Los Alamos NATIONAL LABORATORY

Experimental aspects of quarkonium structure

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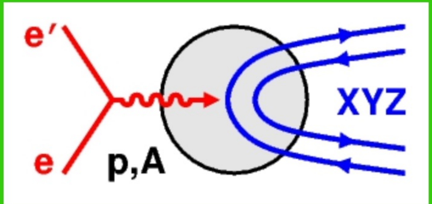


Exotic heavy meson spectroscopy and structure with EIC: Next-level physics and detector simulations

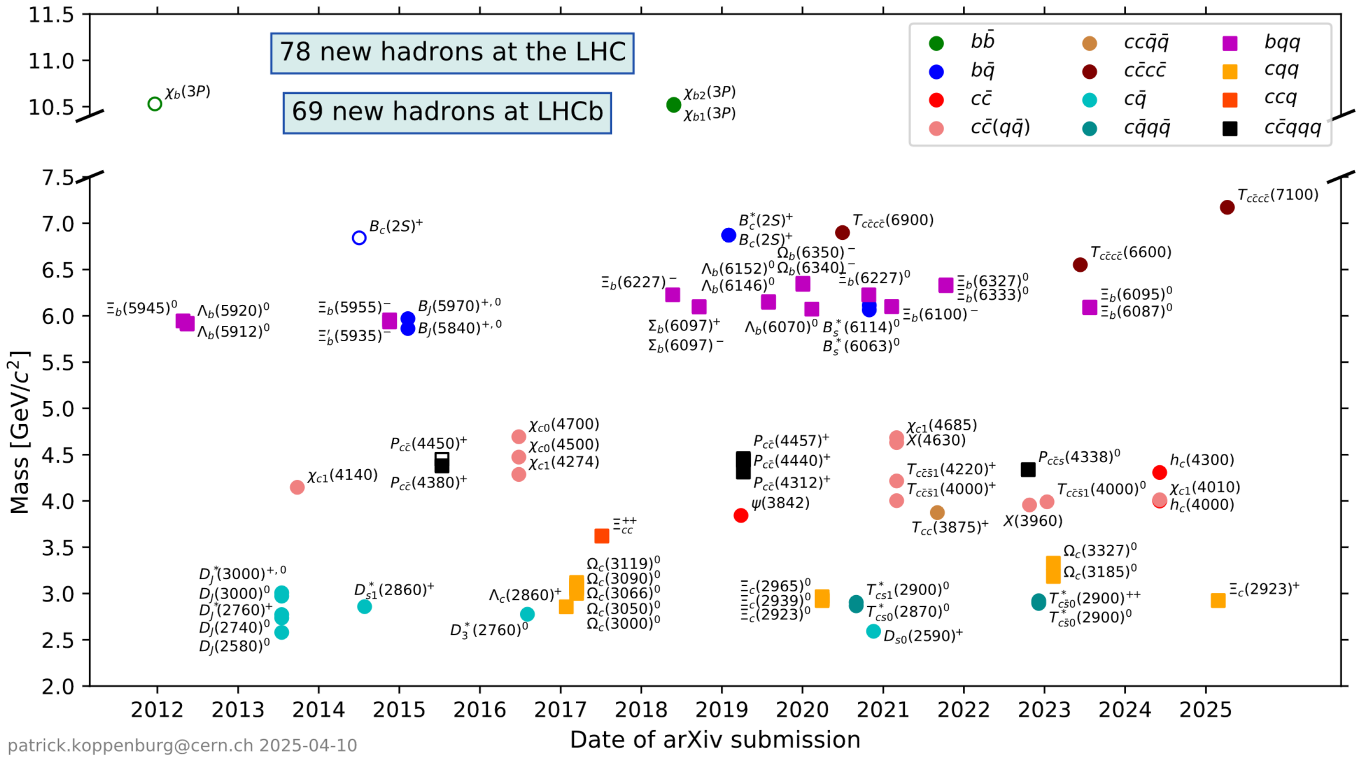
Apr 14 – 17, 2025
CFNS, Stony Brook University

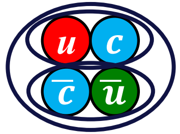
Center for Frontiers in Nuclear Science

Outline

- First measurement of photoproduction of exotic heavy quark states
- First measurement of X(3872) production in jets
- First results on exotic quarkonia in medium
  - X(3872) in *pp*/*p*Pb/PbPb at the LHC

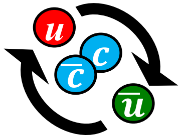
New hadrons discovered at the LHC





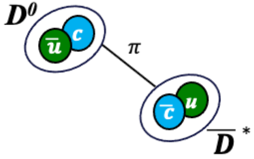
Compact tetraquark/pentaquark

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



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

Hadronic Molecules



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

~90% of the new particles were discovered by LHCb

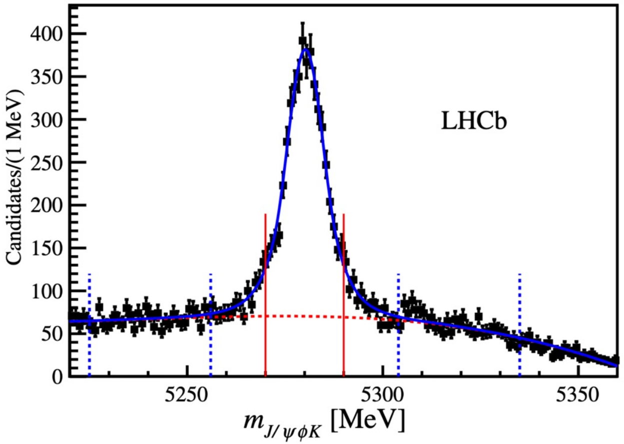
Mixtures

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

b hadron decays

- Reconstruct the decay $B^+ \to J/\psi\phi K^+$



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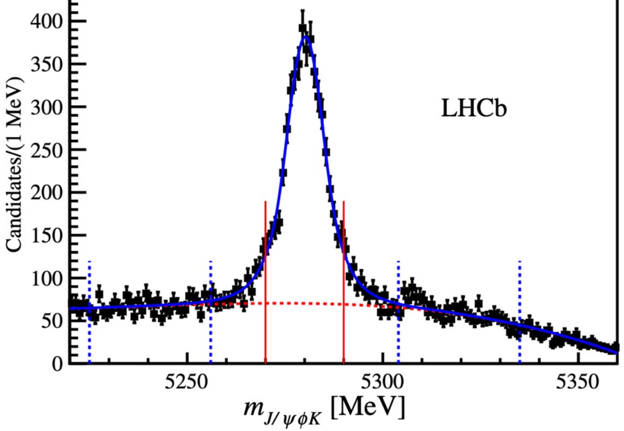
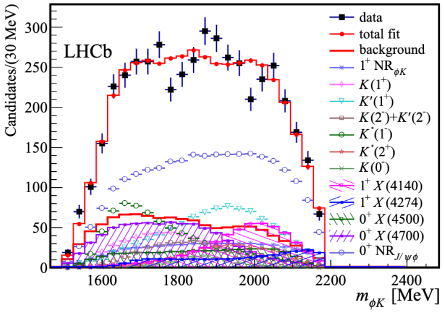
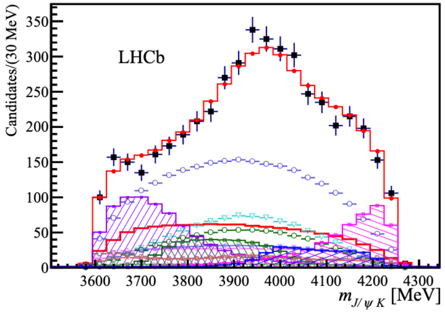
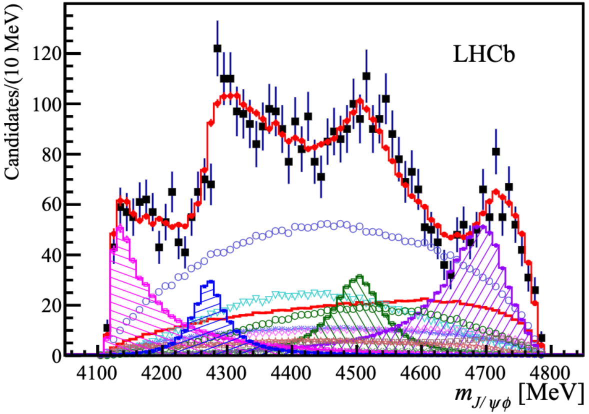


- Inspect combinations of daughter products for intermediate states

PRL 118, 022003 (2017), PRD 95 012002 (2017), PRL 127, 082001 (2021)







b hadron decays

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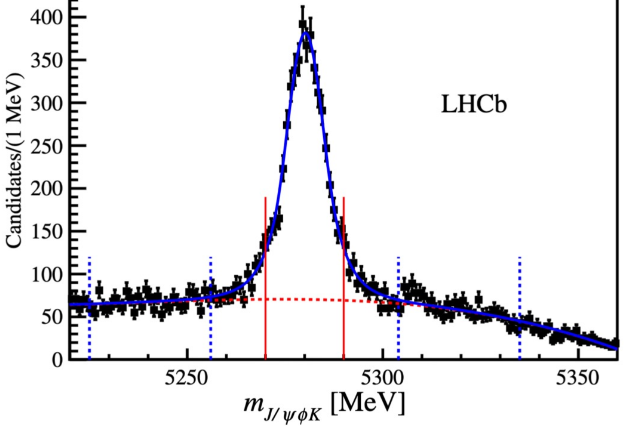
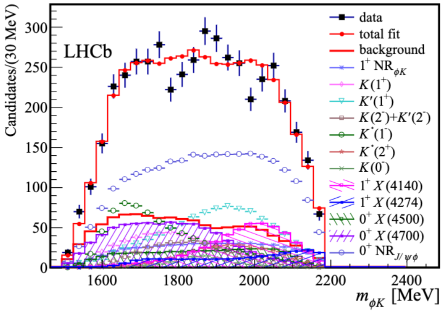
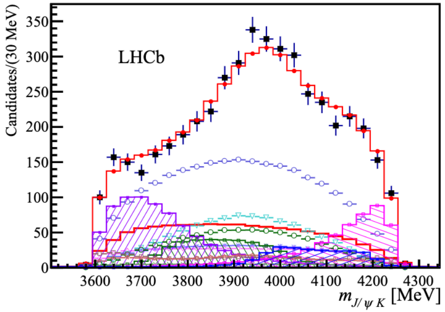


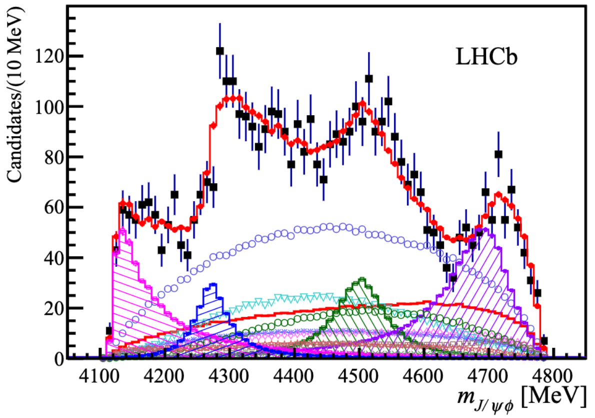
- Inspect combinations of daughter products for intermediate states

- Amplitude analysis requires four new $J/\psi\phi$ resonances to describe data.

PRL 118, 022003 (2017), PRD 95 012002 (2017), PRL 127, 082001 (2021)

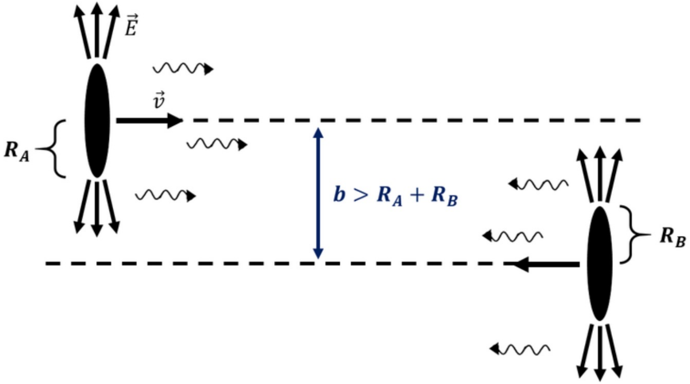


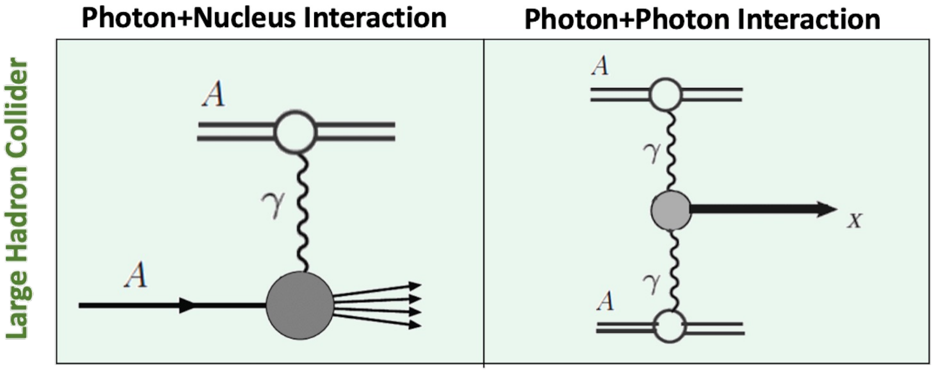




Central Exclusive Production/Ultra-Peripheral Collisions

- Photon-induced interactions on protons/nuclei can be studied with these events

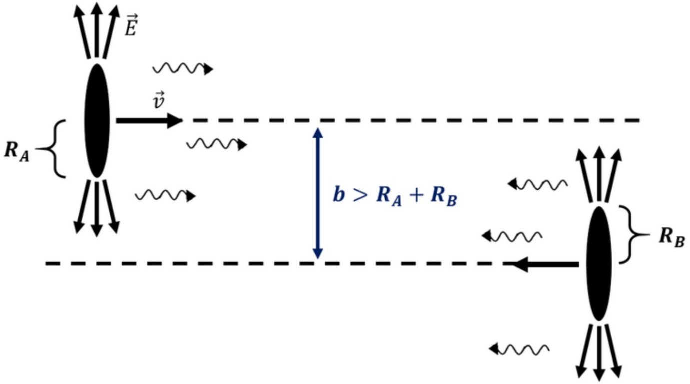


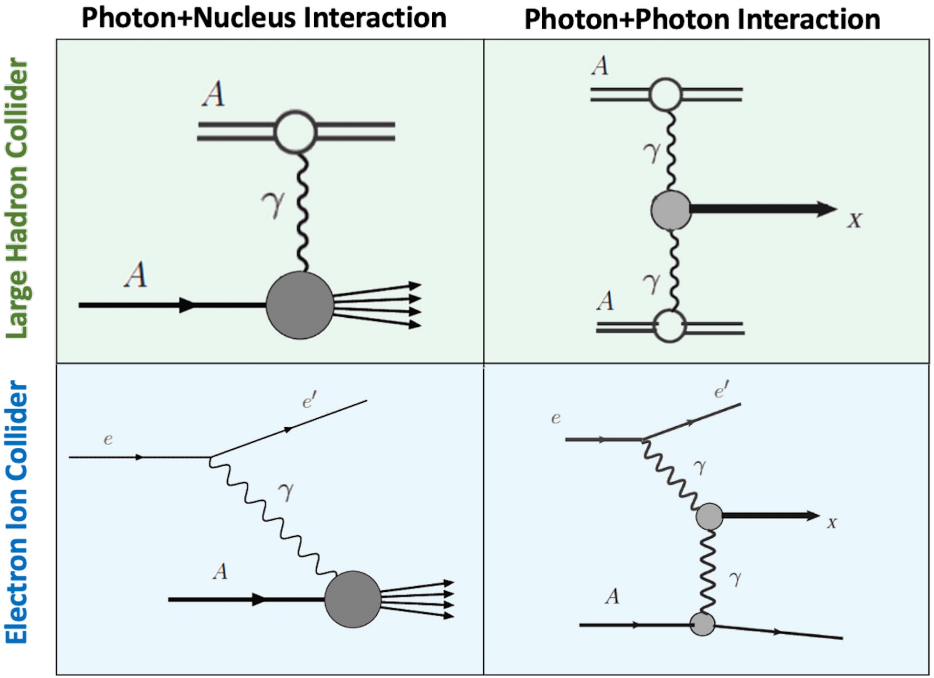


- Beam particles pass each other at ~few fm

Central Exclusive Production/Ultra-Peripheral Collisions

- Photon-induced interactions on protons/nuclei can be studied with these events

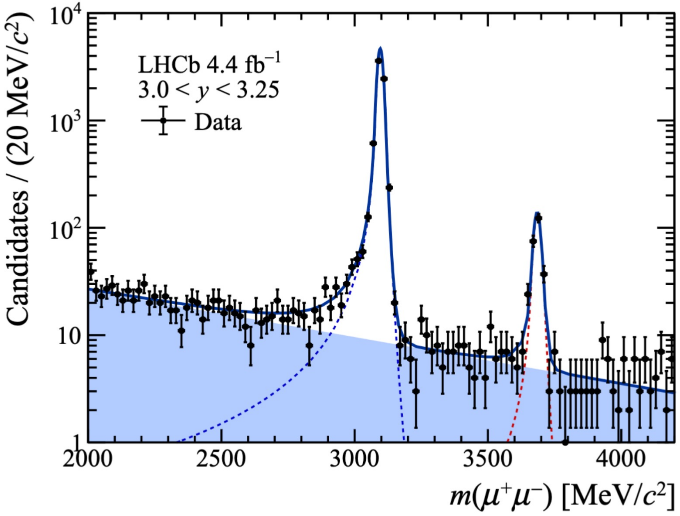


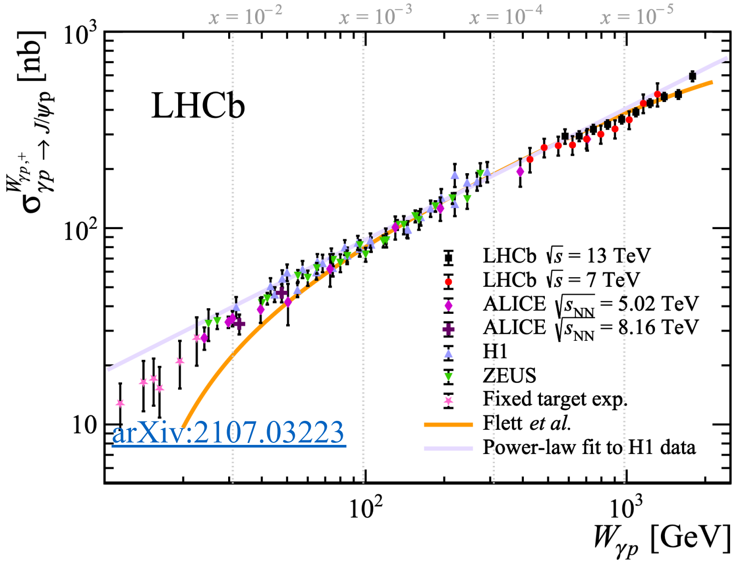


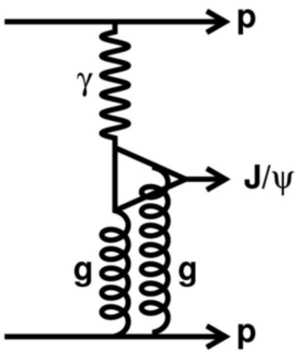
- Beam particles pass each other at ~few fm
- Very similar to electron-ion interactions in many respects

