Workshop on
QCD Physics & Study of the QCD Phase Diagram and New-type Topologic Effect
Jul. 17－25, 2019, Weihai, China

Recent Measurements of Quarkonia Production with STAR

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Outline

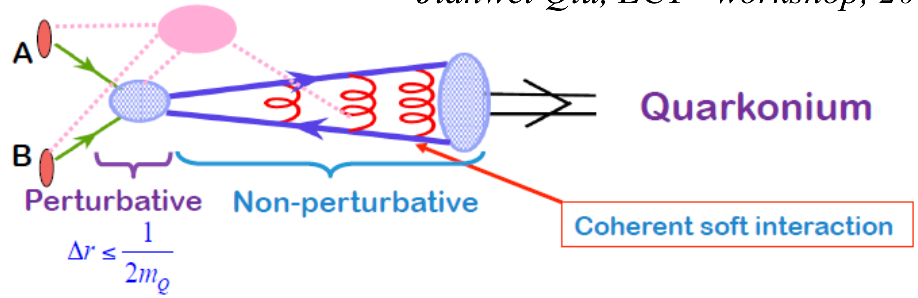
- Quarkonium production in p+p
  - J/ψ spectra in 500/510 GeV p+p — arXiv: 1905.06075, sub. to PRD
  - J/ψ polarization in 200 GeV p+p — Internal review, target journal: PRD
- Quarkonium production in A+A
  - J/ψ suppression in 200 GeV Au+Au — arXiv: 1905.13669, sub. to PLB
  - ϒ suppression in 200 GeV Au+Au — In preparation, target journal: PRL
- Coherent photoproduction in non-UPC A+A
  - Low-p_T J/ψ in peripheral Au+Au — arXiv: 1904.11658, sub. to PRL

J/ψ production mechanism in p+p

J/ψ has been discovered for 45 years, but its production mechanism is not fully understood yet

- Test of QCD at the boundary of the perturbative and non-perturbative regimes

Jianwei Qiu, ECT workshop, 2016*



Approximation: on-shell pair + hadronization

$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_n \int dq^2 \left[\sigma_{AB\to[Q\bar{Q}](n)}(q^2)\right] F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$$

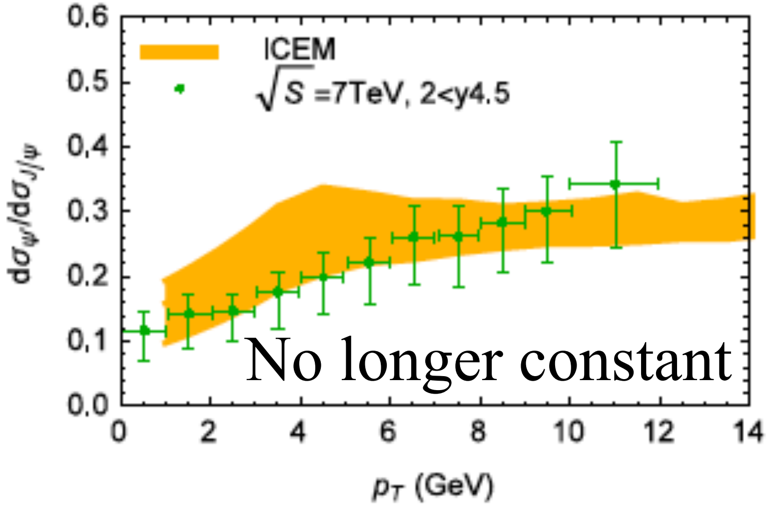
Hadronization:

- Color Singlet Model (CSM): 1975 –
  Only the pair with right quantum numbers
- Color Evaporation Model (CEM): 1977 –
  All pairs with mass less than open heavy flavor threshold
- Nonrelativistic QCD (NRQCD): 1986 –
  All pairs with various probabilities: LDMEs

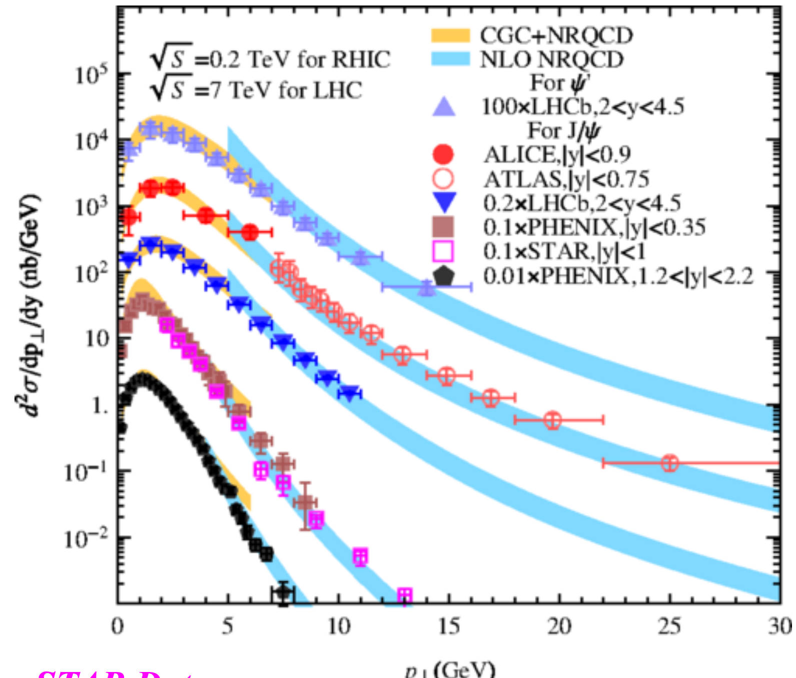
J/ψ production mechanism in p+p

Recent developments:

- CSM at NNLO*
- Improved CEM
- NLO NRQCD
- CGC+NRQCD



Y.-Q. Ma, R. Vogt, PRD94, 114029 (2016)



STAR Data:
PRC80, 041902 (2009), PLB722, 55 (2013)

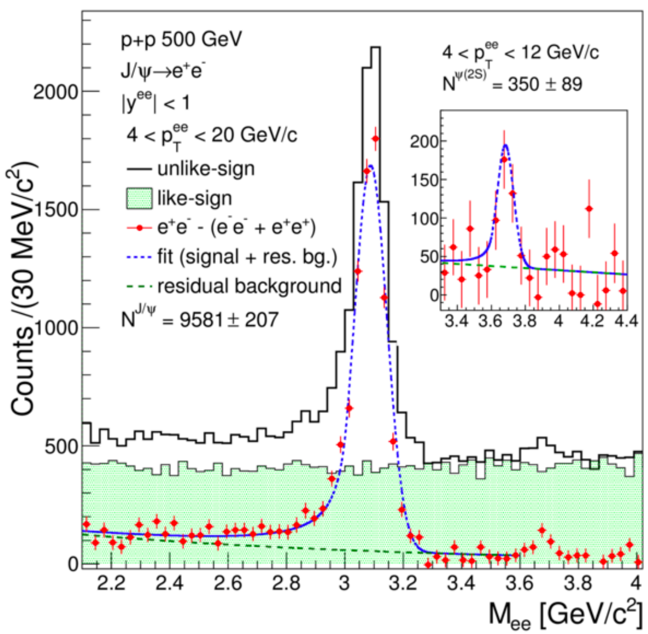
NLO NRQCD:
Y.-Q.Ma, K.Wang, and K.T.Chao, PRD 84, 114001 (2011)

CGC+NRQCD:
Y.-Q. Ma and R. Venugopalan, PRL113, 192301 (2014)

New data can provide important test/constraint of the new theories!

