Exotic and conventional quarkonia in medium and implications for the EIC

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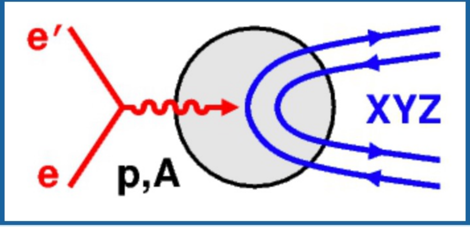
durham@lanl.gov



Exotic heavy meson spectroscopy and structure with EIC

Center for Frontiers in Nuclear Science

15-19 August 2022

Outline

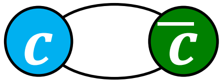
- Conventional quarkonia measurements in medium
  - Effects we can study
  - Example: Charmonia and model comparisons

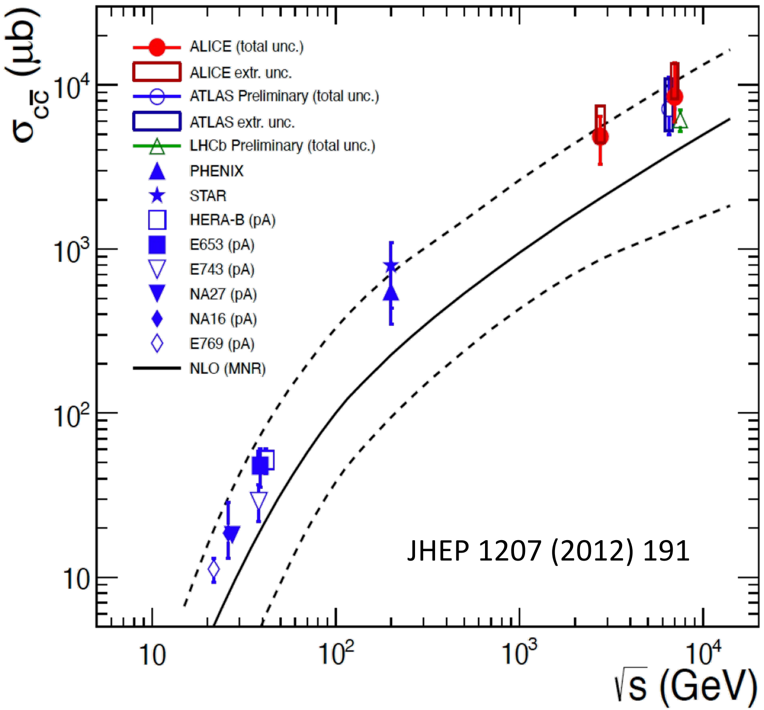
- First results on exotic quarkonia in medium
  - X(3872) in *pp*/*p*Pb/PbPb at the LHC

- EIC – hadronization inside the nucleus becomes important

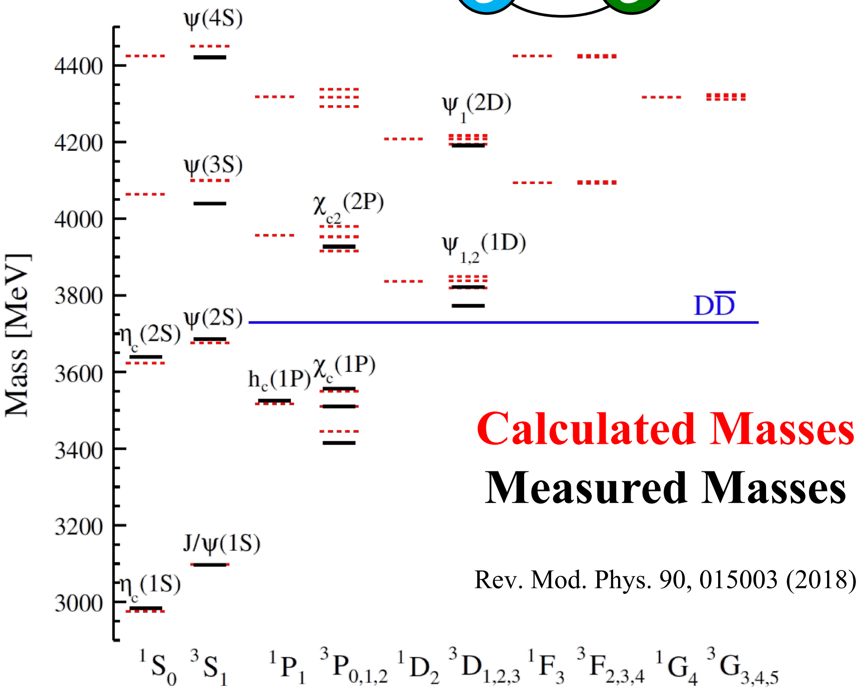
- Summary

Conventional charmonia





pQCD describes charm production across wide range of collisions energies

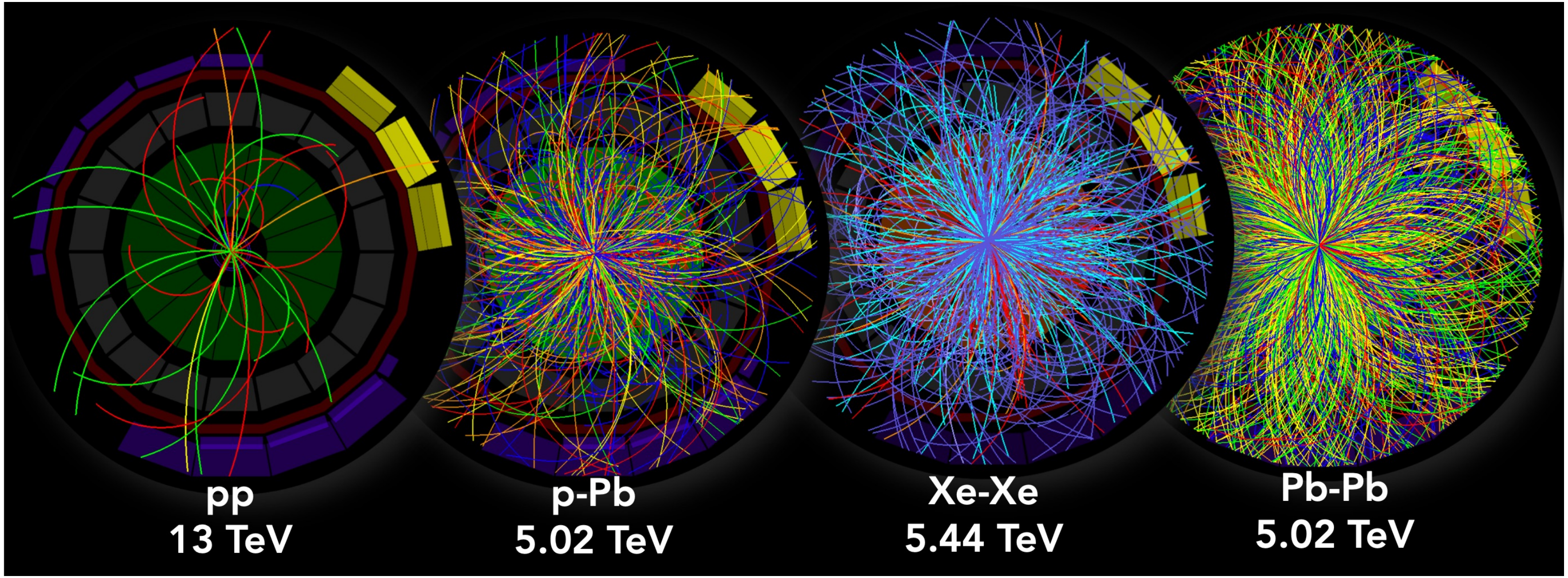


Rich structure of bound quarkonia states accessible experimentally and theoretically

Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium → Increasing T, N_{ch} → Dense medium

- Use (mostly) understood quarkonia states to as a calibrated probe of non-perturbative effects in dense many-body hadronic systems.



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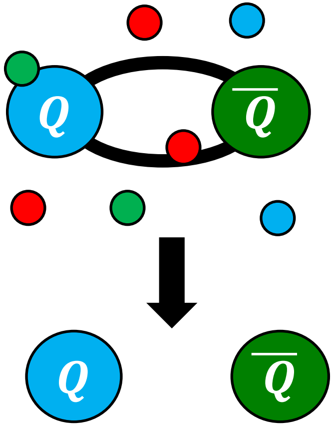

Dissociation via interactions with comoving particles

Sensitive to binding energy

Heavy $Q\bar{Q}$ states in the QCD medium

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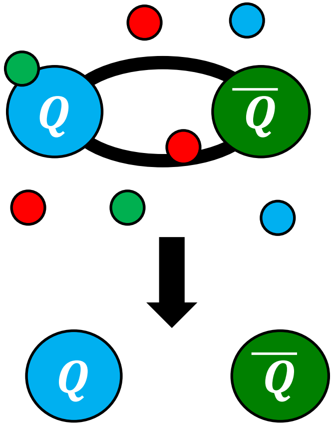

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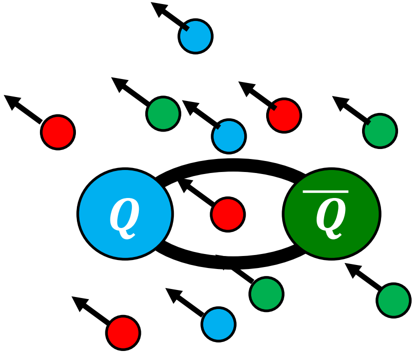

Hydrodynamic flow induced by pressure gradients (initial state?)

Sensitive to number of constituent quarks n_{cq}

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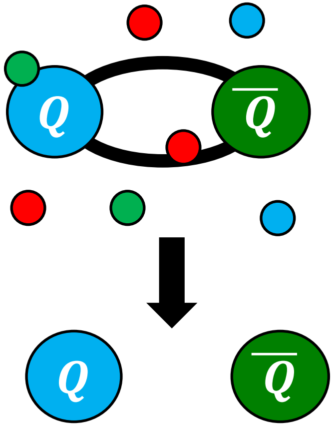

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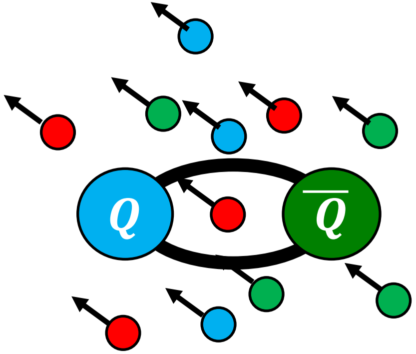

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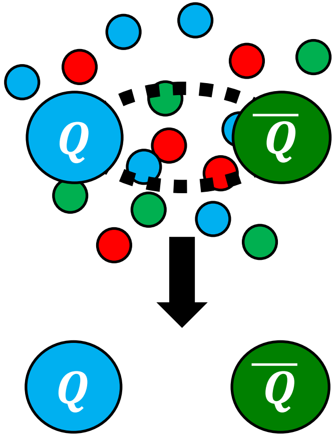
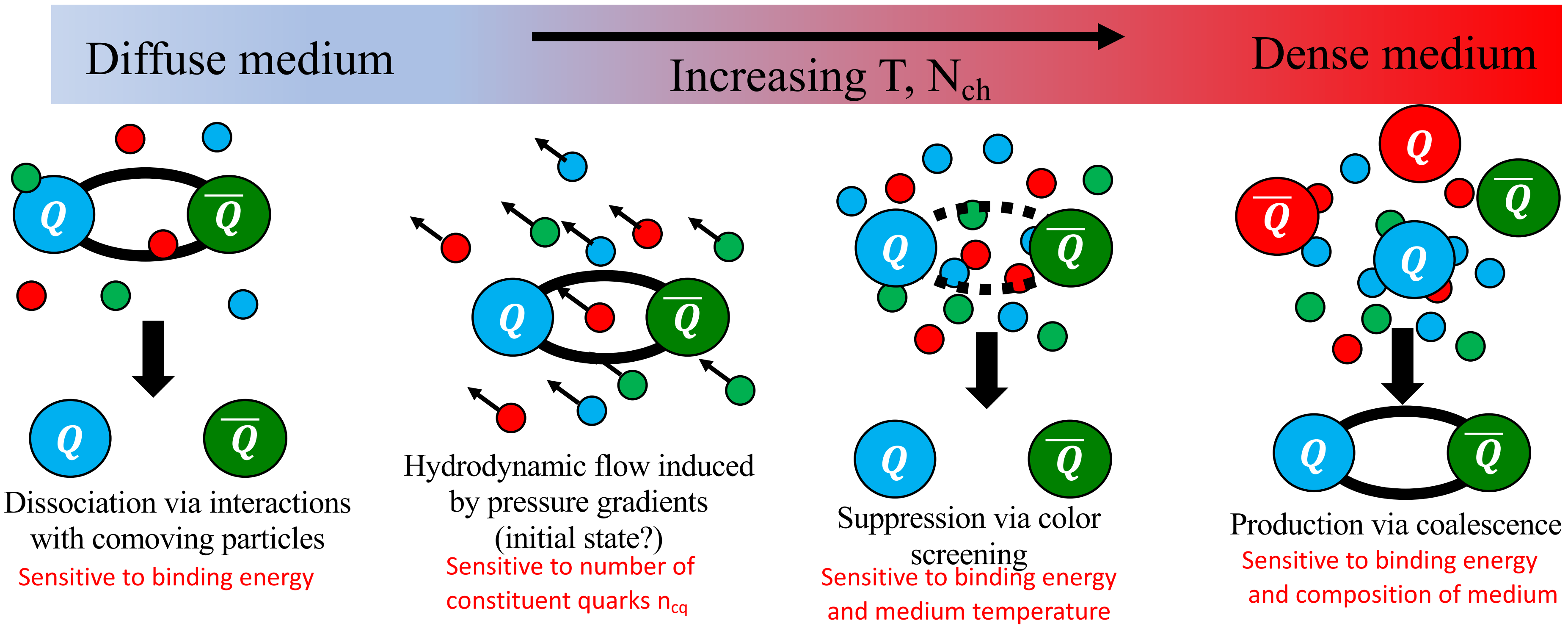


Suppression via color screening

Sensitive to binding energy and medium temperature

Heavy $Q\bar{Q}$ states in the QCD medium



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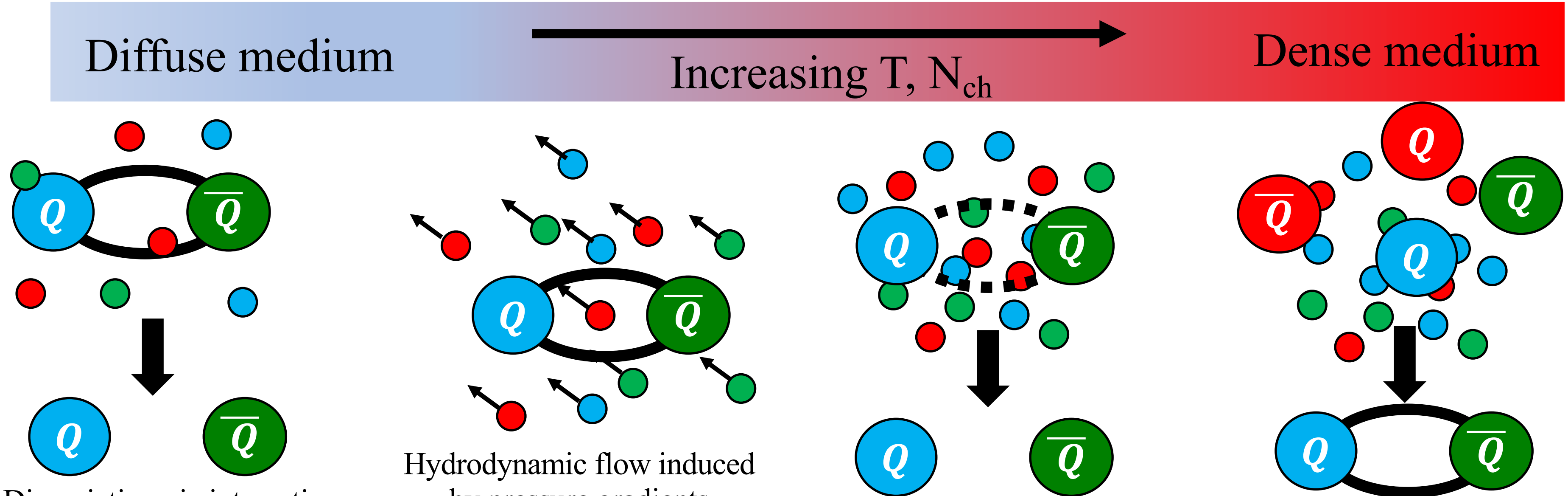


Dissociation via interactions with comoving particles
Sensitive to binding energy

Hydrodynamic flow induced by pressure gradients (initial state?)
Sensitive to number of constituent quarks n_{cq}

Suppression via color screening
Sensitive to binding energy and medium temperature

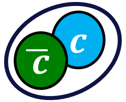
Production via coalescence
Sensitive to binding energy and composition of medium

Experimentally, we use different collision systems/kinematic regions to prepare environments where these different competing effects dominate.

