XYZ states
Status and Perspectives

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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

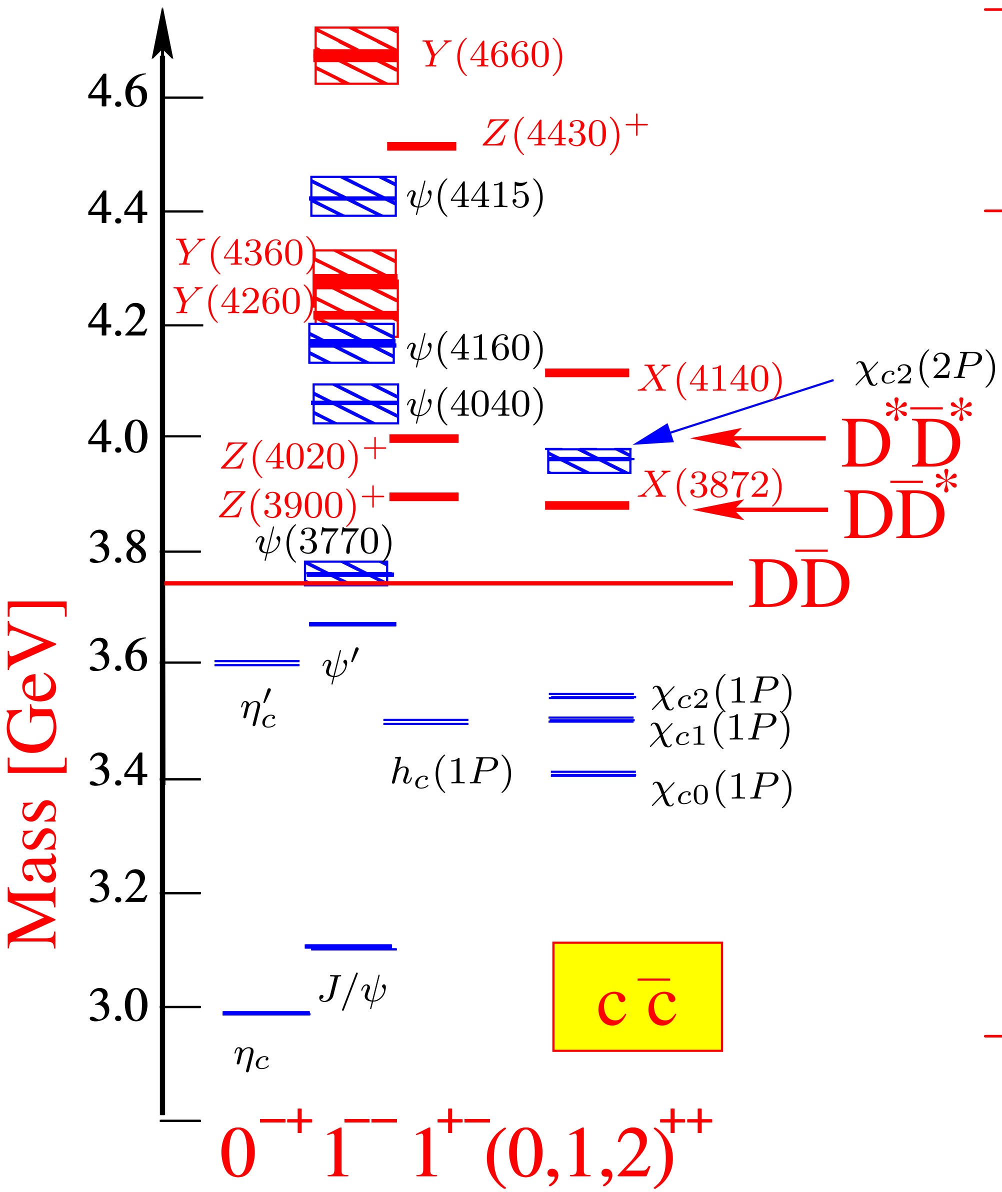
R.F. Lebed, R.E. Mitchell, E.S. Swanson, Prog. Part. Nucl. Phys. 93 (2017) 143

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

with focus on molecular states: F.-K. Guo et al., Rev. Mod. Phys. 90(2018)015004

Charmonium after 2002

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 charged states in bottomonium-sector

Charged states

2012: Discovery of charged states that

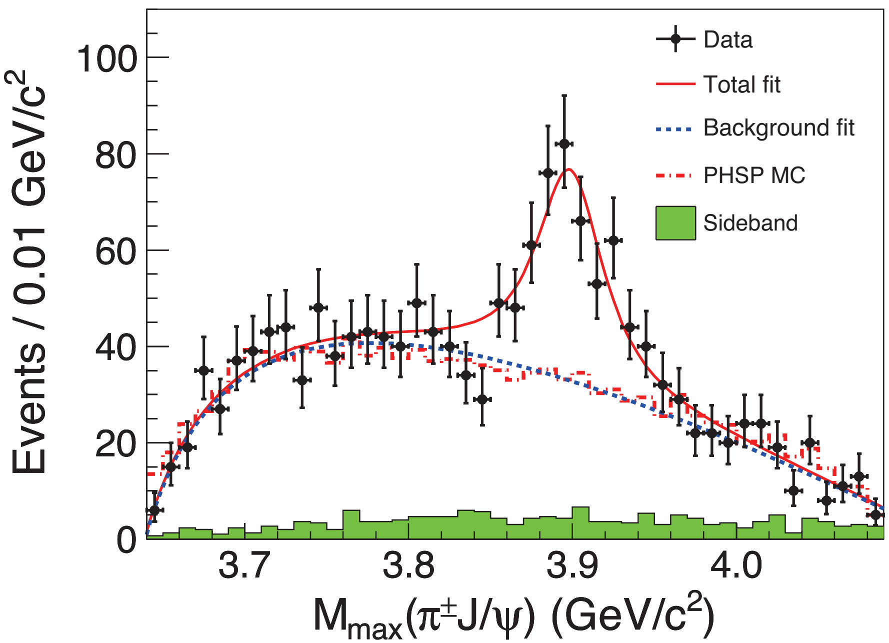
→ have masses in the quarkonium mass range;

