Towards understanding the XYZ states lessons from their lineshapes

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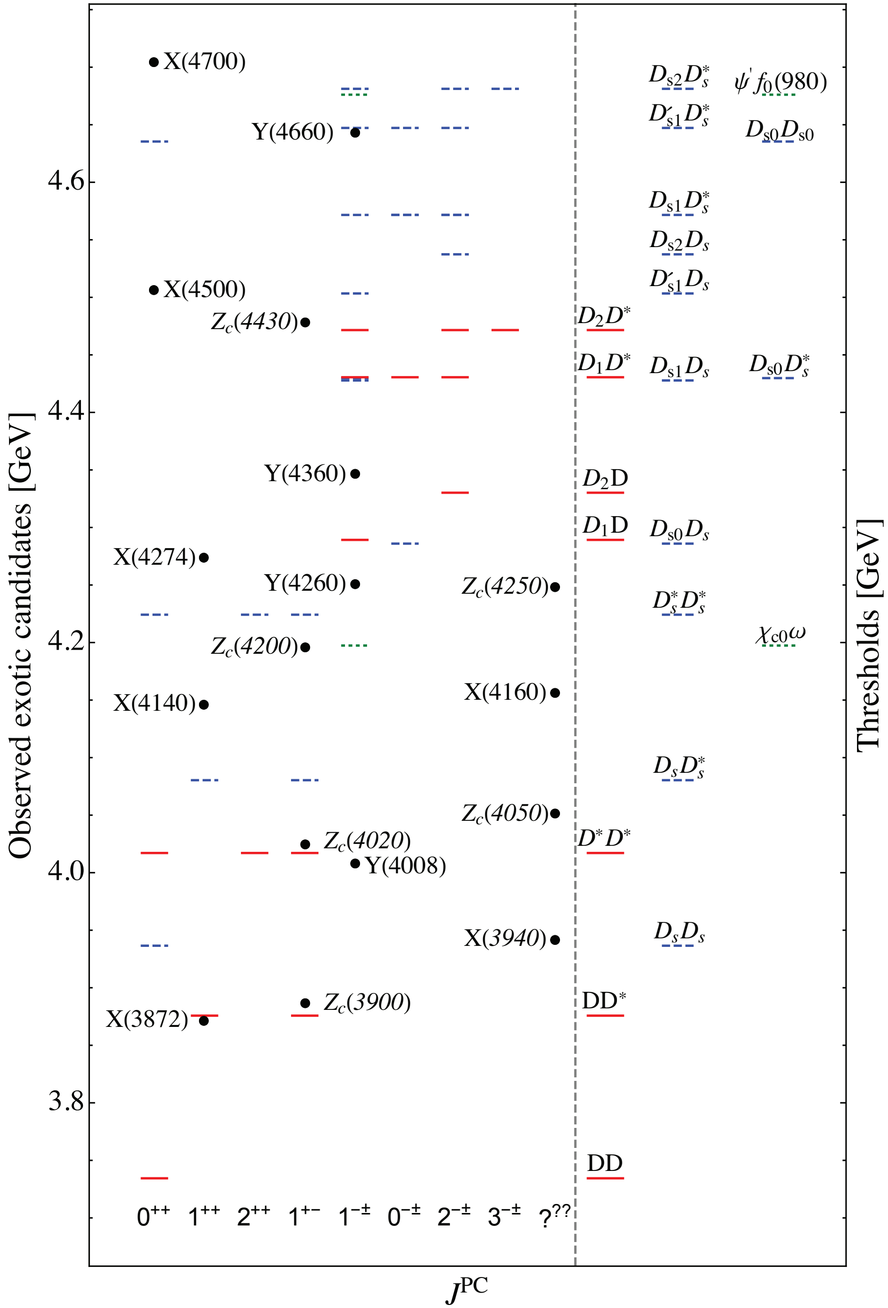
Key reference: Review article

F. K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B. S. Zou, “Hadronic molecules”, arXiv:1705.00141 [hep-ph]

Setting the stage ...



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

→ All exotic candidates above open flavor thresholds

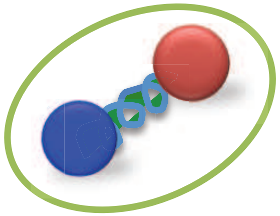
→ Many (not all) states near S-wave thresholds of narrow states Filin et al., PRL 105, 019101 (2010) Guo et al., PRD84, 014013 (2011)

→ States not near all those thresholds

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

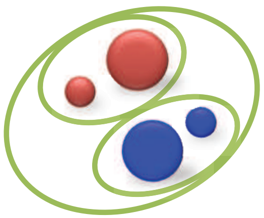
... does $Y(4008)$ exist?

Proposals



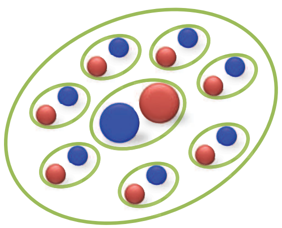
Hybrid

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



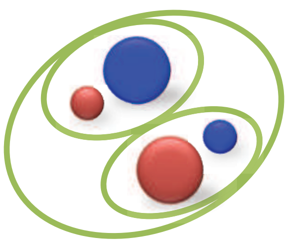
Tetraquark

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

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

for near threshold states

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):

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

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

Are there mesonic molecules?

