Decays and productions of hadronic molecules

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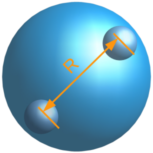
For more details and references:

FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, arXiv:1705.00141

Hadronic molecules (I)

- Many XYZ states are candidates of hadronic molecules (main component): composite system of hadrons (⇒ information for hadron-hadron interaction)
- For the constituents to be identified as hadrons, one must have
  $(E_B = m_1 + m_2 - M)$
  size: $R \sim \frac{1}{\sqrt{2\mu E_B}} \gg r_{\text{hadron}} \sim \frac{1}{\Lambda_{\text{QCD}}}$ (for hadrons containing light quarks)



  ☞ only well defined concept at large distances

  ☞ well-separated scales, can be studied using EFT

Braaten, Kusunoki, Fleming, Mehen, FKG, Hanhart, Meißner, Baru, Nefediev, . . .

- Only narrow hadrons can be considered as components of hadronic molecules, $\Gamma_h \ll 1/r$, r: range of forces

Filin *et al.*, PRL105(2010)019101; FKG, Meißner, PRD84(2011)014013

Hadronic molecules (II)

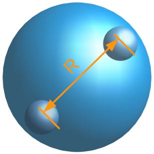
- Once the same quantum numbers, always mix with other components
- Given a process ⇒ energy/momentum scales
  - ☞ to include all relevant d.o.f. at the given scale
  - ☞ to study a near-threshold structure, the threshold channel is necessary, unless very weak coupling,

    no matter what model was used as the starting point

    ⇒ for $X(3872)$ and $Z_c(3900)$: has to consider $D\bar{D}^*$
- Only the quantities at the momentum scale $\sim 1/R$ measures the hadronic molecular component

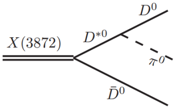
  ⇒ not all processes are sensitive to it !

  - ☞ long-distance processes
  - ☞ short-distance processes



$X(3872)$, $Y(4260)$ and $Z_c(3900)$ (I)

- Suppose that the $X(3872)$, $Y(4260)$ and $Z_c(3900)$ are hadronic molecules:
  - ☞ $X(3872)$: $J^{PC} = 1^{++}$, $D\bar{D}^*$ — Törnqvist, PLB590(2004)209; …
  - ☞ $Y(4260)$: $J^{PC} = 1^{--}$, $D_1(2420)\bar{D}$ — Wang, Hanhart, Zhao, PRL111(2013)132003
  - ☞ $Z(3900)$: $J^{PC} = 1^{+-}$, $D\bar{D}^*$ — Wang et al. (2013); FKG et al., PRD88(2013)054007; …
- Features of hadronic molecules:
  - ☞ spin partners predictable — talk by A. Nefediev
  - ☞ couple strongly to their components
    $\Rightarrow$ special line shapes — talk by C. Hanhart
  - ☞ can decay through the decays of their components
    examples:
    $X(3872) \to D^0\bar{D}^0\pi^0$, $X(3872) \to D^0\bar{D}^0\gamma$
    Voloshin (2004); …



  - ☞ seemingly unrelated processes may be related; …

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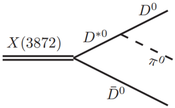

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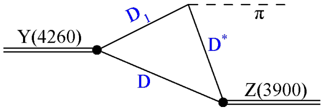
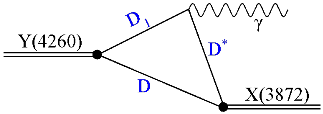
$X(3872)$, $Y(4260)$ and $Z_c(3900)$ (II)

Wang et al., PRL111(2013)132003; Cleven et al., PRD90(2014)074039; FKG et al., PLB725(2013)127

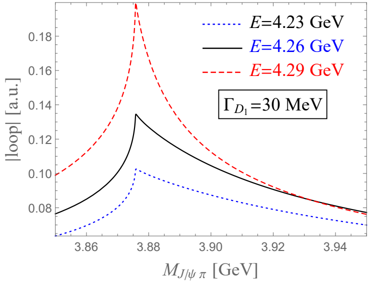
- Production of $X(3872)$ and $Z_c(3900)$ in $Y(4260)$ decays

