Production of Exotic States

Alessandro Pilloni

Stony Brook, May 30th, 2018

Outline

- The original problem (2009)
- The role of Final-State interactions (2009-2010)
- A recent revival (2017)
- Other exotics (2014-2015)
- Comparison with nuclei (2015)

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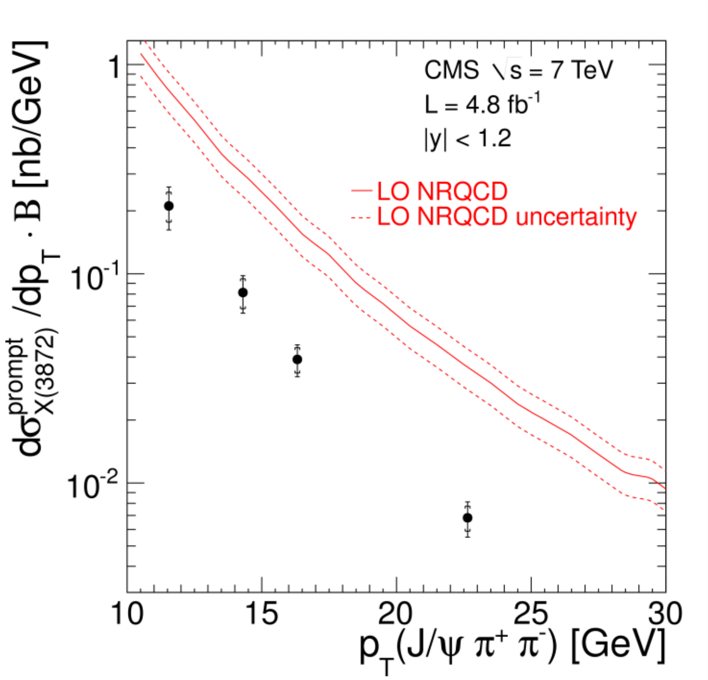
Prompt production of $X(3872)$



CMS, JHEP 1304 (2013) 154

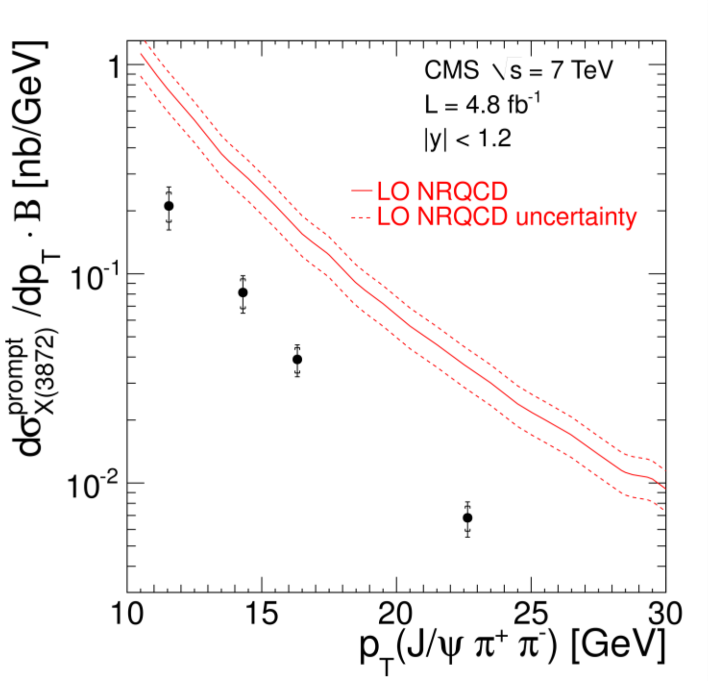
The question is:

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

$M = 3871.69 \pm 0.17$ MeV
$E_B = M_{DD^*} - M_X = 10 \pm 200$ keV (PDG)
$\Gamma < 1.2$ MeV @90%

The width of the D^* and of the $X(3872)$ are neglected, according to Weinberg's spirit
The $X(3872)$ is considered a (stable) bound state of (stable) $\bar{D}^0 D^{*0}$

Prompt production of $X(3872)$



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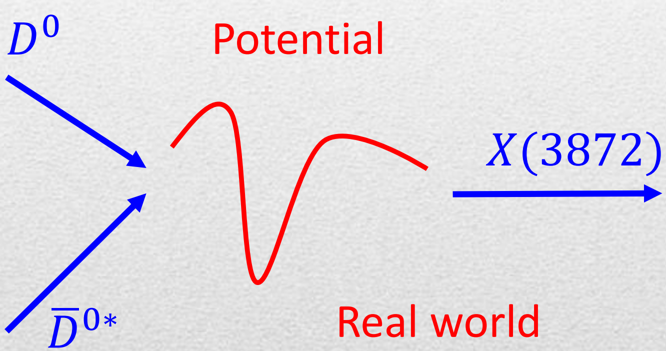
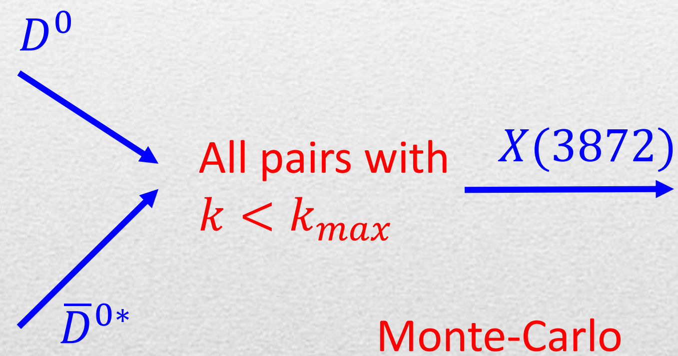
$$k_B = \sqrt{2\mu E_B} \sim 20 \text{ MeV}, \qquad R = \frac{1}{k_B} \sim 10 \text{ fm}$$

Hadronic molecules with MC simulations

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





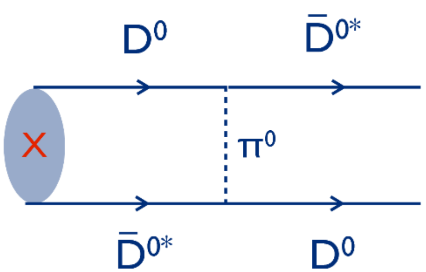
$$\sigma\big(p\bar{p} \to X(3872)\big) \sim \int d^3k \; |\langle X|D\bar{D}^*\rangle\langle D\bar{D}^*|p\bar{p}\rangle|^2 < \int_{k<k_{max}} d^3k \; |\langle D\bar{D}^*|p\bar{p}\rangle|^2$$

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

Estimating k_{max}

The choice of k_{max} is crucial. By phase space argument, the cross section scales as k_{max}^3, small changes have huge impacts on the results

D mesons interact via π^0-exchange:



$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-m_\pi r_0}}{r_0} = |E_B| \simeq 0.25 \text{ MeV}$$

using the fact that $g^2/4\pi \sim 10$ we find a characteristic size

(1) $r_0 \simeq 8 \text{ fm} \quad \Rightarrow \quad \Delta k \sim 1/2r_0 \simeq 20 \text{ MeV}$

(uncertainty principle)

(2) $k_0 = \dfrac{\sqrt{\lambda(m_X^2, m_D^2, m_{D^*}^2)}}{2m_X} \simeq 30 \text{ MeV}$

C. Sabelli (2009)

Alternative, one can model the binding potential.

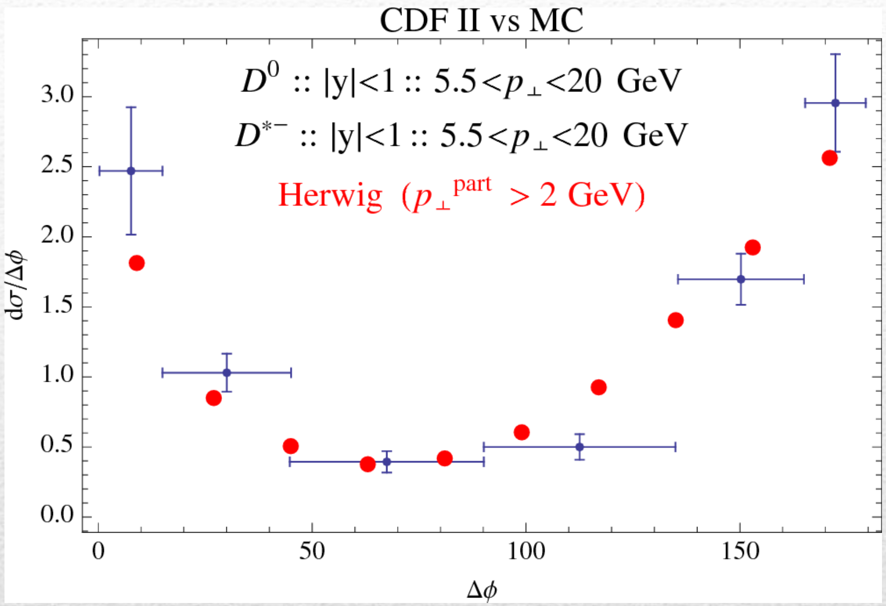
For example, a simple square well with this corresponds to:

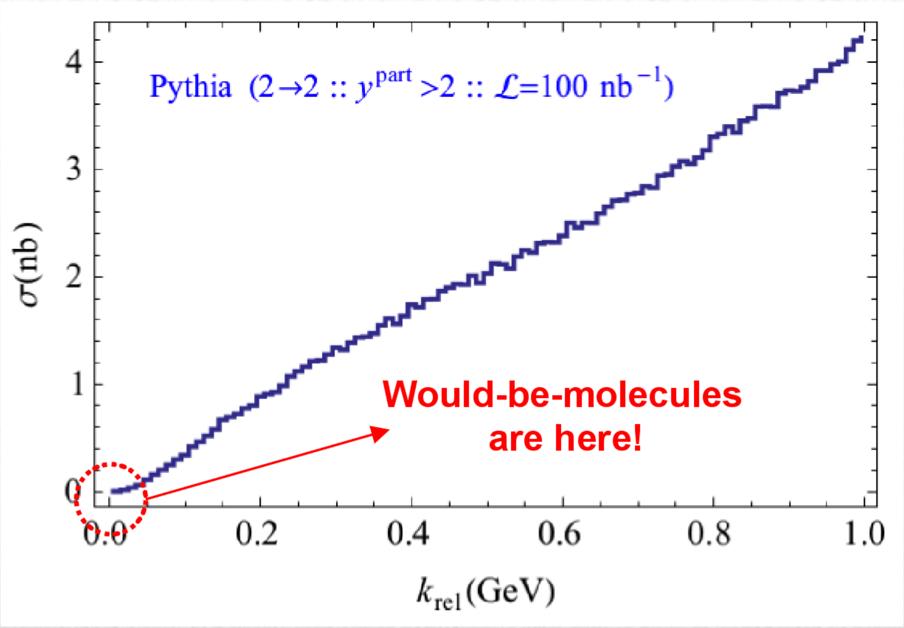
$$\sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV},$$
$$\sqrt{\langle r^2 \rangle} \approx 10 \text{ fm}$$

to compare with deuteron:

$$E_B = -2.2 \text{ MeV},$$
$$\sqrt{\langle k^2 \rangle} \approx 80 \text{ MeV},$$
$$\sqrt{\langle r^2 \rangle} \approx 4 \text{ fm}$$

2009 Results





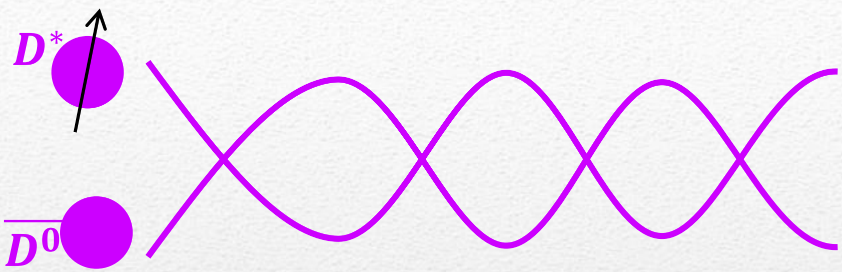
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

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} -- Part II



A solution can be Final State Interactions (rescattering of DD^*)

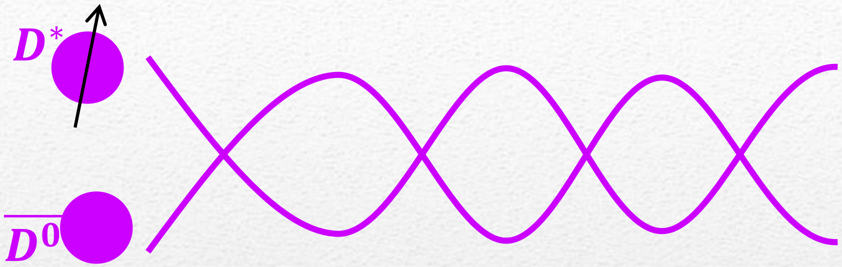
Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -N A_{prod}^{on} \cdot \frac{e^{i\delta}\sin\delta}{k a_{NN}}$$

Watson-Migdal model for FSI, the on-shell elastic scattering matrix multiplies the production amplitude

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

Estimating k_{max} -- Part II



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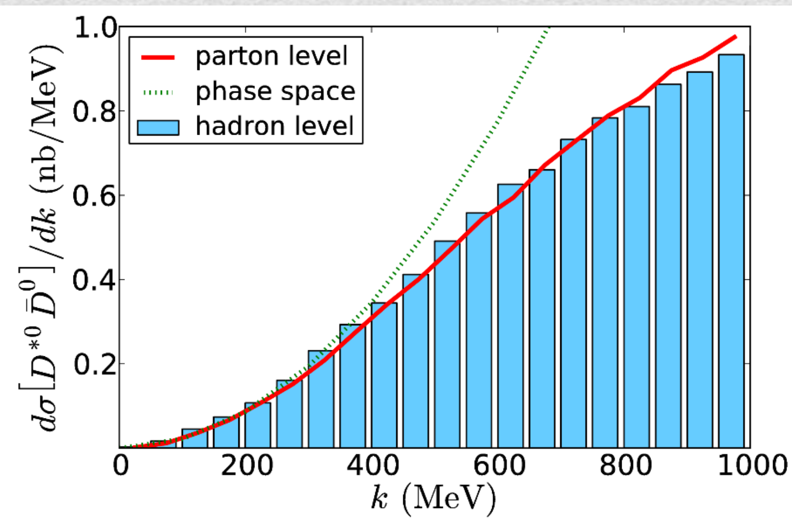
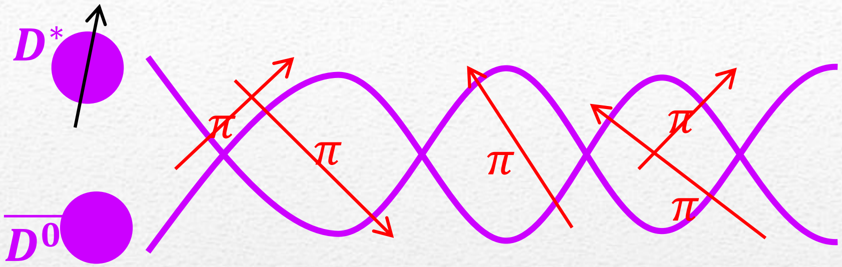


To take into account the rescattering correctly, one needs to integrate up to the scale of the mediator,

$$\sigma_{FSI}(p\bar{p} \to DD^*|k < 2m_\pi) \approx 23\text{ nb}$$
$$\sigma(p\bar{p} \to DD^*|k < 5m_\pi) \approx 230\text{ nb}$$

Estimating k_{max} -- Part III & IV



Watson-Migdal approach requires the DD^* to recoil onto some debrys. The 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, the D and D^* only talk with each other

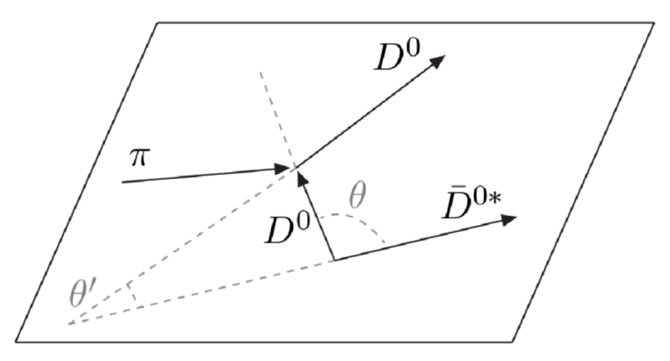
Artoisenet and Braaten, PRD83, 014019

What is the role of 2-body unitarity in a 100-body high energy collision?

A new mechanism?