Central Exclusive Production/Ultra-Peripheral Collisions

- Detailed studies of conventional hadrons in CEP/UPC exist



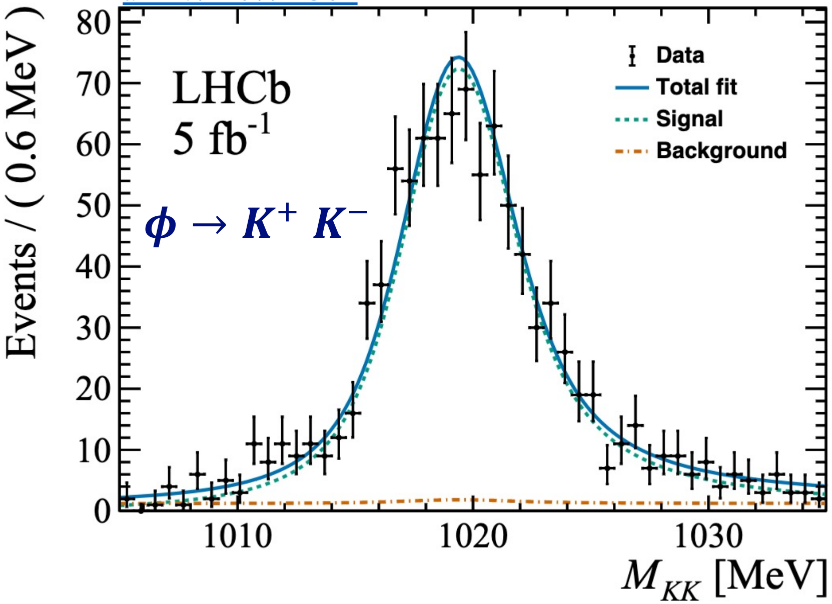


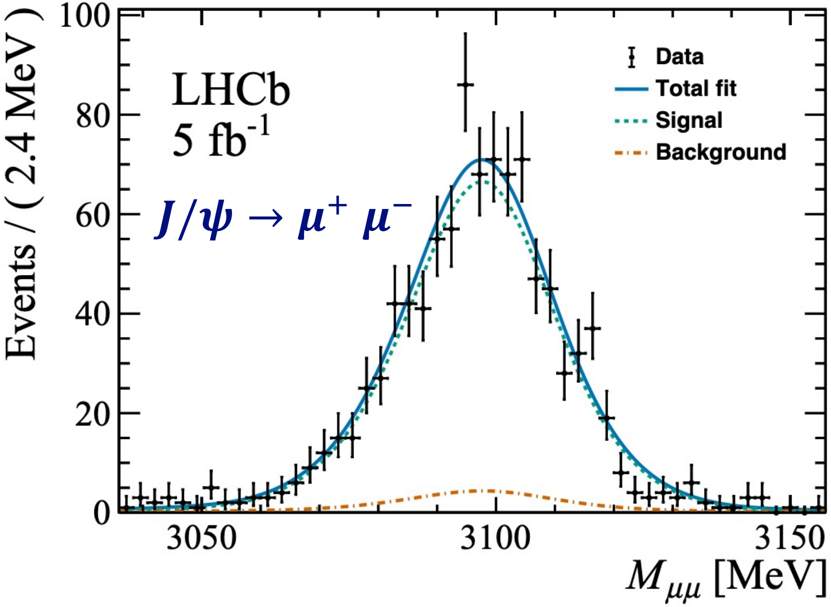


- There is increasing interest in the production of exotic hadrons in these events:
  PRD94, 094024 (2016), PRC100, 024620 (2019), PLB 805135447 (2020), PLB 810 136249 (2021), EPJC 81 710 (2021), PRD 104 114029 (2021), PRD 109 016007 (2024)

Central exclusive production (pp) of $J/\psi\phi$

arXiv:2407.14301

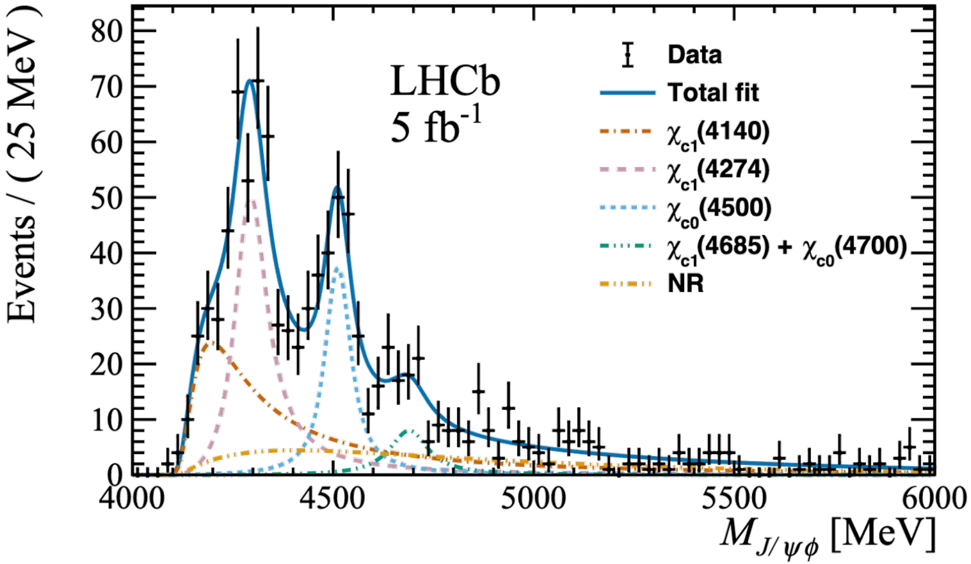




- Select events with exactly four tracks: two muons, two kaons
- Veto additional activity with forward/backward shower counters
- Clear signals for $\phi(1020)$ and J/ψ

Central exclusive production (pp) of $J/\psi\phi$

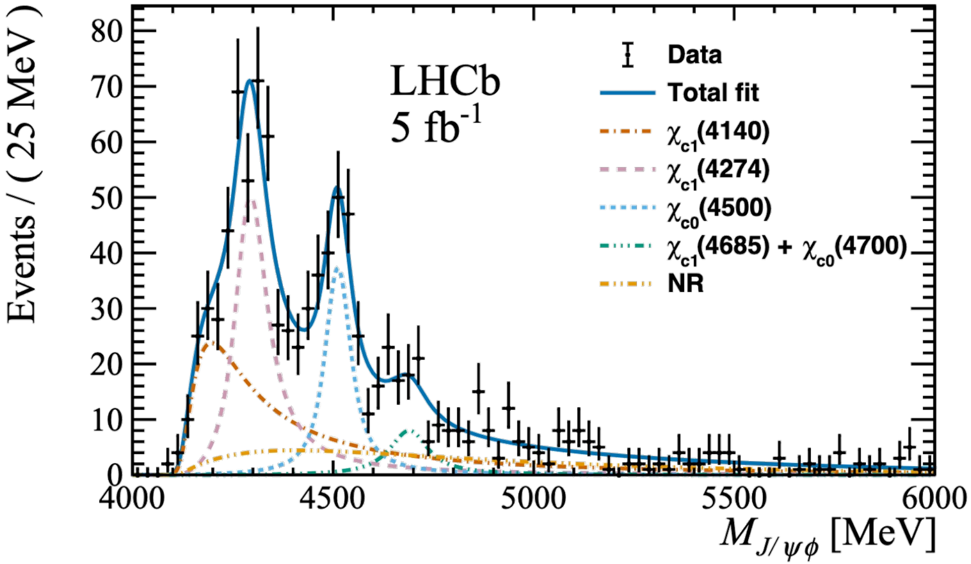
arXiv:2407.14301

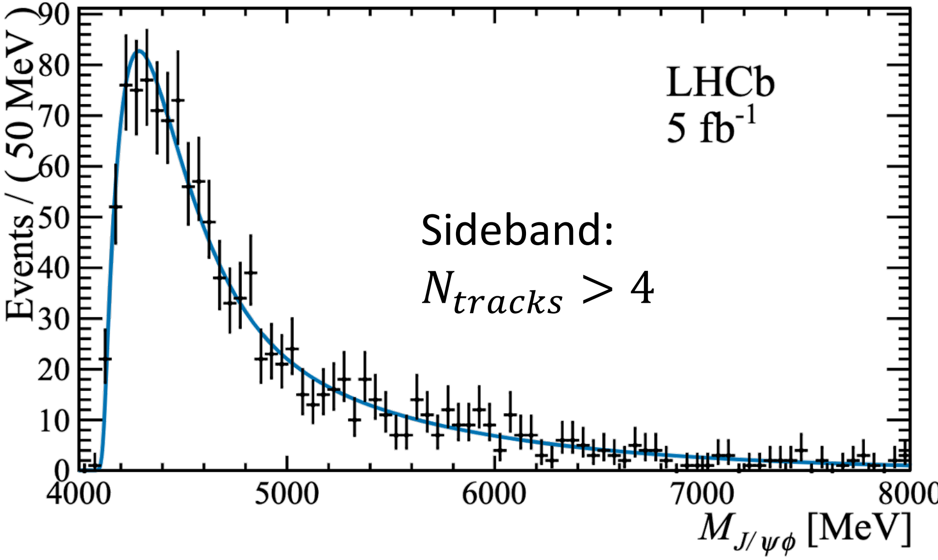


- Structures apparent in CEP data (exactly 4 tracks)

Central exclusive production (*pp*) of $J/\psi\phi$

arXiv:2407.14301

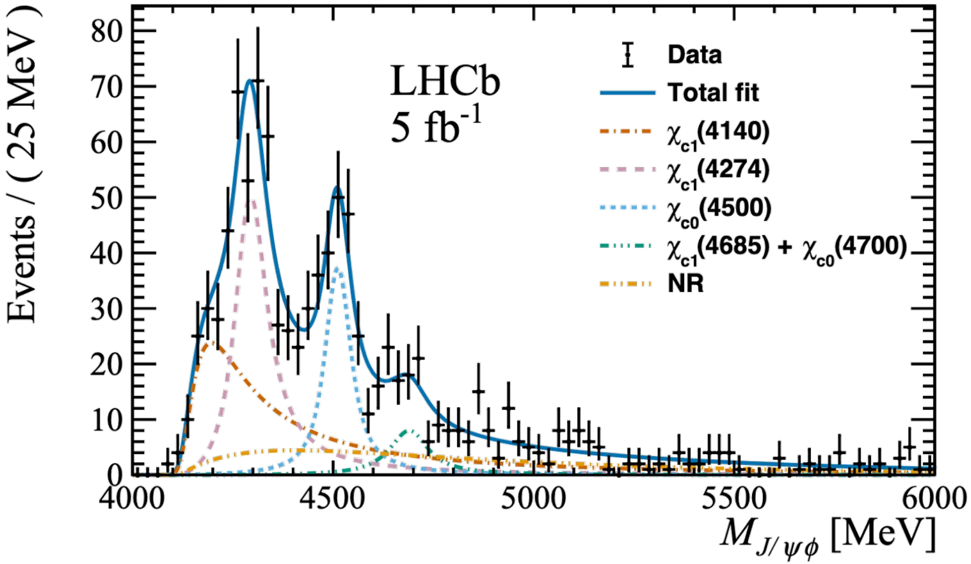




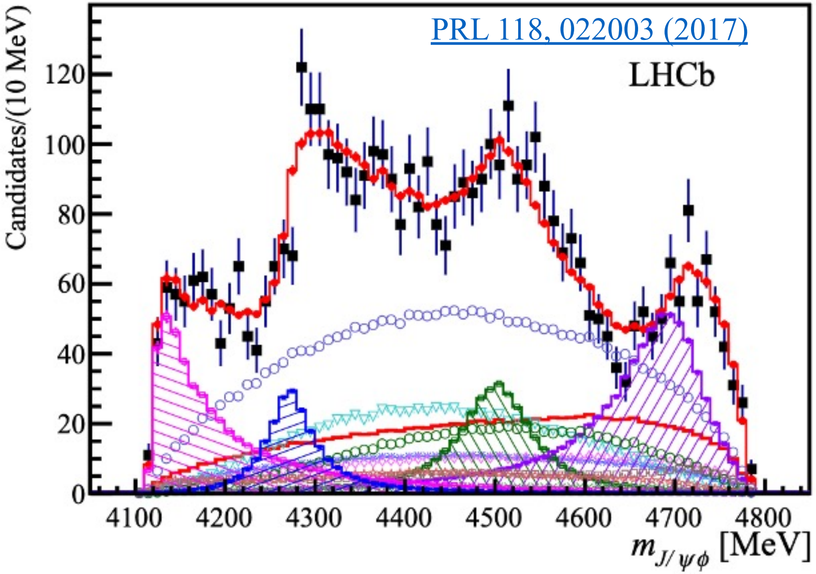
- Structures apparent in CEP data (exactly 4 tracks)
- Gone when looking at "sideband" of events with more activity

Central exclusive production (pp) of $J/\psi\phi$

arXiv:2407.14301



$B^{\pm} \to J/\psi\phi K^{\pm}$

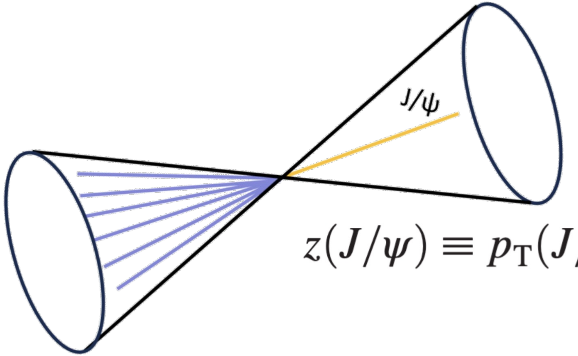


- Consistent with tetraquark candidates previously observed in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays

Concept proven: CEP/UPCs provide totally new method to produce and study exotic hadrons

J/ψ in jets

- Charmonia provides a platform for testing perturbative and non-perturbative QCD
- Charmonia in jets provides new way to examine production mechanisms



$$z(J/\psi) \equiv p_{\mathrm{T}}(J/\psi)/p_{\mathrm{T}}(\mathrm{jet})$$

J/ψ in jets

- Charmonia provides a platform for testing perturbative and non-perturbative QCD
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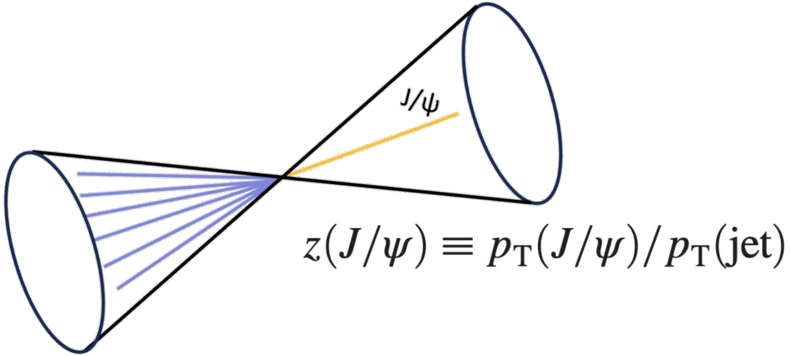

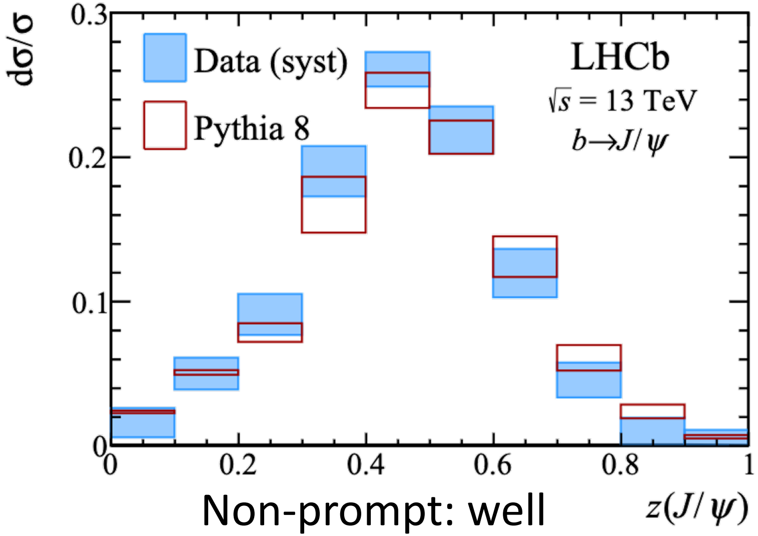

Non-prompt: well described by PYTHIA

J/ψ in jets

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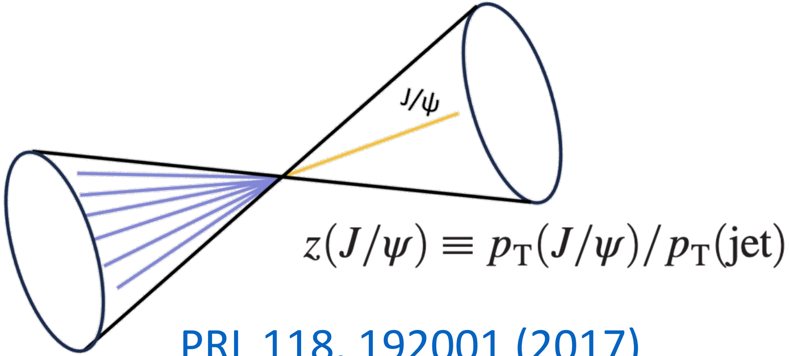
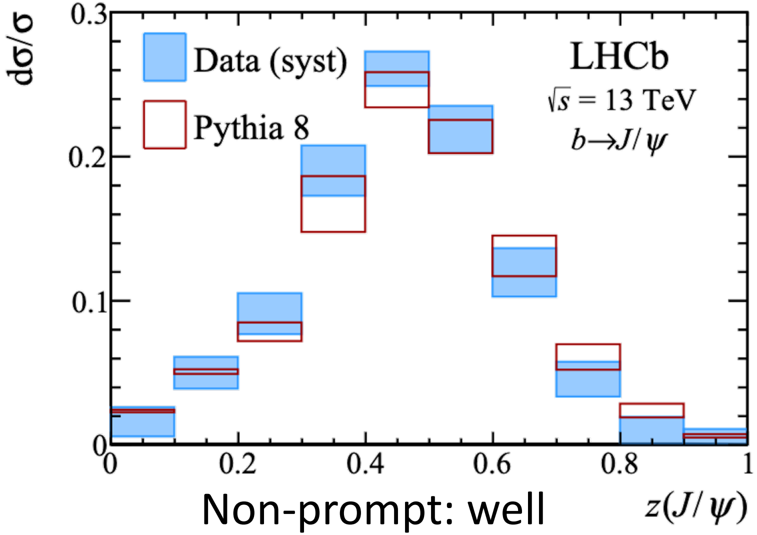


PRL 118, 192001 (2017)



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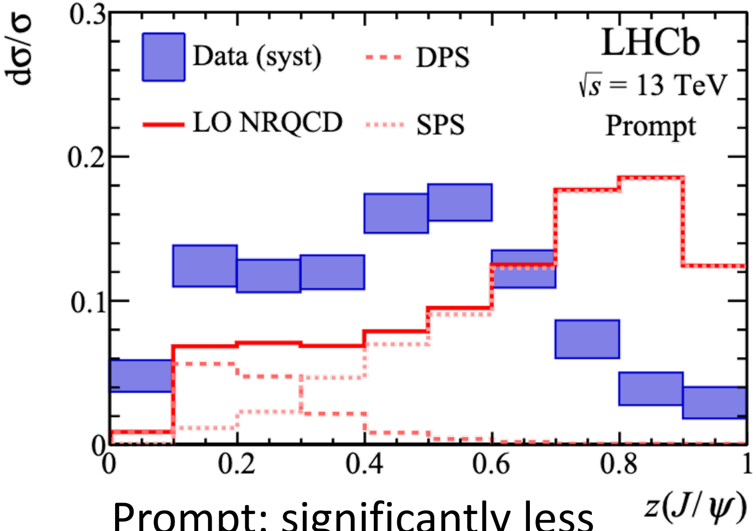
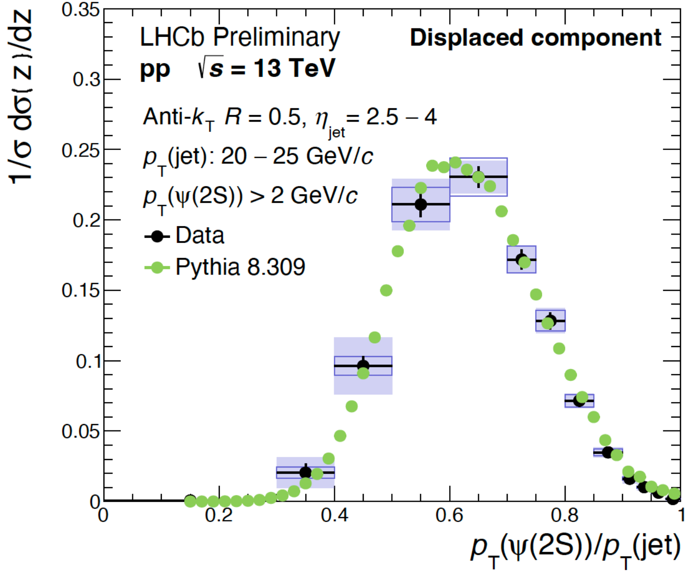