Example: $\psi(2S)$ suppression

$J/\psi(1S)$

$E_b \approx 600\ MeV$



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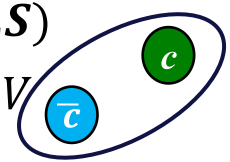
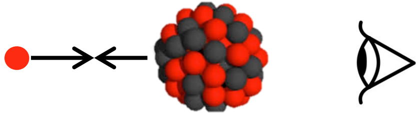
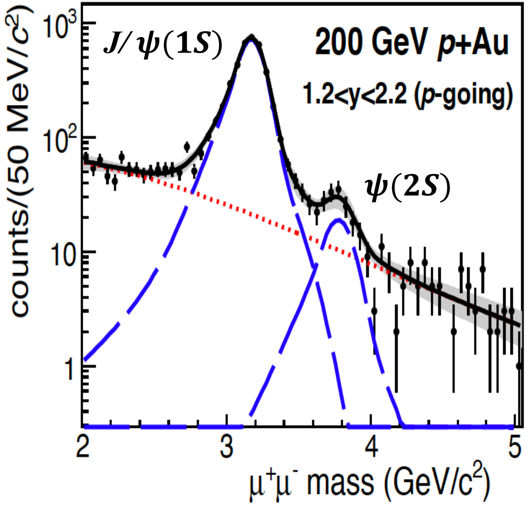
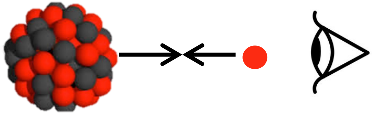
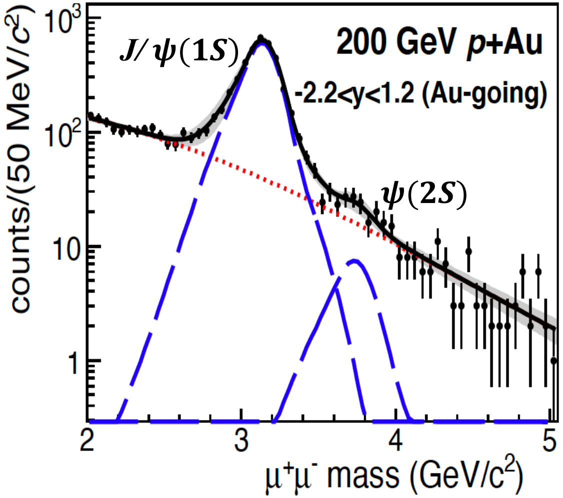






Relatively *low* particle density





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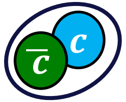

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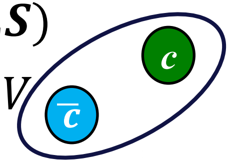
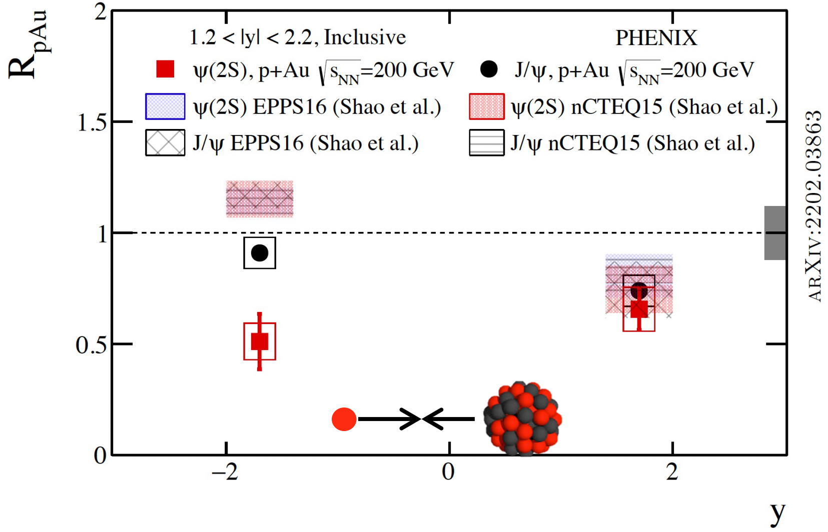


$$R_{pA} = \frac{\sigma_{pA}}{N_{coll} \times \sigma_{pp}}$$



- Weakly bound $\psi(2S)$ state more suppressed than J/ψ in nucleus-going direction

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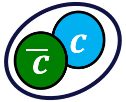

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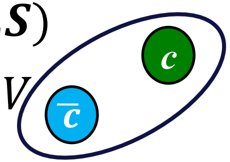

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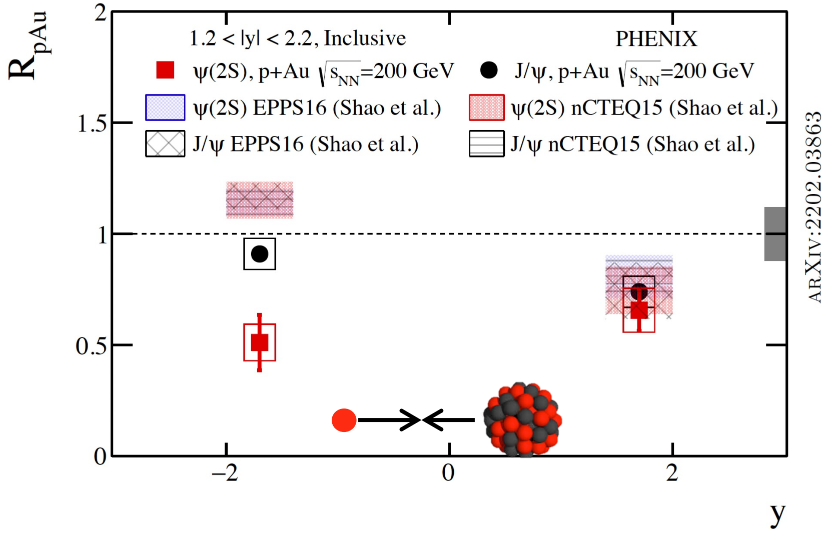

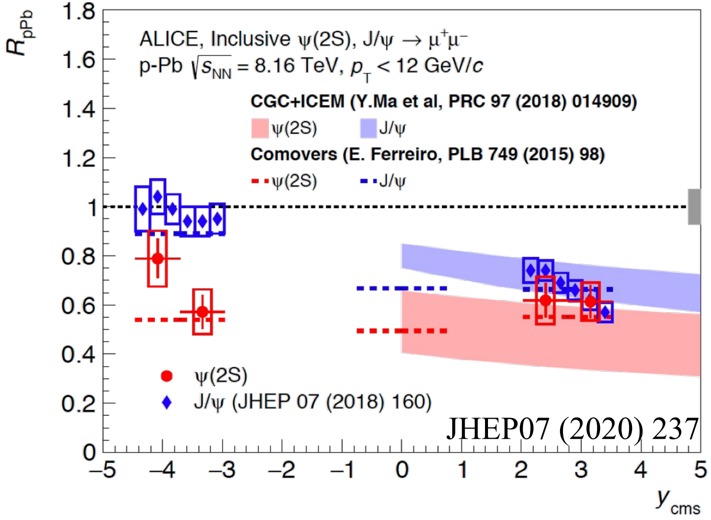

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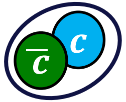

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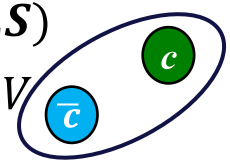

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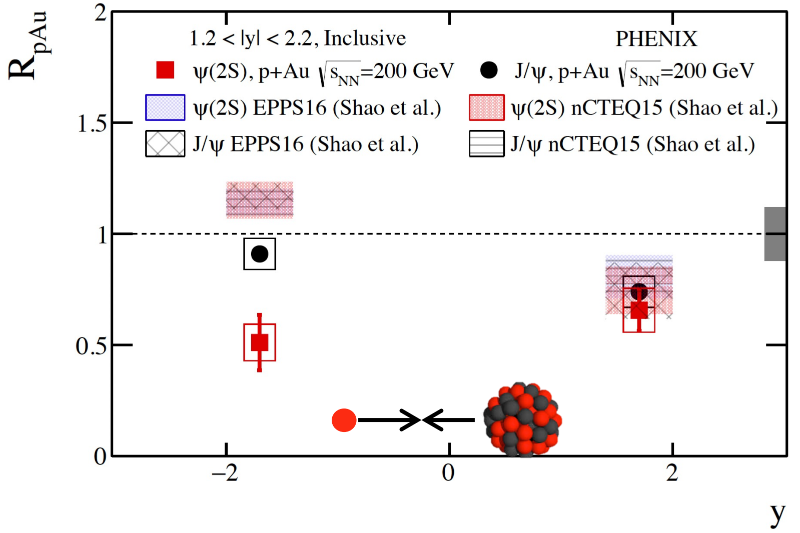

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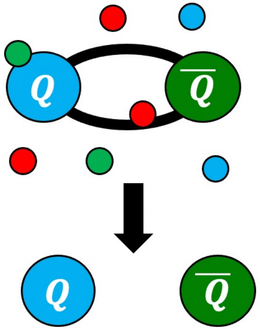
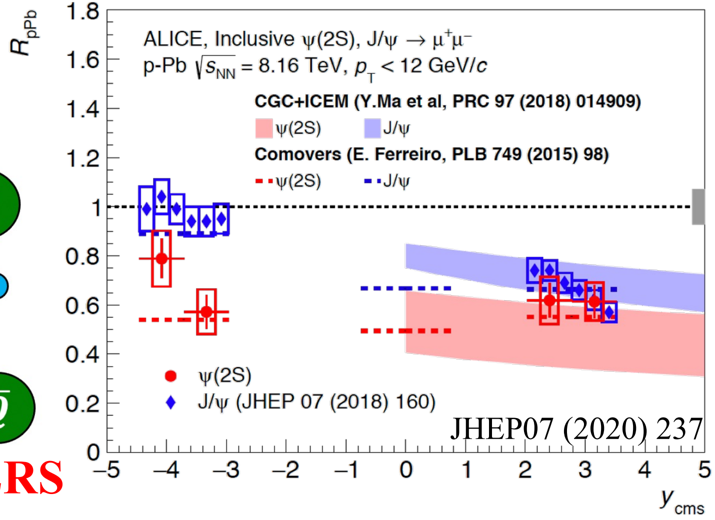
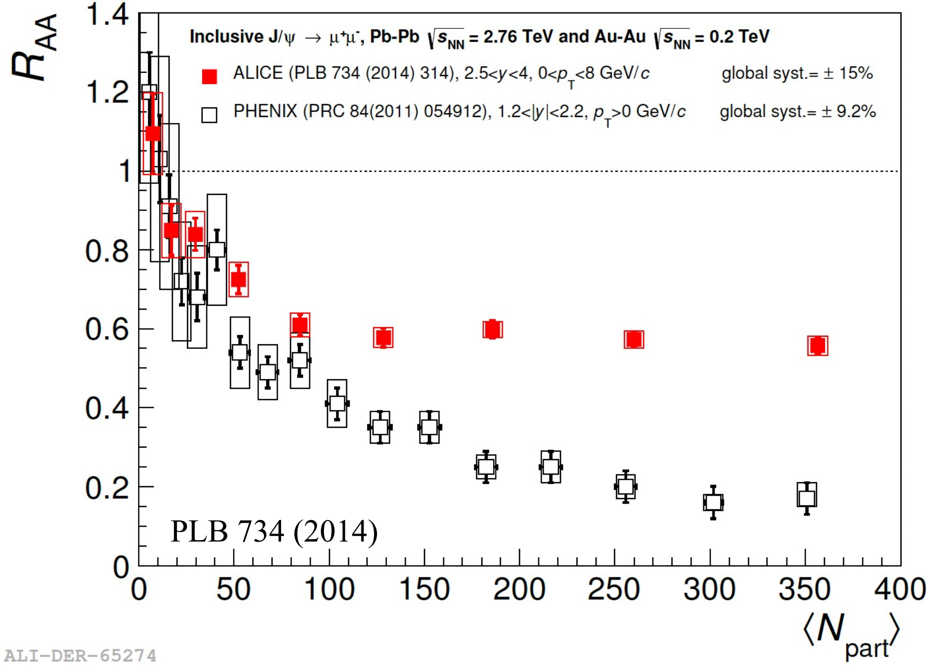


COMOVERS

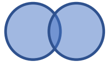


- Weakly bound $\psi(2S)$ state more suppressed than J/ψ in nucleus-going direction
- Models require some final-state interaction to reproduce data
- Quark-gluon plasma not expected to be dominant effect in small collision systems

