AN ALTERNATIVE LOOK AT XZ RESONANCES

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Implications of LHCb measurements and future prospects
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OUTLINE

• Quick reminder of XYZ puzzle
  1. Flash experimental recap
  2. The diquarkonium model: successes and open questions

• A dynamical selection rule
  1. The formalism: interplay between diquarkonium and continuous meson-meson spectrum
  2. Isospin violation of the X(3872), its charged partners and siblings in the bottom sector

• What can we learn from LHCb run 2?
  1. A hunting guide for new tetraquark resonances
  2. Prompt production

• Summary and conclusions
THE XYZ PUZZLE

IT’S GETTING CROWDED HERE...

- The past 13 years witnessed an incredible proliferation of many unexpected charmonium-like resonances (and two bottomonium-like) that do not fit into the quarkonium picture.

- Some of them are manifestly 4-quark states:
  
  \[ \mathcal{Z}_c(3900)^\pm \rightarrow J/\psi \pi^\pm/(D\bar{D}^*)^\pm \]
  
  \[ \mathcal{Z}_c'(4020)^\pm \rightarrow h_c \pi^\pm/(D^*\bar{D}^*)^\pm \]
  
  \[ \mathcal{Z}(4430)^\pm \rightarrow \psi(2S)\pi^\pm/J/\psi \pi^\pm \]
  
  \[ \mathcal{Z}_b(10610)^\pm \rightarrow \Upsilon(nS)\pi^\pm/h_b(nP)\pi^\pm/(B\bar{B}^*)^\pm \]
  
  \[ \mathcal{Z}_b(10650)^\pm \rightarrow \Upsilon(nS)\pi^\pm/h_b(nP)\pi^\pm/(B^*\bar{B}^*)^\pm \]

- Despite the experimental advances, a common (and accepted) theoretical description of the nature of these states is still missing.
The diquarkonium model type-II can accommodate the observed resonances by combining different spins and angular momenta for the diquark and antidiquark.

In the S-wave sector, one can easily accommodate the X(3872), the Z_{c}(3900) and the Z_{c}(4020).

Introducing excited states (both radial and orbital) also allows one to reproduce the vector states (Y(4008), Y(4260), Y(4360) and Y(4660)), as well as the Z(4430).

The predicted spectrum is

The states recently observed by LHCb in the $B^+ \to K^+ (J/\psi \phi)$ channel can also be interpreted as diquarkonia [$c\bar{s}$][c$\bar{s}$] [LHCb coll. – arXiv:1606.07898 and 1606.07895]

[Maiani, Polosa, Riquer – PRD94 (2016) no.5 054026]
DIQUARKONIUM
OPEN QUESTIONS

- The main drawback of the diquarkonium model is that the predicted spectrum is very populated.

- For example:
  1. Both the $Z_c(3900)$ and the $Z_c(4020)$ are observed in the full isospin multiplet. Where are the predicted charged partners of the $X(3872)$?
  2. The $1^{+-}$ states are also observed in the bottom sector ($Z_b(10610)$ and $Z_b(10650)$). Where is the bottom analogue of the $X(3872)$?
  3. Where are the $0^{++}$ and $2^{++}$ states?

- Also, the proximity of many states to meson-meson thresholds is not considered in the model.
DIQUARKONIUM

NEED FOR SELECTION RULES?

- The (current) absence of many of the predicted states might point to the need for selection rules.

- Some observations:
  1. It is unlikely that the many close-by thresholds play no role whatsoever.
  2. All the well assessed 4-quark resonances lie close and above some meson-meson thresholds: $\delta(X) \simeq 0; \quad \delta(Z_c) \simeq +7.8 \text{ MeV}; \quad \delta(Z'_c) \simeq +6.7 \text{ MeV}; \quad \delta(Z_b) \simeq +2.7 \text{ MeV}; \quad \delta(Z'_b) \simeq +1.8 \text{ MeV}$

- We introduce a possible mechanism that might provide “dynamical selection rules” to explain the presence/absence of resonances from the experimental data.
Suppose you have a pair of particles that:

A. Can interact via two different potentials

B. Have an energy such that they lie in the continuous spectrum of one potential and close to the discrete spectrum of the other

C. The eigenstates of one potential are orthogonal to those of the other

Our pair of particles is here!

The P-to-P process in perturbation theory can happen with the following interaction potential:

$$ H_I = H_{PQ} E - \frac{1}{H_{QQ}} + i \epsilon H_{QP} $$

Interaction within the closed channel

Interactions between open and closed channels
SELECTION RULES
DIQUARKONIA AND MESON-MESON PAIRS

• We consider:

  Open channel = meson-meson pairs ($\Psi_m$)

  Closed channel = diquarkonia ($\Psi_d$)

• If the two wave functions are orthogonal, a meson pair-to-meson pair transition happens with an amplitude:

  $$T_{mm} \sim \frac{|\langle \Psi_d | H_I | \Psi_m \rangle|^2}{E_m - E_d + i\epsilon}$$

  $E_m$ = energy of the meson-meson pair
  $E_d$ = estimated from diquarkonium spectrum