Prompt: significantly less isolated than NRQCD prediction

ψ(2S) in jets

- The same measurement can also be done with ψ(2S)
  - Very little feeddown, unlike J/ψ

LHCb-PAPER-2024-021



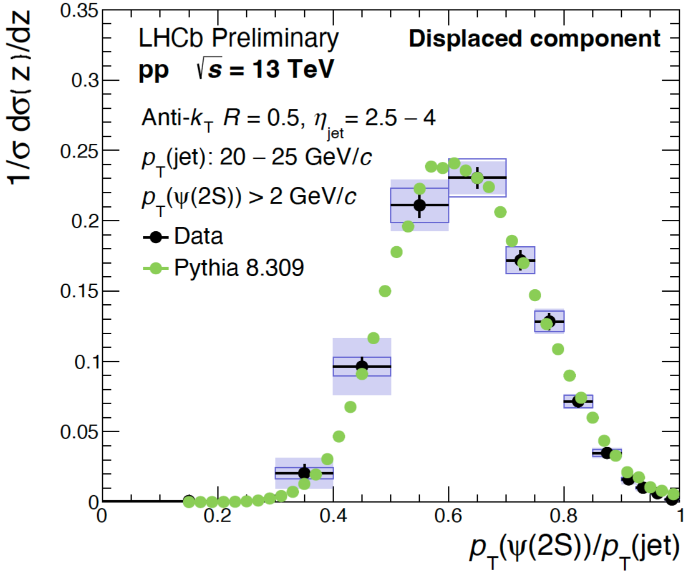
$b \rightarrow \psi$(2S) : well described by PYTHIA

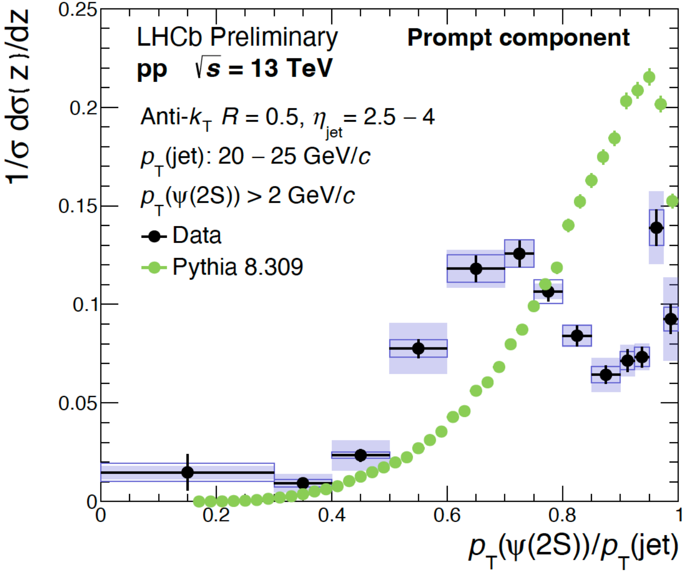
Very similar to $b \rightarrow J/\psi$

ψ(2S) in jets

- The same measurement can also be done with $\boldsymbol{\psi}$(2S)
  - Very little feeddown, unlike $\boldsymbol{J/\psi}$

LHCb-PAPER-2024-021





$\boldsymbol{b \rightarrow \psi}$(2S) : well described by PYTHIA
Very similar to $\boldsymbol{b \rightarrow J/\psi}$

Prompt: less isolated than NRQCD prediction
Two component structure: different production mechanisms?

$X(3872)$ in jets

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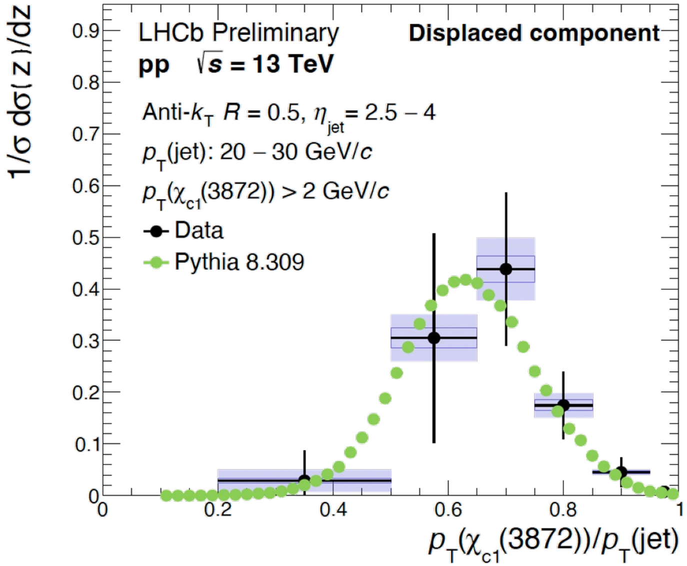

$b \rightarrow X(3872)$: well described by PYTHIA

Very similar to $b \rightarrow J/\psi$

$X(3872)$ in jets

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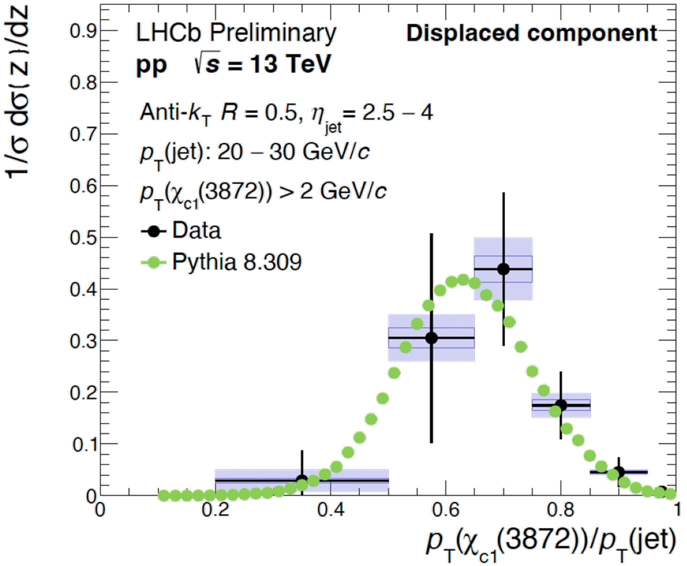
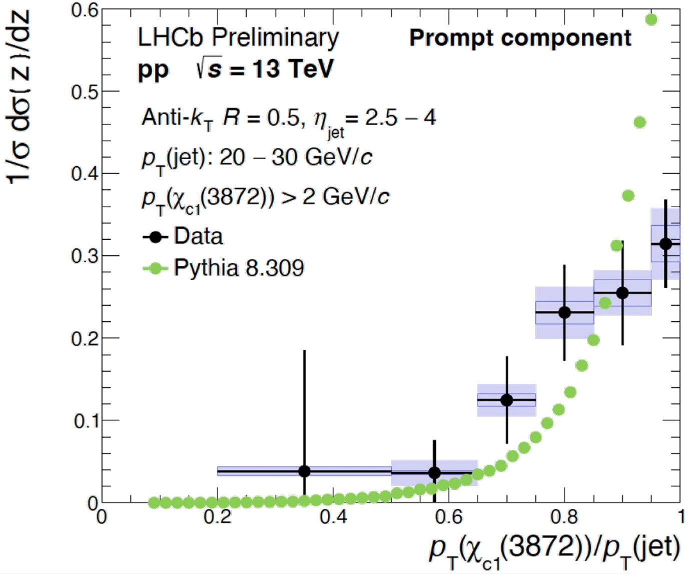
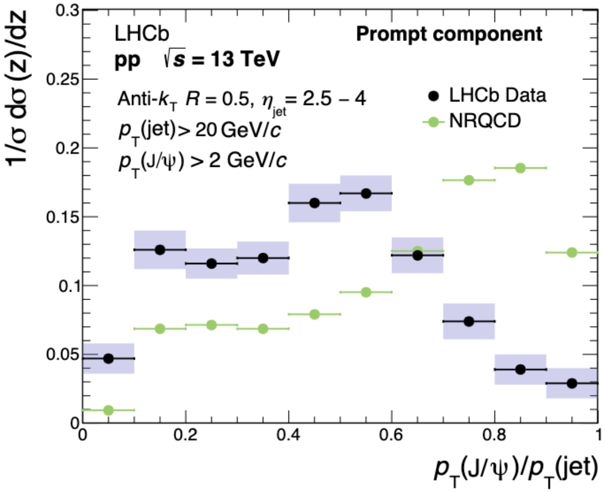




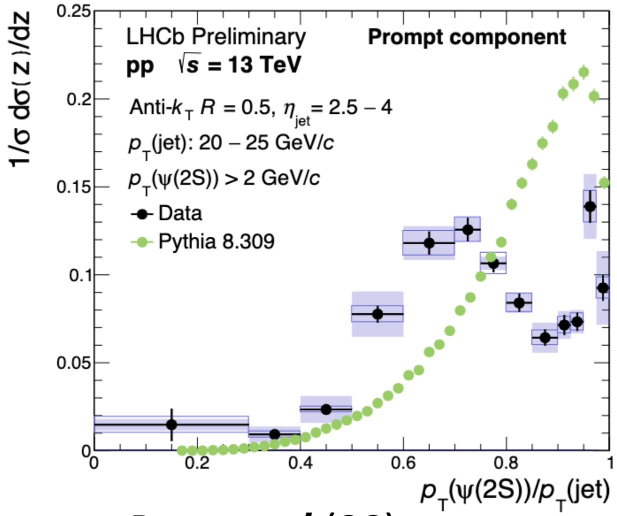
$b \rightarrow X(3872)$: well described by PYTHIA
Very similar to $b \rightarrow J/\psi$

Prompt: Rises towards isolation, very different from conventional $c\bar{c}$ state ψ(2S)

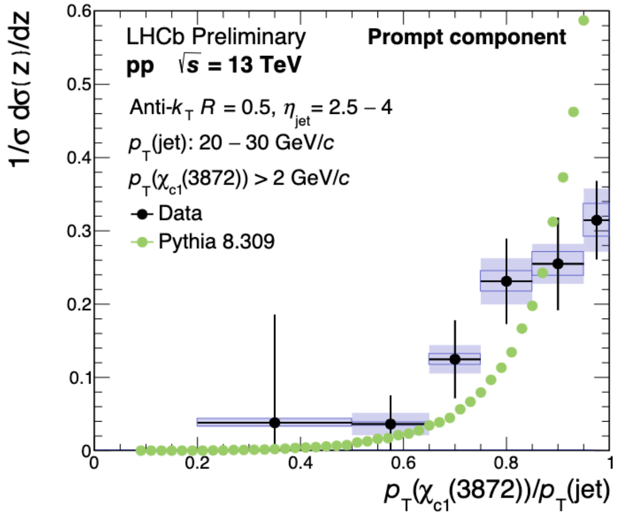
Compare: prompt J/ψ , ψ(2S), X(3872)



Prompt J/ψ: less isolated than expected



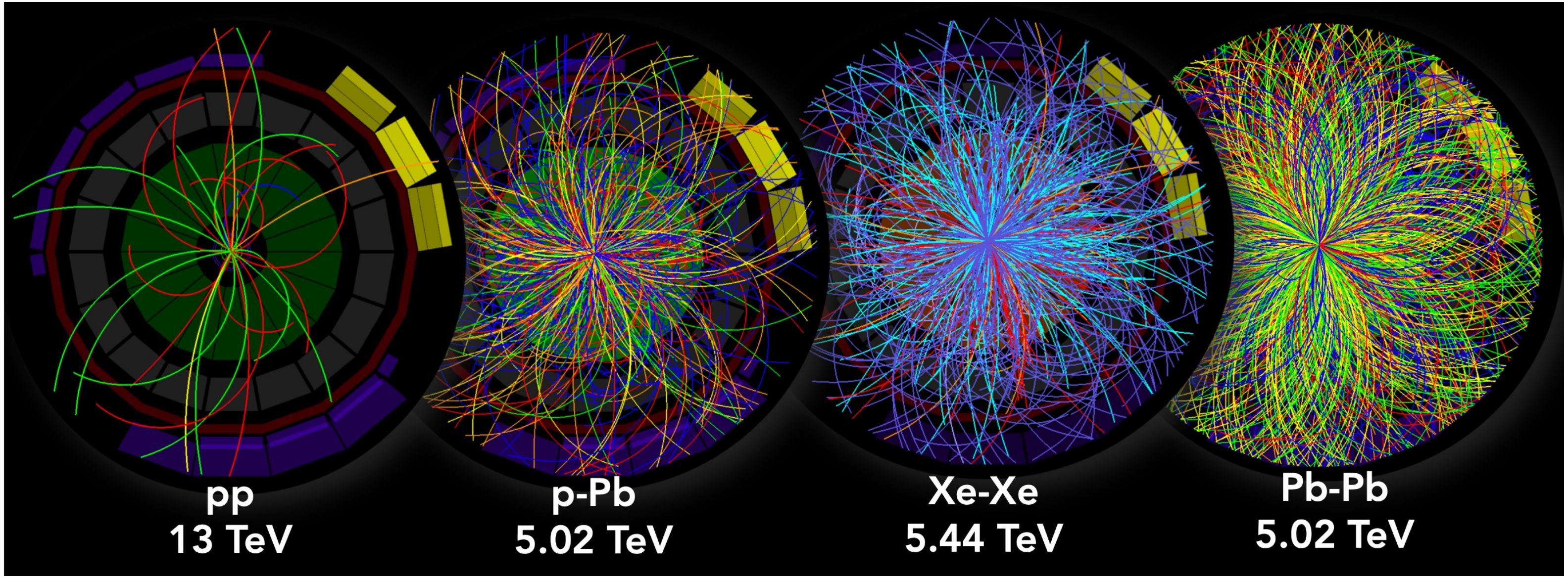
Prompt ψ(2S):
Two component structure:
Different production mechanisms?



Prompt X(3872):
More isolated than conventional charmonia

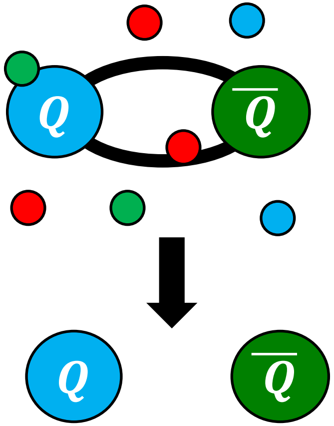
Heavy $Q\bar{Q}$ states in the QCD medium

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



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

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

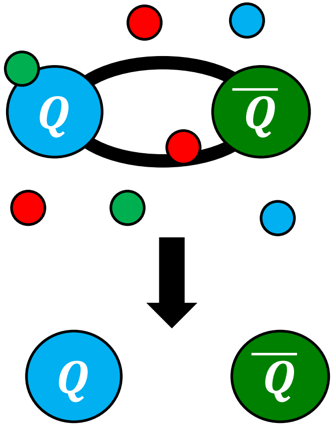


Dissociation via interactions with comoving particles

Sensitive to binding energy

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

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



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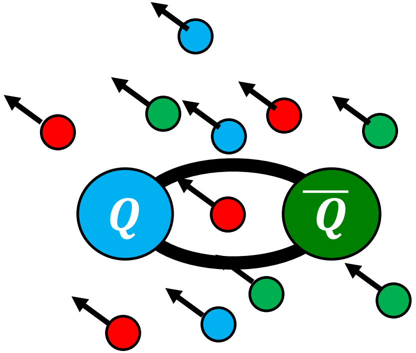
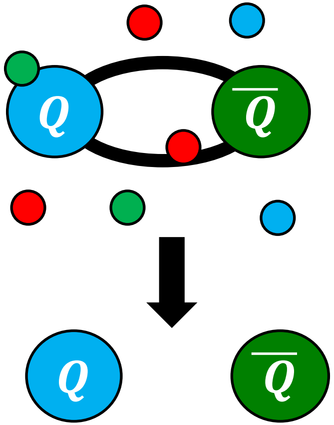


Hydrodynamic flow induced by pressure gradients (initial state?)

Sensitive to number of constituent quarks n_{cq}

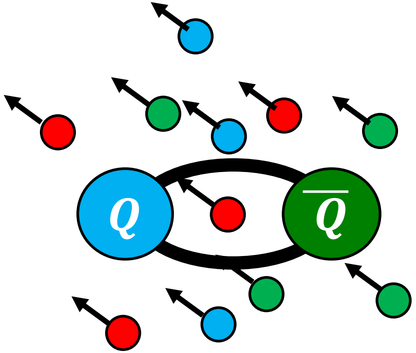
Heavy $Q\bar{Q}$ states in the QCD medium

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



Dissociation via interactions with comoving particles

Sensitive to binding energy



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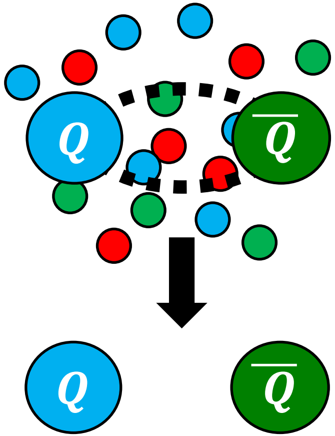
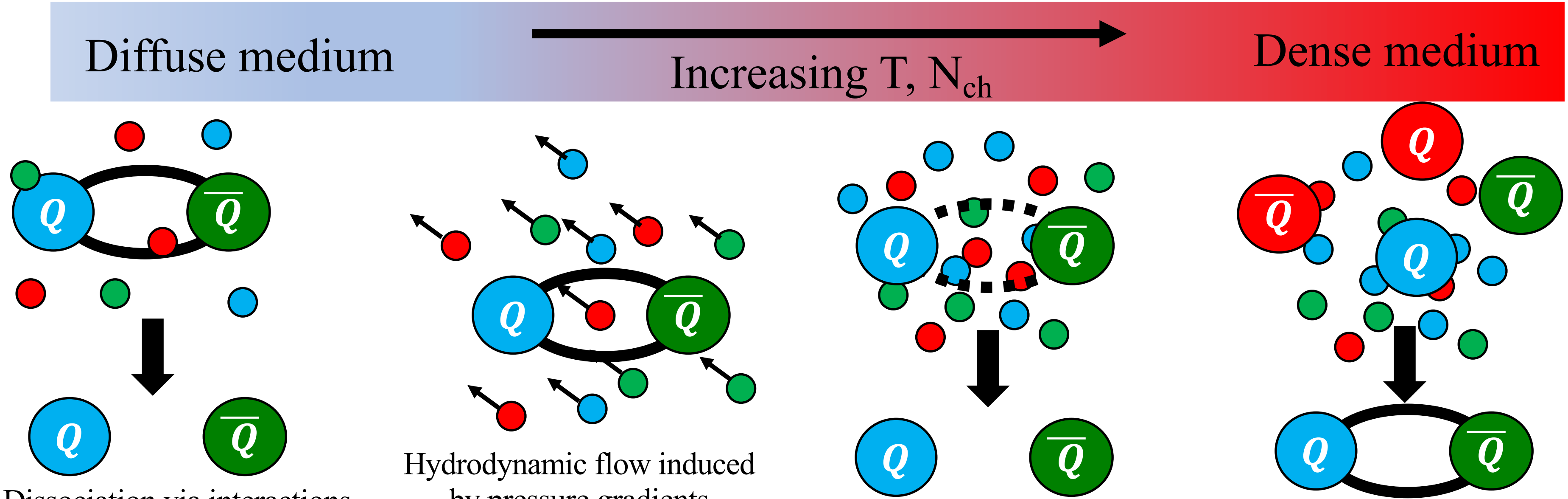


