A short review of QM 2022 -- Charmonium Spectrum

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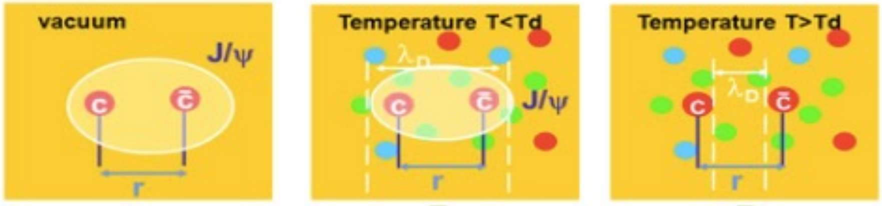
2022/04/29

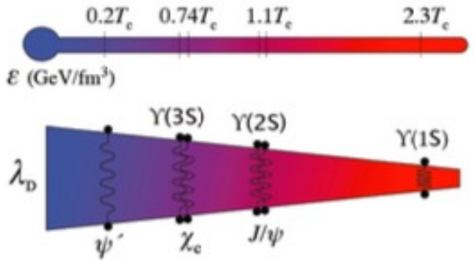
Why heavy flavors

- **Early creation:** heavy quarks created in initial hard scatterings experience the entire evolution of the quark-gluon plasma (QGP) ($m_q >> T_{QGP}$)
- **Include Both pQCD and non-perturbative :** can be calculated down to low p_T in pQCD ($m_q >> \Lambda_{QCD}$), the process to form the heavy mesons involves soft momentum scales
- **Probes to QGP properties:** dissociation (static and dynamic) and (re-)generation

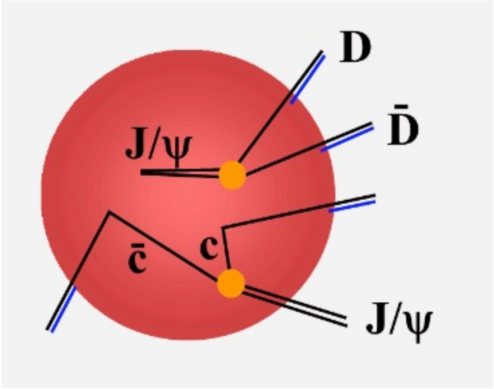


$$r_{q\bar{q}} \sim 1/E_{\text{binding}} > r_D \sim 1/T$$

	J/ψ	ψ(2S)	Υ(1S)	Υ(2S)	Υ(3S)
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200



Thermometer?



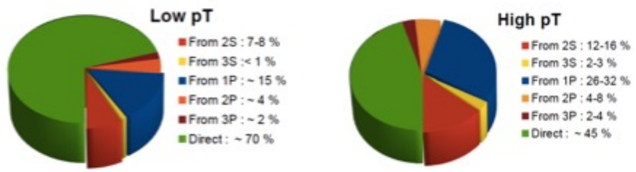
Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115

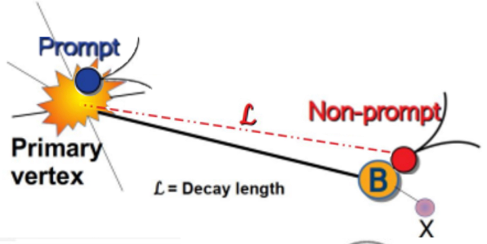
- ✓ Large abundance of qqbar increasing their combining probability to form quarkonium.
- ✓ Compete with dissociation.
- ✓ Dominate at central and semi-central collisions.

Other effects

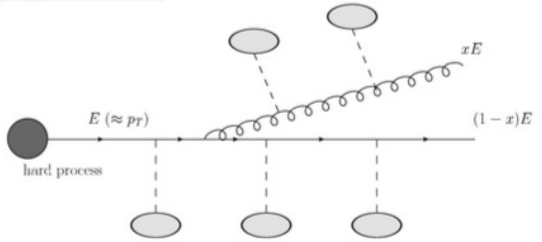
- **Formation time:**
  - ☐ high p_T hadrons fly out the medium faster
- **Feed-down** contribution to prompt yields:
  - ☐ decay from excited states
- **Non-prompt** contribution:
  - ☐ such as decay from open hadrons
- Medium-induced **energy loss**:
  - ☐ parton energy loss
- **Cold Nuclear Matter effects (CNM):**

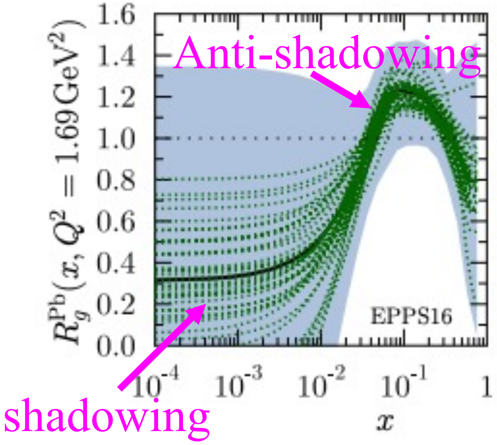
  the effects induced by the presence of the nuclei in the initial-state
  - ☐ nPDF;
  - ☐ Coherent energy loss;
  - ☐ Nuclear absorption;
  - ☐ Co-movers

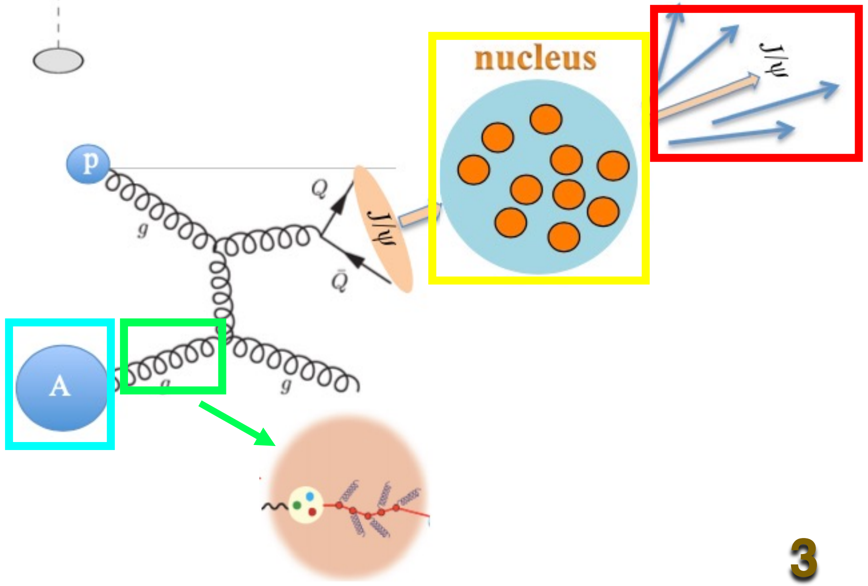




Lifetime of b hadrons ($\mathcal{O}(500)$ $\mu m/c$)







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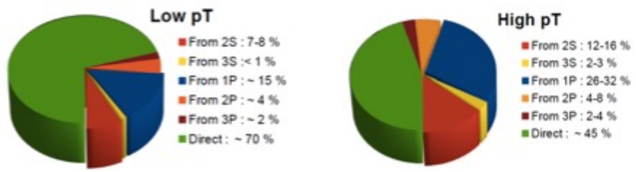

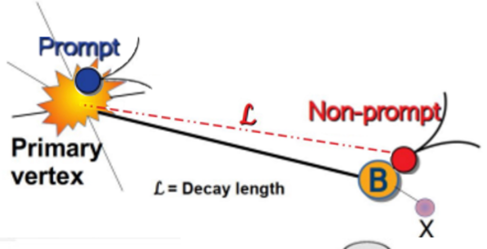

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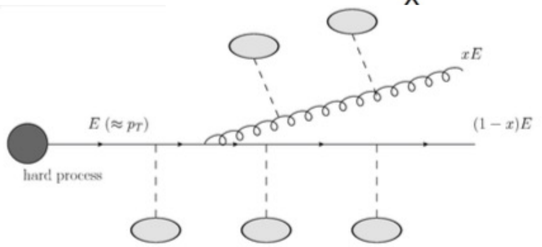

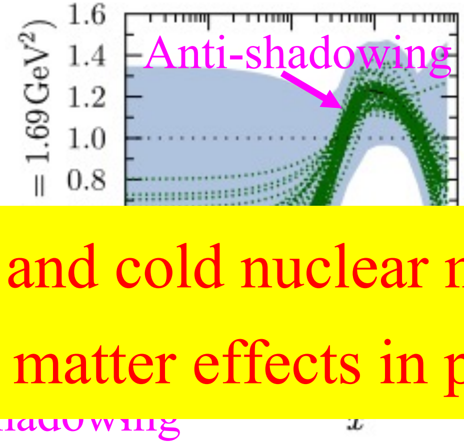

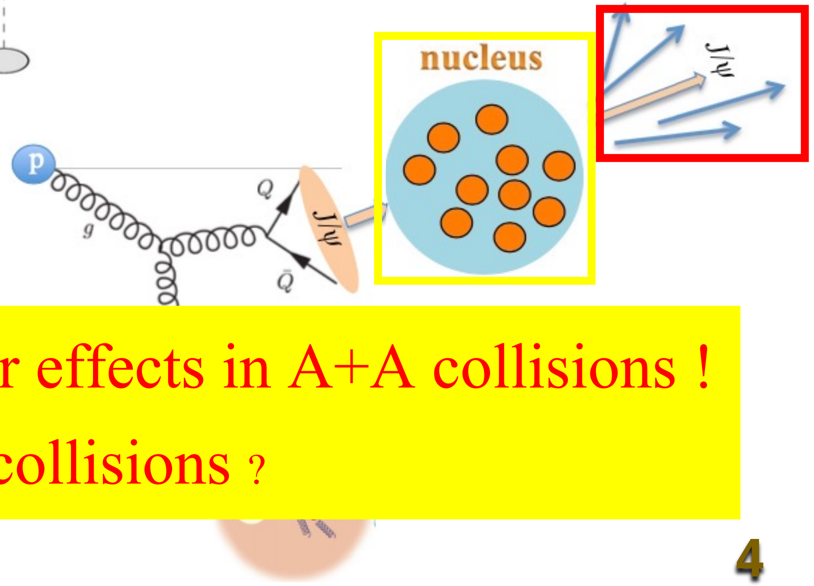

Hot medium and cold nuclear matter effects in A+A collisions !

Cold nuclear matter effects in p+A collisions ?

Charmonium in p+p

LHCb – J/ψ

New

J/ψ production in pp collisions at 5 TeV

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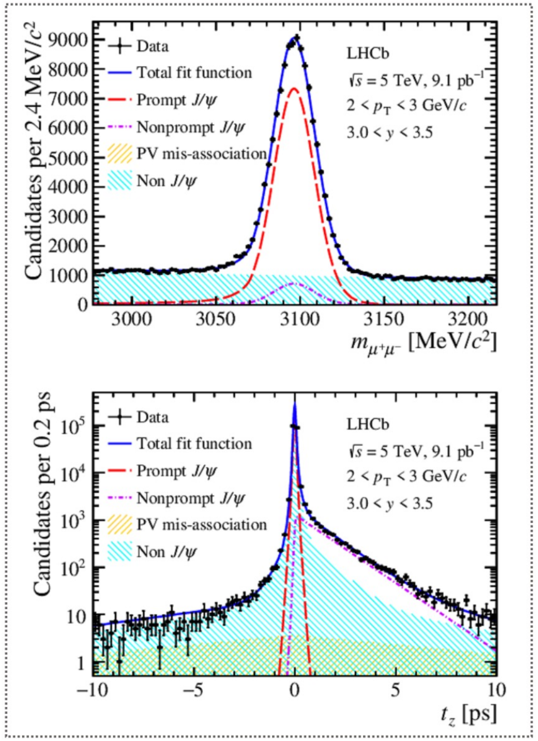
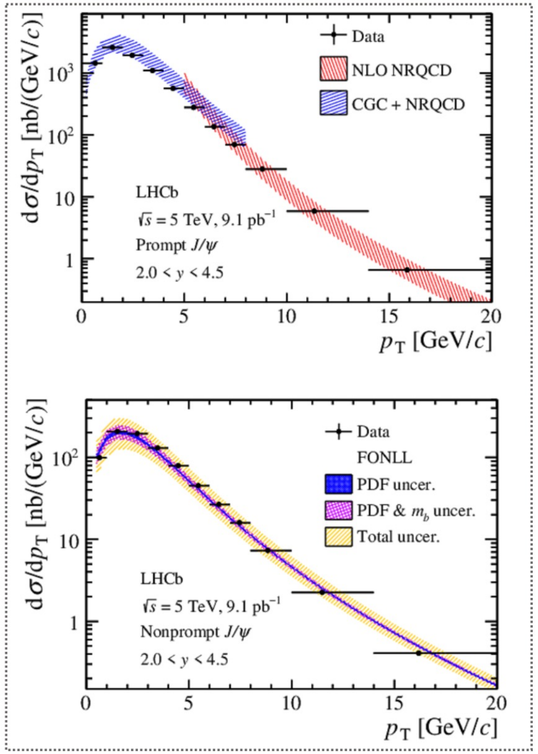
Simultaneous fit



$$t_z = \frac{z_{J/\psi} - z_{PV}}{p_z} \times m_{J/\psi}$$

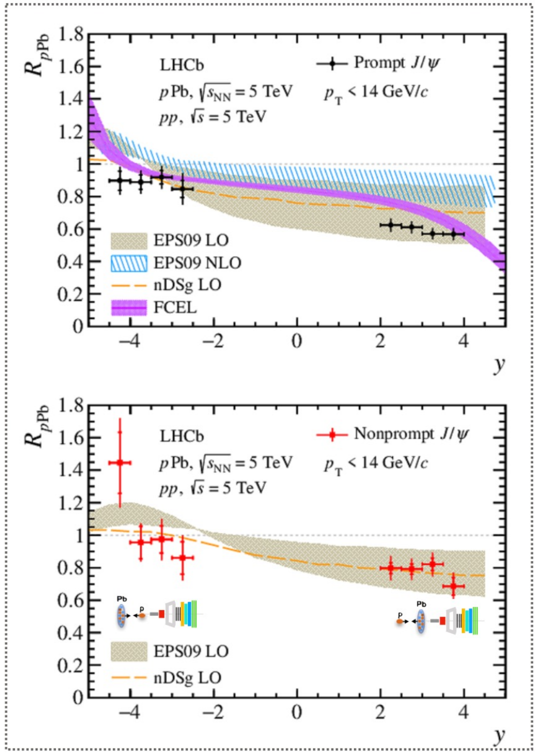
Cross-sections



- Agreement between data/NRQCD.