J/ψ reconstruction in p+p at 500/510 GeV

$4<p_T<20$ GeV/c

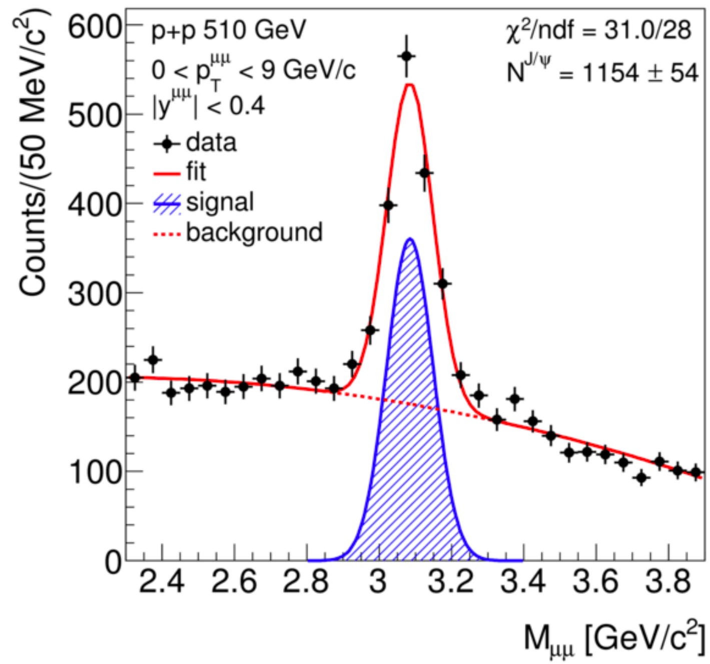


Run11 500 GeV data

BEMC+TPC

J/ψ, ψ(2S)→ee

$0<p_T<9$ GeV/c



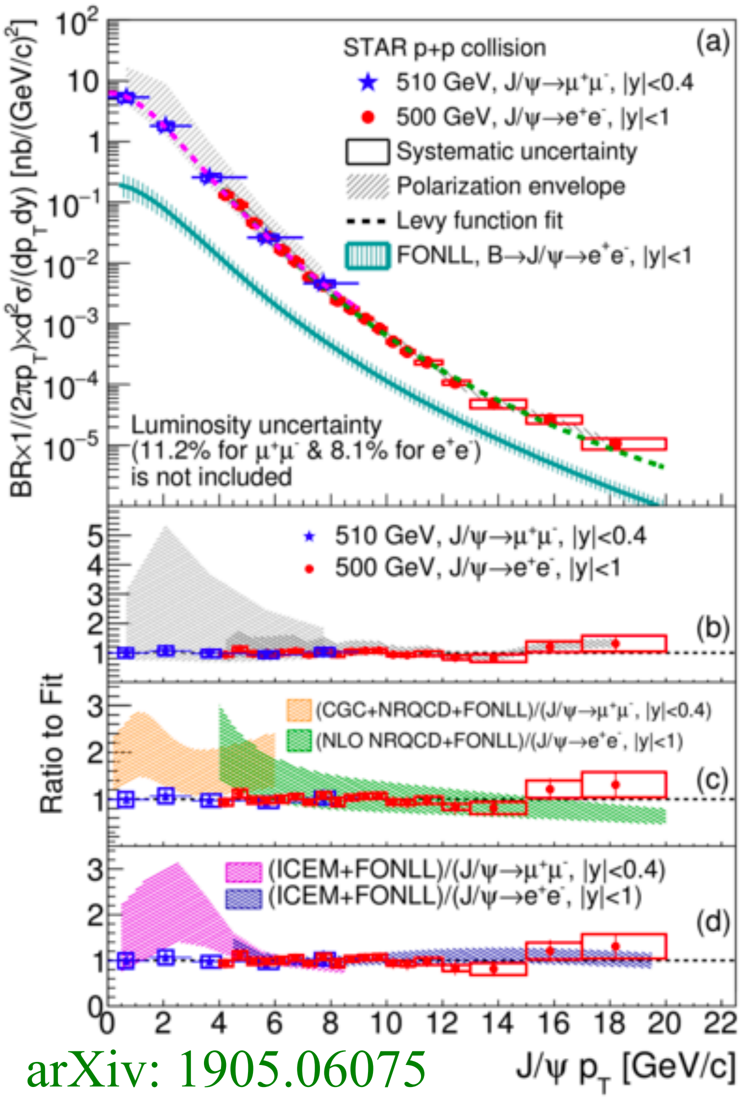
Run13 510 GeV data

MTD+TPC

J/ψ→μμ

arXiv: 1905.06075, submitted to PRD

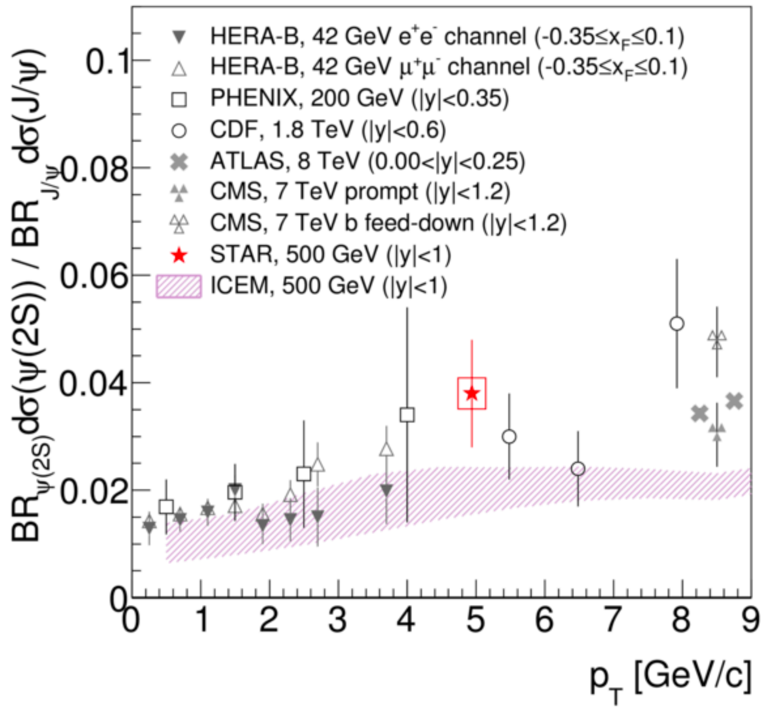
J/ψ p_T spectrum in 500/510 GeV p+p



arXiv: 1905.06075

- J/ψ cross-section measured in the p_T range of 0-20 GeV/c at mid-rapidity
- Huge uncertainty from polarization envelope at low p_T
- B→J/ψ estimated by FONLL
- CGC+NRQCD systematically higher than data, but within pol. envelope
- NLO NRQCD describes data above 6 GeV/c
- ICEM has similar situation as CGC+NRQCD at low p_T and NLO NRQCD at high p_T

$\psi(2S)$ over J/ψ ratio vs. p_T



arXiv: 1905.06075

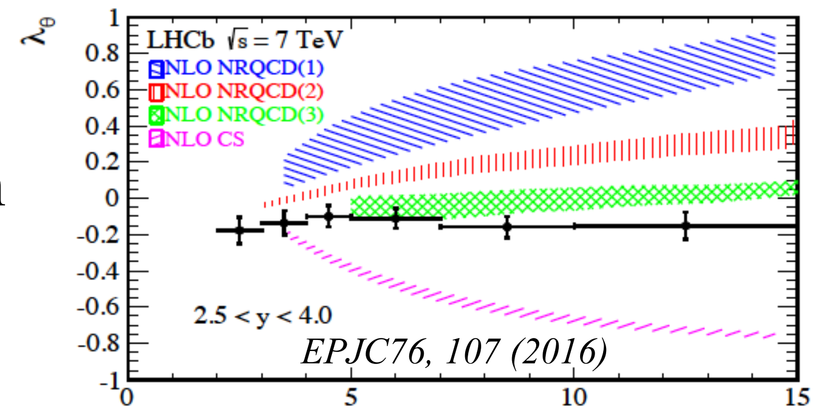
0.038 ± 0.010 (stat.) ± 0.003 (syst.) at $4<p_T<12$ GeV/c and $|y|<1$

Consistent with world-wide data, no obvious energy dependence

Consistent with ICEM prediction within uncertainties

J/ψ polarization in p+p collisions

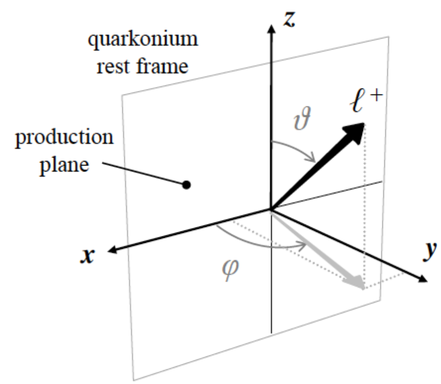
Measurements of quarkonium polarization provides crucial constraints on production mechanism

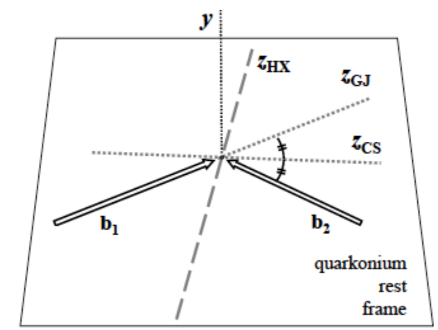


NRQCD(1) Butenschoen & Kniehl
NRQCD(2) Gong et al.
NRQCD(3) Chao et al.

Also helps to shrink the uncertainty on p_T spectrum measurements

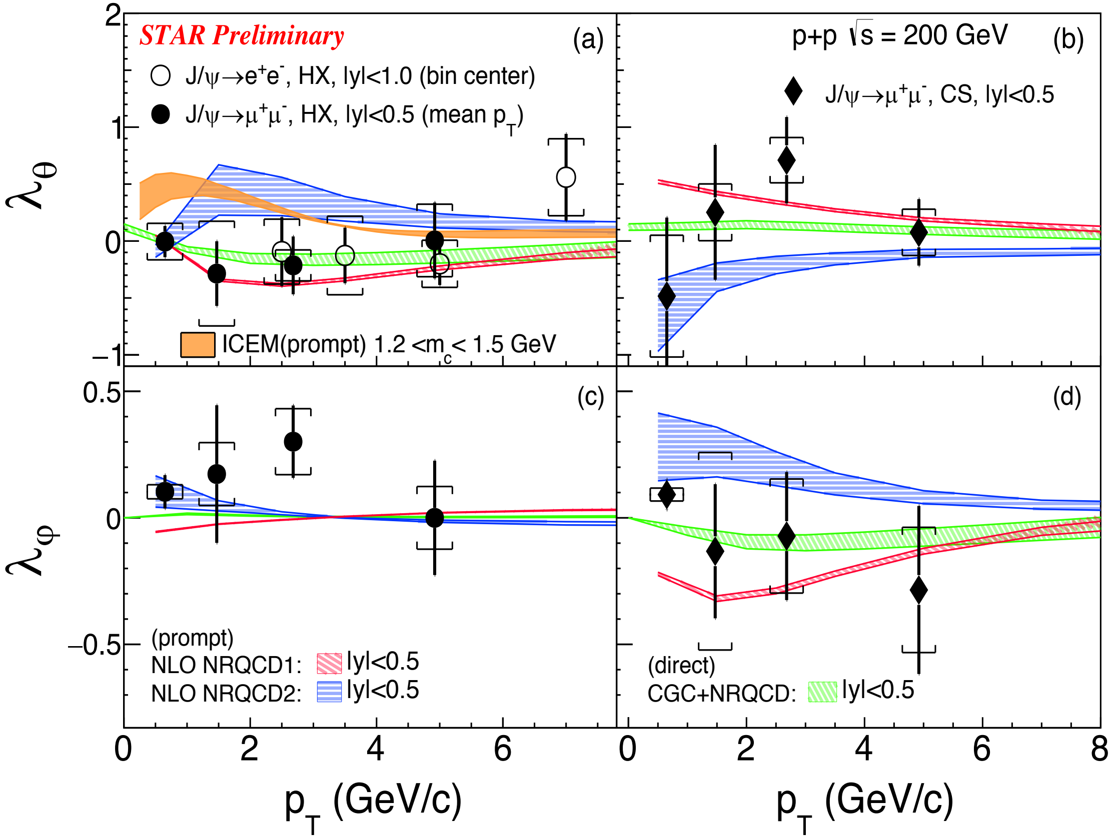
Can be measured through the angular distribution of lepton in quarkonium rest frame with respect to certain quantization axis





