



X(3872) production in small systems

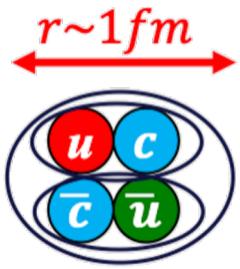
Matt Durham
durham@lanl.gov

LHC Physics conference
7 June 2021

X(3872) – an enduring puzzle

AKA $\chi_{c1}(3872)$

- The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle, PRL 91 262001 (2003)
 - A new charmonium state? Eichten, Lane, Quigg PRD 69, 094019 (2004)
 - Charmonium hypothesis **disfavored** by measured mass and quantum numbers, LHCb PRL 110 222001 (2013)
 - Tetraquark state? Expected since Gell-Mann and Zweig proposed quark model but never conclusively observed.

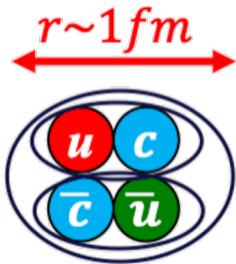


Tightly bound via color
exchange between diquarks
Small radius, ~1 fm

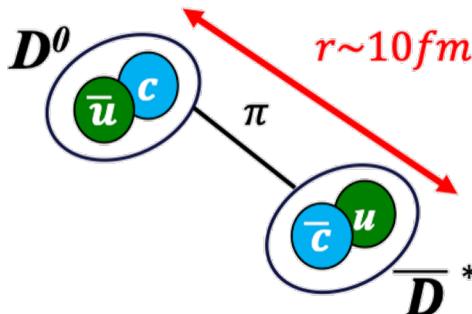
X(3872) – an enduring puzzle

AKA $\chi_{c1}(3872)$

- The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle, PRL 91 262001 (2003)
 - A new charmonium state? Eichten, Lane, Quigg PRD 69, 094019 (2004)
 - Charmonium hypothesis **disfavored** by measured mass and quantum numbers, LHCb PRL 110 222001 (2013)
 - Tetraquark state? Expected since Gell-Mann and Zweig proposed quark model but never conclusively observed.
- Mass is consistent with mass of $D^0 + \bar{D}^{*0}$: $(M_{D^0} + M_{\bar{D}^{*0}}) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12 \text{ MeV}/c^2$ LHCb JHEP 08(2020)123
 - Hadronic molecule?



Tightly bound via color exchange between diquarks
Small radius, $\sim 1 \text{ fm}$

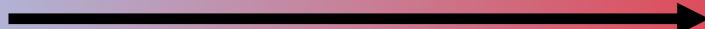


VERY small binding energy
VERY large radius, $\sim 10 \text{ fm}$

Hundreds of theory papers exploring various possibilities, no broad consensus

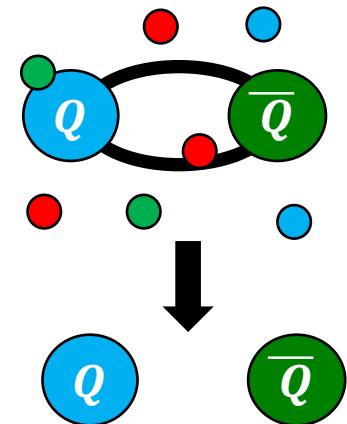
Heavy quark states in the QCD medium

Diffuse medium



Dense medium

Increasing T, N_{ch}



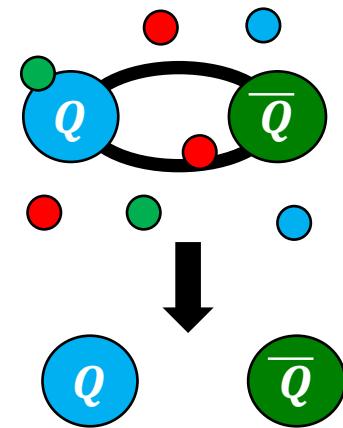
Dissociation via interactions
with comoving particles

Heavy quark states in the QCD medium

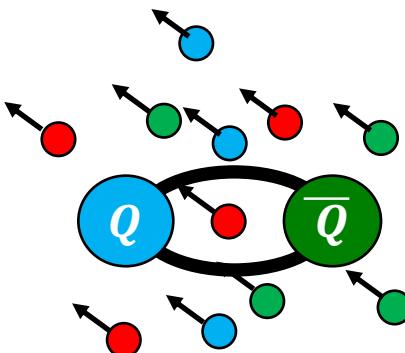
Diffuse medium

Increasing T, N_{ch}

Dense medium



Dissociation via interactions
with comoving particles



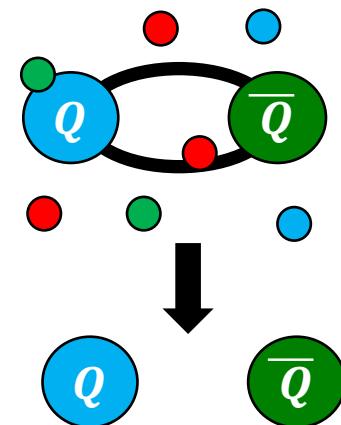
Hydrodynamic flow induced
by pressure gradients
(initial state?)

Heavy quark states in the QCD medium

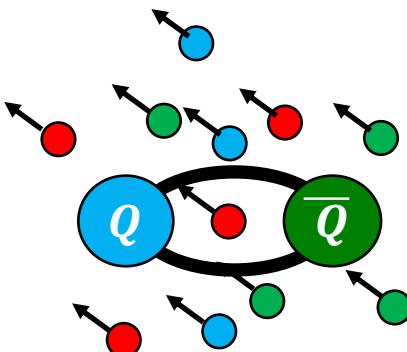
Diffuse medium

Increasing T, N_{ch}

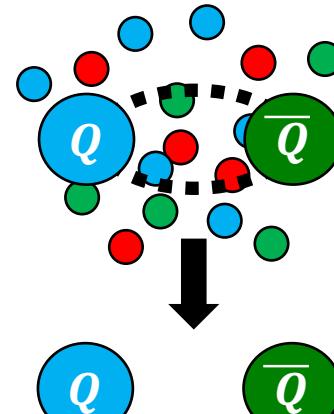
Dense medium



Dissociation via interactions
with comoving particles



Hydrodynamic flow induced
by pressure gradients
(initial state?)



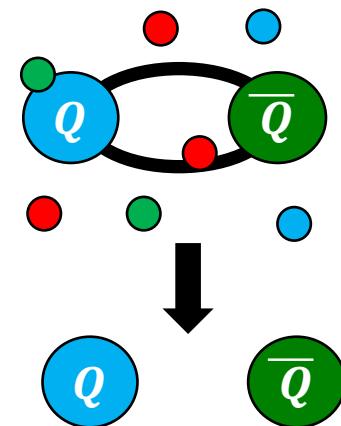
Suppression via color
screening

Heavy quark states in the QCD medium

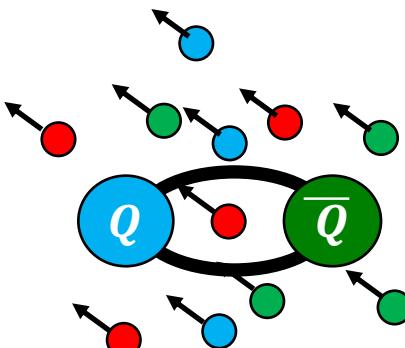
Diffuse medium

Increasing T, N_{ch}

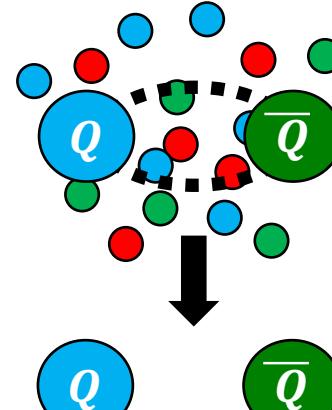
Dense medium



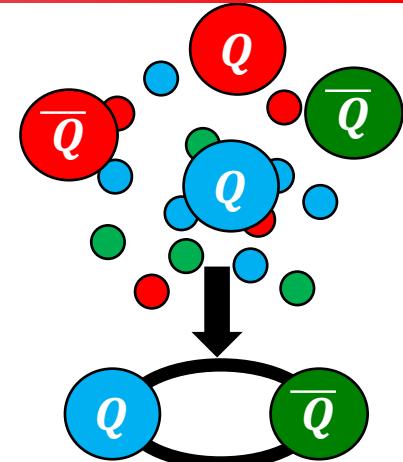
Dissociation via interactions
with comoving particles



Hydrodynamic flow induced
by pressure gradients
(initial state?)



