ON THE STRUCTURE OF THE $X(3872)$: LESSONS FROM HIGH MULTIPLICITY pp COLLISIONS

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HADRON 2021

Talk mostly based on:

AE, Ferreiro, Pilloni, Polosa, Salgado — EPJC (2021), 2006.15044

For a review on exotics see e.g.:

AE, Pilloni, Polosa — Phys.Rept. (2017), 1611.07920

Lebed, Mitchell, Swanson — Prog.Part.Nucl.Phys. (2017), 1610.04528

Guo, Hanhart, Meißner, Wang, Zhao — Rev.Mod.Phys. (2018), 1705.00141

OUTLINE

- Brief review on XYZ
  1. Exotic hadrons and their nature
  2. Prompt production
- Hints from high-multiplicity pp collisions
  1. The comover model
  2. Deuteron and the $X(3872)$ in high-multiplicity pp collisions
- Conclusions

BRIEF REVIEW

Exotic hadron spectrum

- Proliferation of new states in the quarkonium sector

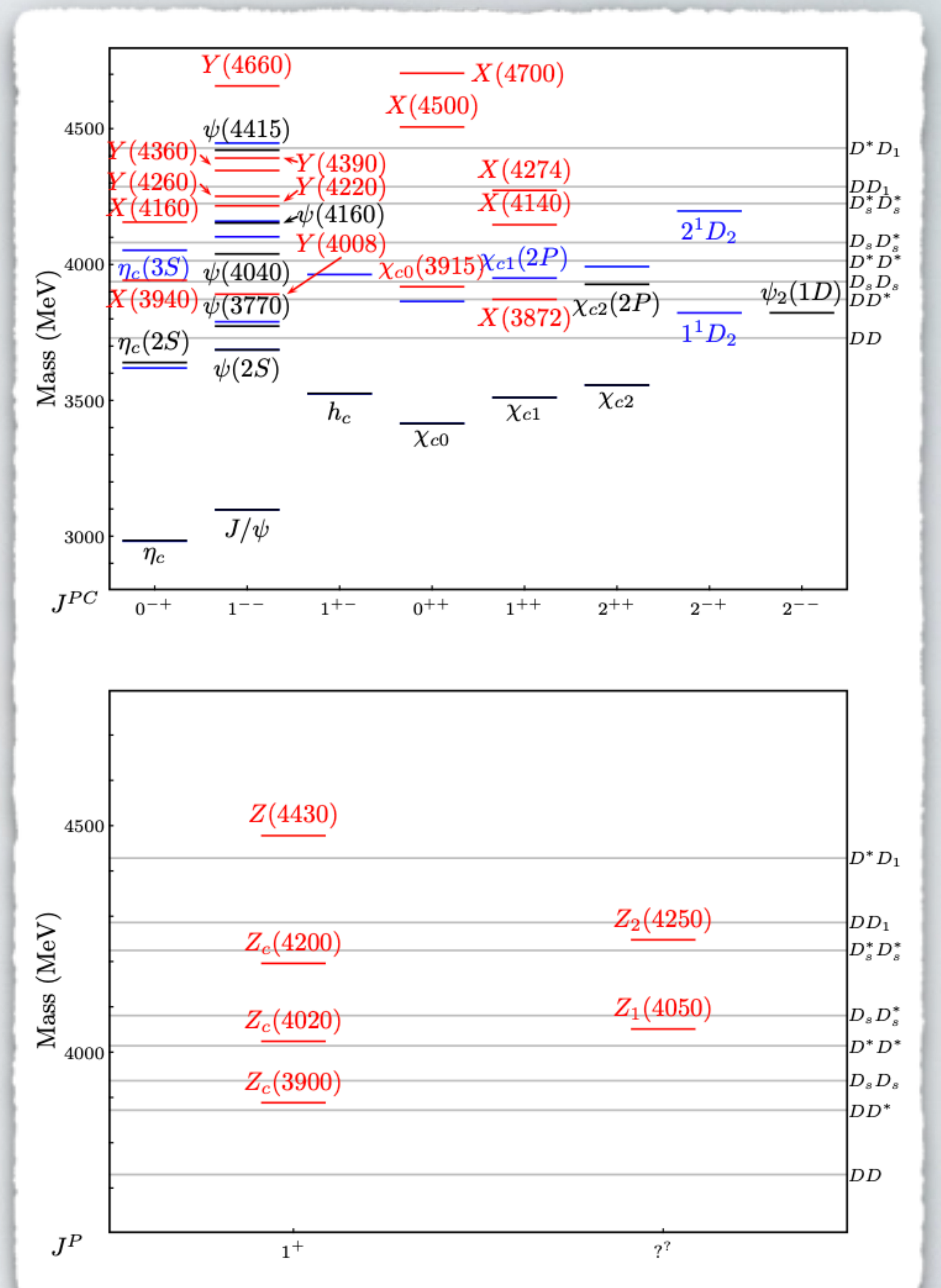
- Their properties do not match standard quarkonia predictions

- The charged ones are manifestly 4-quark states:

$$Z_c^+(3900) \to J/\psi\, \pi^+$$

$c\bar{c}$ pair too heavy to be produced from the vacuum

Does not have the same quantum numbers as the vacuum



[AE, Pilloni, Polosa — Phys.Rept. (2017), 1611.07920]

BRIEF REVIEW

$X(3872)$

- Most notable example is the $X(3872)$, discovered by BELLE in 2003

- Impressive fine tuning of its mass:

$$M_X - M_{D^0} - M_{D^{*0}} \lesssim 100 \text{ keV}$$

- Despite the tiny available phase space decays copiously in $D^0\bar{D}^{*0}$:

$$BR\left(X \to D^0\bar{D}^0\pi^0\right) \simeq 40\,\% \quad \text{(might be less…)}$$

- Strong decays violate isospin:

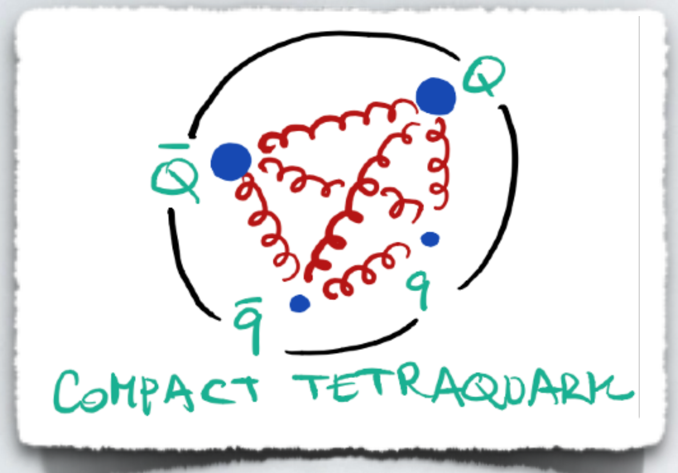
$$\Gamma\left(X \to J/\psi\,\omega\right) = \left(4.4^{+2.3}_{-1.3}\right)\%\,, \quad \Gamma\left(X \to J/\psi\,\rho\right) = \left(4.1^{+1.9}_{-1.1}\right)\%$$

[Li, Yuan — PRD (2019), 1907.09149]

EXOTIC MESONS

Possible interpretations

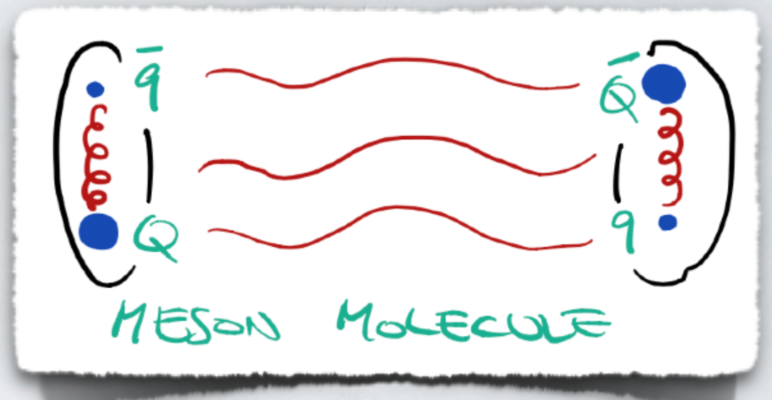
- Two competing interpretations



[see e.g. Maiani et al. — PRD (2014), 1405.1551]

1. Comprehensive description of the spectrum
2. Explains isospin violation
3. Slightly larger than an ordinary hadron ($d_{tetra} \simeq 1.3$ fm)

but… overpopulated



[see e.g. Guo et al. — Rev.Mod.Phys. (2018), 1705.00141]

