Los Alamos NATIONAL LABORATORY

Recent results on heavy quark dynamics in small systems

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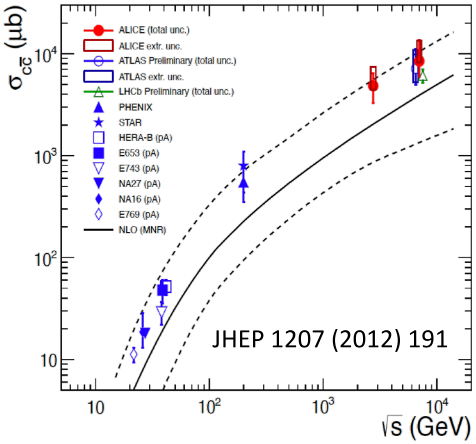
ECT* Workshop
Nov 2021

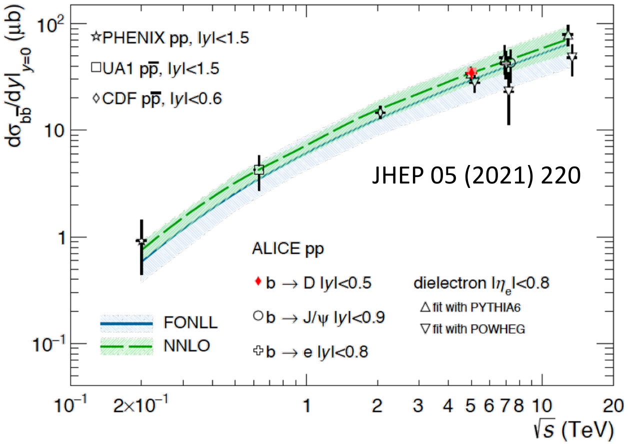
Outline

- Brief introduction
- Effects on conventional quarkonia in small systems
  - Recent PHENIX results on J/$\boldsymbol{\psi}$, $\boldsymbol{\psi(2S)}$
- Effects on exotic quarkonium in small systems
  - Detailed look at X(3872) and $\boldsymbol{T_{cc}^{+}}$ in medium
- Outlook: Fixed-target collisions at the LHCb

Heavy quark production at colliders

- Not present in incoming beam particles – must be manufactured
- Mass $\gg \Lambda_{QCD}$, perturbative methods applicable





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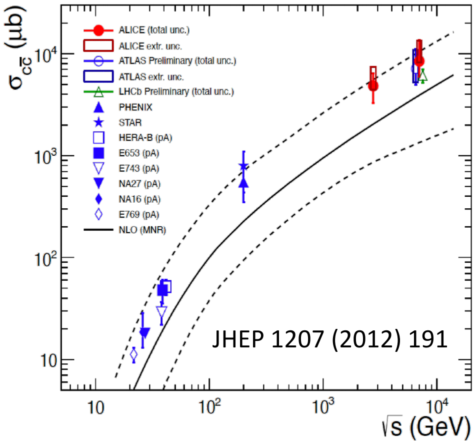
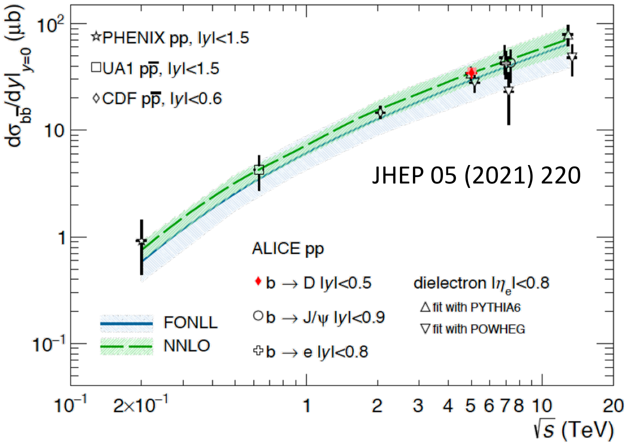
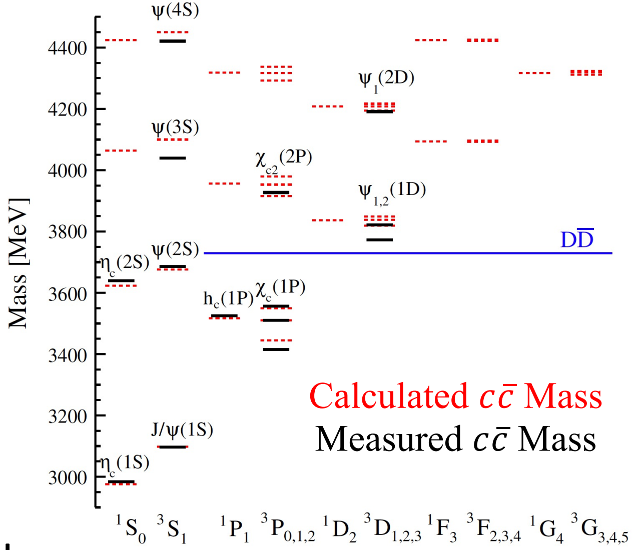
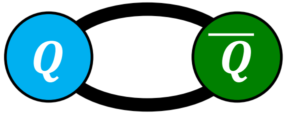




Rev. Mod. Phys. 90, 015003 (2018)



- Allowed bound states understood through potential models



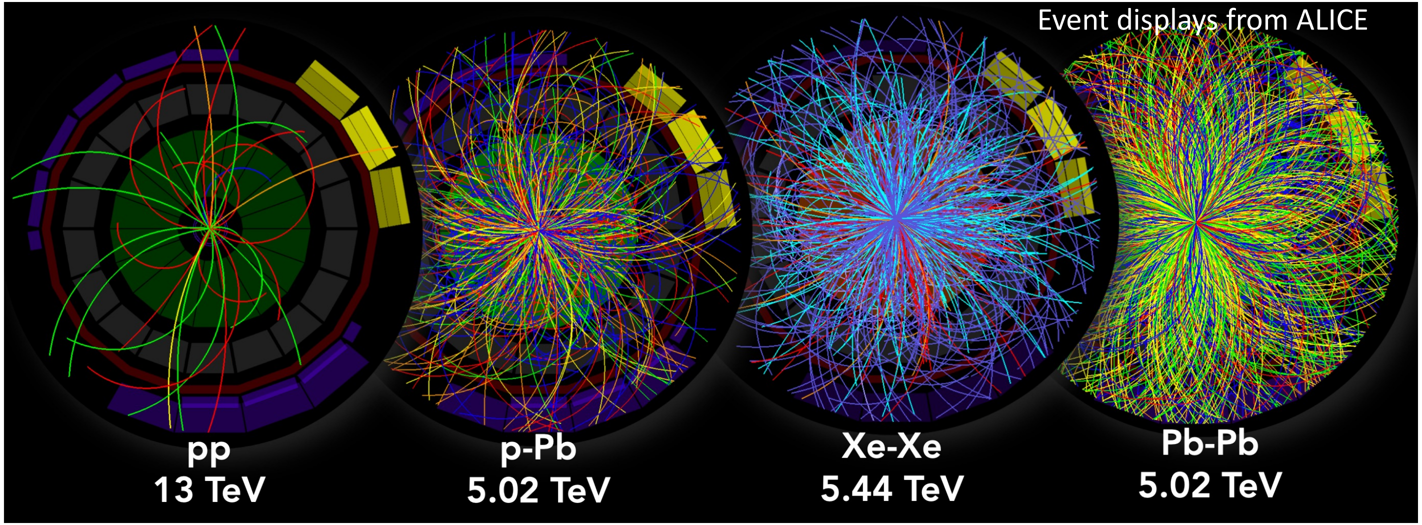
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

PRD 72, 054026 (2005)

The QCD medium

Diffuse medium (pp,pA) → Increasing T, $N_{charged}$ → Dense medium (pA, AA)

Use quarkonia states to probe non-perturbative effects in dense many-body hadronic systems



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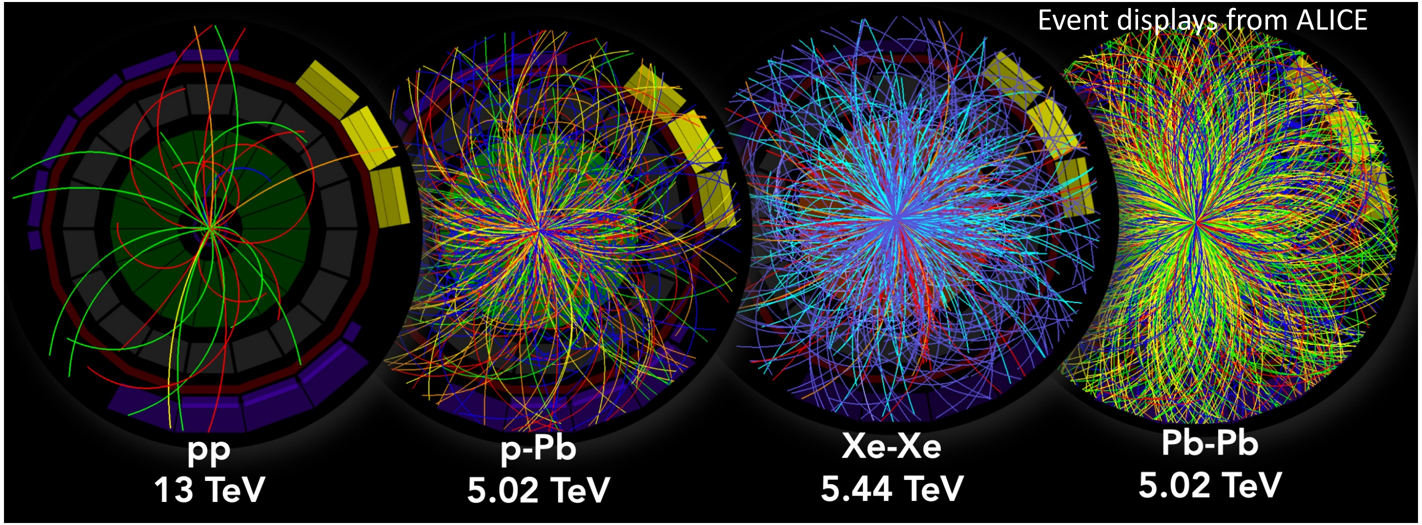
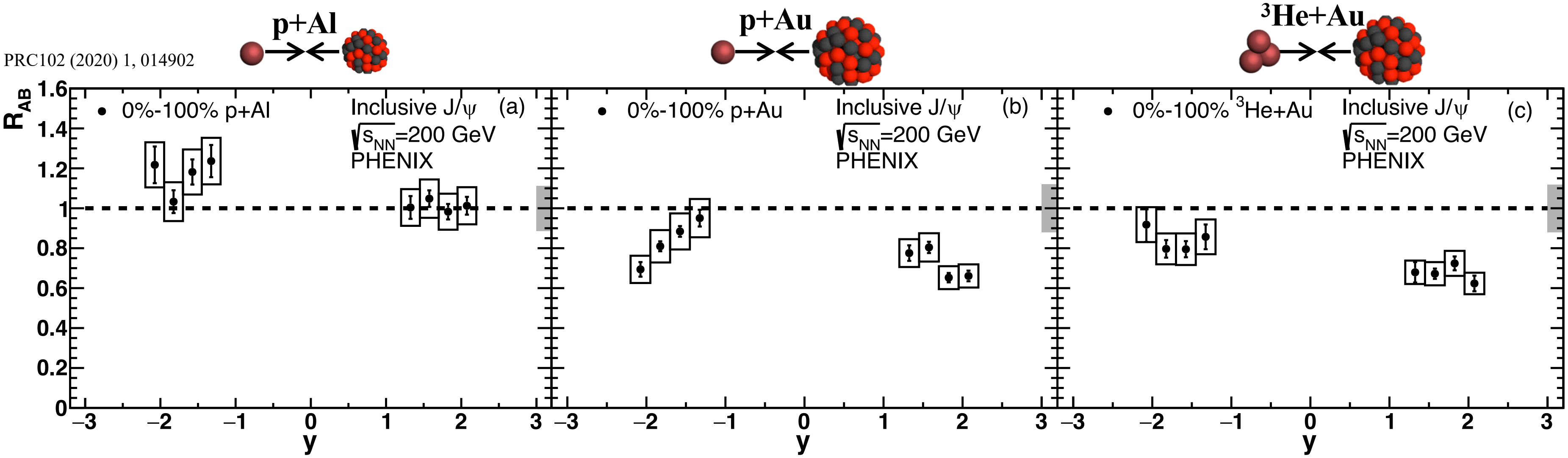


Use interactions in a QCD medium to probe poorly understood heavy quark states.

J/ψ in small systems at PHENIX

PRC102 (2020) 1, 014902



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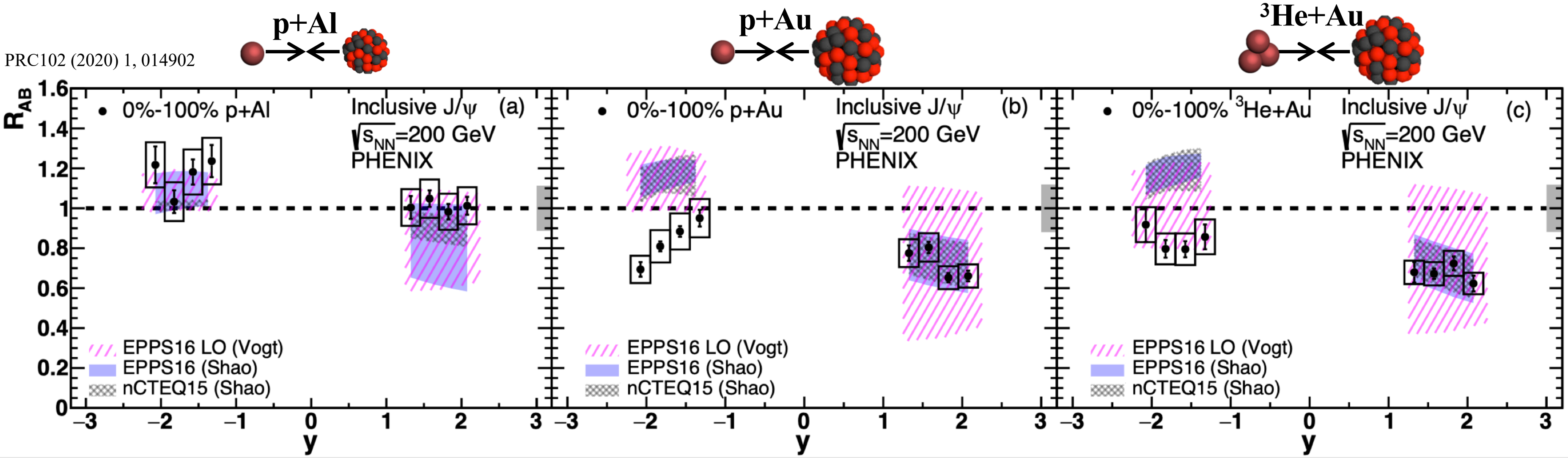

- Forward rapidity (p or 3He-going direction):
  - Data generally in agreement with nPDF calculations
- Backward rapidity (A-going direction):
  - Data from Au nucleus is **inconsistent with nPDF calculation**:
    - Additional effects *required* to explain data

nPDF calculations reweighted to include LHC data
Kusina, Lansberg, Schienbein, Shao,
Phys. Rev. Lett. 121, 052004 (2018)

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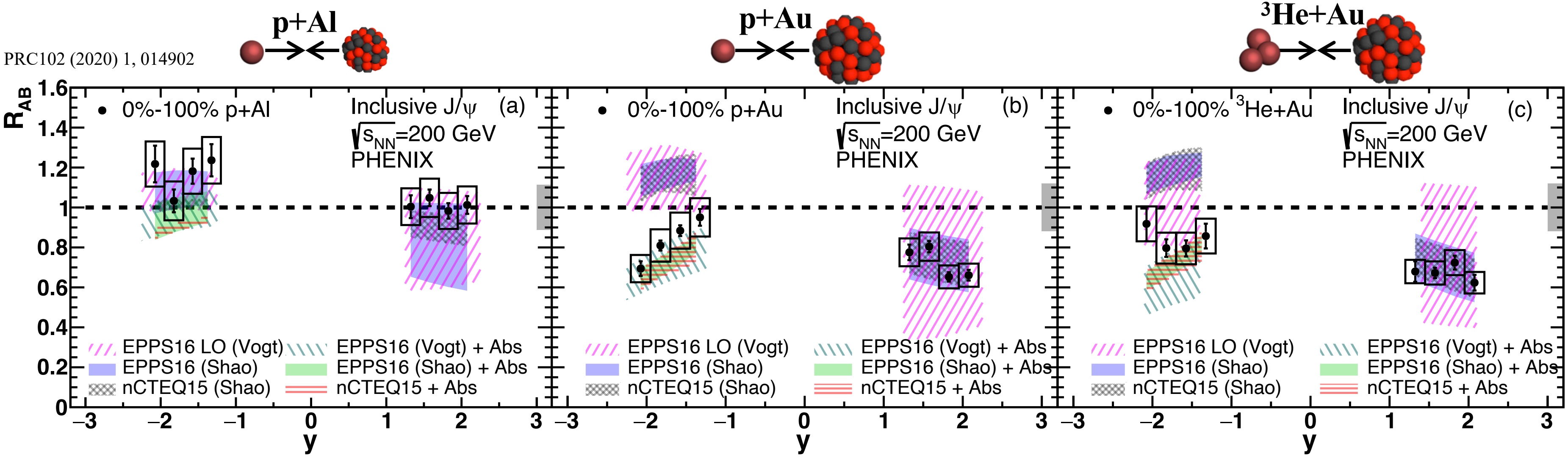