→ decay with $\bar{Q}$ and Q in the final state

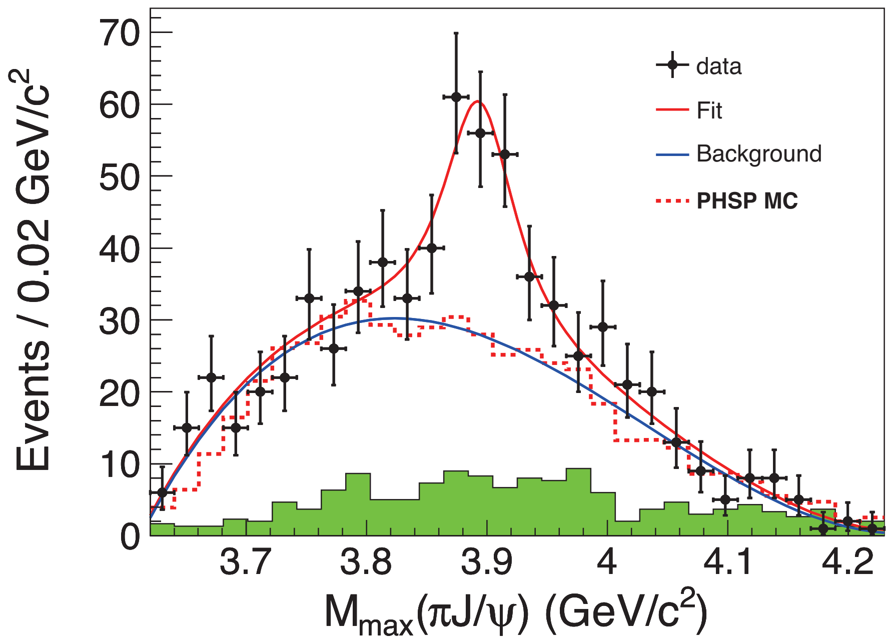
→ must contain at least 4 quarks

Example: $Z_c(3900)$ close to $\bar{D}D^*$ threshold

BES-III (China), 2013

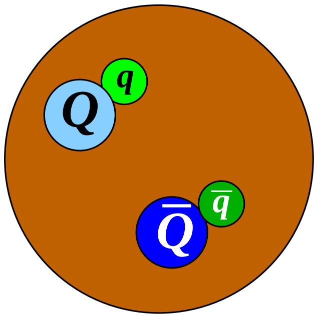


Belle (Japan), 2013



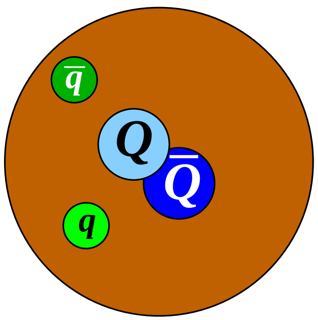
Proposals

Focus: Multi-Quark States



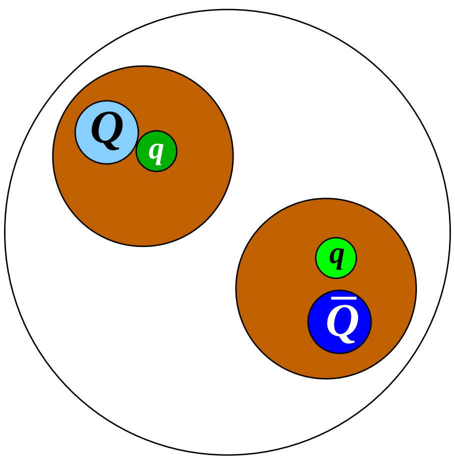
Tetraquark

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



Hadro-Quarkonium

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



Hadronic-Molecule

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

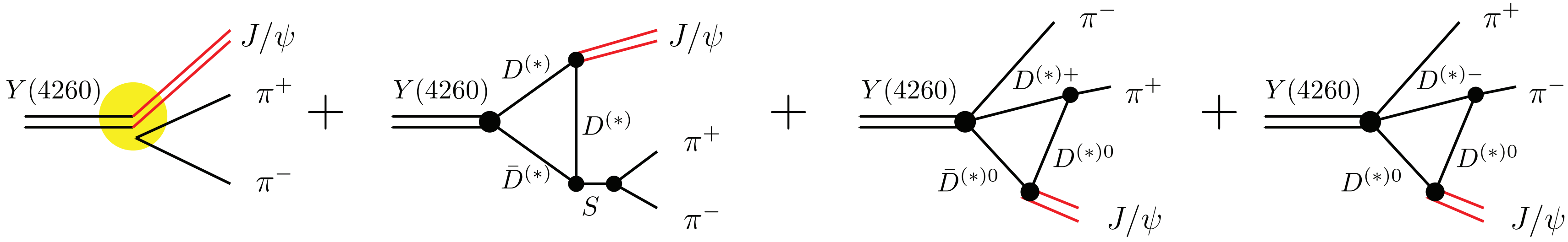
Bohr radius = $1/\gamma = 1/\sqrt{2\mu E_b}$

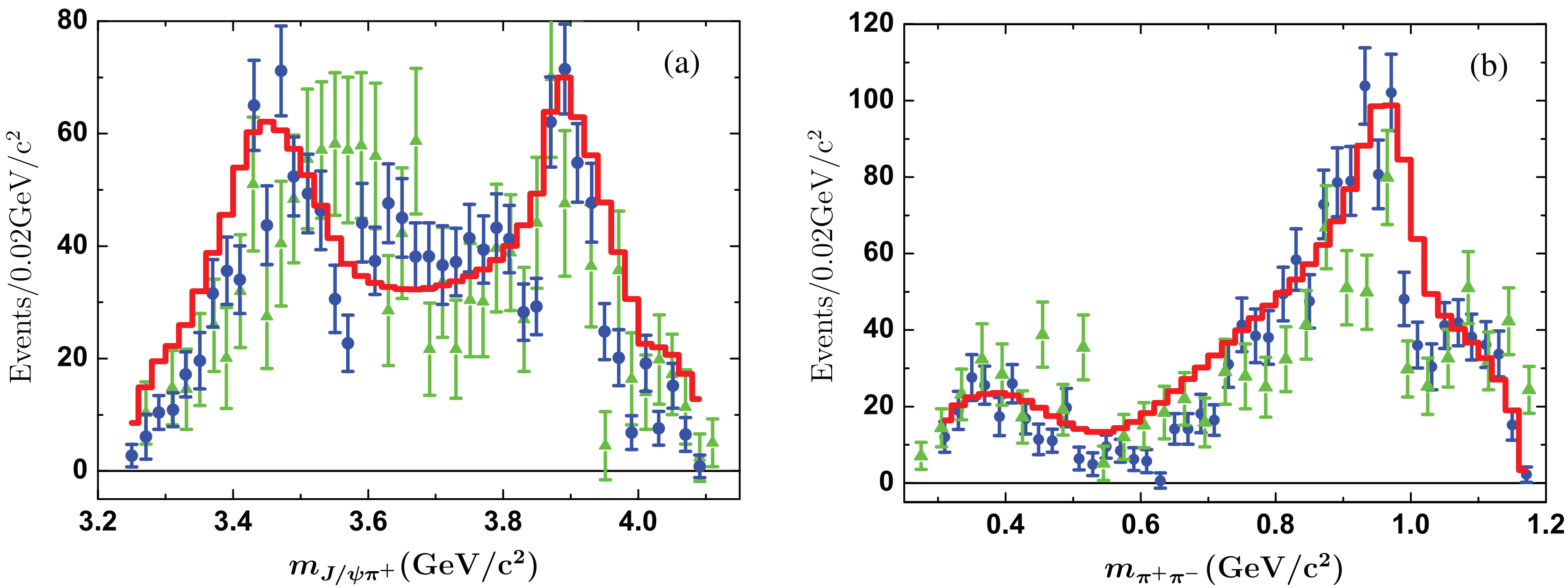
$\gg 1$ fm $\gtrsim$ confinement radius

for near threshold states

(Some) XYZ-states threshold effects?