1. Naturally explains closeness to threshold
2. Explains isospin violation
3. Very large state ($d_{mol} \simeq 10$ fm)

but… less systematic and cannot explain the prompt production of the X

PROMPT PRODUCTION

The problem

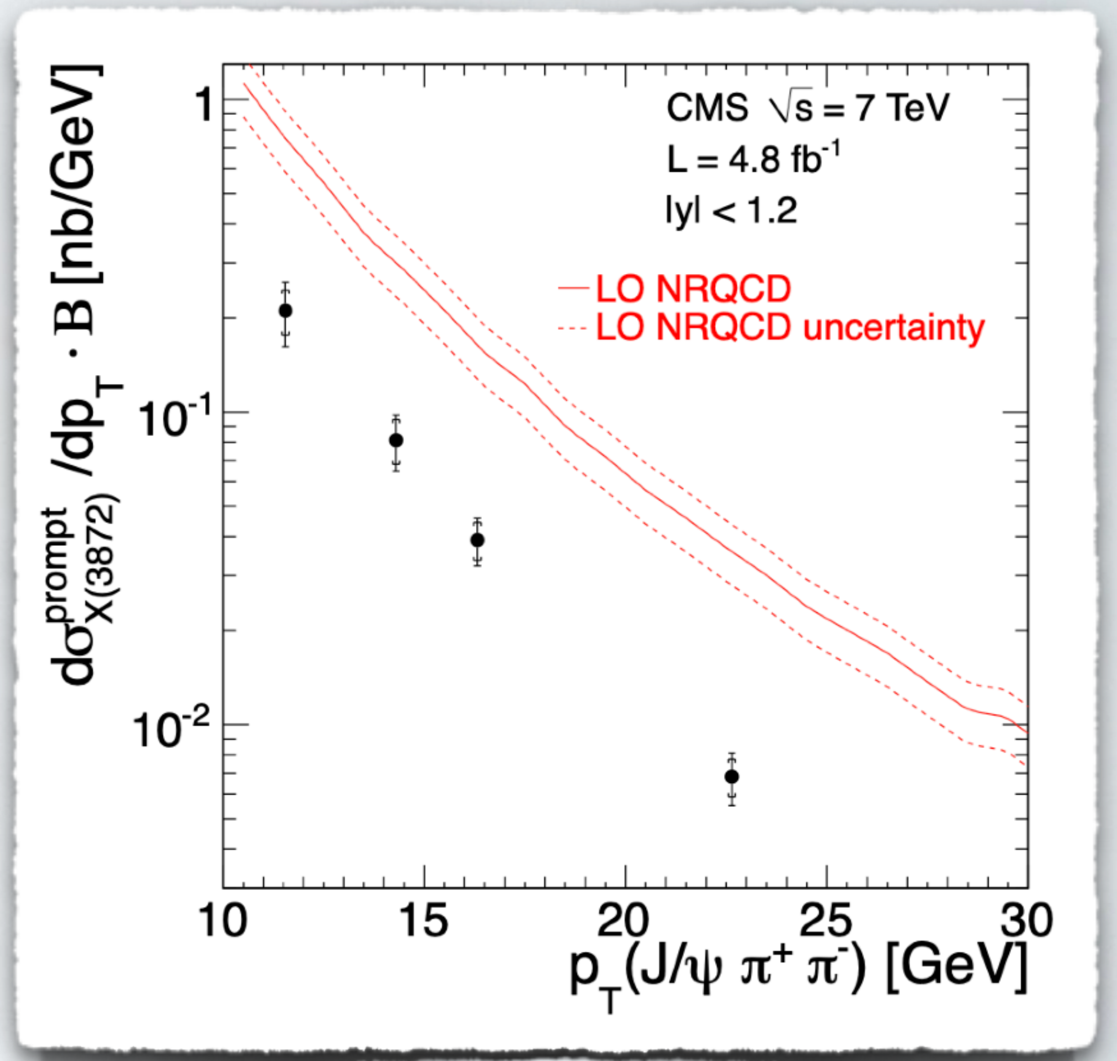
- The $X(3872)$ is produced prompt at high-p_T both at Tevatron and LHC

[see e.g. CDF — PRL (2007), hep-ex/0612053; CMS — JHEP (2013), 1302.3968]

$$\sigma_{prompt}\left(pp \to X\right) \sim 30 \div 70 \text{ nb}$$

[Artoisenet, Braaten — PRD (2010), 0911.2016]

- How can such a loosely bound molecule be produced promptly from a $D^0\bar{D}^{*0}$ pair with relative momentum $k \gtrsim 10$ GeV?



[CMS — JHEP (2013), 1302.3968]

PROMPT PRODUCTION

Monte Carlo

- Upper bound on the prompt production cross section

$$\sigma_{prompt}\left(pp \to X\right) \leq \sigma_{max}\left(pp \to D^0\bar{D}^{*0}\right) \simeq \sigma\left(pp \to D^0\bar{D}^{*0}\,\middle|\,k_{rel} < \Lambda\right)$$

can estimate from MC simulations

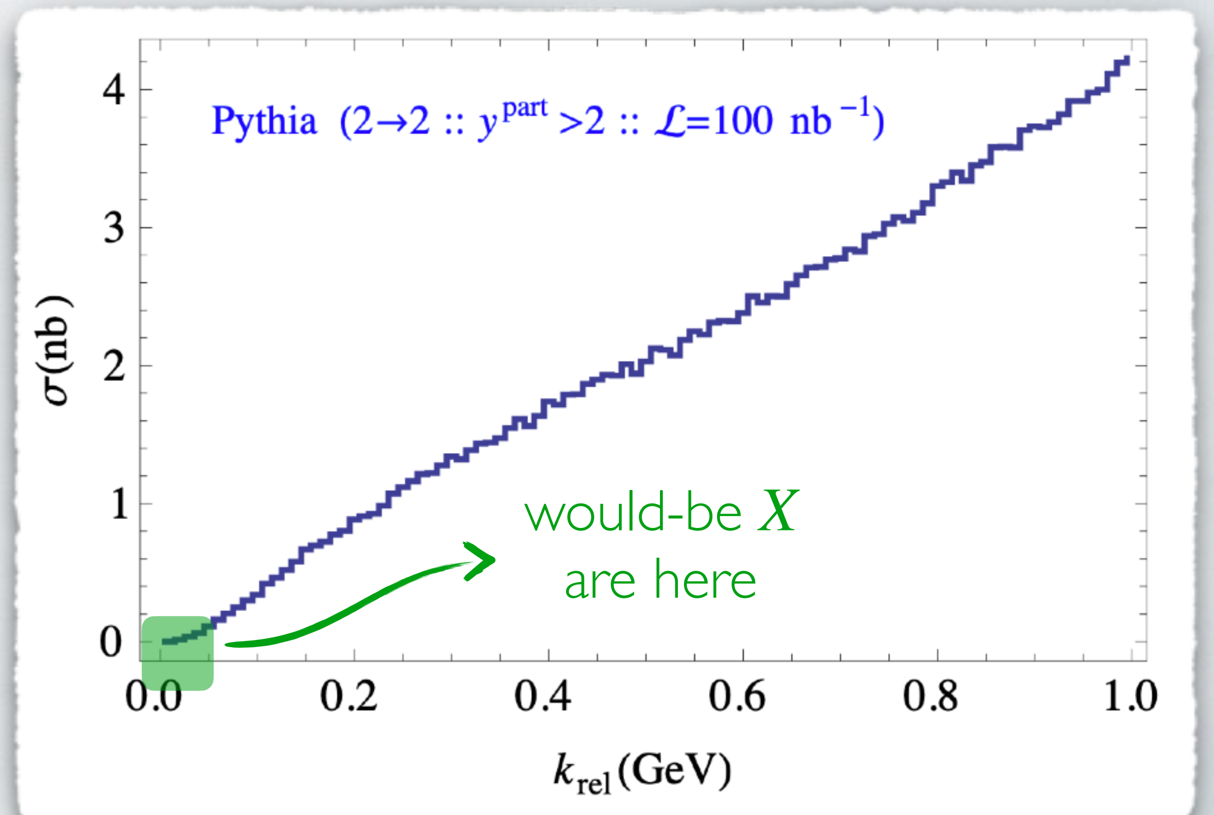
- From the spread of the wave function of the X $\longrightarrow$ $\Lambda \simeq 30$ MeV

- From Monte Carlo: $\sigma_{MC} \sim 10^{-2}\sigma_{exp}$!

[Bignamini et al. — PRL (2009), 0906.0882]