Properties of molecular states

→ Potential the strongest in S–waves

→ Potential i.g. contains short and long ranged contributions

A. A. Filin et al., PRL 105 (2010) 019101

→ Interaction channel dependent

▷ isovector meson exchanges give

$$\langle \vec{\tau}_{(1)} \cdot \vec{\tau}_{(2)} \rangle = 2I(I+1) - 3$$

Thus: Either $I = 1$ or $I = 0$ states (not both) for given J^{PC}, if, e.g., ρ-exchange or π-exchange significant

M. B. Voloshin & L. B. Okun, JETPL 23 (1976) 333; N. A. Tornqvist, PRL 67 (1991) 556.

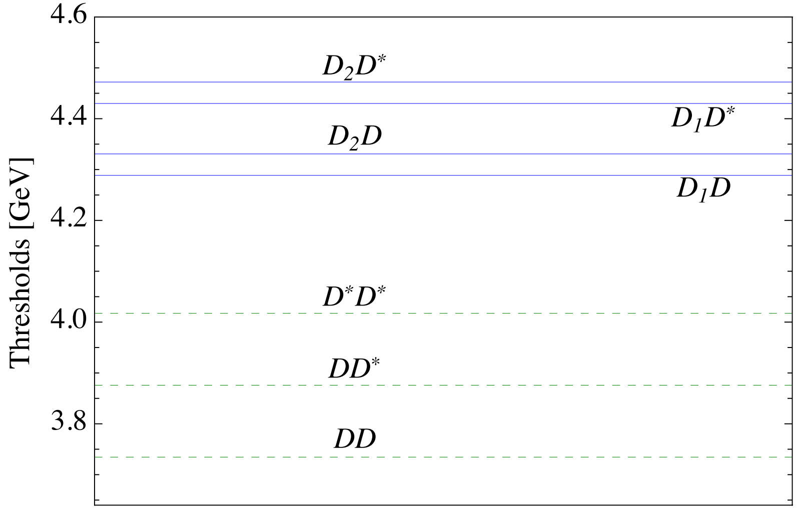
▷ Switching C also induces sign change

▷ Potentially large coupled channel effects

→ Interaction particle dependent (no $\pi D\bar{D}$ vertex)

Getting more concrete

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



$3^{-\pm}$: 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^{++}: $DD - D^*D^*$;

$\to$ 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

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

c.f. for hadrocharmonium: $M(0^-) - M(1^-) \simeq -100$ MeV

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

Example: $\{B, B^*\}$ and $\{\bar{B}, \bar{B}^*\}$ scatt.

Baru et al., arXiv:1704.07332

→ Potential: contact terms + 1-π- and 1-η-exchange
In the symmetry limit one gets (2 parameters)

→ No new parameter from meson exchange: $g_b = g_c \approx 0.57$
PDG (from $D^* \to D\pi$); ALPHA coll. PLB740 (2015) 278 (lattice)

→ All partial waves need to be included Baru et al. PLB 763 (2016) 20

→ 3 (0^{++}, 1^{++}, 2^{++}) states degenerate with Z_b: W_{bJ}
1 (0^{++}) degenerate with Z_b': W_{b0}'
Bondar et al., PRD 84 (2011) 054010; Voloshin, PRD 84 (2011) 031502;
Mehen & Powell, PRD 84 (2011) 114013; Nieves & Valderrama, PRD 86 (2012) 056004.

→ Z_b and Z_b' degenerate only with additional symmetry
M. B. Voloshin, PRD 93 (2016) 074011

→ Spin symmetry violation via $M_D \neq M_{D^*}$ strongly enhanced via S-D coupling → Additional decay channels
Albaladejo et al., EPJC 75 (2015) no.11, 547; Baru et al. PLB 763 (2016) 20

