Unconventional meson states with two or more heavy quarks

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

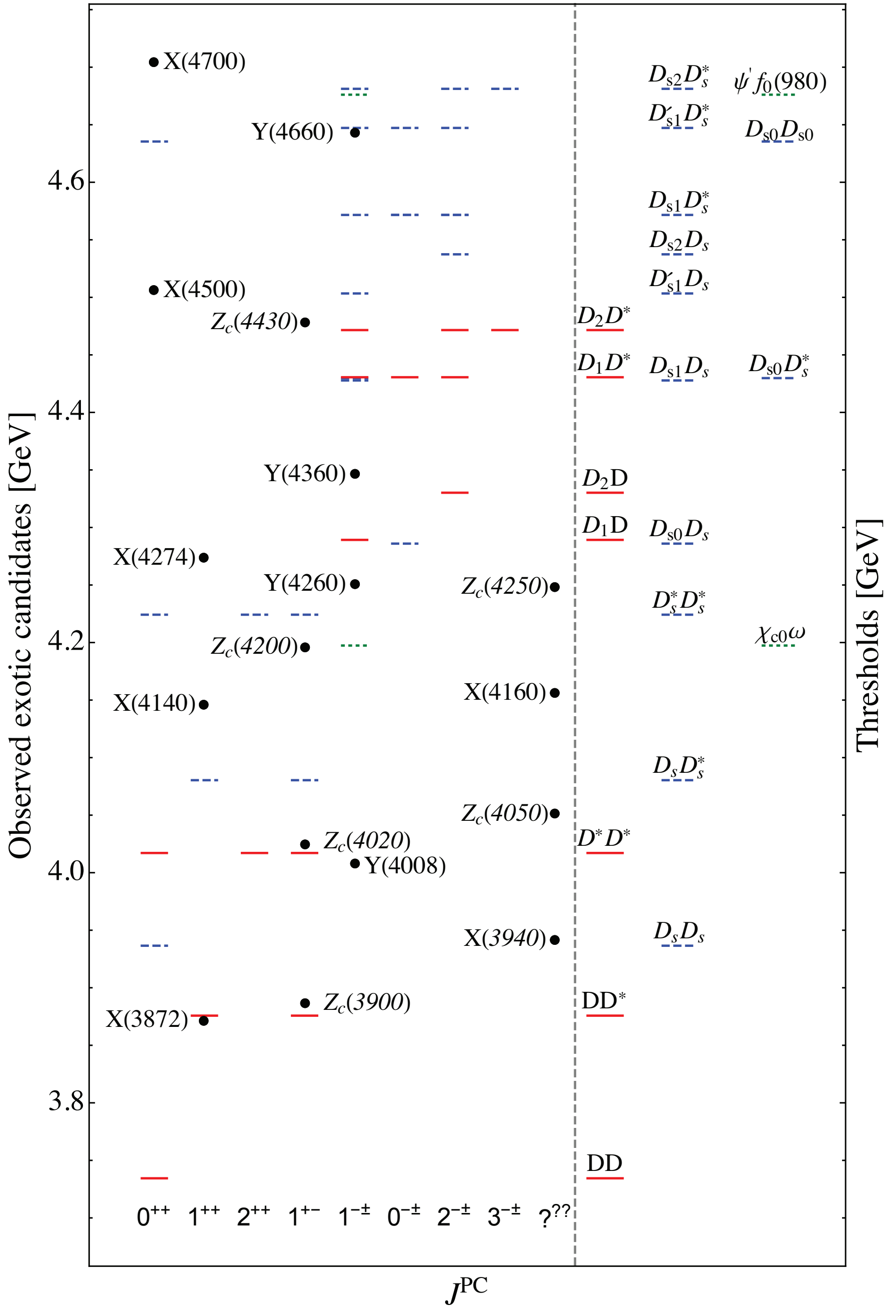
S.L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003

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

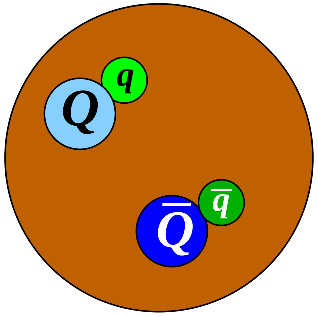
There are many exotics with $\bar{Q}Q$ ...



Guo et al. RMP90(2018)015004

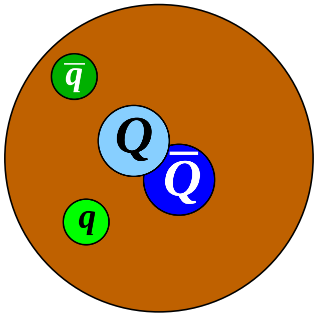
- → All exotic candidates above open flavor thresholds
- → Many (not all) states near S-wave thresholds of narrow states Filin et al., PRL 105, 019101 (2010) Guo et al., PRD84, 014013 (2011)
- → States not near all those thresholds
- → There are charged states that contain $\bar{Q}Q$
- → Lightest negative parity exotic ($Y(4260)$) significantly heavier than lightest positive parity exotics ($X(3872)$ & $Z_c(3900)$)

Proposals - Multi-Quark States



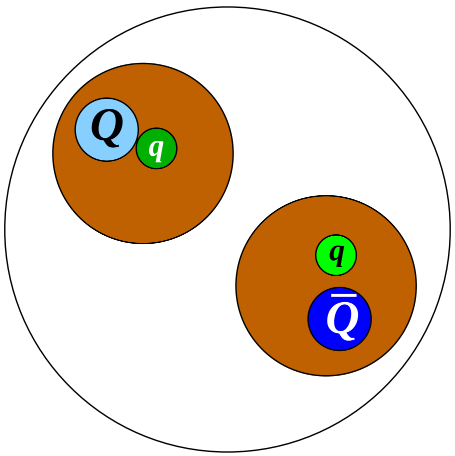
Tetraquark

→ Compact object formed from (Qq) and $(\bar{Q}\bar{q})$



Hadro-Quarkonium

→ Compact $(\bar{Q}Q)$ surrounded by light quarks



Hadronic-Molecule

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

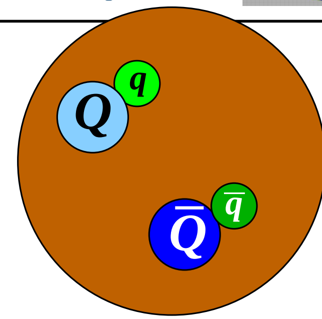
Bohr radius = $1/\gamma = 1/\sqrt{2\mu E_b}$

