Spectroscopy of Heavy Exotics

Christoph Hanhart

Forschungszentrum Jülich

Recent Review articles

A. Esposito, A. Pilloni, A.D. Polosa, Phys. Rep. 668 (2016) 1

H.X. Chen, W. Chen, X. Liu, S.L. Zhu, Phys. Rep. 639 (2016) 1

A. Ali, J.S. Lange, S. Stone, Prog. Part. Nucl. Phys. 97 (2017) 123

R.F. Lebed, R.E. Mitchell, E.S. Swanson, Prog. Part. Nucl. Phys. 93 (2017) 143

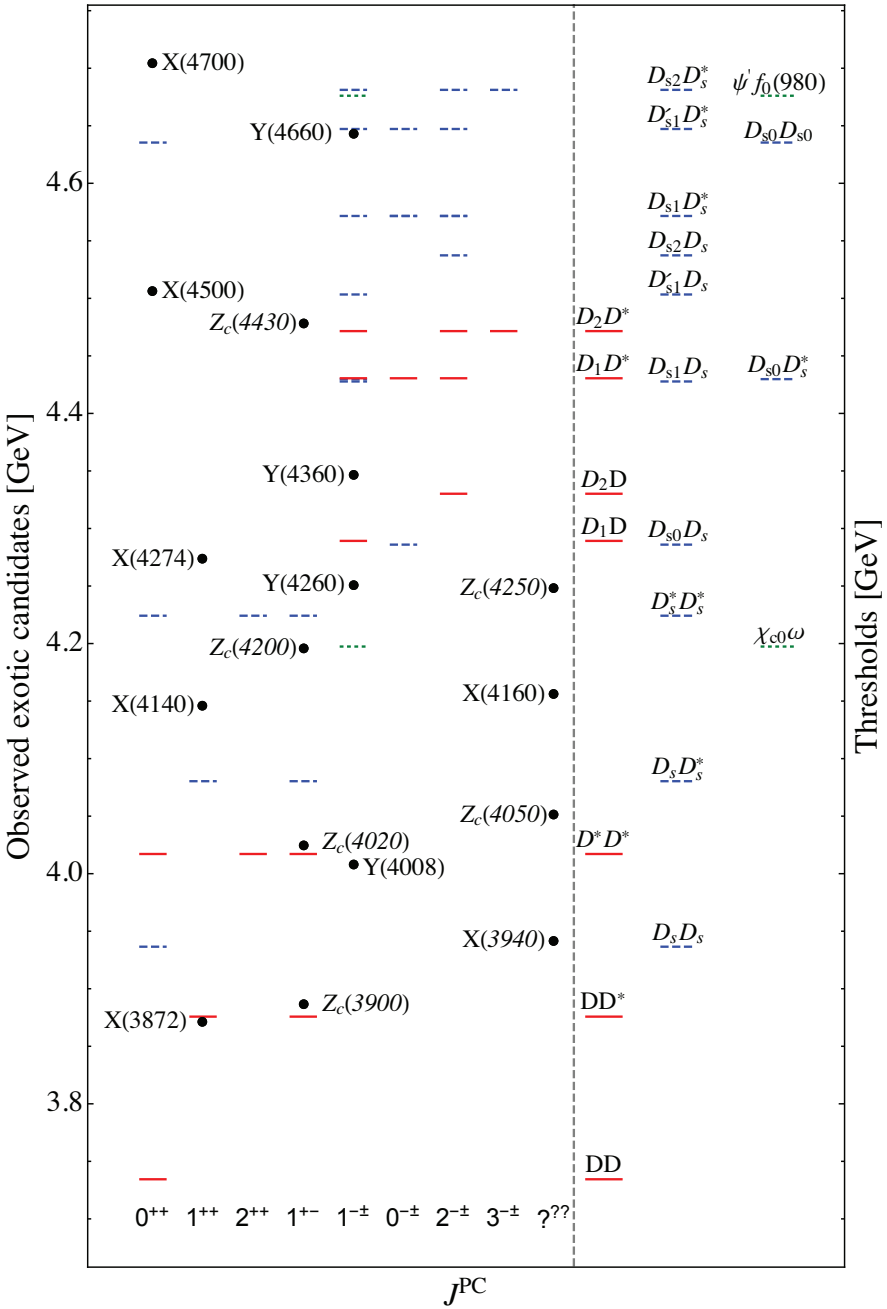
S.L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003

N. Brambilla, S. Eidelman, C.H., A. Nefediev, C.-P. Shen, C.E. Thomas, A. Vairo, C. Yuan, Phys. Rept. 873 (2020) 1

with focus on molecular states:

F.-K. Guo, C.H., U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Rev. Mod. Phys. 90(2018)015004

There are many exotics with $\bar{Q}Q$ ...



Guo et al. RMP90(2018)015004

→ All exotic candidates above open flavor thresholds

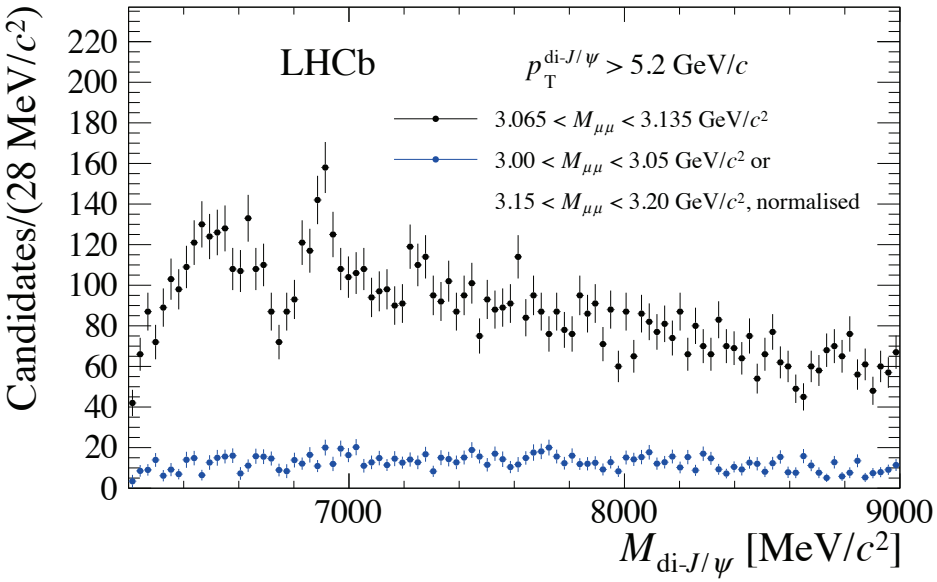
→ Many (not all) states near S-wave thresholds of narrow states Filin et al., PRL 105, 019101 (2010) Guo et al., PRD84, 014013 (2011)

→ States not near all those thresholds

→ There are charged states that contain $\bar{Q}Q$

→ Lightest negative parity exotic ($Y(4220)$) significantly heavier than lightest positive parity exotics ($X(3872)$ & $Z_c(3900)$)

