# Learning on exotic (XYZ) systems from pPb collisions at the HL LHC

*Learning on X(3872): From pp to PbPb collisions*

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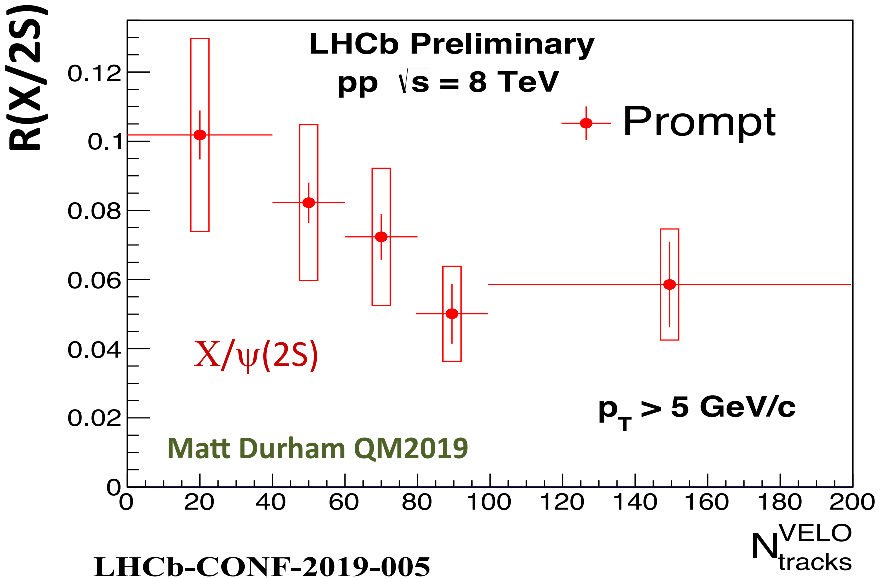
# Results in proton-proton collisions: the nature of the X(3872)

pp

- Measurements by the LHCb collaboration in pp collisions showed a significant decrease in the ratio of prompt χ(3872) to ψ(2S) cross-sections, $\sigma_{\chi(3872)}/\sigma_{\psi(2S)}$, with increasing charged-particle multiplicity.

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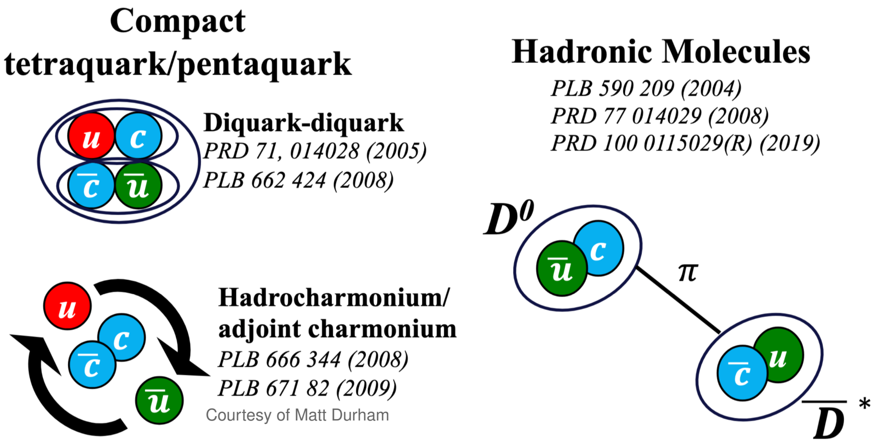
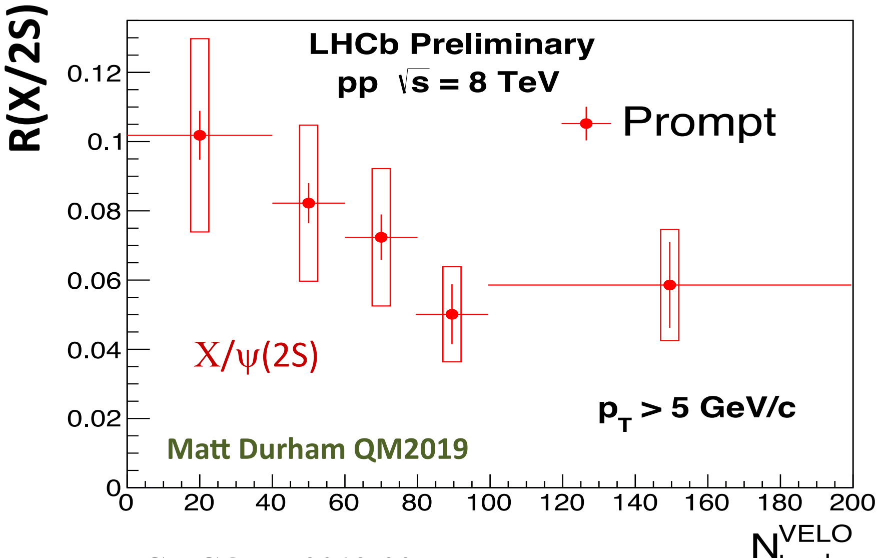