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

for near threshold states

I will review ideas on how to disentangle these structures

Heavy Tetraquarks

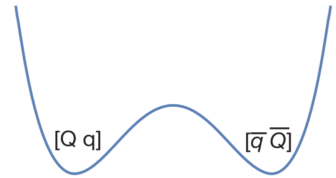


→ Straightforward extension of the quark model

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

without tensor force very light 3^{--}

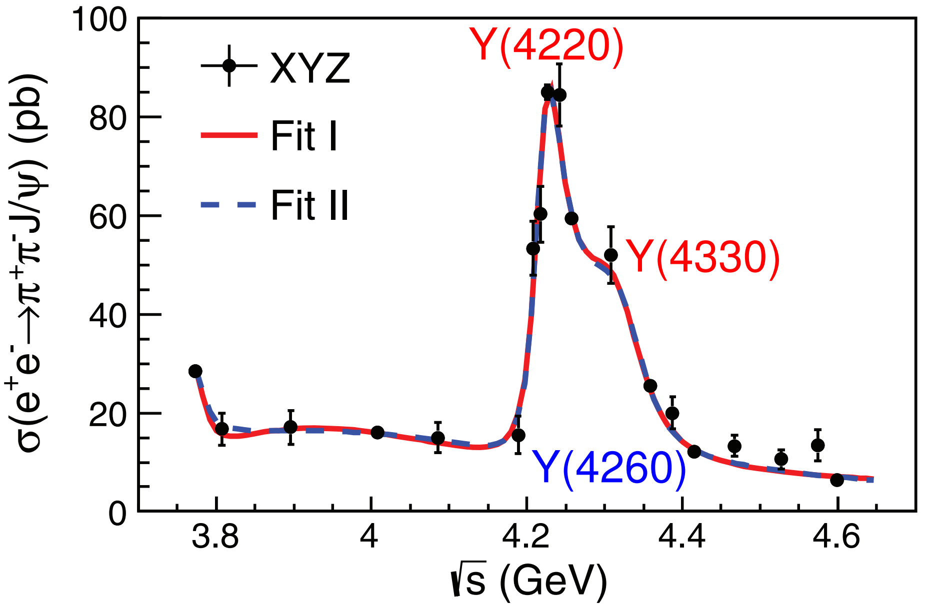
Cleven et al., PRD 92(2015)014005

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

Results for negative parity states

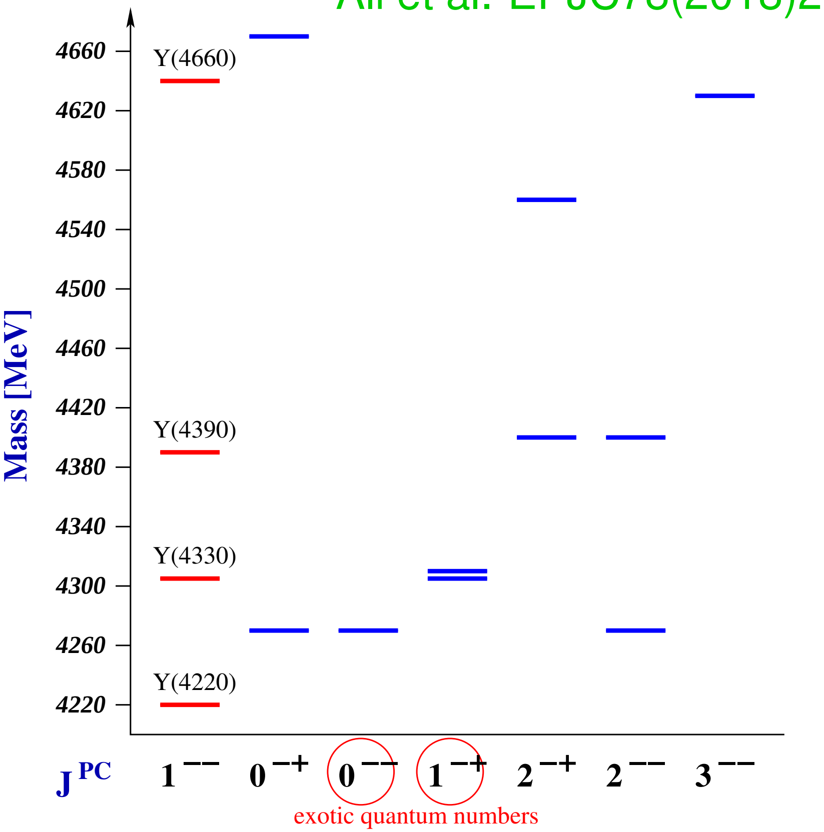
→ four 1^{--} ground states

→ 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

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

Recently growing number of claims for those tetraquarks, e.g.