.... and there are more



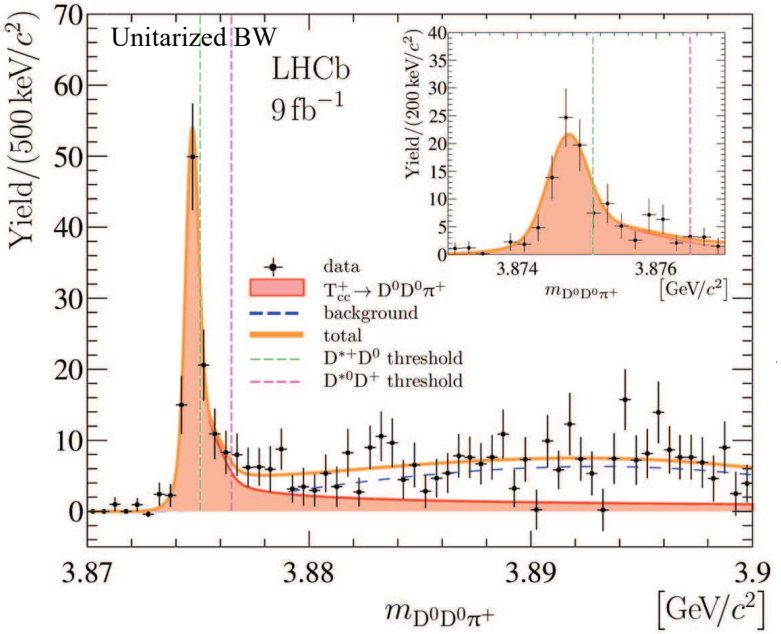
LHCb 2020, arXiv:2006.16957

→ Several (?) states found in $J/\psi J/\psi$

→ Must contain (at least) $\bar{c}\bar{c}cc$

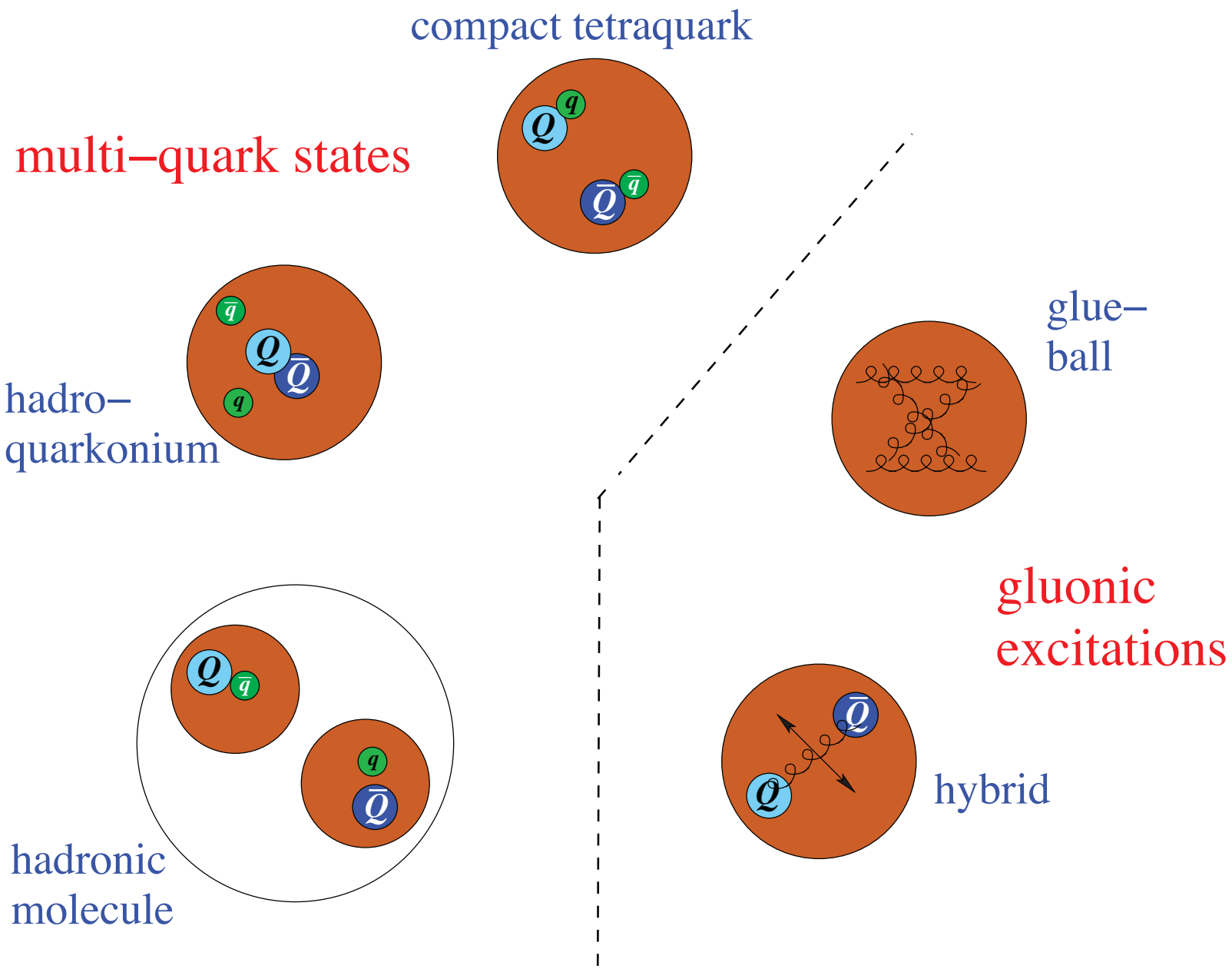
→ A new state T_{cc} very near DD^* threshold