Nuclear modification factor

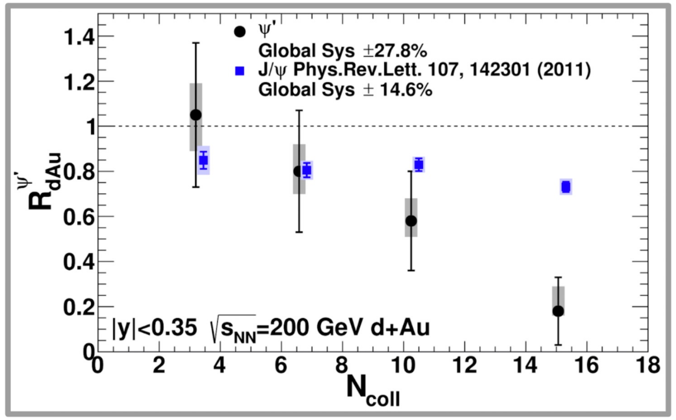
$$R_{pA} = \frac{\sigma_{pPb}}{208 \times \sigma_{pp}}$$

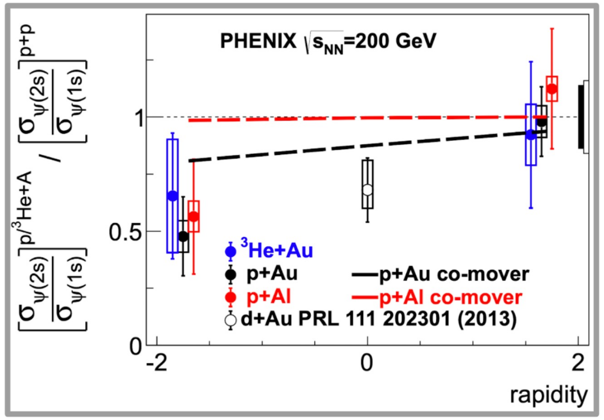


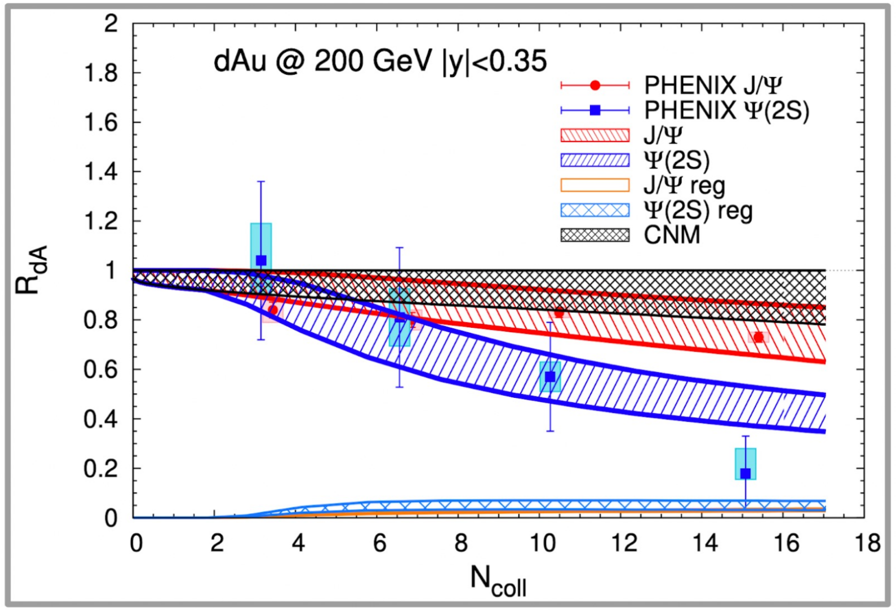
- Updated R_{pA} results with new pp data !
- Good agreement with data/FCEL.
- Tension between data and EPS09 NLO.

Charmonium in p/d+A

PHENIX – J/ψ and $\psi(2s)$

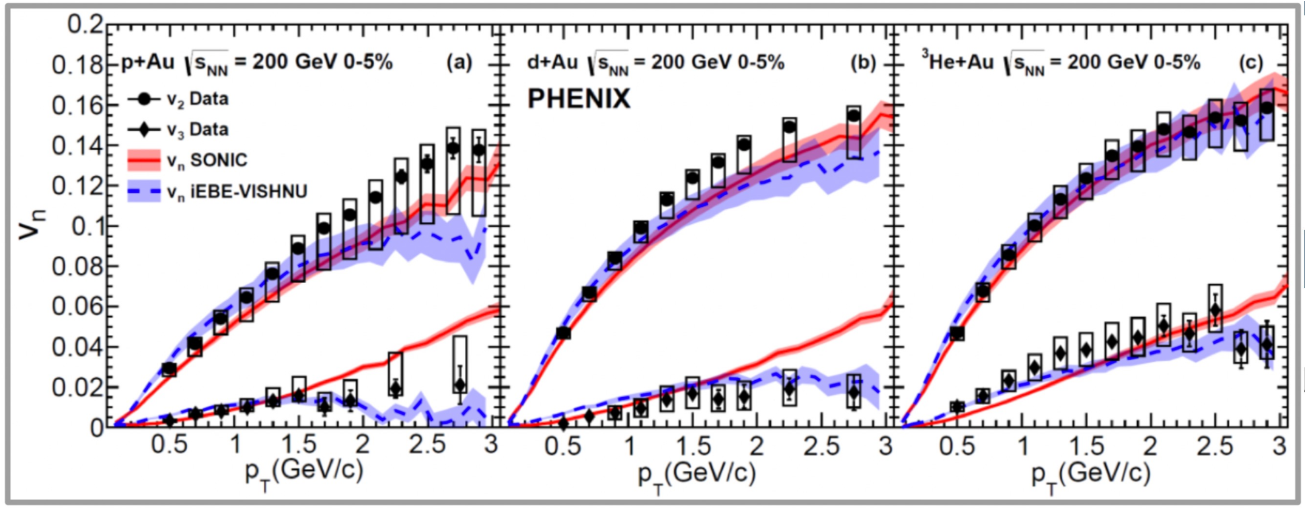






- Strong suppression observed for $\psi(2S)$ with respect to J/ψ
  - Would not be expected if only CNM effects are present
  - Reproduced by Co-Movers model - *Phys.Lett.B 749 (2015)*

?

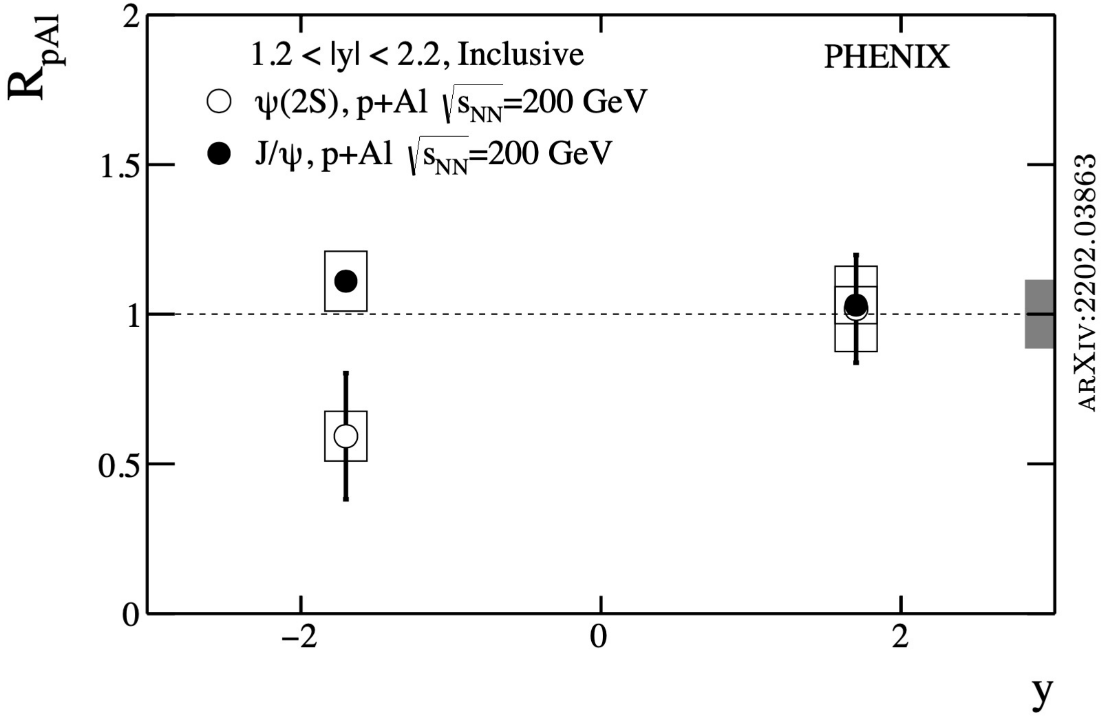


Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions

PHENIX – J/ψ and $\psi(2s)$

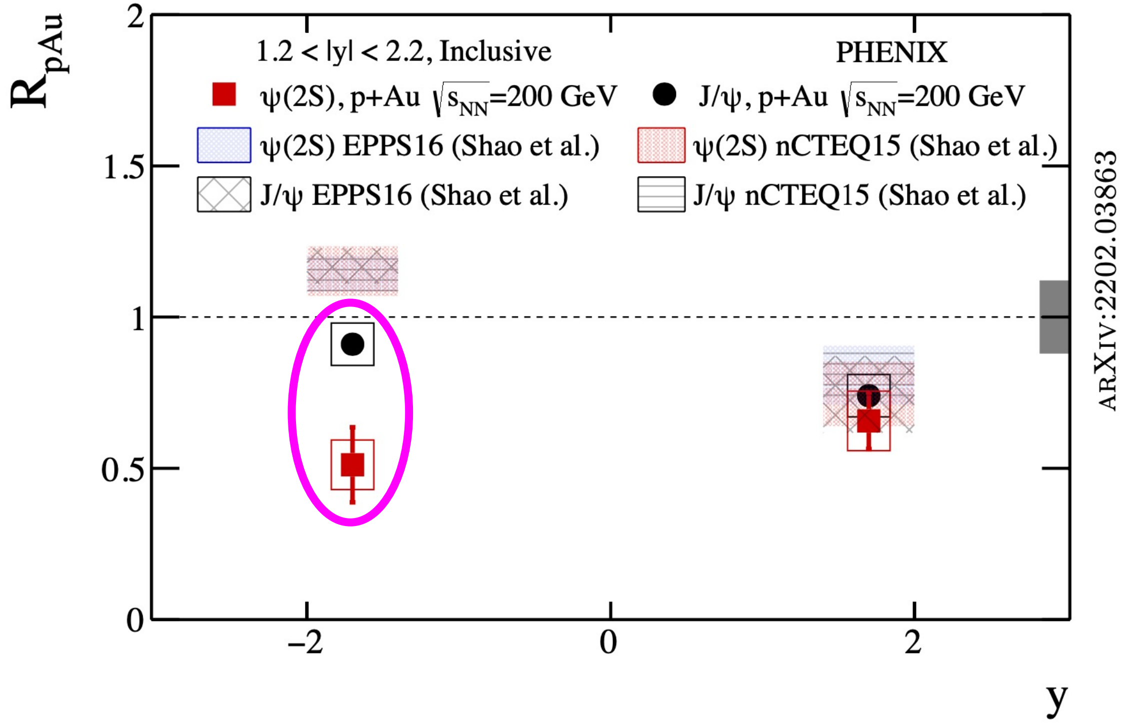
Charmonia Nuclear Modification in p+Al Collisions



- At forward rapidity, J/ψ and ψ(2S) modification consistent with unity
- At backward rapidity, nuclear absorption cannot explain suppression in ψ(2S) modification
    - ψ(2S) suppression could be due to final state effects, however error bars sizeable

PHENIX – J/ψ and $\psi(2s)$

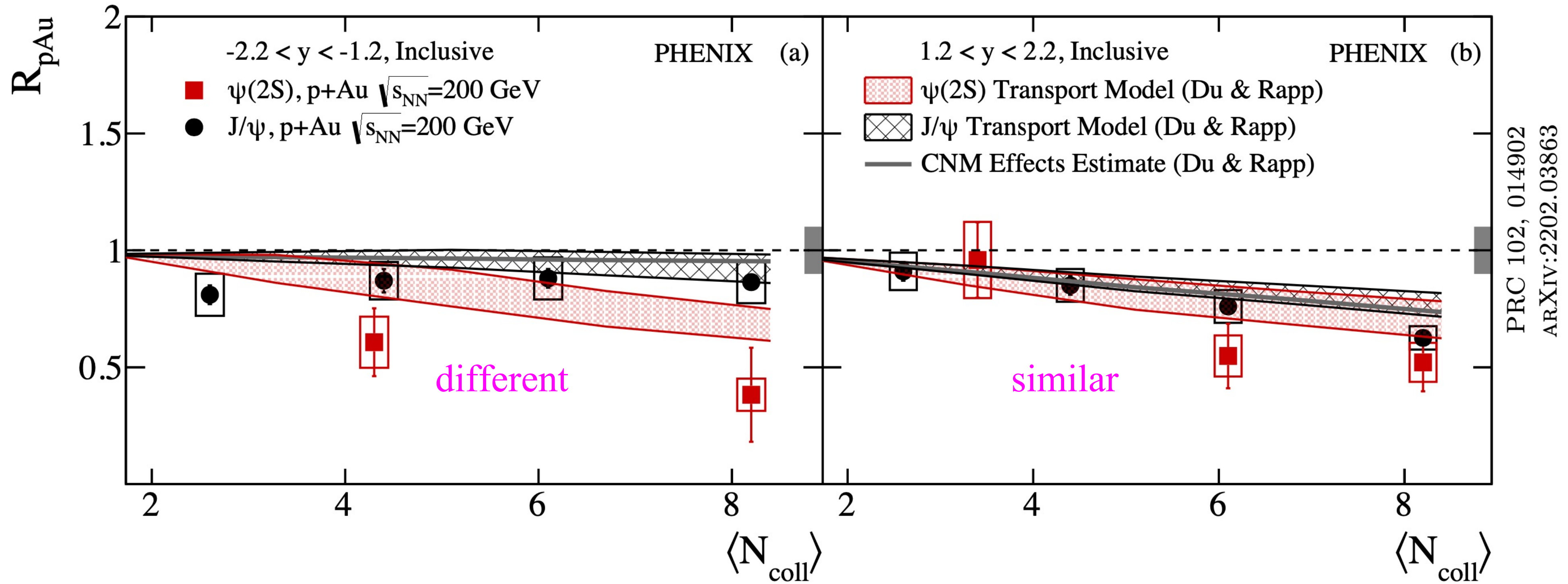
Charmonia Nuclear Modification in p+Au Collisions



- At forward rapidity, J/ψ and ψ(2S) modification show similar suppression
  - Data well described by EPPS16 and nCTEQ15 shadowing predictions
- At backward rapidity, nPDF effects alone cannot describe ψ(2S) modification

