Theoretical update on the XYZ states ... and beyond

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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

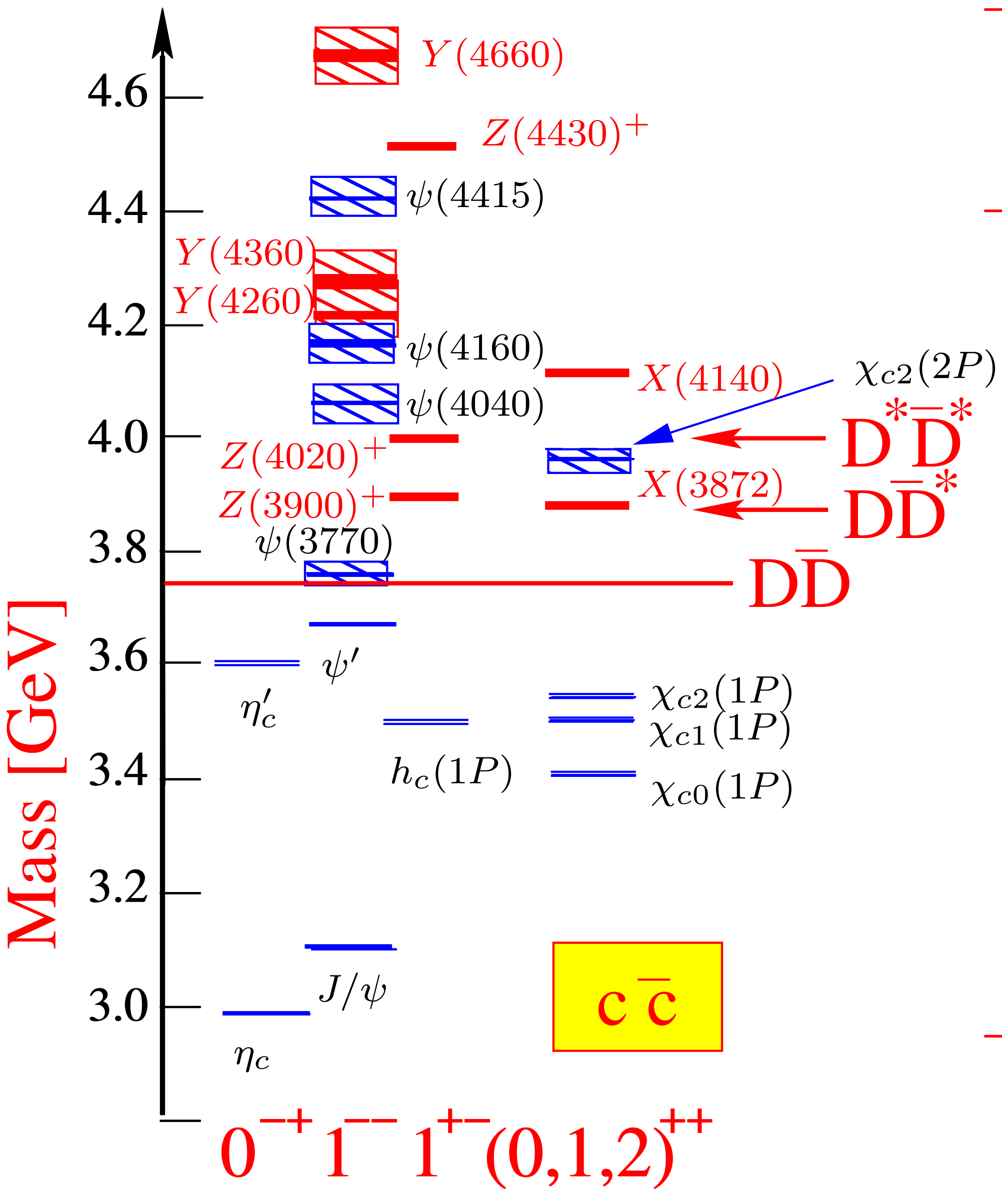
S.L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003

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

Charmonium after 2002: XYZ-states

A new particle Zoo!



→ missing low lying states found

→ Above the $\bar{D}D$ threshold:

- ▷ Many new states (24 claimed, 10 estd.)
- ▷ most of them incompatible with quark model in mass & properties (22 of 24, 8 of 9)

→ Two states in bottomonium-sector

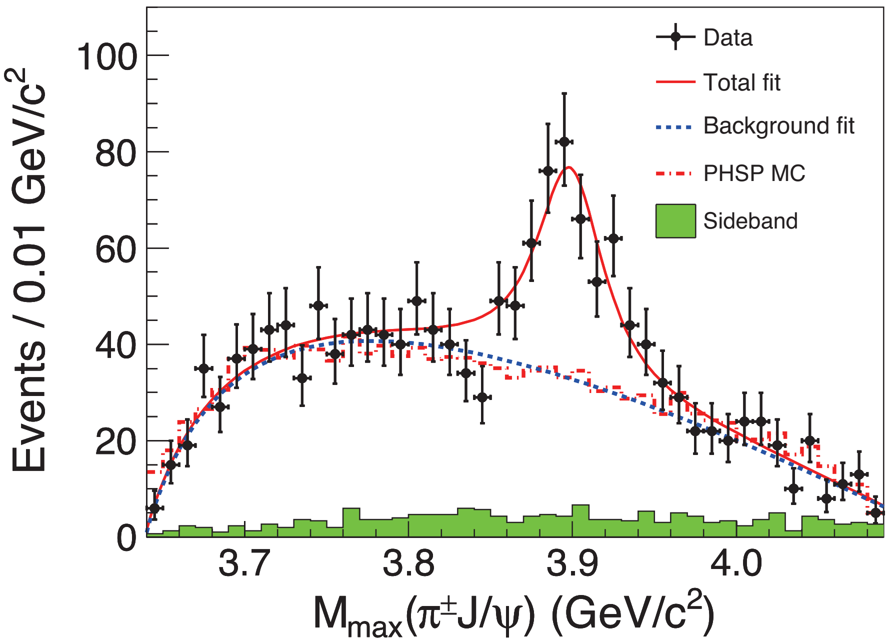
Explicit Exotics: Z-states

2012: Discovery of charged states at Belle in $\Upsilon(5S) \to [(\bar{Q}Q)\pi]\pi$

