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Recent results on quarkonia from STAR experiment

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for the STAR collaboration

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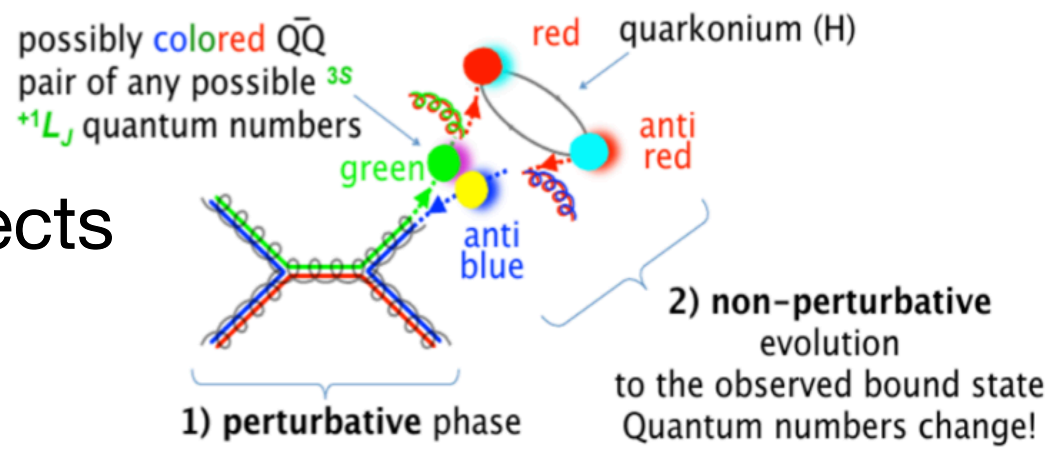
Quarkonium physics at STAR

Production in p+p

- Production mechanism
- Reference for hot/cold nuclear matter effects

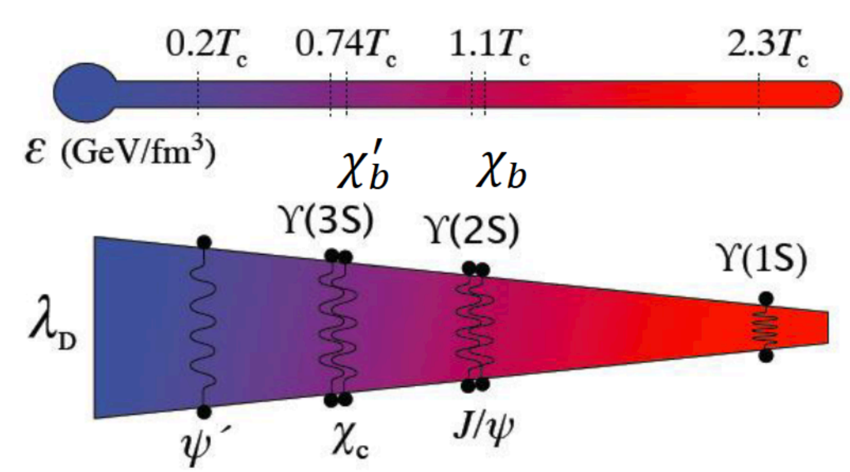


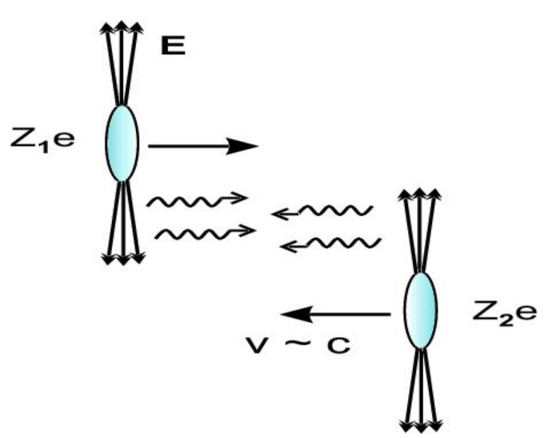
Production in p/d/He+A

- Cold nuclear matter effect
  - nPDFs, Nuclear absorption, Co-mover interactions etc.

Production in A+A

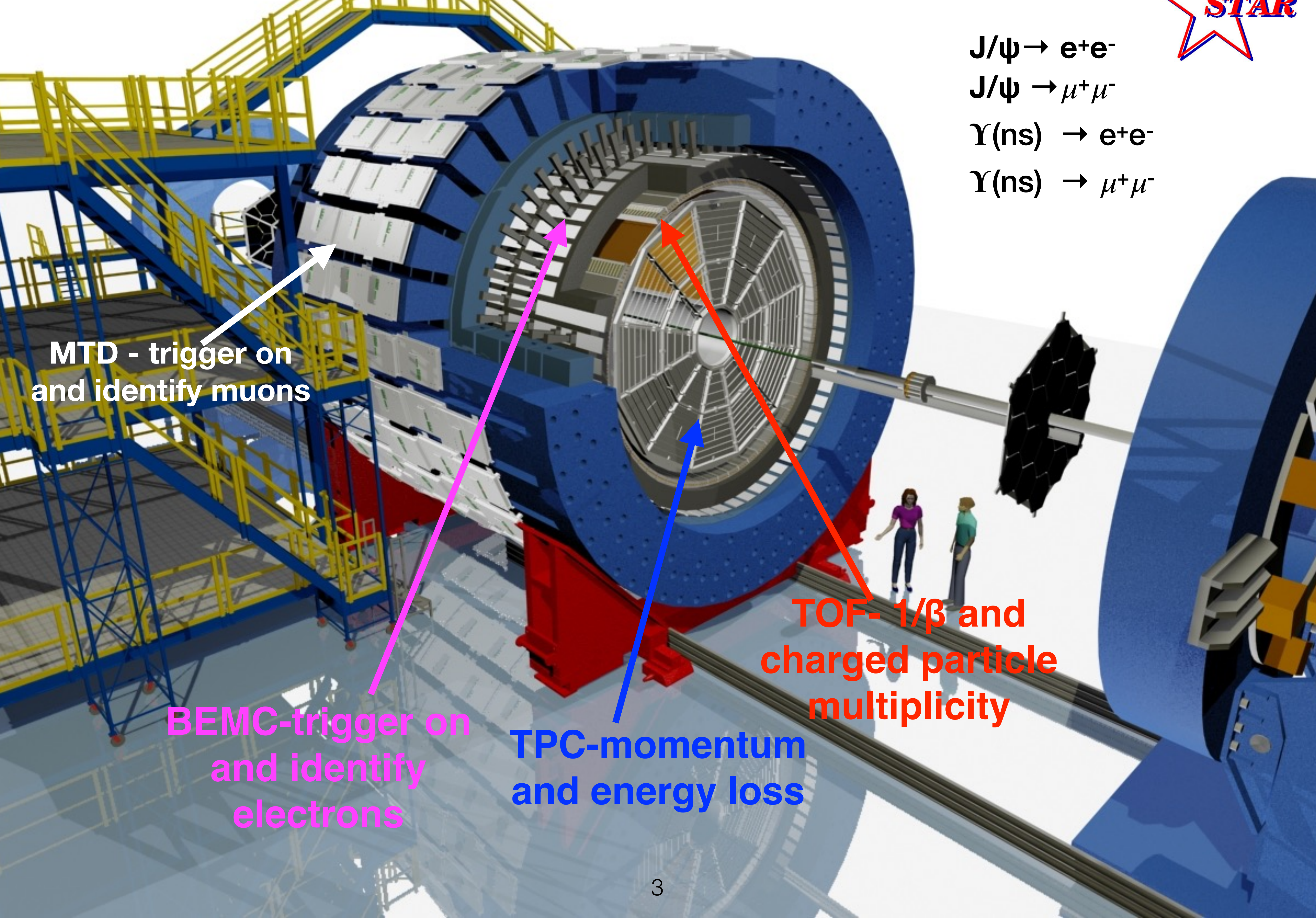
- Probing QGP and its properties
- Coherent photoproduction process in HIC





The Solenoid Tracker At RHIC (STAR)

$J/\psi \to e^+e^-$
$J/\psi \to \mu^+\mu^-$
$\Upsilon(ns) \to e^+e^-$
$\Upsilon(ns) \to \mu^+\mu^-$

