AN ALTERNATIVE LOOK AT XZ RESONANCES

Angelo Esposito
Columbia University

Implications of LHCb measurements and future prospects
CERN 2016

Talk mostly based on: *A.E., A. Pilloni, A.D. Polosa — arXiv:1603.07667 + work in progress*

Recent reviews: H. Chen, W. Chen, X. Liu, S. Zhu — arXiv:1601.02092
A.E., A.L. Guerrieri, F. Piccinini, A. Pilloni, A.D. Polosa — arXiv:1411.5997

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:

$$Z_c(3900)^\pm \to J/\psi\pi^\pm/(D\bar{D}^*)^\pm$$

$$Z_c'(4020)^\pm \to h_c\pi^\pm/(D^*\bar{D}^*)^\pm$$

$$Z(4430)^\pm \to \psi(2S)\pi^\pm/J/\psi\pi^\pm$$

$$Z_b(10610)^\pm \to \Upsilon(nS)\pi^\pm/h_b(nP)\pi^\pm/(B\bar{B}^*)^\pm$$

$$Z_b(10650)^\pm \to \Upsilon(nS)\pi^\pm/h_b(nP)\pi^\pm/(B^*\bar{B}^*)^\pm$$

- Despite the experimental advances, a common (and accepted) theoretical description of the nature of these states is still missing