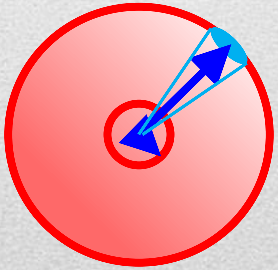
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the DD^* pairs

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

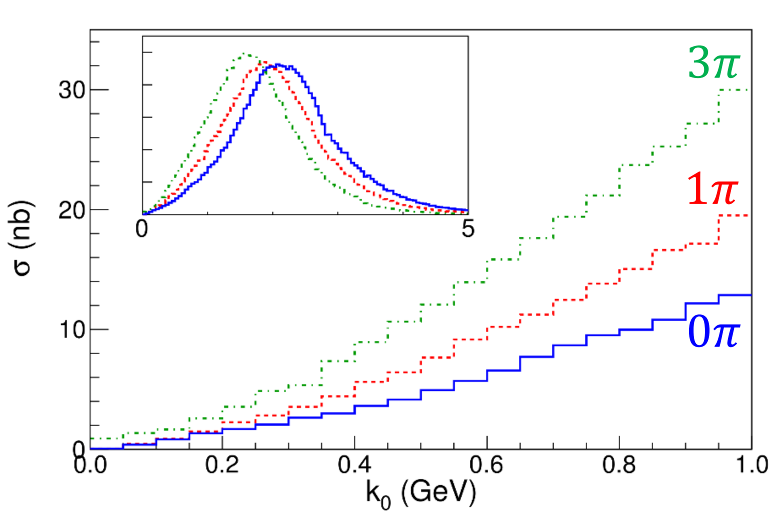


The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

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



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

Note on $X(3872)$ production at hadron colliders and its molecular structure

Miguel Albaladejo,[1] Feng-Kun Guo,[2,3] Christoph Hanhart,[4]
Ulf-G. Meißner,[5,4] Juan Nieves,[6] Andreas Nogga,[4] and Zhi Yang[5]

v:1709.09101v1 [hep-ph] 26 Sep 2017

Comment on 'Note on $X(3872)$ production at hadron colliders and its molecular structure'

A. Esposito[a], B. Grinstein[b], L. Maiani[c], F. Piccinini[d], A. Pilloni[e], A.D. Polosa[f], V. Riquer[c]

arXiv:1709.09631v1 [hep-ph] 27 Sep 2017

Comment on "Comment on 'Note on $X(3872)$ production at hadron colliders and its molecular structure' "

Wei Wang
INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology,
School of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai 200240, China

I discuss the production mechanism of hidden flavored exotic hadrons in high energy process. I demonstrate that some arguments of *A. Esposito* (arXiv: 1709.09631) on the production of $X(3872)$ are questionable.

0382v1 [hep-ph] 29 Sep 2017

Very recently there is a debate on how to understand the production of the $X(3872)$ [1, 2]. The fact that the $X(3872)$ hadron can be c … gnment of the $X(3872)$. Ref. [3] l … Using a momentum cutoff set by t … n data. This choice of the momen … 2].
The aim of this note i … ood in Ref. [2, 4]. I will first us … adron's low-energy structure. The … (3872). At last I will briefly comm … ectured mechanism.
$e^+e^- \to \rho^0\pi^0$. At h … $_{QCD}$ is the confinement scale, ex … ne may separate the interactions … actions above the factorization sc … duction to the soft-collinear effect …
Matching onto effective field theory is equivalent to integrate out the highly virtual states. A vector meson such as

Estimating k_{max} -- Part V

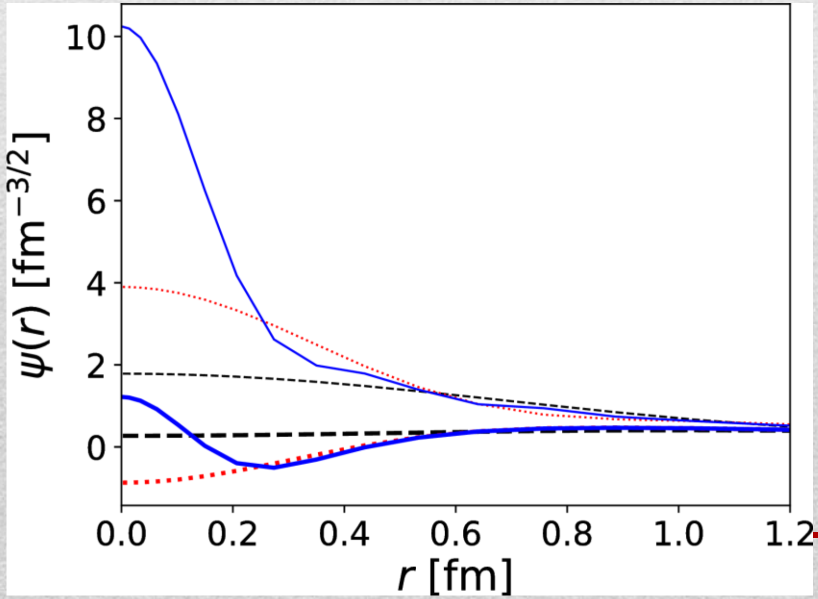
$$
\begin{aligned}
\sigma(\bar{p}p \to X) &\sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 \\
&\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0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

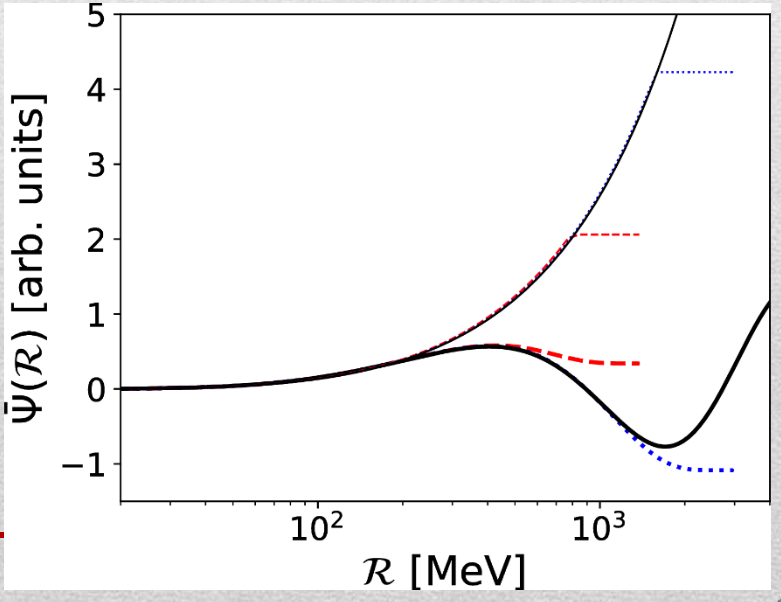
The estimate of the k_{max} has been brought back

Albaladejo *et al.* arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_R d^3\mathbf{k} \, \psi(\mathbf{k})$$





Estimating k_{max} -- Part VI

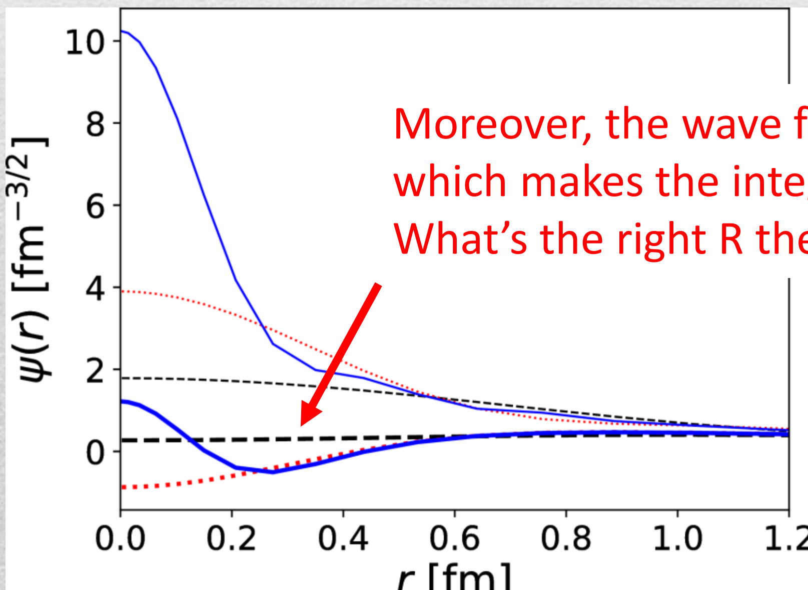
However, the integral of the wave function may not be well defined.
For example, if one considers the wave function in the scattering length approximation,

Esposito, AP *et al.* arXiv:1709.09631

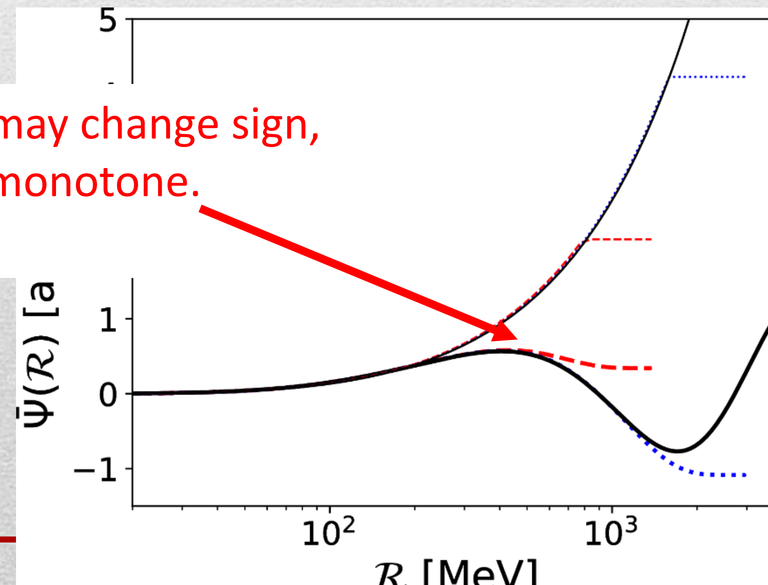
$$\psi(\mathbf{k}) = \frac{1}{\pi}\frac{a^{3/2}}{a^2k^2+1}$$ it's not integrable

A physical value should rather be based on expectation values which involve $|\psi(\mathbf{k})|^2$

For example, an estimate using the virial theorem gives $k \sim 100$ MeV for the deuteron



Moreover, the wave function may change sign, which makes the integral nonmonotone.
What's the right R then?