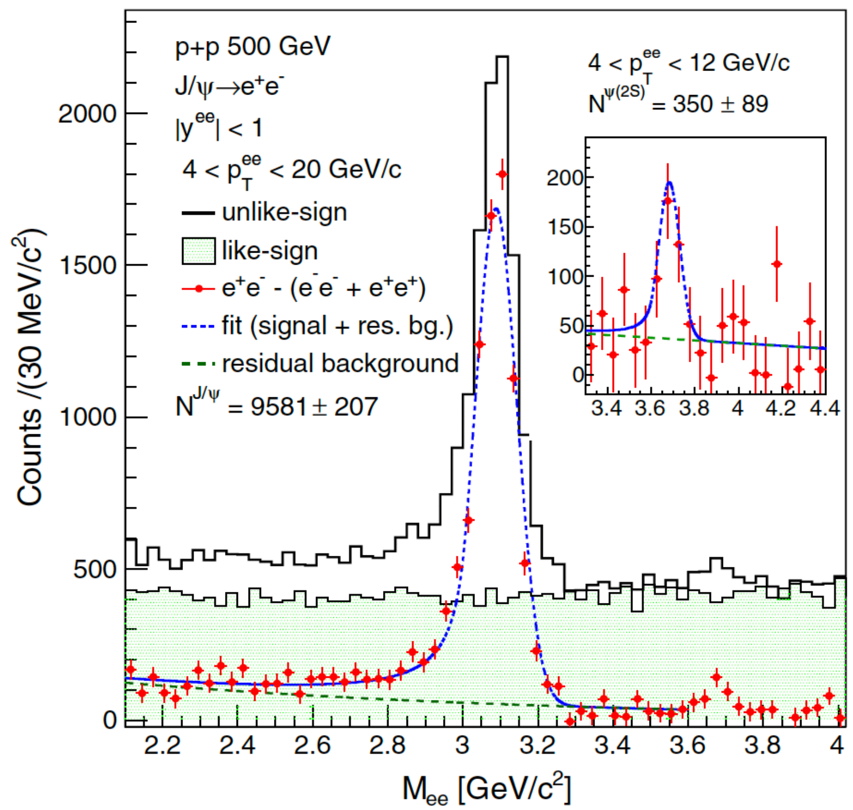


Quarkonia at STAR

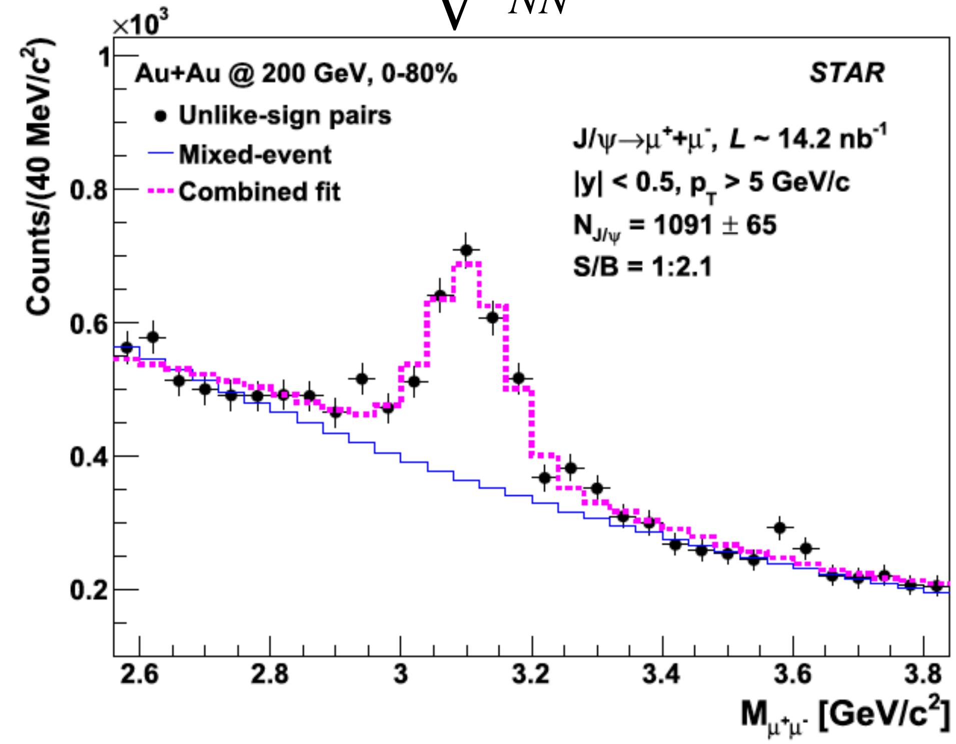
$p + p @ \sqrt{s} = 500 GeV$

$Au + Au \sqrt{s_{NN}} = 200 GeV$

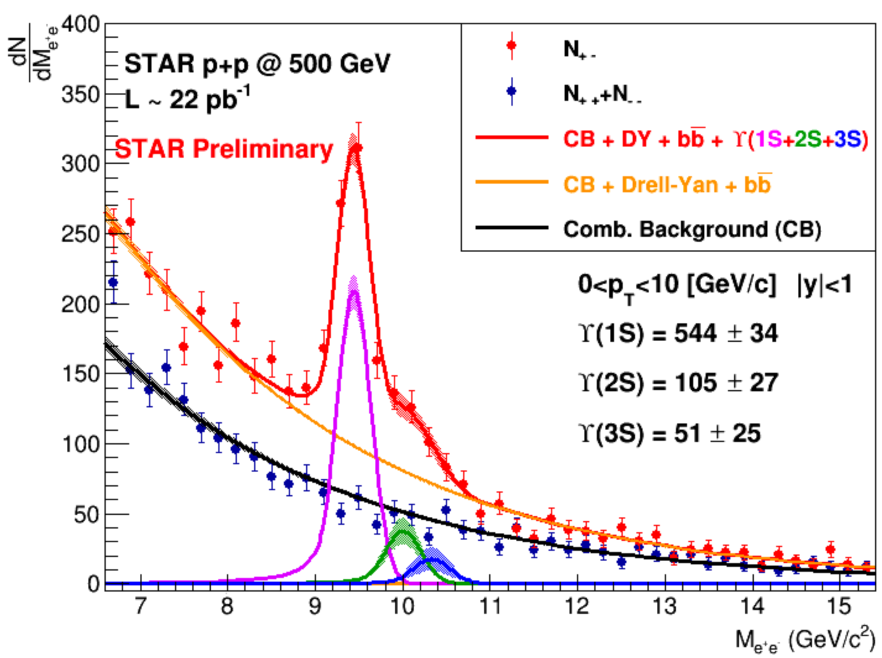
$J/\psi \rightarrow e^+e^-$



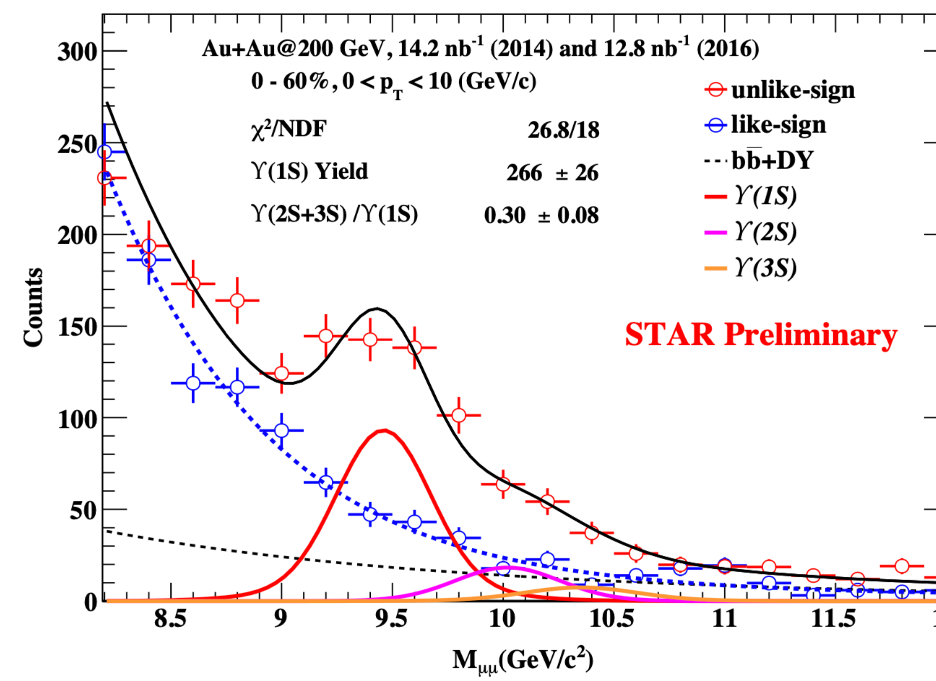
$J/\psi \rightarrow \mu^+\mu^-$



$\Upsilon \rightarrow e^+e^-$



$\Upsilon \rightarrow \mu^+\mu^-$



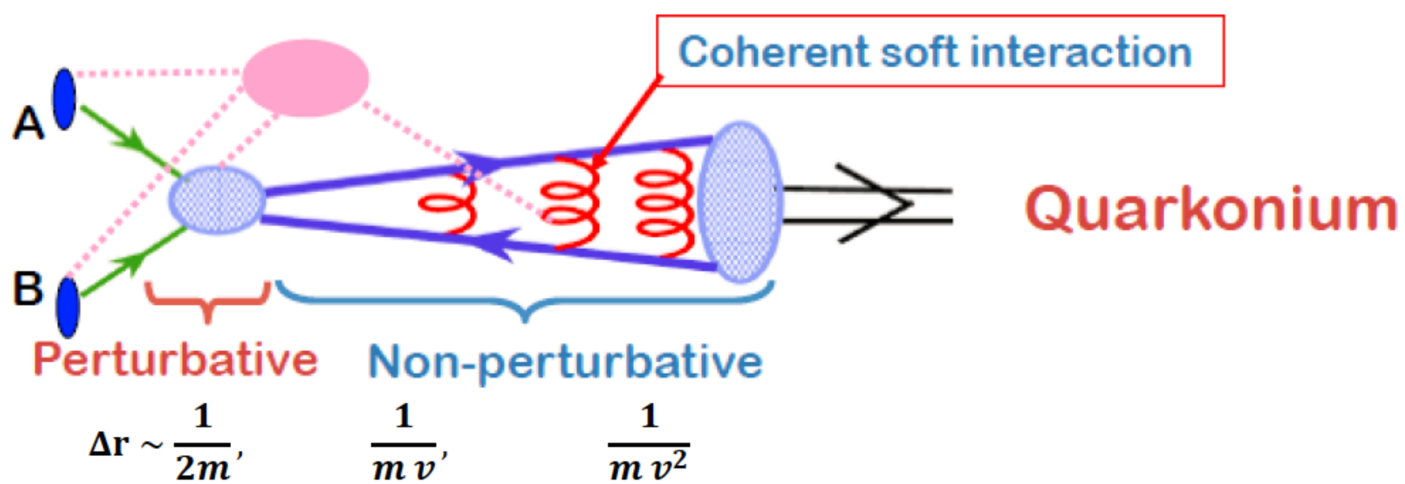
p+p collisions

Quarkonia production

- Heavy quarkonium: an ideal laboratory for testing the interplay between **perturbative** and **nonperturbative** QCD

Bound state of $Q\bar{Q}$ pair under strong interaction
The simplest system in QCD: two-body problem

Charmonium: m~1.3 GeV, $v^2 \approx 0.3$
Bottomonium: m~4.5 GeV, $v^2 \approx 0.1$

