Production of Tetraquarks at the LHC

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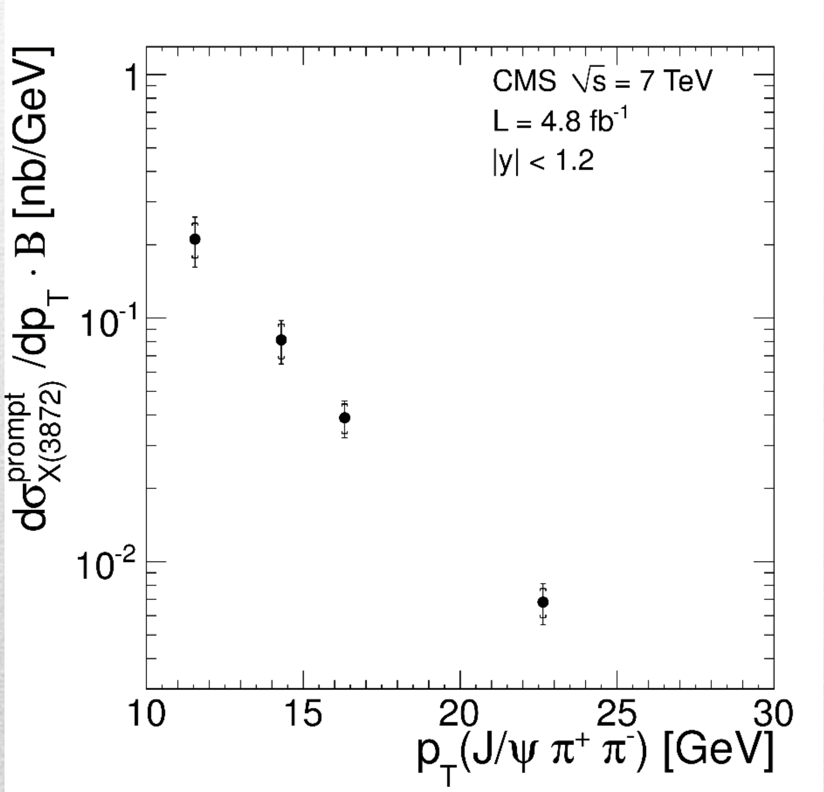
HADRON2015
Newport News – September 17th, 2015

INFN Istituto Nazionale di Fisica Nucleare

Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003
Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

Prompt production of $X(3872)$

In this talk we will comment data and MC simulations about the prompt production of hadronic molecules at hadron colliders



CMS, JHEP 1304 (2013) 154

The question is:

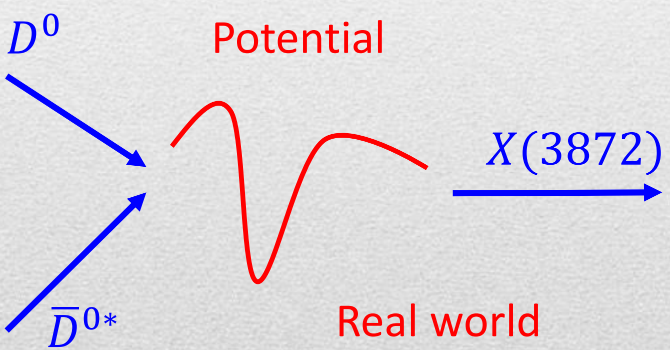
«Are large prompt production cross sections at hadron colliders compatible with a loosely bound molecule interpretation?»

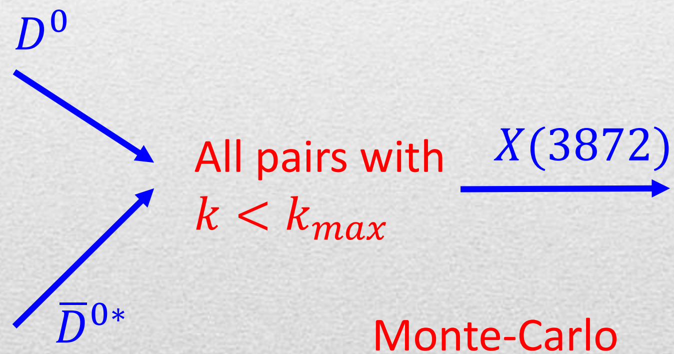
Hadronic molecules with MC simulations

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?)

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

Q. What is a molecule in MC? **A.** «Coalescence» model





$$\sigma\big(p\bar{p} \to X(3872)\big) \sim \int d^3k \; |\langle X|D\bar{D}^*\rangle\langle D\bar{D}^*|p\bar{p}\rangle|^2 < \int_{k<k_{max}} d^3k \; |\langle D\bar{D}^*|p\bar{p}\rangle|^2$$

This should provide an upper bound for the cross section

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001
Kadastic, Raidan, Strumia PLB683 (2010) 248

Estimating k_{max}

The binding energy is $E_B \approx -0.16 \pm 0.31 \text{ MeV}$ (PDG): very small!
In a simple square well model this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 10 \text{ fm}$$

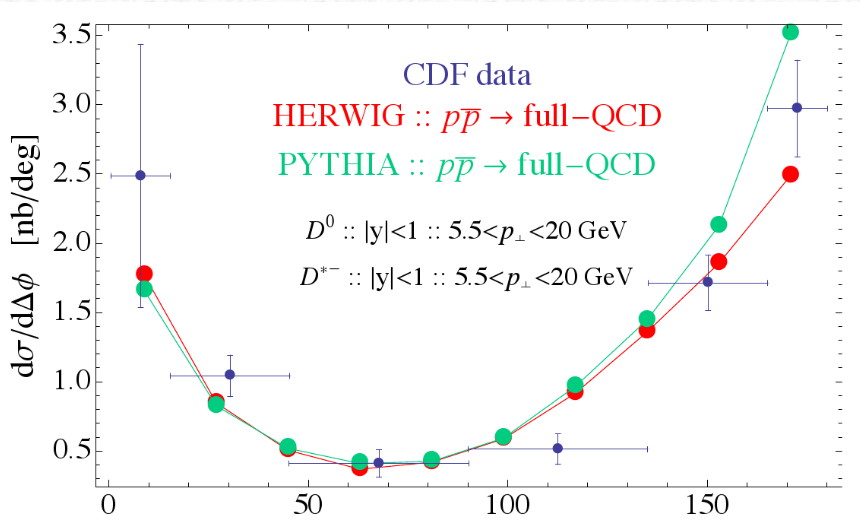
$$\left(\begin{array}{c} \text{binding energy reported by NU, PRD91, 011102} \\ E_B \approx -0.013 \pm 0.192 \text{ MeV: } \sqrt{\langle k^2 \rangle} \approx 30 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 30 \text{ fm} \end{array} \right)$$