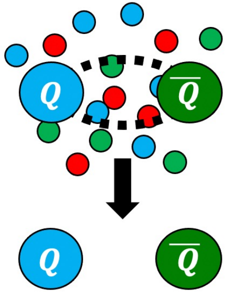
Example: J/ψ in AA - RHIC vs LHC



- J/ψ modification quite different between RHIC and LHC
- Charm cross section at LHC ~10x cross section at RHIC



$$R_{AA} = \frac{\sigma_{AA}}{N_{coll} \times \sigma_{pp}}$$



COLOR SCREENING

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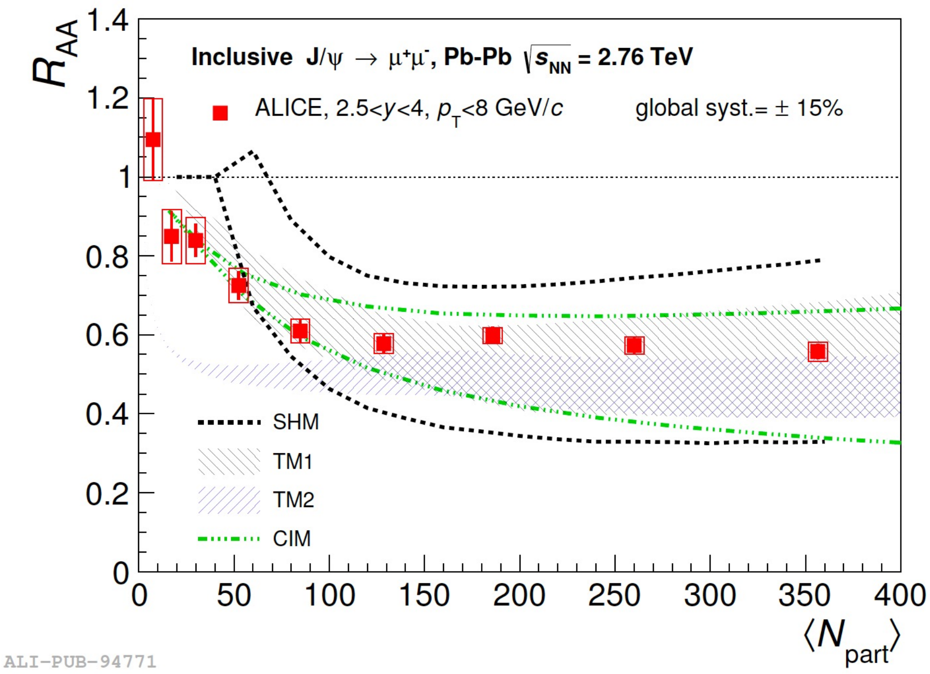

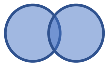

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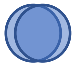

- J/ψ modification quite different between RHIC and LHC
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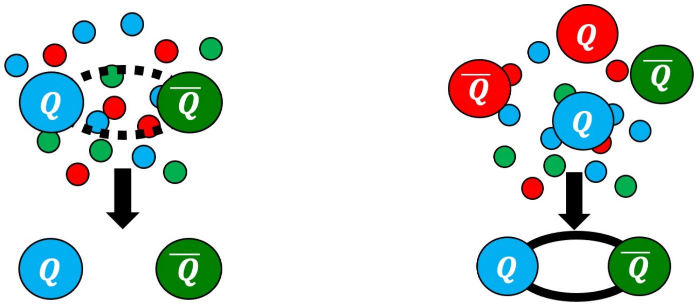
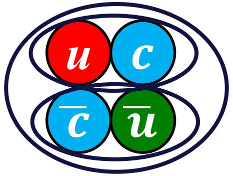
- Models which incorporate J/ψ production via charm coalescence describe data



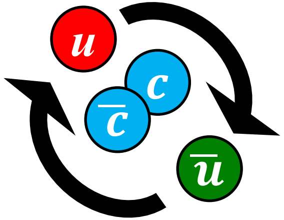
Application to exotics

- Using known states (charmonia), we have identified effects that are sensitive to the state's structure: binding energy/size
- We can apply similar techniques to study an unknown state: X(3872)

Compact

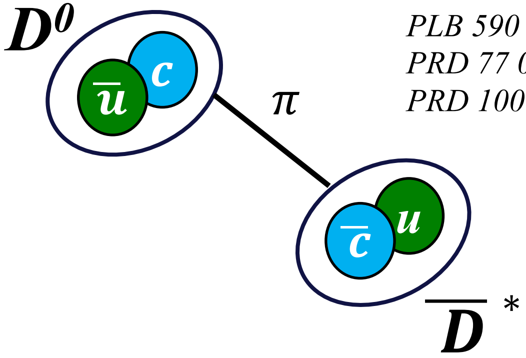


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

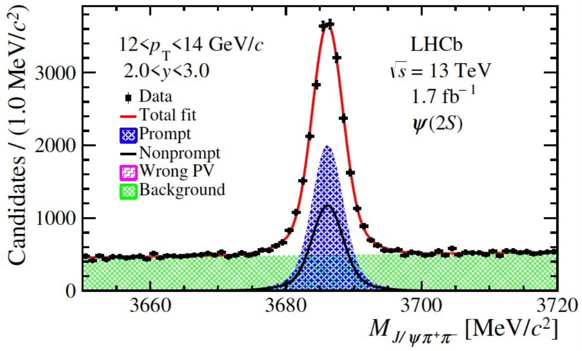
Molecule

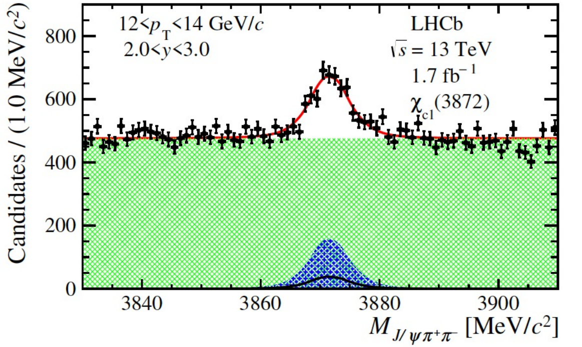


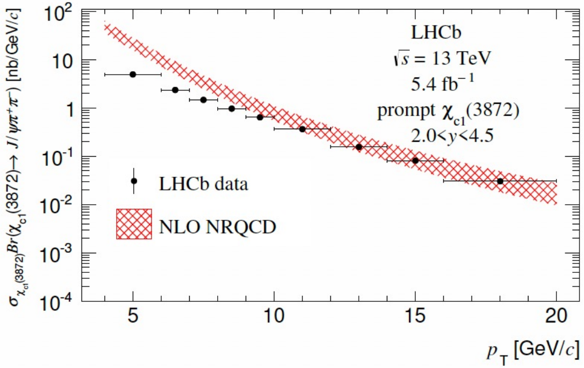
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

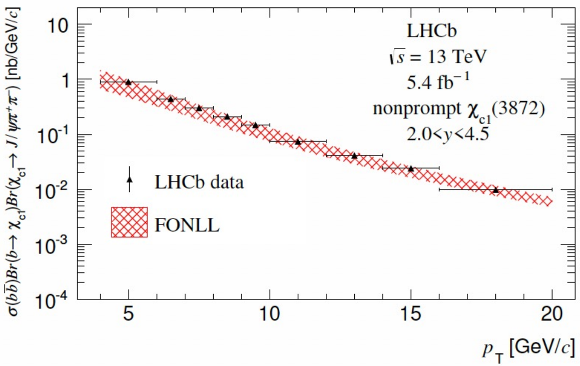
X(3872) production in *pp*

JHEP01 (2022) 131









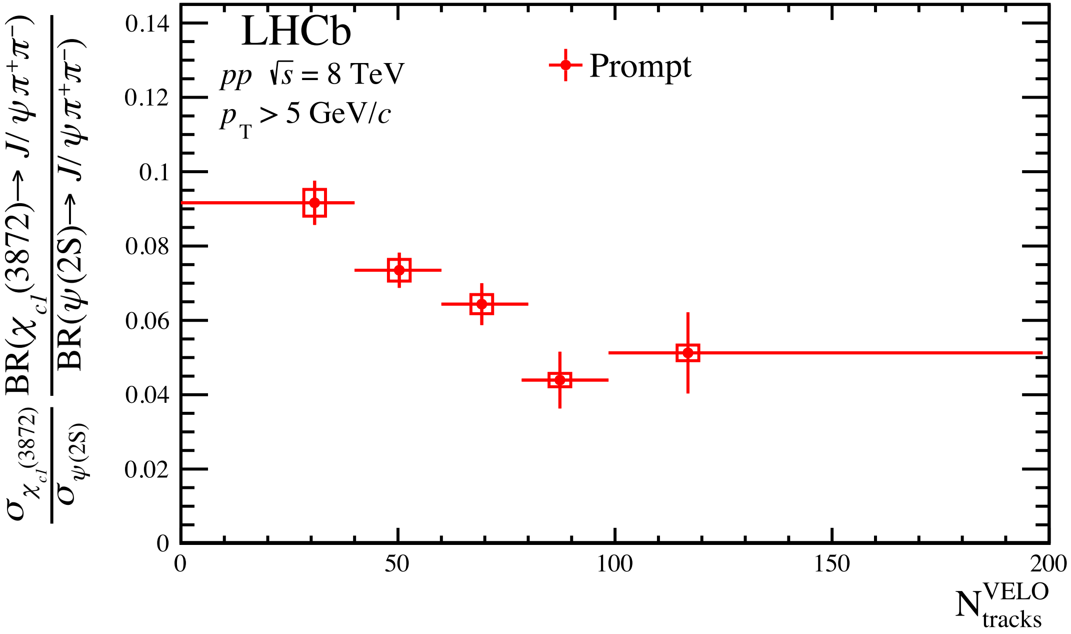
- NRQCD calculation matches high-p_T data well (tuned to ATLAS/CMS)
- Overpredicts yield at lower p_T
- **Room for additional effect**

- FONLL describes non-prompt X(3872) production well

Examine X(3872)/ψ(2S) ratio for direct comparison between exotic hadron and well-known conventional charmonium

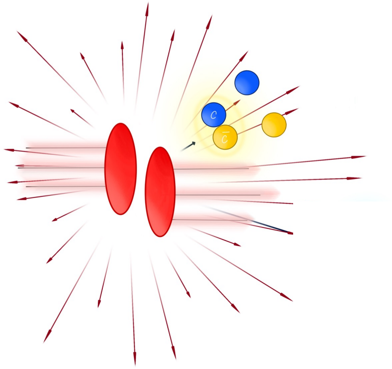
X(3872)/ψ(2S) vs multiplicity

PRL 126, 092001 (2021)



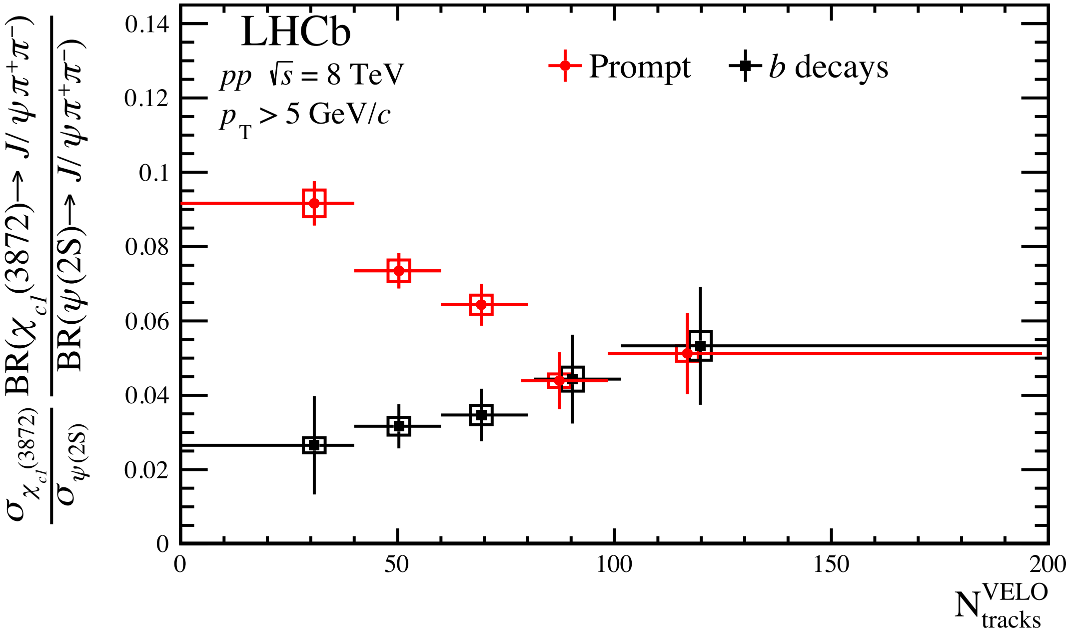
Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases



X(3872)/ψ(2S)

PRL 126, 092001 (2021)



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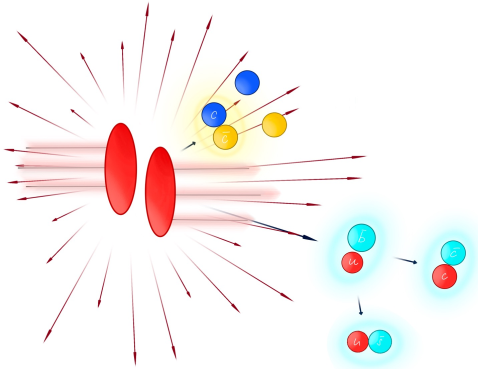
***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.



