Heavy Exotics: Concepts, Insights and Perspectives

Focus: Exotic quarkonium-like states

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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

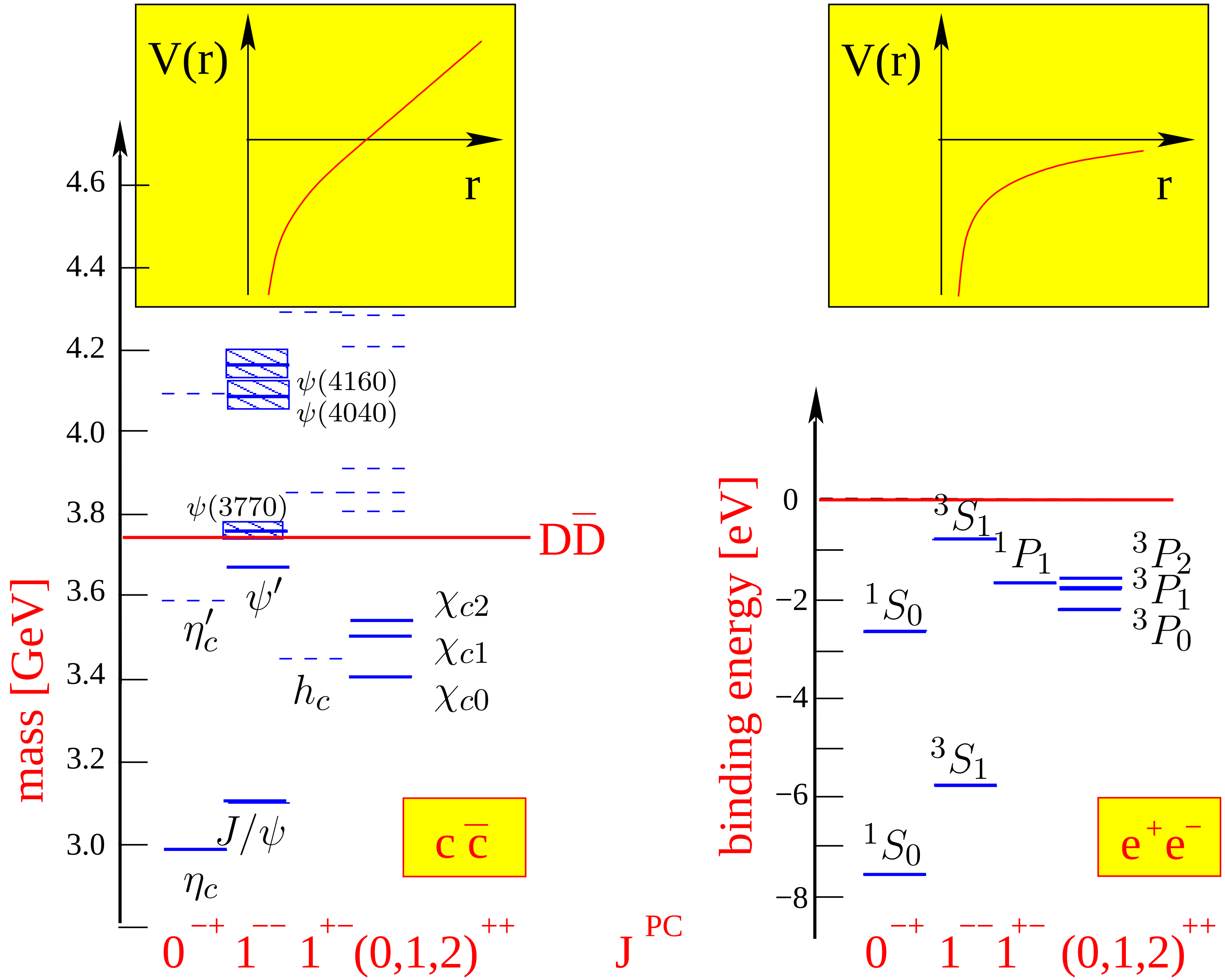
R.F. Lebed, R.E. Mitchell, E.S. Swanson, Prog. Part. Nucl. Phys. 93 (2017) 143