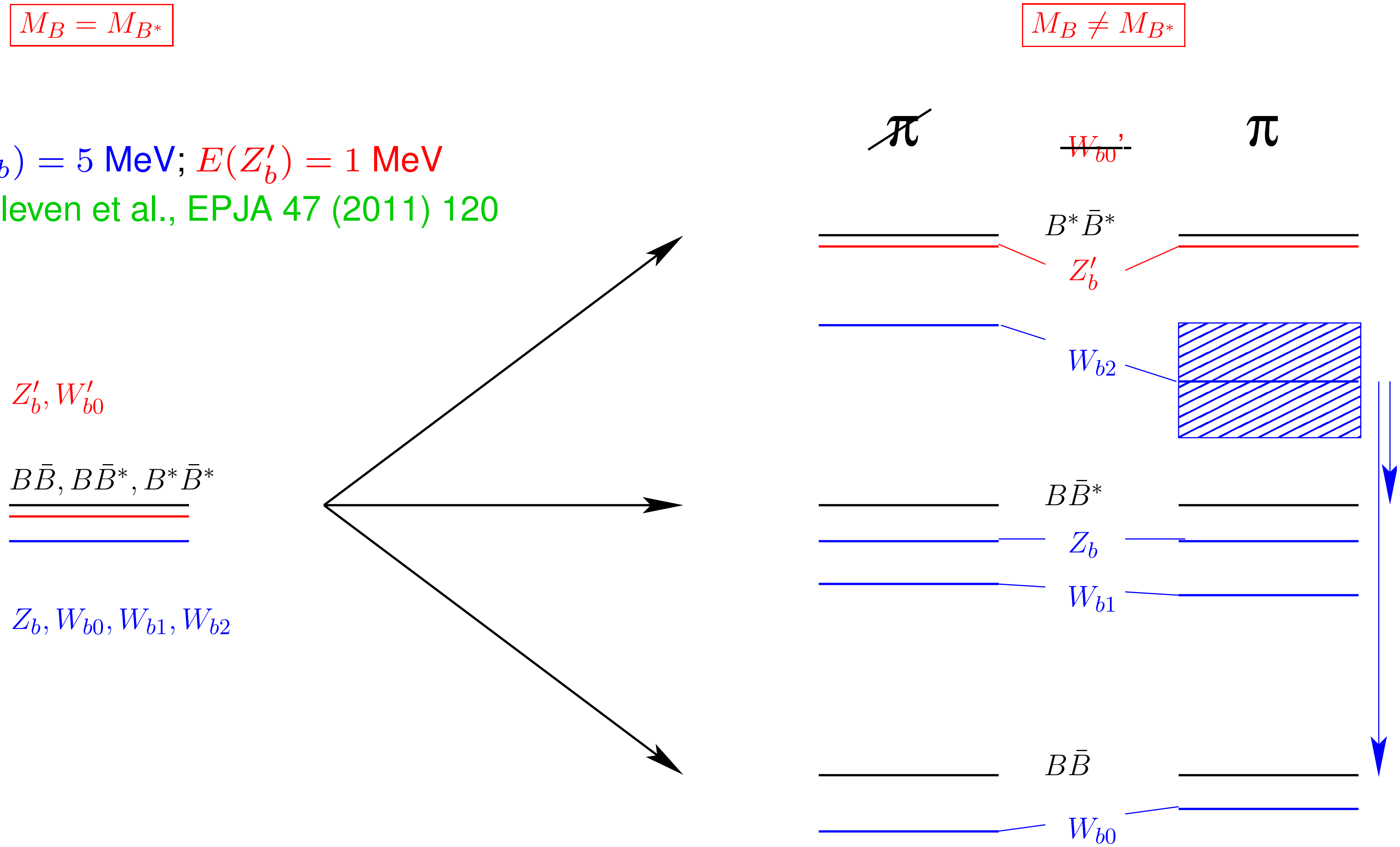
Spin symmetry violation

Baru et al., arXiv:1704.07332

When lifting spin symmetry, specific pattern emerges:

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

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



Spin symmetry violation

Baru et al., arXiv:1704.07332

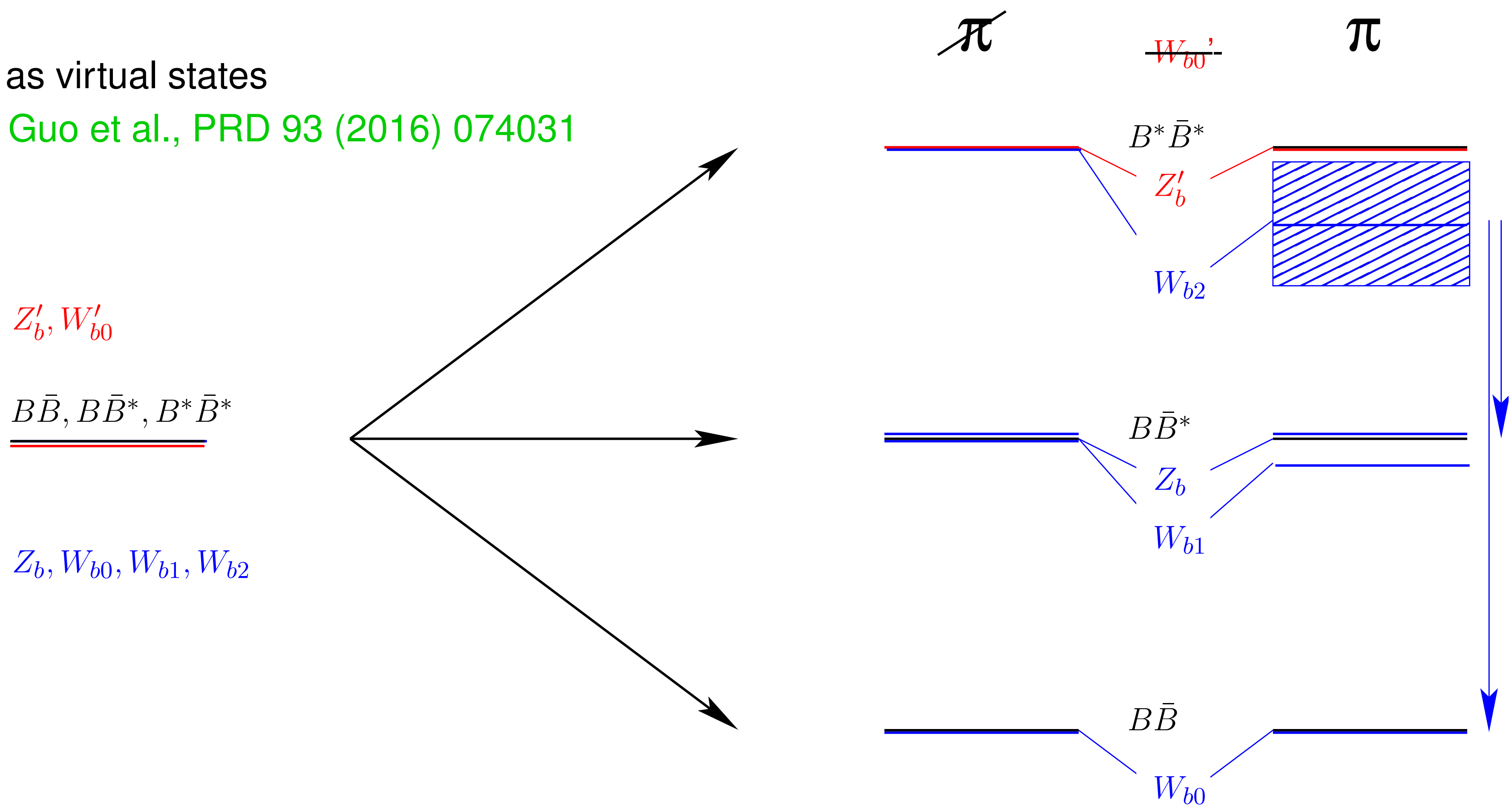
Location of spin partners very sensitive to $Z_b^{(\prime)}$ bindings

$M_B = M_{B^*}$

$M_B \neq M_{B^*}$

both as virtual states

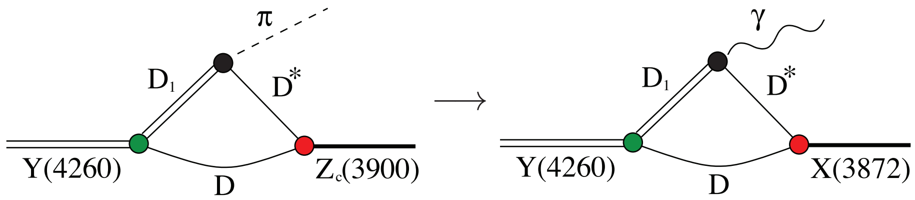
F.-K. Guo et al., PRD 93 (2016) 074031



Remarks on decays ...