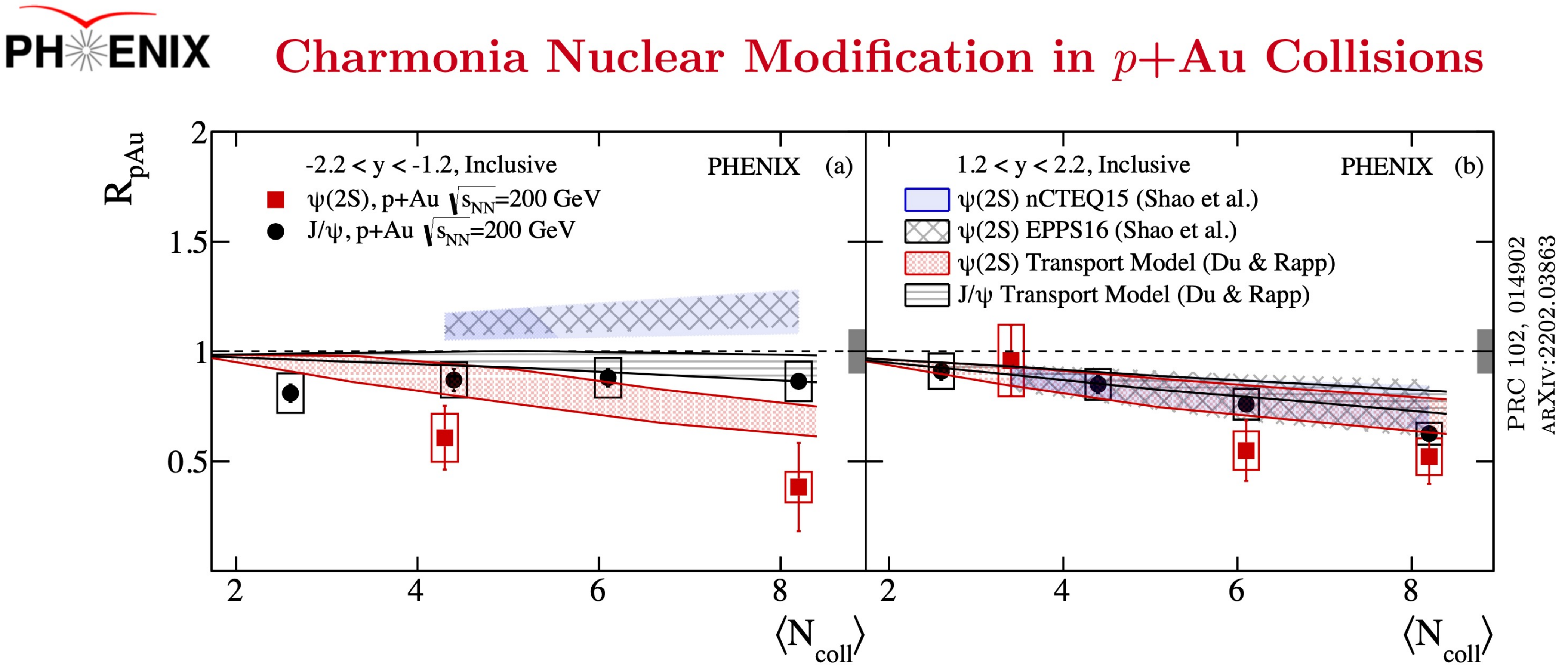
PHENIX – J/ψ and $\psi(2s)$

Charmonia Nuclear Modification in p+Au Collisions



- Cold nuclear matter estimate shown at both rapidities
- Largest contribution to Transport Model at forward rapidity from EPS09 shadowing
- At backward rapidity, model predicts stronger hot nuclear matter effects for $\psi(2S)$ state

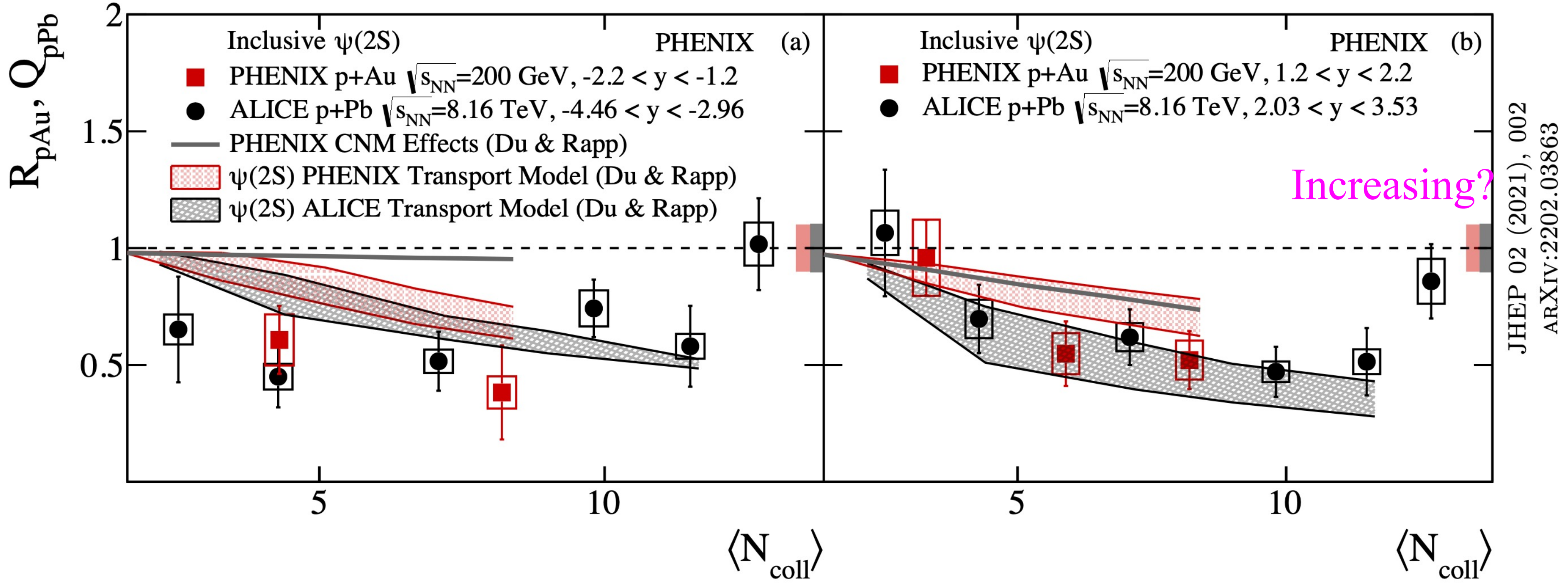
PHENIX – J/ψ and $\psi(2s)$



- At forward rapidity, J/ψ and ψ(2S) modification well described by shadowing models
  - Consistent with cold nuclear matter effects
- At backward rapidity, charmonium inconsistent with shadowing effects alone

PHENIX – J/ψ and $\psi(2s)$

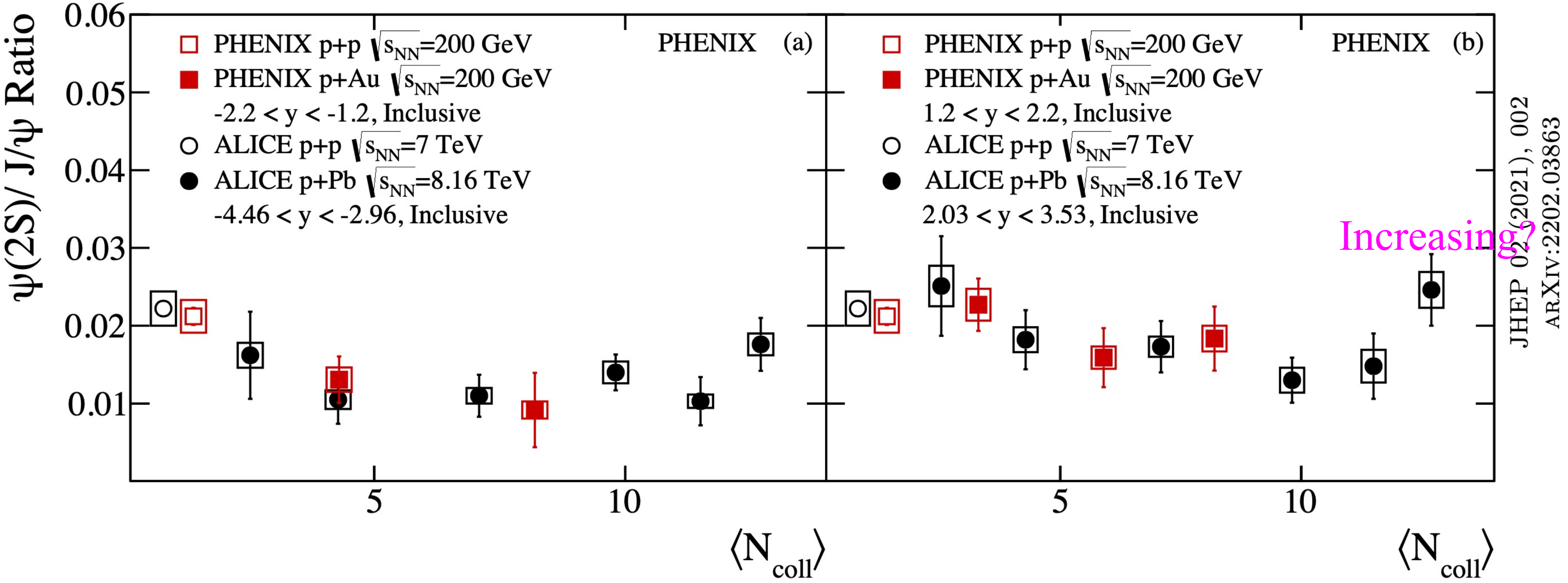
ψ(2S) Nuclear Modification at RHIC and LHC



- Initial state effects expected to be different at RHIC and LHC energies
  - Larger mean p_T values at LHC lead to higher Q^2 values; different Bjorken-x probed
- Both transport models at backward rapidity predict similar degree of suppression

PHENIX – J/ψ and $\psi(2s)$

ψ(2S) to J/ψ Ratio at RHIC and LHC

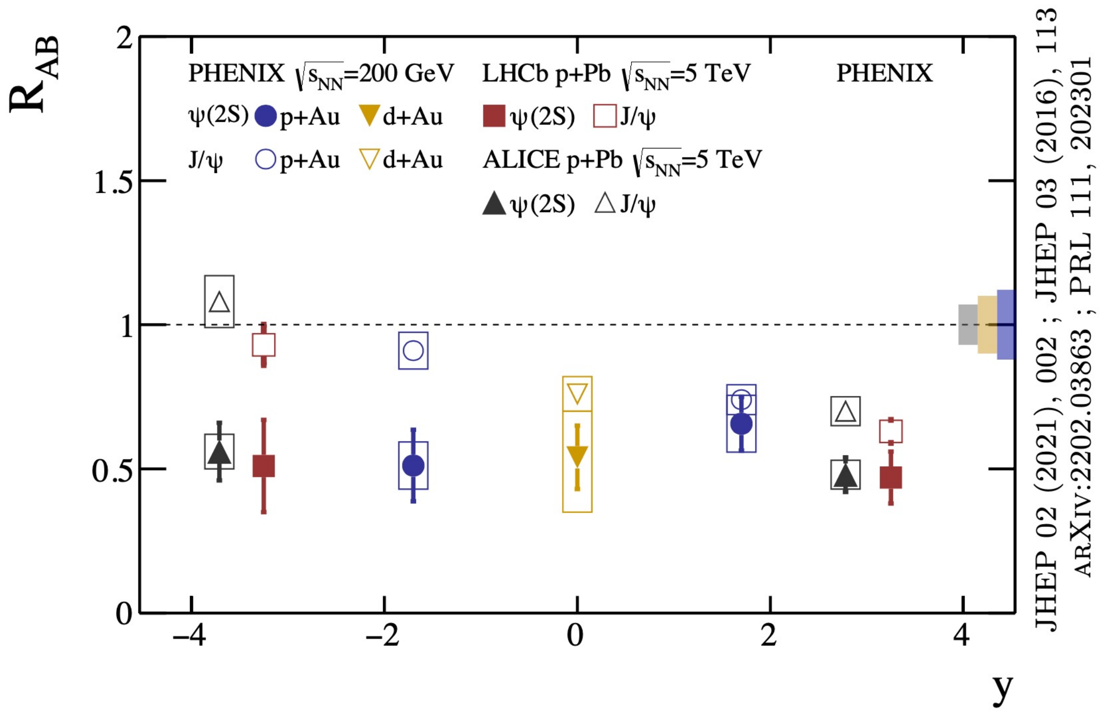


- The ψ(2S) to J/ψ ratio in p+p collisions at RHIC, LHC show no clear energy dependence
- Comparison of the p+A to p+p ratio strongly suggests the presence of final state effects in p+A collisions at backward rapidity, as initial state effects expected to largely cancel

PHENIX – J/ψ and $\psi(2s)$

PHENIX

Charmonium Modification at RHIC and LHC



- J/ψ and ψ(2S) modification similar at forward rapidity
  - Suggests initial state effects dominate charmonium production
- PHENIX, LHCb, and ALICE consistent with increasing final state effects in A-going direction

PHENIX – J/ψ and $\psi(2s)$

PHENIX

Conclusion

① Nuclear absorption cannot explain ψ(2S) suppression at backward rapidity in p+A collisions

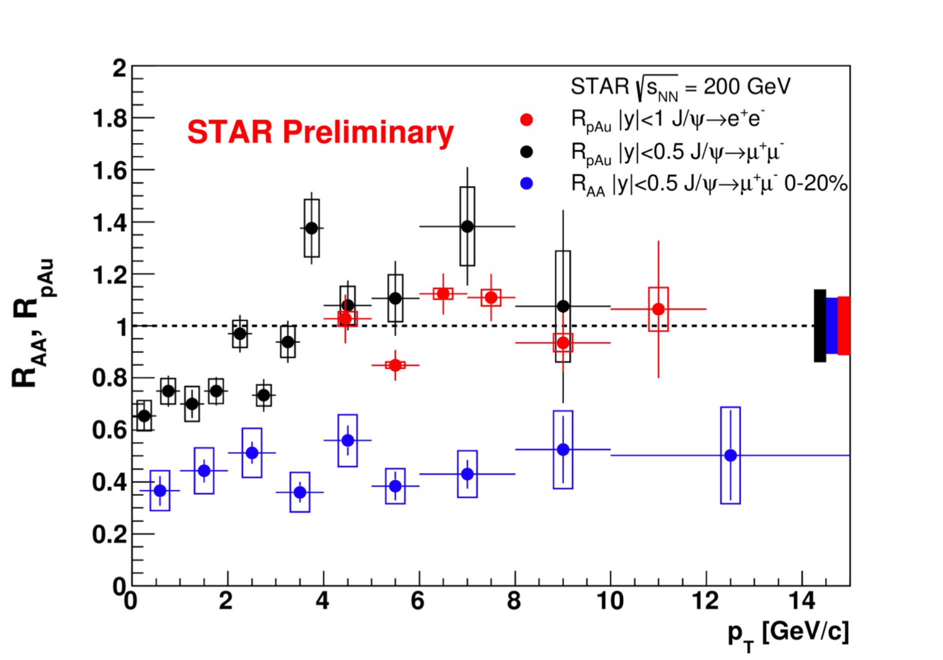
② **At forward rapidity, PHENIX J/ψ, ψ(2S) modification consistent with EPPS16, nCTEQ15 shadowing predictions**

③ Final state effects on charmonium states appear very similar at RHIC, LHC energies

④ **Comparison of ψ(2S) to J/ψ ratio in p+A versus p+p collisions strongly suggests presence of final state effects in p+A collisions at backward rapidity**

