Theory of hadronic molecules applied to the XYZ states

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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]

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 $E_B = m_1 + m_2 - M$

- $E_B^{\text{deuteron}} = 2.22$ MeV
- $E_B^{\text{hypertriton}} = (0.13 \pm 0.05)$ MeV (to Λd)

→ 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?

Properties of molecular states

→ Potential the strongest in S–waves

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

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

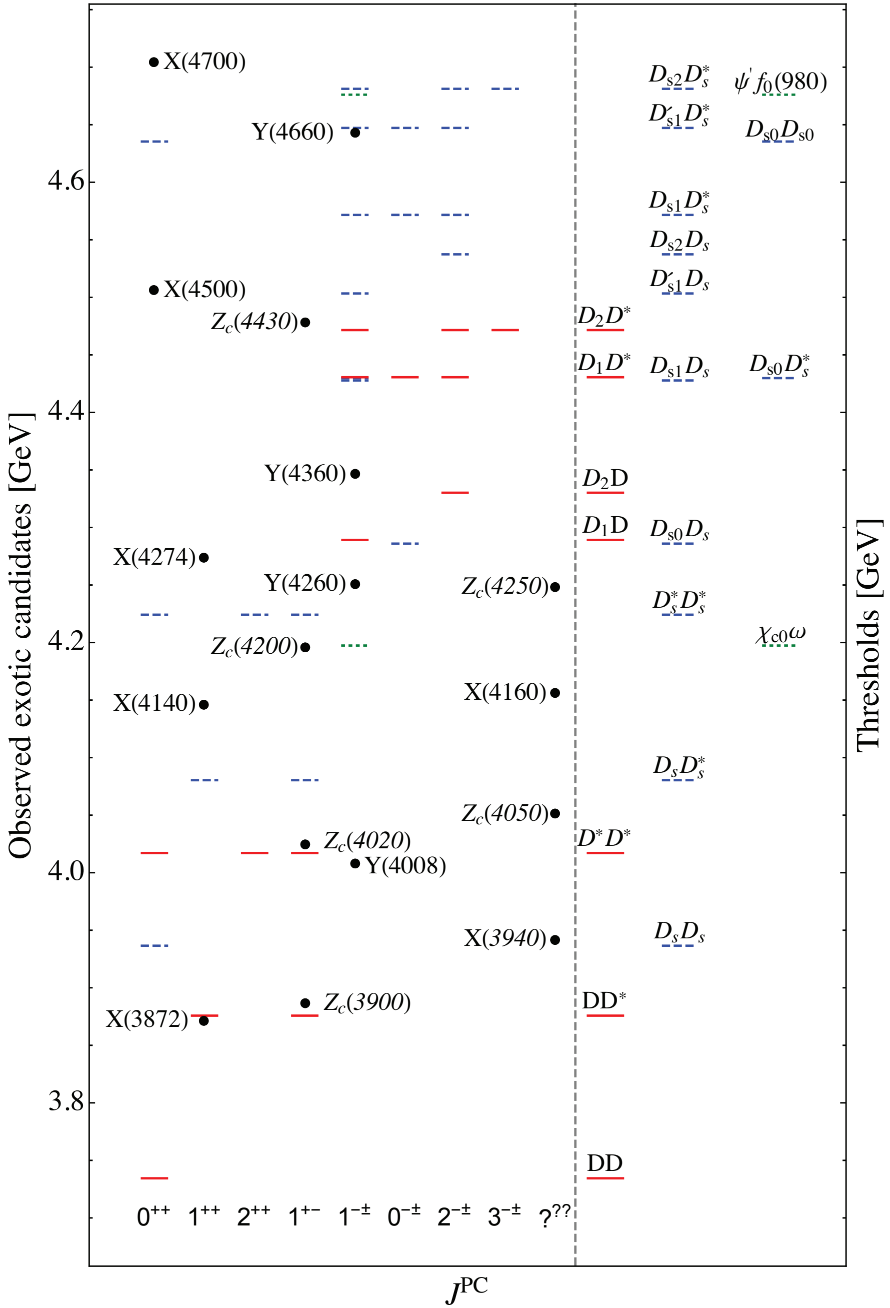
Voloshin & Okun, JETPL 23 (1976) 333; Tornqvist, PRL 67 (1991) 556.

