FCPPL Quarkonium production Workshop 2019

22-23 April 2019, Tsinghua University, China

Recent quarkonium results from STAR

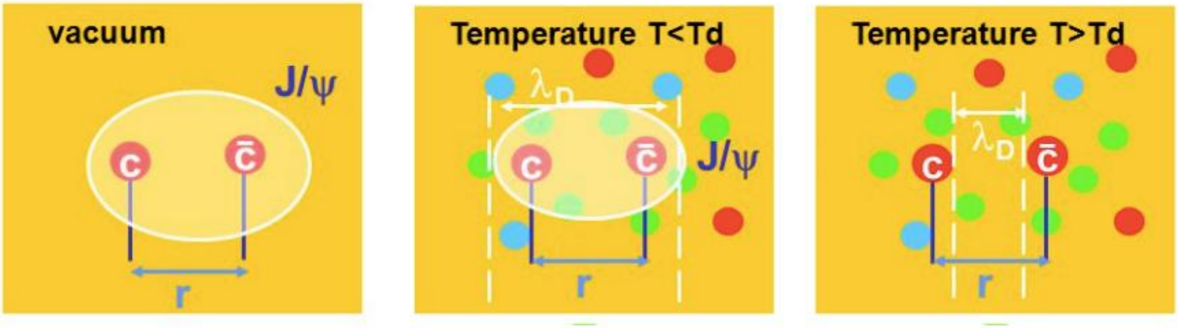
Wangmei Zha

University of Science and Technology of China

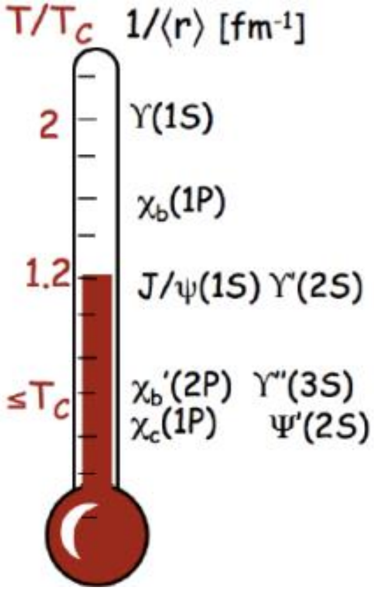
The promise

- Evidence of deconfinement:
  - ✓ The heavy quark-antiquark potential is screened by the deconfined quarks and gluons in medium → dissociation
    - J/ψ suppression was proposed as a smoking gun of QGP formation.

T. Matsui and H. Satz, *PLB***178** *(1986) 416*



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



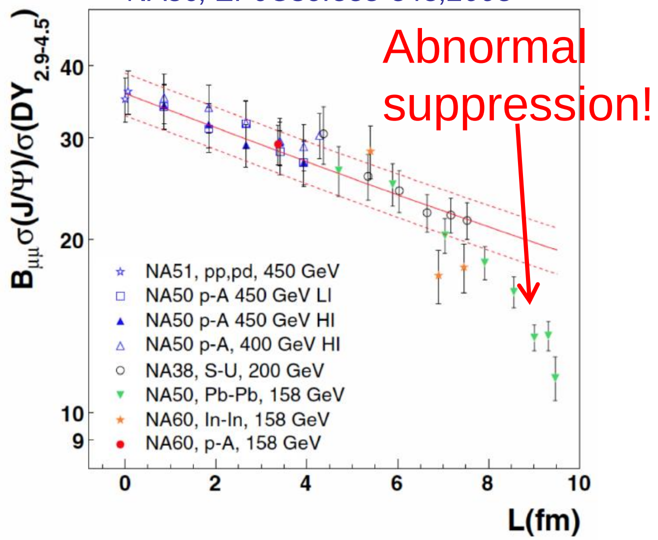
A. Mocsy, *EPJC***61** *(2009) 705*

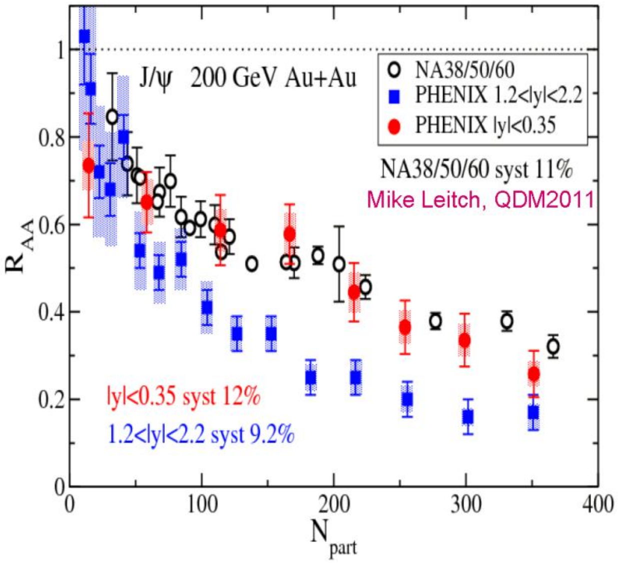
- Thermometer:
  - ✓ Different quarkonium states with different binding energies dissociate at different temperatures → sequential melting

Not so easy

- Production mechanism in p+p collisions
  - ✓ The soft process for quarkonium formation is non-perturbative (CSM, CEM, NRQCD….)
- Cold Nuclear Matter (CNM) effects
  - ✓PDF modification in nucleus: shadowing/anti-shadowing
  - ✓Gluon saturation, color glass condensate
  - ✓Initial state energy loss
  - ✓Nuclear absorption
  - ✓Cronin effect
  - ✓Interaction with co-movers
- Hot medium effects
  - ✓ Regeneration
    - -Much smaller for bottomium at RHIC
  - ✓ Medium induced energy loss
    - - Color-octet states
  - ✓ Formation time

NA50, *EPJC**39**:335-345,2005*

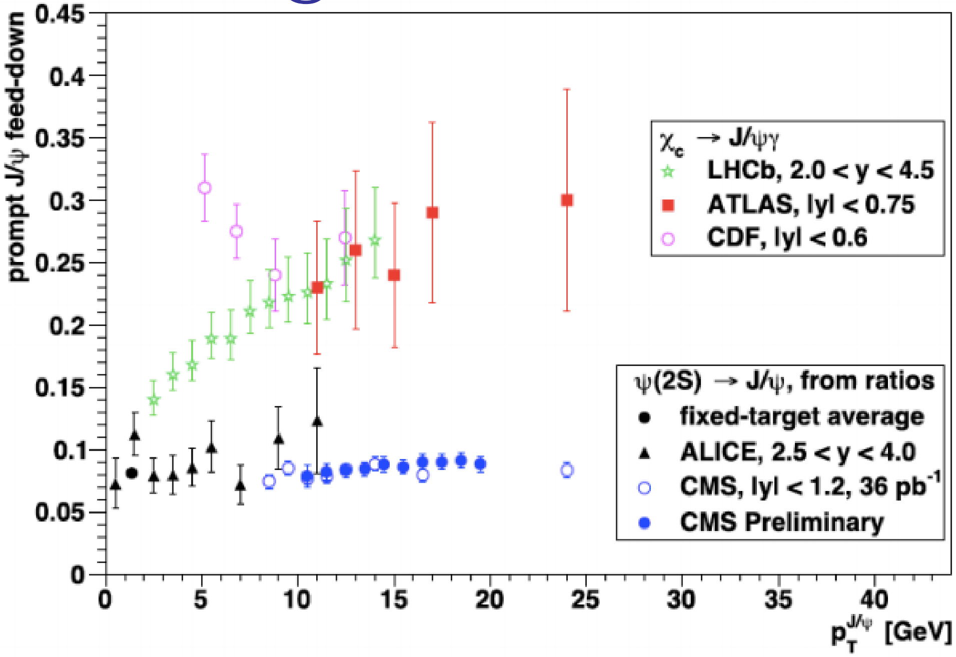




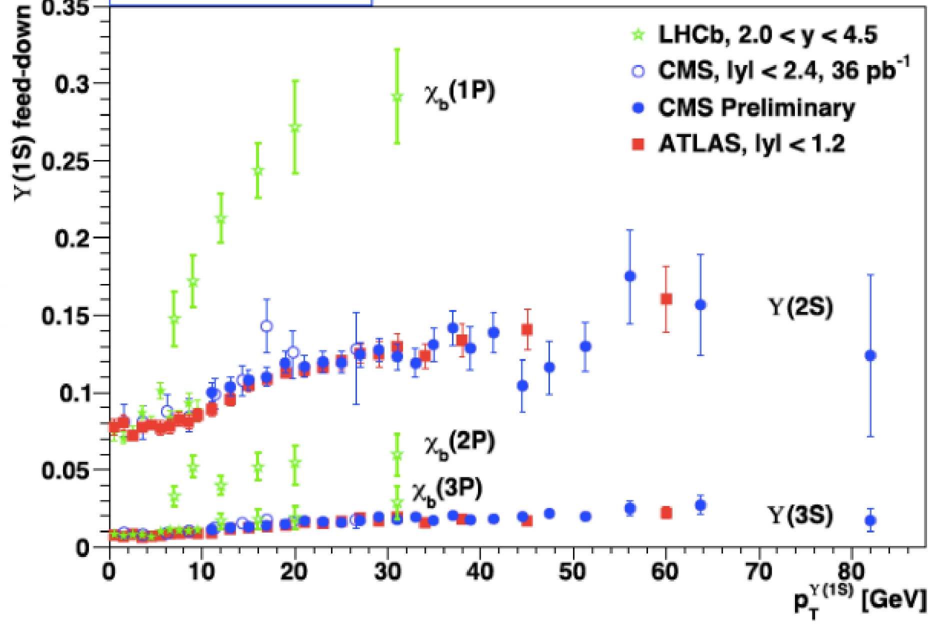
PHENIX: *PRC**84** (2011) 054912*

Even more complicated

Weohri@Quarkonium'14



Υ(1S) from all

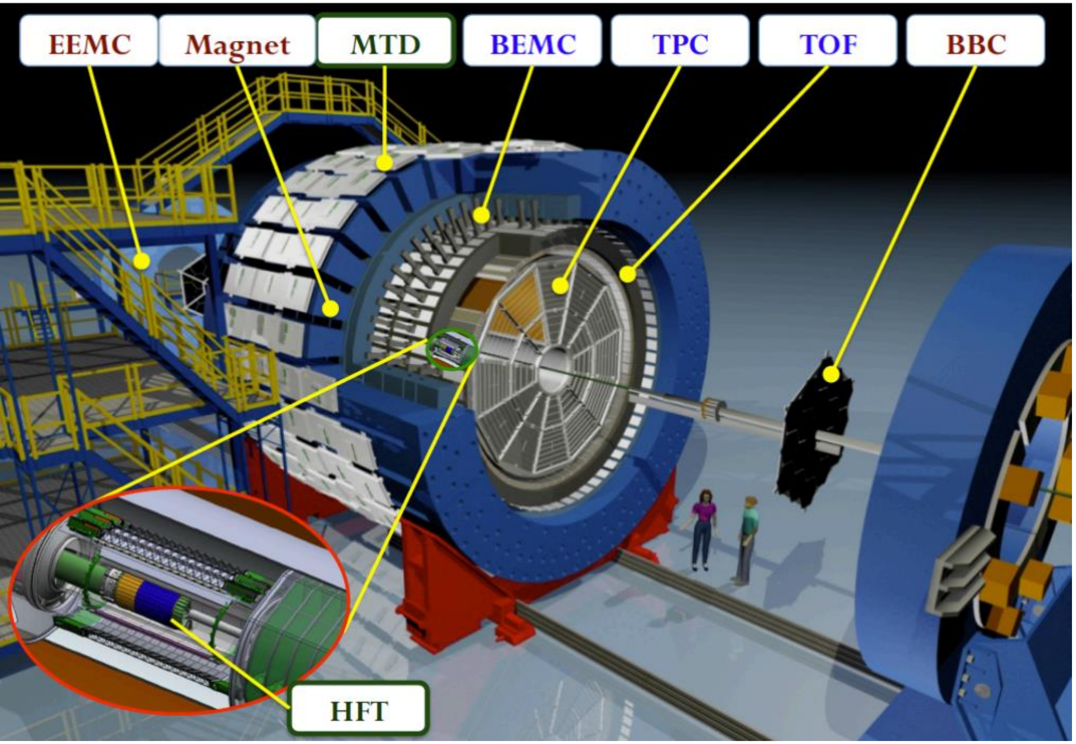


J/ψ feed-down	
χ_c	10-30% (vs. p_T)
$\psi(2S)$	~ 8%
B-hadron	0-50% (vs. p_T, $\sqrt{s}$)