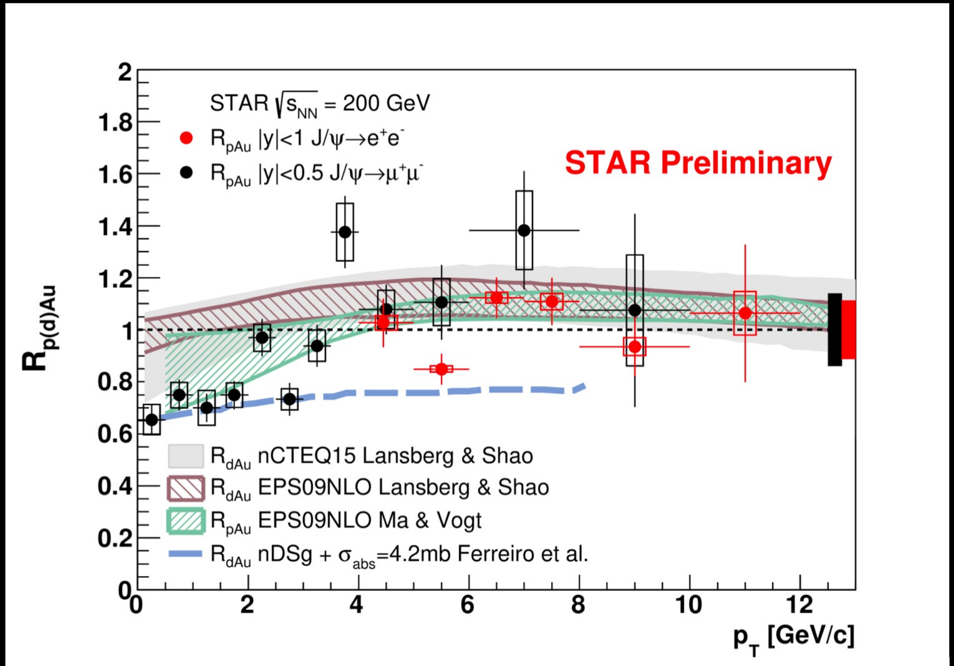
STAR -- J/ψ

J/ψ R_{pAu} at $\sqrt{s_{NN}}$ = 200 GeV



STAR, Phys. Lett. B 825 (2022) 136865
STAR, Phys. Lett. B 797 (2019) 134917

- R_{pAu} < 1 at low p_T
- R_{pAu} is consistent with unity at mid to high p_T
- The suppression in Au + Au collisions at mid to high p_T is dominated by HNM effects



STAR, Phys. Lett. B 825 (2022) 136865
Ma & Vogt, EPS09+NLO, Private Comm.
Lansberg & Shao, nCTEQ15, EPS09+NLO, Eur.Phys.J. C77 (2017) no.1, 1
Ferreiro et al., nDSg+σ_{abs}, Few Body Syst. 53 (2012) 27

R_{pAu} result is consistent with model calculations taking nPDF into account, but at high p_T disfavor the one with additional nuclear absorption

STAR -- J/ψ

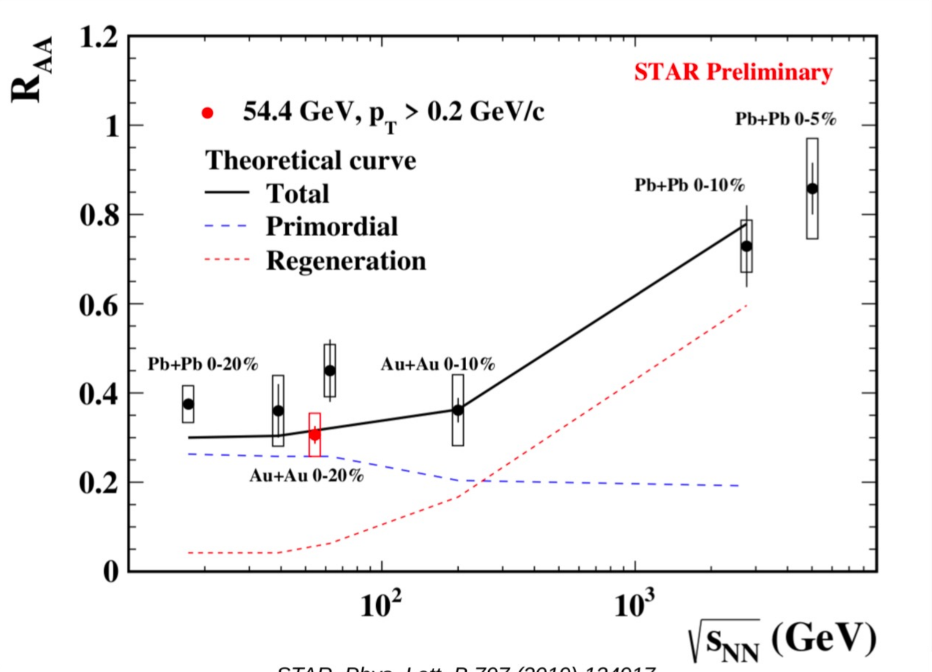
Summary

- J/ψ R_{pAu} at $\sqrt{s_{NN}}$ = 200 GeV
  - Suppressed at low p_T; consistent with unity at mid to high p_T
  - R_{AA} suppression at mid to high p_T is dominated by HNM effects

Charmonium in A+A

STAR -- J/ψ

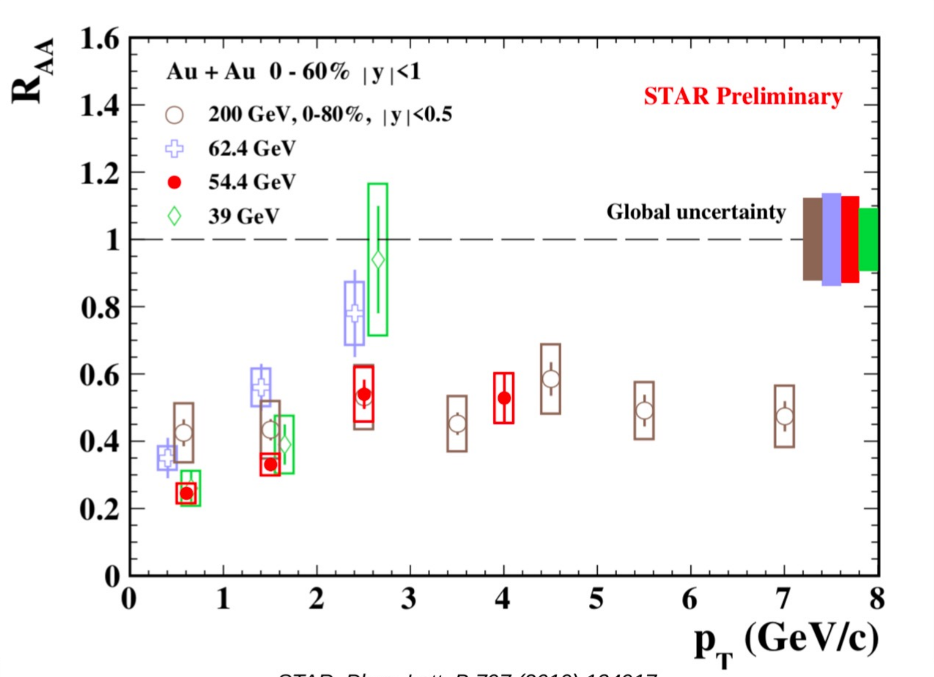
Energy Dependence of J/ψ R_{AA}



STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13-20
ALICE, Nucl. Phys. A 1005 (2021) 121769
ALICE, Phys. Lett. B 734 (2014) 314
X. Zhao, R. Rapp, Phys. Rev. C 82, 064905

Data are consistent with a transport model including primordial and regeneration contributions

*Model calculation is in 0-20% centrality

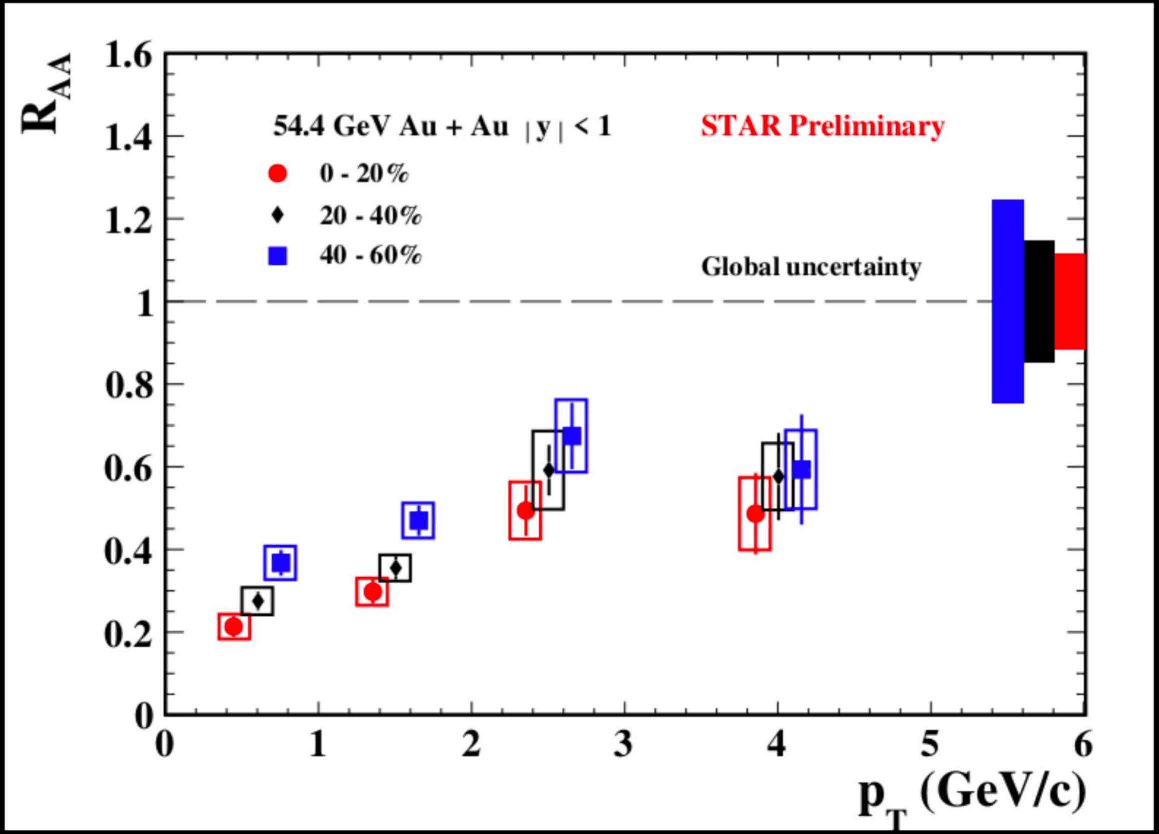


STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13

- R_{AA} increases with p_T at $\sqrt{s_{NN}}$ = 39, 54.4 and 62.4 GeV (but not 200 GeV) below 3 GeV/c
  - Could be due to more regeneration contribution at low p_T at 200 GeV
- $\sqrt{s_{NN}}$ = 54.4 GeV: improved precision

STAR -- J/ψ

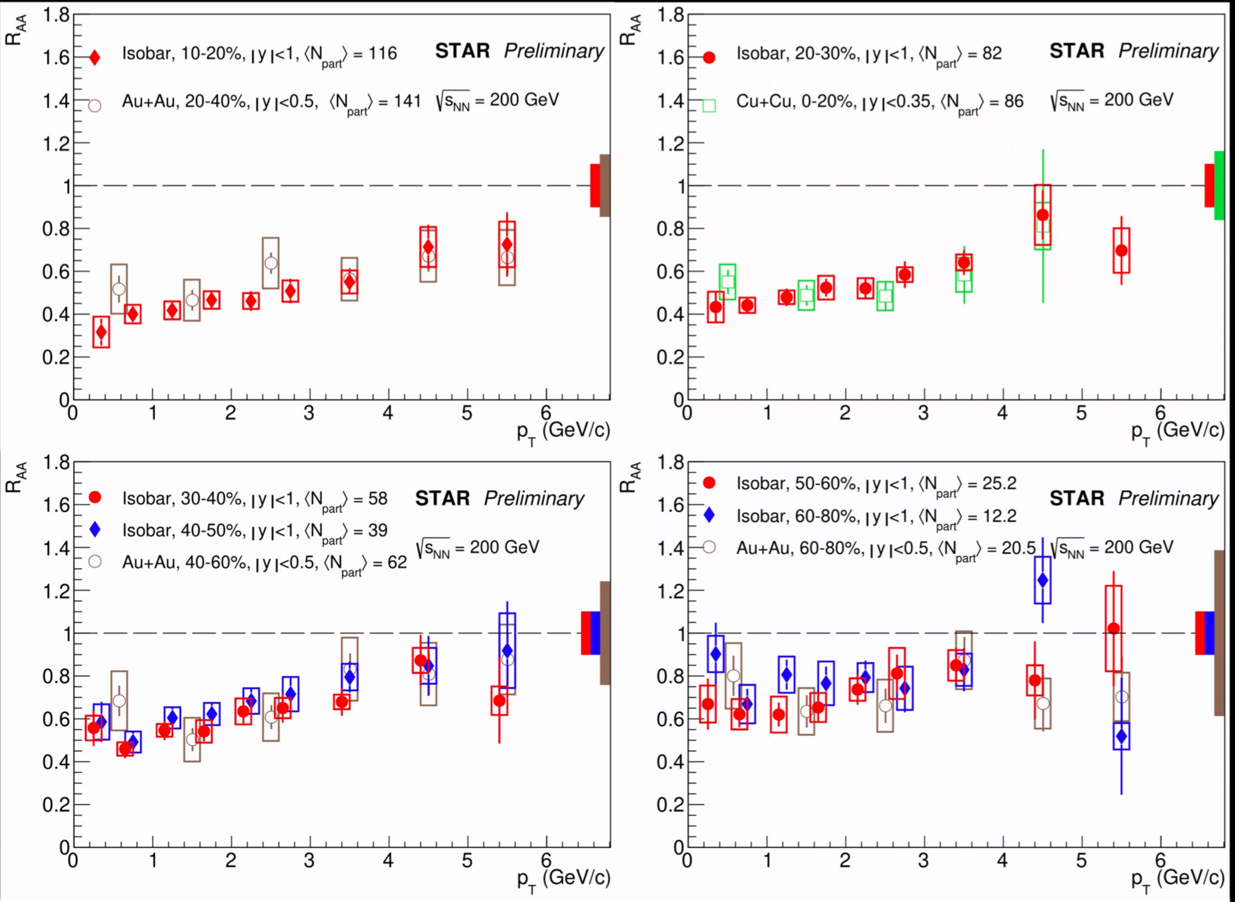
J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 54.4 GeV



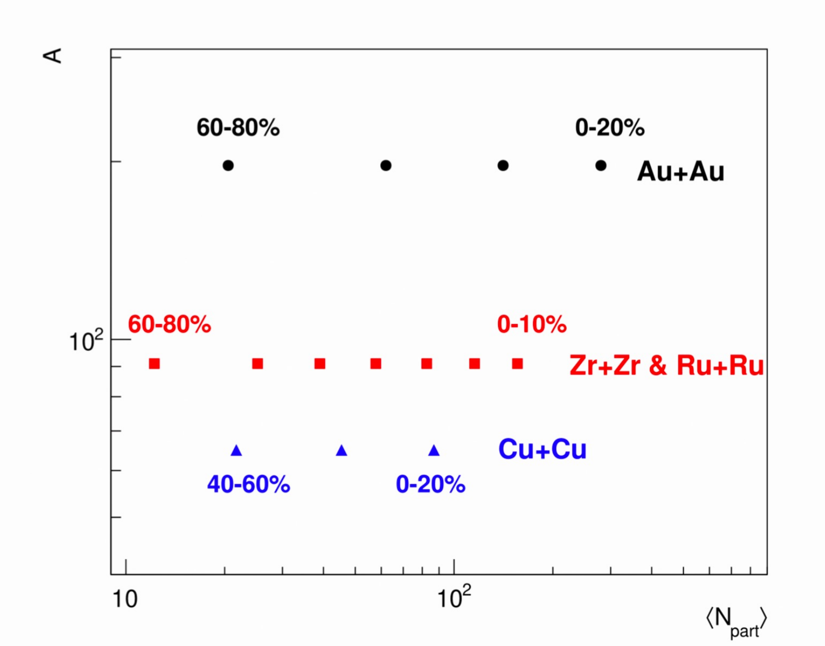
- Suppression observed across centrality
- Larger suppression in more central collisions as they are more impacted by the HNM effects

