Lecture series on
QCD Exotics in the Heavy Quark Sector
Part III: The $\bar{Q}Q$ sector

Christoph Hanhart

Forschungszentrum Jülich

Outline

Lecture I: Tools

- → Lattice QCD
- → Effective field theories (ChPT, HQEFT)
- → Unitarisation
- → Large N_c

Lecture II: The single heavy sector

- → Goldstone–Boson D-meson scattering
- → The positive parity D-mesons
- → Predictions and tests

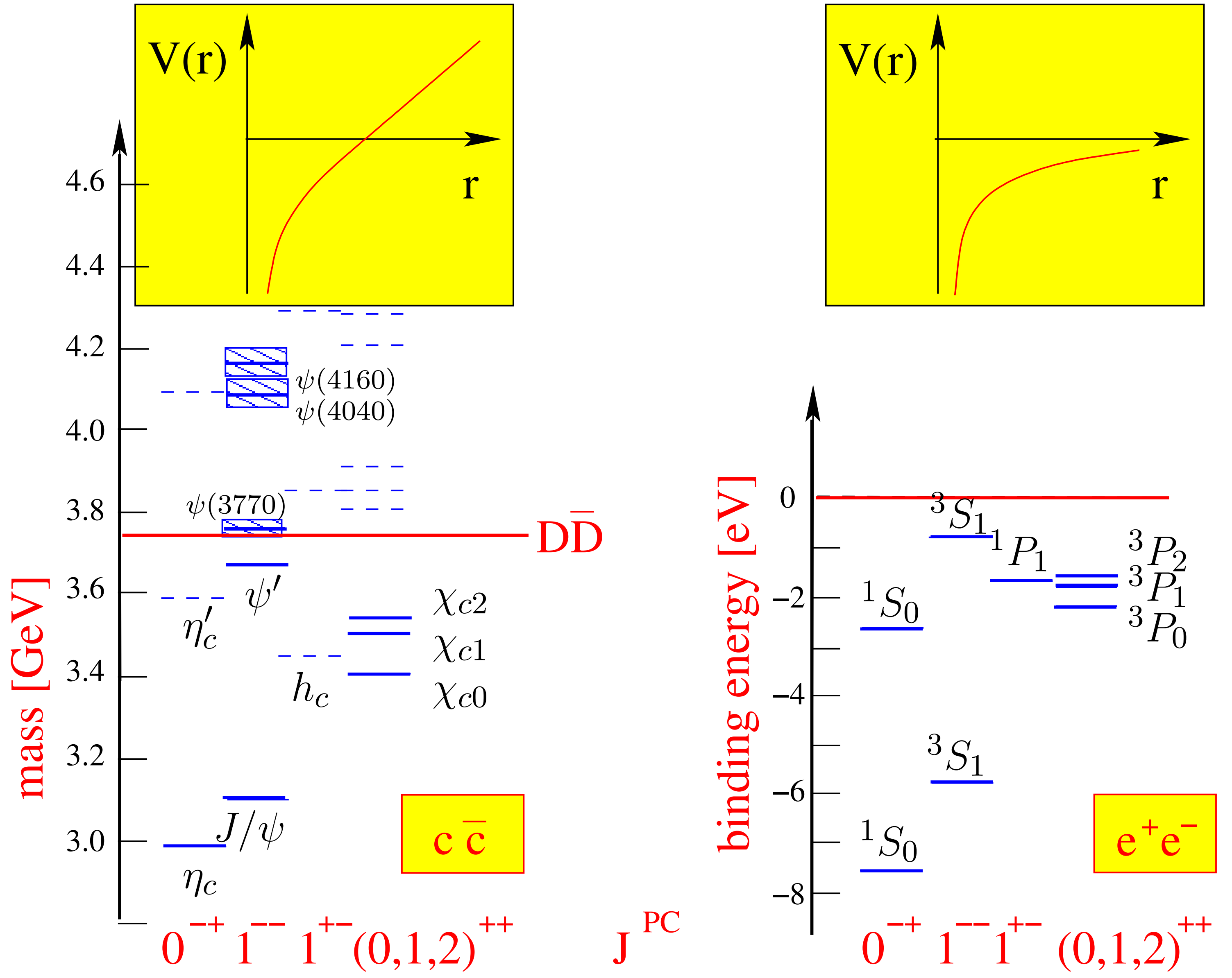
Lecture III: The $\bar{Q}Q$ sector

- → The XYZ-stories

In this lecture series the focus is on mesons

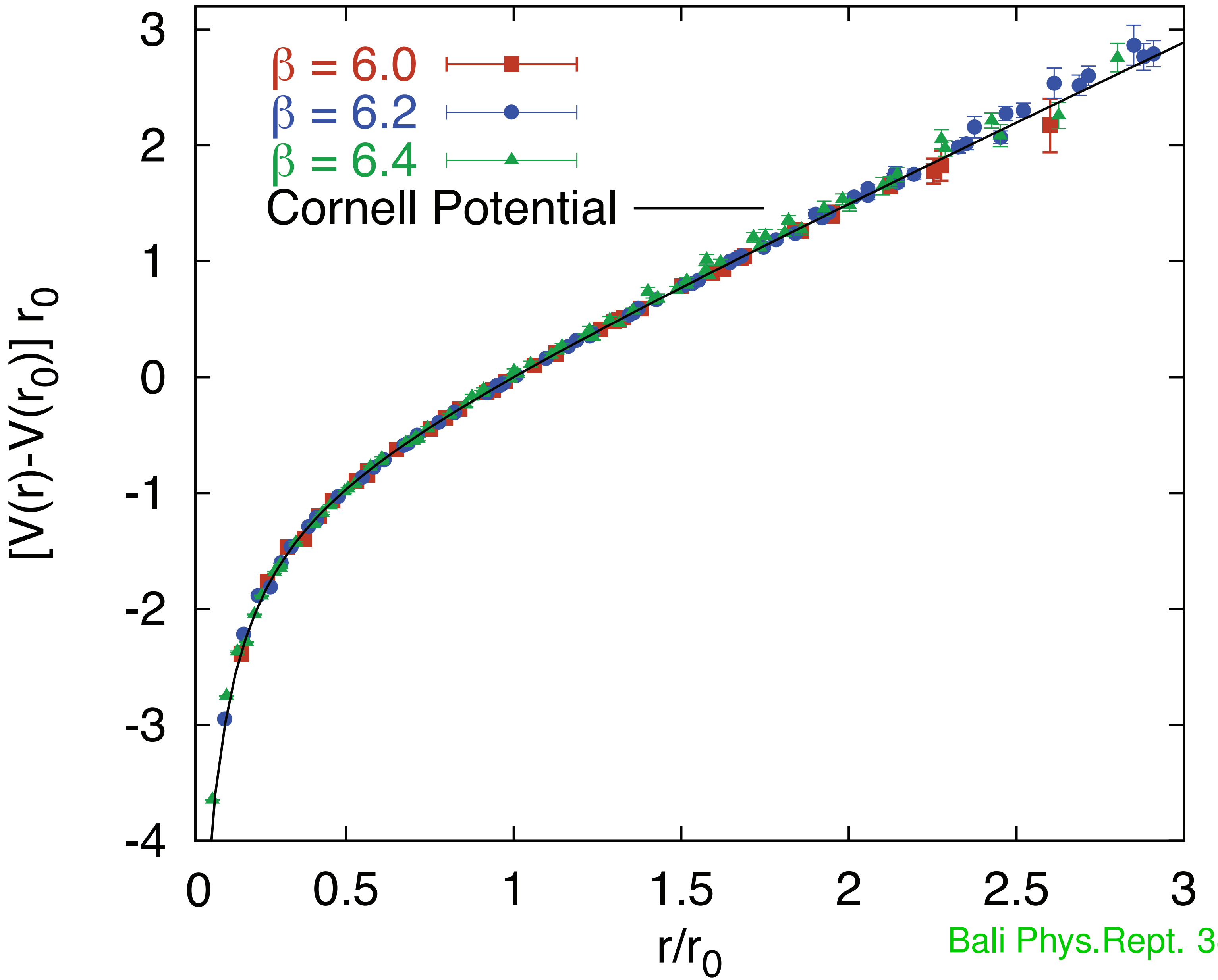
Charmonium before 2003

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



$\bar{Q}Q$ potential from lattice

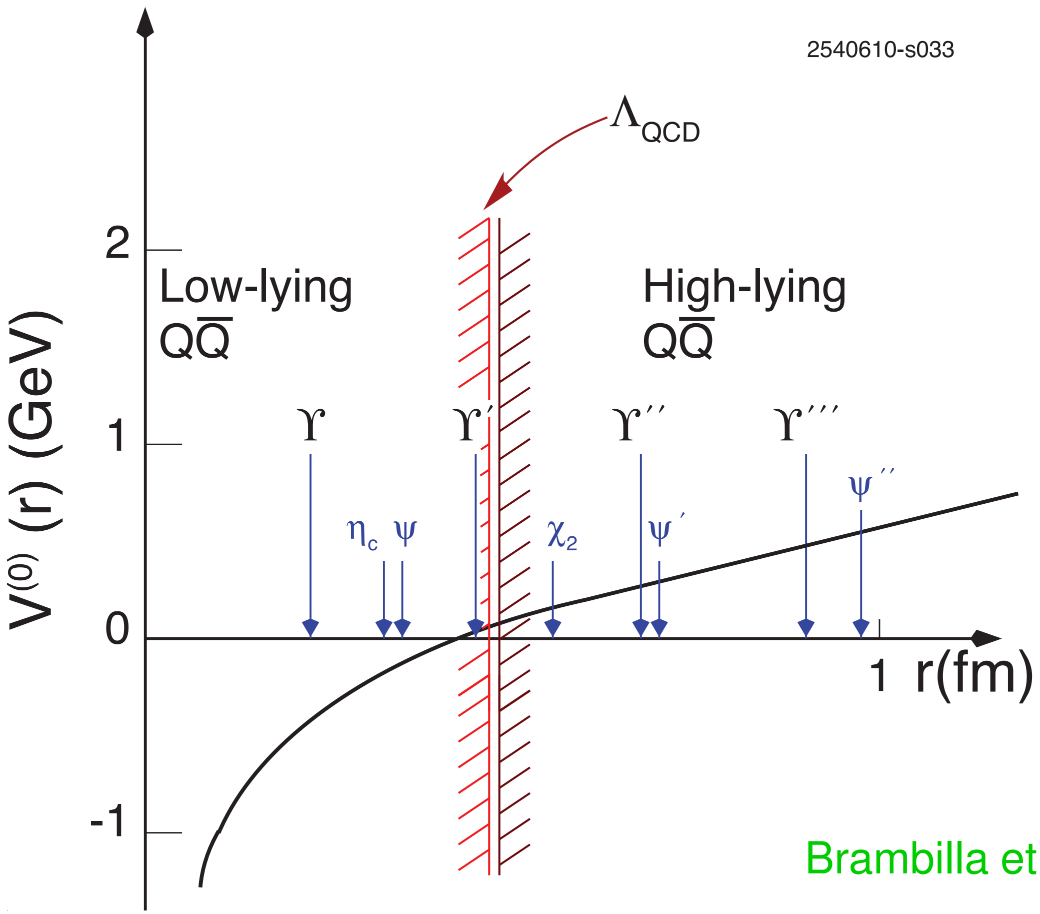
Potential of two static color sources



Bali Phys.Rept. 343(2001)1

EFT: (p)NRQCD