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

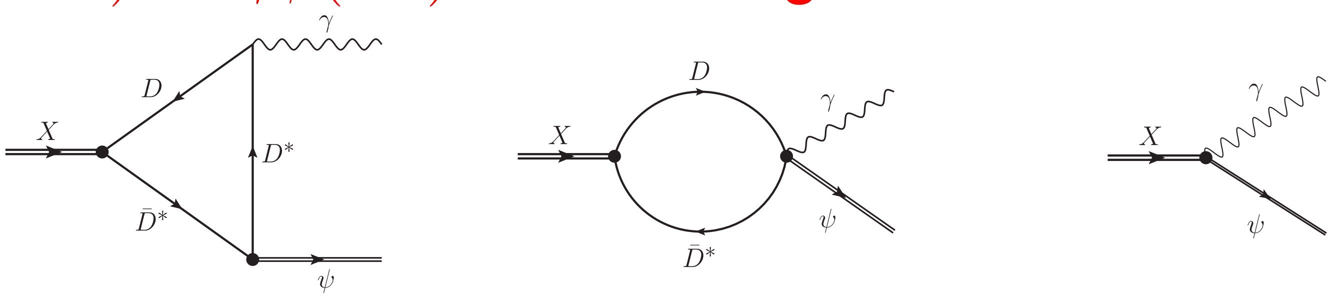
Q. Wang, C. H., Q. Zhao, PRL111 (2013) no.13, 132003



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

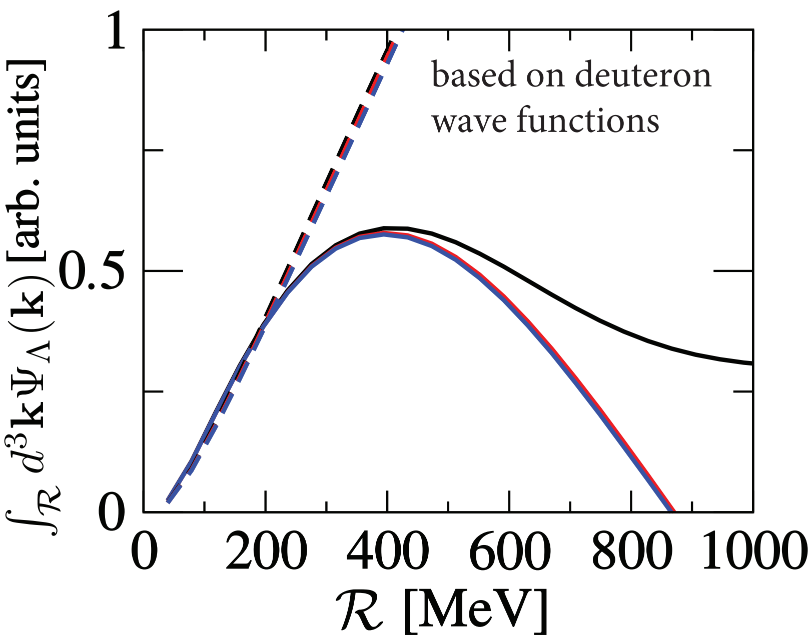
can be easily described within molecular approach

Guo et al., PLB 742 (2015) 394

Production at high P_T

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

Bignamini et al., PRL 103 (2009) 162001



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

Bignamini et al.:

$\mathcal{R} \sim \sqrt{m E_b} \sim 40$ MeV

$\to$ Test on deuteron

Albaladejo et al. subm. to PRL

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!

Interim Summary & Perspectives

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- → The hadronic molecule picture can explain naturally many properties of the XYZ states

- → Spin symmetry violations predicted strikingly different for different scenarios
  (more pronounced for negative parity states)

  M. Cleven et al., PRD 92 (2015) 01 4005

- → To disentangle compact tetraquarks from hadronic molecules, existence of $Y(4008)$ must be clarified

- → We need information for various quantum numbers for both bottomonia and charmonia

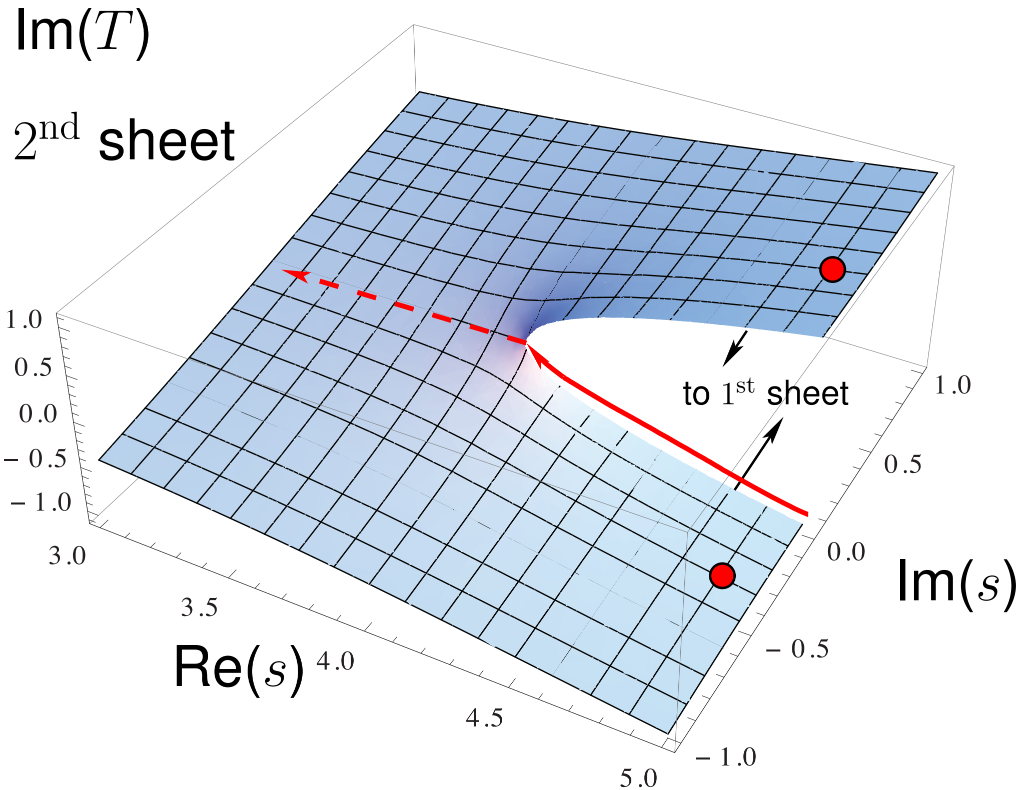
Are there observables directly sensitive to molecular component?