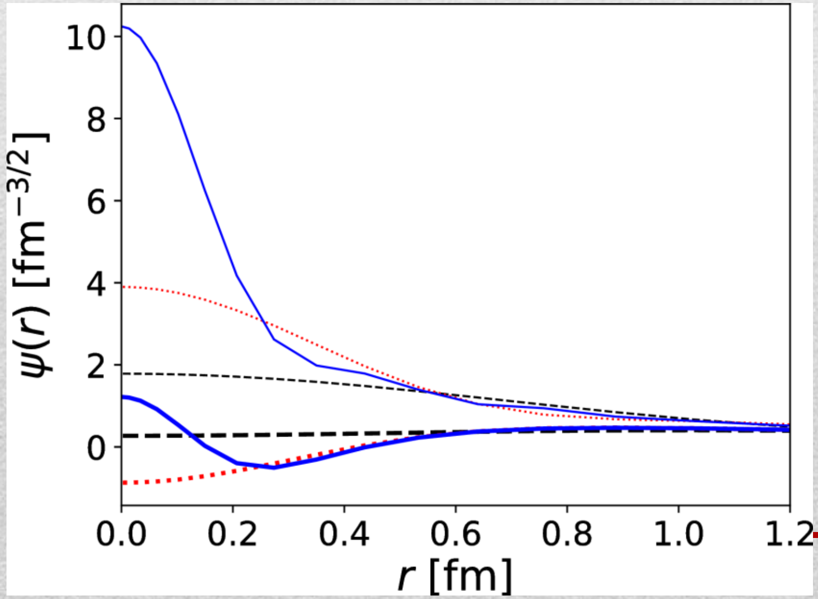
Estimating k_{max} -- Part VI

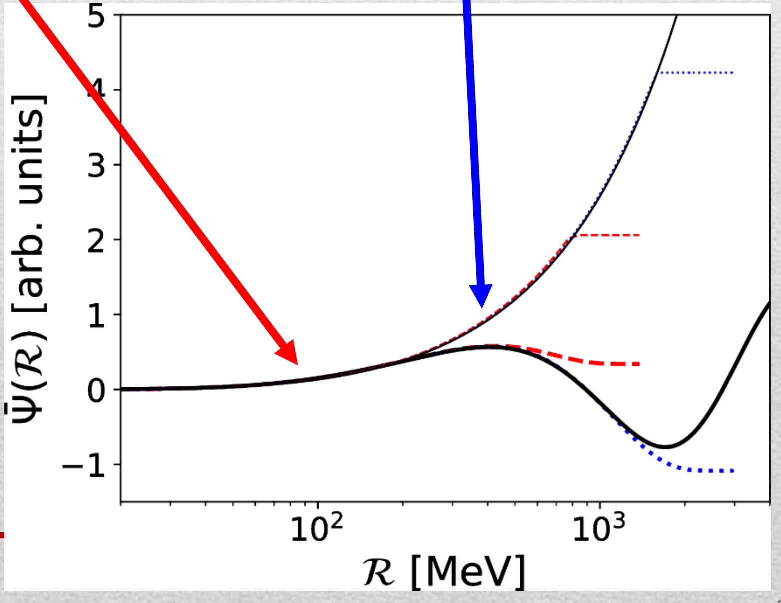
An accurate calculation using several deuteron *S*-wave functions available on the market (for example https://www.phy.anl.gov/theory/research/av18/deut.wfk) give

$$\int_R d^3\mathbf{k}\,|\psi(\mathbf{k})|^2 = 90\% \text{ for } k_{max} = 110 \text{ MeV}$$

This also show that this region is well controlled by pion exchange - universal

This is not!

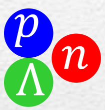




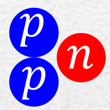
Light nuclei at ALICE

In 2015, ALICE published data on production of light nuclei in Pb-Pb and *pp* collisions

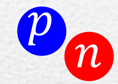
These might provide a benchmark for $X(3872)$ production



