MULTI-QUARK HADRONS

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For a review see:
AE, Pilloni, Polosa — Phys.Rept. 2017; 1611.07920
Guo, Hanhart, Meissner, Wang, Zhao — Rev.Mod.Phys. 2018; 1705.00141
Lebed, Mitchell, Swanson — Prog.Part.Nucl.Phys. 2017; 1610.04528

OUTLINE

- Intro to the exotic hadrons
- Main theoretical interpretations (tetraquarks, molecules, …)
- Prompt production
- Possible observables (high-multiplicity, exotic flavors, specific decay channels, …)
- Conclusion

BRIEF REVIEW

Exotic hadron spectrum

- QCD is the theory of strong interactions

$$S_{QCD} = \int d^4x \left[\sum_f \bar{\psi}^i_f \left(i\gamma^\mu D^{ij}_\mu - m_f\, \delta^{ij} \right) \psi^j_f - \frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} \right]$$

Spin-1/2 quarks (3 colors, 6 flavors)

Spin-1 gluons (8 colors)

- Confinement $\longrightarrow$ only color singlets can be asymptotic states

- More combinations than just mesons and baryons:

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \ldots \qquad \text{meson}$$

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \ldots \qquad \text{baryon}$$

$$\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{3}} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \ldots \qquad \text{tetraquark}$$

$$\mathbf{8} \otimes \mathbf{8} \otimes \ldots \otimes \mathbf{8} = \mathbf{1} \oplus \ldots \qquad \text{glueball}$$

[Gell-Mann – Phys.Lett. (1964)]

and many others…

BRIEF REVIEW

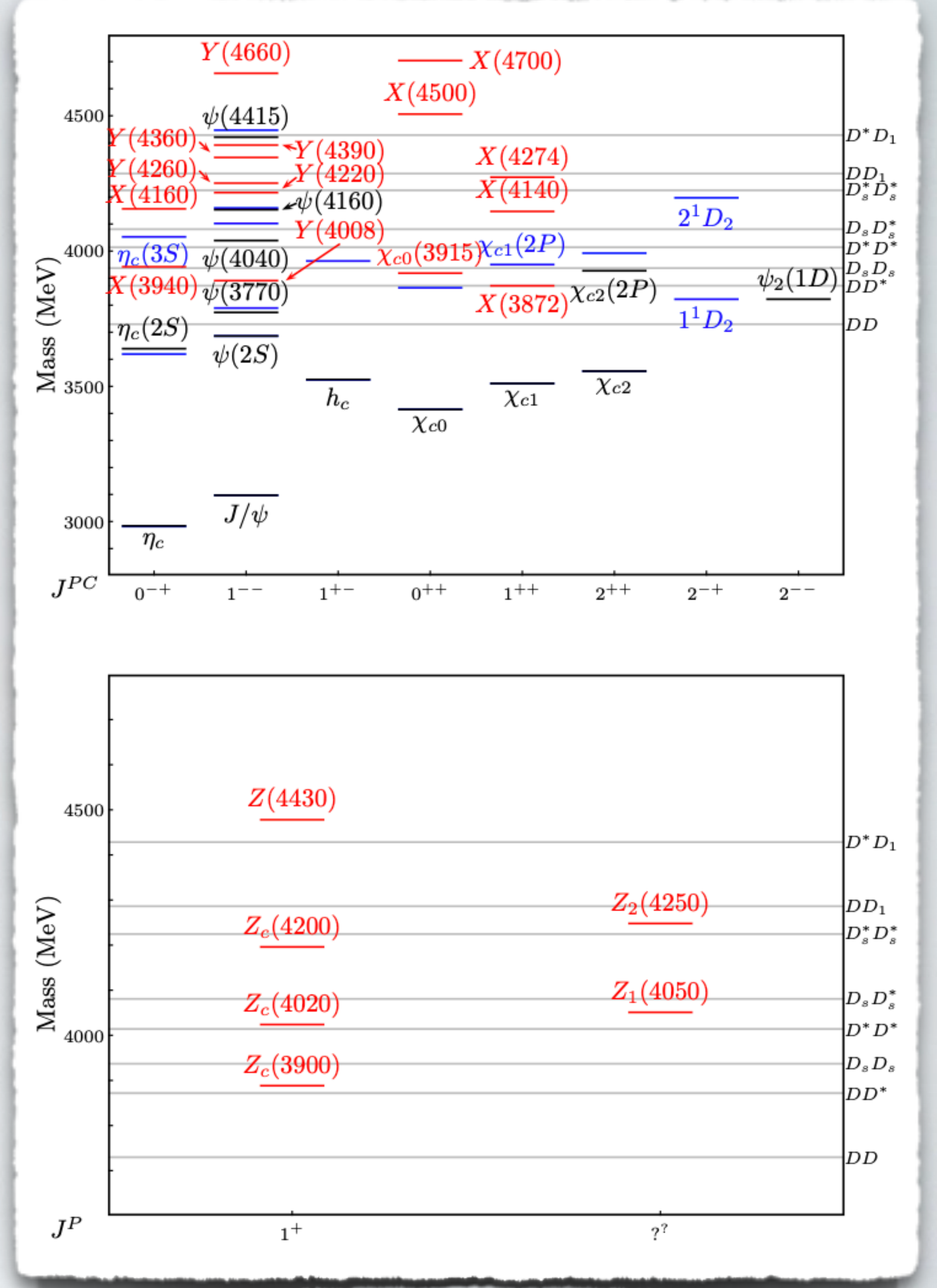
Exotic hadron spectrum

- Proliferation of new states in the quarkonium sector
- Their properties do not match standard quarkonia predictions
- The charged ones are manifestly 4-quark states:

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

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

Does not have the same quantum numbers as the vacuum

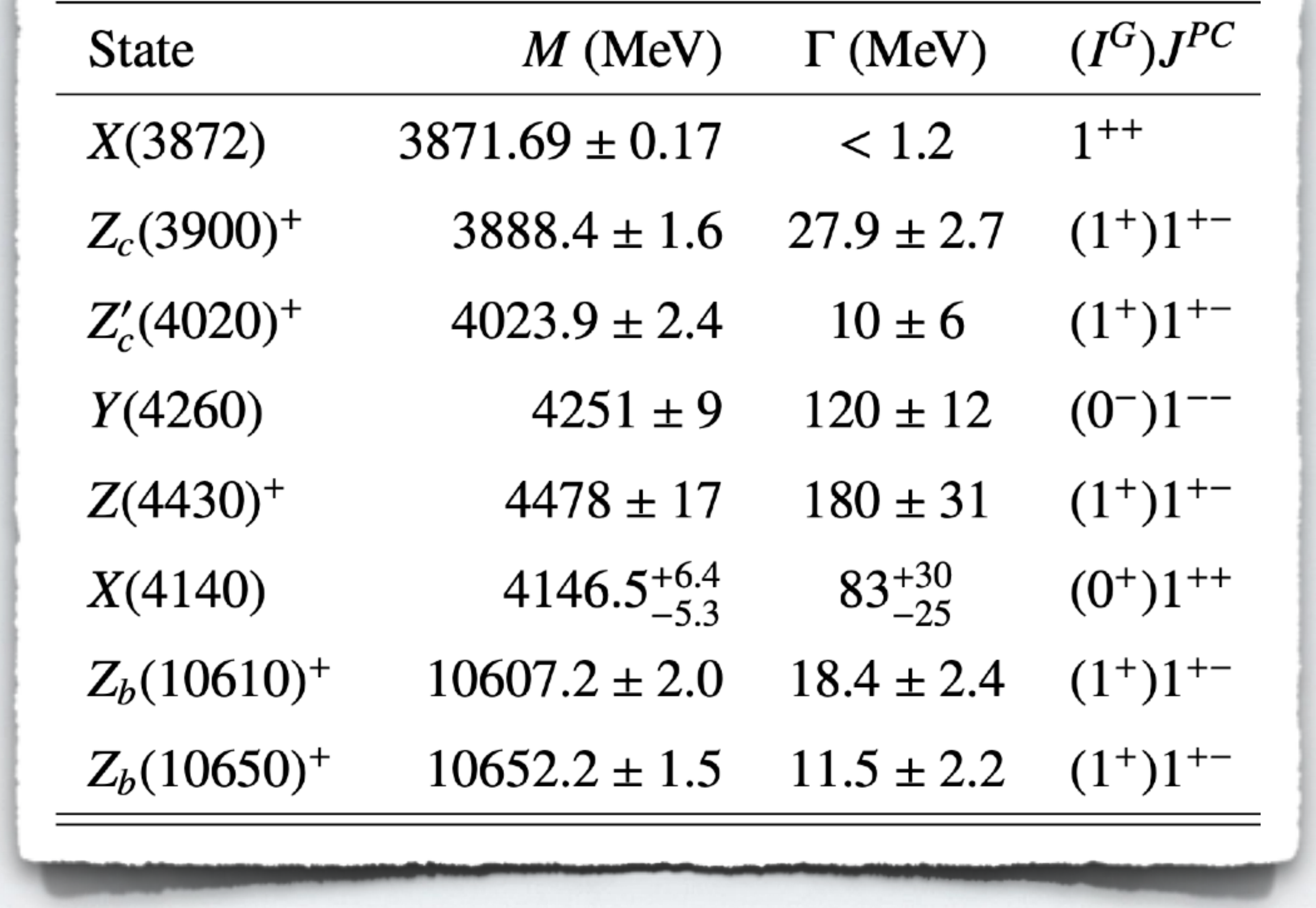


[AE, Pilloni, Polosa — Phys.Rept. (2017), 1611.07920]

BRIEF REVIEW

Best assessed states

- Best assessed states so far (but many more hints or partial observations):



State	M (MeV)	Γ (MeV)	$(I^G)J^{PC}$
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}
$Z_c(3900)^+$	3888.4 ± 1.6	27.9 ± 2.7	$(1^+)1^{+-}$
$Z_c'(4020)^+$	4023.9 ± 2.4	10 ± 6	$(1^+)1^{+-}$
$Y(4260)$	4251 ± 9	120 ± 12	$(0^-)1^{--}$
$Z(4430)^+$	4478 ± 17	180 ± 31	$(1^+)1^{+-}$
$X(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+30}_{-25}	$(0^+)1^{++}$
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	$(1^+)1^{+-}$
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	$(1^+)1^{+-}$

- Plus pentaquarks!