$\Upsilon(1S)$ feed-down	
$\chi_b(1P)$	10-30% (vs. p_T)
$\chi_b(2P+3P)$	~ 5%+1%
$\Upsilon(2S+3S)$	8-13%+1%

STAR detector

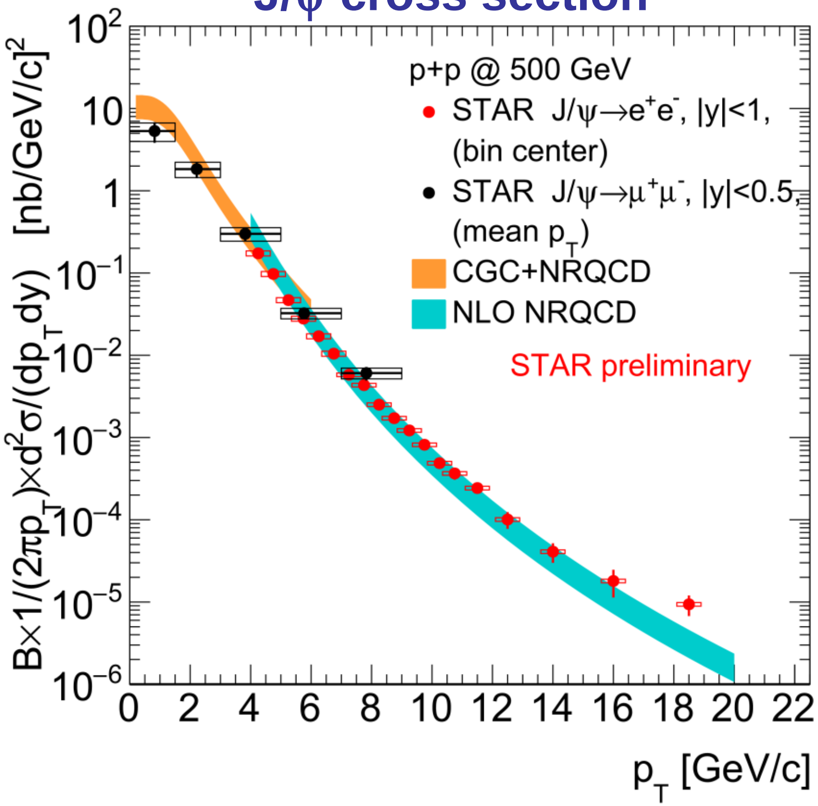
Large acceptance: $|\eta| < 1$, $0 < \phi < 2\pi$



- **Time Projection Chamber (TPC)**
  Charged particle momentum measurement and identification using dE/dx
- **Time of Flight detector (TOF)**
  Particle identification using $1/\beta$
- **Barrel ElectroMagnetic Calorimeter (BEMC)**
  Electron identification using E/p ~ 1, triggering
- **Muon Telescope Detector (MTD)**
  Muon identification, triggering
  $|\eta|<0.5$, ϕ ~ 45%

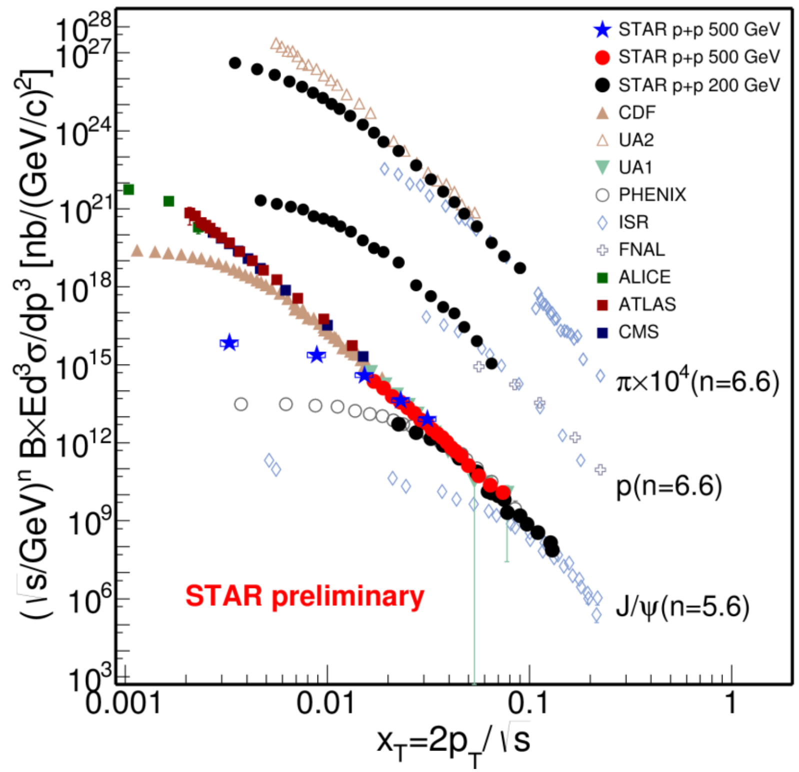
Inclusive J/ψ production in p+p collisions

J/ψ cross section



NLO+NRQCD: H. S. Shao etal, *JHEP**05** 103 (2015)*
CGC+NRQCD: Y. Q. Ma, *PRL**113** 192301 (2014)*

x_T scaling

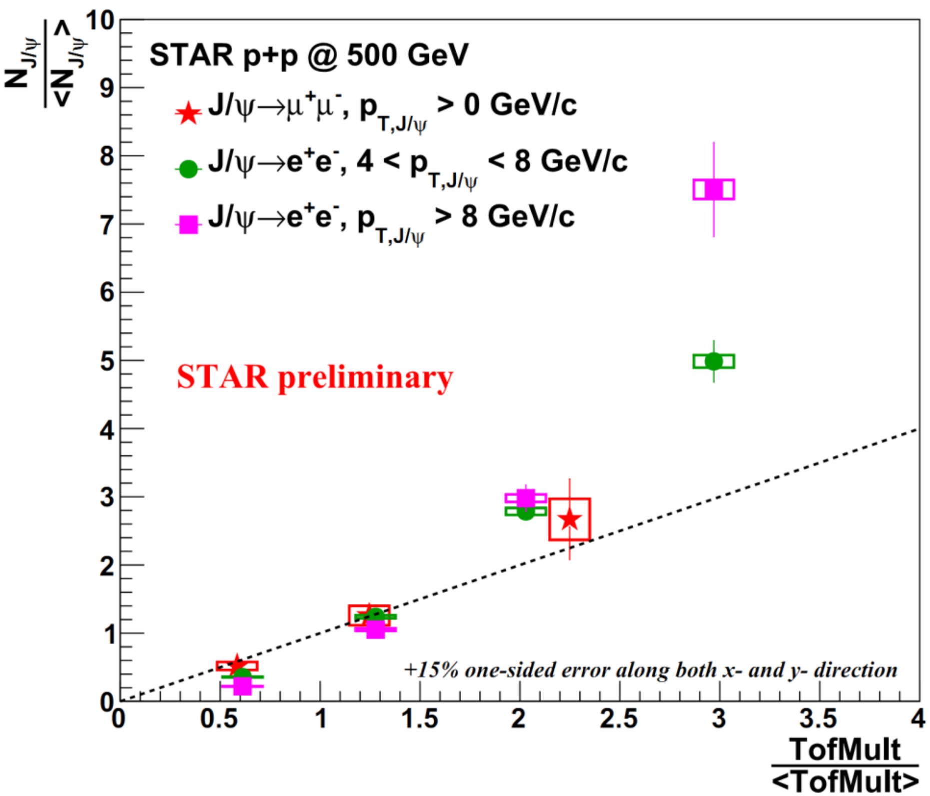


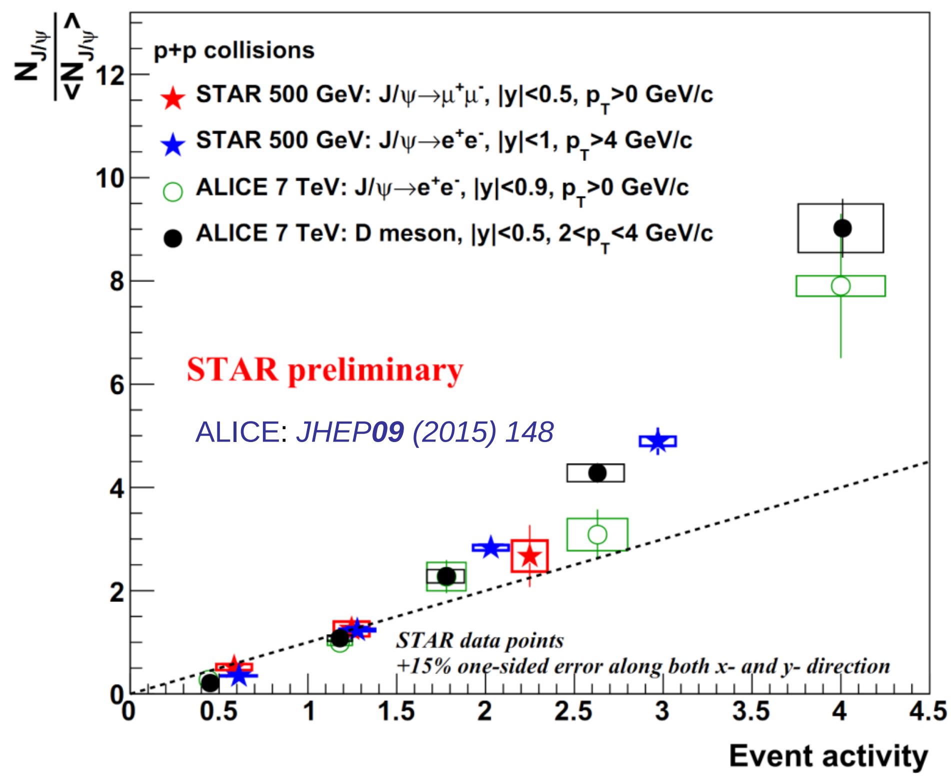
STAR pp200: *PRC**80**, 014902 (2009)*

- J/ψ production measured up to 20 GeV/c at $\sqrt{s}$ = 500 GeV.
  - ✓ Dimuon channel – extends reach to low p_T
  - ✓ CGC+NRQCD and NLO NRQCD predictions agree with data.
  - ✓ Follow x_T scaling at p_T > 4 GeV/c with n=5.6.

J/ψ yield versus event activity

TofMult – Multiplicity of TOF matched tracks with |η| <0.9

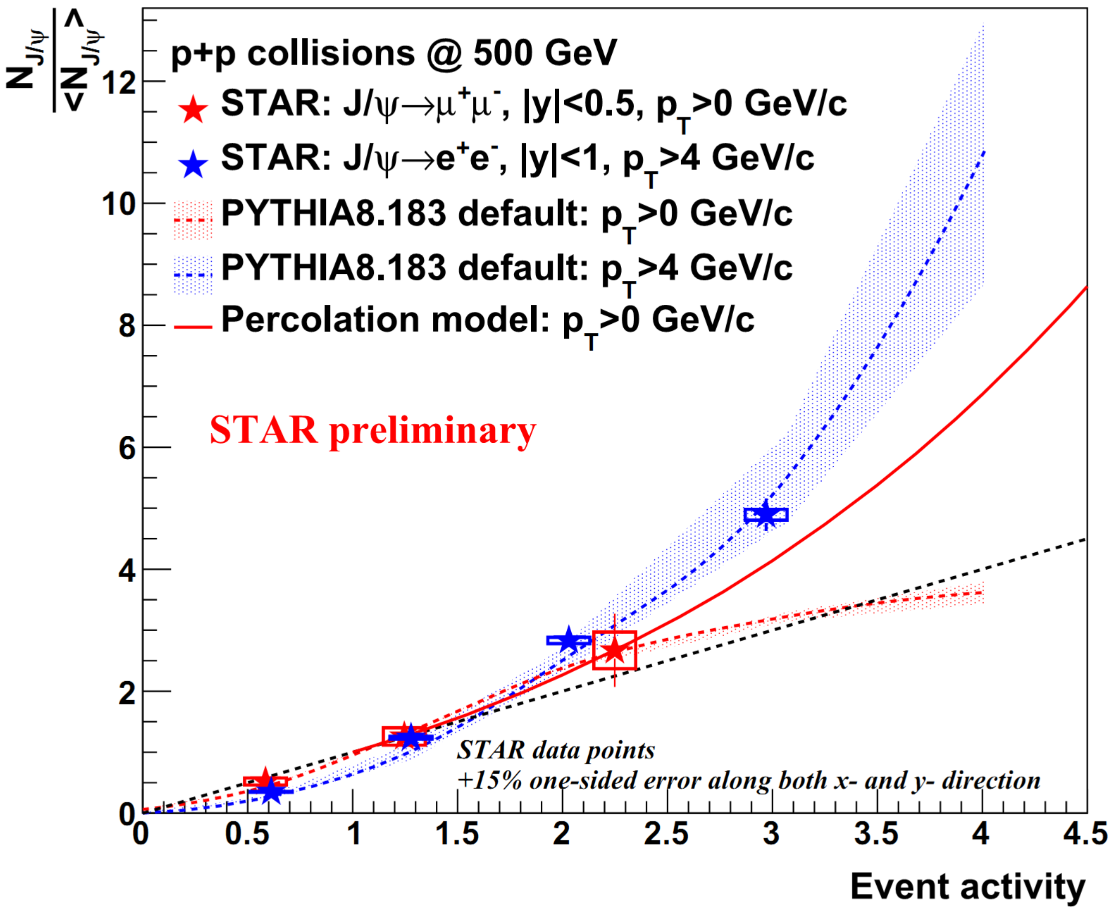




- Stronger-than-linear growth for relative J/ψ yield.
- Different trends for low and high p_T J/ψ.
- Similar trends at LHC and RHIC.