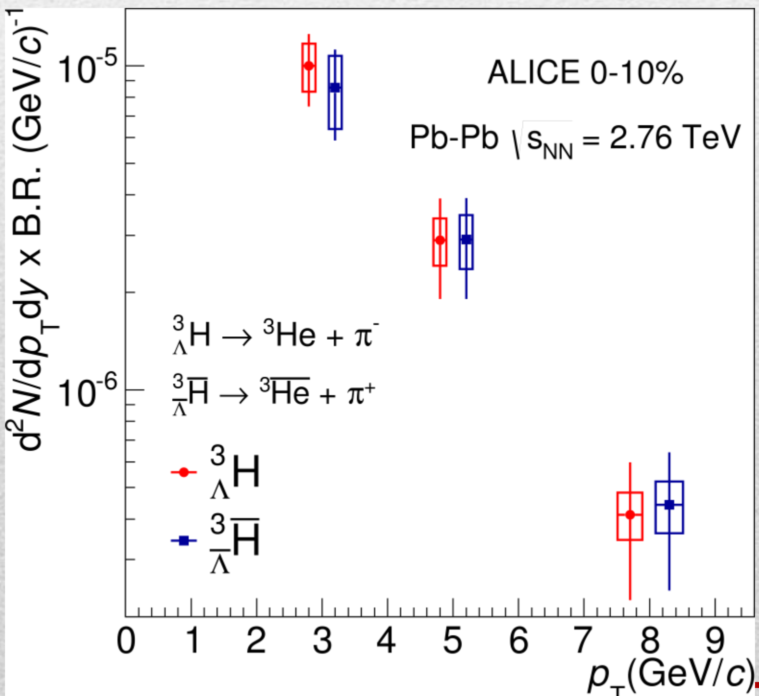
Hypertriton
arXiv:1506.08453

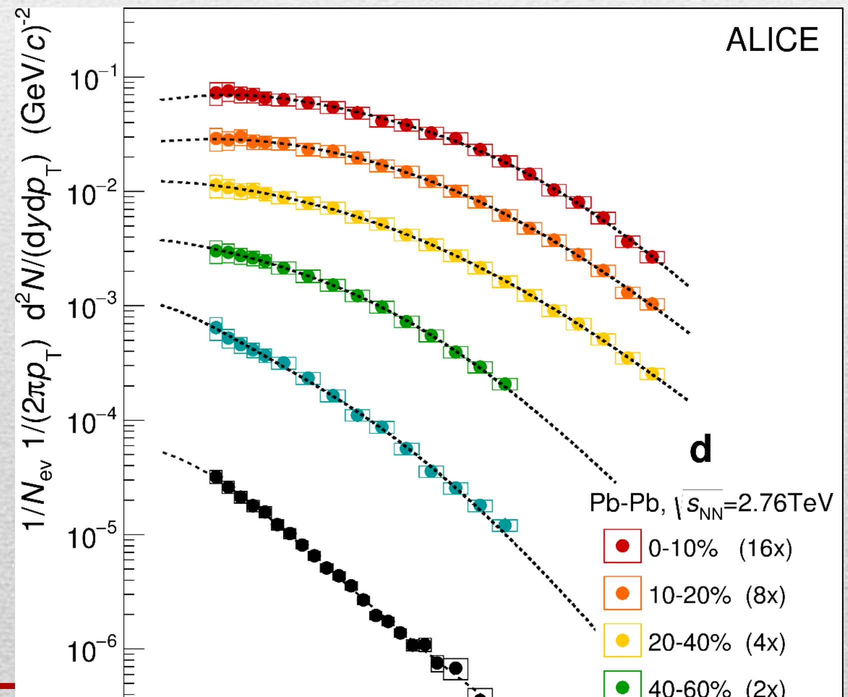


Helium-3
arXiv:1506.08951



Deuteron
arXiv:1506.08951



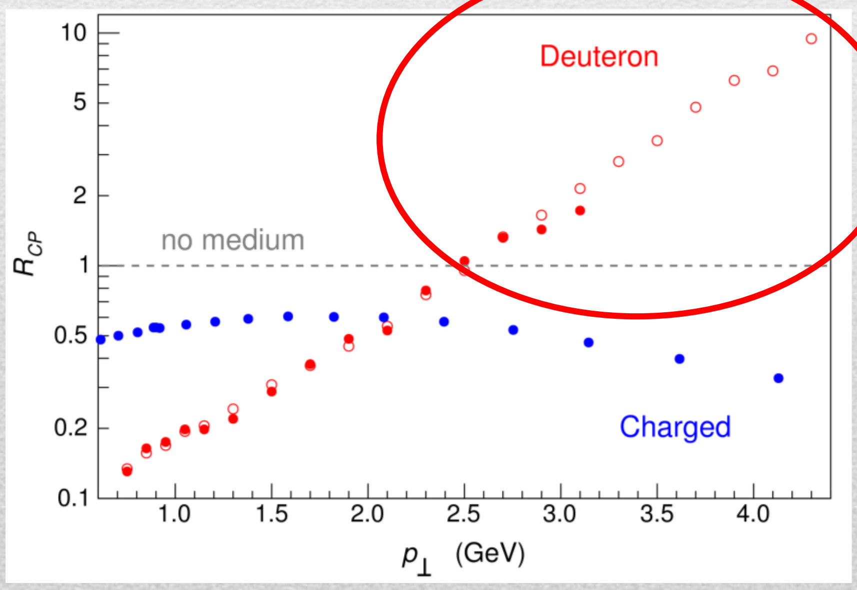


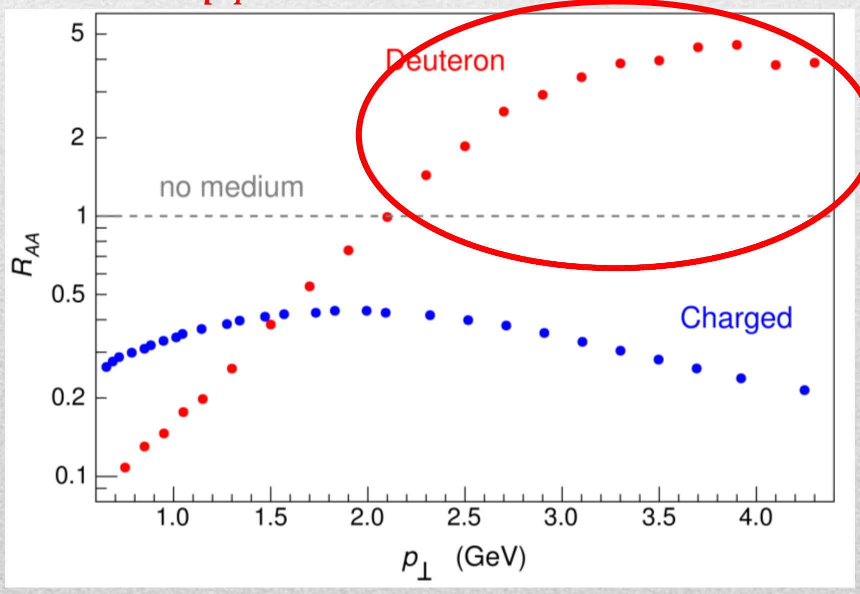
Nuclear modification factors

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

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

Larger than 1 at $p_T > 2.5$ GeV

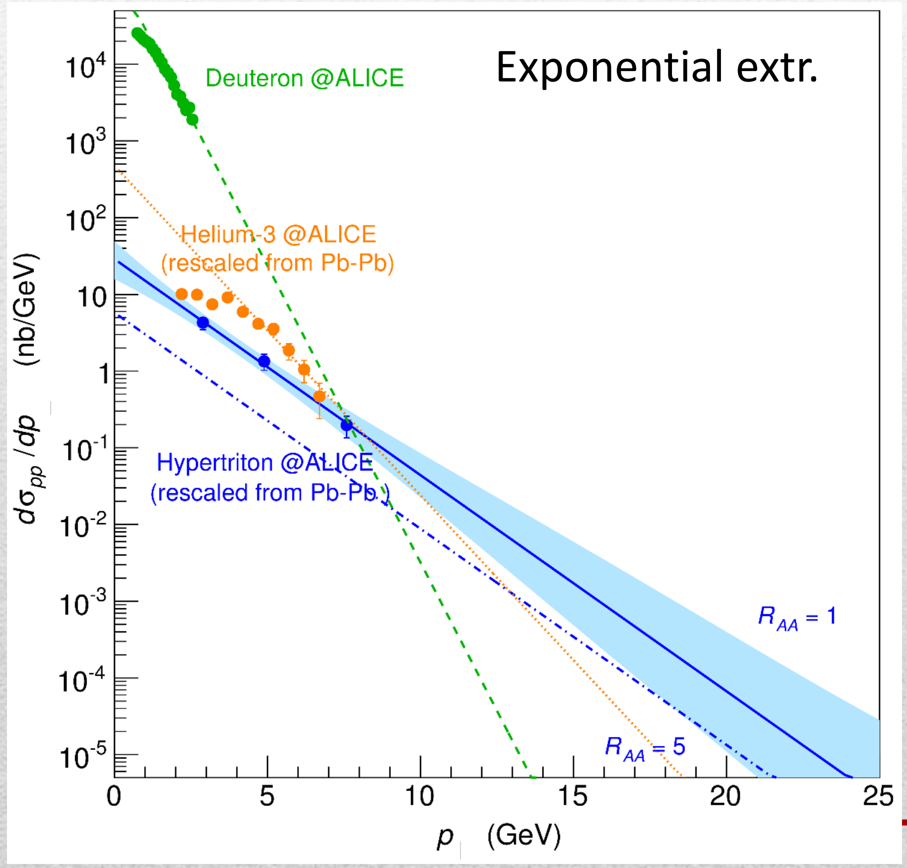


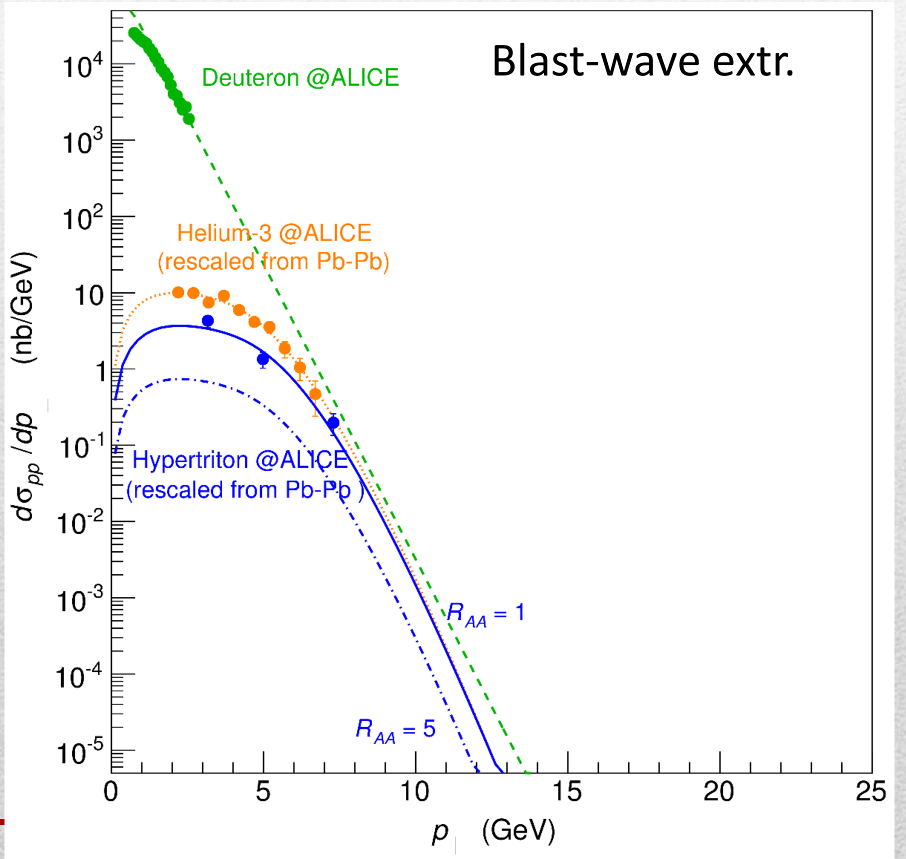


Light nuclei at ALICE

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





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

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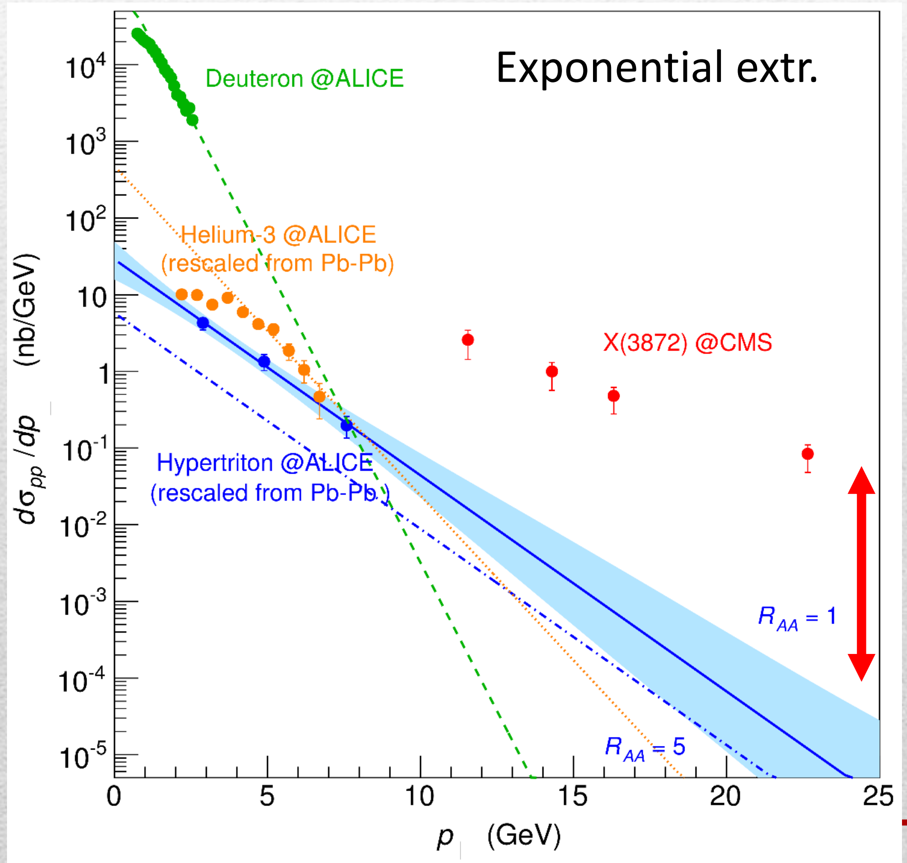
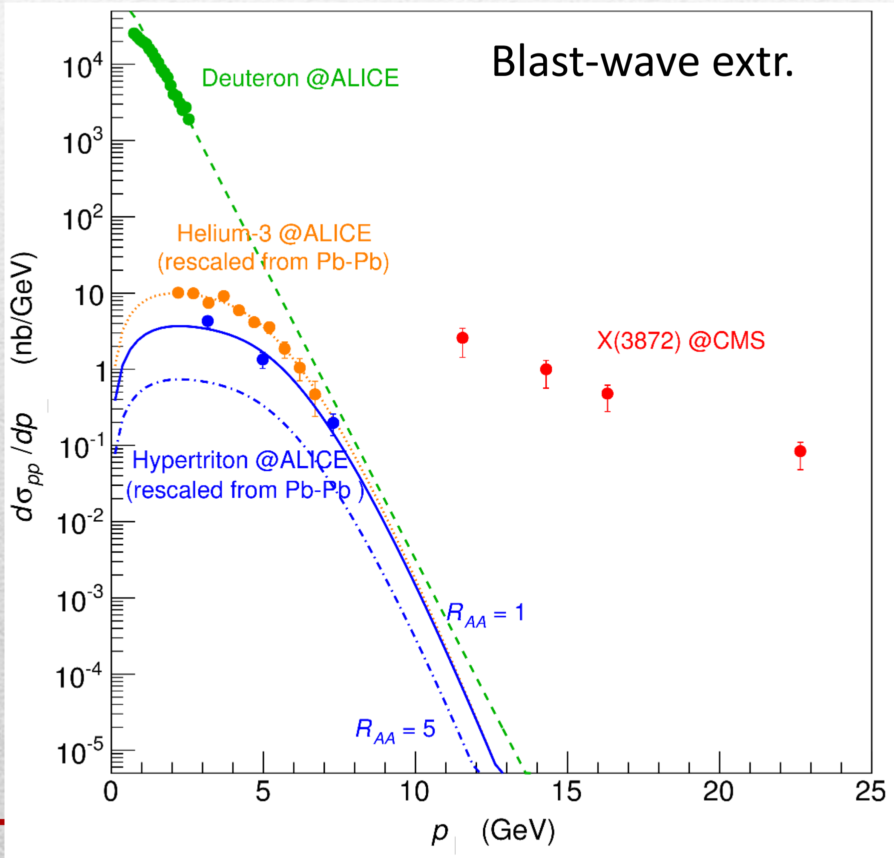
The $X(3872)$ is way larger than the extrapolated cross section





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

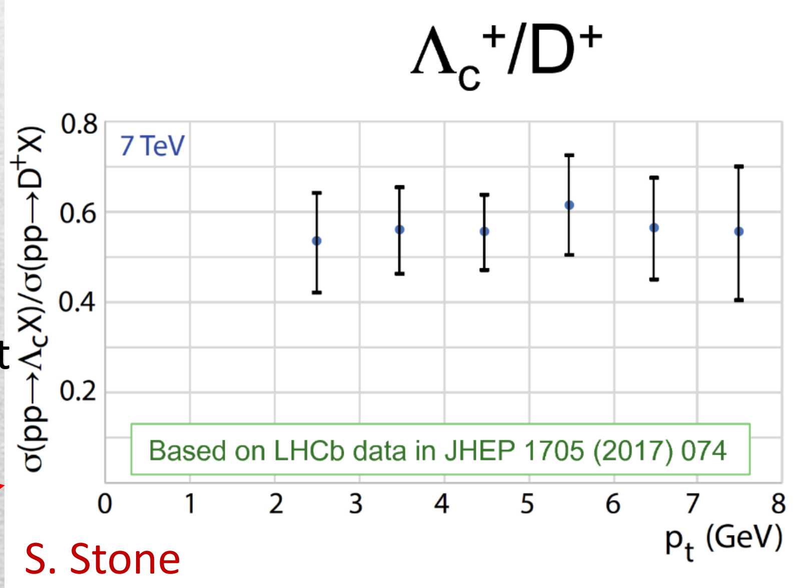
If the production is long-distance dominated, that's pretty much it.

If it's short-distance dominated, one can think on an effect related to the number of quarks involved, in the spirit of constituent counting rules

Brodsky and Lebed, PRD91, 114025
Guo et al., CPC41, 053108