# The nature of the X(3872): comparison with Υ(nS)/Υ(1S) pp

- In fact, the effect found by LHCb is similar to the one previously found for Υ by CMS

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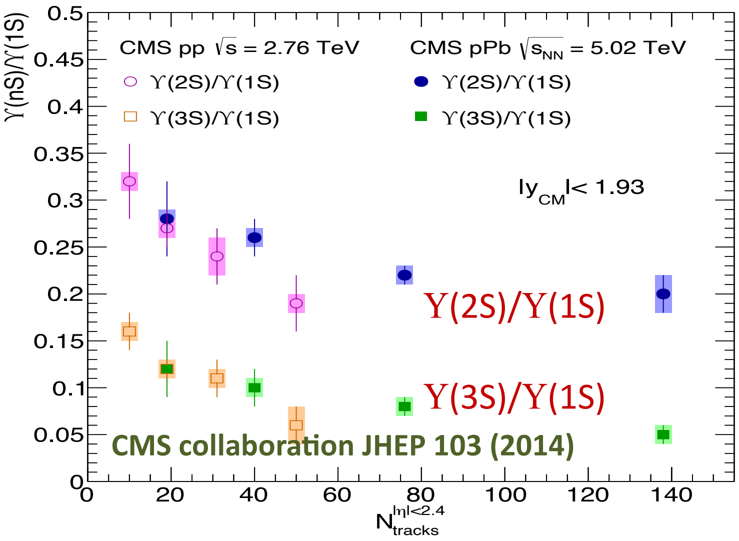

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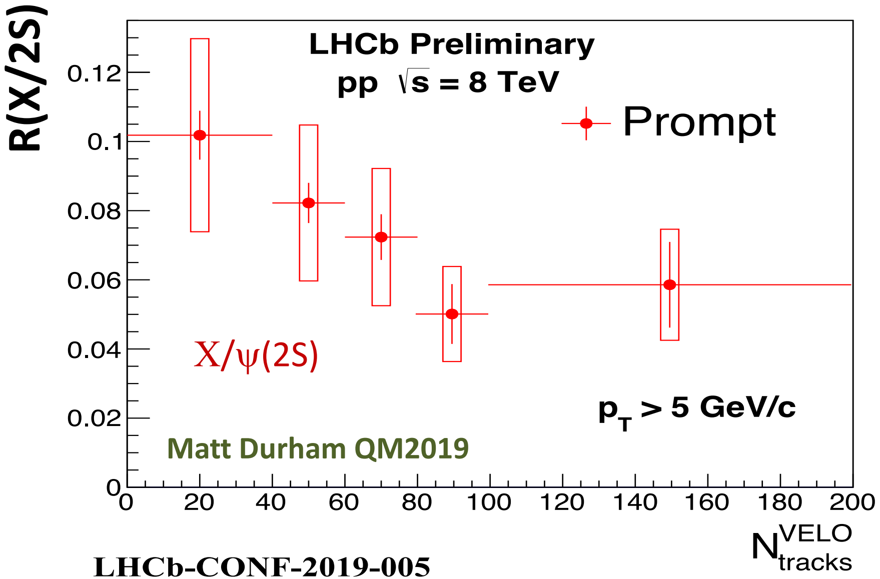
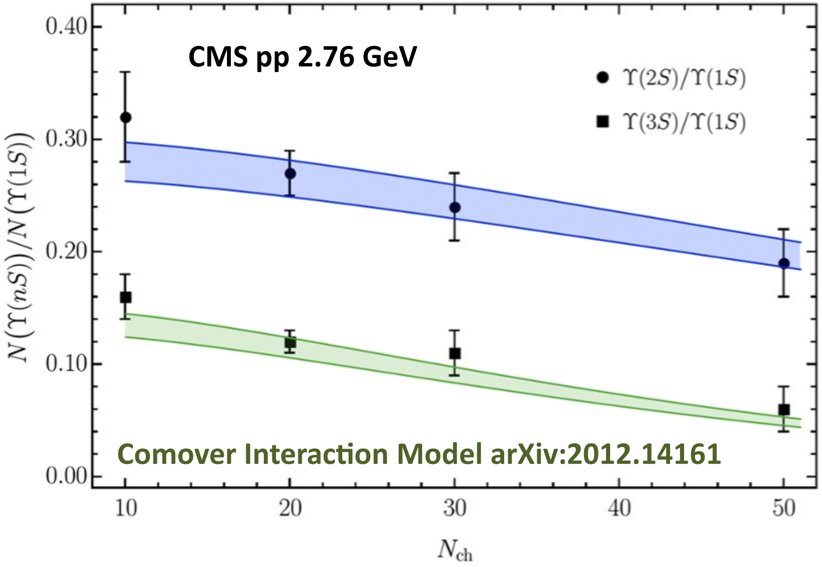



LHCb-CONF-2019-005

Excited-over-ground quarkonium rates
can be reproduced by final-state interactions