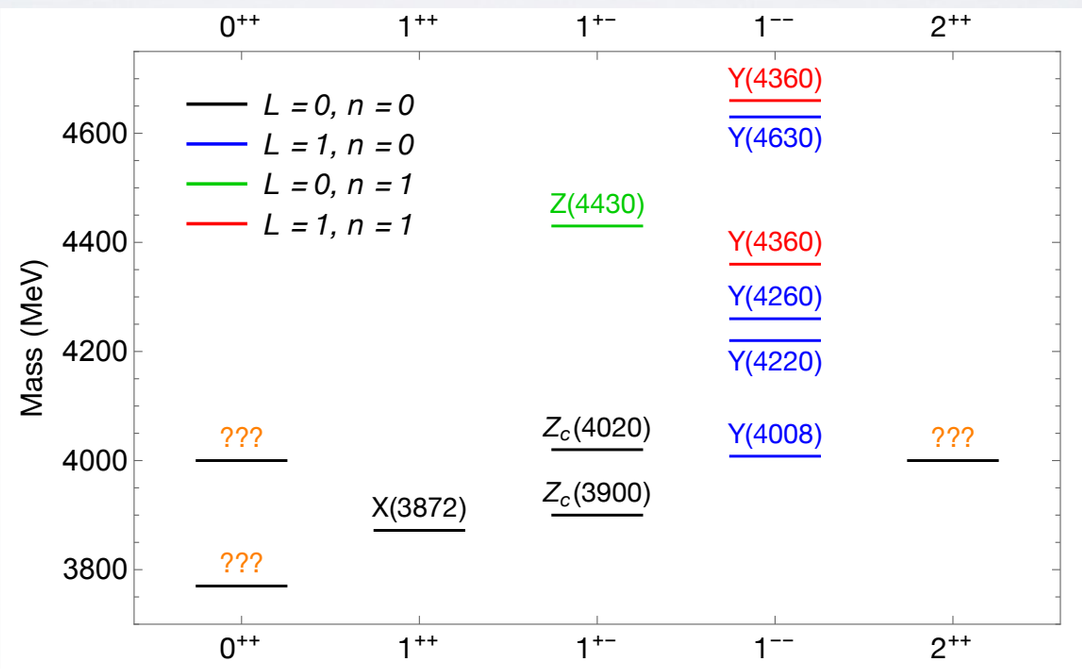
Observed XYZ states

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle (>10), BaBar (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF (11.6), D0 (5.2)
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb (np)
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle (4.3), BaBar (4.0)
				$B \to K(\gamma\, J/\psi)$	Belle (5.5), BaBar (3.5)
					LHCb (> 10)
				$B \to K(\gamma\, \psi(2S))$	BaBar (3.6), Belle (0.2)
					LHCb (4.4)
				$B \to K(D\bar{D}^*)$	Belle (6.4), BaBar (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III (np)
				$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III (8), Belle (5.2)
					CLEO data (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \to \pi^-(\pi^+ h_c)$	BES III (8.9)
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(\omega J/\psi)$	Belle (8), BaBar (19)
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle (7.7), BaBar (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle (5.3), BaBar (5.8)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle (7.4)
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle (5.0), BaBar (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF (5.0), Belle (1.9),
					LHCb (1.4), CMS (>5)
					DØ (3.1)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle (5.5)
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle (7.2)
$Y(4220)$	4196^{+35}_{-30}	39 ± 32	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data (4.5)
$Y(4230)$	4230 ± 8	38 ± 12	1^{--}	$e^+e^- \to (\chi_{c1}\omega)$	BES III (>9)
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle (5.0), BaBar (2.0)
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar (8), CLEO (11)
					Belle (15), BES III (np)
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar (np), Belle (np)
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III (8), Belle (5.2)
				$e^+e^- \to (\gamma\, X(3872))$	BES III (5.3)
$Y(4290)$	4293 ± 9	222 ± 67	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data (np)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle (3.2)
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle (8), BaBar (np)
$Z(4430)^+$	4478 ± 17	180 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle (6.4), BaBar (2.4)
					LHCb (13.9)
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle (4.0)
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle (8.2)
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle (5.8), BaBar (5)
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi(\pi\Upsilon(nS))$	Belle (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle (16)
				$\Upsilon(5S) \to \pi^-(B\bar{B}^*)^+$	Belle (8)
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^-(\pi^+\Upsilon(nS))$	Belle (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle (16)
				$\Upsilon(5S) \to \pi^-(B^*\bar{B}^*)^+$	Belle (6.8)

DIQUARKONIUM

SPECTRUM

- 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)***. [Maiani, Piccini, Polosa, Riquer PRD89 (2014) 114010]
- 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 $[cs][\bar{c}\bar{s}]$ [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

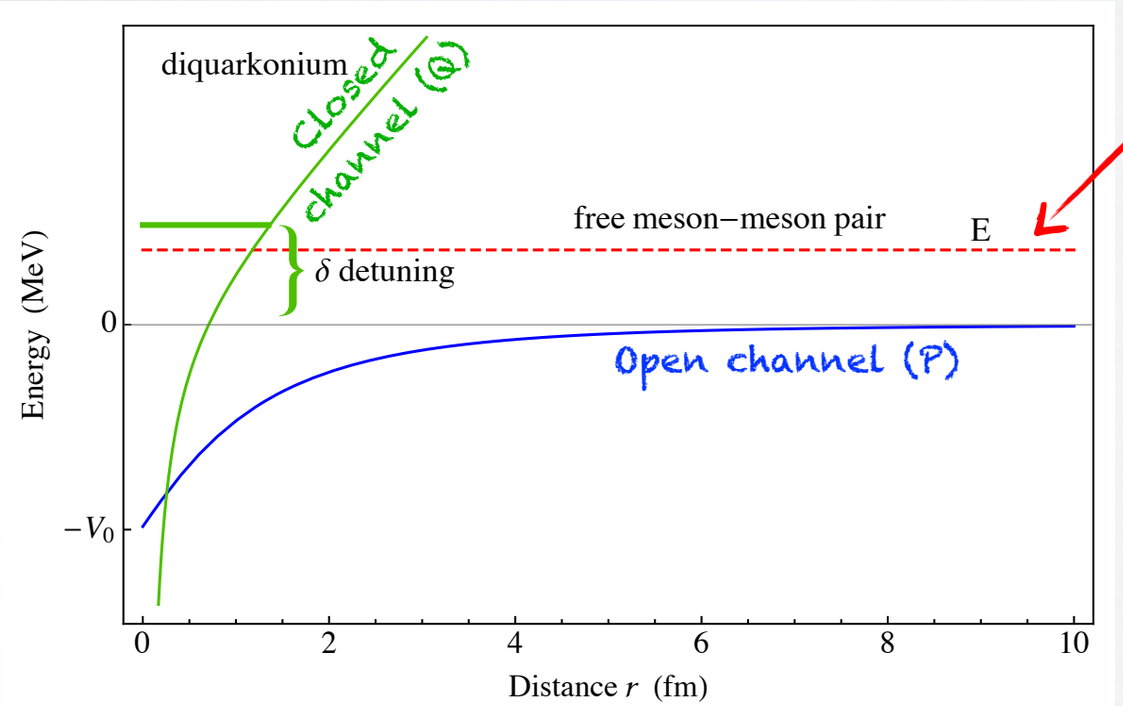
NEED FOR SELECTION RULES?