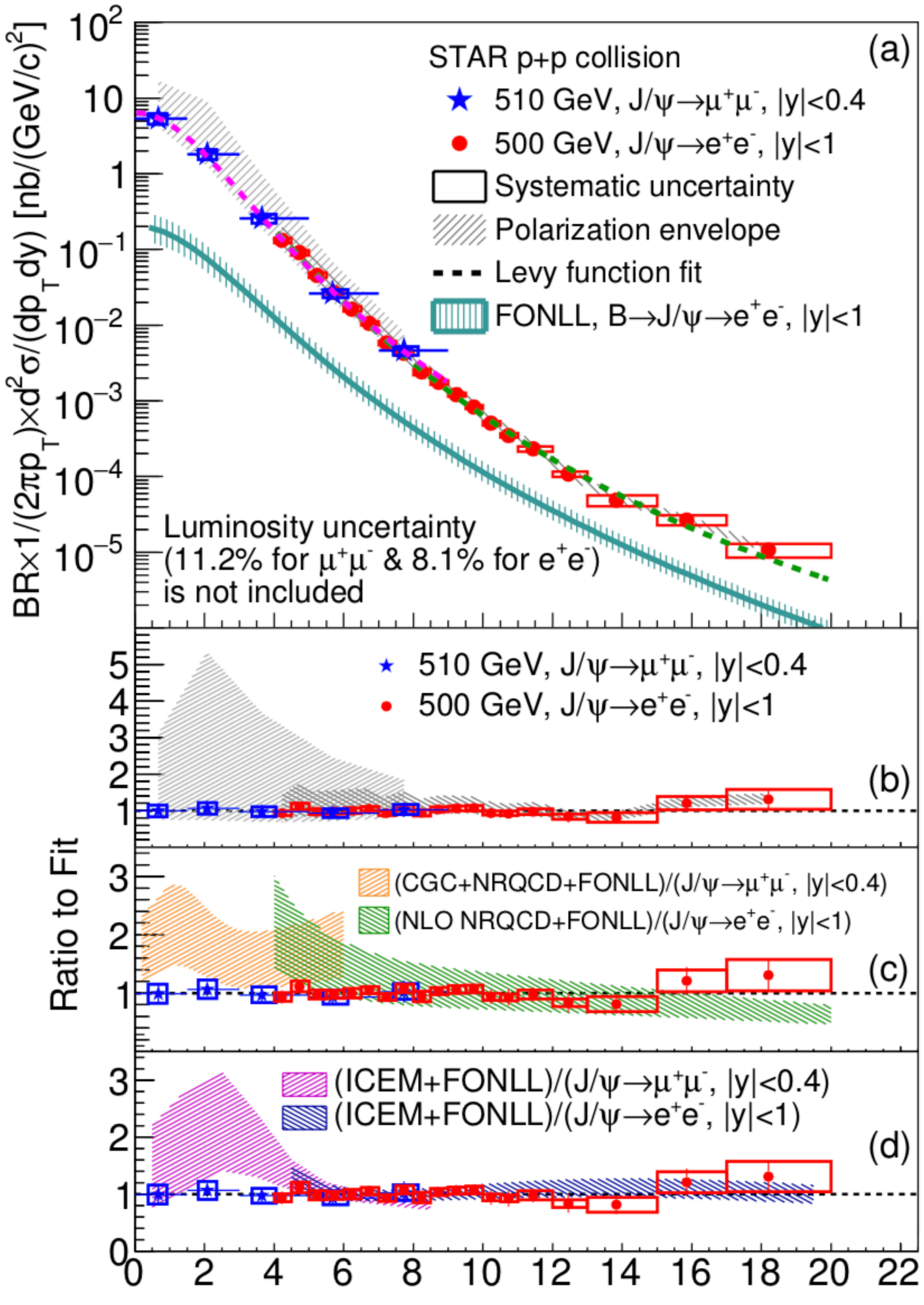


Production of the $Q\bar{Q}$
(large momentum transfer)
pQCD process

$\longrightarrow$

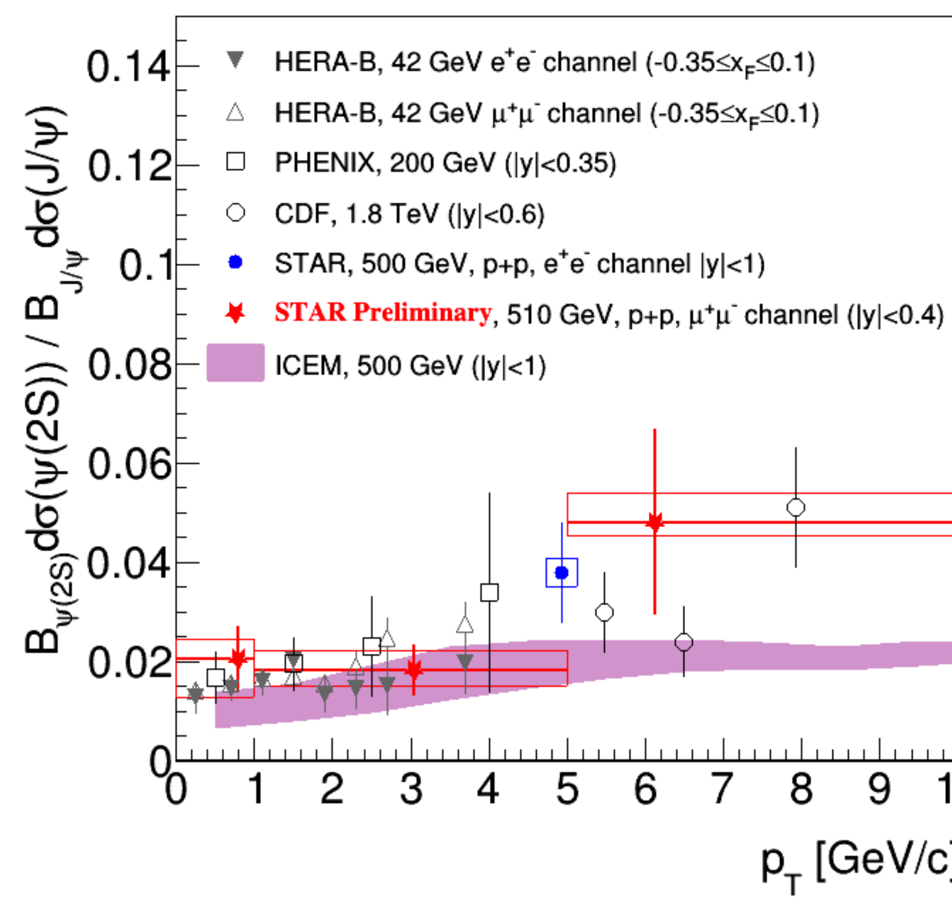
Evolution of the $Q\bar{Q}$ pair into quarkonium
(small dynamical scale)
non-pQCD process

Inclusive J/ψ cross section



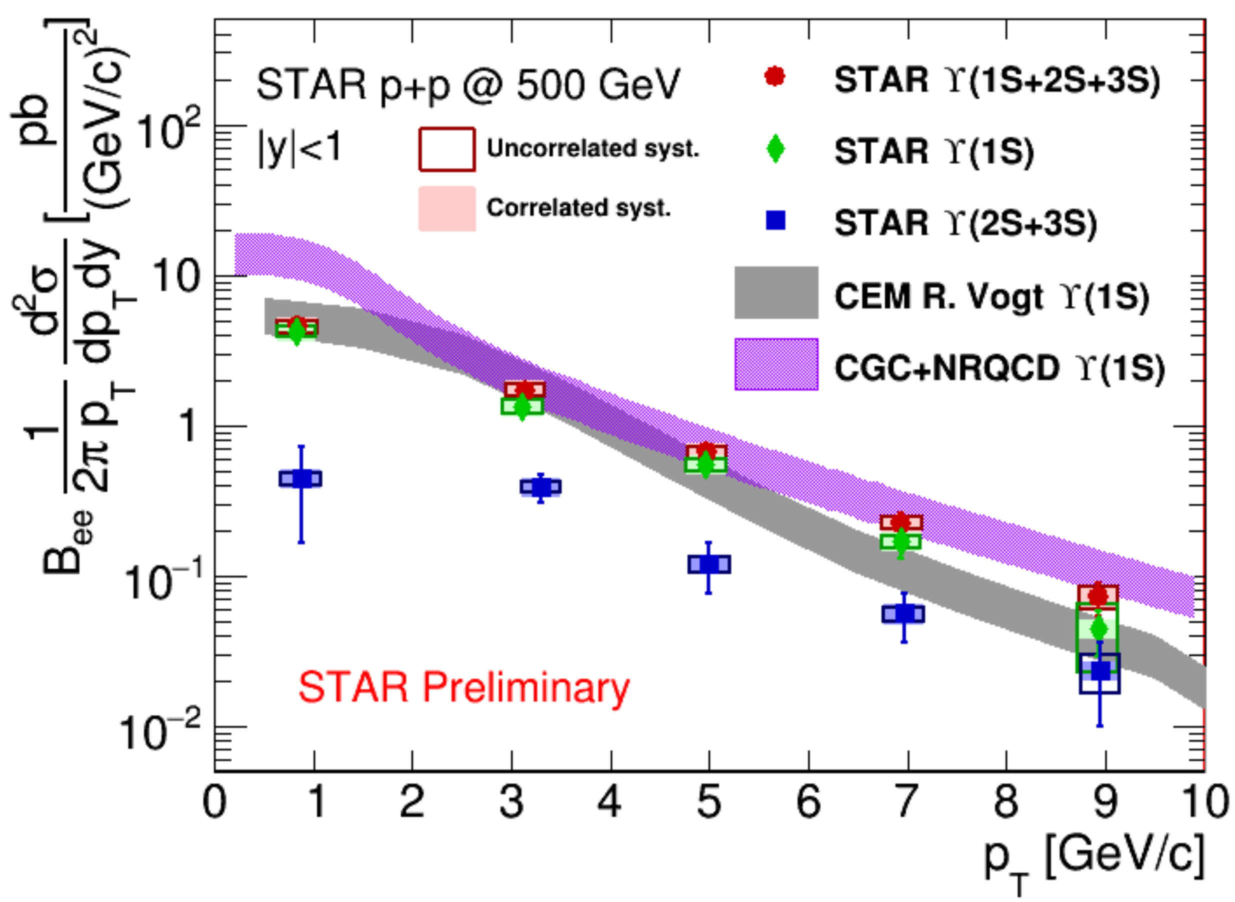
STAR, PRD 100 (2019) 52009

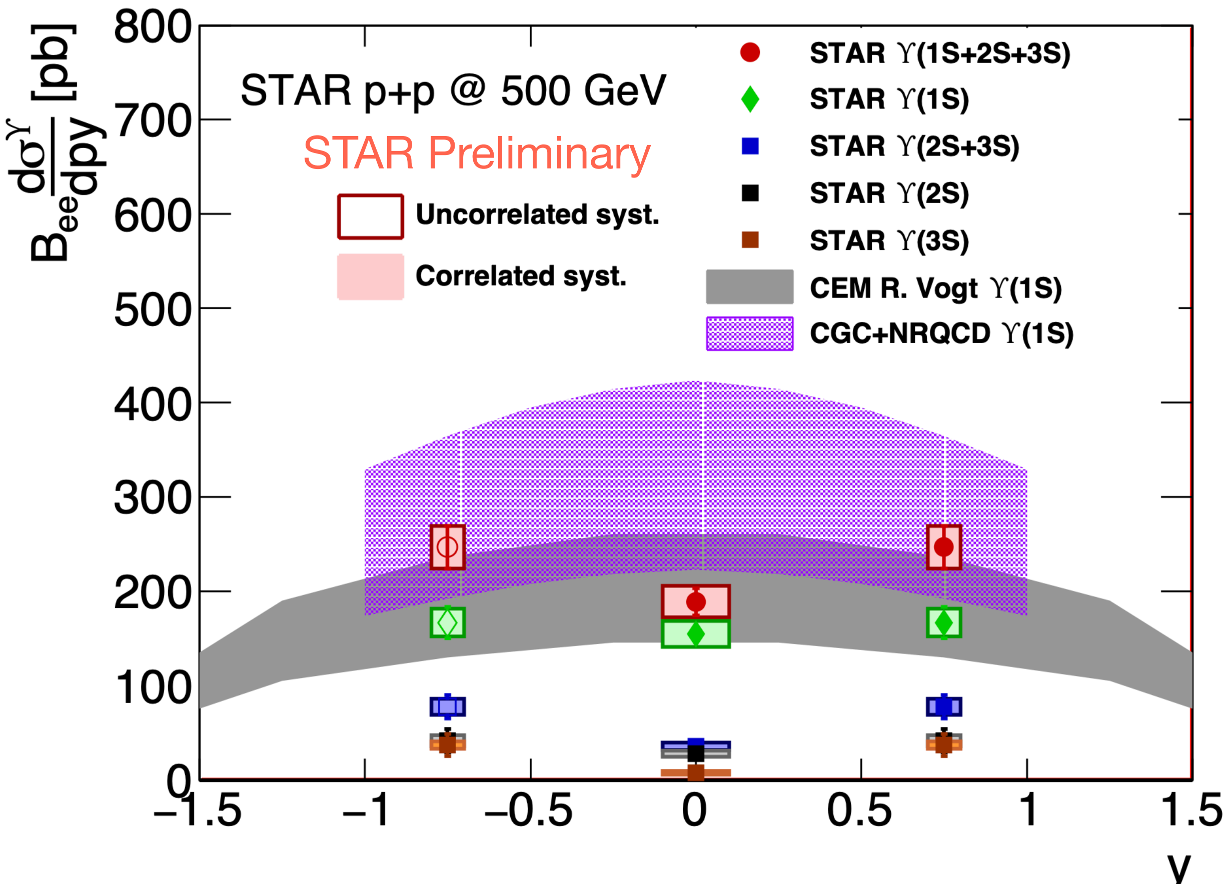
- Precision measurement within large dynamic range (p_T = 0-20 GeV/c)
- Measurements consistent with CGC+NRQCD & NLO NRQCD as well as ICEM calculations, within the polarization envelope