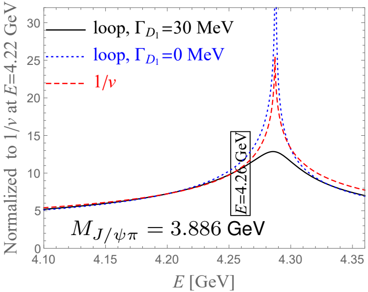




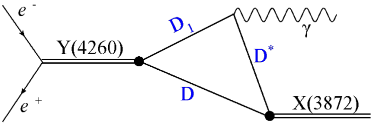
- Two enhancements: large couplings, triangle diagram

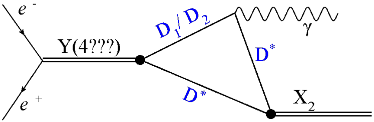
  very sensitive to the cm energy, e.g., for $Z_c(3900)\pi$





Production: $e^+e^- \to \gamma X(3872)$ and γX_2

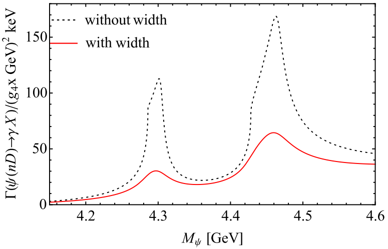


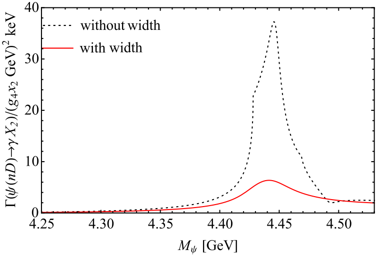


- Predicted production of $\gamma X(3872)$ FKG et al., PLB725(2013)127
  BESIII observed at $\sqrt{s} = 4.26$ GeV BESIII, PRL112(2014)092001
- Spin partner: $e^+e^- \to \gamma X_2$ in energy region FKG, Meißner, Yang, PLB740(2015)42

$$\sqrt{s} \sim 4.26 \text{ GeV} + \left(M_{D_1/D_2} + M_{D^*}\right) - \left(M_{D_1} + M_D\right) \sim [4.4, 4.5] \text{ GeV}$$

can be facilitated if there is an analogue(s) of $Y(4260)$, $Y(4360)$ or $\psi(4415)$?





High energy productions (1)

- Processes driven by short-distance $c\bar{c}$ physics, examples:
  - ☞ production of $X(3872)$ in B decays, at hadron colliders with large p_T

    Braaten et al. (2004,2005,2006,2009); Meng, Gao, Chao (2005); Bignamini et al. (2009); Meng, Han, Chao (2017);. . .
- Often used to blame the $D\bar{D}^*$ molecular interpretation . . .
- Inequality: Bignamini et al., PRL103(2009)162001

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

For $\mathcal{R} \simeq 35$ MeV $\sim$ binding momentum of $X(3872)$,

$\Rightarrow \sigma \leq 0.071$ nb $\ll 37 - 115$ nb CDF, IJMPA20(2005)3765

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&\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
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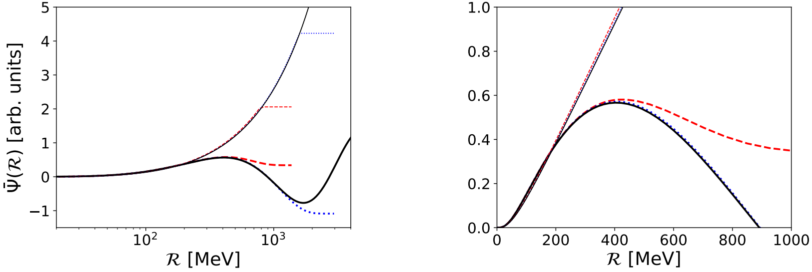
High energy productions (2)