BRIEF REVIEW

$X(3872)$

- Most notable example is the $X(3872)$, discovered by BELLE in 2003

- Impressive fine tuning of its mass:

$$M_X - \left(M_{D^0} + M_{D^{*0}}\right) = 44 \pm 116 \text{ keV}$$

[computed from LHCb — 2005.13419, LHCb — 2005.13422 and PDG]

- Despite the tiny available phase space, it decays copiously in $D^0\bar{D}^{*0}$:

$$BR\left(X \to D^0\bar{D}^0\pi^0\right) > 40\,\%$$

[PDG]

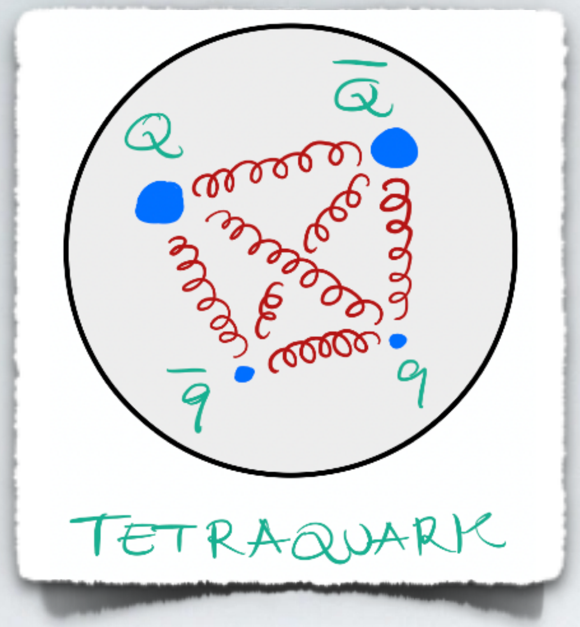
- Strong decays violate isospin:

$$\Gamma\left(X \to J/\psi\,\omega\right) = \left(4.4^{+2.3}_{-1.3}\right)\%\,, \quad \Gamma\left(X \to J/\psi\,\rho\right) = \left(4.1^{+1.9}_{-1.1}\right)\%$$

[Li, Yuan — PRD (2019), 1907.09149]

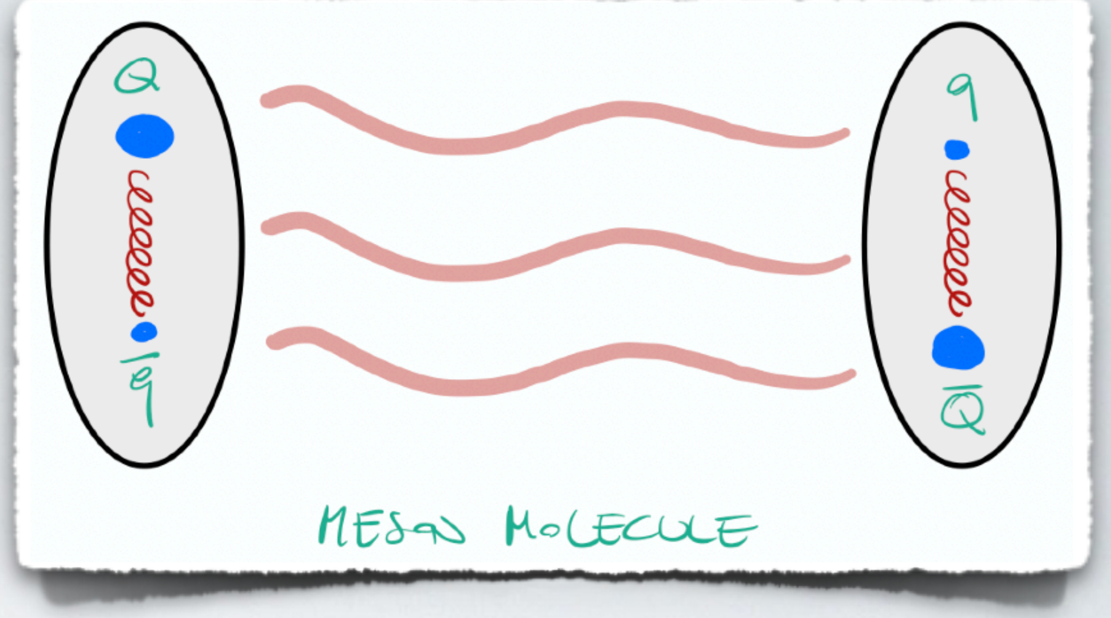
EXOTIC MESONS

Possible interpretations

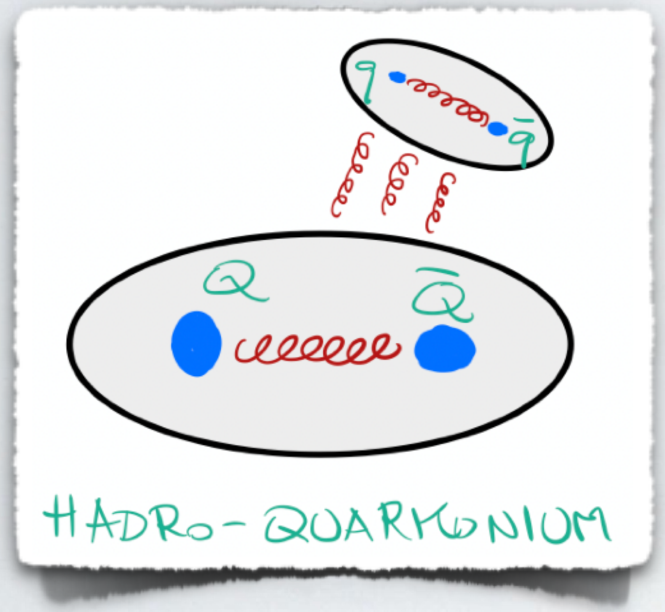


[e.g. Maiani et al. — PRD (2014), 1405.1551]

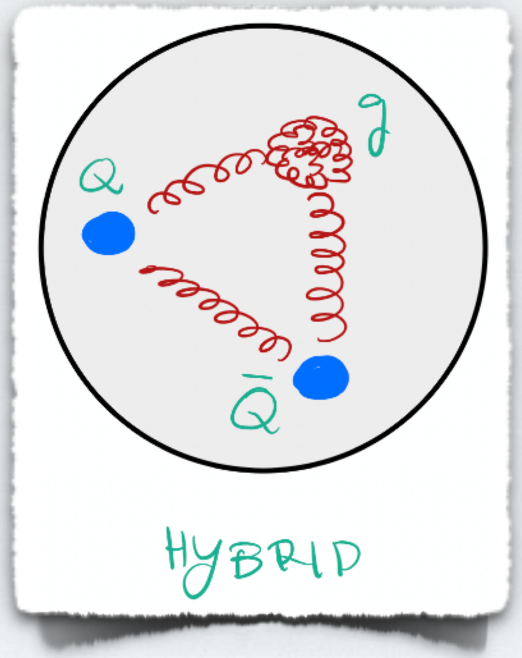
will focus on these



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



[see e.g. Dubynski, Voloshin — PLB (2008), 0803.2224]



[see e.g. Close, Page — PLB (2005), hep-ph/0507199]

[see e.g. Bugg — J.Phys.G (2008), 0802.0934]

EXOTIC MESONS

Compact tetraquarks

- Diquarkonium picture:

$$\mathscr{T}(x) \sim \Big[\epsilon_{ijk} Q^j(x) q^k(x)\Big]\Big[\epsilon^{ilm} \bar{Q}_l(x) \bar{q}_m(x)\Big] = \Big(\bar{Q}(x)Q(x)\Big)\Big(\bar{q}(x)q(x)\Big) - \Big(\bar{Q}(x)q(x)\Big)\Big(\bar{q}(x)Q(x)\Big)$$

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

antidiquark $\in \mathbf{3}_c$

- Phenomenological Hamiltonian for the interaction between constituents:

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

effective diquark mass

chromomagnetic coupling (e.g. $\kappa_{cq} \simeq 67$ MeV)

- Reproduces well the spectrum of observed resonances

[Maiani, Polosa, Riquer — PRD (2014), 1405.1551; for pentaquarks: Maiani, Polosa, Riquer — PLB (2015), 1507.04980]

EXOTIC MESONS

Compact tetraquarks

- Mass eigenstates ≠ isospin eigenstates: $X_u = [cu][\bar{c}\bar{u}]\,, \quad X_d = [cd][\bar{c}\bar{d}]$

- Since $\alpha_s(2m_c)$ is small $\longrightarrow$ mixing between X_u and X_d is suppressed

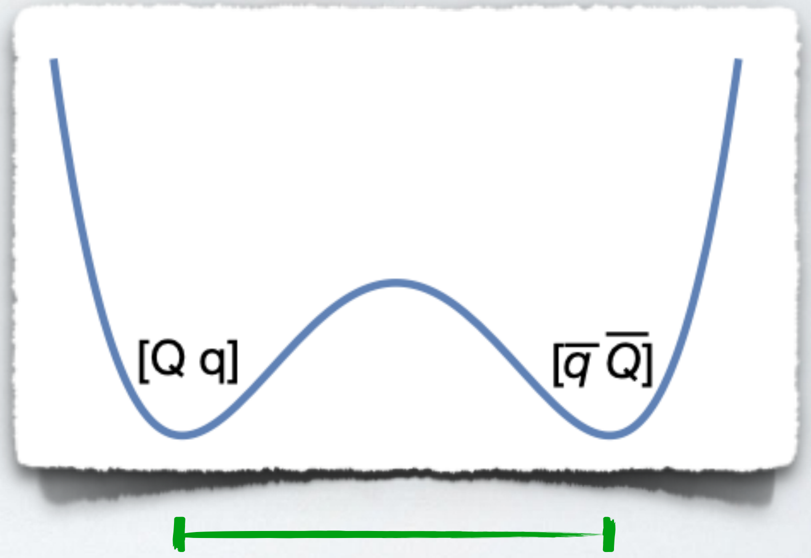
[Rossi, Veneziano — PLB (2004), hep-ph/0404262; Maiani, Piccinini, Polosa, Riquer — PRD (2005), hep-ph/0412098]

- 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]

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

- Tetraquark might be slightly larger than ordinary hadrons



$d_T \simeq 1.3$ fm

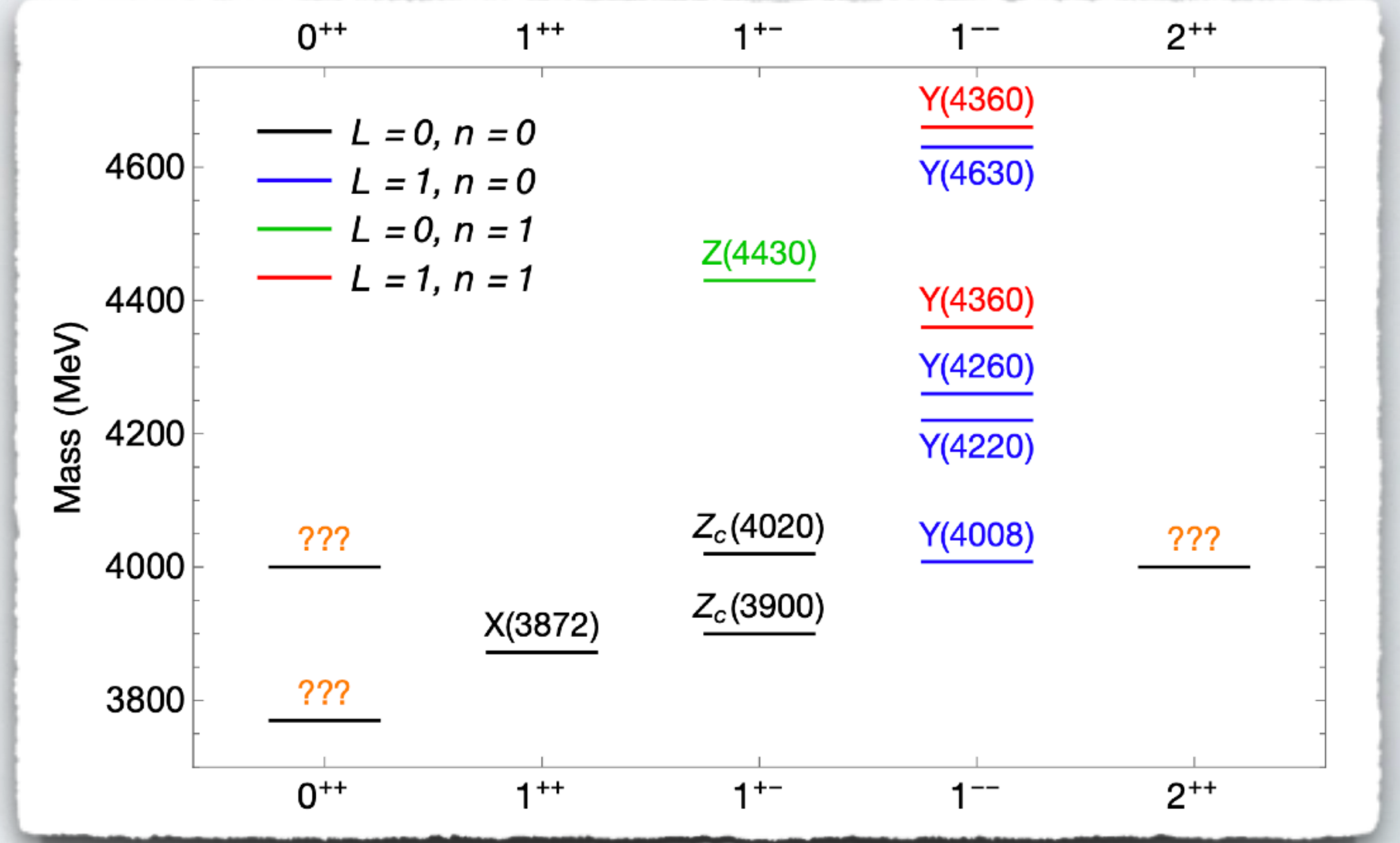
EXOTIC MESONS

Compact tetraquarks

- The simplest tetraquark model leaves some open issues
- In absence of further selection rules, its spectrum is overpopulated

