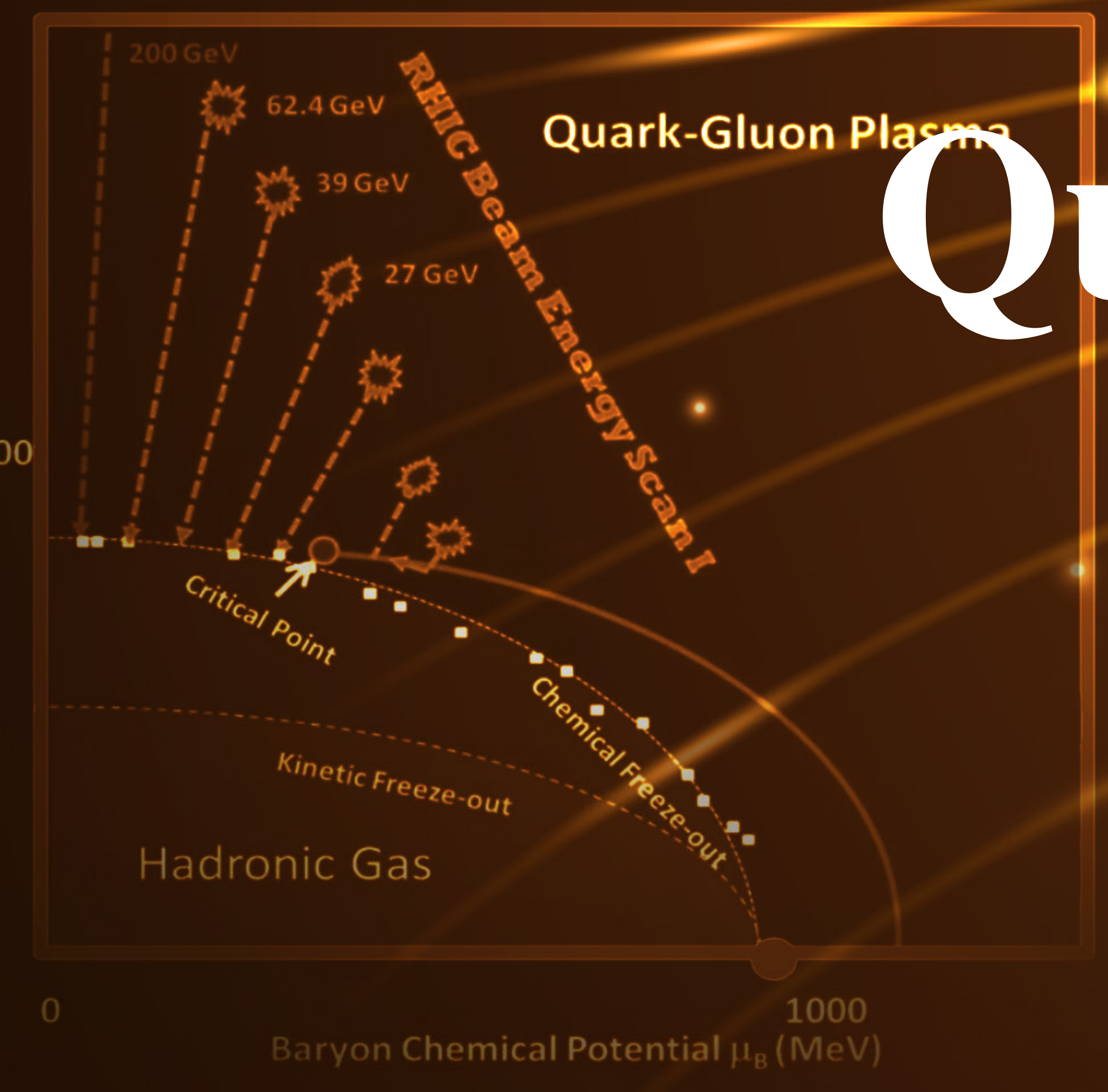
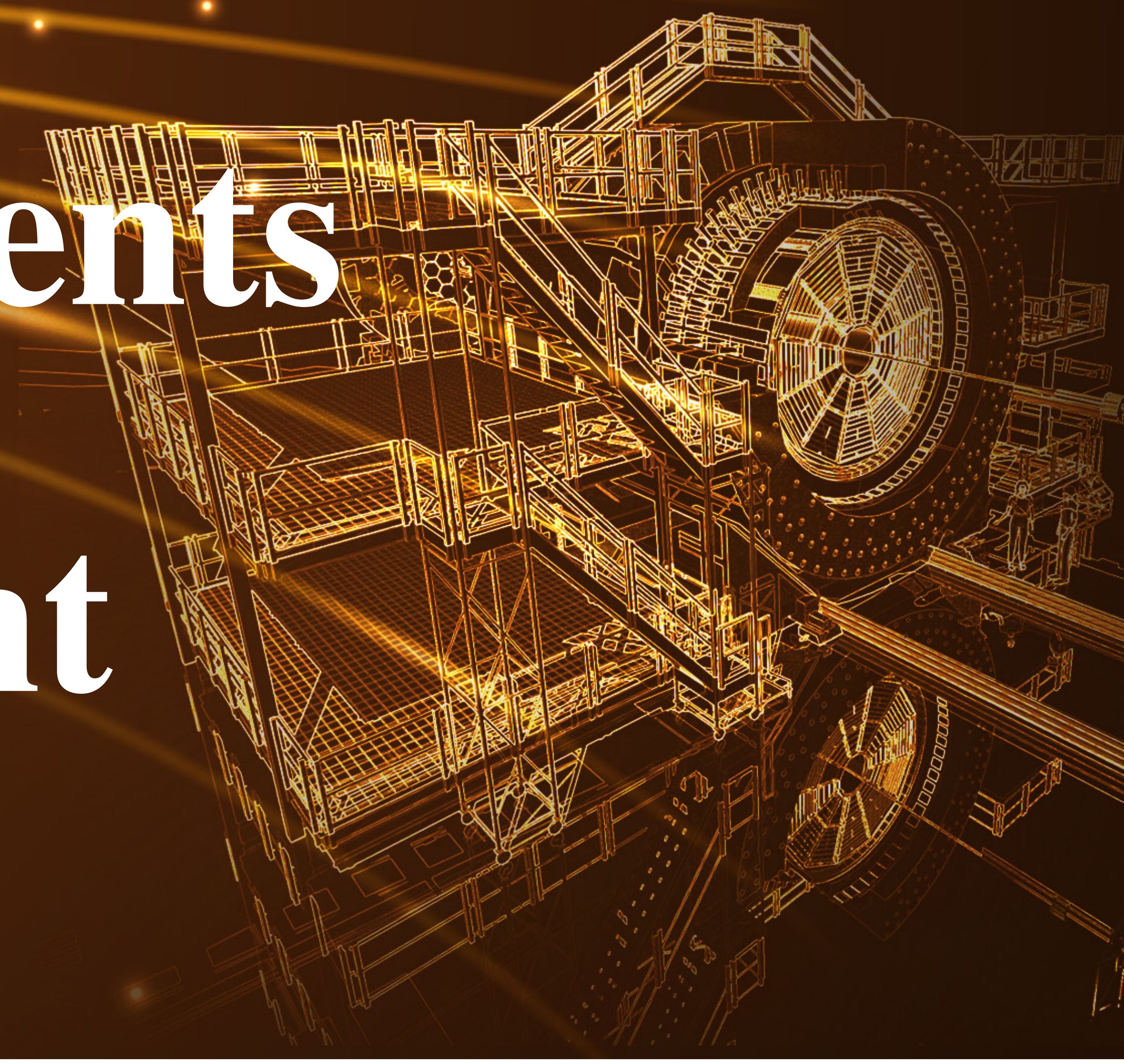


Quarkonium measurements with STAR experiment



Pengfei Wang *(for the STAR Collaboration)*

University of Science and Technology of China

Brookhaven National Laboratory

Outline

- Introduction
- STAR experiment
- Charmonium measurements
- Bottomonium measurements
- Summary

Why Quarkonium?

- **Color-screening: quark-antiquark potential is color-screened in the QGP by the surrounding partons ⇒ *dissociation***