→ Must contain (at least) $\bar{q}\bar{q}cc$



LHCb 2020, arXiv:2109.01038/2109.01056

Proposals for Exotics



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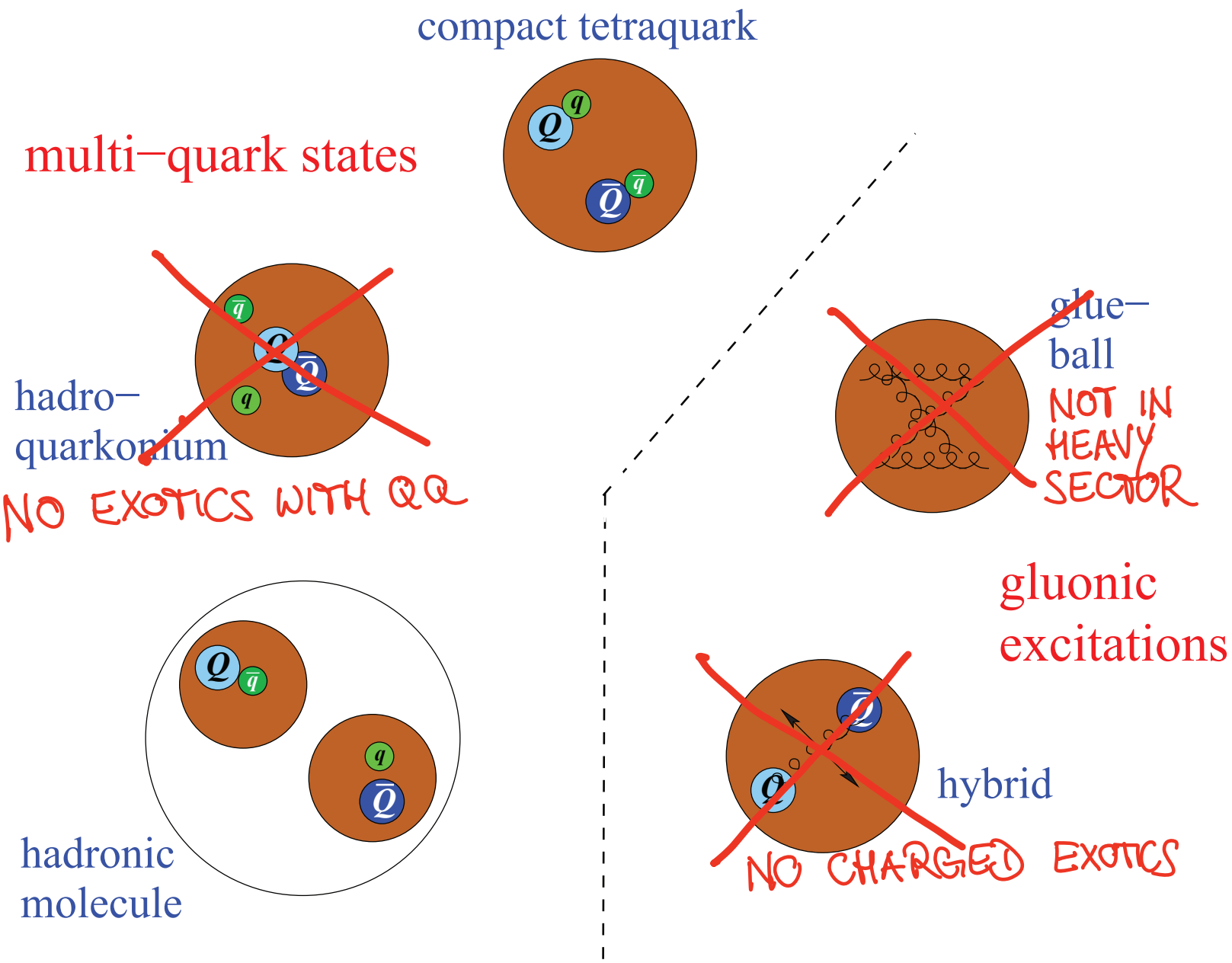
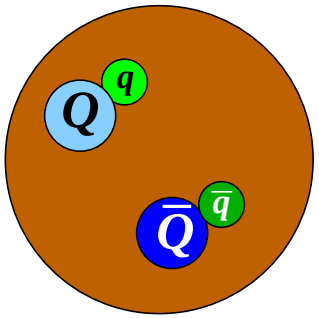
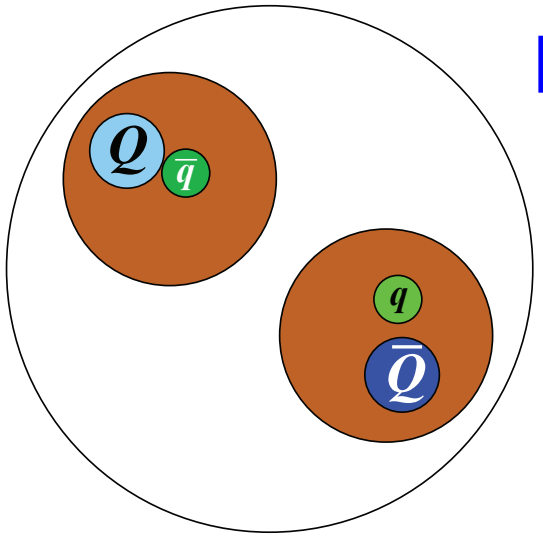


Overview



Tetraquark

$\rightarrow$ Compact object formed from diquarks, (Qq) and $(\bar{Q}\bar{q})$



Hadronic-Molecule

$\rightarrow$ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

Bohr radius = $1/\gamma = 1/\sqrt{2\mu E_b}$

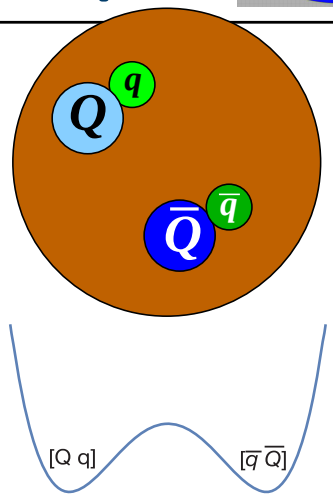
$\gg 1$ fm $\gtrsim$ confinement radius

for near threshold states

Symmetry (violations) as tool to disentangle these structures

Focus here: Heavy Quark Spin Symmetry (HQSS)

Heavy Tetraquarks



→ Straightforward extension of the quark model

M. Gell-Mann, PL8(1964)214

→ Mesons as diquark–anti-diquark systems

Jaffe, PRD15(1977)267, Maiani et al., PRD71(2005)014028

→ Separated by potential well

Selem and Wilczek, hep-ph/0602128; Maiani et al., PLB778(2018)247

alternative approaches, e.g., Cui et al., HEPNP31(2007)7; Stancu, JPG37(2010) 075017

→ To account for spectrum spin-spin interaction needs to be dominant within diquarks

Maiani et al. PRD89(2014)114010

$\Longrightarrow$ certain kind of Spin Symmetry Violation

→ and tensor force, S_{12}, needs to be considered

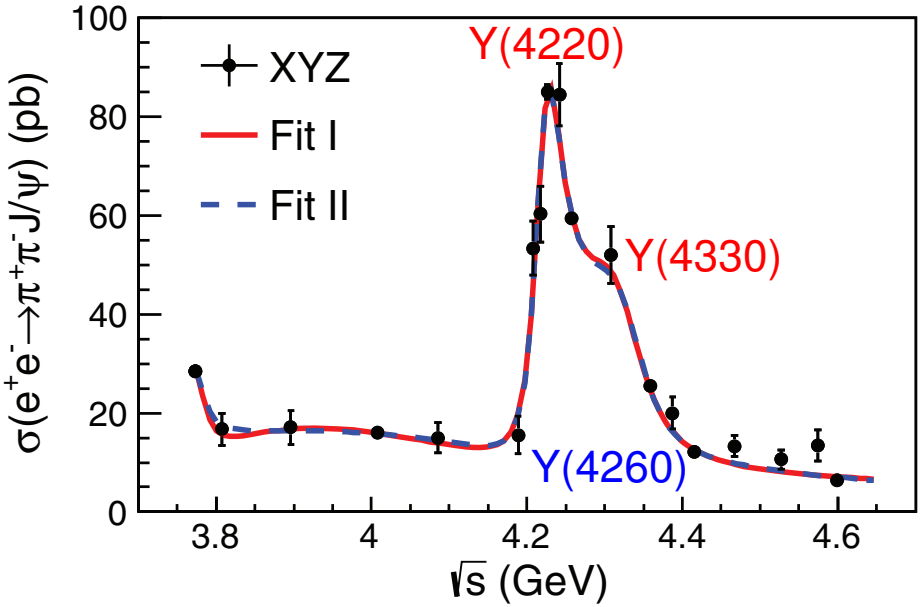
Ali et al. EPJC78(2018)29

$$M = 2M_{\mathcal{Q}} + \frac{B_{\mathcal{Q}}}{2}\mathbf{L}^2 + 2a_Y \mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4}S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)$$

