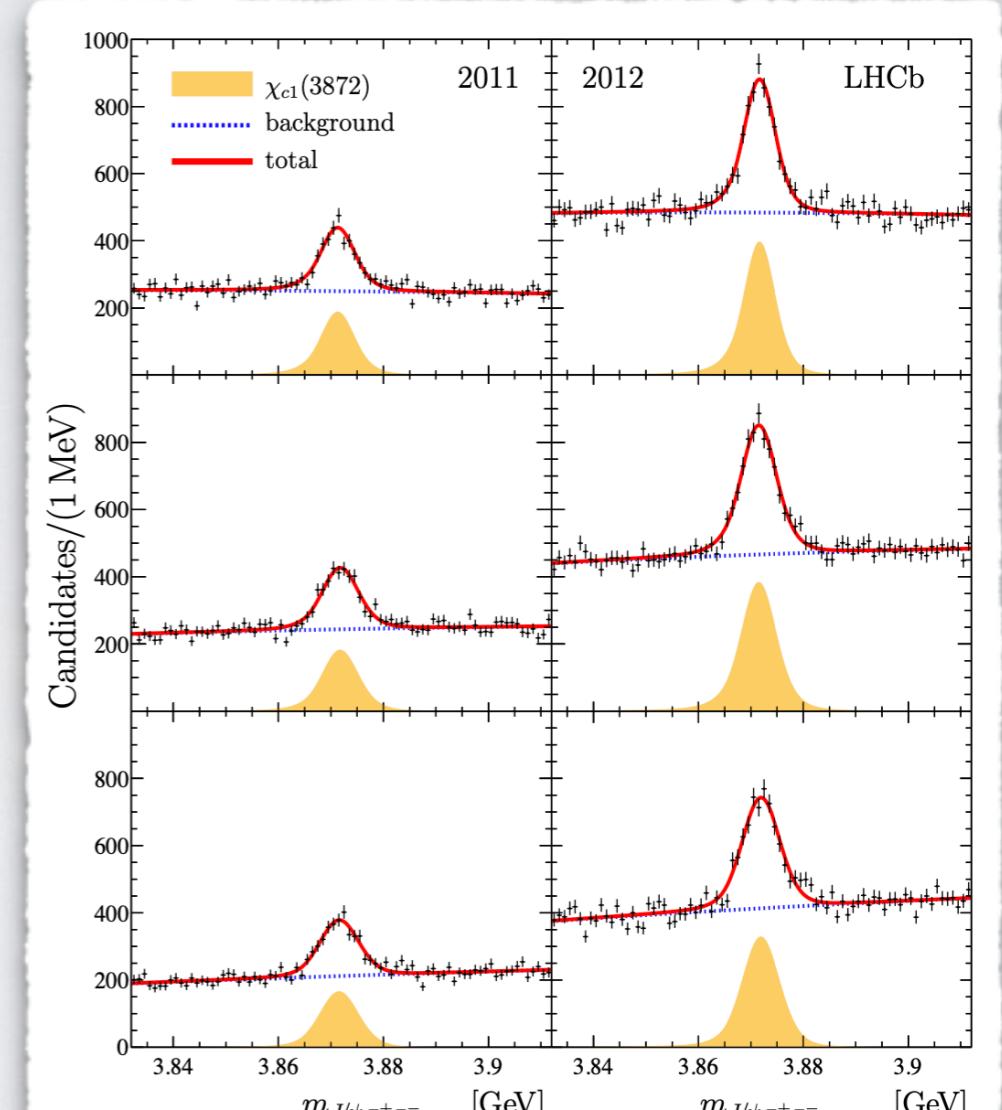
[LHCb – PRD (2020), 2005.13419]

- LHCb lineshape is:

$$f^{-1}(X \rightarrow J/\psi \pi^+ \pi^-) \propto E - m_X^0 + \frac{i}{2} g_{LHCb} \left(\sqrt{2\mu E} + \sqrt{2\mu_+(E - \delta)} \right) + \frac{i}{2} (\Gamma_\rho^0 + \Gamma_\omega^0 + \Gamma_0^0)$$

- Fit to high statistics data returns

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



LINESHAPE OF THE $X(3872)$

The LHCb data

- To apply the composite criterion we must set $\Gamma_\rho^0 = \Gamma_\omega^0 = \Gamma_0^0 = 0$:

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

- 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]

