Hadron Spectroscopy and Exotics
$\rightarrow$ Heavy Exotic Mesons

— Theory —

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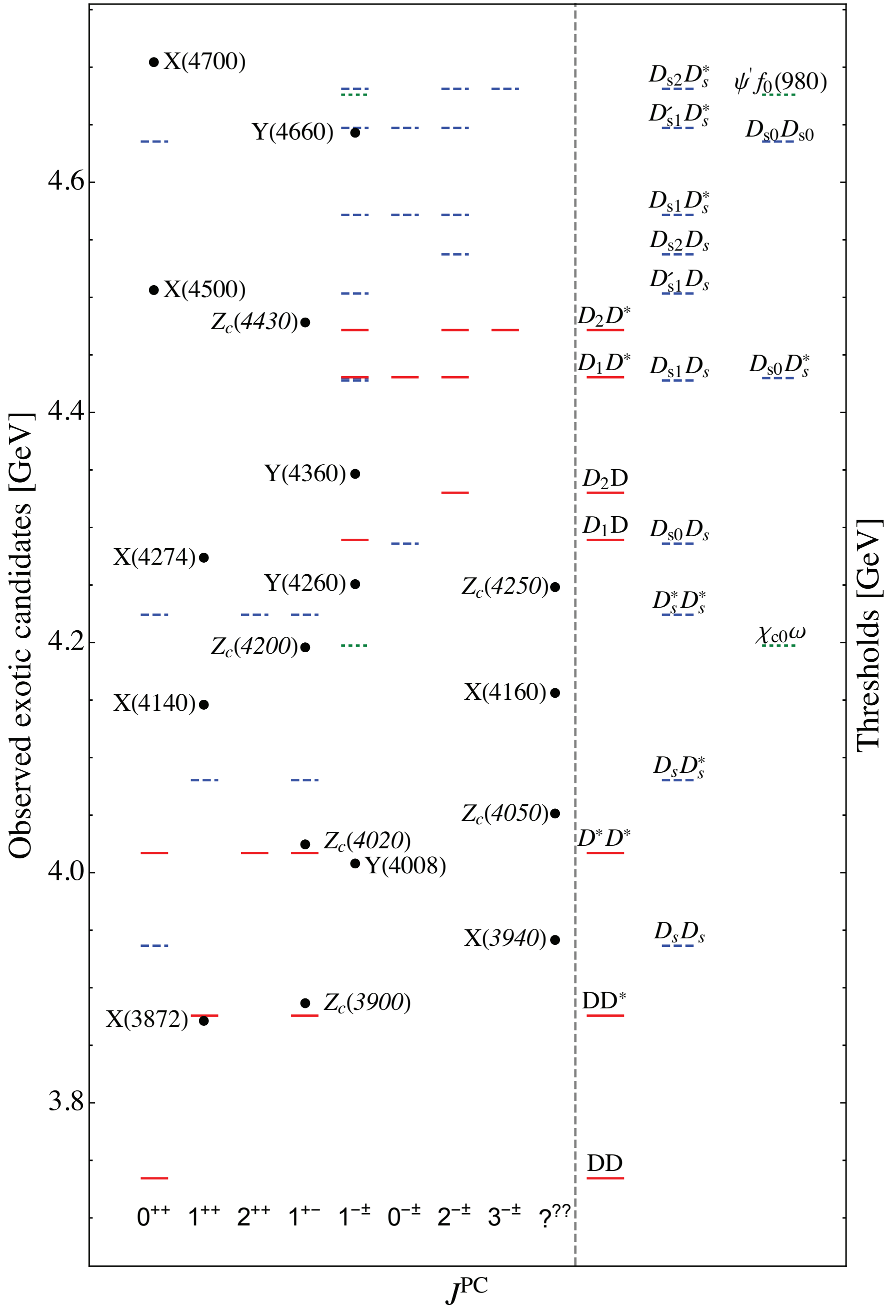
Setting the stage ...



F. K. Guo et al., arXiv:1705.00141 [hep-ph]

→ All exotic candidates above open flavor thresholds

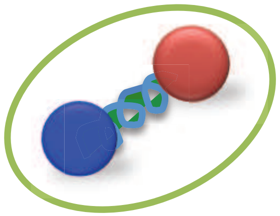
→ Many (not all) states near S-wave thresholds of narrow states Filin et al., PRL 105, 019101 (2010) Guo et al., PRD84, 014013 (2011)

→ States not near all those thresholds

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

... does $Y(4008)$ exist?

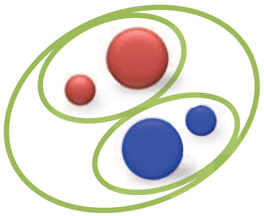
Proposals



Hybrid (not discussed here)

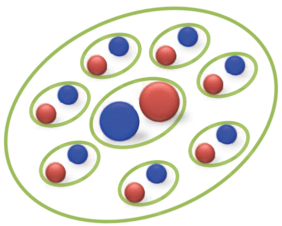
$\rightarrow$ Compact with active gluons and $\bar{Q}Q$

Close & Page, PLB28(2005)215; Zhu, PLB625(2005)212; Kou & Pene, PLB631(2005)164; Kalashnikova & Nefediev, PRD94 (2016)114007