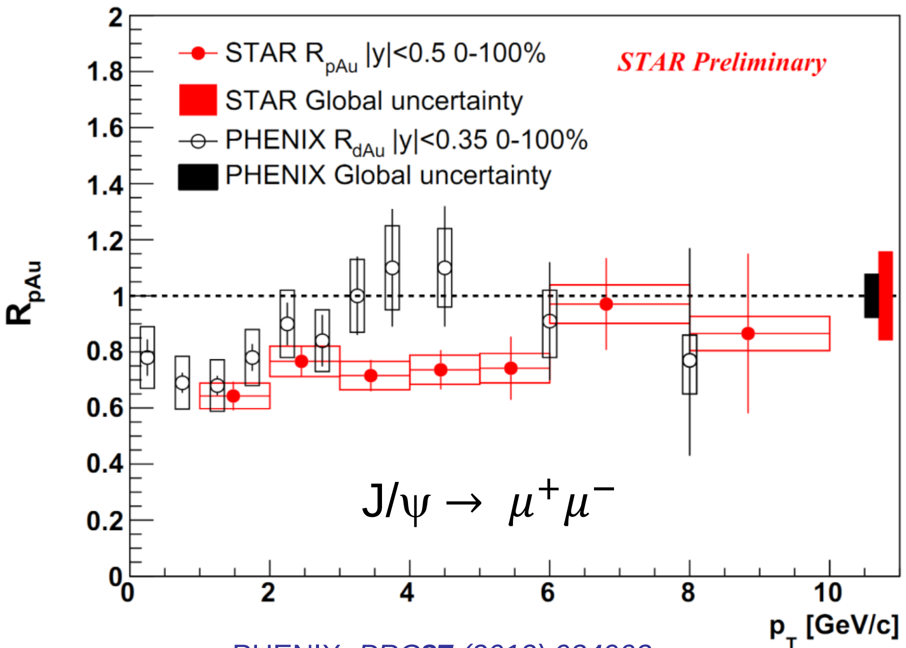
Compare with models

Percolation model: *PRC**86**, 034903 (2012)*

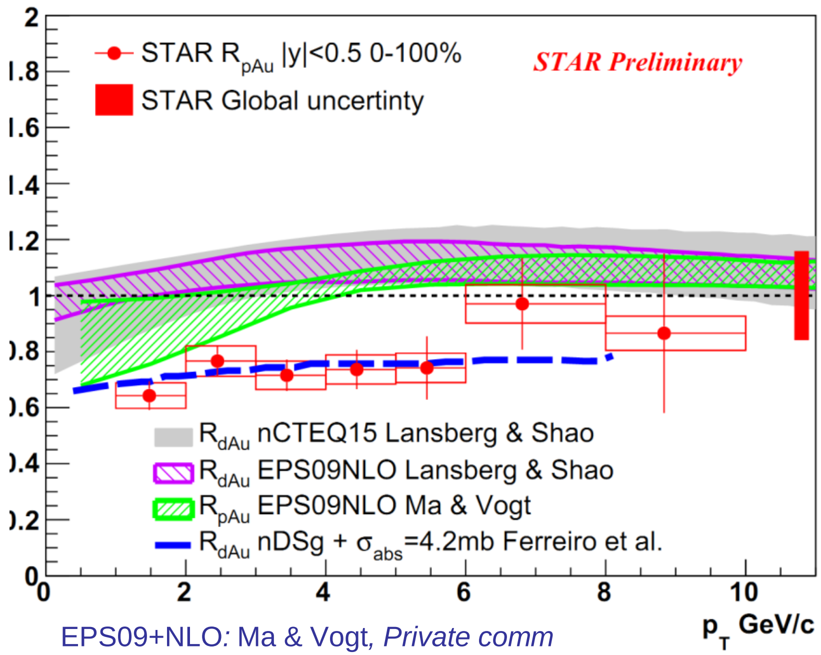


- PYTHIA8 describes the rising trend and p_T dependence in data.
- Percolation model – also qualitatively reproduces the trend in data.
- Measurement for higher multiplicity bins and correction for detector response via unfolding are in progress -> important to distinguish between models.

Inclusive J/ψ modification in p+Au



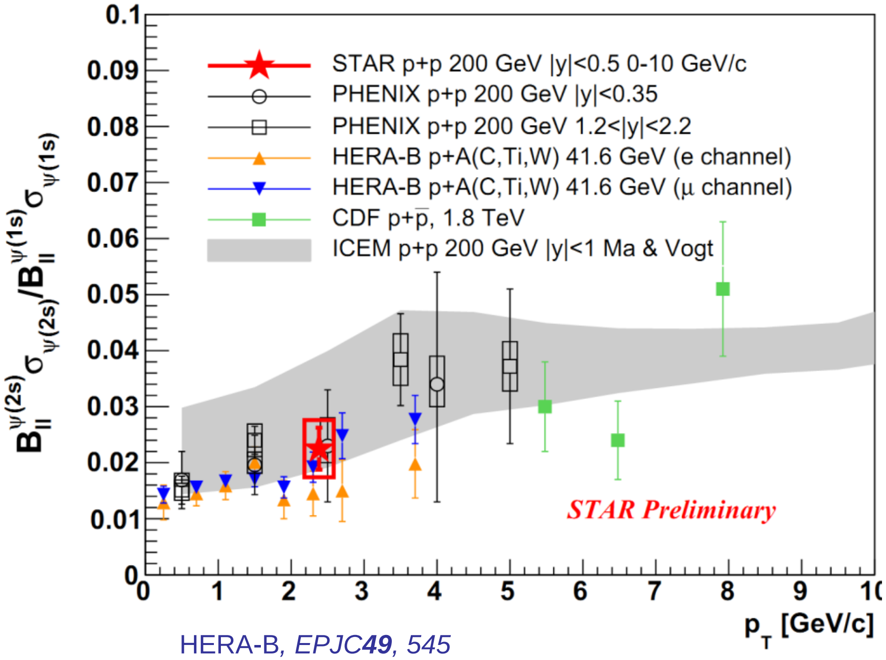
PHENIX, *PRC**87** (2012) 034903*



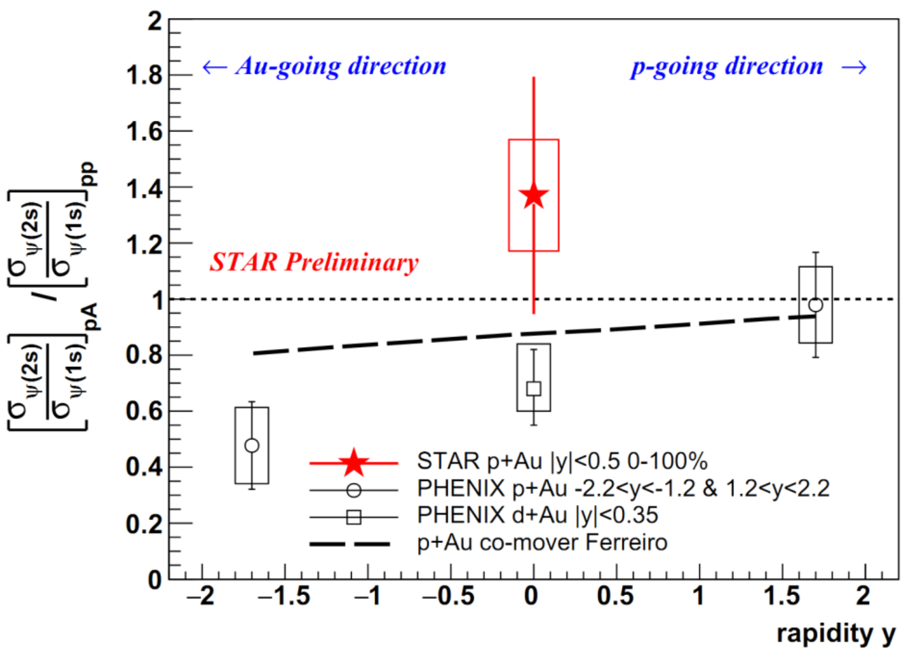
EPS09+NLO*: Ma & Vogt, Private comm*
nCTEQ, EPS09+NLO*:* Lansberg Shao, *EPJC**77** (2017) 1*
*Comp. Phys. Comm.**198**(2016) 238-259*
*Comp. Phys. Comm.**184**(2013) 2562-2570*
Ferreriro et al.*, Few Body Syst.**53**(2012) 27*

- **R_{pAu} vs. R_{dAu}:** Consistent within uncertainties, with a small tension at $3.5 < p_T < 5$ GeV/c (~ 1.4σ).
- **Data vs. model:** Data seem to favor the model calculation with additional nuclear absorption on top of nuclear PDF effects!

ψ(2S)/ J/ψ ratio and double ratio



HERA-B, *EPJC**49**, 545*
PHENIX mid y, *PRD**85** (2012) 092004*
PHENIX forward y, *PRC**95** (2017) 034904*
CDF, 1.8 TeV, *PRL**79** (1997) 572*
ICEM, Ma & Vogt, *PRD**94** (2016) 114029*

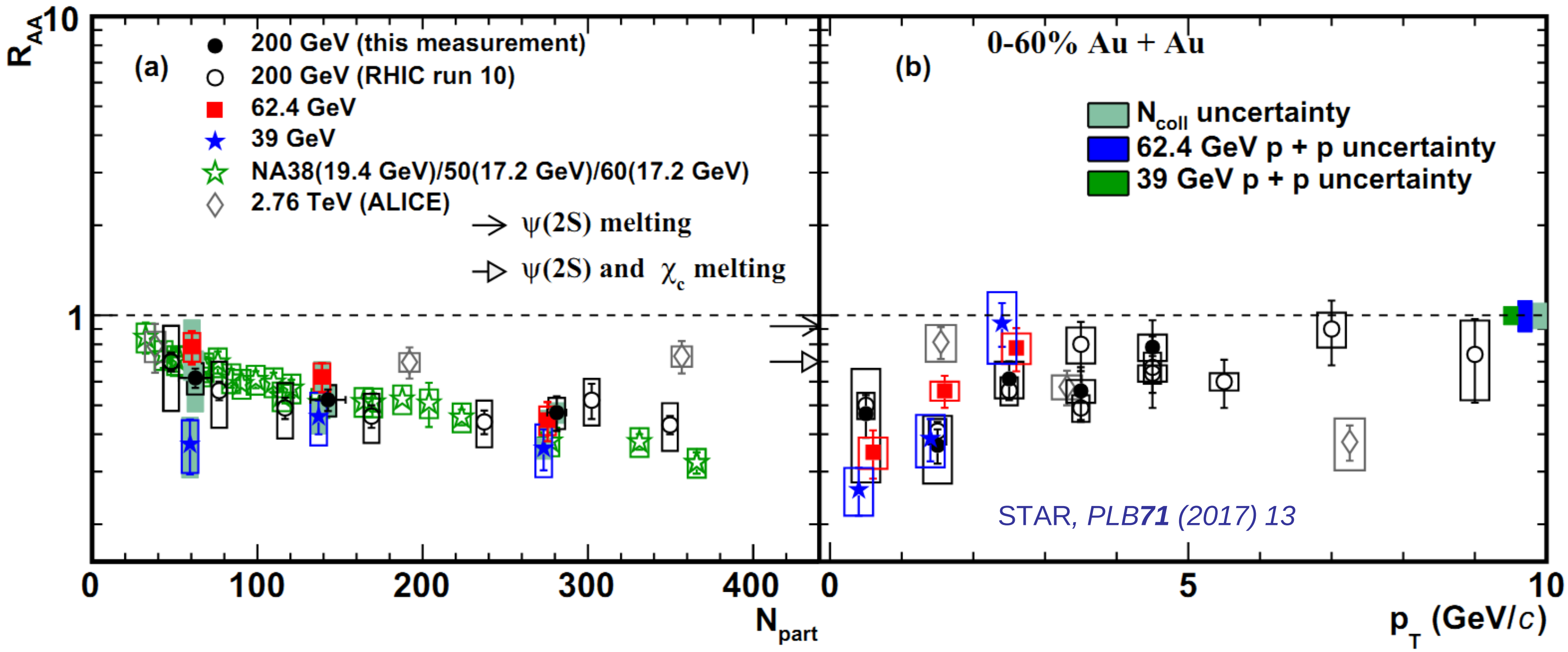


PHENIX p+Au, *PRC**95** (2017) 034904*
PHENIX d+Au, *PRL**111** (2013) 202301*
Co-mover calculation, *Ferreiro, private comm.*