$\to$ must contain sizable $\bar{Q}$ and Q

$\to$ must contain light quarks;

$\boxed{\to \text{must contain at least 4 quarks}}$



Example: $Z_c(3900)$

close to $\bar{D}D^*$ threshold

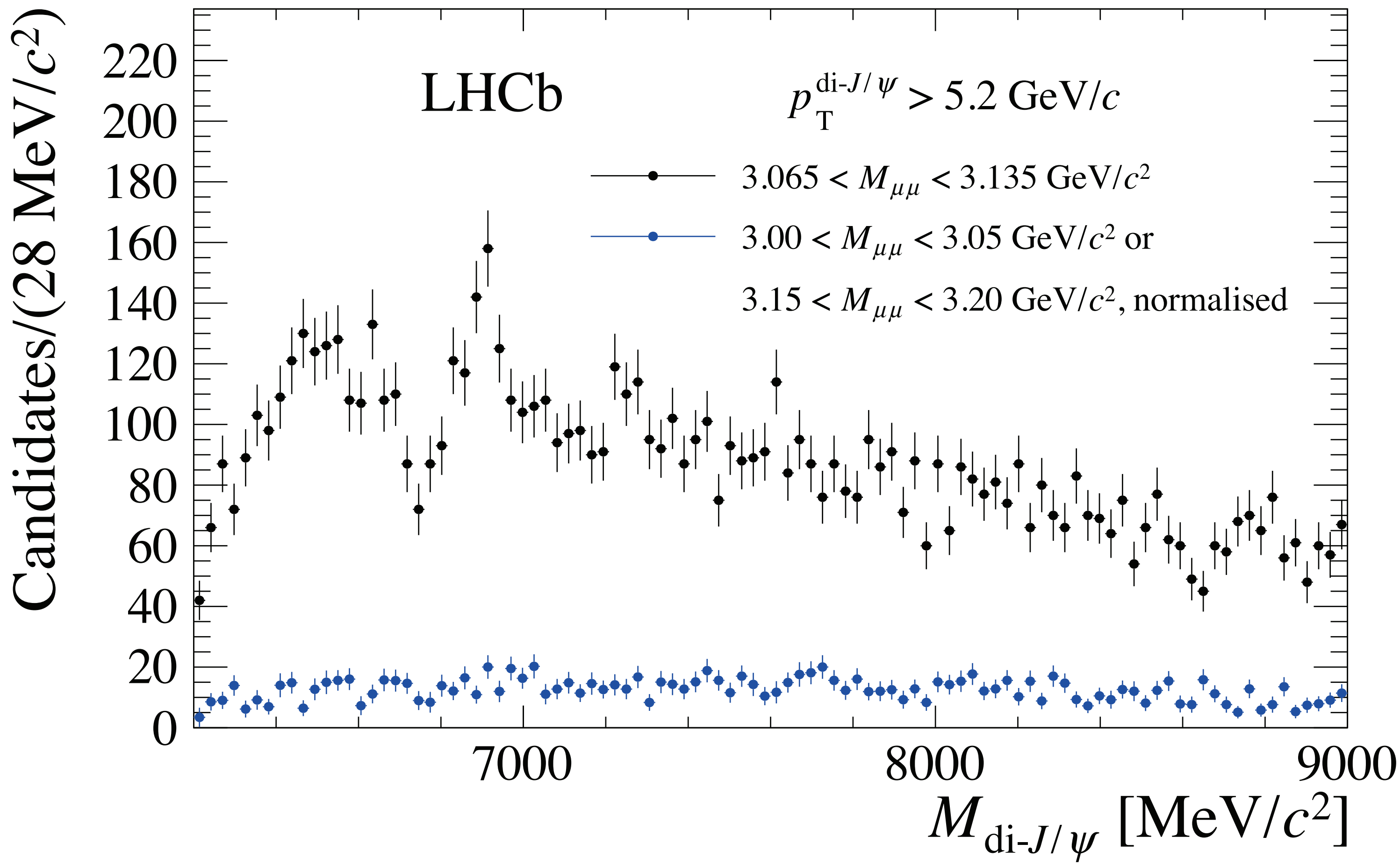
Data:

BES-III (China), 2013

Analogously: States seen in $J/\psi p$ channel must be Pentaquarks

Discovered by LHCb in 2015 and 2019 in $\Lambda_b^0 \to K^- J/\psi p$

... and beyond



LHCb 2020, arXiv:2006.16957

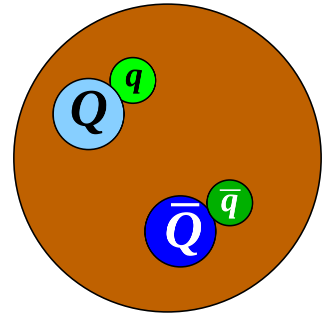
$\rightarrow$ Clear structures found in $J/\psi J/\psi$ final state (above 5σ)