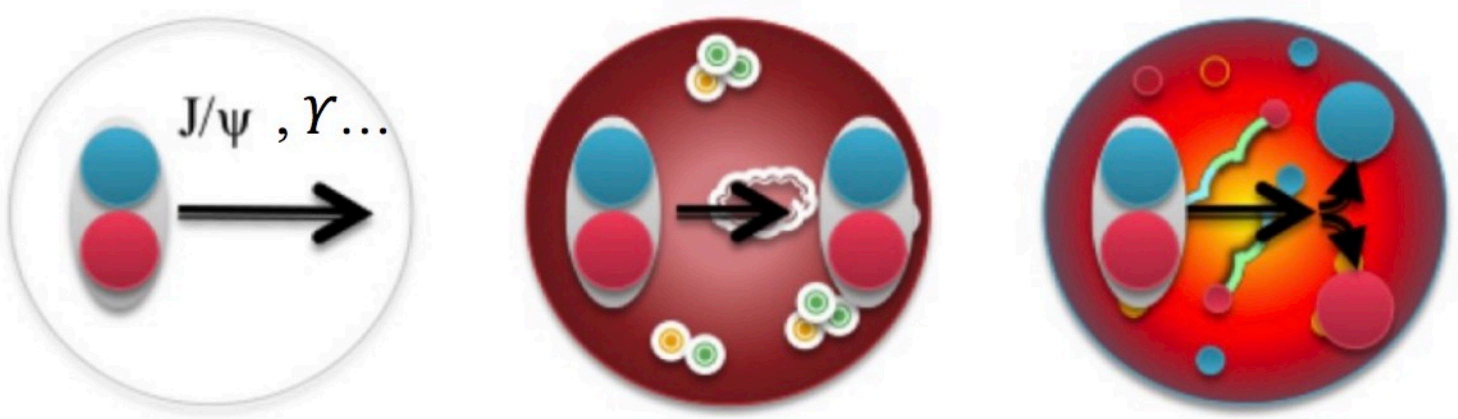
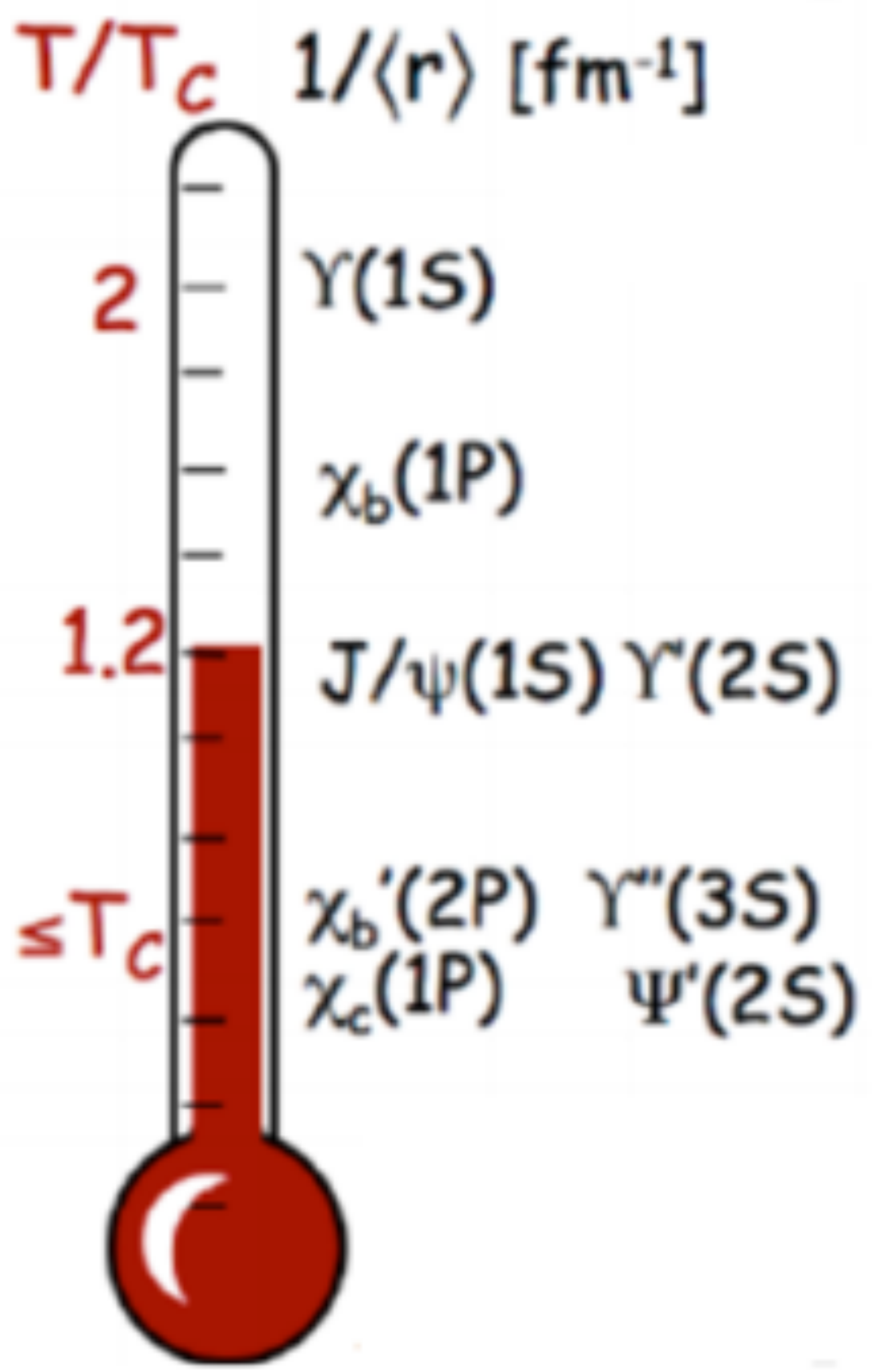


Illustration: A. Rothkopf

T = 0 **0 < T < Tc** **T > Tc**

- **"Thermometer": different states dissociate at different temperatures ⇒ *sequential suppression***

- **However, other effects come into play**
  - **Regeneration**
  - **Feed-down**
  - **Cold Nuclear Matter (CNM) effects**

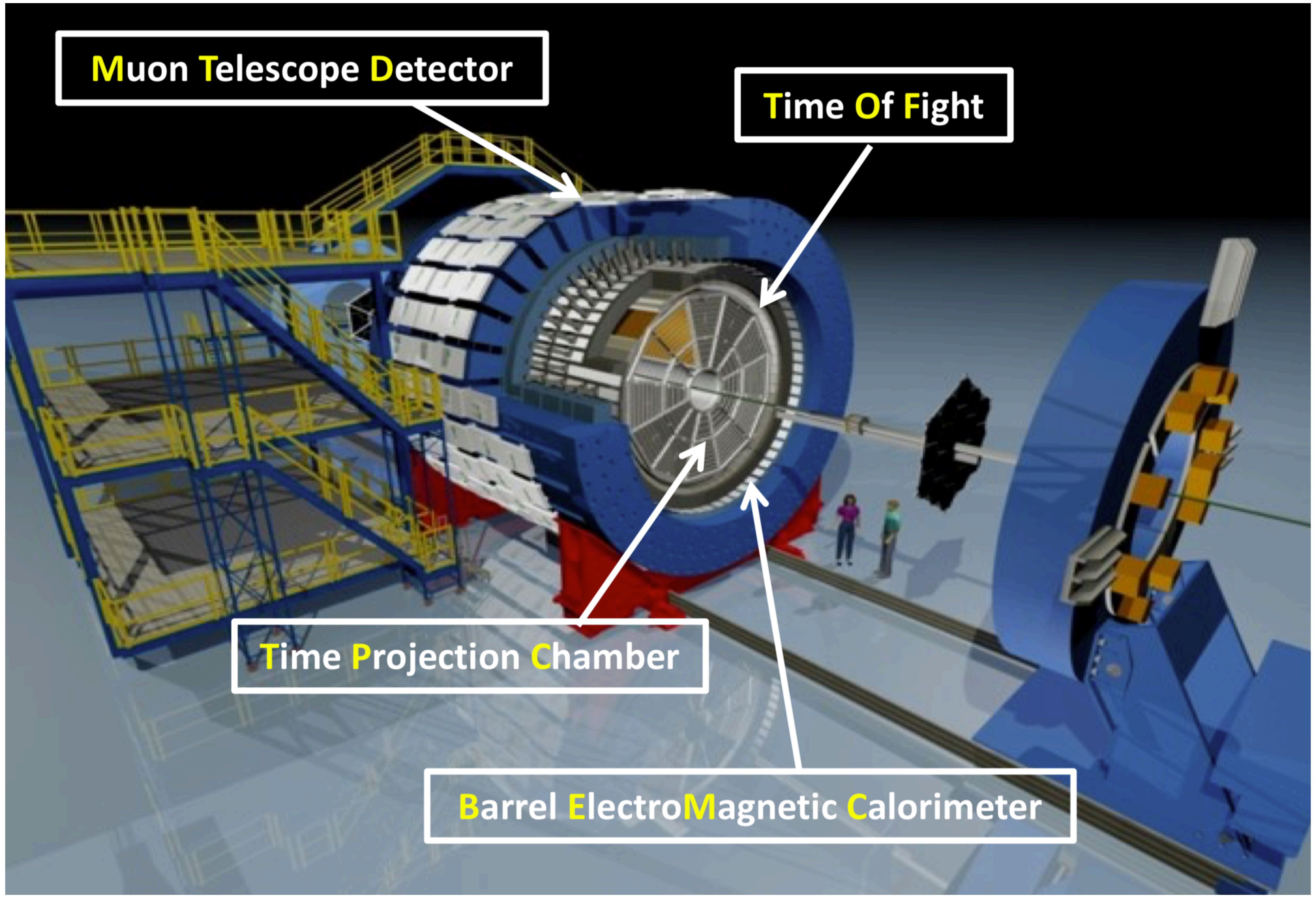


A. Mocsy, EPJ C61 (2009) 705

The Solenoidal Tracker at RHIC

STAR

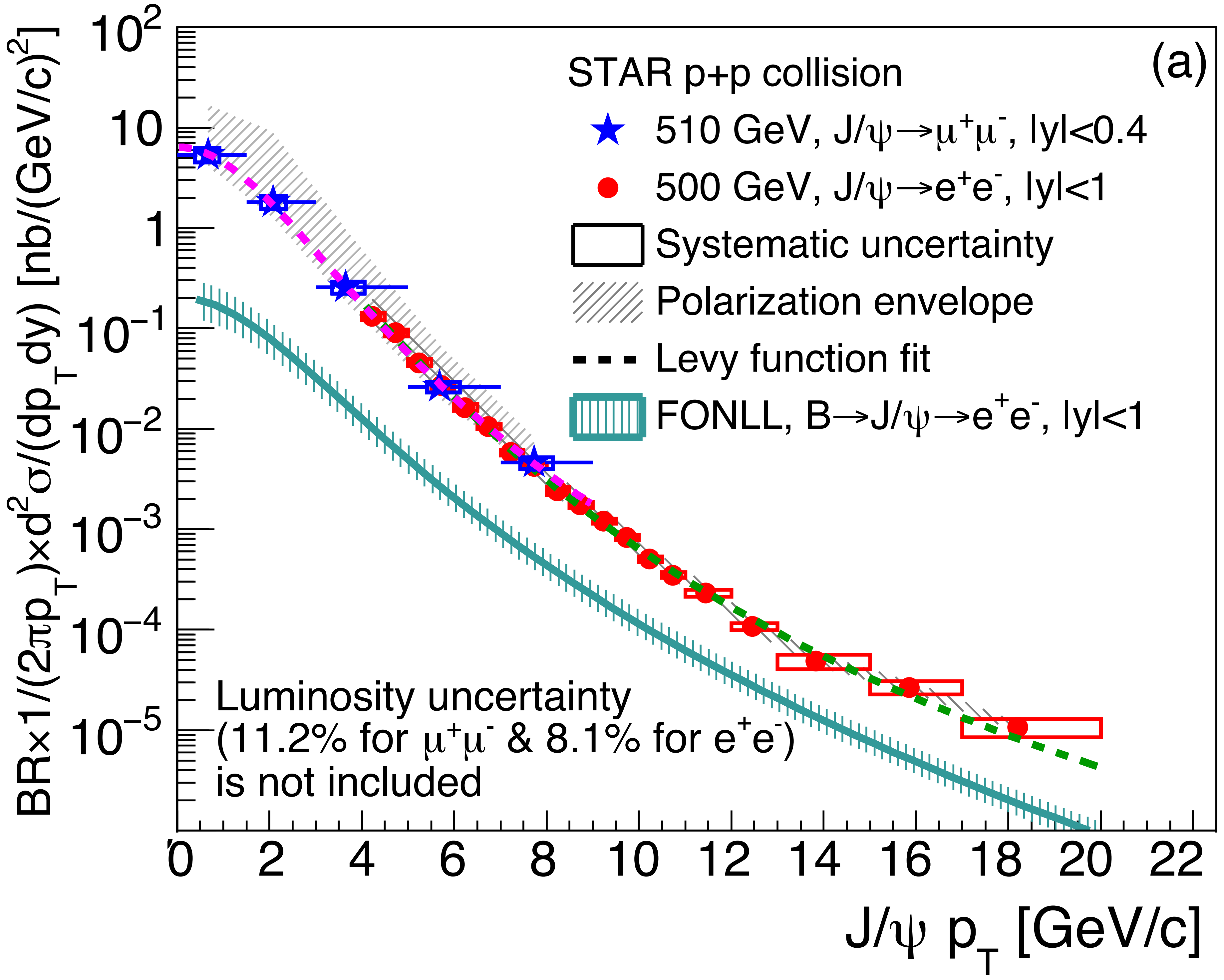
Mid-rapidity coverage : $|\eta| < 1$, $0 < \varphi < 2\pi$