Yes → lineshapes in continuum channel

Interlude: S-matrix

→ For real $s < s_{\rm min}^{\rm thres}$, S is real → Branchpoint at $s = s^{\rm thres}$

→ $S(s^*) = S^*(s) \longrightarrow$ pole at s implies pole at s^*



For narrow resonances:

In resonance region:
only lower pole matters

At threshold:
both poles important!

For broad resonances:

always both important

<u>Keep track of the cuts!</u>

Poles on real axis are called virtual ($2^{\rm nd}$) or bound ($1^{\rm st}$) states

Constructing parameterizations

For shallow bound states

$$T_{\rm NR}(E) = \frac{g_0^2}{E + E_B + g_0^2\mu/(2\pi)(ik+\gamma)}, \quad g_0^2 = \frac{2\pi\gamma}{\mu^2}\left(\frac{1}{\lambda^2} - 1\right)$$

where $k = \sqrt{2\mu E}$ and $\gamma = \sqrt{2\mu E_B}$. In addition

and λ^2=Prob. to find compact comp. in wf.

$\rightarrow$ $\lambda^2 = 1 \Longrightarrow$ Compact state with $g_0^2 = 0$

$\rightarrow$ $\lambda^2 = 0 \Longrightarrow$ Molecular state with $g_0^2 = \infty$

dimensional analysis: $g_0^2 \sim 2\pi\beta/\mu^2$ with $\beta = {}^1/_{\text{range of forces}} \gg \gamma$

Importance of two-body cut measures molecular admixture

This information is contained in the line shapes ...

For virtual states: $\gamma \rightarrow -\gamma$; λ^2 no longer prob.

Inclusion of Inelasticities

Heavy molecules decay also into

$\rightarrow$ heavy quarkonium + light quarks

e.g. $Y(4260) \rightarrow J/\psi\pi\pi$ and $X(3872) \rightarrow J\psi\pi\pi$

$\rightarrow$ decay products of constituents (if those are unstable)

e.g. $Y(4260) \rightarrow D_1\bar{D} \rightarrow [D^*\pi]\bar{D}$ (to be found ...)

$\rightarrow$ lighter open flavor channels

e.g. $W_{b2} \rightarrow D\bar{D}/D\bar{D}^*$ (to be found ...)