- The correct value of Λ is still a matter of debate

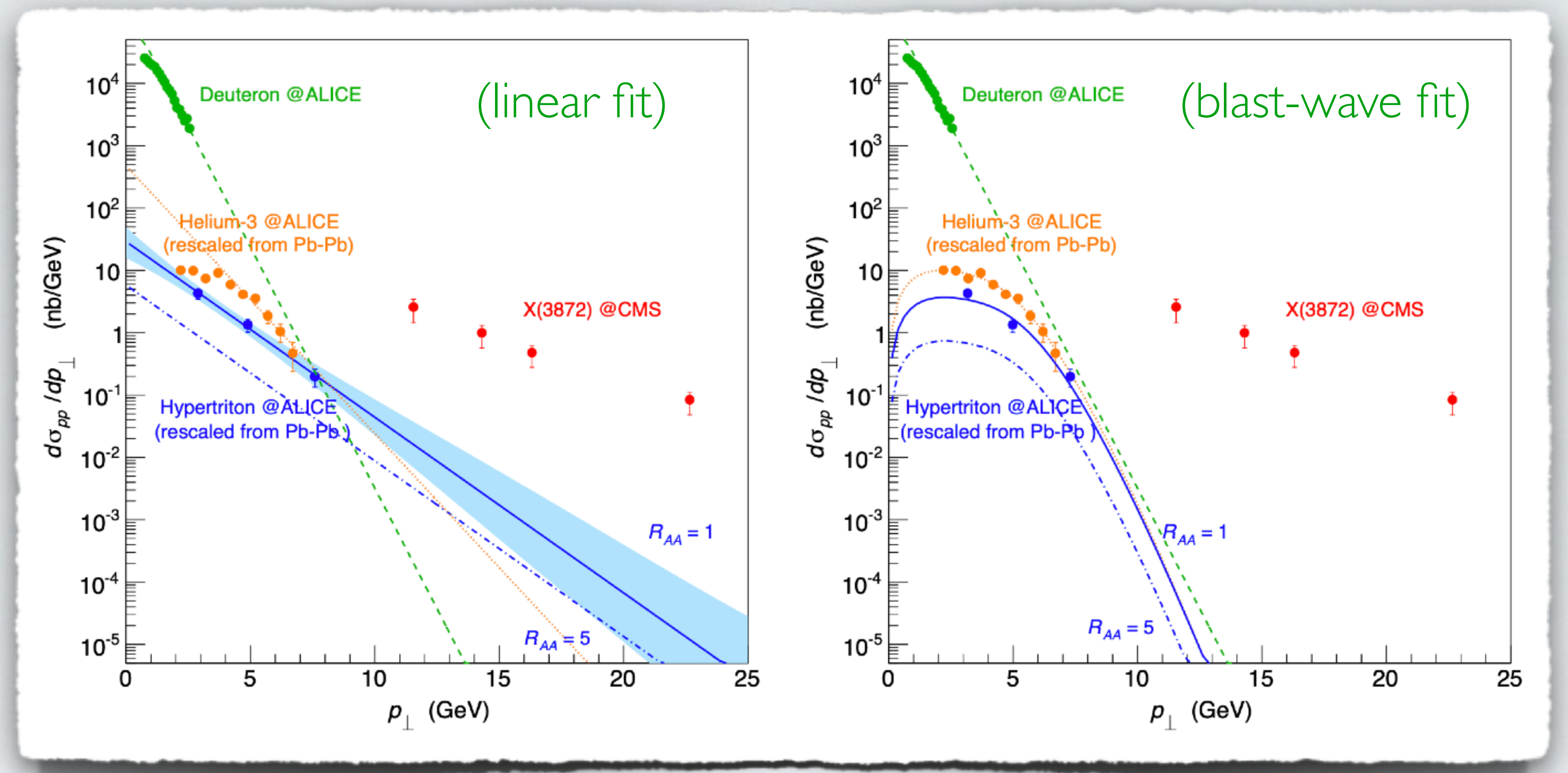
[see e.g. Artoisenet, Braaten — PRD (2010), 0911.2016, Bignamini et al. — PLB (2010), 0912.506, Albaladejo et al. — Chin.Phys.C (2017), 1709.09101]



PROMPT PRODUCTION

Other bone fide molecules

- A stronger statement from the comparison with other loosely bound molecules



[AE, Guerrieri, Maiani, Piccinini, Pilloni, Polosa, Riquer — PRD (2015), 1508.00295]

- No hadronic molecule is produced at high-p_T except for the $X(3872)$

PROMPT PRODUCTION

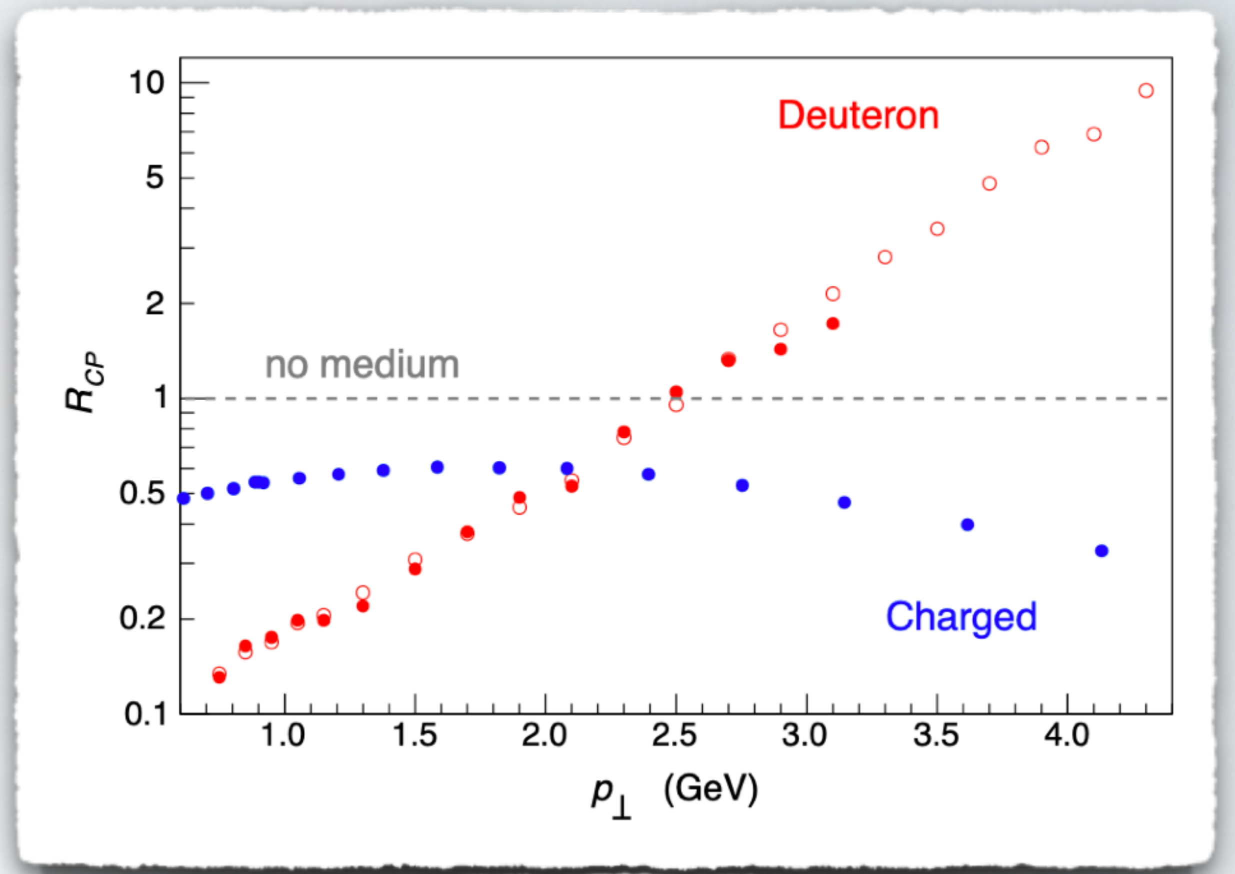
Other bone fide molecules

- Important information from R_{CP} for deuteron vs ordinary hadrons

central collision =
many particles

$$R_{CP} = \frac{\left(\frac{1}{N_{evt}}\frac{d^2N}{dp_T dy}\right)^{0-10\%}_{Pb-Pb} \Big/ N_{coll}^{0-10\%}}{\left(\frac{1}{N_{evt}}\frac{d^2N}{dp_T dy}\right)^{60-80\%}_{Pb-Pb} \Big/ N_{coll}^{60-80\%}}$$

peripheral collision =
fewer particles



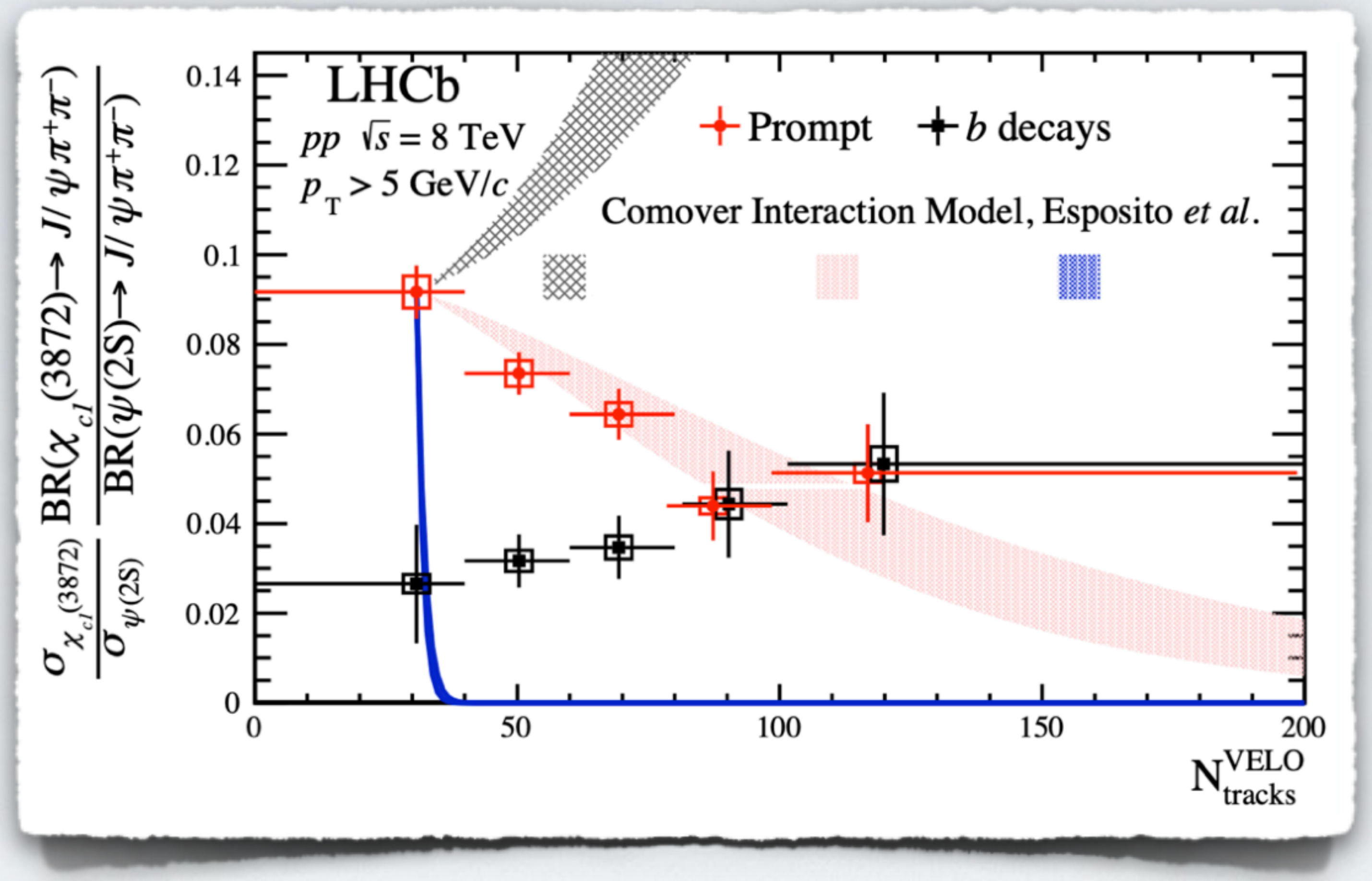
[computed in AE, Guerrieri, Maiani, Piccinini, Pilloni, Polosa, Riquer — PRD (2015), 1508.00295; data from ALICE — PRC (2016), 1506.08951]