Voloshin, PRD94, 074042
Wang, CPC42, 043103

However, it is not easy to make sense of constituent counting rules in inclusive reactions, where you cannot track the energy carried by each quark

They seem to spectacularly fail



Production of other exotics

Other cross sections have been estimated, generally quite large

Guo et al. EPJC74, 9, 3063
Guo et al. CTP, 61, 354

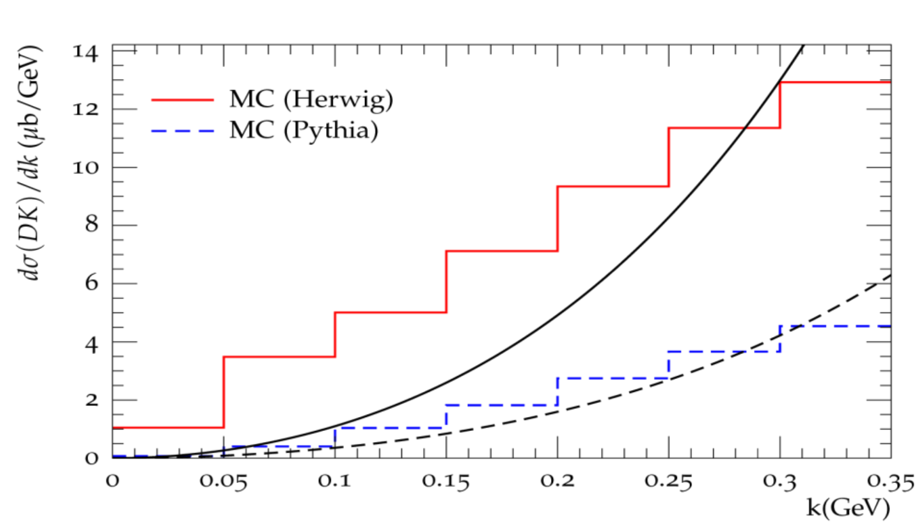
	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26(0.47)	0.06(0.17)	11(13)	1.7(2.0)
LHC 7	4.8(8.0)	1.2(3.0)	187(211)	29(31)
LHCb 7	0.76(1.3)	0.18(0.47)	33(39)	5.5(5.8)
LHC 8	5.9(9.5)	1.4(3.5)	220(240)	34(36)
LHCb 8	0.9(1.4)	0.22(0.56)	40(48)	6.3(6.9)
LHC 14	11(17)	2.6(6.5)	382(423)	61(63)
LHCb 14	1.9(3.0)	0.52(1.2)	84(88)	14(14)

(nb)

X_b	$E_{X_b} = 24$ MeV($\Lambda = 0.5$ GeV)	$E_{X_b} = 66$ MeV($\Lambda = 1$ GeV)
Tevatron	0.08(0.18)	0.61(1.4)
LHC 7	1.5(3.1)	12(23)
LHCb 7	0.25(0.49)	1.9(3.7)
LHC 8	1.8(3.6)	14(27)
LHCb 8	0.3(0.62)	2.2(4.7)
LHC 14	3.2(6.8)	24(51)
LHCb 14	0.65(1.3)	4.9(9.7)

(nb)

Guo et al. JHEP 1405, 138



$$\sigma[D_{sJ}] = \left|\frac{F^2}{2} g_{\rm eff}\right|^2 \left(\frac{d\sigma[HK(\boldsymbol{k})]}{dk}\right)_{\rm MC} \frac{4\pi^2\mu}{k^2 E_K^2 m_H^2}.$$