▷ Switching C also induces sign change

▷ Potentially large coupled channel effects

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

Here: Heavy Quarkonium Sector



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)

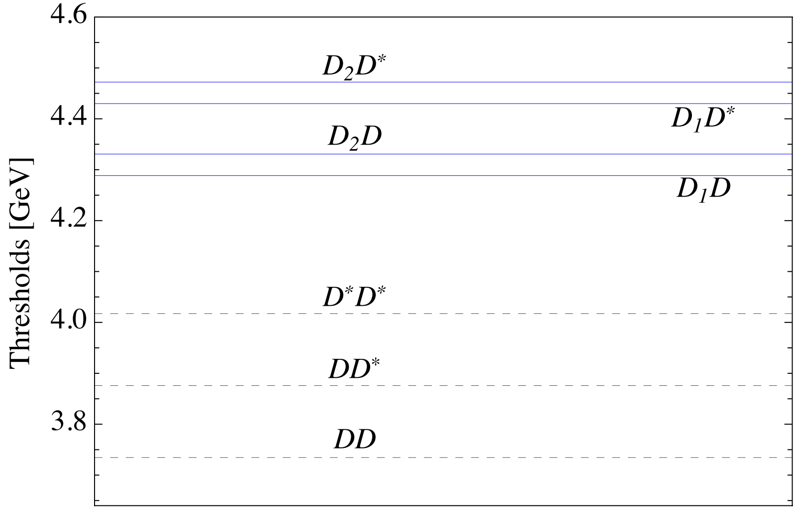
→ States not near all those thresholds

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

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

Getting more concrete

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^{++}: $DD - D^*D^*$;

→ 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

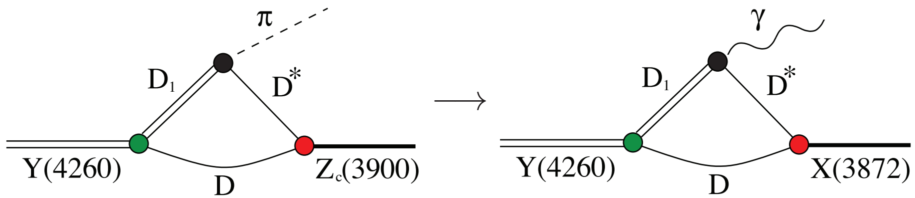
c.f. for hadrocharmonium: $M(0^-) - M(1^-) \simeq -100$ MeV

Cleven et al., PRD 92 (2015) 014005

Remarks on decays

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

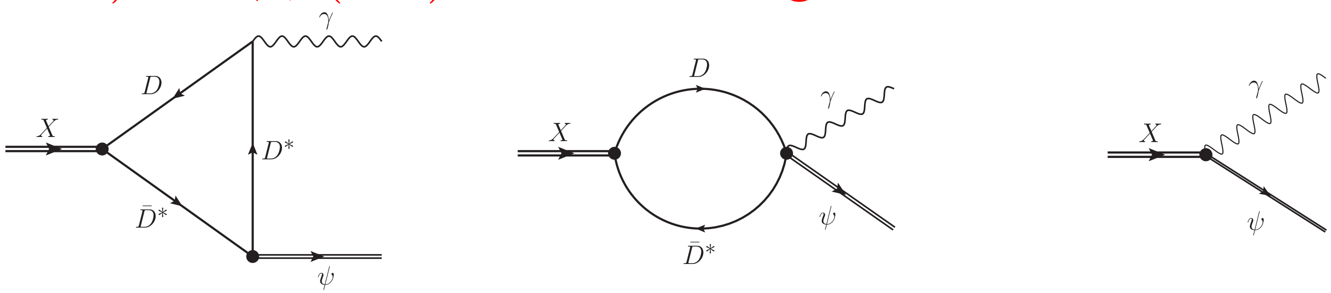
Wang, C. H., Zhao, PRL111 (2013) no.13, 132003