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    - Additional effects *required* to explain data
    - Nuclear absorption at backwards rapidity relieves tension

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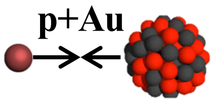
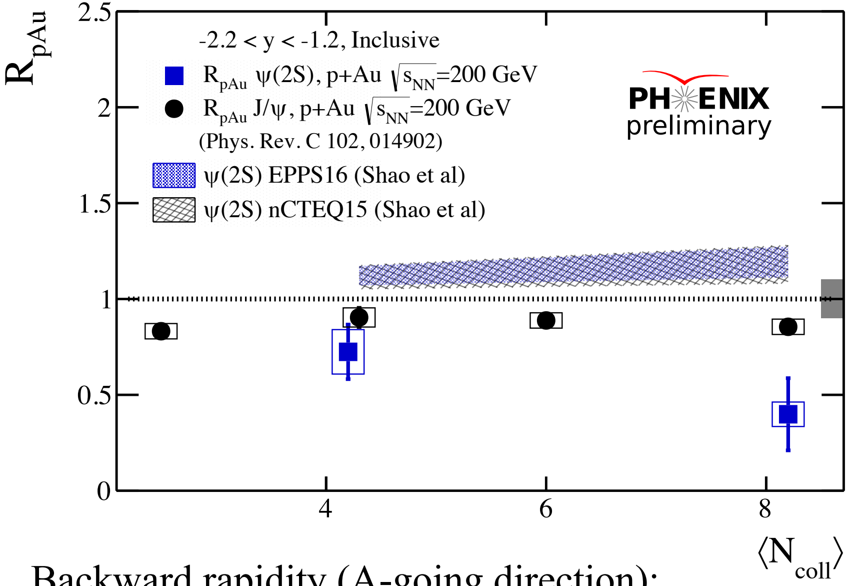
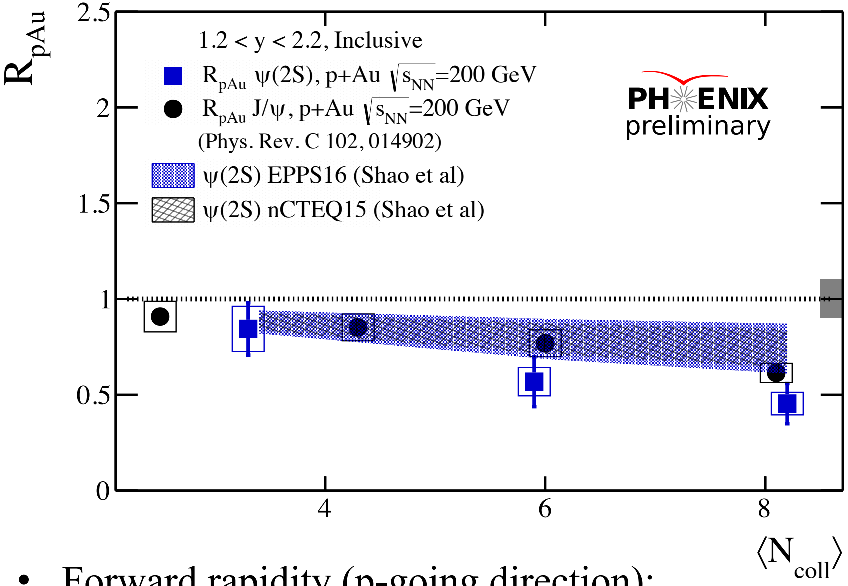
Kusina, Lansberg, Schienbein, Shao,
Phys. Rev. Lett. 121, 052004 (2018)

ψ(2S) in small systems at PHENIX

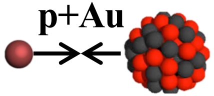


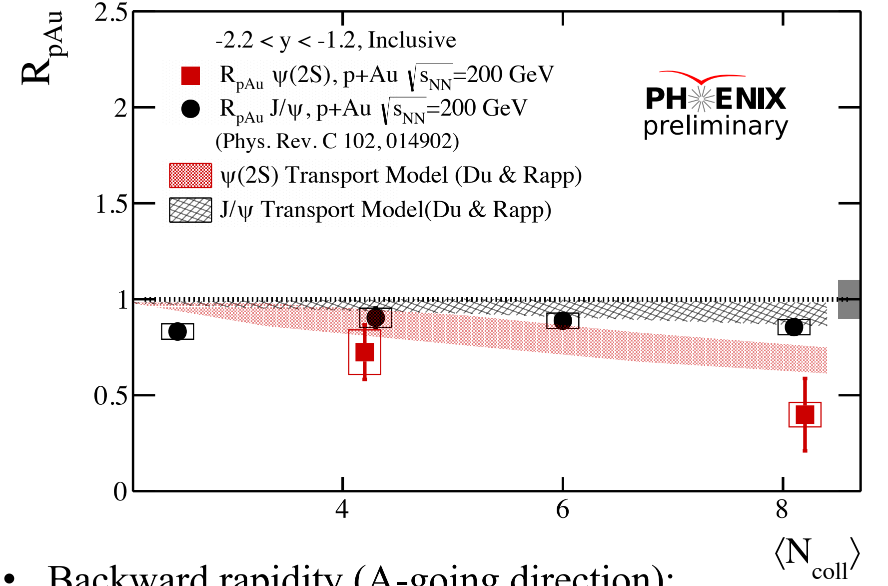


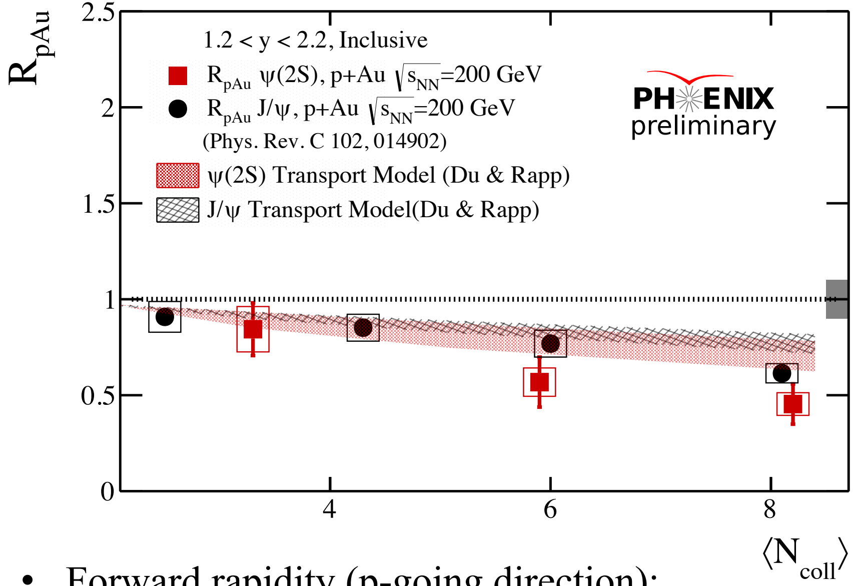


- Backward rapidity (A-going direction):
  - -ψ(2S) may be more suppressed than J/ψ at most central
  - -Inconsistent with nPDF calculation
- Forward rapidity (p-going direction):
  - -J/ψ and ψ(2S) display ~consistent suppression
  - -Data generally in agreement with nPDF calculations

ψ(2S) in small systems at PHENIX







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  - -Transport model consistent with data
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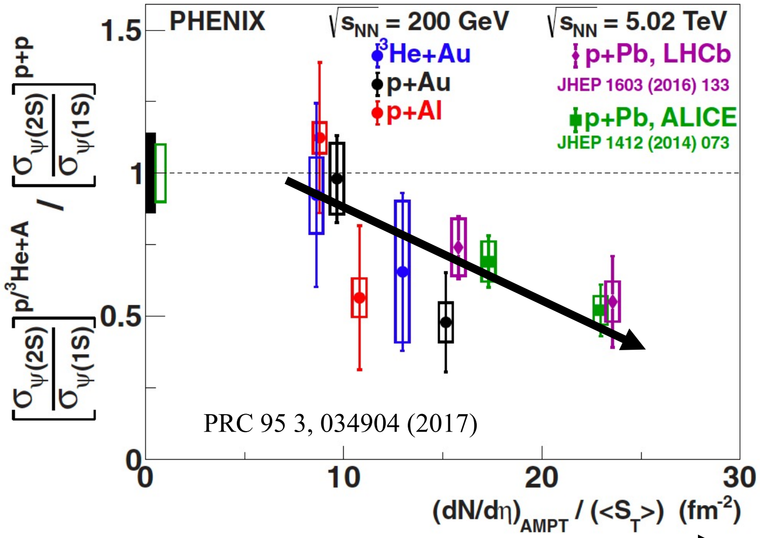
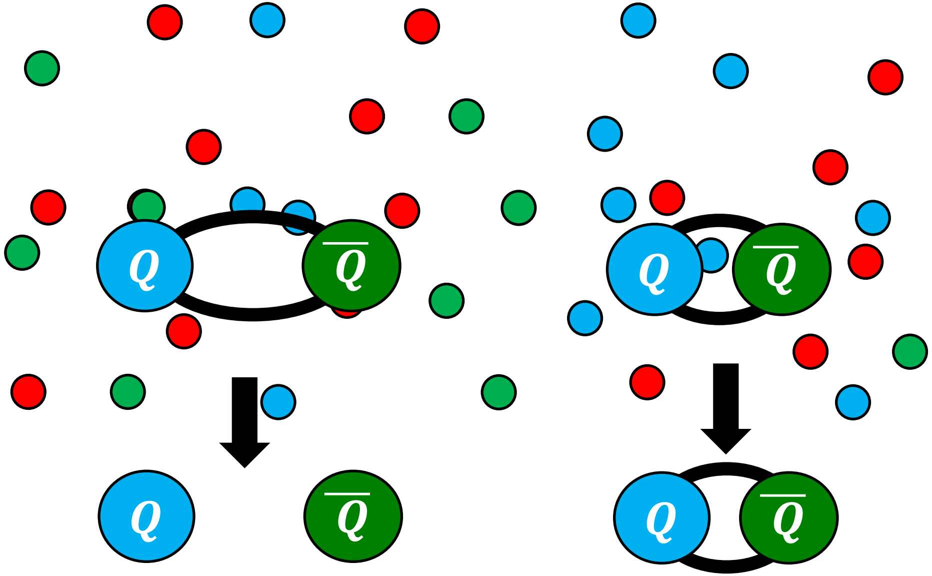
  - -Data generally in agreement with nPDF calculations
  - -Transport model consistent, shadowing dominant

ψ(2S) in small systems at RHIX and LHC



Increasing charged particle density



Comover breakup:

Phys. Lett. B, 393(3):431, (1997)

Phys. Rev. Lett., 78:1006–1009 (1997)

Phys. Lett. B, 749:98, (2015)

Phys. Rev. C, 97:014909 (2018)

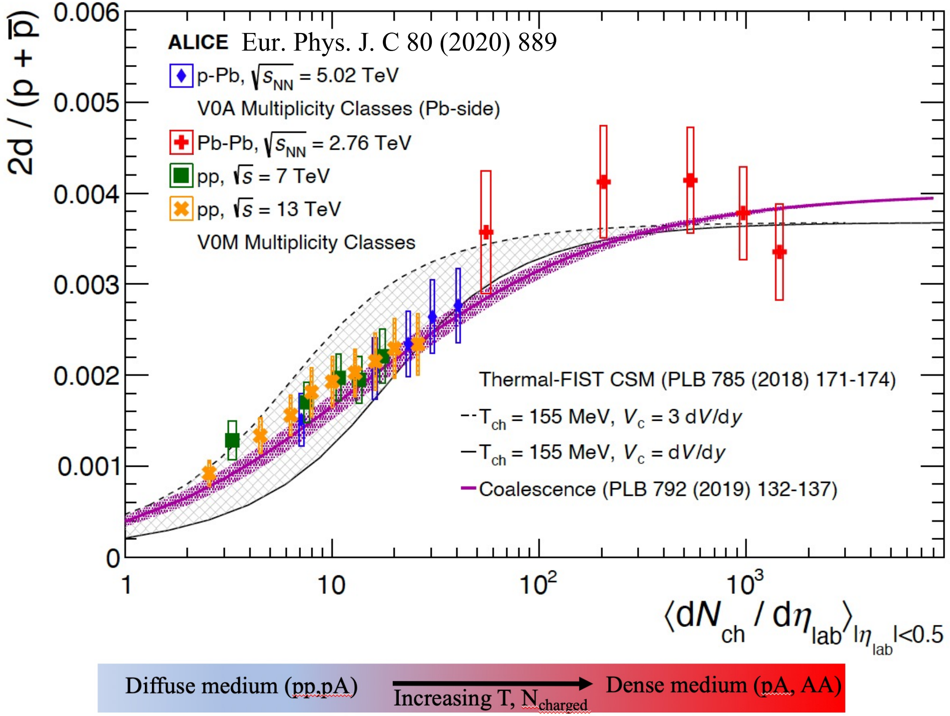
JHEP, 2018(10):94 (2018)

Regardless of mechanism: Effect is sensitive to ***binding energy*** and ***density of medium***

Deuteron production in the QCD medium

Deuteron: weakly bound state of neutron and proton, $E_b \approx 2\ MeV$

Effectively an *np* hadronic molecule



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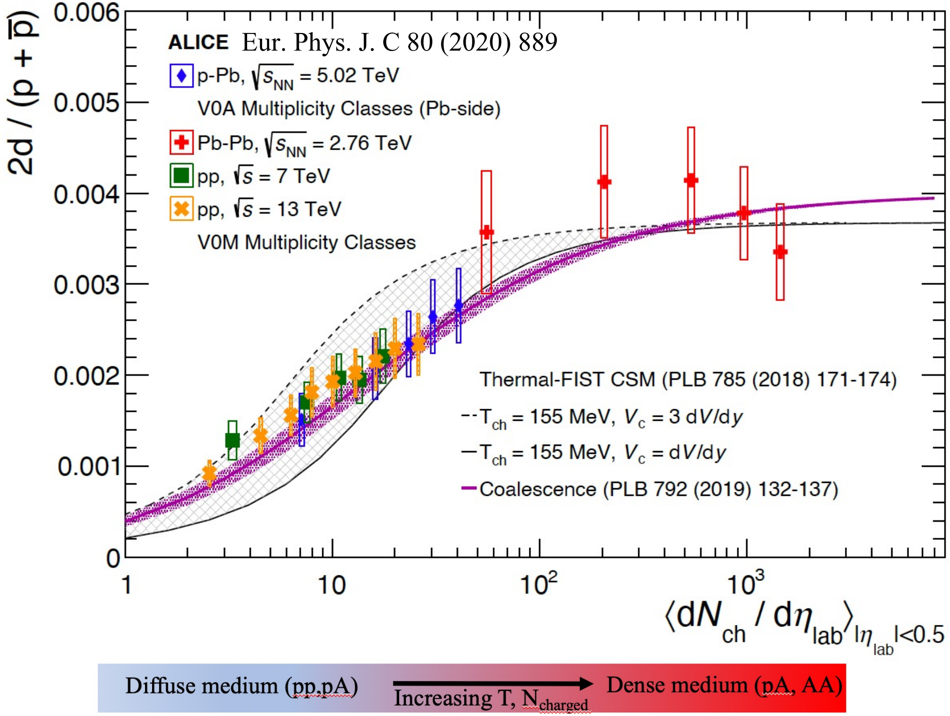
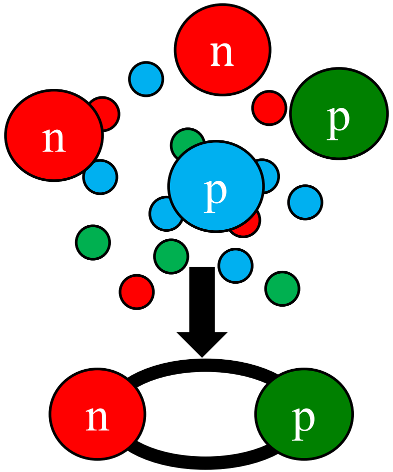


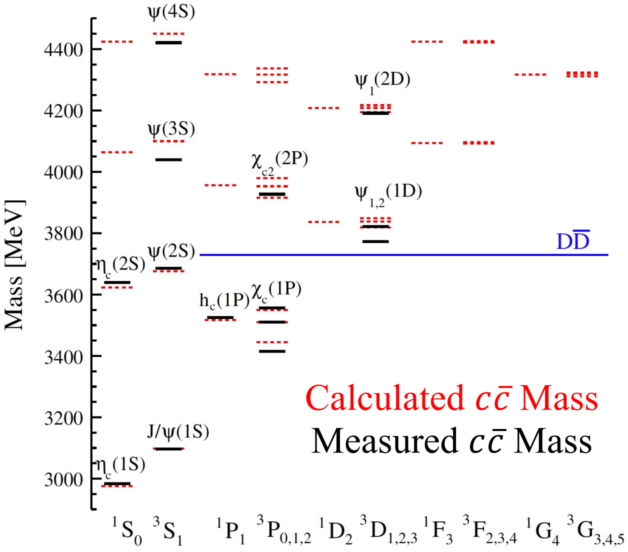
Production relative to protons increases with system density:

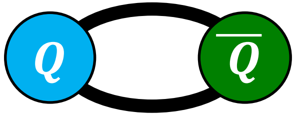


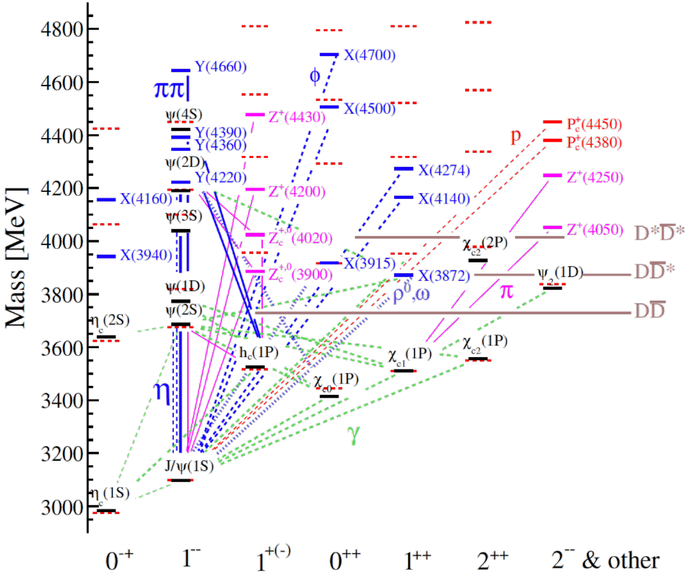
Well described by coalescence models.
Favors production at high multiplicity.