- Additional particles favor the formation of molecules but suppress ordinary hadrons

HIGH-MULTIPLICITY pp COLLISIONS

$X(3872)$ vs $\psi(2S)$

- Comparison between the yield of $X(3872)$ and of $\psi(2S)$ as a function of final state multiplicity in pp collisions by LHCb



[LHCb — PRL(2021), 2009.06619]

- Many particles in the event $\longrightarrow$ the X is suppressed with respect to the $\psi(2S)$

THE COMOVER MODEL

Generalities

- The interaction with final state comoving particles can help create/destroy a hadron

[see e.g. Baym — PLB (1984)]

- For a <u>compact</u> state in pp collisions the number evolves following

heavy hadron number

destruction cross section

comover density at initial time (Glauber model)

$$\tau \frac{dN_{\mathcal{Q}}}{d\tau} = - \langle v\sigma \rangle_{\mathcal{Q}} \, \rho_c \, N_{\mathcal{Q}}$$

- In the comover interaction model one takes

$$\langle v\sigma \rangle_{\mathcal{Q}} \sim \pi r_{\mathcal{Q}}^2$$

- This has proved to be quantitatively successful at describing quarkonium yields as function of multiplicity in pPb and PbPb

[see e.g. Ferreiro — PLB (2015), 1411.0549; Ferreiro, Lansberg — JHEP (2019), 1804.04474]

THE COMOVER MODEL

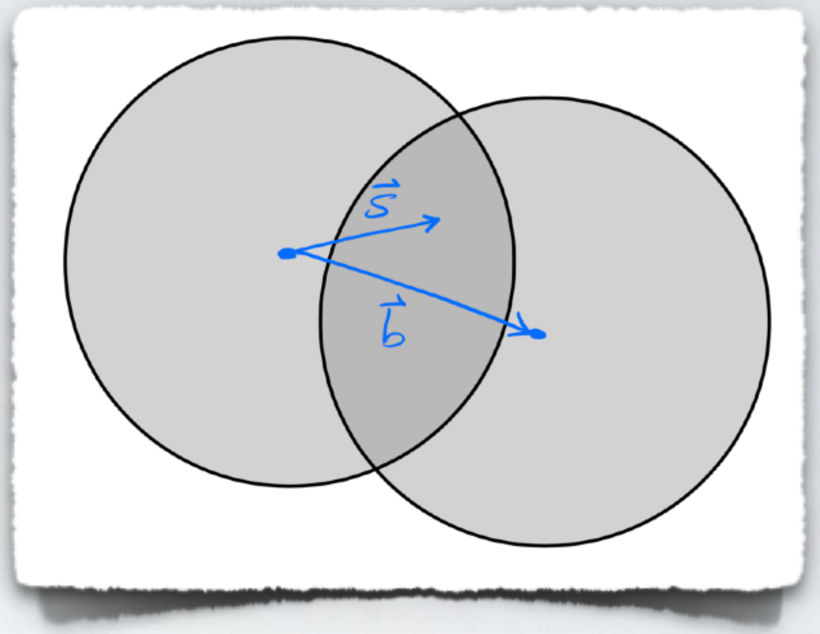
Generalities

- The solution of the evolution equation depends on position and impact parameter

$$N_{\mathcal{Q}}(\mathbf{b}, \mathbf{s})$$

impact parameter

position in the nucleus



- The solution must be convoluted with the comover density profile normalized to give the minimum bias number of tracks per event, $\rho_c(\mathbf{b}, \mathbf{s})$

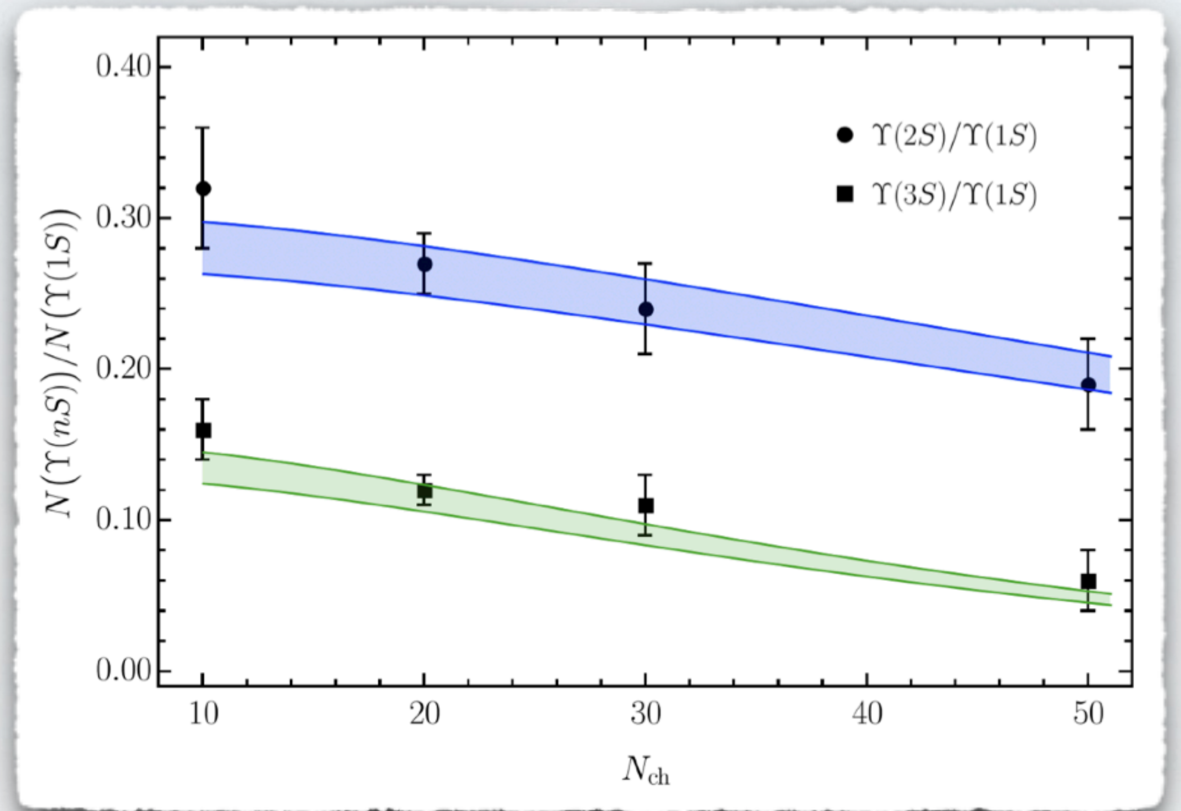
- For a qualitative estimate one can use average quantities, $\rho_c \sim 3N_{ch}/2\sigma_{pp}$

[see e.g. Ferreiro – PLB (2015), 1411.0549; Ferreiro, Lansberg – JHEP (2019), 1804.04474]

THE COMOVER MODEL

Bottomonia in *pp* collisions

- Further validate the model using CMS data on bottomonia in high-multiplicity *pp* collisions for the first time ⟶ no fit! [Ferreiro, Lansberg – JHEP (2019), 1804.04474]
- Very good agreement with data



[CMS – JHEP (2014), 1312.6300 and AE, Ferreiro, Pilloni, Polosa, Salgado – EPJC (2021), 2006.15044]