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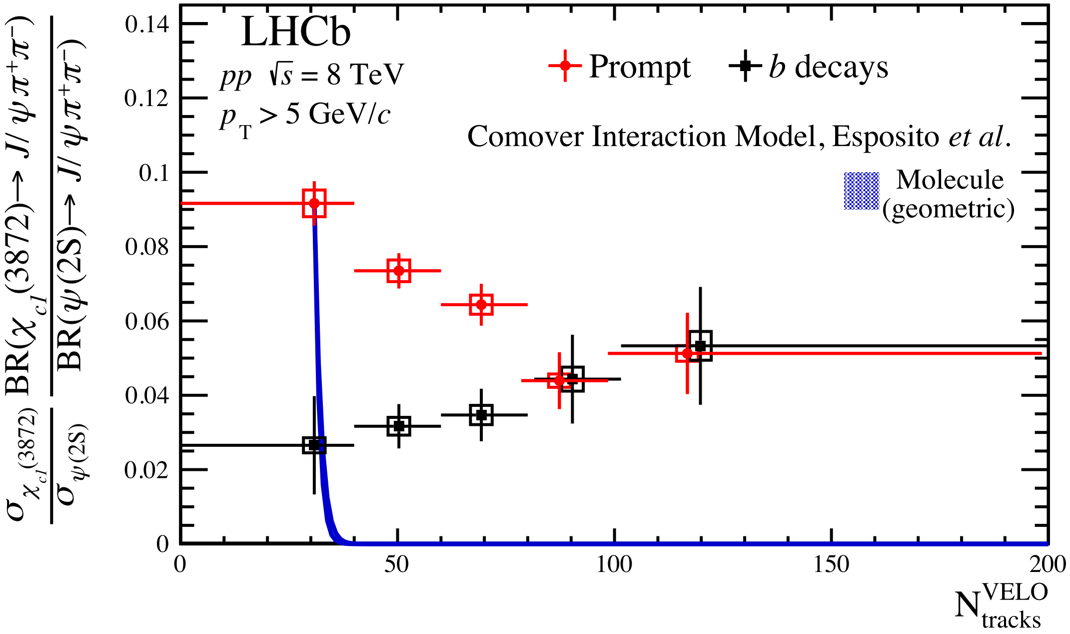
PRL 126, 092001 (2021)



Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

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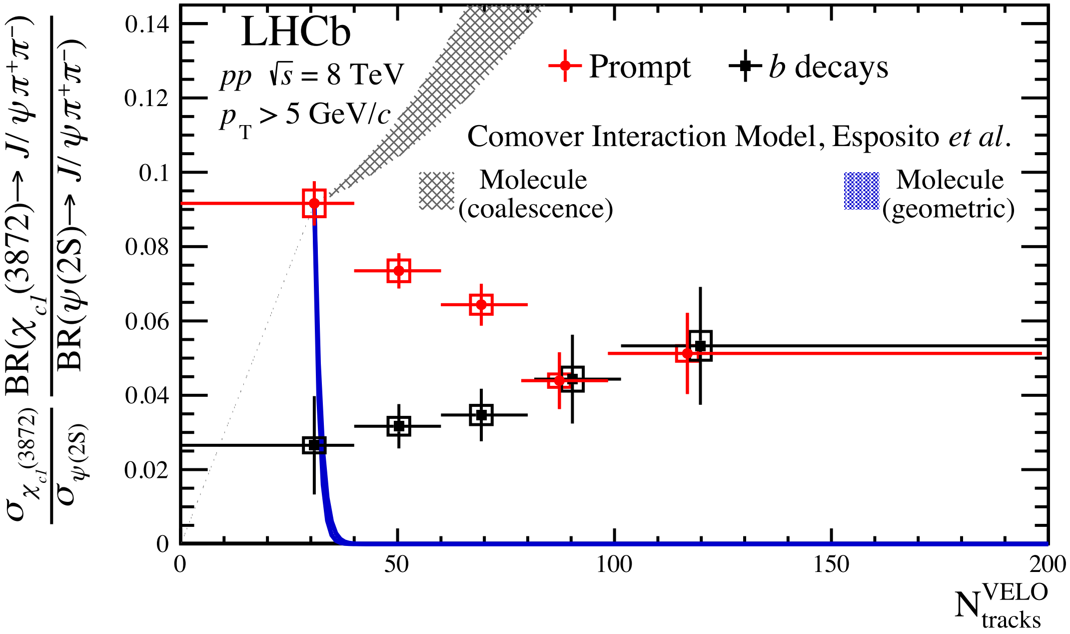
Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

$$\langle v\sigma \rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c}\right)^n \right\rangle$$

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



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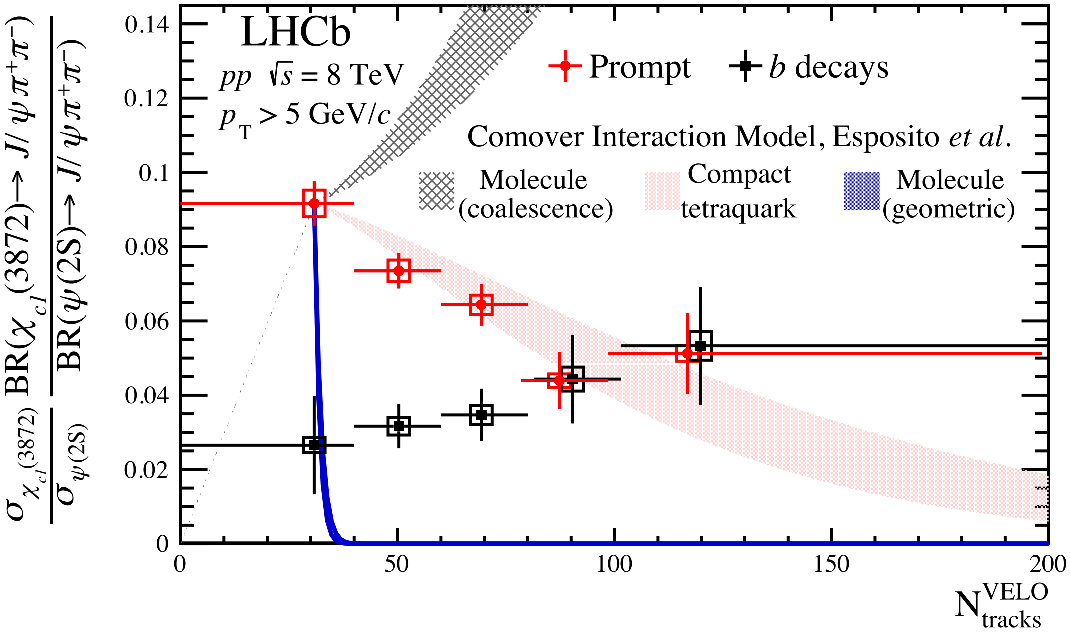

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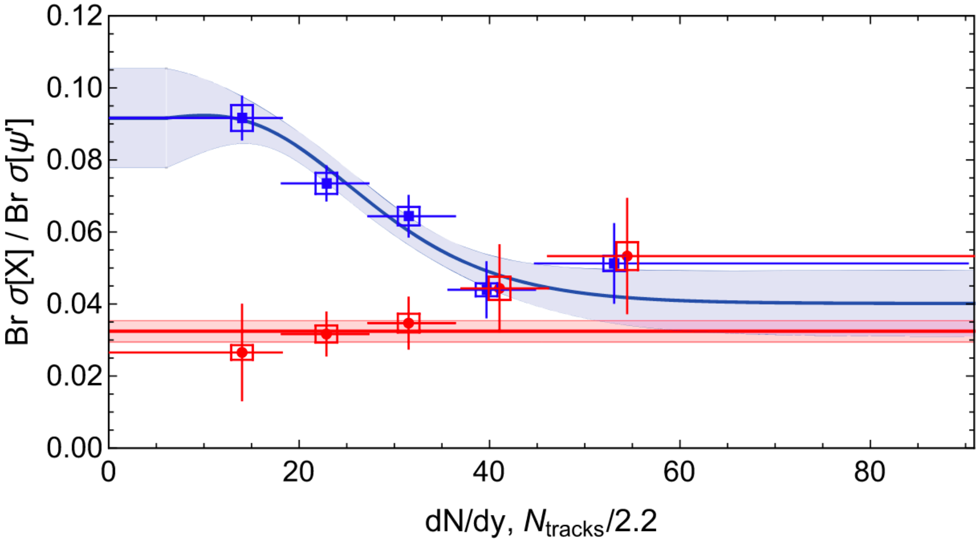
Coalescence of D mesons into molecular X(3872) increases ratio

Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases – consistent with data

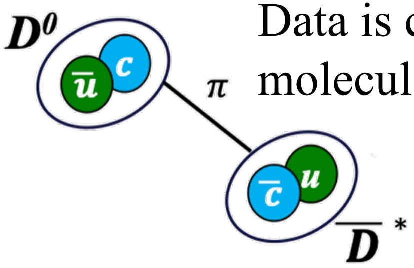
Comover model: constituent interaction

Different method of calculating breakup cross section:
Braaten, He Ingles, Jiang Phys. Rev. D 103, 071901 (2021)



Breakup cross section approximated as sum of cross section for molecule constituents:

$$\sigma^{\text{incl}}[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$



Data is consistent with this molecular interpretation.

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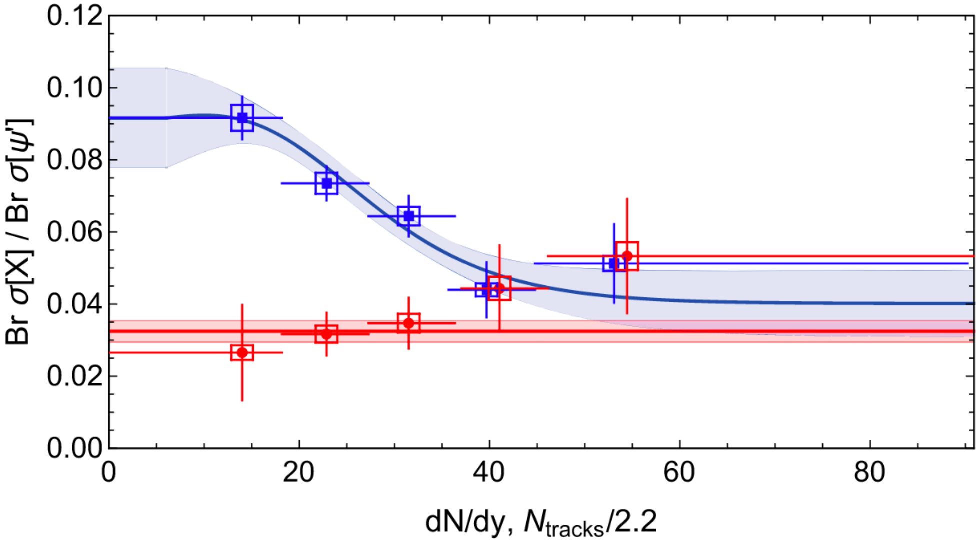
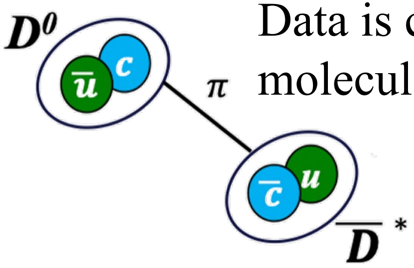


Breakup cross section approximated as sum of cross section for molecule constituents:

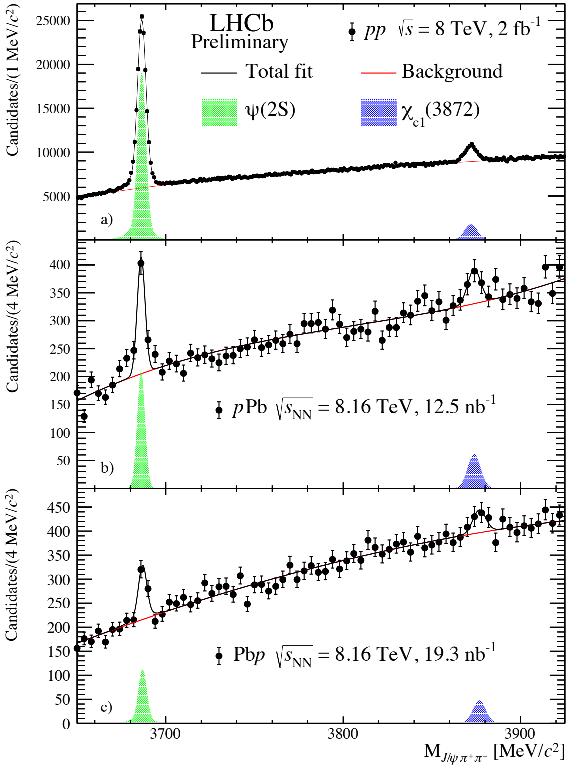
$$\sigma^{\mathrm{incl}}[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$



Data is consistent with this molecular interpretation.

X(3872) /ψ(2S) in *p*Pb

LHCb-CONF-2022-001



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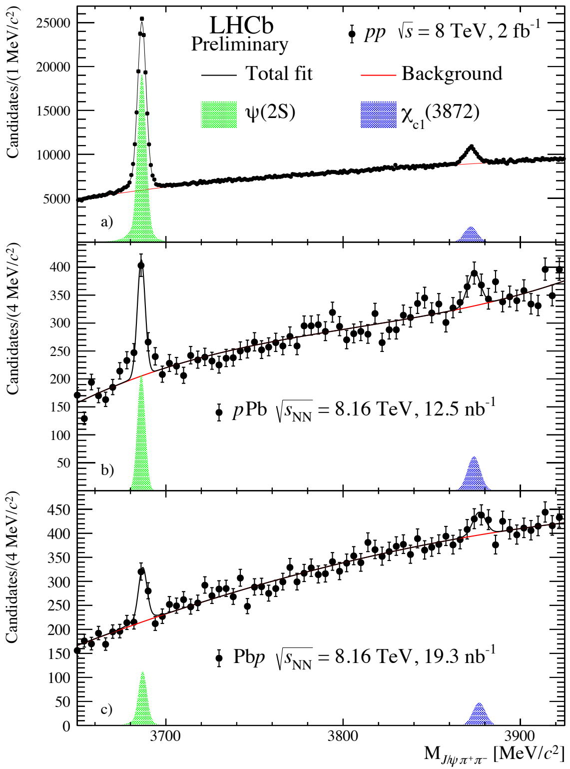
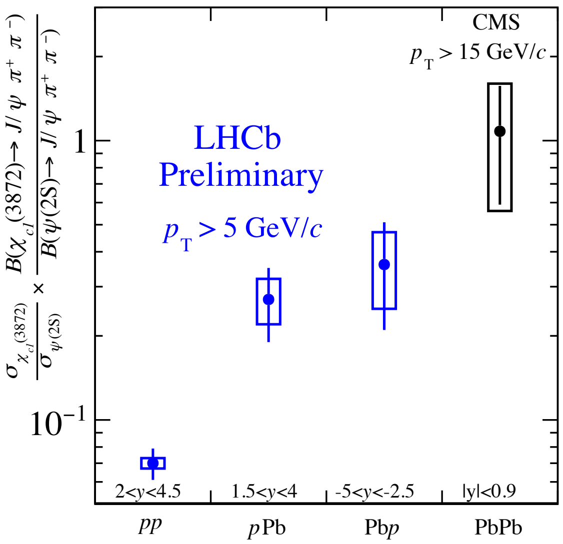
LHCb-CONF-2022-001



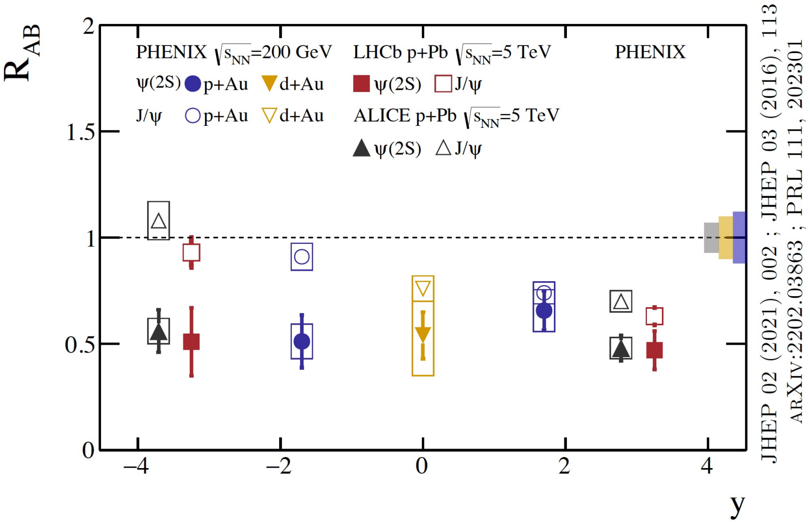


- Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium
- Initial state effects (eg shadowing) should largely cancel in ratio
- Enhancing effects start to out compete breakup?