- First ψ(2S) to J/ψ ratio vs. p_T from STAR
- Results are consistent with ICEM prediction

Υ differential cross section





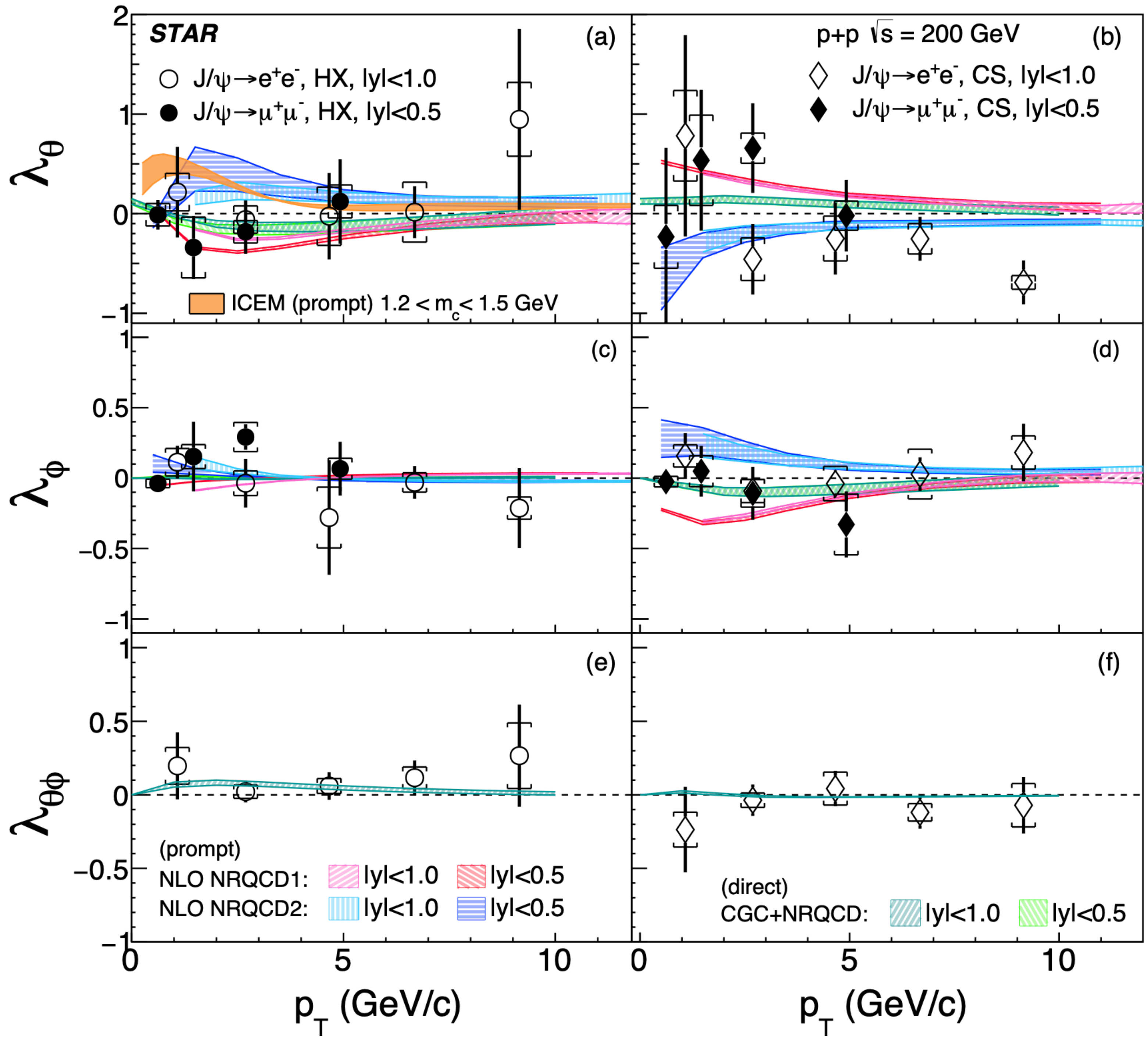
CEM: R. Vogt, PRC 92 (2015) 034909

CGC+NRQCD: Hao Han et. al, PRD 94 (2016) 014028;

Yan-Qing Ma et. al, PRL 113 (2014)192301

- CEM predictions describe the inclusive Υ(1S) production
- CGC+NRQCD calculation of direct Υ(1S) overestimates the inclusive Υ(1S) measurement

J/ψ polarization



$$\frac{d^2N}{dcos\theta d\phi} \sim 1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi$$
$$+\lambda_{\theta\phi} sin2\theta cos\phi$$

- λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ are consistent with 0 in both HX and CS frames
- NRQCD calculations with two different sets of LDMEs and CGC+NRQCD calculation are all consistent with data within uncertainties

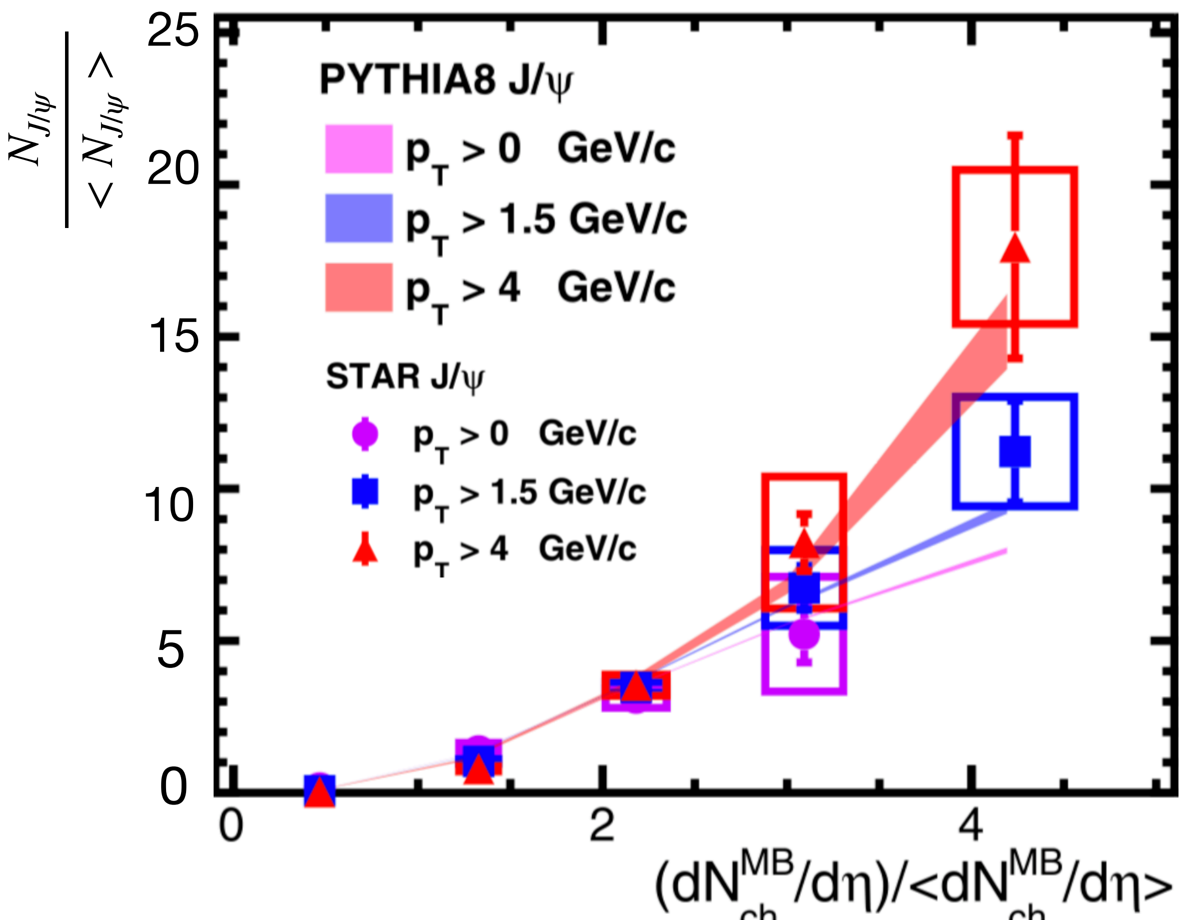
Accepted by PRD (arxiv:2007.04732)

NRQCD1: Hong-fei Zhang et.al., PRL 114 (2015) 092006

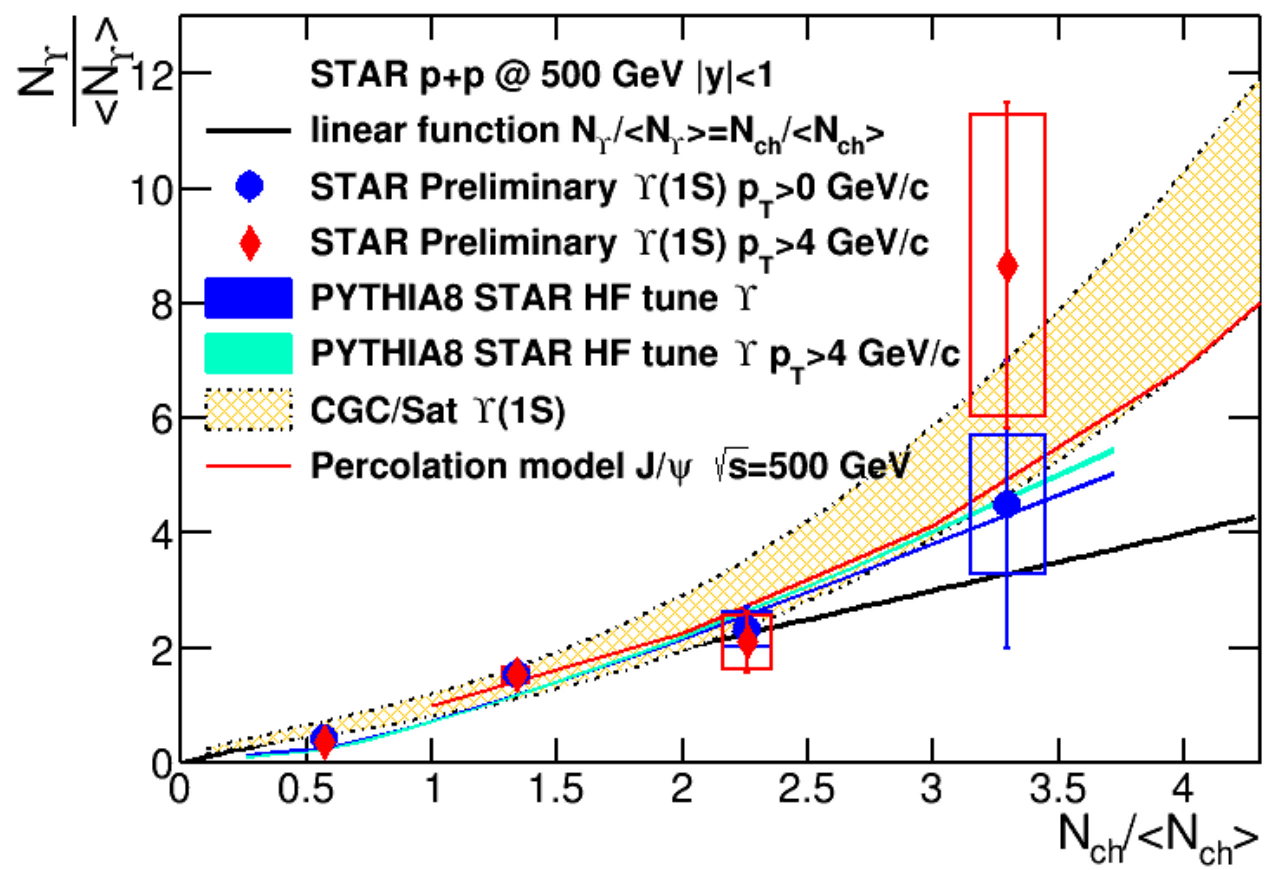
NRQCD2: Bin Gong et al., PRL 110 (2013) 042002