- Measured ψ(2S)/J/ψ ratio in p+p 200 GeV is consistent with world-wide data.
- First ψ(2S) to J/ψ double ratio measurement between pp and pAu at mid-rapdity at RHIC:

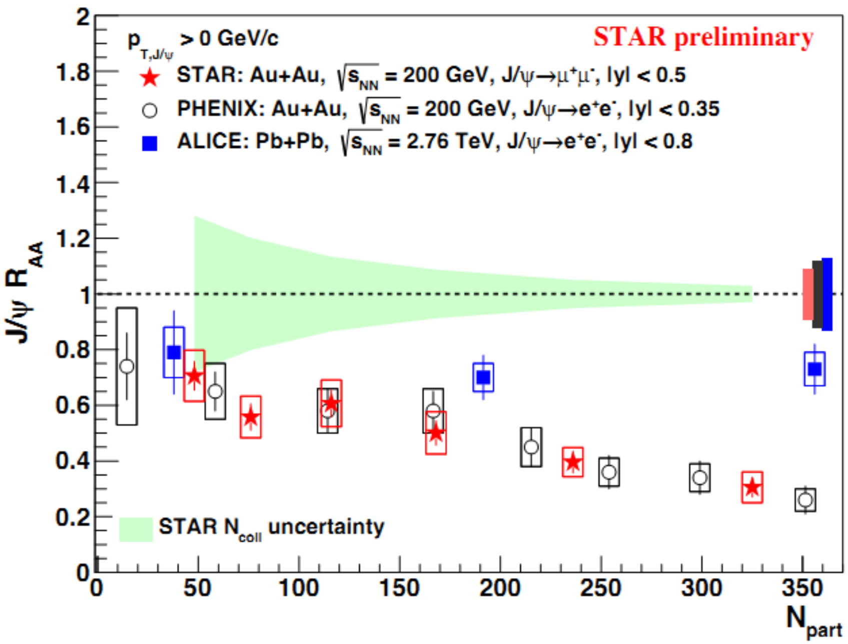
1.37 ±0.42(stat.) ±0.19(syst.).

Energy dependence of R_{AA}

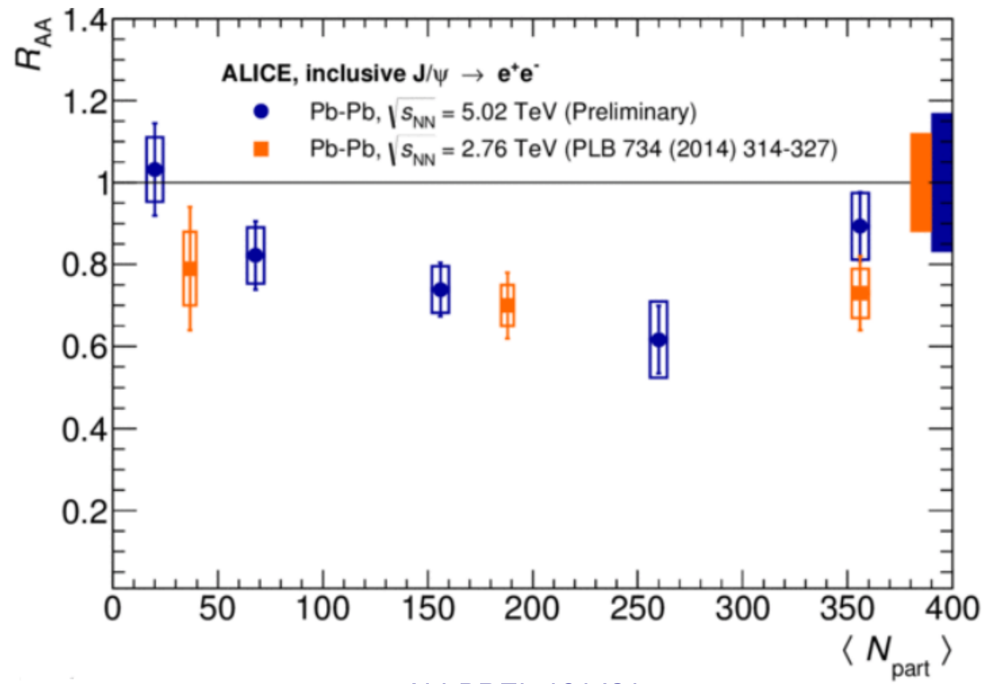


- Significant suppression of J/ψ production in Au+Au collisions observed at $\sqrt{s_{NN}}$ = 39 - 200 GeV.
- No significant energy dependence observed for R_{AA} from 17.2 – 200 GeV.

J/ψ modification in A+A collisions at low p_T



ALICE: *PLB**734** (2014) 314*
PHENIX: *PRL**98** (2007) 232301*

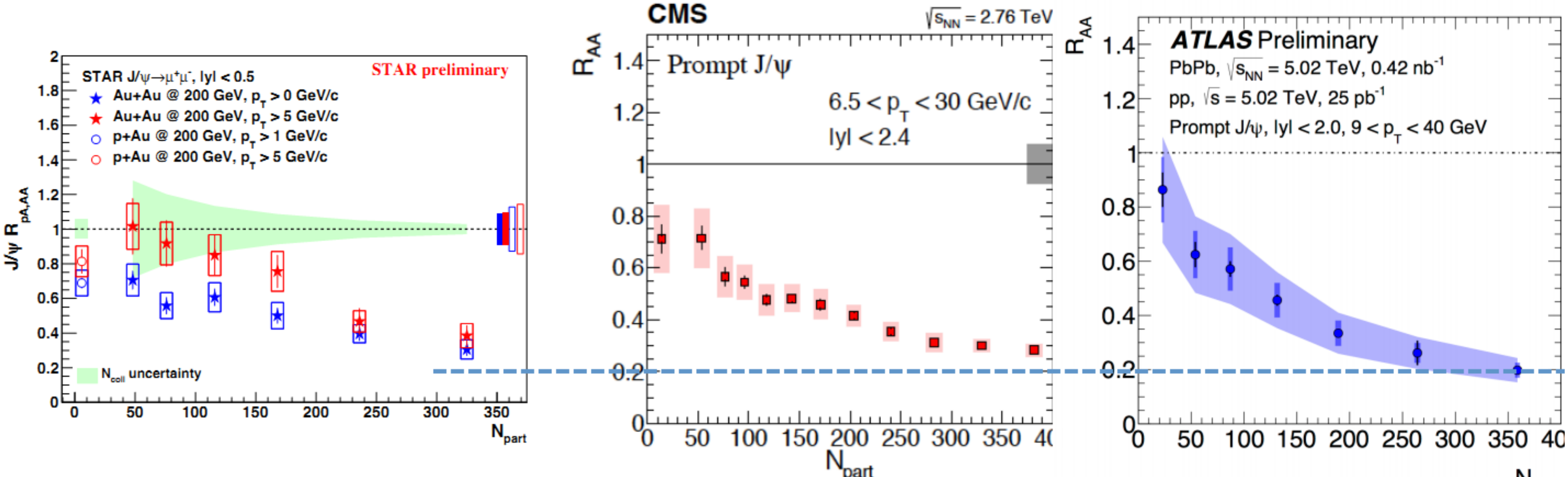


ALI-PREL-121481

- At RHIC, R_{AA} decreases considerably towards central collisions.
- At the LHC, R_{AA} is more or less flat.
- For central collisions, R_{AA}(200 GeV) < R_{AA}(2.76 TeV) ~ R_{AA}(5.02 TeV)
  - ✓ RHIC: Dissociation overweighs regeneration
  - ✓ LHC: Regeneration dominates

J/ψ modification in A+A collisions at high p_T

√s = 0.2 TeV | √s = 2.76 TeV | √s = 5.02 TeV

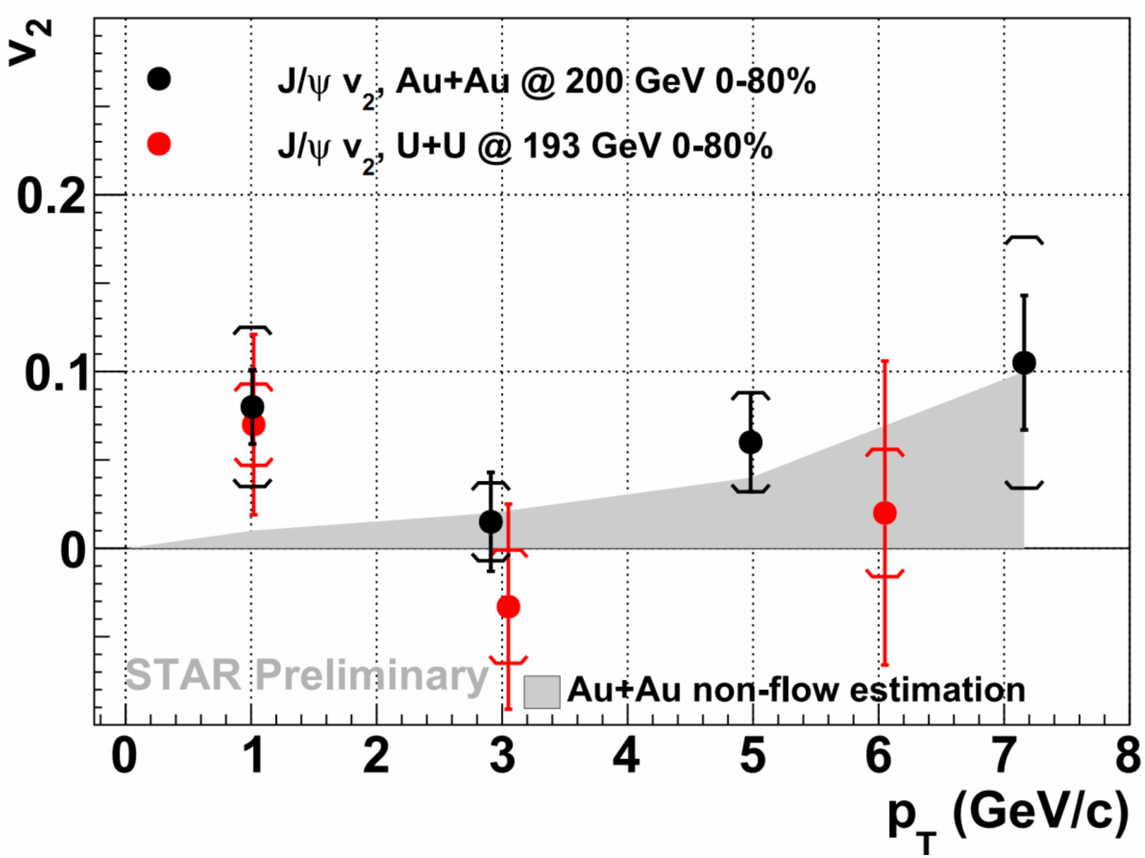


CMS: *EPJC**77** (2017) 252*

ATLAS-CONF-2016-109

- Decreasing R_{AA} towards central collisions at all collision energies.
- For all centralities, R_{AA}(200 GeV) > R_{AA}(2.76 TeV) ~ R_{AA}(5.02 TeV)
  - ✓ Dissociation in effect