Relevant scales: $M_Q \gg p \sim M_Q v \sim 1/r \gg E \sim M_Q v^2$

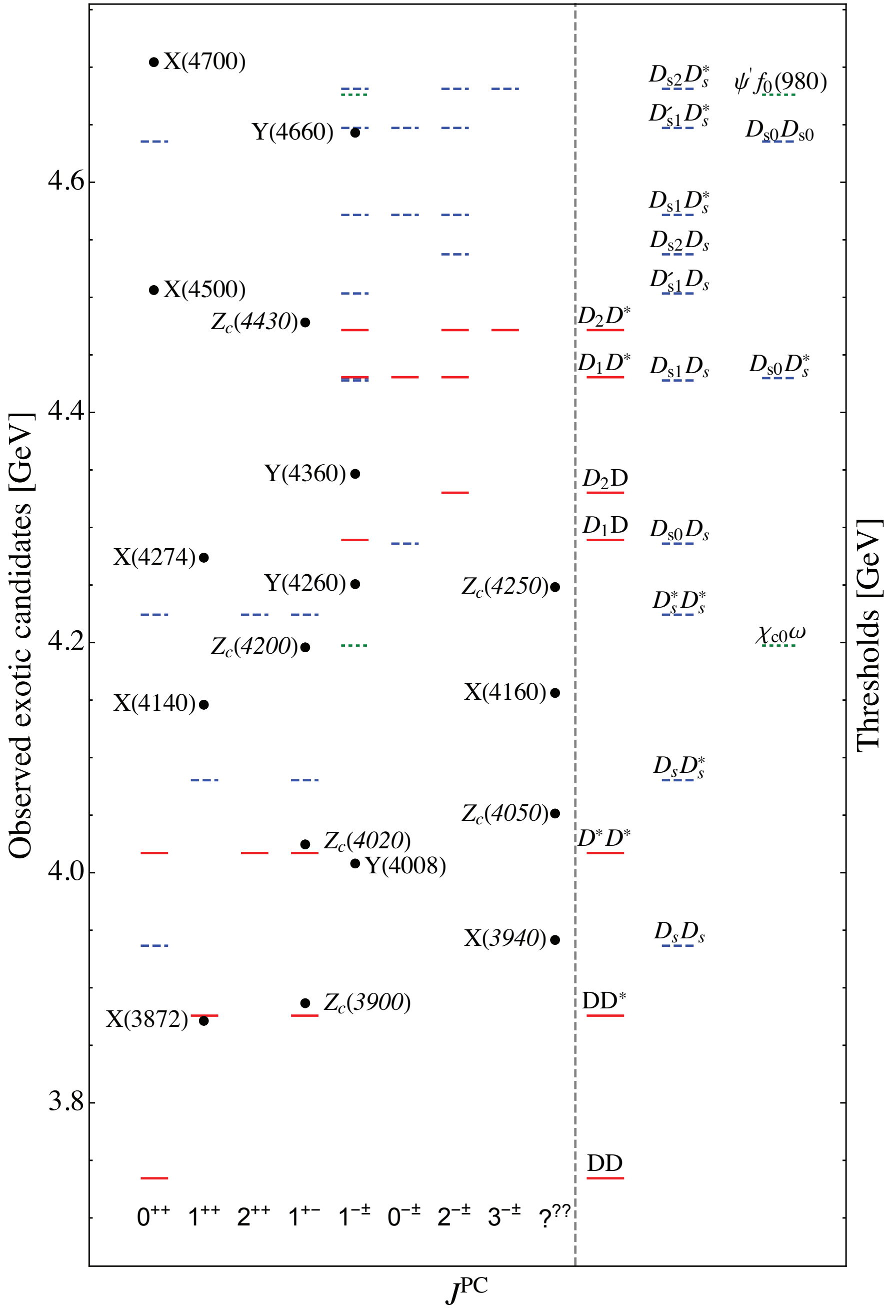


Brambilla et al., EPJC71(2011)1534

→ For systems with small radii: precision calculations

→ Transition to non-perturbative regime can be studied

However, there are many exotics ...



Guo et al. RMP90(2018)015004

→ All exotic candidates above open flavor thresholds

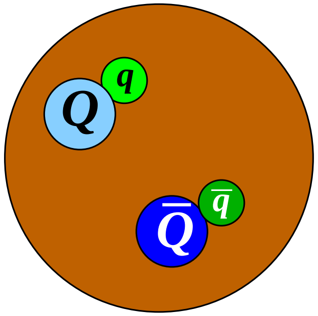
→ Many (not all) states near S-wave thresholds of narrow states Filin et al., PRL 105, 019101 (2010) Guo et al., PRD84, 014013 (2011)

→ States not near all those thresholds

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

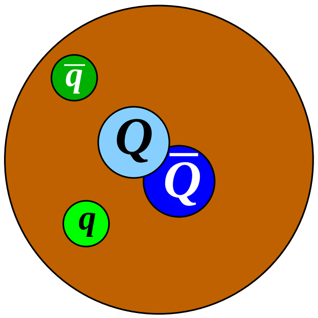
→ Lightest negative parity exotic ($Y(4260)$) significantly heavier than lightest positive parity exotics ($X(3872)$ & $Z_c(3900)$)