Suppression via color screening

Sensitive to binding energy and medium temperature

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



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}

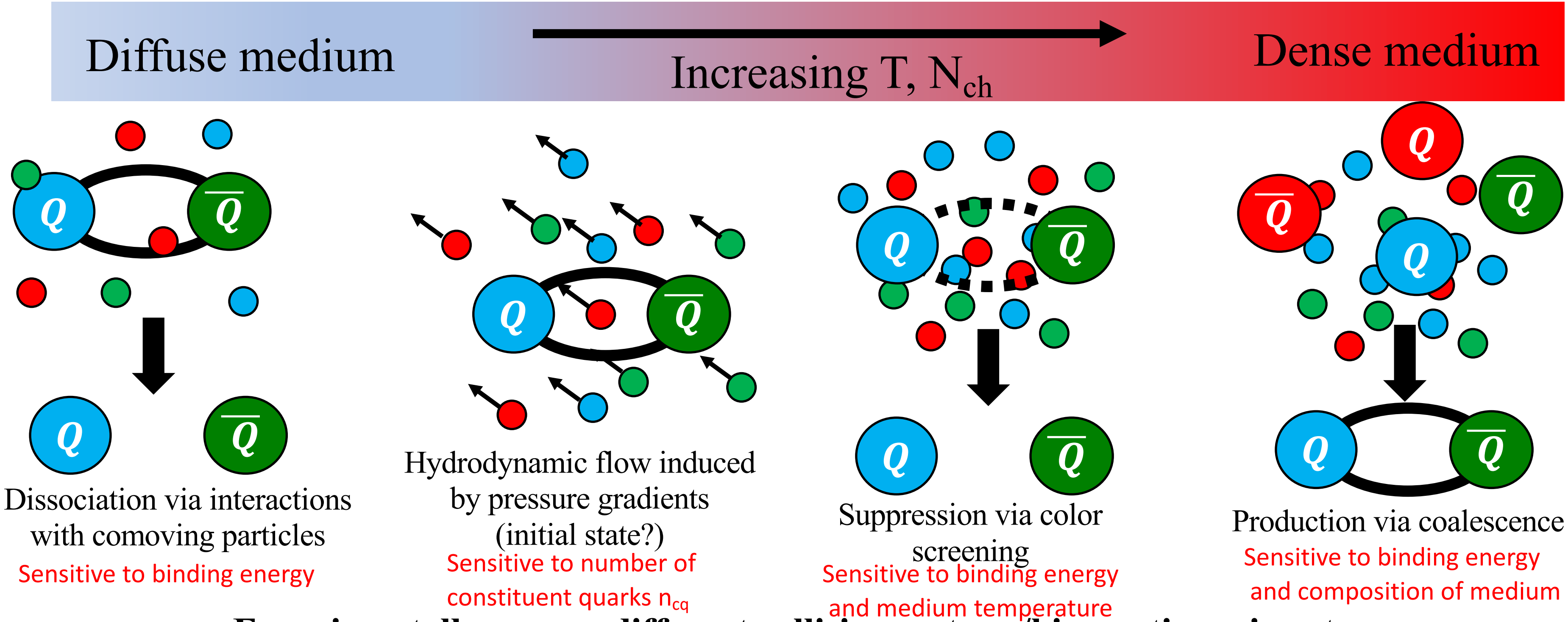
Suppression via color screening

Sensitive to binding energy and medium temperature

Production via coalescence

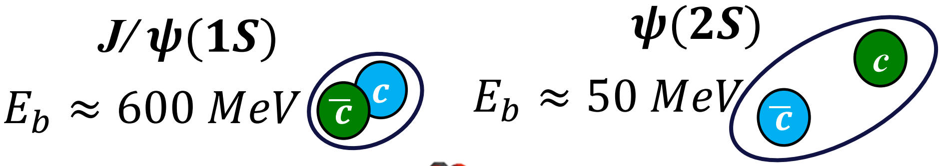
Sensitive to binding energy and composition of medium

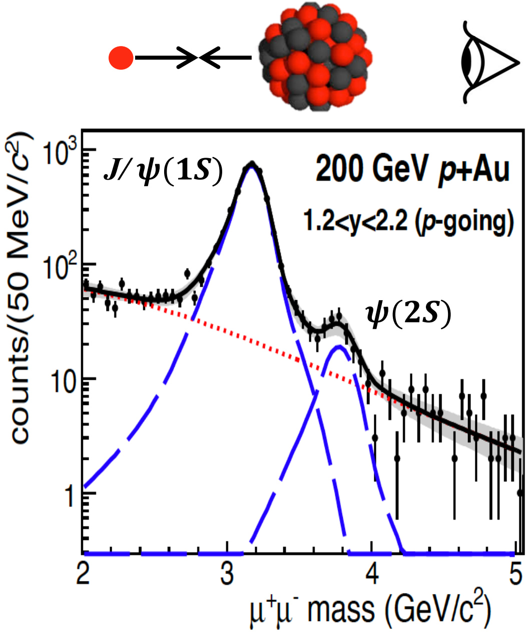
Heavy $Q\bar{Q}$ states in the QCD medium



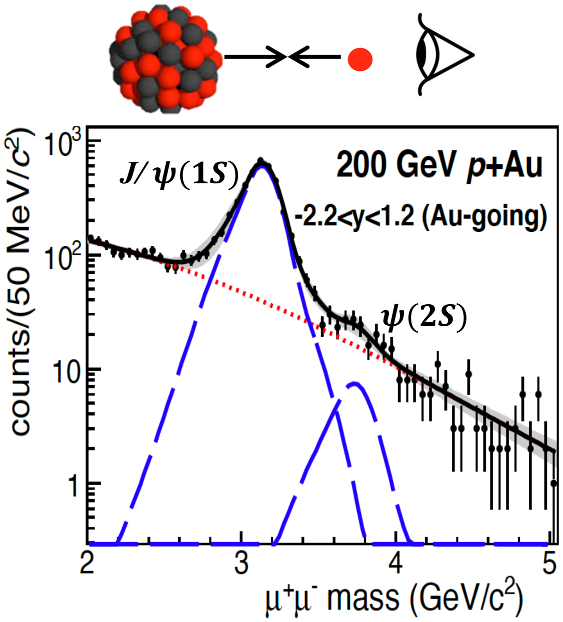
Experimentally, we use different collision systems/kinematic regions to prepare environments where these different competing effects dominate.

Example: $\psi(2S)$ suppression





Relatively *low* particle density

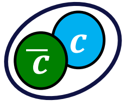


Relatively *high* particle density

Example: $\psi(2S)$ suppression

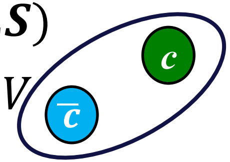
$J/\psi(1S)$

$E_b \approx 600\ MeV$



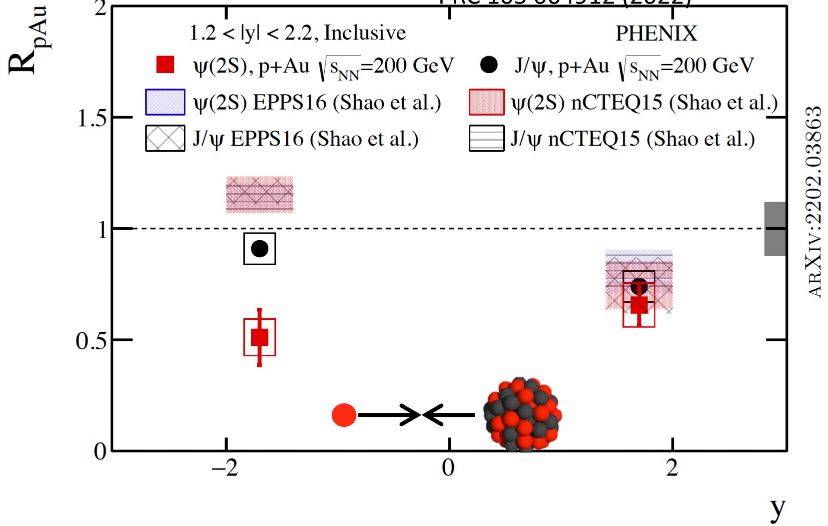
$\psi(2S)$

$E_b \approx 50\ MeV$



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

PRC 105 064912 (2022)

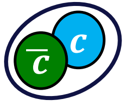


- Weakly bound $\psi(2S)$ state more suppressed than J/ψ in nucleus-going direction

Example: $\psi(2S)$ suppression

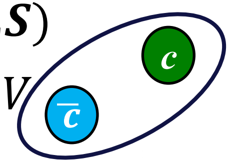
$J/\psi(1S)$

$E_b \approx 600\ MeV$



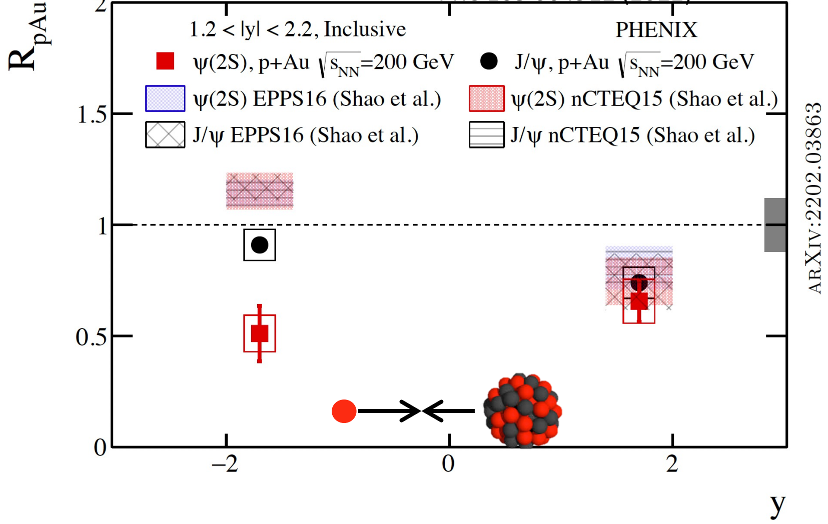
$\psi(2S)$

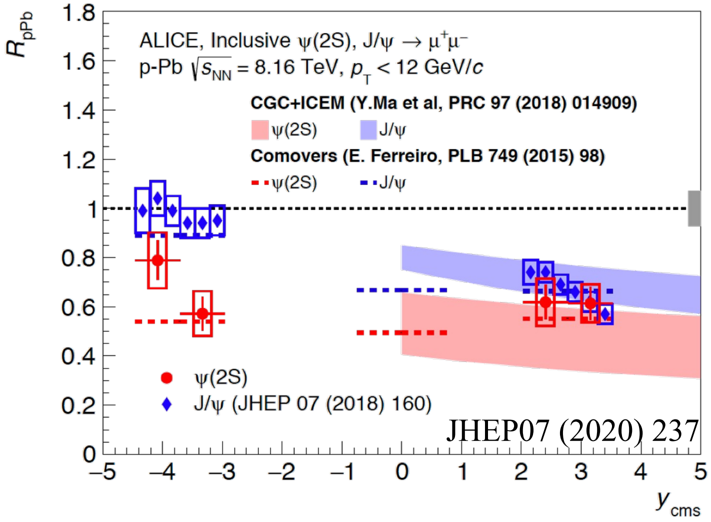
$E_b \approx 50\ MeV$



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

PRC 105 064912 (2022)





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

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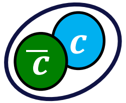

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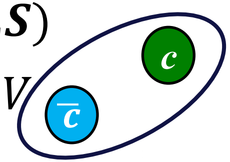

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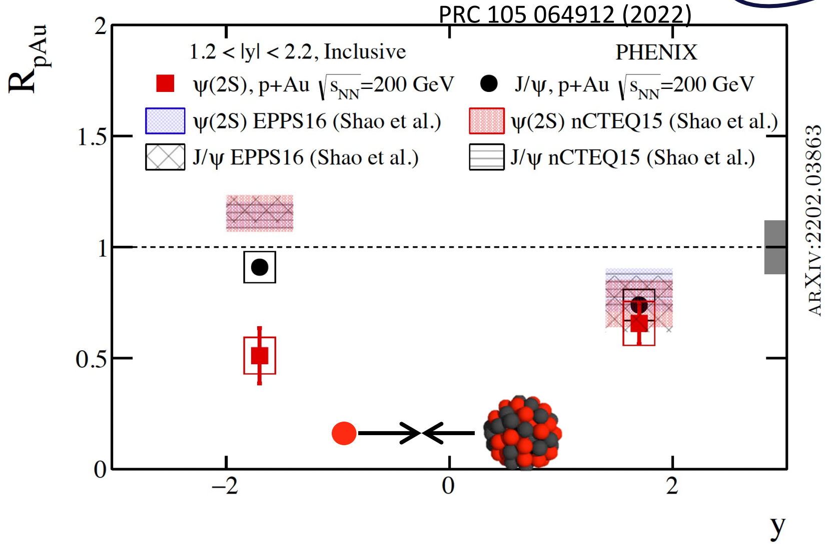
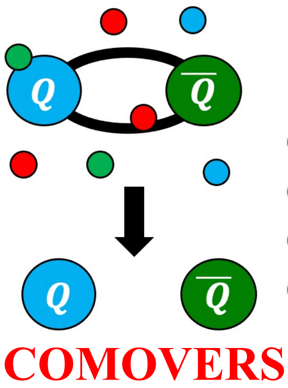
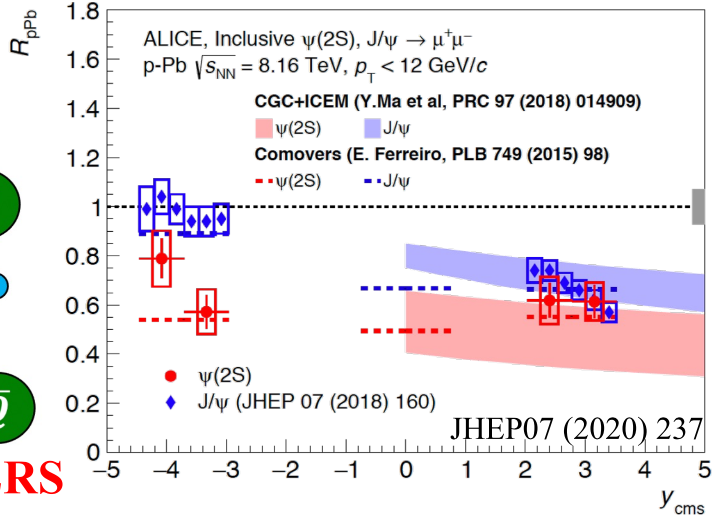
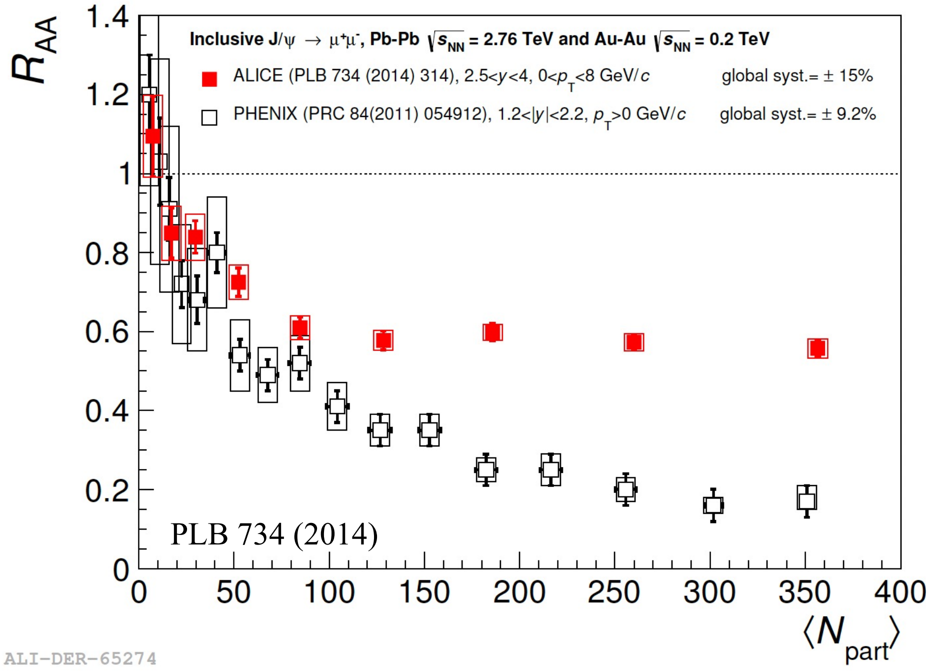






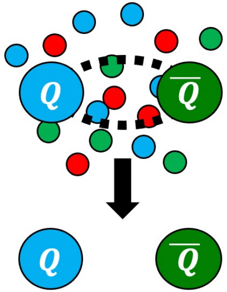
- Weakly bound $\psi(2S)$ state more suppressed than J/ψ in nucleus-going direction
- Models require some final-state interaction to reproduce data
- Quark-gluon plasma not expected to be dominant effect in small collision systems

Example: J/ψ in AA - RHIC vs LHC



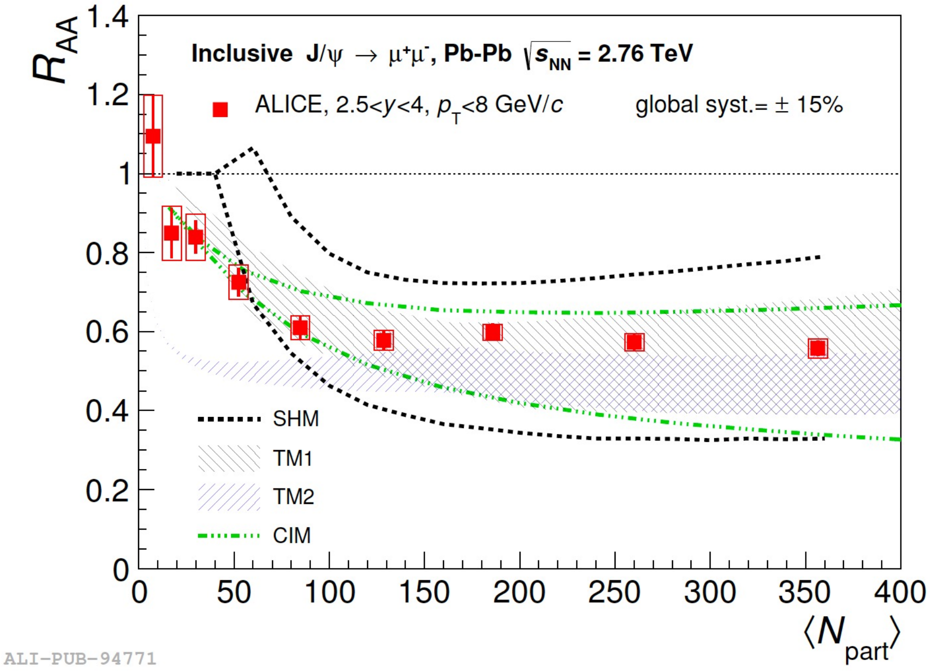
$$R_{AA} = \frac{\sigma_{AA}}{N_{coll} \times \sigma_{pp}}$$

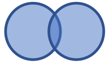
- J/ψ modification quite different between RHIC and LHC
- Charm cross section at LHC ~10x cross section at RHIC



COLOR SCREENING

Example: J/ψ in AA - RHIC vs LHC





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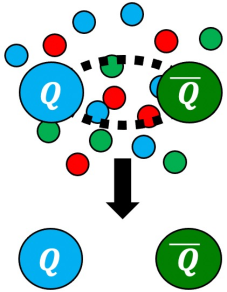
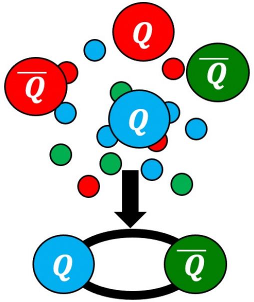
- Models which incorporate J/ψ production via charm coalescence describe data