THE COMOVER MODEL

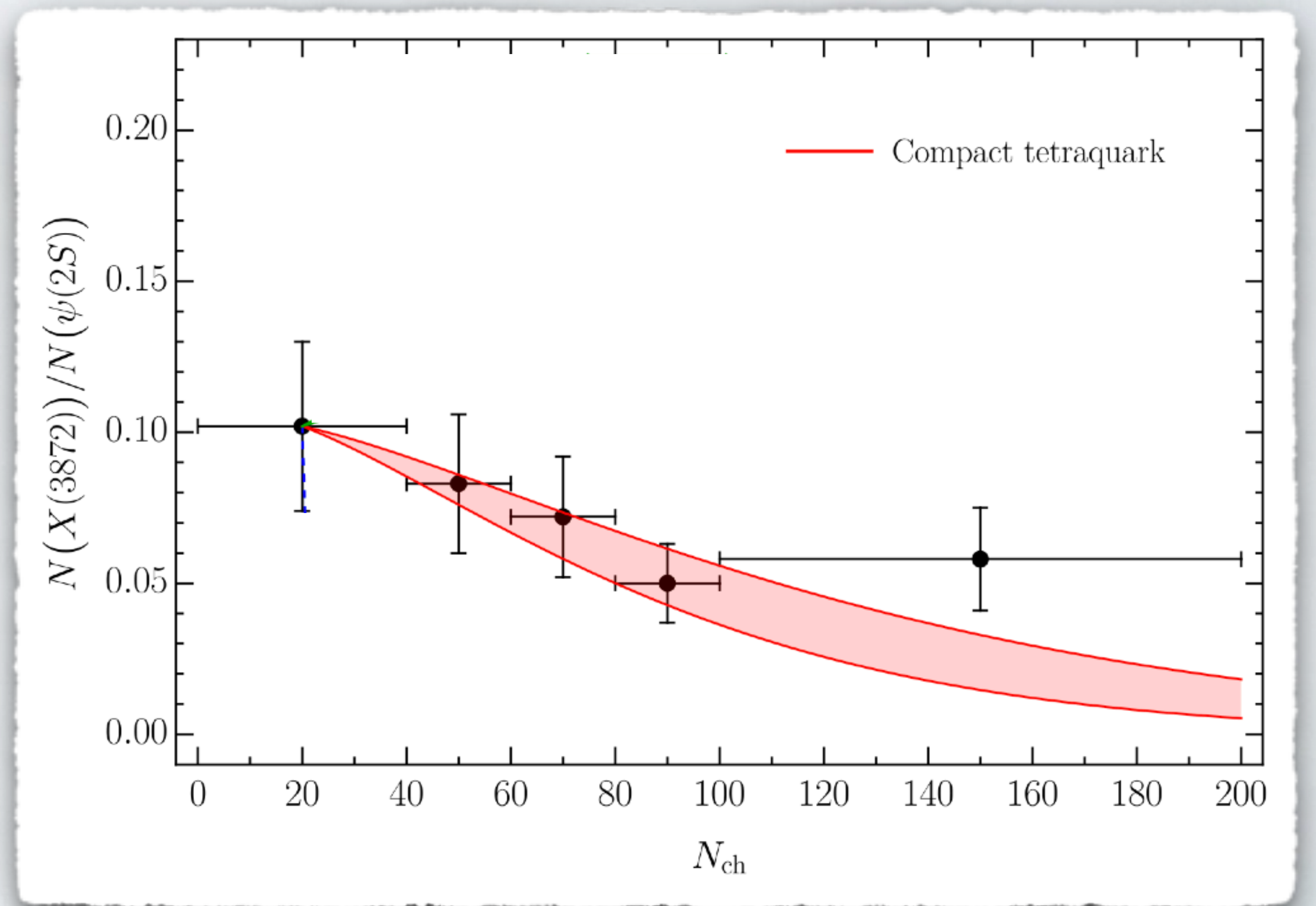
Compact tetraquarks

- Apply the model to the compact tetraquark hypothesis $\longrightarrow$ slightly larger than quarkonia

$$\begin{cases} r_{4q} \simeq 0.65 \text{ fm} \\ r_{\psi(2S)} \simeq 0.45 \text{ fm} \end{cases} \Longrightarrow \begin{cases} \langle v\sigma \rangle_{4q} \simeq 11.61 \text{ mb} \\ \langle v\sigma \rangle_{\psi(2S)} \simeq 5.15 \text{ mb} \end{cases}$$

- Again very good agreement with the LHCb data!

[AE, Ferreiro, Pilloni, Polosa, Salgado — EPJC (2021), 2006.15044]



THE COMOVER MODEL

Molecules in the geometrical model

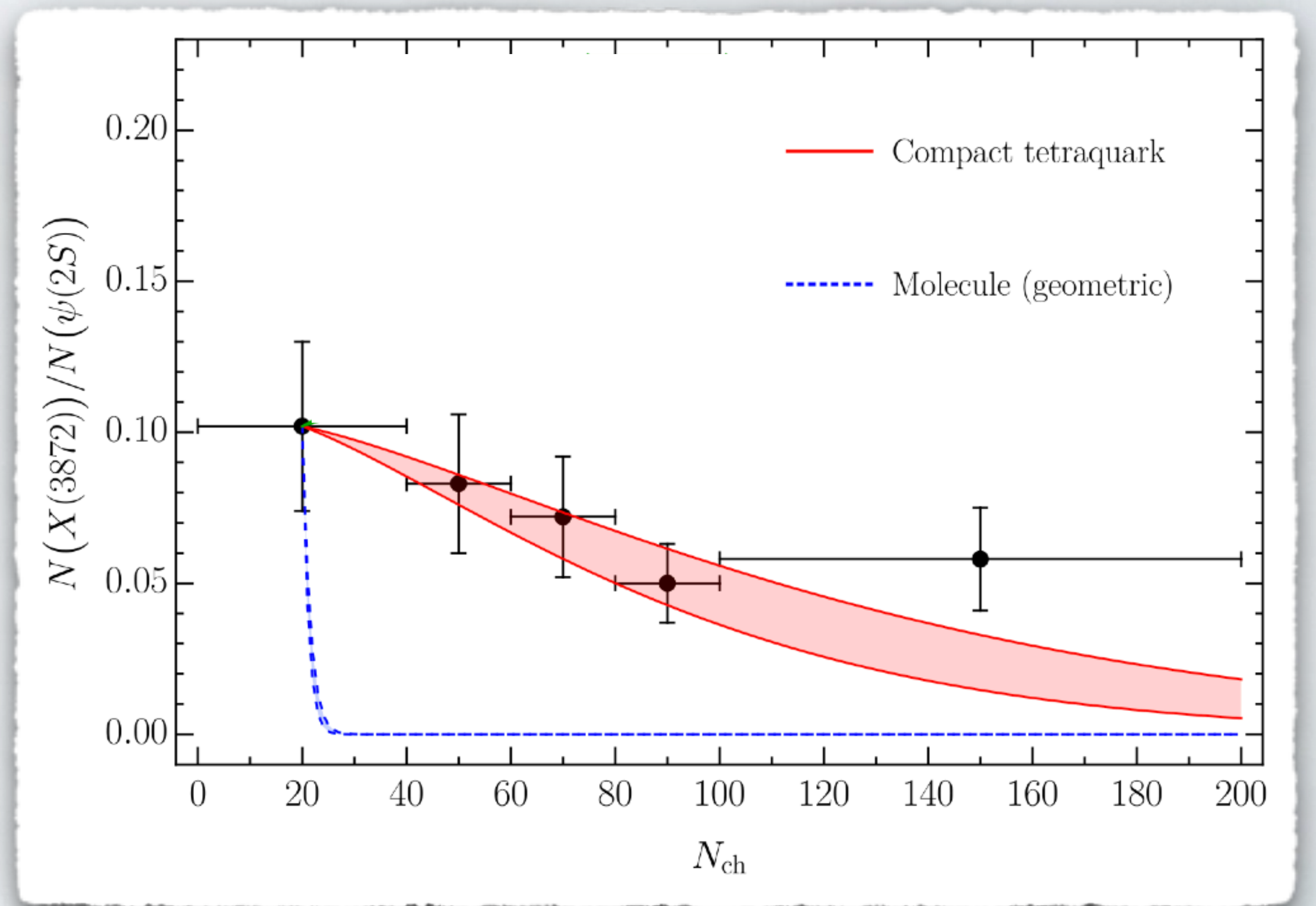
- Consider naively applying the geometric model to hadronic molecules ⟶ large extension ⟶ huge suppression from the interaction with comovers

$$r_{mol} \simeq 6.6 \text{ fm} \quad \Longrightarrow \quad \langle v\sigma \rangle_{mol} \simeq 1197 \text{ mb}$$

- Suppression way too large to reproduce the data

[AE, Ferreiro, Pilloni, Polosa, Salgado — EPJC (2021), 2006.15044]