Exotic heavy quark states

Rev. Mod. Phys. 90, 015003 (2018)



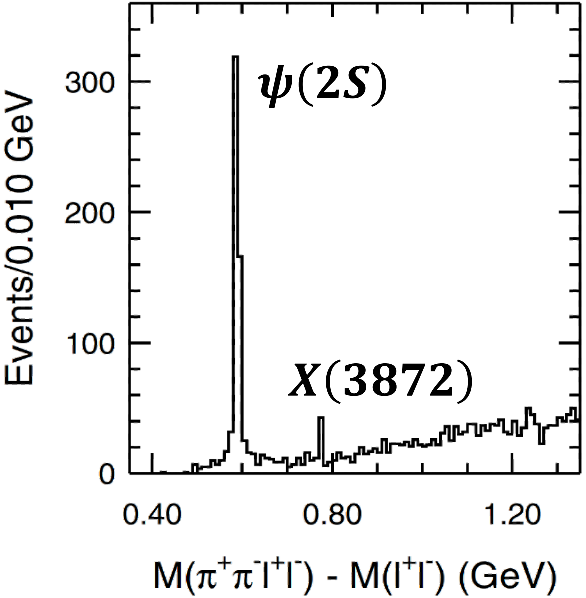




Wide range of explanations: tetra- or pentaquarks, hadronic molecules, glueballs, mixtures…
Given wide range of states, multiple structures likely

An enduring puzzle: X(3872)

Belle Collaboration
PRL 91 262001 (2003)



- The first heavy exotic hadron, discovered in $J/\psi\pi^+\pi^-$mass spectrum from B decays by Belle in 2003

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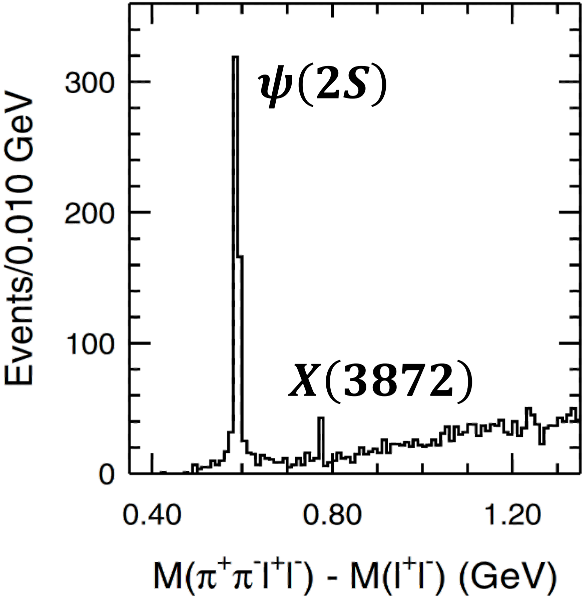

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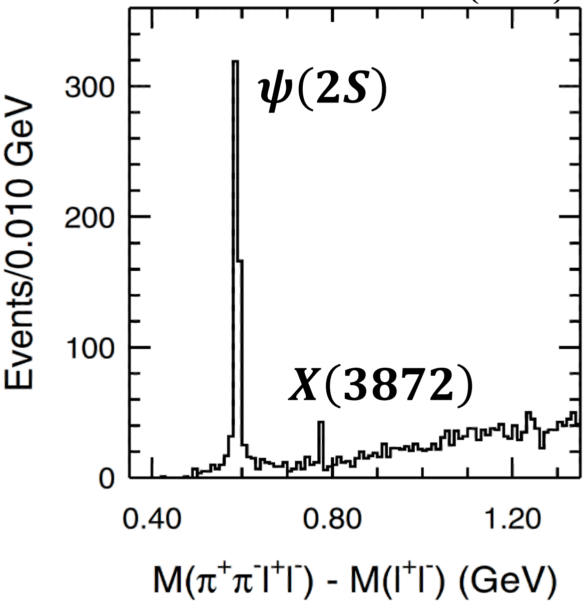

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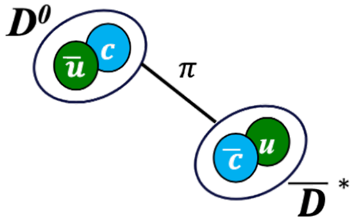
- Mass is consistent with sum of D^0 and $\overline{D}^{*0}$ masses:

$$\left(M_{D^0} + M_{\bar{D}^{*0}}\right) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12 \text{ MeV}/c^2$$

$D^0\overline{D}^*$ Molecule



VERY **small binding energy**
VERY **large radius, ~10 fm**

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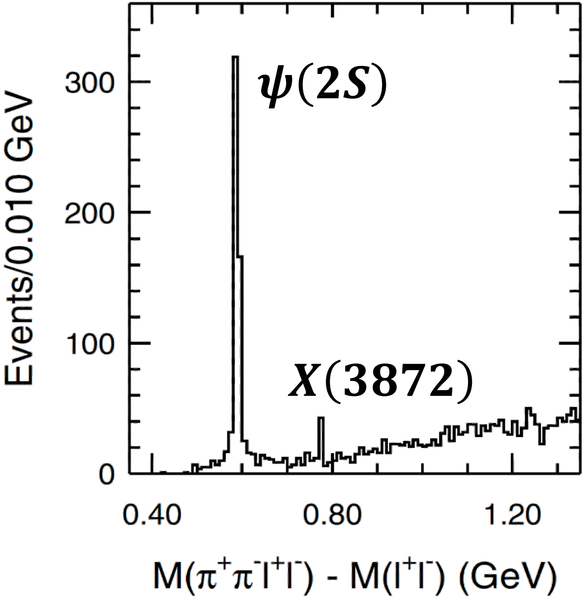

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- Large prompt production fraction (~80%) – inconsistent with D meson coalescence in pp*

VERY small binding energy
VERY large radius, ~10 fm

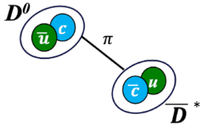
Tightly bound via color exchange between diquarks
Small radius, ~1 fm

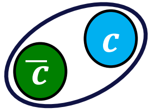
*Tension in theoretical literature:
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
Artoisenet, Braaten
PRD 81 114018 (2010)

Exotic states – X(3872) production

PRL 126 092001 (2021)

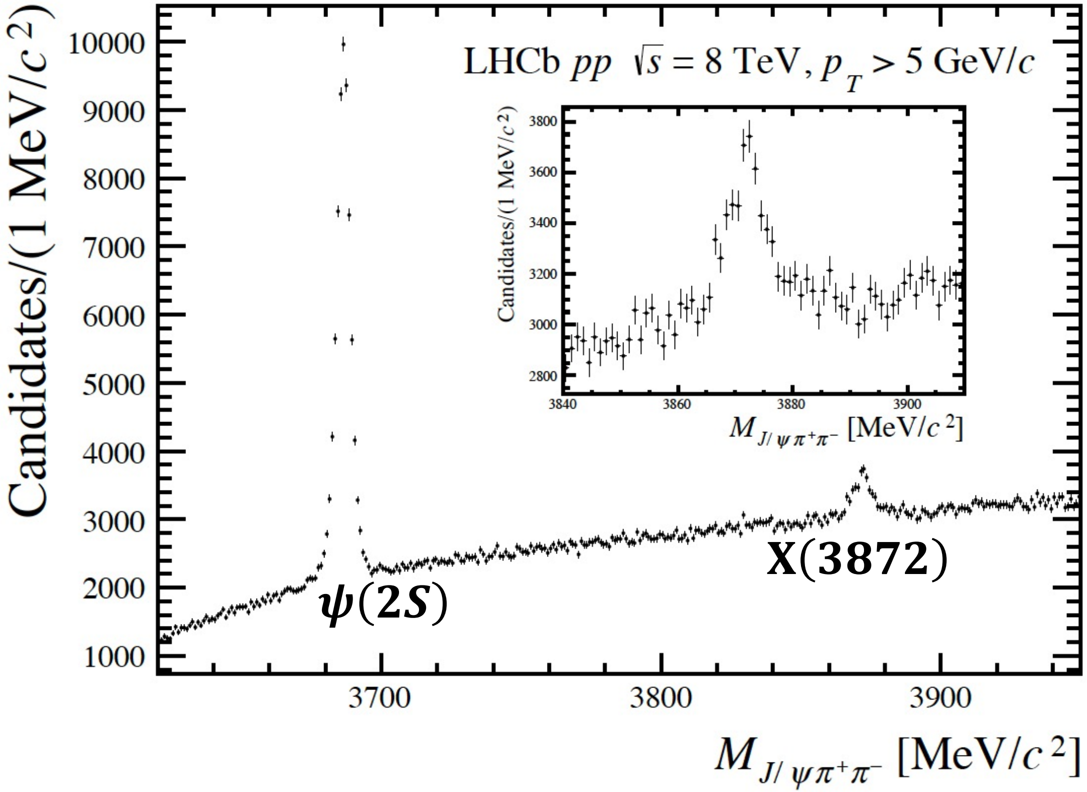
$X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho(\rightarrow \pi^+\pi^-)$





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

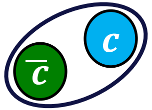
Ratio of $X(3872)/\psi(2S)$ gives direct comparison between well-known charmonium state and poorly understood exotic, also cancels some uncertainties.



Exotic states – X(3872) production

arXiv:2109.07360

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



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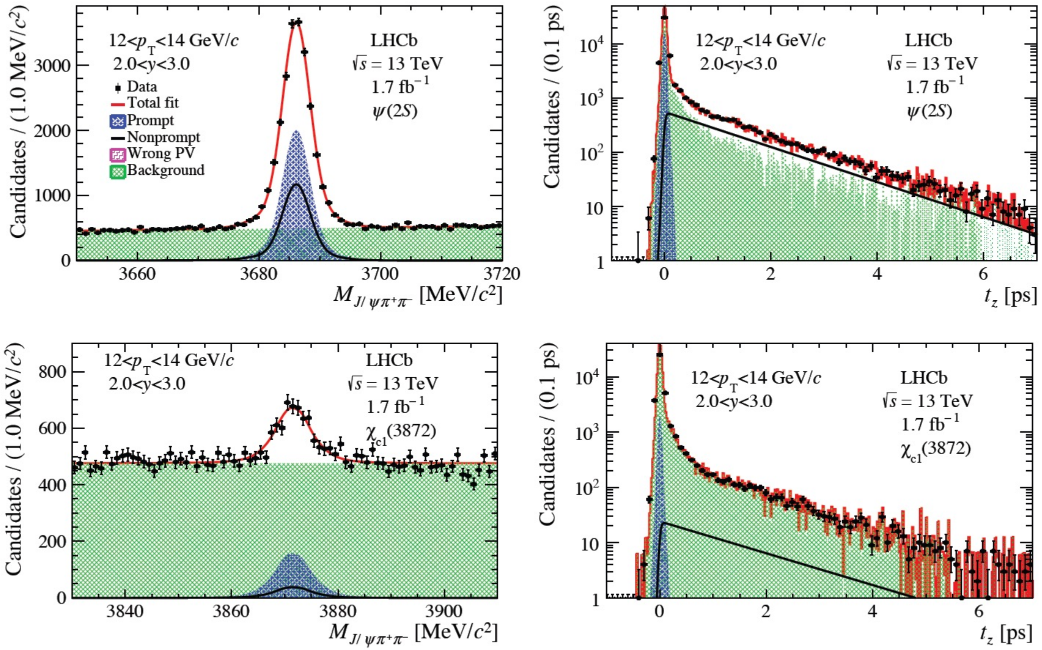

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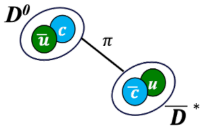

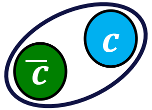

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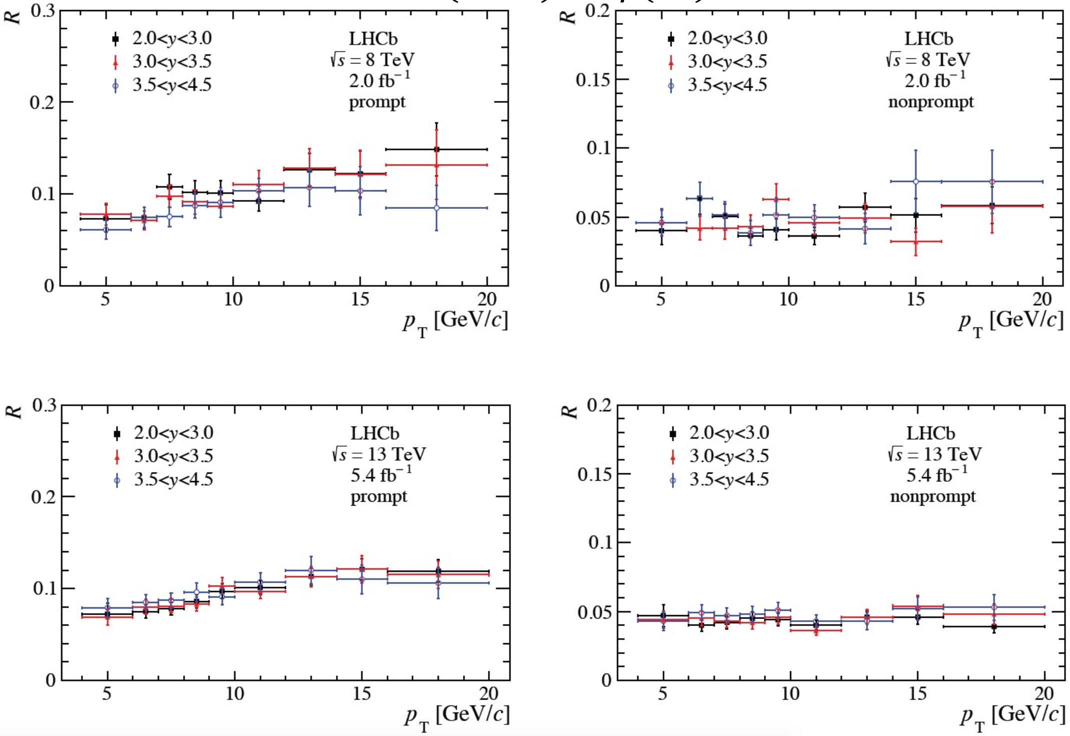
$\sigma_{X(3872)} / \sigma_{\psi(2S)}$



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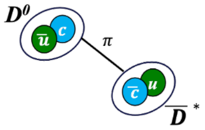

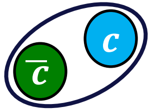

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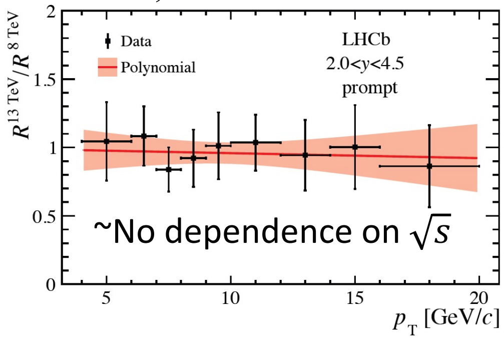