	$D_{s0}^*(2317)$	$D_{s1}(2460)$	$D_{sJ}(2860)$	$D_{s2}(2910)$
LHC 7	2.5(0.83)	2.1(0.91)	0.21(-)	0.27(-)
LHCb 7	0.61(0.15)	0.5(0.17)	0.05(-)	0.06(-)
LHC 8	2.9(0.94)	2.4(1.0)	0.24(-)	0.32(-)
LHCb 8	0.74(0.18)	0.61(0.2)	0.06(-)	0.08(-)
LHC 14	5.5(1.6)	4.7(1.7)	0.5(-)	0.65(-)
LHCb 14	1.6(0.35)	1.3(0.38)	0.13(-)	0.17(-)

(μb)

Production of $Y(4260)$ and $P_c(4450)$

Given the new lineshape by BESIII, we need to rethink the binding energy of the $Y(4260)$

J. Nys and AP, to appear

	Constituents	Bind. Energy	Bind. Mom.	Mediator
$X(3872)$	$\bar{D}^0 D^{*0}$	~ 100 keV	~ 50 MeV	1π (~ 300 MeV)
$Y(4260)$	$\bar{D} D_1$	~ 70 MeV	~ 400 MeV	2π (~ 600 MeV)
$P_c(4450)$	$\bar{D}^* \Sigma_c$	~ 10 MeV	~ 150 MeV	1π (~ 300 MeV)

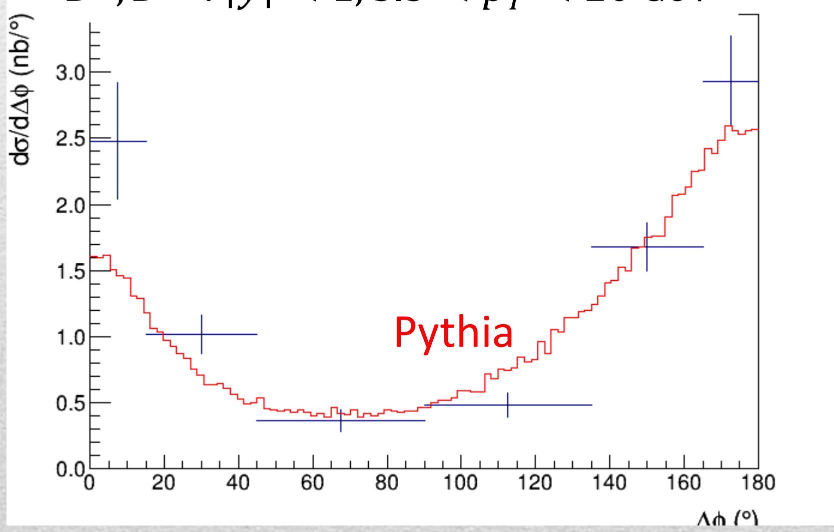
If the states are purely hadron molecule, all the properties depend on the position of the pole with respect to threshold – all the features are universal

Production of $Y(4260)$ and $P_c(4450)$

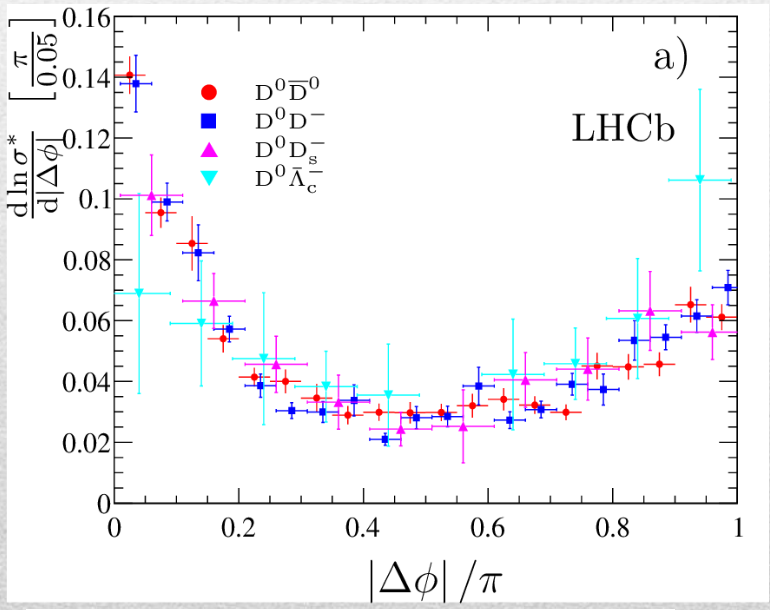
We can use Pythia to simulate the production of event, and calculate the relative production of $Y(4260)$ and $P_c(4450)$ with respect to the $X(3872)$ J. Nys and AP, to appear

We tune our MC on charm pair production

CDF data, $\sqrt{s} = 1.96$ TeV
D^0, D^{*-}: $|y| < 1, 5.5 < p_T < 20$ GeV



For baryons we can double check with LHCb data



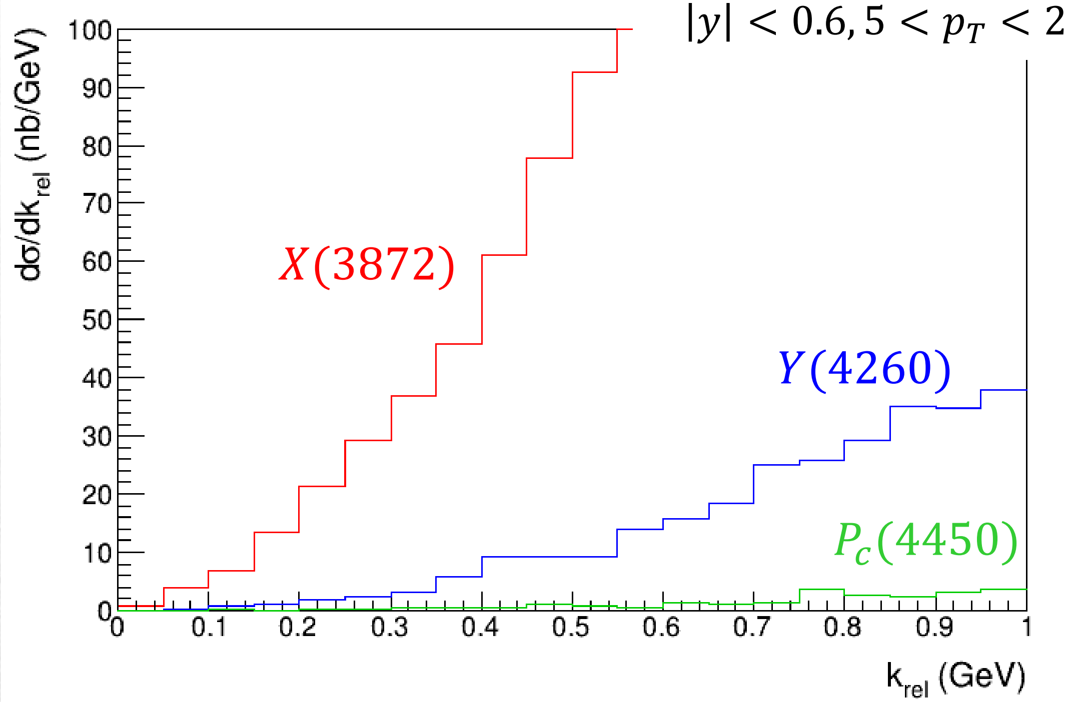
LHCb, $\sqrt{s} = 7$ TeV, JHEP 1206, 141
all: $2 < y < 4, 3 < p_T < 12$ GeV

Production of $Y(4260)$ and $P_c(4450)$

Naively, the fragmentation function of the D_1 is 1/10 of the D^*, but the cross section scales as k_{max}^3

J. Nys and AP, to appear

Pythia $p\bar{p}$, $\sqrt{s} = 1.96$ TeV
$|y| < 0.6, 5 < p_T < 20$ GeV



	No FSI	With FSI
$Y(4260)/X$	23	0.75
$P_c(4450)$/X	1.0	0.01

The production of $Y(4260)$ is expected to be at worse comparable with the $X(3872)$

Points for discussion

- Short distance physics is out of control of (leading order) EFTs,
so what?
- Model-dependent is not an insult. One can actually calculate (short distance) quantities and see how they vary with models.
- In particular, the role of compact components in the wave function may be relevant.
Saying that short distance is out of control is hiding the dust under the carpet
- Production of exotics are an interesting business. No compelling evidence for anything but the $X(3872)$