Prompt X(3872)/ ψ(2S) = 0.27 ± 0.08 ± 0.05 in forward pPb
Prompt X(3872)/ ψ(2S) = 0.36 ± 0.15 ± 0.11 in backward pPb
Falls between pp (~0.1) and PbPb (~1.0)

X(3872) /ψ(2S) in *p*Pb

We know $\psi(2S)$ is suppressed in *p*A collisions:



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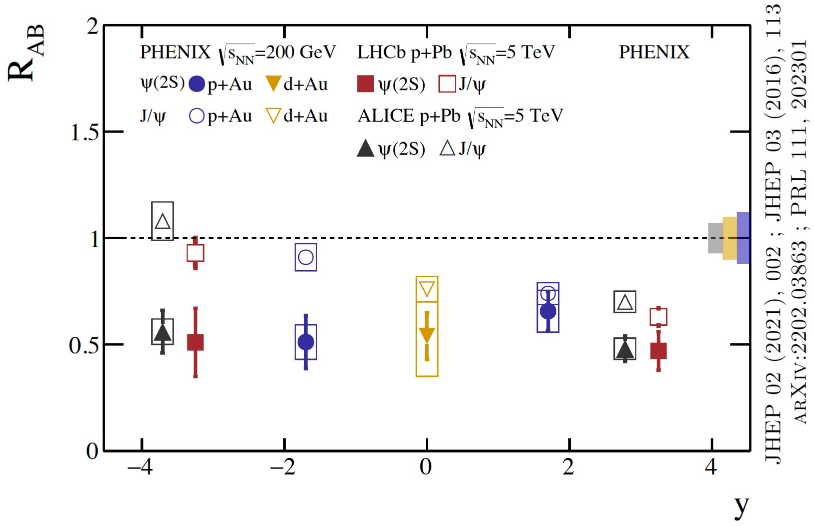


2017 PREDICTION: X(3872) enhanced in pA

Nuclear effects on tetraquark production by double parton scattering

F. Carvalho (Diadema, Sao Paulo Fed. U.), F.S. Navarra (Sao Paulo U.)

2017

8 pages

Part of Proceedings, 12th Conference on Quark Confinement and the Hadron Spectrum (Confinement XII) : Thessaloniki, Greece

Published in: *EPJ Web Conf.* 137 (2017) 06004

Contribution to: Confinement XII

Published: 2017

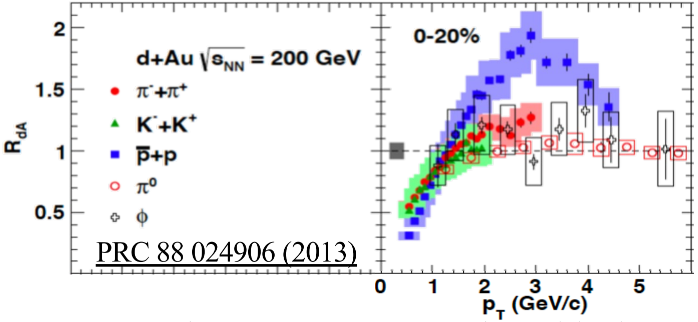
DOI: 10.1051/epjconf/201713706004

Abstract. In this work we study the nuclear effects in exotic meson production. We estimate the total cross section as a function of the energy for *pPb* scattering using a version of the color evaporation model (CEM) adapted to Double Parton Scattering (DPS). We fond that the cross section grows significantly with the atomic number, indicating that the hypothesis of tetraquark states can be tested in pA collisions at LHC.

Enhanced DPS has since been observed in pPb:
PRL 125 212001 (2020)

Both of these effects drive X(3872)/ψ(2S) ratio upwards

Coalescence in small systems (?)



Baryon enhancement at RHIC – can be explained by quark coalescence: PRL 93, 082302 (2004)

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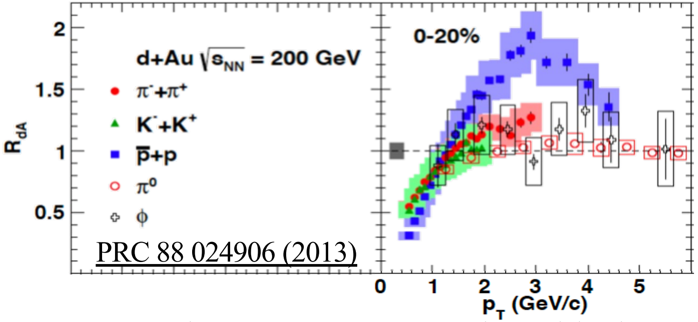

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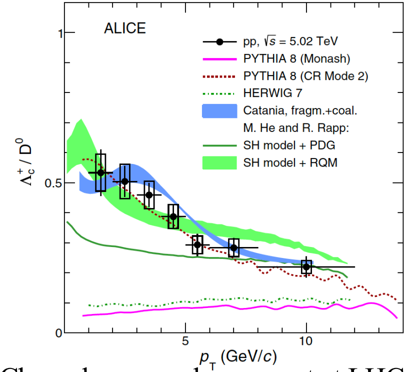

Charm baryon enhancement at LHC relative to e^+e^- – can be explained by coalescence

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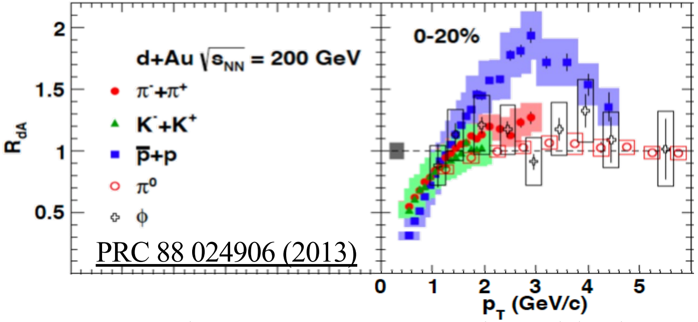

PRC 88 024906 (2013)

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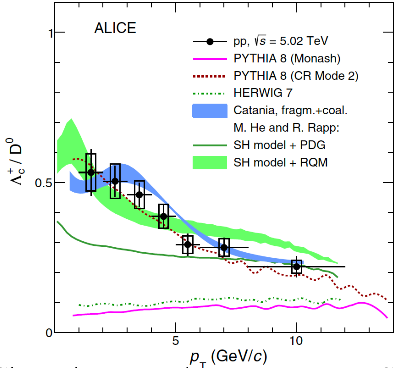

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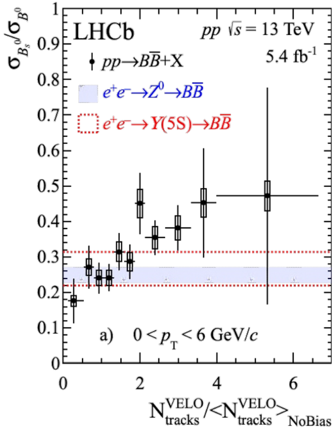

B_s/B^0 enhancement at high mult – expected from coalescence?

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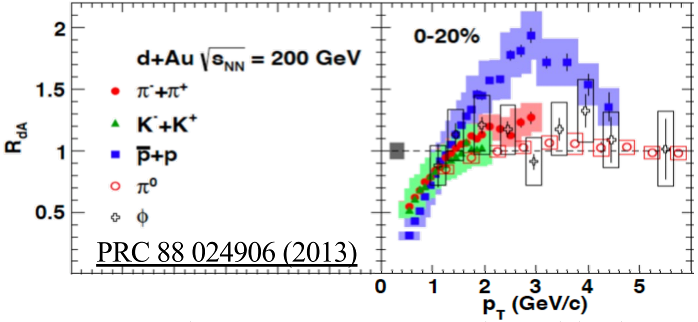

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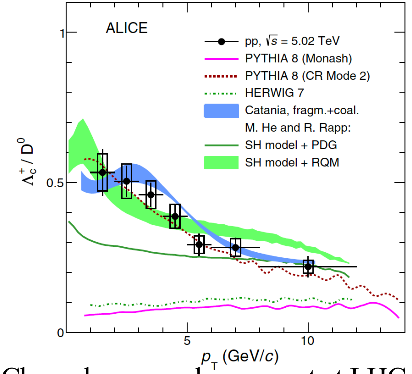

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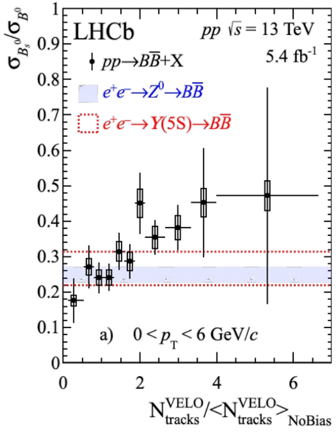

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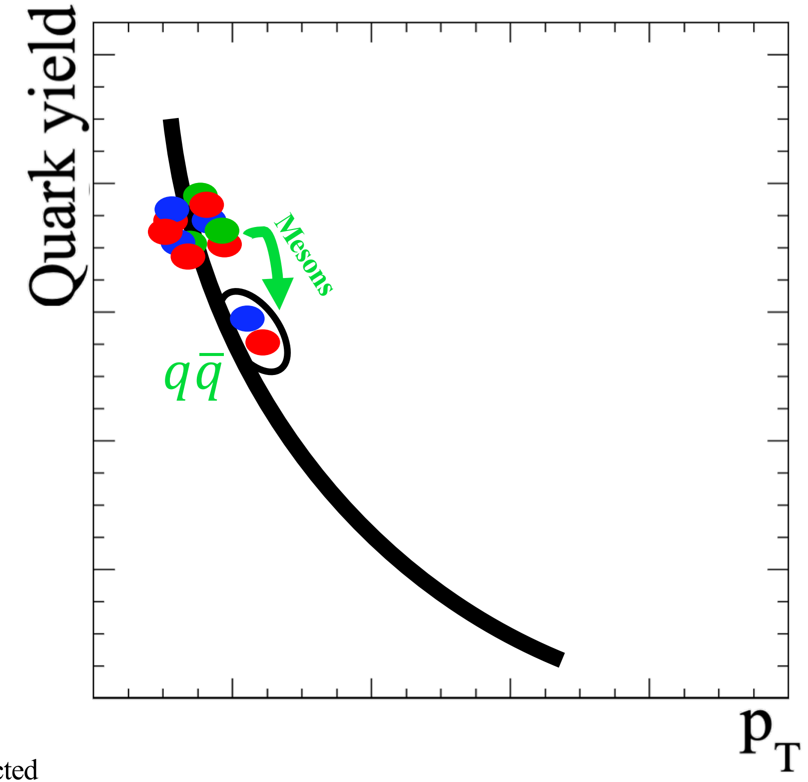

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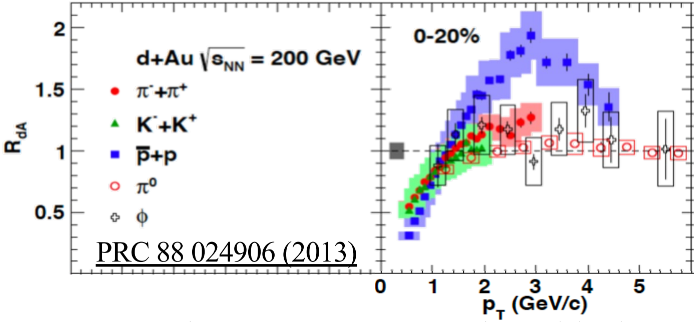

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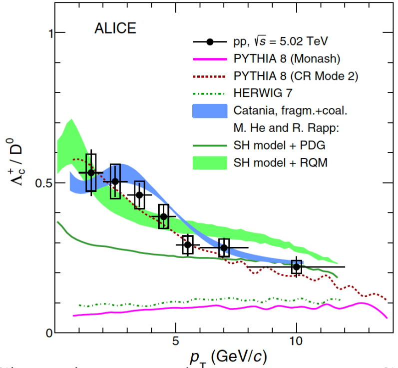

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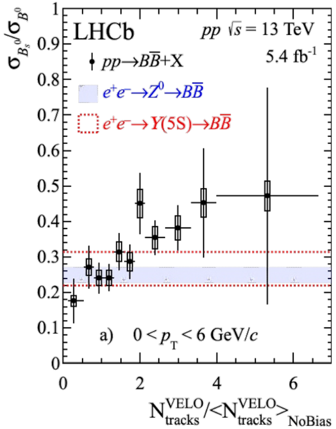

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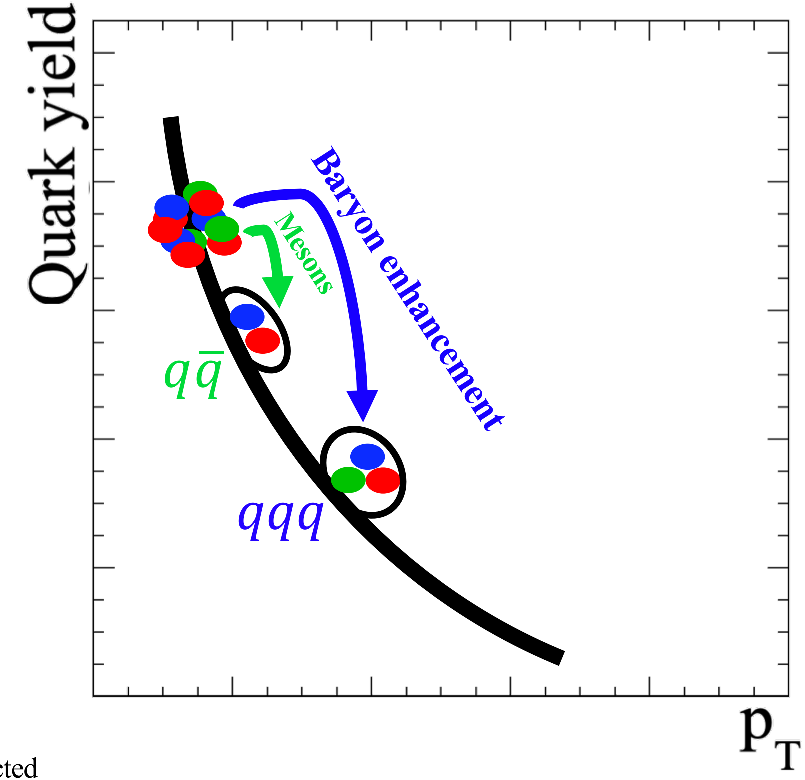

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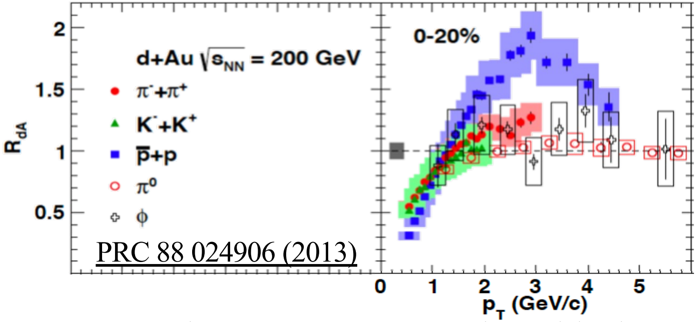