Accordingly the lineshapes are more rich and more telling

However, challenging experimentally, since this calls for

$\rightarrow$ good statistics

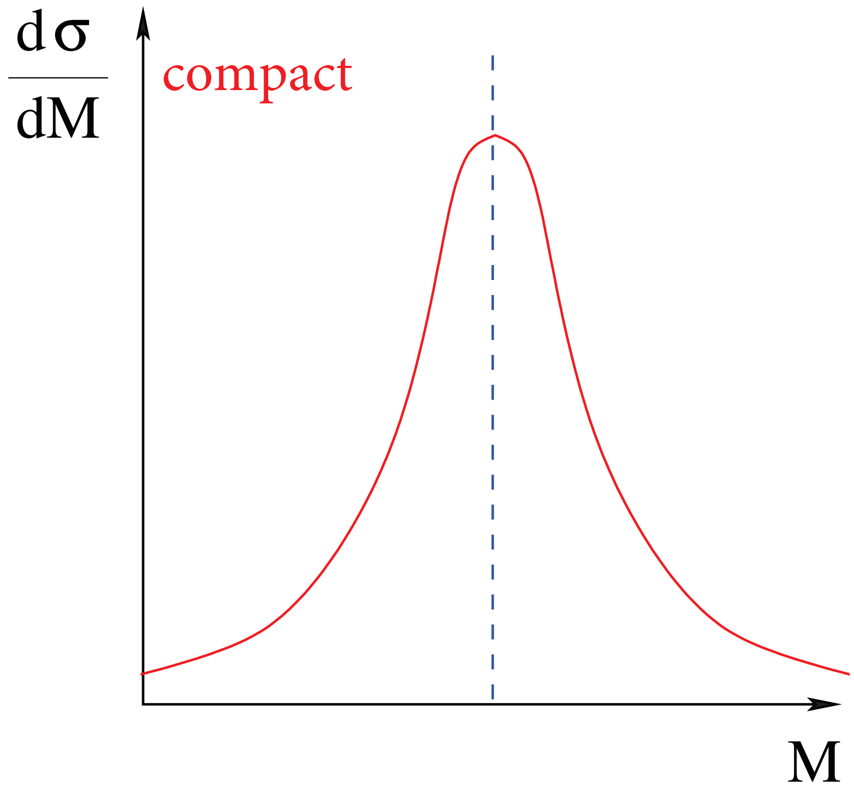
$\rightarrow$ high resolution

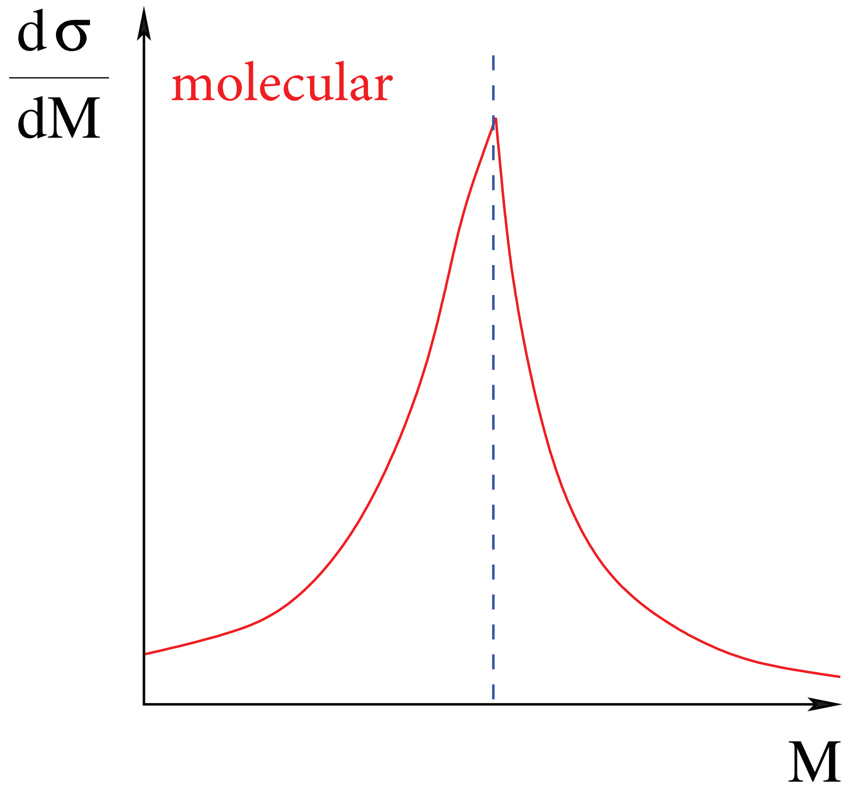
Coupling to inelastic channels

$$T_{\rm NR}(E) = \frac{g_0^2}{E+E_B+g_0^2\mu/(2\pi)(ik+\gamma)}$$

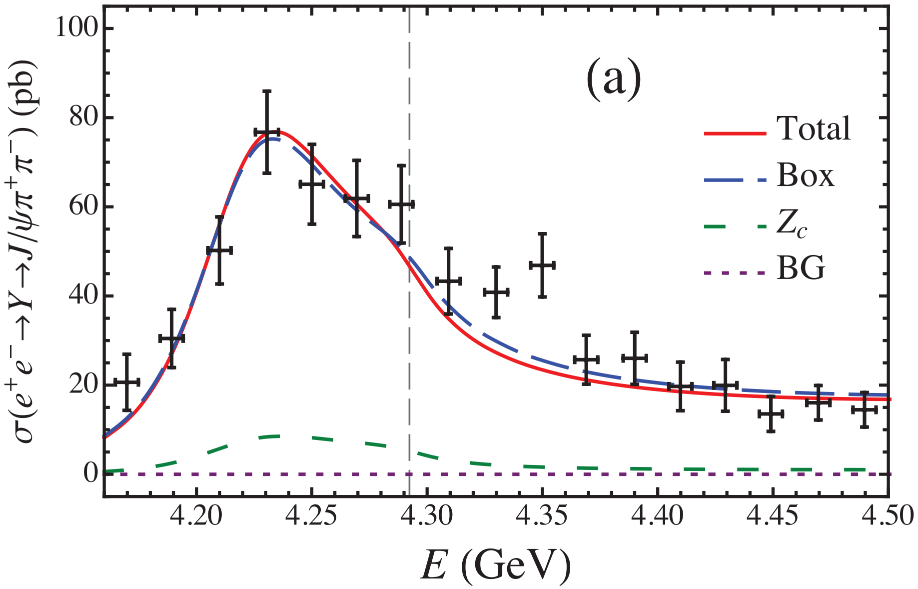
$$\Longrightarrow \frac{\{g_0^2,\Gamma_0/(2\rho)\}}{E+E_B+g_0^2\mu/(2\pi)(ik+\gamma)+i\Gamma_0/2}$$