$\rightarrow$ from QCD sum rules — Du et al., PRD87(2013)014003

$\rightarrow$ from lattice QCD — Francis et al. PRL118(2017)142001

$\rightarrow$ 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:

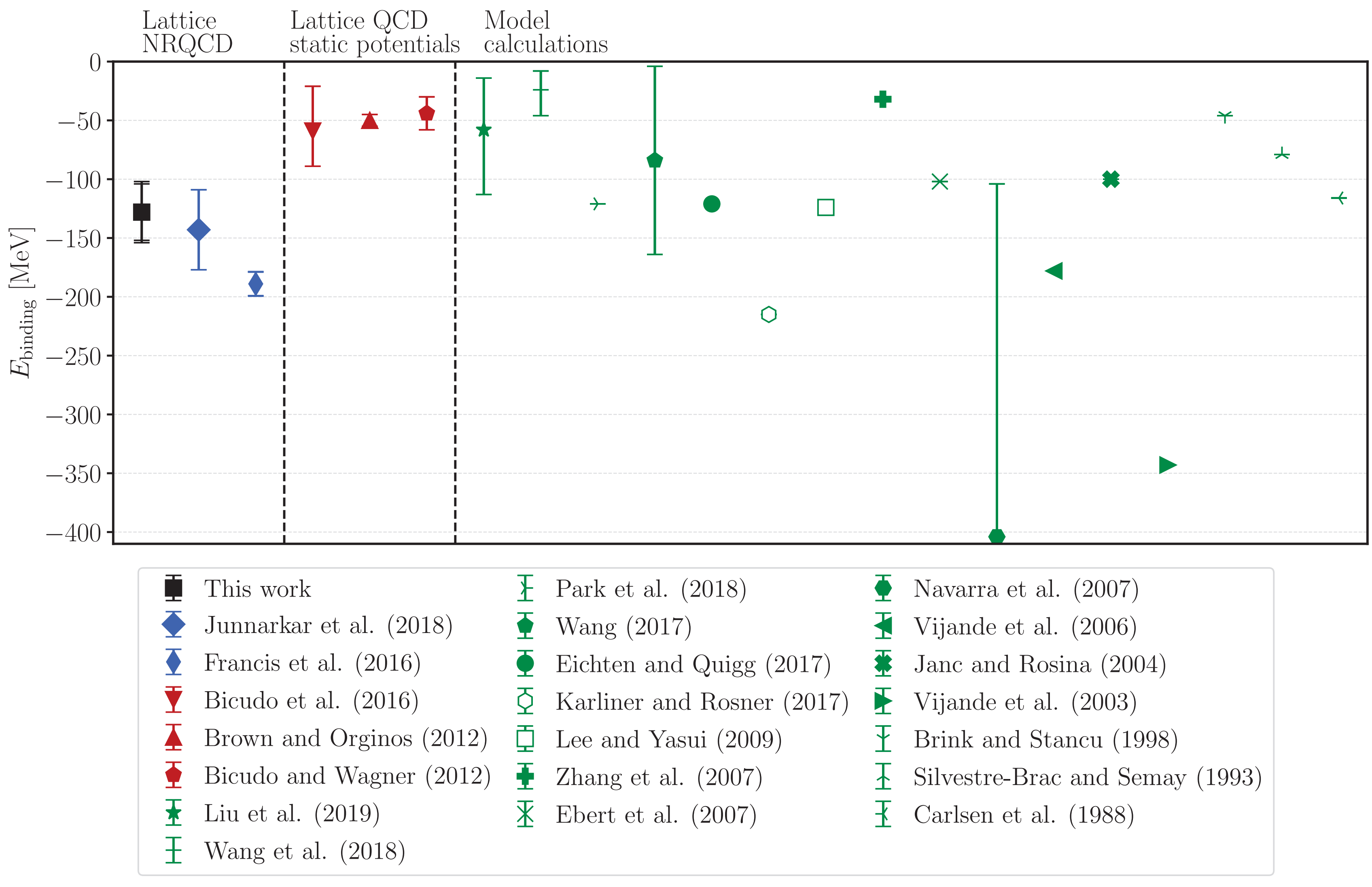
expansion in $r_{QQ}/r_q \sim \Lambda_{\rm QCD}/(M_Q v)$ — Savage and Wise, PLB248(1990)177

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

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

$\rightarrow$ states in bb with $J^P = 1^+$ (up to 350 MeV below BB^* thres.)

Comparison of various studies



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

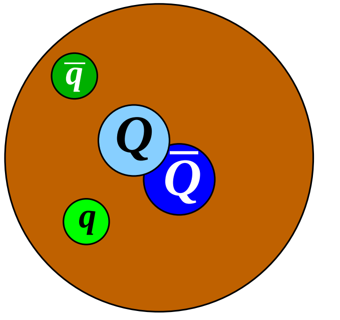
Might be measureable via displaced B_c vertices

T. Gershon and A. Poluektov, JHEP01(2019)019

Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455

→ Extra states are viewed as compact $\bar{Q}Q$ surrounded by light quarks

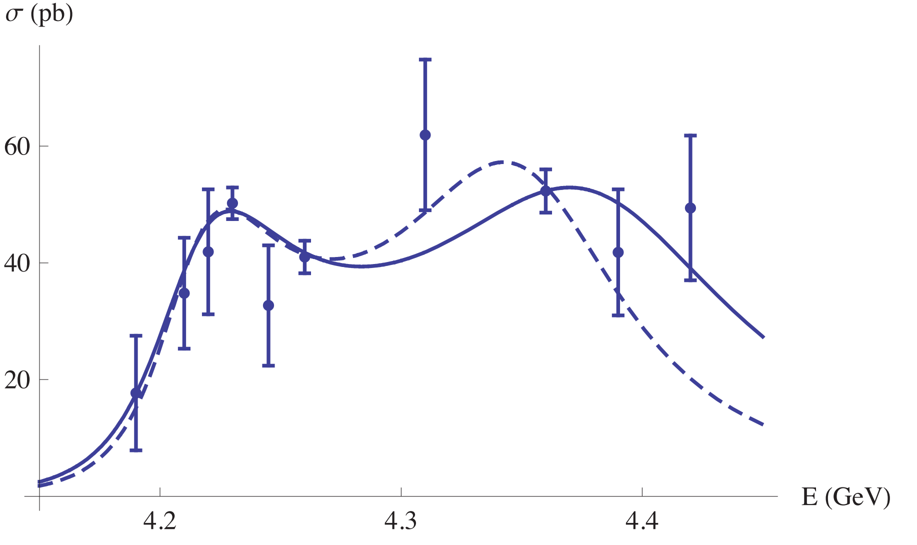


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ Heavy quark spin symmetry demands that spin of the core is conserved in decay to charmonia