# The nature of the X(3872): interaction with the medium

pp

- Boltzman equation governing the quarkonium density:

$$\tau \frac{d\rho^{\mathcal{Q}}}{d\tau}(b,s,y) = -\sigma^{co-\mathcal{Q}}\, \rho^{co}(b,s,y)\, \rho^{\mathcal{Q}}(b,s,y)$$

$$\sigma^{\text{co}-\mathcal{Q}}(E^{\text{co}}) = \sigma^{\mathcal{Q}}_{\text{geo}} \times \left(1 - \frac{E^{\mathcal{Q}}_{\text{thr}}}{E^{\text{co}}}\right)^n$$

**EFG, Lansberg JHEP 10 (2018)**

$\sigma^{\mathcal{Q}}_{\text{geo}} \simeq \pi r^2_{\mathcal{Q}}$, where $r_{\mathcal{Q}}$ is the quarkonium Bohr radius

$E^{\mathcal{Q}}_{\text{thr}} = 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$, *i.e.* the threshold energy

$E^{co} = \sqrt{p^2 + m^2_{co}}$ energy of the comovers

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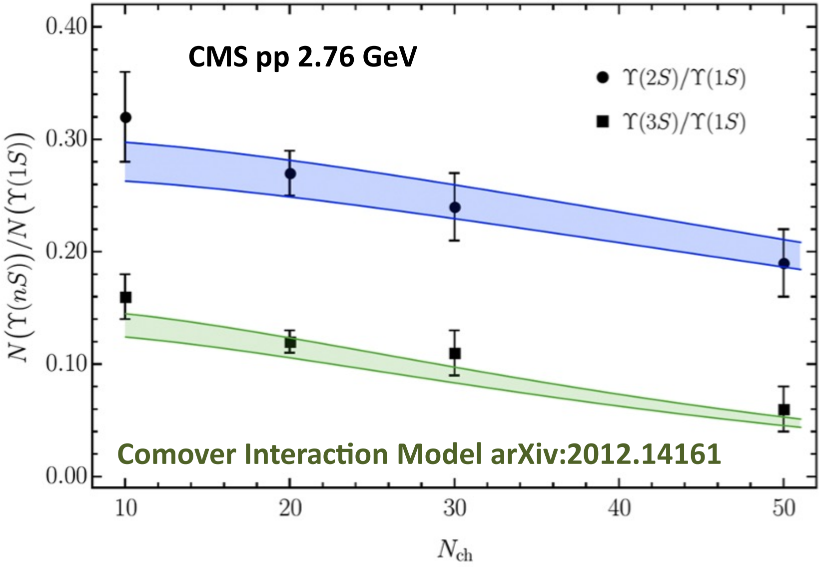

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EFG, Lansberg JHEP 10 (2018)

Originally proposed for pA and AA collisions

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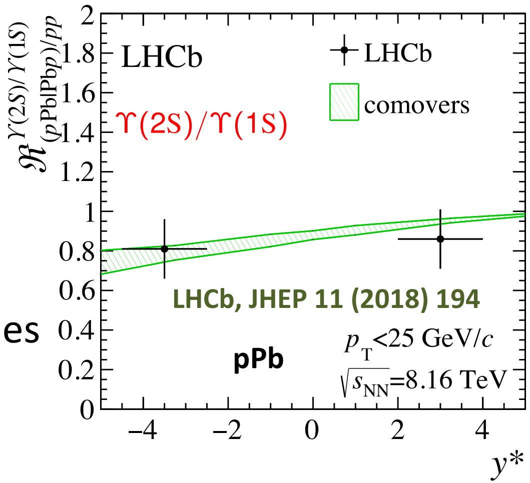
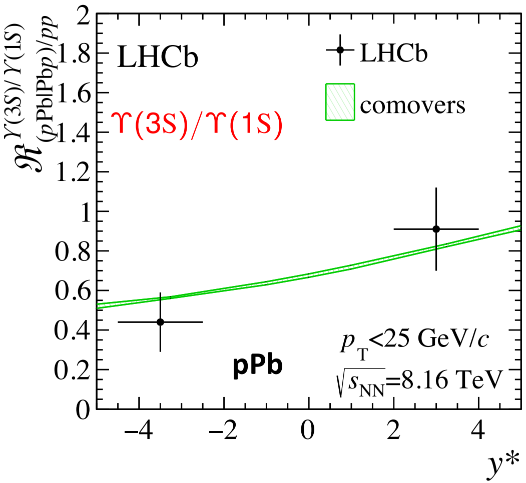
In a comover model: suppression from scatterings of the nascent $\mathcal{Q}$ with comoving medium constituted by particles with similar rapidities Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)