Bugg PLB598(2004)8; Chen et al. PRD84(2011)094003; Swanson PRD91(2015)034009



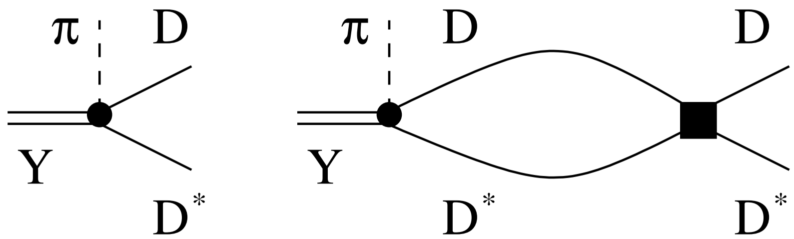


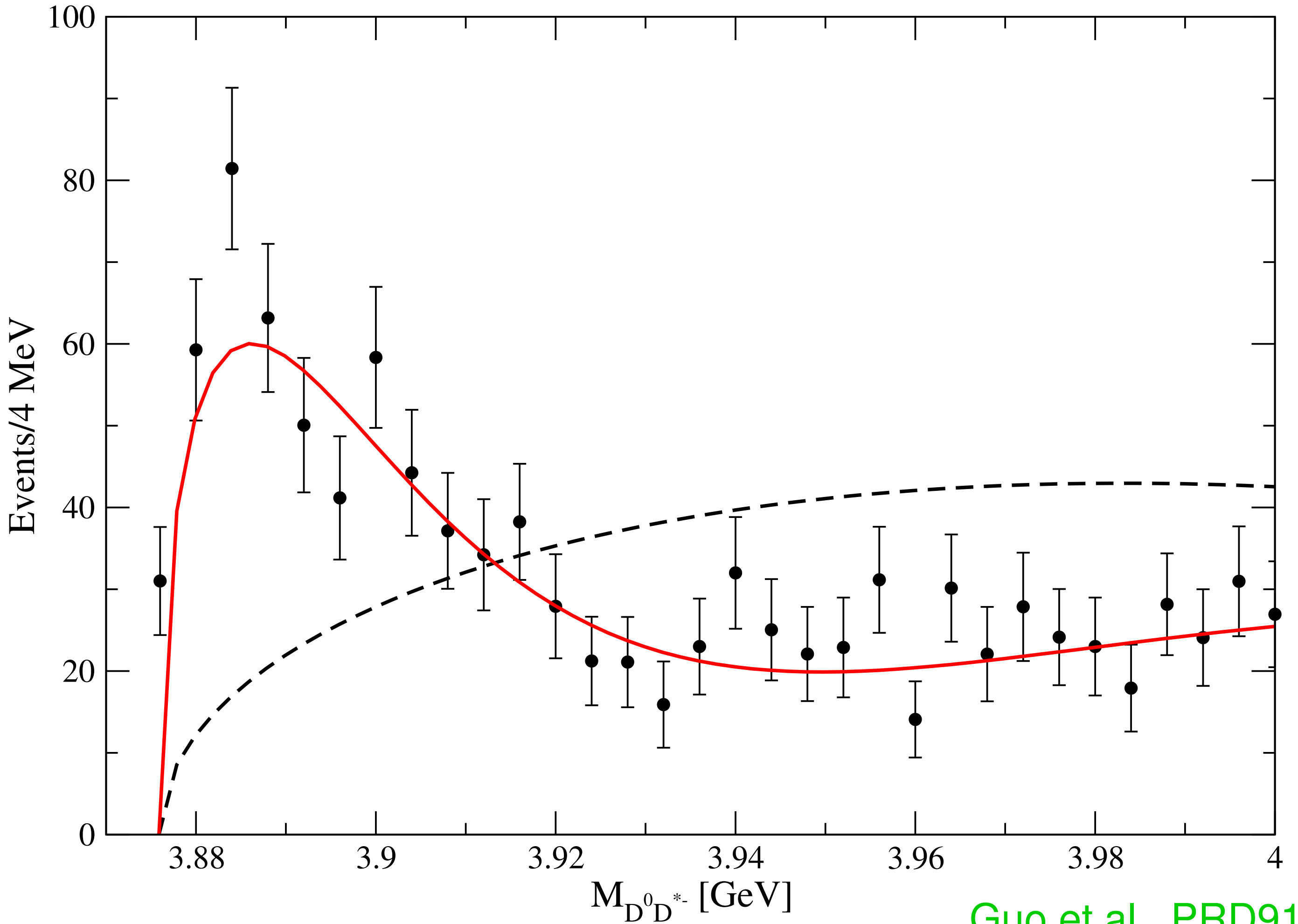
Chen et al., PRD88(2013)036008

Could it be that the origin of $Z(3900)$ is a threshold cusp followed by perturbative rescattering? $\Longrightarrow$ study elastic channel