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

Heavy Tetraquarks

→ Straightforward extension of the quark model

M. Gell-Mann, PL8(1964)214

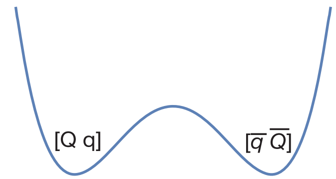


→ Mesons as diquark–anti-diquark systems

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

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

Maiani et al. PRD89(2014)114010



→ 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

→ and tensor force, S_{12}, needed

Ali et al. EPJC78(2018)29

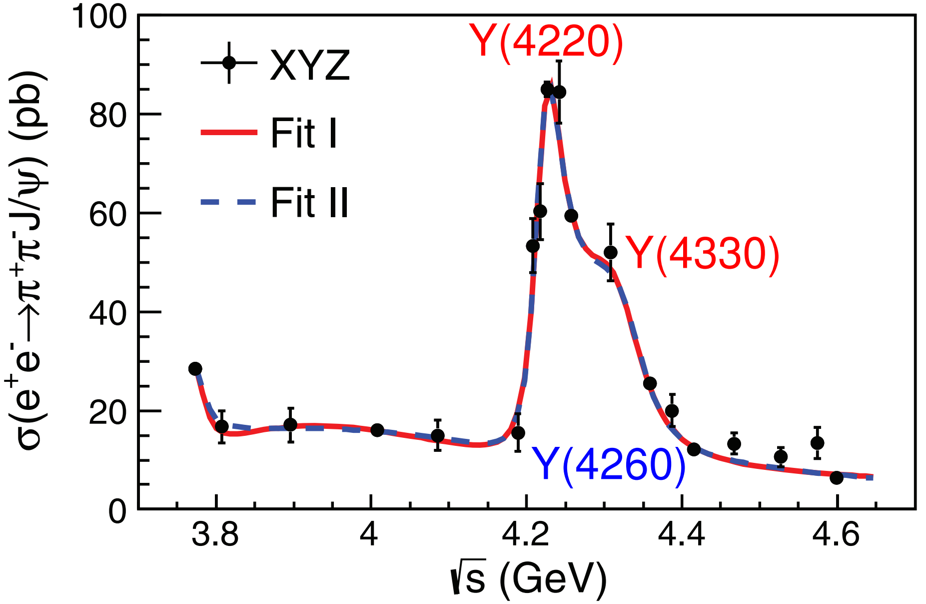
$$\boxed{M = 2M_Q + \frac{B_Q}{2}\mathbf{L}^2 + 2a_Y \mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4} S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)}$$

- Already many ground states
- Each level has isovector and isoscalar state ($cf.$ ρ and ω)

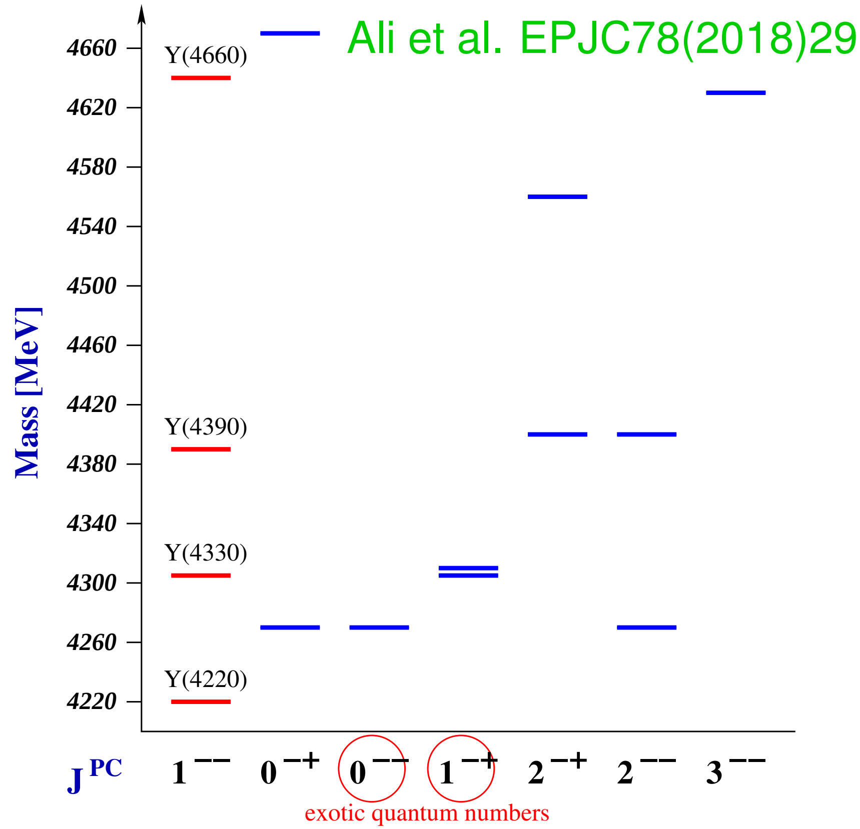
Results for negative parity states

→ four 1^{--} ground states

→ BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001



→ Threshold proximities accidental?

→ Many more states predicted than observed!

Maybe since di-quark picture too restrictive/constraining?

Extension of potential needed?

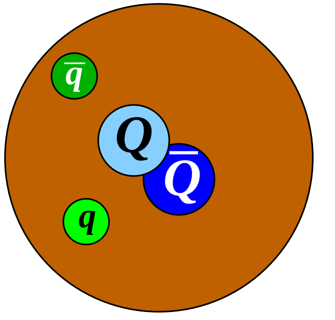
Richard et al., PRD95(2017)054019

J.F. Giron, R.F. Lebed, PRD102(2020)1

Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455

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

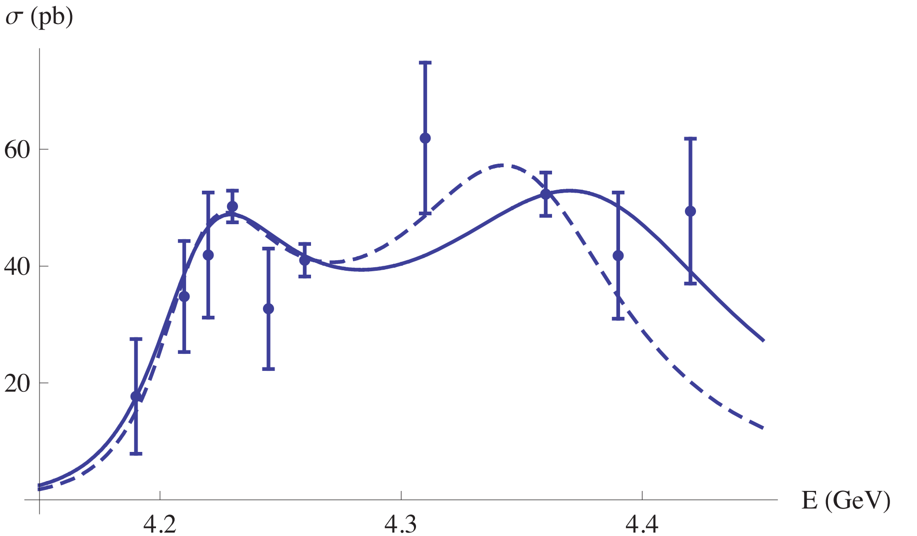


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ 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