Suppression via color
screening



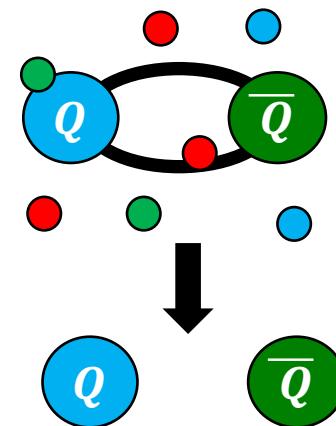
Production via coalescence

Heavy quark states in the QCD medium

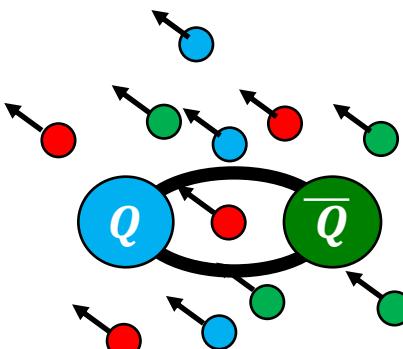
Diffuse medium

Increasing T, N_{ch}

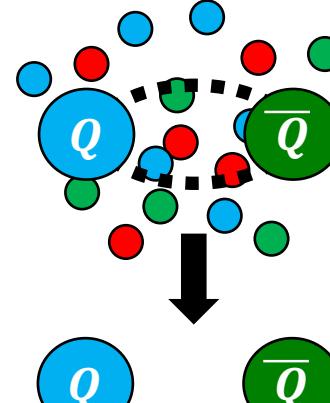
Dense medium



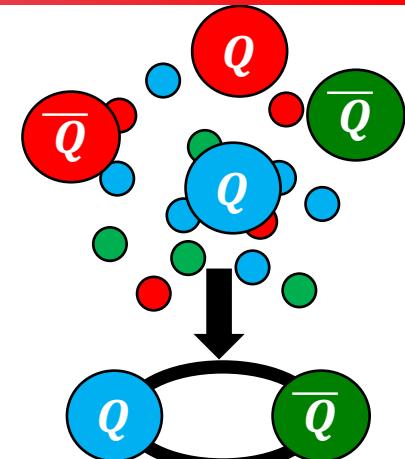
Dissociation via interactions
with comoving particles



Hydrodynamic flow induced
by pressure gradients
(initial state?)



Suppression via color
screening



Production via coalescence

We prepare these environments experimentally by varying beam species, energy, and kinematic regions measured.

LHCb data – 8 TeV pp

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

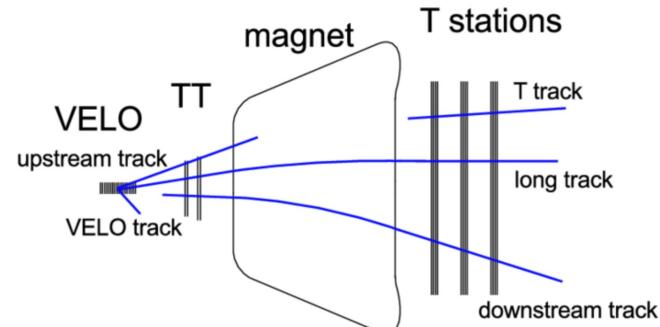
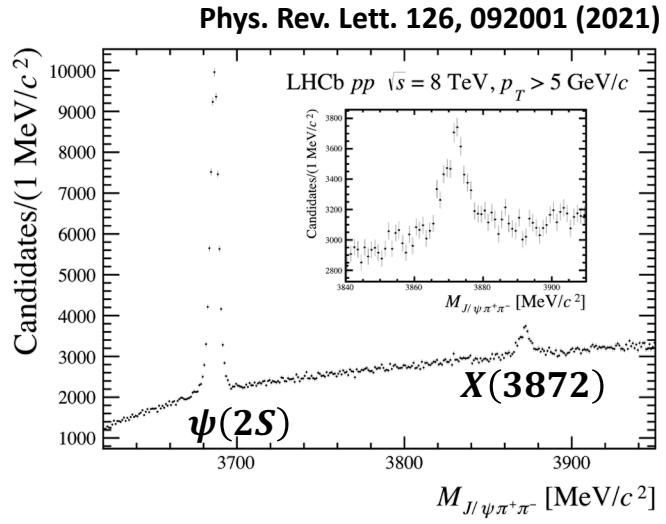
$$X(3872) \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \rho(\rightarrow \pi^+ \pi^-)$$

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

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

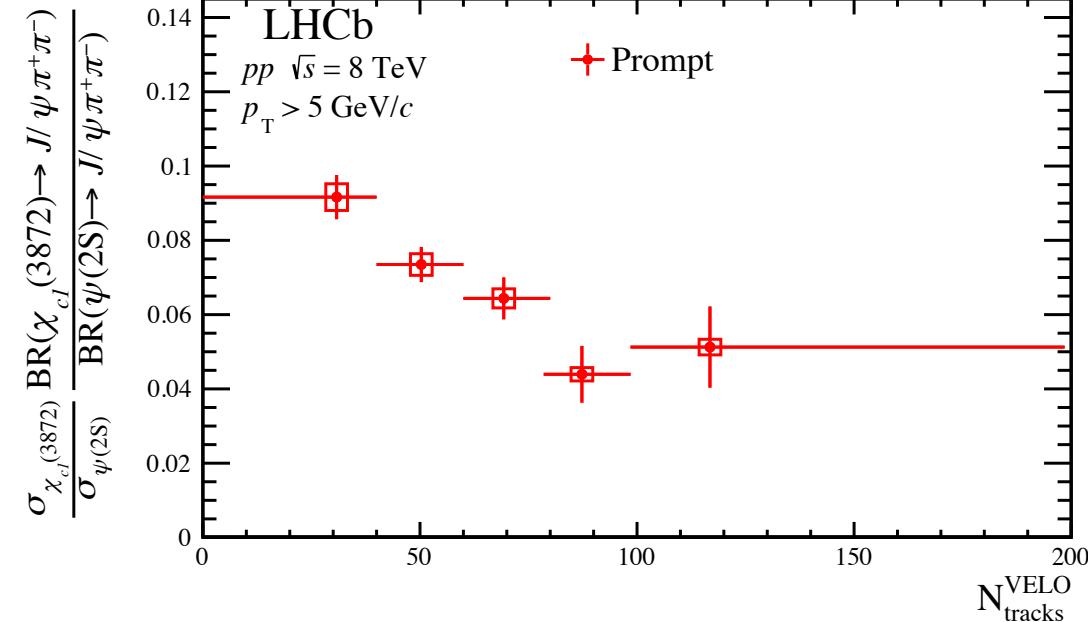
$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi \pi^+ \pi^-]}$$

- Expose X(3872) to different hadronic environments by choosing events with varying charged particle multiplicity
- Events characterized by number of tracks reconstructed in LHCb vertex detector, N_{tracks}^{VELO}



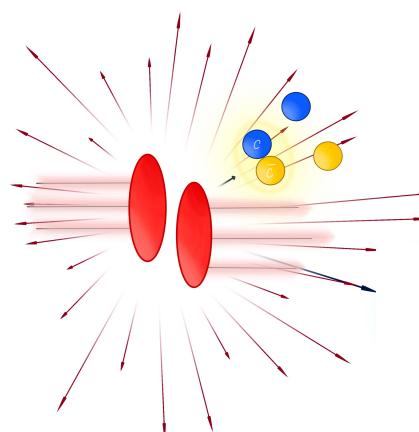
X(3872)/ψ(2S) vs multiplicity in pp

Phys. Rev. Lett. 126, 092001 (2021)