For criticism to our point of view see Swanson Int.J.Mod.Phys.E25(2016)1642010

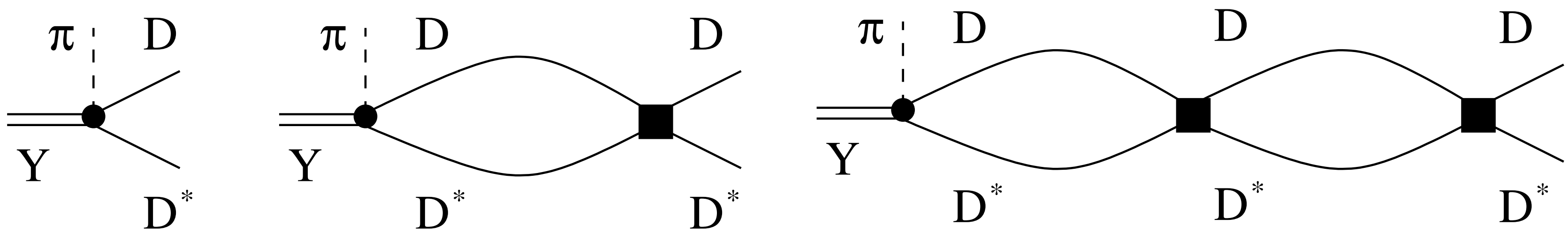
Why the argument is wrong

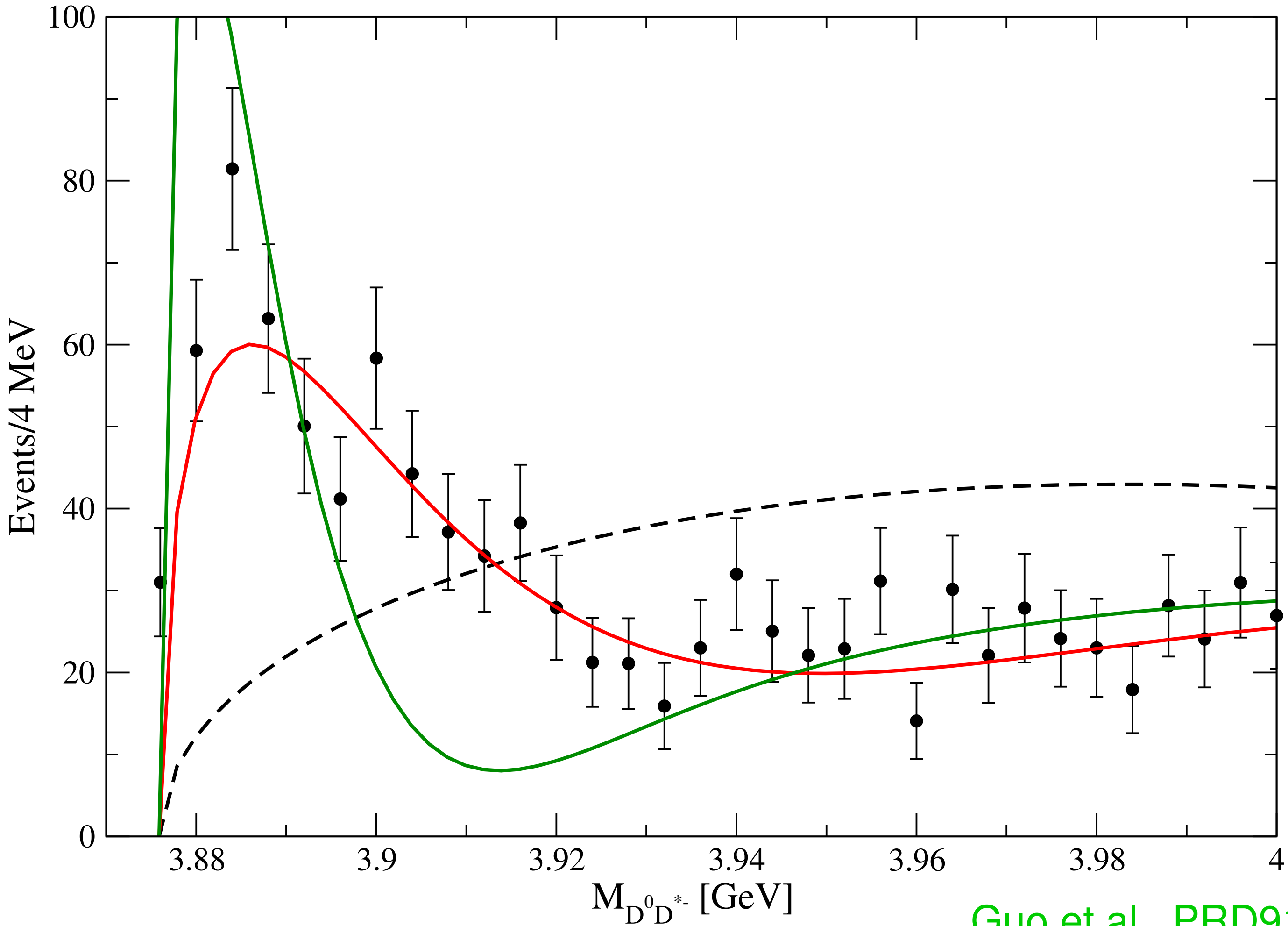




Guo et al., PRD91(2015)051504

Why the argument is wrong





Guo et al., PRD91(2015)051504

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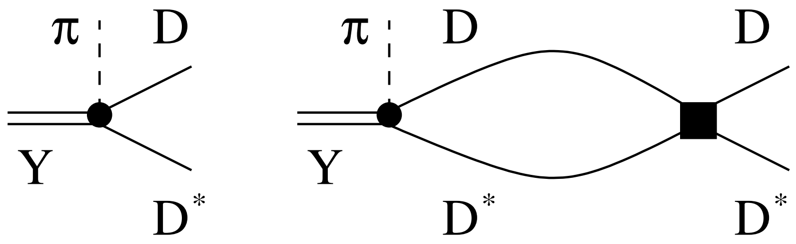
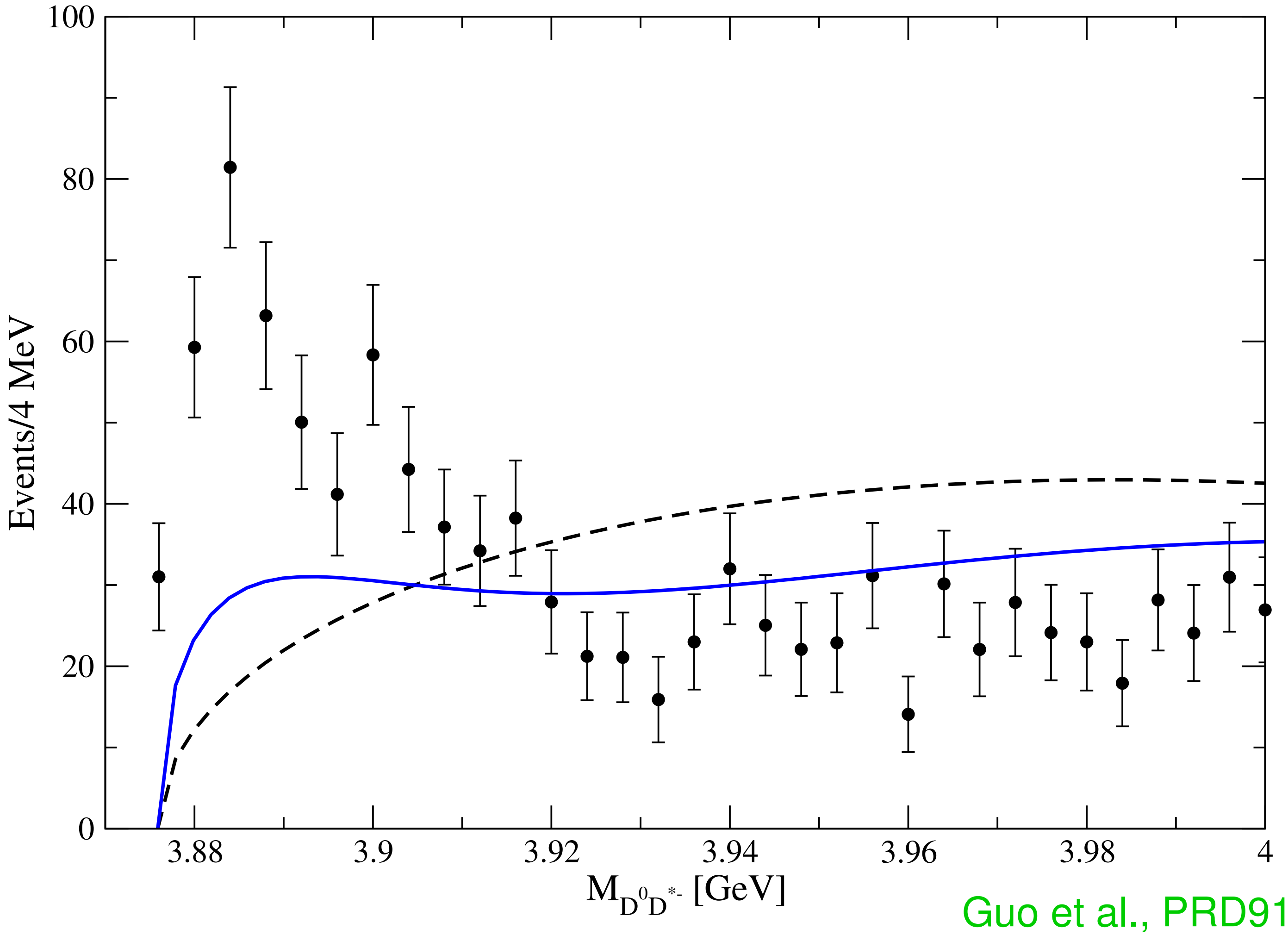
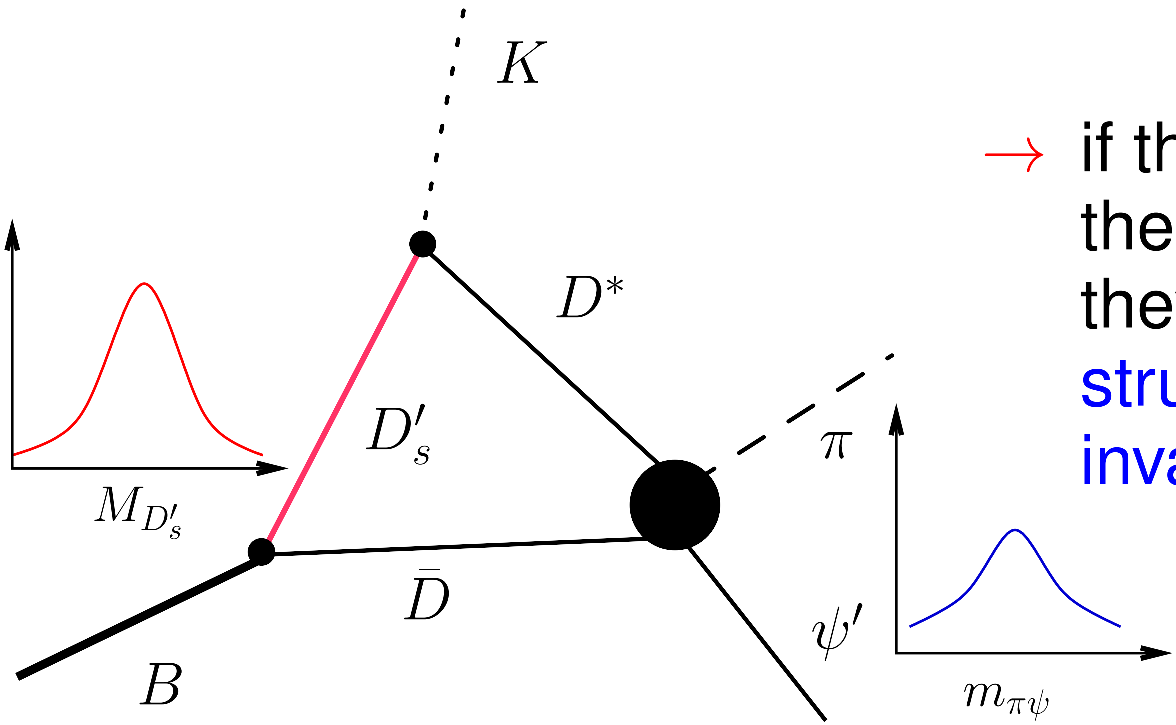