[see e.g. Maiani, Polosa, Riquer — PLB (2018), 1712.05296]

1. Where are the charged partners of the $X(3872)$?
2. Where are the spin-0 and spin-2 states?
3. How about the analogue of the $X^{0,\pm}$ in the beauty sector?



EXOTIC MESONS

Hadronic molecules

- Many exotic resonances are close to meson-meson thresholds ⟶ they could be examples of hadronic molecules

  [see e.g. Tornqvist – PLB (2004), hep-ph/0402237; Swanson – PLB (2004), hep-ph/0311229]

- Loosely bound states of color singlets kept together by nuclear forces ⟶ large states with diameter up to ~ 14 fm

$$|E_B| \ll \frac{k^2}{2\mu} \quad \Longrightarrow \quad r_0 \simeq 1 \Big/ \sqrt{2\mu\,|E_B|} \gg 1 \big/ m_\pi$$

- Most notable example: deuteron

- The molecular model has the attractive feature that thresholds are not just an accident

EXOTIC MESONS

Hadronic molecules

- Dominance of the $D^0\bar{D}^{*0}$ decay for a loosely bound molecule is natural

coupling molecule - constituents

$\gamma \equiv \sqrt{2\mu E_B}$

$$\frac{g_{XD\bar{D}^*}}{4\pi} \simeq 4M_X^2\left(\frac{\gamma}{\mu}\right)\left(1-\lambda^2\right)$$

probability of finding a compact component in the state

`[see e.g. Weinberg, PRD (1965); Guo et al. — Rev.Mod.Phys. (2018), 1705.00141]`

- Isospin violation in the decay of the $X(3872)$ is explained because

$$M_X - M_{D^0\bar{D}^{*0}} \simeq 0\,, \qquad M_X - M_{D^+D^{*-}} \simeq -8 \text{ MeV}$$

- The X is then mostly $D^0\bar{D}^{*0}$ (both $I=0$ and $I=1$) ⟶ isospin violation

EXOTIC MESONS

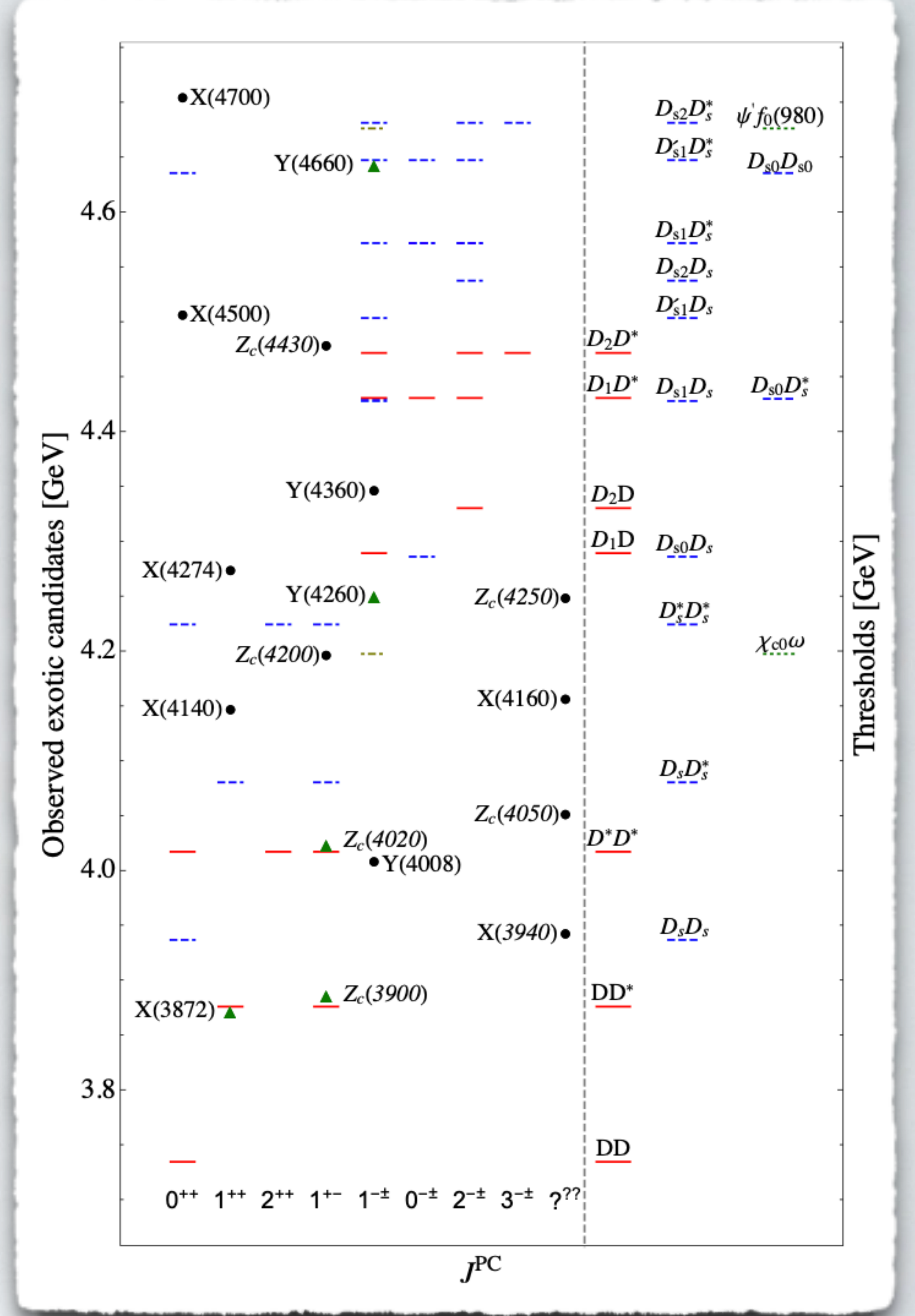
Hadronic molecules

- The simplest molecular model has issues too

- It is too populated as well ⟶ many possible combinations of bound states but very few seen

- Somewhat ad hoc: observe a state ⟶ look for hadron pairs ⟶ find effective potential that binds them

- Most notably it cannot easily explain the observed prompt production cross section of the $X(3872)$



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

EXOTIC MESONS

Recap

- Discriminating feature between tetraquarks and molecules → typical size
- Both theoretical pictures present successes and failures

Tetraquark	Hadronic molecule
Same idea behind well known meson/baryon spectrum	Borrows tools and ideas from nuclear physics
Based on symmetries: universal	Natural closeness to threshold
Some predicted states have not been observed	Lacks universality
	Cannot easily explain prompt production

PROMPT PRODUCTION

The problem

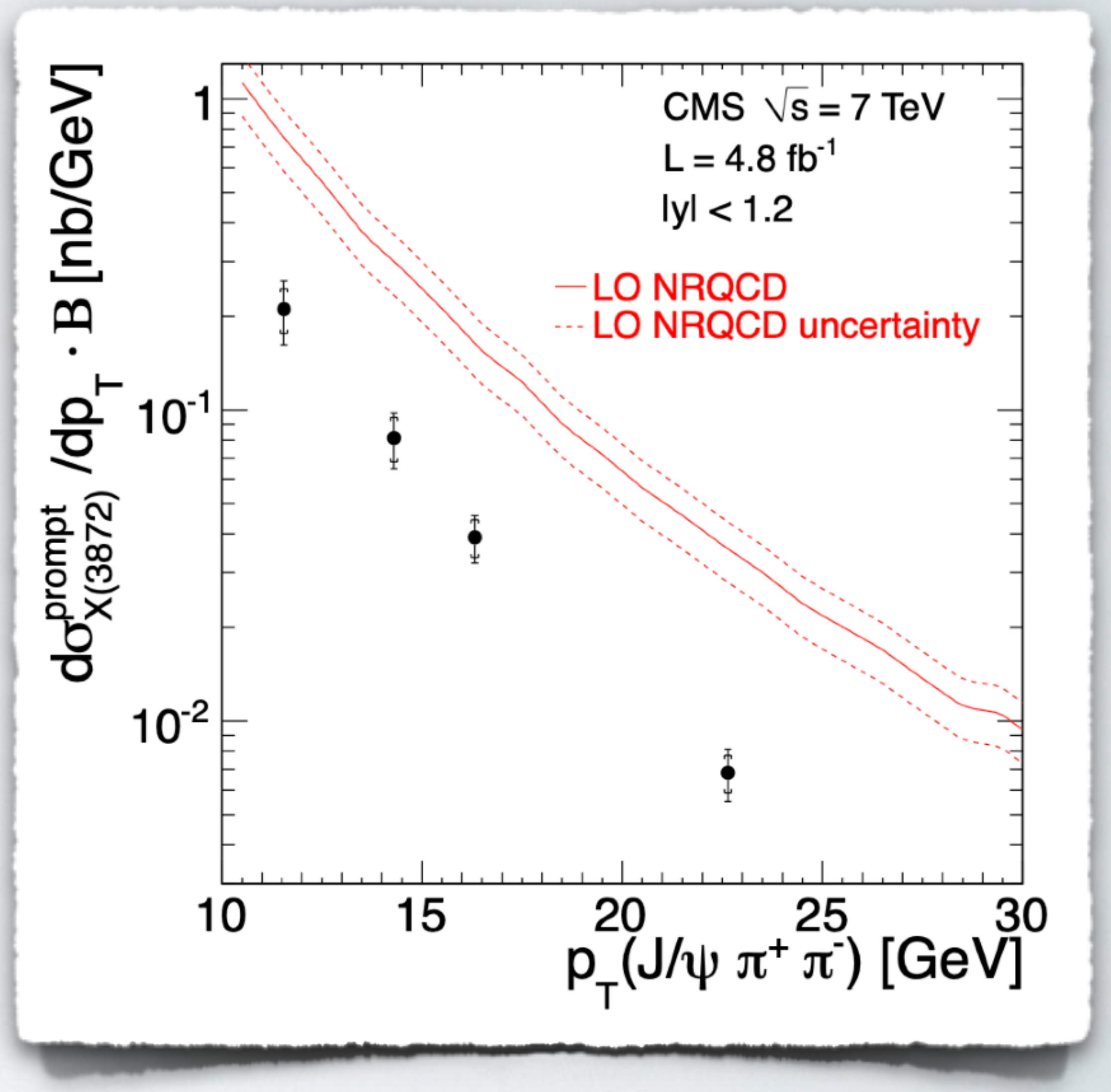
- The $X(3872)$ is produced prompt at high-p_T both at Tevatron and LHC

[see e.g. CDF — PRL (2007), hep-ex/0612053; CMS — JHEP (2013), 1302.3968]

$$\sigma_{prompt}\left(pp \to X\right) \sim 30 \div 70 \text{ nb}$$

[Artoisenet, Braaten — PRD (2010), 0911.2016]

- How can such a loosely bound molecule be produced promptly from a $D^0\bar{D}^{*0}$ pair with relative momentum $k \gtrsim 10$ GeV?