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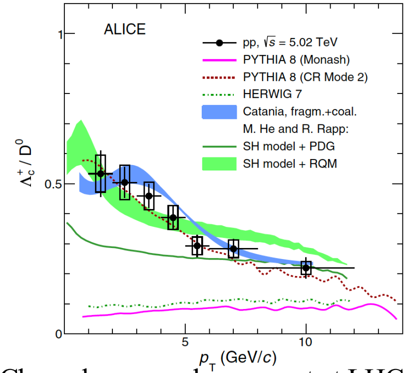

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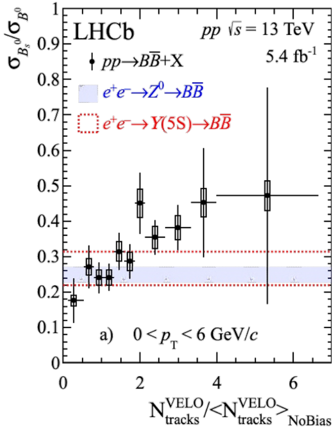

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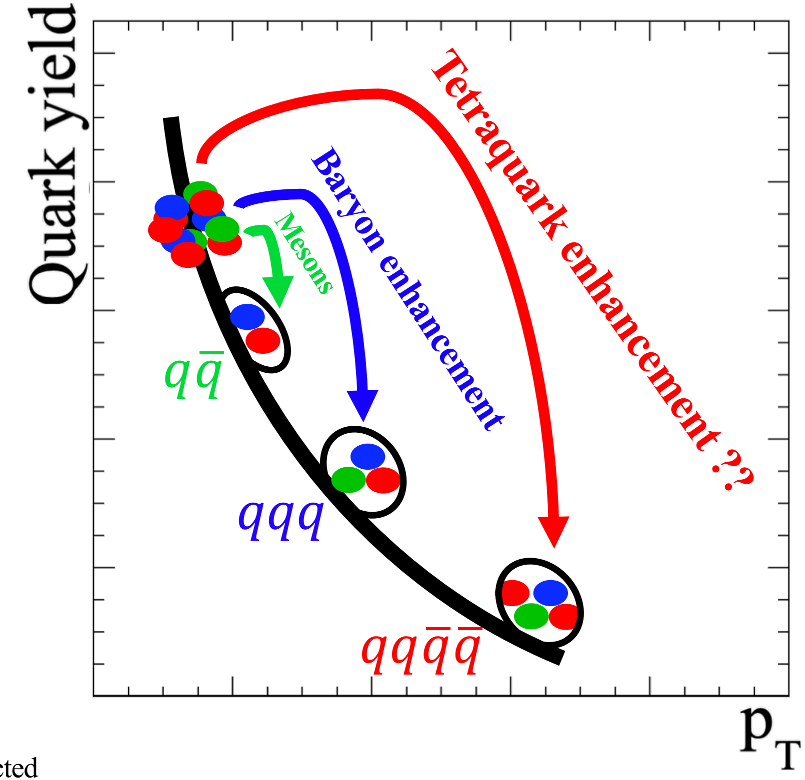
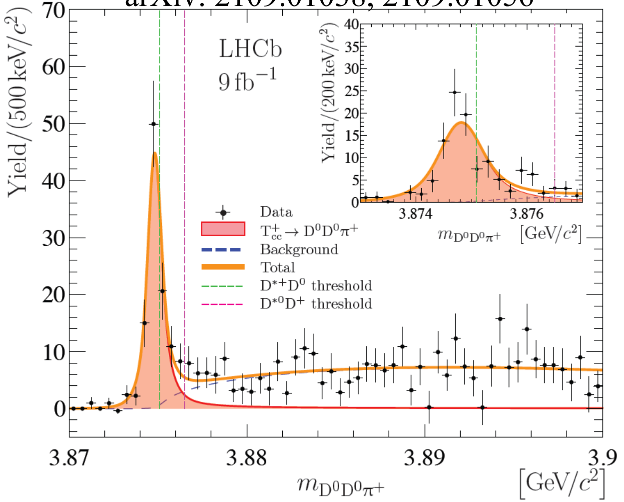


Newest exotic: T_{cc}^{+}

arXiv: 2109.01038, 2109.01056



New state consistent with $cc\bar{u}\bar{d}$ tetraquark recently found:

Similar to X(3872), mass quite close to DD threshold
Big difference: contains cc or $\bar{c}\bar{c}$, rather than $c\bar{c}$

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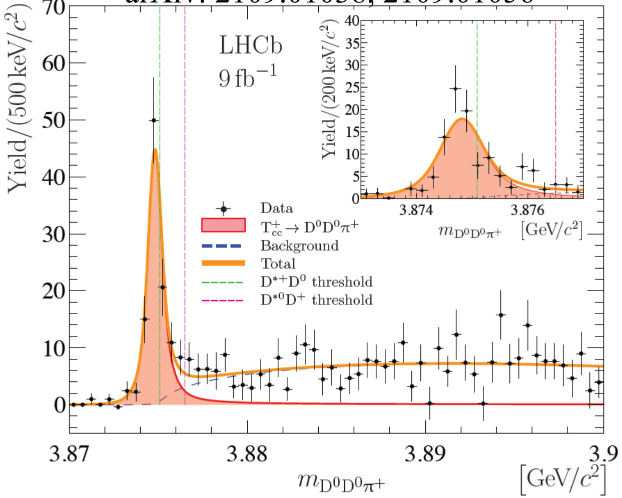

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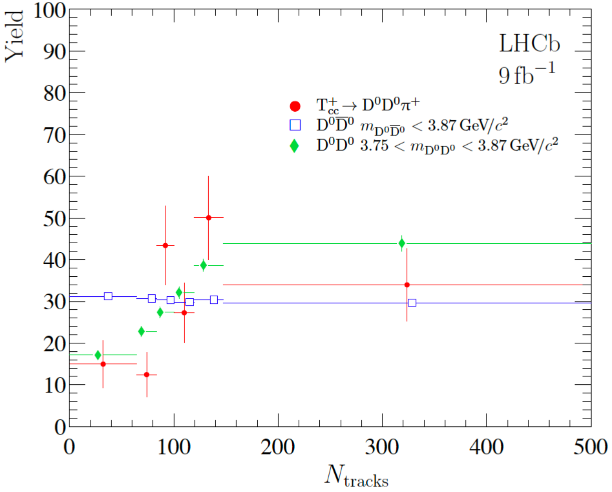

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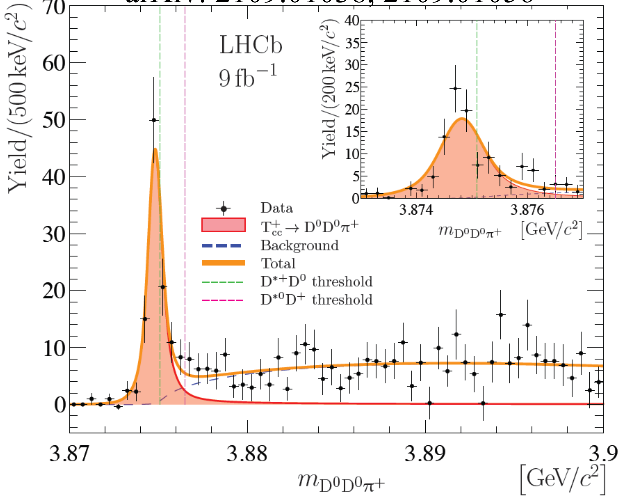

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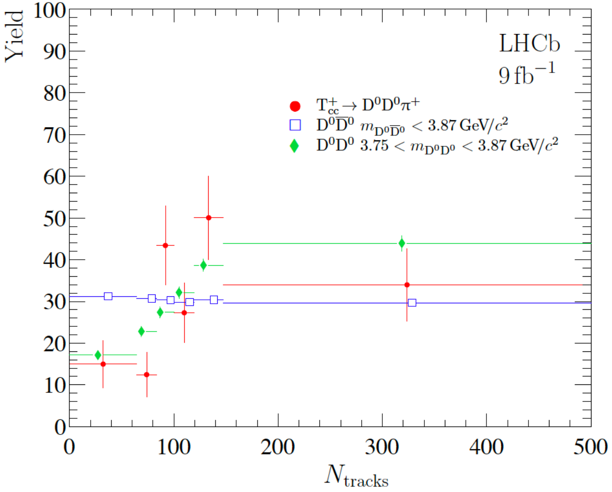
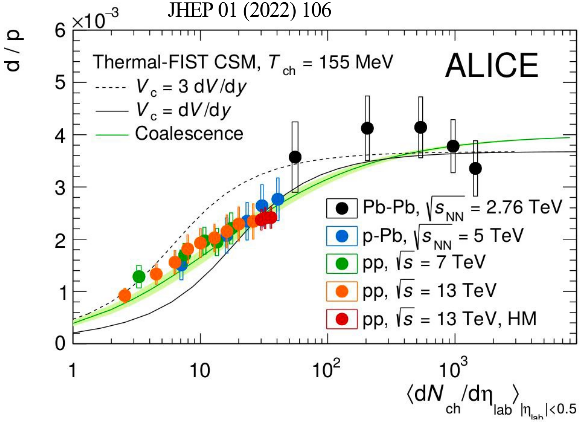


JHEP 01 (2022) 106

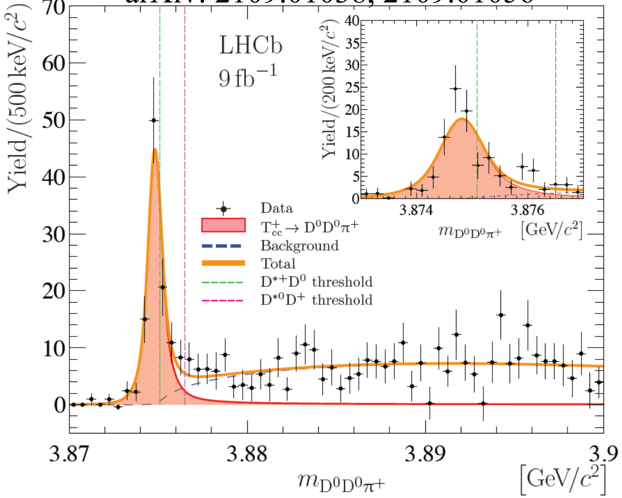


Yield favors higher multiplicity collisions, reminiscent of deuteron.

Evidence for hadronic molecule structure?

Newest exotic: T_{cc}^{+}

arXiv: 2109.01038, 2109.01056



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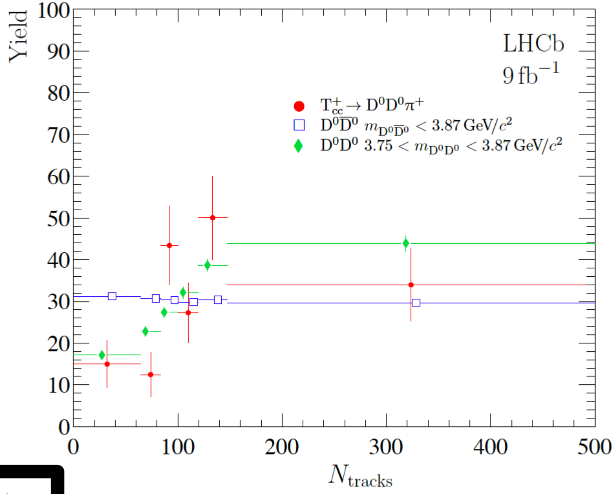
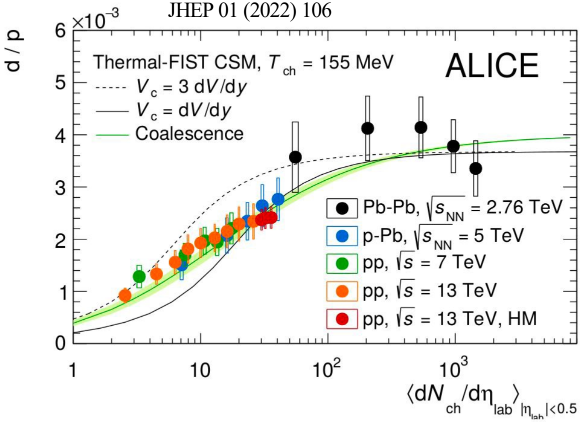


JHEP 01 (2022) 106



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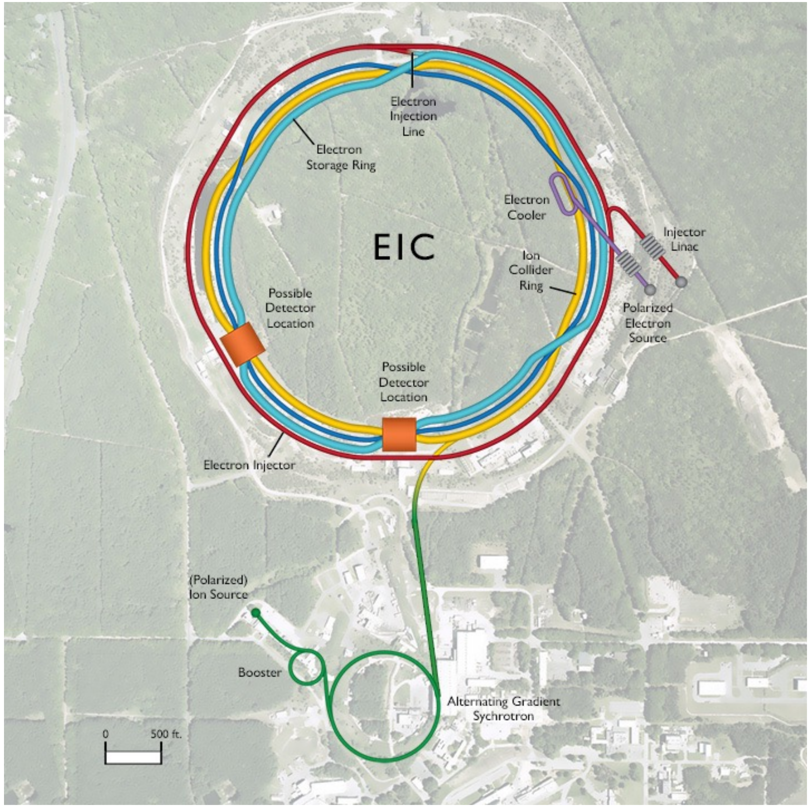
DD distribution, dominated by DPS

HUGE enhancement expected in PbPb due to coalescence: PRD 104 L111502 (2021)

Yield favors higher multiplicity collisions, reminiscent of deuteron.
Evidence for hadronic molecule structure?