Results for negative parity states

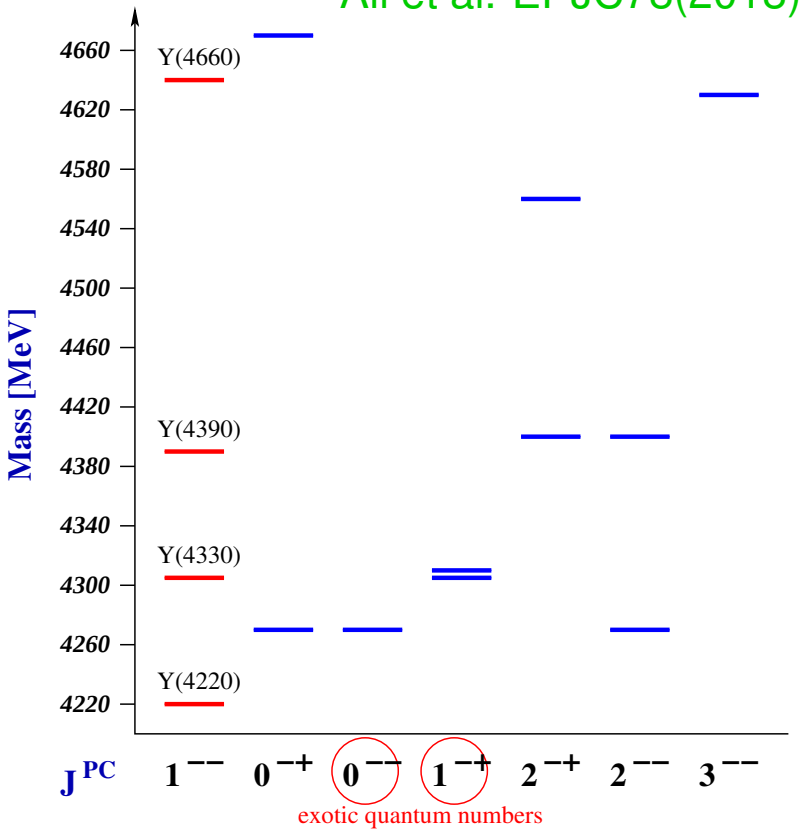
→ four 1^{--} ground states

→ BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001

Ali et al. EPJC78(2018)29

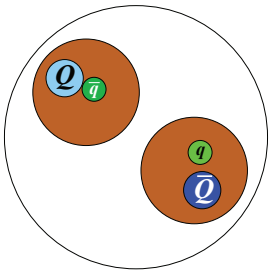


→ Many more states predicted than observed!

- ▷ Maybe since di-quark picture too restrictive/constraining?
  Richard et al., PRD95(2017)054019
- ▷ Maybe more states in the peaks? Maiani et al., PRD102(2020)034017

Hadronic Molecules

recent review article: Guo et al., Rev. Mod. Phys. 90(2018)015004



→ are few-hadron states, bound by the strong force

→ do exist: light nuclei.
e.g. deuteron as pn & hypertriton as Λd bound state

→ are located typically close to relevant continuum threshold;
e.g., for $E_B = m_1 + m_2 - M$ ($\gamma = \sqrt{2\mu E_B}$ $\mu = m_1 m_2/(m_1+m_2)$)

- ▷ $E_B^{\rm deuteron} = 2.22$ MeV ($\gamma = 40$ MeV)
- ▷ $E_B^{\rm hypertriton} = (0.13 \pm 0.05)$ MeV (to Λd) ($\gamma = 26$ MeV)

→ can be identified in observables (Weinberg compositeness):

$$\frac{g_{\rm eff}^2}{4\pi} = \frac{4M^2\gamma}{\mu}(1-\lambda^2) \;\rightarrow\; a = -2\left(\frac{1-\lambda^2}{2-\lambda^2}\right)\frac{1}{\gamma}\,; \quad r = -\left(\frac{\lambda^2}{1-\lambda^2}\right)\frac{1}{\gamma}$$

where $(1-\lambda^2)$=probability to find molecular component in bound state wave function

Are there mesonic molecules?

General considerations

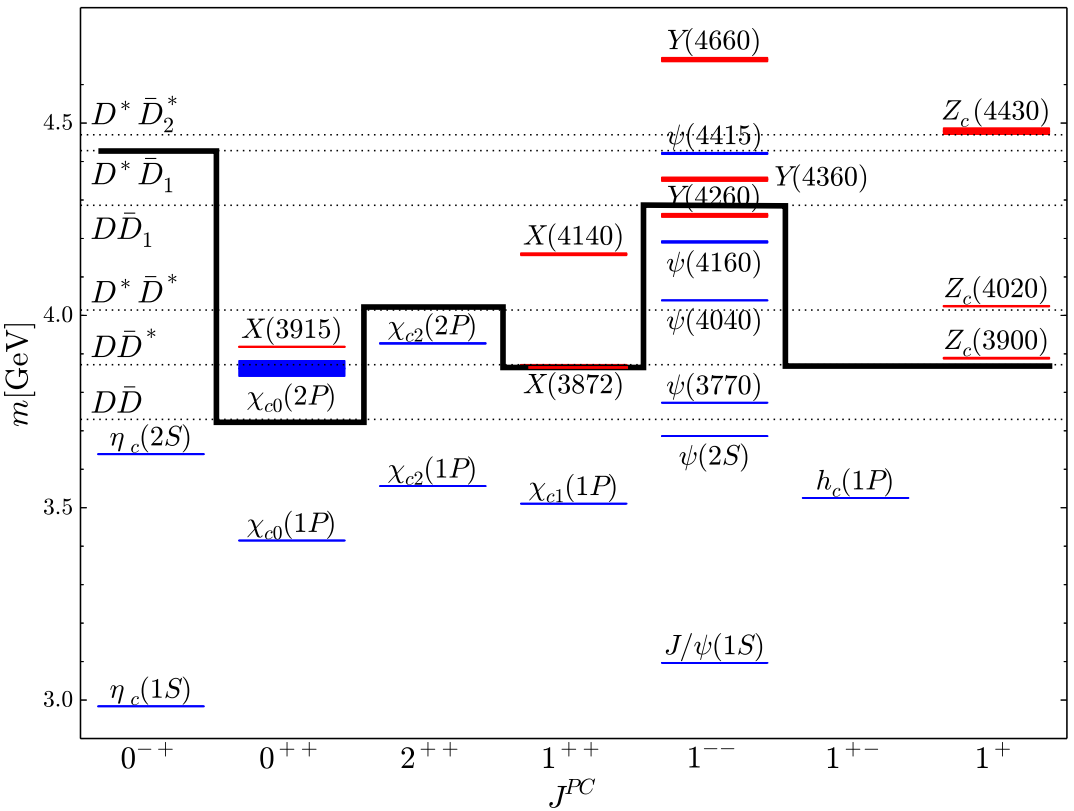
Constituents must be narrow. Heavy candidates (M, Γ in MeV)

$D\ (0^-, M = 1865, \Gamma \simeq\ \ 0);\ D^*(1^-, M = 2007, \Gamma \simeq 0.1)$

$D_1(1^+, M = 2420, \Gamma \simeq 30);\ D_2^*(2^+, M = 2460, \Gamma \simeq 50)$

$D_0(2300)$ and $D_1(2430)$ with $\Gamma = 300$ MeV too broad ...