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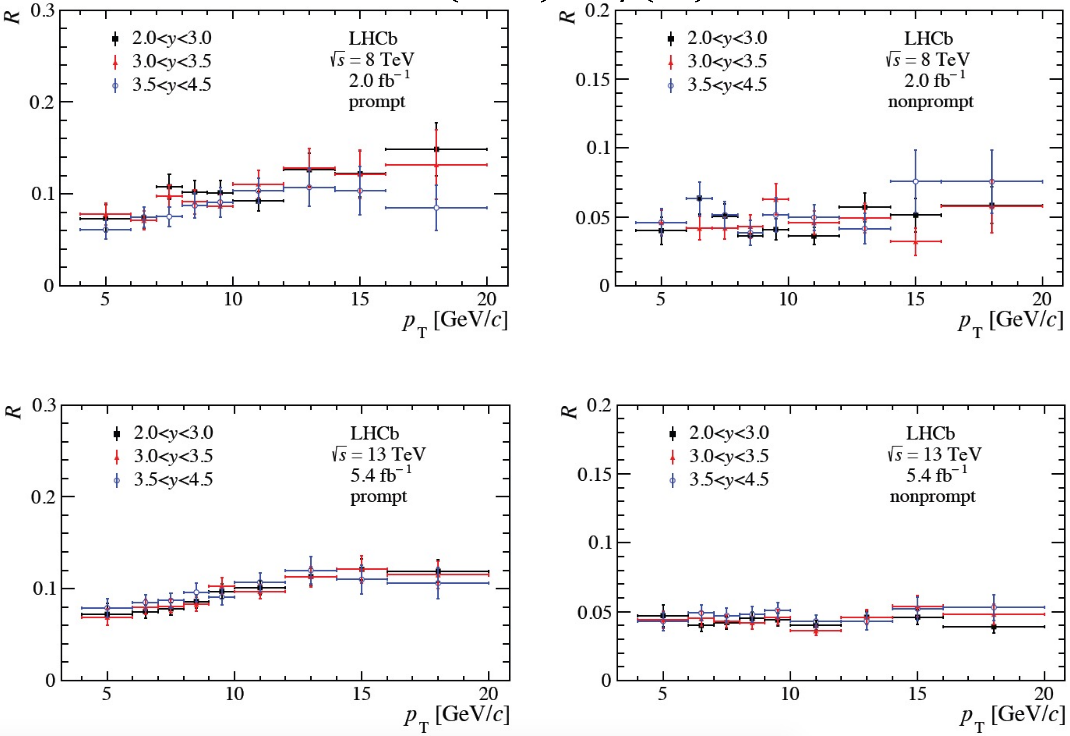

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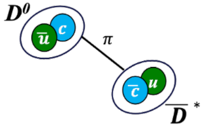

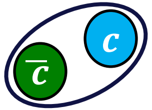

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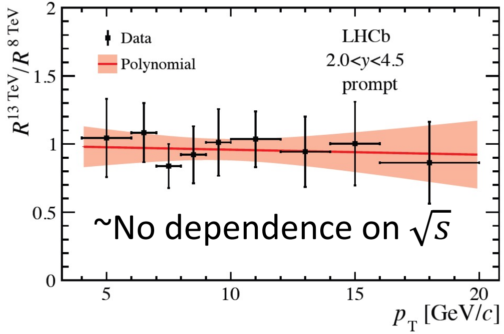

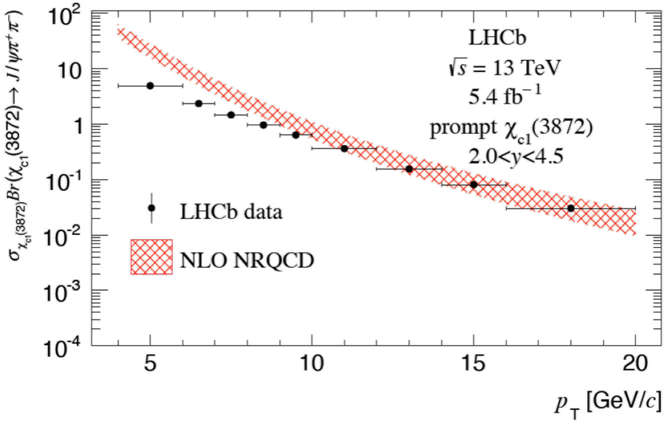

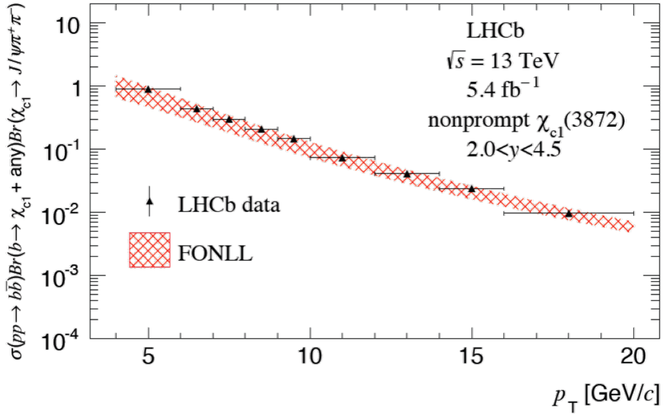

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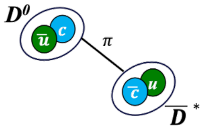

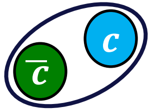

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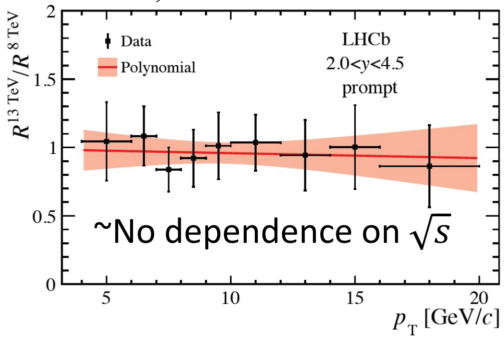
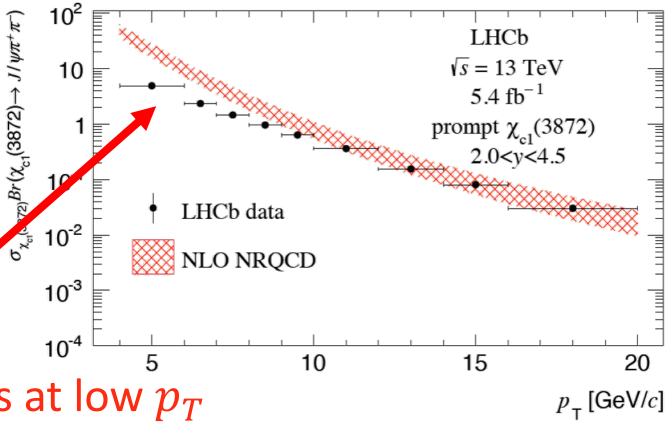
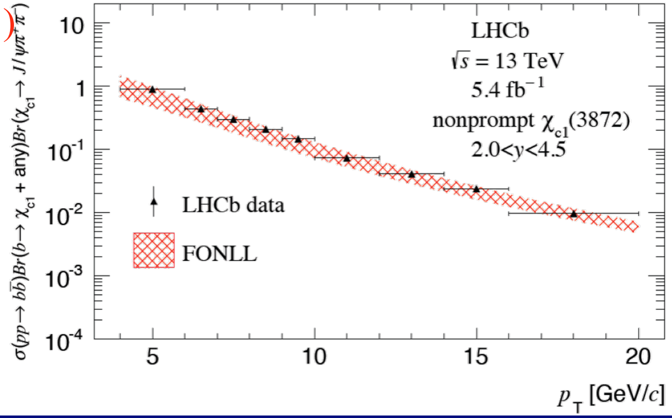


~No dependence on $\sqrt{s}$



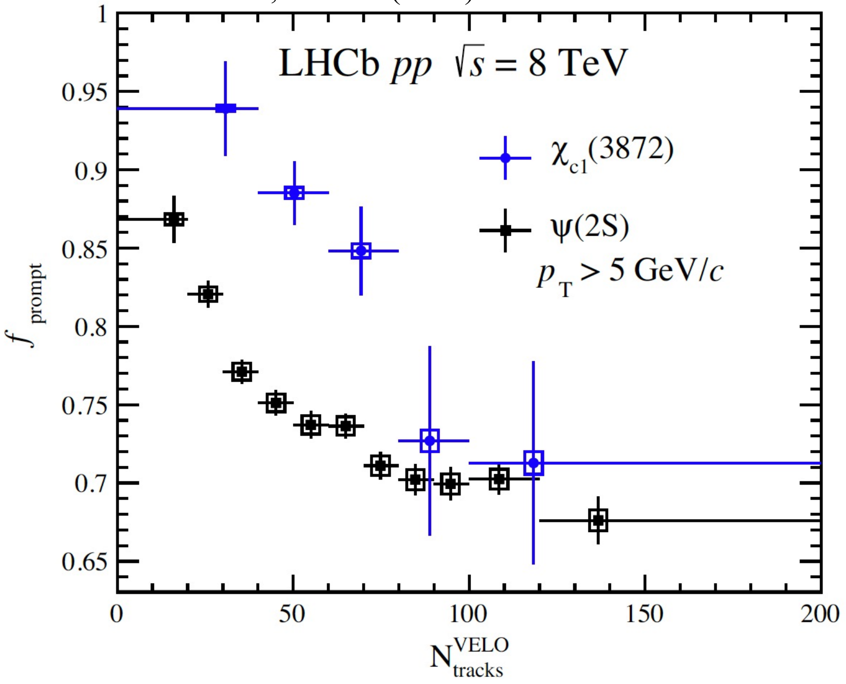
Room for additional effects at low p_T

PRL 126 092001 (2021)



Prompt and non-prompt vs multiplicity

PRL 126, 092001 (2021)



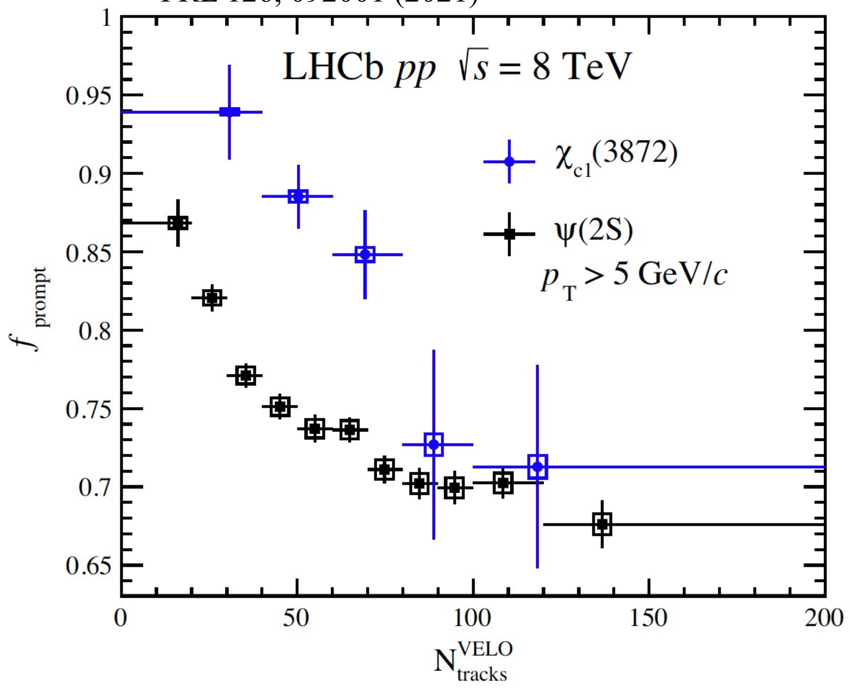
$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$

- Significant modification of both $\boldsymbol{X(3872)}$ and $\boldsymbol{\psi(2S)}$ production as event activity increases:

- The $\boldsymbol{b}$ decay component, which is produced in vacuum can serve as an unmodified reference sample.

Prompt and non-prompt vs multiplicity

PRL 126, 092001 (2021)



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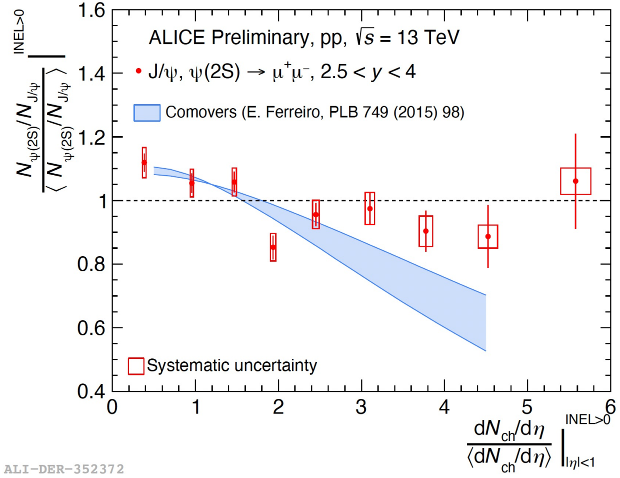
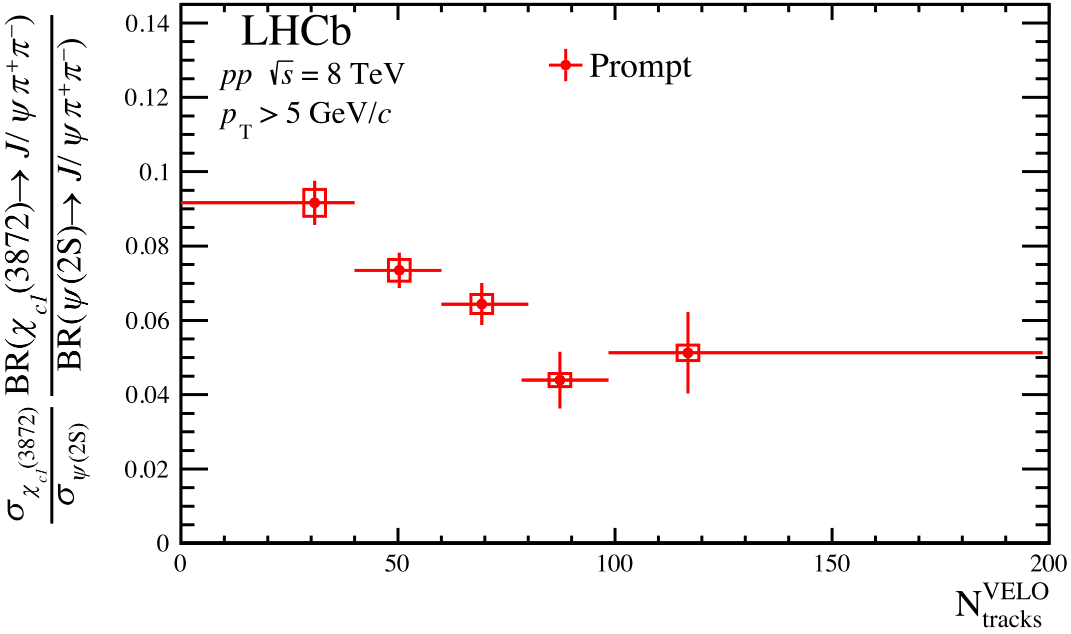


A different way of looking at $\boldsymbol{\psi(2S)}$ modification in pp

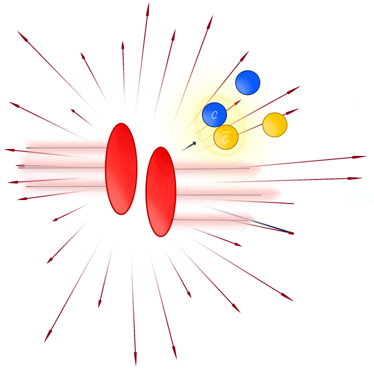
X(3872)/ψ(2S) vs multiplicity

PRL 126, 092001 (2021)

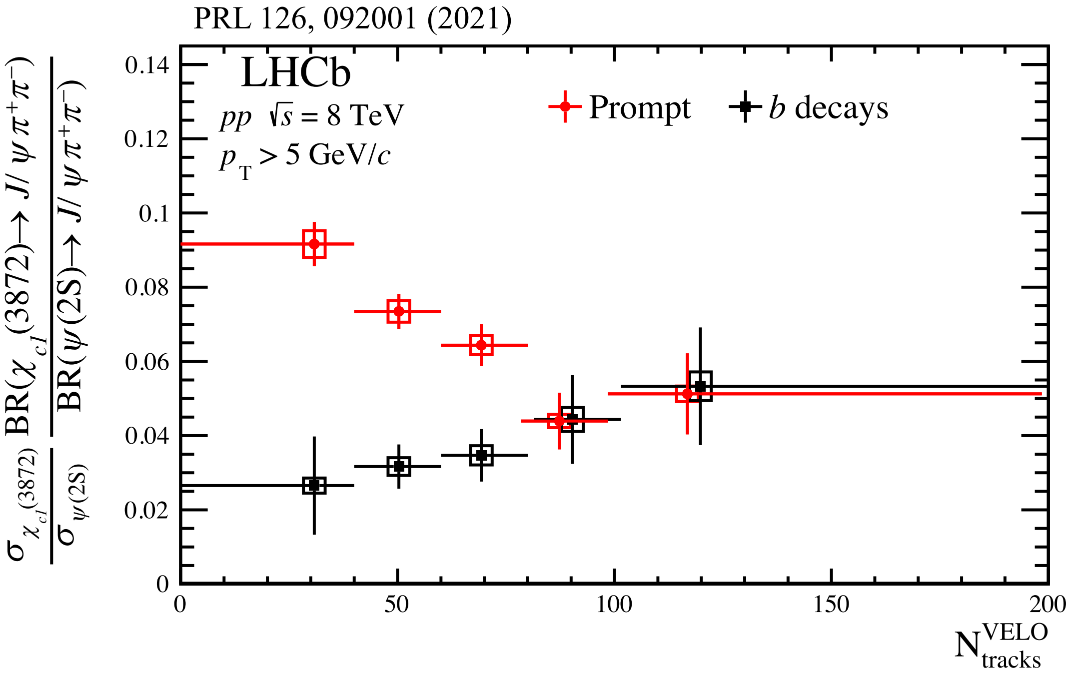


Prompt component:

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



X(3872)/ψ(2S)



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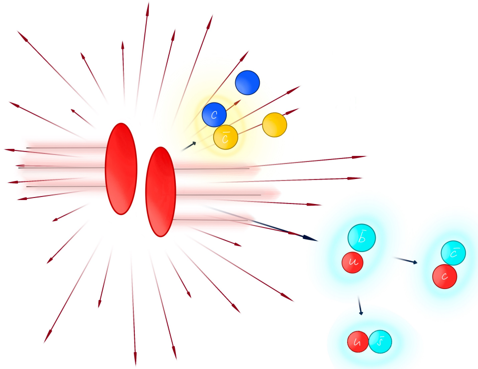
Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.