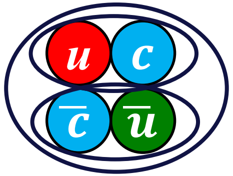
COLOR SCREENING + CHARM COALESCENCE

Los Alamos NATIONAL LABORATORY

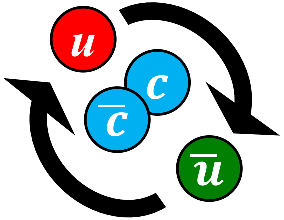
Application to exotics

- 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

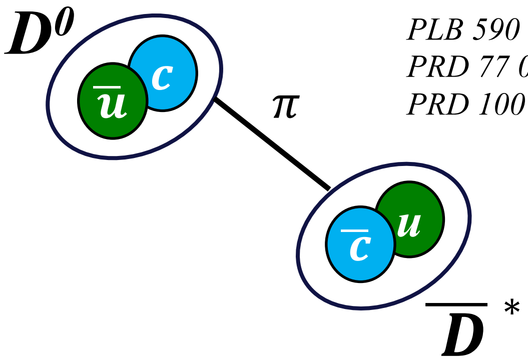


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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

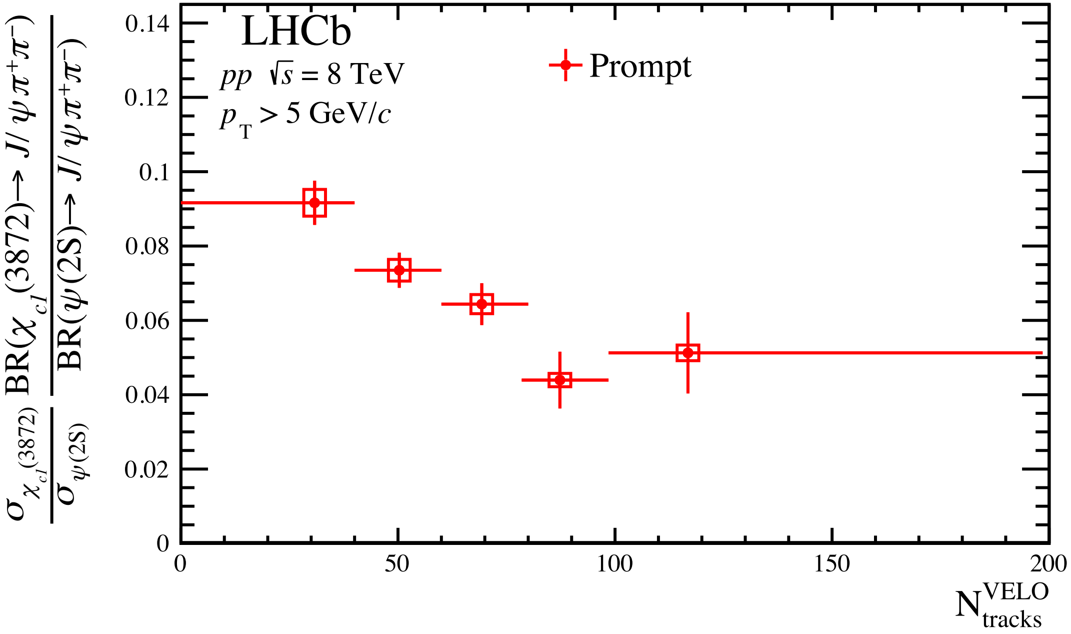
Molecule



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

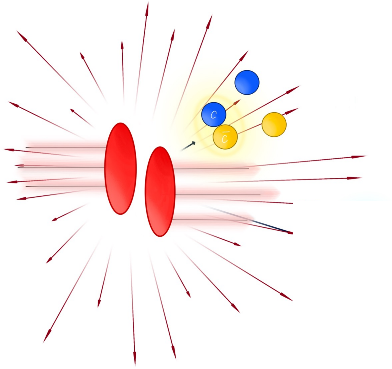
X(3872)/ψ(2S) vs multiplicity

PRL 126, 092001 (2021)

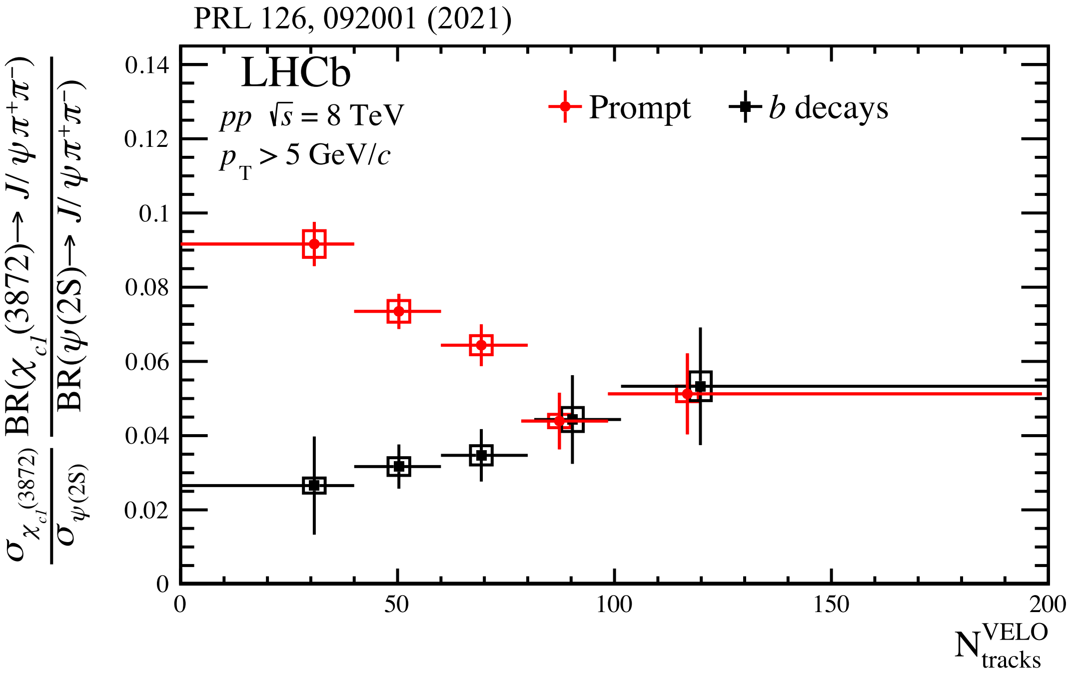


Prompt component:

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



X(3872)/ψ(2S)



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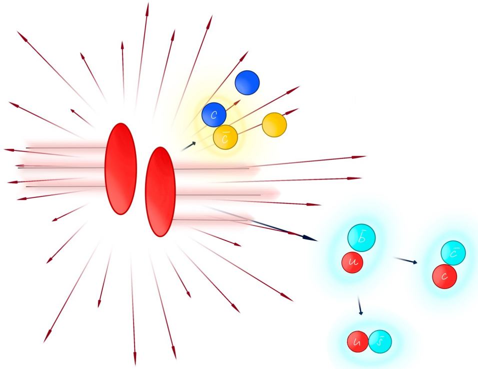
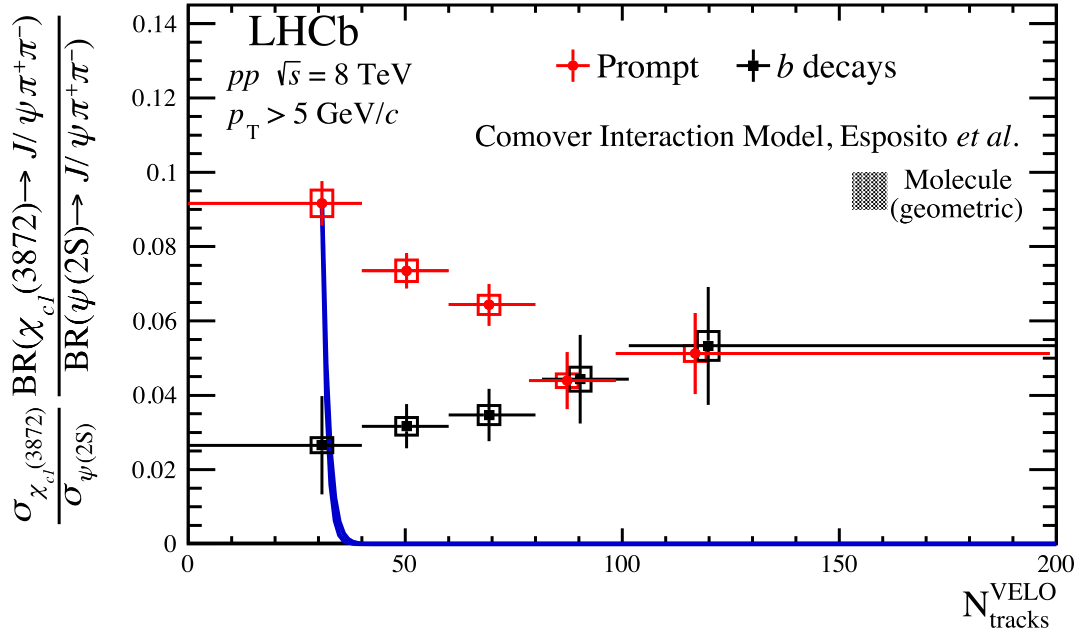
***b*-decay component:**

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



X(3872)/ψ(2S)

PRL 126, 092001 (2021)



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Calculations from EPJ C 81, 669 (2021)

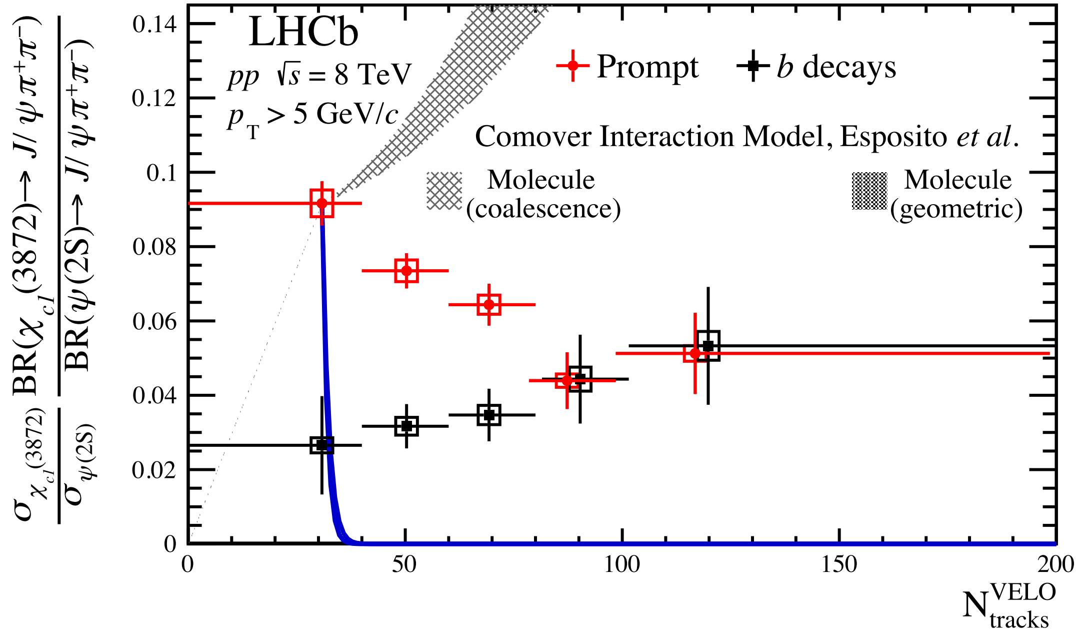
Break-up cross section:

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

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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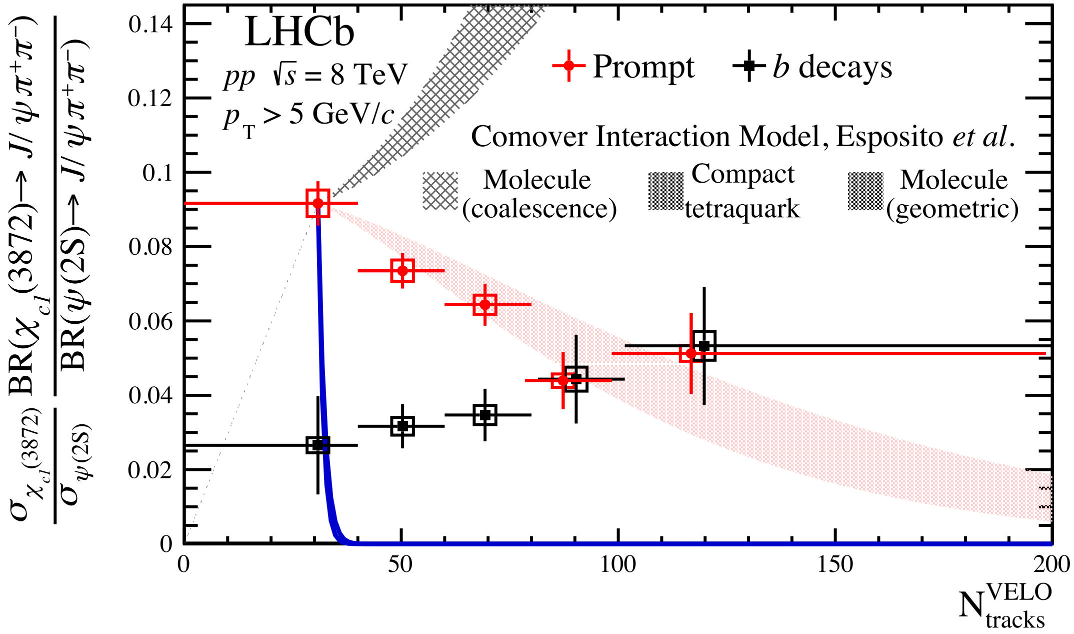

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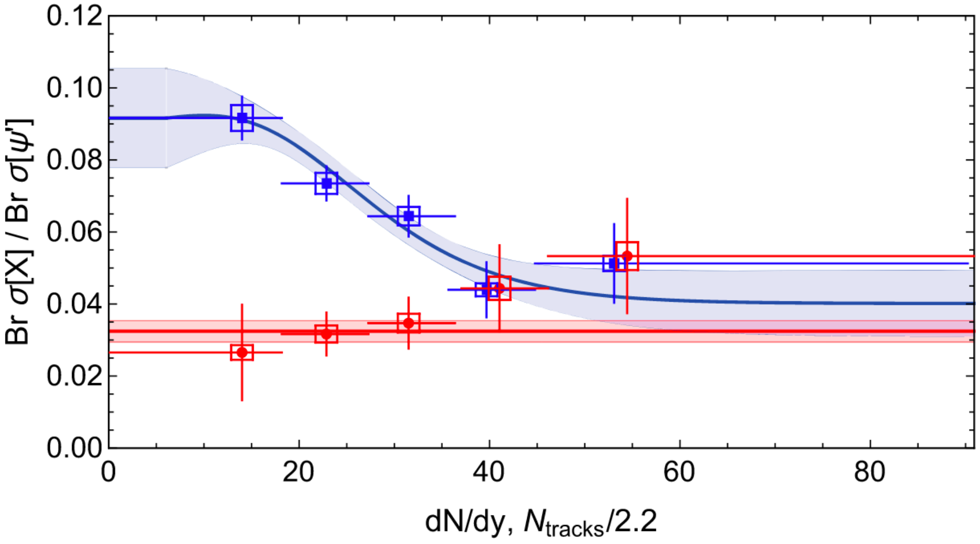
Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases – consistent with data

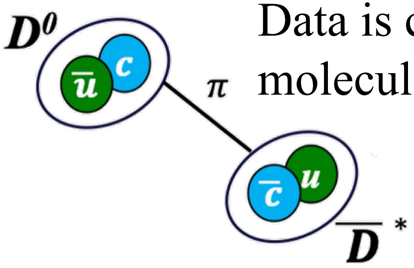
Comover model: constituent interaction

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:

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



Data is consistent with this molecular interpretation.

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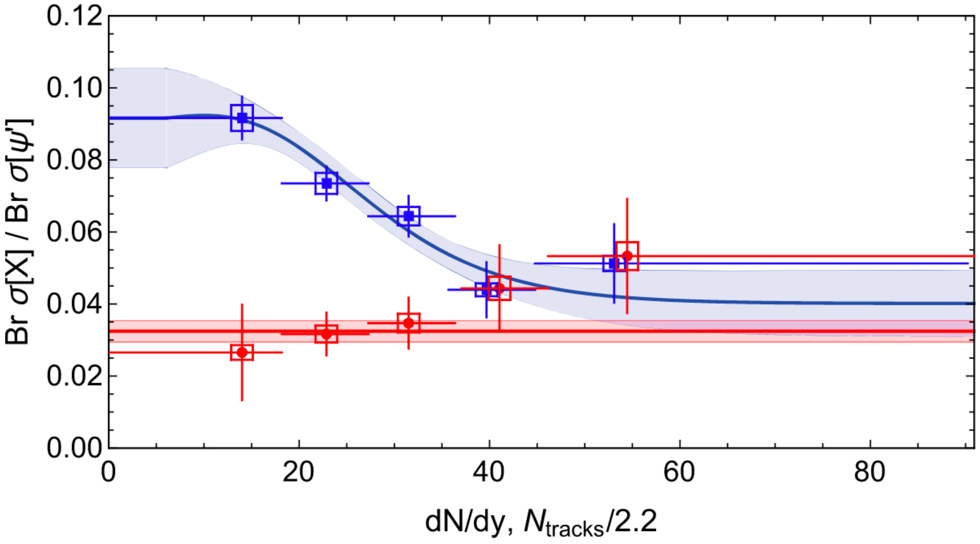

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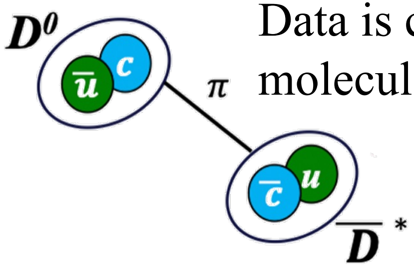

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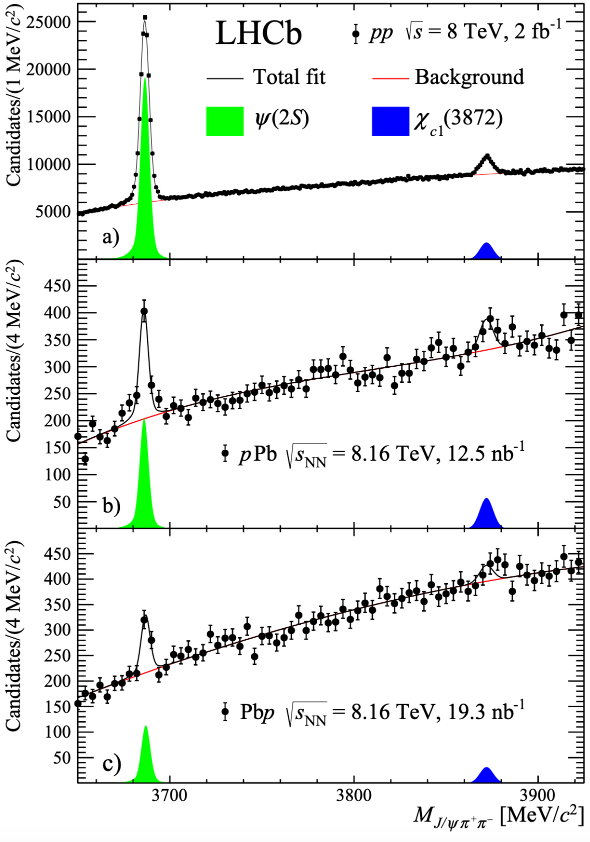
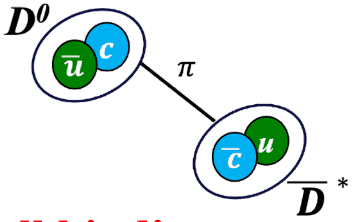
X(3872) in *p*Pb

PRL 132 242301 (2024)