Spectrum driven by $D-D^*$ and D_1-D_2 mass differences



Spin symmetry violation

→ Explains mass gap between $J^P = 1^+$ and 1^- states:
$M_{Y(4220)} - M_{X(3872)} = 348$ MeV
$\simeq M_{D_1(2420)} - M_{D^*} = 410$ MeV

→ Predicts, e.g.,
$M(0^-) - M(1^-) \simeq$
$M_{D^*} - M_D \simeq +100$ MeV,
if it exists

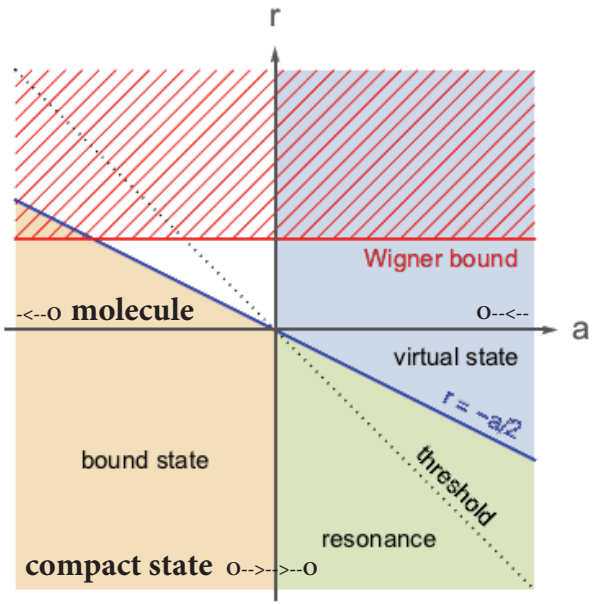
Note: for compact tetraquark:
$M(0^-) - M(1^-) \simeq +50$ MeV

Cleven et al., PRD 92 (2015) 014005

Weinbergs analysis and generalisation

S. Weinberg, PR137(1965)B672, I. Matuschek et al., EPJA57(2021)3

Assume attractive interaction (bound state $a<0$, all others $a>0$)



Weinberg (for bound states):

Molecules:

$|a| \gg |r|$ and $|r| \simeq$ range

Compact states:

$|a| \ll |r|$ and $r < 0$ with $|r| \gg$ range

What happens when a changes sign? (r fixed)

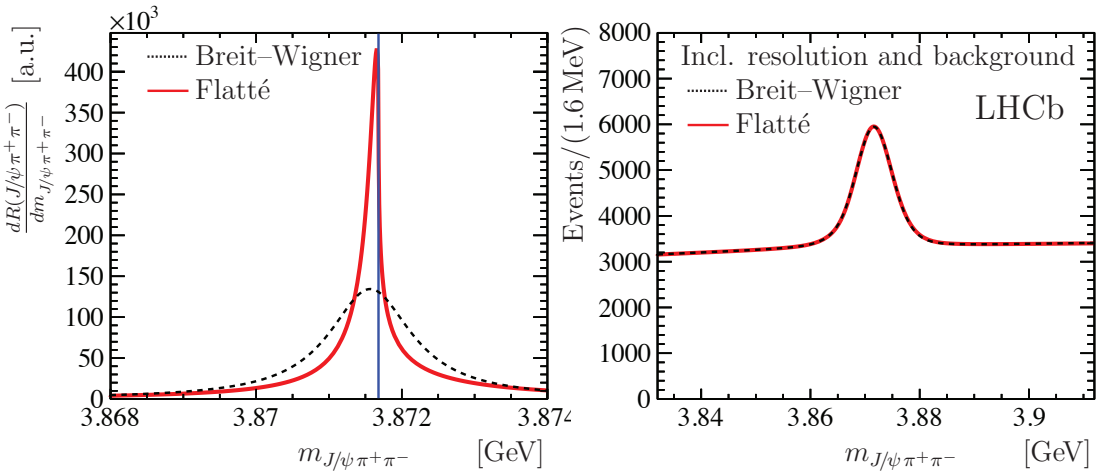
Molecule: turns into a virtual state (and eventually a resonance)

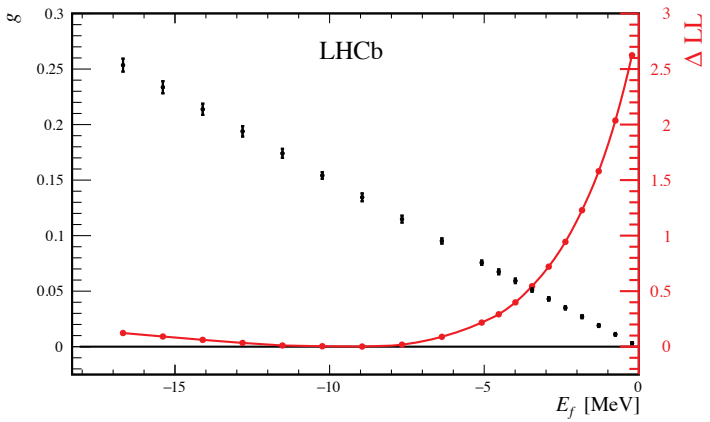
Compact state: turns into a resonance directly

Subsummed in compositness: $\bar{X} = 1/\sqrt{1 + |2r/a|}$

other approaches: Sekihara, Hyodo, Oset, Oller, Nieves, Jido ...
mostly relying on on-shell factorisation of the potential; little about virtual states

$\chi_{c1}(3872)$ also known as $X(3827)$





LHCb, PRD102(2020)092005

Data analysed employing for the rate C.H. at al., PRD76(2007)034007

$$\frac{\Gamma_\rho(E)}{\left|E - E_f + \frac{i}{2}[g(\sqrt{2\mu_1 E} + \sqrt{2\mu_2(E-\delta)}) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0]\right|^2}$$

with E_f fixed to -7.18 MeV: $g = 0.108 \pm 0.003$ such that

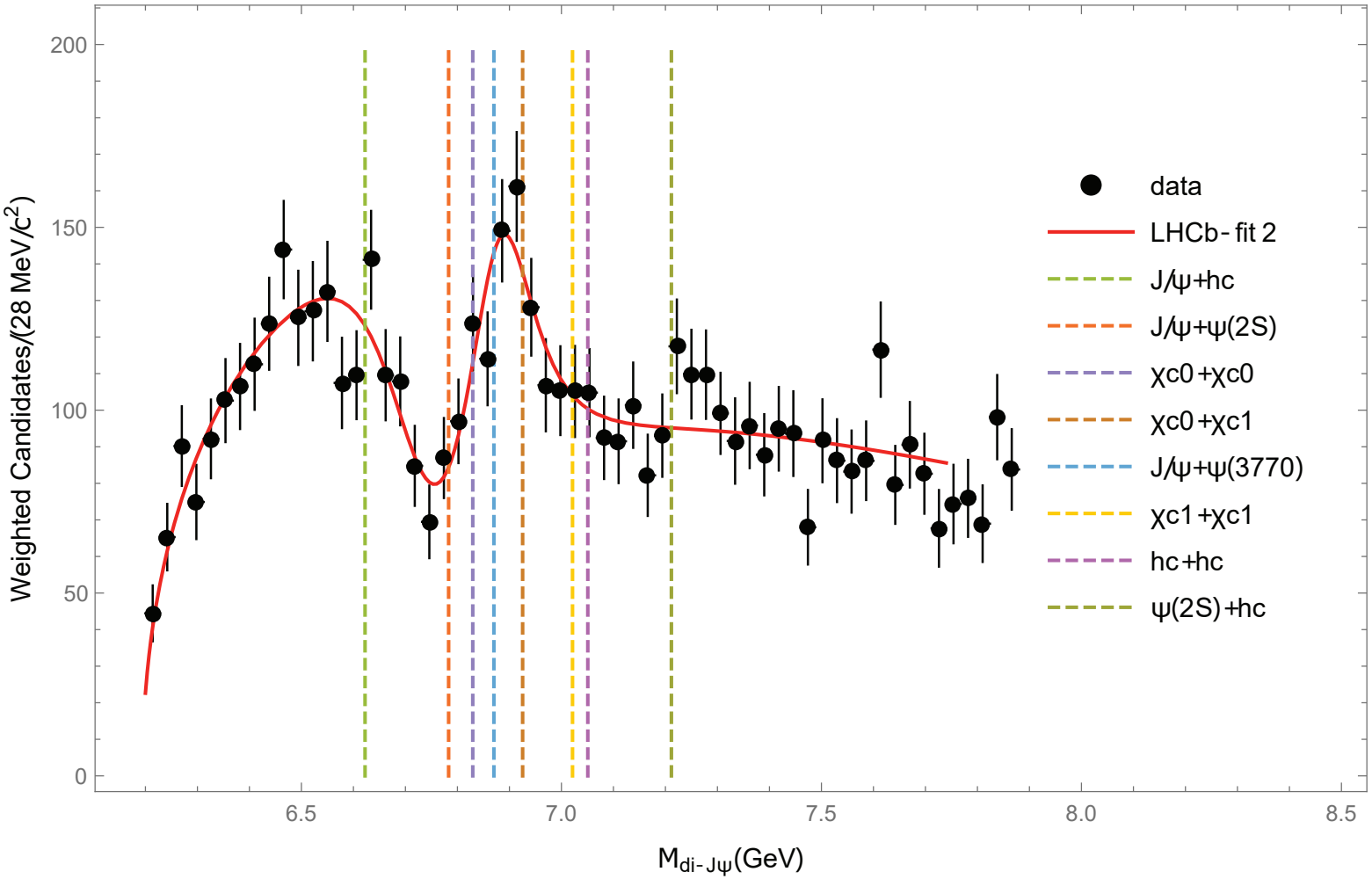
$$r = -2/(\mu_1 g) - \sqrt{\mu_2/(2\mu_1^2\delta)} \simeq (-3.8 - 1.4)\ \text{fm} \gg 1/M_\pi$$