- The deuteron as an example   Albaladejo et al., Chin.Phys.C, in print [arXiv:1709.09101]



- $\mathcal{R}$ must be much larger, $\mathcal{R} \sim 300$ MeV see also: Artoisenet, Braaten, PRD81(2010)114018

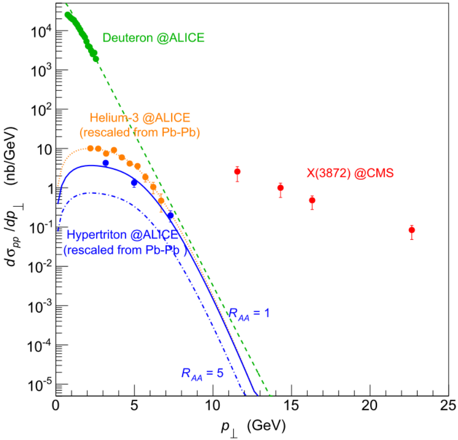
$\sigma(pp/\bar{p} \to X)$ [nb]	Exp.	Λ=0.1 GeV	Λ=0.5 GeV	Λ=1.0 GeV
CDF [IJMPA20(2005)3765]	37-115	0.07 (0.05)	7 (5)	29 (20)
CMS [JHEP1304(2013)154]	13-39	0.12 (0.04)	13 (4)	55 (15)

here $\Lambda \simeq 2\sqrt{2/\pi}\mathcal{R} \simeq 1.6\mathcal{R}$

High energy productions (3)

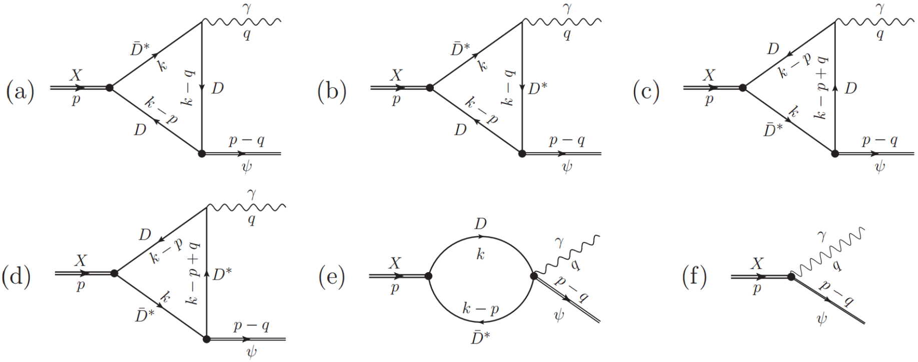
- A comparison of the production of the light nuclei and $X(3872)$, e.g.

Esposito et al., PRD92(2015)034028 :



- but deutron and X are very different at short distances:
  - ☞ deutron: 6 quarks
  - ☞ X: dominantly produced by $c\bar{c}$ at short distances

FKG, Hanhart, Kalashnikova, Meißner, Nefediev, PLB742(2015)394



The ratio $$\frac{\mathcal{B}(X(3872) \to \psi'\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$ LHCb, NPB886(2014)665

is insensitive to the molecular component of the $X(3872)$:

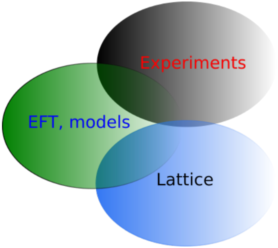
- ☞ loops are sensitive to unknown couplings $g_{\psi DD}/g_{\psi' DD}$
- ☞ loops are divergent, needs a counterterm (short-distance physics)!

see also Mehen, Springer, PRD83(2011)094009; Molnar et al., arXiv:1601.03366

Summary

- should go beyond the mass spectrum because coupling strength contains important structure information ⇒ decays and productions
- hadronic molecular component should be detected in processes sensitive to long-distance physics
- high-energy processes:

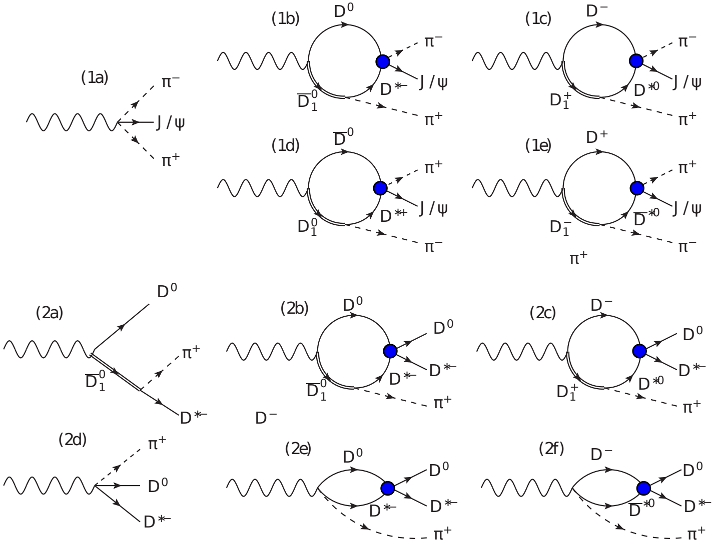
short-distance part	⊗	long-distance part	
cross section		line shapes	see talk by C. Hanhart
insensitive to		sensitive to	the hadronic molecular component



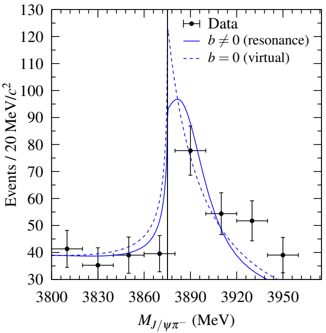
Thank you !

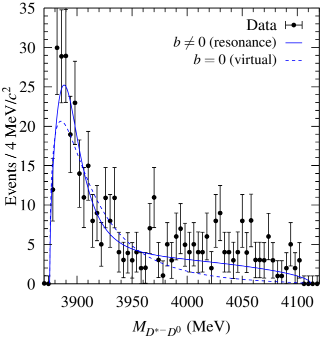
Backup slides

Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337



More about $Z_c(3900)$





M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	[1] (BESIII)	$J/\psi\ \pi$
3895 ± 8	32 ± 18	[2] (Belle)	$J/\psi\ \pi$
3886 ± 5	19 ± 5	[3] (CLEO-c)	$J/\psi\ \pi$
3884 ± 5	12 ± 6	[4] (BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	[5] (BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$
$3831 \pm 26^{+7}_{-28}$	virtual state	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$
$3844 \pm 19^{+12}_{-21}$	virtual state	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi,\ \bar{D}^* D$

resonance pole

or virtual state

Decays: $X(3872) \to D^0\bar{D}^0\pi^0$

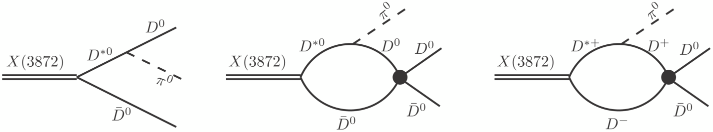
- A long-distance process, thus can be studied in nonrelativistic EFT
- Already studied by many authors

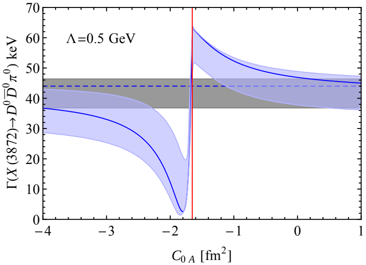
Voloshin (2004); Fleming et al (2007); Braaten, Lu (2007); Hanhart et al (2007); . . .

Our new insight: FKG et al., EPJC74(2014)2885

If there is a near-threshold $D\bar{D}$ hadronic molecule $\Rightarrow$ a large impact

Problem: one unknown contact term C_{0A}





☞ grey band: tree-level result (consistent with Fleming et al., PRD76(2007))

☞ vertical line: a $D\bar{D}$ bound state at threshold