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

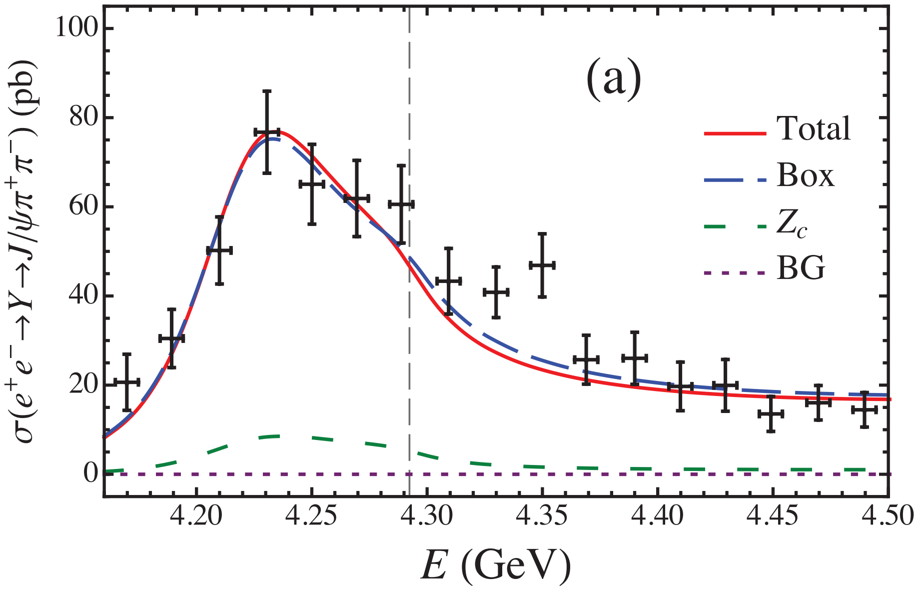


In particular: $$R = \frac{\mathcal{B}(X(3872) \to \gamma\psi')}{\mathcal{B}(X(3872) \to \gamma J/\psi)} \simeq 2.5$$ Aaij et al. [LHCb], NPB 886 (2014) 665

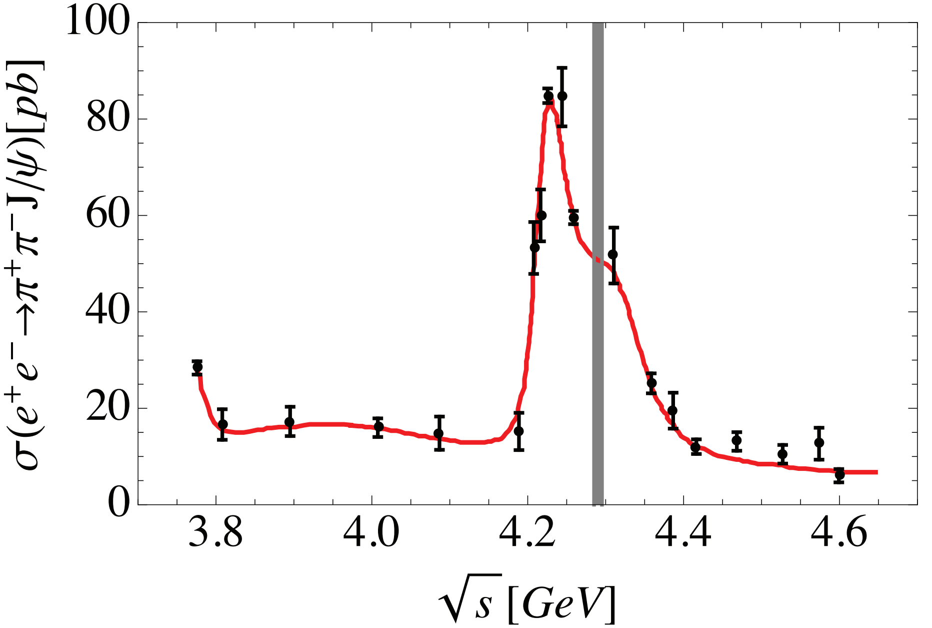
can be easily described within molecular approach