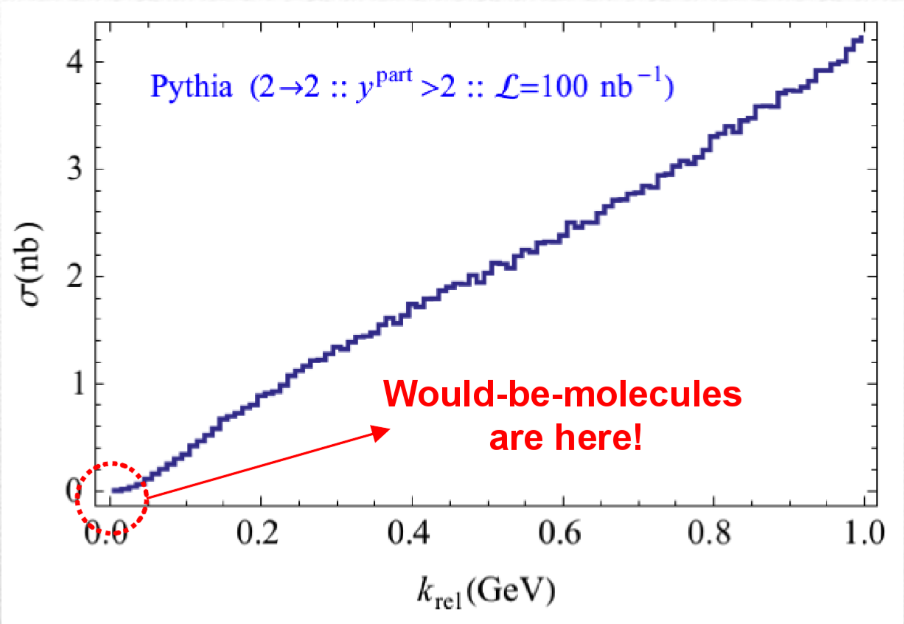
to compare with deuteron: $E_B = -2.2 \text{ MeV}$

$$\sqrt{\langle k^2 \rangle} \approx 80 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 4 \text{ fm}$$

We assume $k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV}$, some other choices are commented later

Results





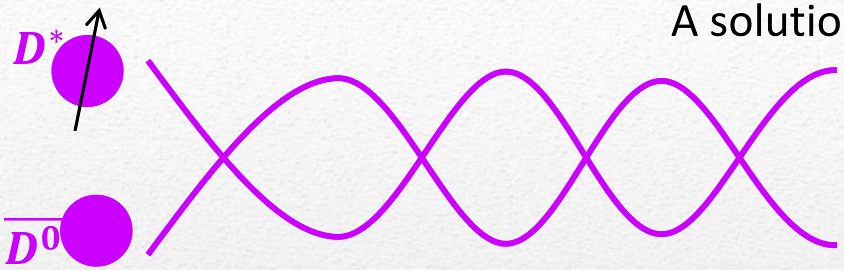
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

We get $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 0.1$ nb $@\sqrt{s} = 1.96$ TeV

Experimentally $\sigma(p\bar{p} \to X(3872)) \approx 30 - 70$ nb!!!

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Estimating k_{max}



A solution can be FSI (rescattering of DD^*) , which allow k_{max} to be as large as $5m_\pi \sim 700$ MeV

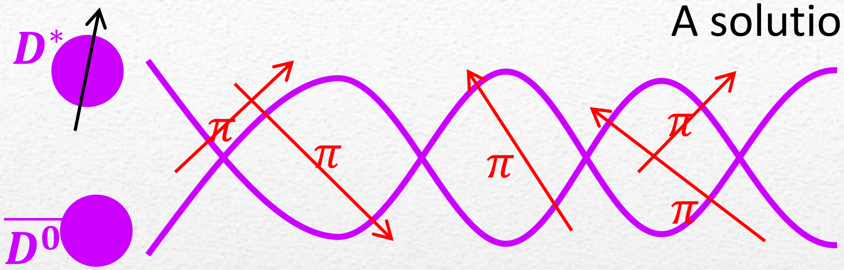
$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -NA^{on}_{prod} \cdot \frac{e^{i\delta}\sin\delta}{ka_{NN}}$$

$$\sigma\big(p\bar{p} \to X(3872)\big) \to \sigma(p\bar{p} \to DD^*|k < k_{max}) \times \frac{6\pi\sqrt{2\mu\, E_B}}{k_{max}}$$

Estimating k_{max}



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$\sigma(p\bar{p} \to DD^* | k < k_{max}) \approx 230\ \mathrm{nb}$

Artoisenet and Braaten, PRD81, 114018

However, the applicability of Watson theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten, PRD83, 014019

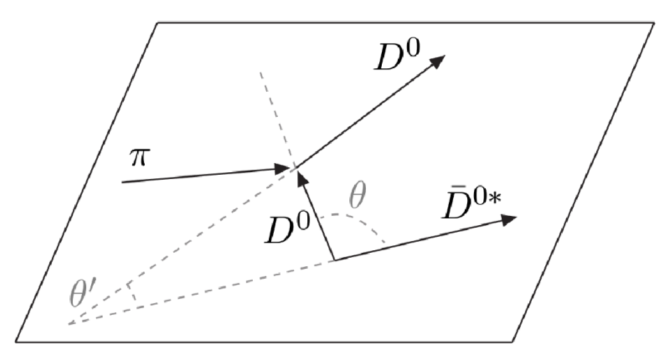
Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354
use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty,
limits on predictive power

A new mechanism?

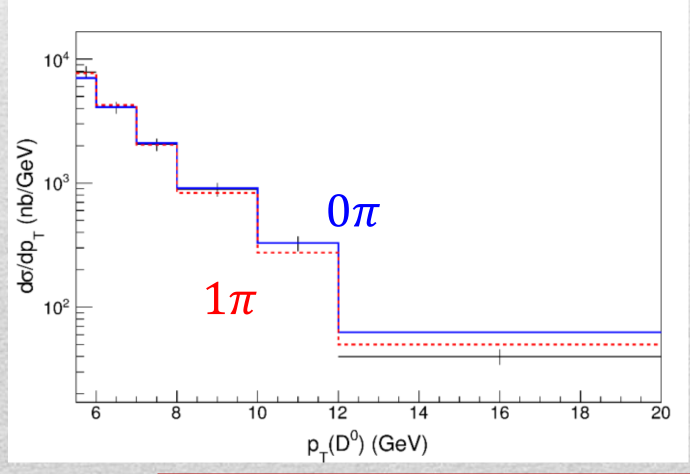
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the DD^* pairs

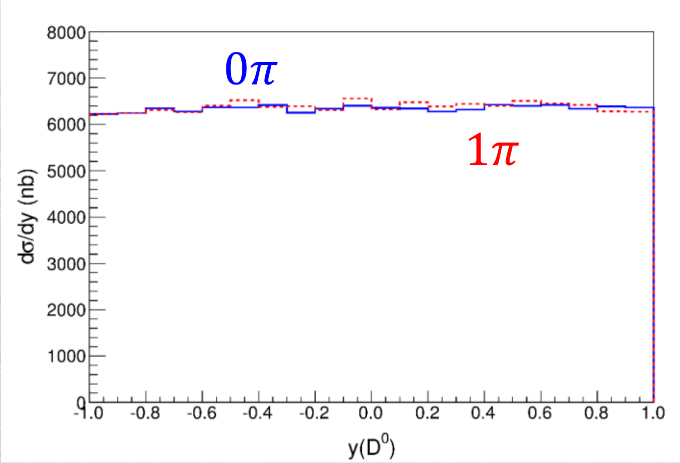
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003



The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100\ \mathrm{keV}$





This picture could spoil existing meson distributions used to tune MC
We verify this is not the case up to an overall K factor

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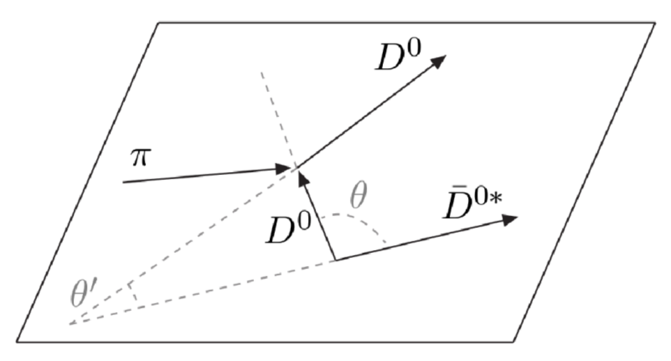