Does this mean $X(3872)$ is a compact state? A. Esposito et al.,2108.11413

$\Longrightarrow$ refit LHCb data with correlations removed!

Back to the double J/ψ spectrum

Are these states tetraquarks or molecules?
There are many thresholds in the mass range:



Double J/ψ spectrum

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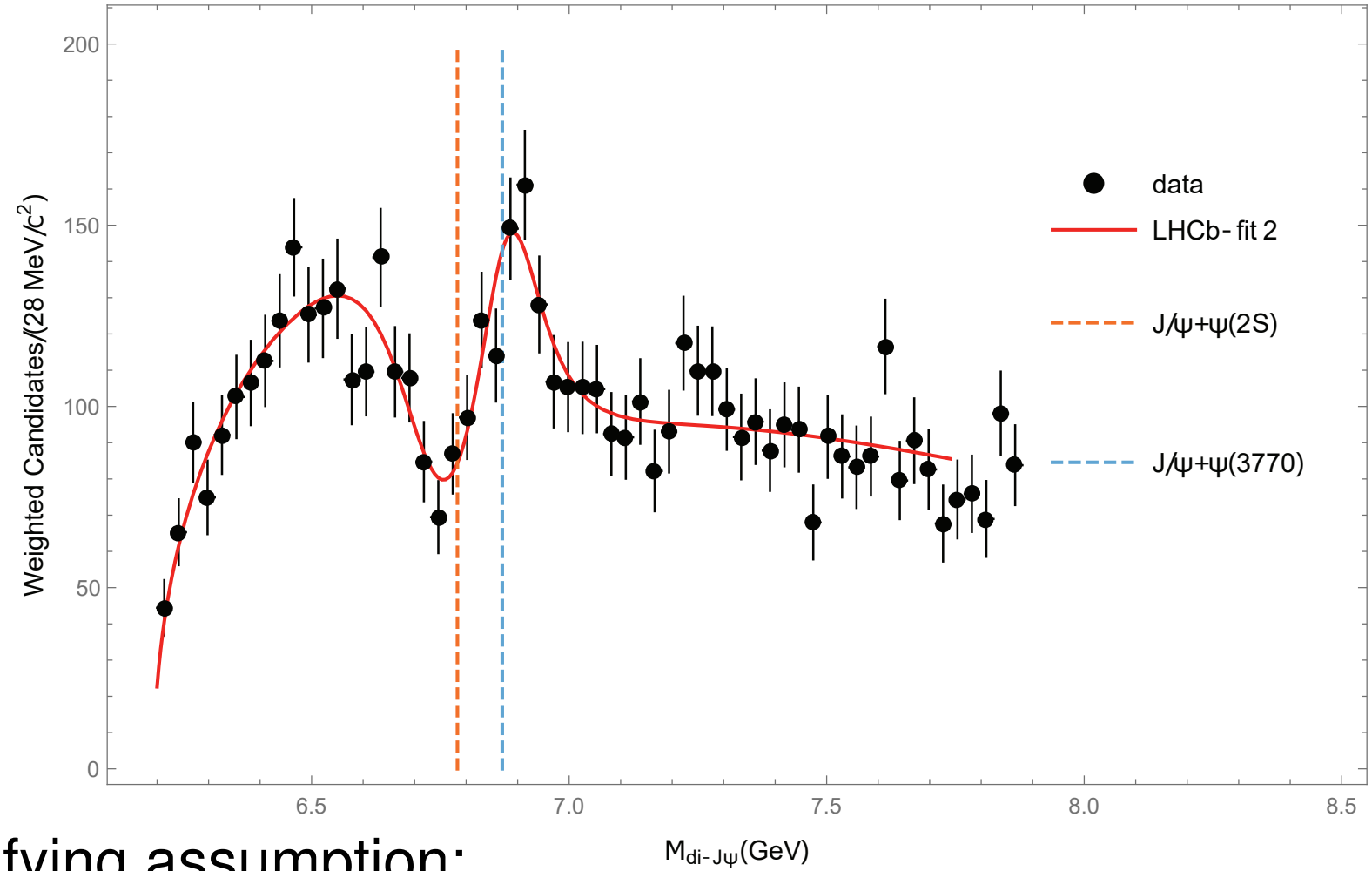


Simplifying assumption:

only vector-vector channels matter (motivated by HQSS)