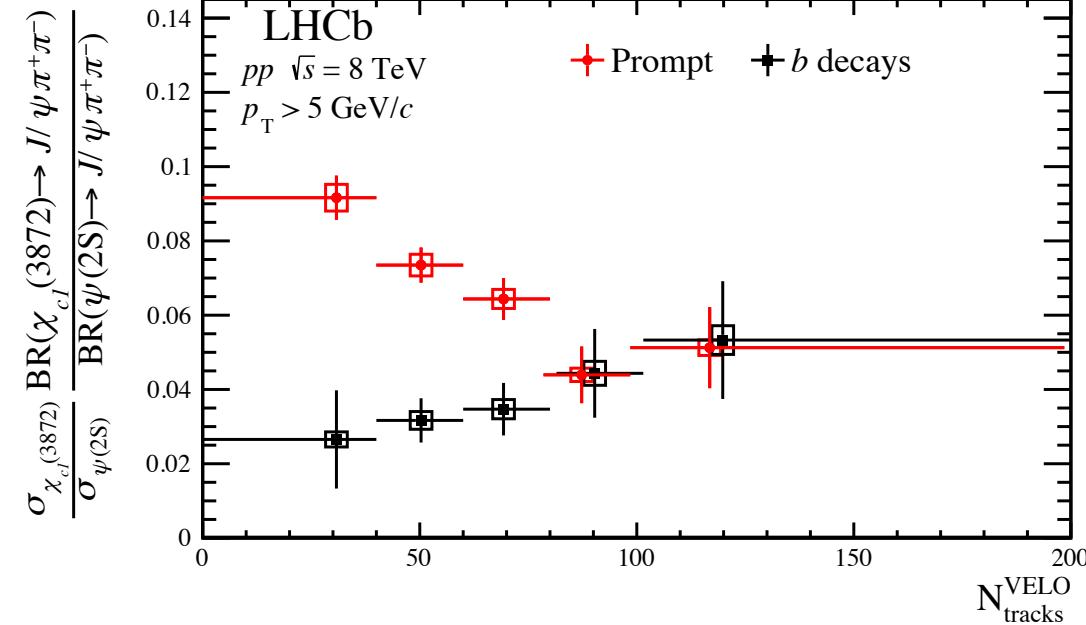
Prompt component:

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



X(3872)/ψ(2S) vs multiplicity in pp

Phys. Rev. Lett. 126, 092001 (2021)

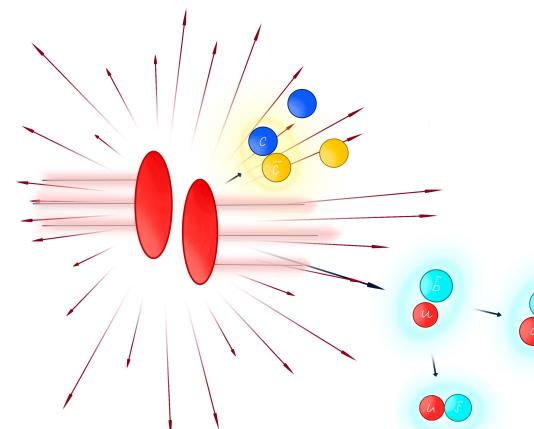


Prompt component:

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

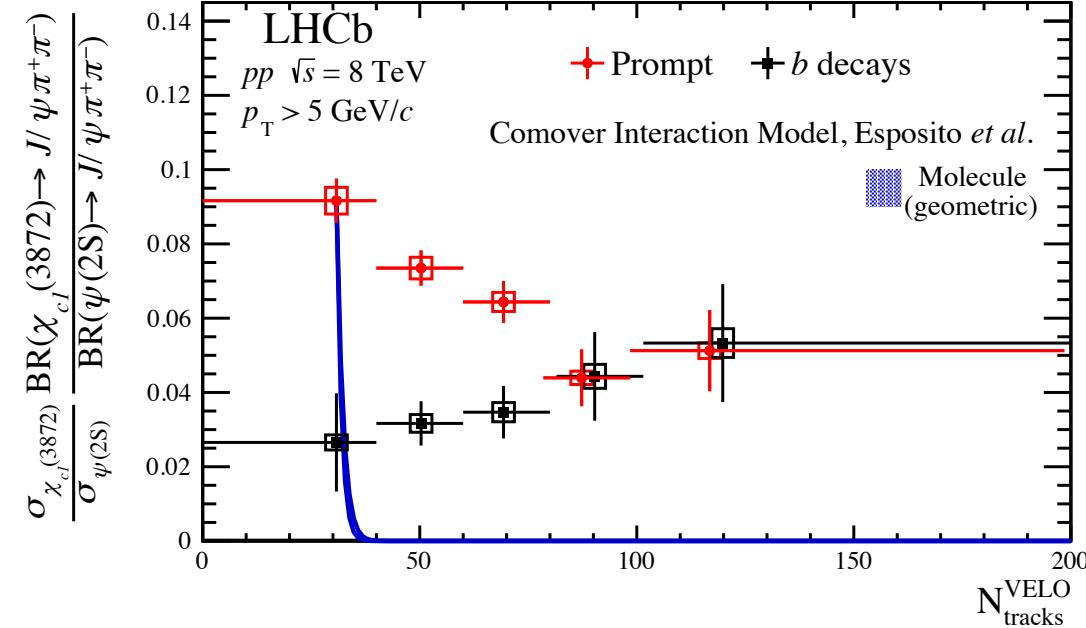
b -decay component:

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



Comover Model I

Phys. Rev. Lett. 126, 092001 (2021)



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

Prompt component:

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

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.

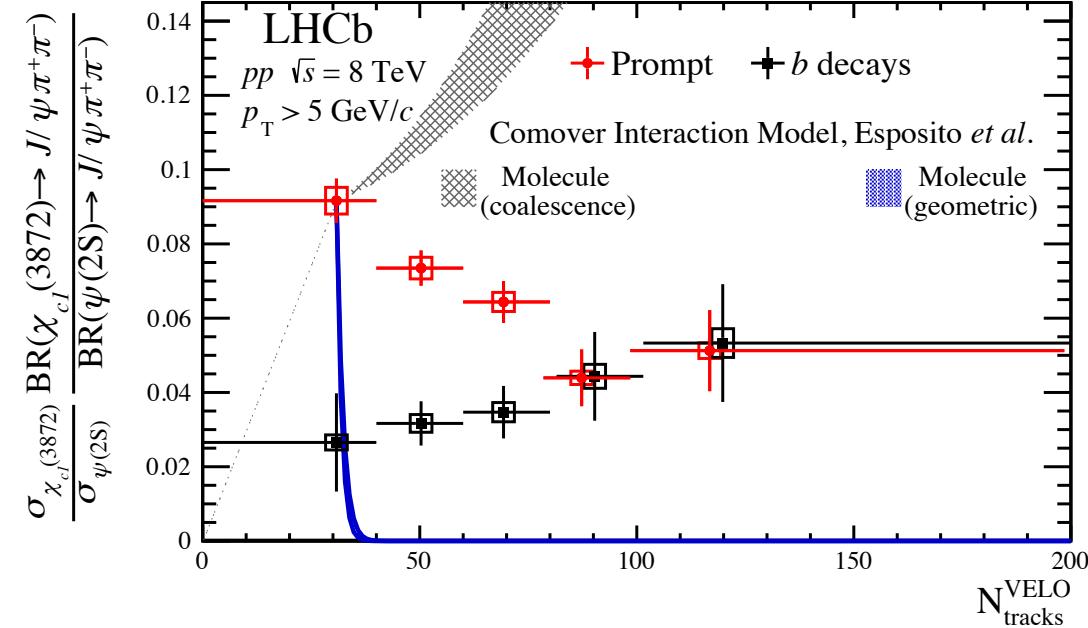
Calculations from arXiv:2006.15044

Break-up cross section:

$$\langle v\sigma \rangle_Q = \sigma_Q^{\text{geo}} \left\langle \left(1 - \frac{E_Q^{\text{thr}}}{E_c} \right)^n \right\rangle$$

Comover Model I

Phys. Rev. Lett. 126, 092001 (2021)



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

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

Prompt component:

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

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.