- This effective description cannot apply to extended loosely bound molecules



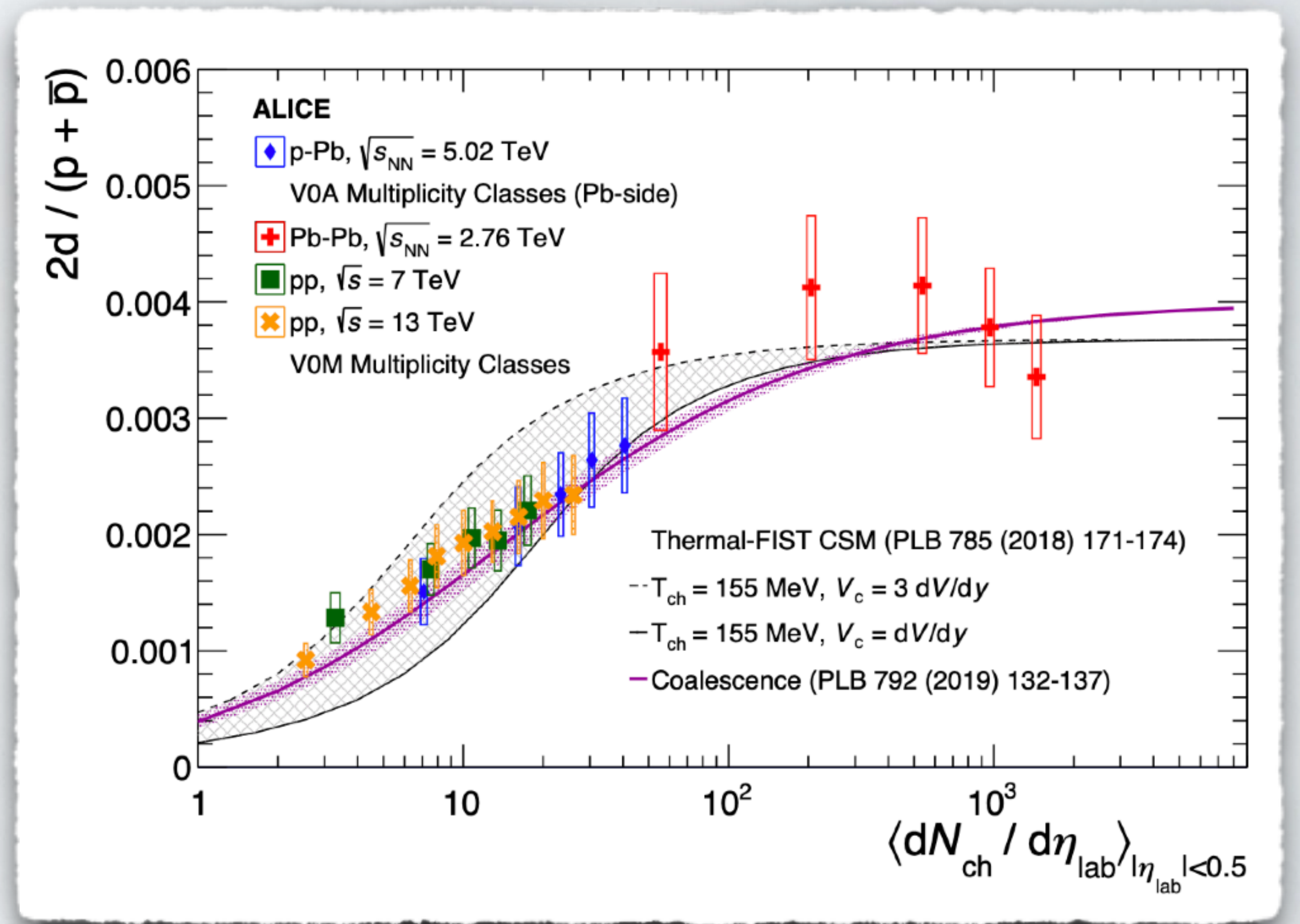
MOLECULES IN HIGH-MULTIPLICITY EVENTS

Deuteron

- Creation/destruction of hadronic molecules is more complicated than that
- Recent data show that the comovers favor the creation of molecules

- Higher multiplicity ⟶ more nucleons are turned into deuterons

- Important to better describe destruction and coalescence of hadron molecules

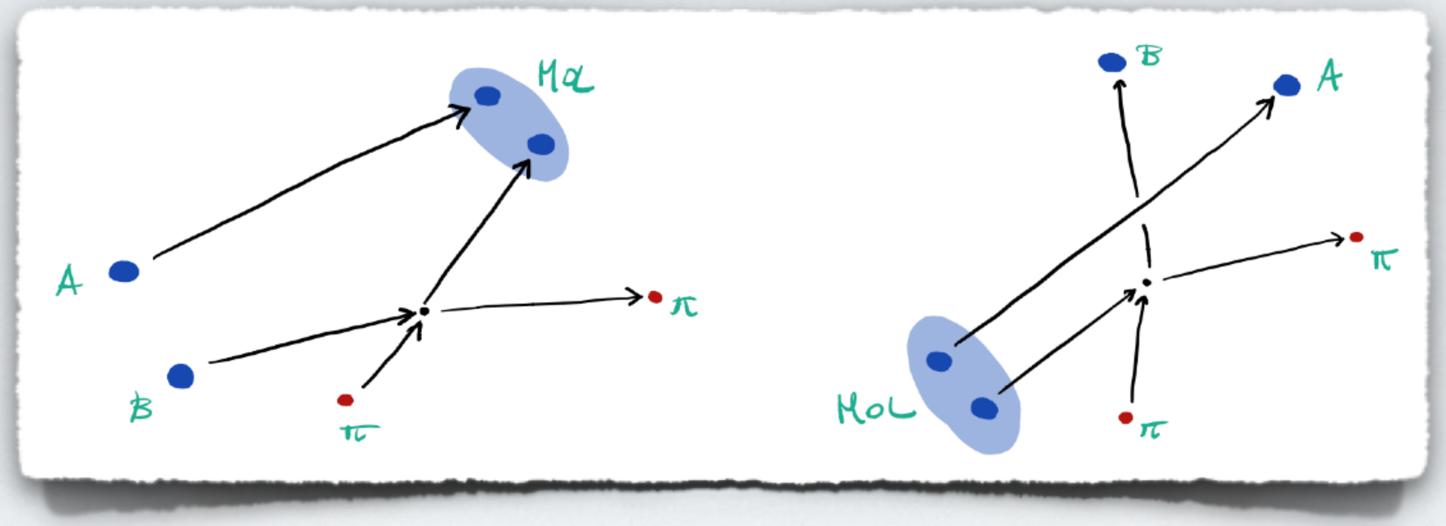


[ALICE — PLB (2019), 1902.09290; ALICE — 2003.03184]

MOLECULES IN HIGH-MULTIPLICITY EVENTS

Destruction and coalescence

- The interaction with comovers can destroy or create a hadronic molecule
  [see e.g. AE, Piccinini, Pilloni, Polosa — J.Mod.Phys. (2013), 1305.0527; Guerrieri, Piccinini, Pilloni, Polosa — PRD (2014), 1405.7929; Cho et al. — PRL (2011), 1011.0852]



- The number of molecules evolves according to

# of free constituents

# of molecules

$$\tau \frac{dN_m}{d\tau} = \rho_c N_{hh} \langle v\sigma \rangle_m - \rho_c N_m \langle v\sigma \rangle_{hh}$$

creation of a molecule

destruction of a molecule

MOLECULES IN HIGH-MULTIPLICITY EVENTS

Destruction and coalescence

- Creation of a molecule

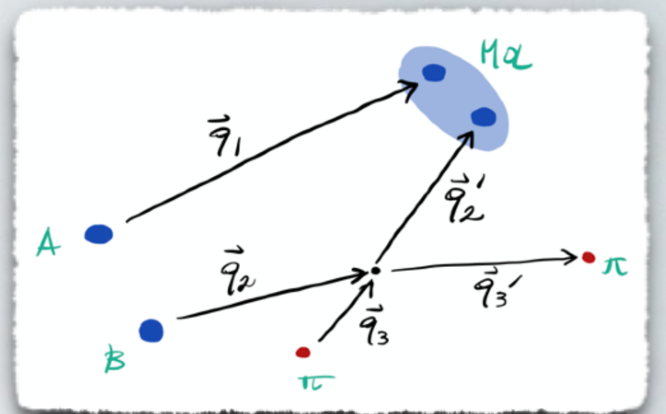
$$\langle v\sigma\rangle_m = \int_{k<\Lambda} \frac{d^3q_1}{(2\pi)^3}\frac{d^3q_2'}{(2\pi)^3}\int\frac{d^3q_2}{(2\pi)^3}\frac{d^3q_3}{(2\pi)^3}\frac{d^3q_3'}{(2\pi)^3}\,\delta_P\,W\big(q_2,q_3;q_2',q_3'\big)\,f_{hh}(q_1,q_2)f_c(q_3)$$

effective pion-constituent matrix element

final state molecules

distribution of free constituents

distribution of comovers (pions)

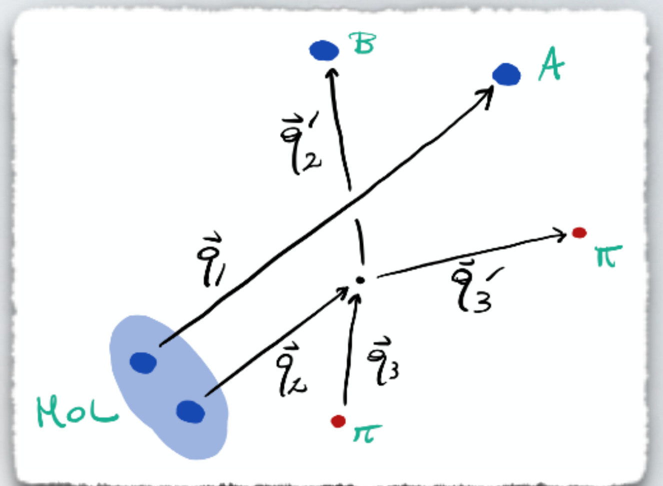


- Destruction of a molecule

$$\langle v\sigma\rangle_{hh} = \int_{k<\Lambda} \frac{d^3q_1}{(2\pi)^3}\frac{d^3q_2}{(2\pi)^3}\int\frac{d^3q_2'}{(2\pi)^3}\frac{d^3q_3}{(2\pi)^3}\frac{d^3q_3'}{(2\pi)^3}\,\delta_P\,W\big(q_2,q_3;q_2',q_3'\big)\,f_m(q_1,q_2)f_c(q_3)$$

initial state molecules

distribution of molecules



- The matrix element is taken from heavy meson χPT
- The distribution of free constituents and comovers are taken from MC (Pythia)
- The distribution of molecules is taken from data