CGC+NRQCD: Yan-Qing Ma et al., JHEP 12 (2018) 057

Quarkonium production vs N_{ch}



STAR, PLB 786 (2018) 87-93



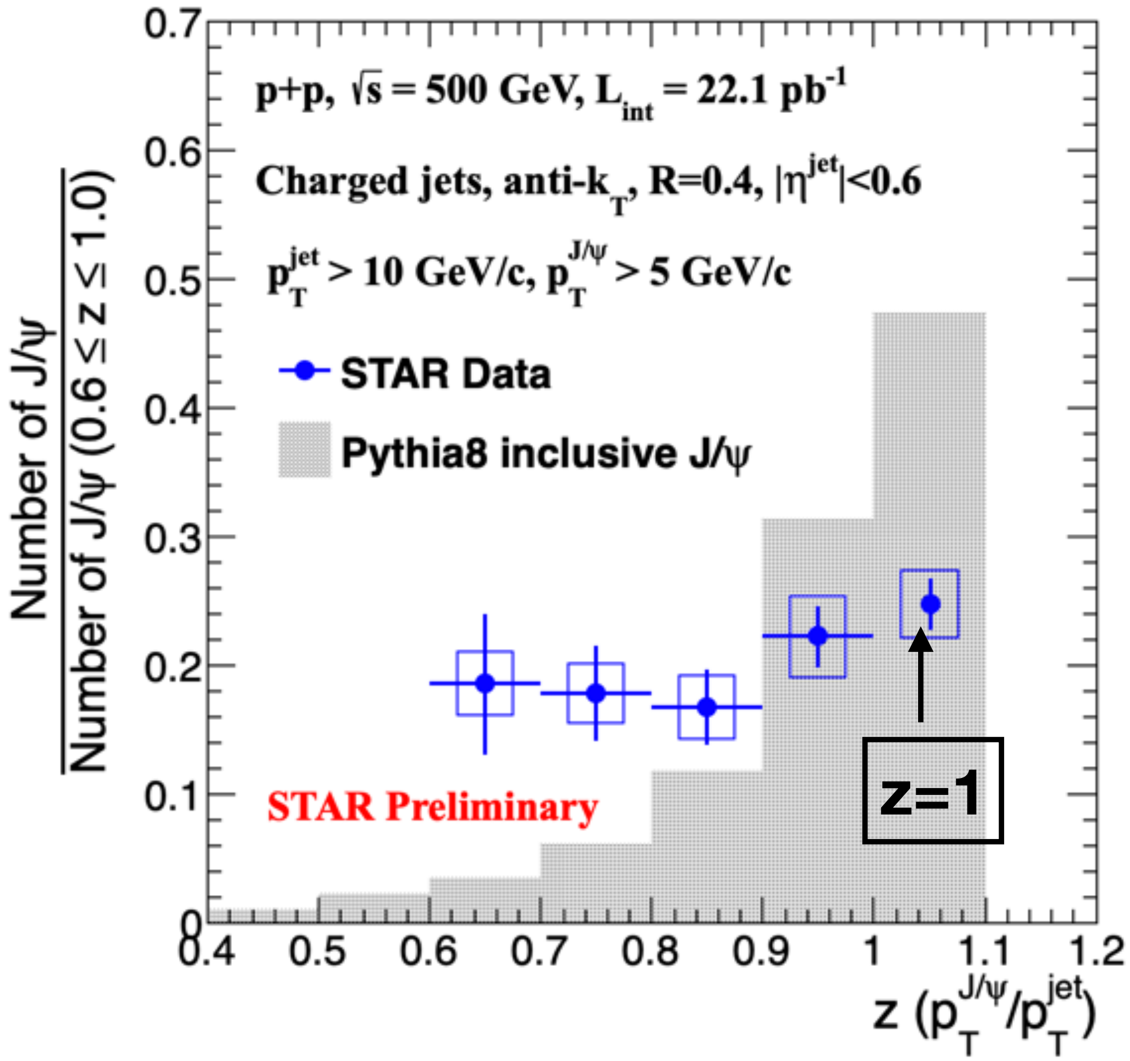
E. Levin, et al., EPJC, 97(5) (2019) 376

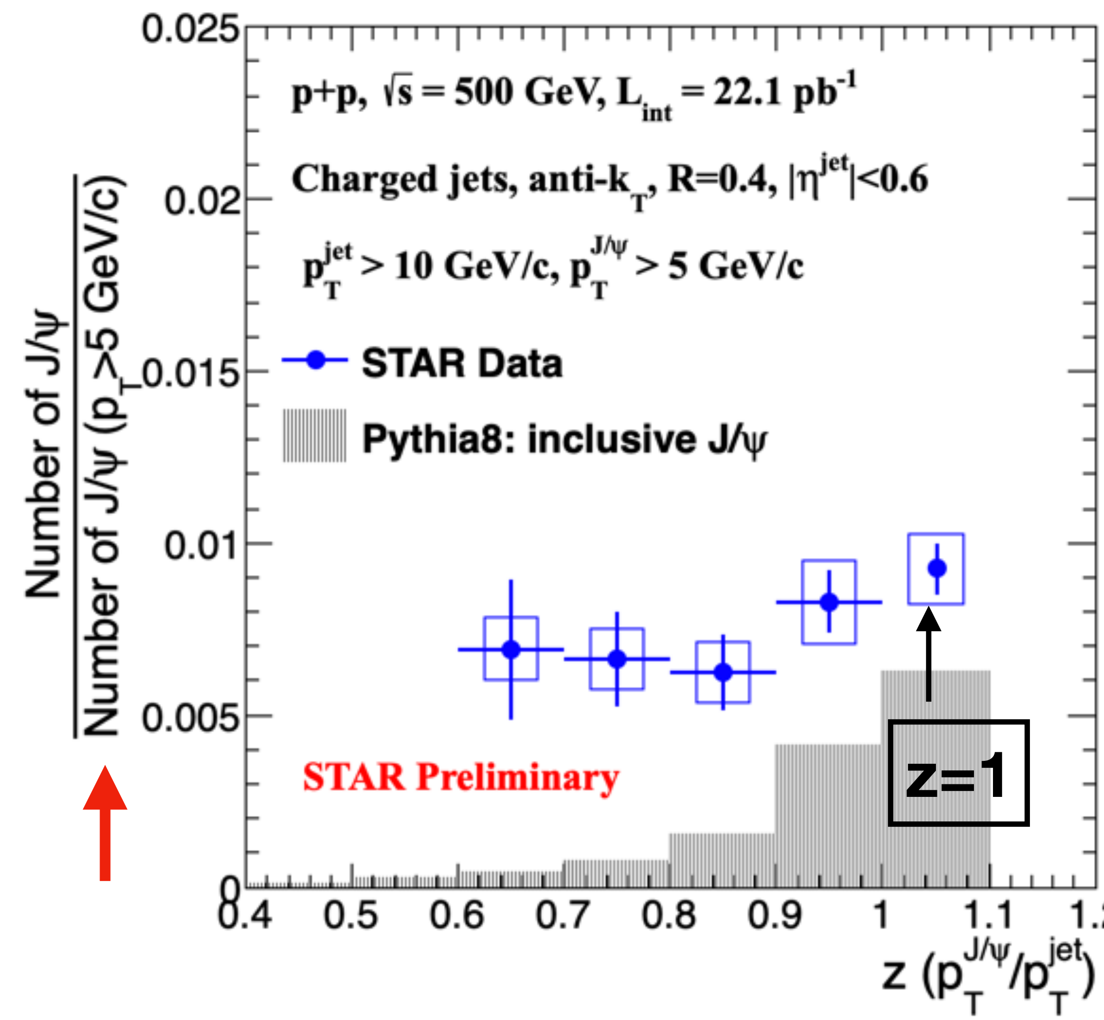
E. Ferreiro, et al., PRC 86 (2012) 034903

- Similar increasing trends of J/ψ and ϒ yields vs. mid-rapidity activity
  - Interplay between hard and soft process
- PYTHIA8 and String Percolation models reproduce the trend in data for both J/ψ and ϒ
- CGC/Saturation model describes ϒ data within large uncertainties

J/ψ production within a jet

jet: charged particles + J/ψ

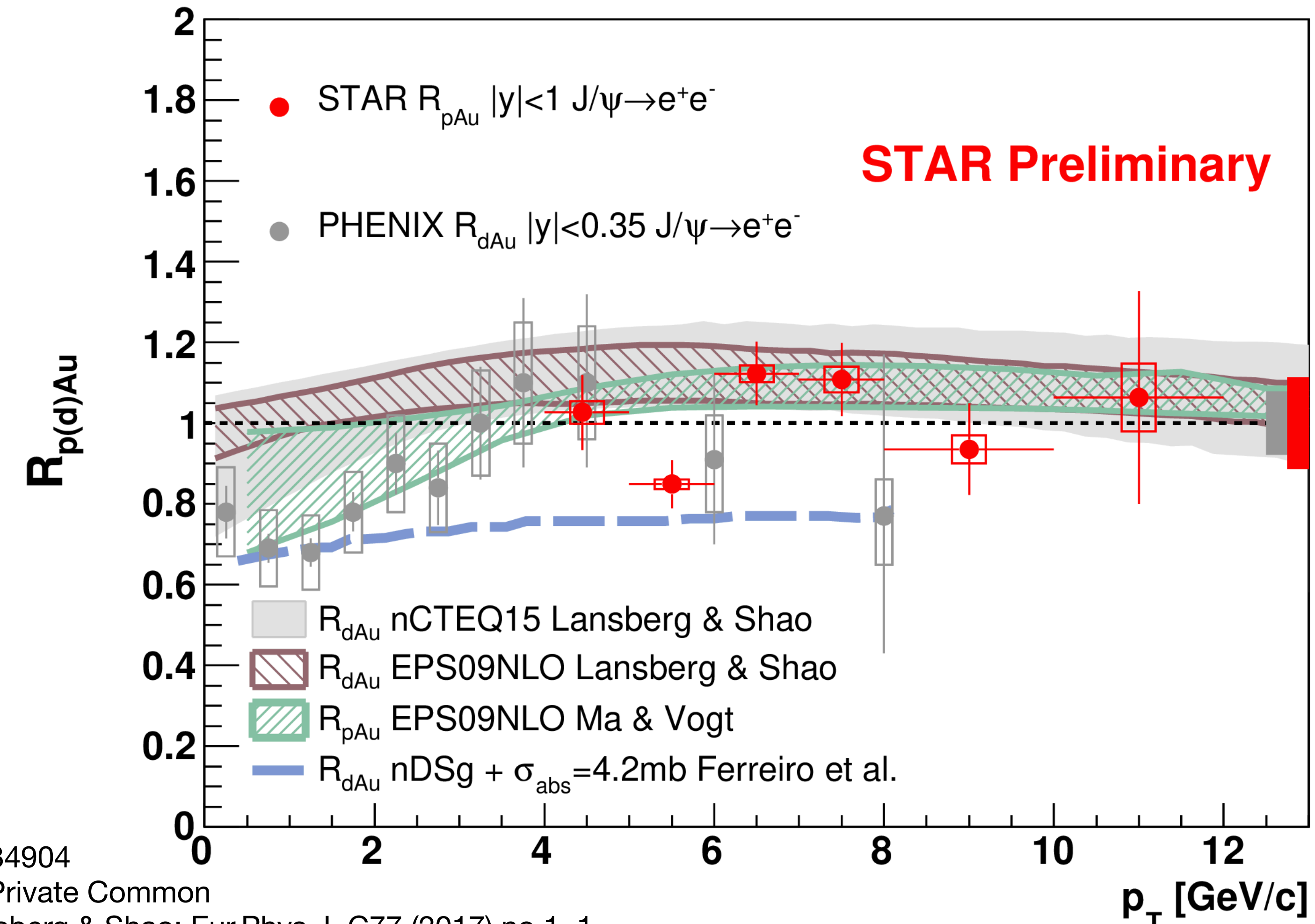




- Charged jet to J/ψ fragmentation function :
  - No significant z dependence observed within uncertainties
- Different trends and probabilities of producing a J/ψ in charged jet for the measured kinematics range between data and Pythia8