• The rate for this process is then:

  $$\Gamma = -16\pi^3 \rho \text{Im}(T_{mm})$$

  $$= 16\pi^4 \rho |\langle \Psi_d | H_I | \Psi_m \rangle|^2 \delta \left( \frac{p^2}{2M_1} + \frac{p^2}{2M_2} - \delta \right)$$

• The expected width is the average over momenta that allow for the existence of a diquarkonium ($p \lesssim \bar{p} \simeq 50 - 100$ MeV)

• This gives:

  $$\bar{\Gamma} \sim A \sqrt{\delta}$$

  Only includes the smallest detuning

  Depends on the masses of the meson pair and on the transition matrix element
SELECTION RULES
DIQUARKONIA AND MESON-MESON PAIRS

• The previous result relies on some crucial assumptions:
  1. \( \delta > 0 \): the diquarkonium level must lie above the meson-meson threshold
  2. \( \delta \lesssim \bar{p}^2 / M \): only the closest threshold contributes to the width of the diquarkonia
  3. \( \Psi_d \) and \( \Psi_m \) are orthogonal to each other

• DISCLAIMER: This is not a molecule! (a) Our states all lie above threshold
  (b) The discrete level pertains to the diquarkonium potential, not the meson-meson one

• A fit with the observed resonances gives:

All the resonances can be fitted with:
\[
A = (10.3 \pm 1.3) \text{ MeV}^{1/2} \\
\chi^2 / \text{DOF} = 1.2 / 5
\]
**SELECTION RULES**

**ISOSPIN VIOLATION OF THE X(3872)**

- An example of selection rule:

- Consider the down quark part of the X(3872) in the diquarkonium picture:

  \[ \Psi_d = X_d = [cd]_0[c\bar{d}]_1 + [cd]_1[c\bar{d}]_0 \sim (D^*-D^+ - D^{*-}D^-) + i(\psi \times \rho^0 - \psi \times \omega^0) \]

  Fierz rearrangement

- The closest threshold from below is \( \Psi_m \sim \bar{D}^0D^{*0} \quad \rightarrow \quad \Psi_d \perp \Psi_m \) ✓

- But if we consider the up quark part of the X(3872):

  \[ \Psi_d = X_u = [cu]_0[\bar{c}u]_1 + [cu]_1[\bar{c}u]_0 \sim (\bar{D}^{*0}D^0 - D^{*0}\bar{D}^0) - i(\psi \times \rho^0 + \psi \times \omega^0) \]

- But then \( \Psi_d \not\perp \Psi_m \) X

- Only \( X_d \) is produced via this mechanism ➔ isospin violation ➔ no hyperfine neutral doublet
SELECTION RULES

THE $X^{\pm}$ AND THE $X_b$

- The procedure can be applied to other cases:

- $X^+$ (A) Diquark model predicts $M(X^\pm) \simeq M(X^0)$
  (B) Closest orthogonal threshold is $D^+\bar{D}^0$, $\bar{D}^0D^{++}$
  (C) Detuning is negative $\delta \simeq -5$ MeV < 0 $\rightarrow$ the state is not formed!

- $X_b$ (A) Diquark model predicts $M(X_b) \simeq M(Z_b) \simeq (10607 \pm 2)$ MeV
  (B) The closest orthogonal threshold is $M(B^0B^{*0}) = (10604.4 \pm 0.3)$ MeV
  (C) This could either be above threshold (very narrow state) or below (no state at all)
  (D) Experimentally the diquark model overpredicts the mass of the $X$:
    $M(Z_c) - M(X) \simeq 32$ MeV
  (E) We favor the below threshold scenario $\rightarrow$ no $X_b$ should be seen
LHCB RUN 2: WHAT CAN WE LEARN?
WHERE TO LOOK FOR RESONANCES

• The new LHCB run 2 will give access to a data sample of $\sim 300 \text{ fb}^{-1}$ dramatically higher statistics!
• These new data could be used to confirm/disprove the effectiveness of our mechanism
• How to implement our program:
  1. For fixed $J^{PC}$ write a diquarkonium state $\Psi_d$ and compute its mass $M(\Psi_d)$
  2. Fierz rearrange the diquarkonium into meson-meson states
  3. Look for meson-meson thresholds with the same $J^{PC}$ such that $\Psi_d \perp \Psi_m$ and $0 < \delta \lesssim \bar{p}^2 / 2M$
  4. If there are none, the state will not be observed
  5. If there is only one, the width of the state will be given by $\Gamma = A \sqrt{\delta}$

• The previous points can be used as guidelines to hunt for new tetraquarks and to confirm/disprove our argument
LHCB RUN 2: WHAT CAN WE LEARN?

PROMPT PRODUCTION

- It is also really important to look for tetraquarks in prompt production.
- Pure molecular models cannot explain copious production with high $p_T$ at the vertex of the collisions.

[Images of plots showing different reactions and data points, indicating comparisons with ALICE and CMS results.]

- Prompt production is a clear **discriminant between meson molecules and diquarkonia**.