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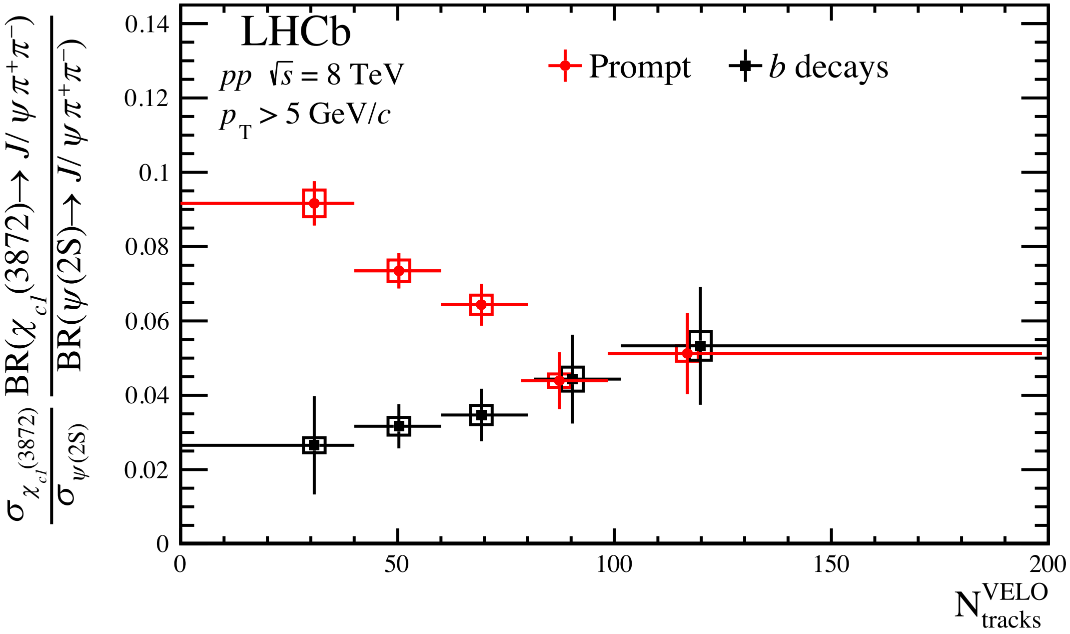
PRL 126, 092001 (2021)



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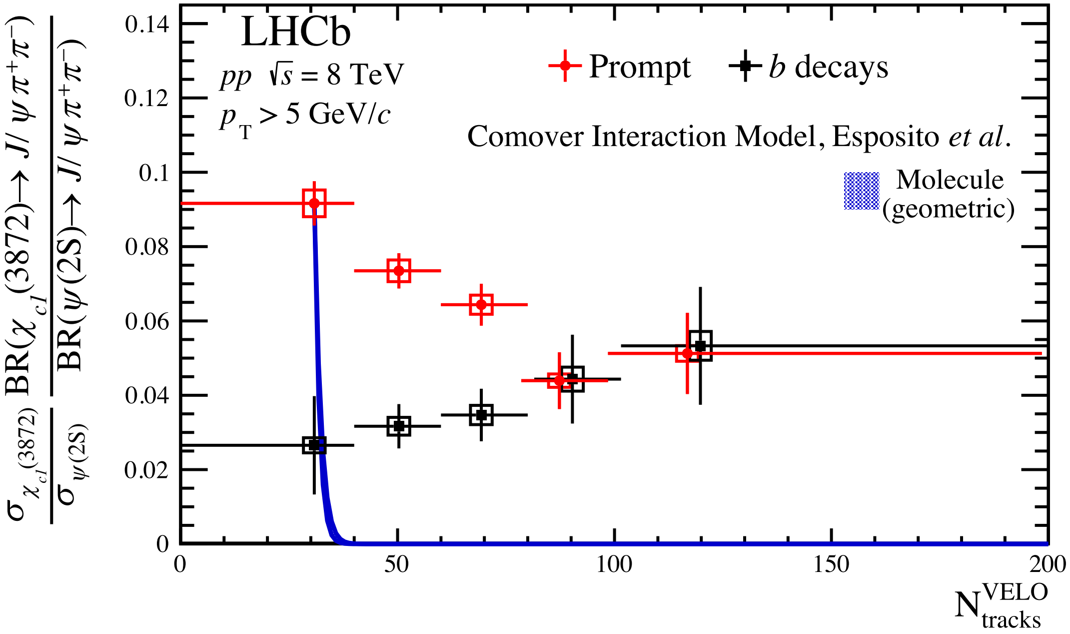
Various *B* mesons may have different branching fractions to X(3872):
JHEP 01 (2017) 117, PRL 125 152001 (2020)

Does *b* hadron chemistry vary with multiplicity?
New LHCb results expected soon.

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



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Calculations from EPJ C 81, 669 (2021)

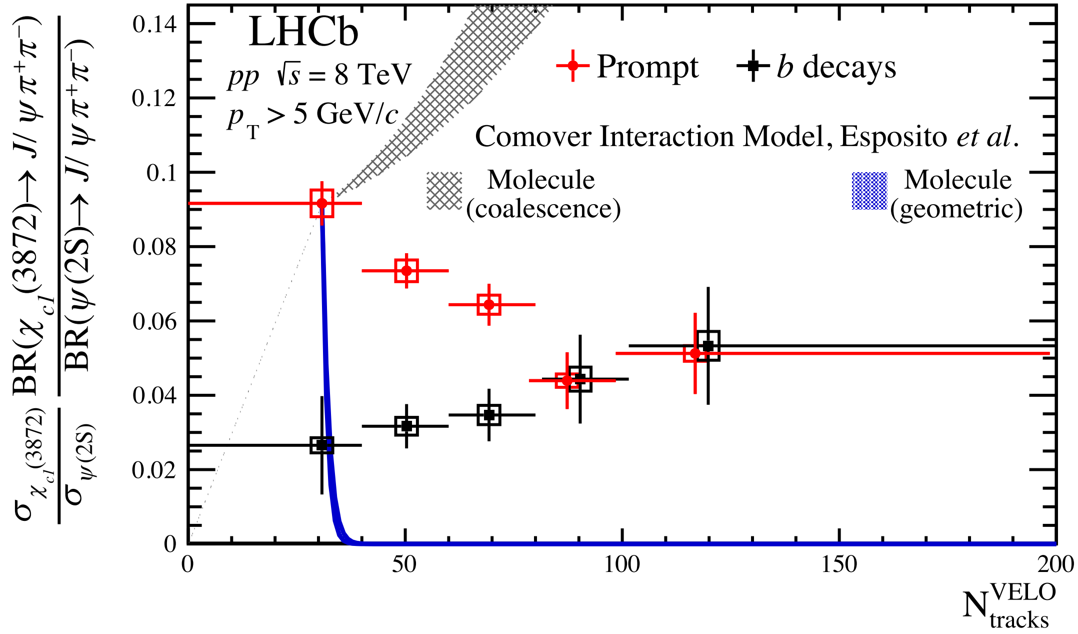
Break-up cross section:

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

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

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



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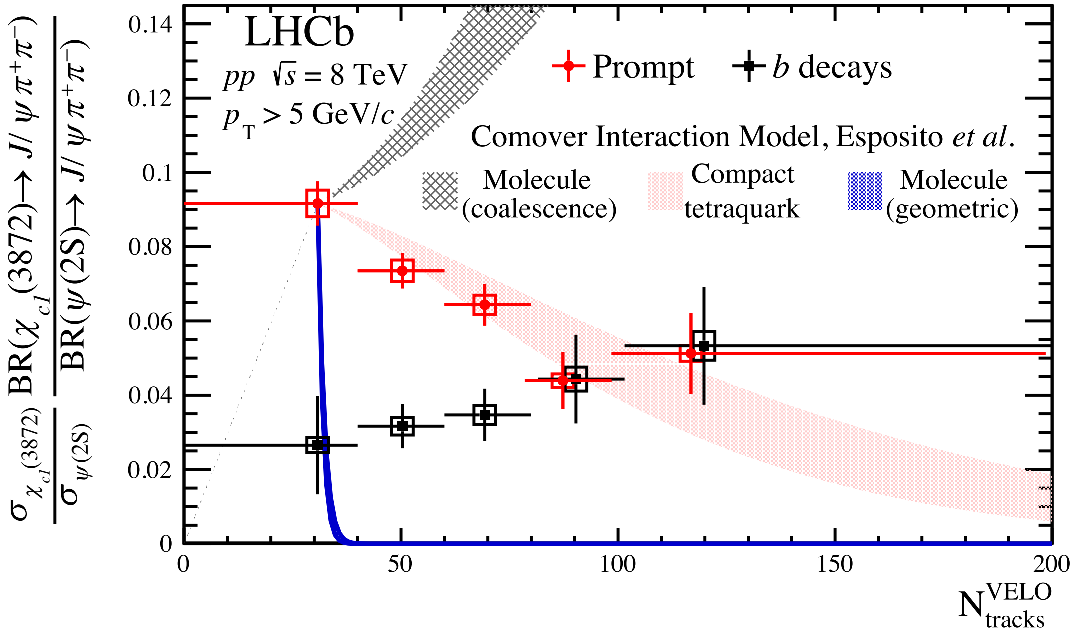

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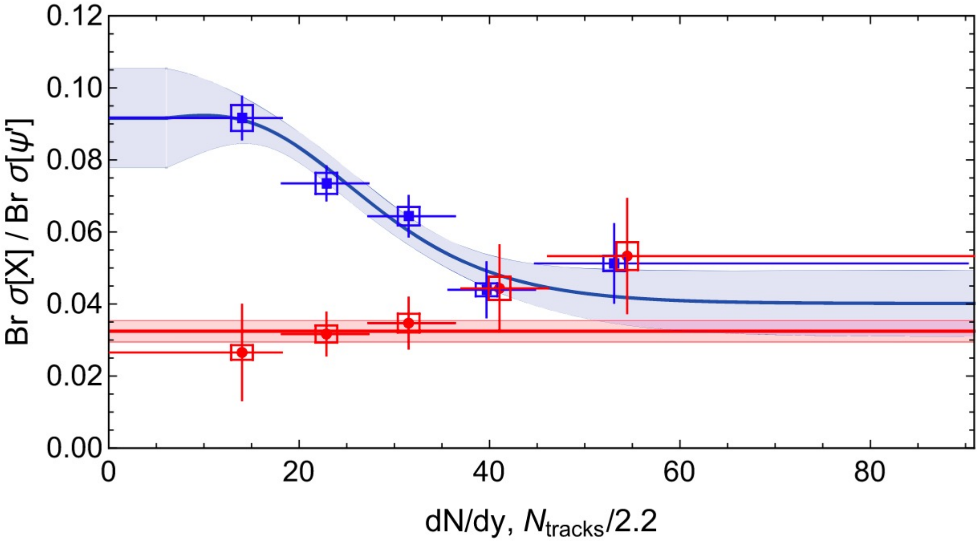
Coalescence of D mesons into molecular X(3872) increases ratio

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

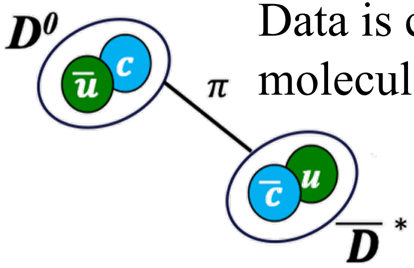
Comover model: constituent interaction

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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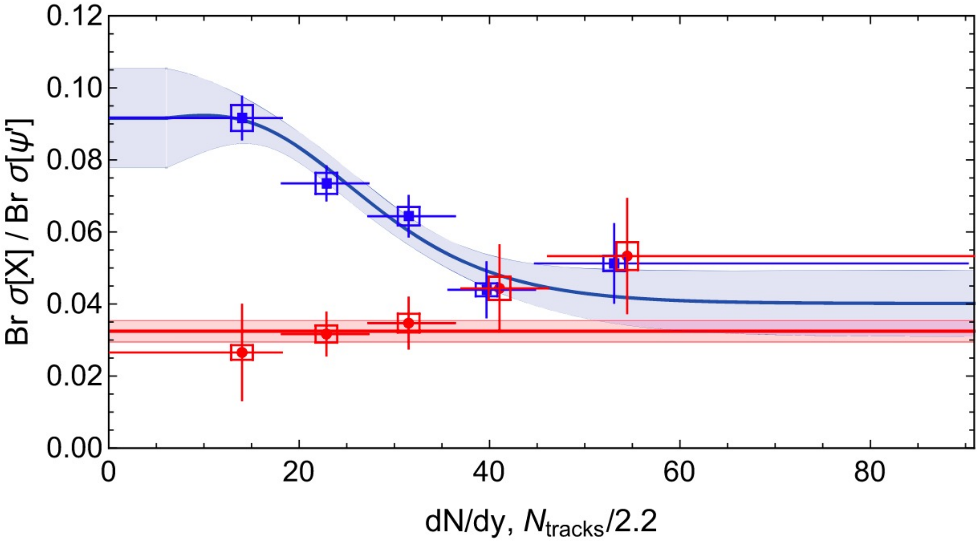

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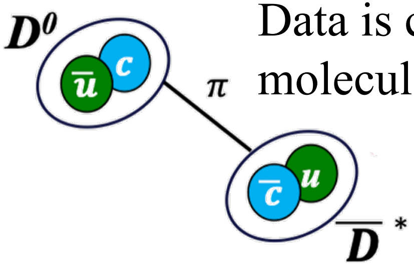
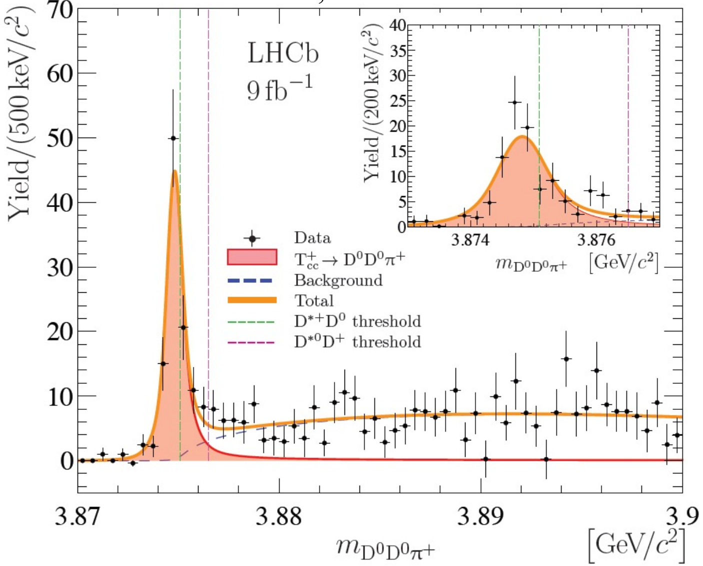


Data is consistent with this molecular interpretation.

If breakup is due to scattering of individual constituents, would all $c\bar{c}$ have equal suppression?
Not observed in charmonium or bottomonium systems.