p+A collisions

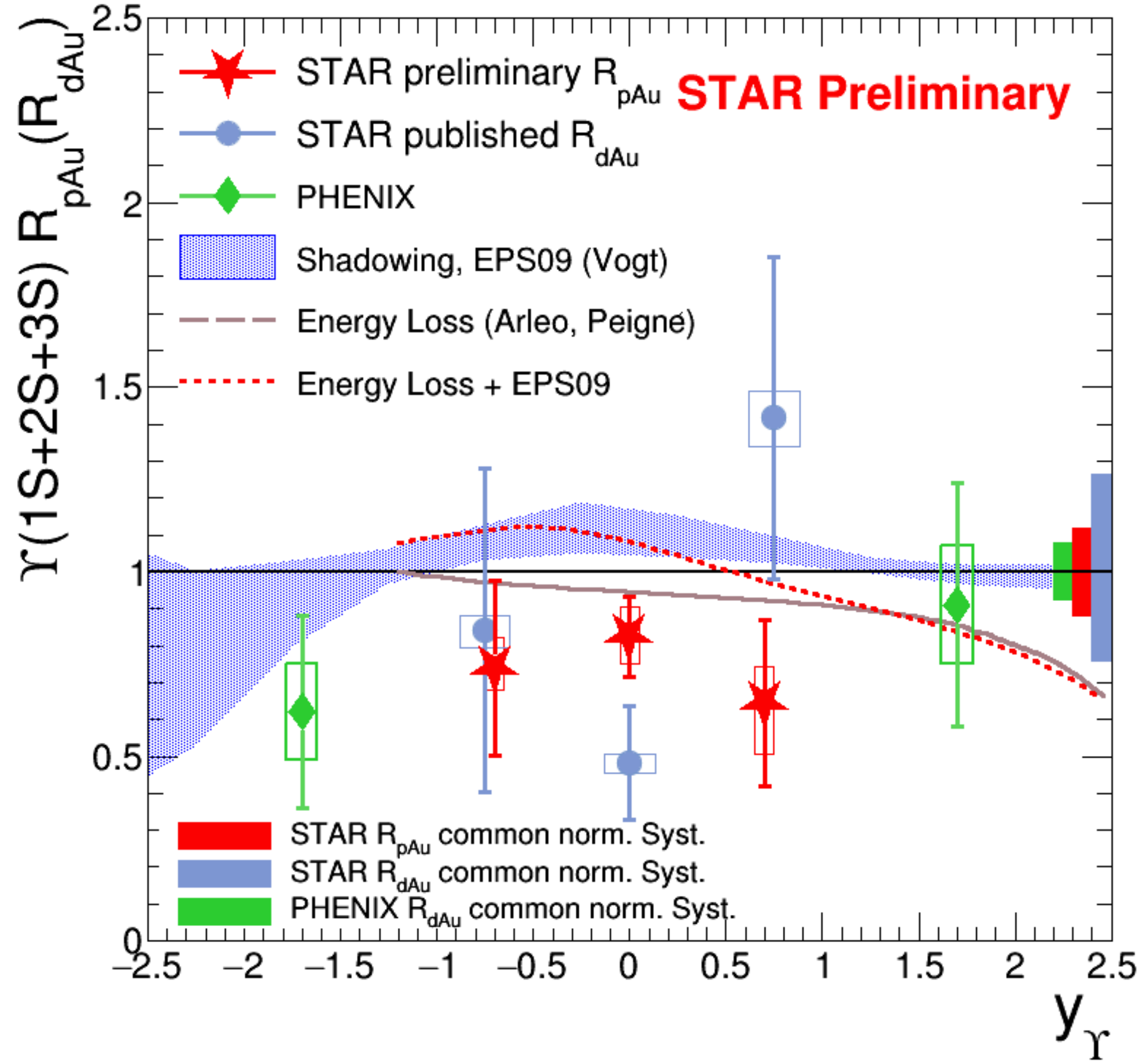
J/ψ R_{pAu}



PHENIX, PRC 87 (2013) 034904
EPS09+NLO, Ma & Vogt, Private Common
nCTEQ, EPS09+NLO, Lansberg & Shao: Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259 Comp. Phys. Comm. 184 (2013) 2562-2570; Ferreriro et al., Few Body Syst. 53 (2012) 27

- R_{pAu} consistent with unity at high p_T, suggesting no modifications due to the CNM effects
  - And in agreement with models with nPDF effects
- Consistent with PHENIX R_{dAu}, indicating similar cold nuclear matter effects in p+Au and d+Au collisions

Υ R_{pAu}



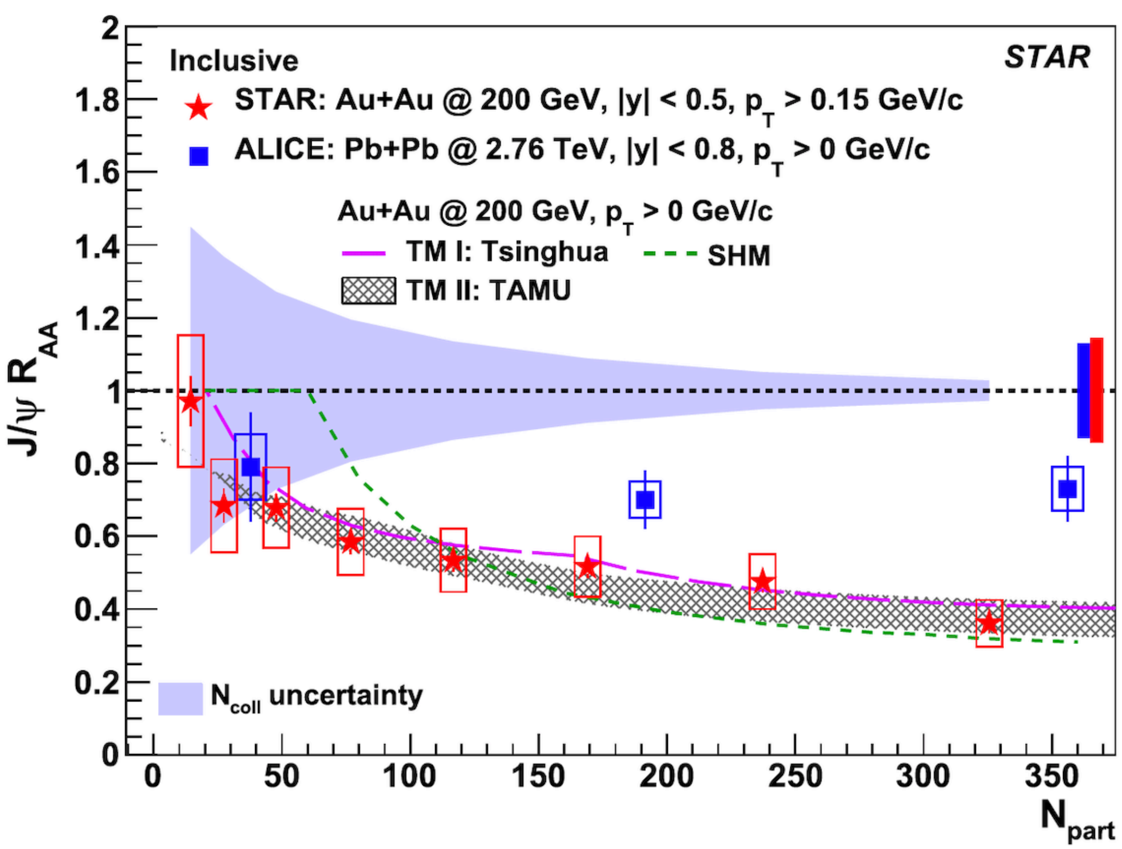
STAR, PLB 735 (2014) 127
PHENIX, PRC 87 (2013) 044909
Energy Loss: Francois Arleo et al., JHEP 1303 (2013)122

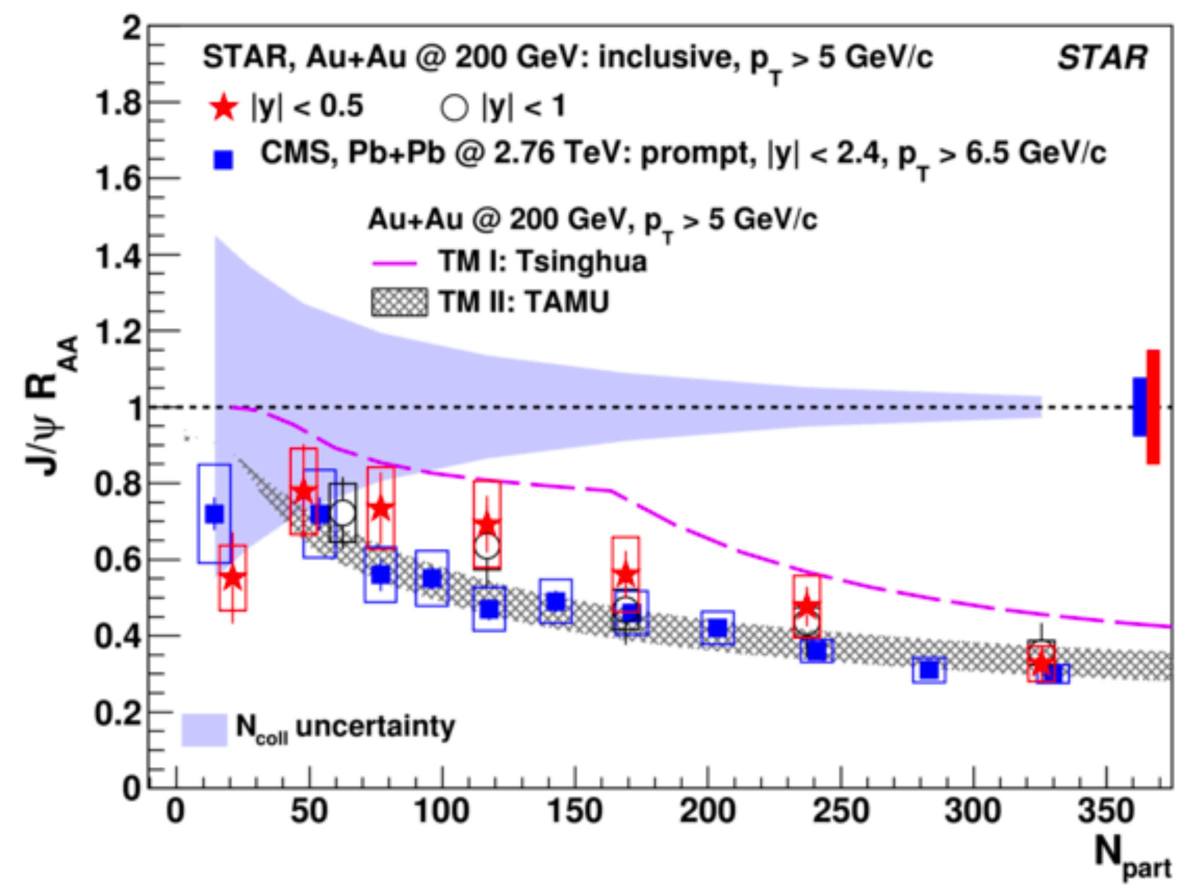
- Improved precision over previous d+Au results (~50% smaller statistical uncertainty)
- Indication of more suppression than that from models with nPDF effects and energy loss in cold nuclear matter