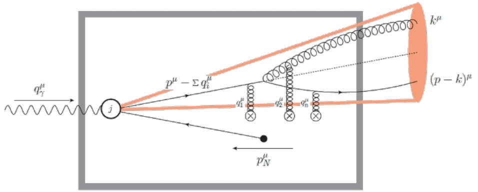
What can EIC tell us about exotics



Charm production inside the nucleus probes:

- Parton structure of nucleons
- nPDF modifications
- QCD energy loss

In the kinematic range accessed by the EIC, hadronization ***inside the nucleus*** becomes an important effect on observables

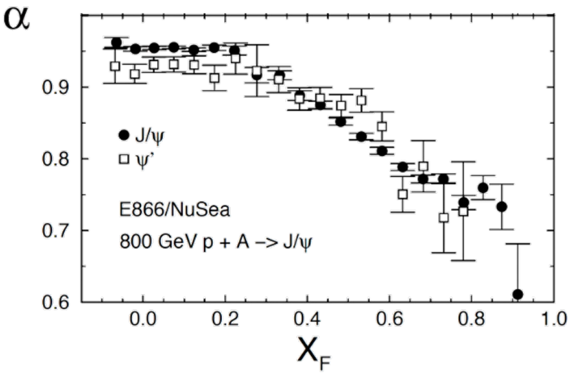


Vitev, 1912.10965

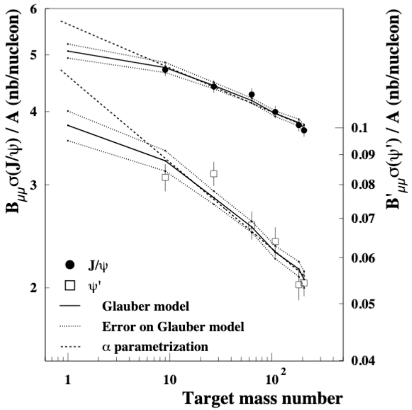
Filtering States with the Nucleus

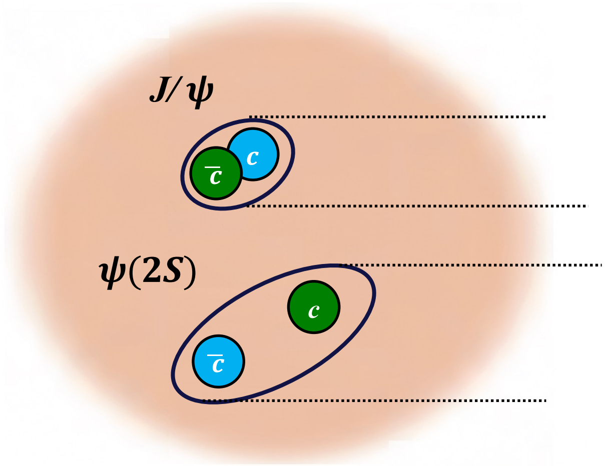
- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair

E866, PRL 84 (2000) 3256-3260



NA50, EPJC 48 329 (2006)

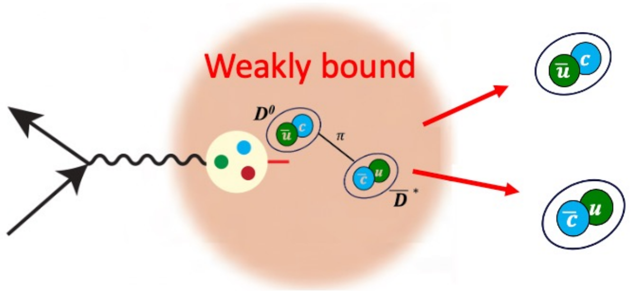




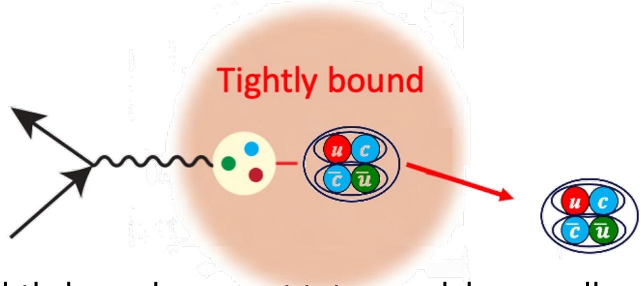
- Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906
- Explains trends observed in fixed target data at FNAL, SPS
- As expected, fails at RHIC (hadronization occurs outside nucleus) PHENIX PRL 111 202301 (2013)

Filtering States with the Nucleus – X(3872)

Apply the same idea to exotic state X(3872):

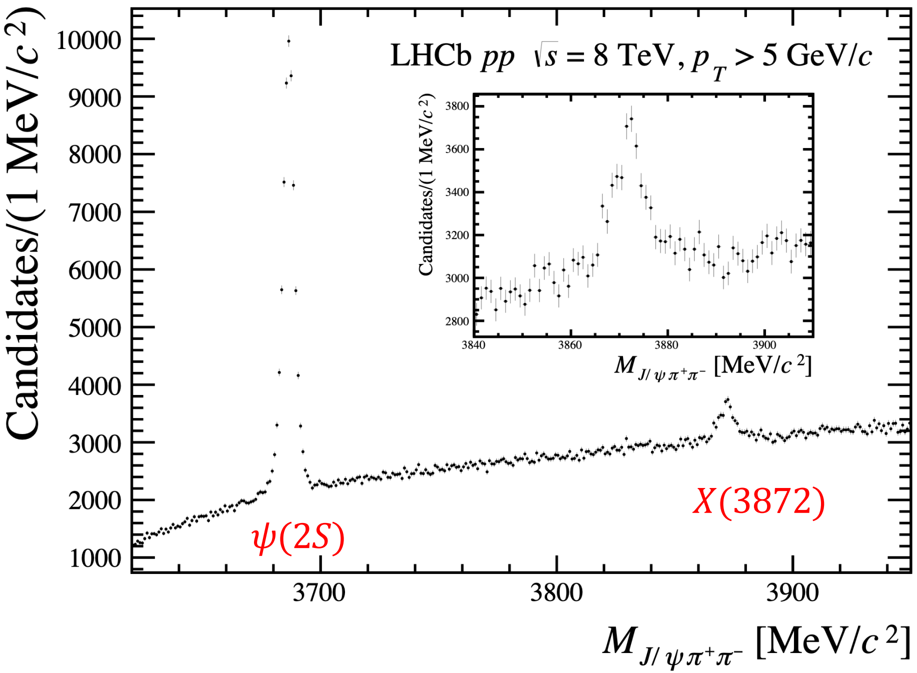


Weakly bound hadronic molecule has large radius, samples large volume of nucleus

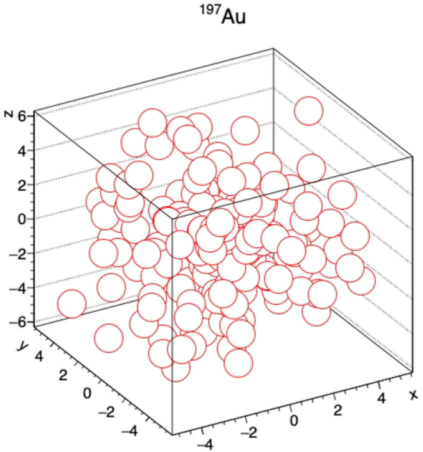


Tightly bound compact tetraquark has small radius, could more easily escape nucleus unscathed

The well-known conventional $\psi(2S)$ and exotic X(3872) are both accessible through $J/\psi\pi^+\pi^-$ decays:



Propagation through Nuclei



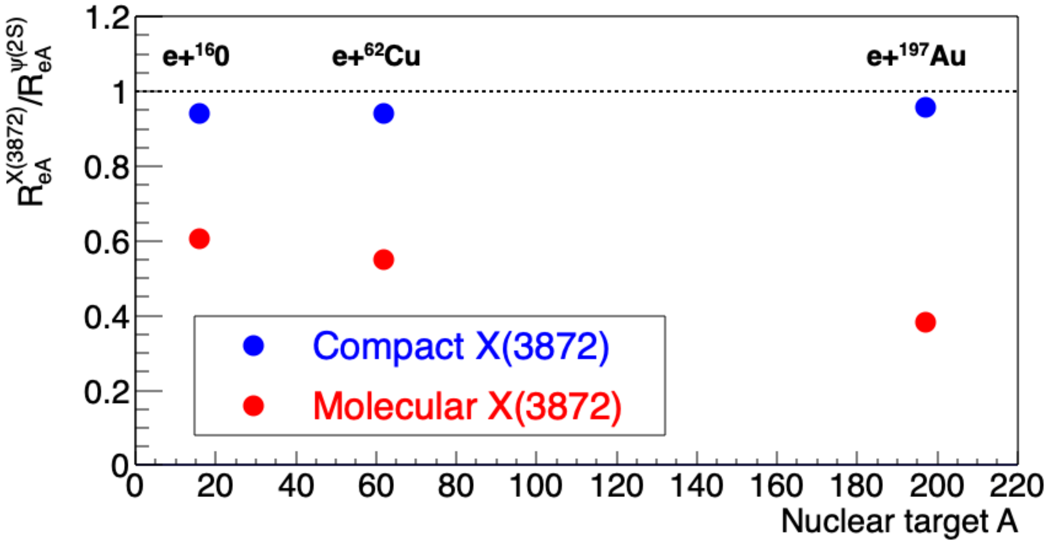
- In Monte Carlo simulation, populate a Glauber nucleus, using parameters from PHOBOS model: arXiv:1408.2549
- Randomly select starting point for $Q\bar{Q}$ pair
- Propagate $Q\bar{Q}$ along z axis

- Following model of Arleo *et al.* in Phys Rev C, 61 054906 (2000), expand $Q\bar{Q}$ radius as a function of time:

$$r_{c\bar{c}}(\tau) = \begin{cases} r_0 + v_{c\bar{c}}\ \tau & \text{if } r_{c\bar{c}}(\tau) \leq r_i \\ r_i & \text{otherwise} \end{cases}$$

- Calculate radius-dependent cross section: $\sigma_{(c\bar{c})_1 N} = \sigma_{\psi N}(s) \cdot (r_{c\bar{c}}/r_{\psi})^2$
- If the state comes within a distance of $\sqrt{\sigma_{c\bar{c}}/\pi}$ to a nucleon, consider it disrupted.
- Three cases: $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm

Relative modification of X(3872)/ $\psi(2S)$ at EIC

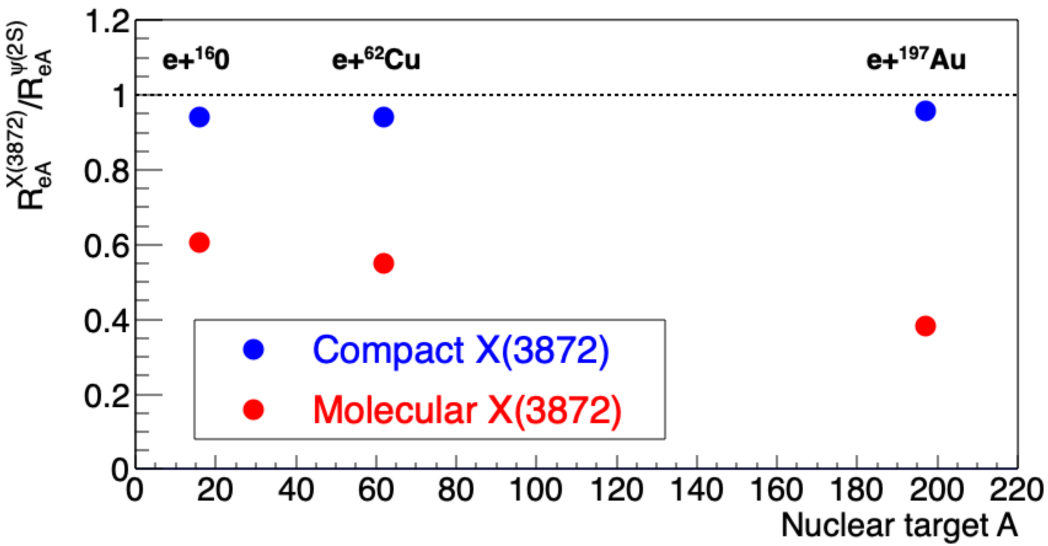


$$\frac{R_{eA}^{X(3872)}}{R_{eA}^{\psi(2S)}} = \frac{\sigma_{eA}^{X}}{\sigma_{eA}^{\psi}} \Bigg/ \frac{\sigma_{ep}^{X}}{\sigma_{ep}^{\psi}}$$

- **Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.**

- **Large difference between model of molecular X(3872) and $\psi(2S)$.**

Relative modification of X(3872)/ $\psi(2S)$ at EIC



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- **Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.**

- **Large difference between model of molecular X(3872) and $\psi(2S)$.**

- What uncertainties do we expect on this data from EIC?
- Need to know X(3872) production rate in EIC collisions
- Current data is from:
  - B factories (via decays, not so relevant for prompt production)
  - Tevatron and LHC (~TeV to ~10 TeV)

Summary

- Heavy quark hadrons are an important probe of the nuclear medium created in heavy ion collisions
- We can flip this around and use the medium to probe poorly understood hadrons
- Utilizing hadronization *inside the nucleus* at the EIC gives us a new way to probe the structure of exotic hadrons

Los Alamos is supported by the Dept. of Energy/Office of Science/Nuclear Physics,

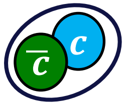
Dept. of Energy Early Career Awards program, and

Los Alamos National Laboratory Lab Directed Research and Development.