STAR -- J/ψ

J/ψ R_{AA} in Isobar Collisions

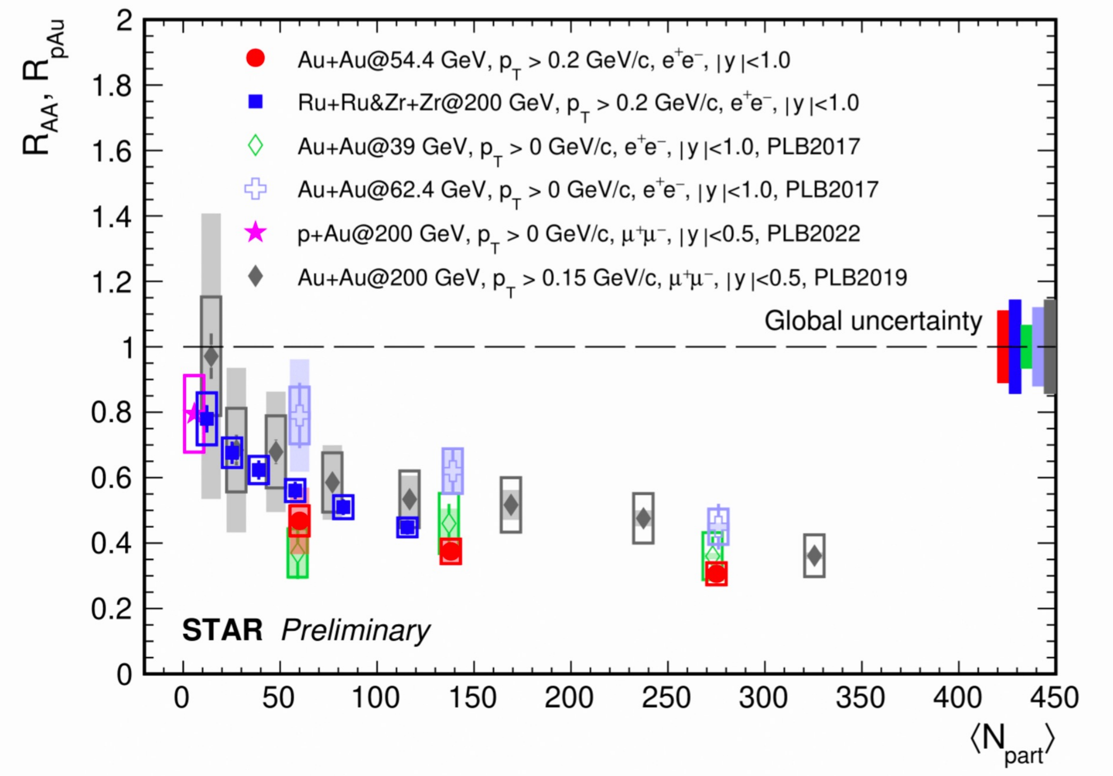


STAR, Phys. Lett. B 797 (2019) 134917
PHENIX, Phys. Rev. Lett. 101 (2008) 122301



STAR -- J/ψ

J/ψ R_{AA} vs <N_{part}>



STAR, Phys. Lett. B 825 (2022) 136865
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13

- R_{AA} decreases with <N_{part}> at RHIC energy
- No significant energy and species dependence of R_{AA}

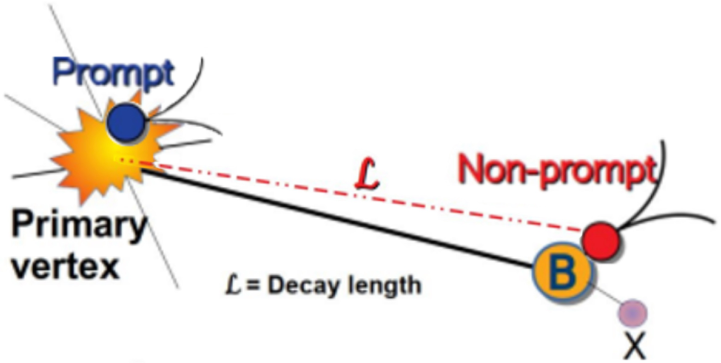
Yan Wang, Apr 8, 2022
Poster Session 3 T11_2

STAR -- J/ψ

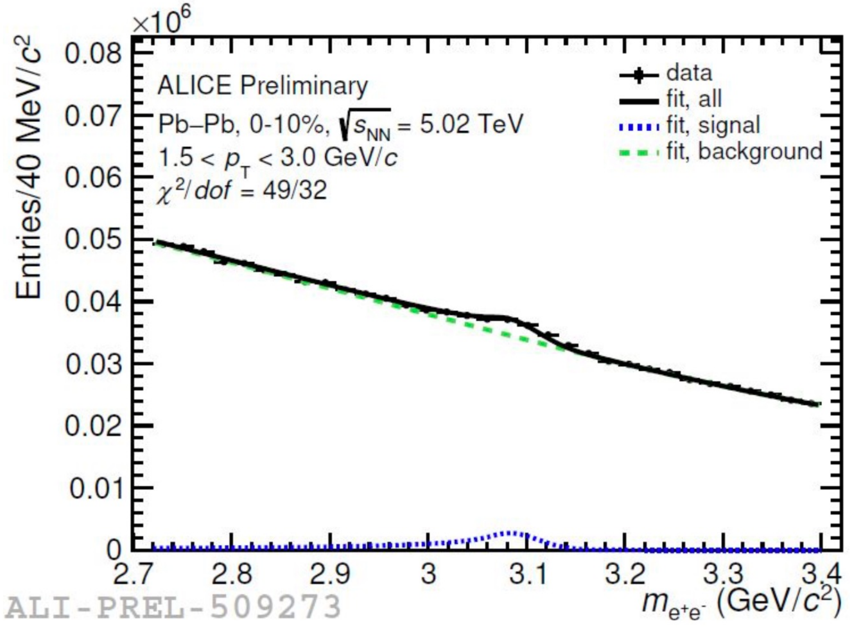
Summary

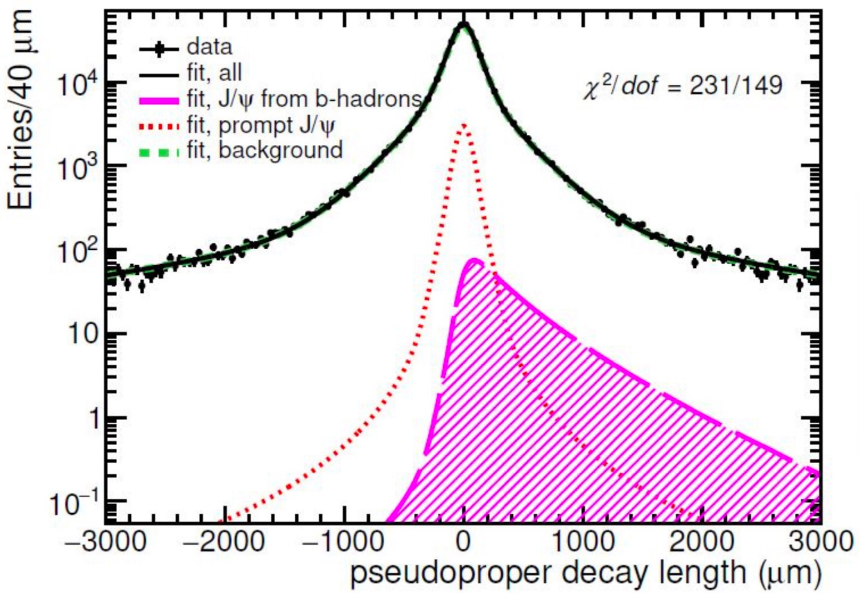
- J/ψ R_{AA} measured at $\sqrt{s_{NN}}$ = 54.4 GeV in Au+Au collisions and at $\sqrt{s_{NN}}$ = 200 GeV in isobar collisions
  - No significant energy and species dependence at the same <N_{part}> between $\sqrt{s_{NN}}$ = 39 and 200 GeV
  - Suppression seems to be driven by system size <N_{part}>

ALICE -- J/ψ

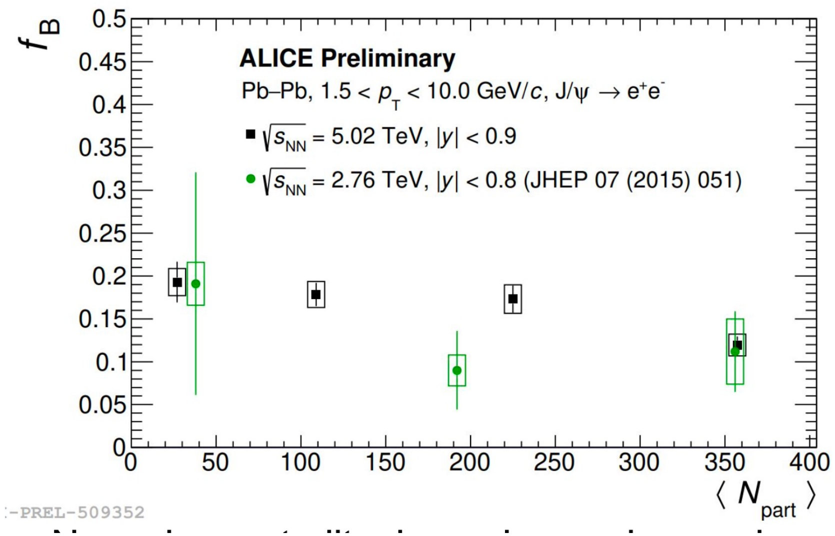


$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

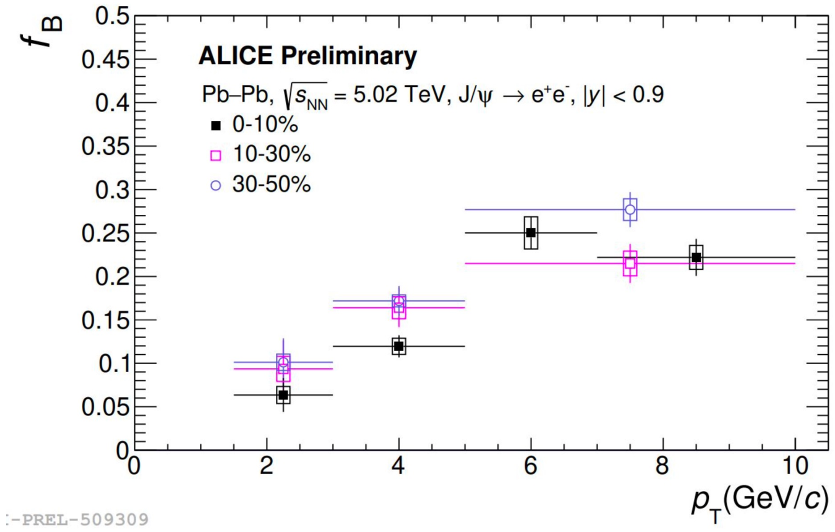




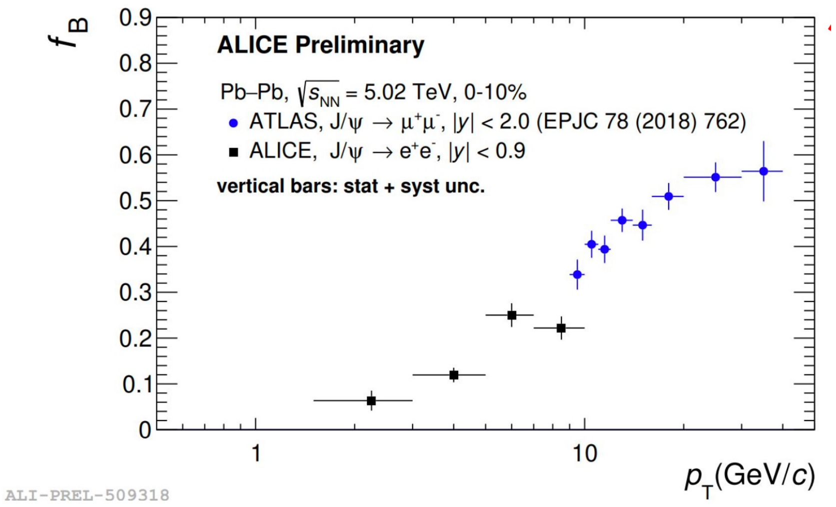
ALICE -- J/ψ



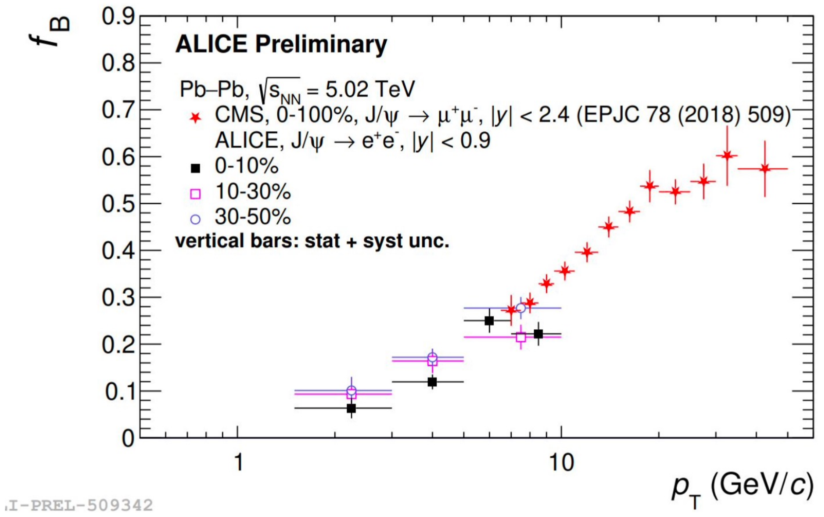
ALICE Preliminary
Pb–Pb, 1.5 < pT < 10.0 GeV/c, J/ψ → e+e-
√sNN = 5.02 TeV, |y| < 0.9
√sNN = 2.76 TeV, |y| < 0.8 (JHEP 07 (2015) 051)
fB
⟨ Npart ⟩



ALICE Preliminary
Pb–Pb, √sNN = 5.02 TeV, J/ψ → e+e-, |y| < 0.9
0-10%
10-30%
30-50%
fB
pT(GeV/c)



ALICE Preliminary
Pb–Pb, √sNN = 5.02 TeV, 0-10%
ATLAS, J/ψ → μ+μ-, |y| < 2.0 (EPJC 78 (2018) 762)
ALICE, J/ψ → e+e-, |y| < 0.9
vertical bars: stat + syst unc.
fB
pT(GeV/c)
ALI-PREL-509318