[CMS — JHEP (2013), 1302.3968]

PROMPT PRODUCTION

Monte Carlo

- Upper bound on the prompt production cross section

$$\sigma_{prompt}\left(pp\to X\right)\leq\sigma_{max}\left(pp\to D^0\bar{D}^{*0}\right)\simeq\sigma\left(pp\to D^0\bar{D}^{*0}\Big|k_{rel}<\Lambda\right)$$

can estimate from MC simulations

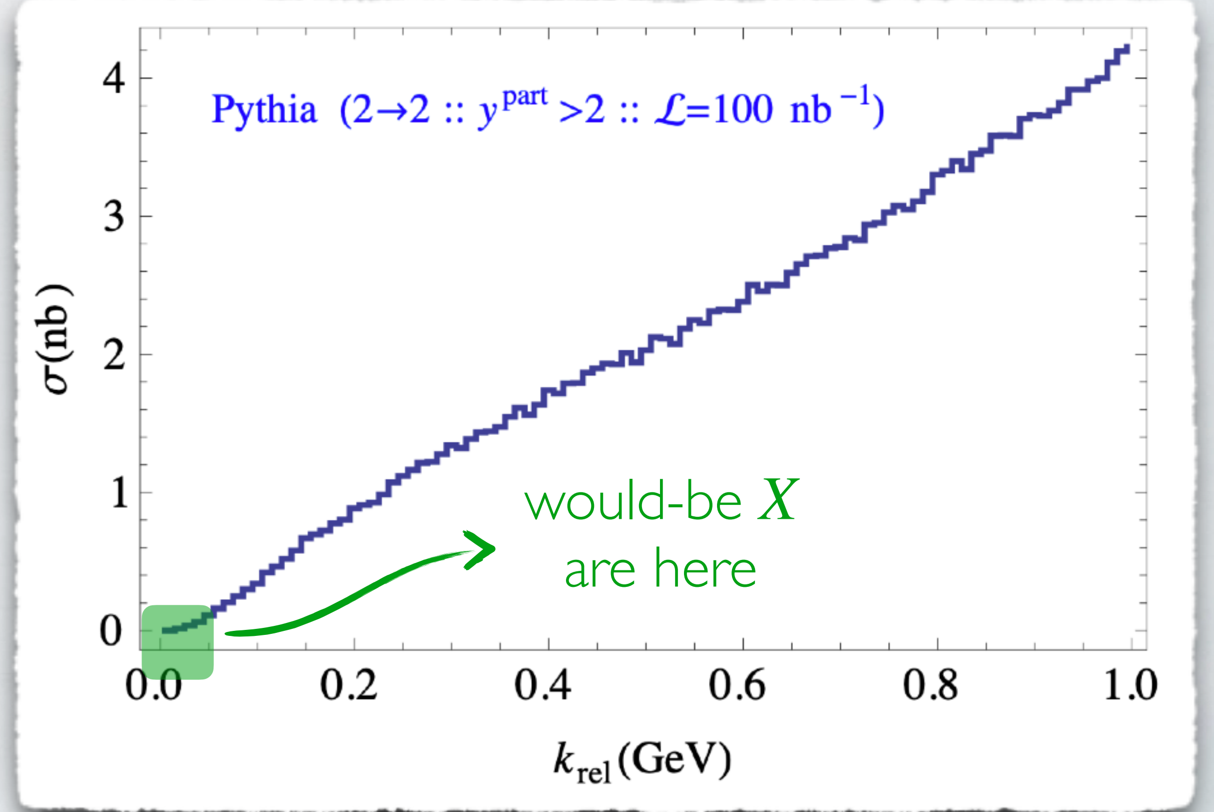
- From the spread of the wave function of the X $\longrightarrow$ $\Lambda\simeq 30$ MeV

- From Monte Carlo one obtains

$$\sigma_{Pythia}\simeq 0.11\text{ nb}$$

$$\sigma_{Herwig}\simeq 0.071\text{ nb}$$

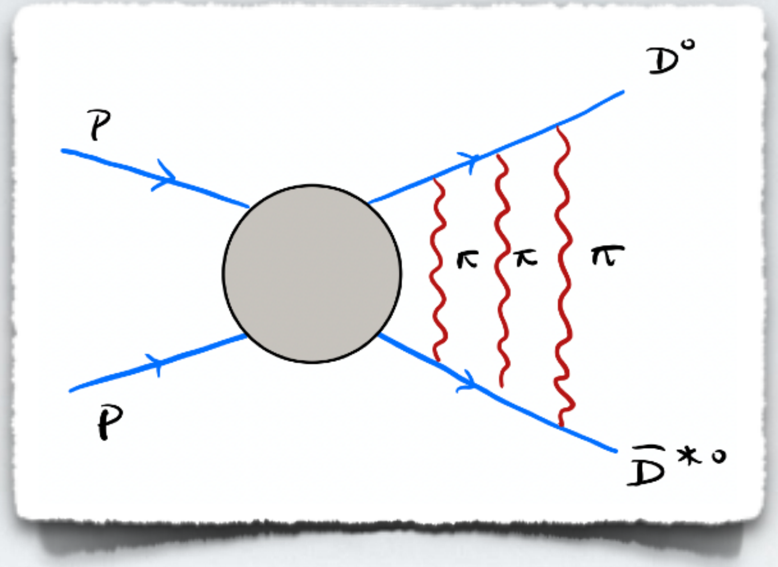
[Bignamini et al. — PRL (2009), 0906.0882]



PROMPT PRODUCTION

Final State Interactions

- Is Λ just the spread of the wave function?
- Including Final State Interactions between the $D^0\bar{D}^{*0}$ one can extend $\Lambda \sim m_\pi$



- For $\Lambda = 2.7\, m_\pi \simeq 360$ MeV one reproduces the experimental cross section

[Artoisenet, Braaten — PRD (2010), 0911.2016]

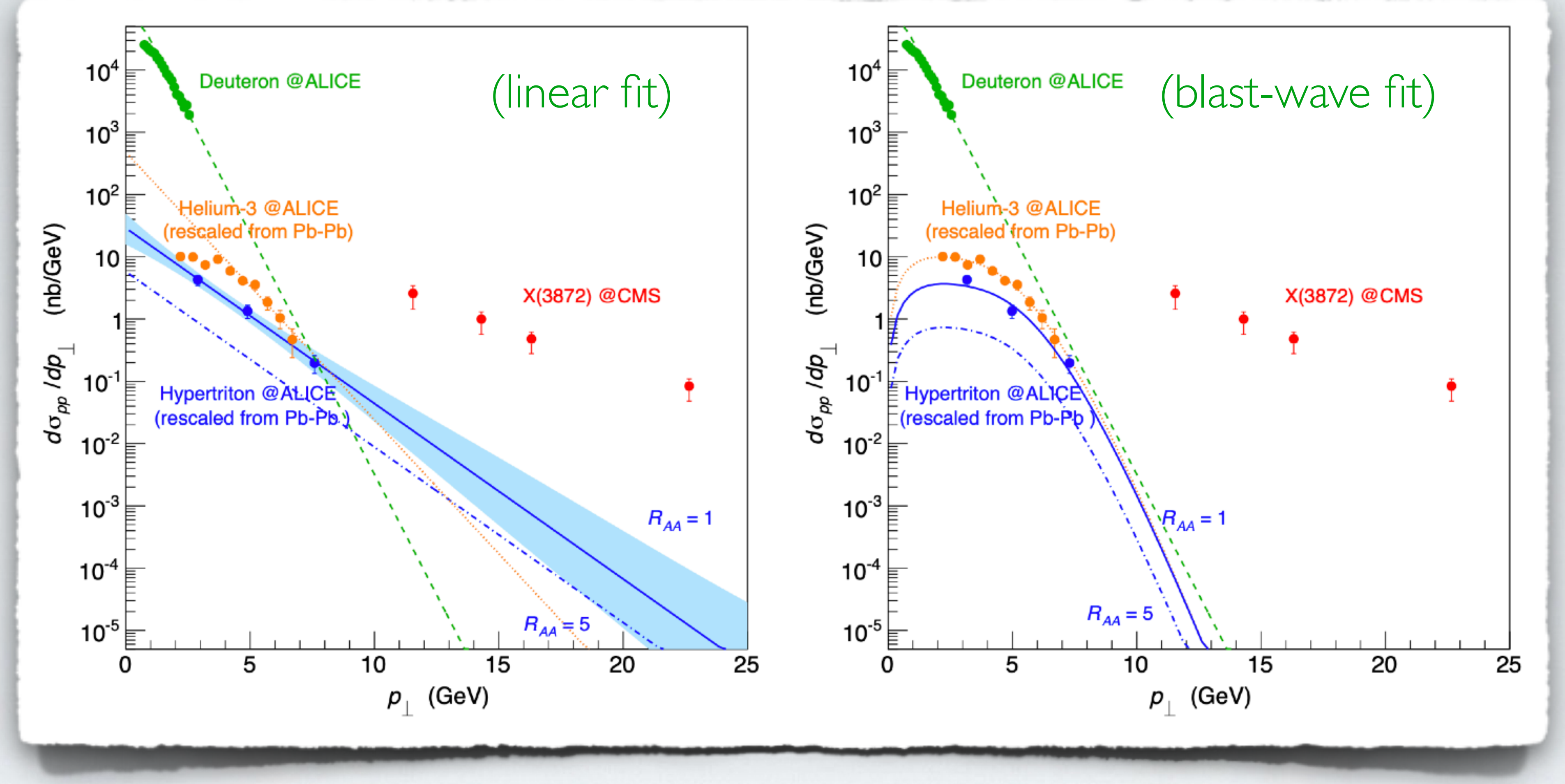
- The use of Final State Interactions in this context has been questioned…

[Bignamini et al. — PLB (2010), 0912.5064]

PROMPT PRODUCTION

Other bone fide molecules

- A stronger statement from the comparison with other loosely bound molecules



[AE, Guerrieri, Maiani, Piccinini, Pilloni, Polosa, Riquer — PRD (2015), 1508.00295]

- No hadronic molecule is produced at high-p_T except for the $X(3872)$

PROMPT PRODUCTION

A $c\bar{c}$ component

- Definitely viable solution:

$$|X\rangle = \sqrt{Z_{mol}}\,|D^0\bar{D}^{*0}\rangle + \sqrt{Z_{c\bar{c}}}\,|\chi_{c1}(2P)\rangle \qquad \text{with:} \qquad Z_{c\bar{c}} = (28 \div 44)\,\%$$