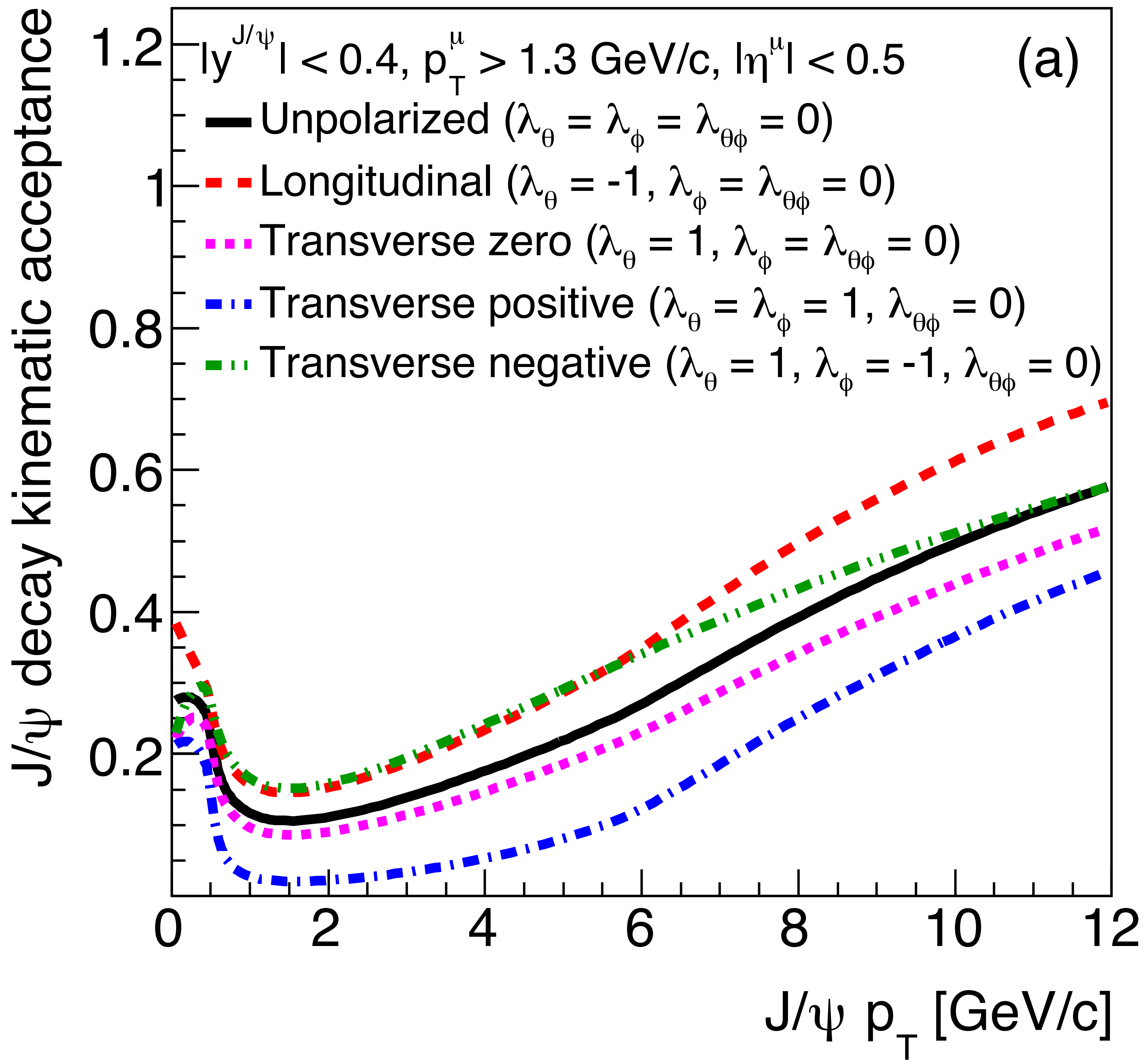


- **TPC**
  - Tracking, PID
- **TOF**
  - Measure time of flight
- **BEMC**
  - Trigger and identification of high-p_T electrons
- **MTD** ($|\eta| < 0.5$, 45% in φ)
  - Dimuon trigger and muon identification
  - Less Bremsstrahlung: helps separate Υ(2S+3S) from Υ(1S)

Inclusive J/ψ in p+p@500/510 GeV

arXiv:1905.06075 submitted to PRD





- **J/ψ production cross-section is precisely measured with a wide p_T range from 0 to 20 GeV/c**
- **Different polarization assumptions are considered to constrain the polarization envelope**

Inclusive J/ψ in p+p@500/510 GeV

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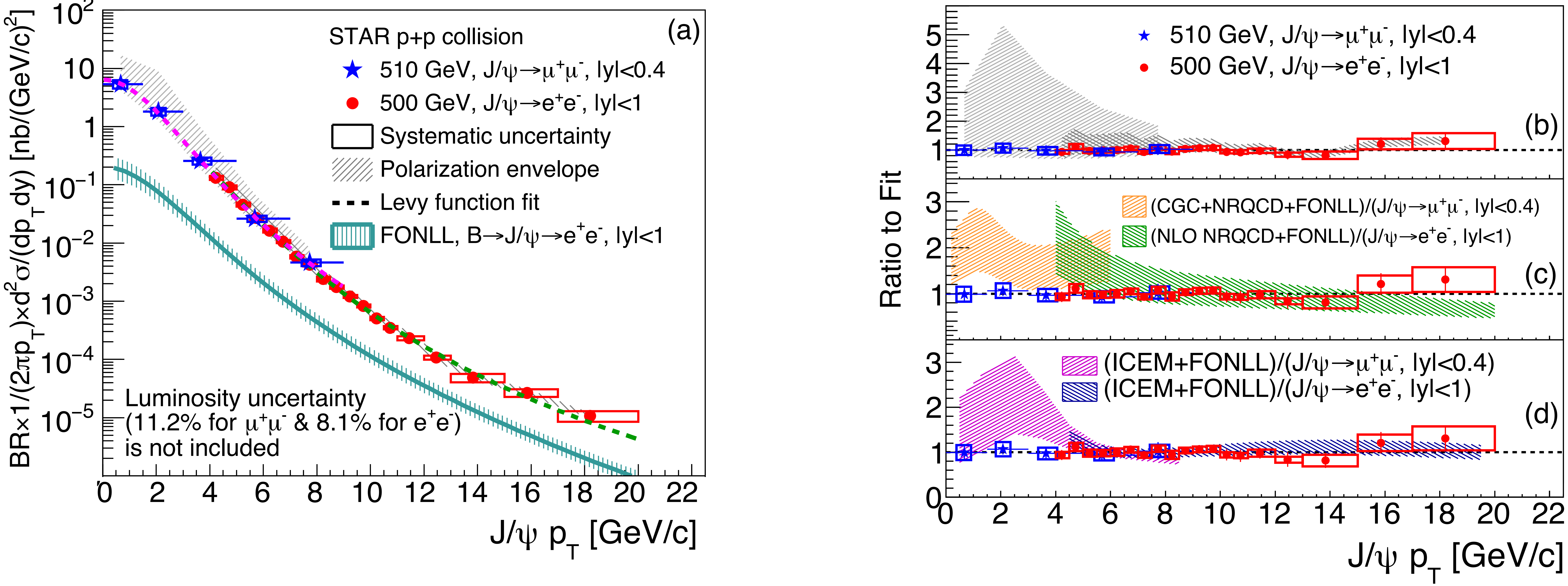
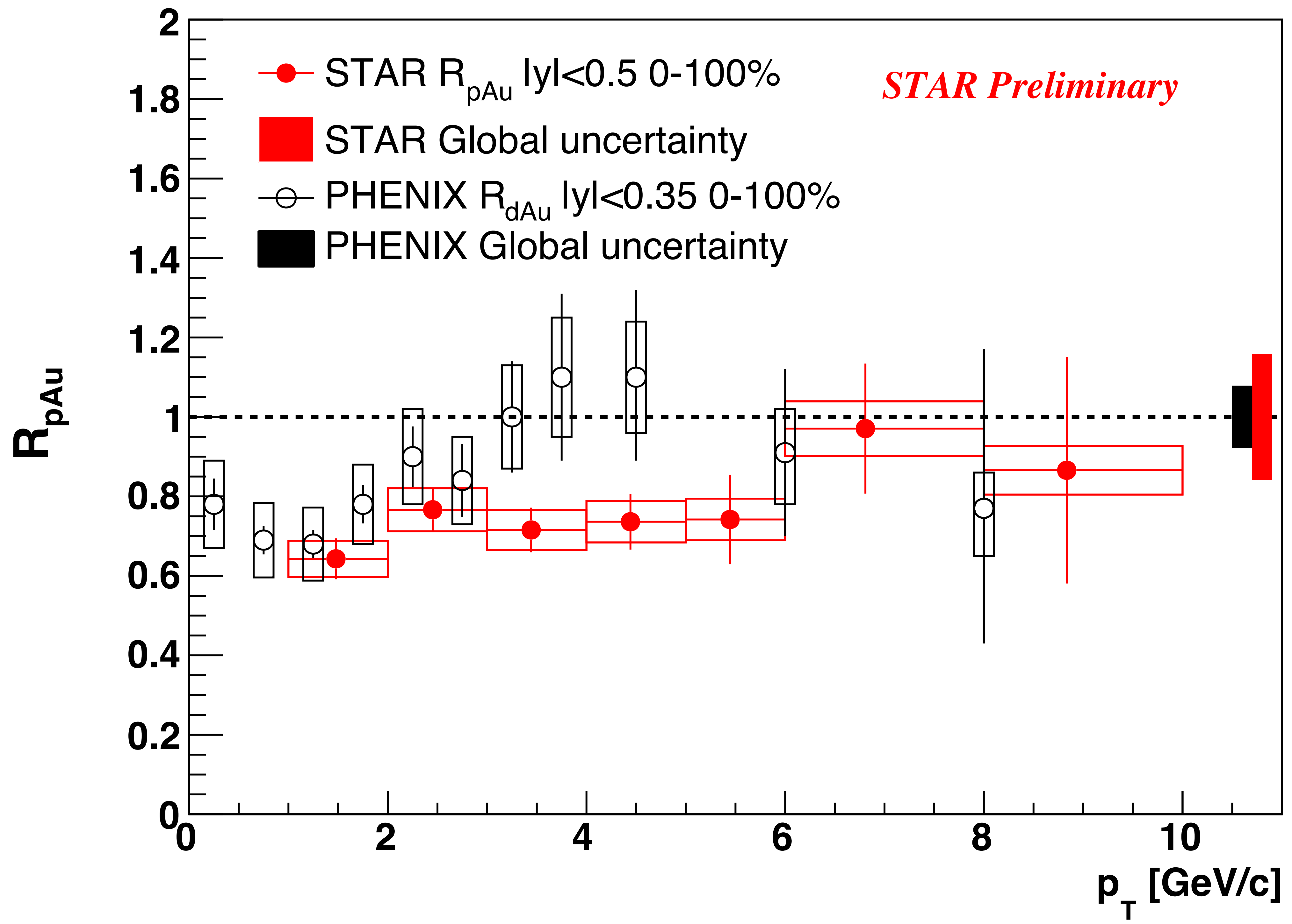