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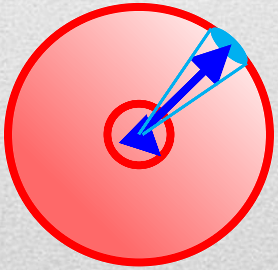
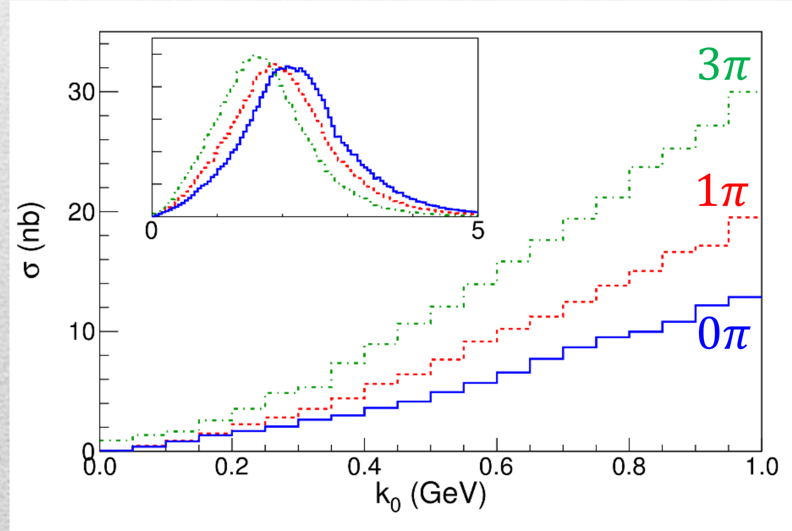


By comparing hadronization times of heavy and light mesons, we estimate up to ~ 3 collisions can occur before the heavy pair to fly apart

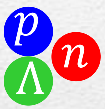


We get $\sigma\left(p\bar{p} \to X(3872)\right) \sim 5\ \mathrm{nb}$, still not sufficient to explain all the experimental cross section

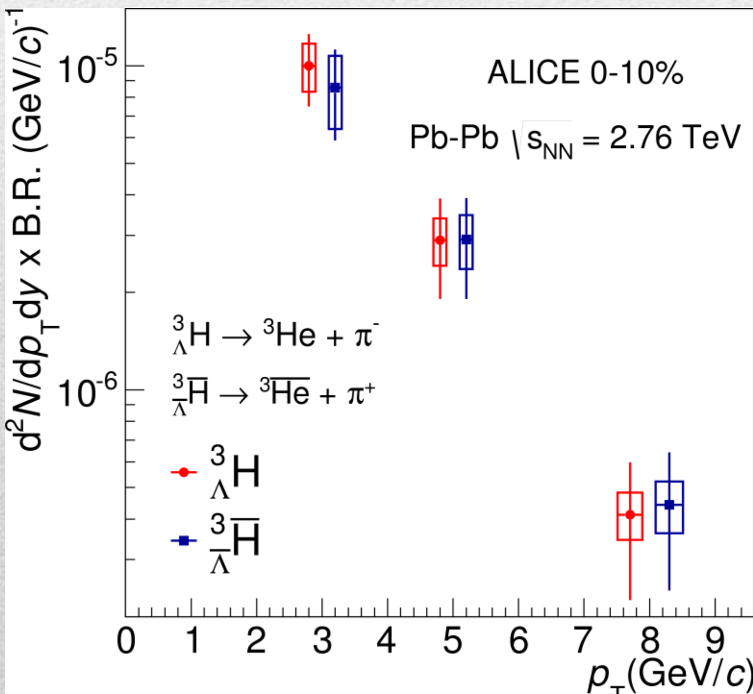
Light nuclei at ALICE

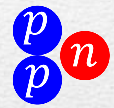
Recently, ALICE published data on production of light nuclei in Pb-Pb and *pp* collisions