[for deuteron see ALICE — PLB (2019), 1902.09290; for the X see CMS — JHEP (2013), 1302.3968]

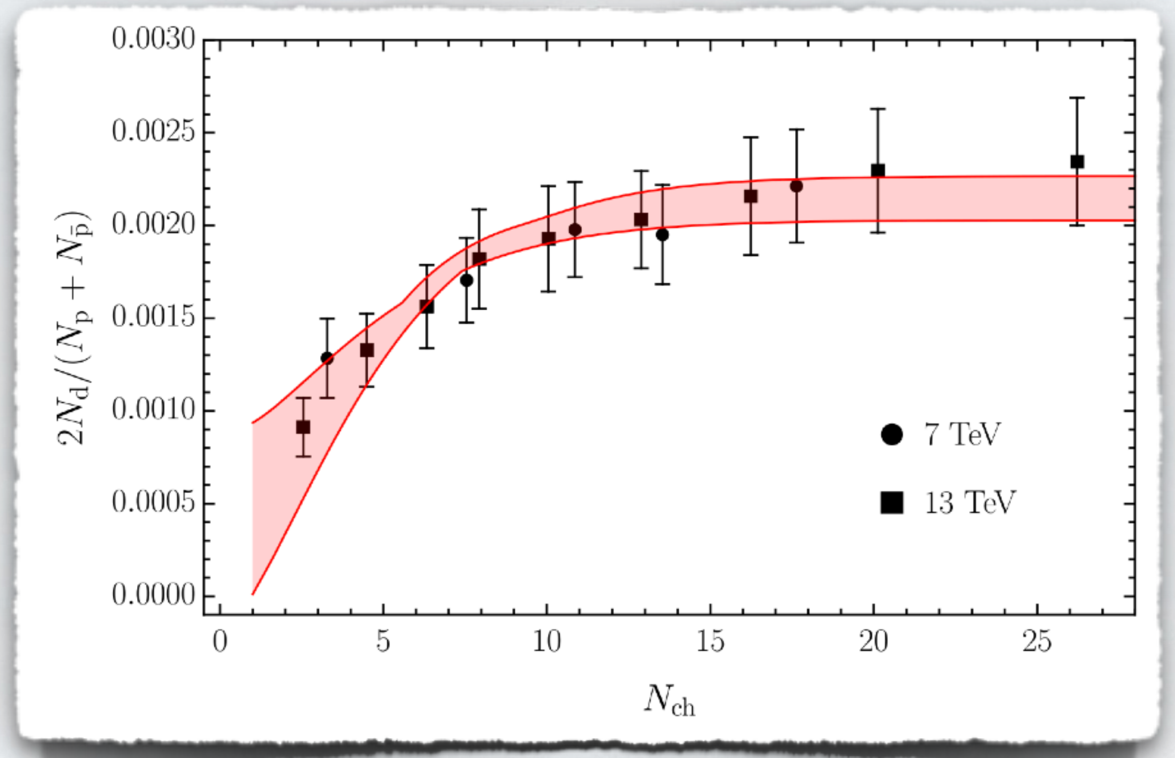
MOLECULES IN HIGH-MULTIPLICITY EVENTS

Deuteron again

- The coalescence momentum for deuteron is known to be $\Lambda = 50 \div 250$ MeV
- Averaging over distributions we get

$$\langle v\sigma \rangle_m \simeq \left(\Lambda/150 \text{ MeV}\right)^3 \times 0.51 \text{ mb}\,; \qquad \langle v\sigma \rangle_{hh} \simeq 4.34 \text{ mb}$$

- Very good agreement with data



[AE, Ferreiro, Pilloni, Polosa, Salgado — EPJC (2021), 2006.15044]

MOLECULES IN HIGH-MULTIPLICITY EVENTS

$X(3872)$

- For the $X(3872)$ the same approach gives ($\Lambda = 30 \div 360$ MeV):

$$\langle v\sigma\rangle_m \simeq \left(\Lambda/50\ \text{MeV}\right)^3 \times 3.1\times10^{-5}\ \text{mb}\,, \quad \langle v\sigma\rangle_{hh} \simeq 0.50\ \text{mb}$$

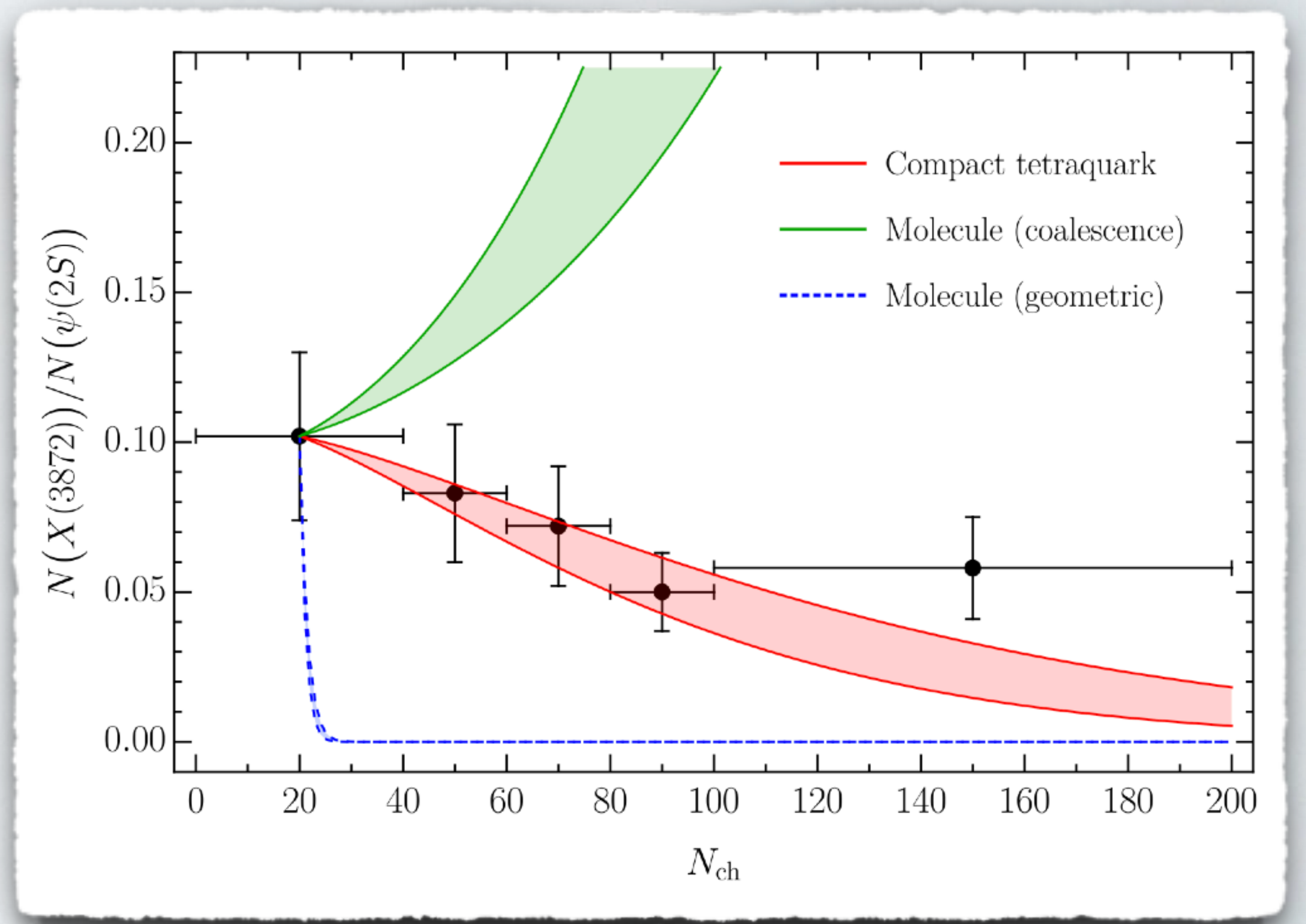
[in good agreement with Cho et al. — PRL (2011), 1011.0852; and Cho, Lee — PRC (2013), 1302.6381]

- How is the X produced promptly?

1. Through $D^0\bar{D}^{*0}$ $\longrightarrow$ $\dfrac{N_m^0}{N_{hh}} = 0$

2. Through $\chi_{c1}(2P)$ $\longrightarrow$ $\dfrac{N_m^0}{N_{hh}} = 1$

- Again qualitatively different from data



[AE, Ferreiro, Pilloni, Polosa, Salgado — EPJC (2021), 2006.15044]

COMMENTS AND CONCLUSION

- Data on the production of the $X(3872)$ in high multiplicity pp collisions together with two simple and well tested ideas seem to speak in favor of a compact nature

- ALICE data point to the fact that comovers increase the yield of molecules rather than decrease it

- How about the p_T dependence?

- How about pPb and PbPb?