- **J/ψ production cross-section is precisely measured with a wide p_T range from 0 to 20 GeV/c**
- **Different polarization assumptions are considered to constrain the polarization envelope**
- **The calculations from CGC+NRQCD, NLO NRQCD and ICEM, are in reasonable agreement with the data within the polarization envelope.**

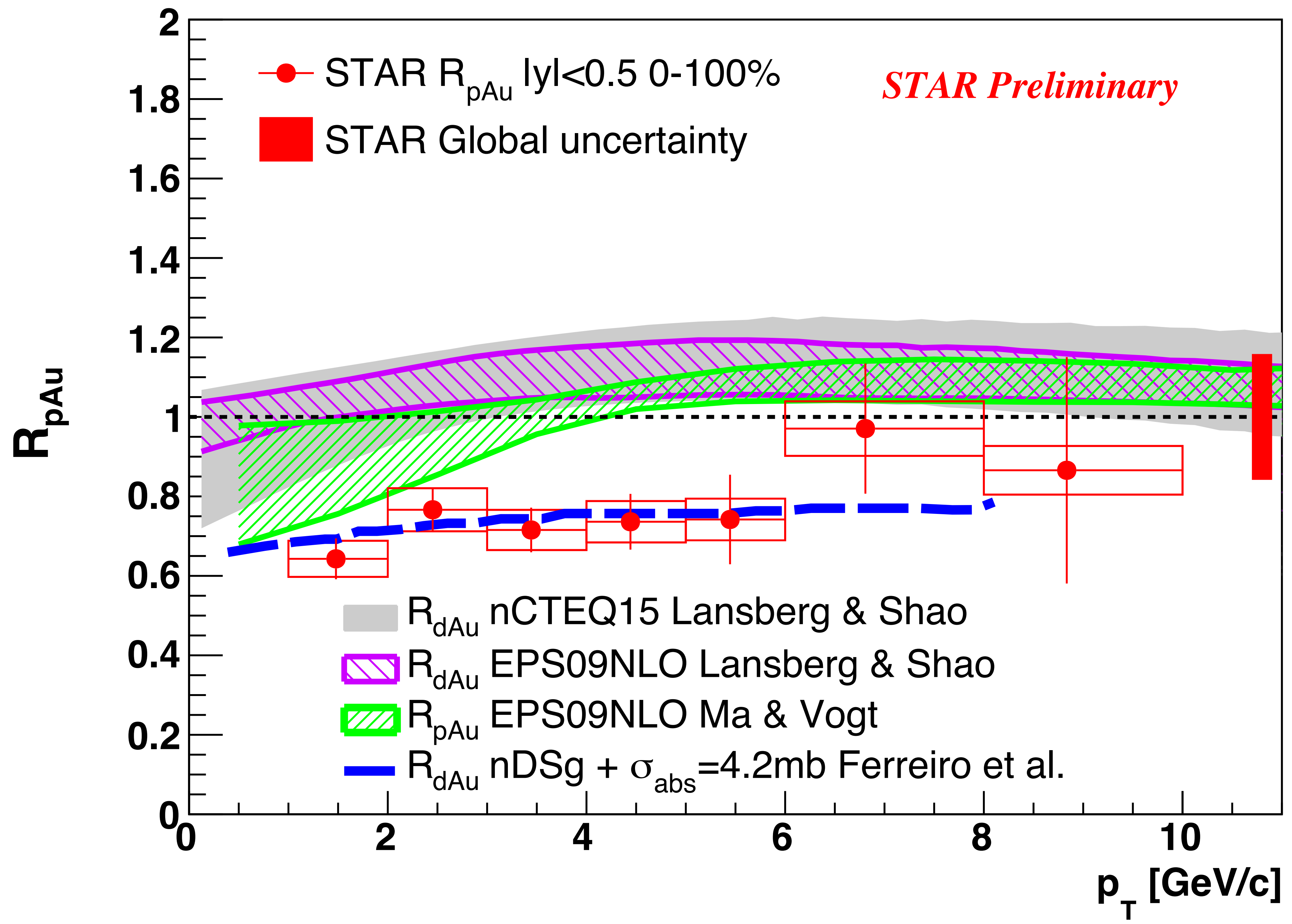
J/ψ R_{pAu} at 200 GeV



PHENIX, PRC 87 (2012) 034903

- R_{pAu} is less than unity at low p_T and is consistent with unity at high p_T ⇒ suppression at low p_T
- R_{pAu} is consistent with R_{dAu} within uncertainties ⇒ similar CNM effects in these collision systems
  – There seems to be difference at $3.5 < p_T < 5$ GeV/c with a significance of 1.4σ

J/ψ R_{pAu} at 200 GeV



EPS09+NLO, Ma & Vogt, Private Comm.

nCTEQ, EPS09+NLO, Lansberg & Shao, Eur. Phys. J. C77 (2017) 1

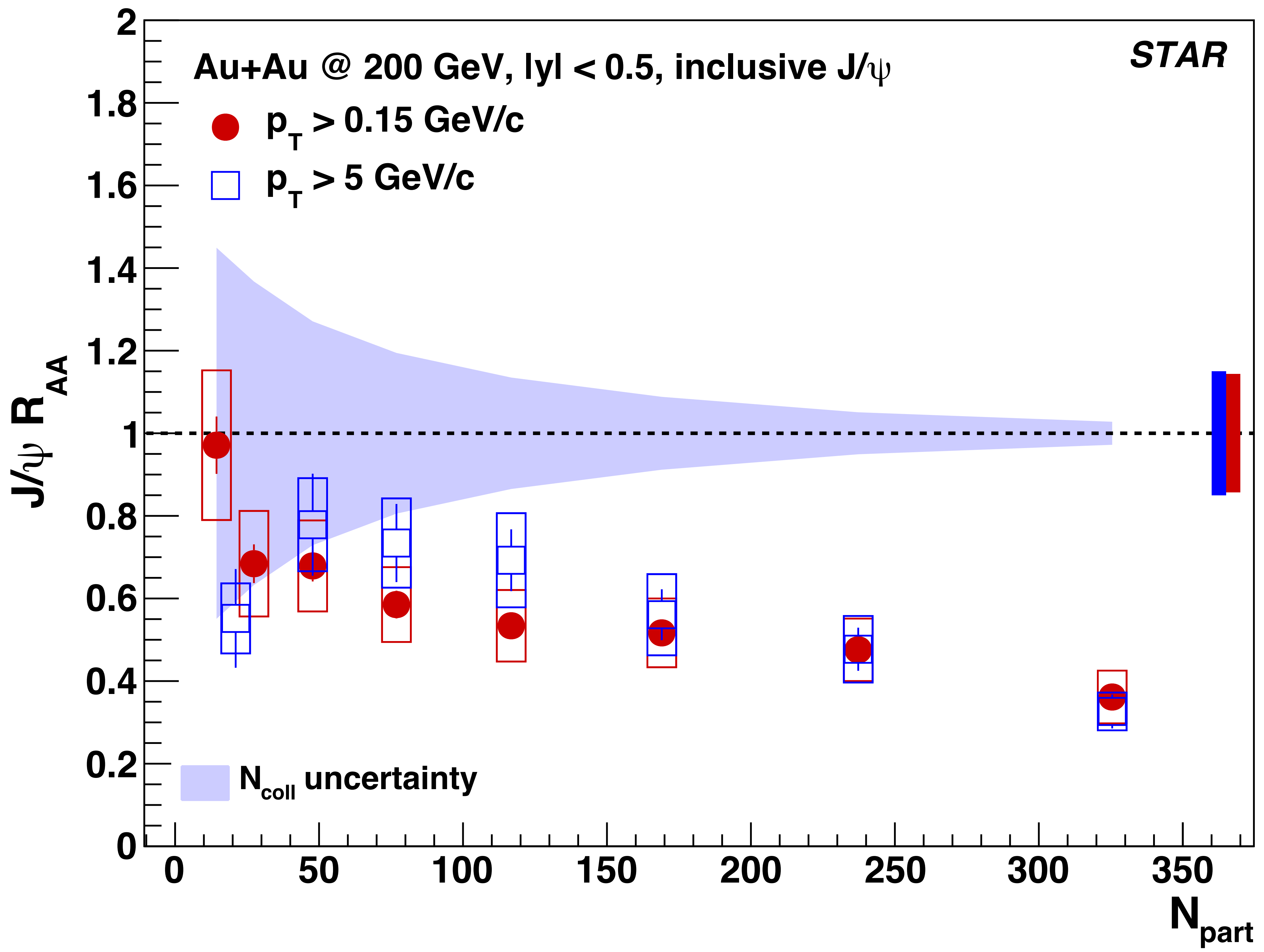
Comp. Phys. Comm. 198 (2016) 238

Comp. Phys. Comm. 184 (2013) 2562

Ferreriro et al., Few Body Syst. 53 (2012) 27

- **Model calculations with only nPDF effects describe the data at high p_T, but underpredicts the suppression at $3.5 < p_T < 5$ GeV/c**
- **Additional nuclear absorption is favored by data**