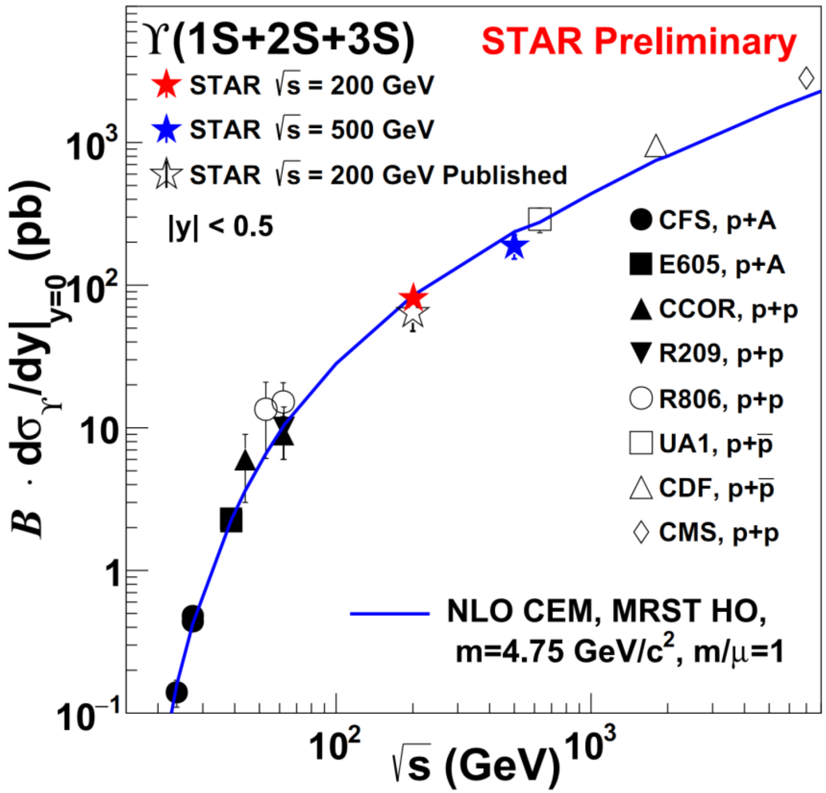
J/ψ v_2 in U+U collisions



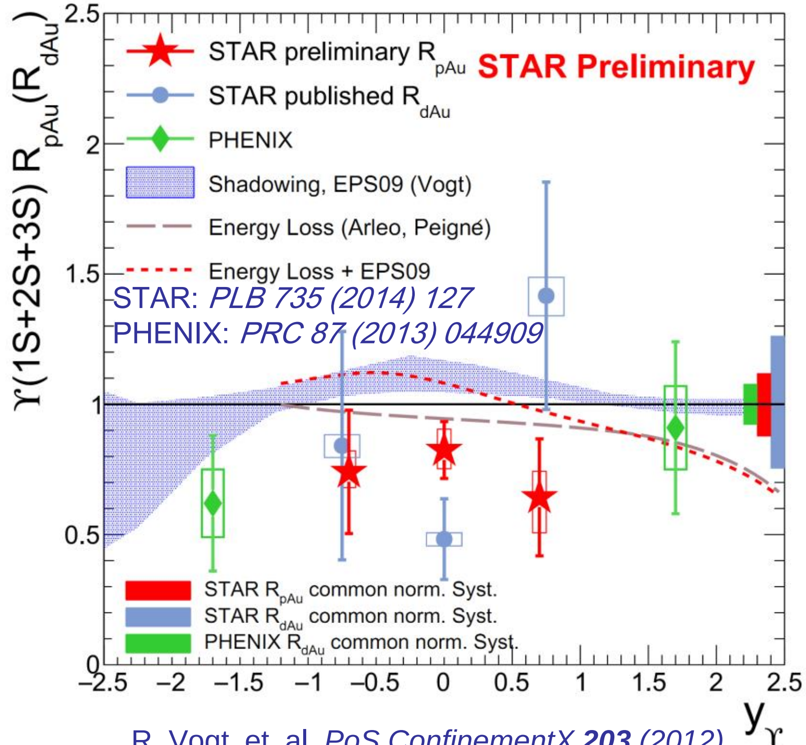
Au+Au results:
Run 2010 and
2011 combined

- The first measurement of J/ψ v_2 in U+U collisions.
  - ✓ U+U and Au+Au results are consistent within uncertainties.
- J/ψ v_2 is consistent with zero above 2 Gev/c within uncertainties.

ϒ results in p+p and p+Au collisions



R. Vogt ,*Phys. Rept.* ***462*** *(2008) 125*

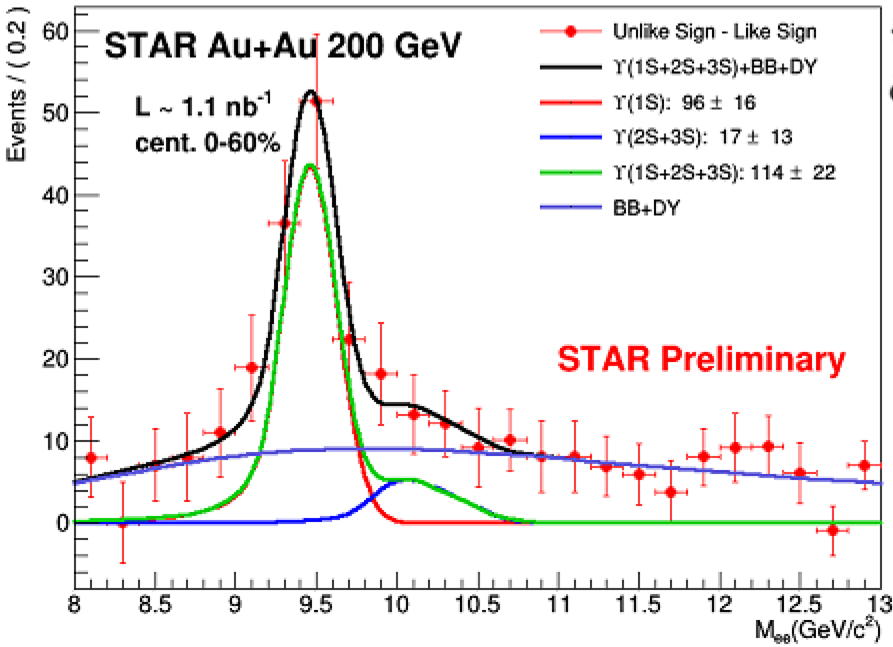


R. Vogt, et. al, *PoS ConfinementX* ***203*** *(2012)*
F. Arleo, S. Peigne, *JHEP* ***1303*** *(2013) 122*
K. J. Eskola, et. al, *JHEP* ***0904*** *(2009) 065*

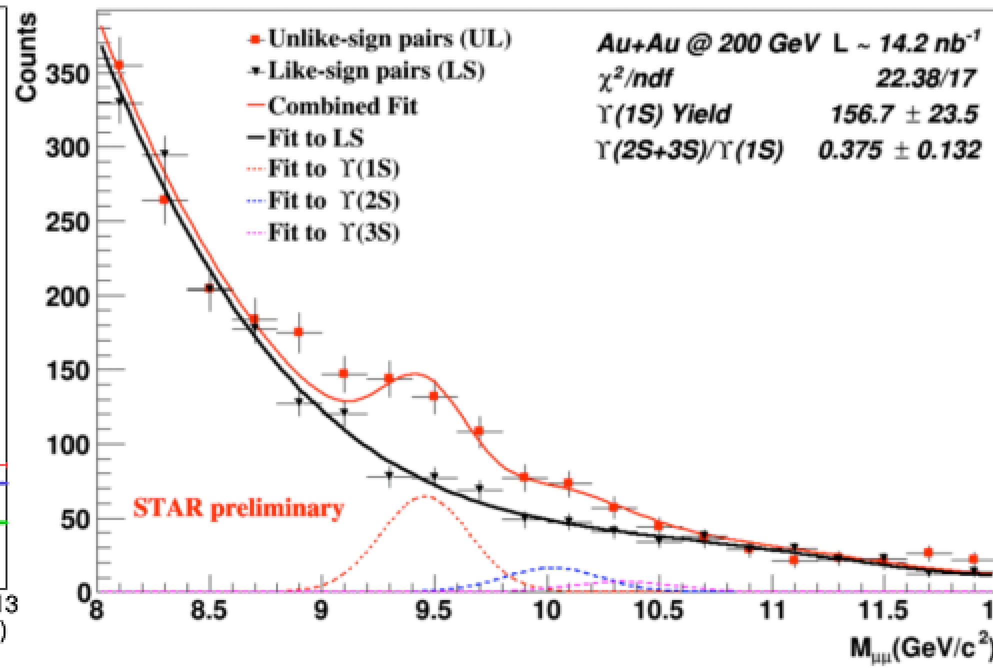
- p+p: σ= 81 ±5(stat.) ±8(syst.) pb for 200 GeV
  - ✓ Baseline for A+A collisions with improved precision
  - ✓ Consistent with the Color Evaporation Model (CEM) prediction
- p+Au: $R_{pAu} = 0.82 \pm 0.10$ (stat.) $^{+0.08}_{-0.07}$ (syst.) ±0.10 (global)
  - ✓ Quantify CNM effects

Υ signal in A+A collisions

$\Upsilon \rightarrow e^+e^-$, 2011 data

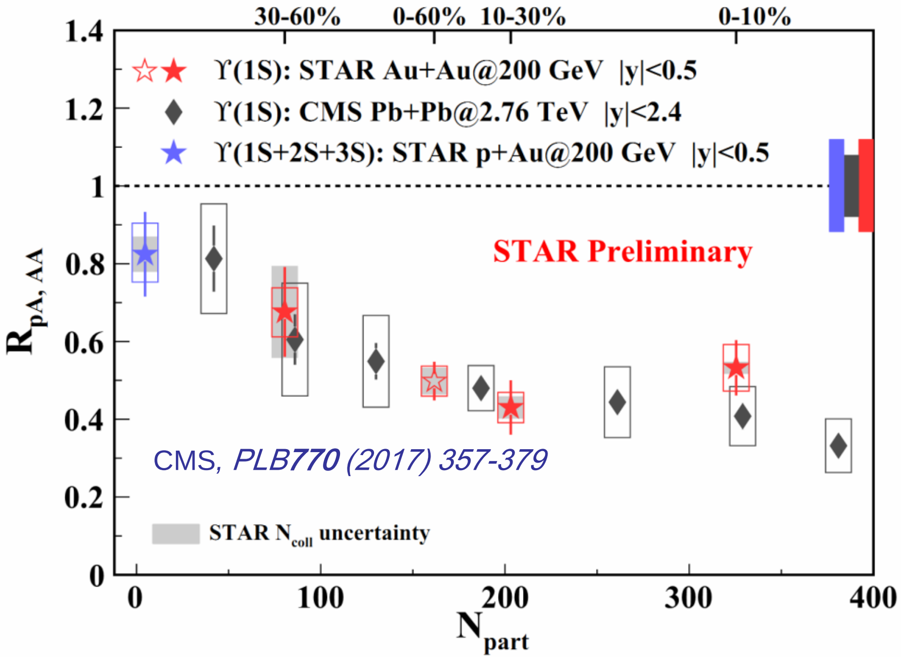


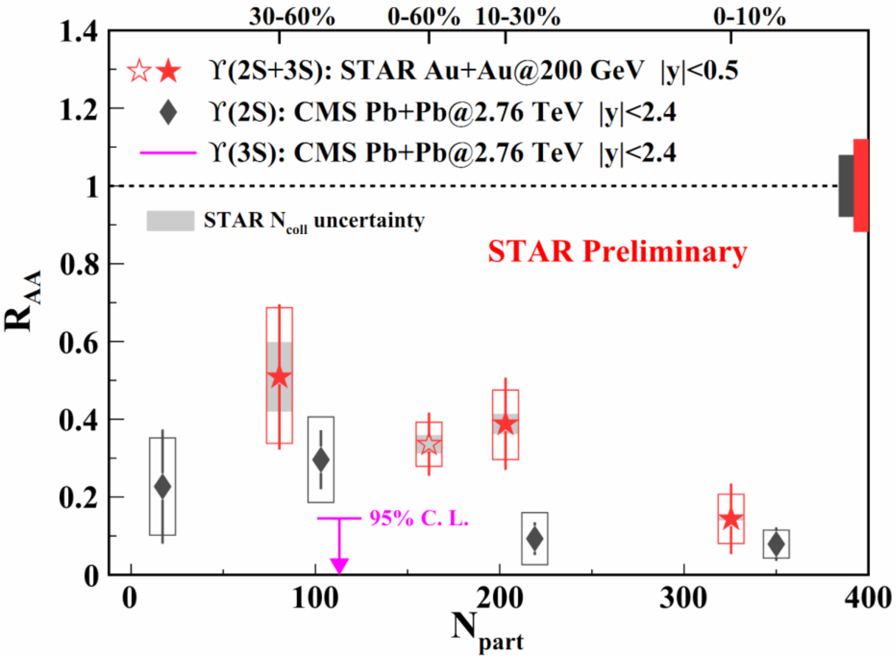
$\Upsilon \rightarrow \mu^+\mu^-$, 2014 data