Newest LHCb 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 $D^{*+}D^0$ threshold

$$\delta m_{\rm BW} = -273 \pm 61 \pm 5\,^{+11}_{-14}\,{\rm keV}/c^2$$

Big difference: contains cc or $\bar{c}\bar{c}$, rather than $c\bar{c}$

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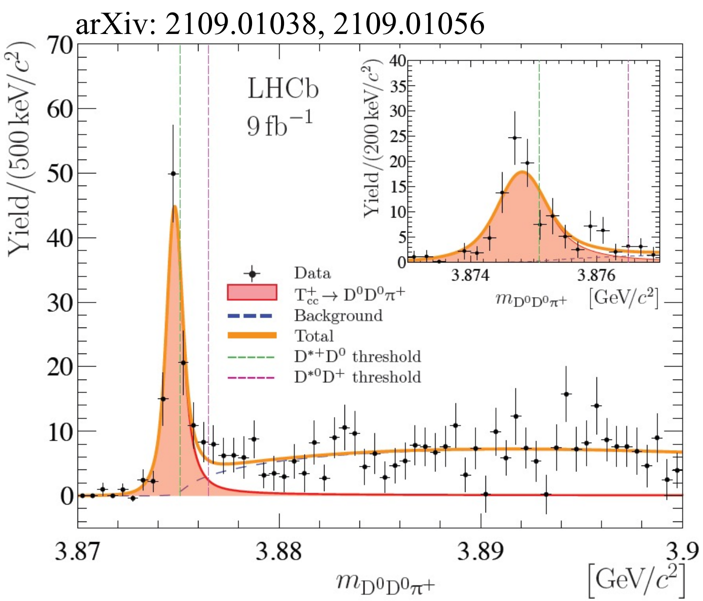

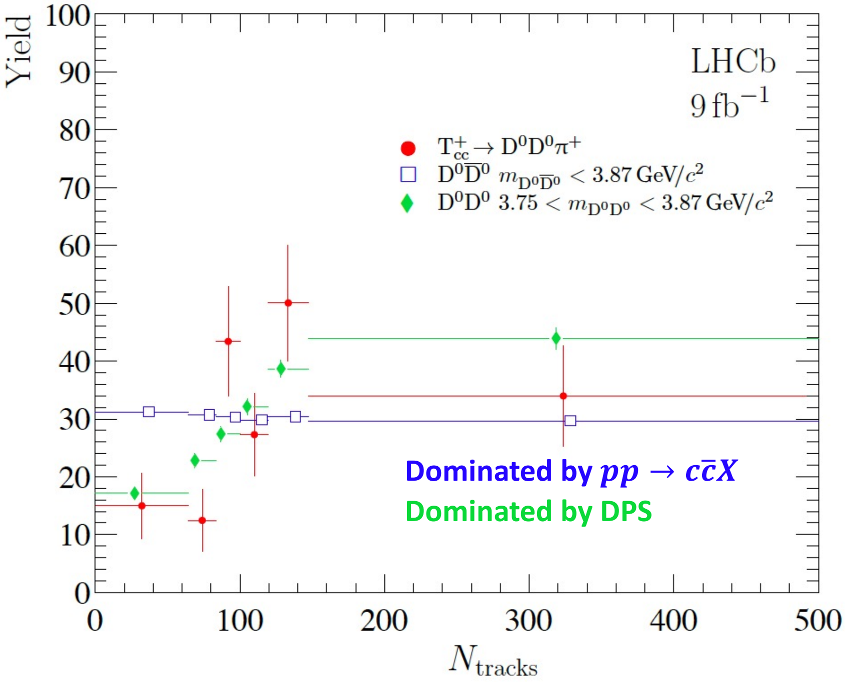

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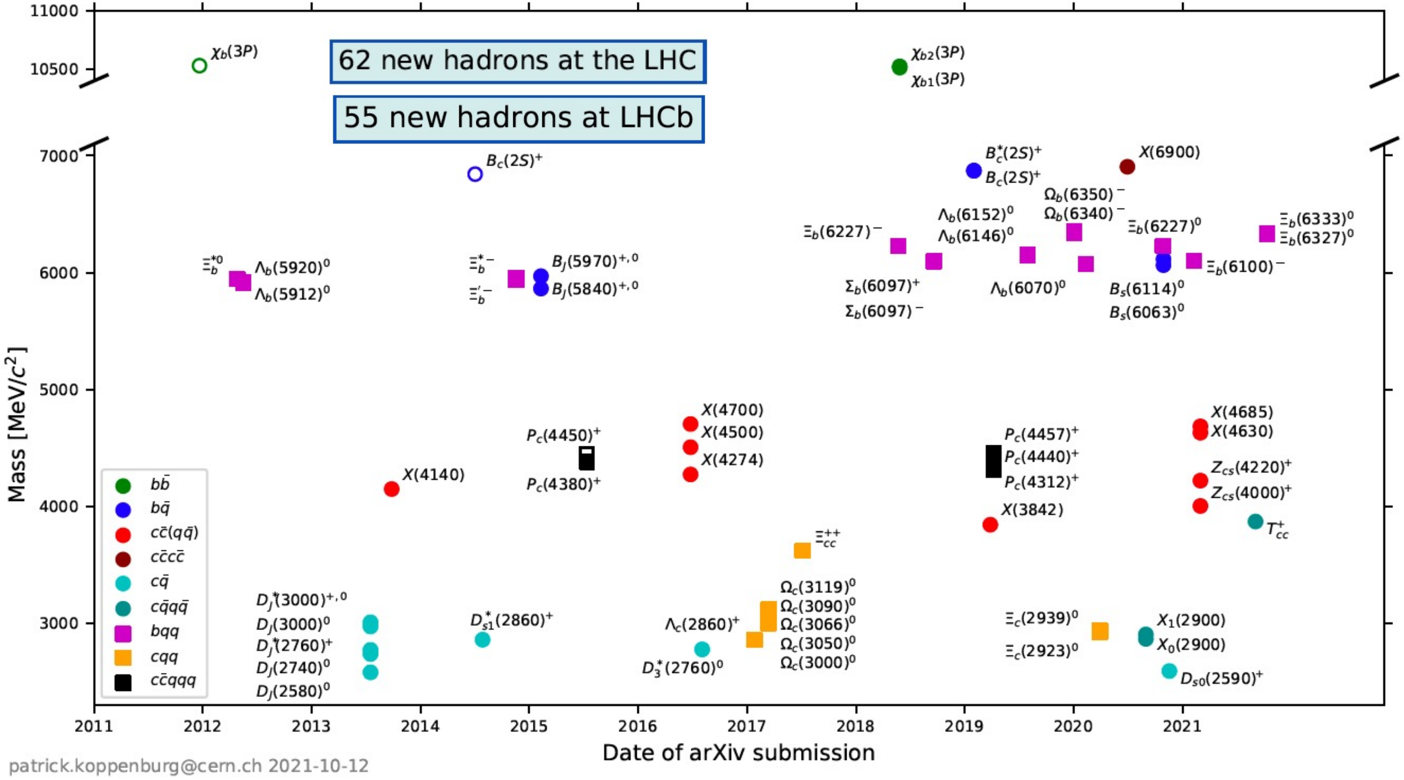
Yield favors higher multiplicity collisions, reminiscent of deuteron, and multiplicity dist is similar to D^0D^0. Evidence for hadronic molecule structure?

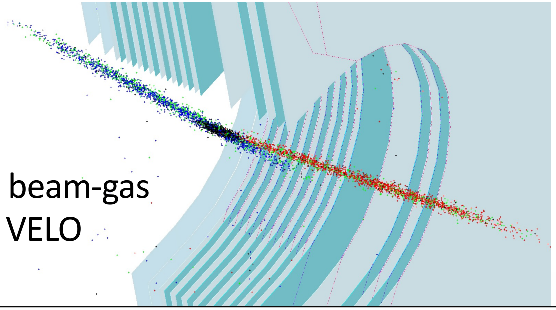
New Particles at the LHC



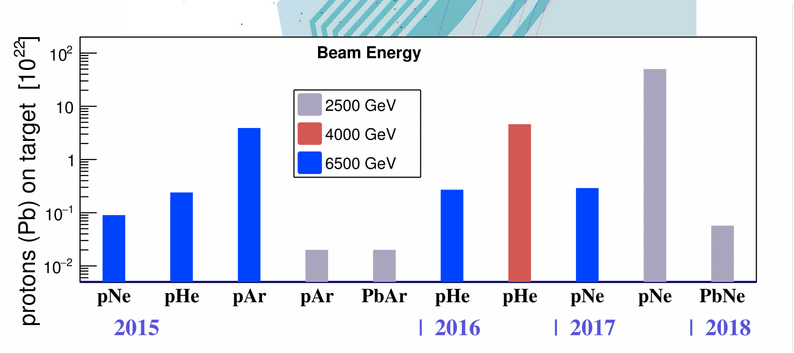
https://www.nikhef.nl/~pkoppenb/particles.html

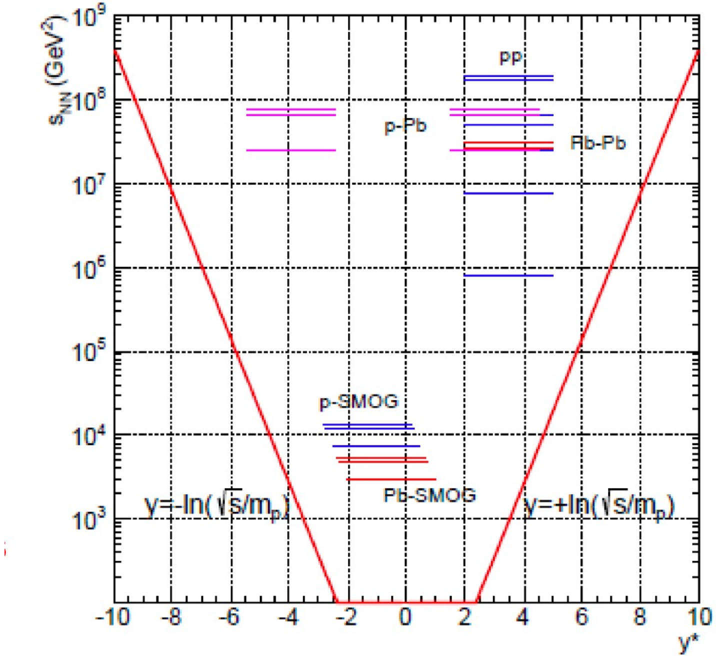
Fixed target configuration - SMOG

System for **M**easurement of **O**verlap with **G**as
A unique capability at LHCb: inject noble gas into beampipe
Originally intended for precise luminosity measurements:
Precision on 2012 pp data is ±1.16%, best ever at bunched beam collider
JINST **9** P12005 (2014)



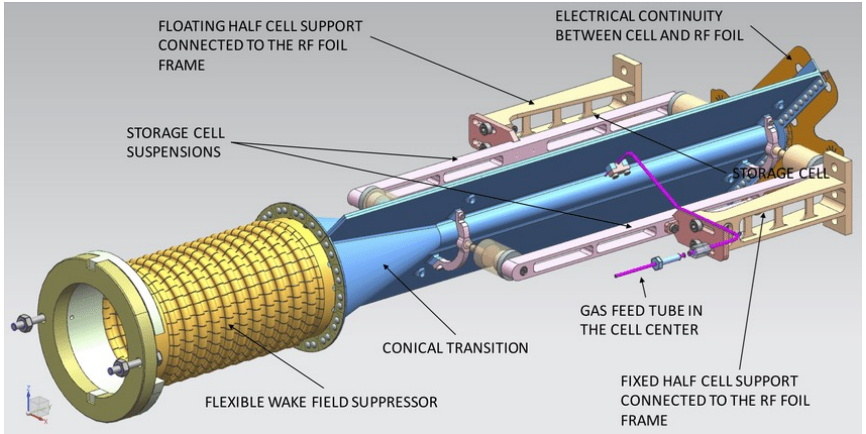
Reconstructed beam-gas vertices inside VELO





Measurements so far:
Charm production in p+He and p+Ar: PRL 122 132002 (2019)
Antiproton production in p+He: PRL 121 222001 (2018)

Near future: SMOG II at LHCb



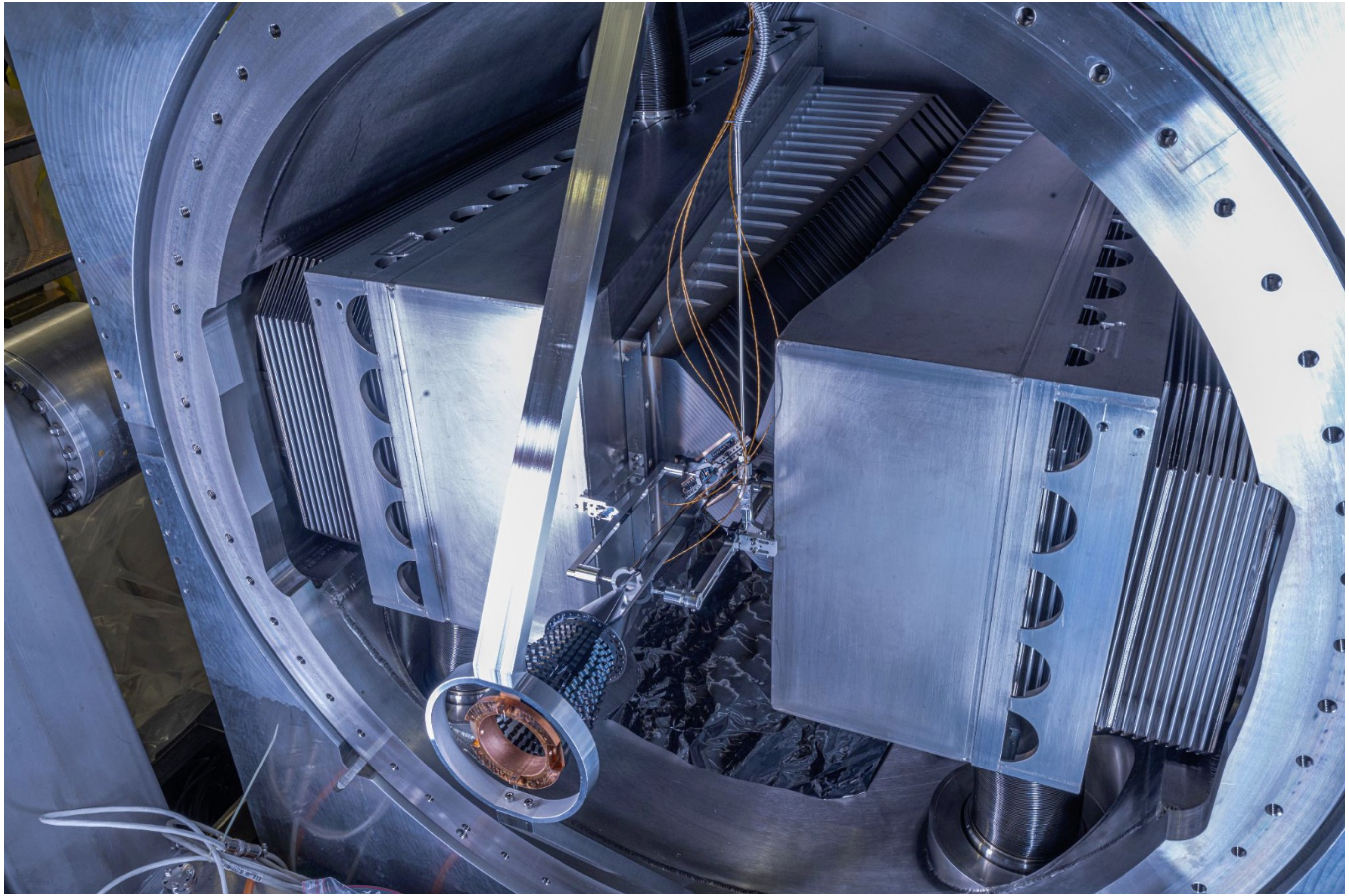
https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

Example SMOG2 pAr at 115 GeV for one year

Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

- Upgraded SMOG 2 system at LHCb allows greatly increased rates of beam+gas collisions at LHCb
- Variable target gases – allows hadronic environment to be adjusted (H, He, …, Xe)
- Access to exotic states near RHIC energies
- Can potentially run concurrent with proton+proton collisions – large data sets

SMOG II installed at LHCb



Summary

- Over the years at fixed target experiments and colliders, we have developed tools to use quarks to probe the nuclear medium.

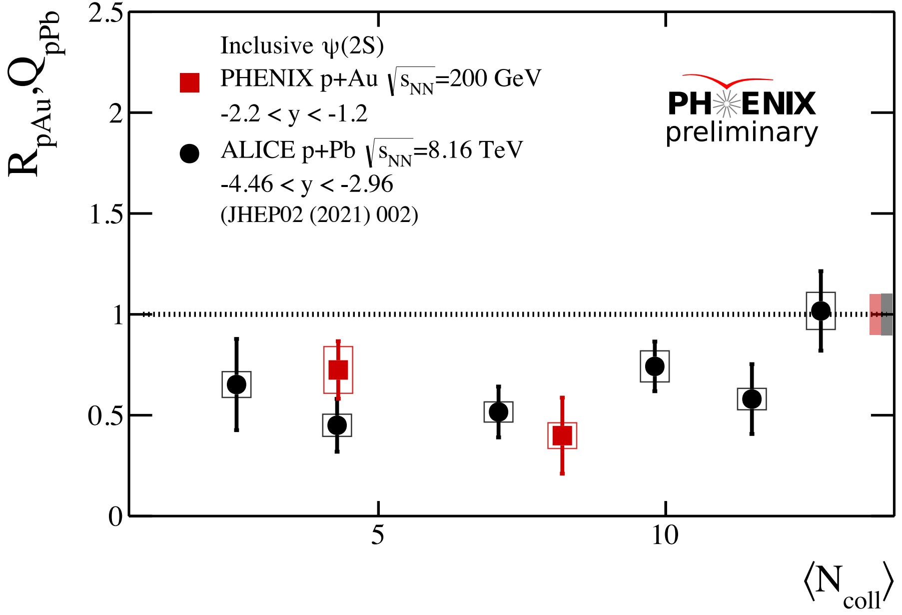
- We can in turn use what we have learned about the nuclear medium to probe newly discovered, poorly understood hadrons.