- 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: $\delta(X) \simeq 0;$ $(DD^* \text{ or } J/\psi\rho)$ $\delta(Z_c) \simeq +7.8 \text{ MeV};$ (DD^*) $\delta(Z_c') \simeq +6.7 \text{ MeV};$ (D^*D^*) $\delta(Z_b) \simeq +2.7 \text{ MeV};$ (BB^*) $\delta(Z_b') \simeq +1.8 \text{ MeV}$ (B^*B^*)
  3. The color rearrangements of these diquarkonia into meson-meson states is always orthogonal to the closest threshold
- We introduce a possible mechanism that **might provide "dynamical selection rules"** to explain the presence/absence of resonances from the experimental data.

SELECTION RULES

FORMALISM

- 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:

Interaction within the closed channel

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

Interactions between open and closed channels

SELECTION RULES

DIQUARKONIA AND MESON-MESON PAIRS

- We consider:

Open channel = meson-meson pairs (Ψ_m)

Closed channel = diquarkonia ($\Psi_{\mathbf{d}}$)

- If the two wave functions are orthogonal, a <u>meson pair-to-meson pair transition</u> happens with an amplitude:

$$T_{mm} \sim \frac{|\langle \Psi_{\mathbf{d}} | H_I | \Psi_m \rangle|^2}{E_m - E_{\mathbf{d}} + i\epsilon}$$

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

- The rate for this process is then:

$$\Gamma = -16\pi^3 \rho \, \mathrm{Im}(T_{mm})$$
$$= 16\pi^4 \rho |\langle \Psi_{\mathbf{d}} | H_I | \Psi_m \rangle|^2 \delta \left(\frac{p^2}{2M_1} + \frac{p^2}{2M_2} - \delta \right)$$

$$\delta = M_{4q} - M_1 - M_2$$

- 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:

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

Only includes the smallest detuning

Depends on the masses of the meson pair and on the transition matrix element

SELECTION RULES

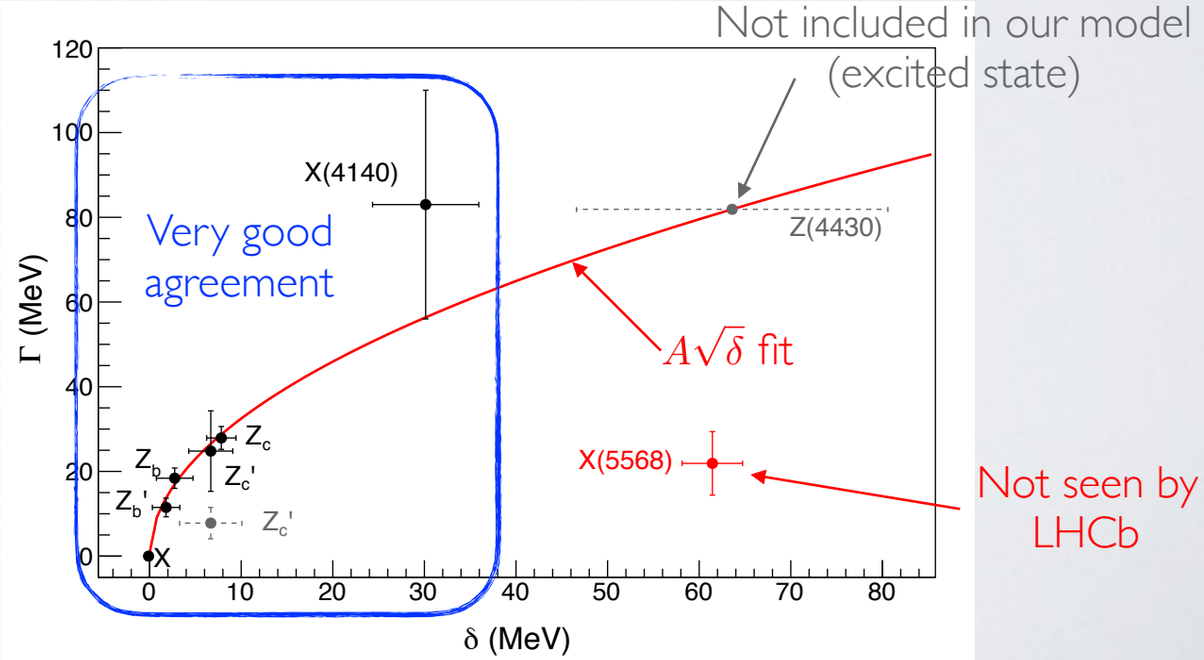
DIQUARKONIA AND MESON-MESON PAIRS

- 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. $\Psi_{\mathbf{d}}$ and Ψ_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:

$$A = (10.3 \pm 1.3)\ \mathrm{MeV}^{1/2}$$

$$\chi^2/\mathrm{DOF} = 1.2/5$$



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:

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

Fierz rearrangement

- The closest threshold from below is $\Psi_m \sim \bar{D}^0 D^{*0}$ $\longrightarrow$ $\Psi_{\mathbf{d}} \perp \Psi_m$ ✓
- But if we consider the up quark part of the *X(3872)*:

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

- But then $\longrightarrow$ $\Psi_{\mathbf{d}} \not\perp \Psi_m$ ✗
- Only X_d is produced via this mechanism $\longrightarrow$ isospin violation
  $\longrightarrow$ 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 $D^+\bar{D}^{*0}$, $\bar{D}^0 D^{*+}$
  (C) Detuning is negative $\delta \simeq -5\ \mathrm{MeV} < 0 \longrightarrow$ the state is not formed!

- X_b *(A)* Diquark model predicts $M(X_b) \simeq M(Z_b) \simeq (10607 \pm 2)\ \mathrm{MeV}$
  (B) The closest orthogonal threshold is $M(B^0 B^{*0}) = (10604.4 \pm 0.3)\ \mathrm{MeV}$
  (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*:

$$M(Z_c) - M(X) \simeq 32\ \mathrm{MeV}$$

  (E) We favor the below threshold scenario $\longrightarrow$ no X_b should be seen

LHCB RUN 2: WHAT CAN WE LEARN?

WHERE TO LOOK FOR RESONANCES

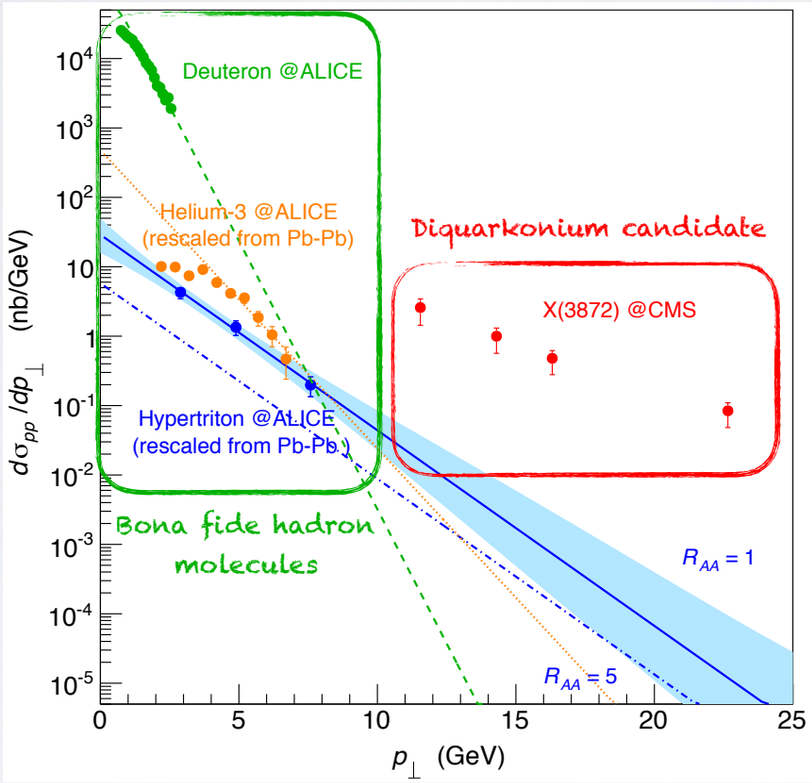
- The **new LHCb run 2** will give access to a data sample of $\sim 300\ \mathrm{fb}^{-1} \longrightarrow$ *dramatically higher statistics!*
- These new data could be used to confirm/disprove the effectiveness of our mechanism
- <u>How to implement our program:</u>
  1. For fixed J^{PC} write a diquarkonium state $\Psi_{\mathbf{d}}$ and compute its mass $M(\Psi_{\mathbf{d}})$
  2. Fierz rearrange the diquarkonium into meson-meson states
  3. Look for meson-meson thresholds with the same J^{PC} such that $\Psi_{\mathbf{d}} \perp \Psi_m$ 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 <u>hunt for new tetraquarks</u> and to <u>confirm/disprove our argument</u>