# Behaviour of X(3872)/ψ(2S) with multiplicity

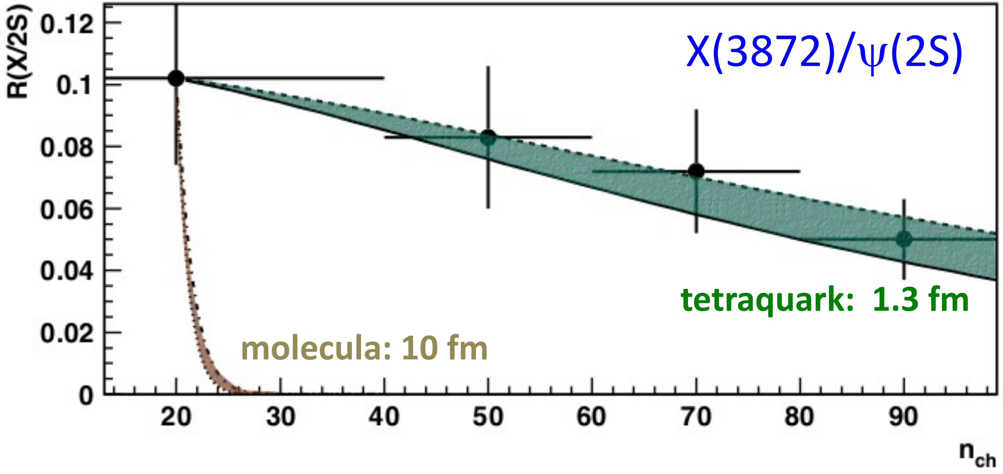
pp

- Let's consider X(3872) as a compact object => interaction cross sections can be calculated

| | $E_{\rm thr}^{\mathcal{Q}}$ | $r_{\mathcal{Q}}$ | $\sigma_{\rm geo}^{\mathcal{Q}}$ | $\sigma^{\rm co-\mathcal{Q}}$ |
|---|---|---|---|---|
| $\psi(2S)$ | 50 MeV | 0.45 fm | 6.36 mb | $5.15 \pm 0.84$ mb |
| $X(3872)$ tetraquark | 200 keV | 0.65 fm | 13.3 mb | $11.61 \pm 1.69$ mb |
| $X(3872)$ molecule | 200 keV | 5.0 fm | 785 mb | $687 \pm 98$ mb |

Esposito, EGF, Pilloni, Polosa, Salgado
Eur.Phys.J.C 81 (2021)
arXiv:2006.15044

Cross sections very close to their geometrical value due to small binding energies involved




- LHCb results strongly supports the idea of X(3872) of typical hadronic size
- A molecular state disappears very quickly by interaction with comovers
- Our conclusion: tetraquark of 1.3 fm

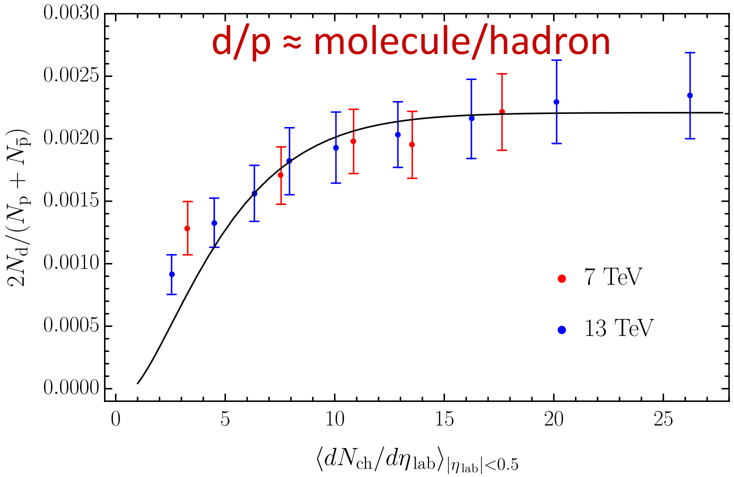
# Coalescence is not the solution

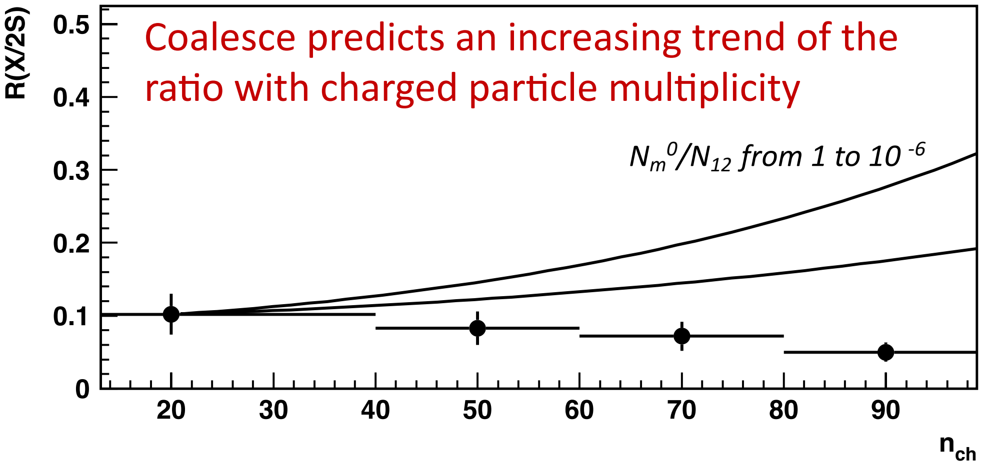
pp

- Accoding to quarkonium data, no secondary charmonium production has been considered for a X(3872) of typical hadronic size
- In case of a X(3872) of molecular nature, coalescence effects, similar to the ones applied to reproduce d/p ratio in pp, can be at play

$$\tau \frac{dN_m}{d\tau} = \langle v\sigma \rangle_m \, \rho_c \, N_{12} - \Big( \langle v\sigma \rangle_m + \langle v\sigma \rangle_{hh} \Big) \, \rho_c \, N_m$$