- Background sources:
  - ✓ Combinatorial background (estimated with $N_{l_+l_+} + N_{l\_l\_}$)
  - ✓ $b\bar{b}$ and Drell-Yan contributions

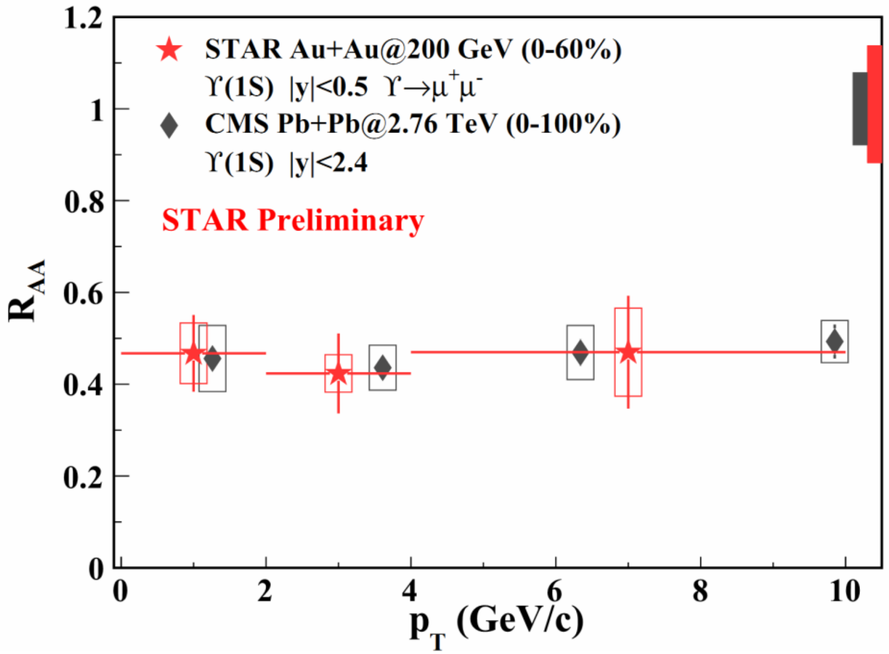
Υ measurements versus centrality

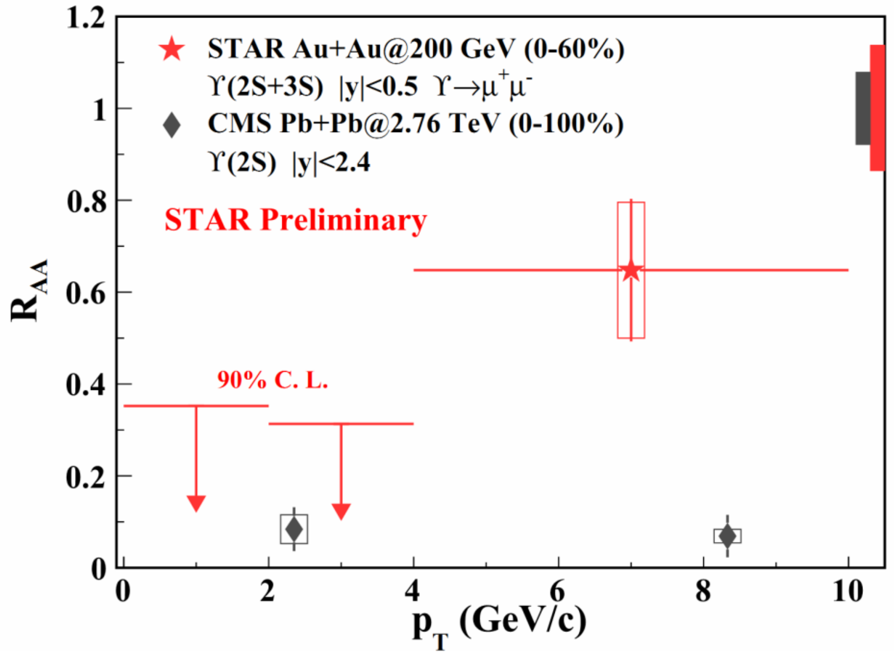




- Indication of more suppression with increasing centrality.
- Υ(2S+3S) is more suppressed than Υ(1S) in central collisions!
  - ✓ Sequential melting
- Comparison with LHC results:
  - ✓ Υ(1S) : Consistent with CMS measurement!
  - ✓ Υ(2S+3S) : Indication of less suppression at RHIC than at LHC.

Υ measurements versus p_T





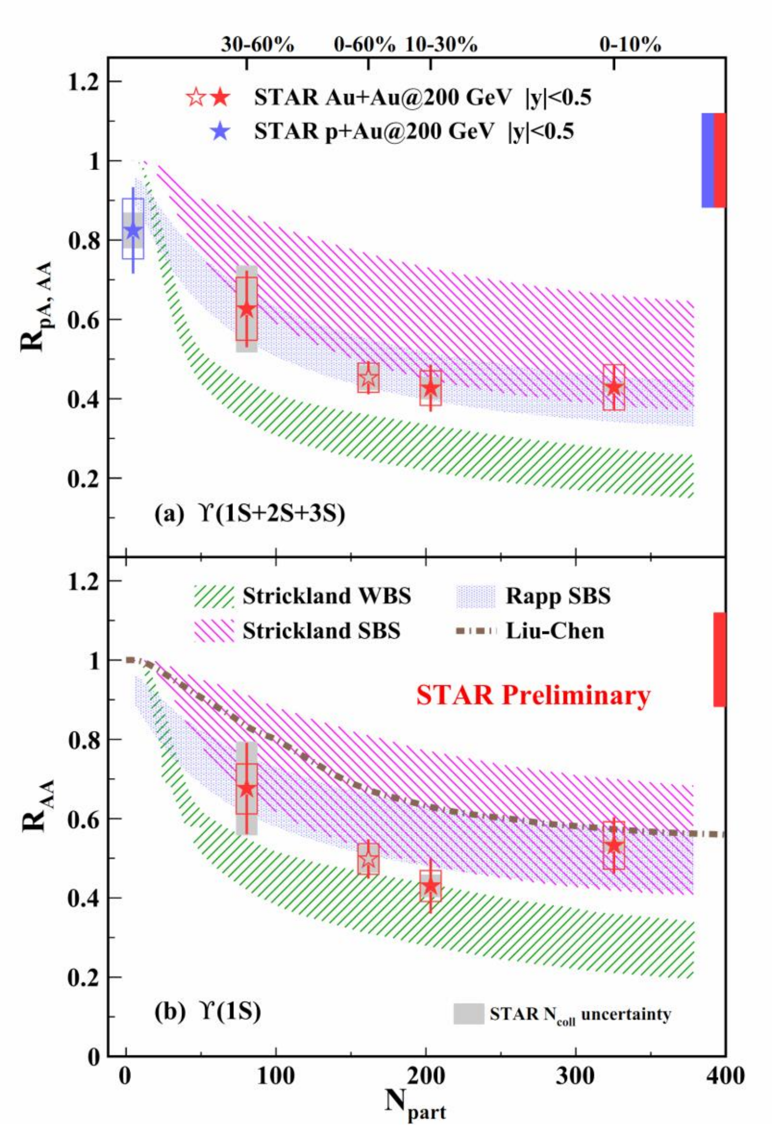
CMS, *PLB770 (2017) 357-379*

- Υ(1S): No obvious dependence on p_T - consistent with CMS result.
- Υ(2S+3S): Indication of less suppression at RHIC at high p_T

Comparison with models

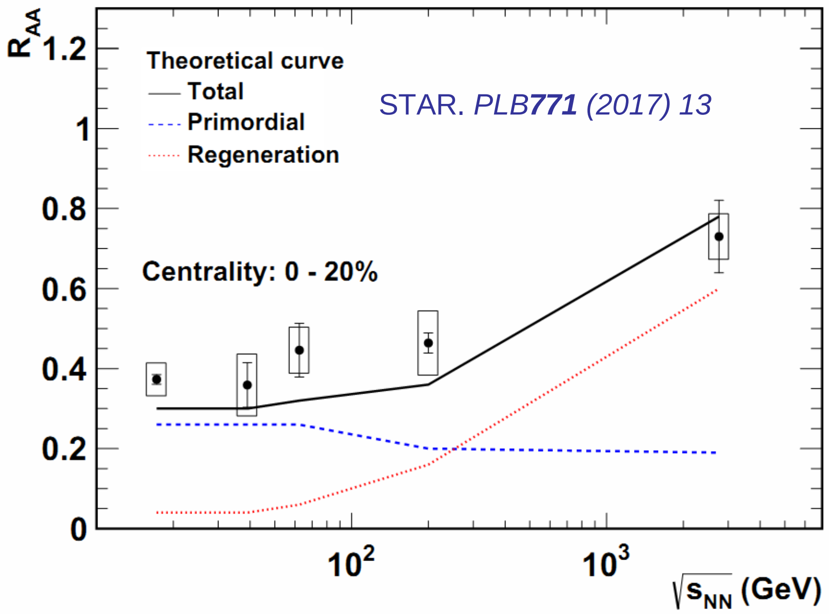
- SBS (Strongly Binding Scenario):
  - ✓ fast dissociation—potential based on internal energy.
- WBS (Weakly Binding Scenario):
  - ✓ slow dissociation—potential based on free energy.
- Strickland, Bazov:
  - ✓ No CNM, no regeneration. *NPA 879 (2012) 25*
- Liu, Chen, Xu, Zhuang:
  - ✓ Dissociation only for excited states, suppression of ground state due to feed-down, SBS. *PLB 697 (2011) 32*
- Emerick, Zhao, Rapp:
  - ✓ Includes CNM, SBS case. *EPJ A48 (2012) 72*

- Data seem to favor the SBS models!



“Dissociation + Regeneration” picture

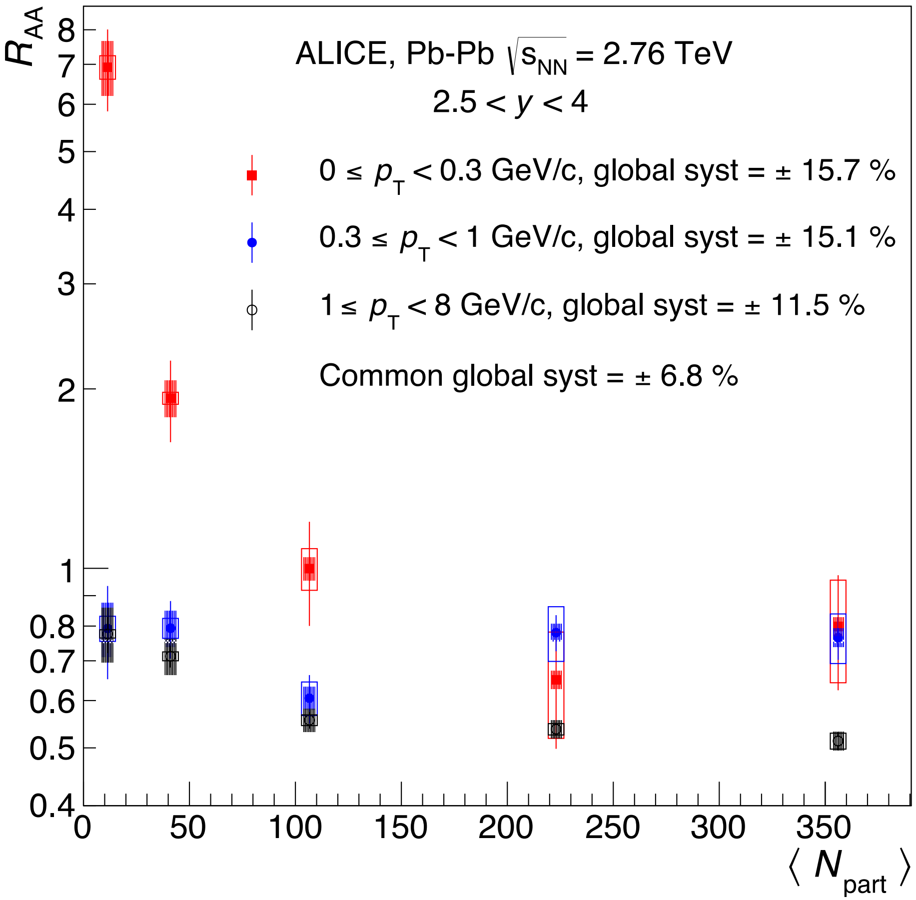
J/ψ as an example!