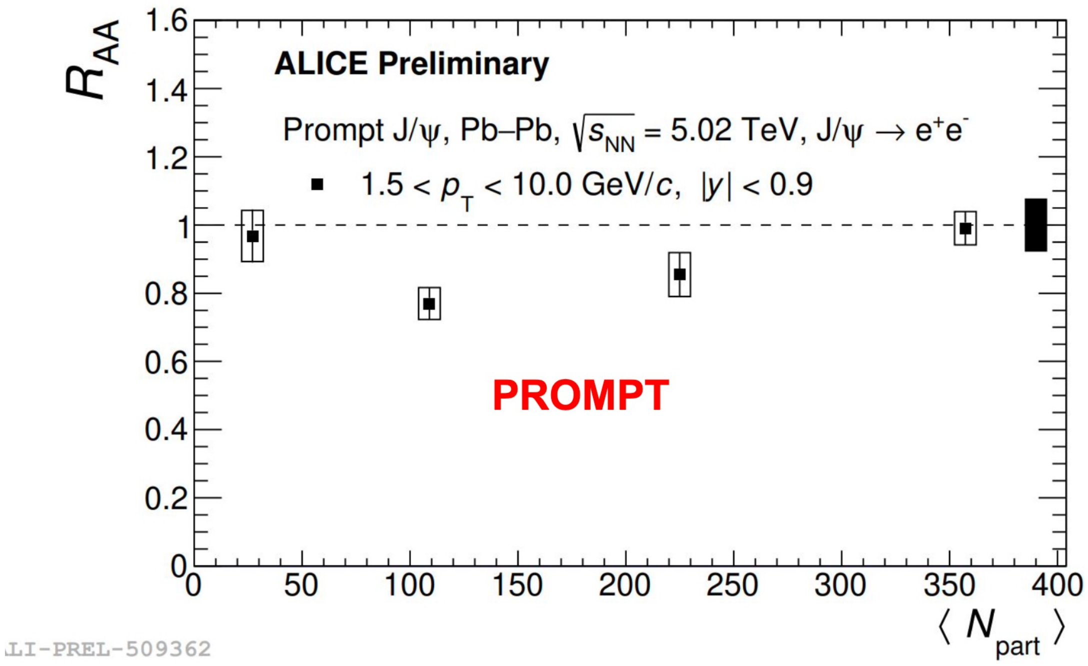


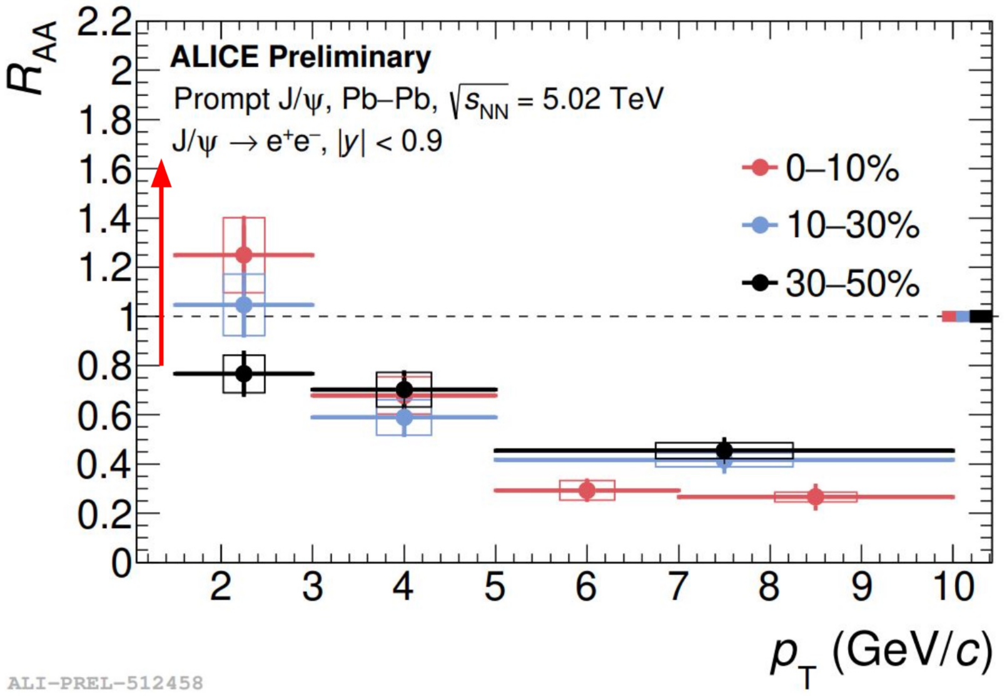
ALICE Preliminary
Pb–Pb, √sNN = 5.02 TeV
CMS, 0-100%, J/ψ → μ+μ-, |y| < 2.4 (EPJC 78 (2018) 509)
ALICE, J/ψ → e+e-, |y| < 0.9
0-10%
10-30%
30-50%
vertical bars: stat + syst unc.
fB
pT (GeV/c)

ALICE -- J/ψ

Prompt J/ψ R_{AA} as a function of ⟨N_{part}⟩ and p_T

mid-y
NEW!





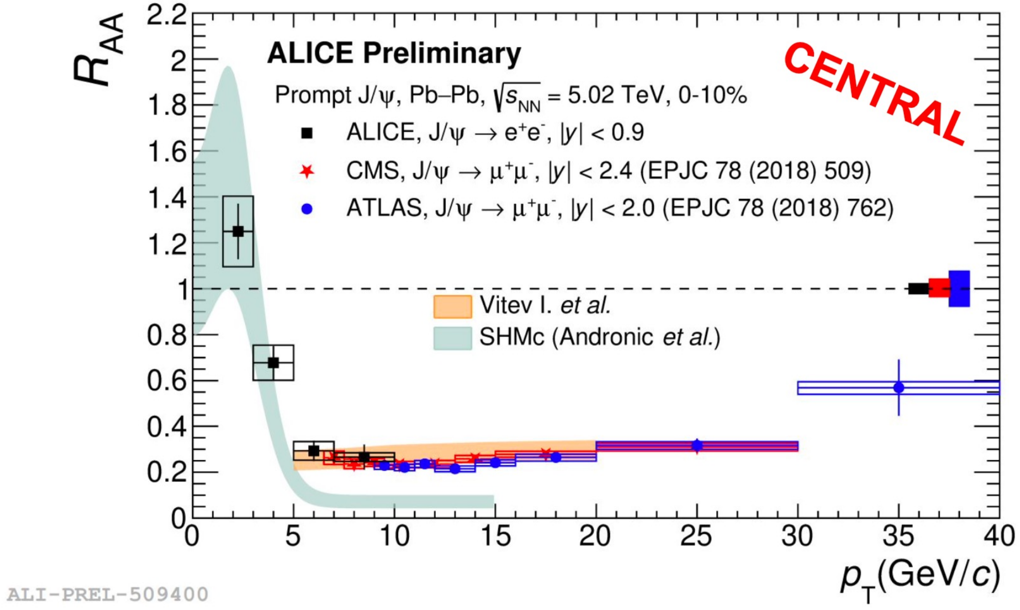
- Prompt J/ψ R_{AA} increases towards more central collisions (effect more visible at low p_T) → expected trend from J/ψ regeneration

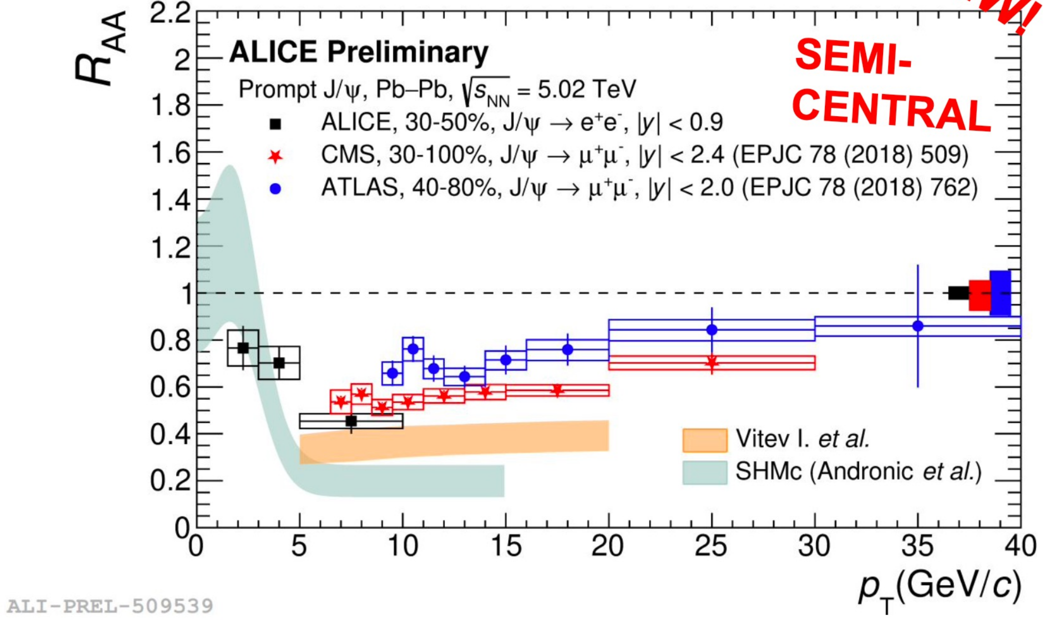
11

ALICE -- J/ψ

Prompt J/ψ R_{AA} in central and semicentral Pb–Pb collisions

mid-y
NEW!





- Increasing R_{AA} at low p_T in central collisions compatible with a regeneration scenario
- Overlapping with ATLAS and CMS measurements in central collisions at high p_T
- Vitev: Dissociation of charmonia via microscopic description of interactions inside the medium
  - ALICE results compatible within uncertainties with the model for p_T > 5 GeV/*c*
- Good agreement with calculations from SHM extended to the charm sector (SHMc) for p_T < 5 GeV/*c*

SHMc: A. Andronic et al., JHEP07 (2021) 035
(+ private communication)
Vitev I. et al. arXiv:1709.02372, arXiv:1906.04186

Qualitatively compatible with transport models TM1 and TM2 at low p_T which include also non-prompt J/ψ (not shown)

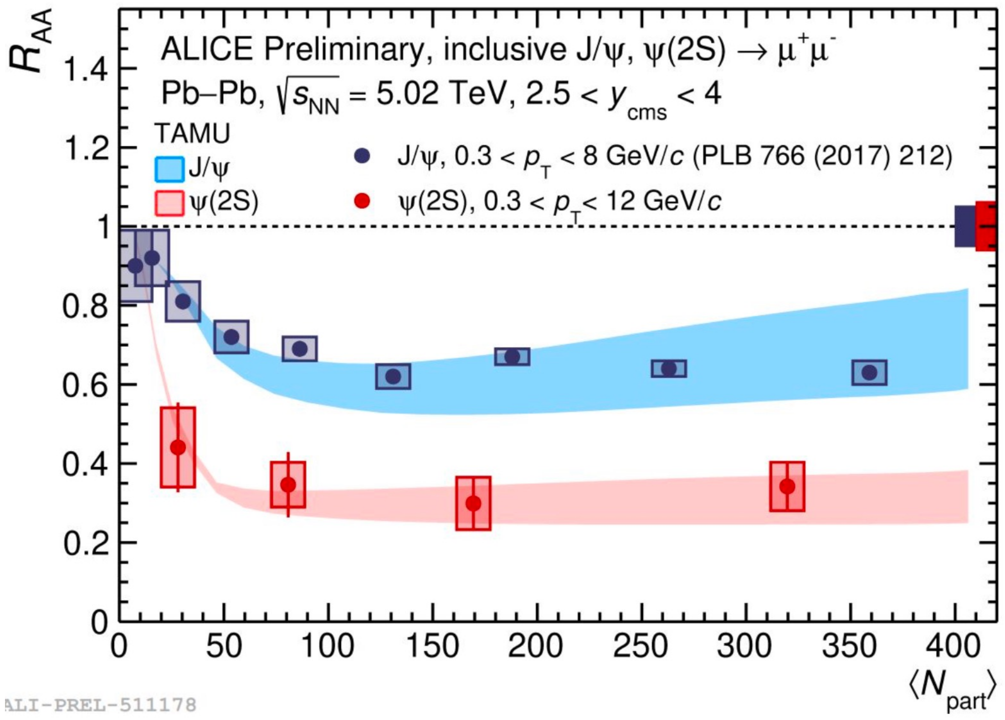
Models shown in the same centrality and rapidity ranges of ALICE measurements

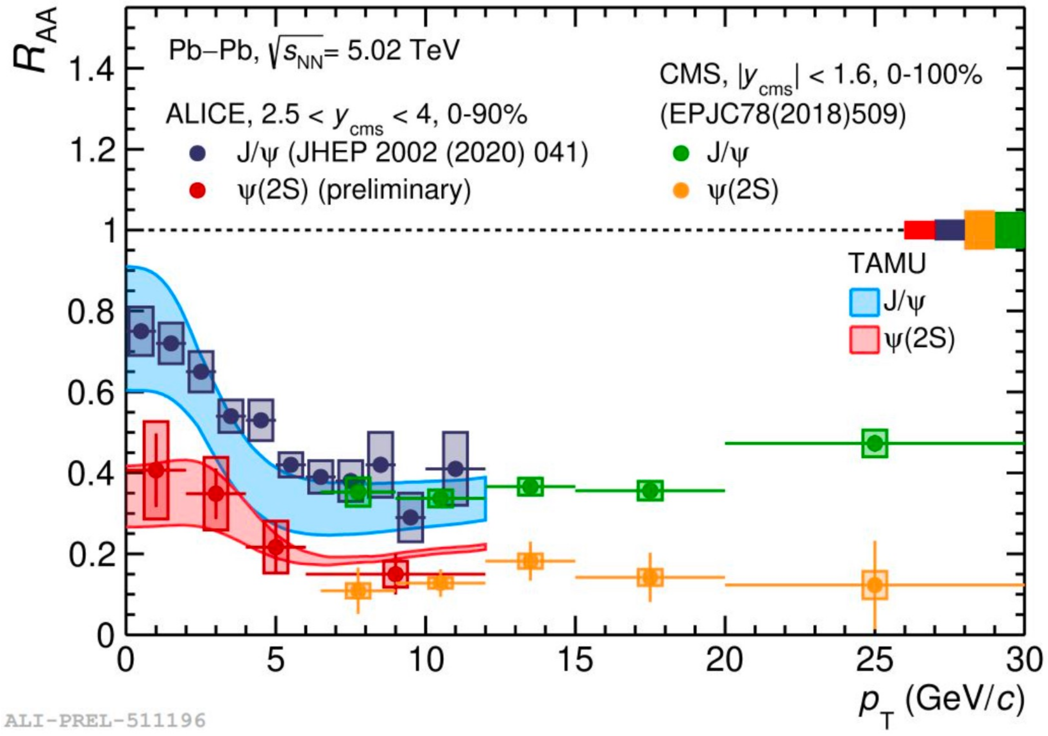
ALICE -- J/ψ and $\psi(2s)$

ψ(2S) and J/ψ R_{AA} as function of centrality and p_T

fwd-y
NEW!