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

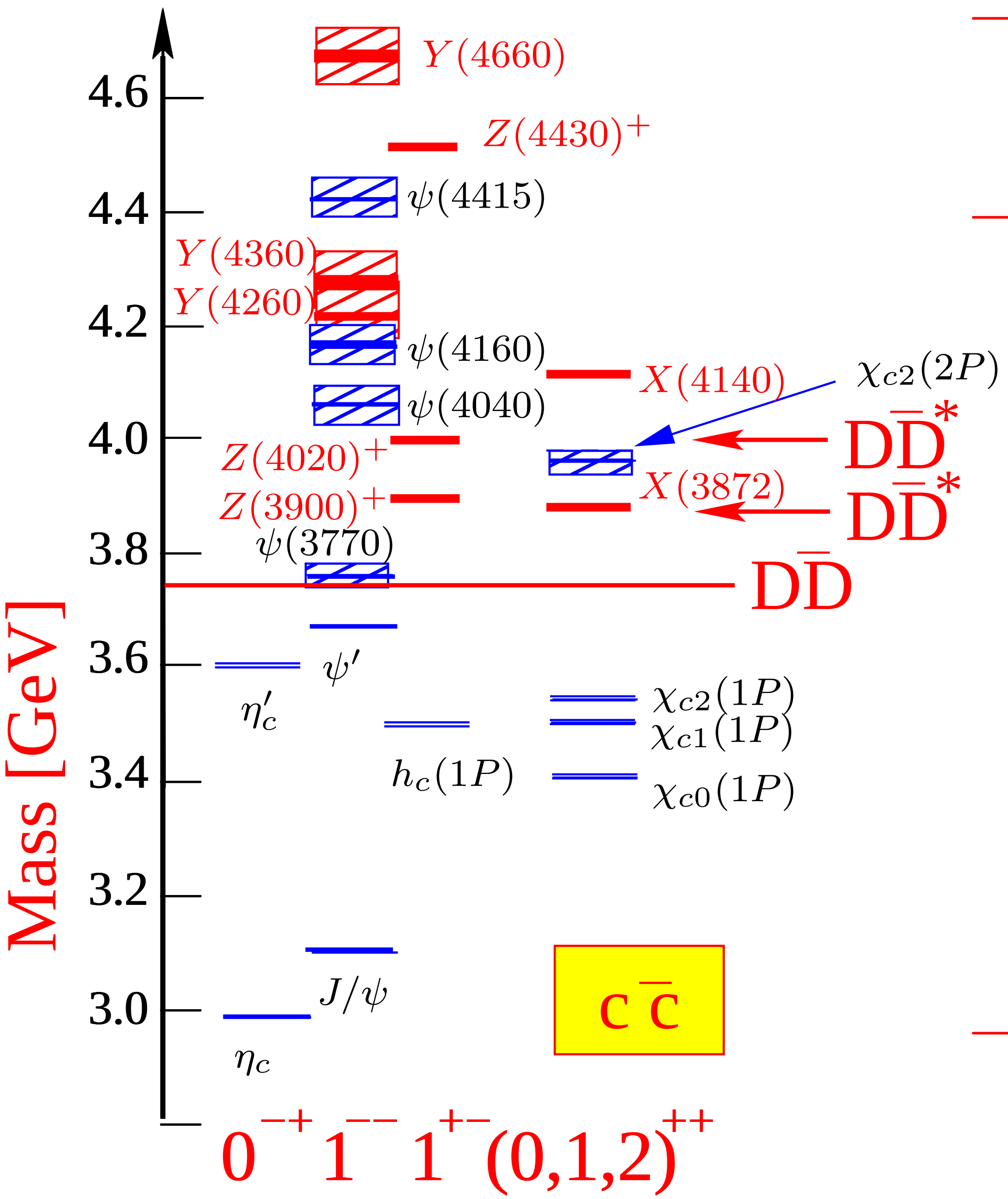
Charmonium before 2003

Quark-Model: Eichten et al. PRD 17 (1978)



Charmonium after 2002

A new particle Zoo!



→ missing low lying states found

→ Above the $\bar{D}D$ threshold:

▷ Many new states (24 claimed, 9 estd.)

▷ most of them incompatible with quark model in mass & properties (23 of 24, 8 of 9)

→ Two charged states in bottomonium-sector

Charged states

2012: Discovery of charged states that

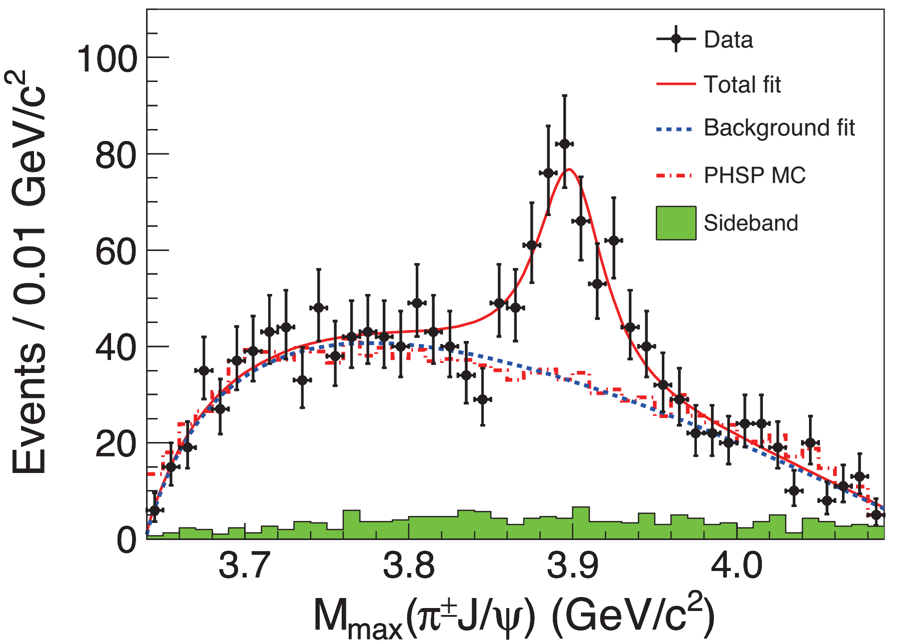
$\rightarrow$ have masses in the quarkonium mass range;

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

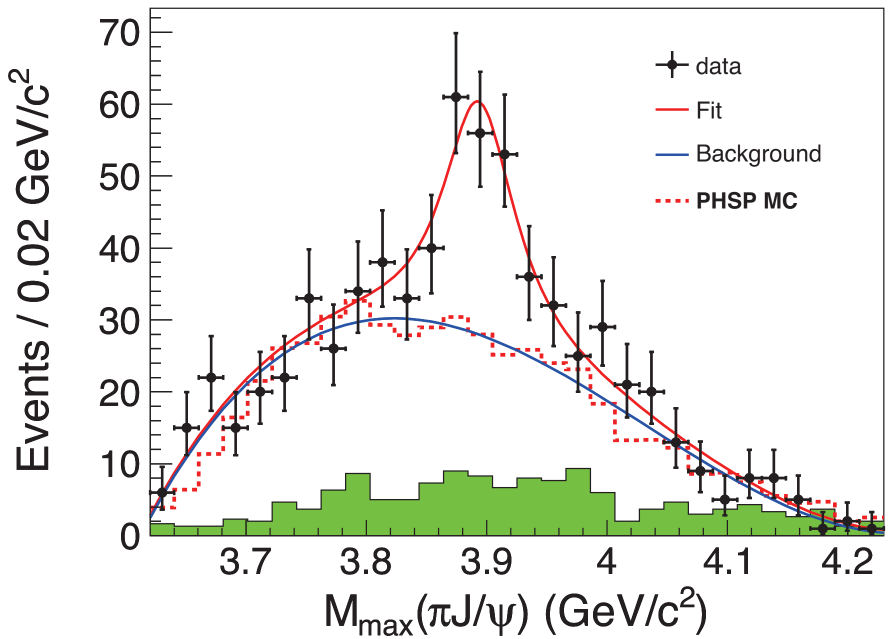
$\boxed{\rightarrow \text{ must contain at least 4 quarks}}$