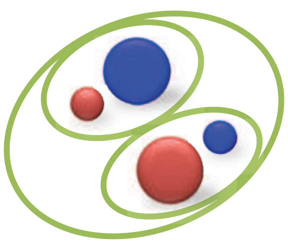
Tetraquark

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

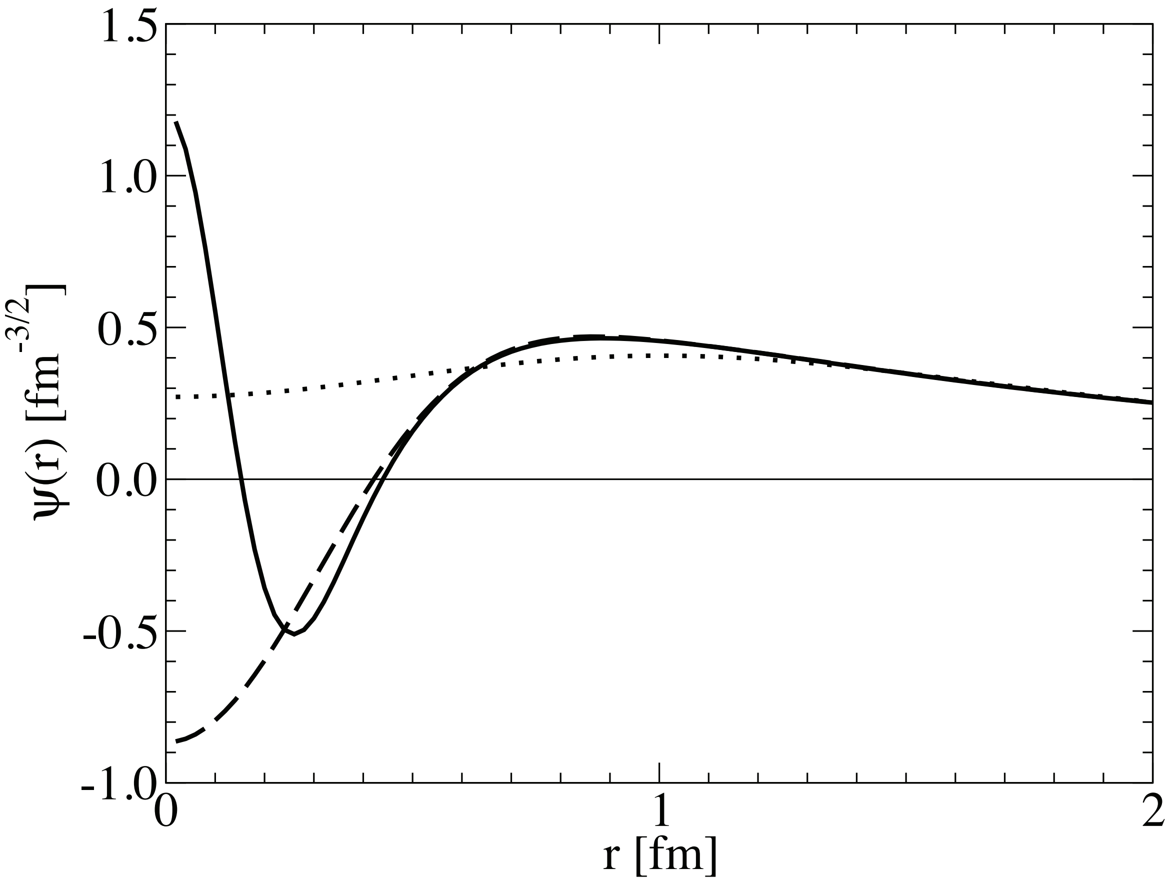
$\gg 1$ fm $\gtrsim$ confinement radius

for near threshold states

What does extended mean?

Example: deuteron wave function for different cut offs

Nogga and C. H., PLB634(2006)210



→ Long range tale universal — proportional to $\exp(-\gamma r)/r$

→ Short range part: in general non vanishing

... but not under control (depends on cut off)

Outline

In this talk I will

→ Introduce three very common models for XYZ states

- ▷ Hadroquarkonium
- ▷ Tetraquarks
- ▷ Hadronic Molecules

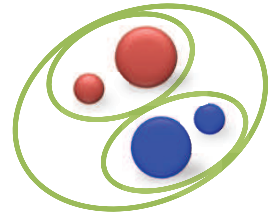
→ and discuss by looking at

- ▷ Spectroscopy for the individual models and
- ▷ X-Production at high p_T and Lineshapes believed to allow one to disentangle compact vs. extended components

what it takes to identify the prominent component of a state

Heavy Tetraquarks

→ Mesons as anti-diquark–diquark systems



→ Straightforward extension of the quark model

→ Originally proposed by Jaffe for light quarks

Jaffe PRD15(1977)267

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

Maiani et al. PRD89(2014)114010

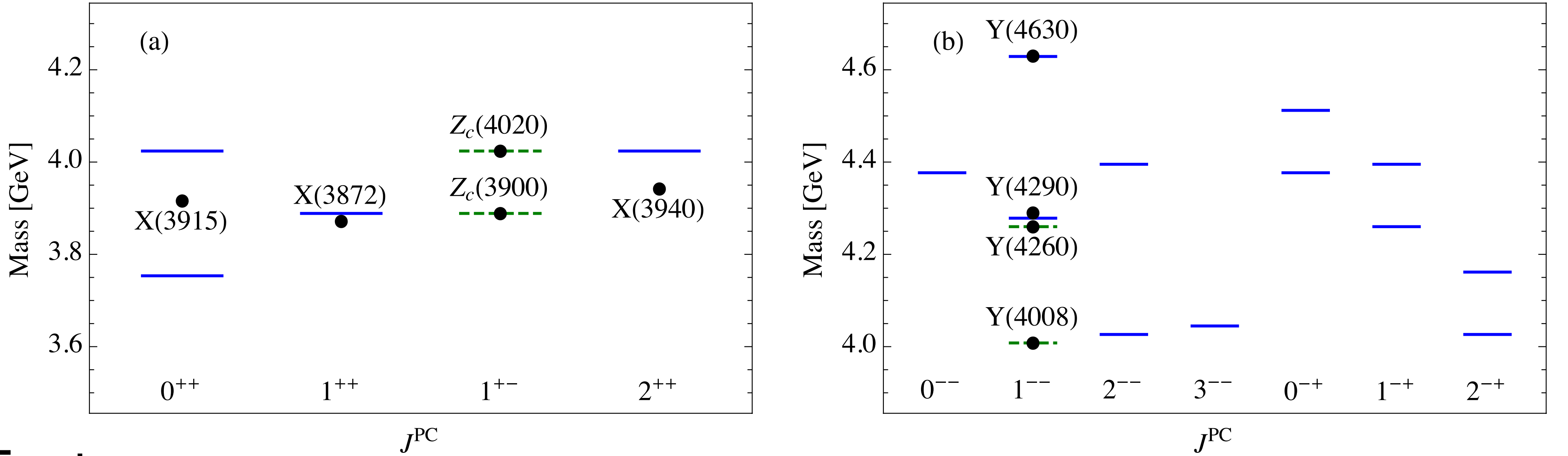
alternative app. e.g.: Cui et al., HEPNP31(2007)7; Stancu, JPG37(2010) 075017

$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}\left[s(s+1) + \bar{s}(\bar{s}+1) - 3\right]$$

- Already many ground states
- Each level has isovector and isoscalar state ($cf.$ ρ and ω)
- The larger J the lighter the state ($a > 0$ from the fit)

Typical results and problems

Cleven et al., PRD 92(2015)014005



Features:

→ very light $J = 3$ state

→ lightest vector state 'only' 100 MeV above $X(3872)$

... however: $Y(4008)$ not seen by BESIII PRL118(2017)092001

→ Many more states predicted than observed!