- Explains both prompt production and production via B-decays

[Butenschoen, He, Kniehl — PRD (2013), 1303.6524; Meng, Han, Chao — PRD (2017), 1304.6710]

- However:

1. From simple potential models $M\left(\chi_{c1}(2P)\right) - M\left(X(3872)\right) \simeq 100$ MeV

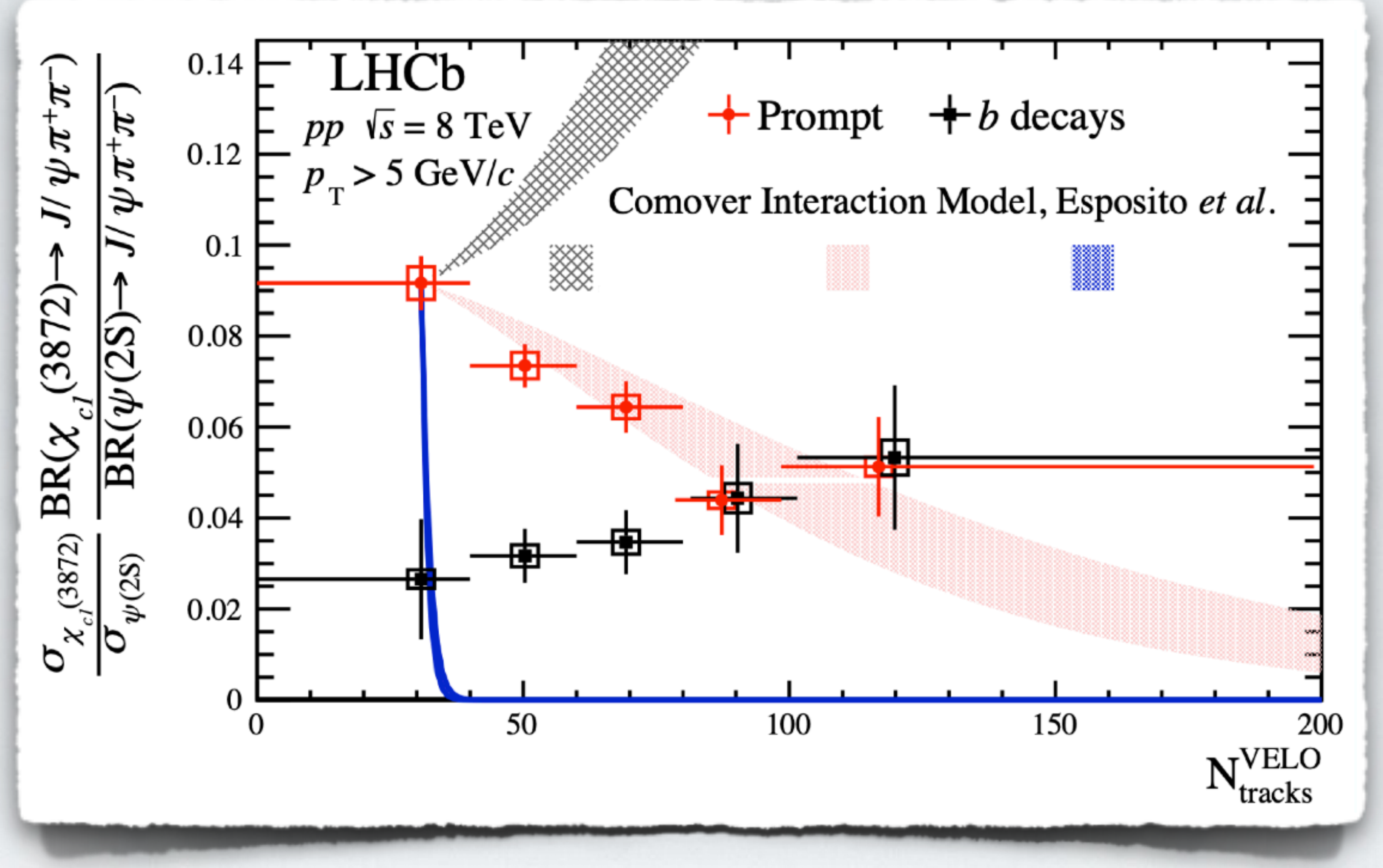
   [see e.g. Braaten, Kusunoki — PRD (2004), hep-ph/0311147]

2. Why not to include a tetraquark or other exotic components?

POSSIBLE OBSERVABLES

High-multiplicity

- Yields of $X(3872)$ vs $\psi(2S)$ as a function of final state multiplicity in pp collisions



[LHCb — PRL (2021), 2009.06619]

- Many particles in the event $\longrightarrow$ the X is suppressed with respect to the $\psi(2S)$

POSSIBLE OBSERVABLES

High-multiplicity

- The interaction with final state comoving particles can help create/destroy a hadron

[see e.g. Baym — PLB (1984)]

- For a compact state in *pp* collisions the number evolves following

heavy hadron number

destruction cross section

$$\tau \frac{dN_{\mathcal{Q}}}{d\tau} = -\langle v\sigma\rangle_{\mathcal{Q}}\, \rho_c\, N_{\mathcal{Q}}$$

comover density at initial time (Glauber model)

- In the comover interaction model one takes

$$\langle v\sigma\rangle_{\mathcal{Q}} \sim \pi r_{\mathcal{Q}}^2$$

- Quantitatively successful for quarkonium yields in *pp*, *p*Pb and PbPb

[see e.g. Ferreiro — PLB (2015), 1411.0549; Ferreiro, Lansberg — JHEP (2019), 1804.04474]

POSSIBLE OBSERVABLES

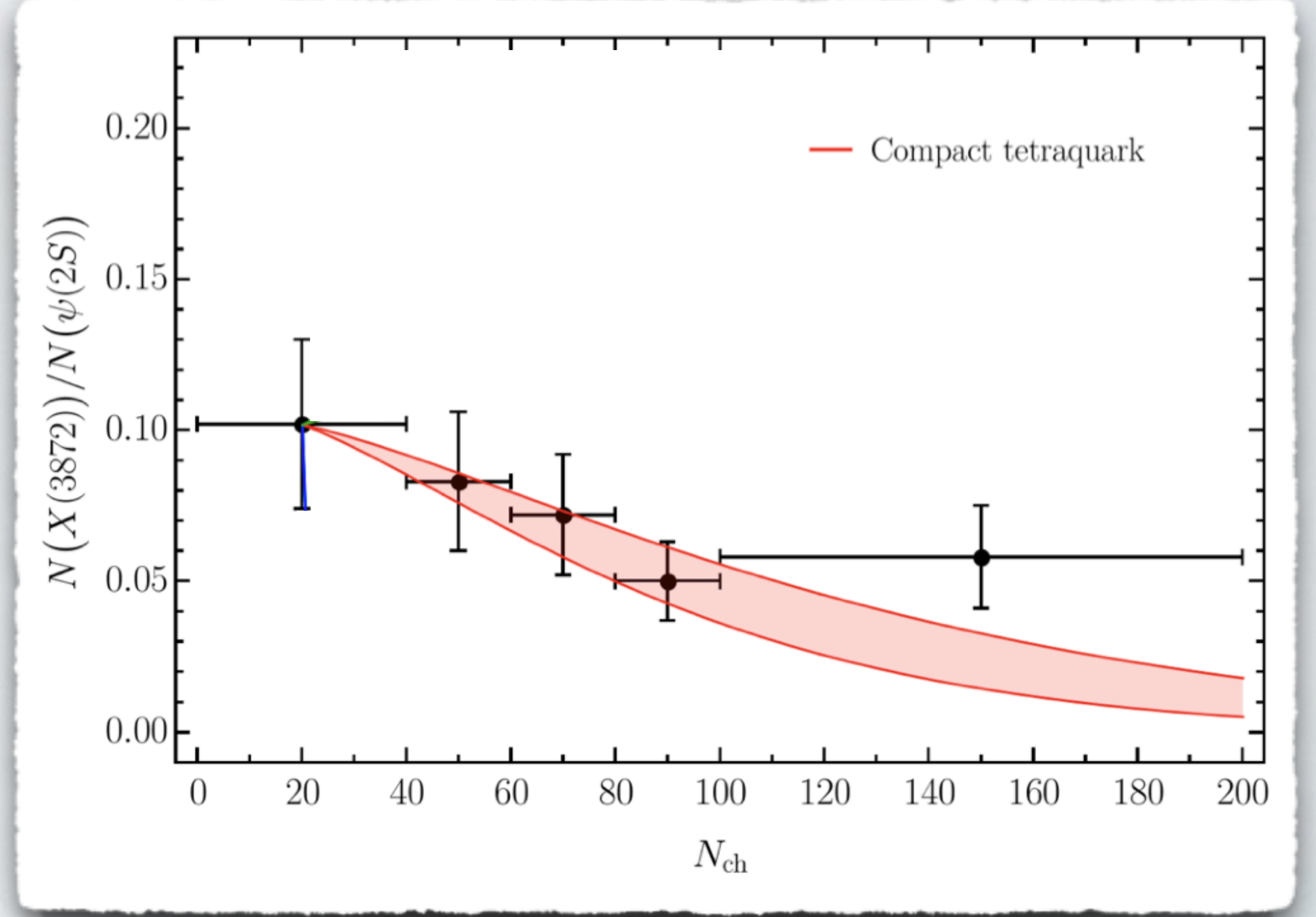
High-multiplicity

- Apply the model to the compact tetraquark hypothesis ⟶ slightly larger than quarkonia

$$\begin{cases} r_{4q} \simeq 0.65 \text{ fm} \\ r_{\psi(2S)} \simeq 0.45 \text{ fm} \end{cases} \Longrightarrow \begin{cases} \langle v\sigma\rangle_{4q} \simeq 11.61 \text{ mb} \\ \langle v\sigma\rangle_{\psi(2S)} \simeq 5.15 \text{ mb} \end{cases}$$

- Good agreement with the LHCb data!