Proposals - Multi-Quark States



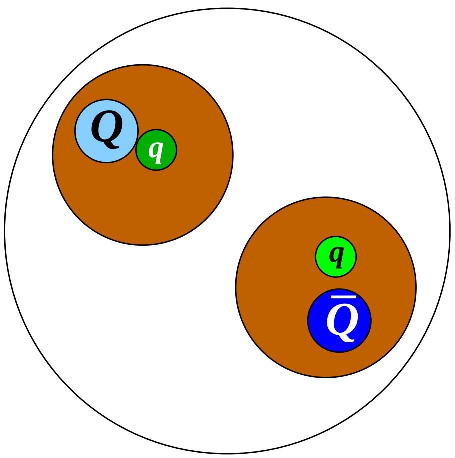
Tetraquark

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

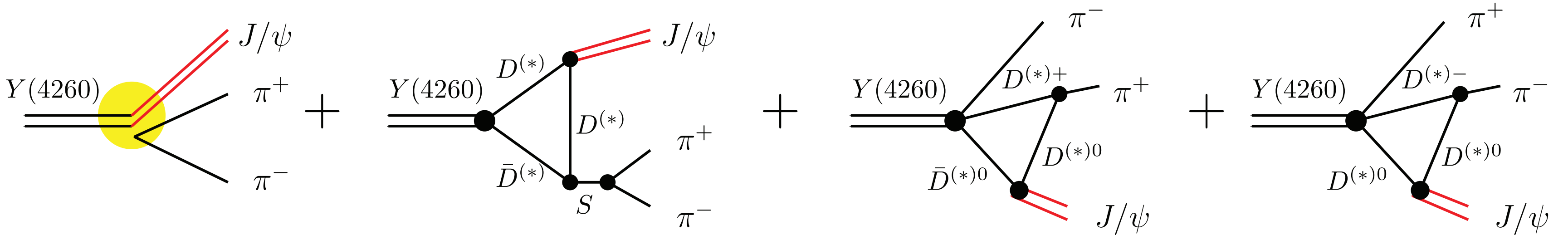
$\gg 1$ fm $\gtrsim$ confinement radius

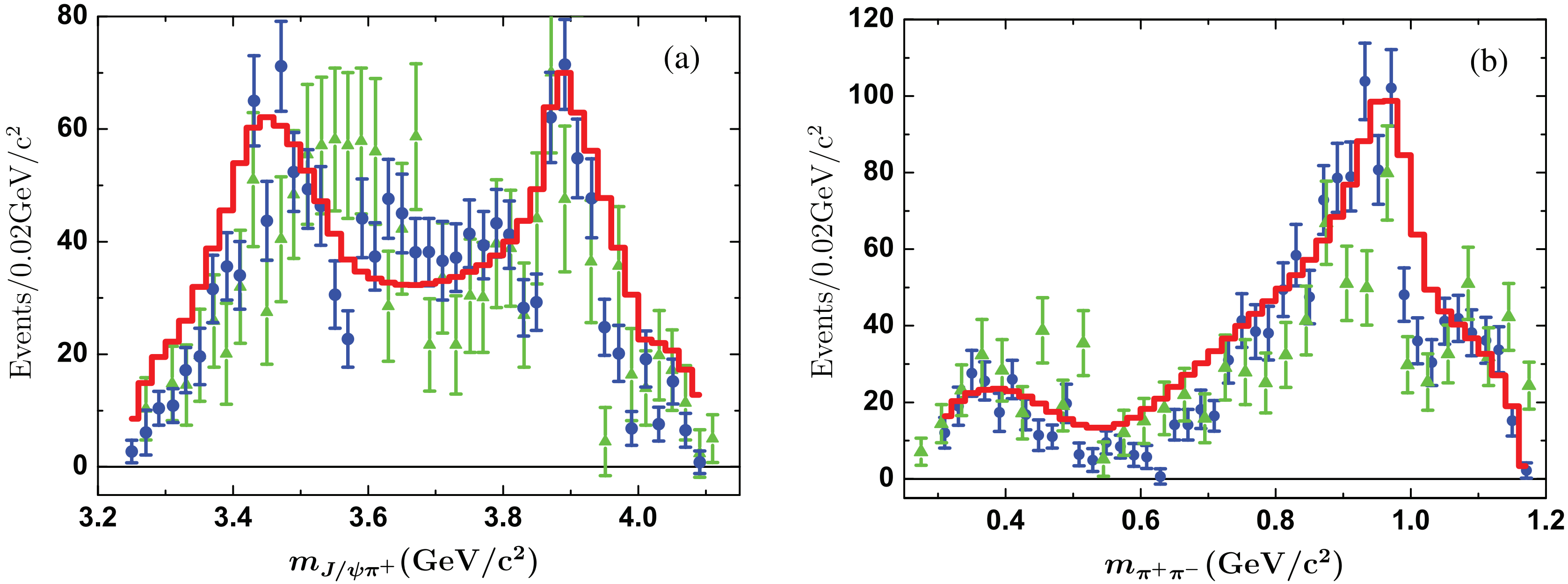
for near threshold states

I will review ideas on how to disentangle these structures

(Some) XYZ-states threshold effects?