- Higher suppression observed for ψ(2S) compared to J/ψ
- Increasing trend of R_{AA} towards low p_T for both J/ψ and ψ(2S)
  - Hint of ψ(2S) production via regeneration!
- Centrality and p_T dependence well reproduced by TAMU model for both J/ψ and ψ(2S)
- Compatible with midrapidity CMS results available for higher p_T





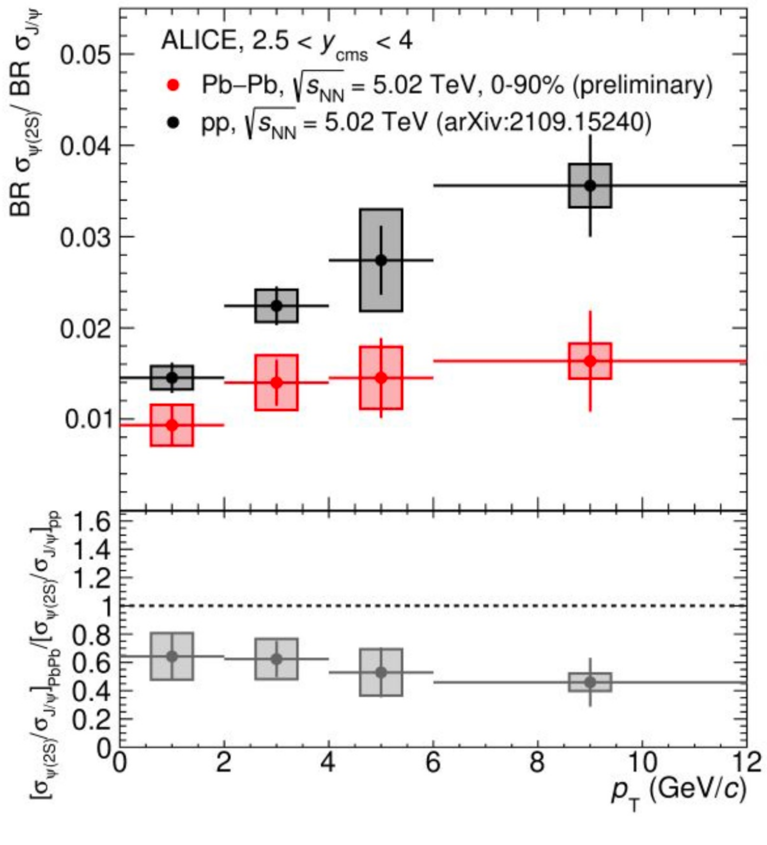
TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

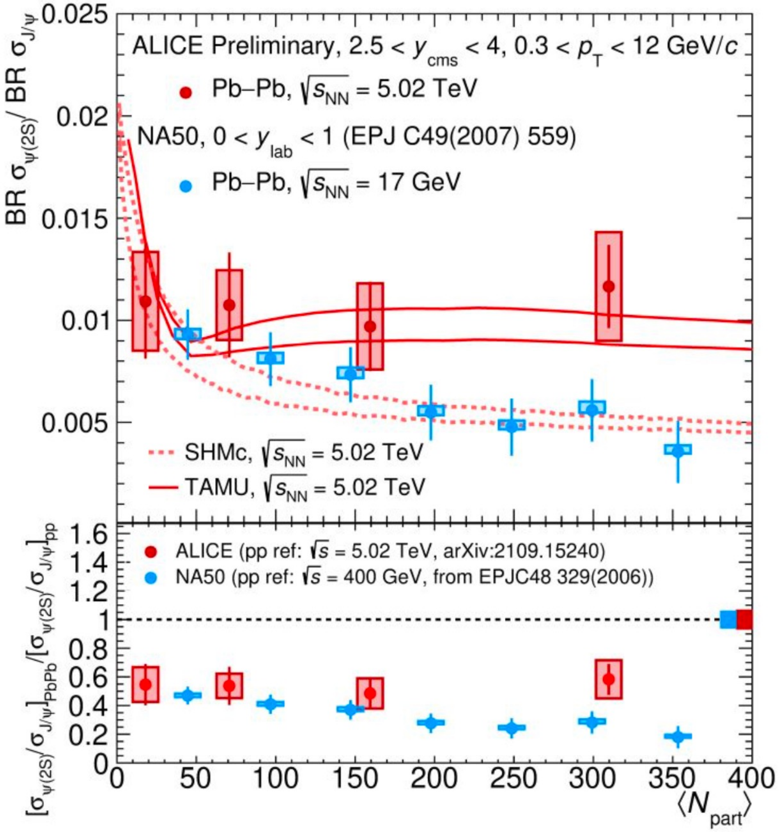
ALICE -- J/ψ and $\psi(2s)$

The ψ(2S) / J/ψ ratio

fwd-y
NEW!

- Initial state effects, such as shadowing, largely cancel in this ratio → smaller theoretical uncertainties
  - Theoretically the ψ(2S)/J/ψ ratio is weakly dependent on the charm production cross section





Comparison with models:

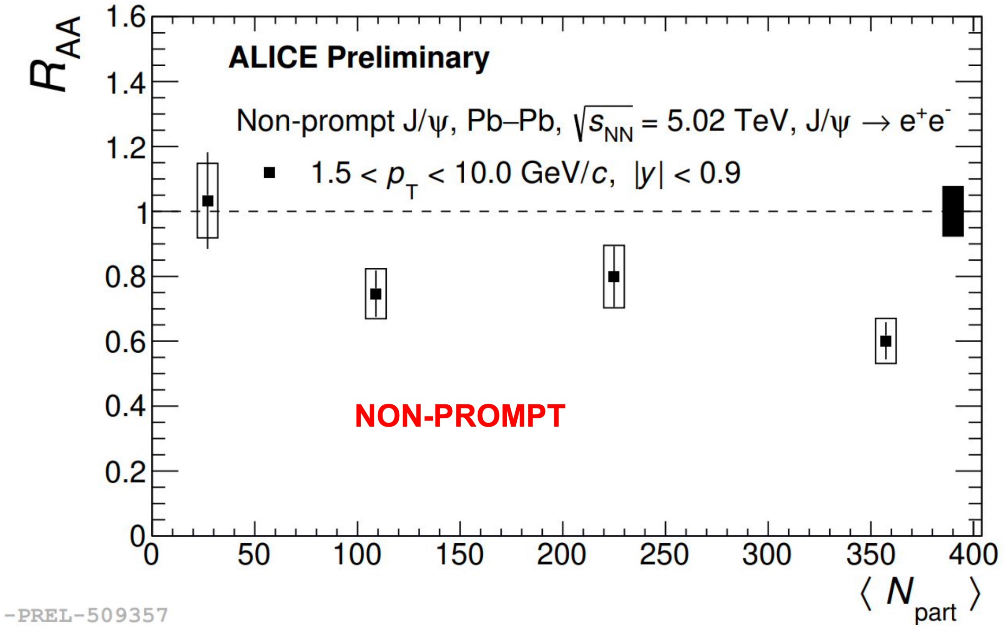
- TAMU reproduces the cross section ratios over centrality
- SHMc tends to underestimate the data in central Pb–Pb collisions

Hint of a larger ψ(2S)/J/ψ ratio in central collisions at LHC w.r.t SPS

- Smaller ψ(2S)/J/ψ ratio in Pb–Pb w.r.t. pp

TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
SHMc: Andronic A. et al., Nature 561, 321–330 (2018)

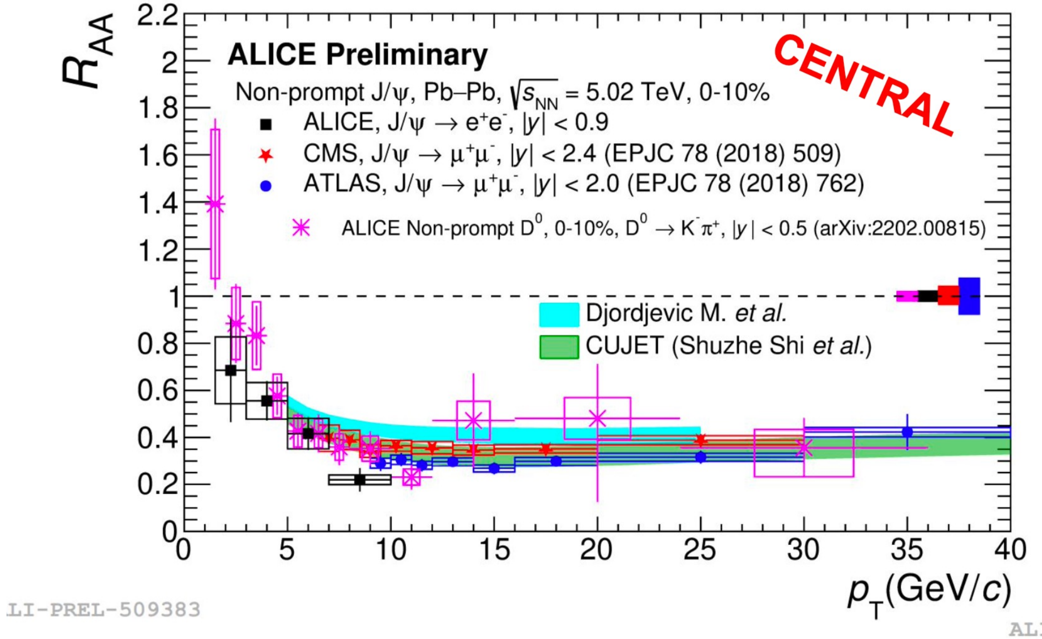
ALICE -- J/ψ

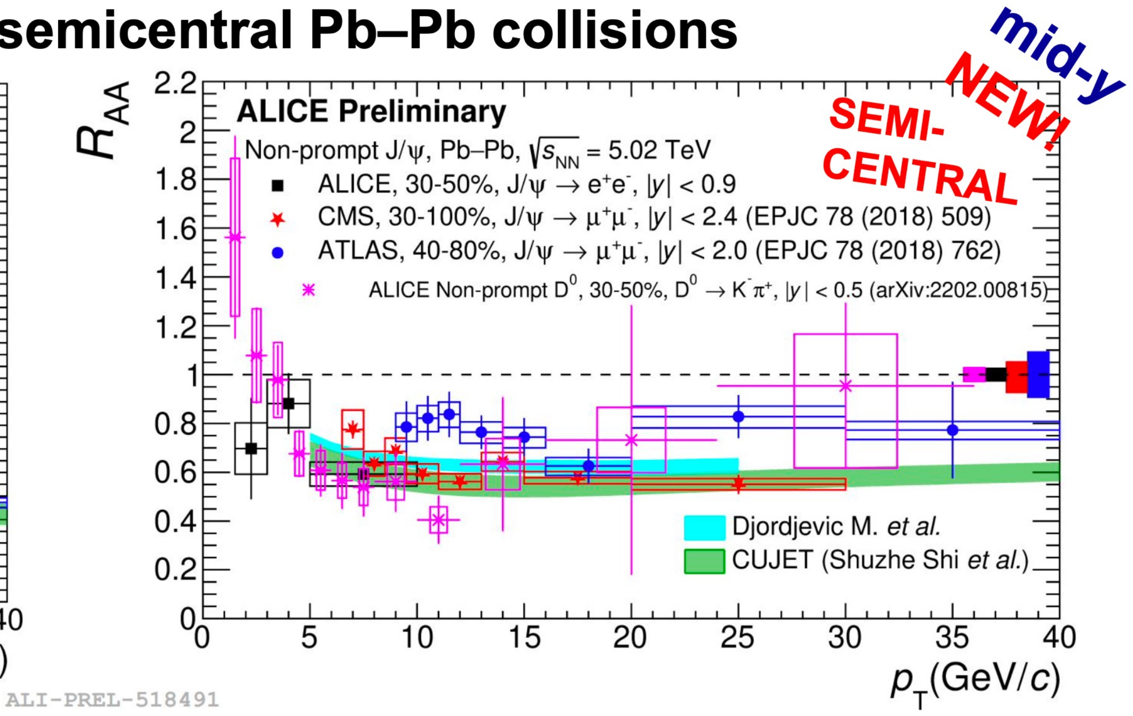


ALICE Preliminary
Non-prompt J/ψ, Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, J/ψ → e^+e^-
1.5 < p_T < 10.0 GeV/c, |y| < 0.9
NON-PROMPT
R_{AA}
⟨ N_{part} ⟩
-PREL-509357

ALICE -- J/ψ

Non-prompt J/ψ R_{AA} in central and semicentral Pb–Pb collisions





- Similar trends for non-prompt J/ψ and non-prompt D^0 R_{AA} (differences can arise due to the decay kinematic in two cases)
  - Strong suppression at high p_T (> 5 GeV/c)
  - Increase towards low p_T (< 5 GeV/c) → hints that heavy quarks are pushed towards lower p_T
- Models containing collisional and radiative energy loss consistent with data (p_T > 5 GeV/c)
- ALICE measurements complementary to ATLAS and CMS

CUJET: Shuzhe S. *et al.* *Chin.Phys.C* 43 (2019) 4, 044101, *Chin.Phys.C* 42 (2018) 10, 104104
Djordjevic M. *et al.* arXiv:2110.01544

ALICE -- J/ψ

Conclusions

Many NEW results!

J/ψ and ψ(2S) R_{AA}

- ψ(2S) and prompt/inclusive J/ψ R_{AA} show similar trends → regeneration at low p_T, suppression at high p_T
- Models implementing charmonium regeneration manage to describe data!
- ψ(2S)/J/ψ described by TAMU model, slightly underestimated by SHMc

Open to hidden charm ratio

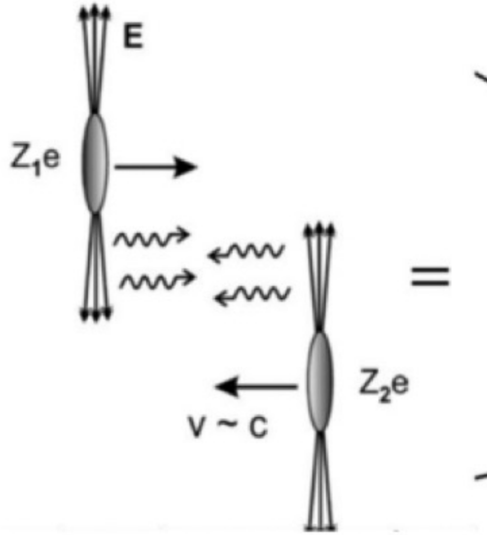
- SHMc describes the D^0 / J/ψ ratio well vs centrality

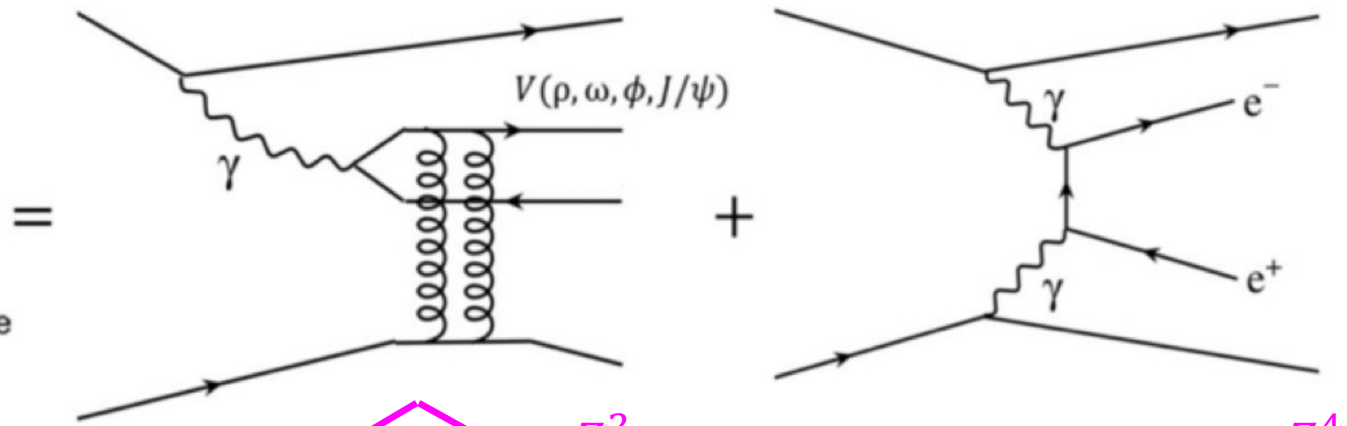
Open beauty R_{AA} via non-prompt J/ψ

- Increasing suppression towards central collisions
- ALICE measurements
  - Extend down to very low p_T
  - Compatible with models implementing energy loss mechanisms!