Quarkonia in the QCD medium

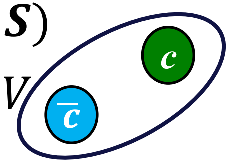
$J/\psi(1S)$

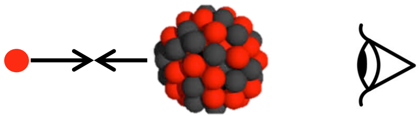
$E_b \approx 600\ MeV$

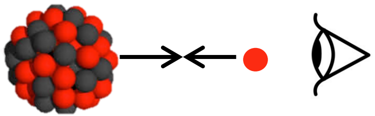


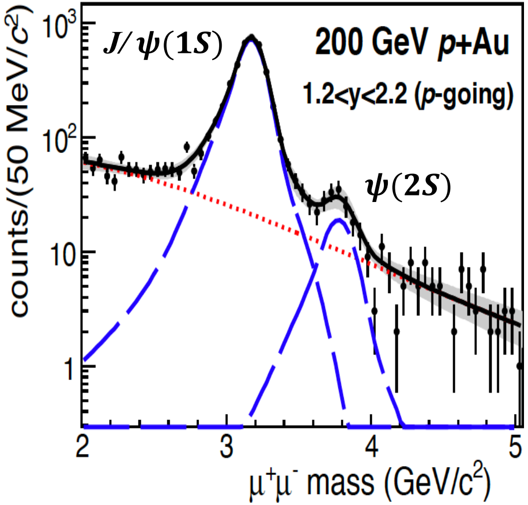
$\psi(2S)$

$E_b \approx 50\ MeV$

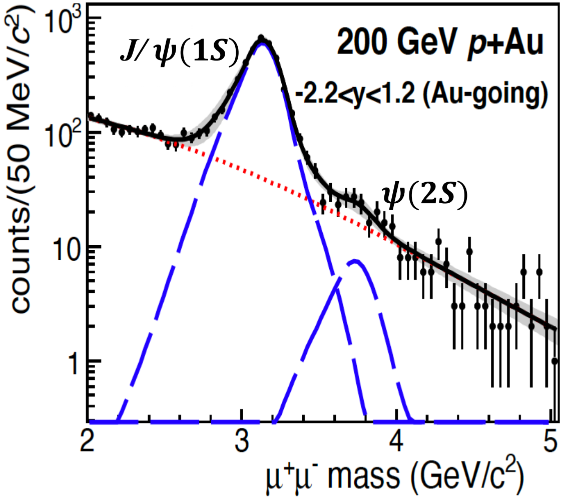




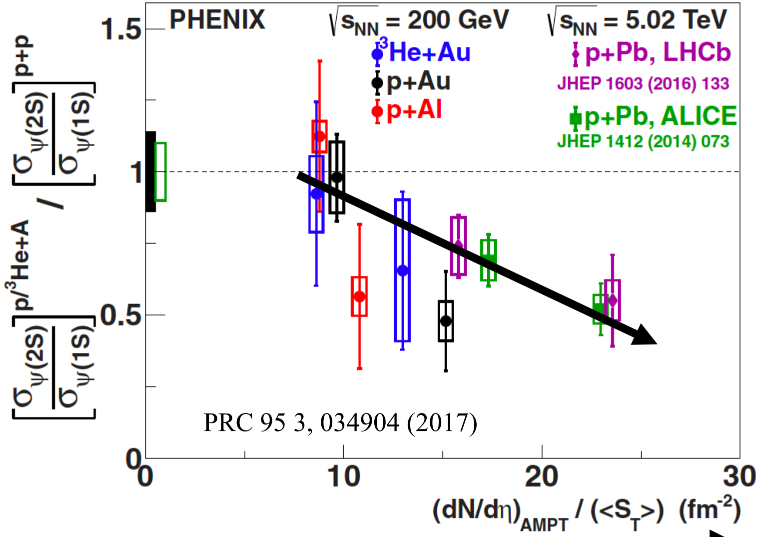




Relatively *low* particle density



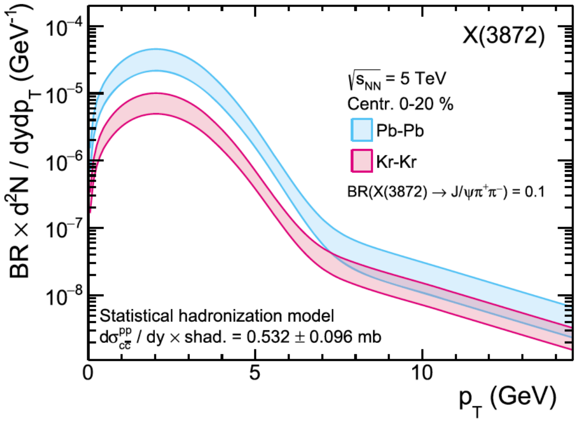
Relatively *high* particle density



Increasing charged particle density

X(3872) in PbPb

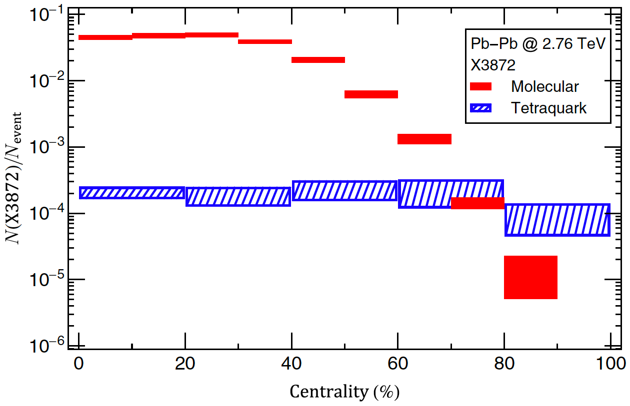
PLB 797 (2019) 134836



SHMC model:
Significant increase in X(3872) predicted for central AA collisions

Yield reaches up to ~1% of J/ψ yield

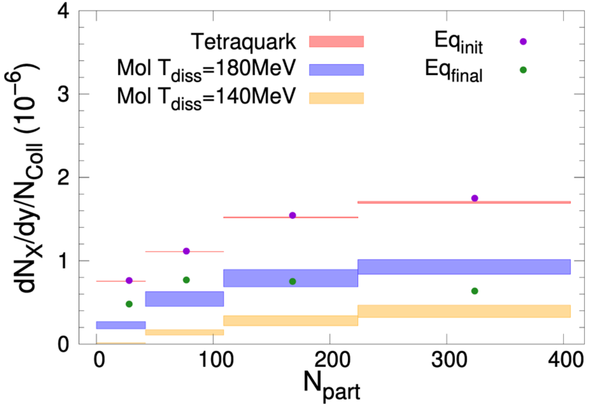
PRL 126 012301 (2021)



AMPT model:
difference in molecule vs diquark-diquark coalescence gives dramatically different yields and centrality dependence:

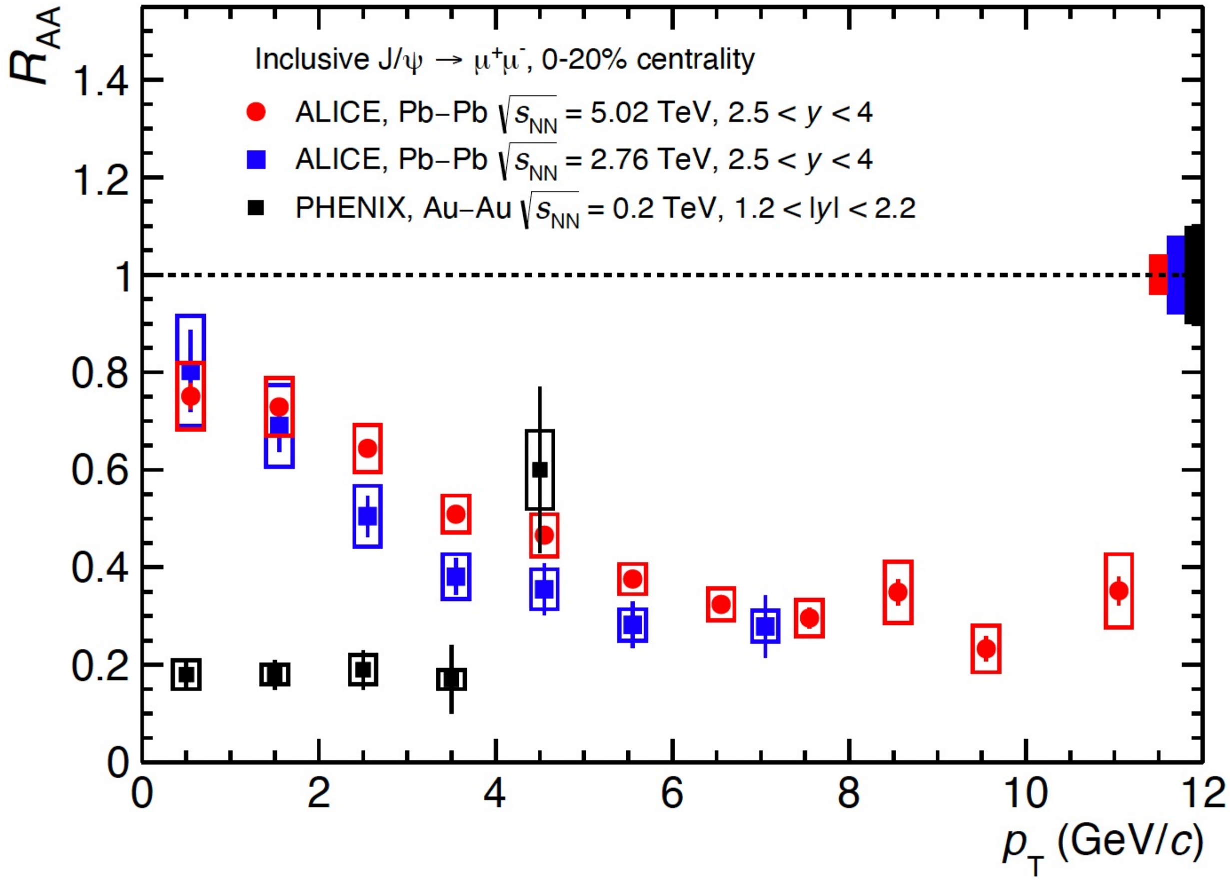
$N_{molecule} > N_{tetraquark}$

EPJA 57 122 (2021)



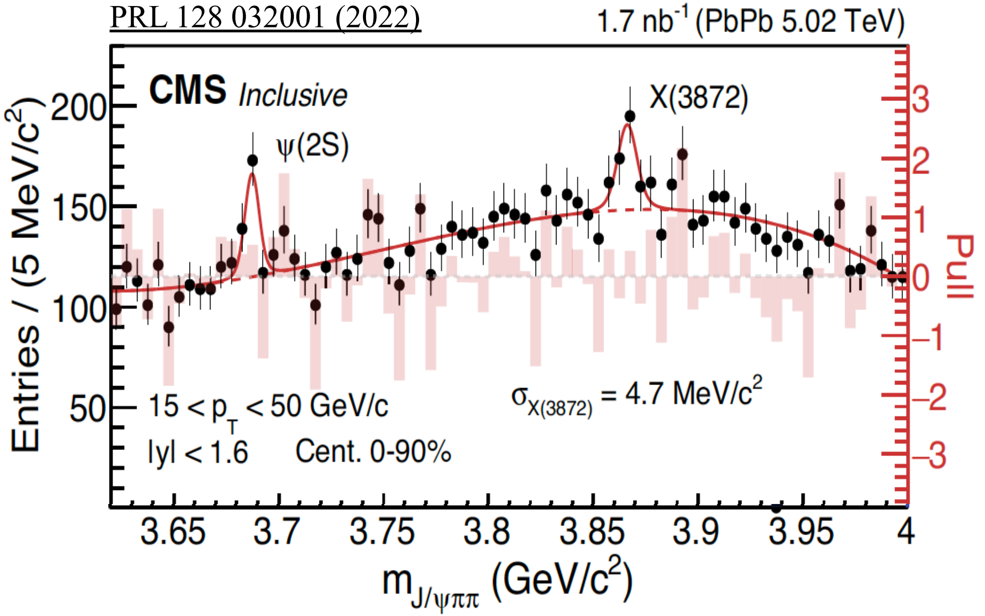
Transport calculation:
molecules have larger reaction rate, formed later in fireball evolution

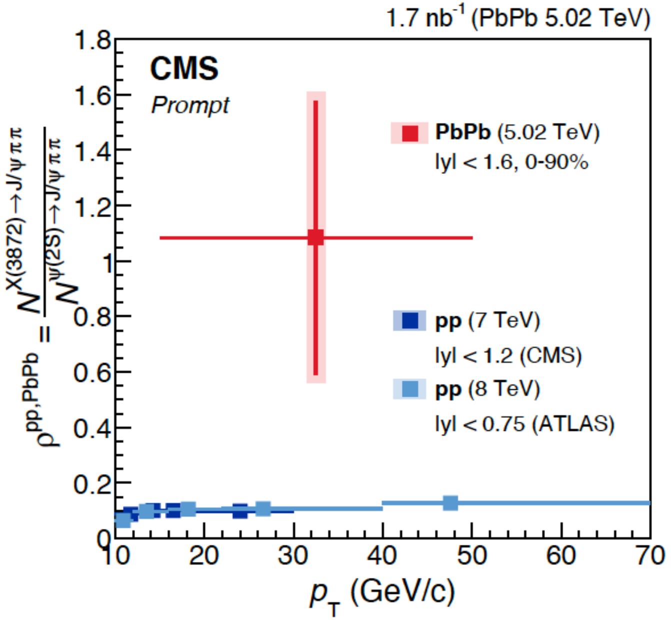
$N_{tetraquark} > N_{molecule}$


Inclusive J/ψ → μ+μ-, 0-20% centrality
ALICE, Pb–Pb √sNN = 5.02 TeV, 2.5 < y < 4
ALICE, Pb–Pb √sNN = 2.76 TeV, 2.5 < y < 4
PHENIX, Au–Au √sNN = 0.2 TeV, 1.2 < |y| < 2.2
RAA
pT (GeV/c)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
2
4
6
8
10
12

X(3872)/ψ(2S) in PbPb

PRL 128 032001 (2022)





Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Coalescence dominates over breakup?

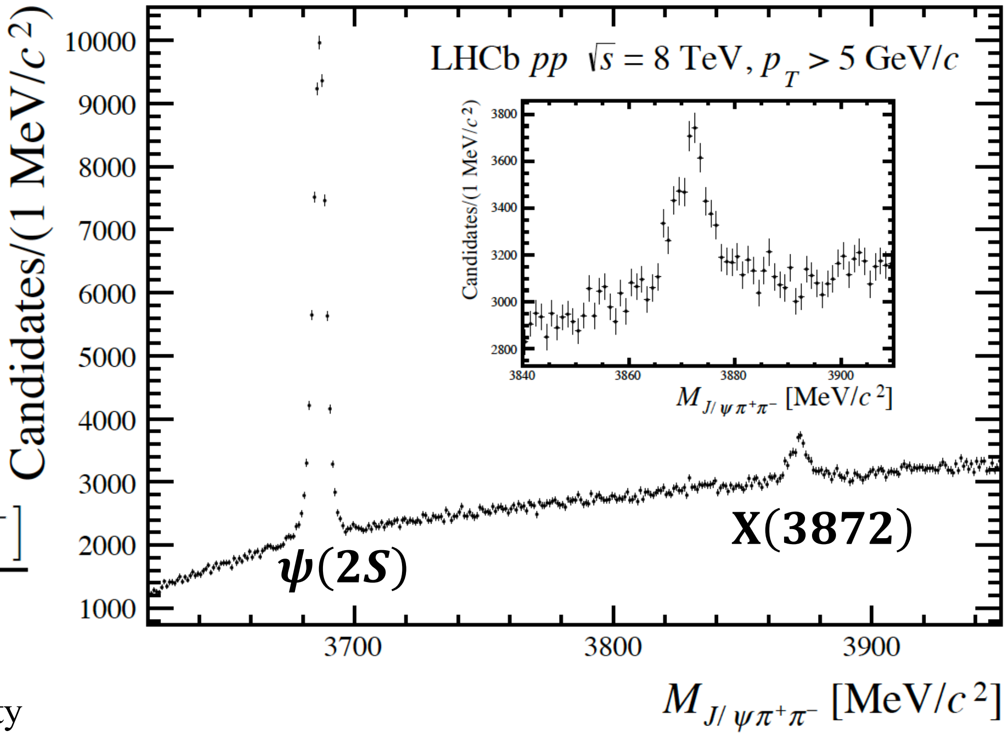
X(3872) measurement at LHCb

Reconstruct the $\mu^+\mu^-\ \pi^+\pi^-$ final state from the decays:

$$X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho(\rightarrow \pi^+\pi^-)$$

$$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$$

PRL 126, 092001 (2021)



Direct comparison between conventional charmonium $\psi(2S)$ and exotic $X(3872)$ via ratio of cross sections:

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]}$$

Select collisions of various charged particle multiplicity to vary density of comoving medium

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Table 1: Charmonium states and binding energies

Satz hep-ph/0512217

state	Υ	χ_{b0}	χ_{b1}	χ_{b2}	Υ'	χ'_{b0}	χ'_{b1}	χ'_{b2}	Υ''
mass [GeV]	9.46	9.86	9.89	9.91	10.02	10.23	10.26	10.27	10.36
ΔE [GeV]	1.10	0.70	0.67	0.64	0.53	0.34	0.30	0.29	0.20

Table 2: Bottomonium states and binding energies