- The interplay of CNM, color screening, and regeneration effects can describe the energy dependence of nuclear modification factor reasonably well!

	Dissociation	Regeneration	CNM
$\sqrt{s}$ ↑	↑	↑	↑
p_T ↑	↓ (?)	↓	↓
y ↑	↓	↓	↑

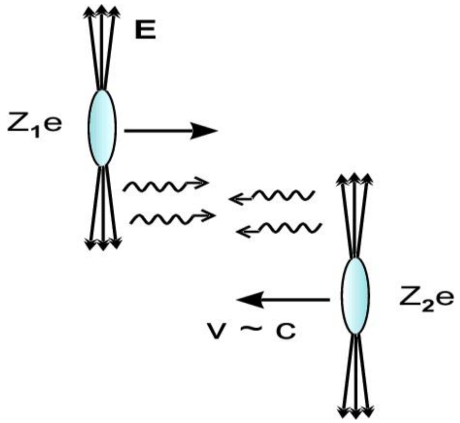
Excess of J/ψ production at very low p_T with ALICE



ALICE, *PRL* ***116****, 222301 (2016)*

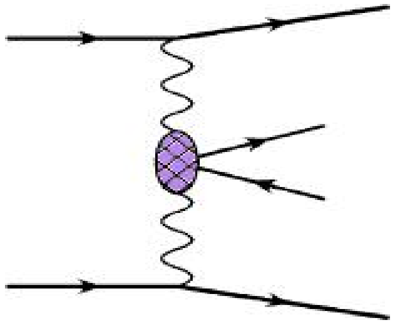
- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!
- Origin from coherent photon-nucleus interactions?

Introduction to photon interactions in A+A



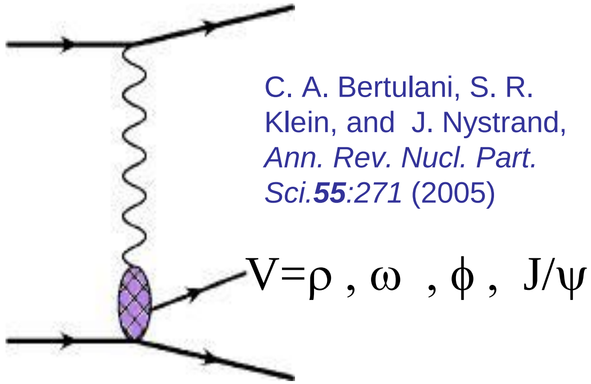
Electromagnetic interaction

=



Photon-photon interactions

+



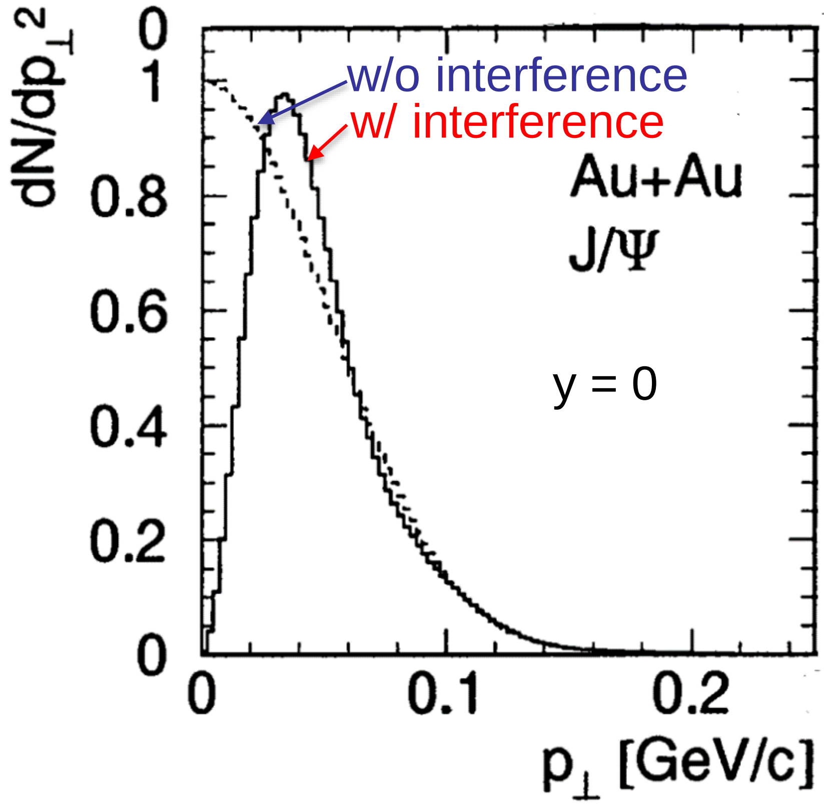
Photon-nucleus interactions

C. A. Bertulani, S. R. Klein, and J. Nystrand, *Ann. Rev. Nucl. Part. Sci.* ***55****:271* (2005)

- This large flux of quasi-real photons makes a hadron collider also a photon collider!
- Photon-nucleus interactions:
  - ✓ Coherent: emitted photon interacts with the entire target nucleus.
  - ✓ Incoherent: emitted photon interacts with nucleon or parton individually.

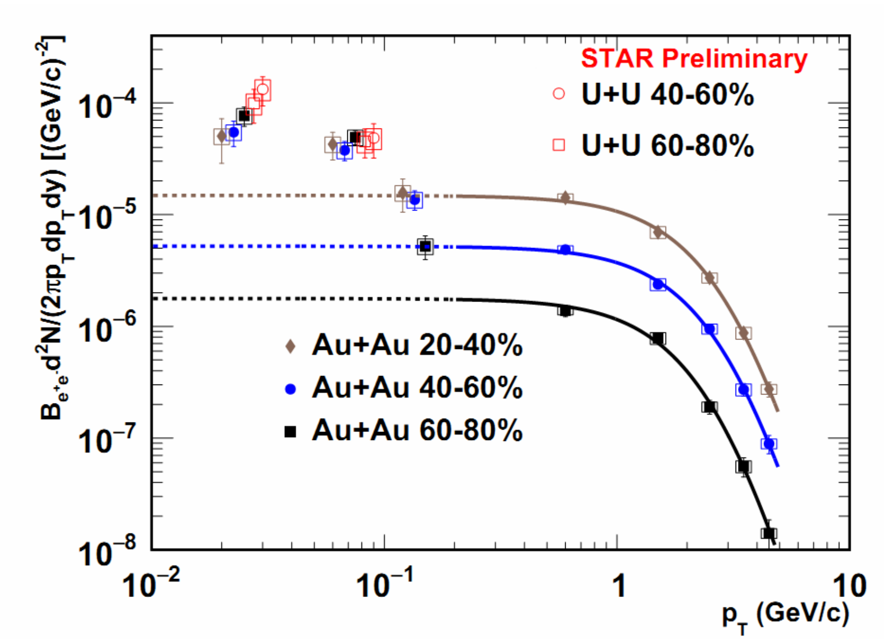
Features of coherent photon-nucleus interaction

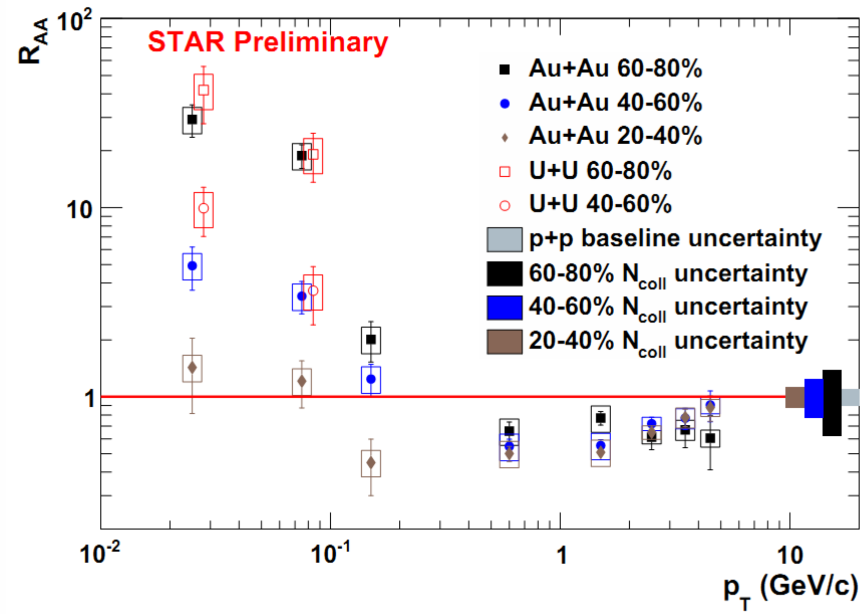
- Coherently:
  - ✓ Both nuclei remain intact
  - ✓ Photon/Pomeron wavelength $\lambda = \frac{h}{p} > R_A$
  - ✓ $p_T < h/R_A$ ~30 MeV/c for heavy ions
  - ✓ Strong couplings ($Z\alpha_{EM}$ ~ 0.6) → large cross sections
- Interference:
  - ✓ Two indistinguishable processes (photon from A_1 or A_2)
  - ✓ Vector meson → opposite signs in amplitude
  - ✓ Significant destructive interference for p_T << 1/<b>



S. R. Klein and J. Nystrand, *PRL* ***84*** *2330 (2000)*

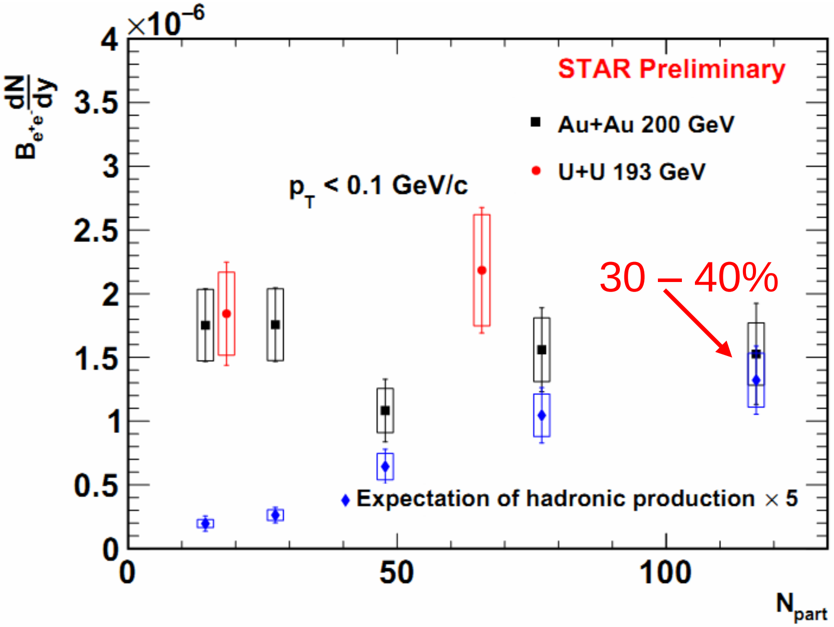
J/ψ production and modification at very low p_T

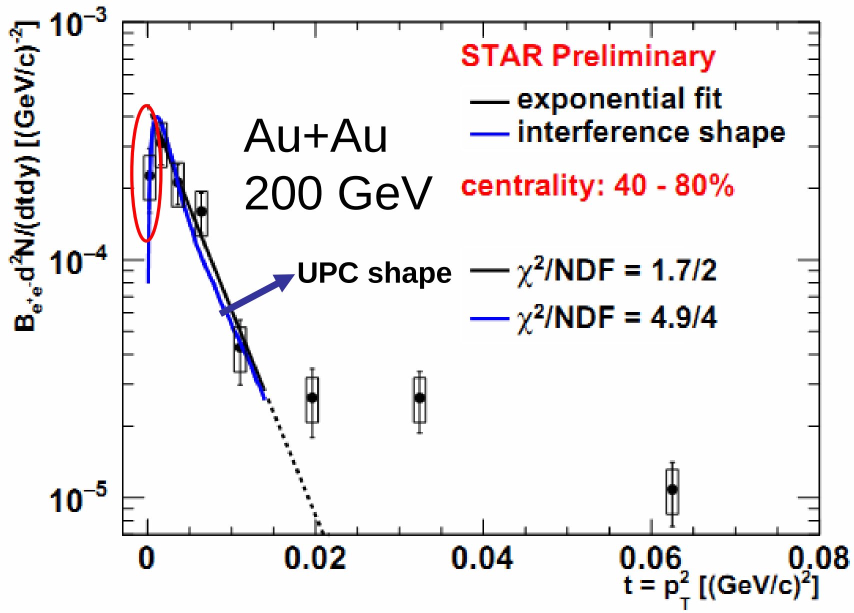




- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %)!
- No significant difference between Au+Au and U+U collisions.