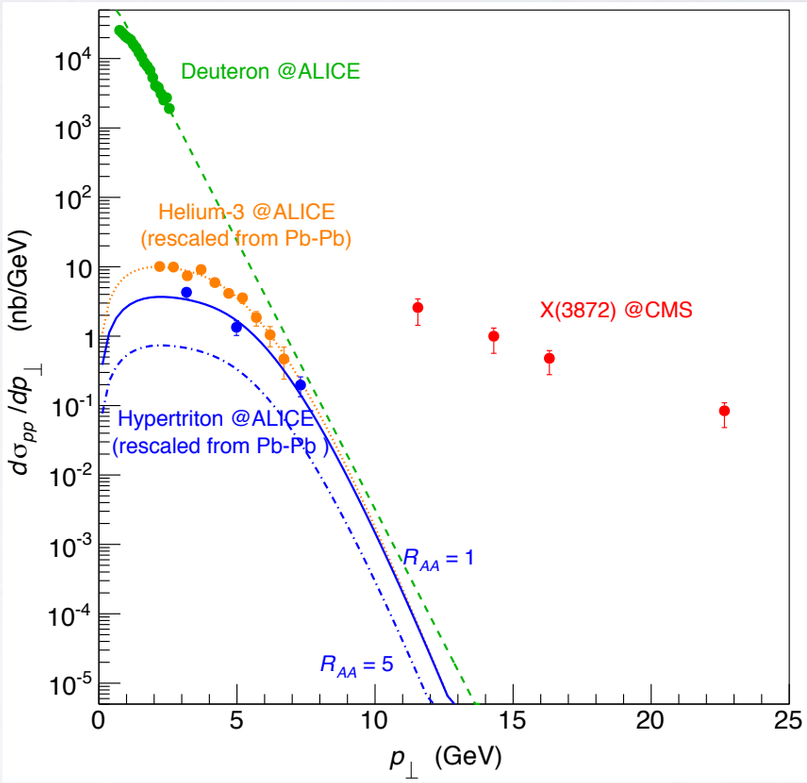
LHCB RUN 2: WHAT CAN WE LEARN?

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



(Exponential fit)



(Blast wave fit)

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

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

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

SELECTION RULES

FORMAL DERIVATION

- Suppose to have two projectors $\mathcal{Q}$ and $\mathcal{P}$ such that: $\mathcal{P} + \mathcal{Q} = \mathbf{1}; \qquad \mathcal{P}\mathcal{Q} = 0$
- The wave function can be split into orthogonal pieces: $\Psi = \Psi_Q + \Psi_P$

  open channel

  closed channel
- And the Schrodinger equation into:

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

with $H_{PP} = \mathcal{P}H\mathcal{P}, \quad H_{QQ} = \mathcal{Q}H\mathcal{Q}, \quad H_{QP} = H^\dagger_{PQ} = \mathcal{Q}H\mathcal{P}$

- 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} = interaction only within the open channel

$H_I = H_{PQ}\dfrac{1}{E - H_{QQ} + i\epsilon}H_{QP}$ = open channel — closed channel — open channel interaction