These might provide a benchmark for $X(3872)$ production

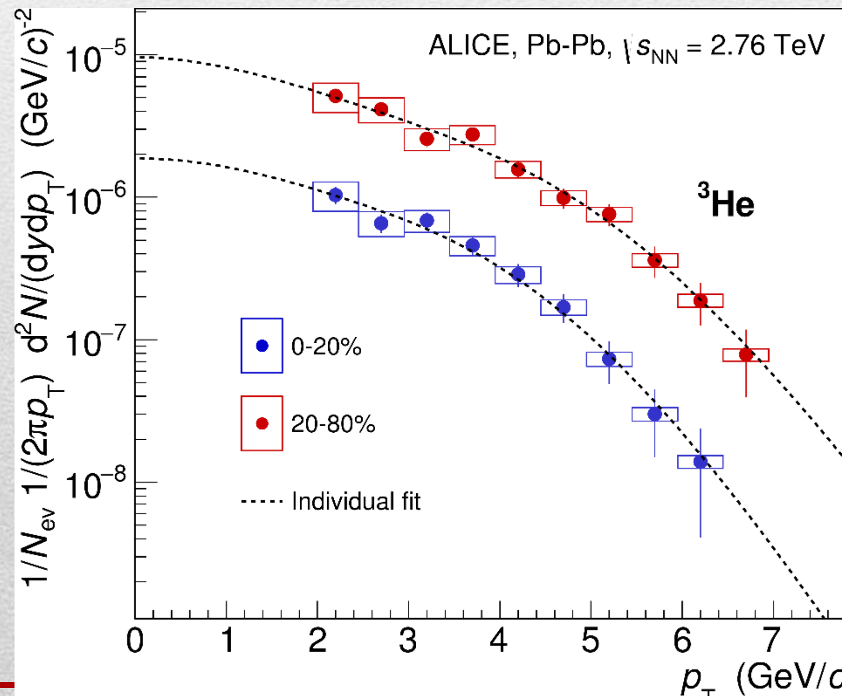


Hypertriton
arXiv:1506.08453

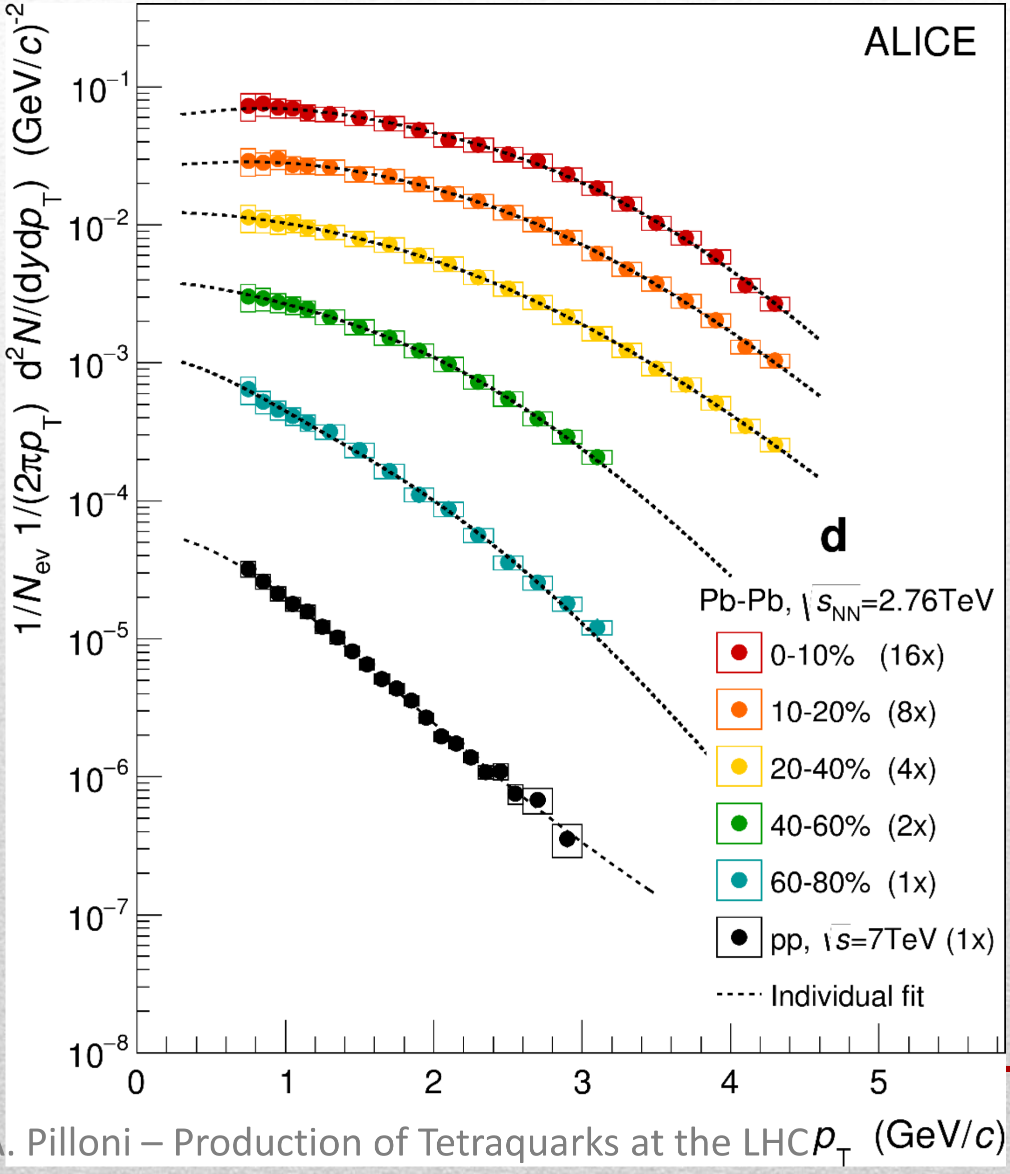


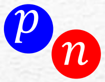


Helium-3
arXiv:1506.08951



Light nuclei at ALICE



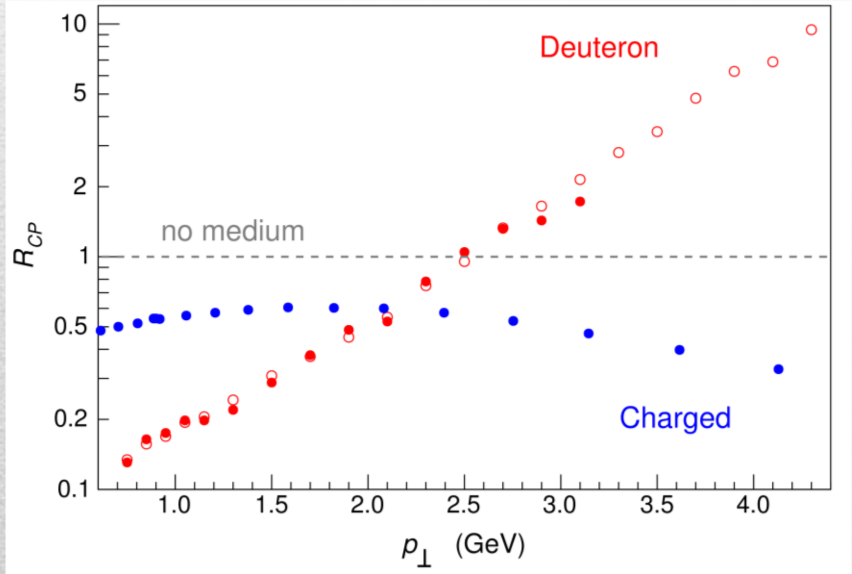


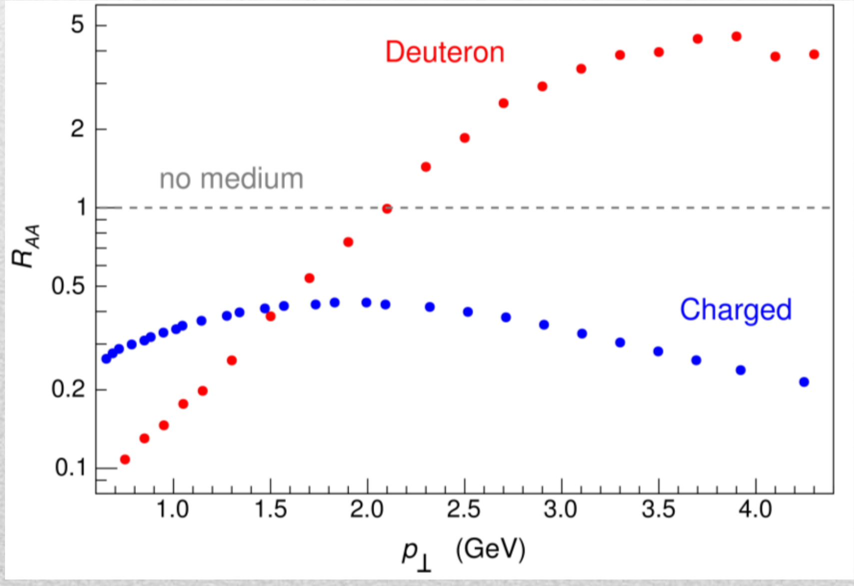
Deuteron
arXiv:1506.08951

Nuclear modification factors

We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

$$R_{CP} = \frac{N_{coll}^{P}\left(\frac{dN}{dp_T}\right)_{C}}{N_{coll}^{C}\left(\frac{dN}{dp_T}\right)_{P}} \qquad R_{AA} = \frac{\left(\frac{dN}{dp_T}\right)_{\text{Pb-Pb}}}{N_{coll}\left(\frac{dN}{dp_T}\right)_{pp}}$$