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



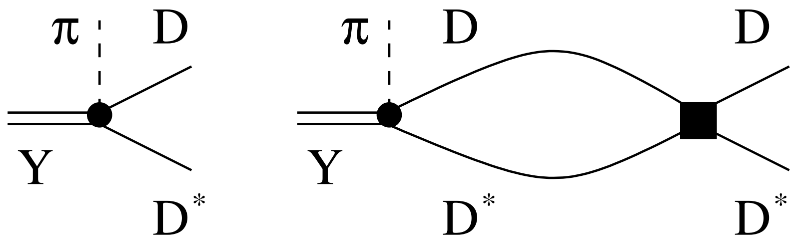


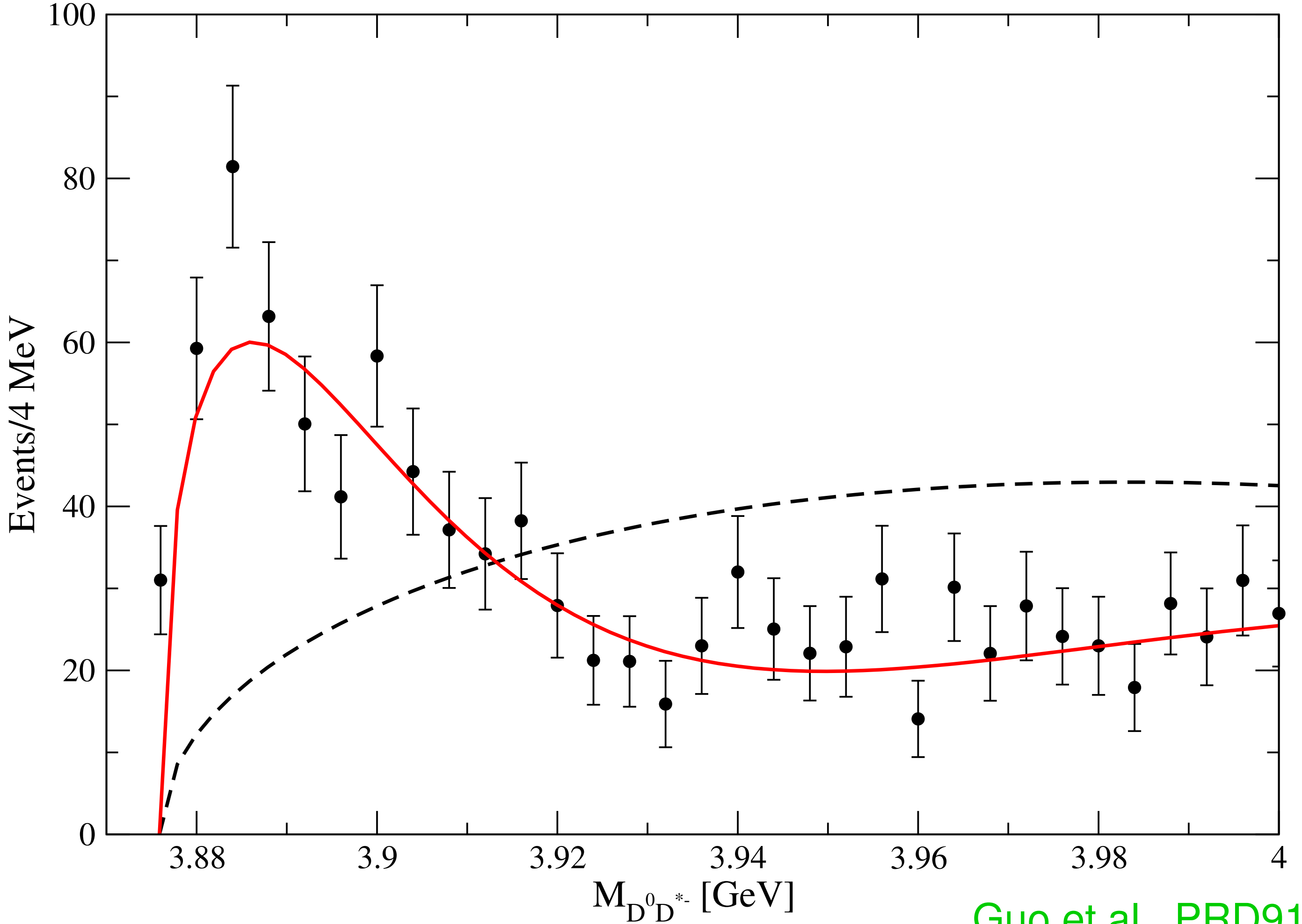
Chen et al., PRD88(2013)036008

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

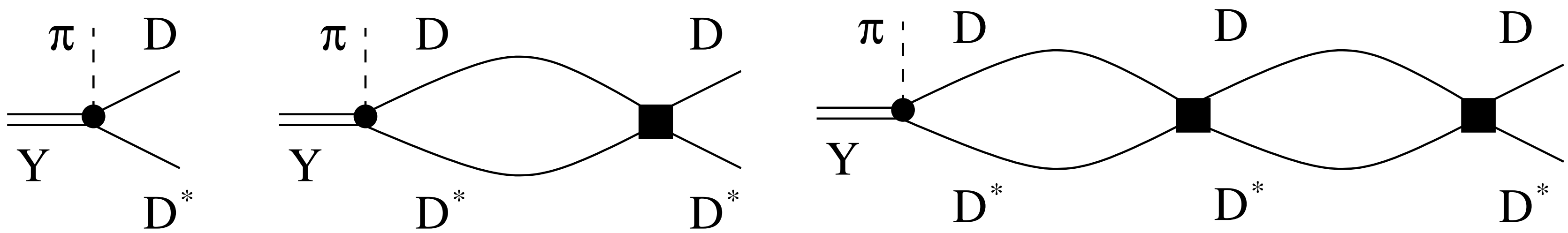
Why the argument is wrong

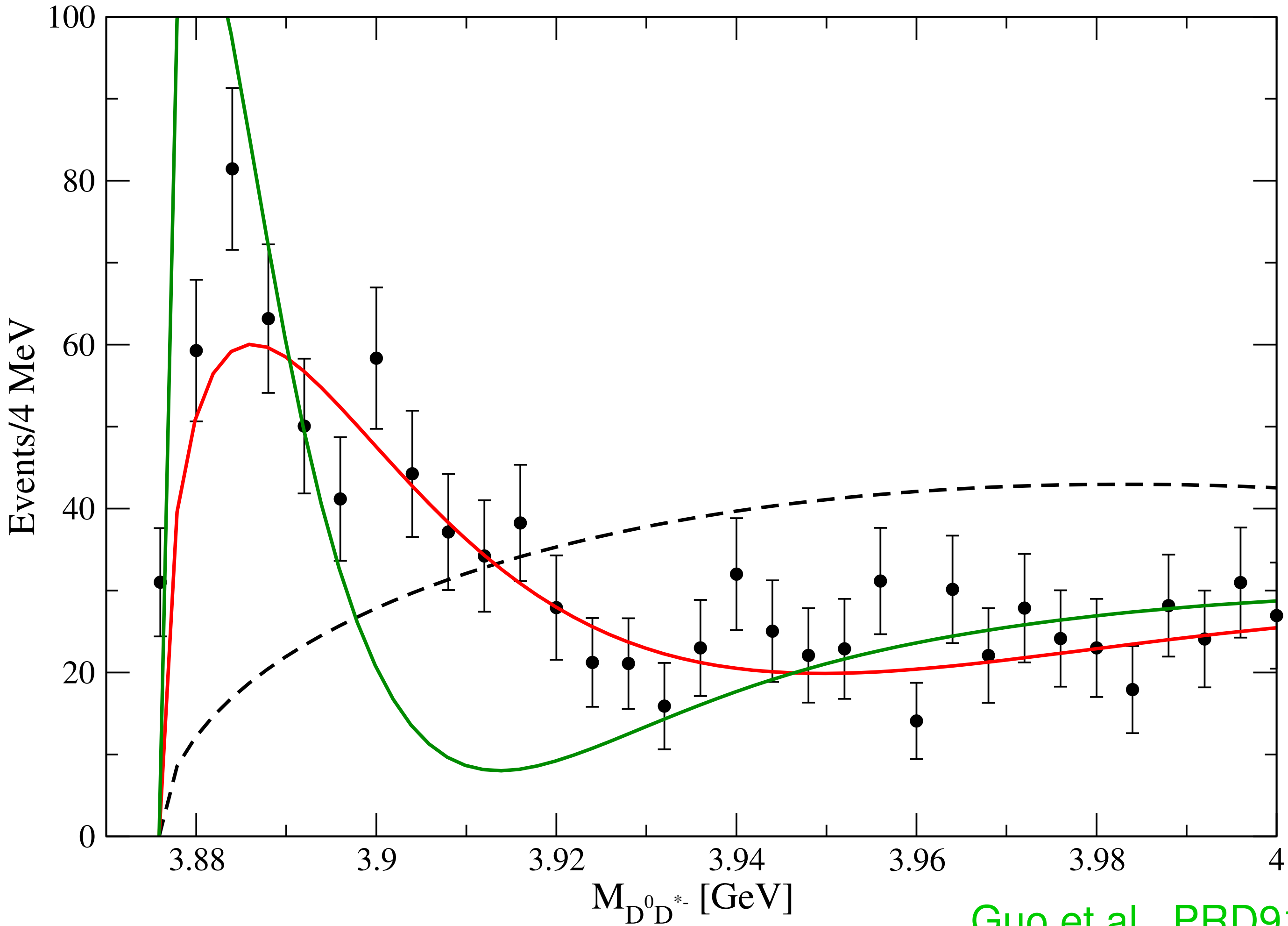




Guo et al., PRD91(2015)051504

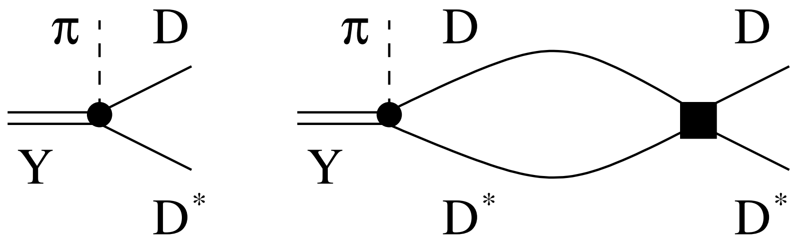
Why the argument is wrong

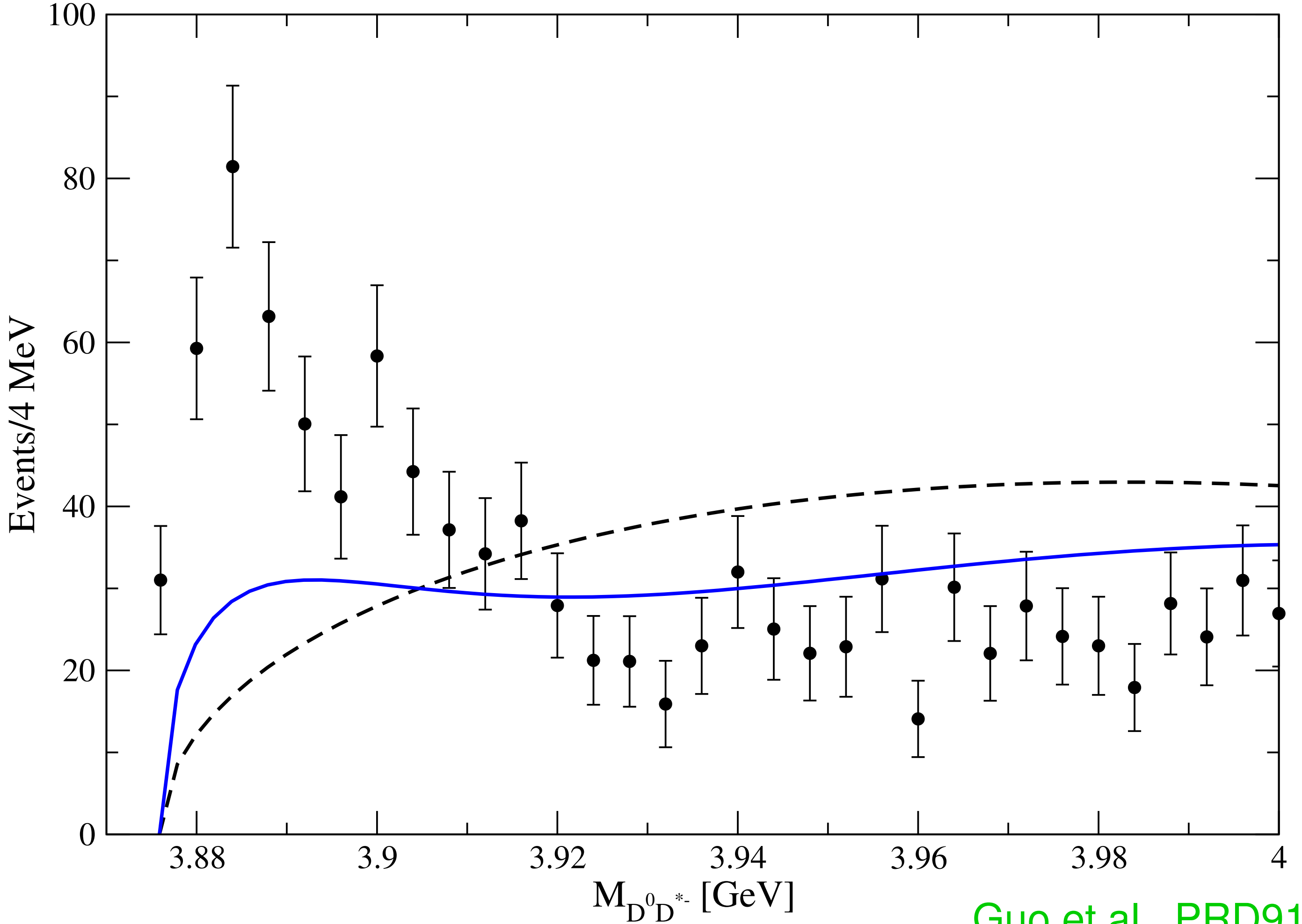




Guo et al., PRD91(2015)051504

Why the argument is wrong

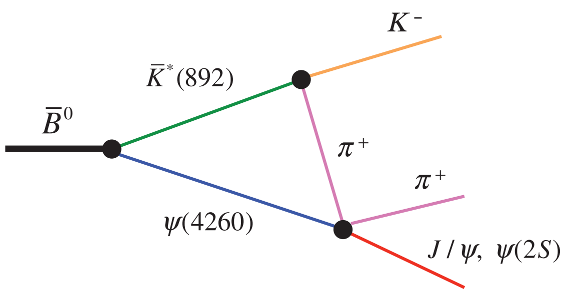


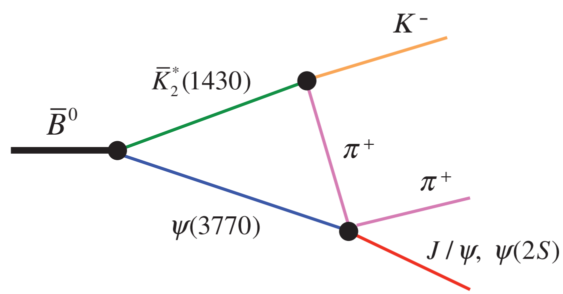


Guo et al., PRD91(2015)051504

(Some) driven by triangle–effects?