$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos 2\varphi+\lambda_{\theta\varphi}\sin 2\theta\cos\varphi).$$

J/ψ polarization in 200 GeV p+p



Final results are in STAR internal review

ICEM: V. Cheung and R. Vogt, PRD98, 114029 (2018)
CGC+NRQCD: Y. Ma et al., JHEP12, 57 (2018)
NRQCD1: H.-F. Zhang et al., PRL114, 092006 (2015) 092006
NRQCD2: B. Gong et al., PRL110, 042002 (2013)

J/ψ polarization measured in both Helicity and Collins-Soper frames

Compared to ICEM, NLO NRQCD and CGC+NRQCD calculations, none of them can be ruled out definitively

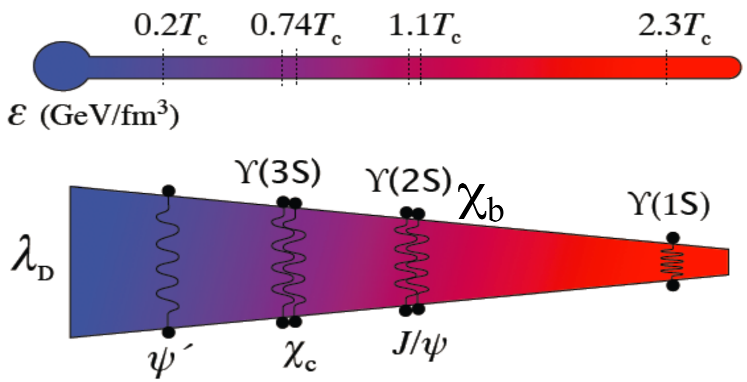
Better precision needed to distinguish models or constrain LDMEs

Quarkonium production in A+A

Dissociation in QGP due to color-screening

➔ ***Signature of QGP formation***

T. Matsui, H. Sazt, PLB174, 416 (1986)



T_d depends on quarkonium size

➔ ***Sequential melting***

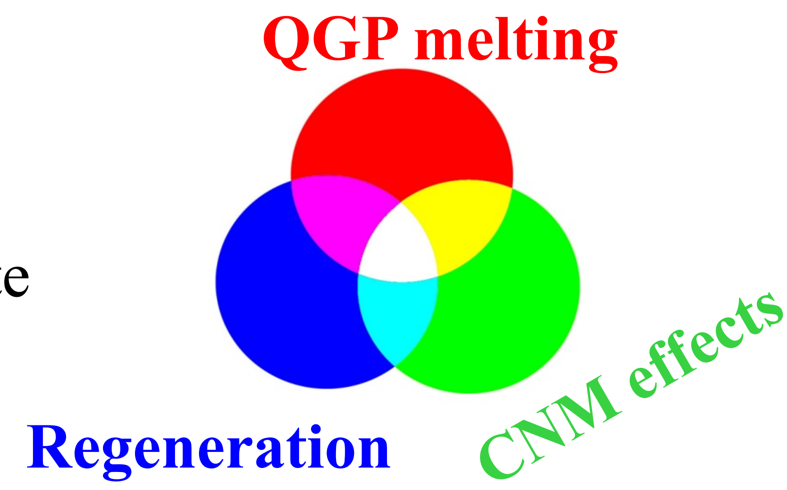
➔ QGP Thermometer

Complications:

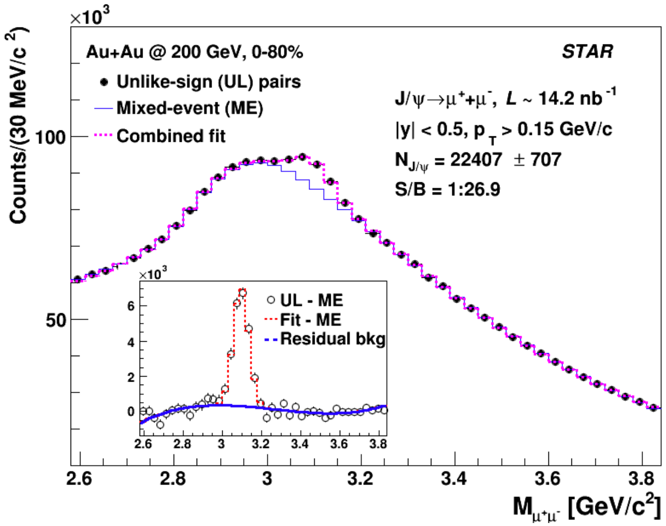
- Regeneration

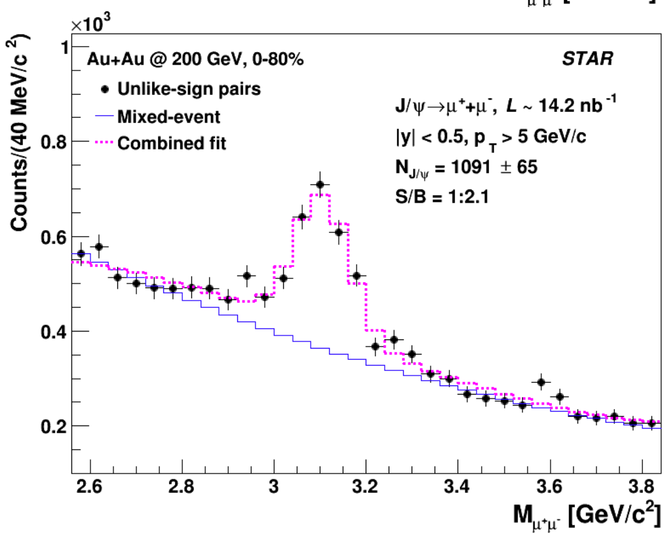
  Deconfinement is a prerequisite

- Cold Nuclear Matter effects

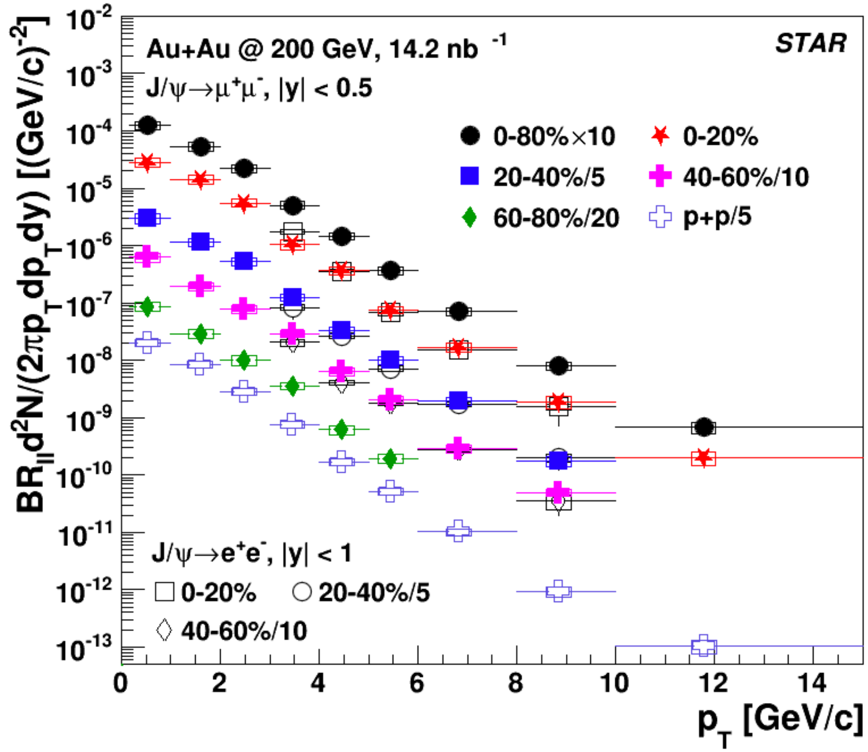


J/ψ production in Au+Au at 200 GeV





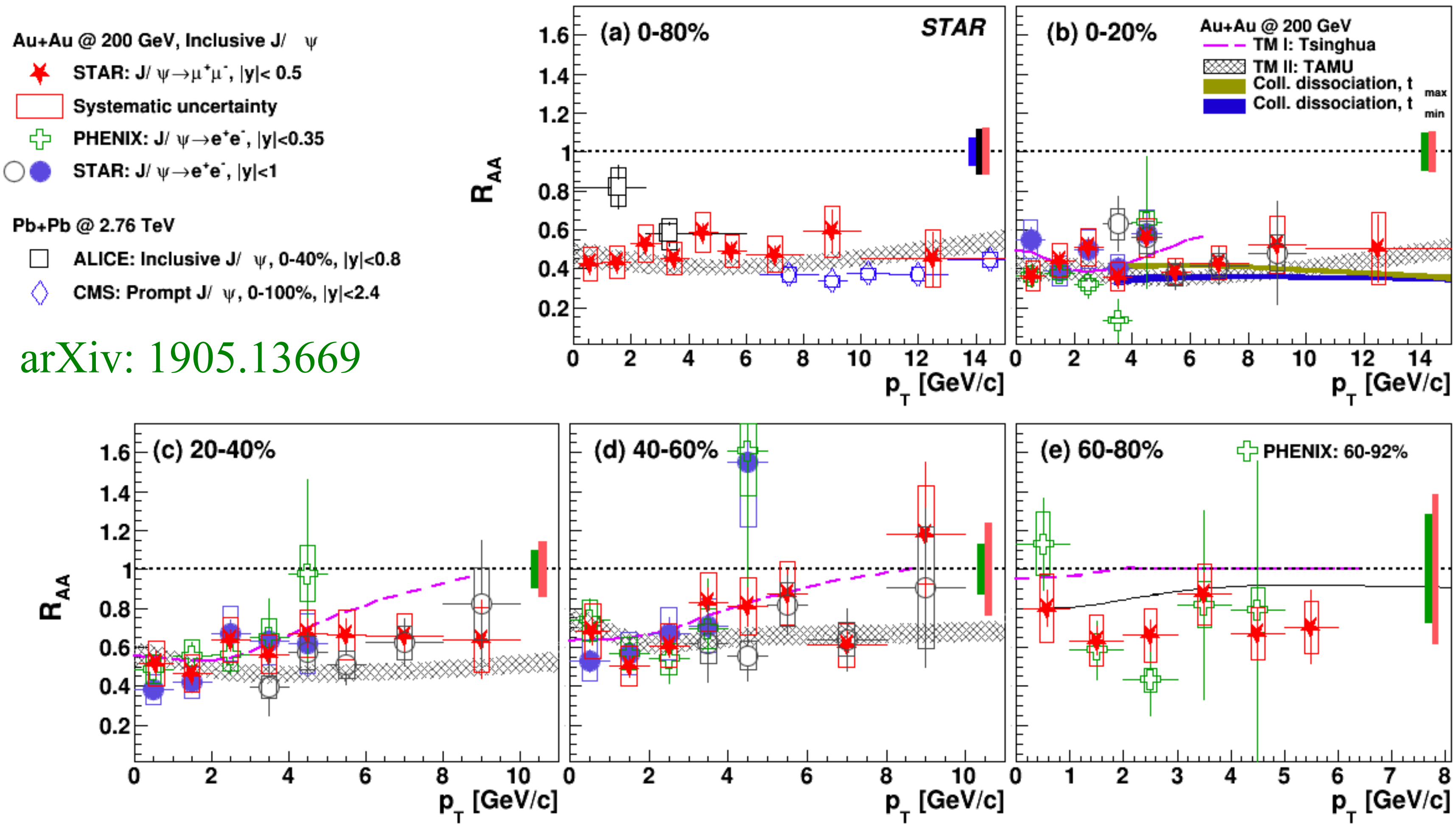
Run14 MTD triggered data



Broad p_T coverage (0-15 GeV/c)

arXiv: 1905.13669, submitted to PLB

J/ψ R_{AA} vs. p_T



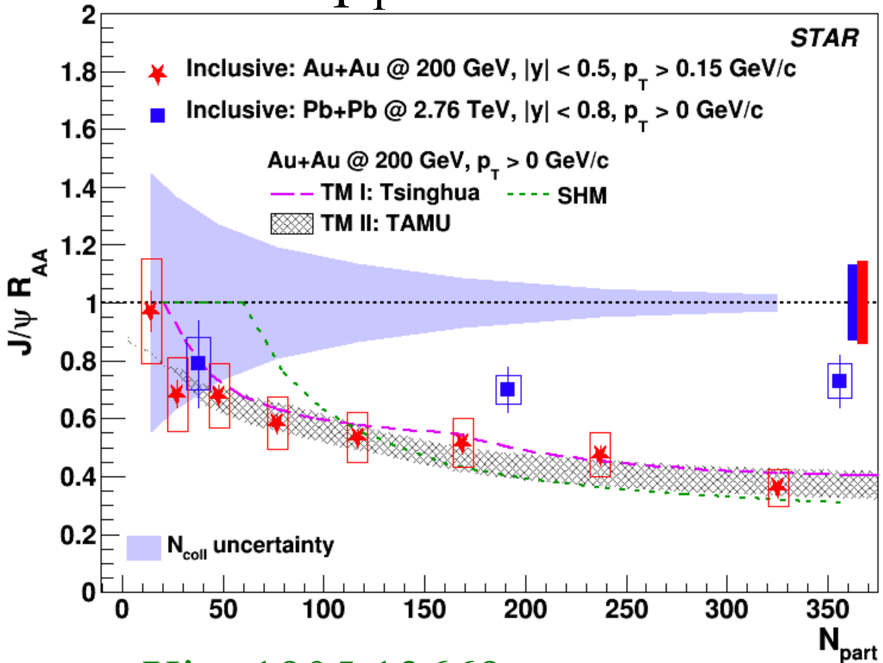
arXiv: 1905.13669

Data at RHIC and LHC show different p_T dependence

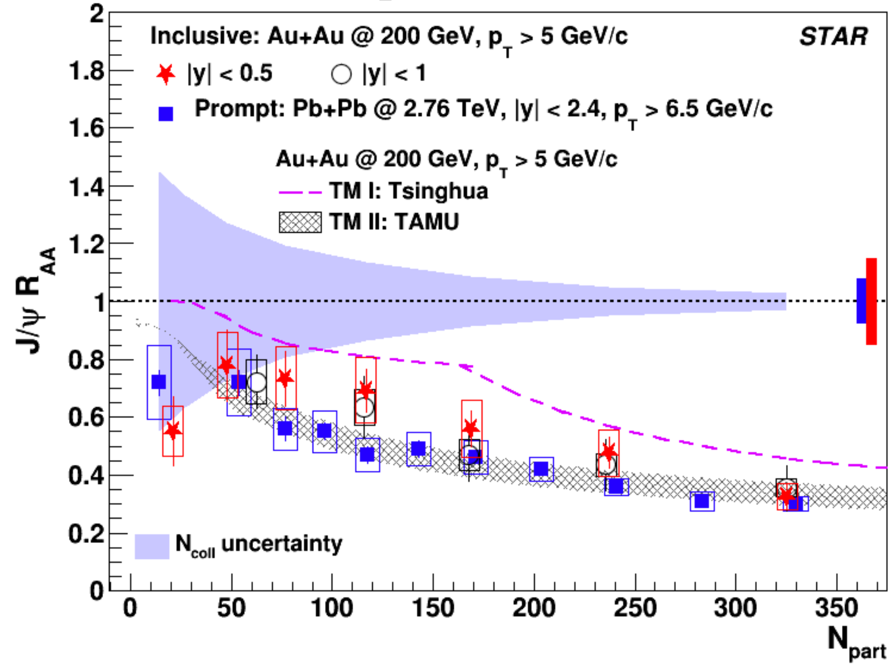
All models shown include feed-down and CNM effects