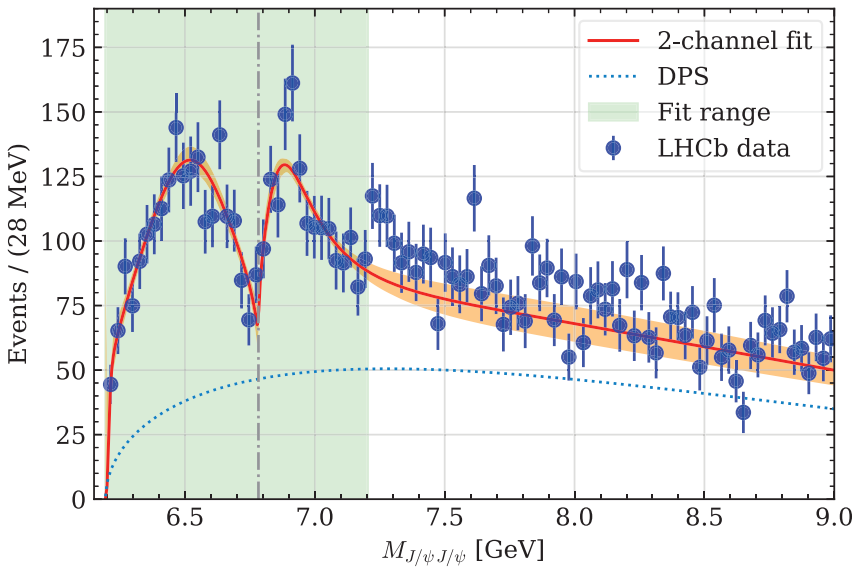
Two models

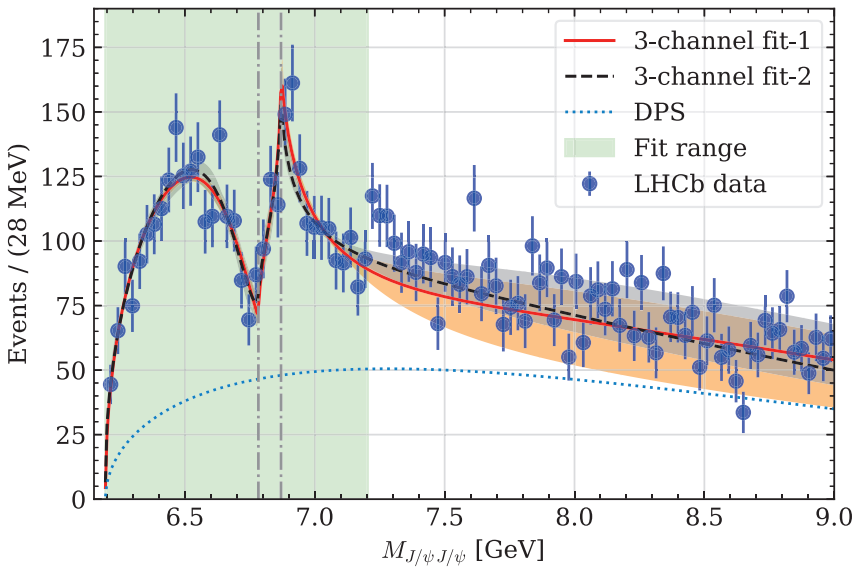
Xiang-Kun Dong et al., PRL126(2021)132001

We calculate $T(E) = V(E) \cdot [1 - G(E)V(E)]^{-1}$, with either

$$V_{2\mathrm{ch}}(E) = \begin{pmatrix} a_1 + b_1 k_1^2 & c \\ c & a_2 + b_2 k_2^2 \end{pmatrix} \text{ or } V_{3\mathrm{ch}}(E) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix},$$

where the $J/\psi J/\psi$, $\psi(3686)J/\psi$ (and $\psi(3770)J/\psi$) were included

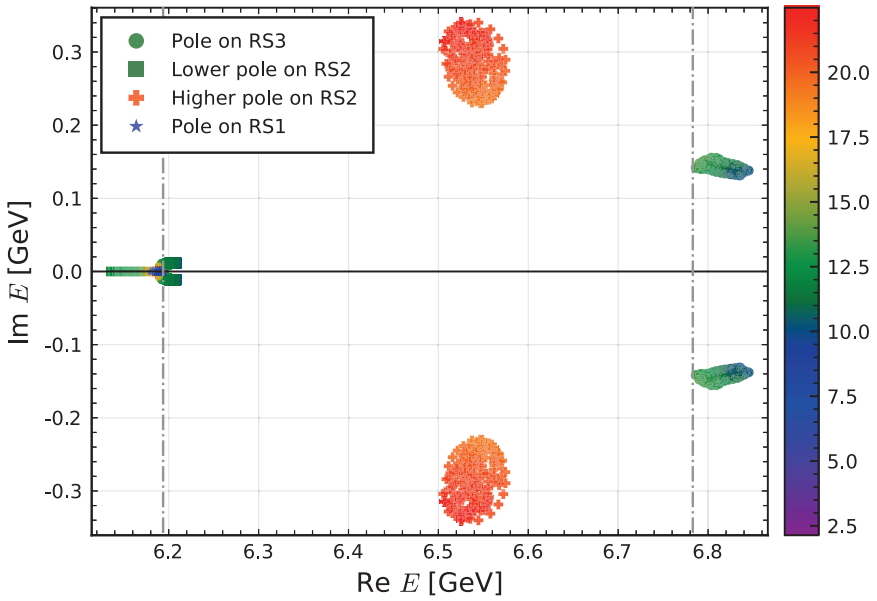




Both models provide excellent description of data

Pole structure

The pole structure is very different:

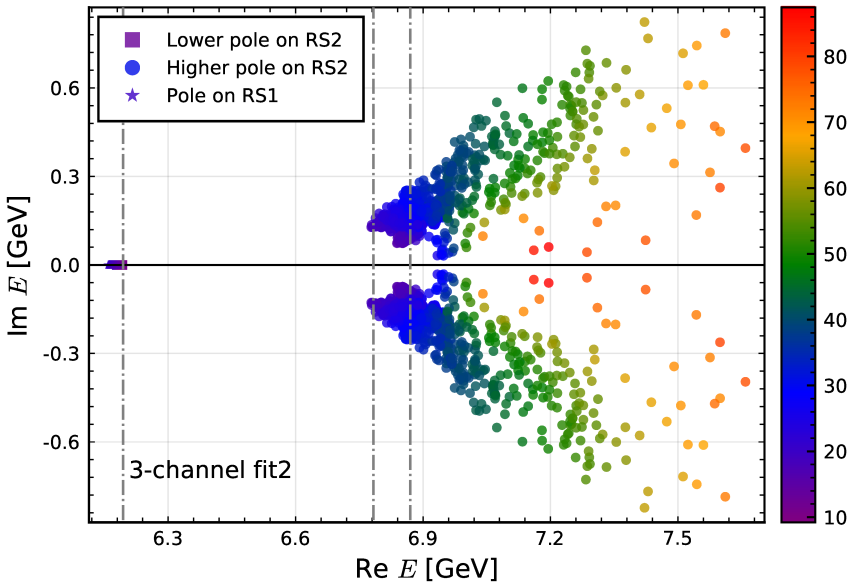


Two channel fit:

In total 3 states:

1 close to $J/\psi J/\psi$-thresh.,

2 to produce structures
(via interplay with threshold)



Three channel fit:

In total 2 states

1 close to $J/\psi J/\psi$-thresh.,

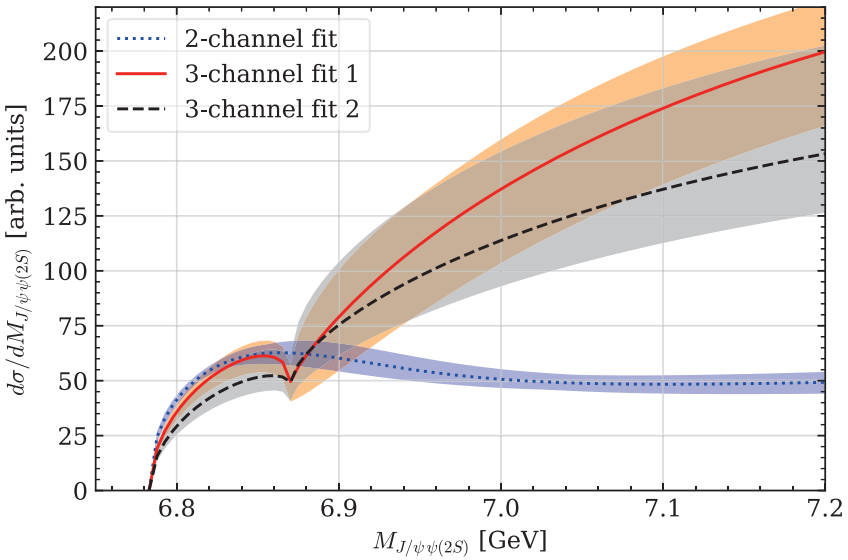
1 to produce structures
(via interplay with thresholds)

Discussion

Very close to threshold state always present!