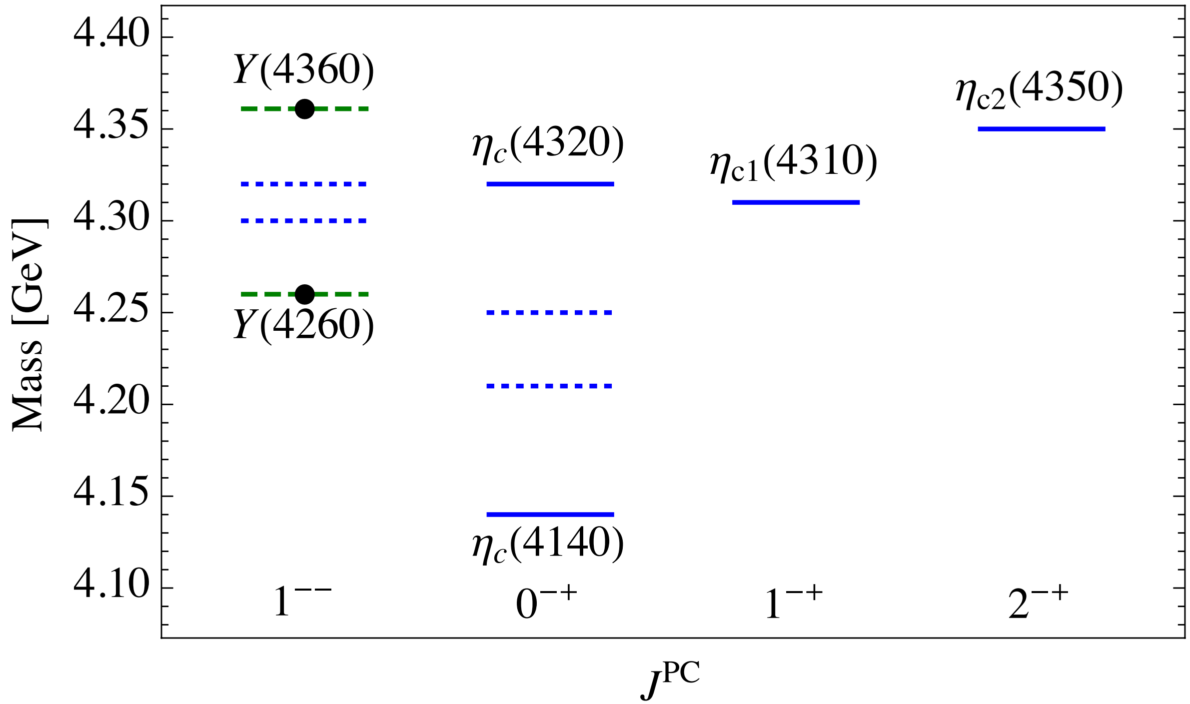
Hadrocharmonium: new states

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 $h_c \to \{\chi_{c0},\ \chi_{c1},\ \chi_{c2}\}$

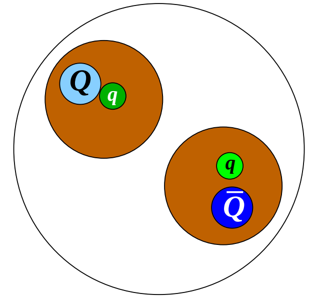


Cleven et al., PRD 92(2015)014005

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



$\rightarrow$ are few-hadron states, bound by the strong force

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

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

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

$\rightarrow$ can be identified in observables (Weinberg compositeness):

$$\frac{g_{\text{eff}}^2}{4\pi} = \frac{4M^2\gamma}{\mu} X_W \text{ with } a = -2\left(\frac{X_W}{1-X_W}\right)\frac{1}{\gamma}\ ;\ r = -\left(\frac{1-X_W}{X_W}\right)\frac{1}{\gamma}$$

where compositness X_W=probability to find molecular component in bound state wave function