Centrality dependence

$p_T > 0.15$ GeV/c



$p_T > 5$ GeV/c



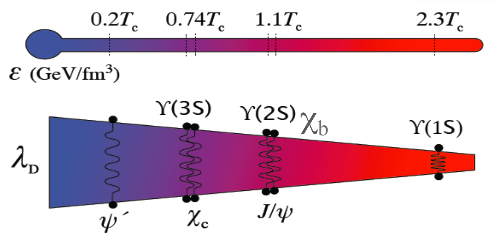
arXiv: 1905.13669

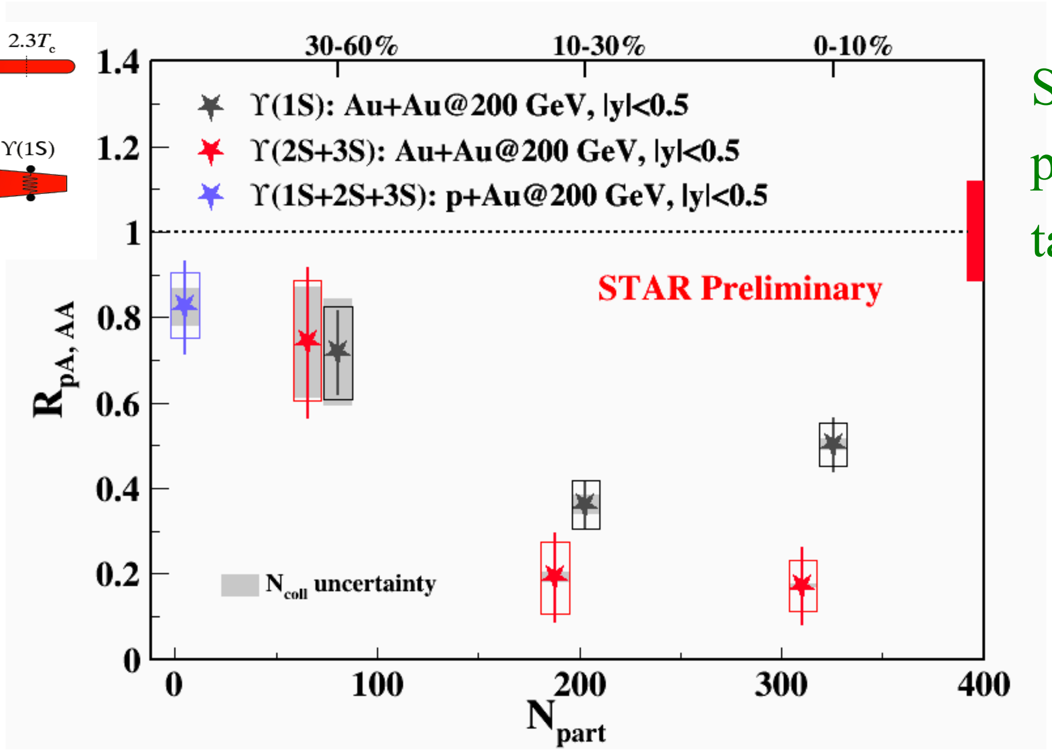
Low p_T: Interplay of dissociation, regeneration and CNM effects

High p_T: Significant suppression in central collisions

→ QGP melting

Upsilon suppression in Au+Au

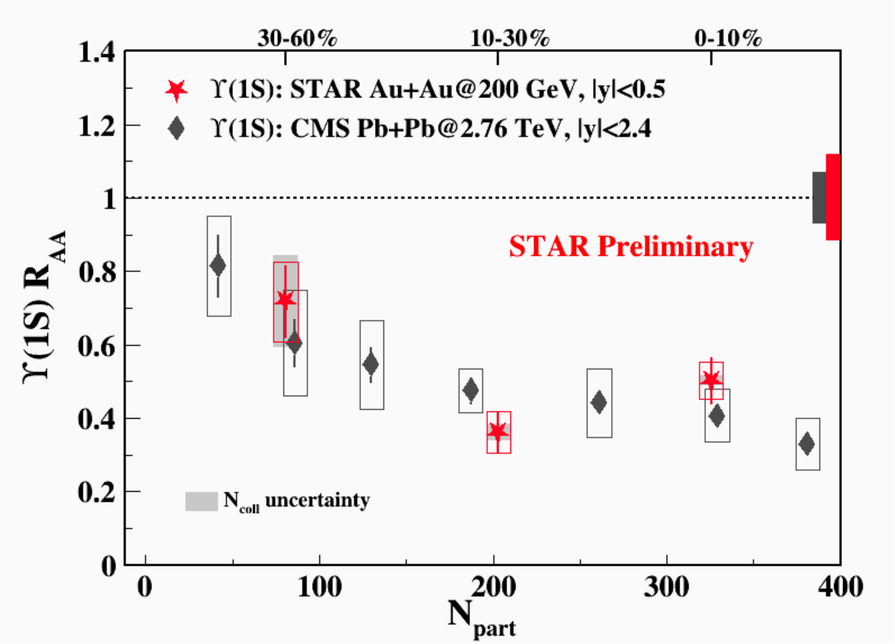


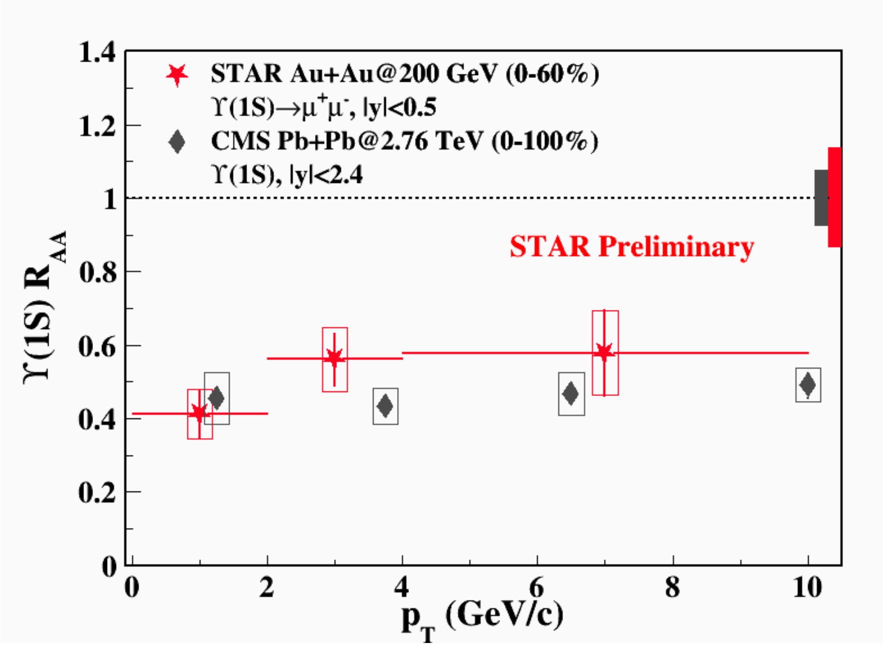


STAR paper in preparation, target journal: PRL

- Most precise ϒ suppression measurements in A+A at RHIC
  ee (2011) and μμ (2014+2016) combined
- More suppression in 0-30% central collisions than peripheral
- ϒ(2S+3S) more suppressed than ϒ(1S) → Sequential melting

Υ(1S) suppression: STAR vs. CMS

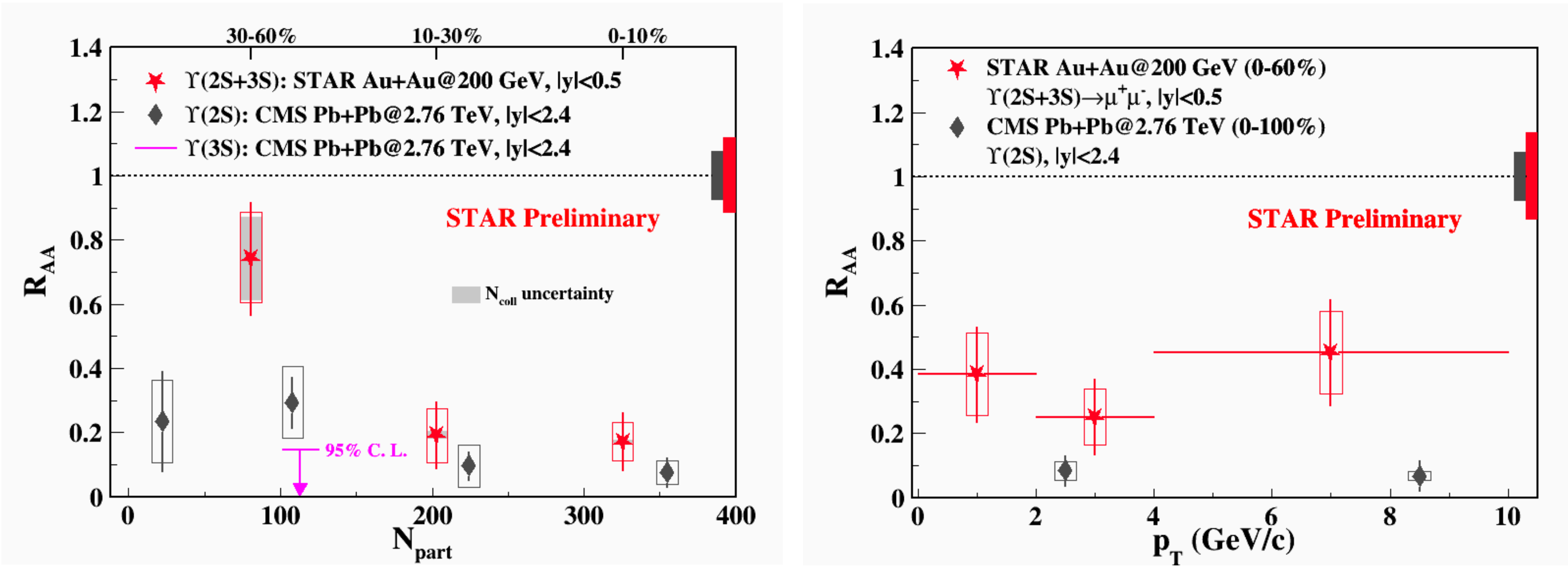




- STAR results compatible with CMS results

  CNM + suppression of excited states?