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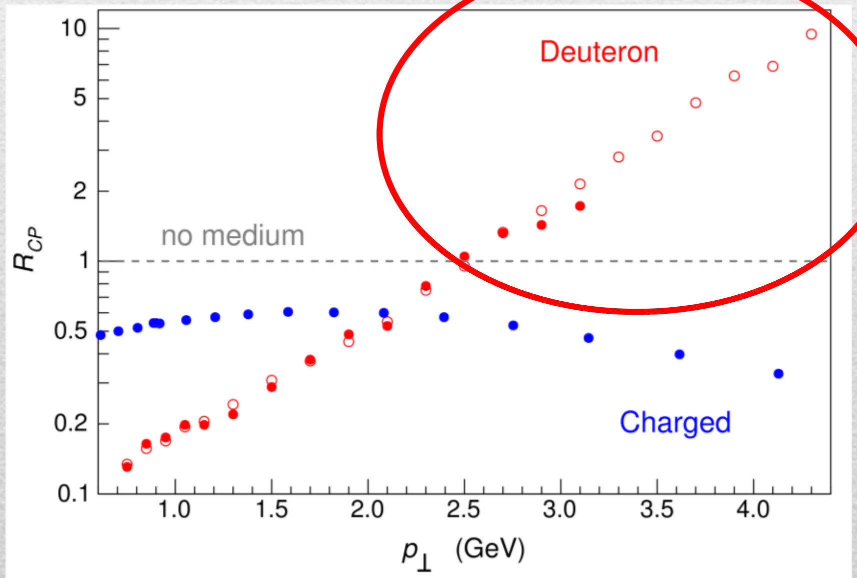
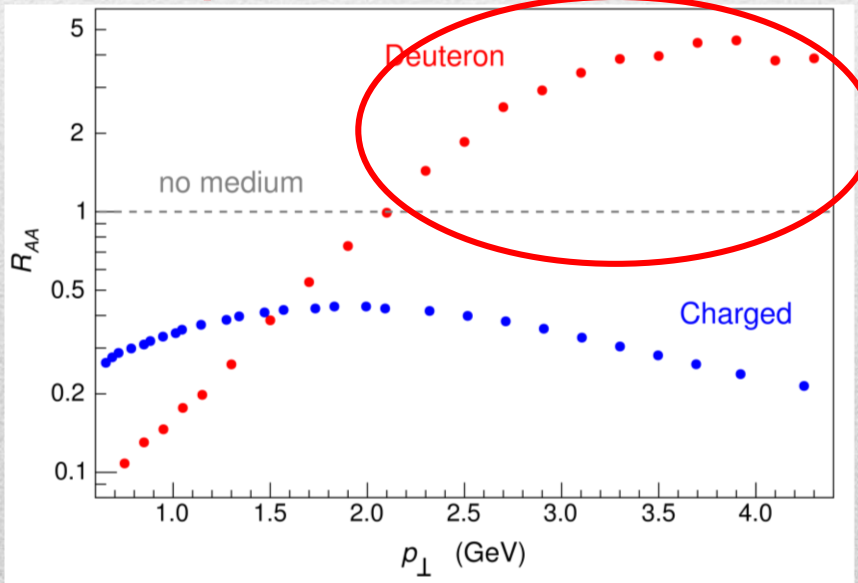
Larger than 1 at $p_T > 2.5$ GeV





Light nuclei at ALICE

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

Constant RAA → same shape in Pb-Pb and pp

$$\left(\frac{d\sigma\left({}^3_\Lambda\mathrm{H}\right)}{dp_\perp}\right)_{pp} = \frac{\Delta y}{\mathcal{B}({}^3\mathrm{He}\,\pi)} \times \frac{\sigma_{pp}^{\mathrm{inel}}}{N_{\mathrm{coll}}}\left(\frac{1}{N_{\mathrm{evt}}}\frac{d^2N({}^3\mathrm{He}\,\pi)}{dp_\perp dy}\right)_{\mathrm{Pb\text{-}Pb}}$$

We extrapolate this data at higher p_T either by assuming an exponential law, or with a blast-wave function, which describes the emission of particles in an espanding medium

The blast-wave function is

$$\frac{dN}{dp_\perp} \propto p_\perp \int_0^R r dr\, m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{\mathrm{kin}}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{\mathrm{kin}}}\right),$$

where $m_\perp$ is the transverse mass, R is the radius of the fireball, I_0 and K_1 are the Bessel functions, $\rho = \tanh^{-1}\left(\frac{(n+2)\langle\beta\rangle}{2}(r/R)^n\right)$, and $\langle\beta\rangle$ the averaged speed of the particles in the medium.

Light nuclei at ALICE

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

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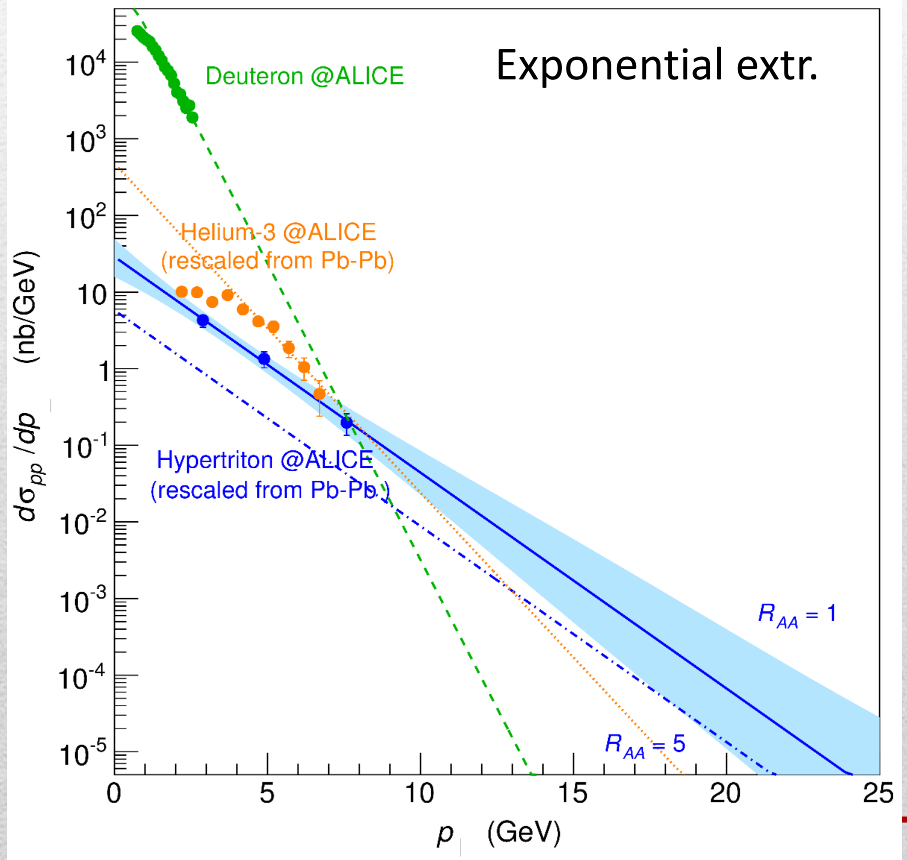
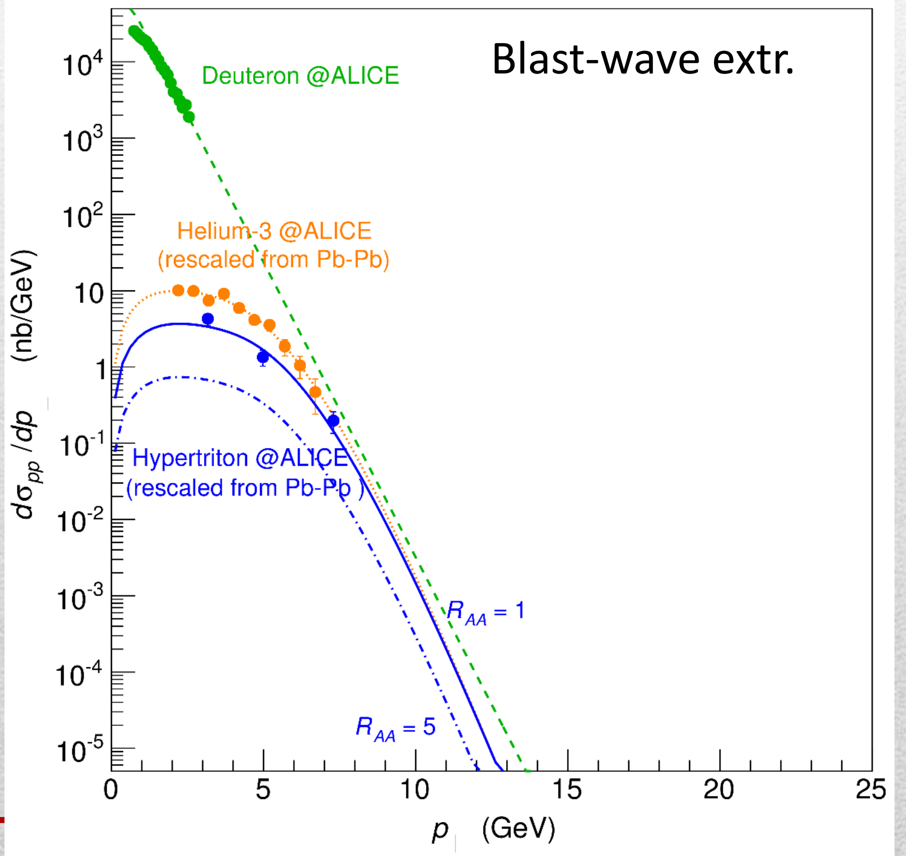