J/ψ R_{AA} vs. centrality

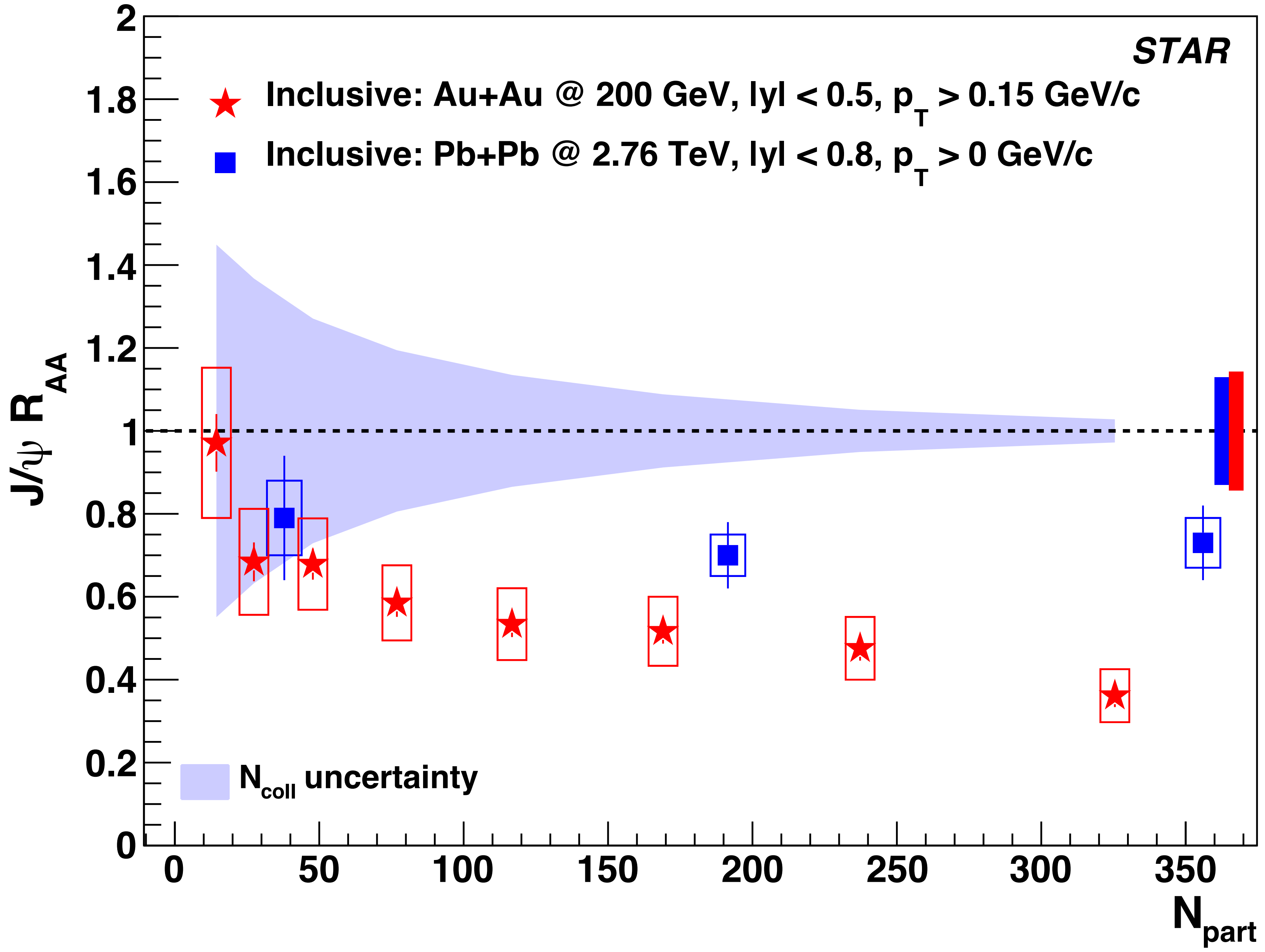


arXiv:1905.13669 submitted to PLB

- **Increasing J/ψ suppression towards central collisions**
- **Central collisions: significant suppression is observed for both low p_T and high p_T (> 5 GeV/c) J/ψ ⇒ interplay of different effects (dissociation, regeneration, CNM, formation time…)**

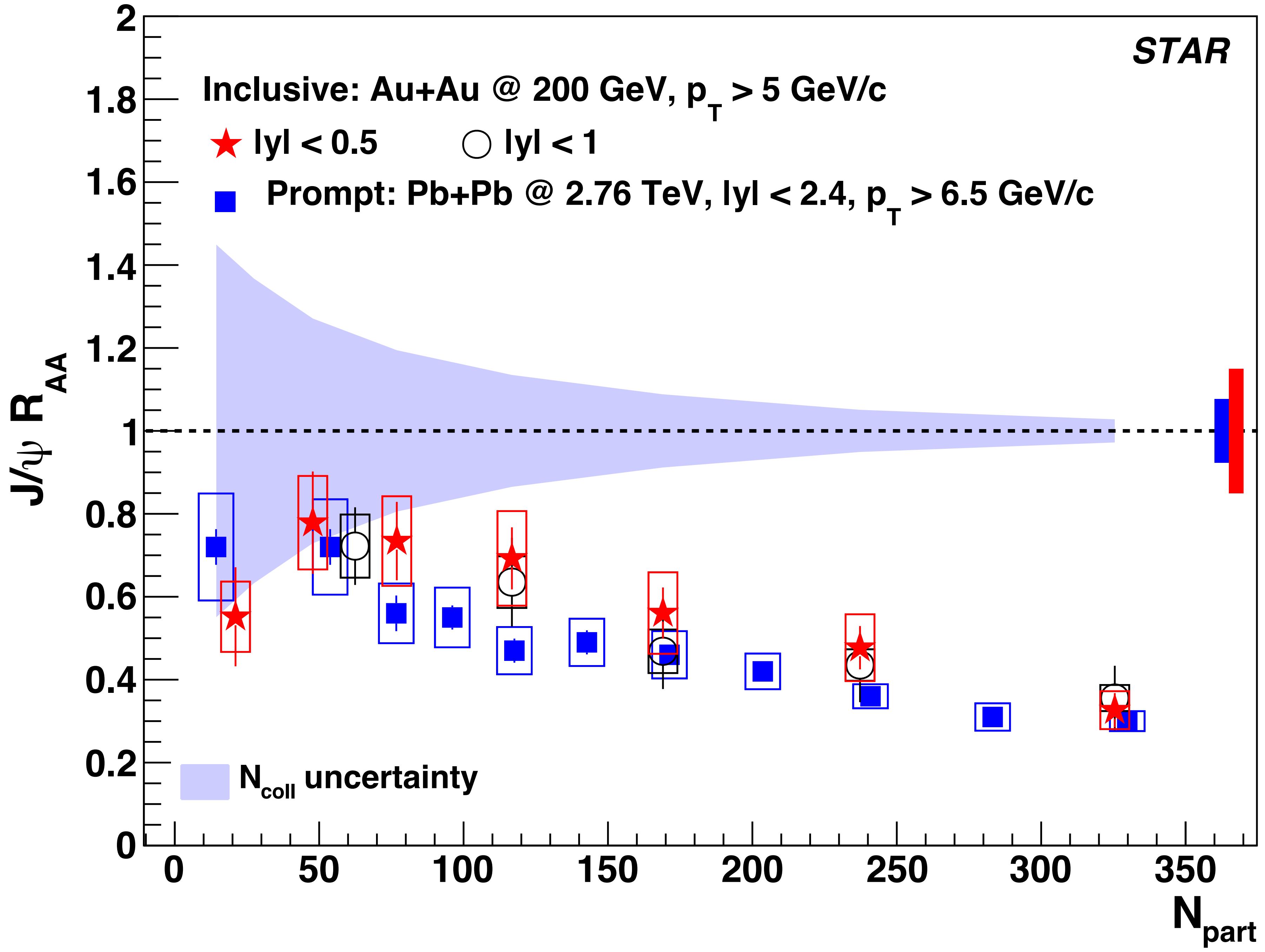
J/ψ R_{AA}: RHIC vs. LHC

p_T > 0.15 GeV/c



p_T > 5 GeV/c

arXiv:1905.13669 submitted to PLB



- **p_T > 0.15 GeV/c: more suppressed at RHIC in semi-central and central collisions ⇒ smaller regeneration contribution due to smaller charm cross-section**
- **p_T > 5 GeV/c: indication of less suppressed at RHIC in semi-central collisions ⇒ lower dissociation rate due to lower temperature**