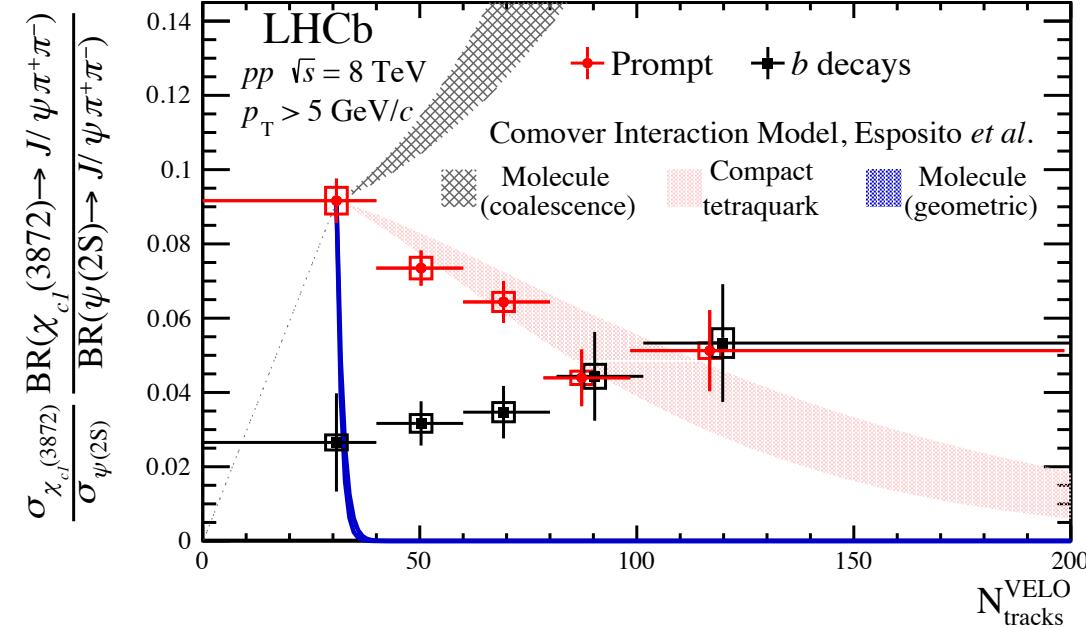
Calculations from arXiv:2006.15044

Break-up cross section:

$$\langle v\sigma \rangle_Q = \sigma_Q^{\text{geo}} \left\langle \left(1 - \frac{E_Q^{\text{thr}}}{E_c} \right)^n \right\rangle$$

Comover Model I

Phys. Rev. Lett. 126, 092001 (2021)



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

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

Prompt component:

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

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.

Calculations from arXiv:2006.15044

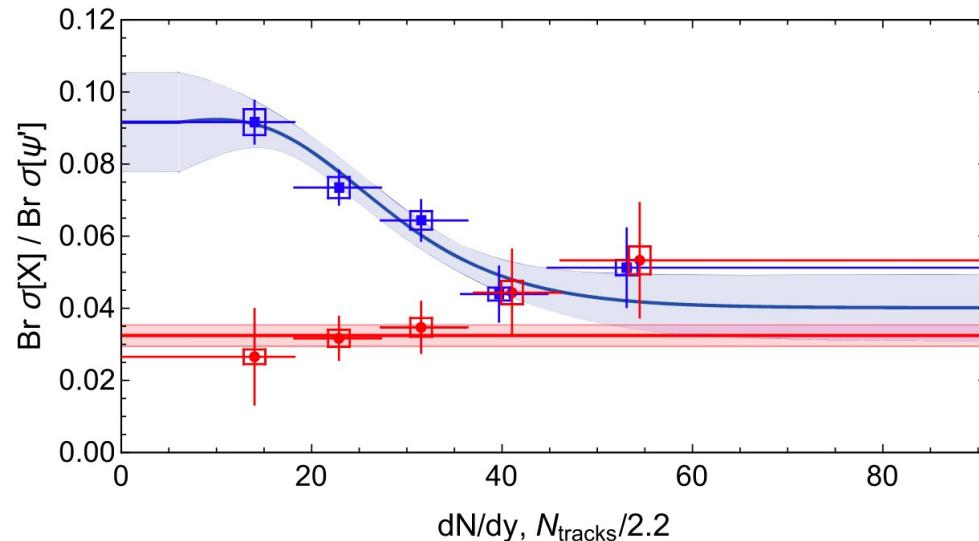
Break-up cross section:

$$\langle v\sigma \rangle_Q = \sigma_Q^{\text{geo}} \left\langle \left(1 - \frac{E_Q^{\text{thr}}}{E_c} \right)^n \right\rangle$$

Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases

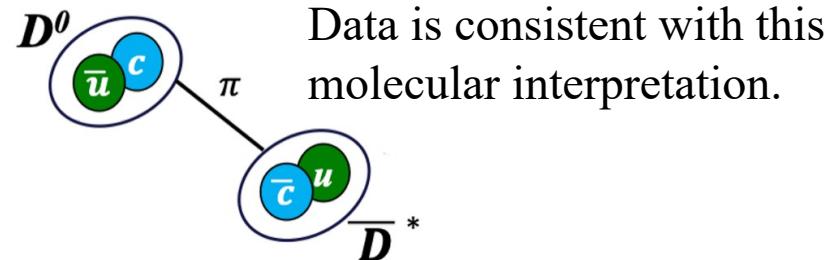
Comover Model II

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:

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



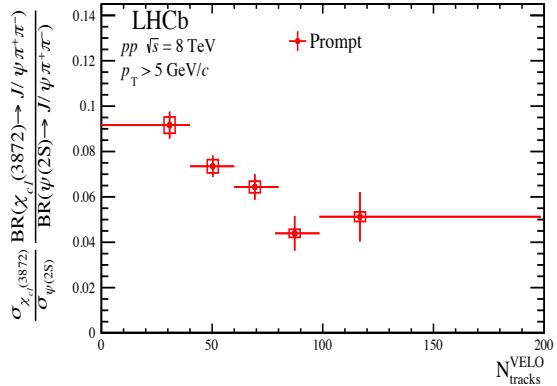
Data is consistent with this molecular interpretation.

Would all $c\bar{c}$ states have same breakup cross section in this model?

Comparisons with other data

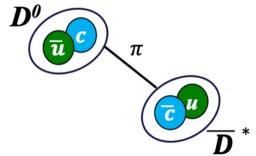


Phys. Rev. Lett. 126, 092001 (2021)

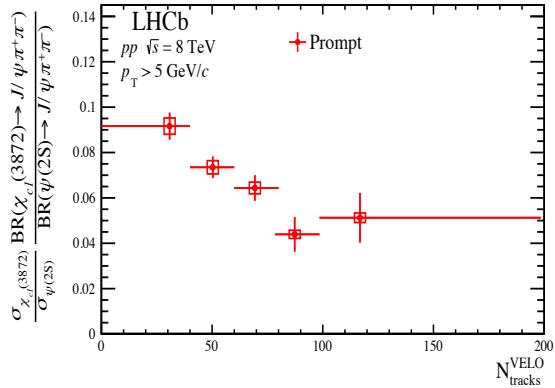


Decrease of $X(3872)$
production relative to
 $\psi(2S)$ as multiplicity
increases.

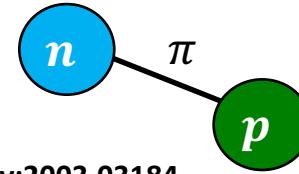
Comparisons with other data



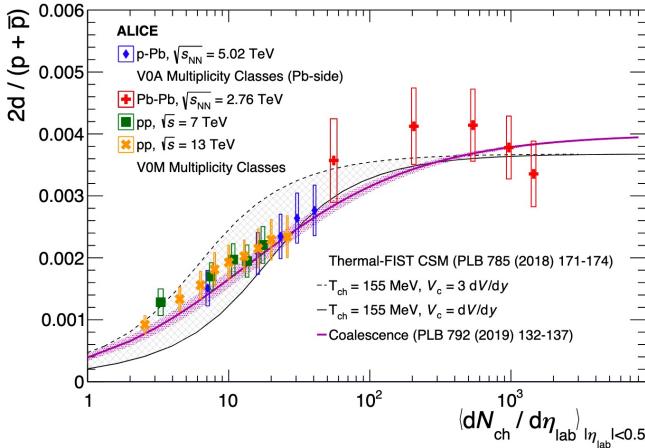
Phys. Rev. Lett. 126, 092001 (2021)



Decrease of $X(3872)$ production relative to $\psi(2S)$ as multiplicity increases.