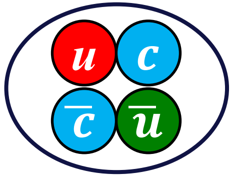


$D^0\overline{D}^*$ *Molecule*



small binding energy
large radius, ~5 fm

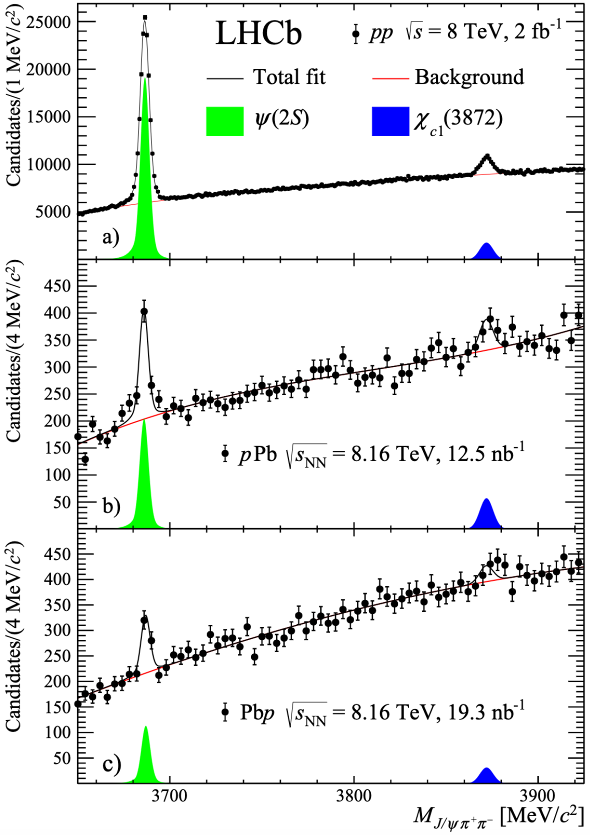
Compact tetraquark

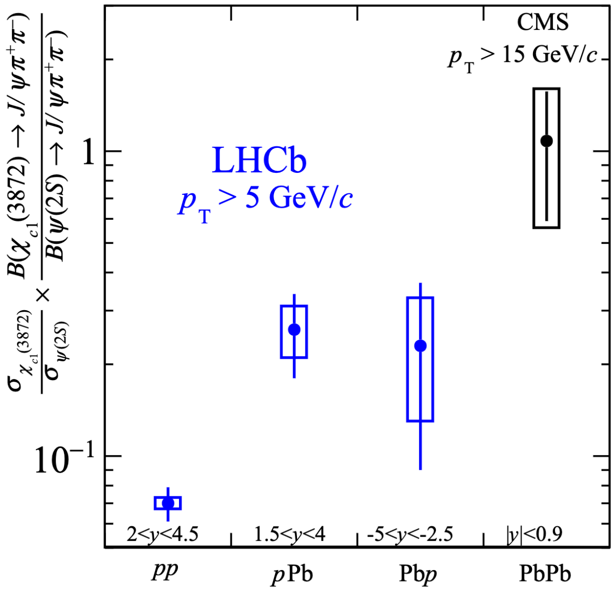


Tightly bound via color exchange between diquarks
***Small* radius, ~1 fm**

X(3872) in *p*Pb

PRL 132 242301 (2024)





Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium

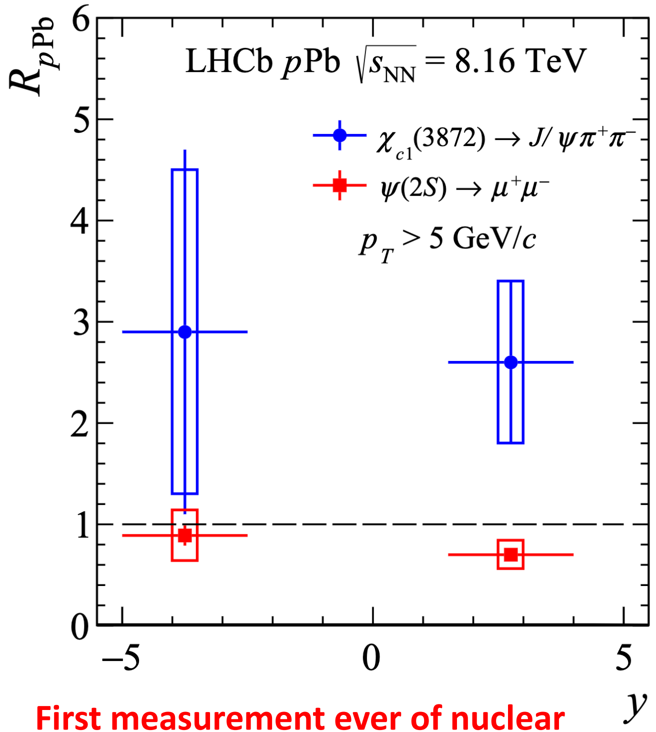
Initial state effects (eg shadowing) should largely cancel in ratio

Enhancing effects start to out compete breakup?
- arXiv:2302.03828

Prompt X(3872)/ ψ(2S) = 0.26 ± 0.08 ± 0.05 in forward pPb
Prompt X(3872)/ ψ(2S) = 0.23 ± 0.15 ± 0.10 in backward pPb
Falls between pp (~0.1) and PbPb (~1.0)
AMBIGUITY between X(3872) enhancement and ψ(2S) suppression

X(3872) in *p*Pb

PRL 132 242301 (2024)



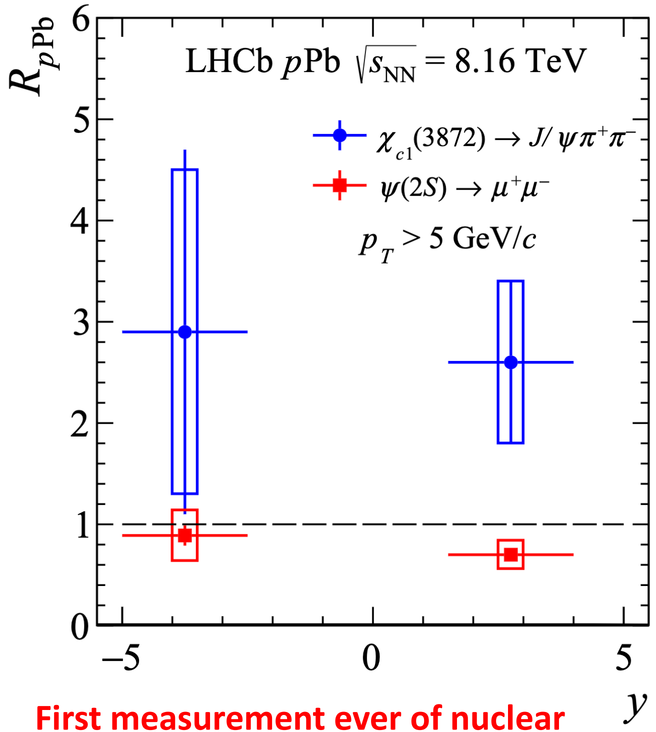
First measurement ever of nuclear modification factor of a tetraquark

Ambiguity lifted by measuring nuclear modification factors:

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

X(3872) in pPb

PRL 132 242301 (2024)



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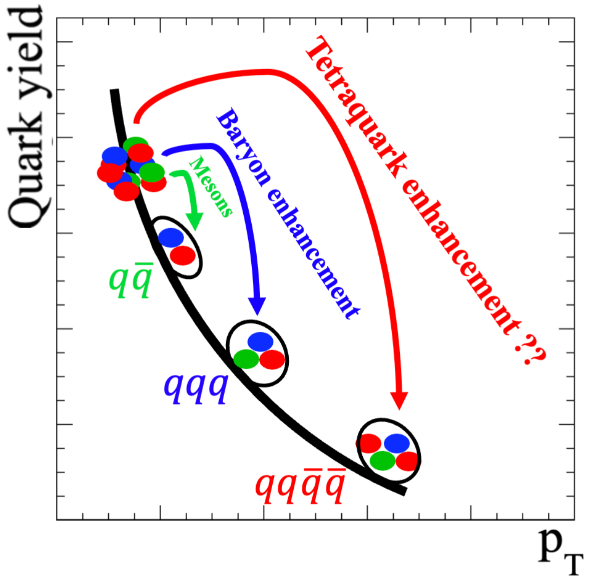
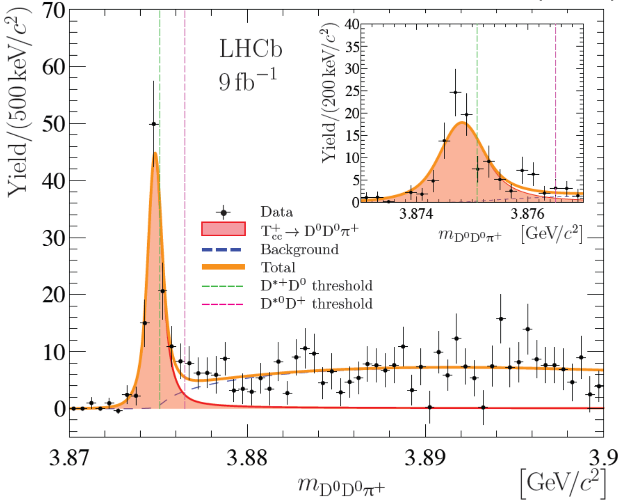
Evidence for enhancement of X(3872) in pPb: Coalescence dominating over breakup?

Similar mechanism for baryon enhancement could also increase tetraquark production



T_{cc}^{+}

Nature Communications, 13, 3351 (2022)

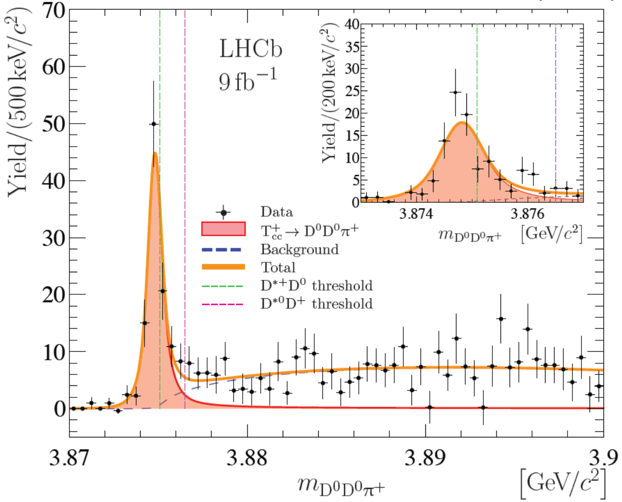


New state consistent with $cc\bar{u}\bar{d}$ tetraquark recently found:

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

T_{cc}^{+}

Nature Communications, 13, 3351 (2022)



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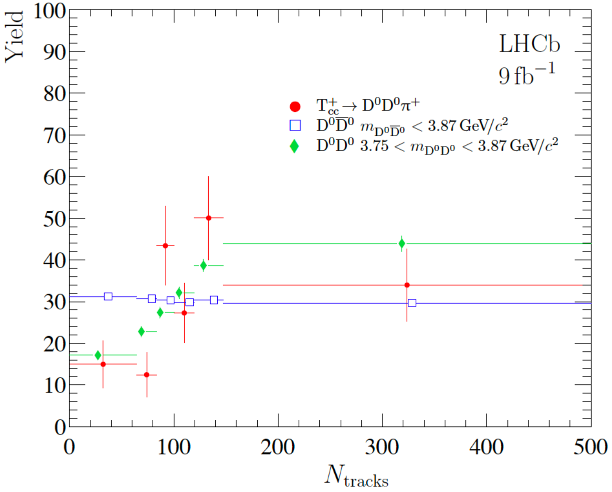
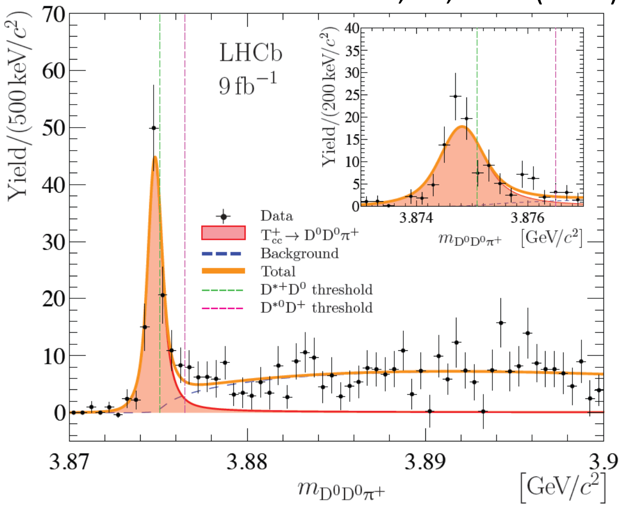


Compare T_{cc}^{+} multiplicity dependence with:
$D\bar{D}$ distribution, dominated by SPS
DD distribution, dominated by DPS

T_{cc}^{+}

Nature Communications, 13, 3351 (2022)



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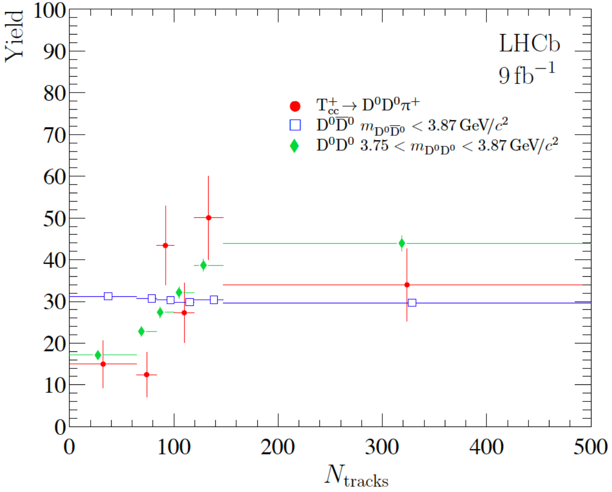
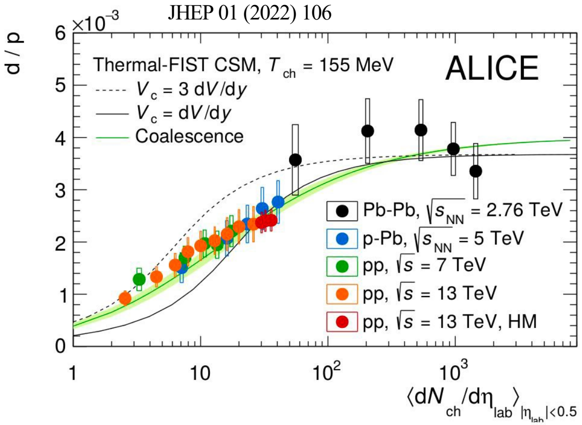


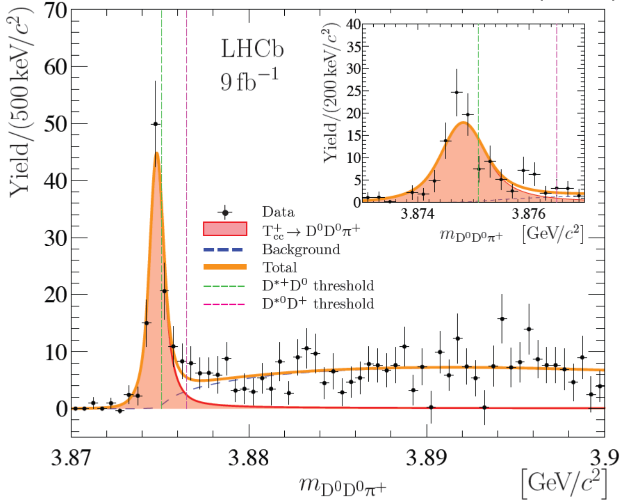


Yield favors higher multiplicity collisions, reminiscent of deuteron.

Evidence for hadronic molecule structure?

T_{cc}^{+}

Nature Communications, 13, 3351 (2022)



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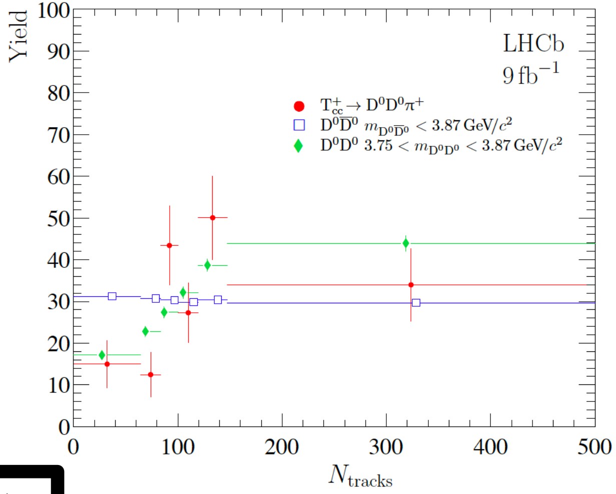
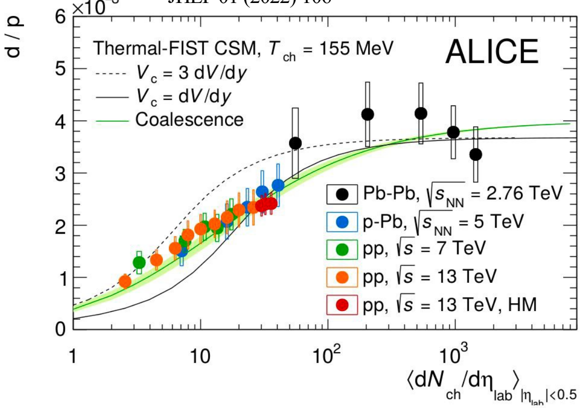


JHEP 01 (2022) 106



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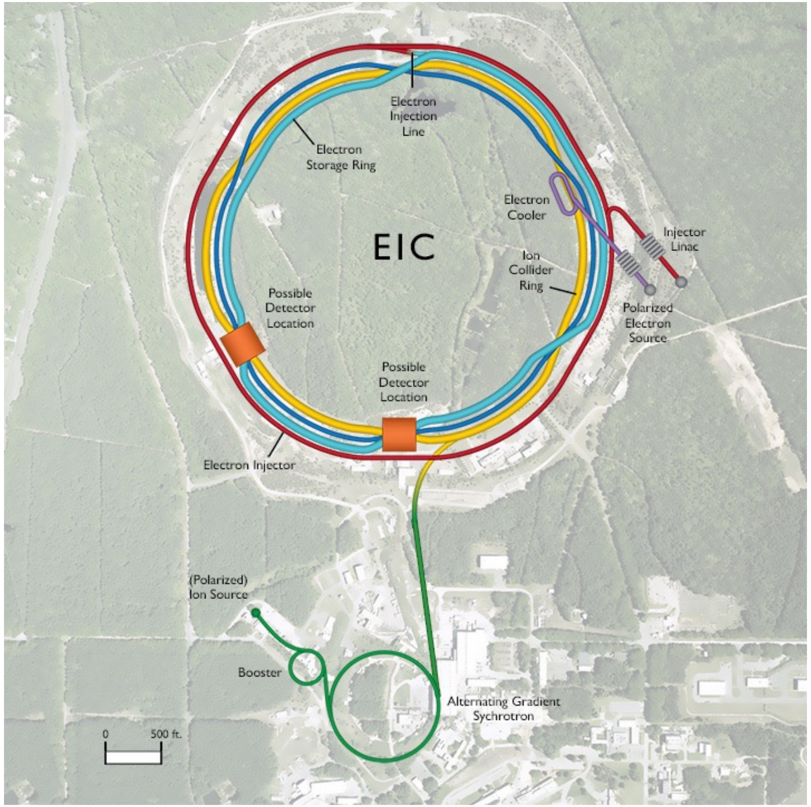
DD distribution, dominated by DPS

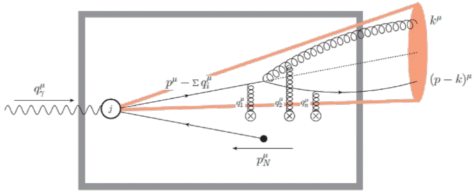
HUGE enhancement expected in PbPb due to coalescence: PRD 104 L111502 (2021)