→ Explaining $e^+e^- \to h_c\pi\pi$ needs mixing between states with $s_{\bar{c}c} = 0$ and $s_{\bar{c}c} = 1$ leading to $Y(4260)$ and $Y(4360)$

Li & Voloshin MPLA29(2014)1450060



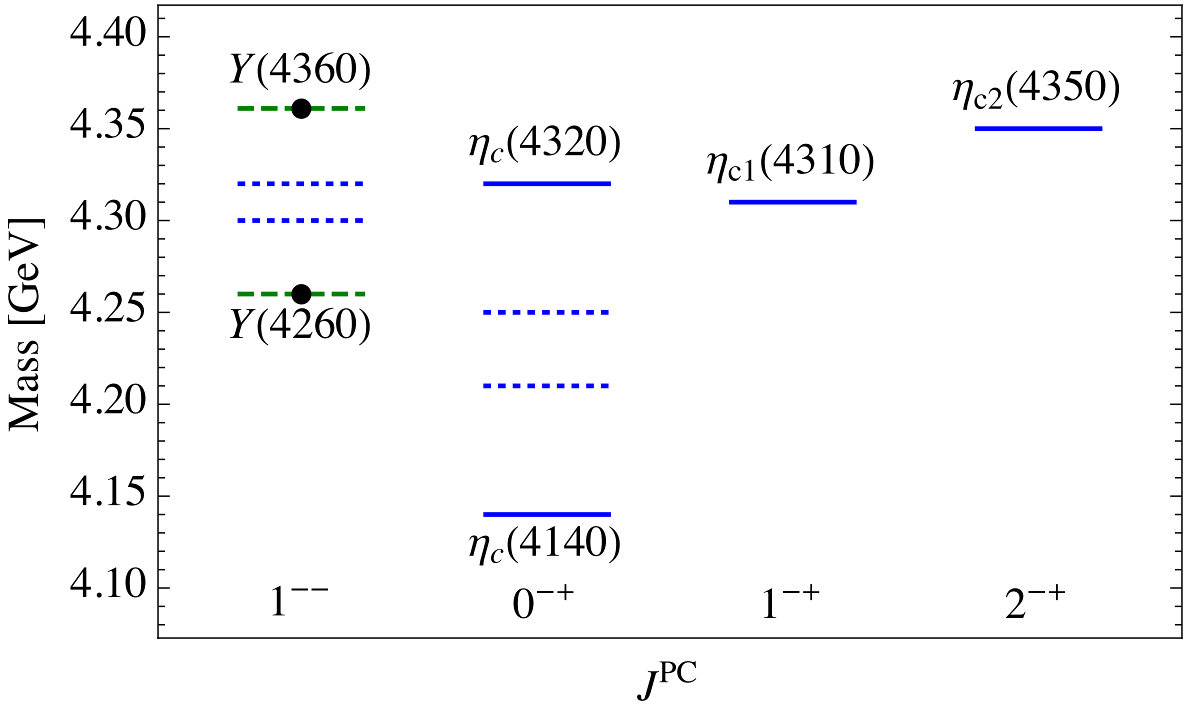
Hadrocharmonium: new states

The above mentioned mixing suggests for the unmixed states:

$$\Psi_3 \sim (1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}} \qquad \Psi_1 \sim (1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}} \ ,$$

where the heavy cores are ψ' and h_c.

$\longrightarrow$ get spin partners via $\psi' \to \eta_c'$ and $h_c \to \{\chi_{c0},\ \chi_{c1},\ \chi_{c2}\}$



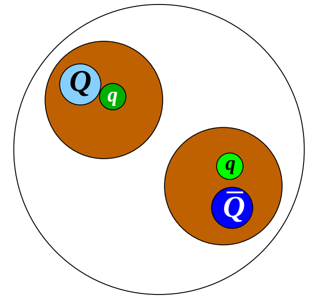
The mentioned mixing violates spin symmetry!

Cleven et al., PRD 92(2015)014005

Special feature: very light 0^{-+} state that should not decay to $D^*\bar{D}$

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):

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

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)

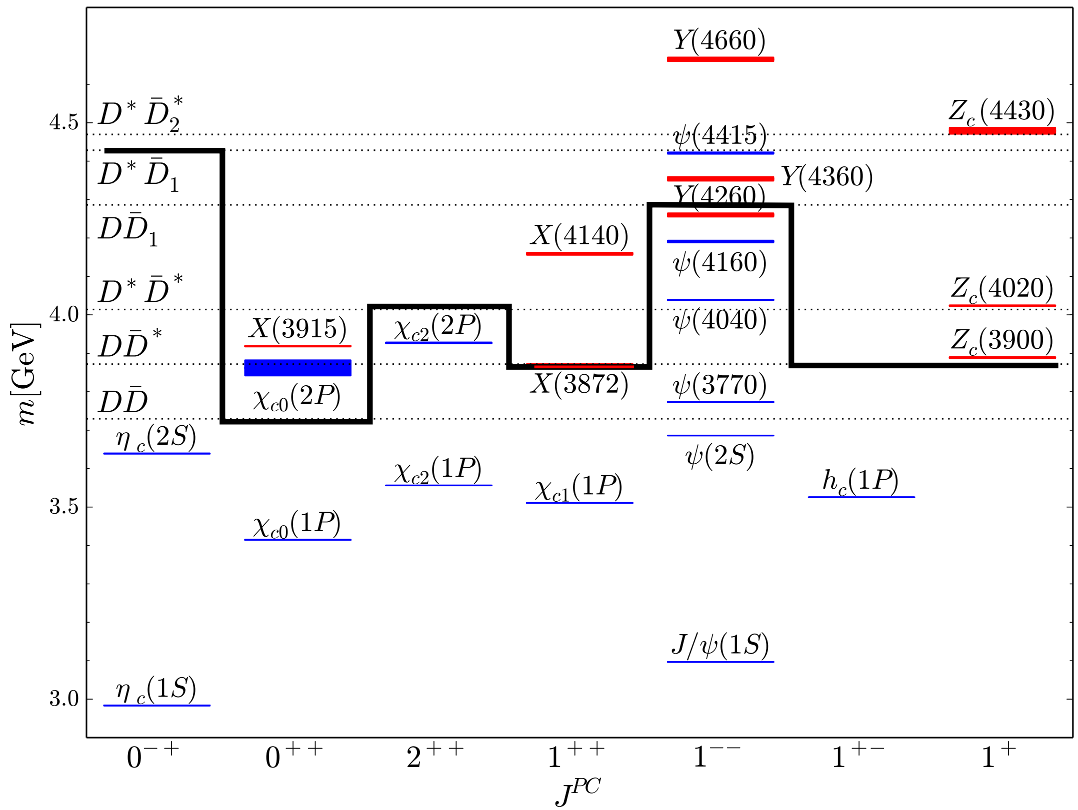
$D\ (0^-, M = 1865, \Gamma \simeq\ 0)$; $D^*(1^-, M = 2007, \Gamma \simeq 0.1)$