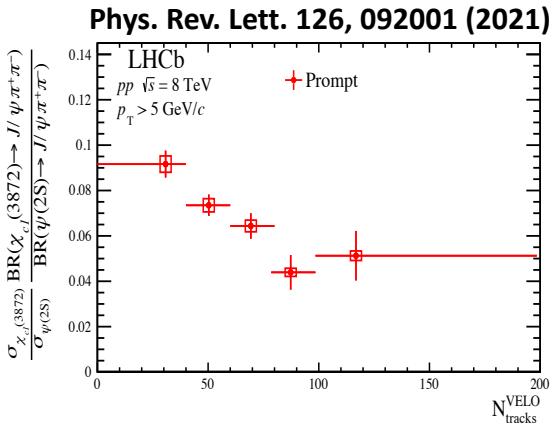
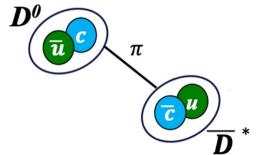


arXiv:2003.03184

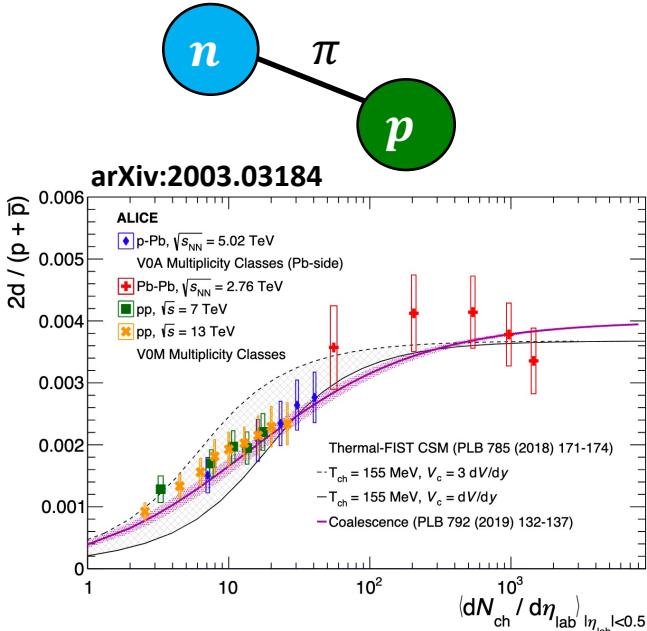


Increase of deuteron production relative to proton production with multiplicity, well described by coalescence models

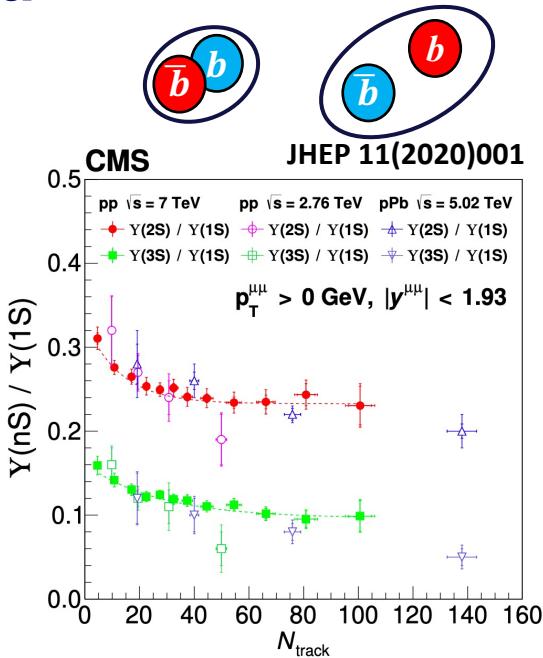
Comparisons with other data



Decrease of $X(3872)$ production relative to $\psi(2S)$ as multiplicity increases.



Increase of deuteron production relative to proton production with multiplicity, well described by coalescence models



Decrease of $Y(2S, 3S)$ production relative to $Y(1S)$ as multiplicity increases.

X(3872) in the QCD medium

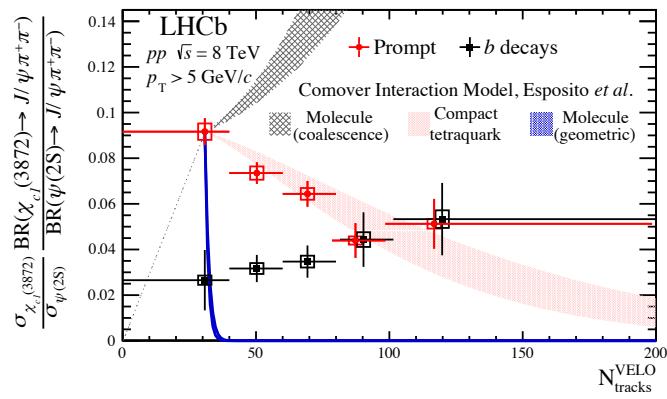
Diffuse medium

Increasing T, N_{ch}

Dense medium

pp

Phys. Rev. Lett. 126, 092001 (2021)

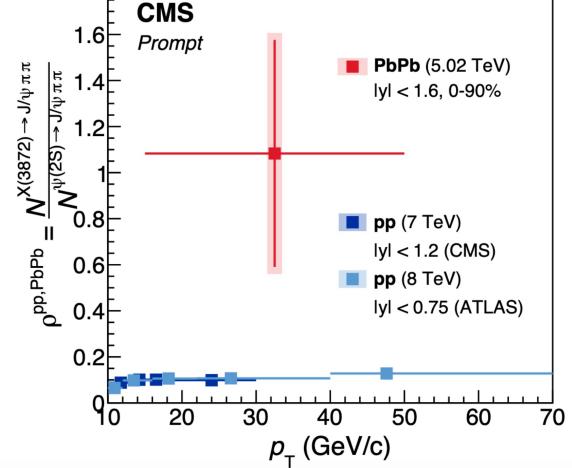


PbPb

2102.13048

CMS
Prompt

1.7 nb⁻¹ (PbPb 5.02 TeV)



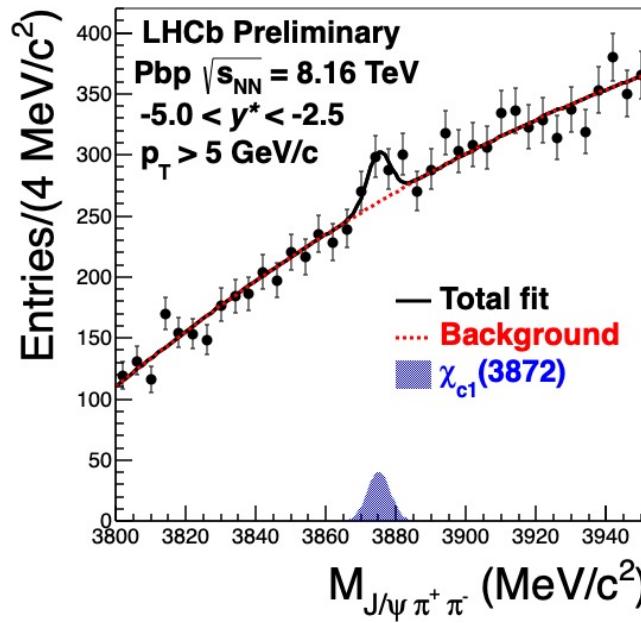
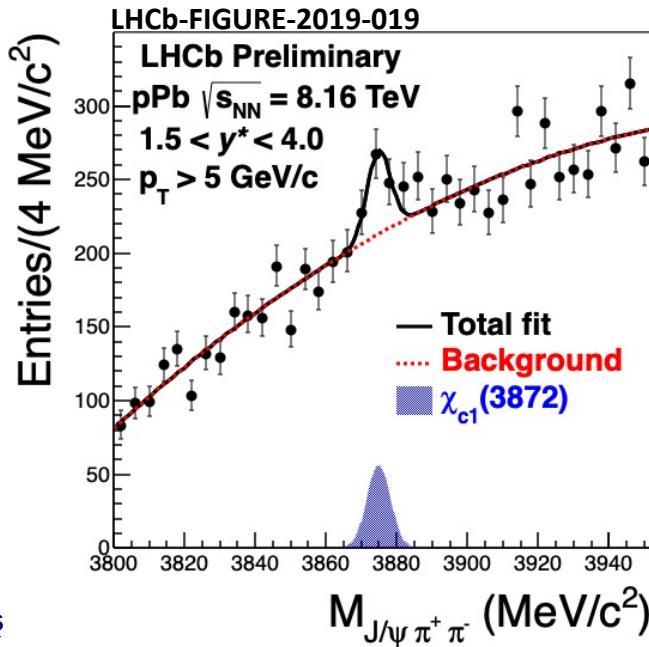
X(3872) in the QCD medium