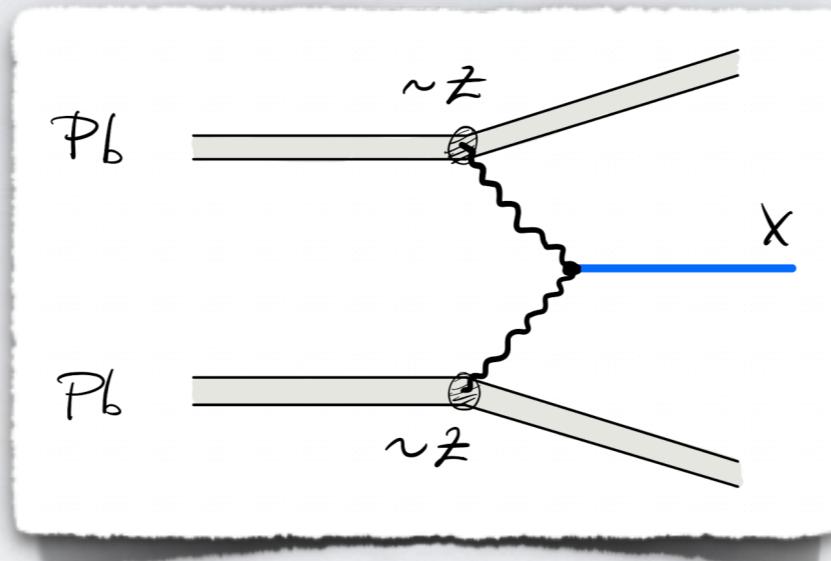
- The effective range is negative and well beyond m_π^{-1} → hallmark of an elementary, interacting object (if confirmed with experimental uncertainty)

TETRAQUARKS IN UPC?

The idea

- Ideal place to look for tetraquarks → ultra-peripheral heavy ion collisions

[see also Bertulani – PRC (2009), 0903.3174; Goncalves, Moreira – PLB (2021), 2101.03798]

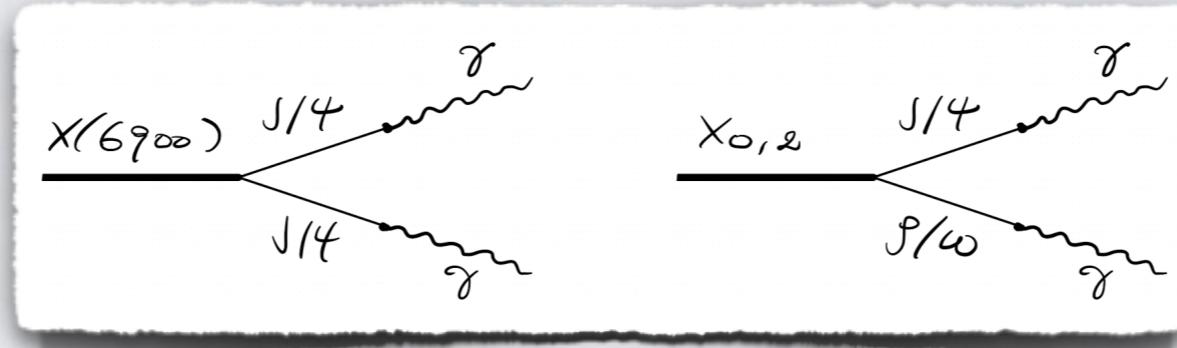


- Excellent background rejection and large photon-photon luminosity (Z^4)
- Optimal to search for scalar and tensor states → $X(6900)$, scalar and tensor $c\bar{c}q\bar{q}$ states

TETRAQUARKS IN UPC?

Results

- Tetraquark-to- $\gamma\gamma$ coupling can be estimate using vector meson dominance



- Assuming $\Gamma(X(6900) \rightarrow J/\psi J/\psi) \simeq \Gamma_{tot}$ and $g_{J/\psi V}(X_{0,2}) \simeq g_{J/\psi V}(X(3872))$:

State, J^{PC}	$\Gamma_{\gamma\gamma}/\mathcal{B}_\psi$ (eV)	$\sigma(\text{PbPb} \rightarrow \text{PbPb}X)/\mathcal{B}_\psi$ (nb)
$X(6900), 0^{++}$	~ 104	~ 282
$X(6900), 2^{++}$	~ 86	~ 1165

State, J^{PC}	$\Gamma_{\gamma\gamma}$ (eV)	$\sigma(\text{PbPb} \rightarrow \text{PbPb}X)$ (nb)
$X_0(\sim 3770), 0^{++}$	~ 6.3	~ 185
$X'_0(\sim 4000), 0^{++}$	~ 6.7	~ 156
$X_2(\sim 4000), 2^{++}$	~ 1.6	~ 187

[AE, Manzari, Pilloni, Polosa – 2109.10359]

- Very high expected cross sections!

CONCLUSION

- In the tetraquark picture, exotic mesons are part of the short distance QCD spectrum ($r \lesssim 1$ fm)
- While the issue is still largely debated, recent data seem to fit very well within this description (new states, prompt production, lineshape)
- If the LHCb analysis is confirmed, it is an unequivocal indication of the existence of an **X(3872)** generated by short distance QCD and interacting with other mesons in a standard way
- An optimal place to look for tetraquarks are ultra-peripheral heavy ion collisions
→ the completion of a multiplet would be of utmost importance

Thank you for your attention!