Nakamura and K. Tsushima, arXiv:1901.07385





Can explain
$Z_c(4430)$ & $Z_c(4200)$
including Argand plot

$\rightarrow$ there should be no structure in $Y(4260)\pi$ and $\psi(3770)\pi$
from $Z_c(4430)$ and $Z_c(4200)$, respectively   Schmid, PR154(1967)1363

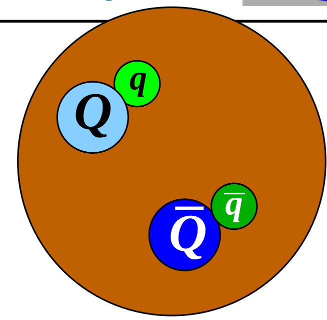
For alternative mechanism for $Z_c(4430)$ see   Pakhlov, PLB702(2011)139

... maybe — but certainly not for all XYZ–states, since

mechanism very sensitive to external invariant masses, and, e.g.,

- $\rightarrow$ $X(3872)$ is seen in B–decays and $Y(4260)$ radiative decays
- $\rightarrow$ $Z_c(3900)^+$ is seen at different energies in e^+e^-
- $\rightarrow$ not applicable to vectors states seen in e^+e^-

Heavy Tetraquarks

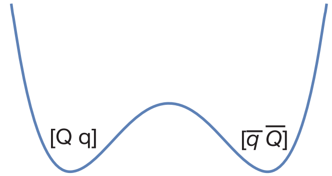


→ Straightforward extension of the quark model

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

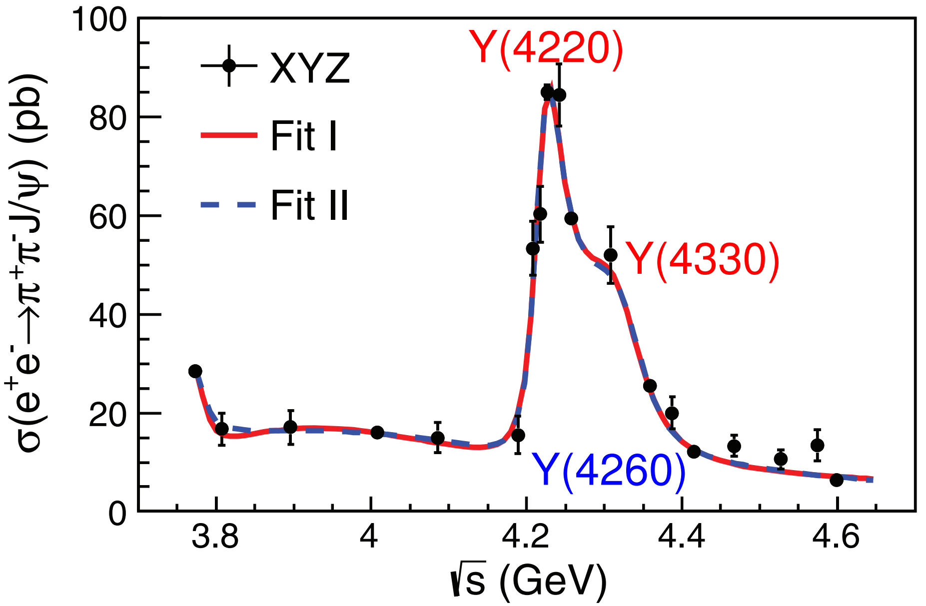
$$M = 2M_Q + \frac{B_Q}{2}\mathbf{L}^2 + 2a_Y\,\mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4}S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)$$

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

Results for negative parity states

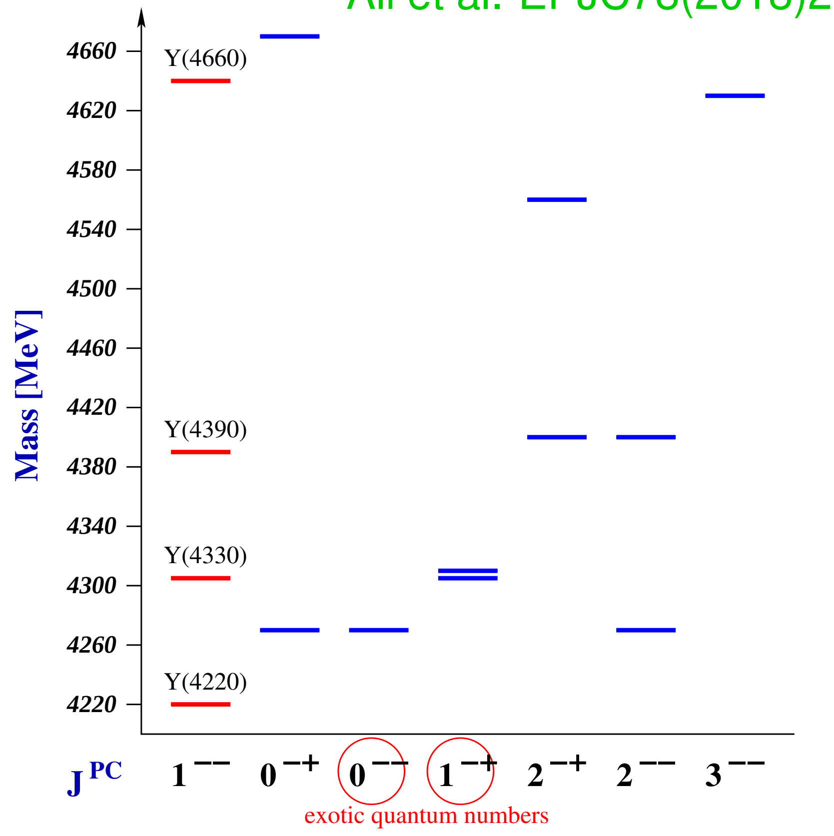
$\to$ four 1^{--} ground states

$\to$ BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001

Ali et al. EPJC78(2018)29



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

$\to$ Many more states predicted than observed!

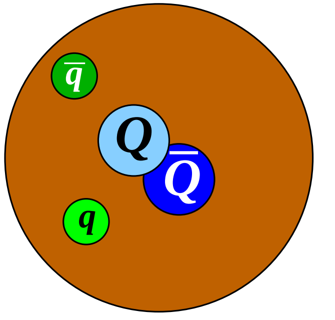
Maybe since di-quark picture too restrictive/constraining?

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

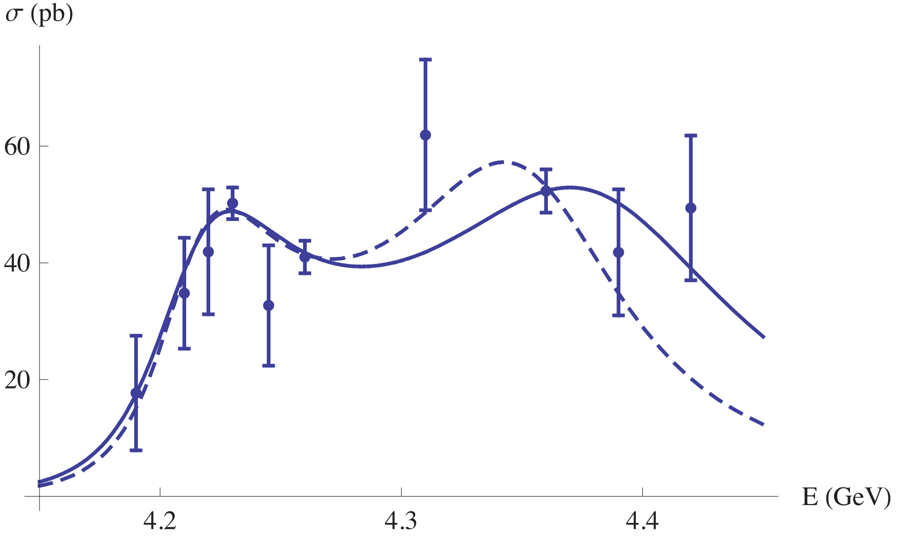


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ 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