$\rightarrow$ signal in inelastic channel(s) for very near threshold state

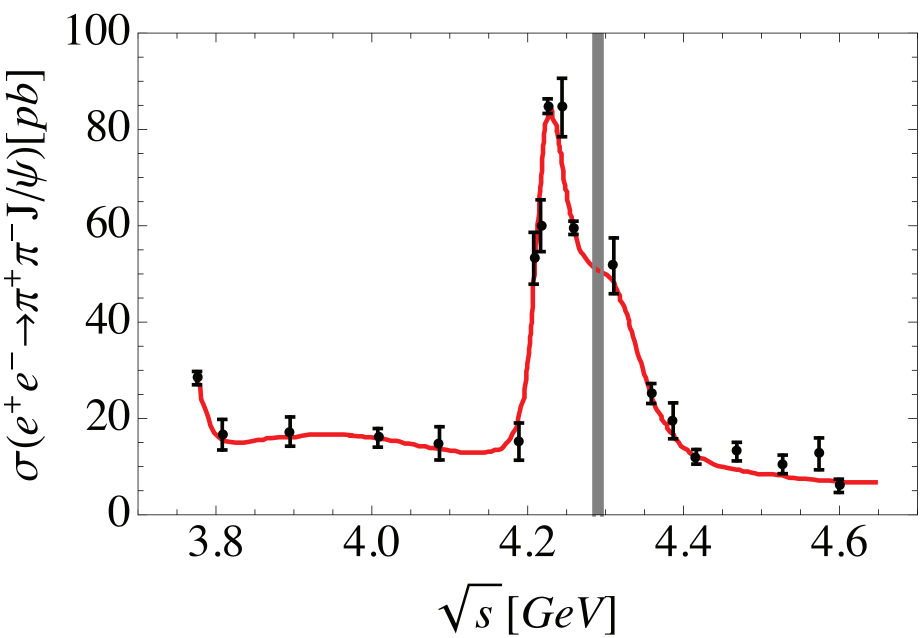




Lineshapes of $Y(4260)$



Cleven et al., PRD90 (2014) 074039



talk by Zhentian SUN for BESIII this morning

IF the $Y(4260)$ were a $D_1\bar{D}$ molecule

$\rightarrow$ it MUST have a large coupling to this channel

$\rightarrow$ this must have an impact on lineshapes

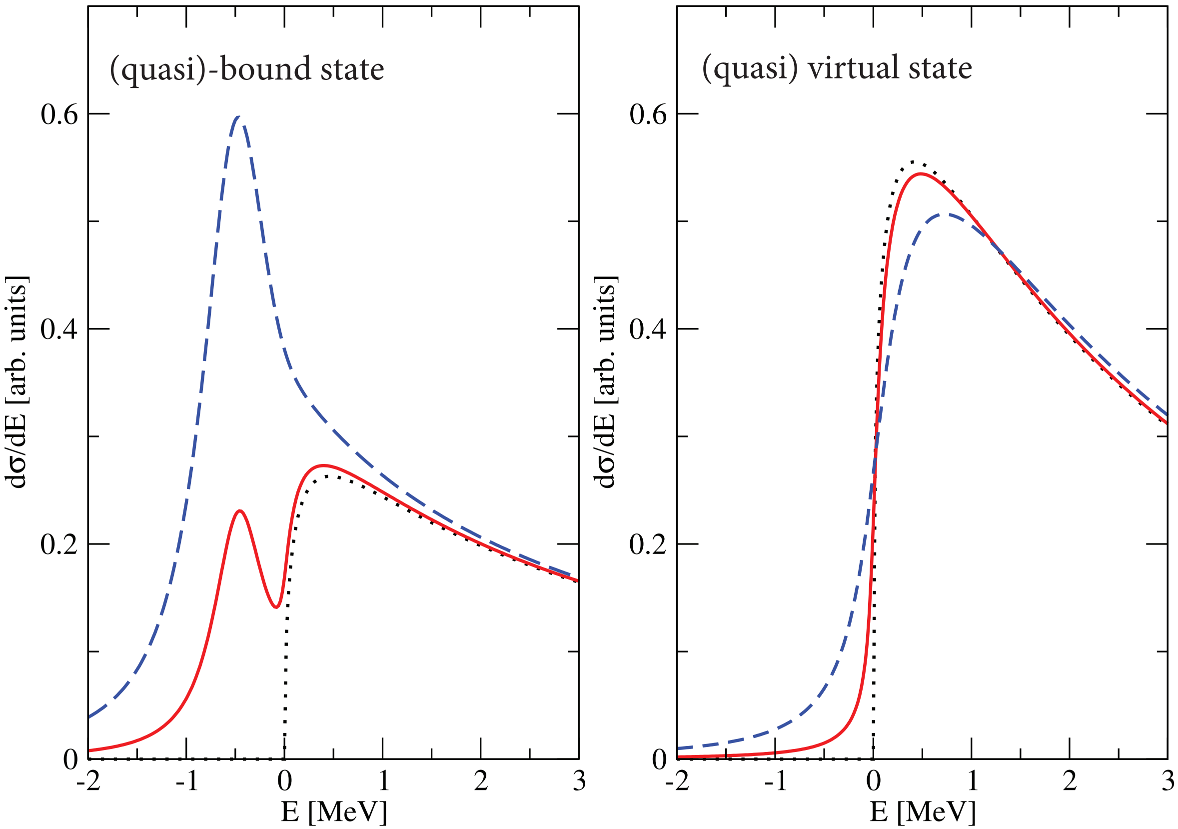
... although it is a not so near threshold state