ALICE JHEP 07 (2015) 051
CMS EPJC 77 (2017) 252

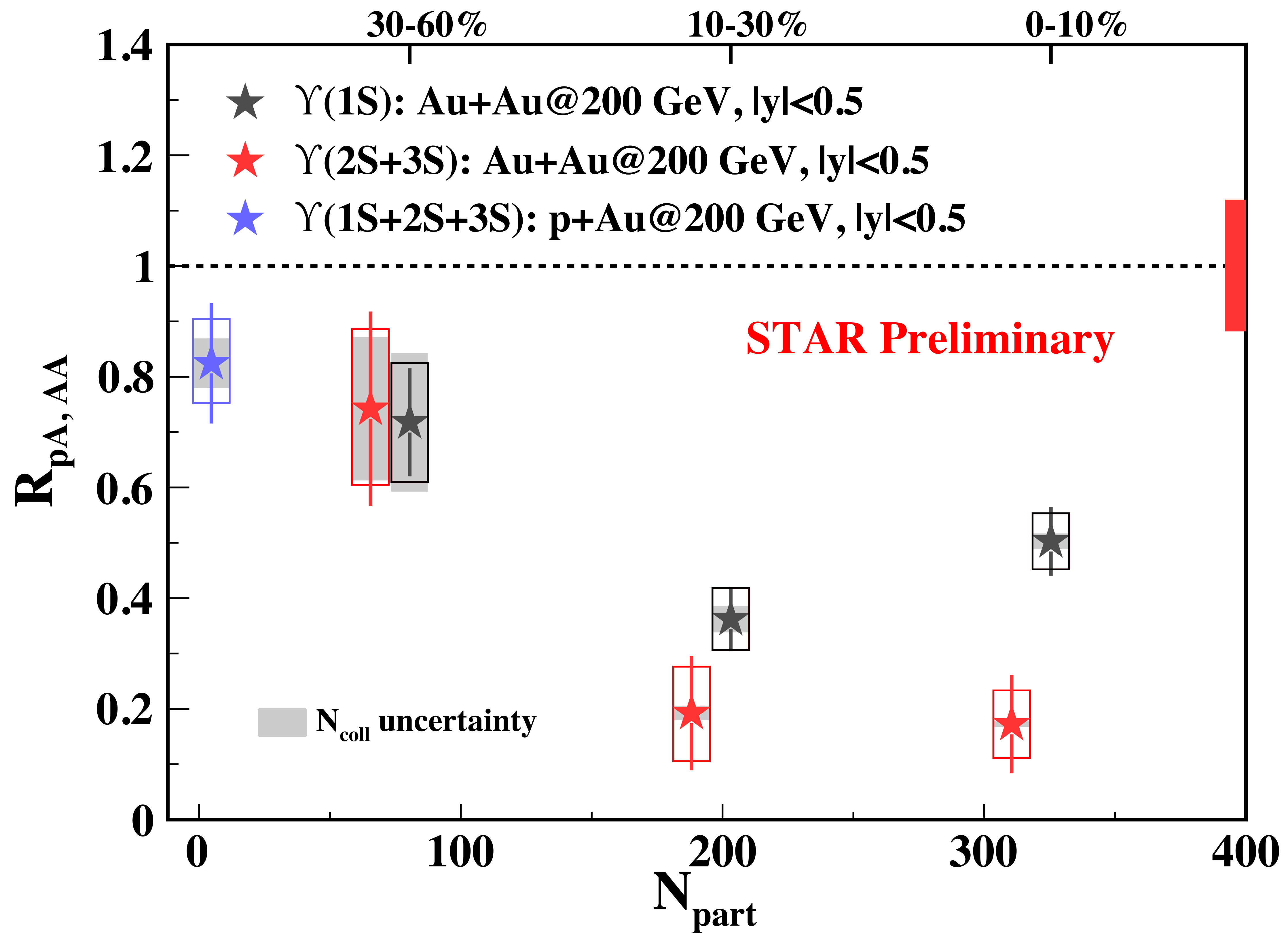
Bottomonium

- **Small production cross-section at RHIC energy**
- **A cleaner probe at RHIC**
  - ✓ Regeneration is smaller compared to J/ψ

    A. Emerick, X. Zhao and R. Rapp: EPJ A48 (2012) 72
    X. Du, M. He, and R. Rapp: PRC 96 (2017) 054901
  - ✓ Co-mover absorption for Υ(1S) is expected to be small

    Z. Lin and C. Ko: PLB 503 (2001) 104

ϒ suppression at RHIC



- **Improved precision of ϒ measurements**
  - Combining 2016 data with those taken in 2014 and 2011 (di-muon and di-electron results are combined)

p+Au:

ϒ(1S+2S+3S)

- **Indicates CNM effects**

Au+Au:

ϒ(1S):

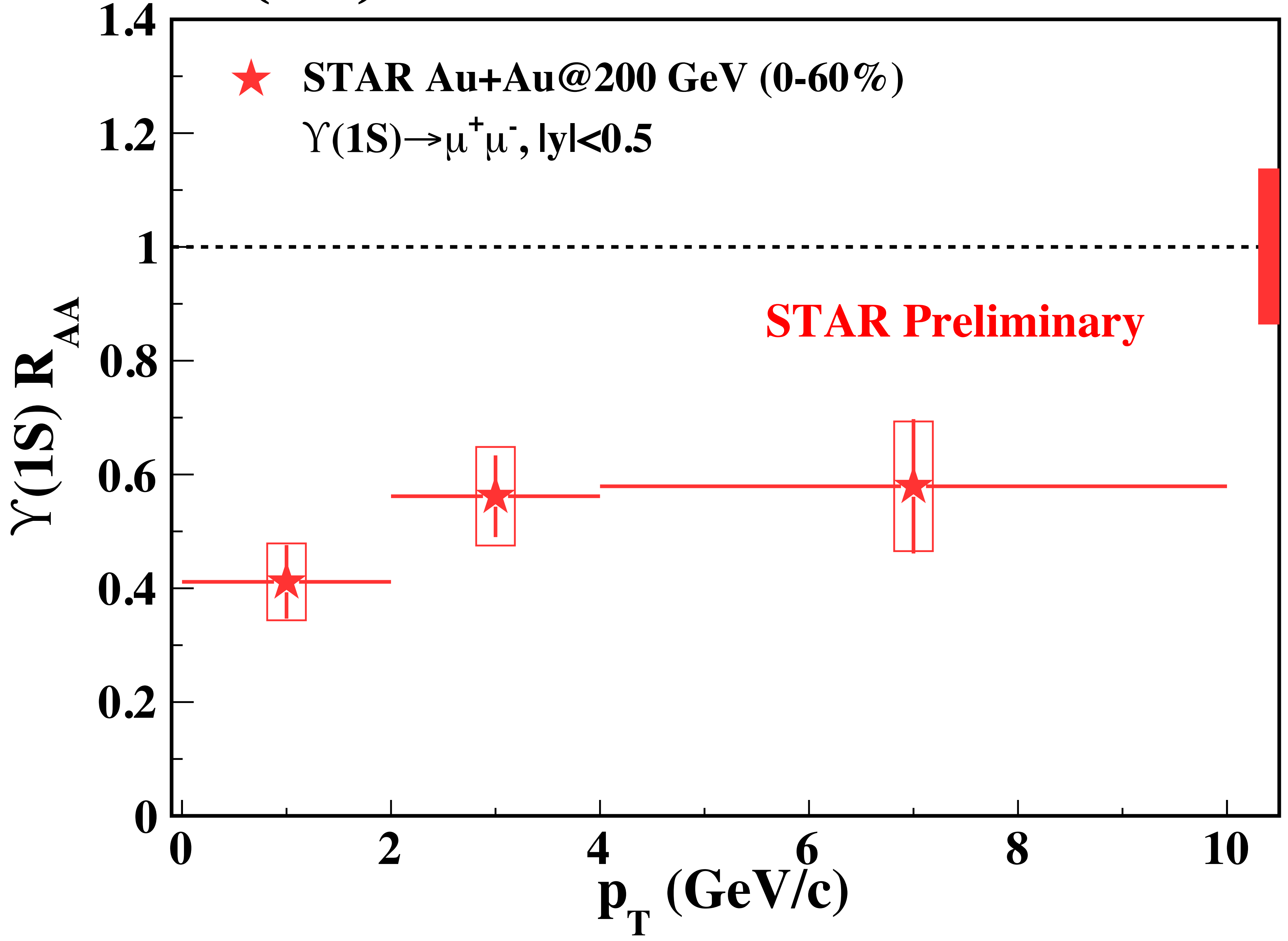
- **Stronger suppression towards central collisions**

ϒ(2S+3S):

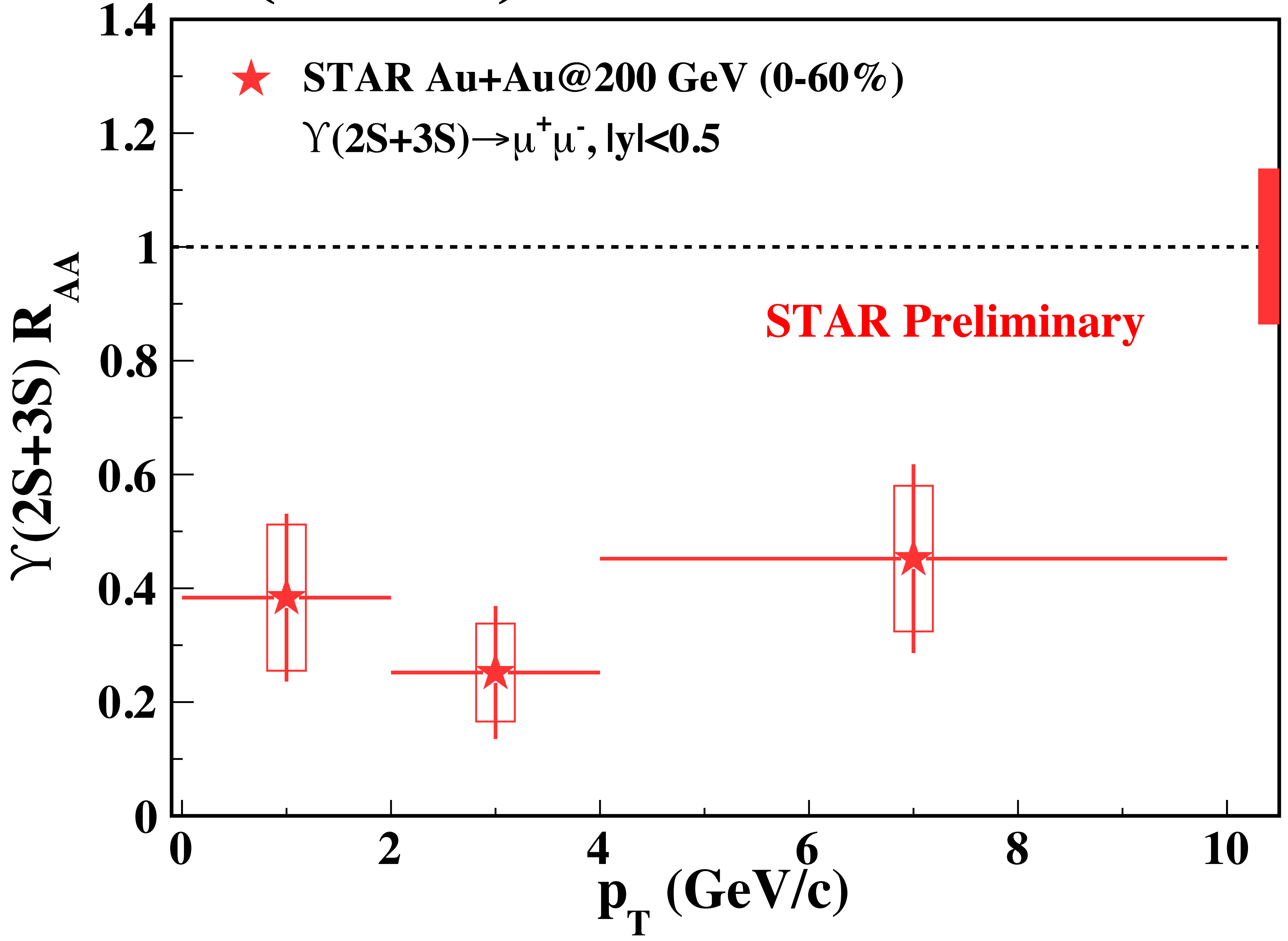
- **Stronger suppression in more central collisions**
- **More suppressed than ϒ(1S) in 0-10% central collisions ⇒ sequential suppression**

Υ suppression at RHIC

Υ(1S):