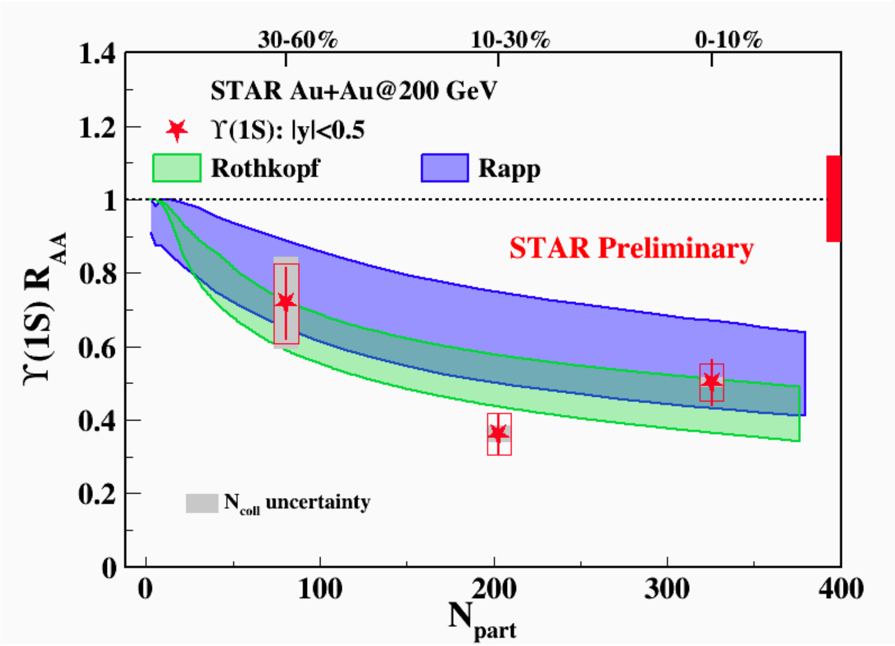
Υ(2S+3S) suppression in A+A



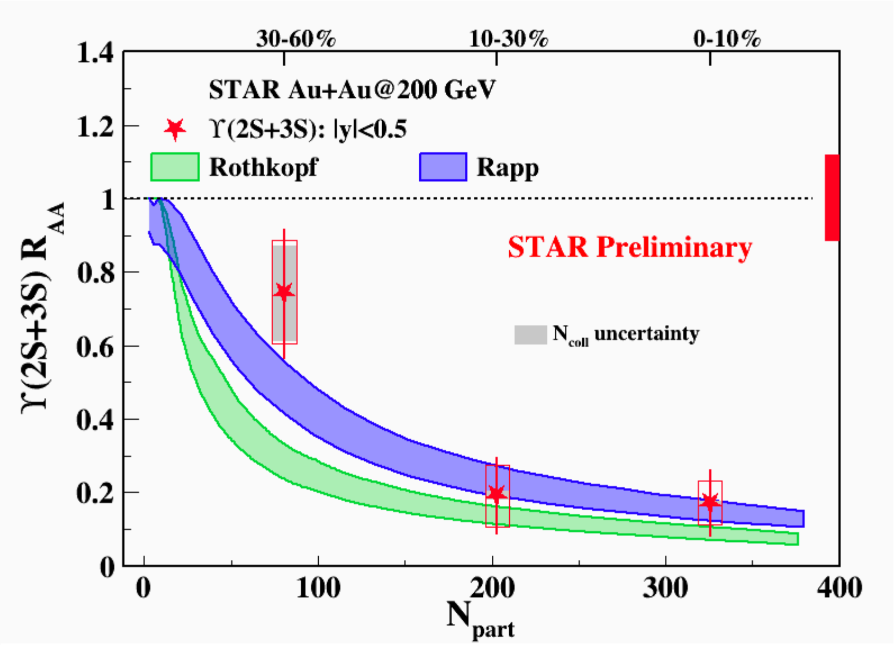
- STAR results systematically higher than CMS results

  Indication of less suppression at RHIC than at LHC

Compare to Models



Krouppa, Rothkopf, and Strickland, PRD 97, 016017 (2018)



Du, He, and Rapp, PRC 96, 054901 (2017)

Rothkopf: Complex potential (lattice QCD); No CNM or regeneration effect

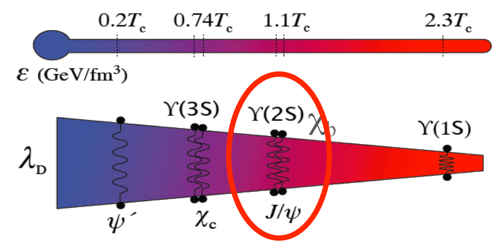
Rapp: T-dependent binding energy; Includes CNM and regeneration effects

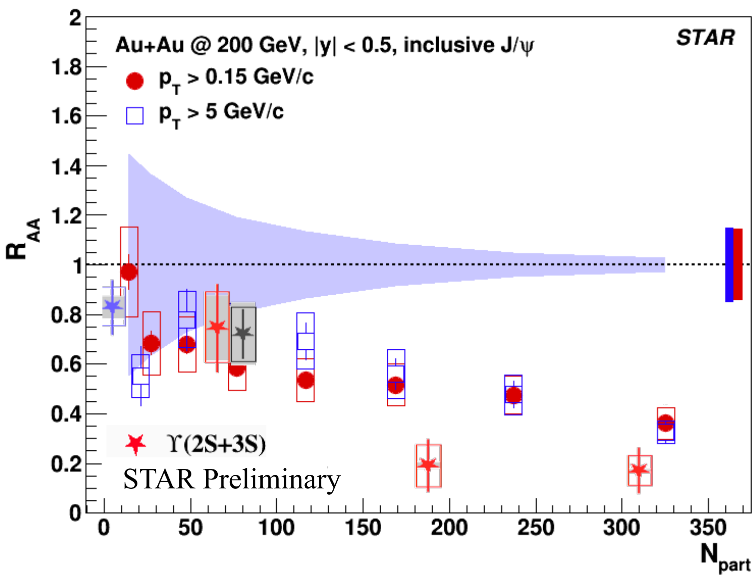
- ϒ(1S): Both models show good agreement with data
- ϒ(2S+3S): Both models agrees with data except Rothkopf in 30-60%

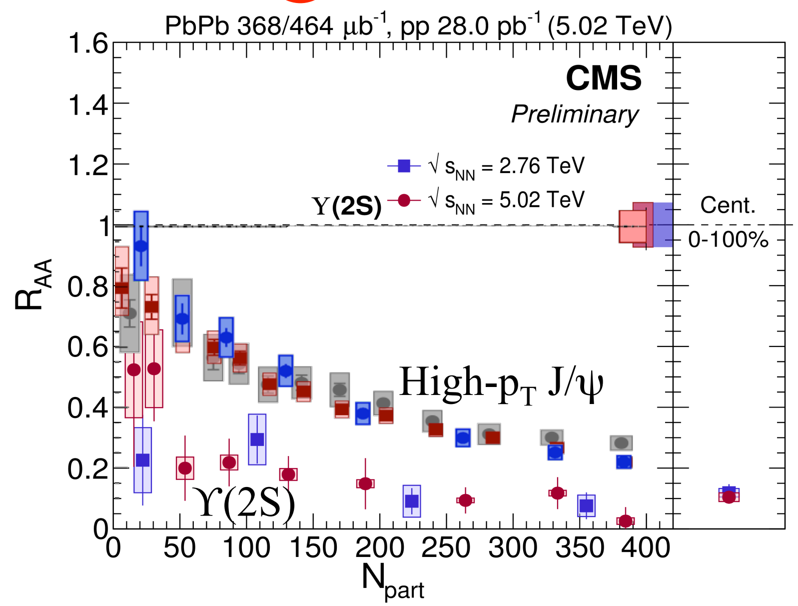
$\Upsilon(2S)$ vs. high-p_T J/ψ

$\Upsilon(2S)$ vs. J/ψ:

Similar size → Similar T_d







$\Upsilon(2S)$ exhibits significant stronger suppression than high-p_T J/ψ

Velocity matters?

Formation time effect? Hadronic dissociation?

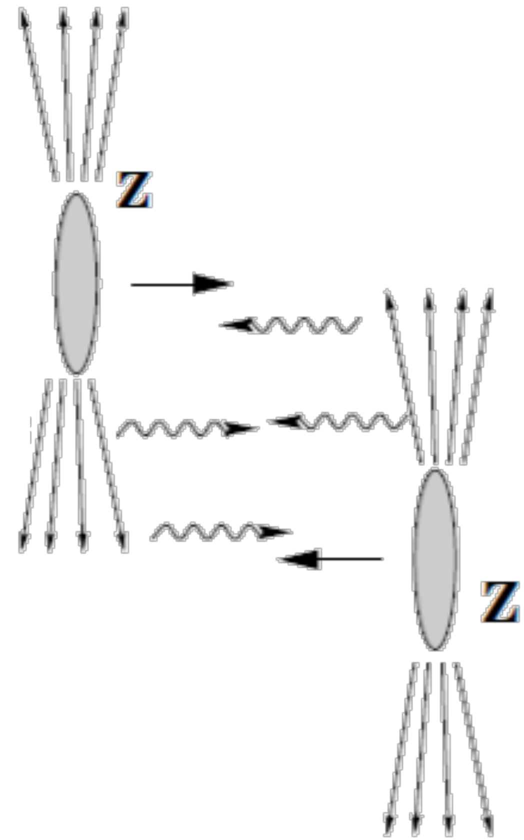
Jet quenching?