The excess yield and dN/dt distribution





- Low p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}.
- No significant centrality dependence of the excess yield!

- Similar structure to that in UPC case!
- Hint of interference!
  - ✓ Interference shape from calculation for UPC case

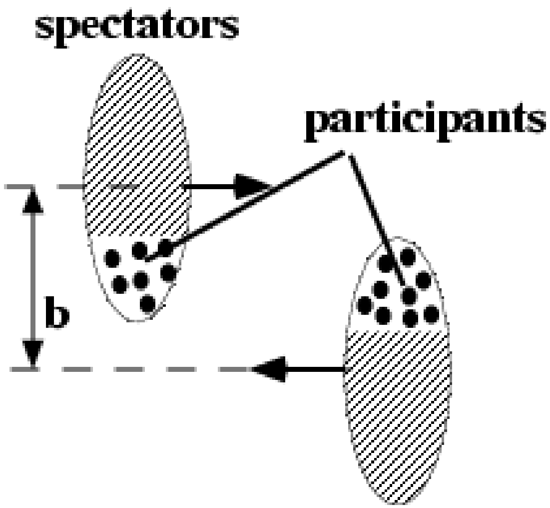
    S. R. Klein and J. Nystrand, *PRL* ***84*** *2330 (2000)*
- Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 $(GeV/c)^{-2}$
  - ✓ Slope w/o the first point: 199 $\pm$ 31$(GeV/c)^{-2}$
    χ^2/NDF = 1.7/2
  - ✓ Slope w/ the first point: 164 $\pm$ 24$(GeV/c)^{-2}$
    χ^2/NDF = 5.9/3

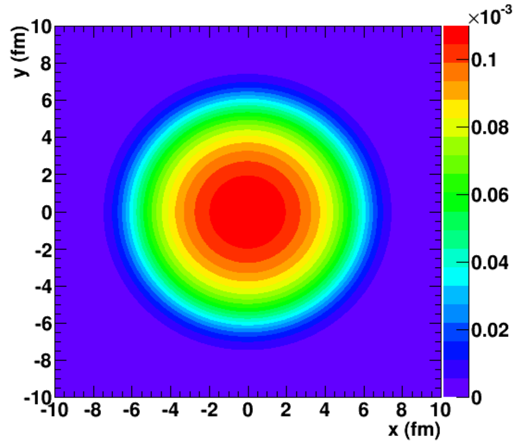
Modeling coherent J/ψ production in A+A collisions

- How does the coherent process stay coherent in violent hadronic collisions?

W. Zha etal., arXiv: 1705.01460

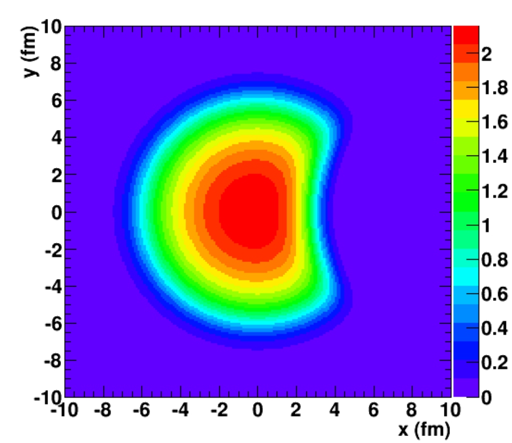
Photon emitter and target





nucleus

OR



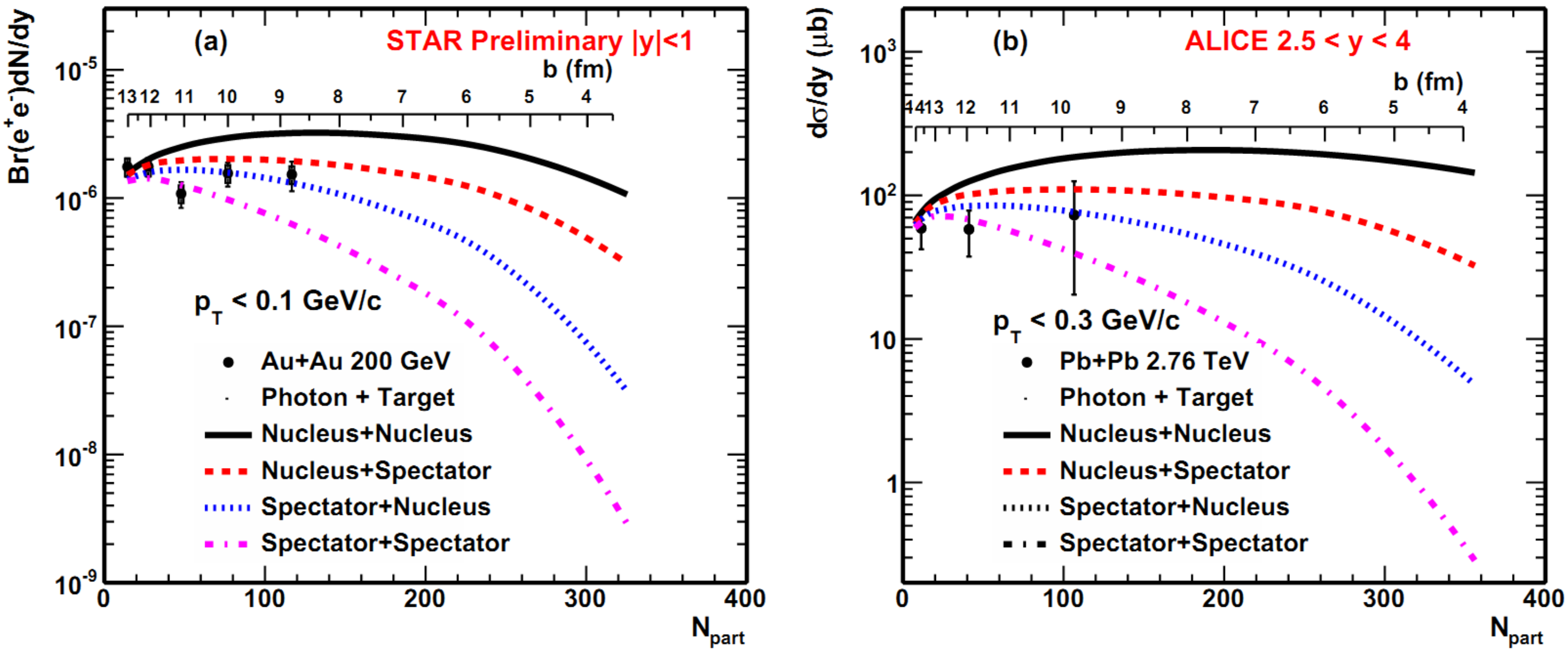
spectator

- The density profile of spectators is from the optical Glauber model!
- The cold and hot medium effects are not considered here.

Photon emitter	Target	
Nucleus	Nucleus	(1)
Nucleus	Spectator	(2)
Spectator	Nucleus	(3)
Spectator	Spectator	(4)

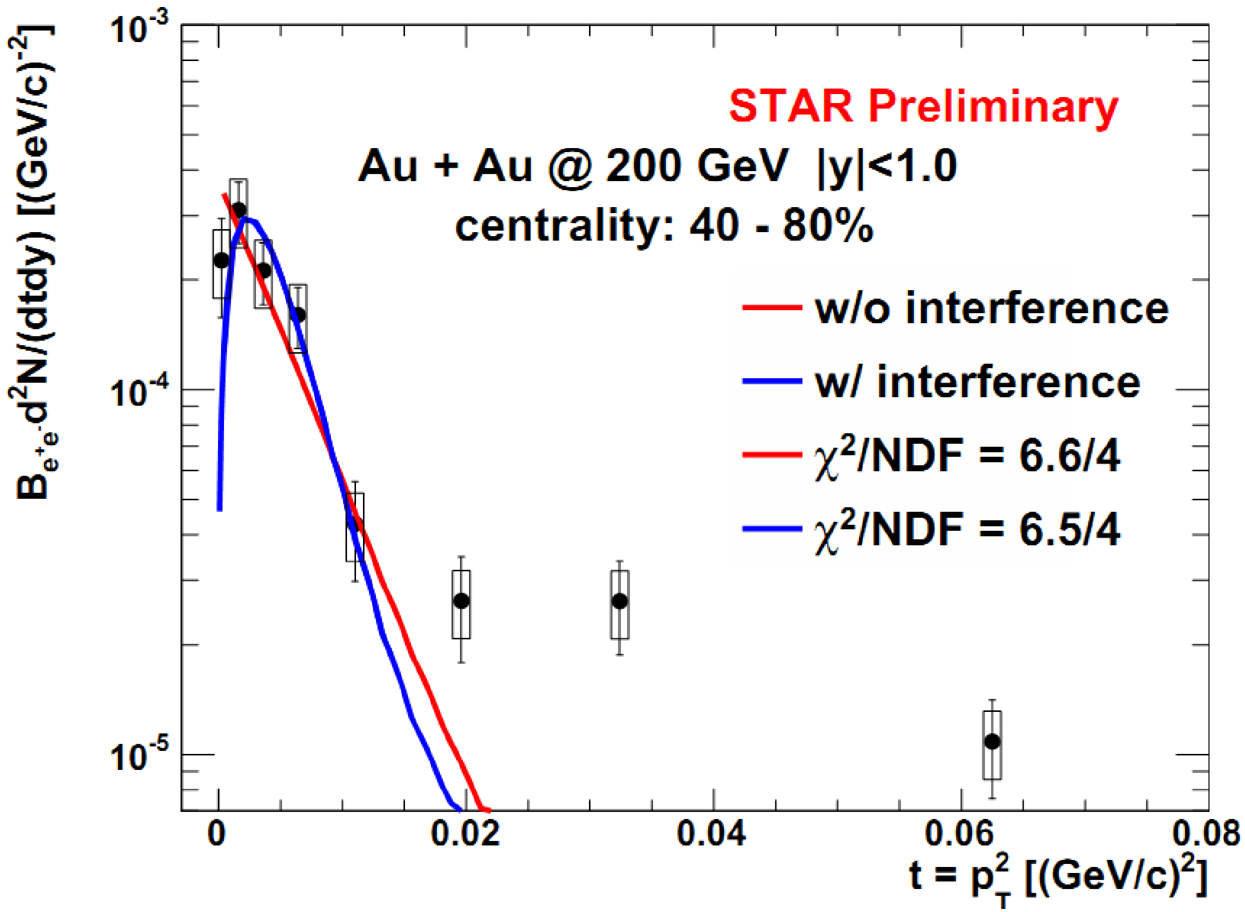
Calculations with different scenarios

W. Zha etal., arXiv: 1705.01460



- Different scenarios have different trends toward central collisions!
- Nucleus+Nucleus: over estimate the data in semi-central collisions.
- Spectator+Spectator: under-predicts the data in semi-central collisions.
- To distinguish the different scenarios, measurements at central collisions are needed!
- Cold Nuclear and hot medium effects are not included in the calculation.

t distribution from model

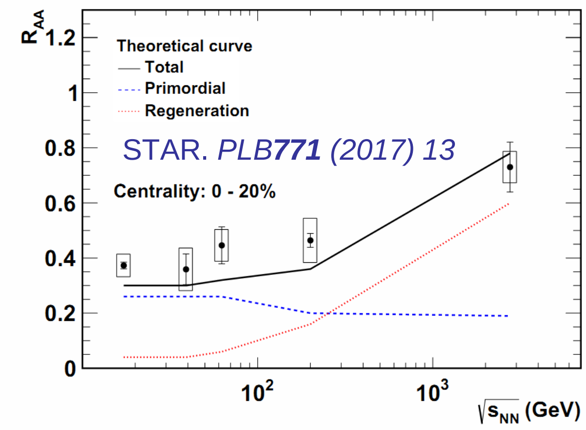


- Both calculations (with and without interference) describe the data reasonably well!
  - ✓ All four scenarios give similar shape, only show results for “Nucleus+Nucleus” .

Summary

- Quarkonium modification in heavy-ion collisions.

	Dissociation	Regeneration	CNM
$\sqrt{s}$ ↑	↑	↑	↑
p_T ↑	↓ (?)	↓	↓
y ↑	↓	↓	↑



- Excess of J/ψ at very low p_T!
  - ✓Consistent with coherent photoproduction!
  - ✓A novel probe to test the medium?