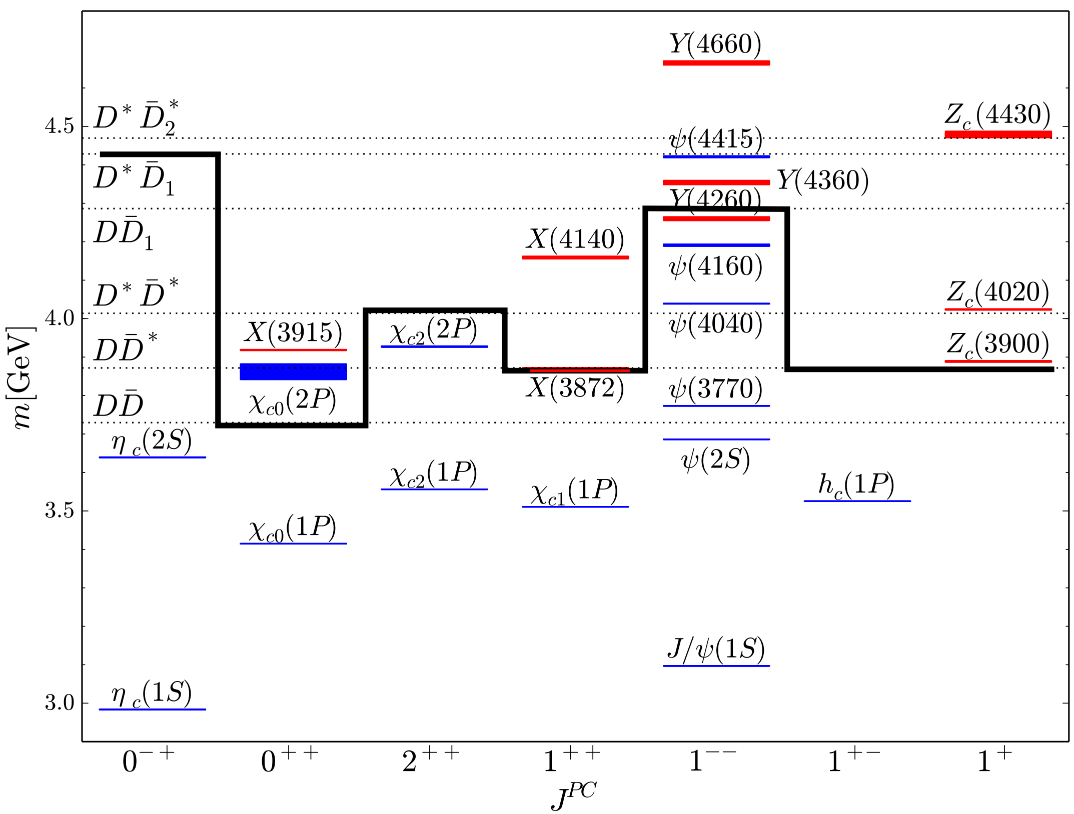
$\boxed{\text{Are there mesonic molecules?}}$

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 ...



$\rightarrow$ 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

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

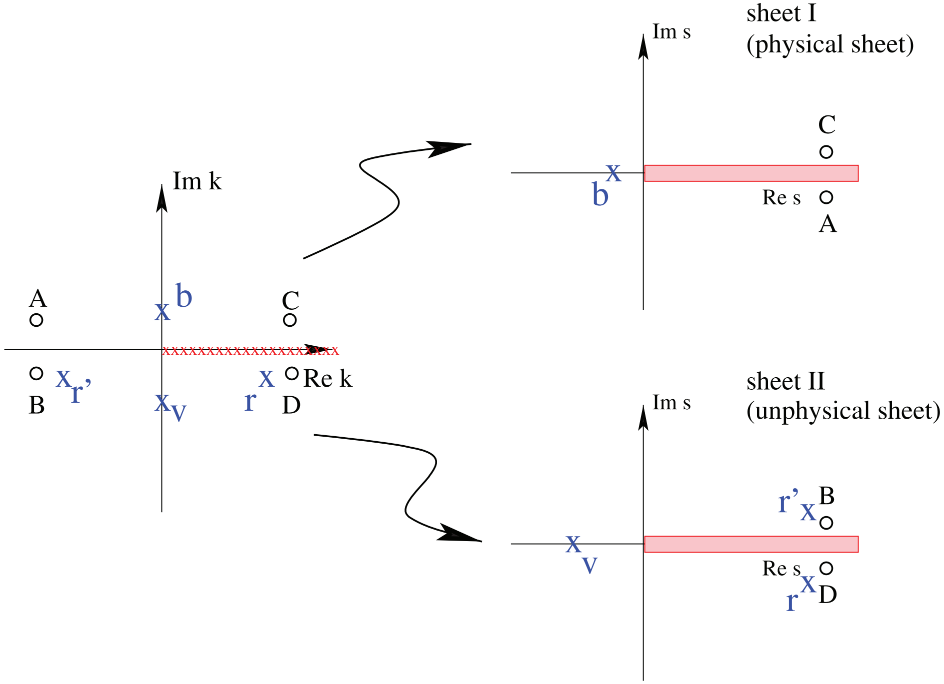
Note: for hadrocharmonium:
$M(0^-) - M(1^-) \simeq -100$ MeV