Guo et al., PLB 742 (2015) 394

Lineshapes of $Y(4260)$



Cleven et al., PRD90 (2014) 074039



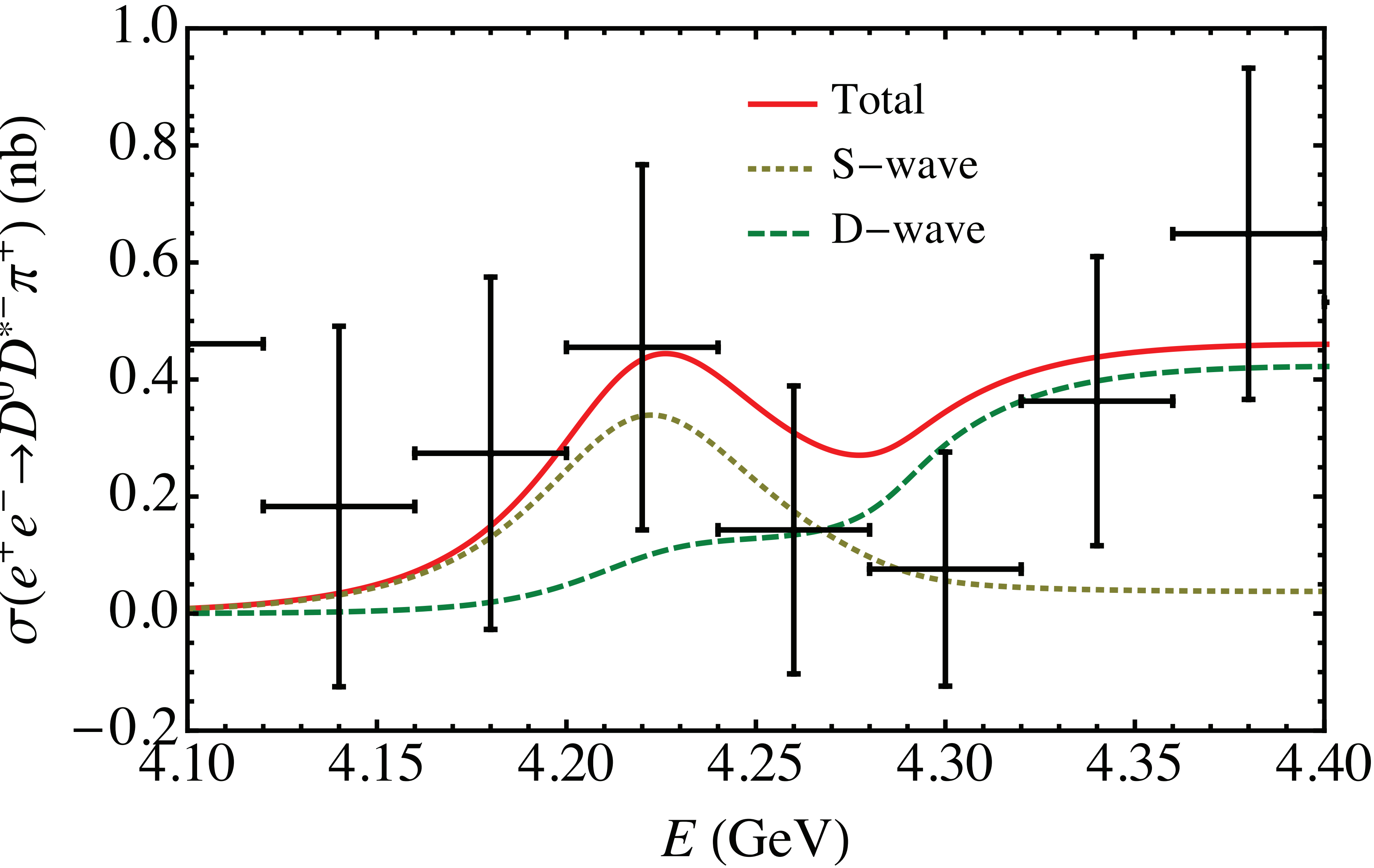
talk by Zhentian SUN for BESIII this morning