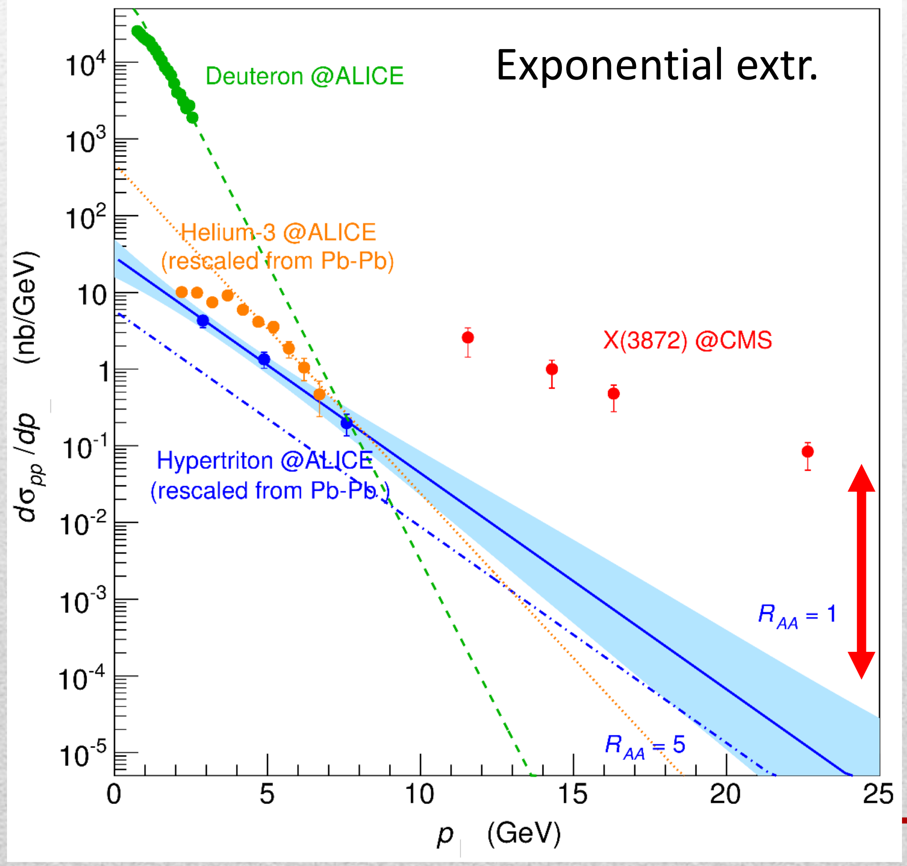


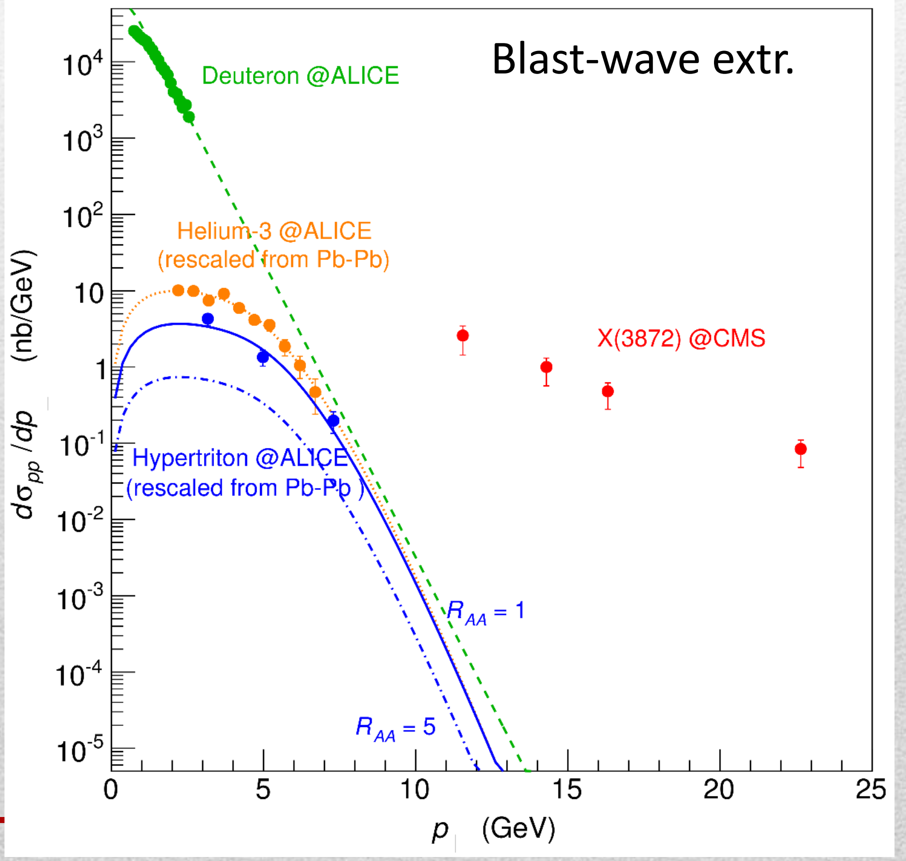
Light nuclei at ALICE vs. $X(3872)$

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

The $X(3872)$ is way larger than the extrapolated cross section





Conclusions

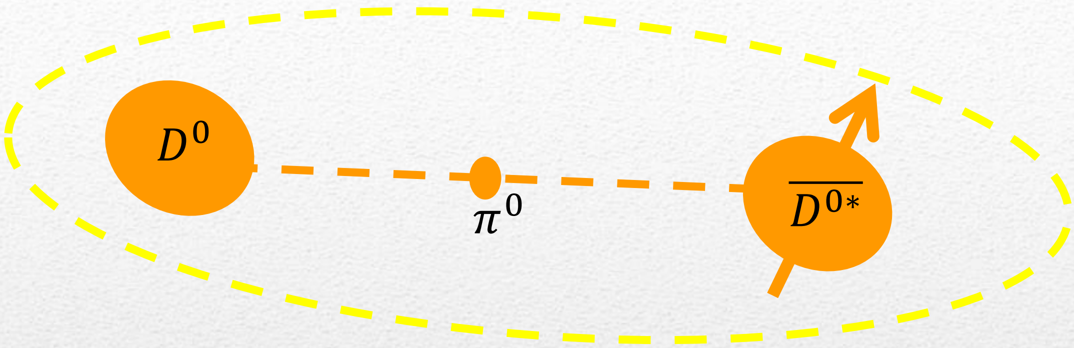
- Large exotics prompt production cross sections are still the main issue of the molecular pictures
- Extrapolations of light nuclei data suggest a different interpretation for the $X(3872)$
- New data on light nuclei production in pp collisions at higher p_T by ALICE (and LHCb?) will provide a conclusive word on the topic

Thank you

BACKUP

Molecule

Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305



$X(3872) \sim \bar{D}^0 D^{*0}$
$Z_c(3900) \sim \bar{D}^0 D^{*+}$
$Z_c'(4020) \sim \bar{D}^{*0} D^{*+}$
$Y(4260) \sim \bar{D} D_1$