Maybe since di-quark picture too restrictive/constraining?

Richard et al., PRD95(2017)054019 and J. Vijande at this conference

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

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

→ from QCD sum rules — Du et al., PRD87(2013)014003

→ from lattice QCD — Francis et al. PRL118(2017)142001

→ from phenomenology

Karliner and Rosner, arXiv:1707.07666; Eichten and Quigg, arXiv:1707.09575

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,

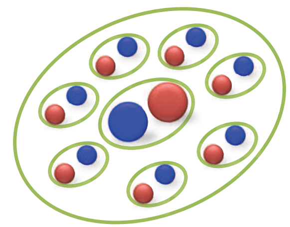
$\Longrightarrow m(QQ\bar{q}\bar{q})$ can be predicted.

→ $J^P = 1^+$ $(bb\bar{u}\bar{d})$ 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

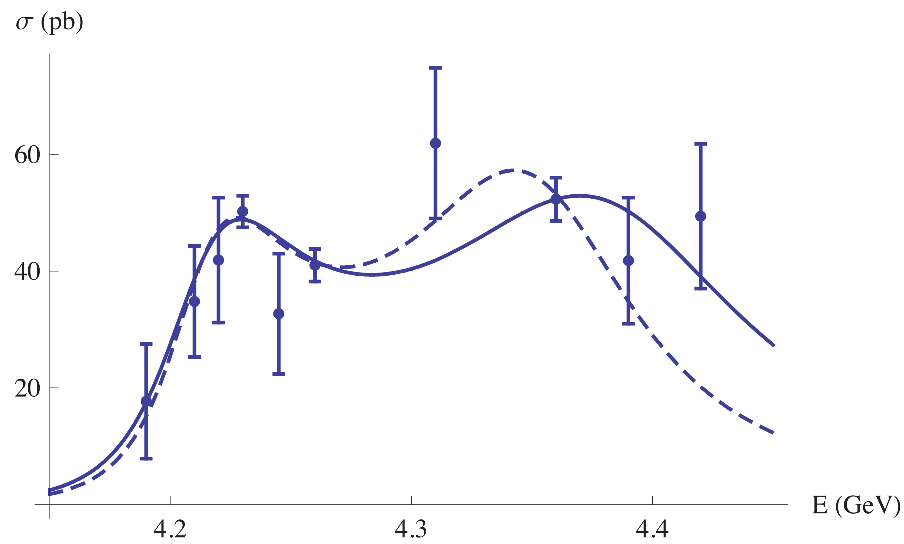


→ Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

→ 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



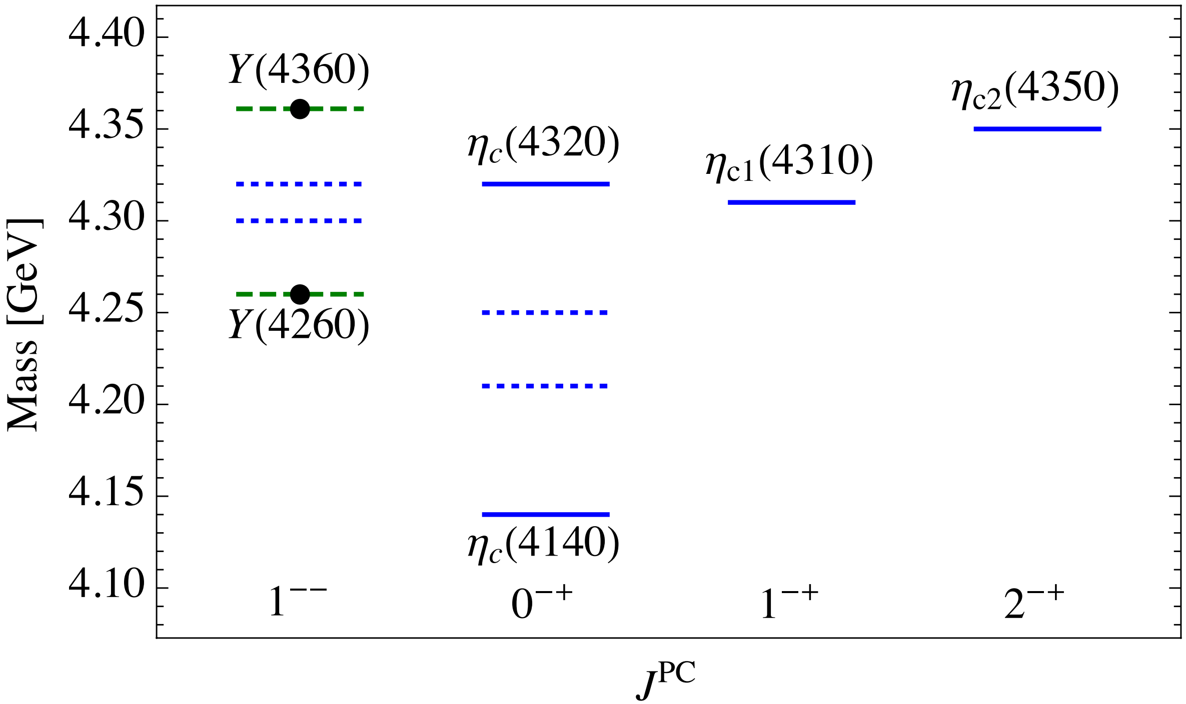
Hadrocharmonium: new states

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

→ 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 $E_B = m_1 + m_2 - M$

▷ $E_B^{\rm deuteron} = 2.22$ MeV

▷ $E_B^{\rm hypertriton} = (0.13 \pm 0.05)$ MeV (to Λd)

→ can be identified in observables (Weinberg compositeness):

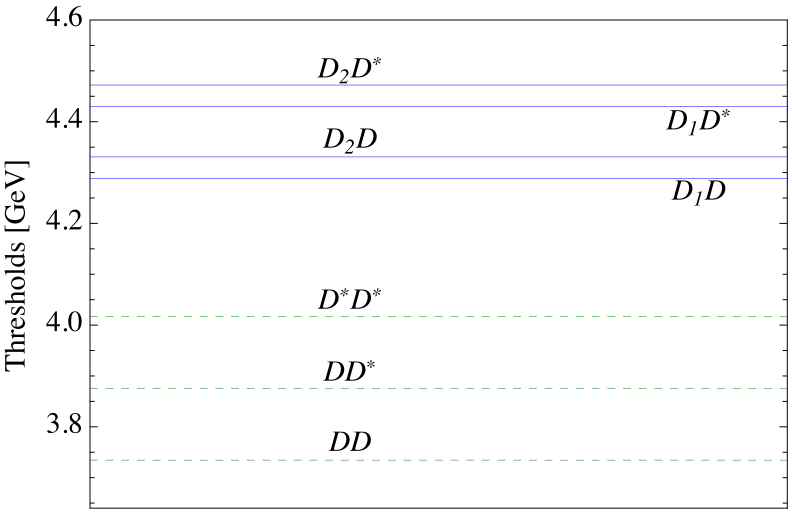
$$\frac{g_{\rm eff}^2}{4\pi} = \frac{4M^2\gamma}{\mu}(1-\lambda^2) \;\to\; a = -2\left(\frac{1-\lambda^2}{2-\lambda^2}\right)\frac{1}{\gamma}\;; \quad r = -\left(\frac{\lambda^2}{1-\lambda^2}\right)\frac{1}{\gamma}$$

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

Are there mesonic molecules?