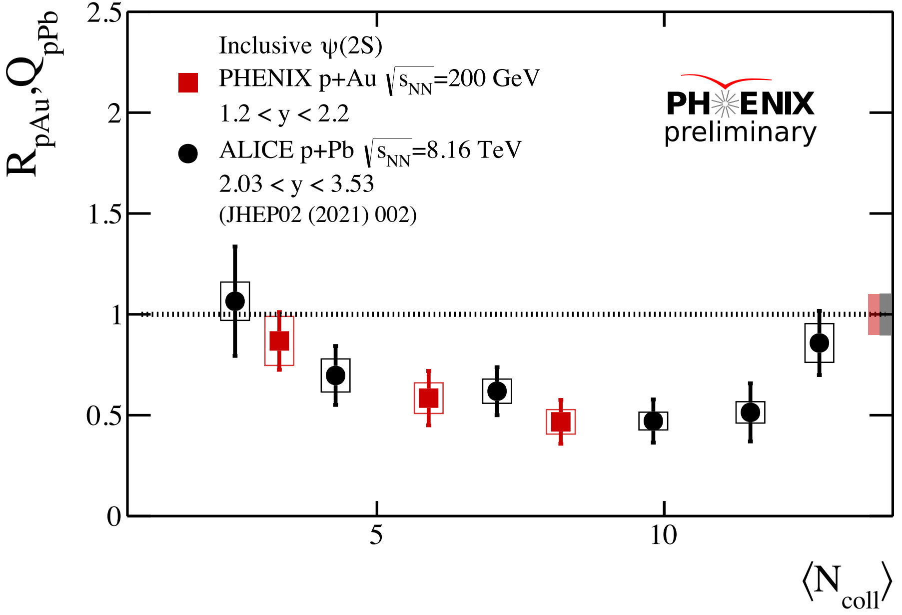
- With the large number of exotic states and future data sets and upgrades, many more discoveries await us.

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

BACKUPS

ALICE and PHENIX RpA





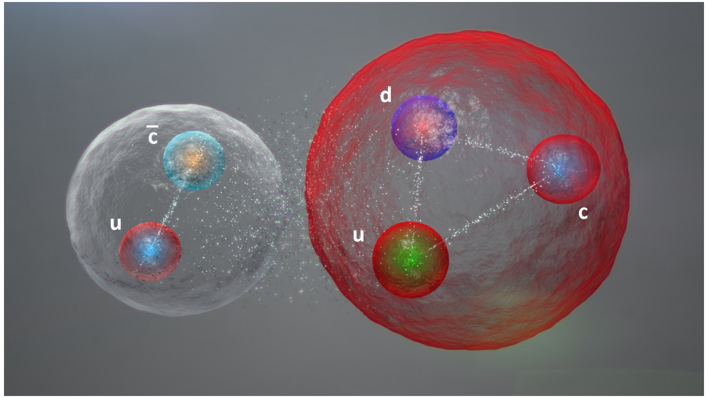
Example: $P_c^{\pm}$ pentaquarks

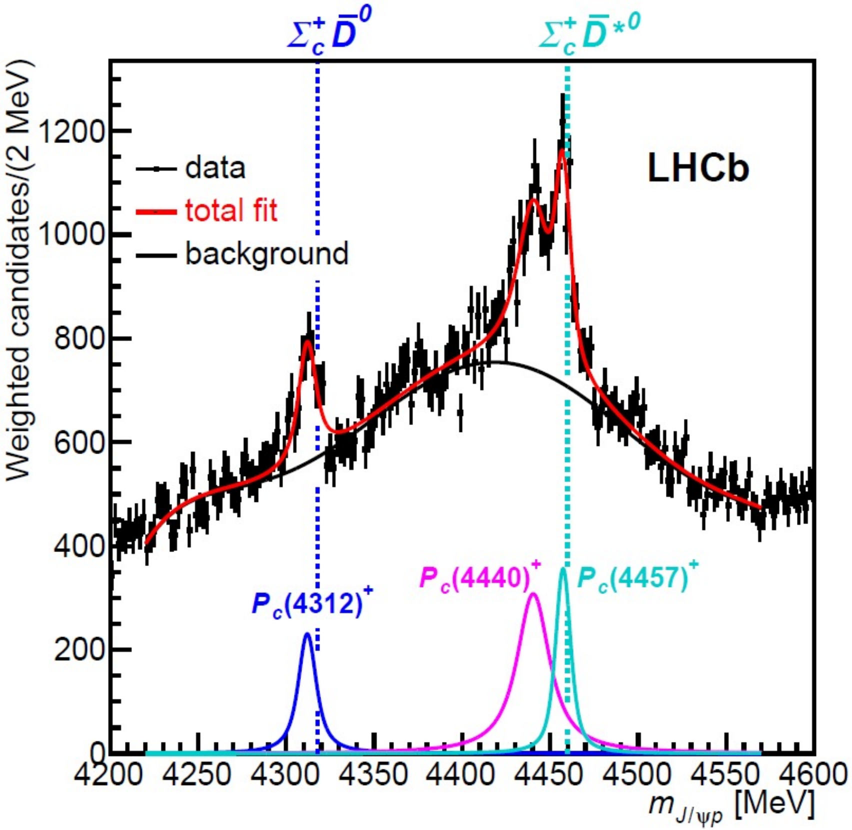
PRL 122 222001 (2019)

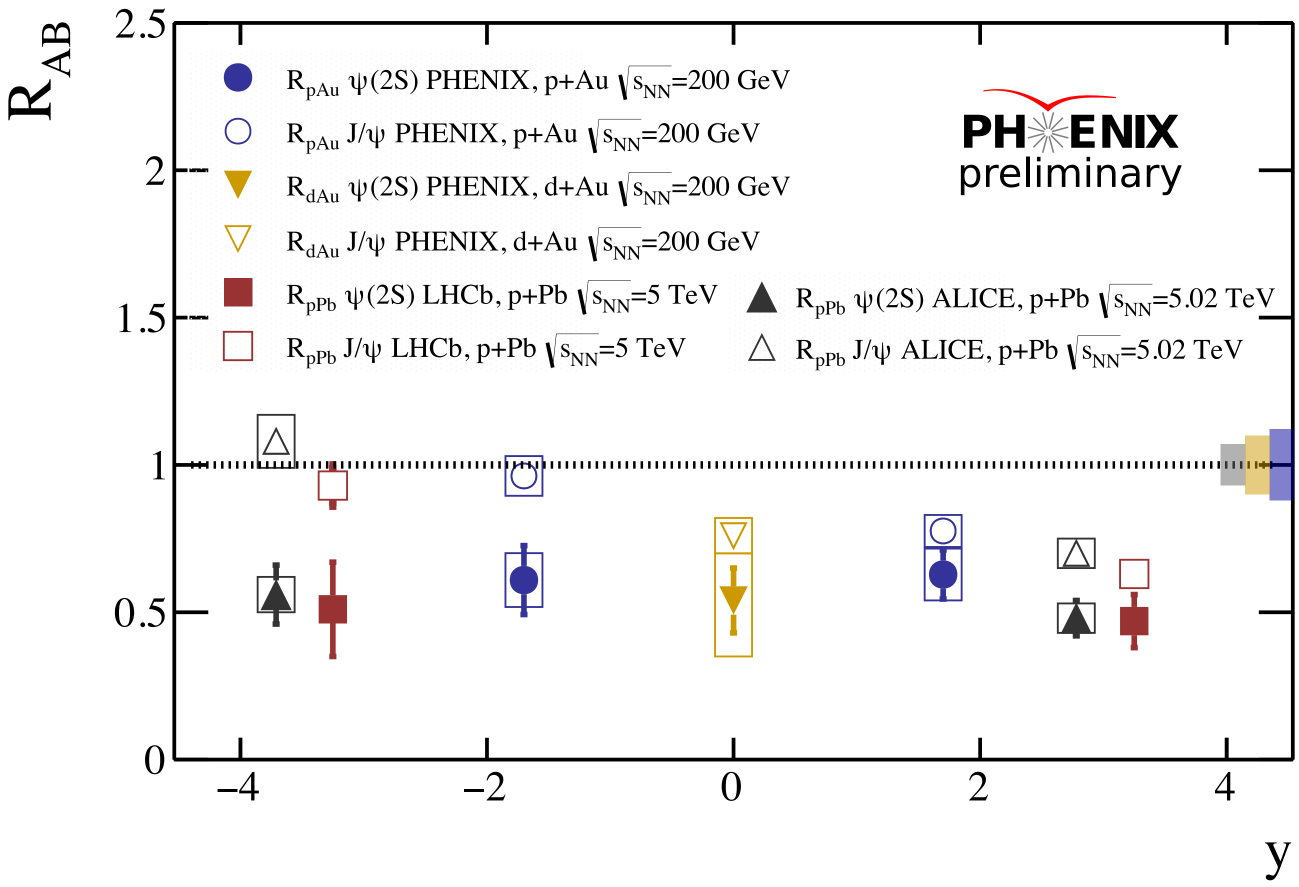
Select daughters from the decay

$$\Lambda_b^0 \to J/\psi\, p K^-$$

Masses are close to meson+baryon thresholds – candidate hadronic molecule






R_{AB}
R_{pAu} ψ(2S) PHENIX, p+Au $\sqrt{s_{NN}}$=200 GeV
R_{pAu} J/ψ PHENIX, p+Au $\sqrt{s_{NN}}$=200 GeV
R_{dAu} ψ(2S) PHENIX, d+Au $\sqrt{s_{NN}}$=200 GeV
R_{dAu} J/ψ PHENIX, d+Au $\sqrt{s_{NN}}$=200 GeV
R_{pPb} ψ(2S) LHCb, p+Pb $\sqrt{s_{NN}}$=5 TeV
R_{pPb} J/ψ LHCb, p+Pb $\sqrt{s_{NN}}$=5 TeV
R_{pPb} ψ(2S) ALICE, p+Pb $\sqrt{s_{NN}}$=5.02 TeV
R_{pPb} J/ψ ALICE, p+Pb $\sqrt{s_{NN}}$=5.02 TeV
PHENIX preliminary
2.5
2
1.5
1
0.5
0
−4
−2
0
2
4
y

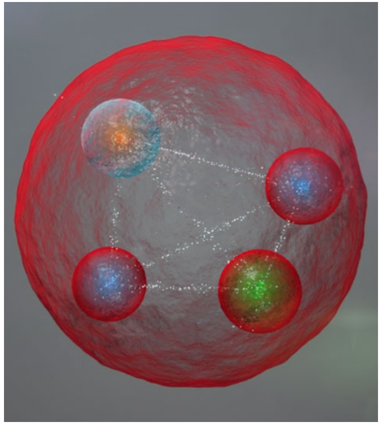
Example: Charged Tetraquark: $Z_c^{\pm}$

Select daughters from the decay

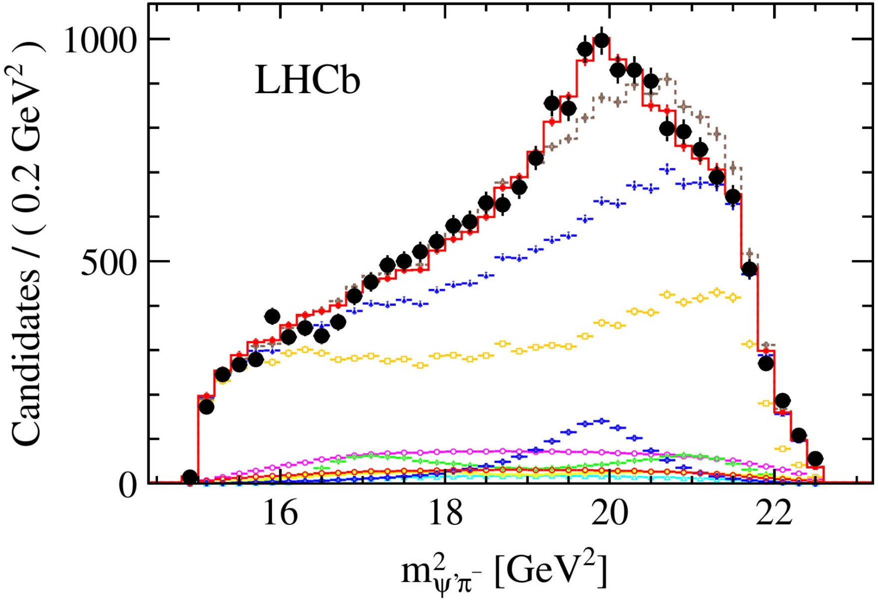
$$B^0 \to \psi(2S) K^+ \pi^-$$

Charged and contains $c\bar{c}$ pair: minimal quark content $c\bar{c}q\bar{q}$

Mass not close to hadron+hadron threshold – candidate compact tetraquark

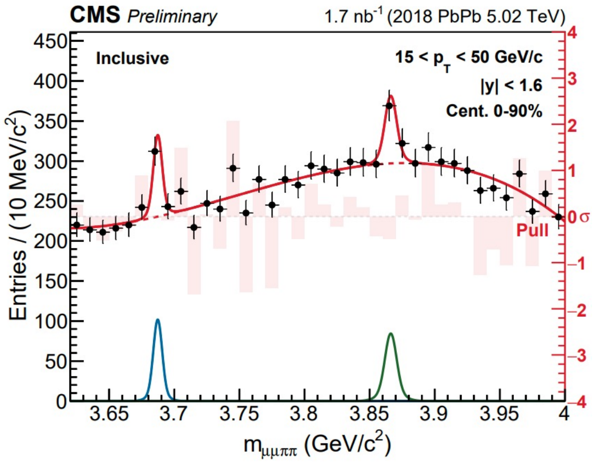


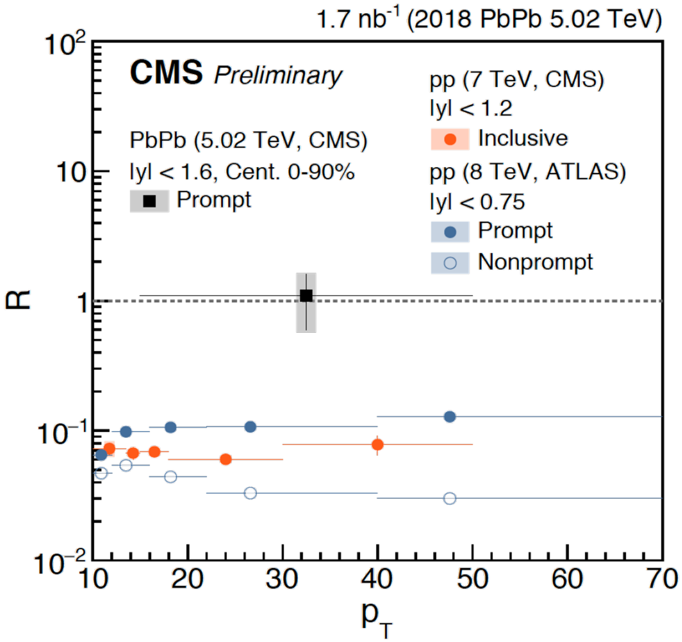
PRL 112 222002 (2014)



Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





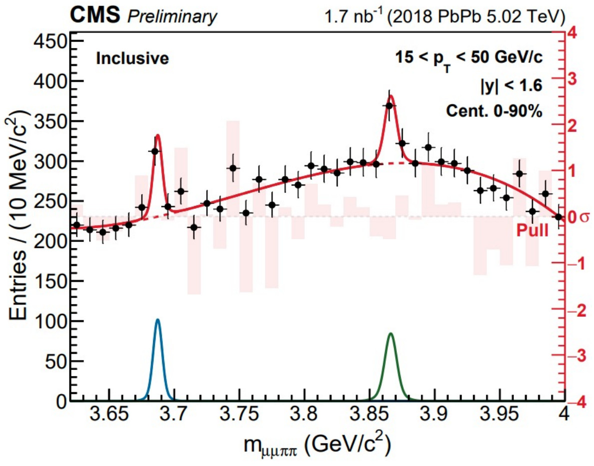
Recombination of X(3872) at pT > 15 GeV?