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

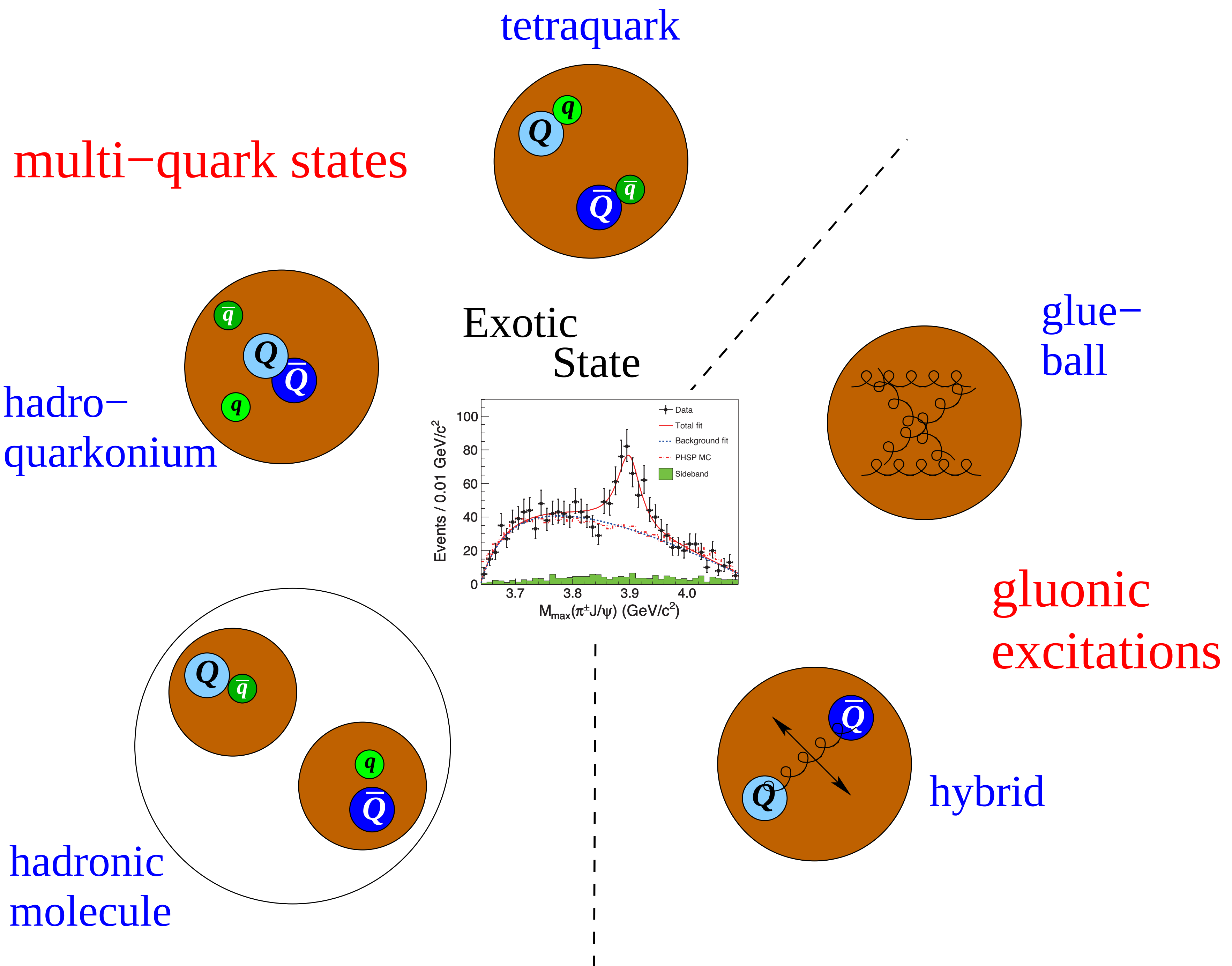
BES-III (China), 2013



Belle (Japan), 2013



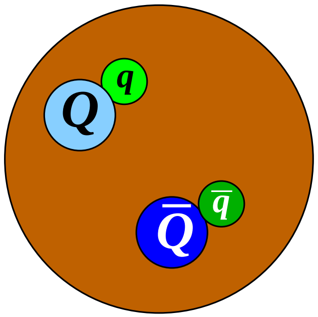
Proposals



tetraquark
multi−quark states
hadro−
quarkonium
Exotic
State
glue−
ball
gluonic
excitations
hybrid
hadronic
molecule
Data
Total fit
Background fit
PHSP MC
Sideband
Events / 0.01 GeV/c²
M_max(π±J/ψ) (GeV/c²)

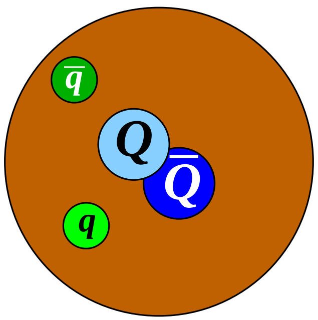
Proposals

Focus: Multi-Quark States



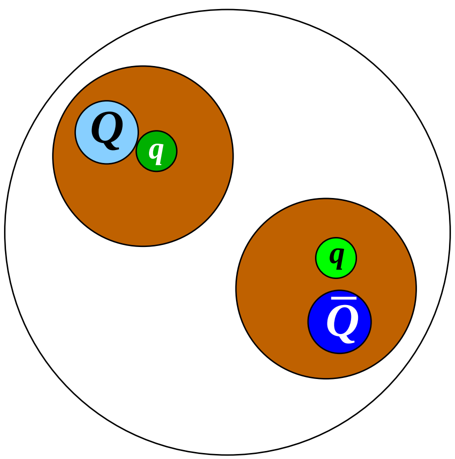
Tetraquark

$\rightarrow$ 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

Outline

In this talk I will

→ present three very common models for XYZ states

- ▷ Hadroquarkonium
- ▷ Tetraquarks
- ▷ Hadronic Molecules

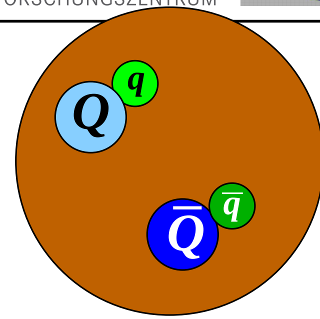
→ and discuss by looking at

- ▷ Spectroscopy
- ▷ Lineshapes

what it takes identify the prominent component of a state

Disclaimer: So far we hunt only for leading component ....

Heavy Tetraquarks

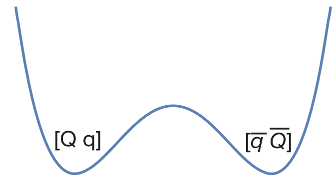


→ Straightforward extension of the quark model

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

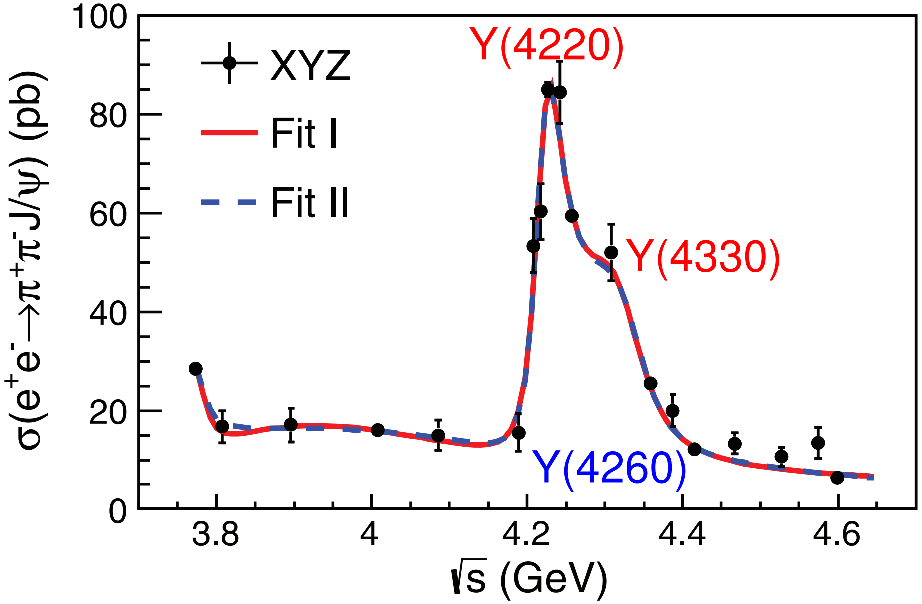
$$\boxed{M = 2M_Q + \frac{B_Q}{2}\mathbf{L}^2 + 2a_Y \mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4}S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)}$$