SELECTION RULES

SUMMARY TABLE

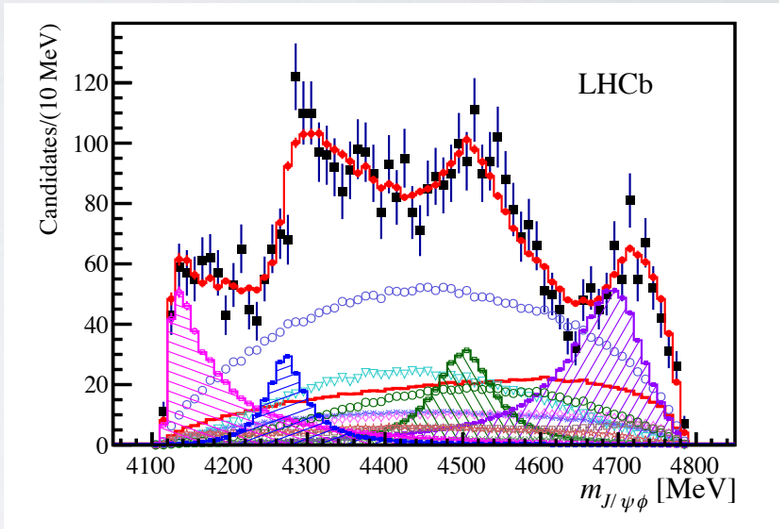
Resonance	Ψ_m	Ψ_d	$M(\Psi_d) \geq M(\Psi_m)$	$\Psi_d \perp \Psi_m$	Exp.
X_u^0	$\bar{D}^0 D^{*0}$	$(\bar{D}^{*0}D^0 - D^{*0}\bar{D}^0)$ $-i\psi \times (\rho^0 + \omega^0)$	yes	no	✗
X_d^0	$\bar{D}^0 D^{*0}$	$(D^{*-}D^+ - D^{*+}D^-)$ $+i\psi \times (\rho^0 - \omega^0)$	yes	yes	✓
X^+	$D^+\bar{D}^{*0} \vee \bar{D}^0 D^{*+}$	$(D^+\bar{D}^{*0} - \bar{D}^0 D^{*+}) - i\psi \times \rho^+$	no	no	✗
Z_c^0	$\bar{D}^0 D^{*0}$	$\eta_c \rho^0 - \psi\pi^0$ $+i\bar{D}^{*0} \times D^{*0} - i\bar{D}^{*-} \times D^{*+}$	yes	yes	✓
Z_c^+	$\bar{D}^0 D^{*+}$	$\eta_c \rho^+ - \psi\pi^+ + i\bar{D}^{*0} \times D^{*+}$	yes	yes	✓
$Z_c'^0$	$\bar{D}^{*0} D^{*0}$	$\eta_c \rho^0 + \psi\pi^0 + (\bar{D}^0 D^{*0} + D^0\bar{D}^{*0})$ $-(D^- D^{*+} + D^+ D^{*-})$	yes	yes	✓
$Z_c'^+$	$\bar{D}^{*0} D^{*+}$	$(\eta_c \rho^+ + \psi\pi^+) - (\bar{D}^0 D^{*+} + D^+\bar{D}^{*0})$	yes	yes	✓
$(X_b^0)_u$	$\bar{B}^0 B^{*0}$	$(\bar{B}^{*0}B^0 - B^{*0}\bar{B}^0)$ $-i\Upsilon \times (\rho^0 + \omega^0)$	no	no	✗
$(X_b^0)_d$	$\bar{B}^0 B^{*0}$	$(B^{*-}B^+ - B^{*+}B^-)$ $+i\Upsilon \times (\rho^0 - \omega^0)$	no	yes	✗
X_b^+	$B^+\bar{B}^{*0} \vee \bar{B}^0 B^{*+}$	$(B^+\bar{B}^{*0} - \bar{B}^0 B^{*+}) - i\Upsilon \times \rho^+$	no	no	✗
$Z_b^{(\prime)0}$, $Z_b^{(\prime)+}$	like Z_cs	like Z_cs	yes	yes	✓

In order for the diquarkonium to manifest itself, both the $\delta > 0$ and the $\Psi_{\mathbf{d}} \perp \Psi_m$ conditions have to be satisfied

SELECTION RULES

THE SPECIAL CASE OF THE X(4140)

- LHCb recently observed the following structures in the $B^+ \to K^+(J/\psi\,\phi)$ channel:
  [LHCb coll. – arXiv:1606.07898 and 1606.07895]
  $$X(4140;1^{++}), \quad X(4274;1^{++}), \quad X(4500;0^{++}), \quad X(4700;0^{++})$$
- Most of them can be accommodated in the diquarkonium picture as $[cs][\bar{c}\bar{s}]$
- In particular, one can tentatively assign
  A. $X(4140) \longrightarrow$ ground state of $\frac{1}{\sqrt{2}}(|1,0\rangle_1 + |0,1\rangle_1) \quad J^{PC} = 1^{++}$
  B. $X(4500) \longrightarrow$ first radially excited state of $|0,0\rangle_0 \quad J^{PC} = 0^{++}$
  C. $X(4700) \longrightarrow$ first radially excited state of $|1,1\rangle_0 \quad J^{PC} = 0^{++}$
  [Maiani, Polosa, Riquer – PRD94 (2016) no.5 054026]



- 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:

$$\Psi_{\mathbf{d}} = [cs]_0[\bar{c}\bar{s}]_1 + [cs]_1[\bar{c}\bar{s}]_0 \sim (D_s^{*-}D_s^+ - D_s^{*+}D_s^-) - i(\psi \times \phi)$$

- The two closest thresholds would be: $\Psi_m = D_s^{*-}D_s^+, \quad \psi \times \phi$
- 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 qq pairs are produced in the color $\mathbf{6}_c$ 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 $\Psi_m = D_s^{*-}D_s^+$

     $$\Gamma \sim A\sqrt{\delta} \sim 77\text{MeV} \quad (\Gamma_{\text{exp}} = (83 \pm 21)\ \text{MeV})$$