General considerations

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

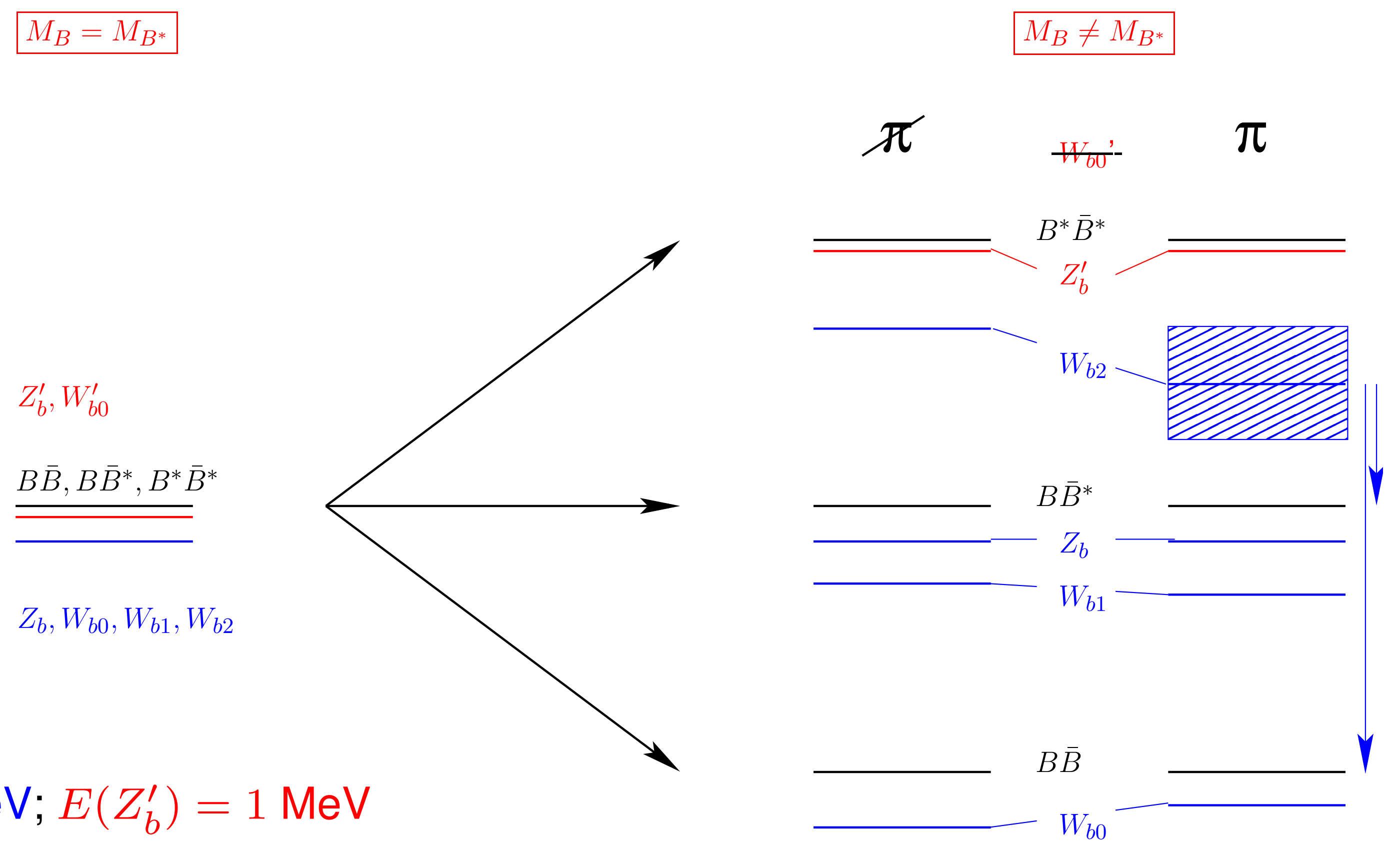
EFT for I=1 $B^{(*)}\bar{B}^{(*)}$ scattering $\to$ Spin multiplets