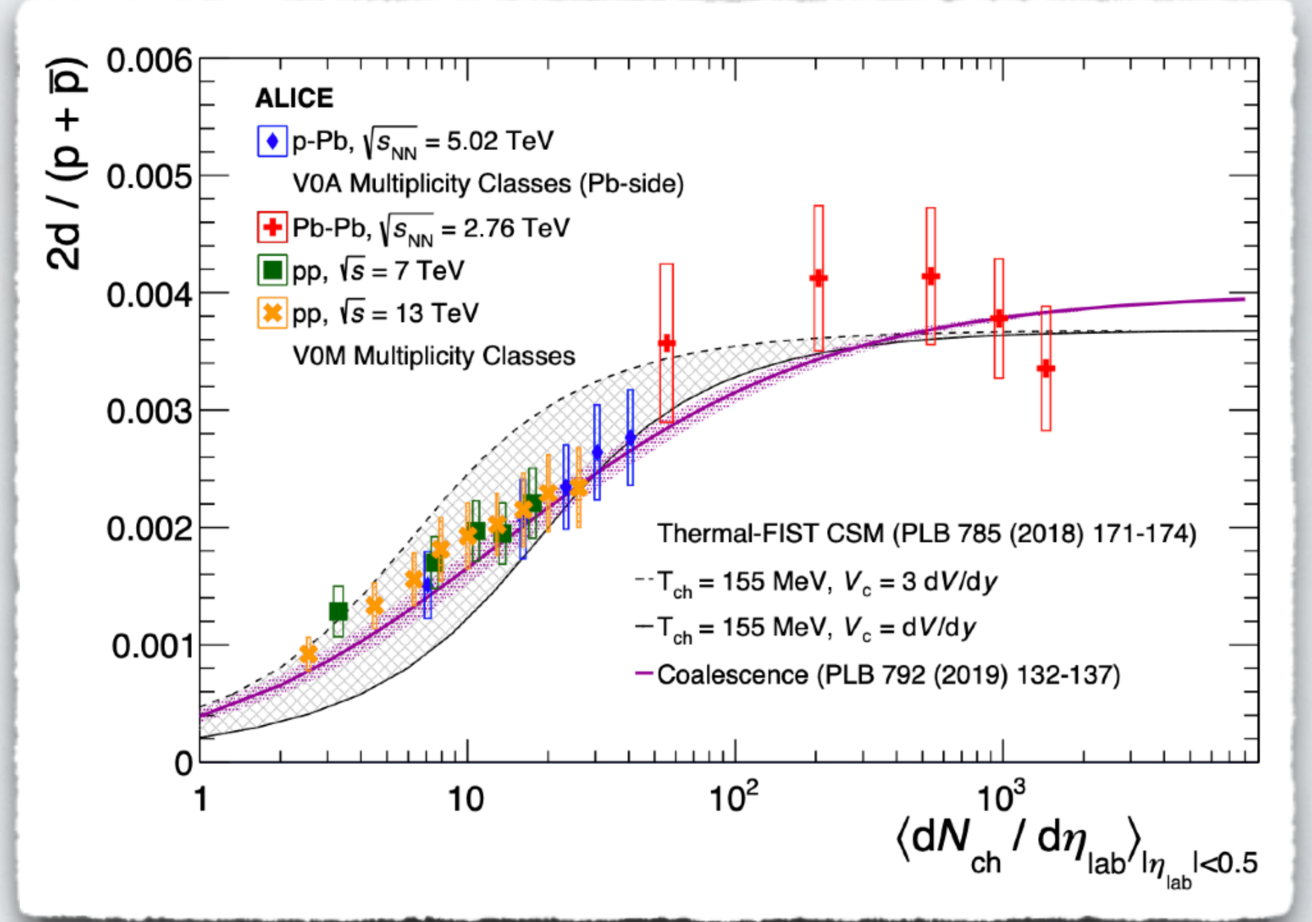
  [AE, Ferreiro, Pilloni, Polosa, Salgado — 2006.15044]



POSSIBLE OBSERVABLES

High-multiplicity

- Creation/destruction of <u>hadronic molecules</u> is more complicated than that
- Recent data show that the comovers favor the creation of molecules
- Higher multiplicity ⟶ more nucleons are turned into deuterons
- Important to better describe destruction and coalescence of hadron molecules



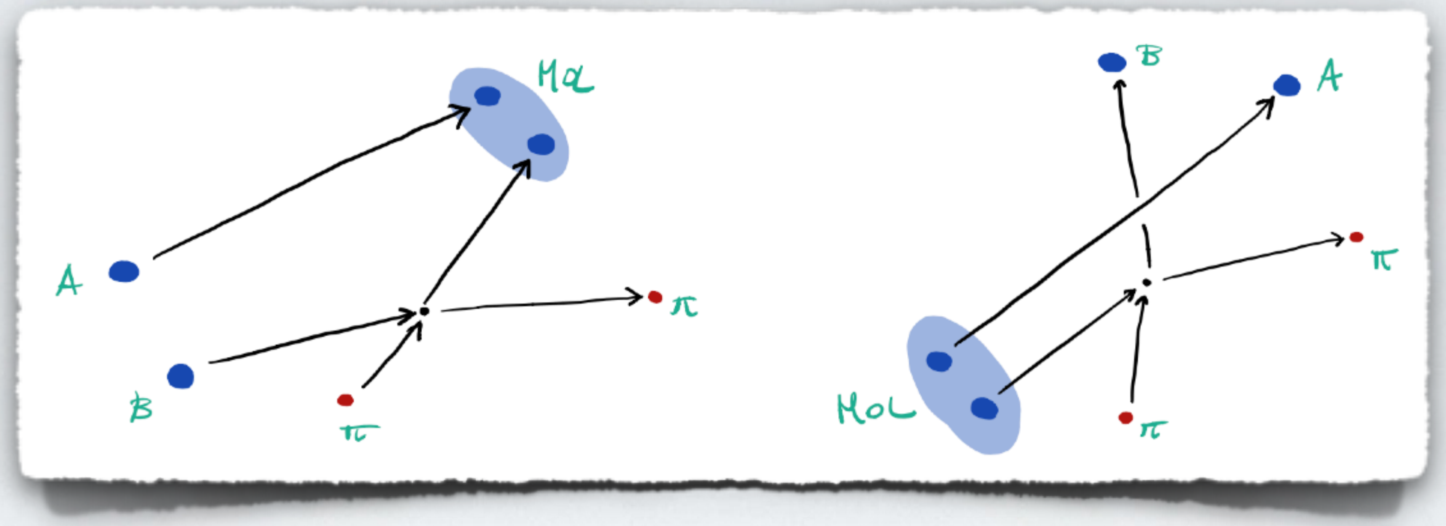
[ALICE — PLB (2019), 1902.09290; ALICE — EPJC (2020), 2003.03184]

POSSIBLE OBSERVABLES

High-multiplicity

- The interaction with comovers can destroy or create a hadronic molecule

[see e.g. AE, Piccinini, Pilloni, Polosa – J.Mod.Phys. (2013), 1305.0527; Guerrieri, Piccinini, Pilloni, Polosa – PRD (2014), 1405.7929; Cho et al. – PRL (2011), 1011.0852]



- The number of molecules evolves according to

# of free constituents

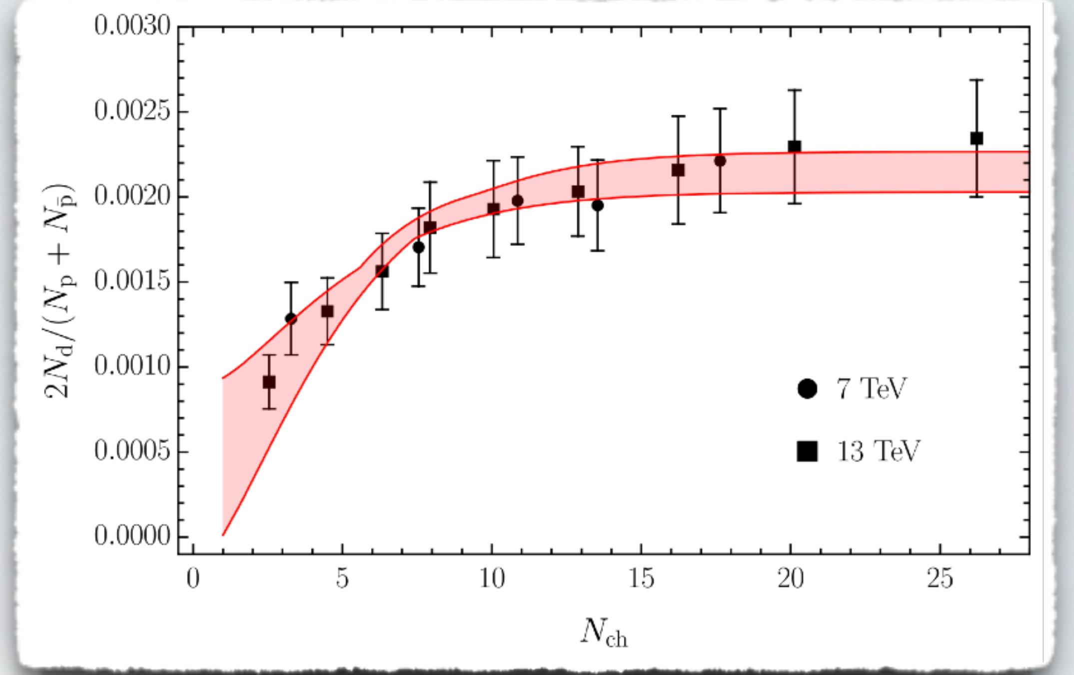
# of molecules

$$\tau \frac{dN_m}{d\tau} = \rho_c N_{hh} \langle v\sigma \rangle_m - \rho_c N_m \langle v\sigma \rangle_{hh}$$

dominated by comover-constituent interactions

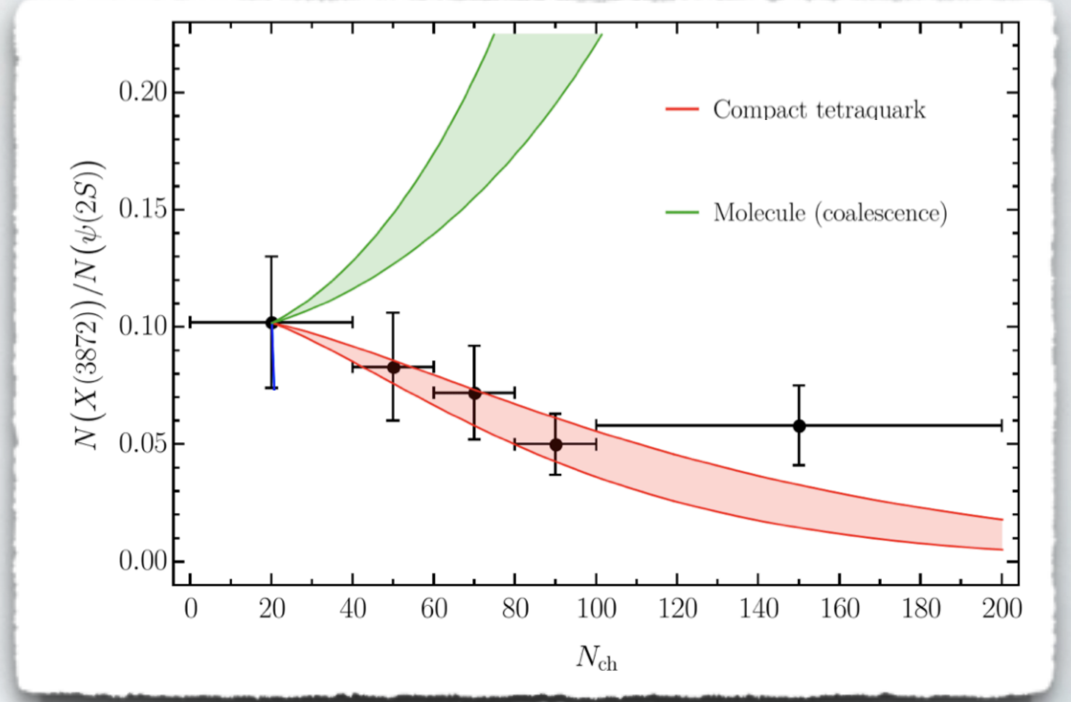
POSSIBLE OBSERVABLES

High-multiplicity



- We test this on deuteron production (coalescence for $k \lesssim 50 \div 250$ MeV)

- Good agreement with data



- Same model applied to the $X(3872)$ (coalescence for $k \lesssim 30 \div 360$ MeV)