BACK UP

WEINBERG'S CRITERION FROM EFT

- Being very close to threshold, tetraquark can be described by a nonrelativistic EFT:

$$\mathcal{L} = \mathcal{L}_{kin} - \epsilon |T|^2 - g(T^\dagger \phi_1 \phi_2 + h.c.) - \lambda |\phi_1|^2 |\phi_2|^2 + \dots$$

bare distance from threshold  higher derivative operators 

$$\epsilon \equiv m_T - m_1 - m_2$$

- From this one can compute the full scattering amplitude for $\phi_1 \phi_2 \rightarrow \phi_1 \phi_2$:

$$i\mathcal{A} = -i \frac{g^2 + (E - \epsilon)\lambda}{E - \epsilon - \frac{\mu}{2\pi}[g^2 + (E - \epsilon)\lambda]\sqrt{-2\mu E - i\varepsilon}}$$

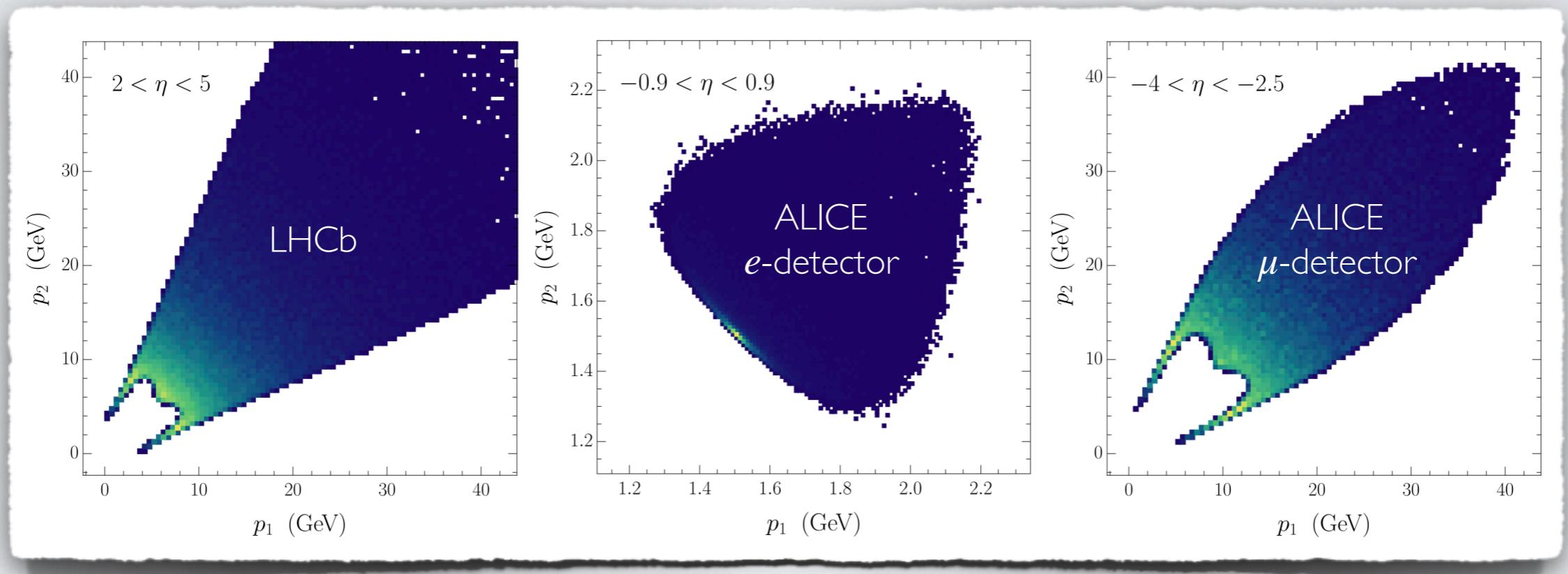
- From which:

negative r_0 only gets contribution from $g \neq 0$

$$a = \frac{\mu}{2\pi} \left(\lambda - \frac{g^2}{\epsilon} \right) + O(m_\pi^{-1}), \quad r_0 = -\frac{g^2}{2\pi a^2 \epsilon^2} + O(m_\pi^{-1})$$

DECAY PRODUCTS IN UPC

- To have an idea of the feasibility of UPC searches we study the momentum distributions of the final state of the $\gamma\gamma \rightarrow X(6900) \rightarrow J/\psi J/\psi$ process in these collisions



- Both LHCb and the ALICE μ -detector should observe rather energetic particles