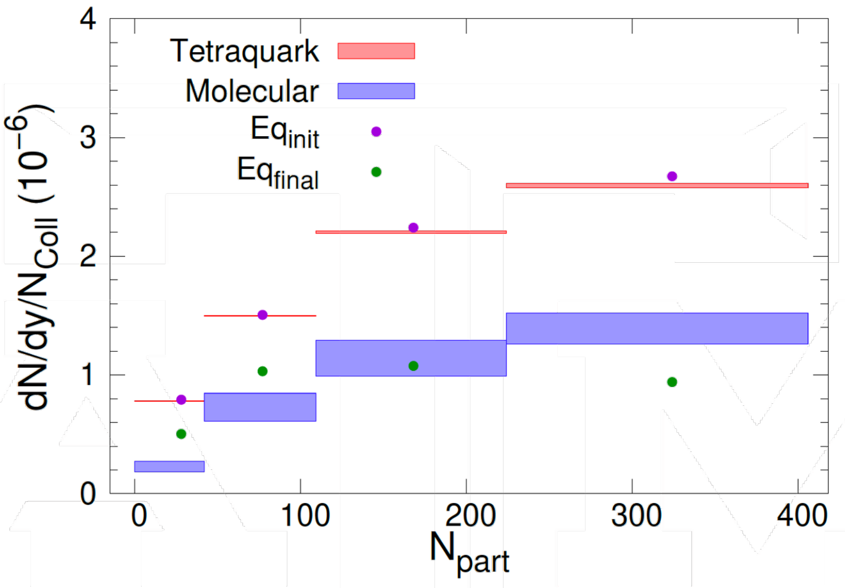
Prompt X(3872)/ $\psi(2S) = 1.10 \pm 0.51 \pm 0.53$ in PbPb at 5 TeV

Prompt X(3872)/ $\psi(2S) \approx 0.1$ in pp at 8 TeV

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





Transport model gives larger yield for compact tetraquark vs. molecule by factor of ~2 in PbPb

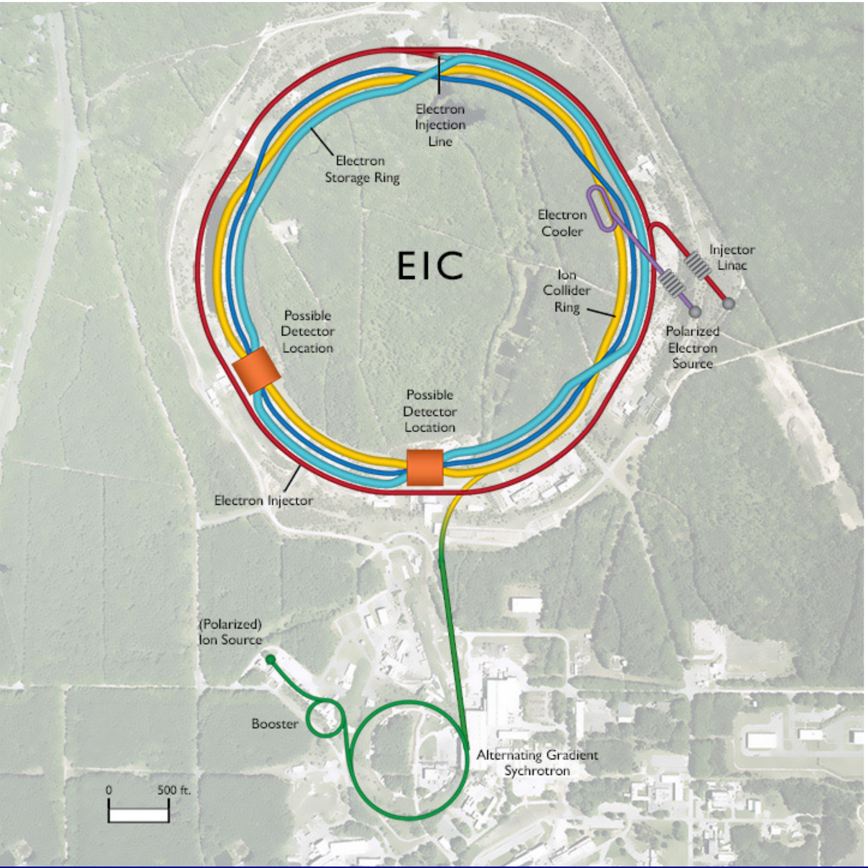
Will be tested with future PbPb data sets.

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

Intriguing data! Inconclusive with these uncertainties.

Future facility: Electron-Ion Collider



EIC site selection at BNL announced Jan 2020, CD-1 July 2021, operational ~2030

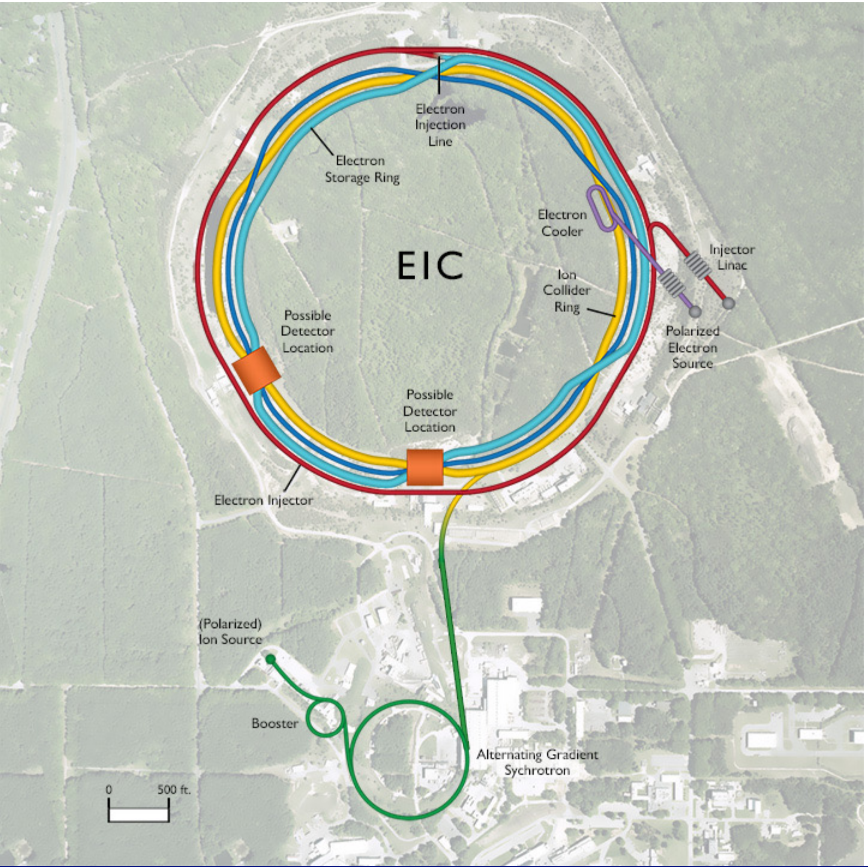
$$\sqrt{s} \sim 20 - 100\ GeV$$

e+*p*, *e*+O, *e*+Al, *e*+Cu, *e*+Au, *e*+U,…

Charm production inside the nucleus probes:

- Parton structure of nucleons
- Parton distribution function modifications
- QCD energy loss

Future facility: Electron-Ion Collider



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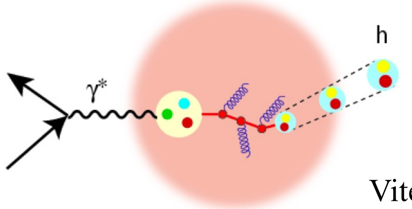
$$\sqrt{s} \sim 20 - 100\ GeV$$

*e+p, e+*O, *e+*Al, *e+*Cu, *e+*Au, *e+*U,…

Charm production inside the nucleus probes:

- Parton structure of nucleons
- Parton distribution function modifications
- QCD energy loss

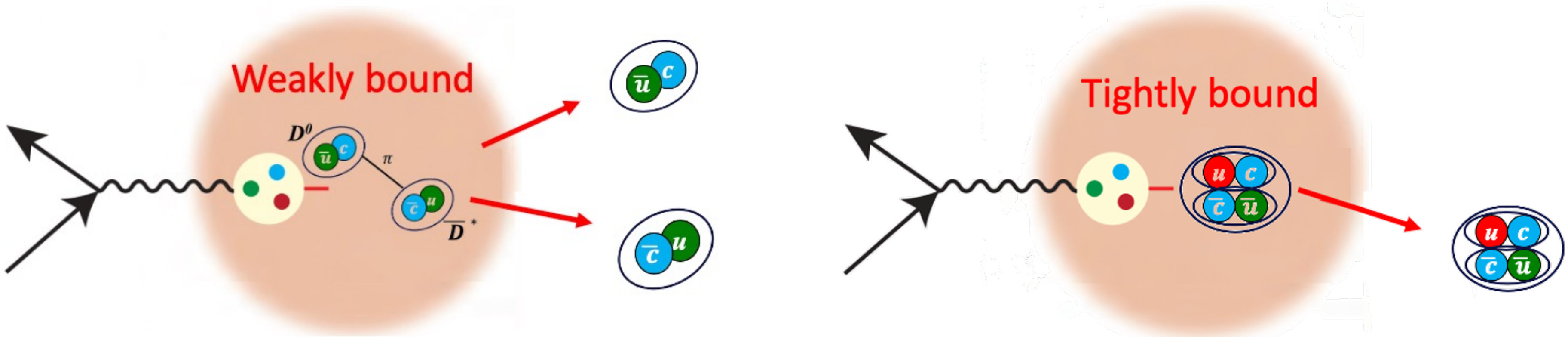
Hadronization inside the nucleus becomes important



Vitev, 1912.10965

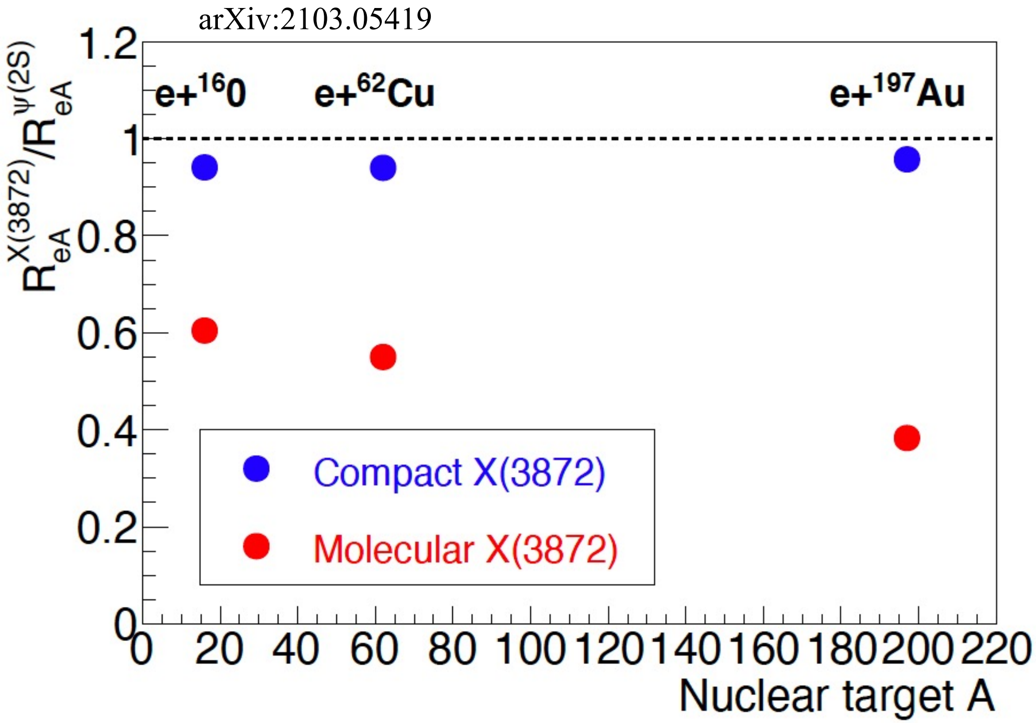
Filtering States with the Nucleus

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



- 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
- Test idea via MC simulation of propagation through nucleus for 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

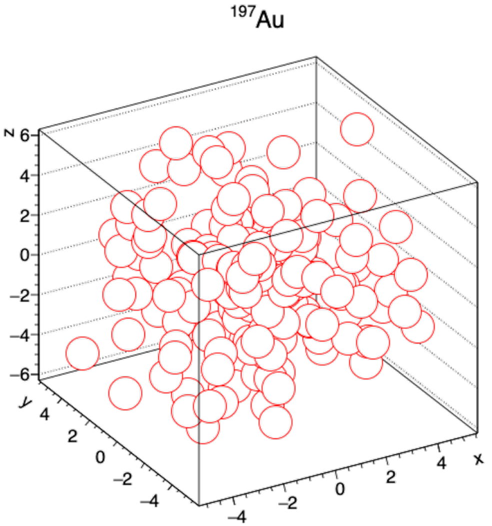


$$\frac{R_{eA}^{X(3872)}}{R_{eA}^{\psi(2S)}} = \frac{\sigma_{eA}^{X}}{\sigma_{eA}^{\psi}} \Big/ \frac{\sigma_{ep}^{X}}{\sigma_{ep}^{\psi}}$$

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

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

X(3872) is only an example, model equally applicable for other exotics accessible at EIC



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: $\sigma_{(c\bar{c})_1 N} = \sigma_{\psi N}(s) \cdot (r_{c\bar{c}} / r_{\psi})^2$

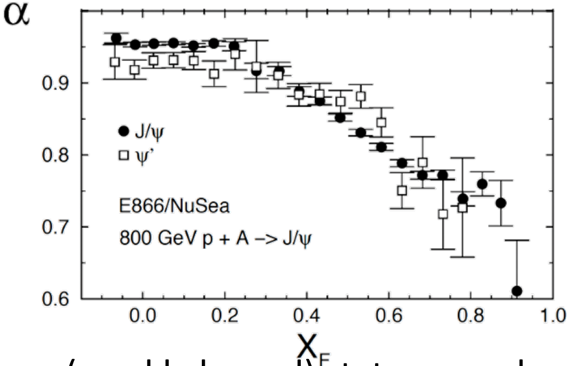
- If the state comes within a distance of $\sqrt{\sigma_{c\bar{c}}/\pi}$ to a nucleon, consider it disrupted.

- Three cases: $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm

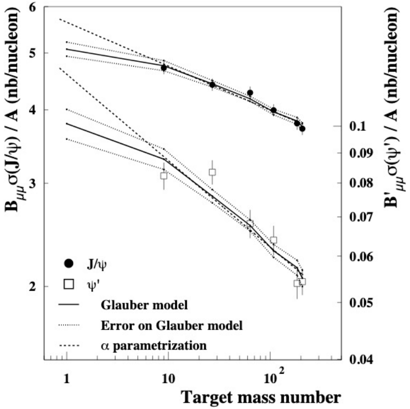
Filtering States with the Nucleus

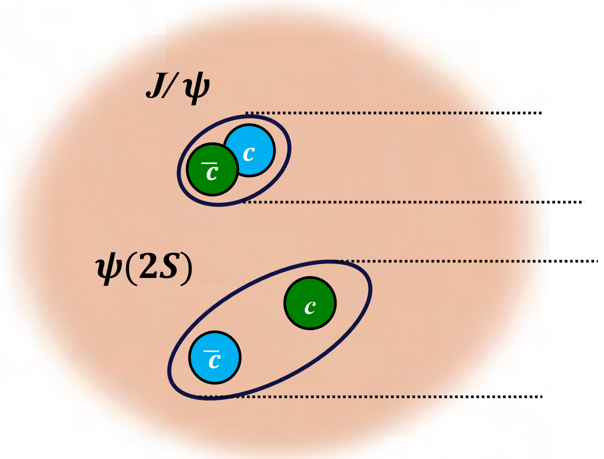
- At the EIC, hadronization inside the nucleus becomes an important effect (Vitev, 1912.10965)
- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair

E866, PRL 84 (2000) 3256-3260



NA50, EPJC 48 329 (2006)





- Larger (weakly bound) states sample a larg[illegible]hile 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)

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

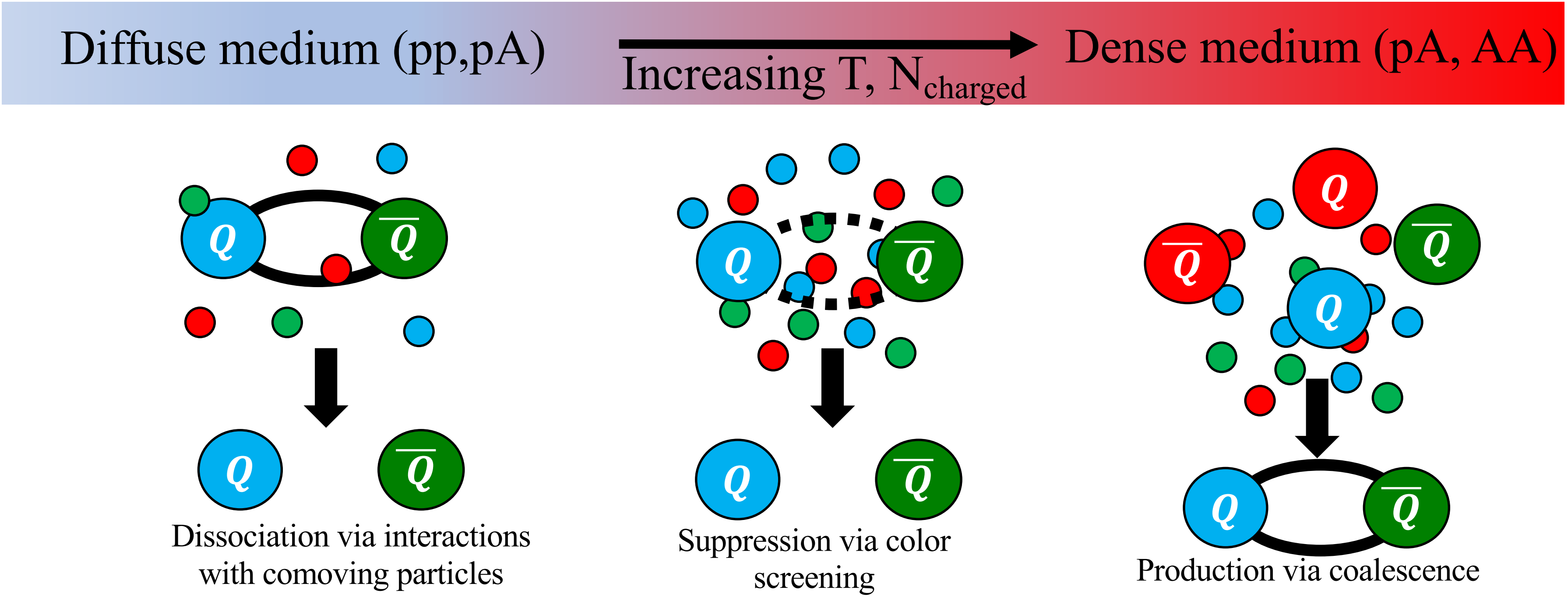
Table 1: Charmonium states and binding energies

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

Quarkonia in the QCD medium



Experimentally, we use different collision systems/kinematic regions to prepare environments where different non-perturbative effects dominate.

Separate prompt/non-prompt production

Simultaneous fit to mass and proper time in each multiplicity bin