Guo et al., PRD91(2015)051504

(Some) driven by triangle–effects?



Pakhlov, PLB702(2011)139

→ if there are excited D_s in the proper mass range, they can produce the structure $Z(4430)$ in the $\pi\psi$ invariant mass

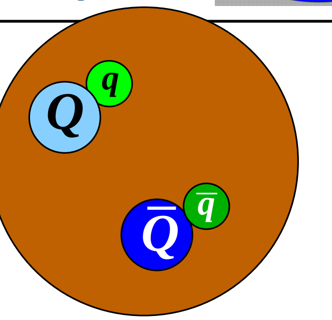
... maybe — but certainly not for all XYZ–states, since mechanism very sensitive to external invariant masses, and, e.g.,

→ $X(3872)$ is seen in B–decays and $Y(4260)$ radiative decays

→ $Z_c(3900)^+$ is seen at different energies in e^+e^-

→ not applicable to vectors states seen in e^+e^-

Heavy Tetraquarks

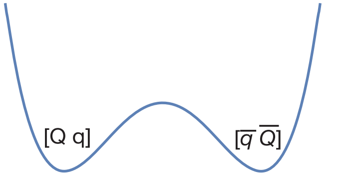


→ Straightforward extension of the quark model

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

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

Ali et al. EPJC78(2018)29

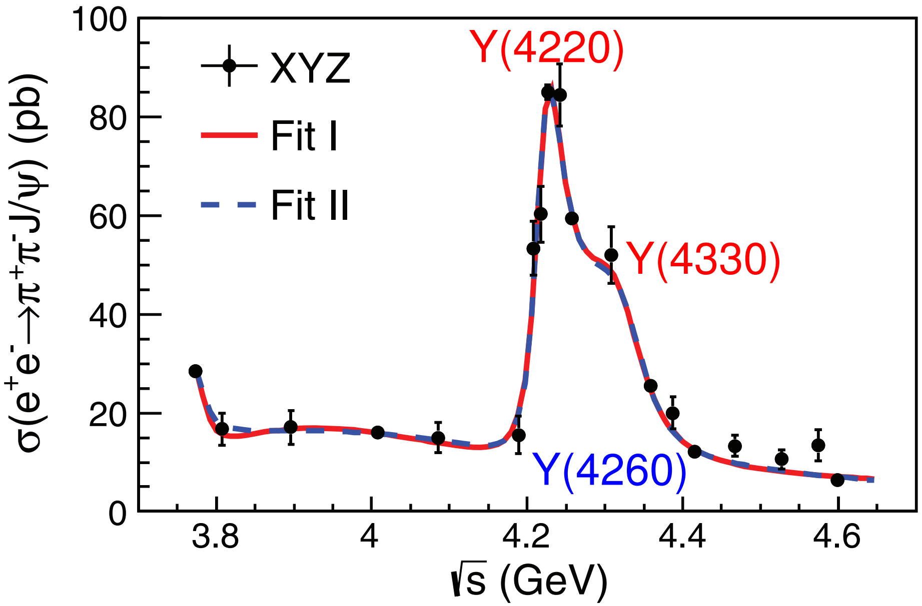
$$M = 2M_Q + \frac{B_Q}{2}\mathbf{L}^2 + 2a_Y \mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4}S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)$$