- Qualitatively different from data

`[AE, Ferreiro, Pilloni, Polosa, Salgado — 2006.15044]`

POSSIBLE OBSERVABLES

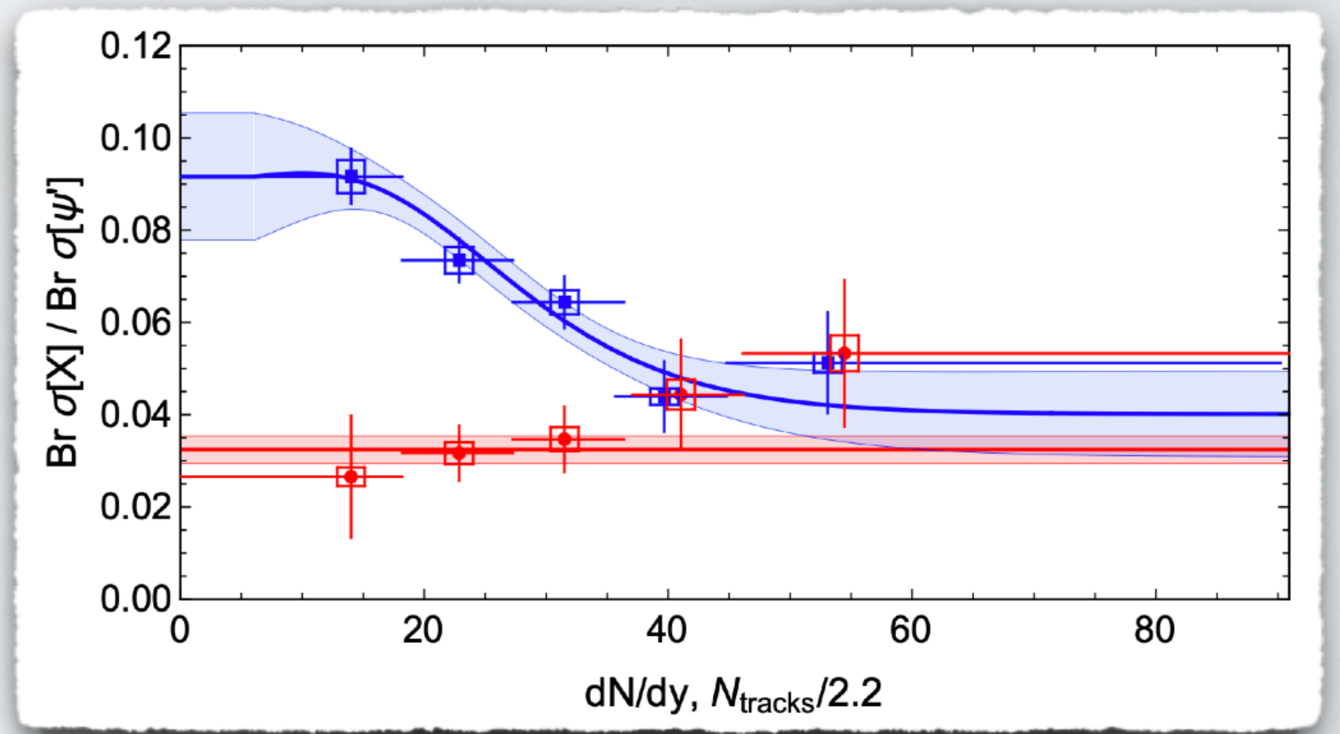
High-multiplicity

- This result as well has been questioned

- Assume meson molecule ⟶ allow for a fraction ($f_{out,\mathcal{Q}}$) of the comovers not to interact with the heavy state ⟶ good fit with data

$$\frac{N\big(X(3872)\big)}{N\big(\psi(2S)\big)} \propto \frac{1+(1/f_{out,X}-1)S_X}{1+(1/f_{out,\psi'}-1)S_{\psi'}}$$

fit from data



[Braaten, He, Ingles, Jiang — 2012.13499]

POSSIBLE OBSERVABLES

High-multiplicity

- Remarks:

1. High-multiplicity collisions can give important insight on the internal structure of the exotic hadrons

2. How does the $X(3872)$, other charmonia and the deuteron behave in pPb and PbPb collisions?

3. What is the behavior with multiplicity and p_T ?

POSSIBLE OBSERVABLES

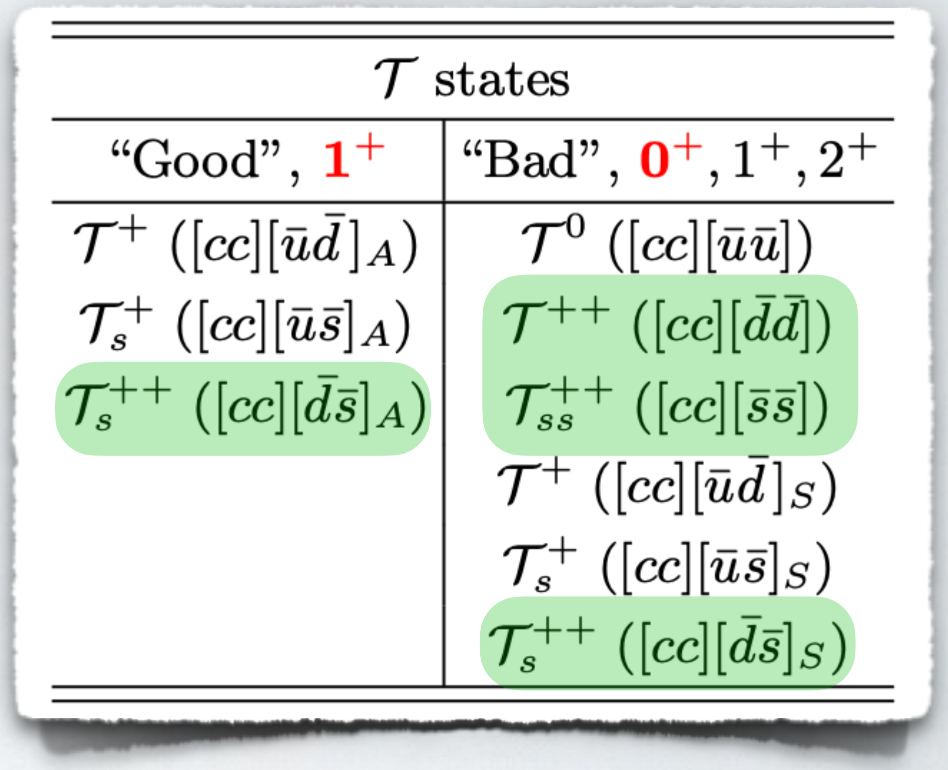
Flavored states

- Another possibility is to look for flavored tetraquarks

$$\mathscr{T} \sim QQ\bar{q}_1\bar{q}_2$$

- Flavor symmetry predicts doubly-charged states

- $\mathscr{T}^{++}$ states cannot be hadronic molecules ⟶ Coulomb repulsion would prevent their formation



$\mathcal{T}$ states

"Good", $\mathbf{1^+}$	"Bad", $\mathbf{0^+}, 1^+, 2^+$
$\mathcal{T}^+$ $([cc][\bar{u}\bar{d}]_A)$	$\mathcal{T}^0$ $([cc][\bar{u}\bar{u}])$
$\mathcal{T}_s^+$ $([cc][\bar{u}\bar{s}]_A)$	$\mathcal{T}^{++}$ $([cc][\bar{d}\bar{d}])$
$\mathcal{T}_s^{++}$ $([cc][\bar{d}\bar{s}]_A)$	$\mathcal{T}_{ss}^{++}$ $([cc][\bar{s}\bar{s}])$
	$\mathcal{T}^+$ $([cc][\bar{u}\bar{d}]_S)$
	$\mathcal{T}_s^+$ $([cc][\bar{u}\bar{s}]_S)$
	$\mathcal{T}_s^{++}$ $([cc][\bar{d}\bar{s}]_S)$

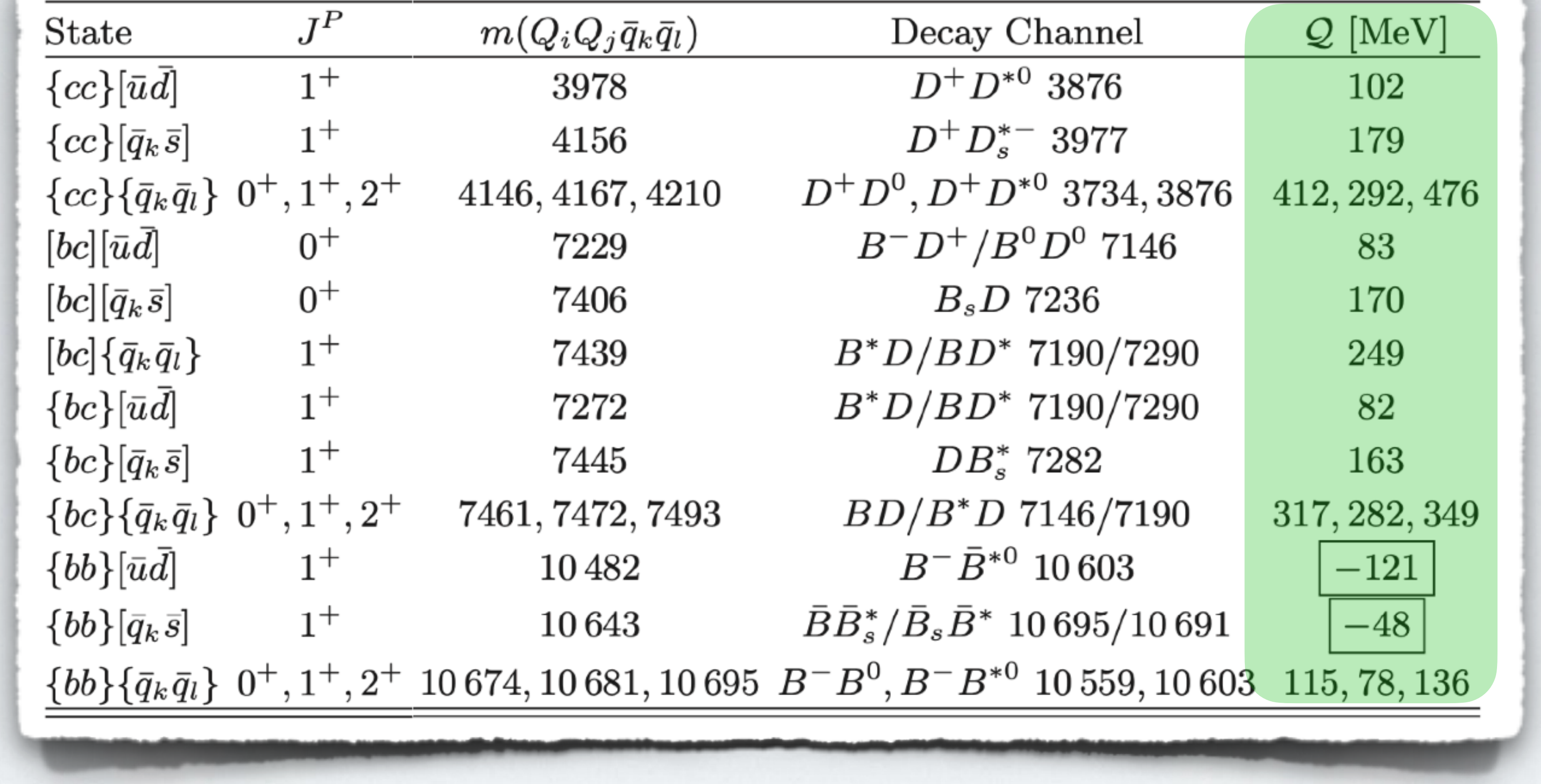
[AE, Papinutto, Pilloni, Polosa, Tantalo — PRD (2013), 1307.2873]