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

Results for negative parity states

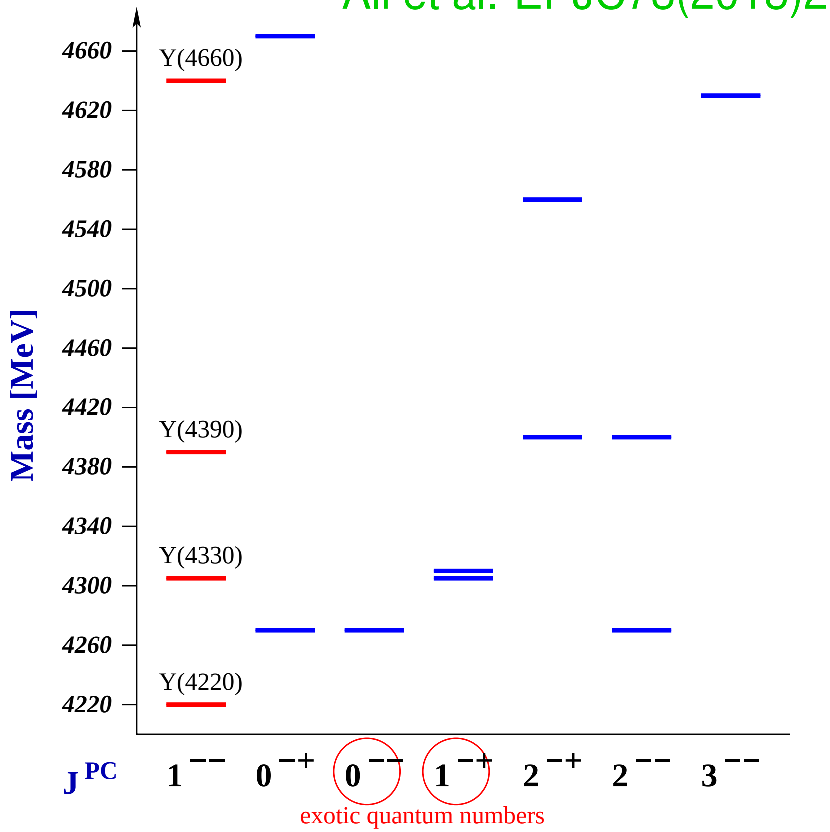
→ four 1^{--} ground states

→ BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001

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

$QQ\bar{q}\bar{q}$ 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 $r_{QQ}/r_{qq} \sim \Lambda_{\rm QCD}/(M_Q v)$ — Savage and Wise, PLB248(1990)177

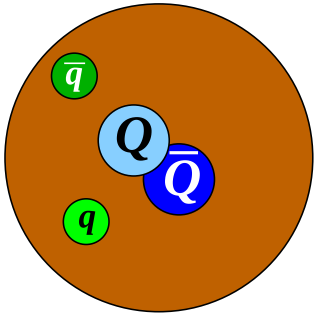
Once $m(QQq)$ is fixed from data or phenomenology,

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

$\rightarrow J^P = 1^+$ $(bb\bar{u}\bar{d})$ system $130 - 215$ MeV below BB^* threshold

Hadrocharmonium

M. B. Voloshin, PPNP61(2008)455



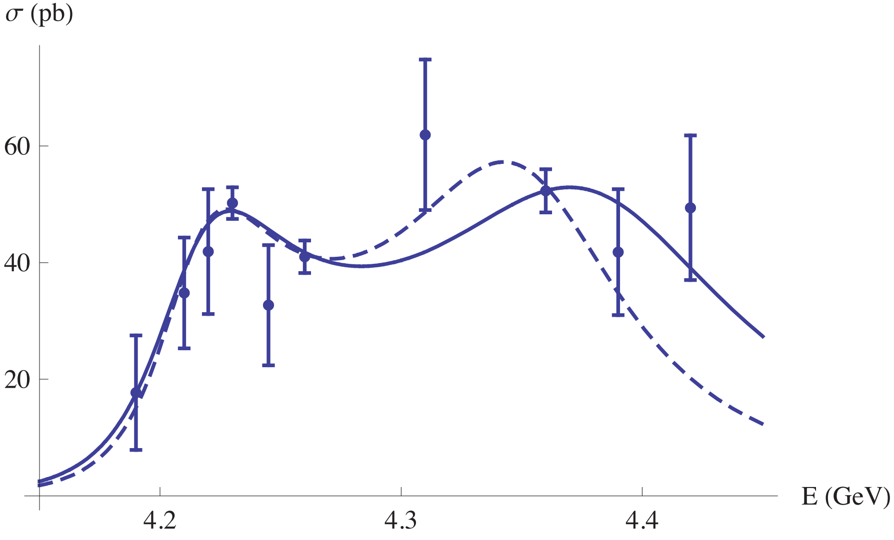
→ Extra states are viewed as compact $\bar{Q}Q$ surrounded by light quarks