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

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

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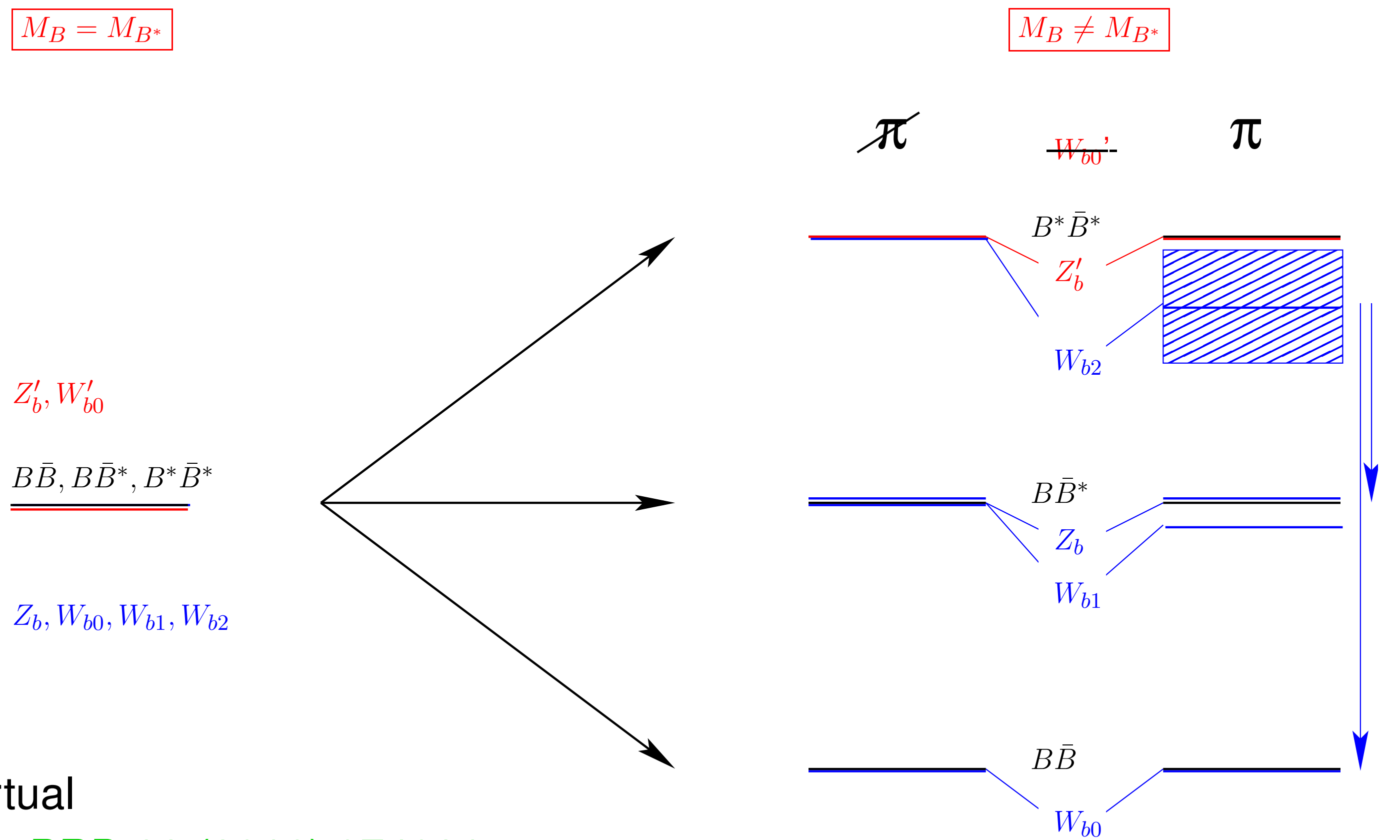
Mass of spin partners very sensitive to $Z_b^{(\prime)}$ masses

Baru et al., JHEP 1706(2017)158



both getting virtual

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

Production of $X(3872)$ at high P_T

$\sigma(\bar{p}p \to X + \text{other particles})$

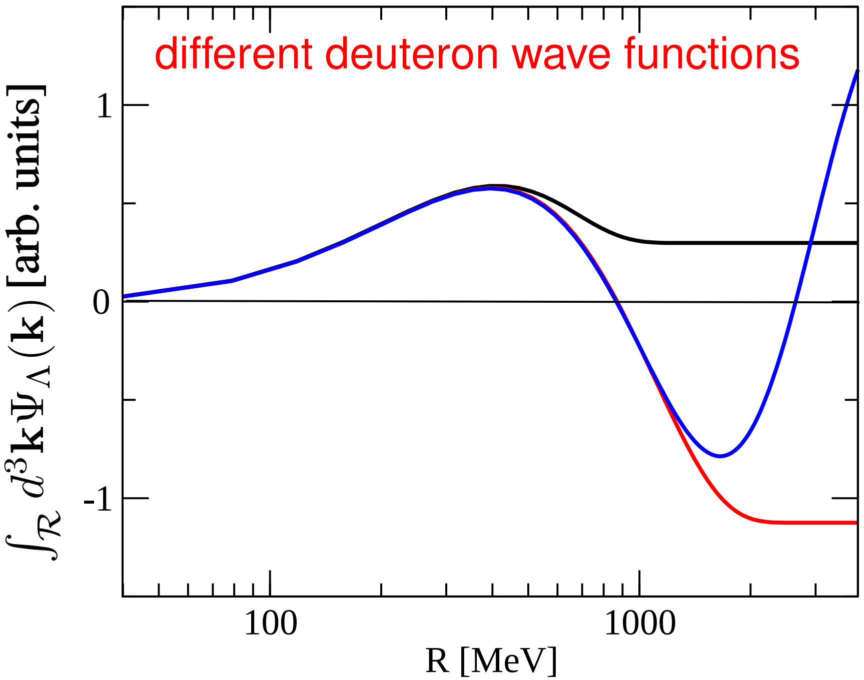
$$\sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

$$\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

$$\leq \int_{\mathcal{R}} d^3\mathbf{k} \, |\Psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} \left| \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2$$

$$\leq \int_{\mathcal{R}} d^3\mathbf{k} \left| \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 ,$$

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

Albaladejo et al., in preparation

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

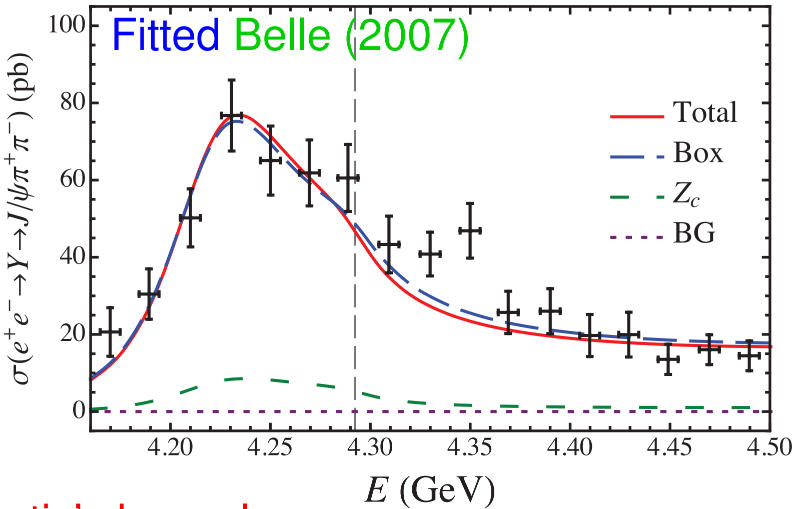
fully consistent!