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

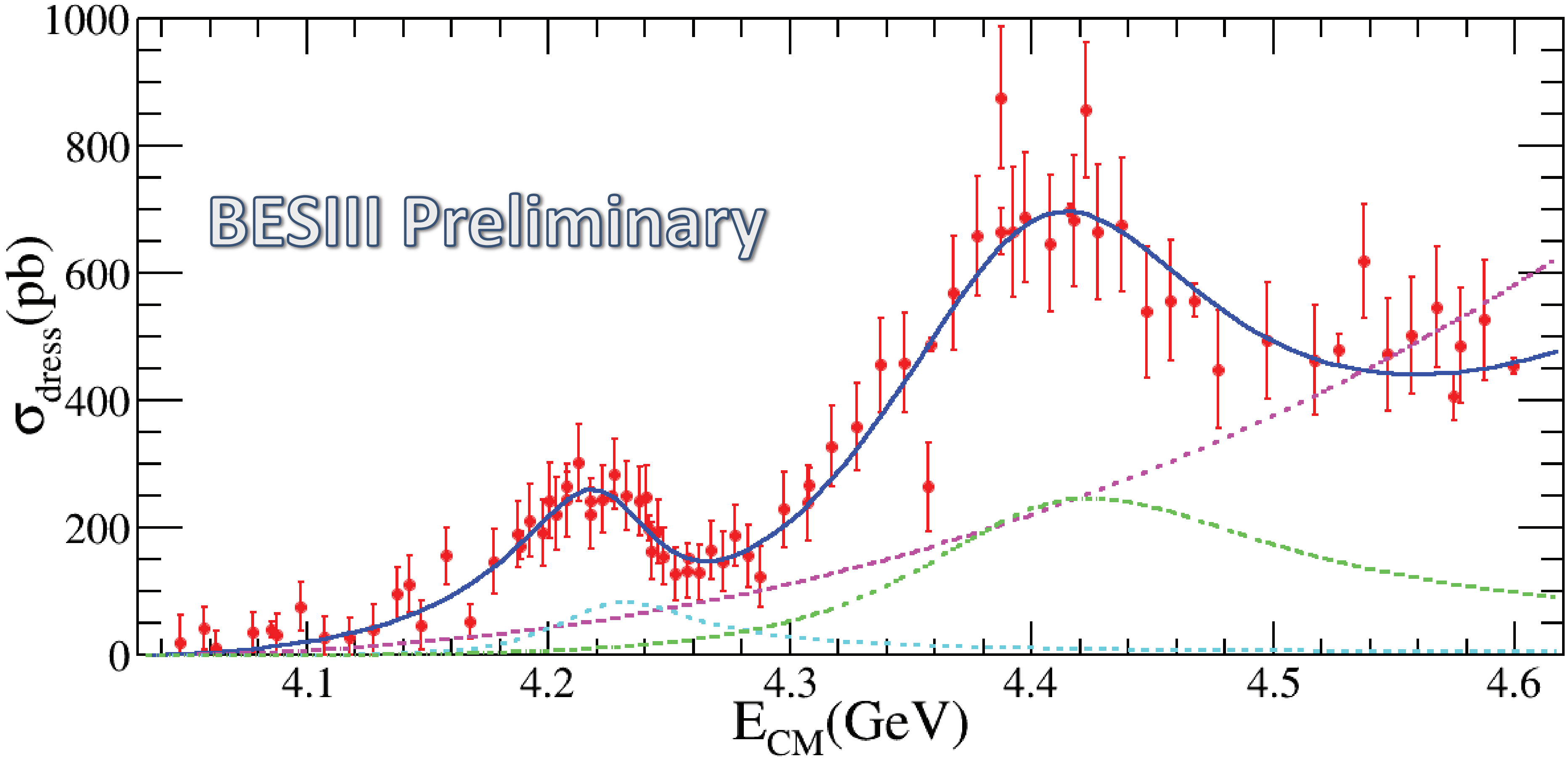
$\mathbf{Y(4260) \to D_1\bar{D} \to [D^*\pi]\bar{D}}$



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

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

Soon there will be new data from BESIII



talk by Zhentian SUN for BESIII this morning

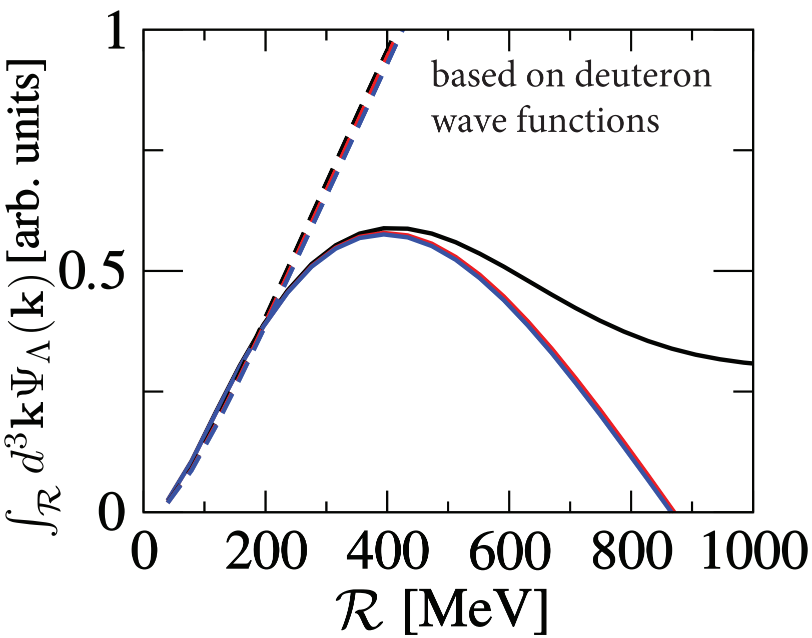
... that confirm the general features!

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

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

$\rightarrow$ Test on deuteron

Albaladejo et al. subm. to PRL

One finds: $\mathcal{R} \sim 400$ MeV using Herwig (Pythia)

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

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

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

†: D^+D^- channel included

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

fully consistent!

Summary & Perspectives

→ So far large bulk of properties of XYZ states consistent with hadronic molecule picture

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

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

Cleven et al., PRD 92 (2015) 014005

- ▷ Z_b spin partners sensitive to input parameters
- ▷ Detailed modeling calls for inclusion of π exchange

→ 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

Thanks a lot for your attention