→ 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



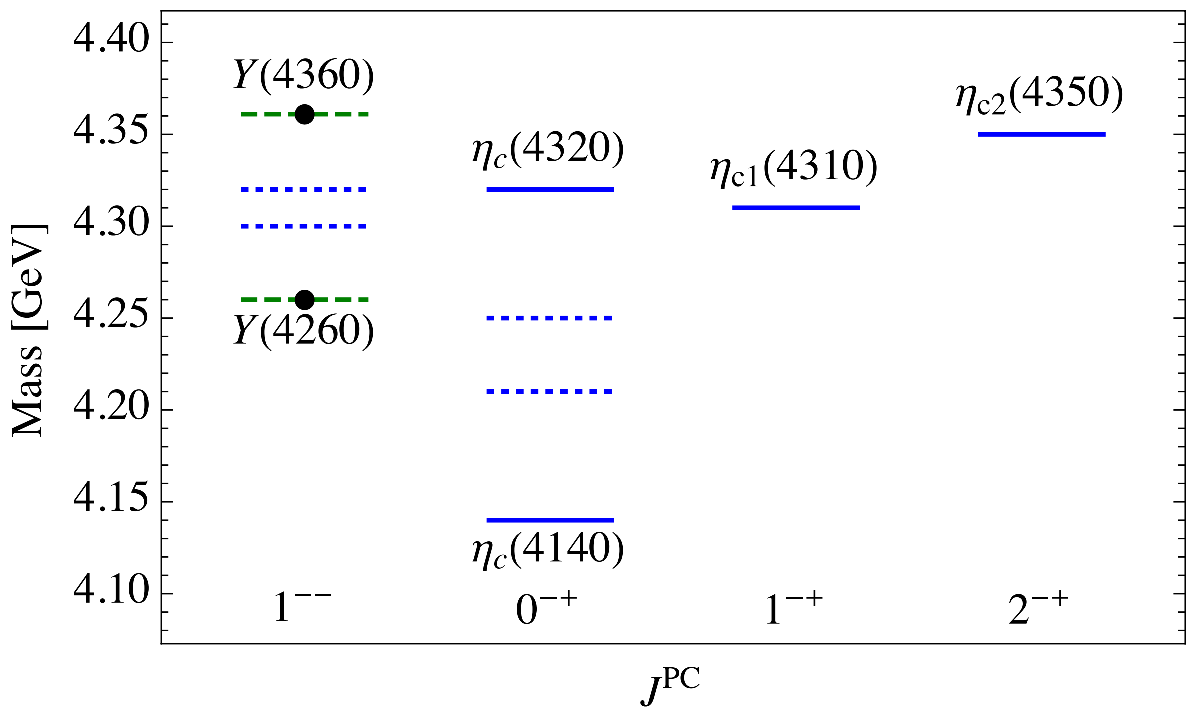
Hadrocharmonium: new states

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

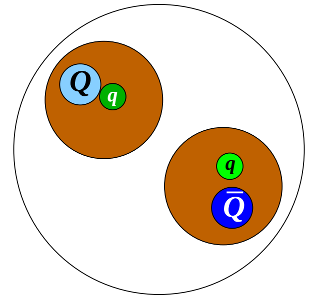


Cleven et al., PRD 92(2015)014005

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):

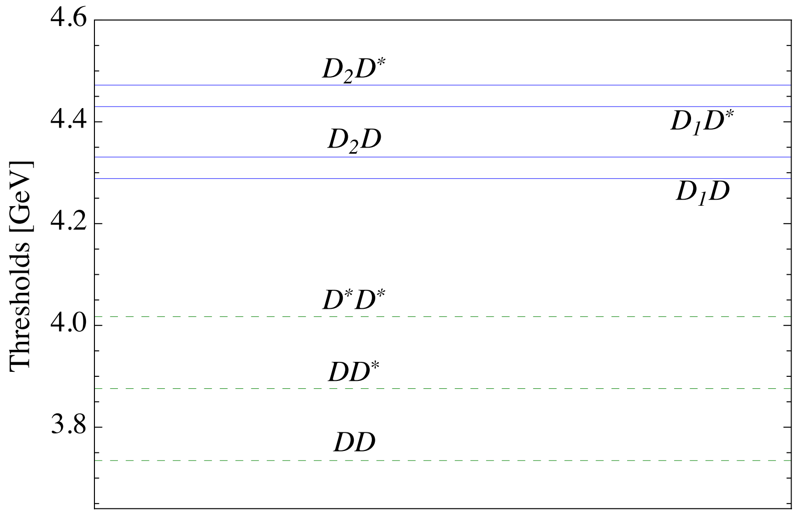
$$\frac{g_{\text{eff}}^2}{4\pi} = \frac{4M^2\gamma}{\mu}(1-\lambda^2) \rightarrow a = -2\left(\frac{1-\lambda^2}{2-\lambda^2}\right)\frac{1}{\gamma}; \quad r = -\left(\frac{\lambda^2}{1-\lambda^2}\right)\frac{1}{\gamma}$$

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

Are there mesonic molecules?

General considerations

Example: $1/2^+$ multiplet $\{D, D^*\}$ and $3/2^-$ multiplet $\{D_1, D_2\}$ $\rightarrow$



$3^{-\pm}$: D^*D_2
$0^{-\pm}$: D^*D_1
$2^{-\pm}$: $D^*D_1 - D^*D_2 - DD_2$
$1^{-\pm}$: $DD_1 - D^*D_1 - D^*D_2$ ($Y(4260), Y(4360)$ ($I=0$))

2^{++}: D^*D^*
1^{++}: DD^* ($X(3872)$ ($I=0$))
1^{+-}: $DD^* - D^*D^*$ ($Z_c(3900)^+, Z_c(4020)^+$ ($I=1$))
0^{++}: $DD - D^*D^*$;

$\rightarrow$ 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

M. Cleven et al., PRD 92 (2015) 014005

Spin symmetry violation

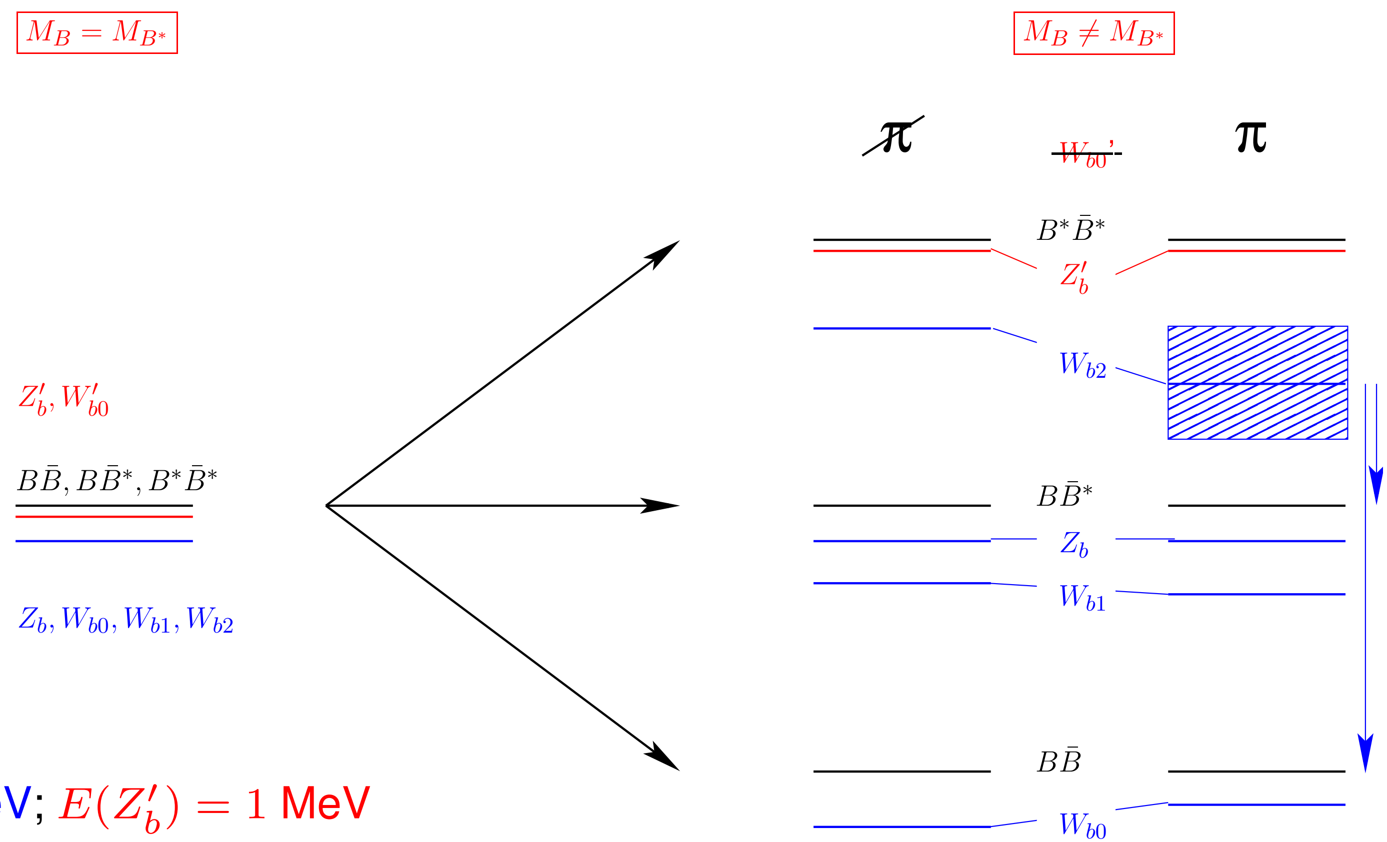
EFT for I=1 $B^{(*)}\bar{B}^{(*)}$ scattering $\to$ Spin multiplets