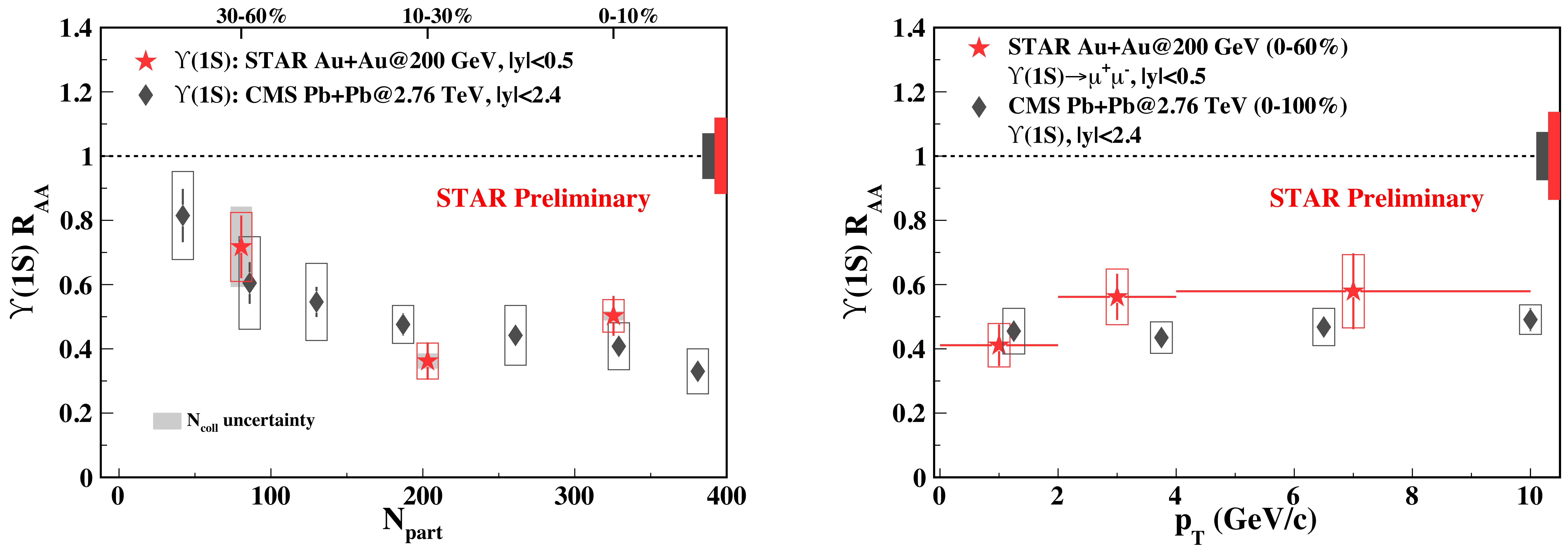
Υ(2S+3S):



Υ(1S) and Υ(2S+3S):

- No significant p_T dependence

Υ(1S) suppression: RHIC vs. LHC

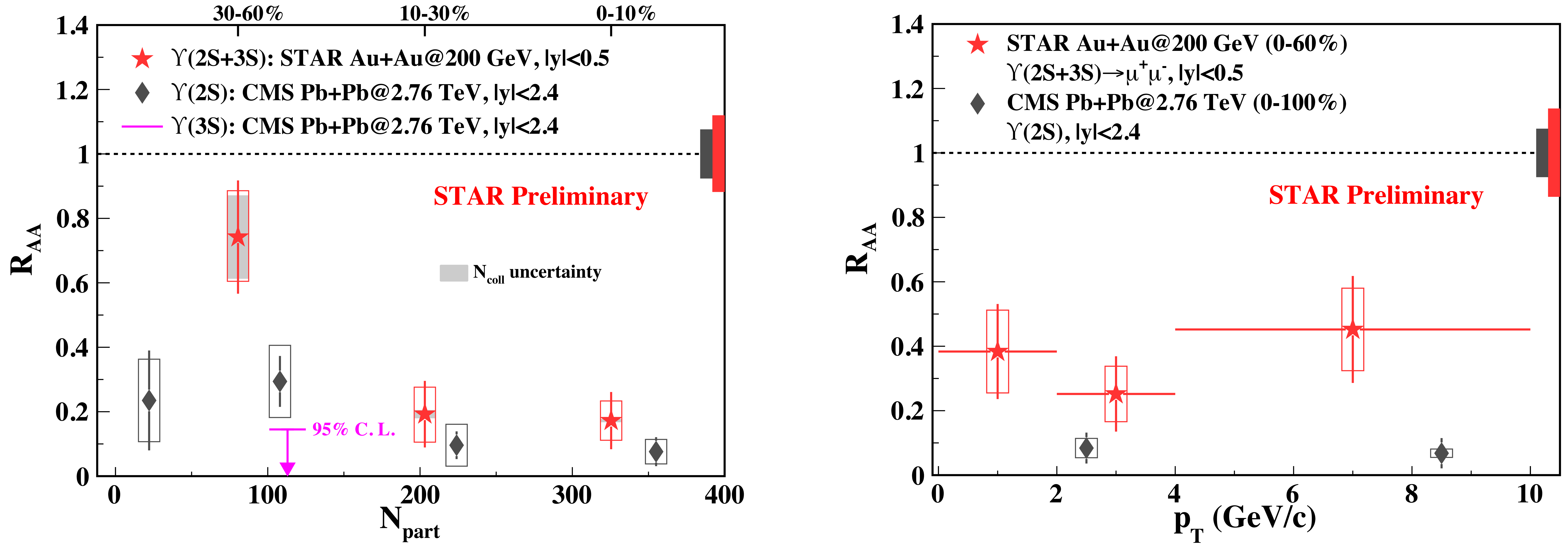


CMS, PLB 770 (2017) 357

Υ(1S) suppression is similar at RHIC and the LHC:

- **Similar CNM effects (~ 20-30%)**
- **Contribution of highly suppressed excited Υ states**

ϒ(2S+3S) suppression: RHIC vs. LHC

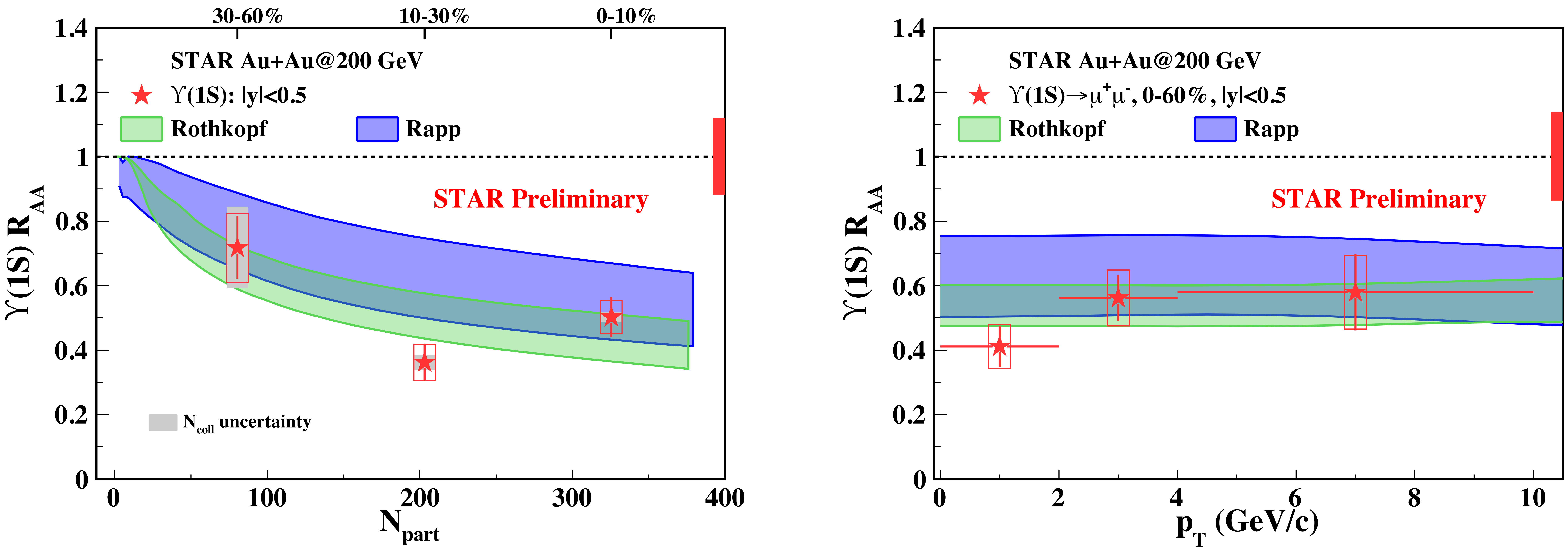


CMS, PLB 770 (2017) 357

ϒ(2S+3S):

- **Indication of less suppression at RHIC than at the LHC in peripheral collisions**

ϒ(1S) suppression: data vs. models



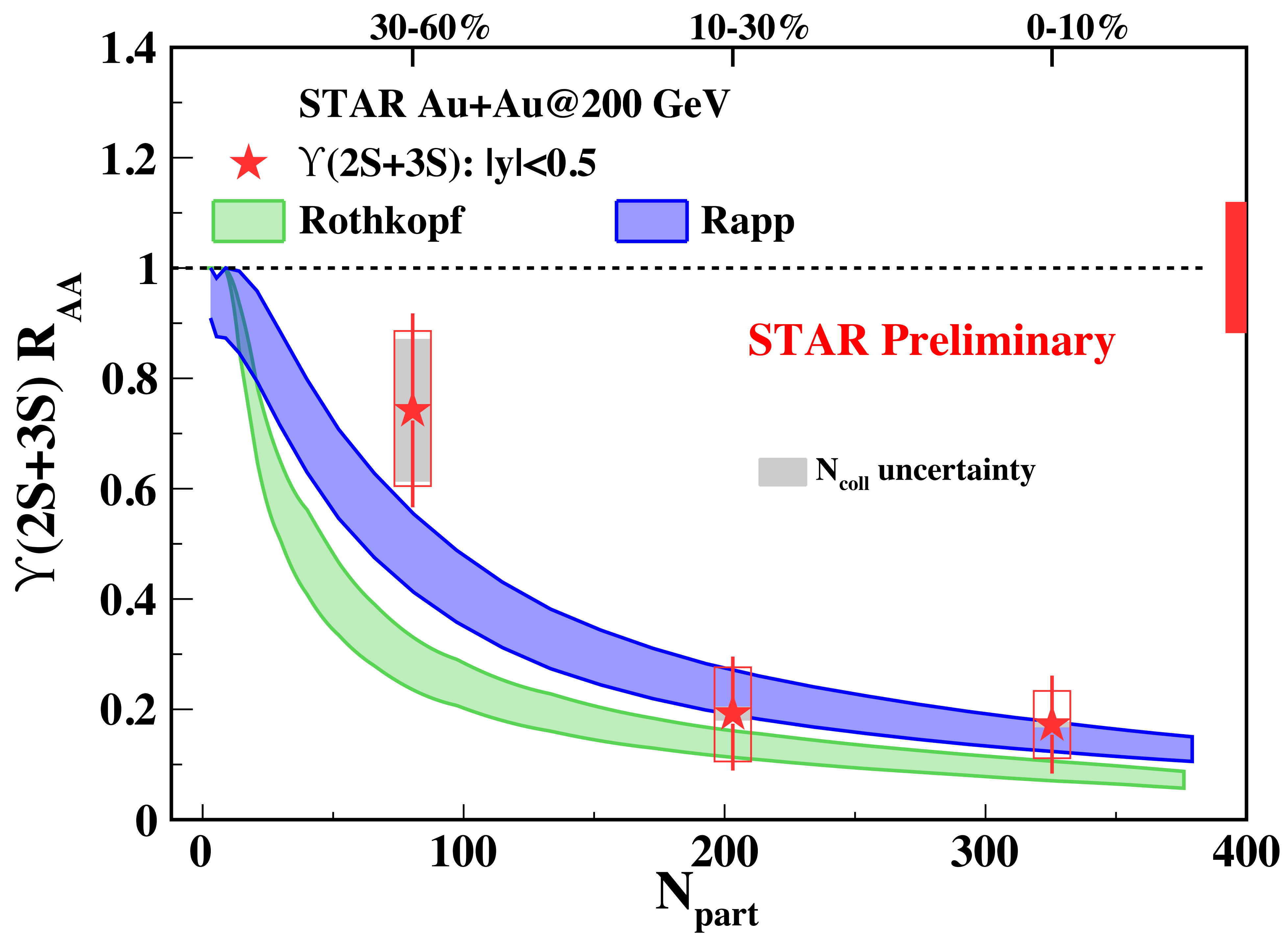
B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)