Electromagnetic Field in Heavy-Ion Collisions

- Strong EM field accompanies the nuclei in relativistic heavy-ion collisions

  $B \sim \gamma Zeb/R^3 \sim O(10^{14}\ Tesla)$ @RHIC

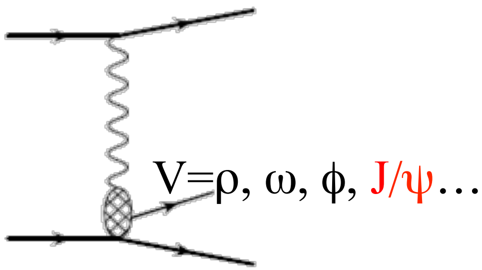
- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux *E. Fermi, Z. Phys. 29, 315 (1924)*



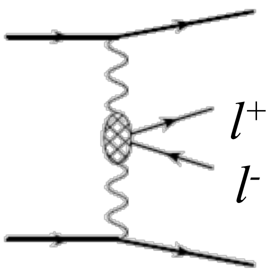
- The quasi-real photons can initiate γA or γγ collisions in relativistic heavy-ion collisions

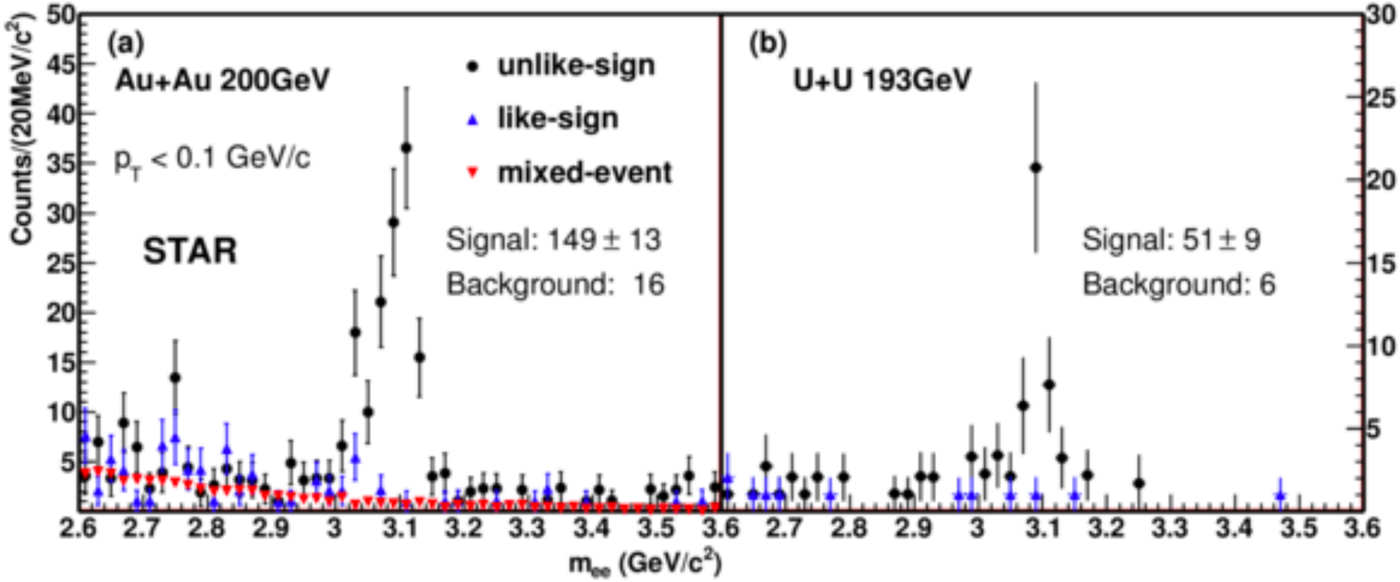
Clear J/ψ signals at very low p_T

γA



γγ



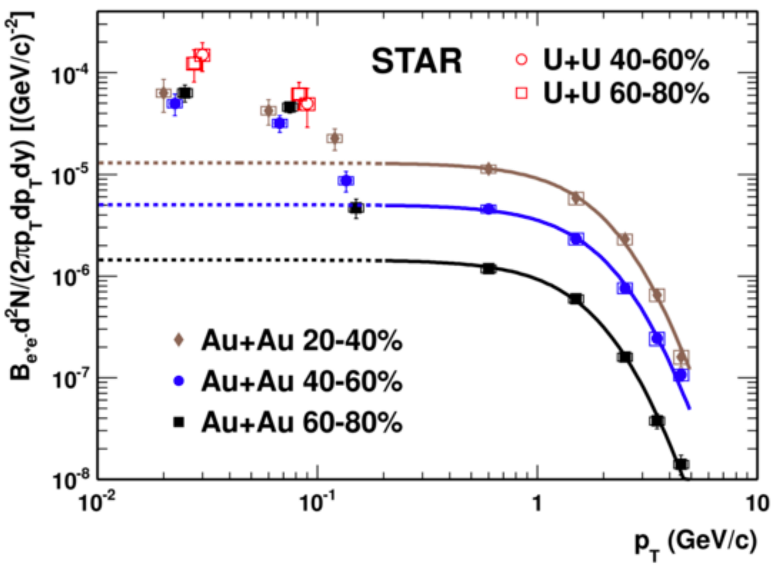


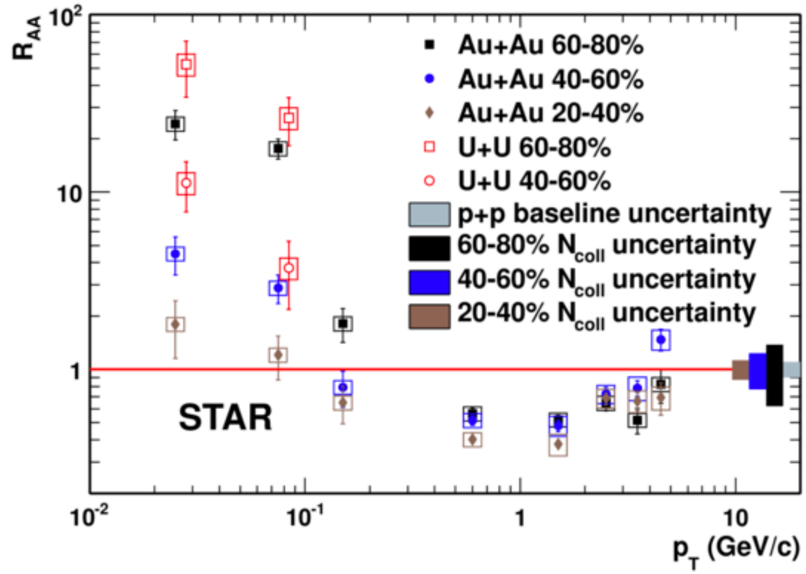
STAR, PRL121, 132301 (2018)

arXiv: 1904.11658, submitted to PRL

Very-low-p_T J/ψ enhancement at STAR

arXiv: 1904.11658





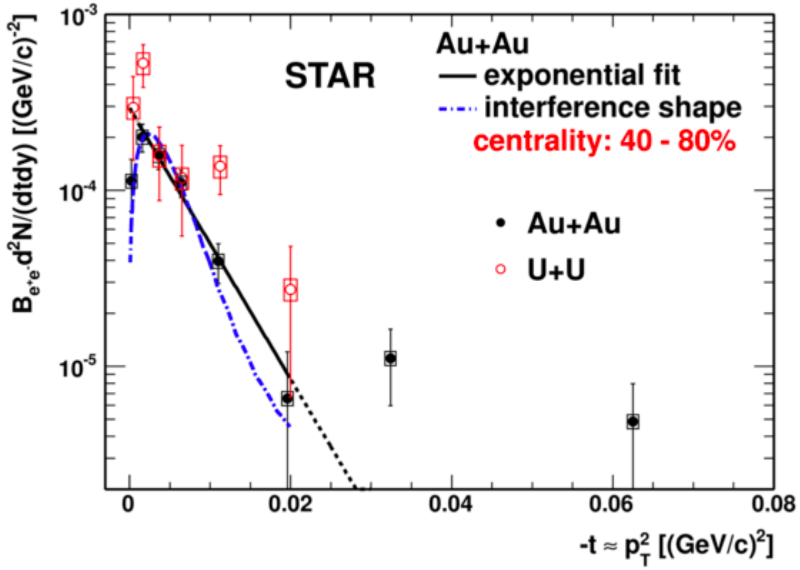
Fit fun. (empirical): $$\frac{a}{\left(1+b^2 p_T^2\right)^n}$$

Significant enhancement of J/ψ yield at p_T<0.1 GeV/c in (semi-)peripheral Au+Au and U+U collisions, R_{AA} ~ 40

Confirm ALICE observation (PRL116, 222301 (2016))

Momentum transfer squared distribution

arXiv: 1904.11658



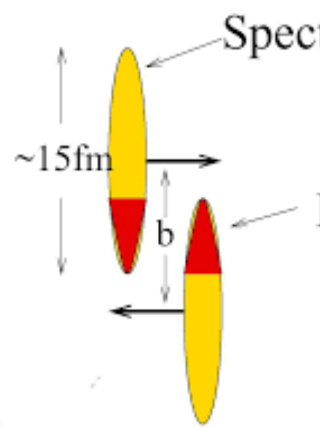
- First -t distribution of J/ψ production at low p_T in non-UPC
- Slope = 177 ± 22 (GeV/c)$^{-2}$ consistent with expected from coherent photoproduction for an Au nucleus (199 (GeV/c)$^{-2}$)
- The drop at the lowest bin may be an indication of interference
  χ^2/ndf = 4.8/4

Modeling Coh. J/ψ Photo-prod. in Non-UPC

$$\sigma(AA \rightarrow AAJ/\psi) = \int d\omega_\gamma \frac{dN_\gamma(\omega_\gamma)}{d\omega_\gamma}\sigma(\gamma A \rightarrow J/\psi A)$$

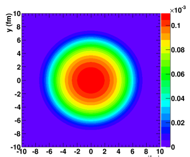
Photon flux:

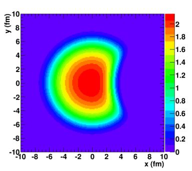
$$\frac{d^3N_\gamma(\omega_\gamma, \vec{x}_\perp)}{d\omega_\gamma d\vec{x}_\perp} = \frac{4Z^2\alpha}{\omega_\gamma}\left|\int \frac{d^2\vec{k}_{\gamma\perp}}{(2\pi)^2}\vec{k}_{\gamma\perp}\frac{F_\gamma(\vec{k}_\gamma)}{|\vec{k}_\gamma|^2}e^{i\vec{x}_\perp\cdot\vec{k}_{\gamma\perp}}\right|^2$$



EM form factor ← Woods-Saxon distribution

From entire nucleus or spectator?