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

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



$E(Z_b) = 5$ MeV; $E(Z_b') = 1$ MeV

M. Cleven et al., EPJA 47 (2011) 120

Spin symmetry violation

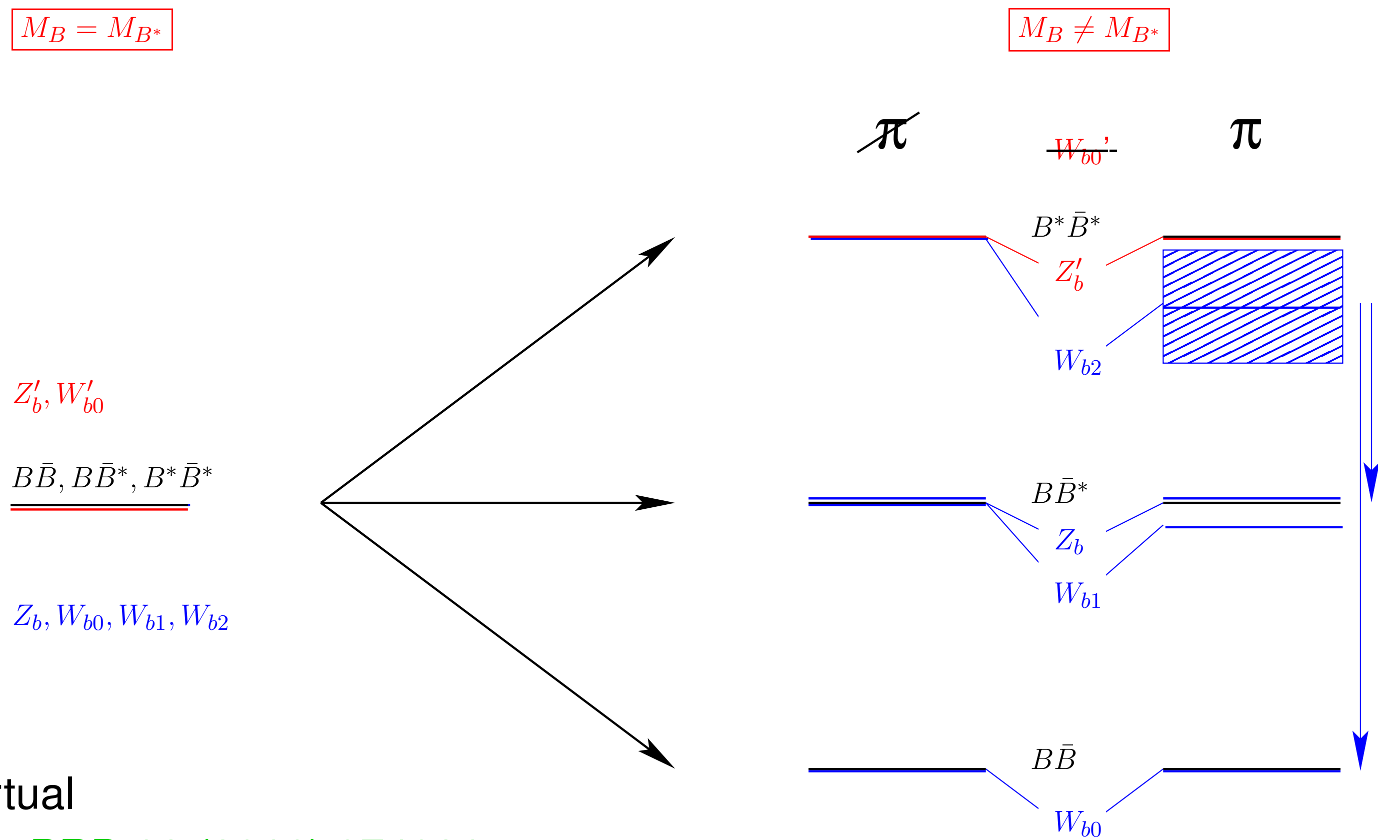
EFT for I=1 $B^{(*)}\bar{B}^{(*)}$ scattering $\to$ Spin multiplets