A deuteron-like meson pair, the interaction is mediated by the exchange of light mesons

- Some model-independent relations (Weinberg's theorem) ✓
- Good description of decay patterns (mostly to constituents) and $\mathrm{X}(3872)$ isospin violation ✓
- States appear close to thresholds ✓ (but $Z(4430)$ ×)
- Lifetime of costituents has to be $\gg 1/m_\pi$, (but why $\Gamma_Y \gg \Gamma_{D_1}$?)
- Binding energy varies from -70 to -0.1 MeV, or even positive (repulsive interaction) ×
- Unclear spectrum (a state for each threshold?) – depends on potential models ×

$$V_\pi(r) = \frac{g_{\pi N}^2}{3} (\vec{\tau_1} \cdot \vec{\tau_2}) \left\{ [3(\vec{\sigma_1} \cdot \hat{r})(\vec{\sigma_2} \cdot \hat{r}) - (\vec{\sigma_1} \cdot \vec{\sigma_2})] \left(1 + \frac{3}{(m_\pi r)^2} + \frac{3}{m_\pi r} \right) + (\vec{\sigma_1} \cdot \vec{\sigma_2}) \right\} \frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

Weinberg theorem

Resonant scattering amplitude

$$f(ab \to c \to ab) = -\frac{1}{8\pi\, E_{CM}} g^2 \frac{1}{(p_a + p_b)^2 - m_c^2}$$

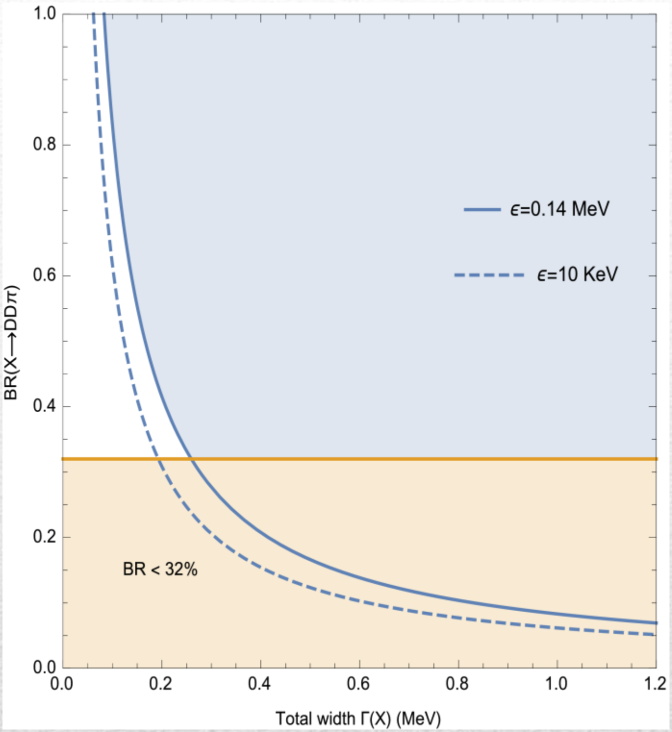
with $m_c = m_a + m_b - B$, and $B, T \ll m_{a,b}$

$$f(ab \to c \to ab) = -\frac{1}{16\pi(m_a + m_b)^2} g^2 \frac{1}{B + T}$$

This has to be compared with the potential scattering for slow particles ($kR \ll 1$, being $R \sim 1/m_\pi$ the range of interaction) in an attractive potential U with a superficial level at $-B$

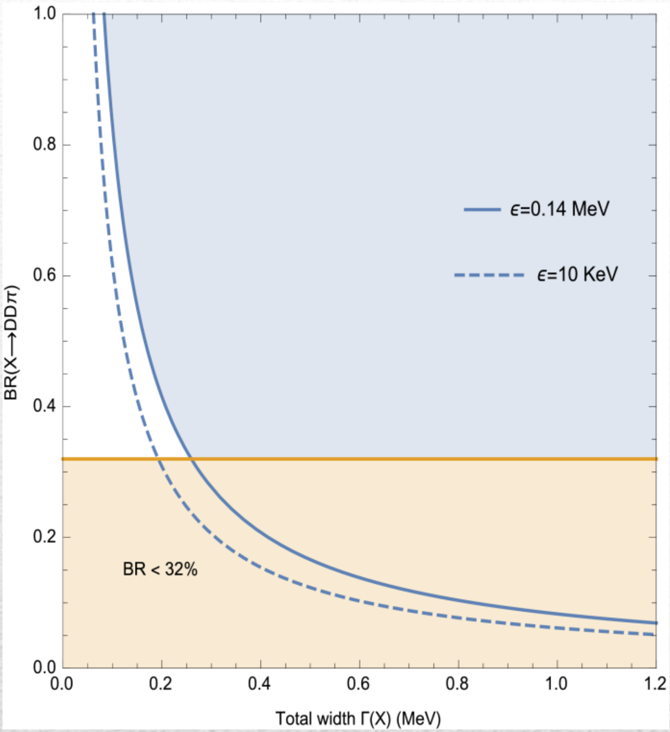
$$f(ab \to ab) = -\frac{1}{\sqrt{2\mu}} \frac{\sqrt{B} - i\sqrt{T}}{B + T}$$

$$B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}$$



Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248

Weinberg theorem



$$B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}, \qquad kR \ll 1$$

This has to be fulfilled by EVERY molecular state, but:

- $X(3872), B = 0, g \neq 0$
- Zs, $B < 0$, repulsive interaction!
- $Y(4260), kR \sim 1.4$

Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248

Feshbach resonances

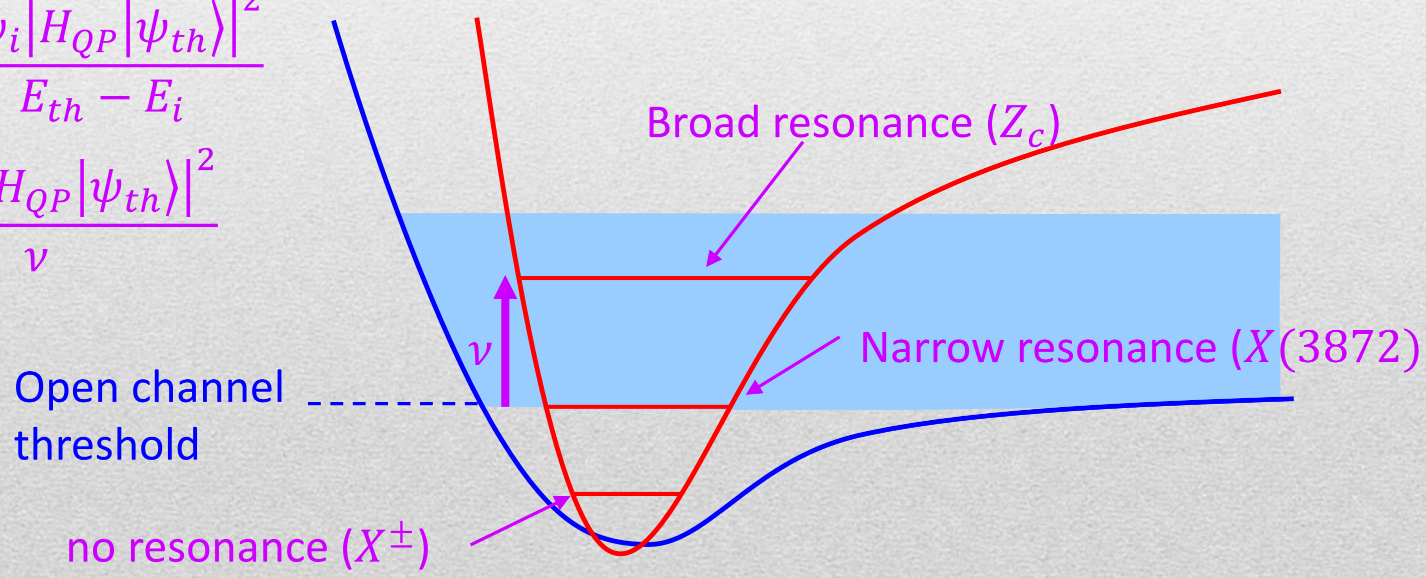
Braaten and Kusunoki, PRD69, 074005
Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