	2-ch. fit	3-ch. fit 1	3-ch. fit 2
$a(\mathrm{fm})$	≤ -0.49 or ≥ 0.48	$-0.61^{+0.29}_{-0.32}$	≤ -0.60 or ≥ 0.99
$r(\mathrm{fm})$	$-2.18^{+0.66}_{-0.81}$	$-0.06^{+0.03}_{-0.04}$	$-0.09^{+0.08}_{-0.05}$
$\bar{X}$	$0.39^{+0.58}_{-0.12}$	$0.91^{+0.04}_{-0.07}$	$0.95^{+0.04}_{-0.06}$

Different models give different nature of $J/\psi J/\psi$ state! E.g. two channel model consistent with compact and composite



The two scenarios can be distinguished easily!

e.g. via $\psi(2S)J/\psi$ final state

Note: existence of $J/\psi J/\psi$ molecules is plausible!

X.-K. Dong et al., 2107.03946, Sci.Bull. in print

$QQ\bar{q}\bar{q}$ tetraquarks

States with two heavy quarks for long predicted:

→ from QCD sum rules — Du et al., PRD87(2013)014003

→ from lattice QCD — Francis et al. PRL118(2017)142001

→ from phenomenology — Ader et al., PRD 25(1982)2370

Karliner and Rosner, PRL119(2017)202001; Eichten and Quigg, PRL119(2017)202002

E.g. from the last work

$$m(QQ\bar{q}\bar{q}) - m(QQq) \simeq m(\bar{Q}\bar{q}\bar{q}) - m(\bar{Q}q)$$

exploiting heavy quark-diquark symmetry:

expansion in $r_{QQ}/r_q \sim \Lambda_{\rm QCD}/(M_Q v)$ — Savage and Wise, PLB248(1990)177

Once $m(QQq)$ is fixed from data or phenomenology,

$\Longrightarrow$ $m(QQ\bar{q}\bar{q})$ can be predicted.

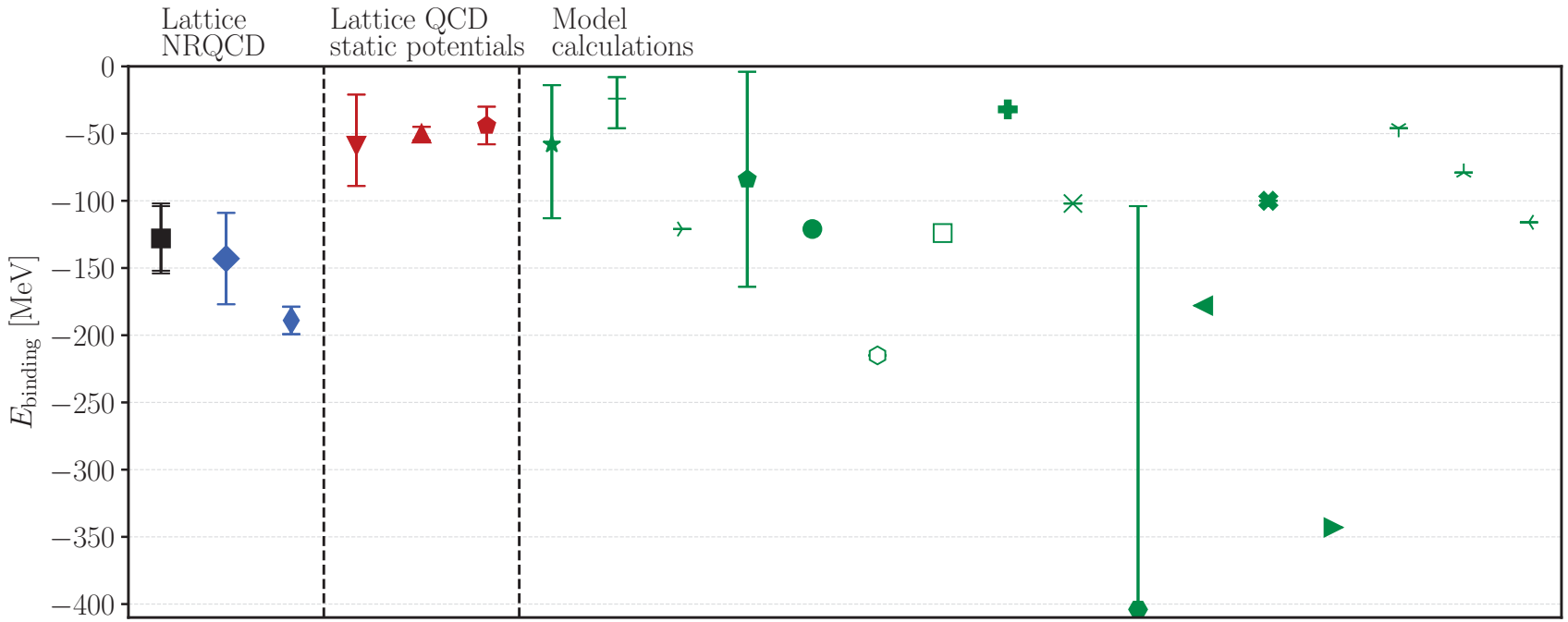
→ Prediction fits to LHCb observation! — esp. Karliner &Rosner, 2017

However: $\bar{X}(T_{cc}) > 0.48$ and 90% confidence level — LHCb, 2109.01056

States that contain bb

bb pair so deeply bound in Coulomb potential that tetraquarks energetically favored

Karliner and Rosner, PRL119(2017)202001



This work
Junnarkar et al. (2018)
Francis et al. (2016)
Bicudo et al. (2016)
Brown and Orginos (2012)
Bicudo and Wagner (2012)
Liu et al. (2019)
Wang et al. (2018)
Park et al. (2018)
Wang (2017)
Eichten and Quigg (2017)
Karliner and Rosner (2017)
Lee and Yasui (2009)
Zhang et al. (2007)
Ebert et al. (2007)
Navarra et al. (2007)
Vijande et al. (2006)
Janc and Rosina (2004)
Vijande et al. (2003)
Brink and Stancu (1998)
Silvestre-Brac and Semay (1993)
Carlsen et al. (1988)

M. Pflaumer at “Experimental and theoretical status of and perspectives for XYZ states”, 04/2021

What is needed for further progress

→ Excellent data especially for different spin states and channels
(spin symmetry violation sensitive to the nature of a state)

→ More refined theory predictions with controlled uncertainties

- Role of the regular $\bar{Q}Q$ states?
  - do they mix in — E. Cincioglu et al., EPJC76(2016)576
  - or not? — I.K. Hammer, CH and A. V. Nefediev, EPJA 52(2016)330
- For molecules: How to construct the potential?
  - With pion exchange perturbative — J. Nieves, M.P. Valderrama, PRD84 (2011) 056015
  - or non-perturbative? — V. Baru et al., PRD84(2011)074029
- Role of two-hadron exchanges? — X.-K. Dong et al., 2107.03946

Thanks a lot for your attention