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

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

Mass of spin partners very sensitive to $Z_b^{(')}$ masses

Baru et al., JHEP 1706(2017)158



both getting virtual

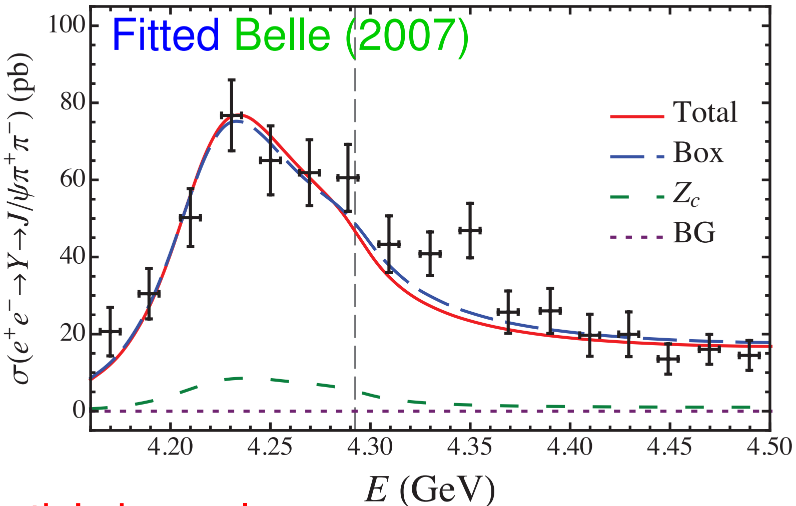
F.-K. Guo et al., PRD 93 (2016) 074031

Lineshapes of $Y(4260)$

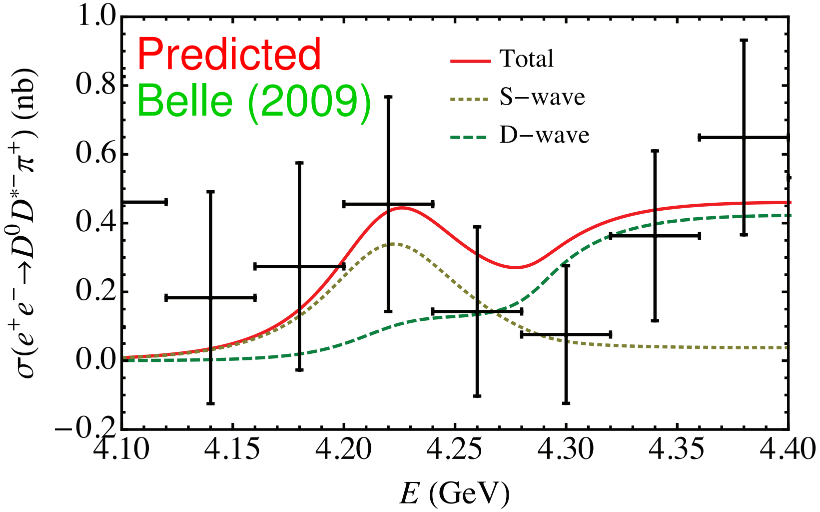
IF the $Y(4260)$ is a $D_1\bar{D}$ molecule it MUST have a large coupling to this channel $\Longrightarrow$ great impact on lineshapes

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

Inelastic channel



'elastic' channel



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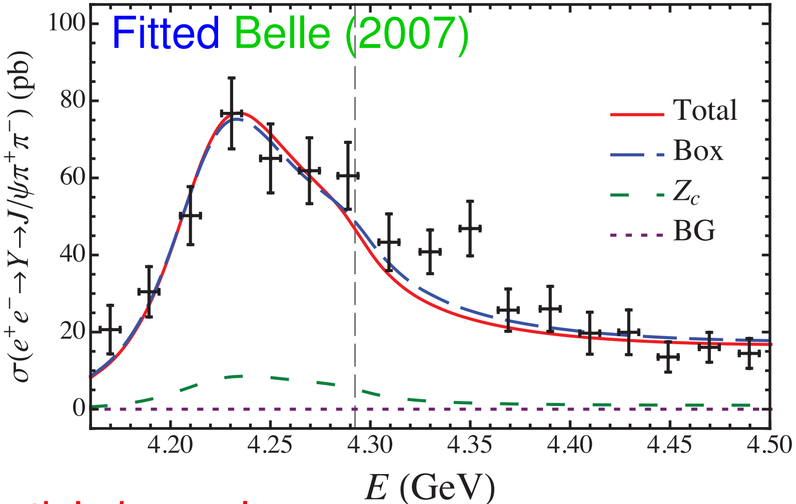

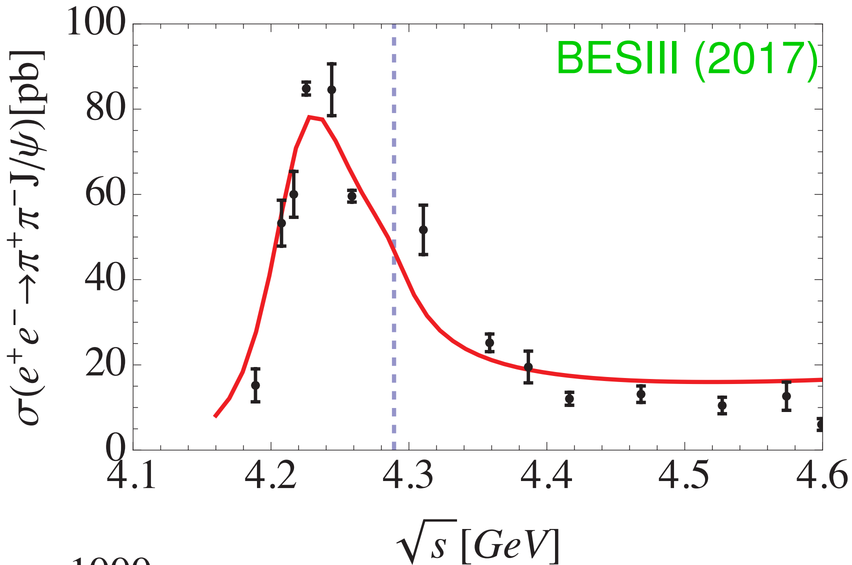

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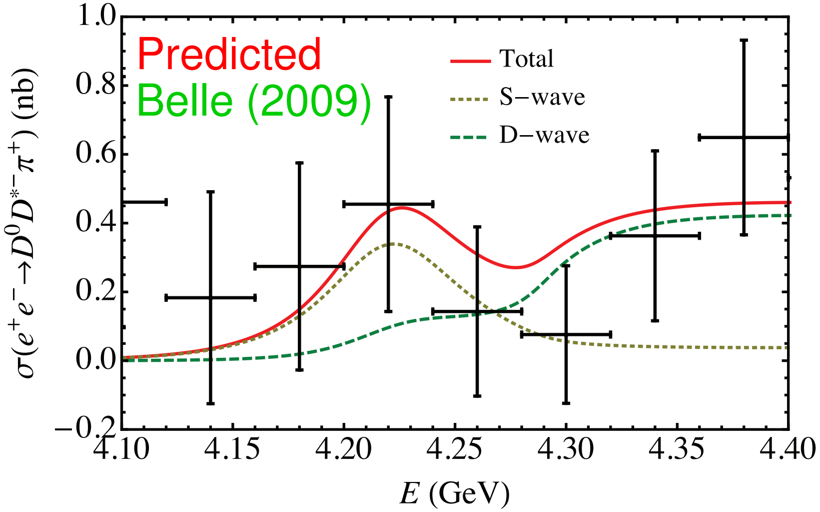
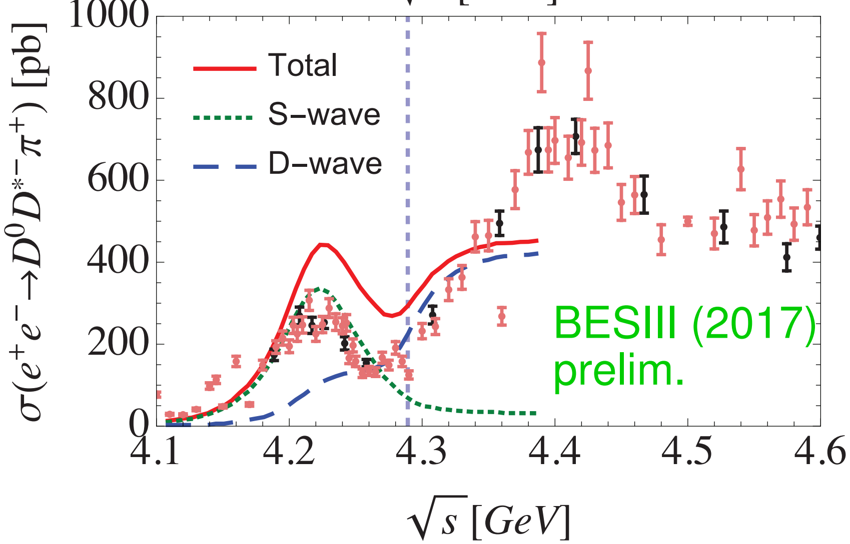
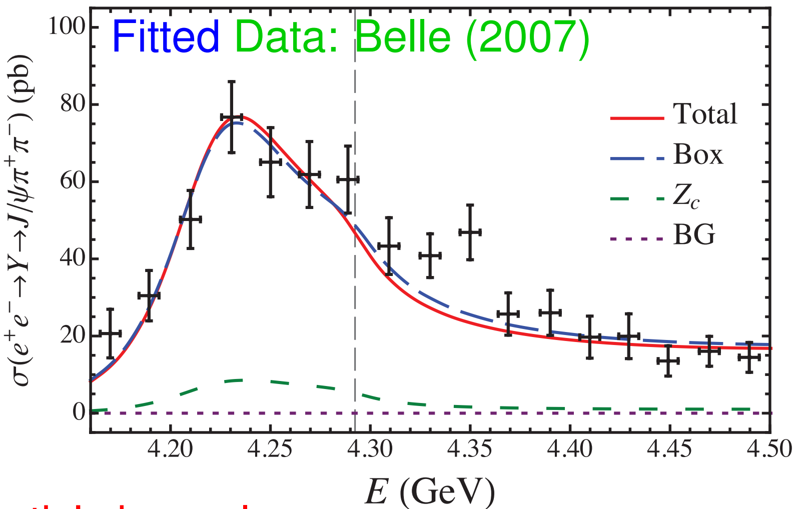