LHCb – J/ψ in UPCs

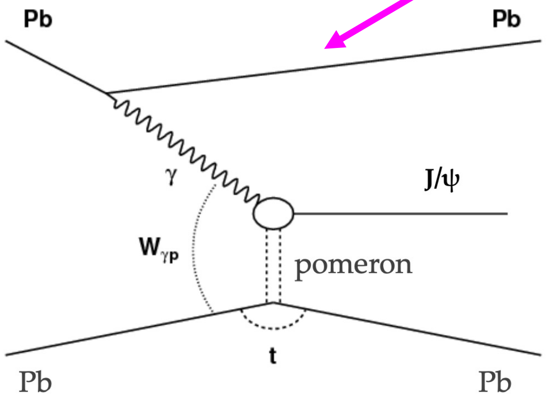
C. A. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271
PHENIX, PLB 679 (2009) 321

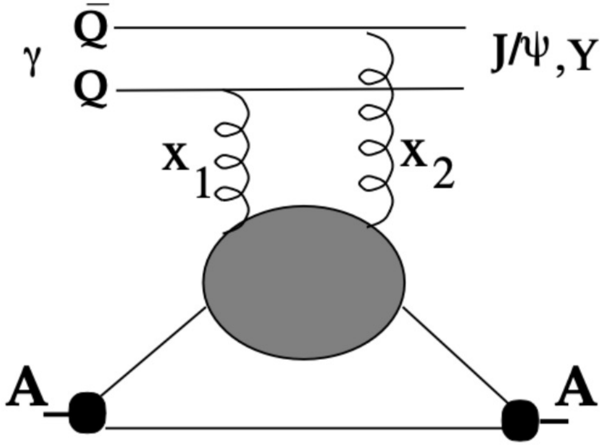




$\propto Z^2$

$\propto Z^4$





LHCb – J/ψ in UPCs

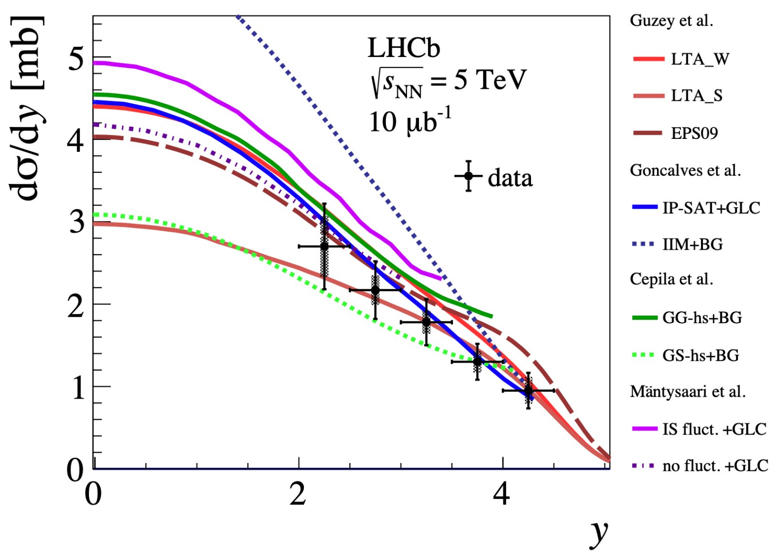
Reconstruction candidates:

- Candidates reconstructed with the dimuon channel
  - Two opposite sign μ with $p_T > 700$ MeV/c
  - $p_T^{\mu\mu} < 1$ GeV/c and $\Delta\varphi^{\mu\mu} > 0.9\pi$

/ψ PbPb UPC @5TeV

$$\sigma = 4.45 \pm 0.24\ (\text{stat}) \pm 0.18\ (\text{syst}) \pm 0.58\ (\text{lumi})\ \text{mb}$$

- Largest uncertainty due to the luminosity
- Good description of the data by the different models
- New results with the 2018 dataset, including ψ(2S), will further constrain theory



Cepila *et al.* PR C97 024901 (2018)
Gonçalves *et al.* PR D96 094027 (2017)
Guzey *et al.* PR C93 055206 (2016)
Mäntysaari *et al.* PL B772 (2017) 832

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LHCb – J/ψ in PCs

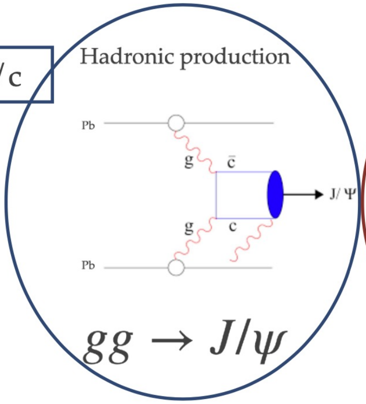
Phys. Rev. C **105**, L032201

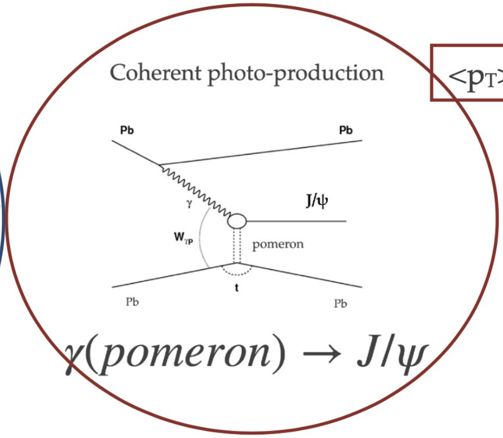
First measurement in PbPb hadronic collisions at LHCb !

Coherent J/ψ in PbPb peripheral collisions

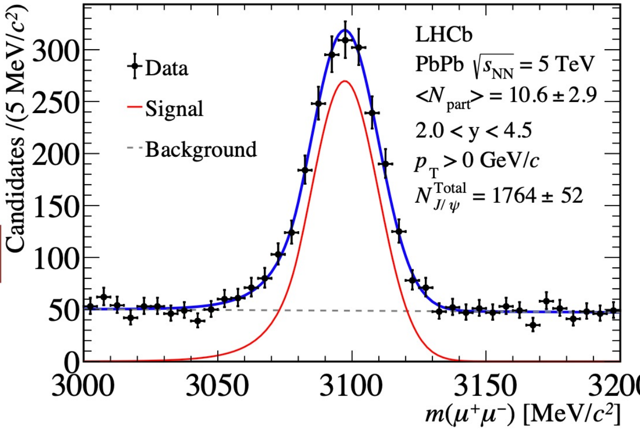
Separate the two contributions through the p_T distribution of the J/ψ

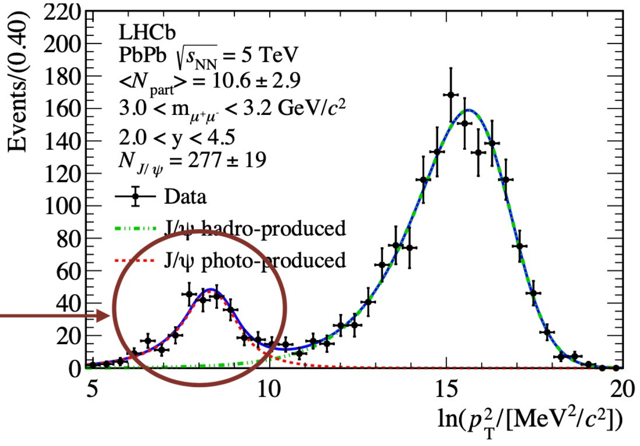
$\langle p_T \rangle$~1-2 GeV/c





$\langle p_T \rangle$ < 300 MeV/c





« Excess » of J/ψ with mean p_T around ~70 MeV/c
Compatible with coherent photo-production

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LHCb – J/ψ in PCs

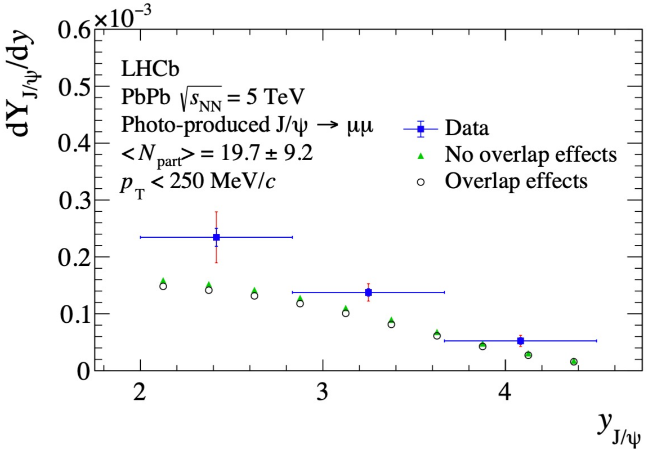
Phys. Rev. C **105**, L032201

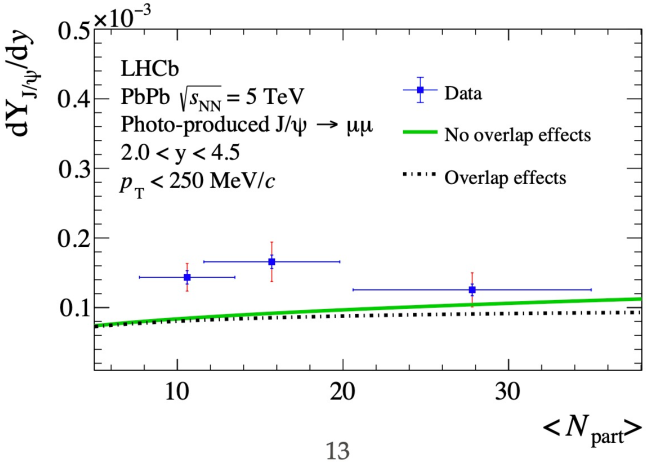
First measurement in PbPb hadronic collisions at LHCb !

Coherent J/ψ in PbPb peripheral collisions

- Consistent with J/ψ photo-production in PbPb hadronic collisions
- Most precise p_T measurement to date
- Shape compatible with model, two assumptions:
  - No effect of the overlap between the nuclei (UPC-like but small IP)
  - Effect of the overlap

W. Zha et al. Phys. Rev. C97 (2018) 044910 / Phy. Rev. C99, 06901(R)





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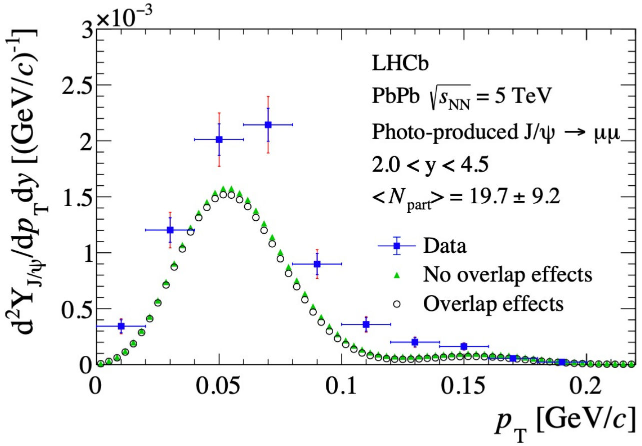
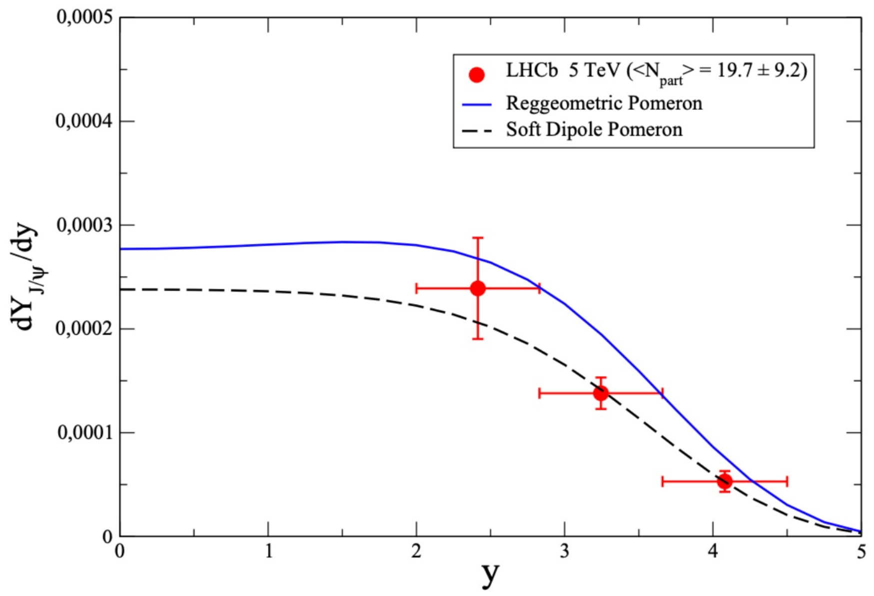


LHCb – J/ψ in PCs

Coherent J/ψ in PbPb peripheral collisions

Vector Dominance Model + Glauber multiple scattering formalism



- Recent preprint shows good agreement with the soft dipole pomeron model

- J/ψ produced by two colorless object
- Mean p_T much lower than (re)combined J/ψ
- Photo-produced J/ψ melted by QGP not « (re)combined »

Better thermometer for QGP ?

LHCb – J/ψ in PCs

Conclusion

- Precise measurement of coherent J/ψ production in UPC PbPb collisions.
- Coherent J/ψ and ψ(2S) measurement with the large 2018 data coming soon !
- Measurement of photo-produced J/ψ in peripheral PbPb collisions.
  - First result using PbPb hadronic collisions in LHCb.
  - Consistent with photo-production in PbPb peripheral collisions.
  - Agreement with last model
- Many results in the future (CEP J/ψ in *p*Pb, lower mass vector mesons…)

Summary

- p+p collisions:

✓ LHCb (J/ψ)

① A new results from LHCb at 5 TeV, good agreement with NRQCD

- p/d+A collisions:

✓ PHENIX (J/ψ and $\psi(2s)$ in p+Au):

① At forward rapidity, nPDF can well describe data

② At background rapidity, it suggest the presence of the final states (similar at RHIC and LHC energy)

✓ STAR (J/ψ in p+Au):

① Suppression at low p_T, consistent with unity at high p_T at mid-rapidity

Summary

➢ A+A collisions:

✓ STAR (J/ψ in Au+Au and isobar):

① No significant energy dependence from 39.9 to 200 GeV

② Seems to be driven by system size ($\langle N_{part} \rangle$)

✓ ALICE (J/ψ in Pb+Pb):

① Consistent with CMS and ATLAS results within uncertainties

✓ LHCb (J/ψ in Pb+Pb UPCs and PCs):

① Consistent with model