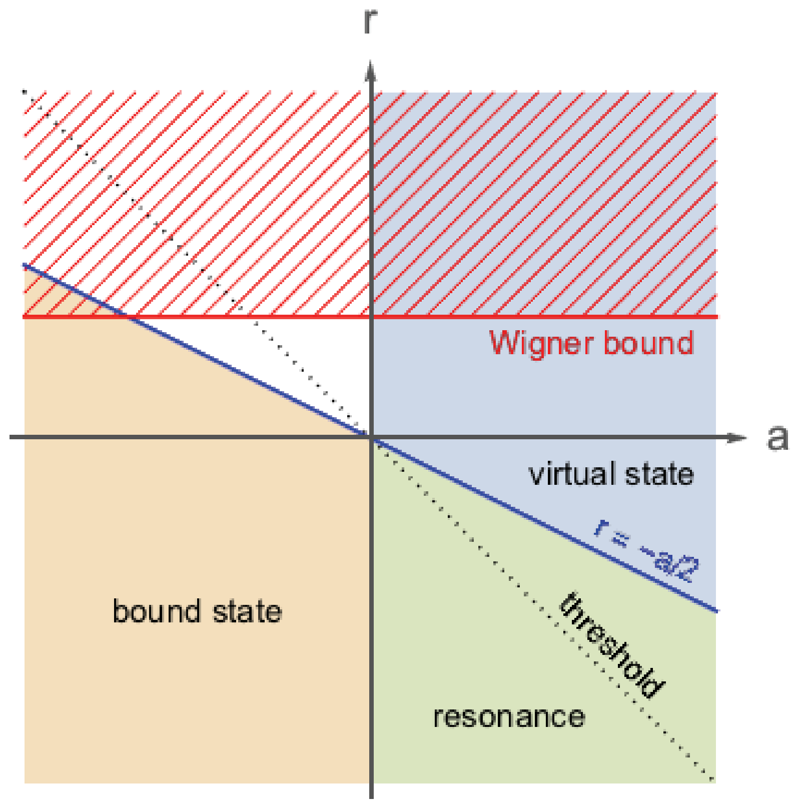
Cleven et al., PRD 92 (2015) 014005

Generalisation of Weinbergs analysis

I. Matuschek et al., arXiv:2007.05329

Model independent criterion for virtual states and resonances





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

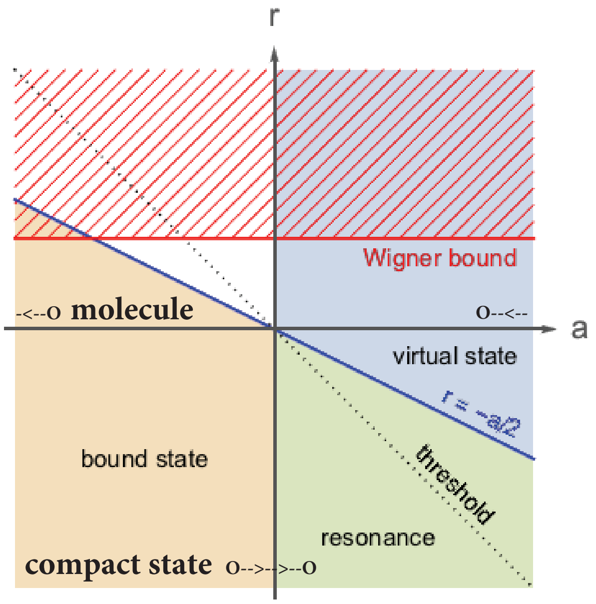
Poles at

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

Generalisation of Weinbergs analysis

I. Matuschek et al., arXiv:2007.05329

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

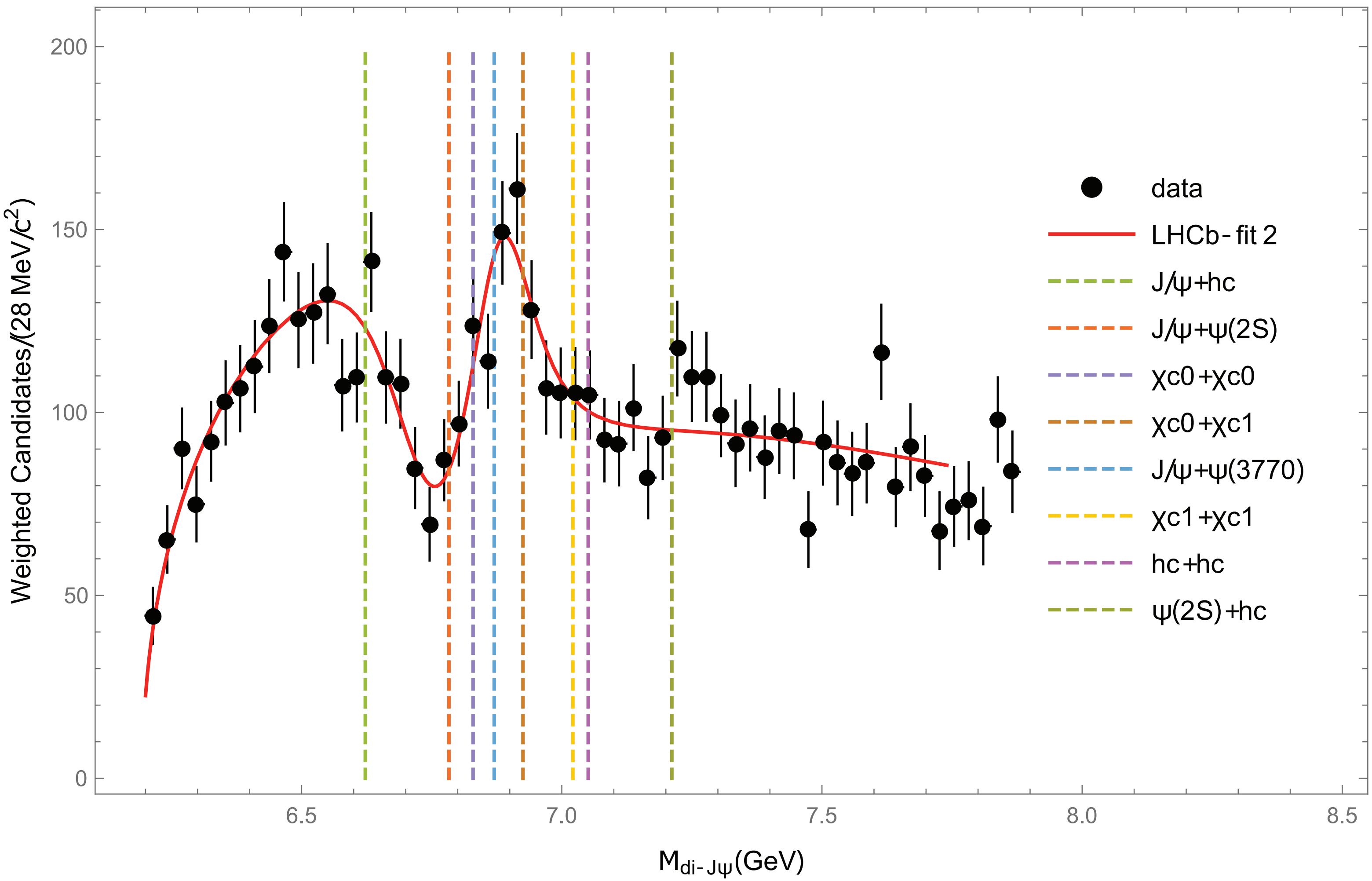
Subsummed in compositness: $\bar{X}_A = 1/\sqrt{1+|2r/a|}$

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

Back to the double J/ψ spectrum

Are these states tetraquarks or molecules?