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

Results for negative parity states

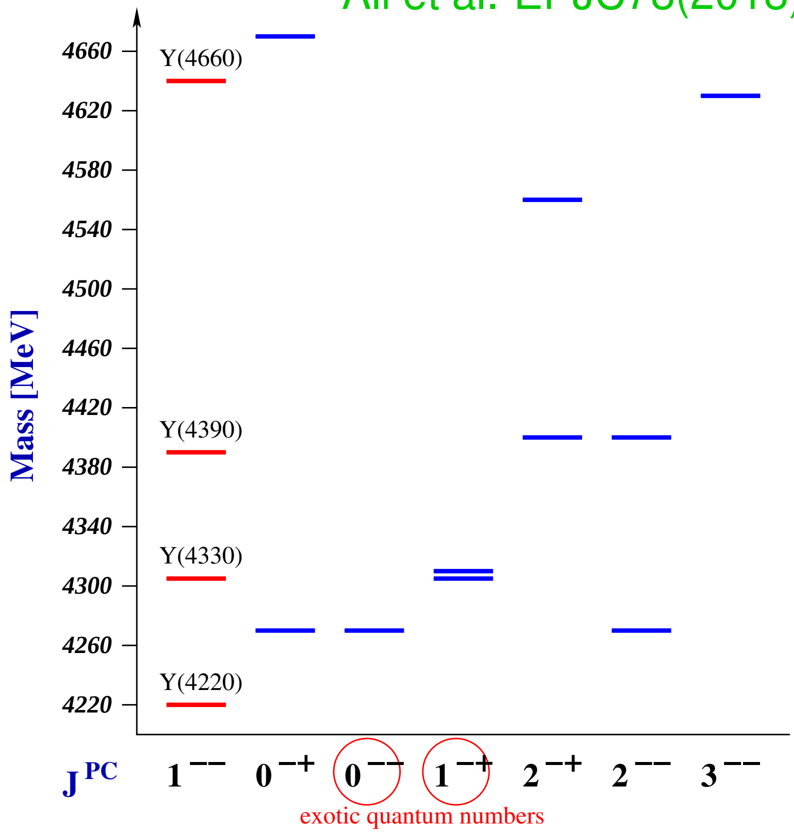
→ four 1^{--} ground states

→ BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001

Ali et al. EPJC78(2018)29



→ Without tensor force very light 3^{--} Cleven et al., PRD 92(2015)014005

→ Many more states predicted than observed!

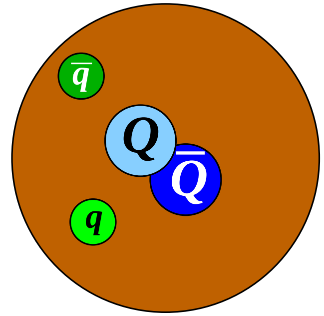
Maybe since di-quark picture too restrictive/constraining?

Richard et al., PRD95(2017)054019

Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455

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

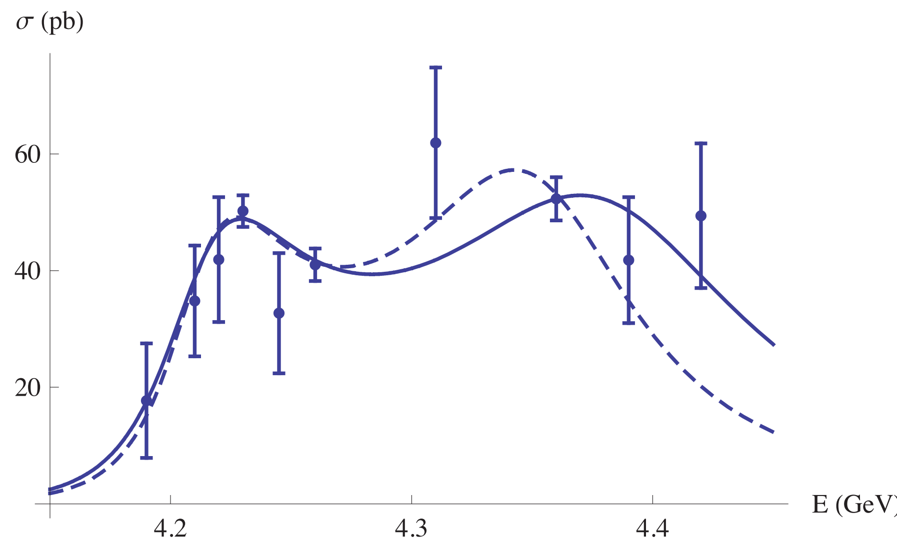


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ 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



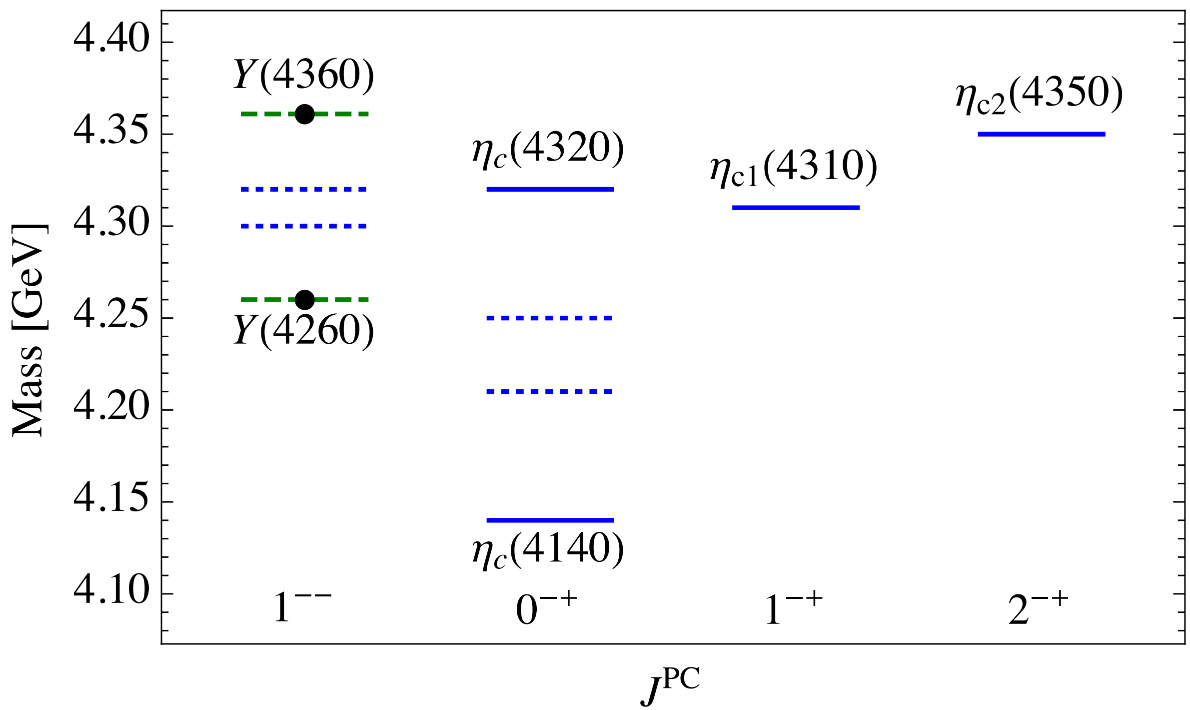
Hadrocharmonium: new states

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

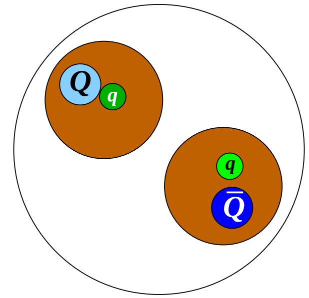


Cleven et al., PRD 92(2015)014005

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):