In cold atoms there is a mechanism that occurs when two atoms can interact with two potentials, resp. with continuum (molecule) and discrete (4q) spectrum
e.g. DD^* has the same quantum numbers as $[cu][\bar{c}\bar{u}]$, the operators mix under renormalization

We add an interaction Hamiltonian H_{QP}

$$a \simeq a_P + C \sum \frac{\left|\langle \psi_i | H_{QP} | \psi_{th} \rangle\right|^2}{E_{th} - E_i}$$

$$\simeq a_{NR} - C \frac{\left|\langle \psi_{res} | H_{QP} | \psi_{th} \rangle\right|^2}{\nu}$$



Feshbach resonances

We impose a cutoff on $\nu < 100$ MeV
$X(3872)$ should be a $I = 0$ state, but $M(1^{++}) < M(D^{+*}D^{-})$
No charged component, isospin violation!

If we assume $\Gamma = A\sqrt{\nu}$, we can use $Z_c(3900)$ as input to extract $A = 10 \pm 5\ \text{MeV}^{1/2}$
This value is compatible for all resonances (caveat: still large errors...)

Open channel	M_{4q} (MeV)	ν (MeV)	Γ (MeV)	$I^G J^{PC}$	name
$D^{*0}\bar{D}^0$	3872	0	0	1^-1^{++}	$X(3872)$
$D^{*+}\bar{D}^0$	3900	24	53	1^+1^{+-}	$Z_c(3900)$
$D^{*+}\bar{D}^0$	4025	8	24	1^+1^{+-}	$Z_c'(4025)$
$\eta_c(2S)\rho^+$	4475	75	>150	1^+1^{+-}	$Z(4430)$
$B^{*+}\bar{B}^0$	10610	3	18	1^+1^{+-}	$Z_b(10610)$
$B^{*+}\bar{B}^{*0}$	10650	1.8	11	1^+1^{+-}	$Z_b'(10650)$

We remark that $\Gamma(Z_b')/\Gamma(Z_b) \approx 0.63, \sqrt{\nu(Z_b')/\nu(Z_b)} \approx 0.77$

Production & Feshbach?

Going back to $pp(\bar{p})$ collisions, we can imagine hadronization to produce a state

$$|\psi\rangle = \alpha|[qQ][\bar{q}\bar{Q}]\rangle_C + \beta|(\bar{q}q)(\bar{Q}Q)\rangle_O + \gamma|(\bar{q}Q)(\bar{Q}q)\rangle_O$$

If $\beta, \gamma \gg \alpha$, an initial tetraquark state is not likely to be produced
The open channel mesons fly apart (see MC simulations)

If Feshbach mechanism is at work, an open state can resonate in a closed one

No prompt production without Feshbach resonances!

For example, we compare the at-threshold $X(3872)$ with the below-threshold $Y(4260)$
CMS $X(3872)$ data: JHEP 1304, 154

$$\frac{\sigma\big(pp \to X(3872)\big) \times BR\left(X(3872) \to J/\psi\, \pi^+\pi^-\right)}{\sigma(pp \to Y(4260)) \times BR\left(Y(4260) \to J/\psi\, \pi^+\pi^-\right)} \sim 10^2$$

$X(3872) \sim$ Deuteron?

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

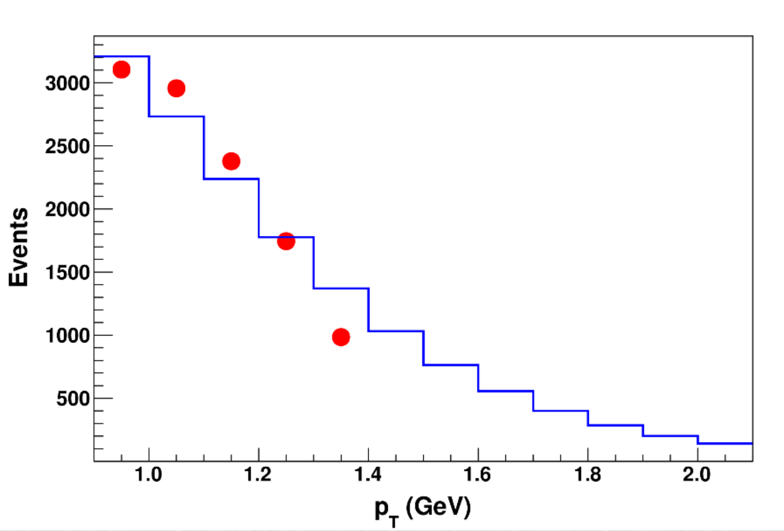
If $X(3872)$ is a deuteron-like molecule, we can compare production cross sections

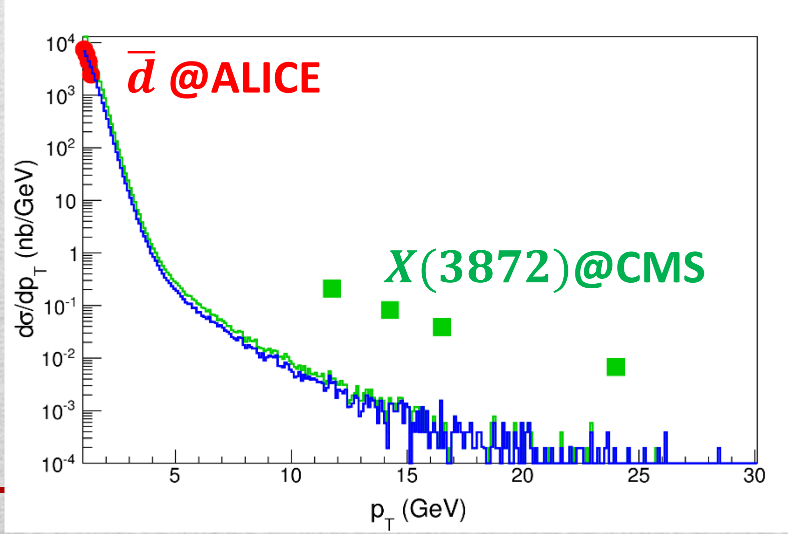
We use antideuteron ALICE data and use MC simulations to extrapolate at high p_T

Since $p_{Tmin} \sim 1\ \mathrm{GeV}$, total cross section is exploding, we cannot normalize data
we choose a K factor to fit data: no dependence on k_{max}

3 orders of magnitude smaller than CMS $X(3872)$ data!

Are they similar objects?





$X(3872) \sim$ Deuteron?

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

We can go backwards by normalizing to CMS $X(3872)$ data, prediction for antideuteron is much larger than previous one

Do not trust MC (yet)!

We wait for data!!!

- ALICE data are preliminary
- MC is not reliable in the $p_T \sim 1$ GeV
- Dependence on hadronization models
- Different fragmentation functions to be considered

ALICE should be able to reach $5 - 8$ GeV in next future

More work is needed to tune properly MC for such exclusive observables