Diffuse medium

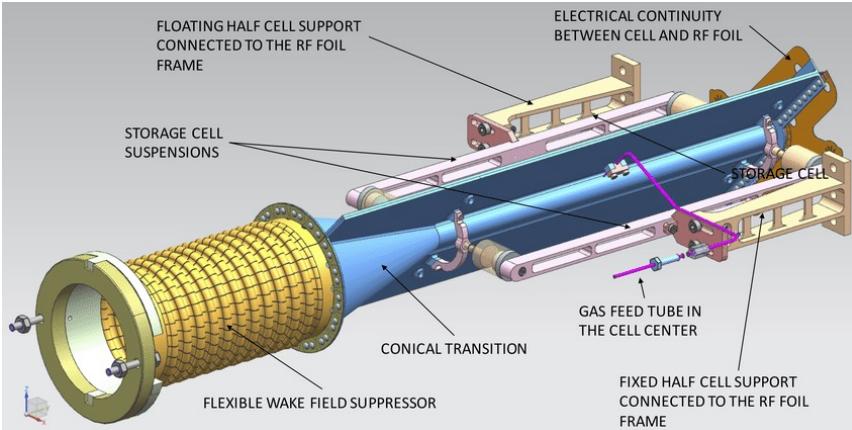
Increasing T, N_{ch}

Dense medium

LHCb pPb data fills critical gap between pp and PbPb



Near future: SMOG 2 at LHCb



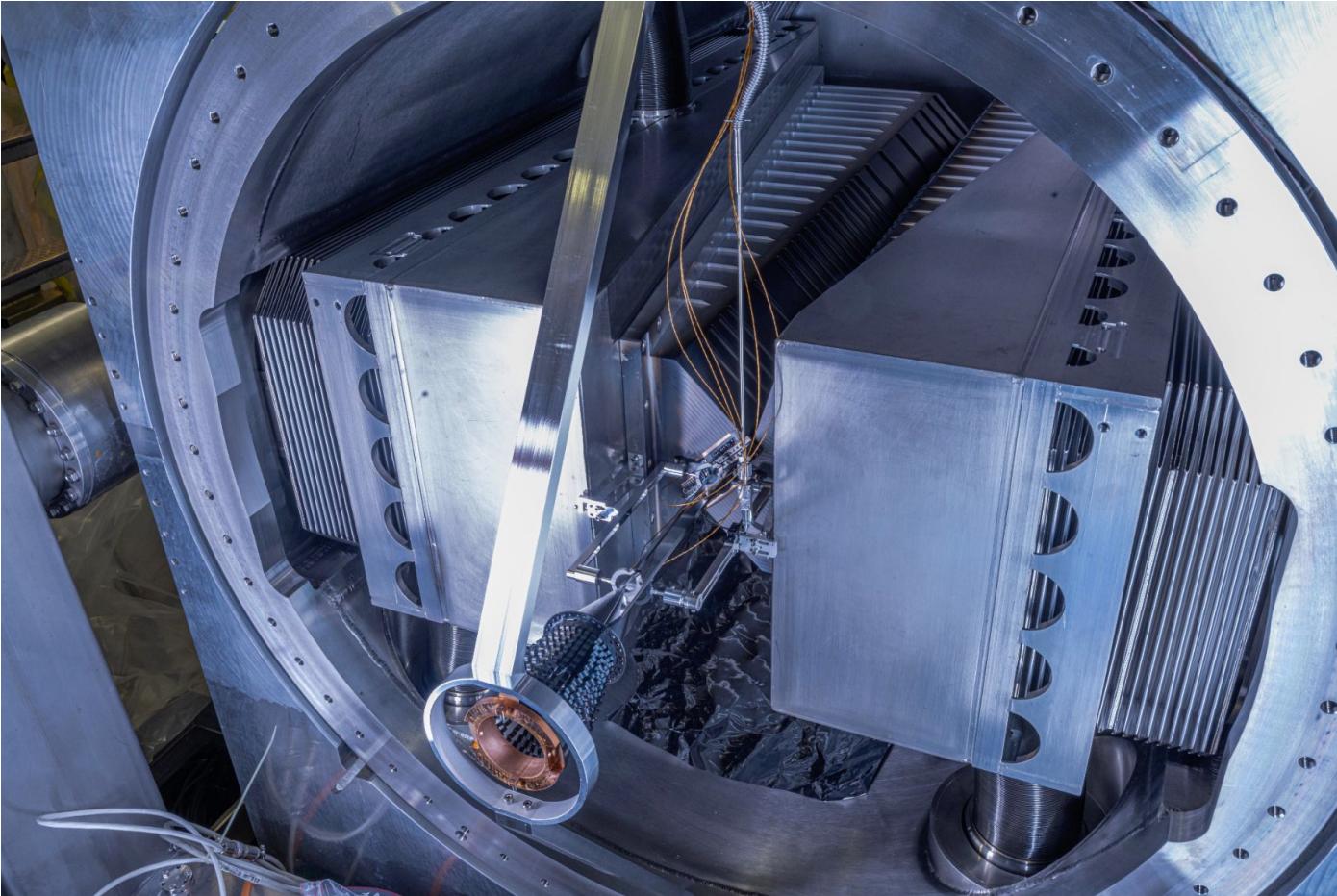
<https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf>

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+injected gas collisions at LHCb
- Variable target gases – allows hadronic environment to be adjusted
- Access to exotic states near RHIC energies – much smaller coalescence at lower \sqrt{s}
- Hadronization *inside the nucleus* may become an important effect

SMOG2 installed at LHCb



Summary

- Interactions of exotic hadrons with the underlying event provide a new way to probe their structure and properties.
- The production of 4-quark states also poses new challenges to models of hadron production and transport in a QCD medium.
- X(3872) structure continues to evade a clear, unified understanding. Additional data required:
 - Expect pPb results in near future
 - New results from SMOG2 fixed target collisions
 - More precise PbPb results with additional data sets



Los Alamos is supported by the US Dept. of Energy

Office of Science/Office of Nuclear Physics and Early Career Awards

BACKUPS

The LHCb Detector

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

Vertex detector (VELO):