$N_m$ # of molecules
$N_{12}$ # of constituent pairs (constant in time)



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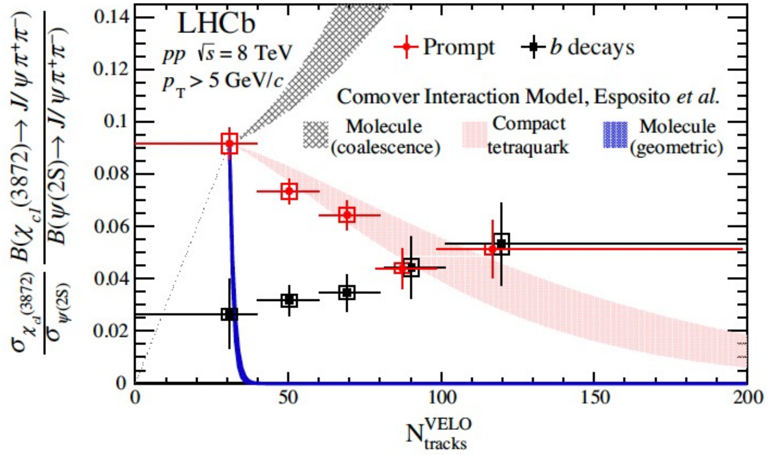
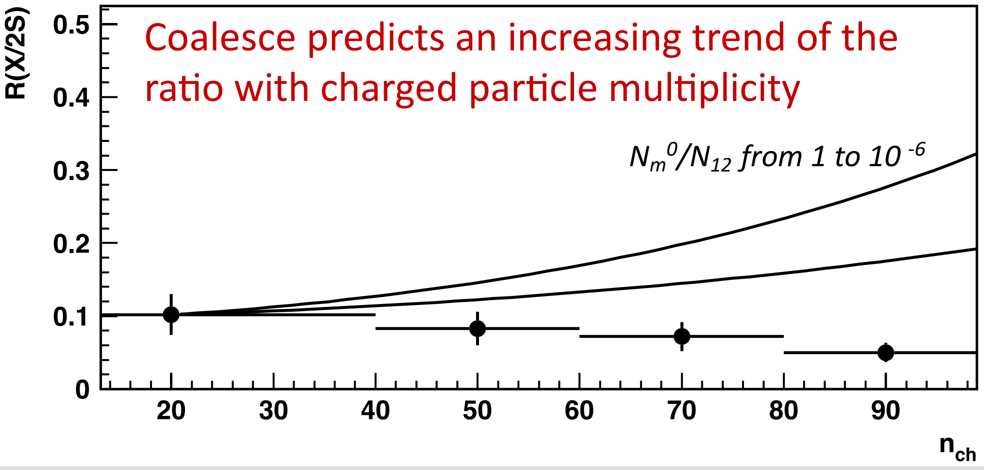
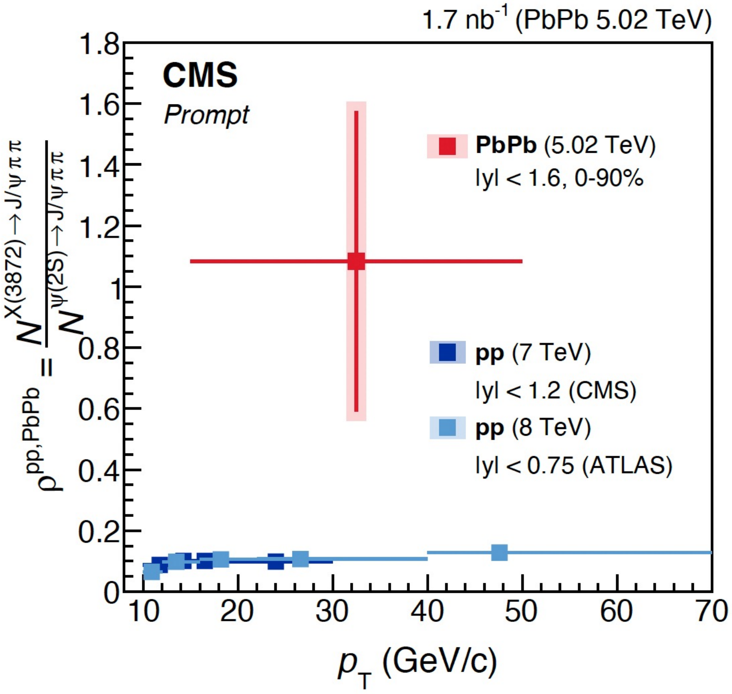


# Results in Pb-Pb collisions: the nature of the X(3872)



- The CMS collaboration has measured the $\sigma_{\chi(3872)}/\sigma_{\psi(2S)}$ ratio in PbPb collisions, and found that the ratio is enhanced relative to pp collisions, although that measurement has large uncertainties.