[A.E., Guerrieri, Maiani, Piccini, Pilloni, Polosa, Riquer — PRD92 (2015) no.3 034028]

Angelo Esposito — An alternative look at XZ resonances

CERN, Oct. 14th 2016
SUMMARY & CONCLUSIONS

• What if the still unobserved tetraquarks are actually not there?

• We propose that an interplay between diquarkonia and meson-meson pairs might act as “dynamical selection rule”

• A diquarkonium state might manifest itself when enhanced by the presence of a close (from below) meson-meson threshold

• There is a relation between detuning and width of the tetraquark — good agreement with data

• The higher statistics of LHCb run 2 can help confirm/disprove our idea as well improve the searches for promptly produced tetraquarks

THANKS FOR YOUR ATTENTION!
BACK UP
Suppose to have two projectors $Q$ and $P$ such that:  $P + Q = 1; \quad PQ = 0$

The wave function can be split into orthogonal pieces:  $\Psi = \Psi_Q + \Psi_P$

And the Schrodinger equation into:

$$(E - H_{PP})\Psi_P = H_{PC}\Psi_Q$$

$$(E - H_{QQ})\Psi_Q = H_{QP}\Psi_P$$

with $H_{PP} = PHP, \quad H_{QQ} = QHQ, \quad H_{QP} = H_{PQ} = QHP$

One can formally solve for the closed channel wave function and obtain an equation for the open channel one:

$$\Psi_Q = \frac{1}{E - H_{QQ} + i\epsilon} H_{QP} \Psi_P$$

$$(E - H_{PP} - H_I)\Psi_P = 0$$

We have:

$H_{PP} = \text{interaction only within the open channel}$

$H_I = H_{PQ} \frac{1}{E - H_{QQ} + i\epsilon} H_{QP} = \text{open channel — closed channel — open channel interaction}$
In order for the diquarkonium to manifest itself, both the $\delta > 0$ and the $\Psi_d \perp \Psi_m$ conditions have to be satisfied.
SELECTION RULES

THE SPECIAL CASE OF THE $X(4140)$

- LHCb recently observed the following structures in the $B^+ \rightarrow K^+(J/\psi \phi)$ channel:
  - $X(4140; 1^{++})$, $X(4274; 1^{++})$, $X(4500; 0^{++})$, $X(4700; 0^{++})$
- Most of them can be accommodated in the diquarkonium picture as $[cs][\bar{c}\bar{s}]$
- In particular, one can tentatively assign
  - A. $X(4140) \rightarrow$ ground state of $\frac{1}{\sqrt{2}}(|1, 0\rangle_1 + |0, 1\rangle_1) \quad J^{PC} = 1^{++}$
  - B. $X(4500) \rightarrow$ first radially excited state of $|0, 0\rangle_0 \quad J^{PC} = 0^{++}$
  - C. $X(4700) \rightarrow$ first radially excited state of $|1, 1\rangle_0 \quad J^{PC} = 0^{++}$

- There is no other $1^{++}$ to accommodate for the $X(4274)$!
- Two alternatives have been proposed:
  - A. The $X(4274)$ is actually either $0^{++}$ or $2^{++}$ (quite unlikely, $J^{PC} = 1^{++}$ @ 5$\sigma$)
  - B. The observed structure is actually two unresolved, almost degenerate lines with $0^{++}$ and $2^{++}$
- The second option is ideal since it would mean that LHCb observed all the accessible $C = +, 1S$ states
SELECTION RULES
THE SPECIAL CASE OF THE $X(4140)$

- How does the $X(4140)$ fit in our scheme?
- It indeed presents some surprises for which a definitive answer is still not clear
- The closed channel, diquarkonium state is:
  \[ \Psi_d = [cs]_0[\bar{c}\bar{s}]_1 + [cs]_1[\bar{c}\bar{s}]_0 \sim (D_s^*-D_s^+-D_s^+D_s^-) - i(\psi \times \phi) \]
- The two closest thresholds would be: \[ \Psi_m = D_s^*-D_s^+, \ \psi \times \phi \]
- None of them are orthogonal! What are we supposed to do now? Three options:
  1. Our mechanism is simply forbidden
  2. We have to consider an orthogonal combination of open channel states:
     \[ \Psi_m = (D_s^*-D_s^+-D_s^+D_s^-) + i(\psi \times \phi) \]
     No single threshold dominance. We expect a state broader than just $A\sqrt{\delta}$. How does it work in this case?
  3. The $gg$ pairs are produced in the color $6_c$ representation. [Wu, Liu, Chen, Liu, Zhu – 1608.07900]
     The closed channel would be: \[ \Psi_s = \{cs\}_0\{\bar{c}\bar{s}\}_1 + \{cs\}_1\{\bar{c}\bar{s}\}_0 \sim \psi \times \phi + D_s^{*+} \times D_s^{*-} \]
     Orthogonality satisfied with \[ \Psi_m = D_s^*-D_s^+ \]
     \[ \Gamma \sim A\sqrt{\delta} \sim 77\text{MeV} \quad (\Gamma_{\exp} = (83 \pm 21) \text{MeV}) \]