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

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

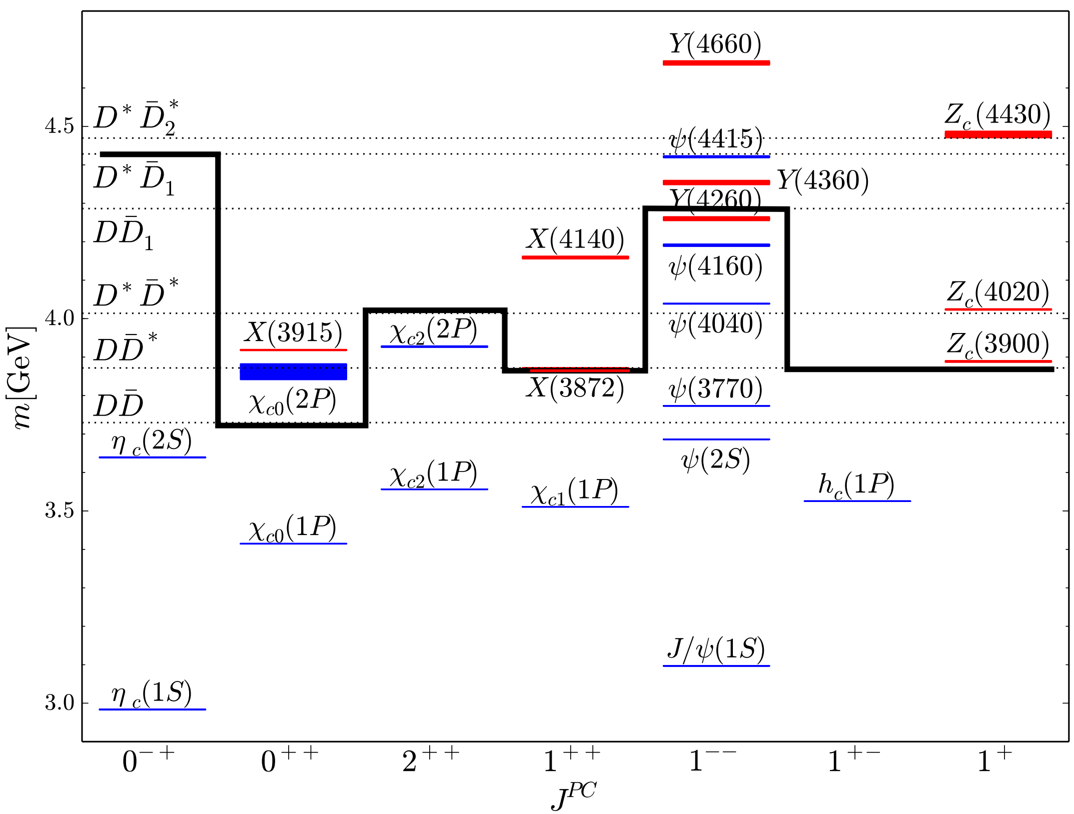
Are there mesonic molecules?

General considerations

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

$D\ (0^-, M = 1865, \Gamma \simeq\ 0)$; $D^*(1^-, M = 2007, \Gamma \simeq 0.1)$
$D_1(1^+, M = 2420, \Gamma \simeq 30)$; $D_2^*(2^+, M = 2460, \Gamma \simeq 50)$

$D_0(2400)$ and $D_1(2430)$ with $\Gamma = 300$ MeV too broad ...



→ 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

Spin symmetry violation

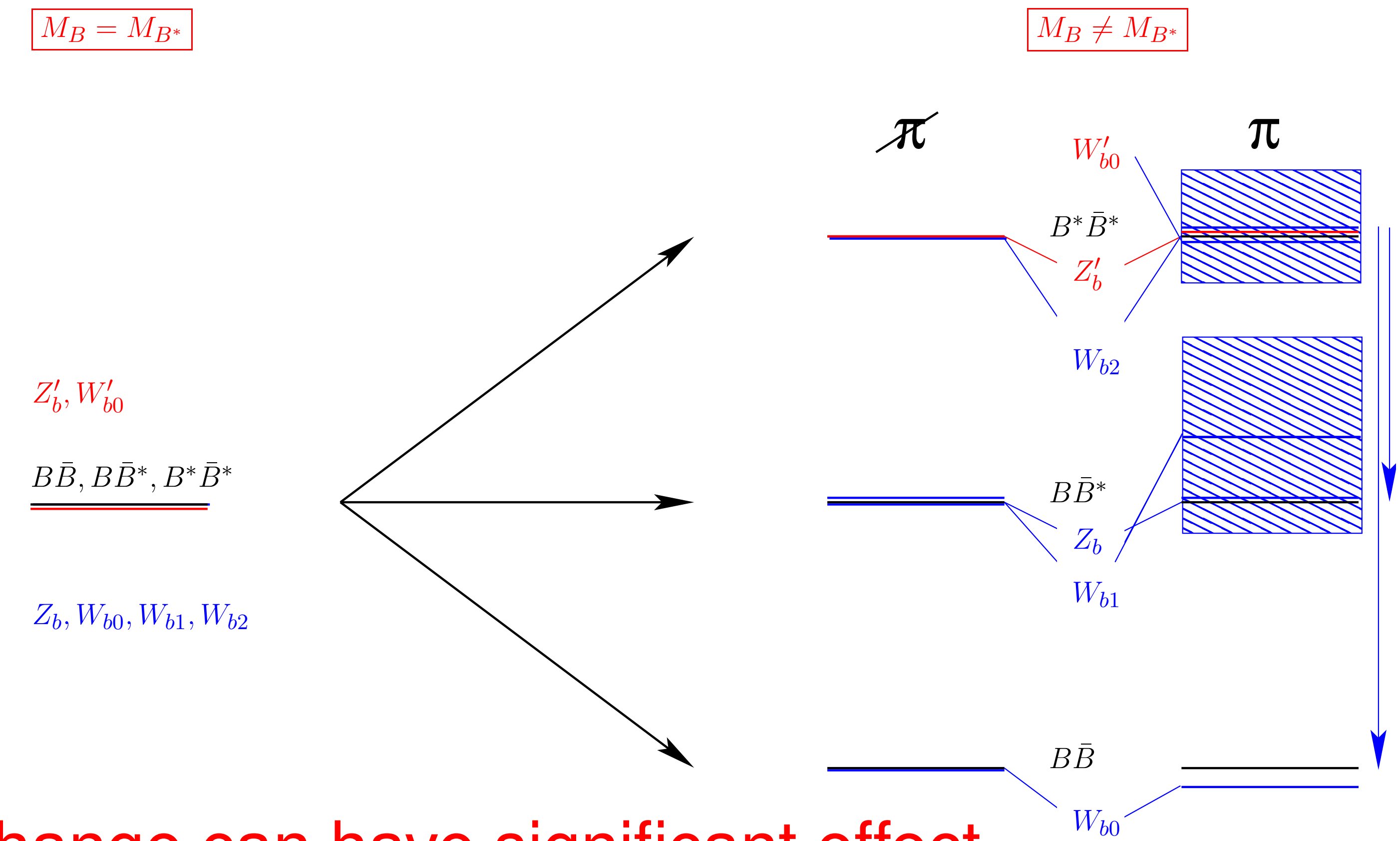
EFT for I=1 $B^{(*)}\bar{B}^{(*)}$ scattering $\rightarrow$ Spin multiplets

$Z_b^{(\prime)}\ J^{PC}{=}1^{+-} \rightarrow W_{bJ}\ J^{PC}{=}J^{++}$

Bondar et al., PRD 84 (2011) 054010; Voloshin, PRD 84 (2011) 031502;
Mehen & Powell, PRD 84 (2011) 114013; Nieves & Valderrama, PRD 86 (2012) 056004.