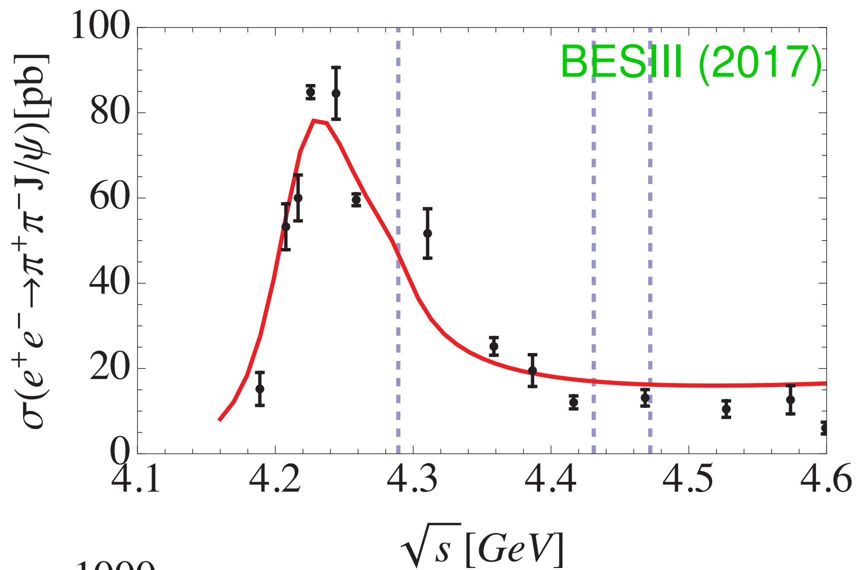


Lineshapes of $Y(4260)$

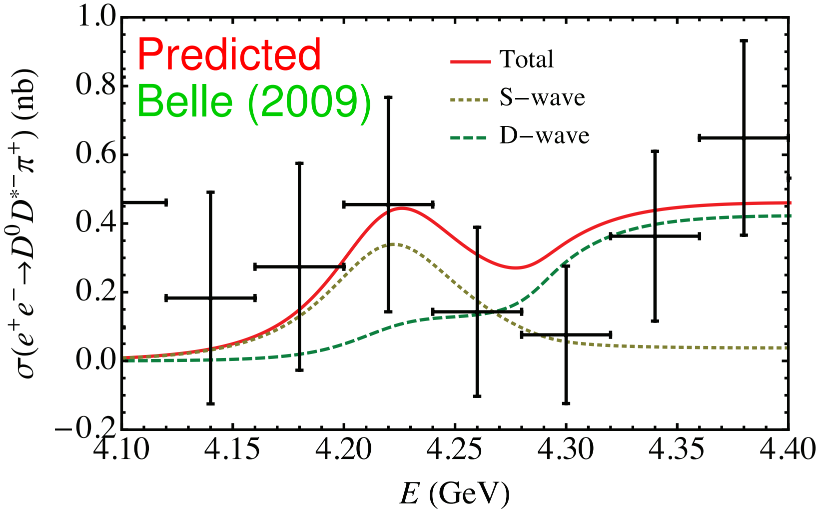
Role of $D_1 D^*/D_2 D^*$ channels and $\psi(4415)$?

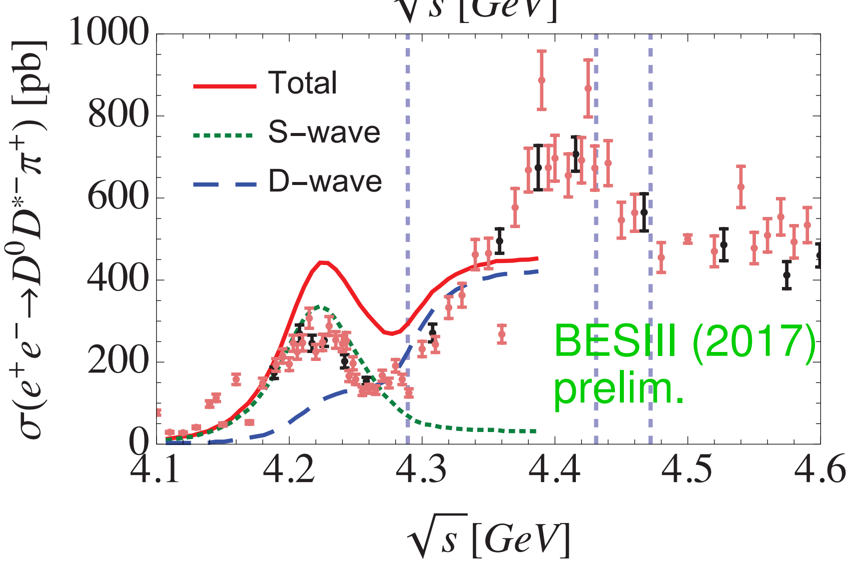
Inelastic channel





'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