Thank you

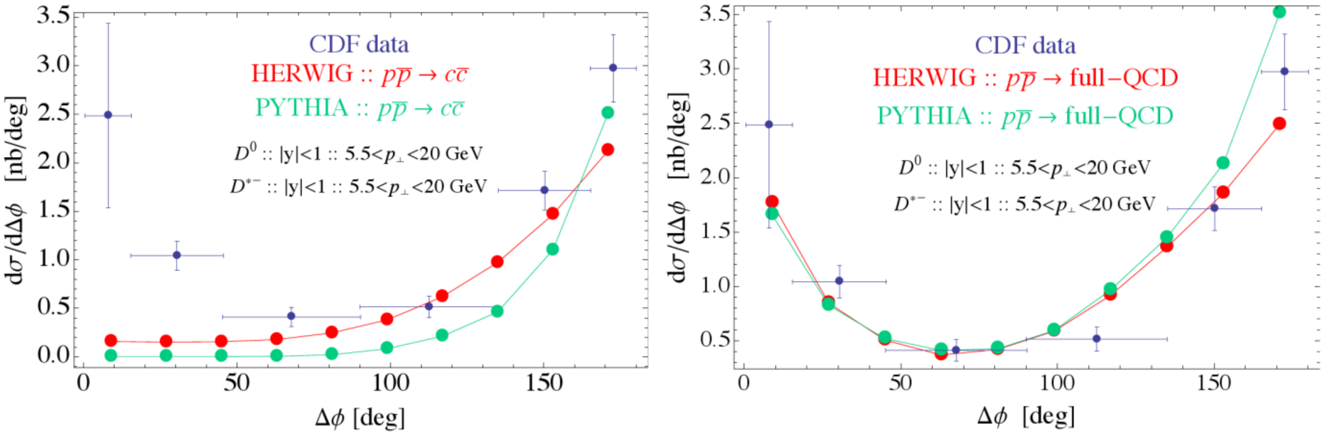
BACKUP

Tuning of MC

Monte Carlo simulations

A. Esposito

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:



The c-cbar run understimate the low angles (low-k_0) region!

Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

Prompt production of $X(3872)$

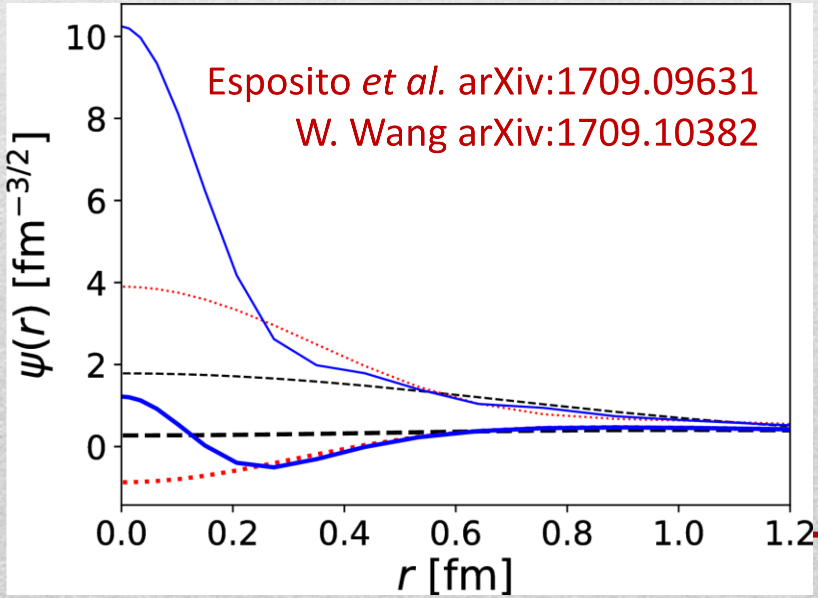
$$
\begin{aligned}
\sigma(\bar{p}p \to X) &\sim \left| \int d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | \bar{p}p \rangle \right|^2 \\
&\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D^0 \bar{D}^{*0}(\mathbf{k}) \rangle \langle D^0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

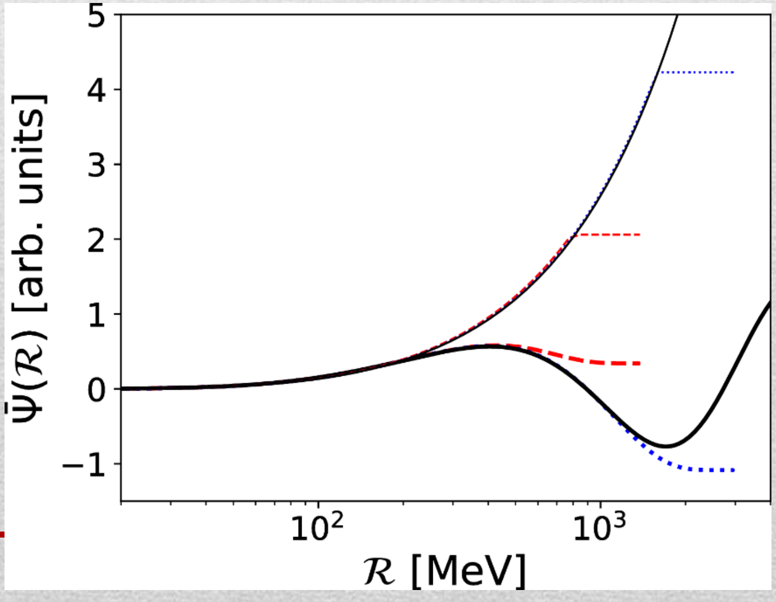
The estimate of the k_{max} has been brought back

Albaladejo *et al.* arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_R d^3\mathbf{k}\, \psi(\mathbf{k})$$





Prompt production of $X(3872)$

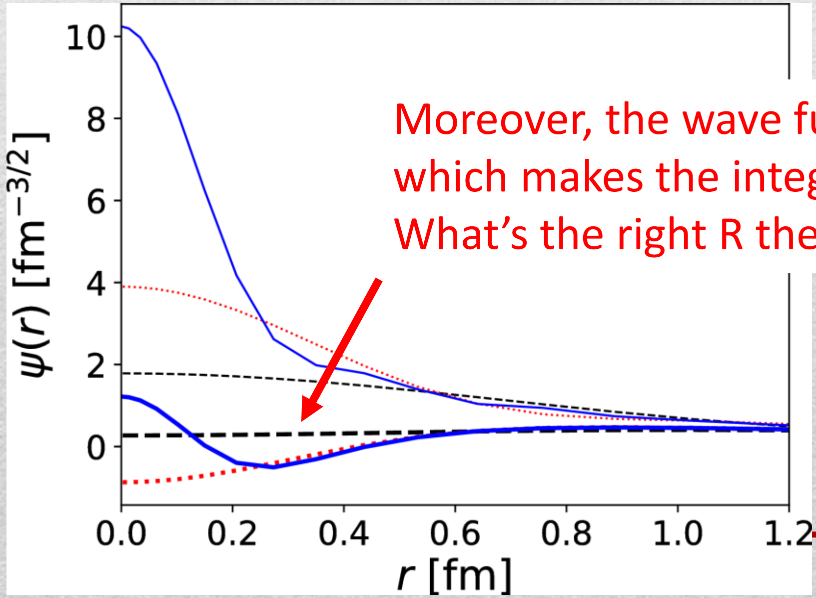
However, the integral of the wave function may not be well defined.
For example, if one considers the wave function in the scattering length approximation,

Esposito *et al.* arXiv:1709.09631

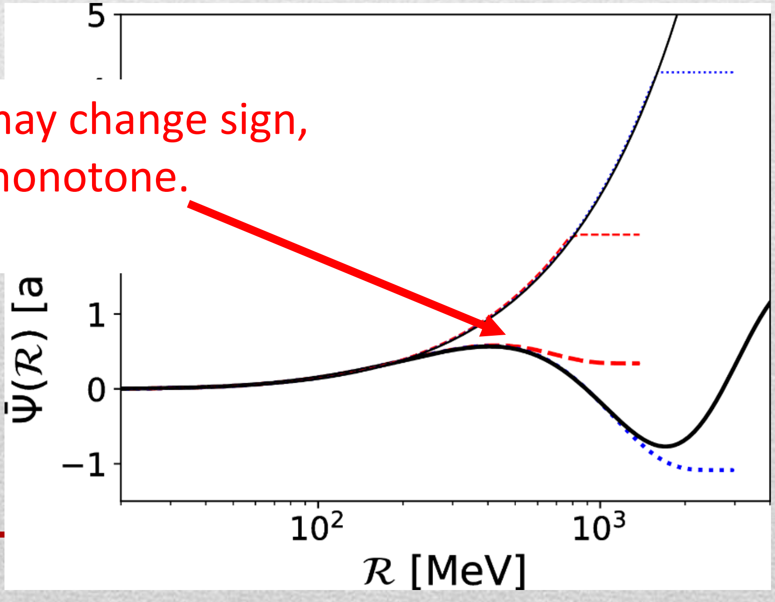
$$\psi(\mathbf{k}) = \frac{1}{\pi}\frac{a^{3/2}}{a^2k^2+1}$$ it's not integrable

A physical value should rather be based on expectation values which involve $|\psi(\mathbf{k})|^2$

For example, an estimate using the virial theorem gives $k \sim 100$ MeV for the deuteron



Moreover, the wave function may change sign,
which makes the integral nonmonotone.
What's the right R then?



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

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

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.