POSSIBLE OBSERVABLES

Flavored states

- Several predictions for flavored states

[e.g. Eichten, Quigg — PRL (2017), 1707.09575; Ali, Parkhomenko, Qin, Wang — PLB (2018), 1805.02535, and many others]



State	J^P	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	4146, 4167, 4210	D^+D^0, D^+D^{*0} 3734, 3876	412, 292, 476
$[bc][\bar{u}\bar{d}]$	0^+	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	7461, 7472, 7493	BD/B^*D 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	1^+	10 482	$B^-\bar{B}^{*0}$ 10 603	$\boxed{-121}$
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	10 643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10 695/10 691	$\boxed{-48}$
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	10 674, 10 681, 10 695	B^-B^0, B^-B^{*0} 10 559, 10 603	115, 78, 136

- Some of them are predicted to be narrow and most of them are far away from threshold

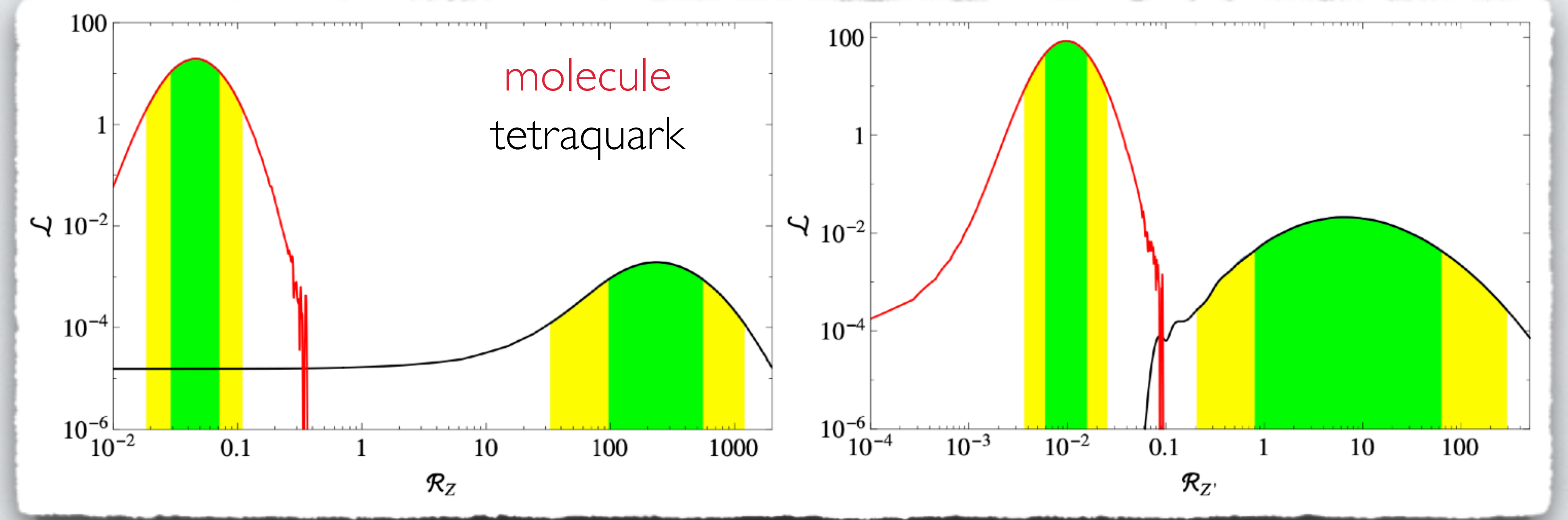
POSSIBLE OBSERVABLES

Peculiar decay channels

- A possible decay channel that can discriminate between a tetraquark structure and a hadronic molecule one is

$$\frac{BR\big(Z_c(3900) \to \eta_c \rho\big)}{BR\big(Z_c(3900) \to J/\psi \pi\big)} \quad \text{and} \quad \frac{BR\,\big(Z_c(4200) \to \eta_c \rho\big)}{BR\big(Z_c(4200) \to h_c \pi\big)}$$

- The branching ratios within the two models are statistically different



[AE, Guerrieri, Pilloni — PLB (2015), 1409.3551]

POSSIBLE OBSERVABLES

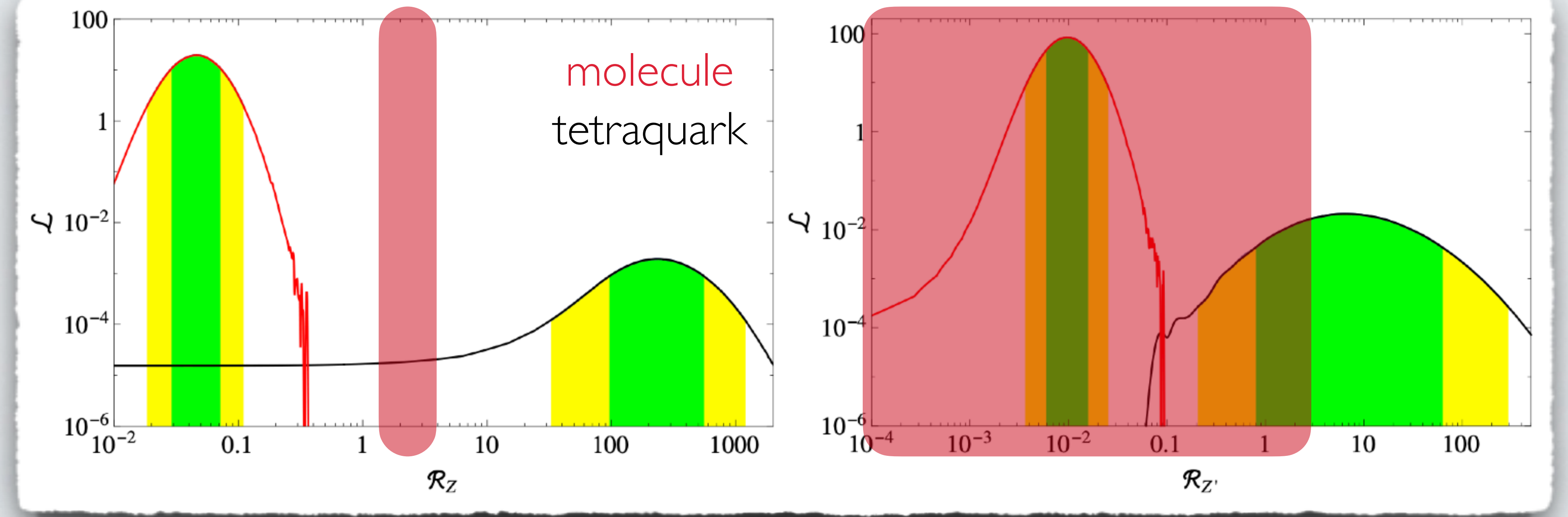
Peculiar decay channels

- Evidence for this decays recently reported by BESIII

[BESIII — PRD (2019), 1906.00831]

- Too low statistics but promising

BESIII values



POSSIBLE OBSERVABLES

$X(6900)$

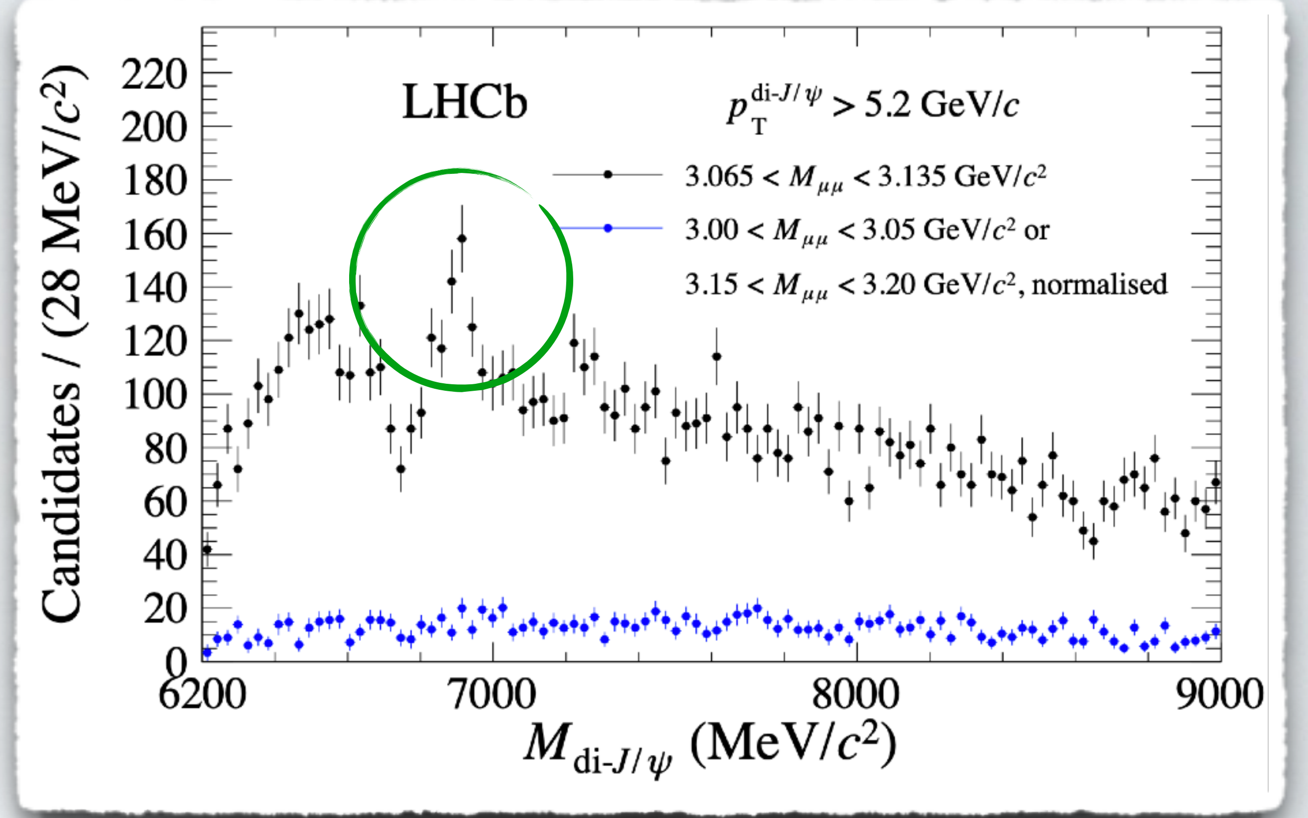
- LHCb has recently observed a resonance in the $J/\psi - J/\psi$ invariant mass spectrum

- The Breit-Wigner mass and width are

$$M\big(X(6900)\big) = 6905 \pm 18 \text{ MeV}$$

$$\Gamma\big(X(6900)\big) = 80 \pm 52 \text{ MeV}$$

- This is ~ 700 MeV above the $J/\psi - J/\psi$ threshold



[LHCb – Sci.Bull. (2020), 2006.16957]

- No light hadrons can create this resonance so far from threshold → did we just observe the first bona fide compact tetraquark?

CONCLUSION

- The observation of exotic hadrons leaves an open problem in the understanding of QCD at low energies
- No fully satisfactory theoretical picture has arisen so far ⟶ the comparison with experiment has highlighted crucial gaps
- For the compact tetraquark to be fully satisfactory some selection rules must be found to explain the lack many states
- Personal opinion: maybe the field has been approached too much as a QCD chemistry ⟶ it might be good to step back and think about the universal features of these states, rather than accounting for each of them separately

Thank you for your attention!