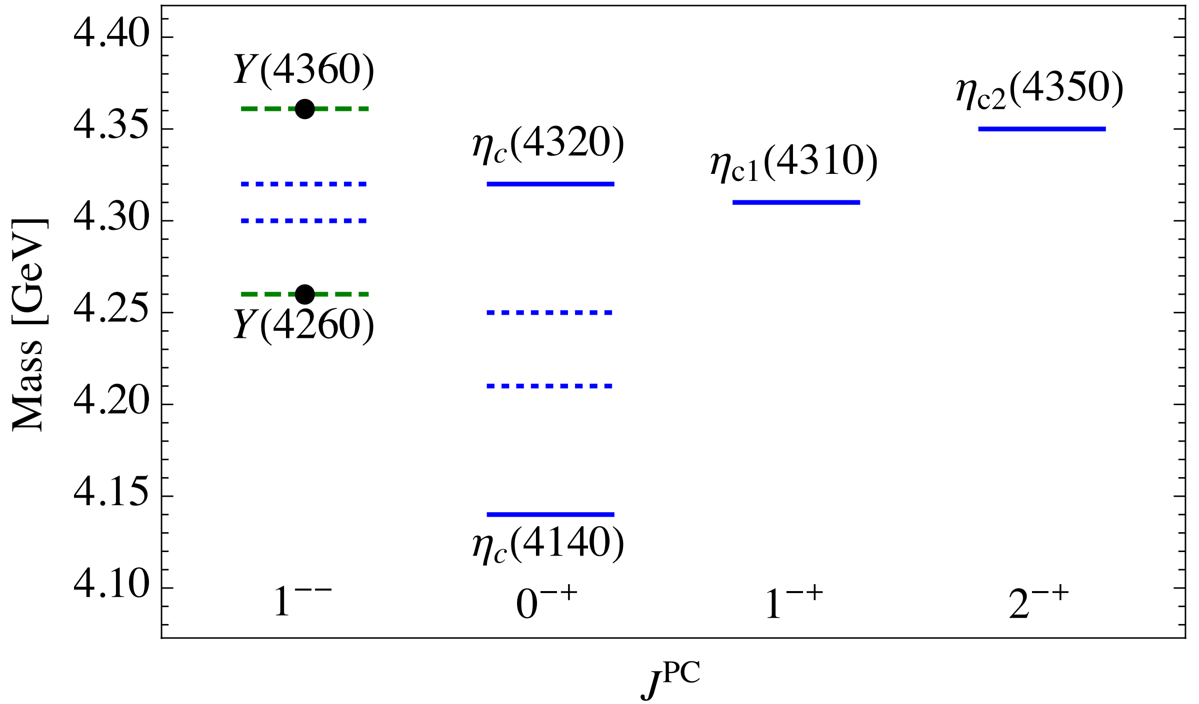
Hadrocharmonium: new states

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

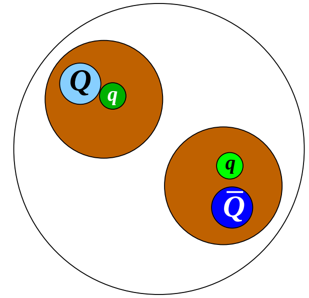


Cleven et al., PRD 92(2015)014005

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



→ 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

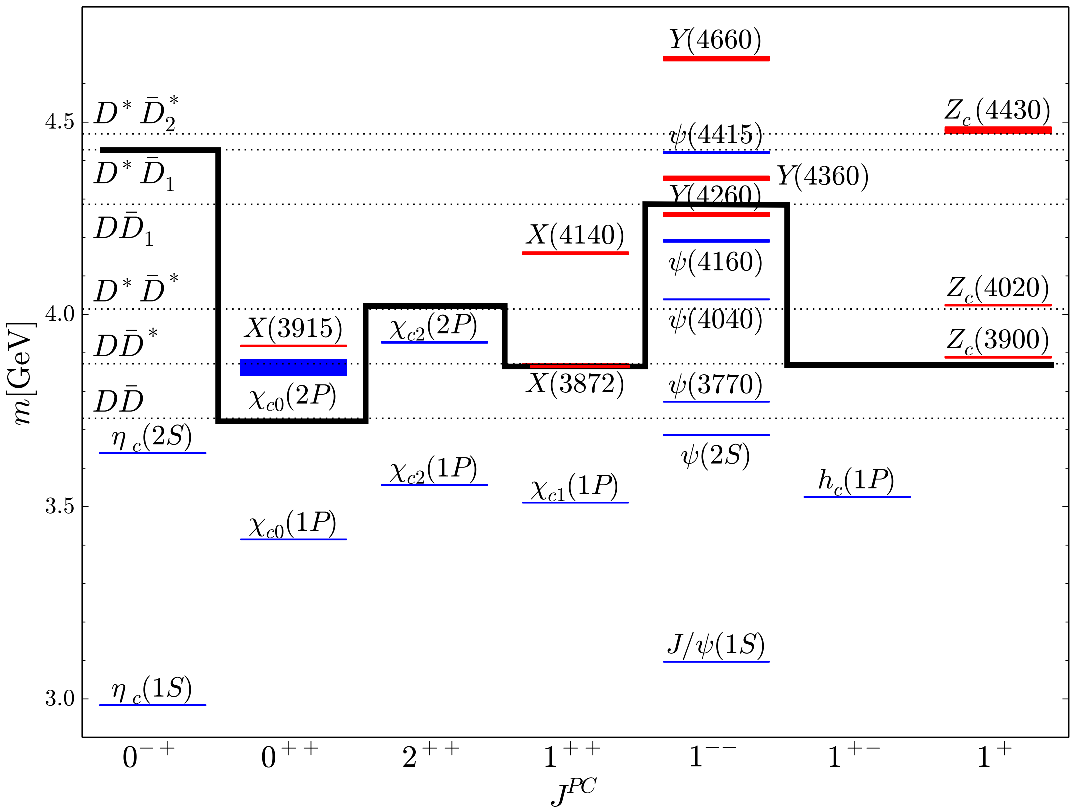
Are there mesonic molecules?

General considerations

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

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

$D_0(2400)$ 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

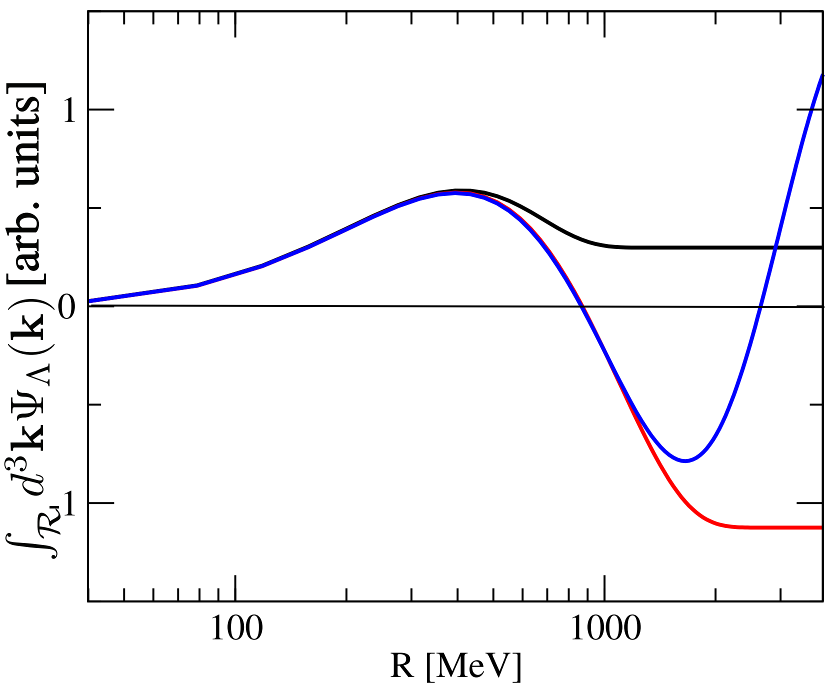
Note: for hadrocharmonium:
$M(0^-) - M(1^-) \simeq -100$ MeV

Cleven et al., PRD 92 (2015) 014005

Production at high P_T

$$\begin{aligned}
&\sigma(\bar{p}p \to X) \\
\sim\ & \left|\int d^3\mathbf{k}\langle X|D^0\bar{D}^{*0}(\mathbf{k})\rangle\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle\right|^2 \\
\simeq\ & \left|\int_{\mathcal{R}} d^3\mathbf{k}\langle X|D^0\bar{D}^{*0}(\mathbf{k})\rangle\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle\right|^2 \\
\leq\ & \int_{\mathcal{R}} d^3\mathbf{k}\,|\Psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k}\,|\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle|^2 \\
\leq\ & \int_{\mathcal{R}} d^3\mathbf{k}\,|\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle|^2\ ,
\end{aligned}$$

Bignamini et al., PRL 103 (2009) 162001



$\mathcal{R}$ must be large enough to saturate wave function

Bignamini et al.:

$\mathcal{R} \sim \sqrt{mE_b} \sim 40$ MeV

$\to$ Test on deuteron

M. Albaladejo et al., CPC41(2017)121001

One finds: $\mathcal{R} \sim 400$ MeV

using Herwig (Pythia)

$\mathcal{R}\sim 60$ MeV$\to\sigma_X\sim 0.1(0.04)$ nb

$\mathcal{R}\sim 300$ MeV$\to\sigma_X\sim 13(4)$ nb†

$\mathcal{R}\sim 600$ MeV$\to\sigma_X\sim 55(15)$ nb†

†: D^+D^- channel included

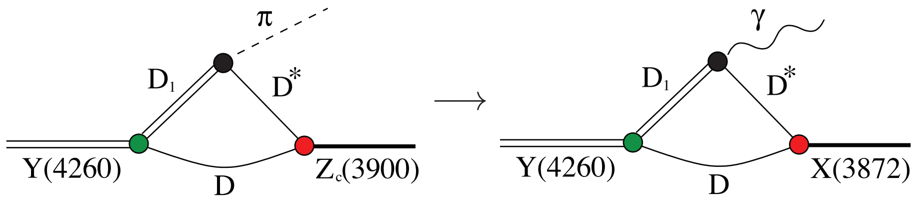
vs $\sigma_{\rm exp.}^{\rm CMS} \sim 13 - 39$ nb $\to$

fully consistent!