When lifting spin symmetry, specific pattern emerges:

Baru et al., PLB763(2016)20, JHEP 1706(2017)158, PRD99(2019)094013



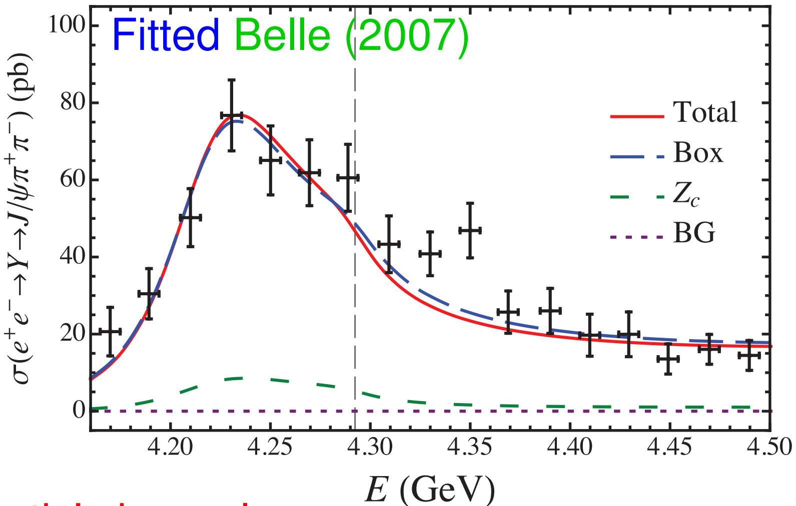
Pion exchange can have significant effect

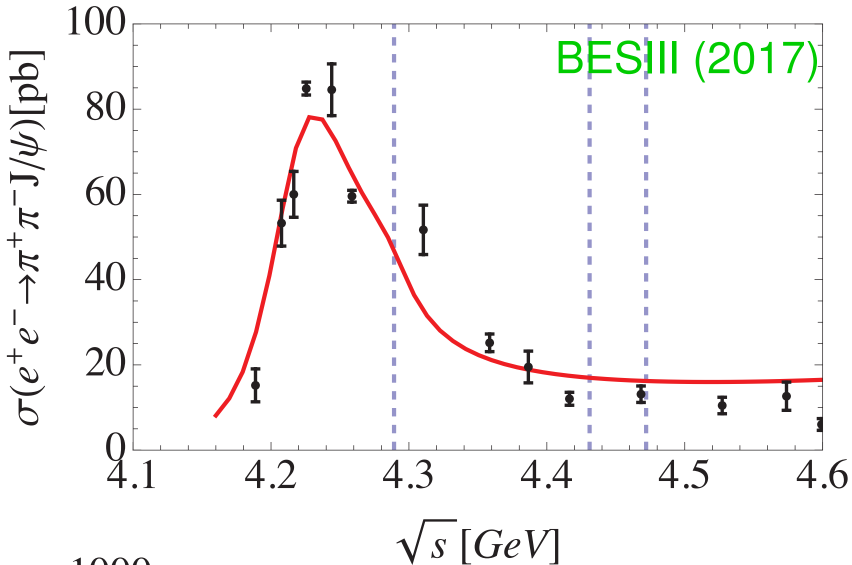
Lineshapes of $Y(4260)$

IF the $Y(4260)$ is a $D_1\bar{D}$ molecule it MUST have a large coupling to this channel $\Longrightarrow$ great impact on lineshapes

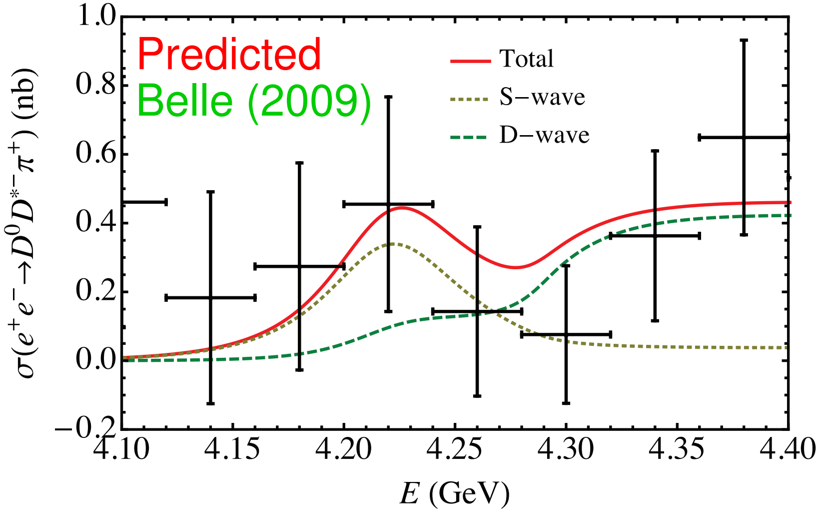
Cleven et al., PRD90 (2014) 074039; see also Qin et al. PRD94(2016)054035

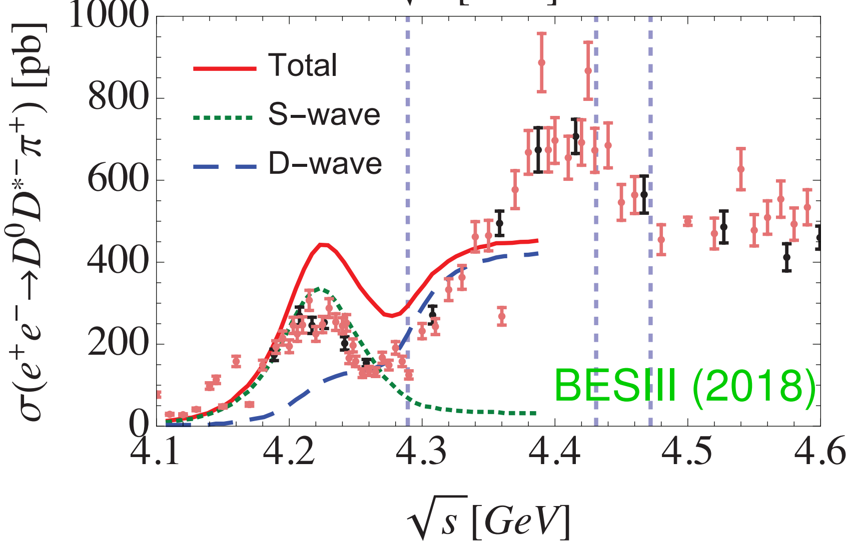
Inelastic channel





'elastic' channel





Summary and Perspectives

→ These are exciting times in (heavy meson) spectroscopy

→ The recent and future data have the potential to allow us to identify the prominent components in XYZ states

to-do for experiment

→ Continue with your great performance! Especially needed:

- ▷ data for different quantum numbers and
- ▷ data for line shapes

to-do for theory

→ Provide more predictions for the different scenarios

→ Go beyond most simple approaches - e.g. study interplay of regular quarkonia with exotics first step: Cincioglu et al., EPJC76(2016)576

Thanks a lot for your attention