Calculations based on quark coalescence, which can occur when quark wavefunctions overlap in position and velocity space, show that production rates of χ(3872) hadrons in nucleus-nucleus collisions are sensitive to its structure.

In some of the models, production of hadronic molecules is expected to be greatly enhanced over compact tetraquarks, although transport calculations reaches the opposite conclusion.

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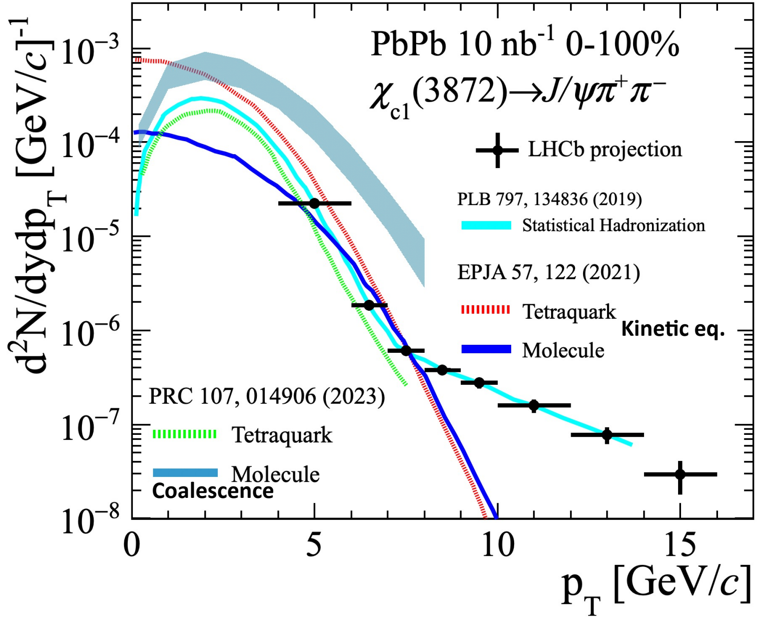


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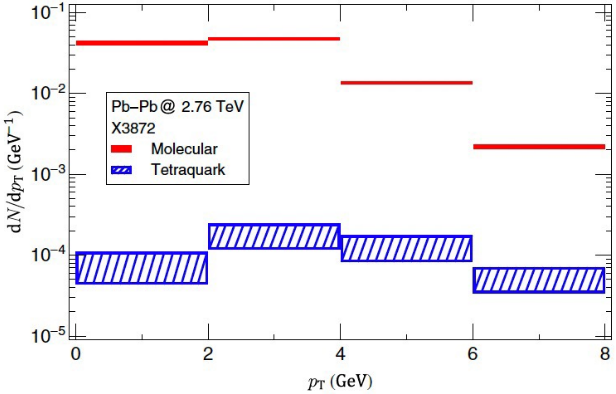
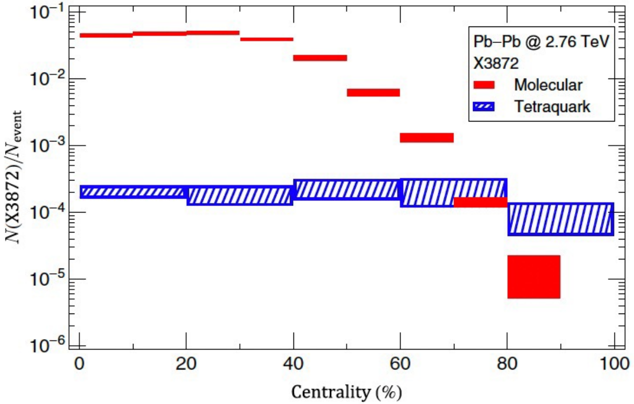
**See Cesar da Silva talk this afternoon!**