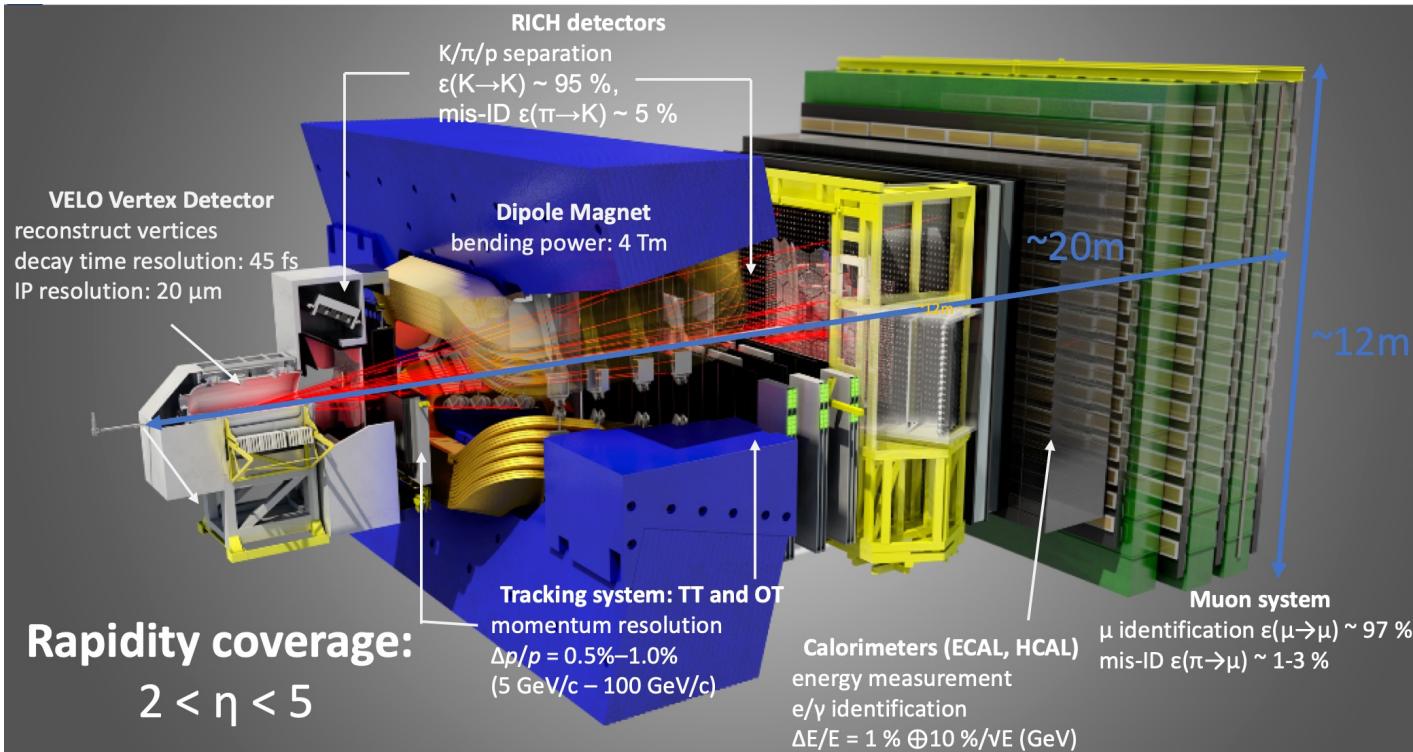
- Separation of prompt and b -decay production
- Number of VELO tracks gives measure of event activity

Two RICH detectors:

- Pion identification

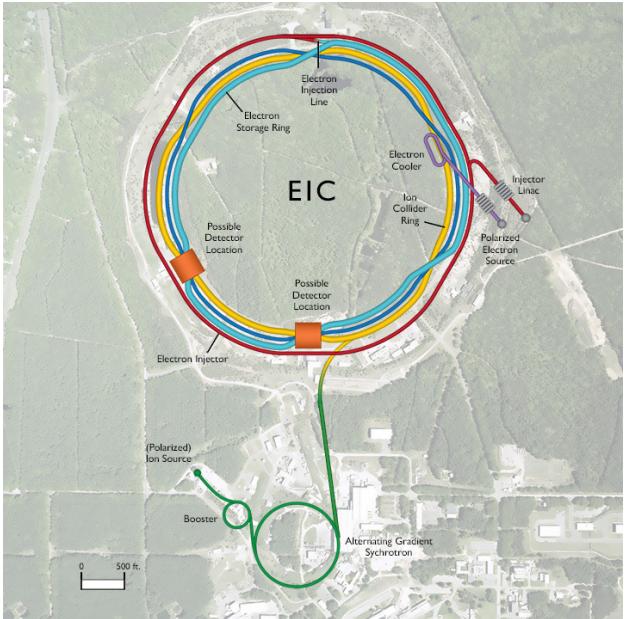
Muon System:

- Layers of absorber/tracking
- Muon hardware trigger

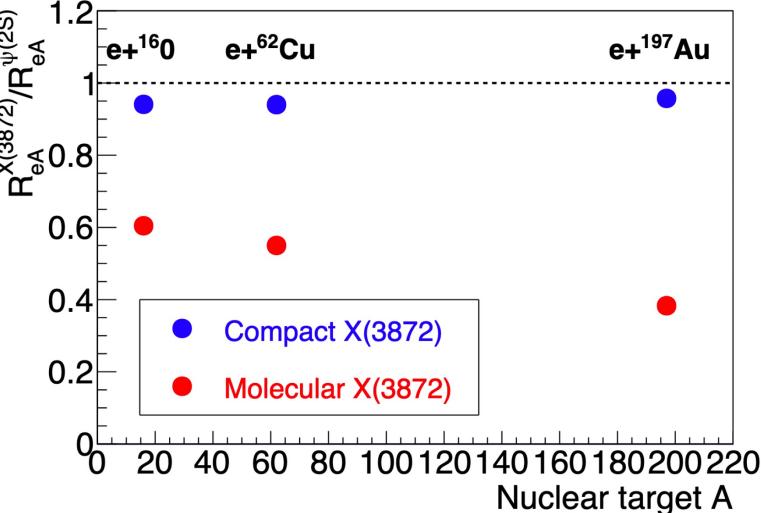
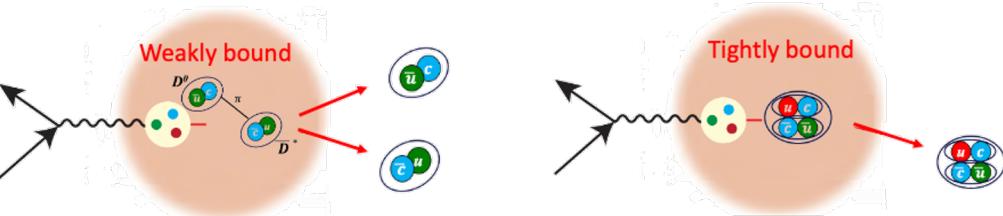


Farther future: Electron-Ion Collider

EIC Yellow Report:
2103.05419



In the kinematic range accessed by the EIC, hadronization *inside the nucleus* becomes an important effect, Vitev 1912.10965



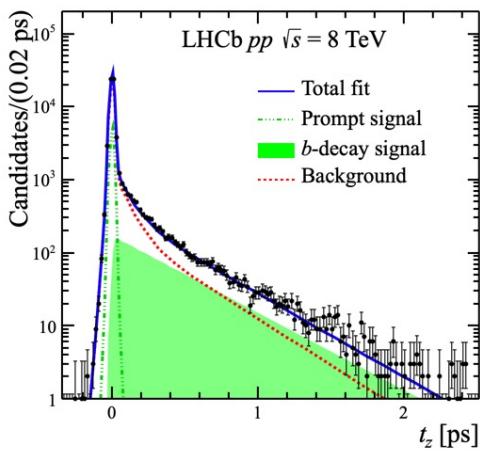
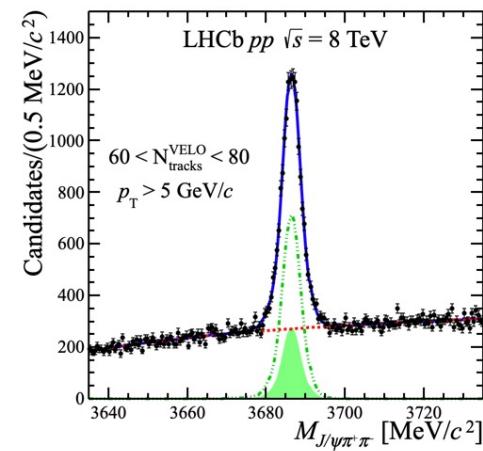
Propagate molecular and compact $X(3872)$ through Glauber nucleus, disrupt if nucleon encountered.