Lineshapes of $Y(4260)$

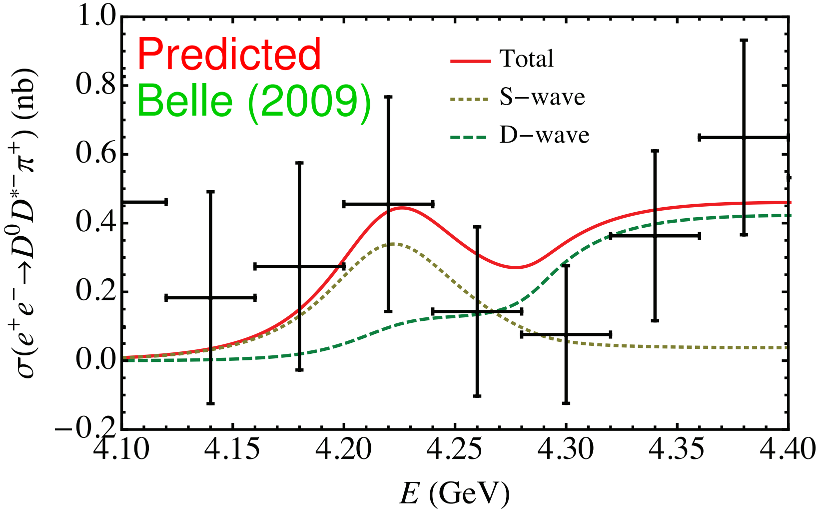
IF the $Y(4260)$ is a $D_1\bar{D}$ molecule it MUST have a large coupling to this channel $\Longrightarrow$ great impact on lineshapes

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

Inelastic channel



'elastic' channel



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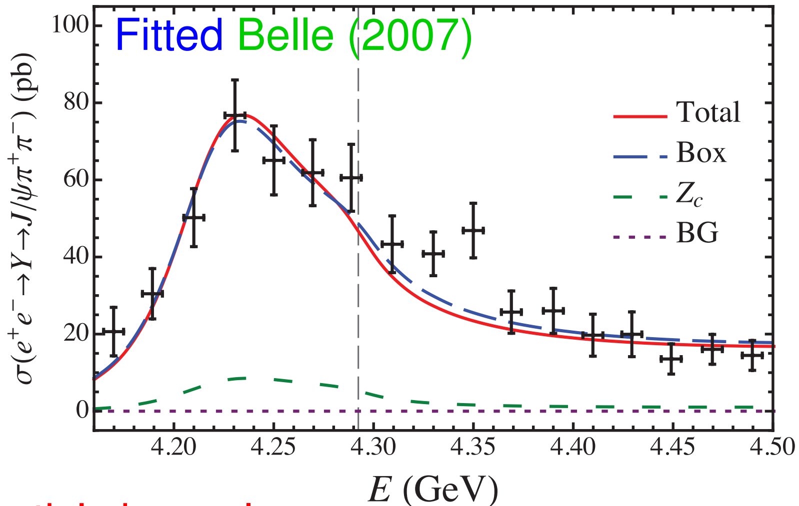

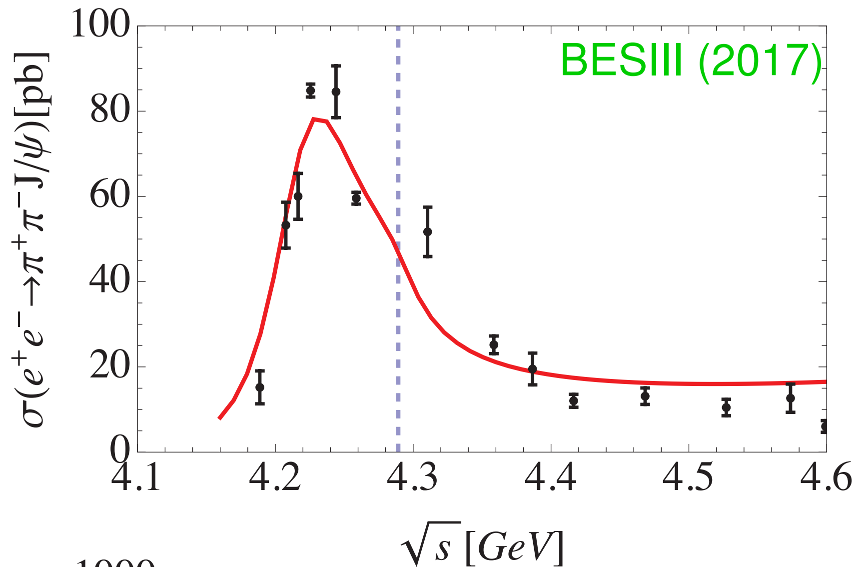

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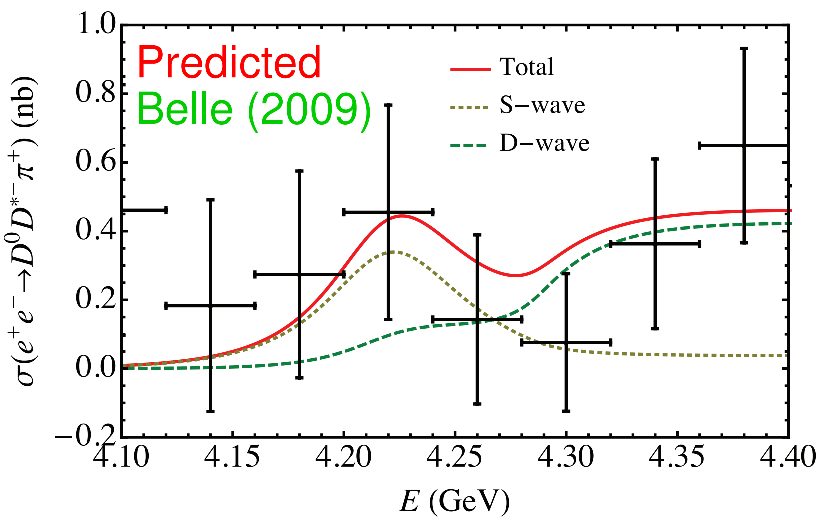
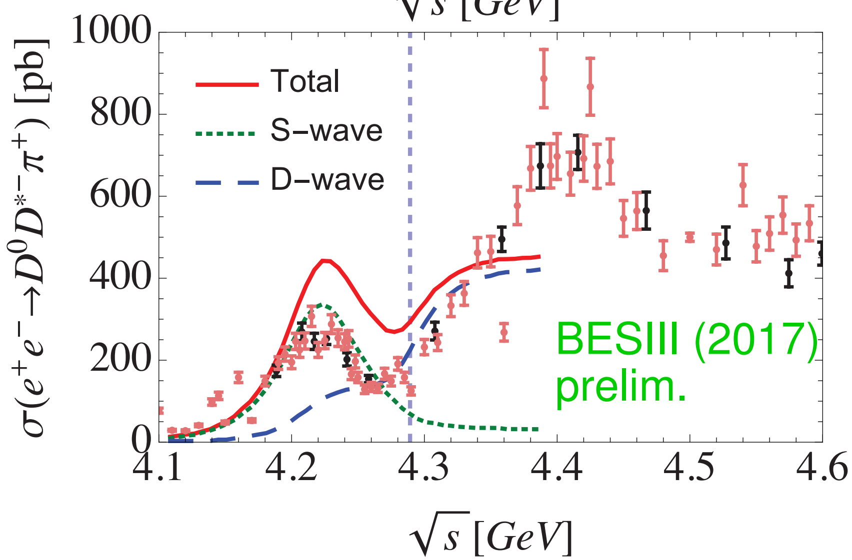
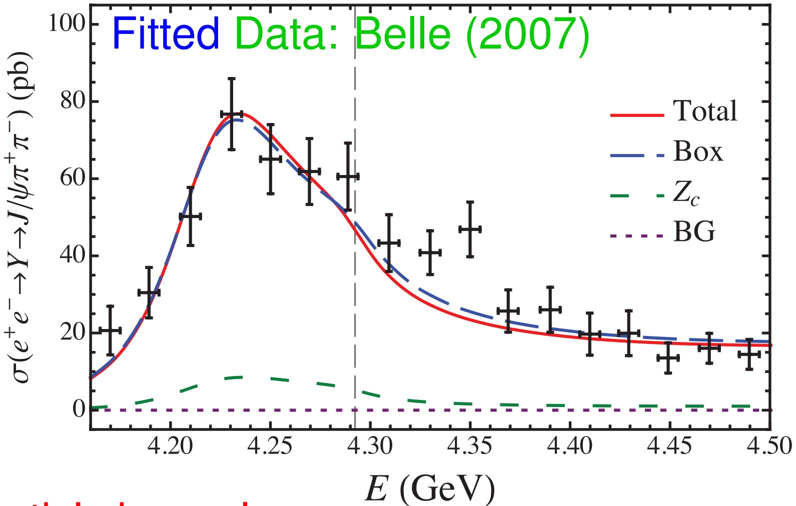