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

$D_0(2400)$ 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:

$M_{Y(4260)} - M_{X(3872)} = 388$ 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

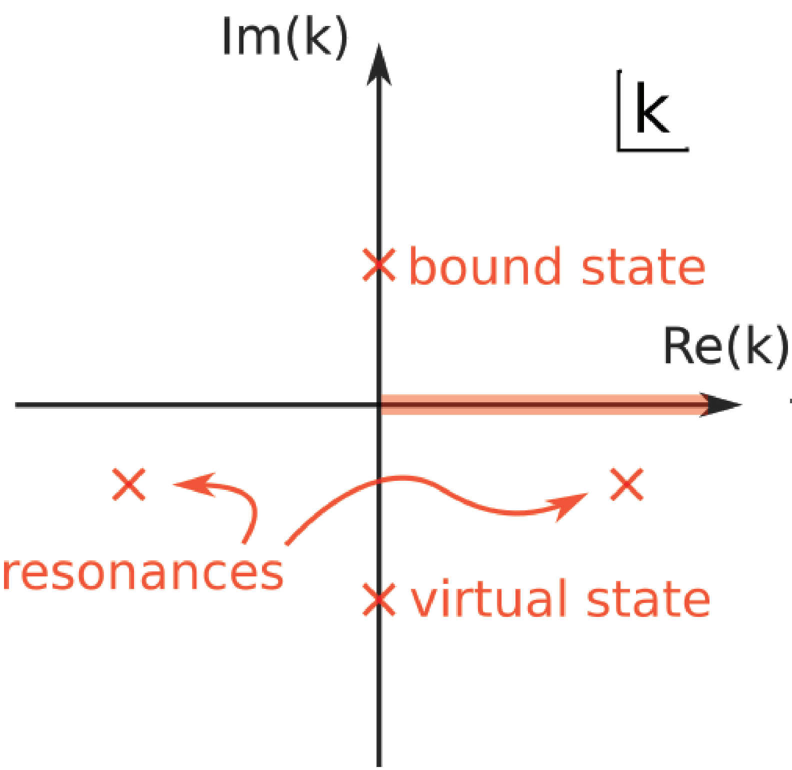
Note: for hadrocharmonium:

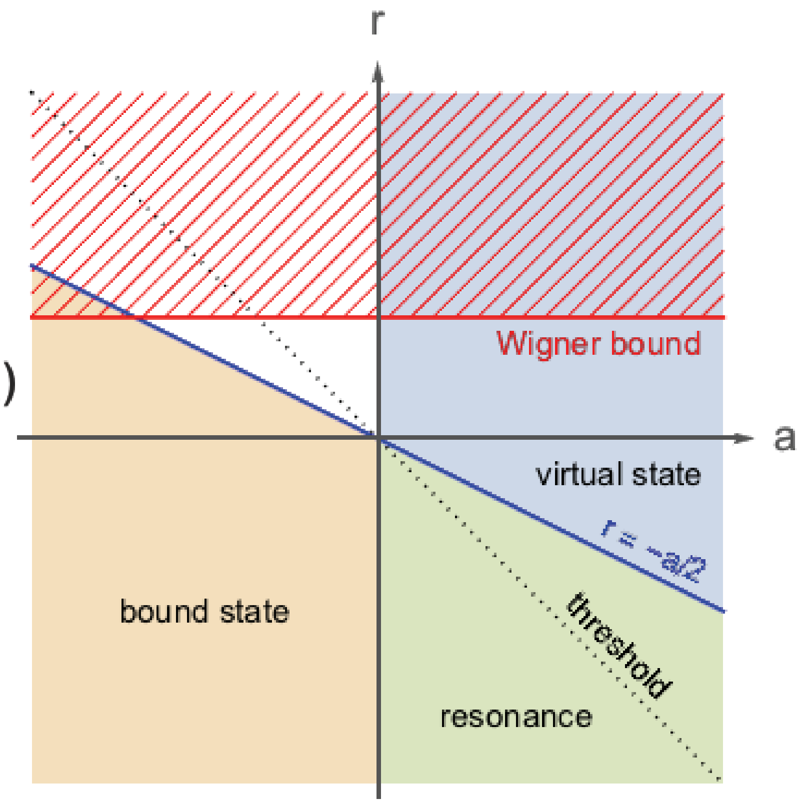
$M(0^-) - M(1^-) \simeq -100$ MeV

Cleven et al., PRD 92 (2015) 014005

I. Matuschek, V. Baru, F. K. Guo and CH, EPJA 57(2021)1019

Model independent criterion for virtual states and resonances





$T(E) = -(2\pi/\mu)1/(1/a + (r/2)k^2 - ik)$, with $k = \sqrt{-2\mu E}$

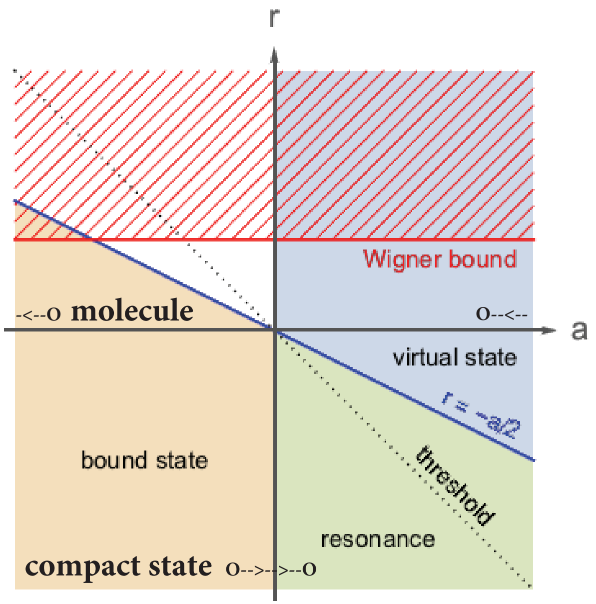
Poles at

$$k = \frac{i}{r}\left(1 \pm \sqrt{1 + \frac{2r}{a}}\right)$$

Generalisation of Weinbergs analysis

I. Matuschek, V. Baru, F. K. Guo and CH, EPJA 57(2021)1019

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)

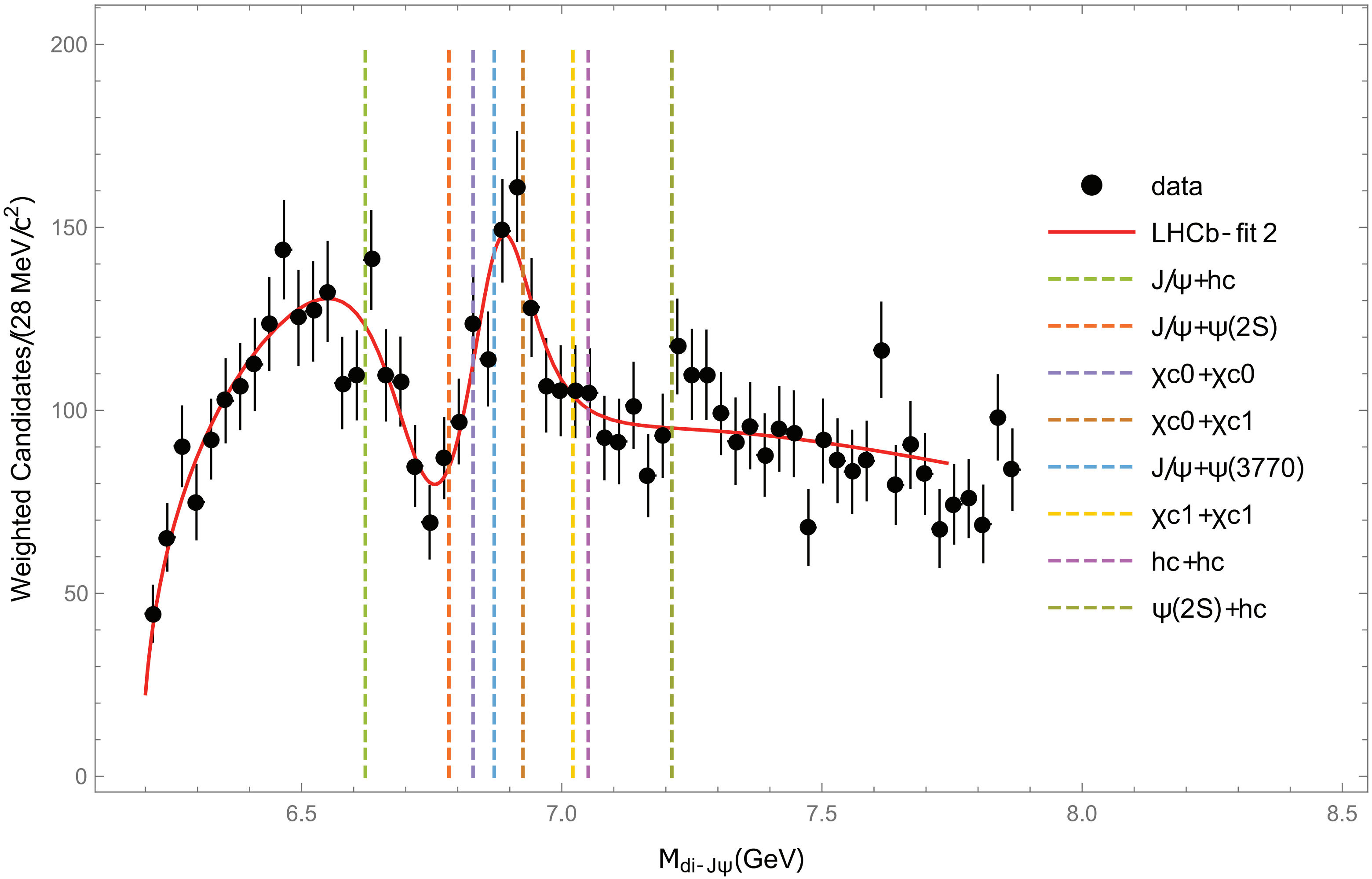
Compact state: turns into a resonance directly