**From Matt Durham, Cesar da Silva, LHCb IFT Workshop July 2024**

**From Laura Tolos, LHCb IFT Workshop July 2024**

- Instantaneous coalescence

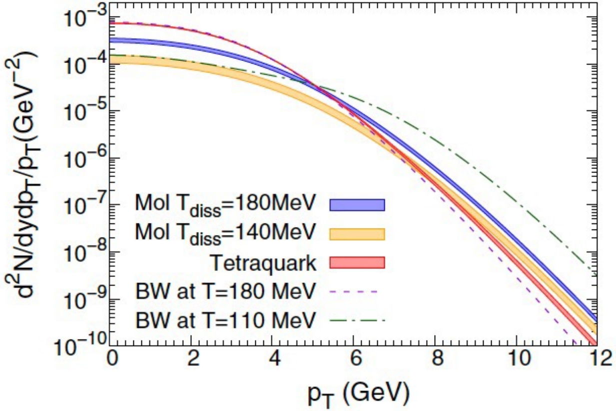


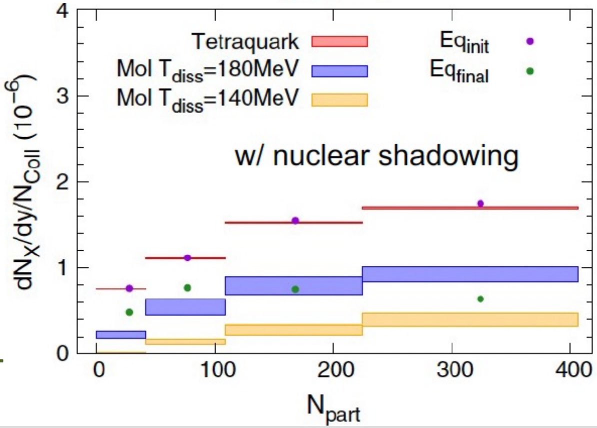

fireball volume leads to about two orders of magnitude higher production yields and stronger centrality dependence for molecule compared to tetraquark

**H. Zhang et al., Phys. Rev. Lett. 126, 012301 (2021)**

- Kinetic-rate eq. approach




molecule formed later than tetraquark in the fireball evolution => molecular yields smaller




**B. Wu et al. Eur. Phys. J. A 57, 122 (2021)**

# The nature of the X(3872): potential approach

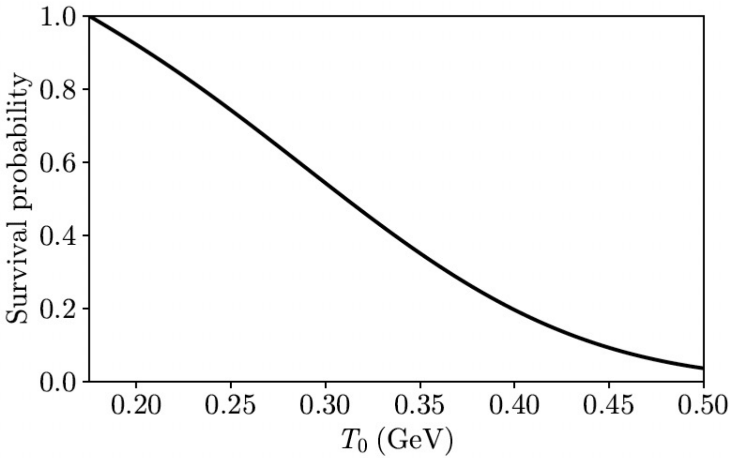
- The heavy quark potential has both a real and an imaginary part
- The origin of the imaginary part is the collision of quarkonium with medium particles
- Schrodinger equation with a complex potential
- We assume that it is a tetraquark
- Two step-approximation:

  Compute the potential taking the heavy quarks as static color sources.

  Solve the Schrodinger equation

Coalescence is missing! Work in progress

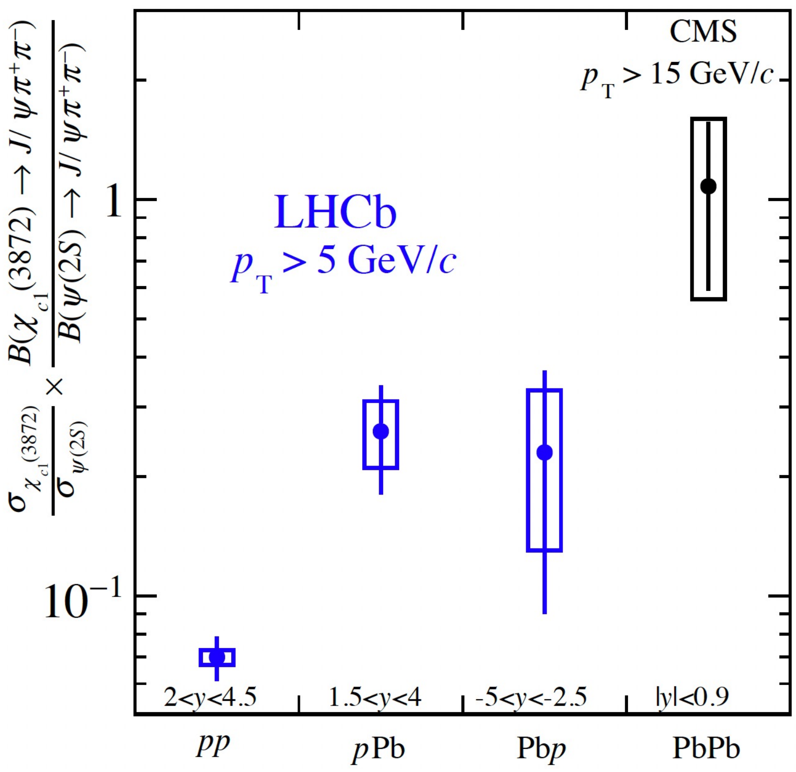
We consider:
A Bjorken expantion starting at $t_0$ = 0.6 fm.
A linear relation between T and $m_D$
We stop the evolution at the time in which T = 175MeV (around the phase transition)