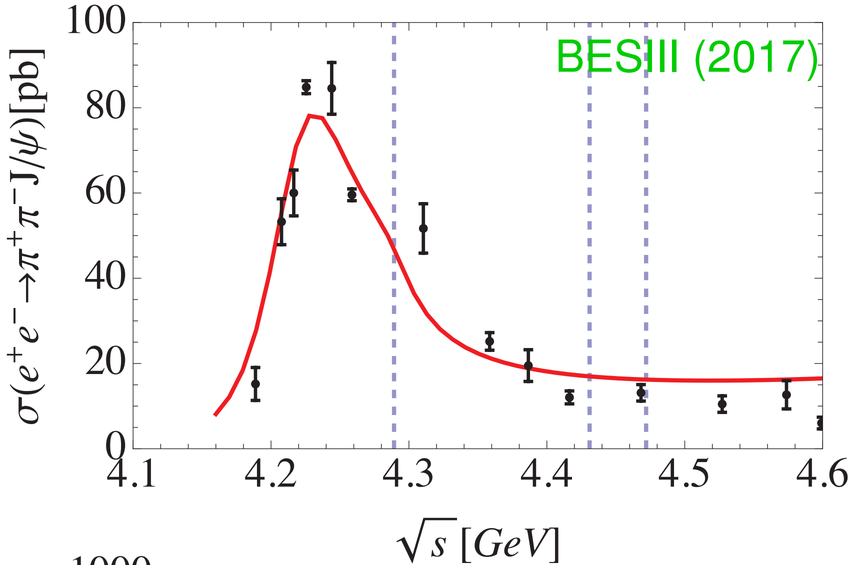


Lineshapes of $Y(4260)$

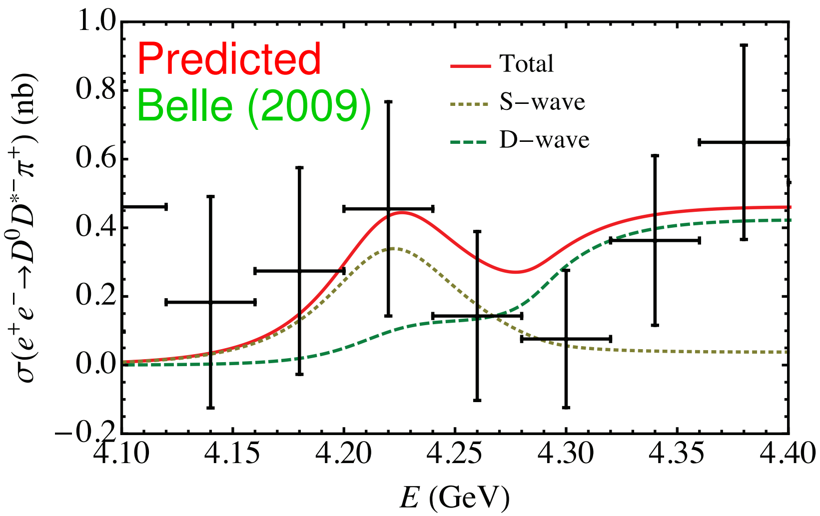
Role of D_1D^*/D_2D^* channels and $\psi(4415)$?