There are many thresholds in the mass range:



Back to the double J/ψ spectrum

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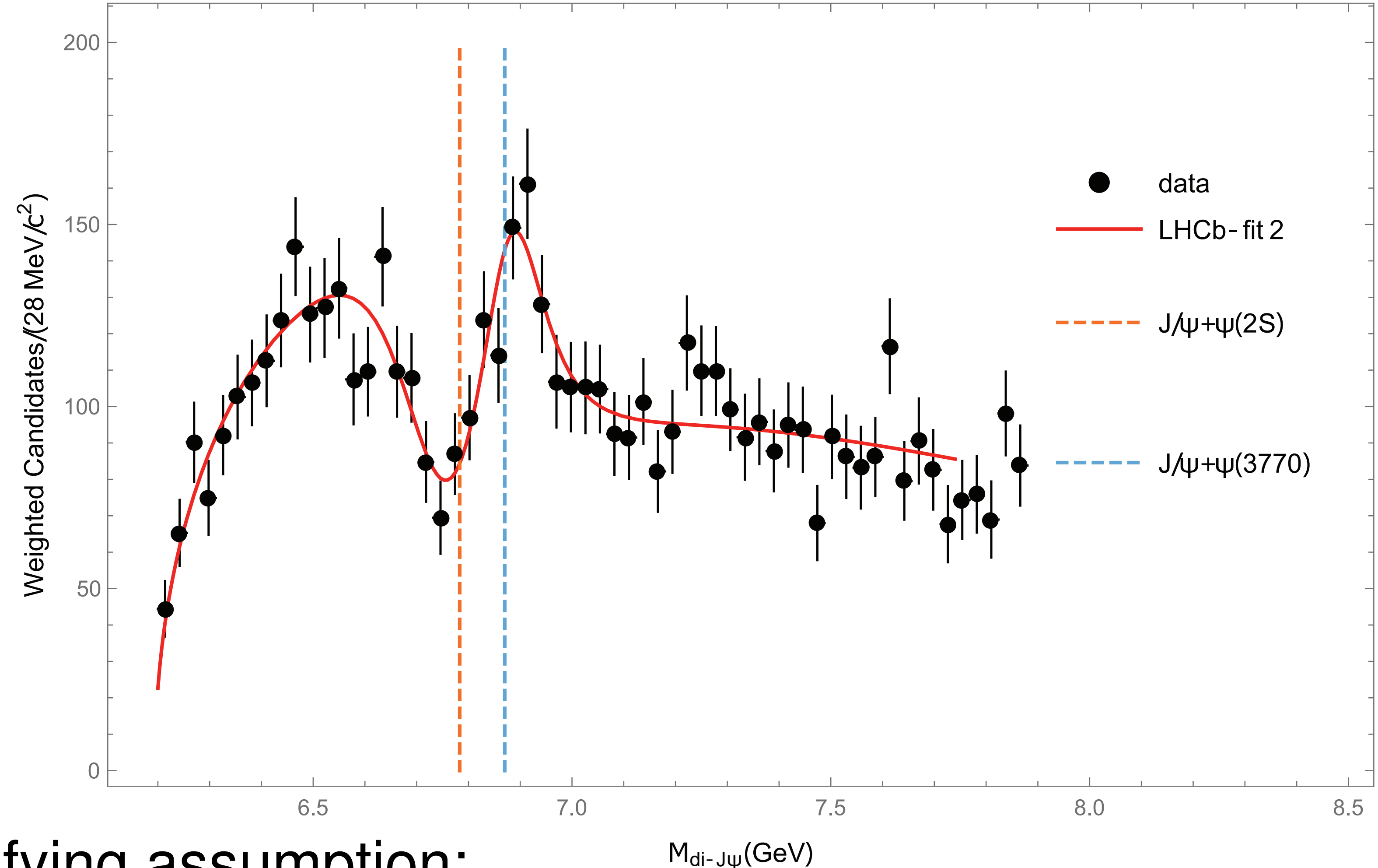


Simplifying assumption:

only vector-vector channels matter

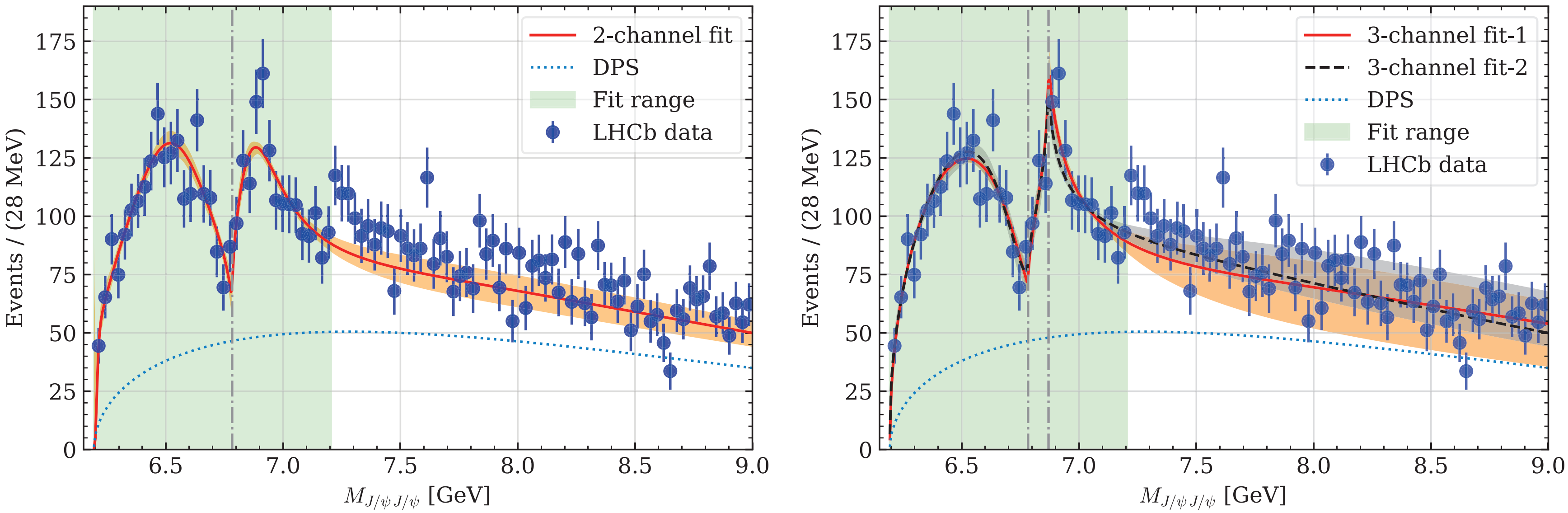
Two models

Xiang-Kun Dong et al., arXiv:2009.07795

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

$$V_{2\mathrm{ch}}(E) = \begin{pmatrix} a_1+b_1k_1^2 & c \\ c & a_2+b_2k_2^2 \end{pmatrix} \text{ or } V_{3\mathrm{ch}}(E) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix},$$