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

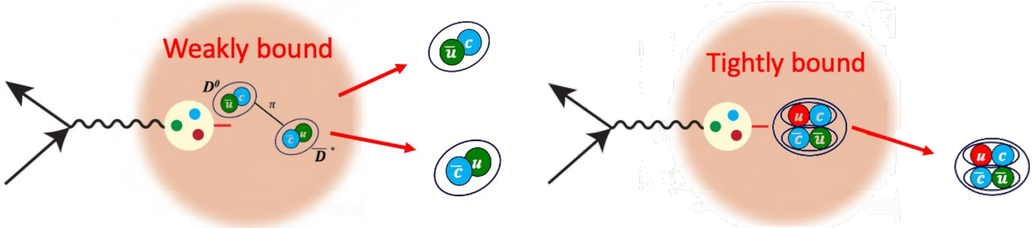
What can EIC tell us about exotics



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

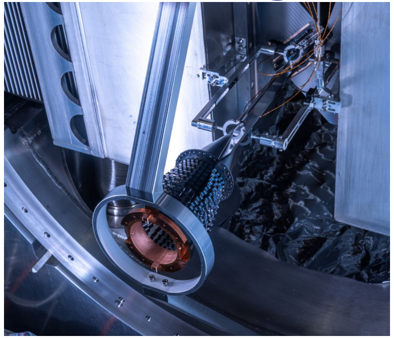


Vitev, 1912.10965



At EIC, use nucleus as a filter to select tightly versus weakly bound states

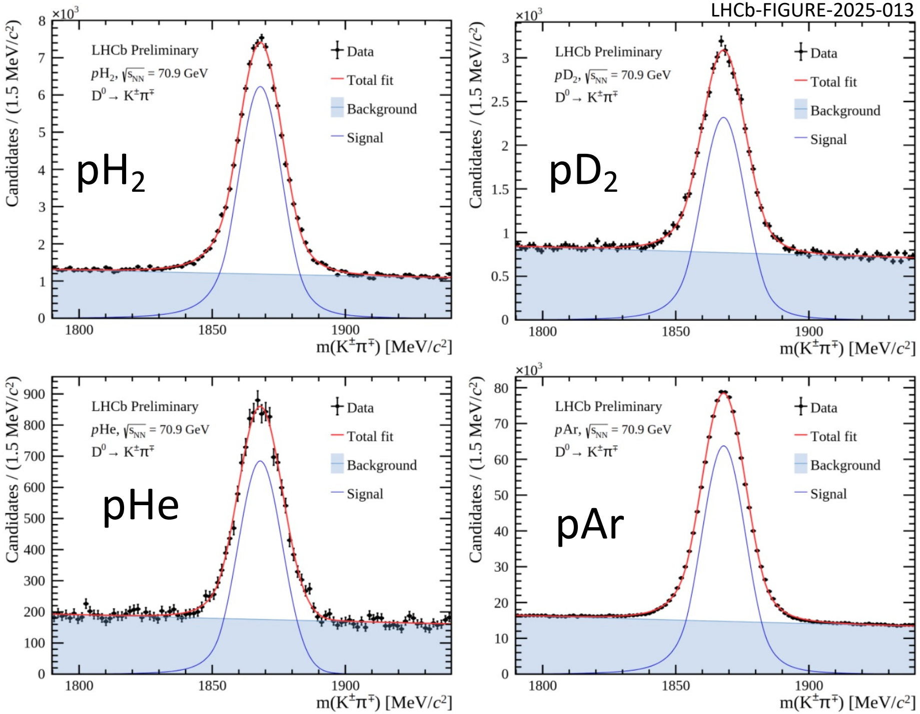
Probing a similar energy range at LHCb



SMOG2: gas storage cell in front of LHCb spectrometer

Operates during *pp* and heavy ion collisions at LHC

2024 SMOG2 data



- New SMOG2 data can have a significant impact on hadronization inside the nucleus in years leading to EIC

- A similar fixed target capability at the EIC could provide:
  - 18 GeV e + gas collisions
  - $\sqrt{s_{NN}}$ ~15 GeV beam+gas collisions

Summary

- Multiple new observables related to the production and properties of exotic hadrons are under investigation at LHCb (and elsewhere)

- Detailed measurements of medium effects on conventional charmonia is being accumulated. We can flip this around and use the medium to probe poorly understood exotic hadrons

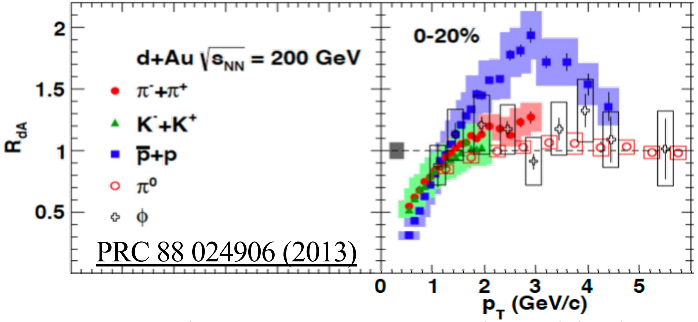
- Utilizing hadronization inside the nucleus at the EIC gives us a new way to probe the structure of exotic hadrons

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

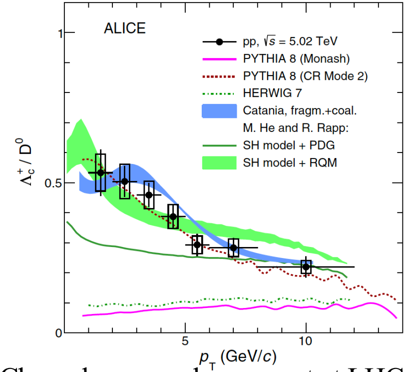
and Dept. of Energy Early Career Awards program

BACKUPS

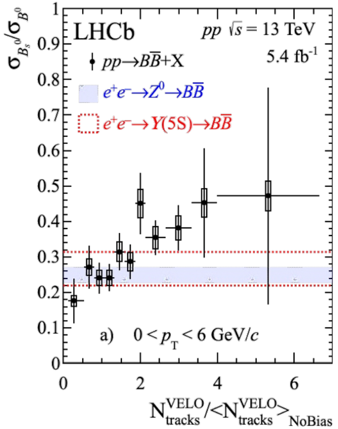
Coalescence in small systems (?)



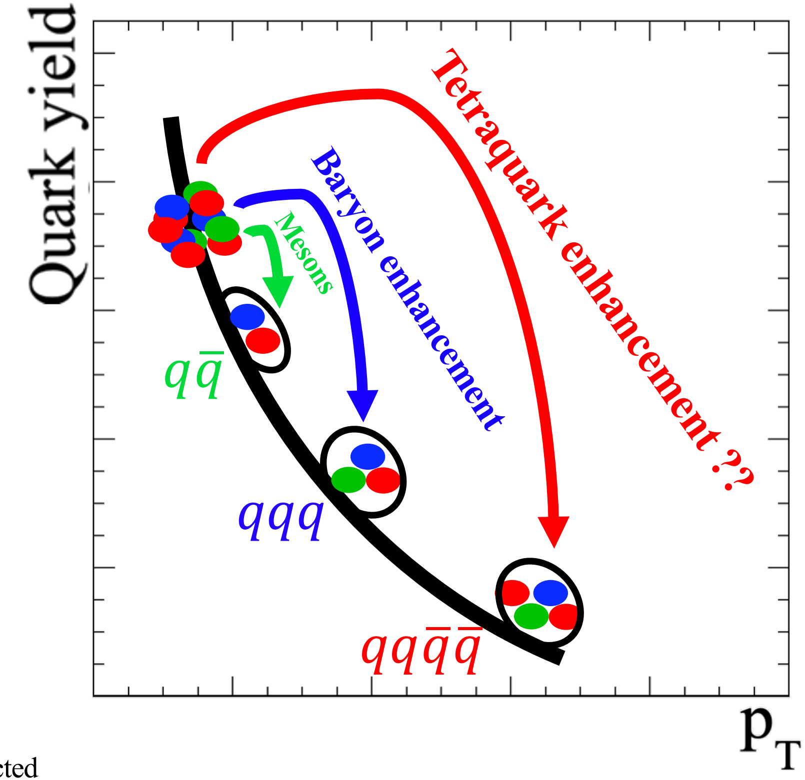
Baryon enhancement at RHIC – can be explained by quark coalescence: PRL 93, 082302 (2004)



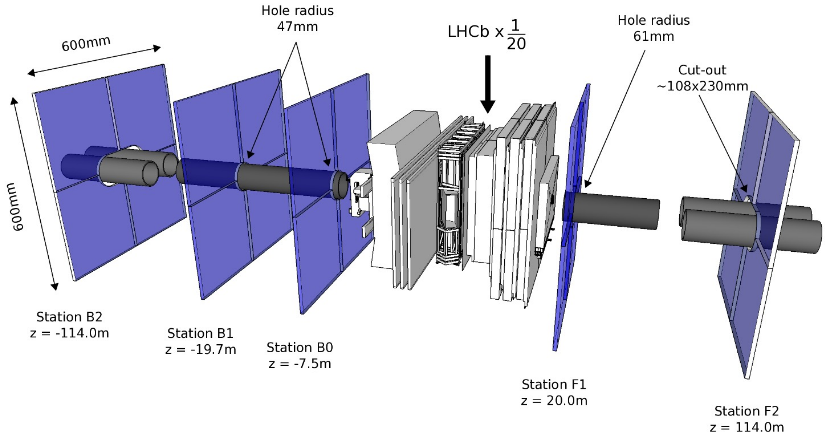
Charm baryon enhancement at LHC relative to e^+e^- – can be explained by coalescence

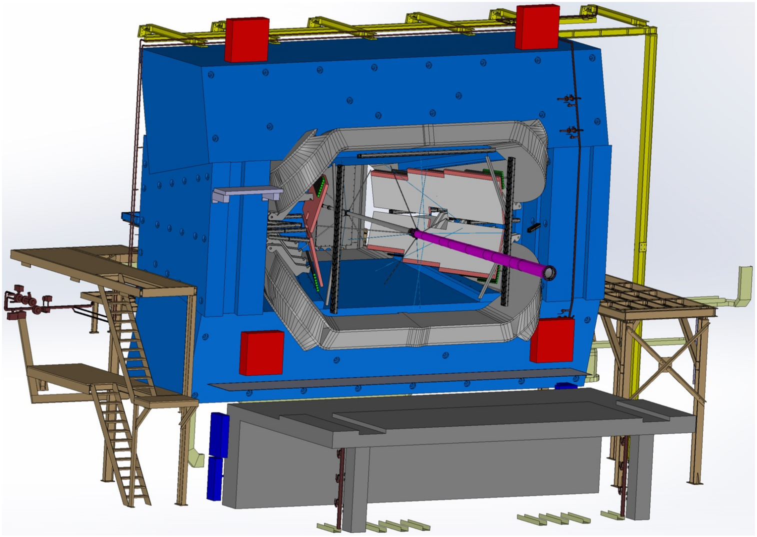


B_s/B^0 enhancement at high mult – expected from coalescence?



LHCb upgrades – directly improving the HI physics program





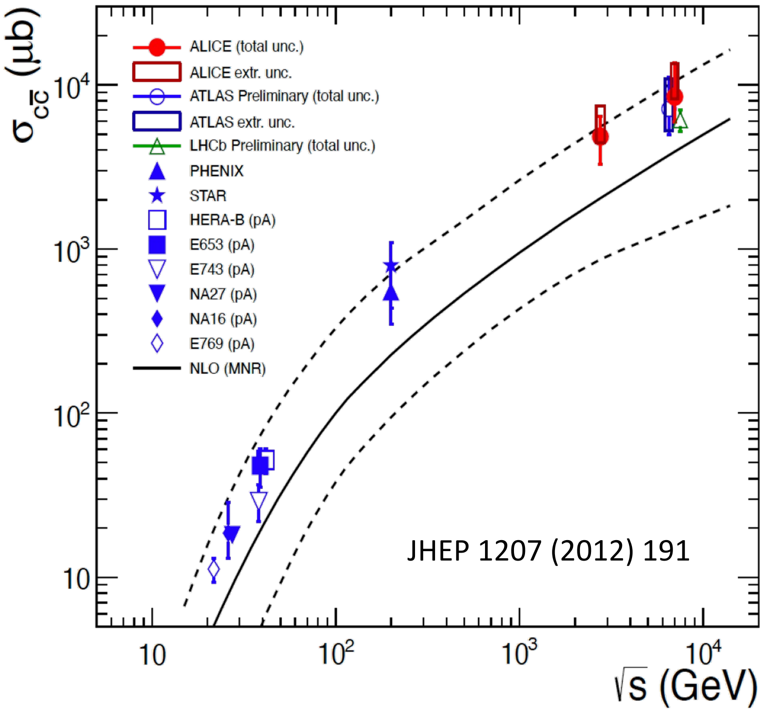
Herschel detector: used to characterized CEP/UPC events by measuring far forward/backward activity. Rad damage and removed after Run 2.

Large Area Scintillator Array for UPCs (LASARUS): Resurrect this capability at LHCb.

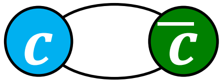
Magnet Station: tracks very soft particles that terminate in dipole.

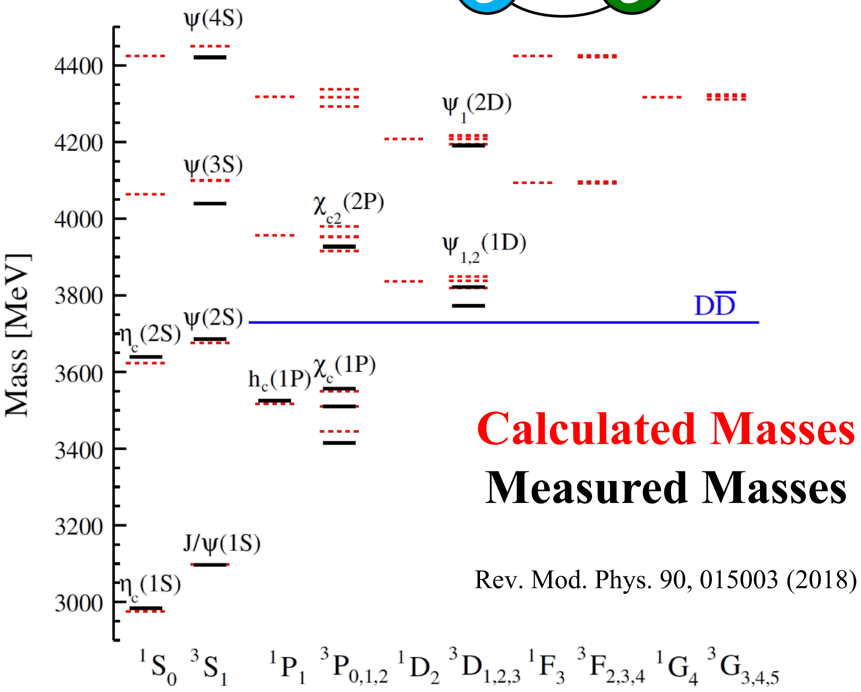
Especially useful for UPC and complex hadronic decay channels of exotics

Conventional charmonia



pQCD describes charm production across wide range of collisions energies

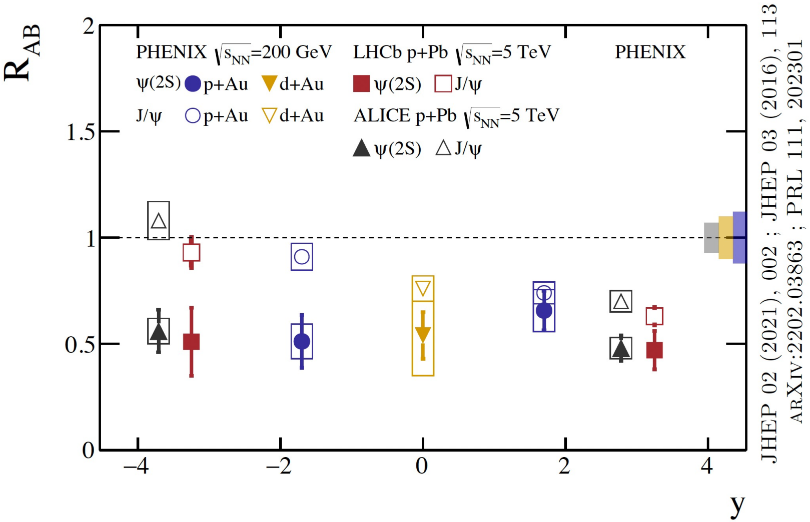




Rich structure of bound quarkonia states accessible experimentally and theoretically

X(3872) /ψ(2S) in *p*Pb

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



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.

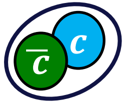
Enhanced DPS has since been observed in pPb:
PRL 125 212001 (2020)