  [see CMS — CMS-PAS-HIN-19-005; Zhang et al. — 2004.00024; Wu et al. — 2006.09945]

- Always crucial to see: are there other bone fide hadronic molecules at high-p_T? Deuteron, hypertriton, Helium-3,…

THANKS FOR YOU ATTENTION!

BACK UP

PROMPT PRODUCTION

Last piece of the controversy

- It has been argued that

X wave function with high momentum regulator λ

$$\sigma\left(p\bar{p}\to X\right) \sim \left| \int d^3k \, \langle X | D^0 \bar{D}^{*0}(\mathbf{k})\rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | p\bar{p}\rangle \right|^2$$

$$\simeq \left| \int_{k<\Lambda} d^3k \, \langle X | D^0 \bar{D}^{*0}(\mathbf{k})\rangle \langle D^0 \bar{D}^{*0}(\mathbf{k}) | p\bar{p}\rangle \right|^2 \propto \left| \int_{k<\Lambda} d^3k \, \psi_\lambda(k) \right|^2$$

almost constant with k

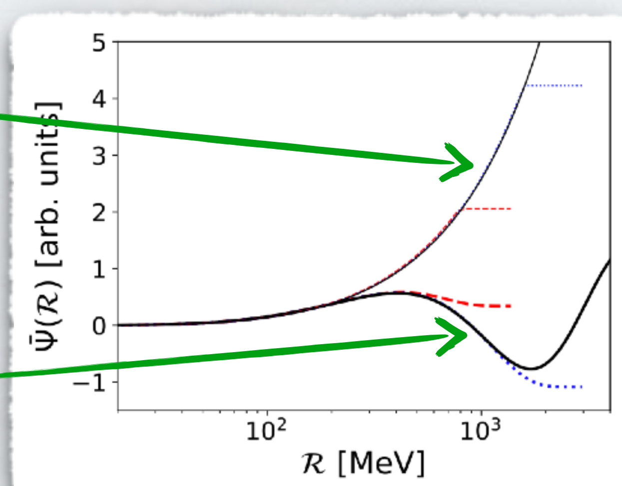
- Claim: the correct value for Λ should be found so that the last integral is saturated

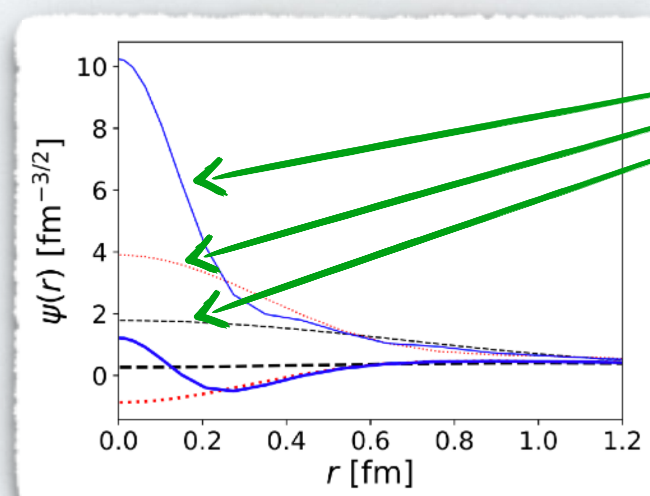
[Albaladejo, Guo, Hanhart, Meißner, Nieves, Nogga, Yang — Chin.Phys.C (2017), 1709.09101]

- For the case of deuteron and of the X one would deduce $\Lambda \simeq 300$ MeV

short range potential only

short range + OPE potential





different regulators λ

PROMPT PRODUCTION

Last piece of the controversy

- Other claim: Λ should not be found with any requirement based on production cross section $\longrightarrow$ it should be found a priori from physical arguments
- The simple virial theorem gives $\overline{B} = -\dfrac{\Lambda^2}{2\mu} + \dfrac{g}{r_0}\overline{e^{-r/r_0}}$
- For deuteron one gets $\overline{B} = 2.2$ MeV , $\bar{r} = 2.1$ fm $\Rightarrow$ $\Lambda = 105$ MeV $\longrightarrow$ the well known value
- For the X instead $\overline{B} \lesssim 0.1$ MeV , $\bar{r} \gtrsim 10$ fm $\Rightarrow$ $\Lambda \simeq 20$ MeV $\longrightarrow$ much smaller
- Moreover, fictitious dependence of the wave function on λ seems to give
  1. Zeros in the amplitude $X \to D^0\bar{D}^{*0}$ when λ varies
  2. Spurious nodes in the ground state spatial wave function

THE COMOVER MODEL

Average cross sections

- In the comover interaction model the average cross section is given by

threshold energy computed wrt the closest OZI-favored mode

index depending on the nature of the comovers. We take $n = 1$

$$\langle v\sigma\rangle_{\mathcal{Q}} = \pi r_{\mathcal{Q}}^2 \int_{E_{\mathcal{Q}}^{thr}}^{\infty} dE_c\, E_c^2 \left(1 - \frac{E_{\mathcal{Q}}^{thr}}{E_c}\right)^n \mathscr{P}\left(E_c\right)$$

distribution of comovers energy

$$\mathscr{P}\left(E_c\right) \propto \left(e^{E_c/T_{eff}} - 1\right)^{-1},$$

with $T_{eff} = 200 \div 300$ MeV

[see e.g. Ferreiro — PLB (2015), 1411.0549; Ferreiro, Lansberg — JHEP (2019), 1804.04474]

- For excited states quarkonia and exotic mesons $E_{\mathcal{Q}}^{thr} \ll E_c$ and hence

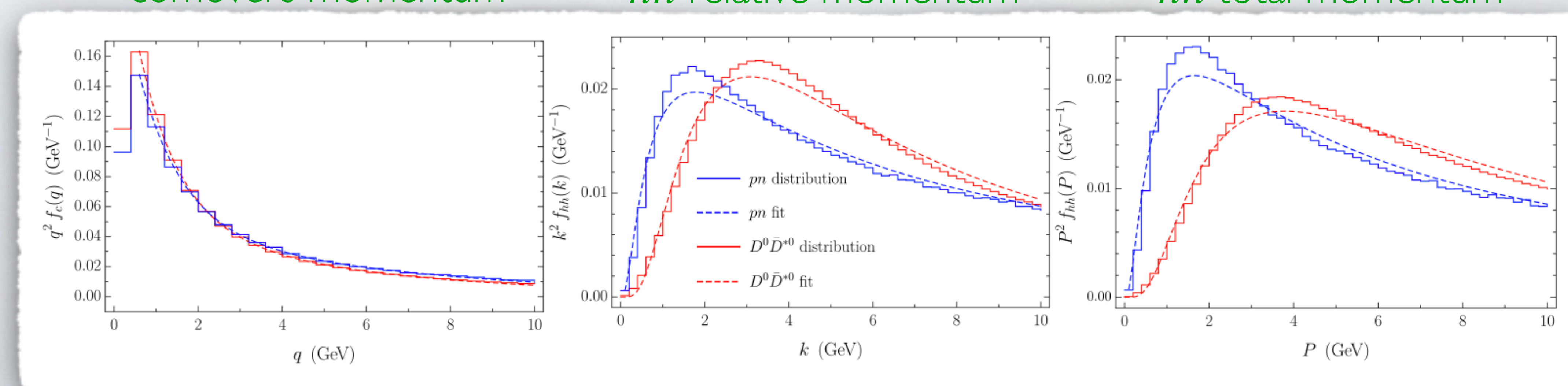
$$\langle v\sigma\rangle_{\mathcal{Q}} \simeq \pi r_{\mathcal{Q}}^2$$

MOLECULES IN HIGH-MULTIPLICITY EVENTS

Average cross sections

- The constituent-comover matrix elements is parametrize with an effective coupling $\mathscr{M}_{\pi h \to \pi h} = g^2$, with $g_p^2/(4\pi) \simeq 10$ and $g_D^2/(4\pi) \simeq 5.1$
- Built to reproduce the elastic scattering cross section for all comovers energies, $E_c \in [0{,}300]$ MeV
- The other ingredients needed to compute the average cross sections are the momentum distributions
- From Pythia

comovers momentum | hh relative momentum | hh total momentum



SOLUTION TO THE EVOLUTION EQUATION

- Solution to the evolution equation

initial number of molecules. $N_m^0/N_{hh} \simeq 10^{-4}$ from Pythia

$$\frac{N_m}{N_{hh}} = \frac{\langle v\sigma\rangle_m}{\langle v\sigma\rangle_m + \langle v\sigma\rangle_{hh}} + \left(\frac{N_m^0}{N_{hh}} - \frac{\langle v\sigma\rangle_m}{\langle v\sigma\rangle_m + \langle v\sigma\rangle_{hh}}\right) e^{-\left(\langle v\sigma\rangle_m + \langle v\sigma\rangle_{hh}\right)\rho_c \ln\left(\rho_c/\rho_c^{pp}\right)}$$

- The number of initial molecules for the deuteron is found from Pythia to be $N_m^0/N_{hh} \simeq 10^{-4}$ $\longrightarrow$ negligible

- The number of initial molecules for the $X(3872)$ depends on the assumed production mechanism. We take:

1. Purely molecular $\longrightarrow$ $N_m^0/N_{hh} \simeq 0$
2. Production via $c\bar{c}$ $\longrightarrow$ $N_m^0/N_{hh} \simeq 1$