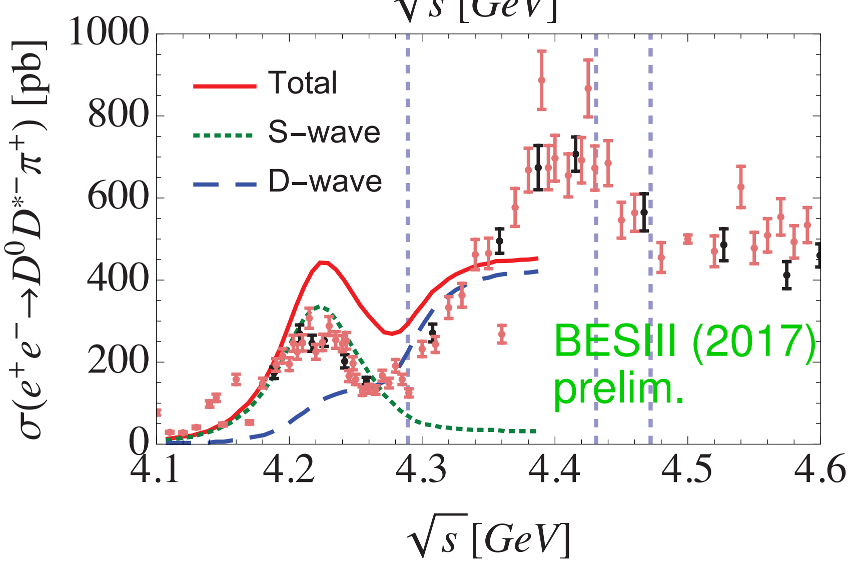
Inelastic channel





'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

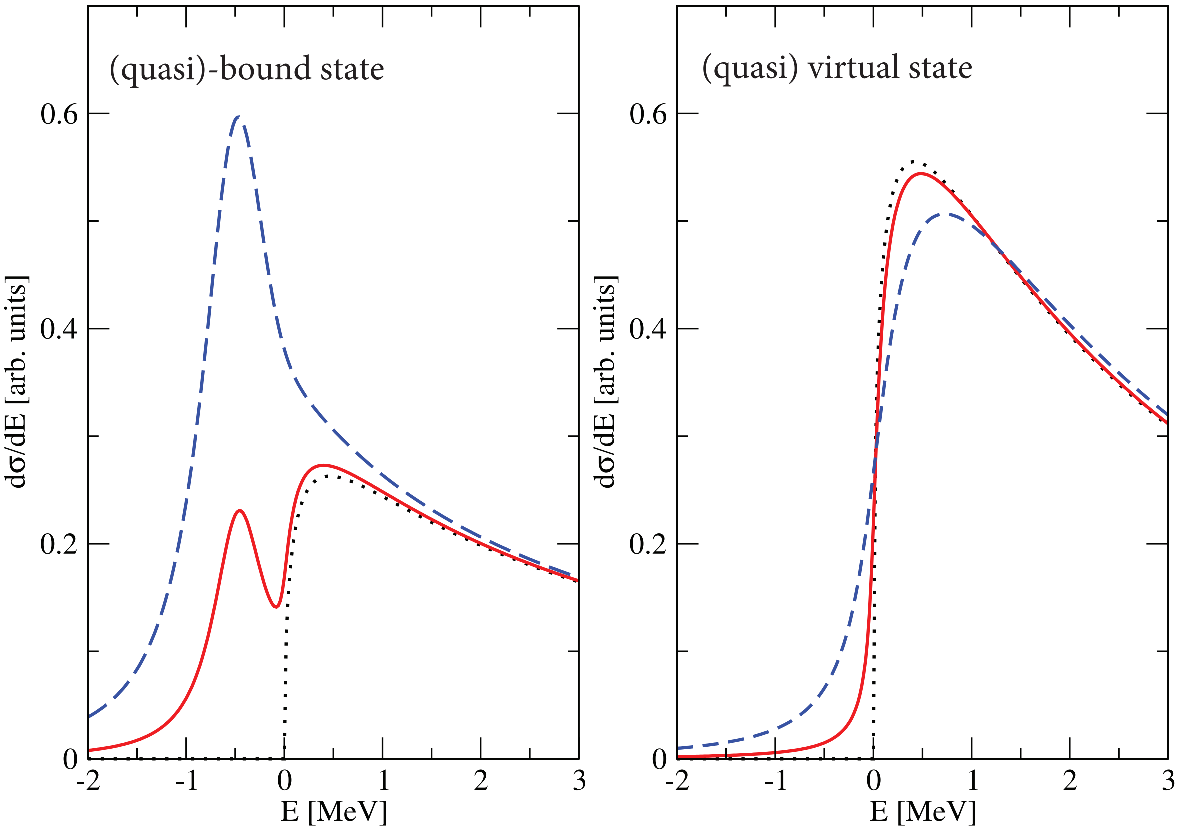
Thanks a lot for your attention

Unstable constituents

Braaten & Lu PRD76 (2007) 094028; C.H. et al., PRD81 (2010) 094028

$$k \to \sqrt{\mu}\sqrt{\sqrt{E^2+\Gamma^2/4}+E} + i\sqrt{\mu}\sqrt{\sqrt{E^2+\Gamma^2/4}-E} + \mathcal{O}(\Gamma/2E_r)\ ,$$

$$\gamma \to \pm\sqrt{\mu}\sqrt{\sqrt{E_r^2+\Gamma^2/4}-E_r} + \mathcal{O}(\Gamma/2E_r)\ ,$$



for $Y \to AB \to [cd]B$ with

$E_r = -0.5$ MeV

$\Gamma_0 = 1.5$ MeV

$g_0^2 = 0.2$ GeV^{-1}

natural value for molecular state

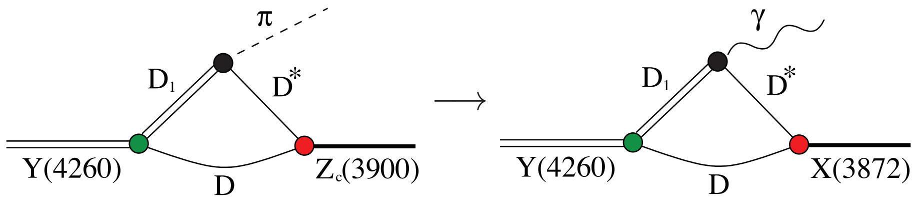
and $\Gamma = 0, 0.1, 1$ MeV

non-Breit-Wigner shapes emerge unavoidably!

Remarks on decays ...

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

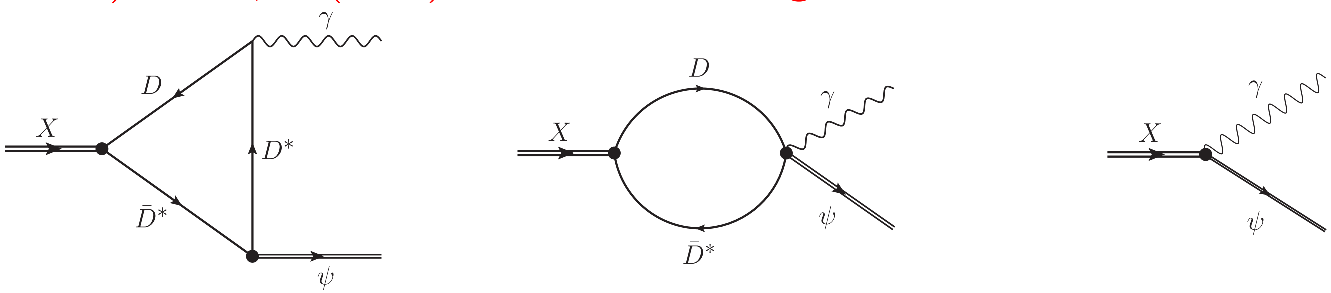
Q. Wang, C. H., Q. Zhao, PRL111 (2013) no.13, 132003



prediction of $Y(4260) \to \gamma X(3872)$ F.-K. 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