Photonuclear scattering:

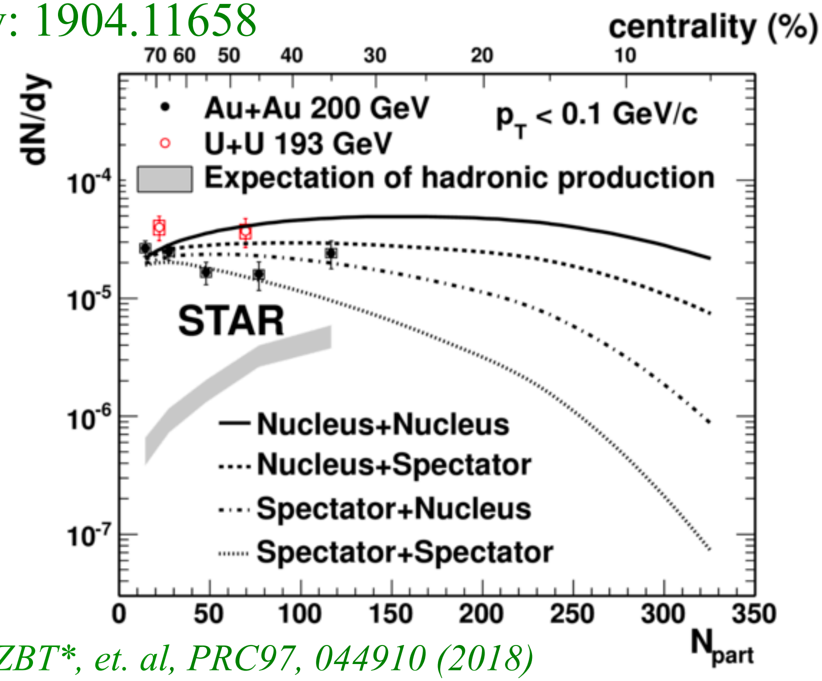
$$\sigma(\gamma A \rightarrow J/\psi A) = \left.\frac{d\sigma(\gamma A \rightarrow J/\psi A)}{dt}\right|_{t=0} \times \int |F_P(\vec{k}_P)|^2 d^2\vec{k}_{P\perp}$$

Form factor for Pomeron ← Nuclear density distribution

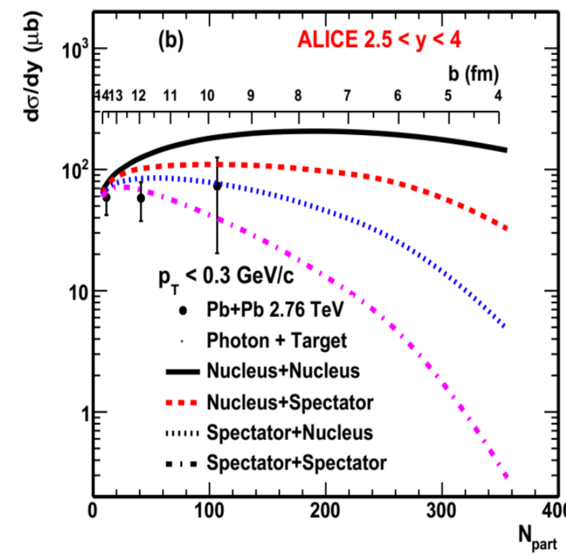
From entire nucleus or spectator?

Centrality Dependence

arXiv: 1904.11658



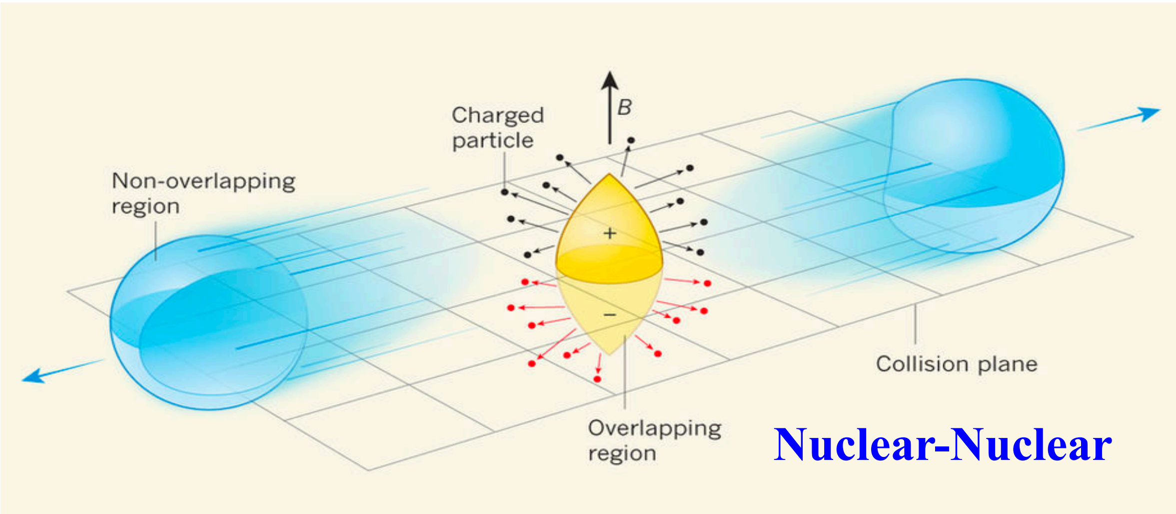
ALICE, PRL116, 222301 (2016)

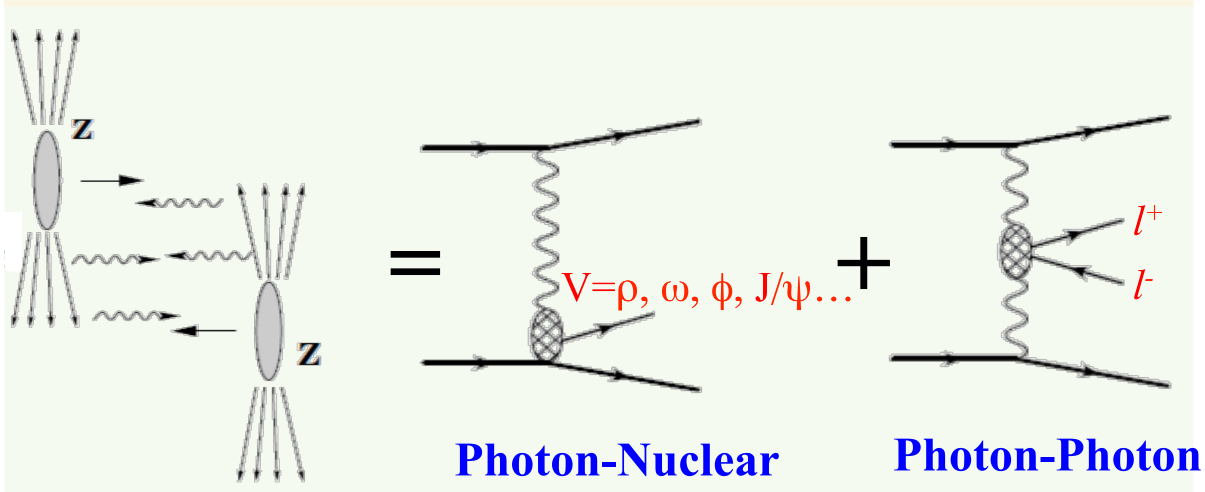


W. Zha, …, ZBT, et. al, PRC97, 044910 (2018)*
W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PRC99, 061901 (R) (2019)*
W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PLB789, 238-242 (2019)*
Z. Cao, …, W. Zha, CPC43, 064103 (2019)*

- All scenarios describe data at b~2R
- "Nucleus+Spectator" and "Spectator+Nucleus" are favored
- Need precise data in central collisions and advanced model with hot medium effects

Coherent Photoproducts in QGP





New probe of QGP:

- Deconfinement
- EM field
- …

EM+QGP:

Chiral Magnetic Effect

…

Summary

- Quarkonium production in p+p
  - J/ψ spectra and polarization can be described by ICEM, CGC+NRQCD and NRQCD calculations within uncertainties
  - Polarization with better precision could test/constraint models
- Quarkonium production in A+A
  - Significant suppression observed for high-p_T J/ψ and ϒs
  - ϒ(2S+3S) shows stronger suppression than ϒ(1S)
  - Consistent with QGP melting picture and provide constraints on QGP properties.
- Coherent photoproduction in non-UPC A+A
  - Observed enhancement consistent with coherent photoproduction