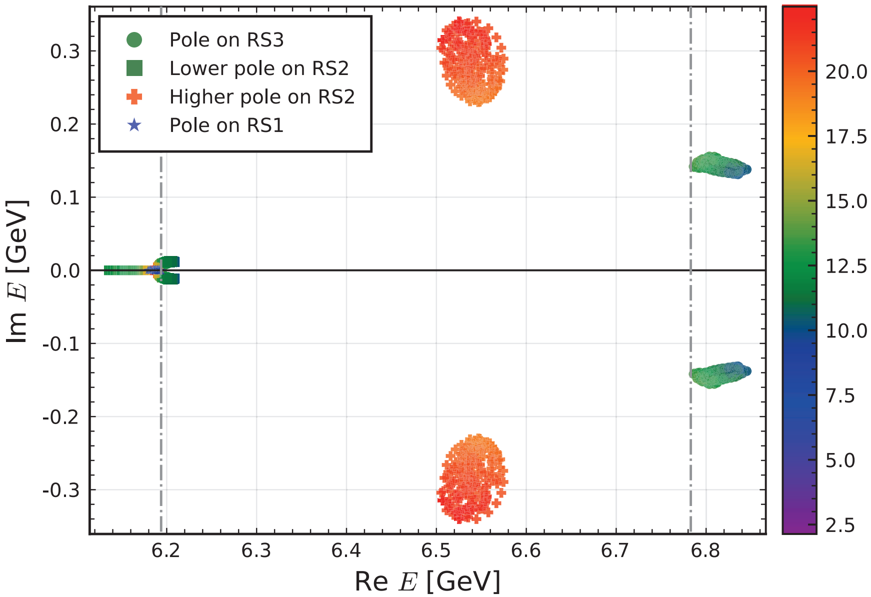
where the $J/\psi J/\psi$, $\psi(3686)J/\psi$ (and $\psi(3770)J/\psi$) were included



Both models provide excellent description of data

Pole structure

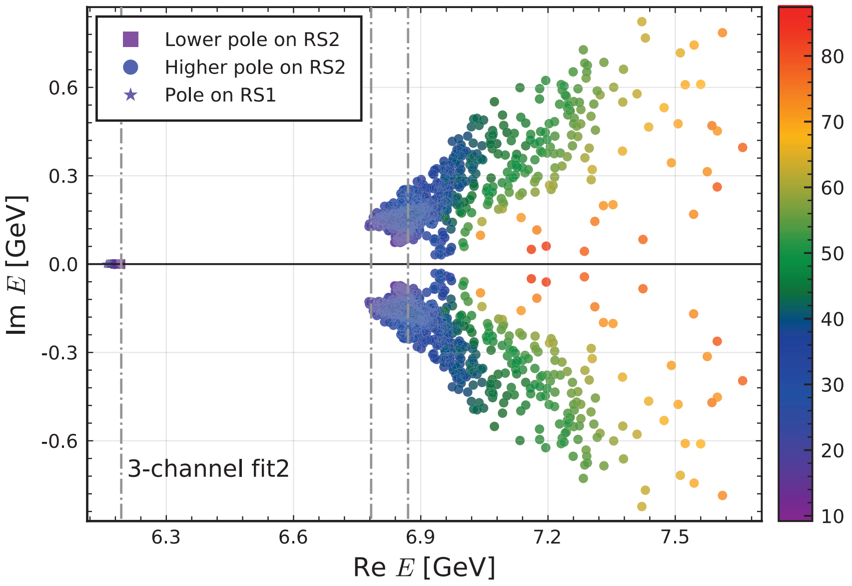
The pole structure is very different:



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.,

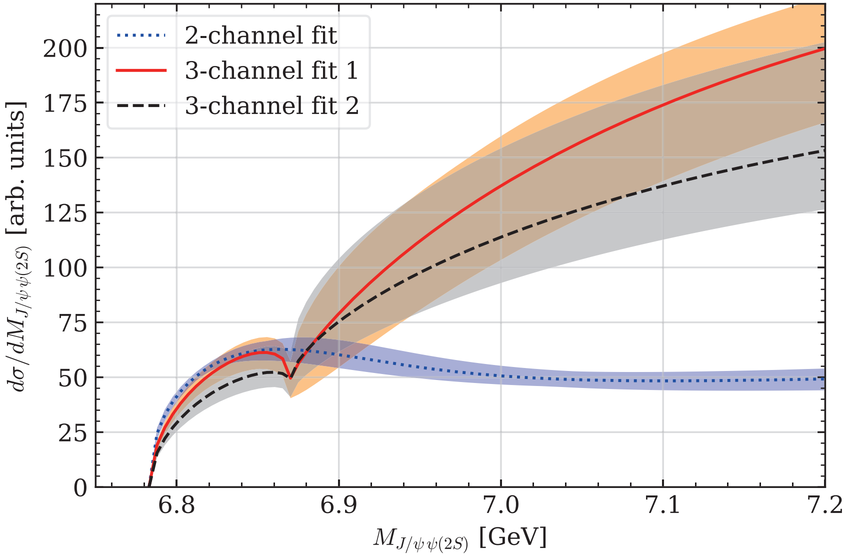
1 to produce structures
(via interplay with thresholds)

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

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 easily distinguished!

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

What is needed for further progress

→ Excellent data especially for different spin states
(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

Thanks a lot for your attention