Remarks on decays

→ Natural explanation for $Y(4260) \to \pi Z_c(3900)$ and

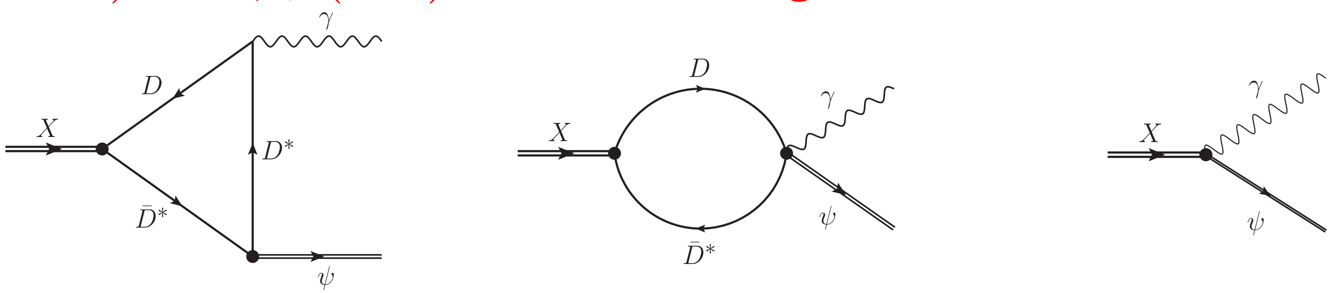
Wang, C. H., Zhao, PRL111 (2013) no.13, 132003



prediction of $Y(4260) \to \gamma X(3872)$ Guo et al., PLB 725 (2013) 127-133

confirmed at BESIII Ablikim et al. PRL 112 (2014), 092001

→ Not all observables sensitive to molecular component!
e.g. $X(3872) \to \gamma\psi(nS)$ has leading order counter term



In particular: $$R = \frac{\mathcal{B}(X(3872) \to \gamma\psi')}{\mathcal{B}(X(3872) \to \gamma J/\psi)} \simeq 2.5$$ Aaij et al. [LHCb], NPB 886 (2014) 665

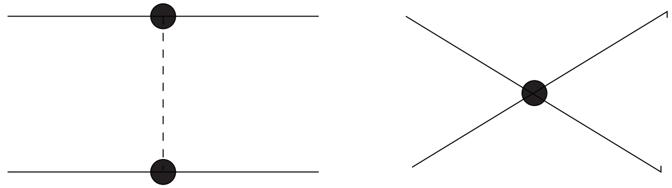
can be easily described within molecular approach

Guo et al., PLB 742 (2015) 394

ChPT for heavy-heavy molecules

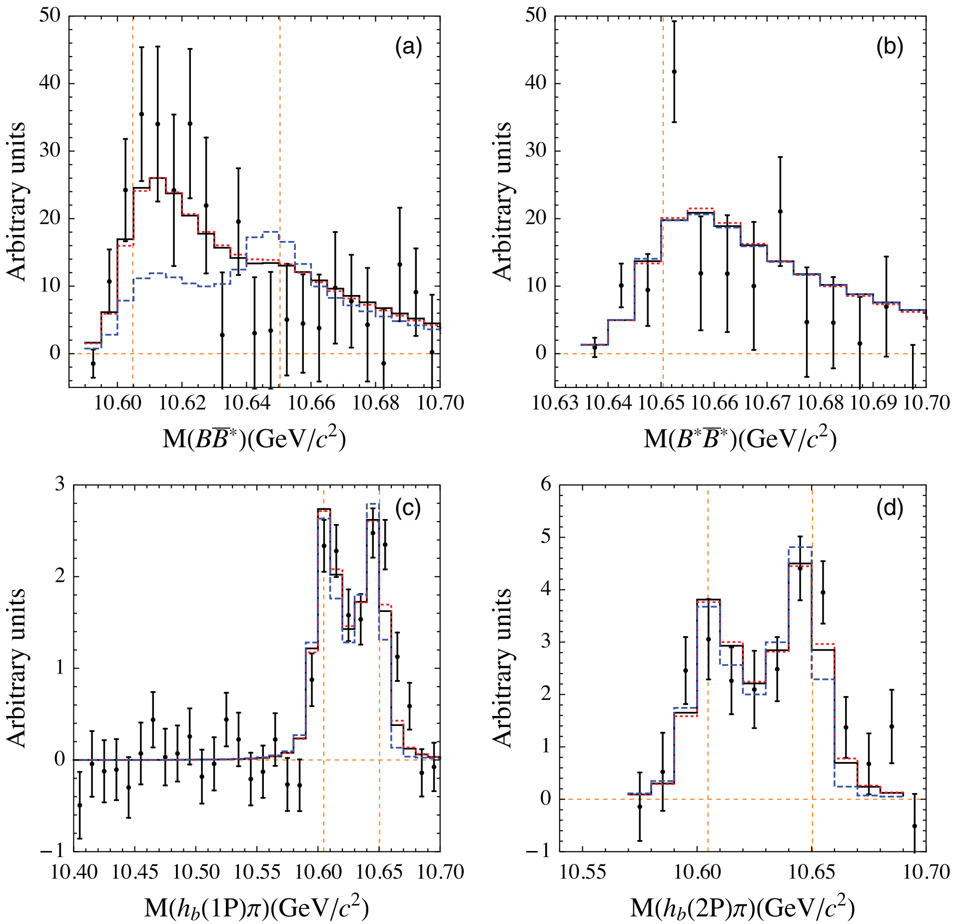
Analogous to nucleon–nucleon system Epelbaum et al., RMP81(2009)1773

LO Potential:



coupled channels:
$B^*\bar{B},\ B^*\bar{B}^*$

Results for Z_b spectra: Q. Wang et al., PRD98(2018)074023



Three different fits:

Black solid:
Constant contact terms only

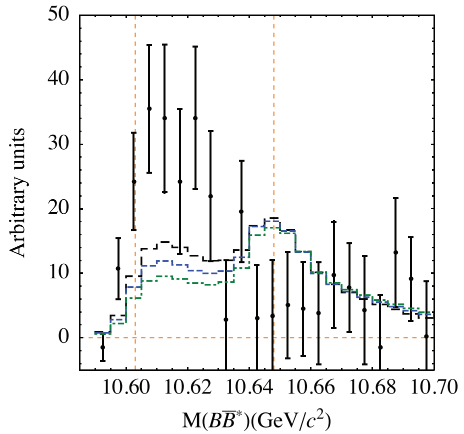
Red dotted:
Constant contact terms
+ 1-π-exch. in S–wave

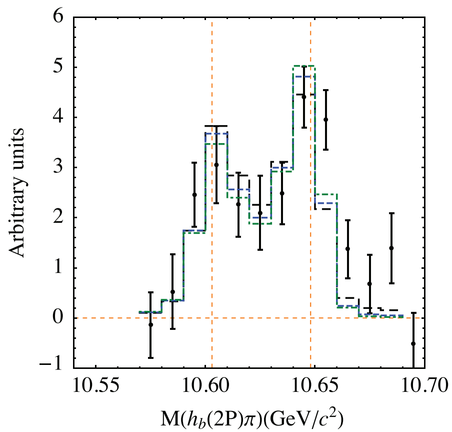
Blue dashed:
Constant contact terms
+ full 1-π-exch.

What's wrong?

At $B^*\bar{B}^*$–threshold $B^*\bar{B}$ momentum ~ 500 MeV

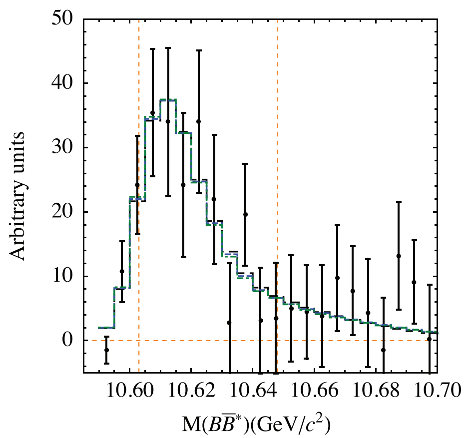
$\Longrightarrow$ No suppression of $S(B^*\bar{B}^*) - D(B^*\bar{B})$ transition

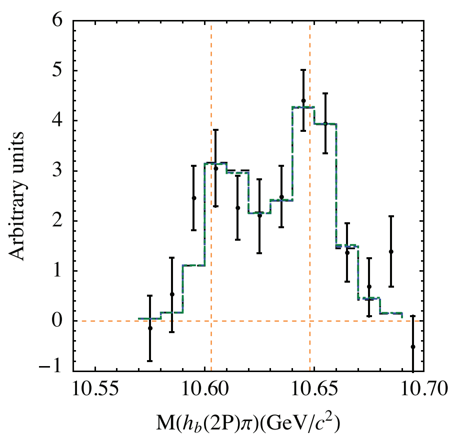




- Strong $B^*\bar{B}^* \to B^*\bar{B}$
- strong Λ dependence
  black: $\Lambda = 800$ MeV
  blue: $\Lambda = 1000$ MeV
  green: $\Lambda = 1200$ MeV

Promote $S-D$ contact term to leading order:





- Fit improves significantly
- Λ dependence gone
- $Z_b' \to B^*\bar{B}$ very small
- NLO $S-S$ CT small