A+A collisions

J/ψ suppression

p_T > 0 GeV/c **p_T > 5 GeV/c**



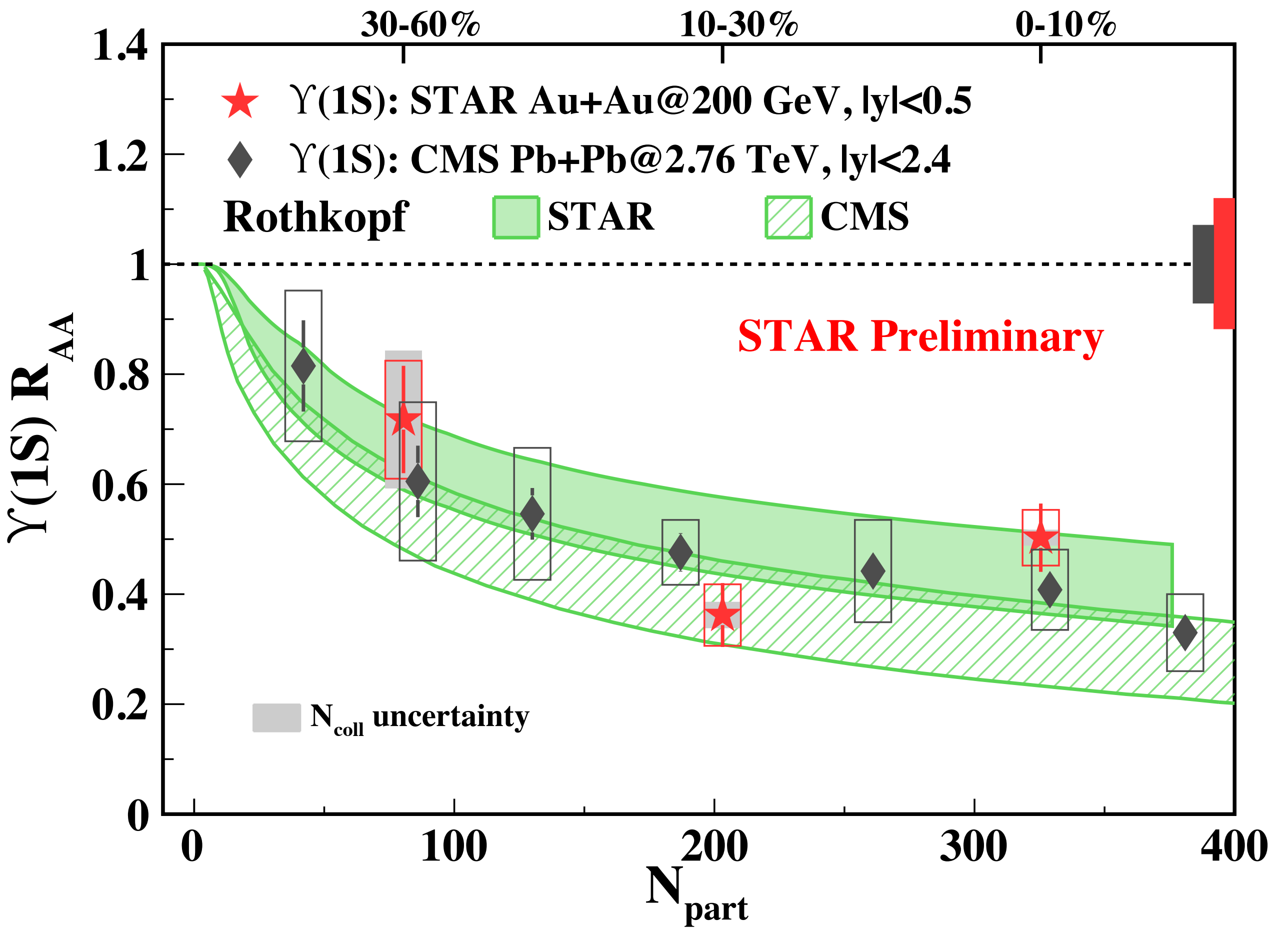


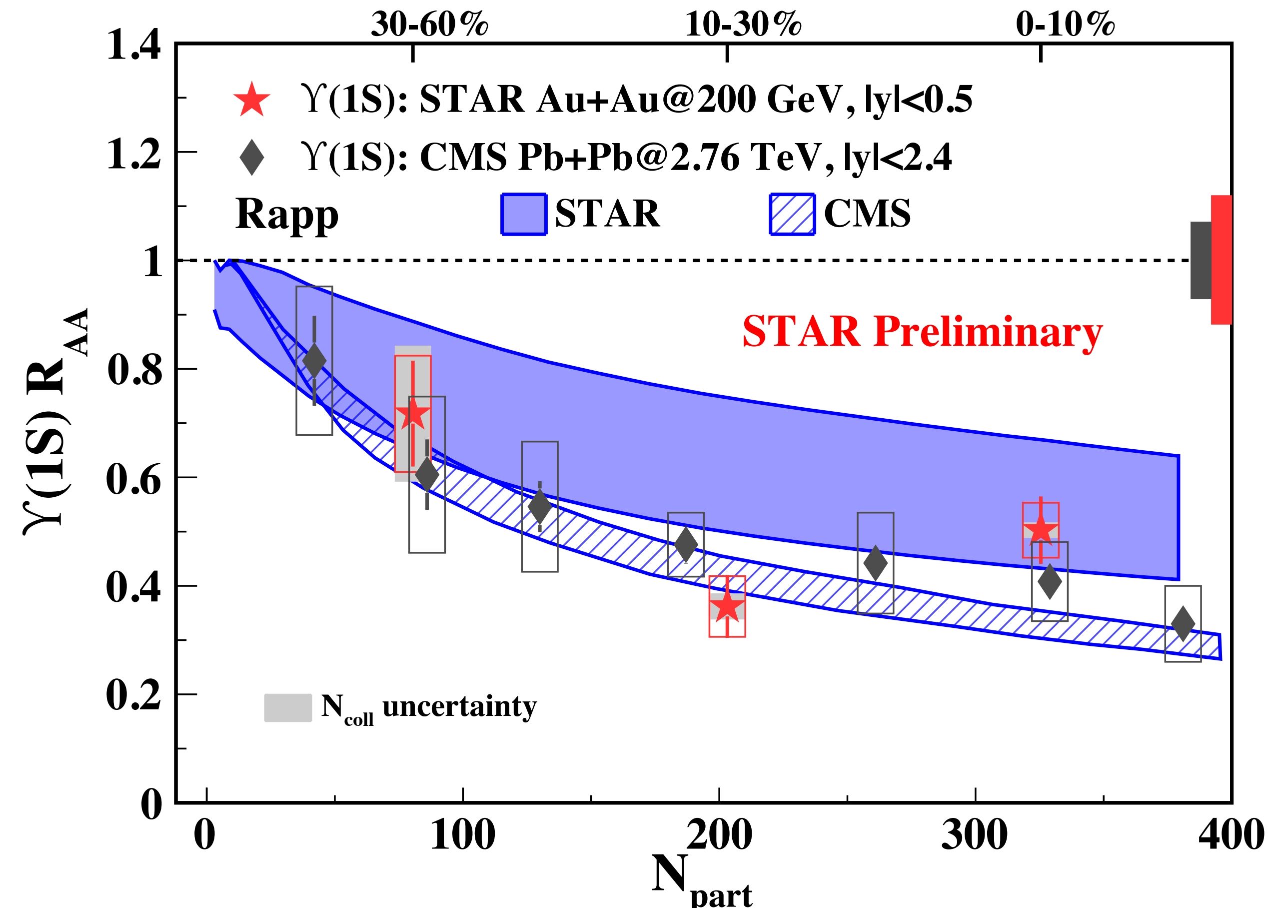
STAR PLB,797 (2019)134917

- Low-p_T: more suppression at RHIC than at LHC in central collisions → smaller charm production cross-section at RHIC and thus smaller regeneration

- High-p_T: J/ψ is strongly suppressed at both RHIC and LHC in (semi-)central collisions → Color Screening

ϒ(1S) suppression





CMS: PLB 770 (2017) 357
Rothkopf: B. Krouppa et al.,PRD 97 (2018) 016017
Rapp: X. Du et al., PRC 96 (2017) 054901

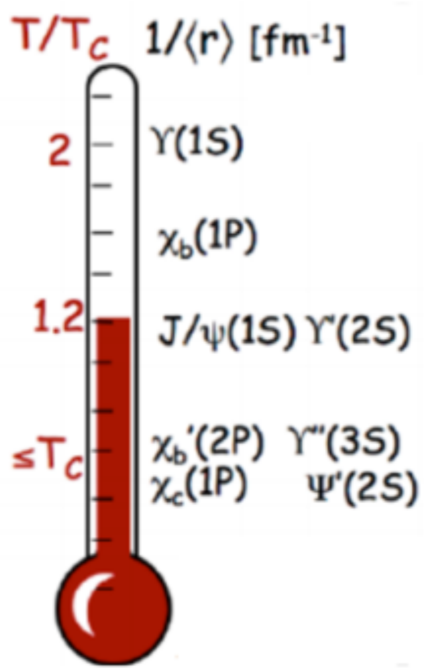
ϒ(1S) R_{AA}:

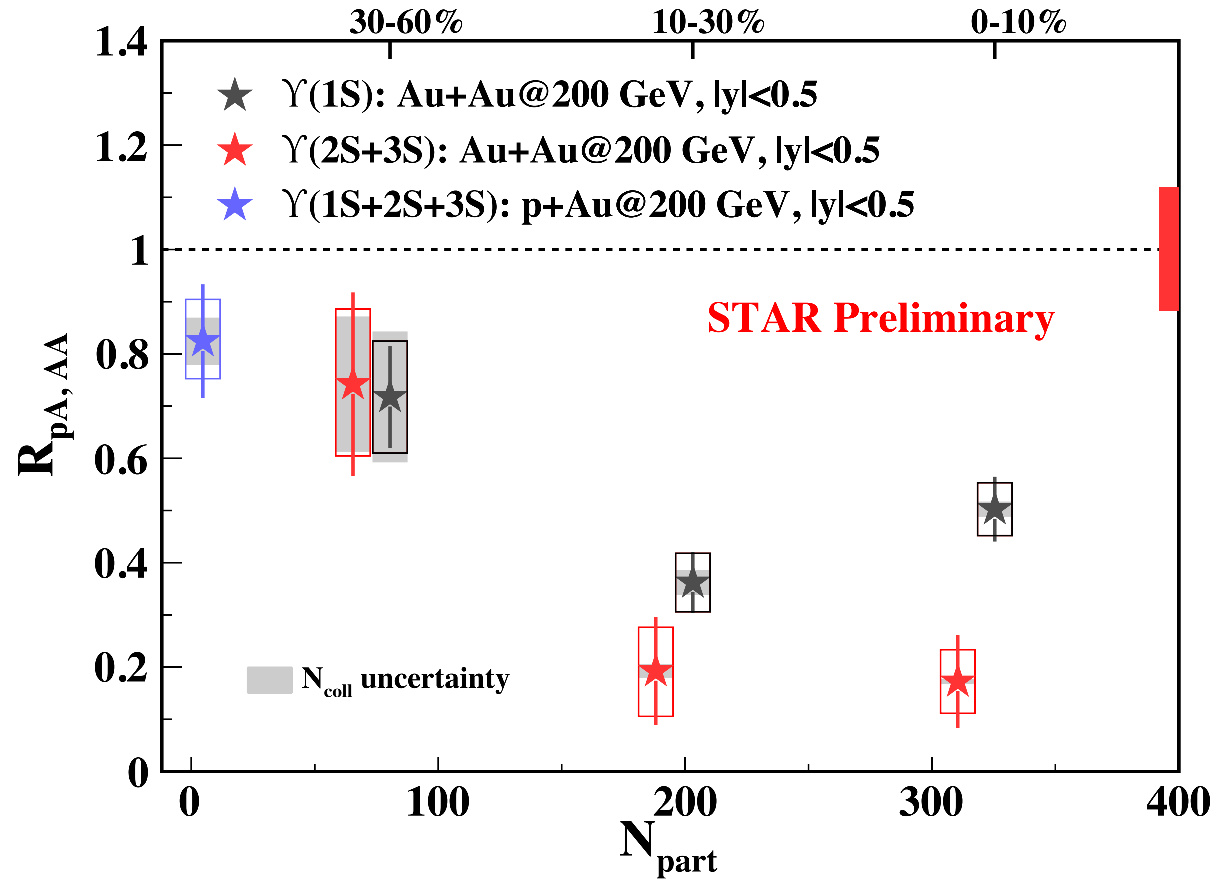
- Stronger suppression towards central collisions
- Both Rothkopf's and Rapp's models describe data

Rothkopf's model: use a lattice-vetted heavy-quark potential

Rapp's model: use in-medium binding energies predicted by thermodynamic T-matrix calculations using internal-energy potentials, from lattice QCD

Υ(2S+3S) suppression

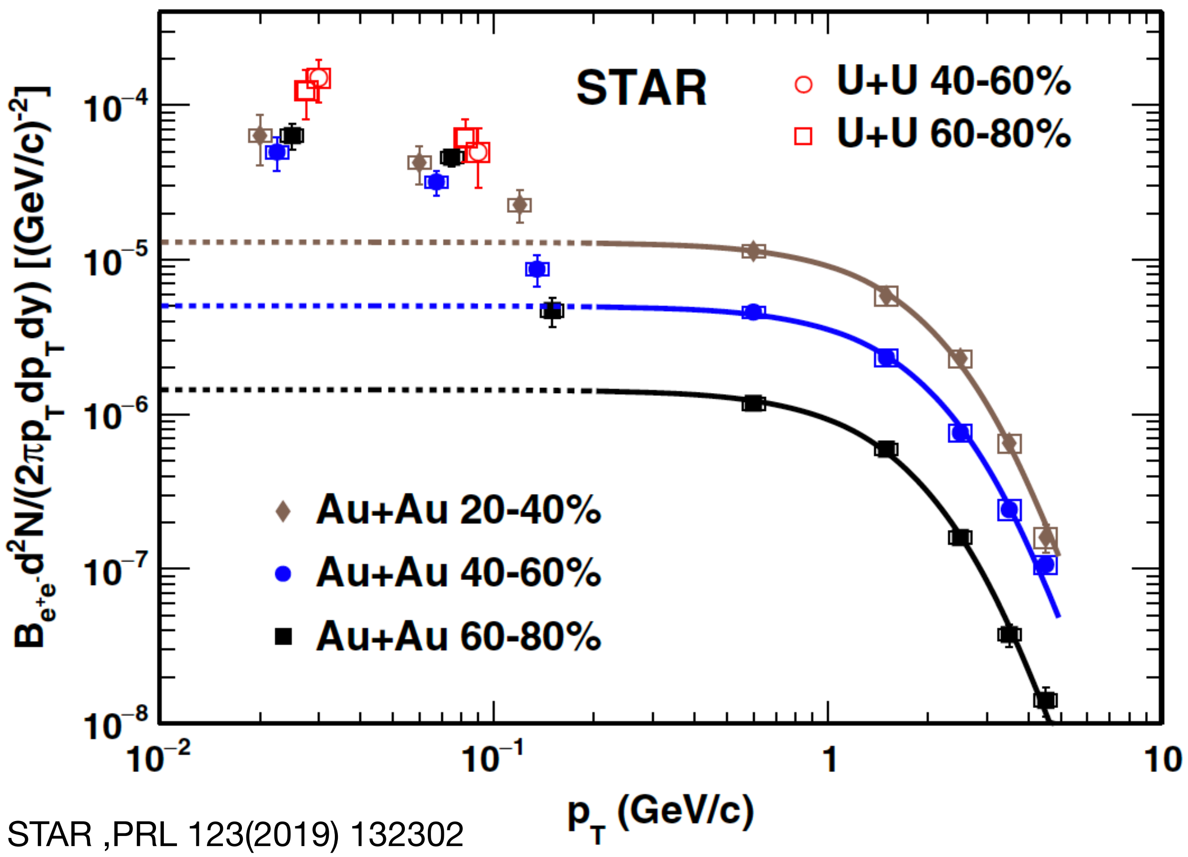




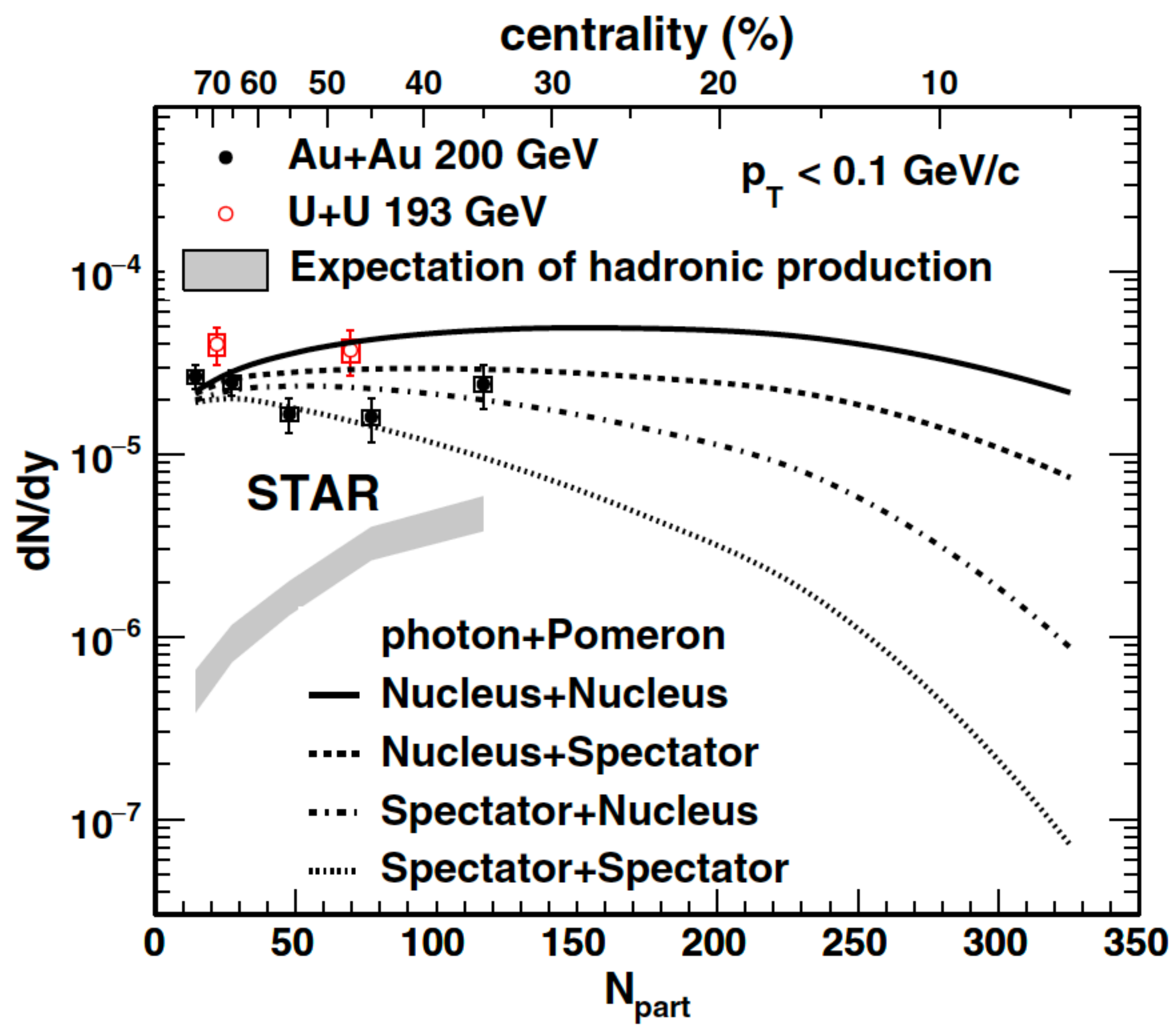
Υ(2S+3S):

- Stronger suppression in more central collisions
- More suppressed than Υ(1S) in 0-10% central collisions — sequential suppression

Very low p_T J/ψ in HIC



STAR ,PRL 123(2019) 132302



- Significant excess of J/ψ observed in 200 GeV Au+Au collisions and 193 GeV U+U collisions at very low-p_T
- Indication of coherent photoproduction process
  - four scenarios can describe the data points in 60-80% centrality
  - favor the nucleus + spectator or spectator + nucleus scenarios in semicentral collisions

Summary

p+p results：

- Quarkonium production study with improving precision
- Quarkonia associated with hadrons are informative observables for quarkonium production mechanism studies

p+Au results：

- The CNM effect are negligible for high-p_T J/ψ (p_T > 4 GeV/c), but not for low-p_T Υ

Au+Au results：

- Strong suppression for J/ψ with p_T > 0.15 GeV/c in 200 GeV Au+Au collisions
- Strong suppression of different Υ states and a sequential suppression picture is observed
- Significant excess of very low-p_T J/ψ in HIC, which likely originates from coherent photon production. Further studies are needed to understand the impact of hadronic interactions to the yields