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

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

Study of the double J/ψ spectrum

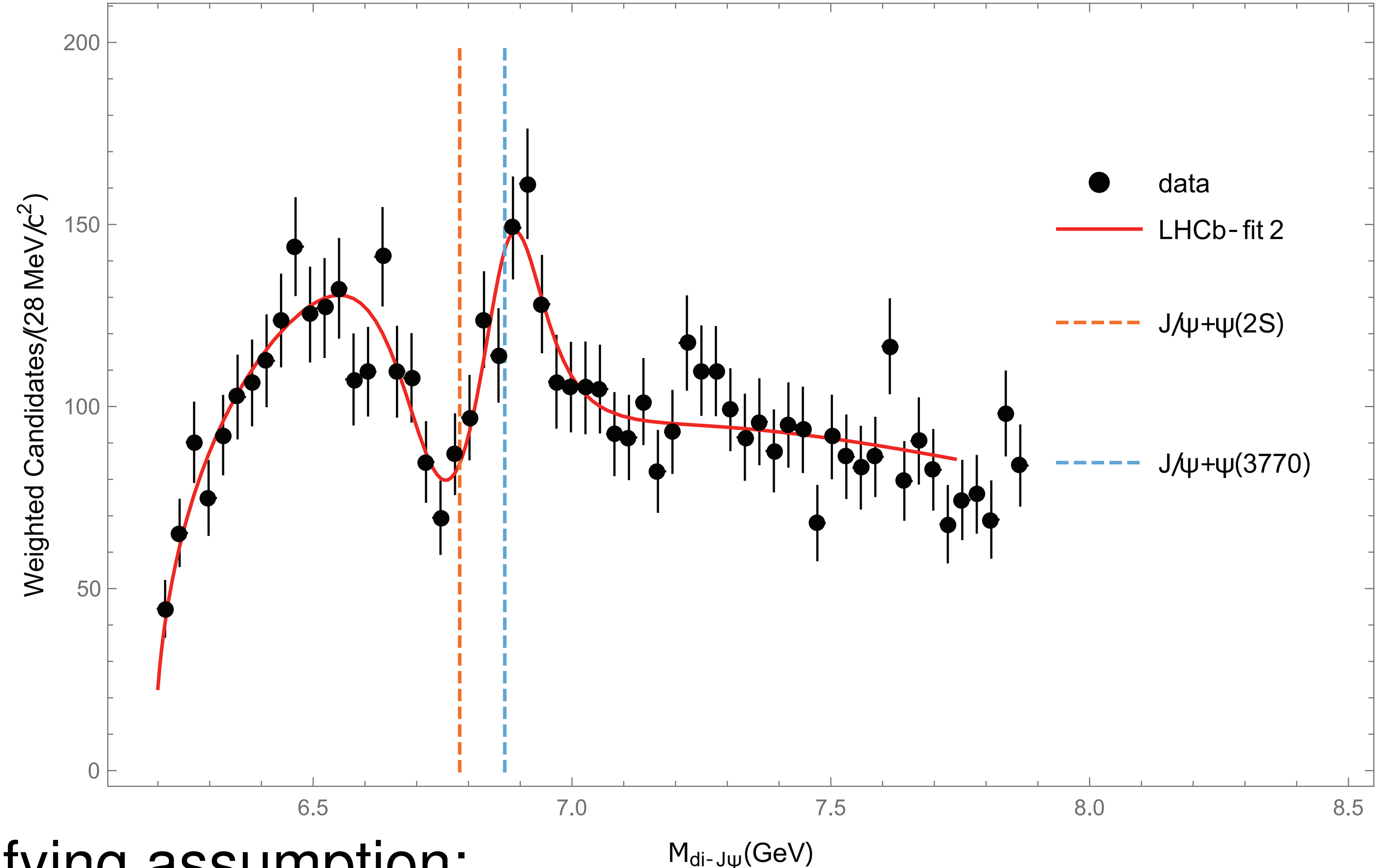
Are these states tetraquarks or molecules?
There are many thresholds in the mass range:



R. Aaij *et al.* [LHCb], Sci. Bull. 65(2020) 1983

Study of the double J/ψ spectrum

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



Simplifying assumption:

only vector-vector channels matter

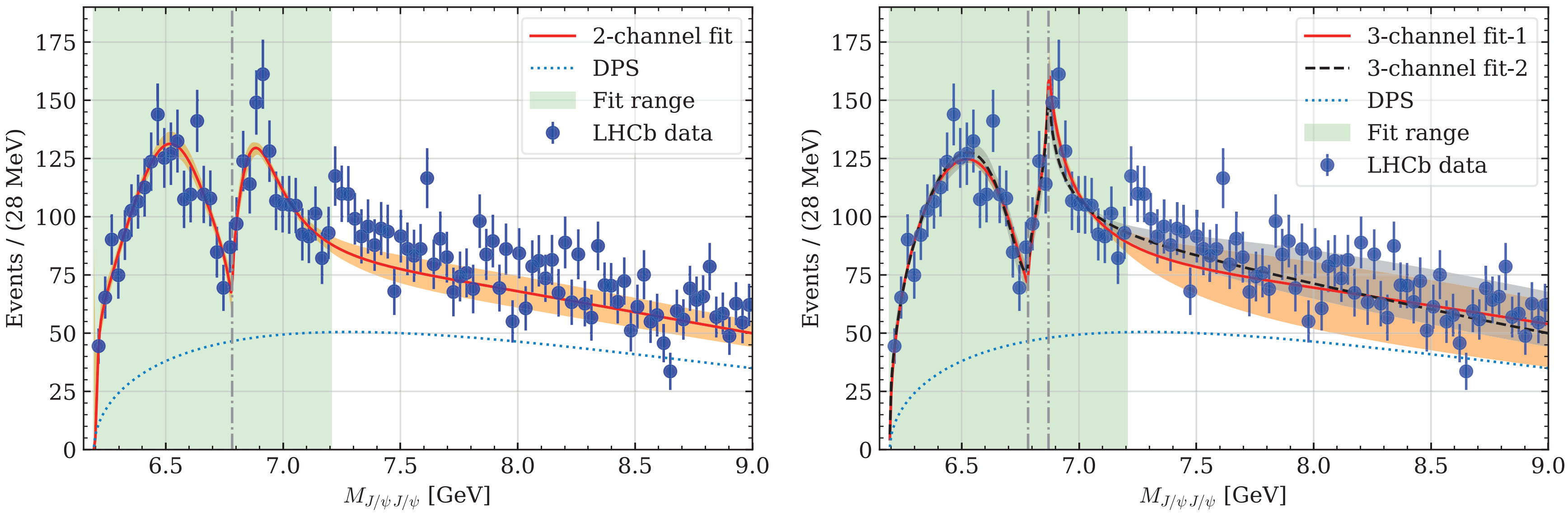
Two models

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

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

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

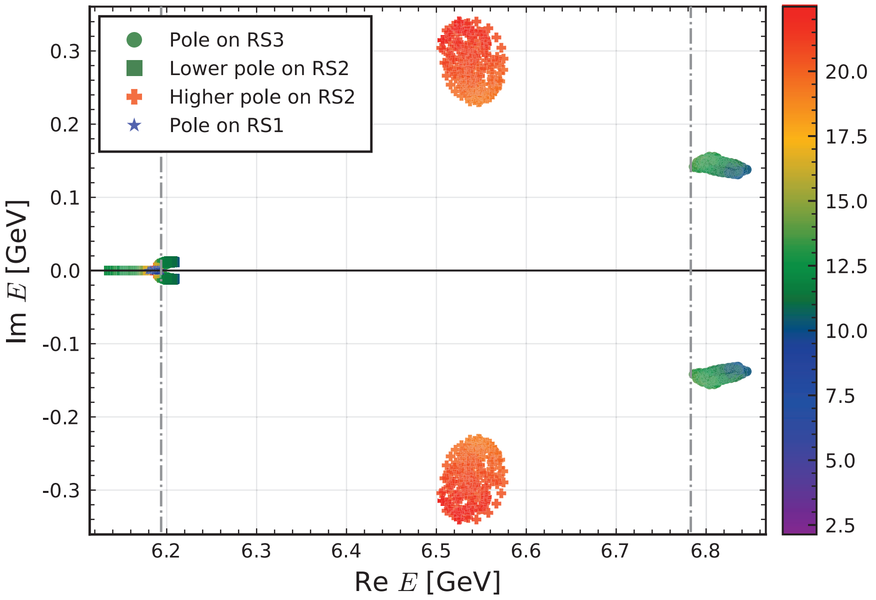
where the $J/\psi J/\psi$, $\psi(3686)J/\psi$ (and $\psi(3770)J/\psi$) were included



Both models provide excellent description of data

Pole structure

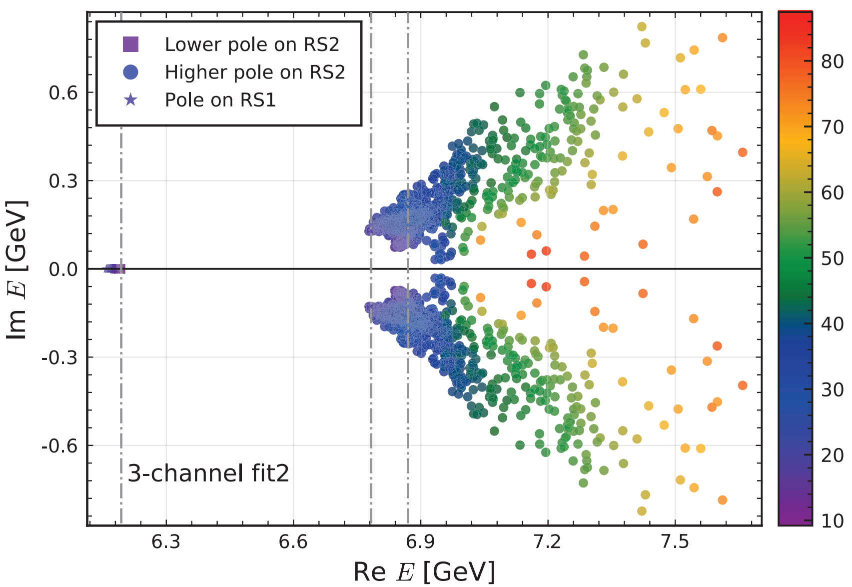
The pole structure is very different:



In total 3 states:

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

2 to produce structures
(via interplay with threshold)



In total 2 states

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

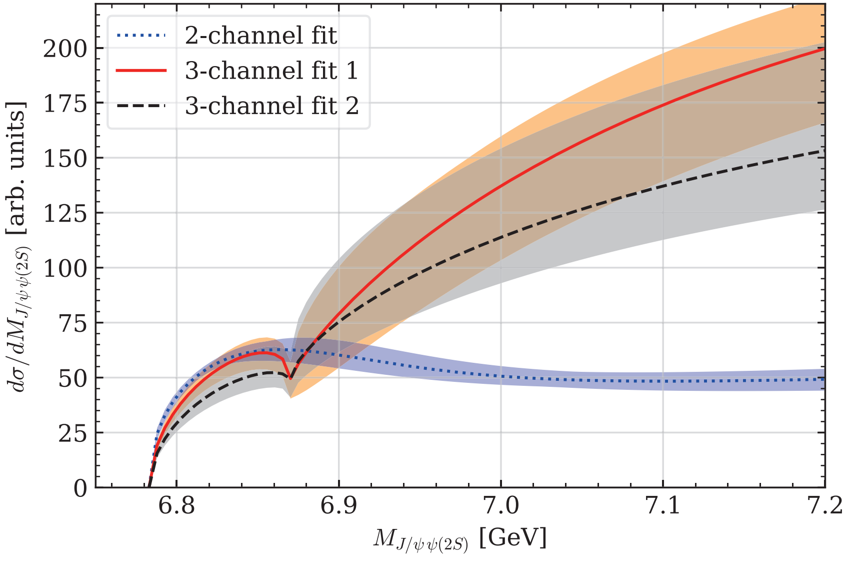
1 to produce structures
(via interplay with thresholds)

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
$r(\mathrm{fm})$	$-2.18^{+0.66}_{-0.81}$	$-0.06^{+0.03}_{-0.04}$	$-0.09^{+0.08}_{-0.05}$
$\bar{X}_A$	$0.39^{+0.58}_{-0.12}$	$0.91^{+0.04}_{-0.07}$	$0.95^{+0.04}_{-0.06}$

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



The two scenarios can be easily distinguished!

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

Summary

We therefore saw:

→ Structure of multiquark states is reflected in the spectrum or in line shapes

→ Symmetries (HQSS, $SU_F(3)$, chiral) play a crucial role

→ Multiplets reflect assumed structure

→ The symmetry breaking is specific for the underlying model

Thus, once we know the spectrum we will know

→ If diquarks or color neutral building blocks form, if any

→ If those are light-light vs. heavy-heavy or heavy-light

→ What it takes to further confirm the picture

Thank you very much for your attention