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

Quarkonia in the QCD medium

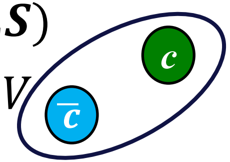
$J/\psi(1S)$

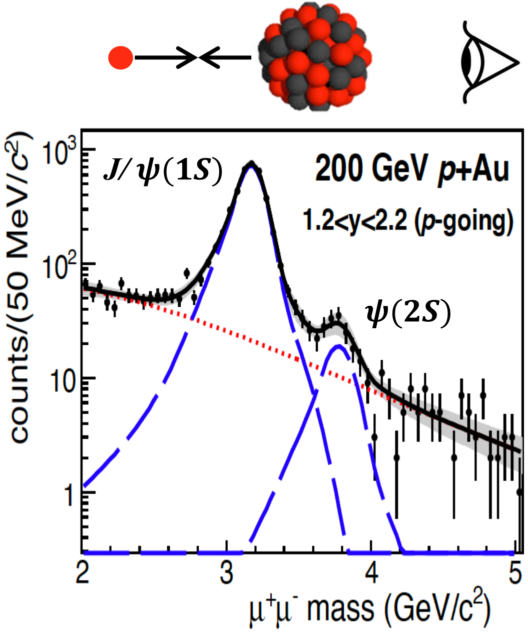
$E_b \approx 600\ MeV$



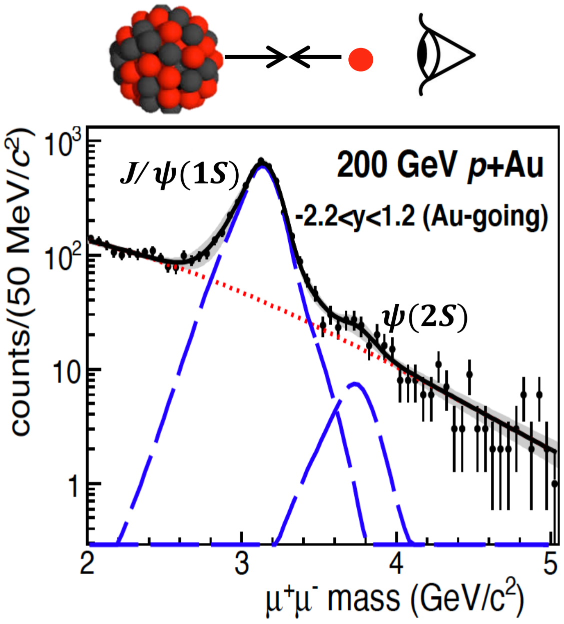
$\psi(2S)$

$E_b \approx 50\ MeV$

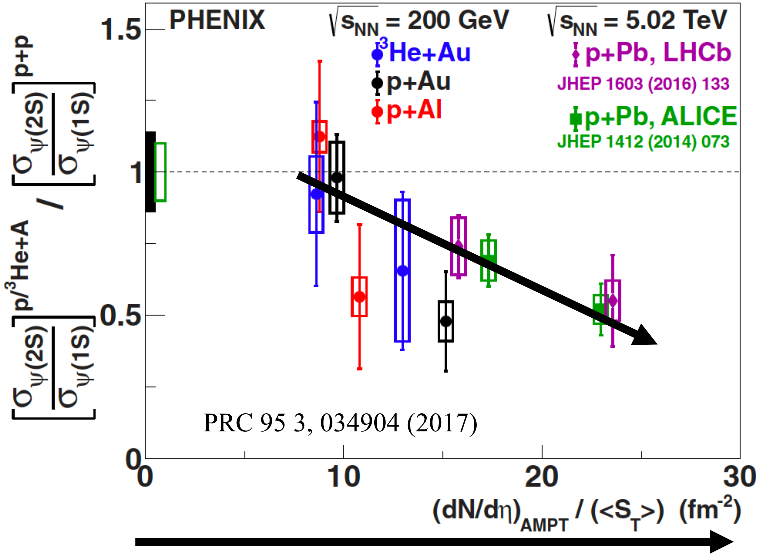




Relatively *low* particle density



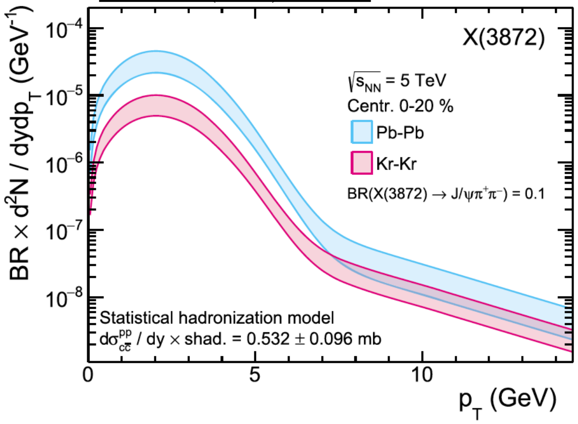
Relatively *high* particle density



Increasing charged particle density

X(3872) in PbPb

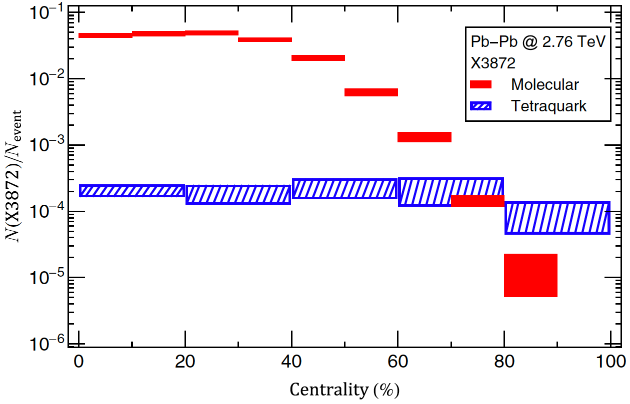
PLB 797 (2019) 134836



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

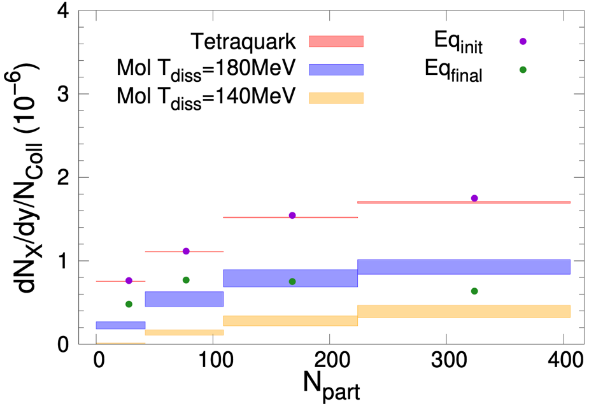
Yield reaches up to ~1% of J/ψ yield

PRL 126 012301 (2021)



AMPT model:
difference in molecule vs diquark-diquark coalescence gives dramatically different yields and centrality dependence:
$N_{molecule} > N_{tetraquark}$

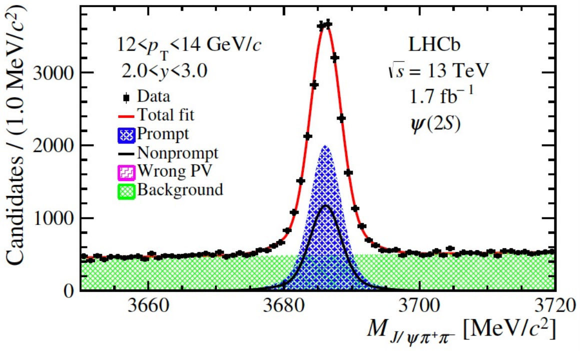
EPJA 57 122 (2021)

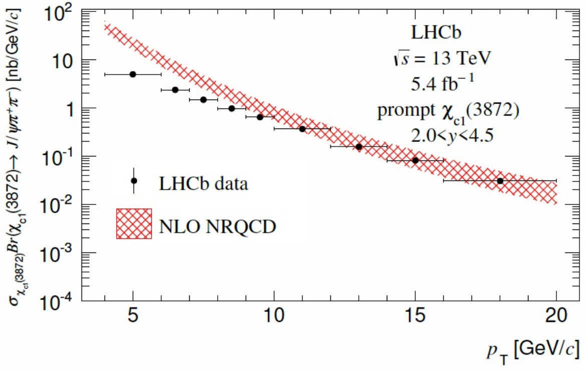


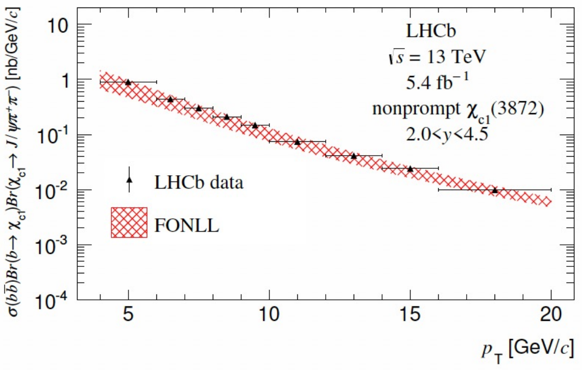
Transport calculation:
molecules have larger reaction rate, formed later in fireball evolution
$N_{tetraquark} > N_{molecule}$

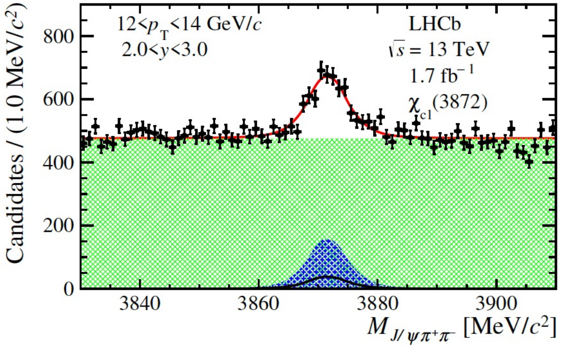
X(3872) production in *pp*

JHEP01 (2022) 131









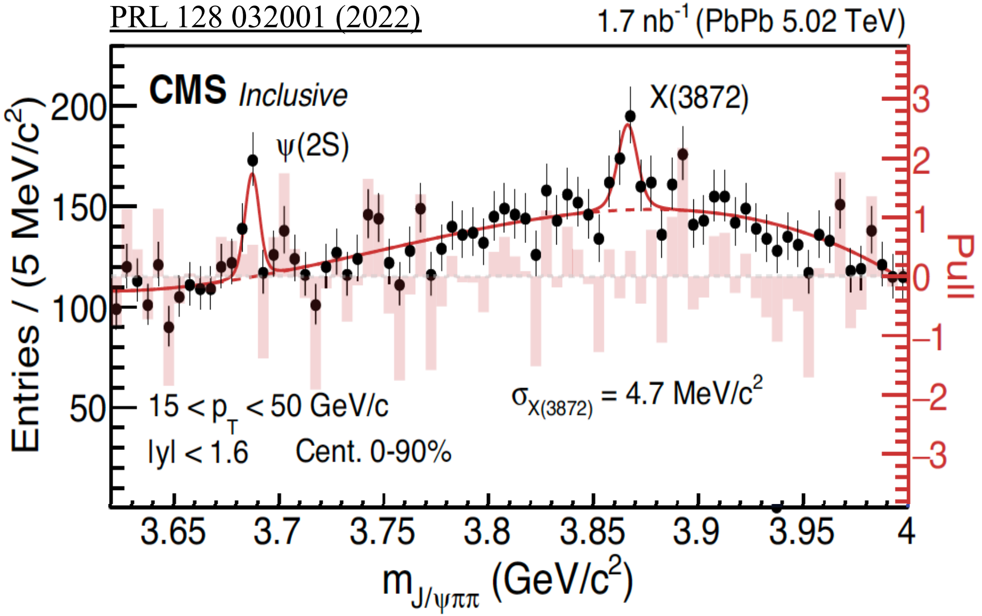
- NRQCD calculation matches high-p_T data well (tuned to ATLAS/CMS)
- Overpredicts yield at lower p_T
- **Room for additional effect**

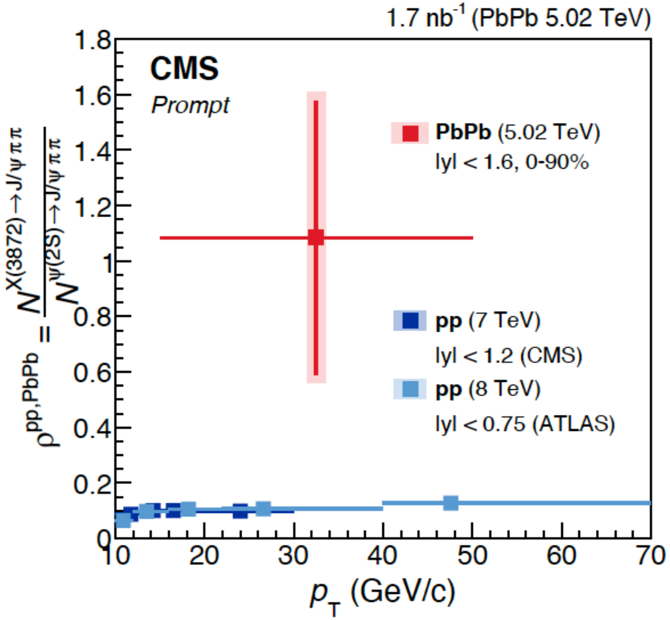
- FONLL describes non-prompt X(3872) production well

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

X(3872)/ψ(2S) 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:

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

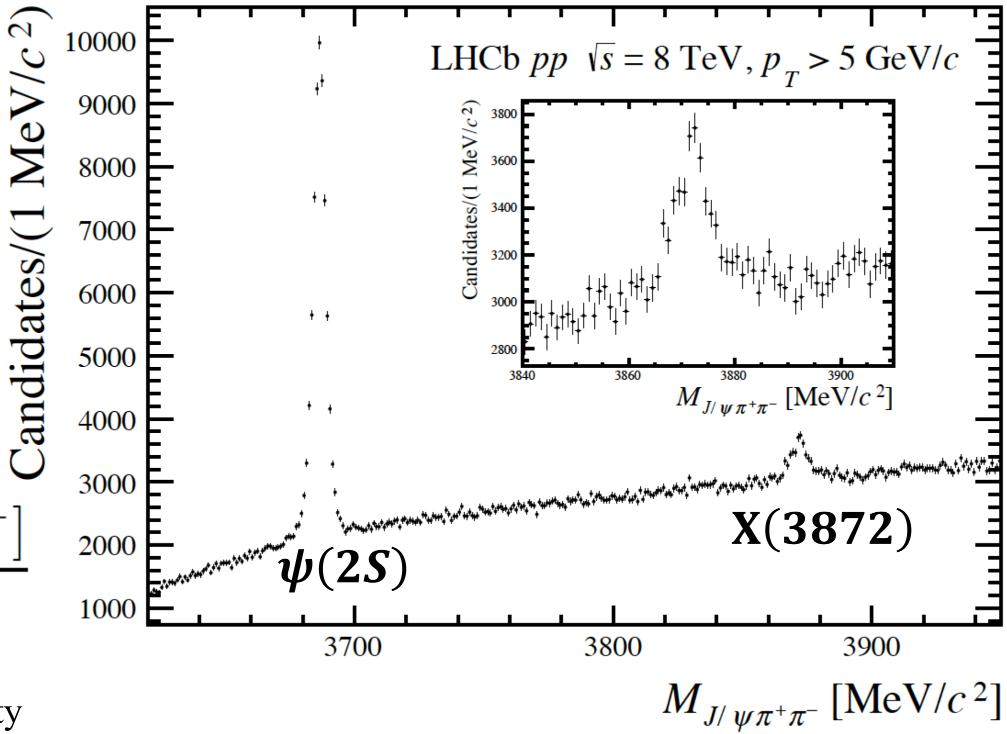
$$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$$

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

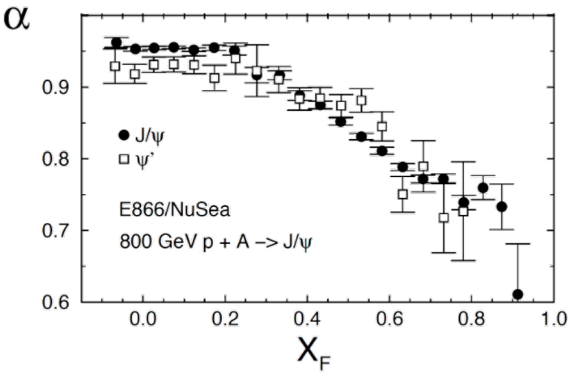
PRL 126, 092001 (2021)



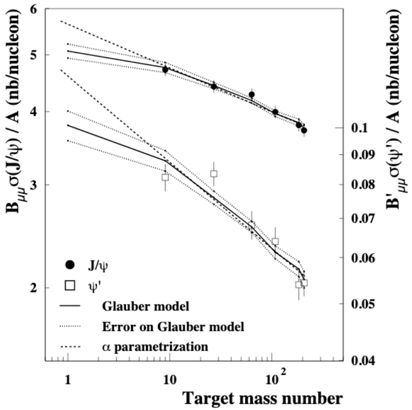
Filtering States with the Nucleus

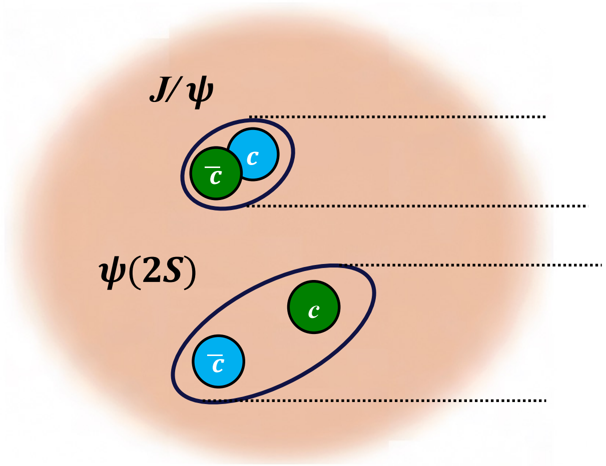
- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair

E866, PRL 84 (2000) 3256-3260



NA50, EPJC 48 329 (2006)

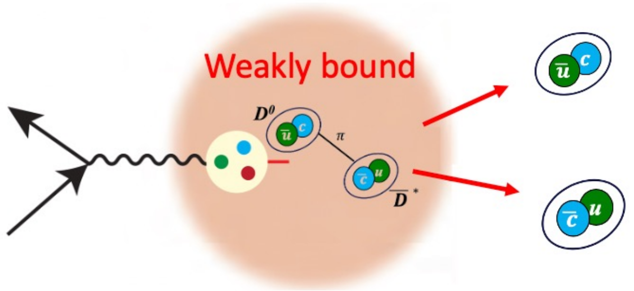




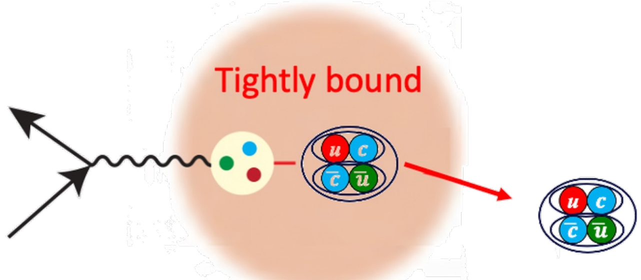
- Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906
- Explains trends observed in fixed target data at FNAL, SPS
- As expected, fails at RHIC (hadronization occurs outside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

Filtering States with the Nucleus – X(3872)

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

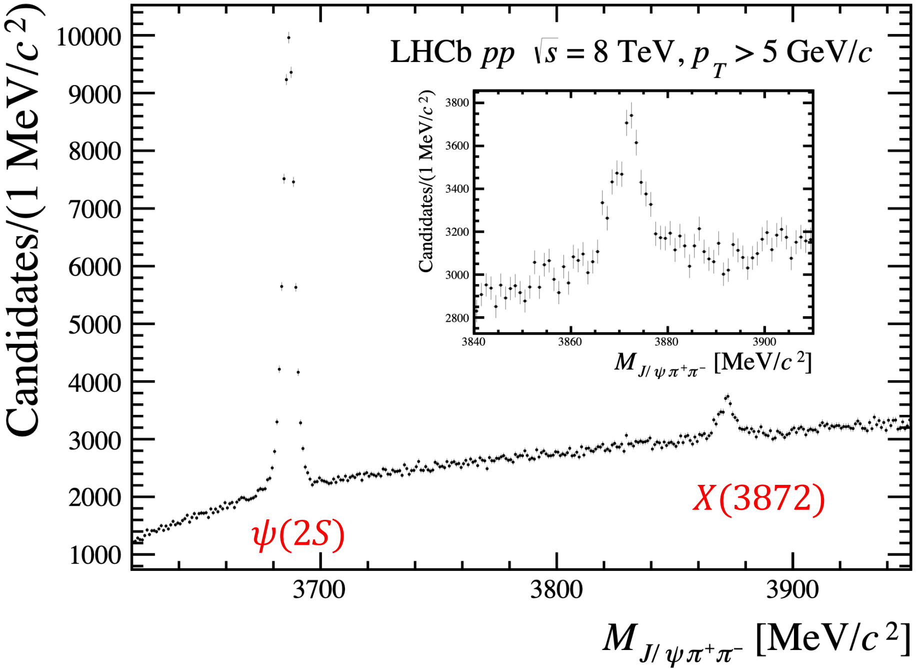


Weakly bound hadronic molecule has large radius, samples large volume of nucleus

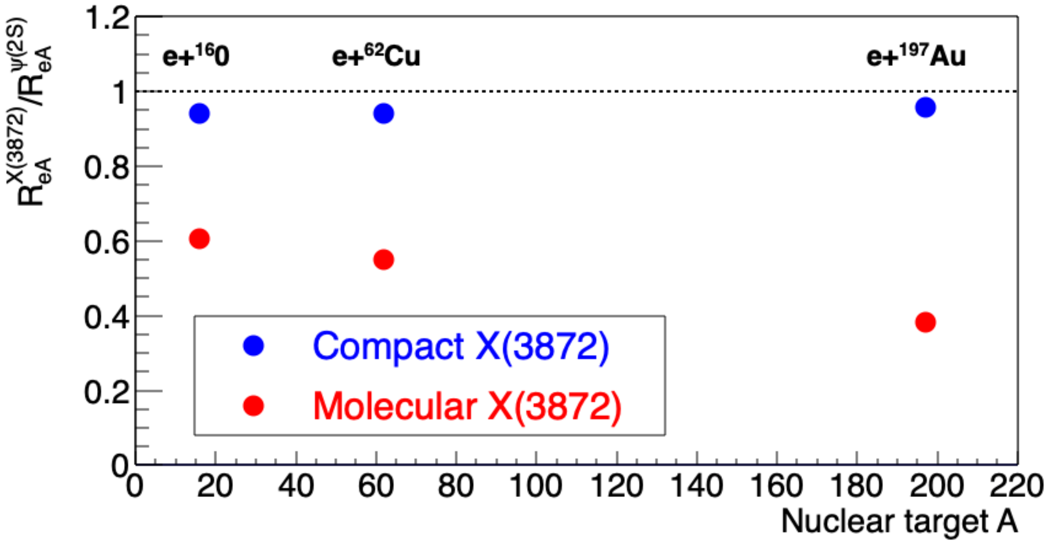


Tightly bound compact tetraquark has small radius, could more easily escape nucleus unscathed

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



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 $\psi(2S)$.**

- 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)

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