Why $Z_b' \not\to B^*\bar{B}$ not understood

Spin symmetry violation

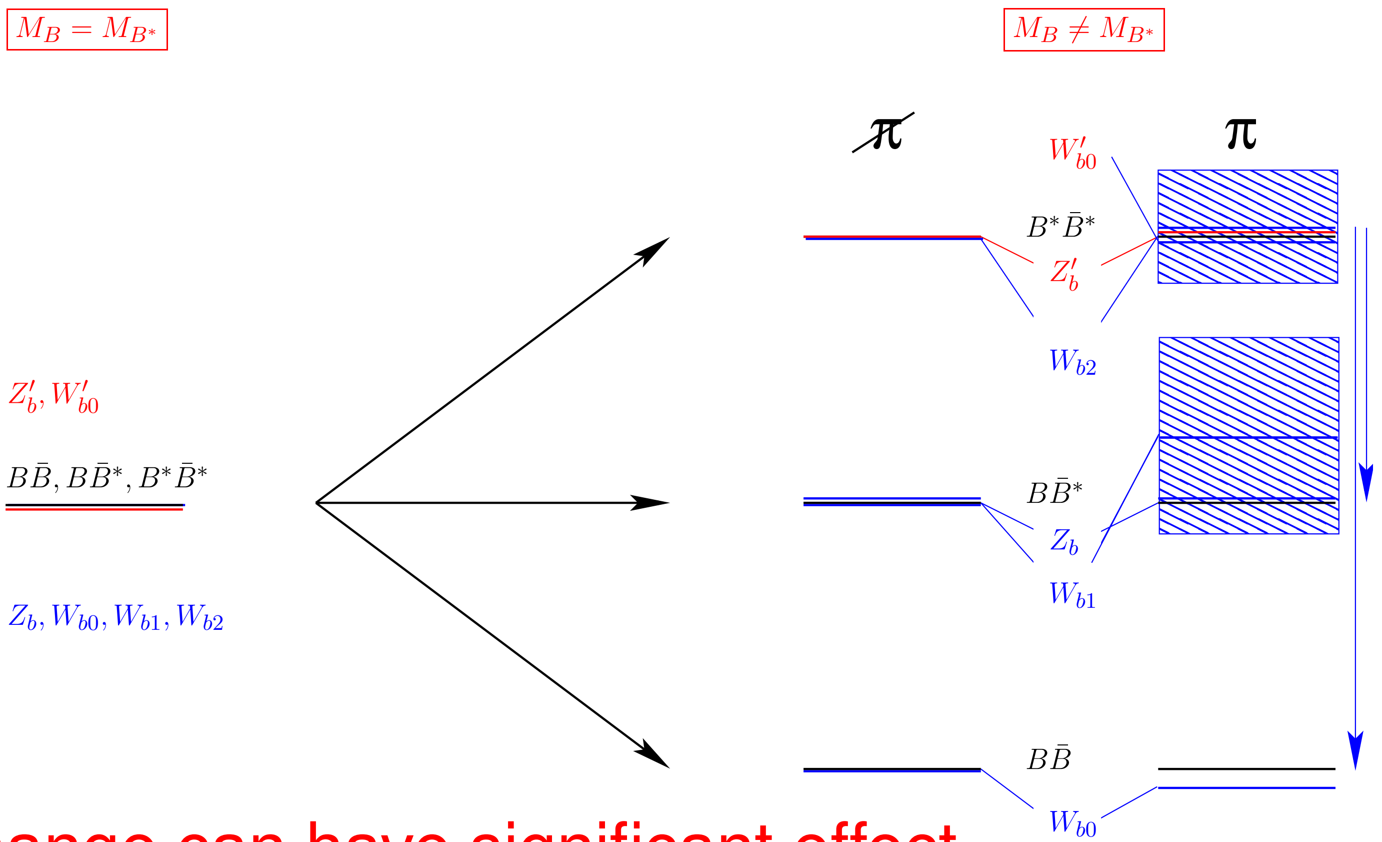
EFT for I=1 $B^{(*)}\bar{B}^{(*)}$ scattering $\to$ Spin multiplets

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

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, PRD99(2019)094013



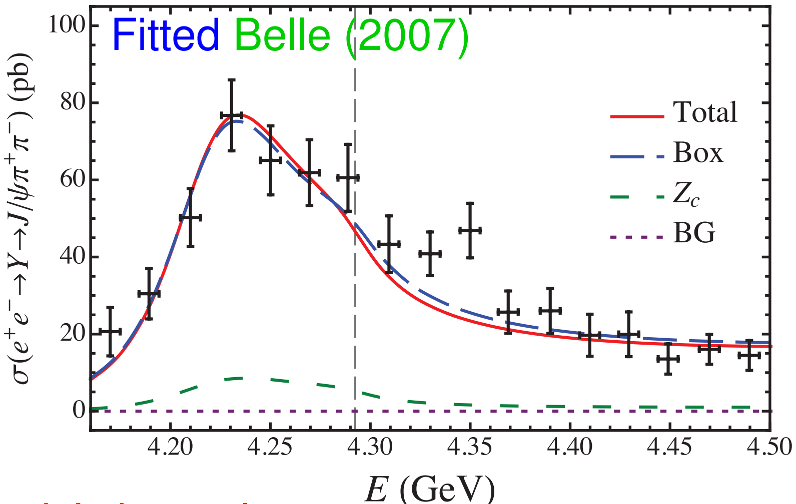
Pion exchange can have significant effect

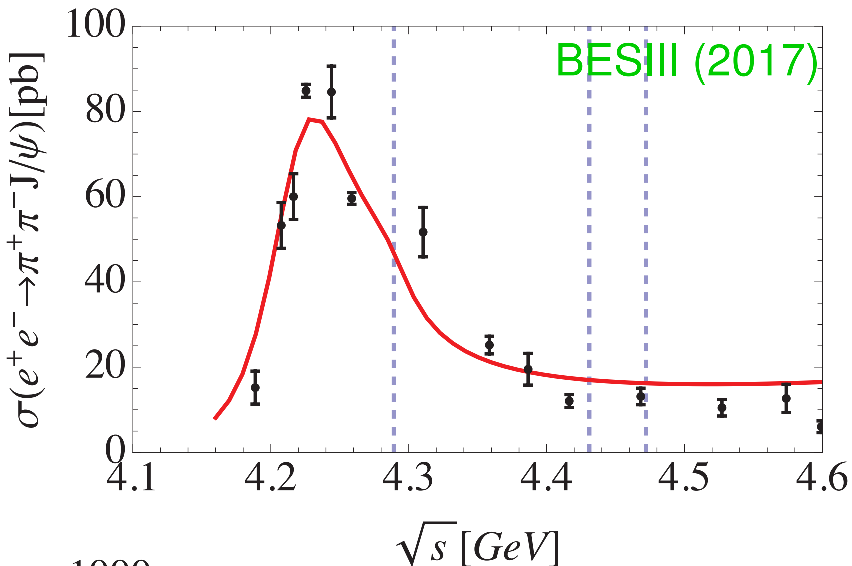
Lineshapes of $Y(4260)$

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

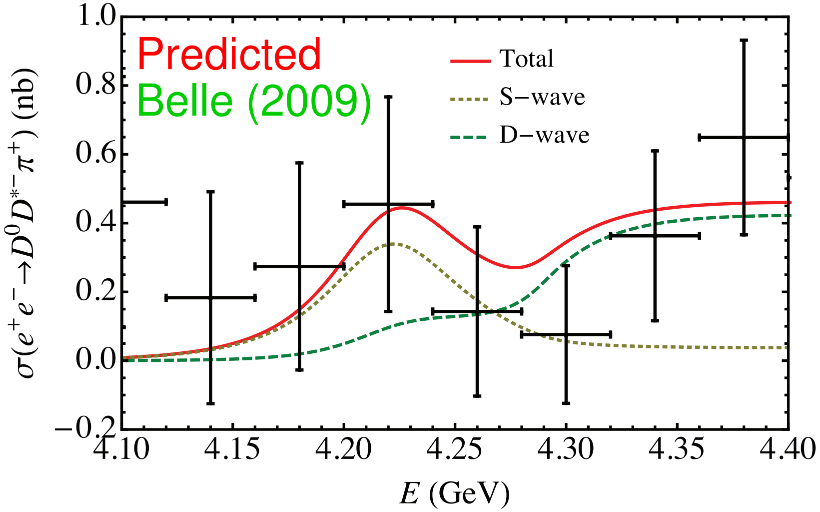
Cleven et al., PRD90 (2014) 074039; see also Qin et al. PRD94(2016)054035

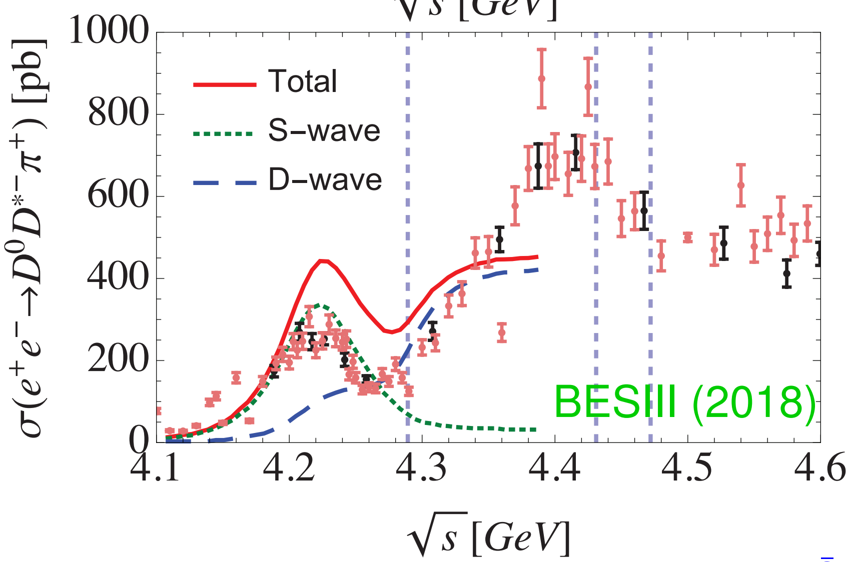
Inelastic channel





'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