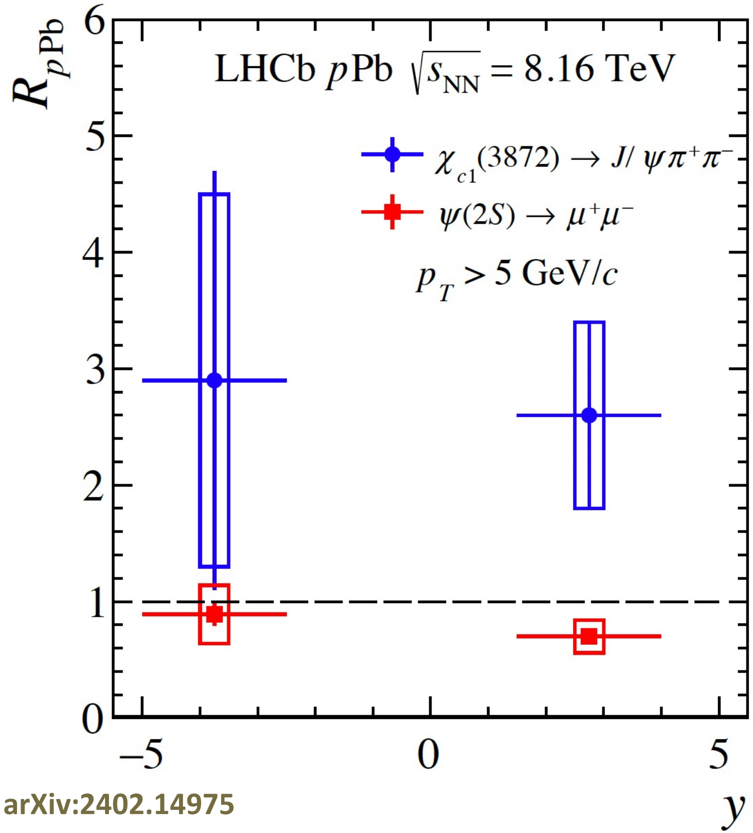



Armesto, Escobedo, EGF, Lopez-Pardo, Phys.Lett.B 854 (2024)

# The nature of the X(3872): How pPb can collisions help

**pPb**




LHCb Collaboration, arXiv:2402.14975

# The nature of the X(3872): How pPb can collisions help

**pPb**

- Collisions of protons with Pb nuclei provide an intermediate stage between the relatively small pp collision system and the large PbPb system, and can shed light on the interplay of various enhancement and suppression mechanisms.
- Calculations of tetraquark production in pPb collisions have predicted that the χ(3872) cross-section could be enhanced relative to pp collisions, due to a higher rate of double-parton scattering.
- An increase of double-parton scattering in pPb collisions relative to pp collisions has been measured by the LHCb collaboration.

**F. Carvalho and F. S. Navarra, Nuclear effects on tetraquark production by double parton scattering, EPJ Web Conf. 137 (2017)**

- An enhancement of proton production relative to pions and kaons has been observed in dAu (STAR, PHENIX) and pPb (ALICE) collisions, which can be explained by coalescence/recombination of three quarks into baryons versus two quarks into mesons. An enhancement of charmed baryons relative to charmed mesons has been observed in pp and pPb collisions (ALICE), relative to expectations from e+e− collisions, which may be explained by quark coalescence/recombination. These effects could be even more pronounced for four-quark states in pA collisions.
- Moreover, late-stage interactions in the hadron gas phase of a heavy-ion collision can also affect the observed yields. Scatterings with the partonic medium could lead to “picking up” of light quarks/antiquarks which then co-move with the $c\bar{c}$ pair, enhancing the probability to form the χ(3872).

Open questions:

- Which approach?
- Which temperature?

Important measurements are needed:

- Production vs number of charged particles
- Production at low $p_T$

# Conclusions

- Measurements by the LHCb collaboration in pp collisions showed a significant decrease in the ratio of prompt χ(3872) to ψ(2S) cross-sections, $\sigma_{\chi(3872)}/\sigma_{\psi(2S)}$, with increasing charged-particle multiplicity.
- These data were interpreted in terms of breakup of the χ(3872) hadrons due to interactions with comoving particles produced in the event, and, from my point of view, favored the interpretation of χ(3872) as a compact tetraquark state. Coalescence not at play in pp collisions.
- The CMS collaboration has measured the $\sigma_{\chi(3872)}/\sigma_{\psi(2S)}$ ratio in PbPb collisions, and found that the ratio is enhanced relative to pp collisions, although that measurement has large uncertainties.
- Calculations based on quark coalescence show that production rates of χ(3872) in nucleus-nucleus collisions are sensitive to its structure. In models based on instantaneous coalesce, production of hadronic molecules is expected to be greatly enhanced over compact tetraquarks, although transport calculations that takes into account the formation time reach the opposite conclusion.
- The suppressing effects of breakup and the enhancing effects of coalescence/recombination are expected to dominate in different multiplicity regimes and different system sizes, and it is currently unknown where the crossover may occur. Collisions of protons with Pb nuclei provide an intermediate stage between the relatively small pp collision system and the large PbPb system, and can shed light on the interplay of various enhancement and suppression mechanisms.