Relative modification shows clear discrimination between models at EIC.

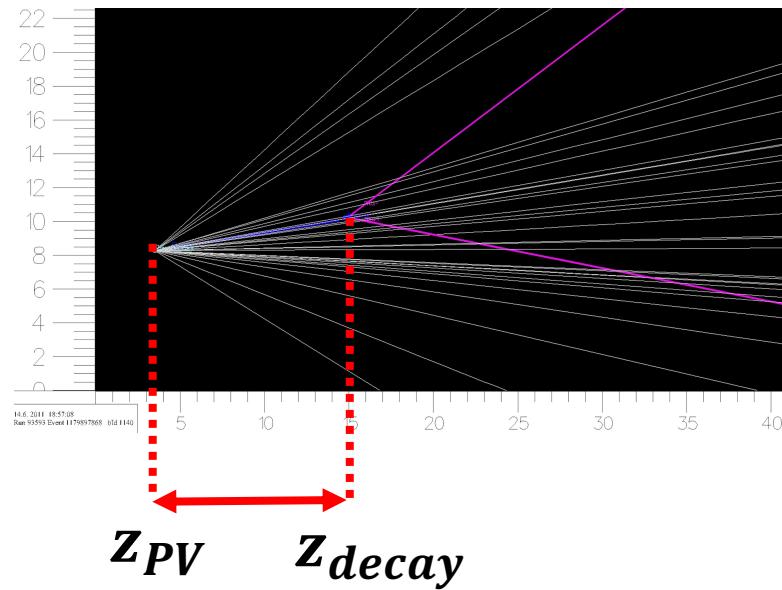
- $e+p$, $e+A$ collider with CM energies 20-100 GeV
- Low backgrounds well suited to reconstruction of XYZ states

Separate prompt/non-prompt production

Simultaneous fit to invariant mass and pseudo proper time spectrum:



$$t_z = \frac{z_{\text{decay}} - z_{\text{PV}}}{p_z} M$$

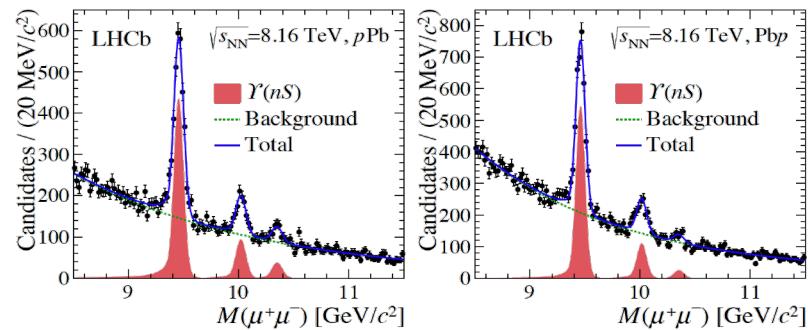
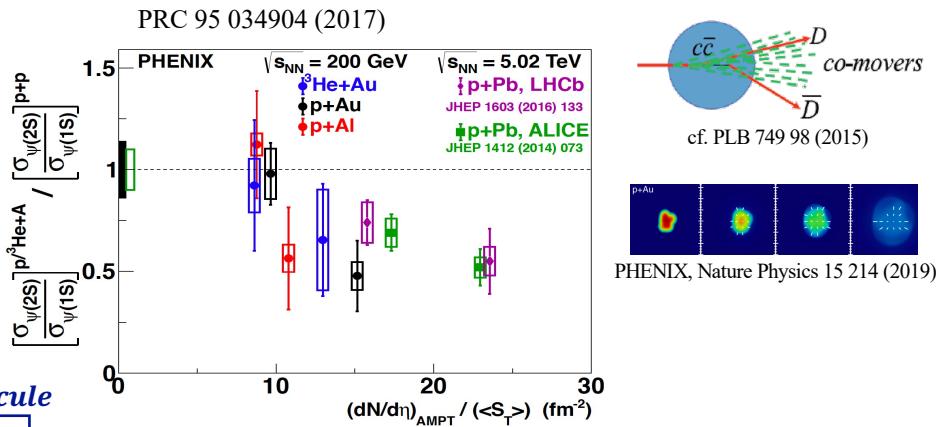


Fit to mass constrains S/B while
fit to t_z constrains prompt fraction

Effects of Binding Energy

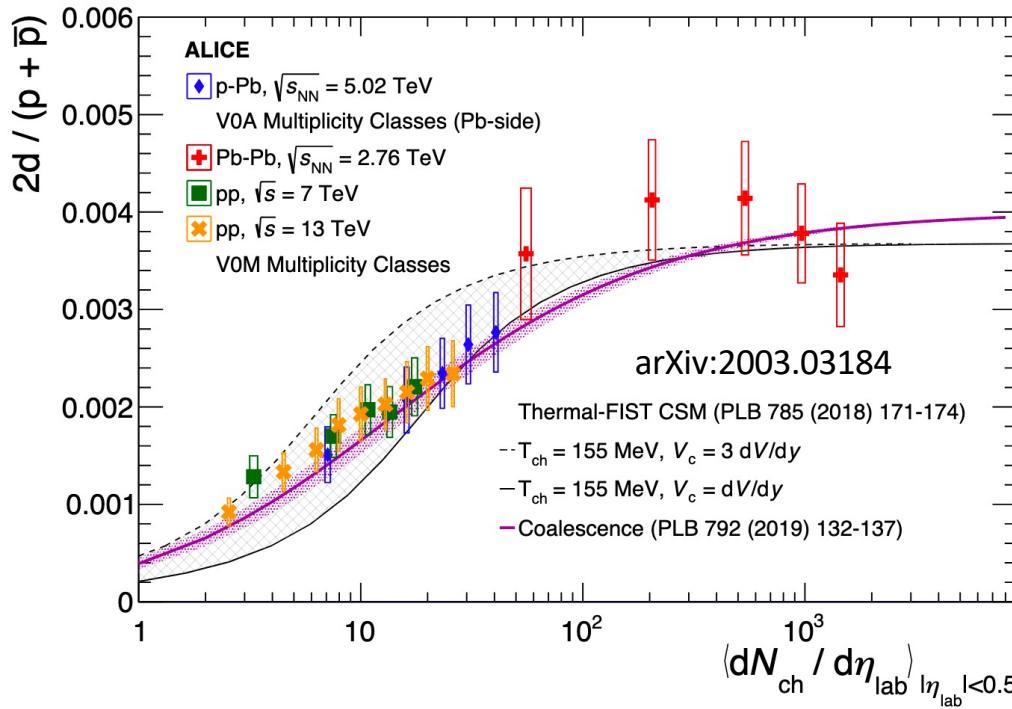
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	$D\bar{D}^*$ Molecule
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00007 ± 0.00012

Satz, J. Phys. G 32 (3) 2006

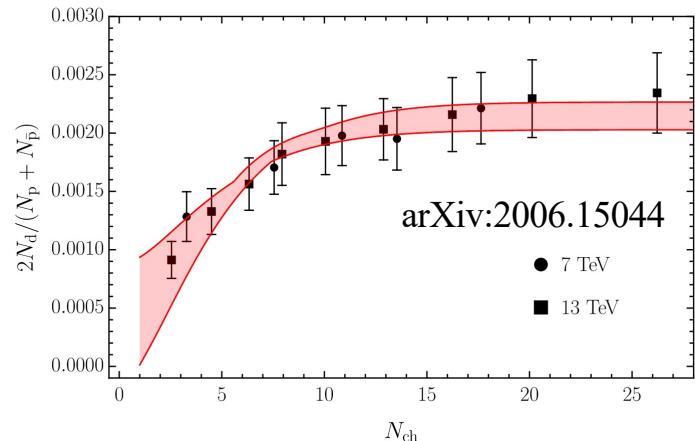


Deuteron production vs multiplicity

The deuteron is often considered a neutron+proton hadronic molecule



In contrast to X(3872)/ψ(2S), the d/p multiplicity dependence is well described by coalescence models



Upsilon comovers model

LHCb, JHEP 11 (2018) 194