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

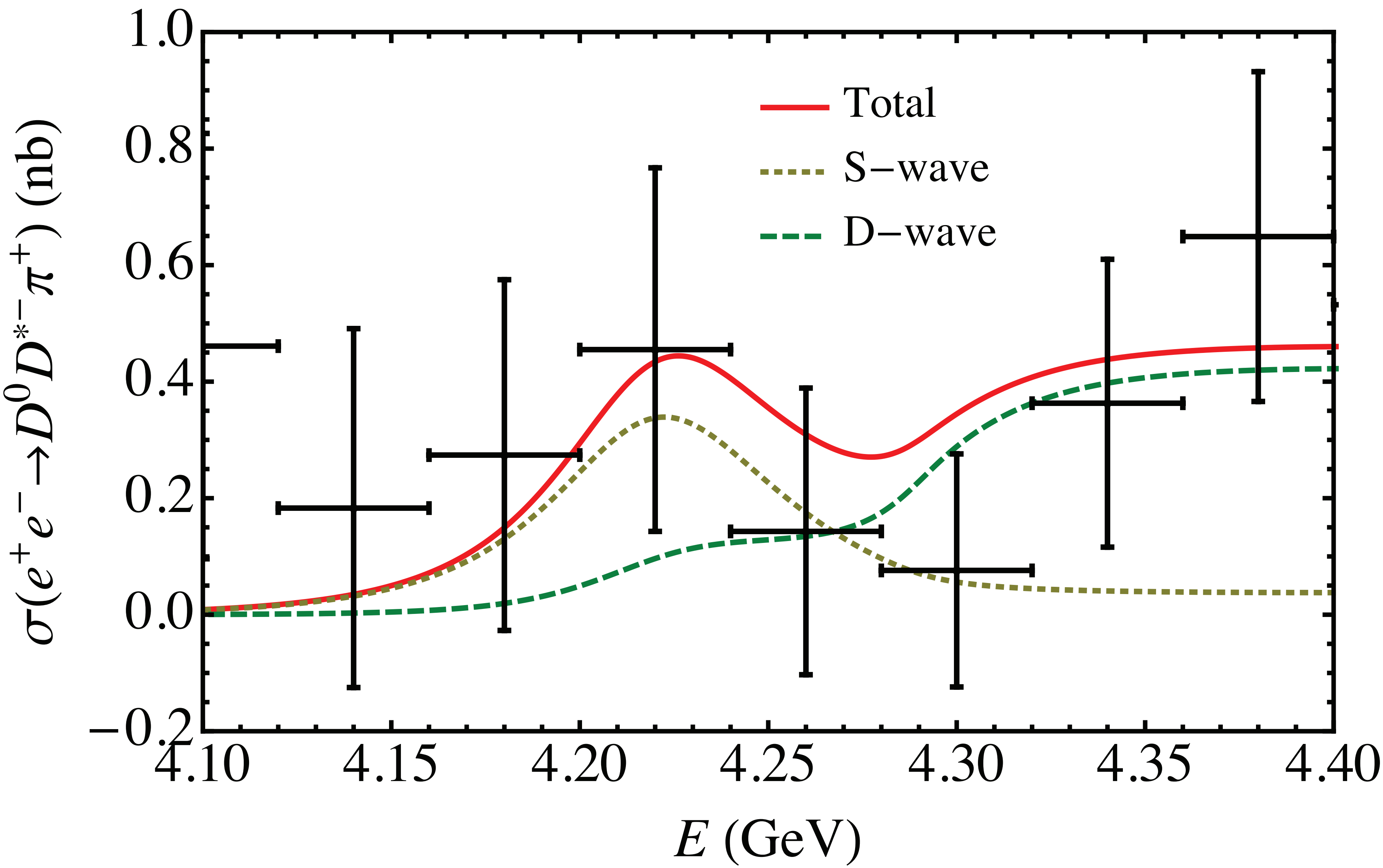
$g_0^2 = 0.2$ GeV^{-1}

natural value for molecular state

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

non-Breit-Wigner shapes emerge unavoidably!

$\mathbf{Y(4260) \to D_1\bar{D} \to [D^*\pi]\bar{D}}$



Cleven et al., PRD90 (2014) 074039; Data: Belle, PRD80 (2009) 091101

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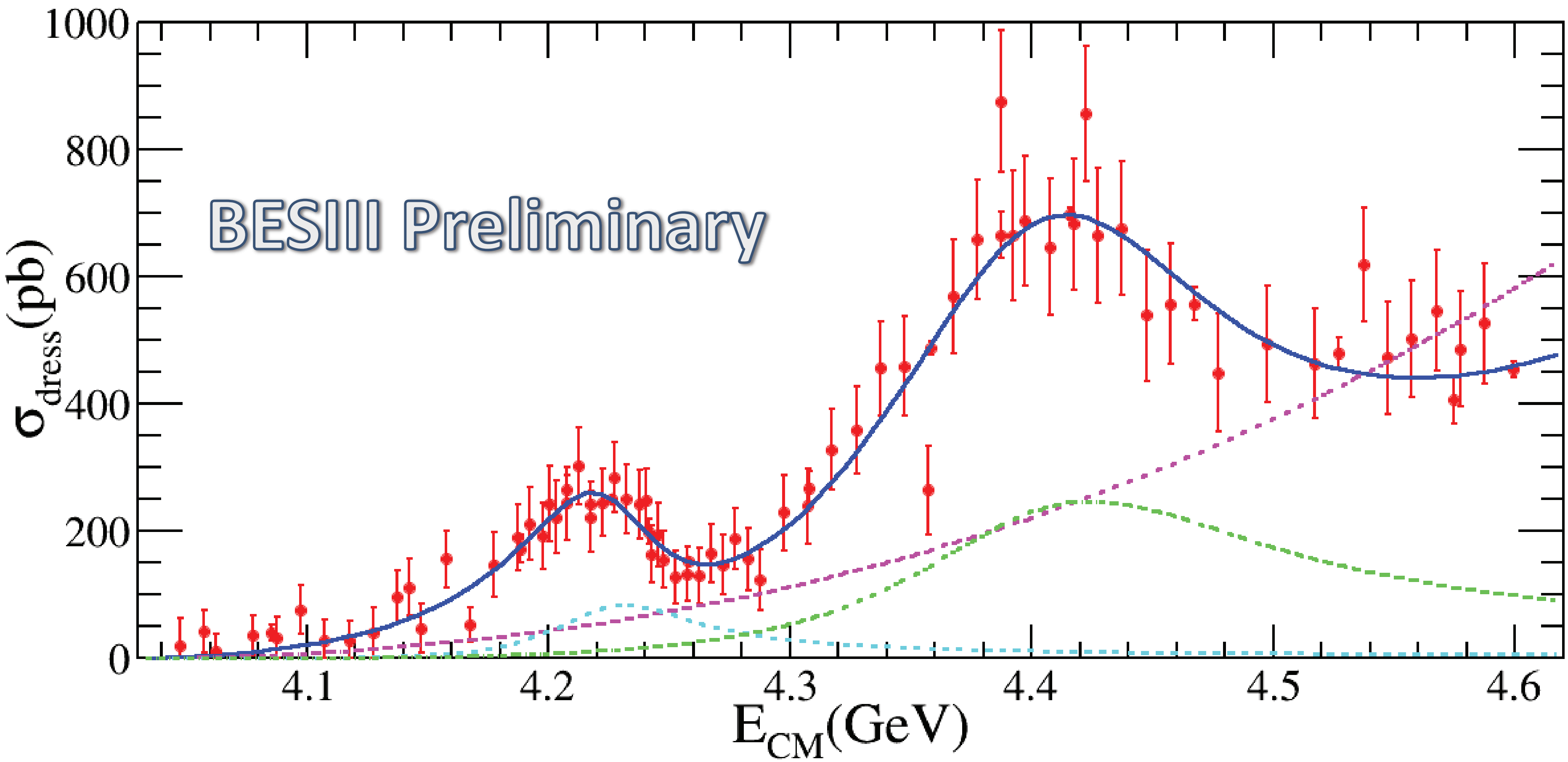
Soon there will be new data from BESIII



talk by C.-Z. Yuan for the BESIII Collaboration (2017)

... that confirm the general features!

Strong support for molecular picture of $Y(4260)$

Summary and Perspectives

→ Lineshapes contain crucial information about the molecular component of a given resonance

→ Especially, there naturally are distortions by (nominal) continuum threshold

What needs to be done?

→ Lineshapes need to be measured with high resolution and good statistics for all exotics

→ Especially, for the additional channels mentioned in the first part of the talk

Great opportunities for LHCb and PANDA

Thank you very much for your attention