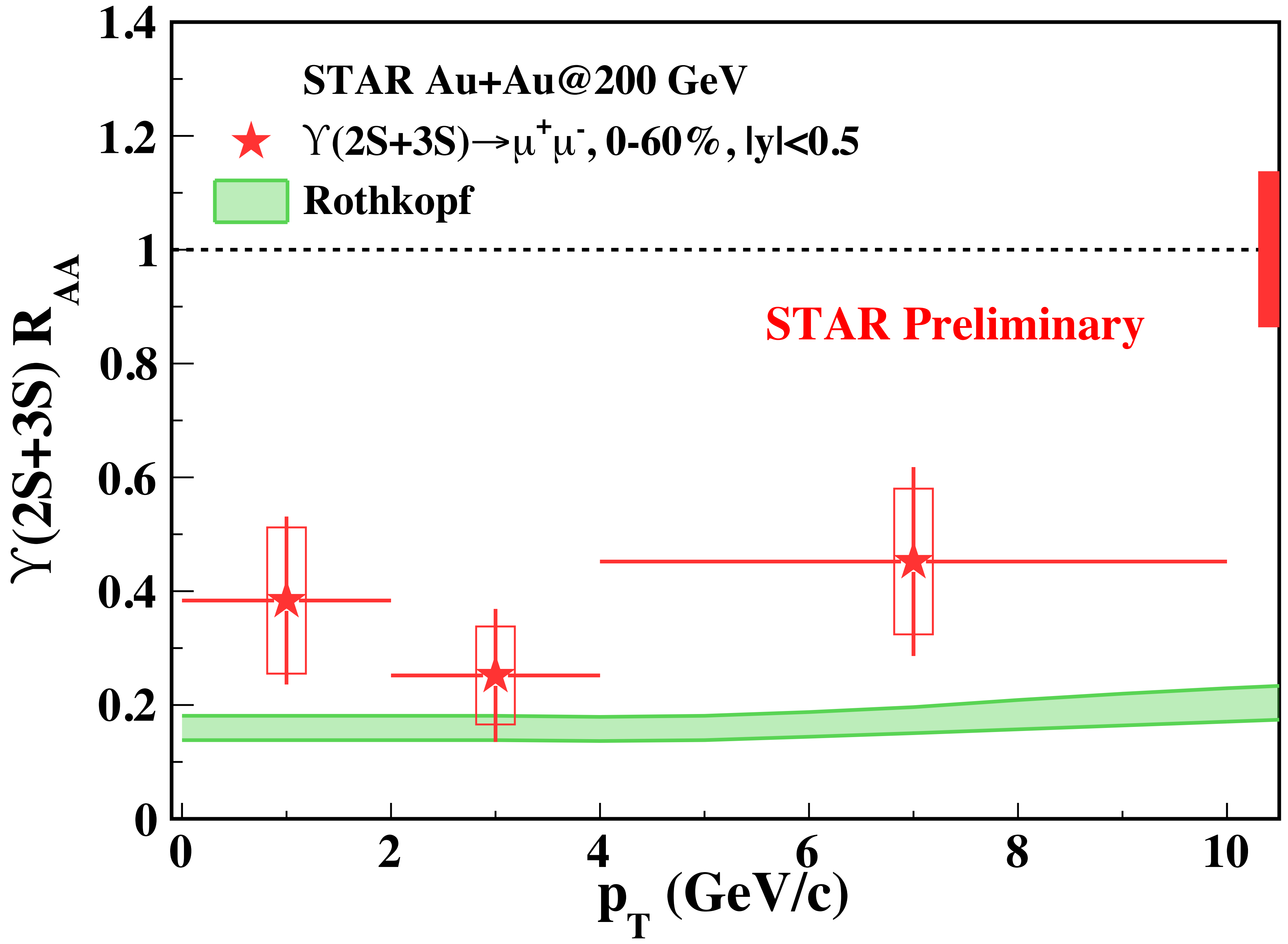
X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)

Both models show good agreement with data:

- **Rothkopf: Complex potential (lattice QCD); No CNM or regeneration effects**
- **Rapp: T-dependent binding energy; Includes CNM and regeneration effects**

Υ(2S+3S) suppression: data vs. models





- Rapp model describes data
- Rothkopf model calculation is lower than data in 30-60%

Summary

- p+p collisions
  - Models describe the quarkonium production cross-section reasonably well (e.g. CEM, NRQCD, etc)
- p+Au collisions
  - J/ψ R_{pA} favors additional nuclear absorption on top of nPDF effect
  - Υ(1S+2S+3S) R_{pA}: indication of Υ suppression due to CNM effects
- Au+Au collisions

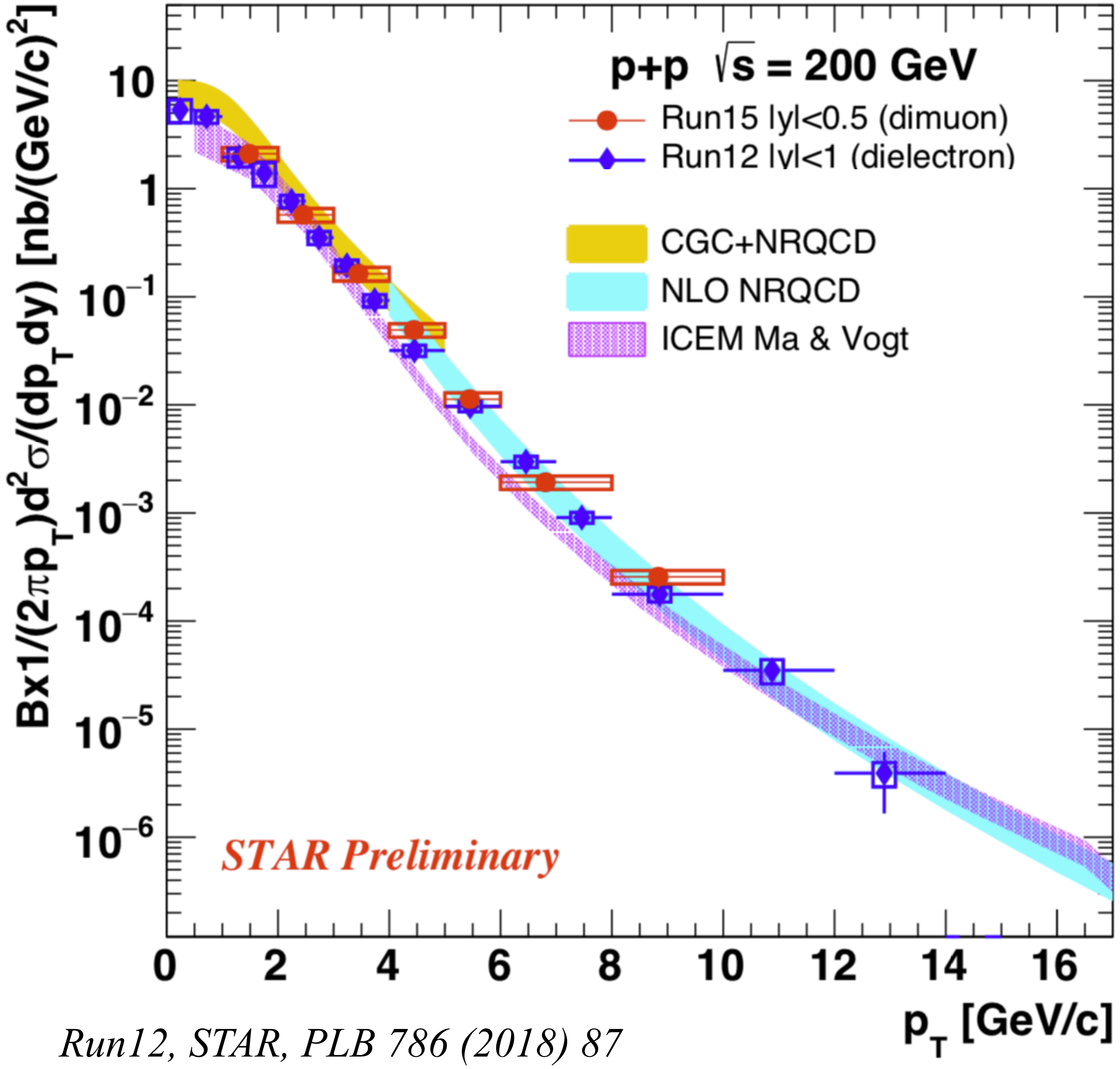
  J/ψ:
  - Increasing J/ψ suppression at high p_T (> 5 GeV/c) towards central collisions ⇒ *dissociation*

  Υ(1S):
  - Indication of increasing suppression towards central collisions
  - Similar suppression as at the LHC
  - Model predictions are consistent with data

  Υ(2S+3S):
  - More suppressed than Υ(1S) in 0-10% central collisions ⇒ *sequential suppression*

Backup

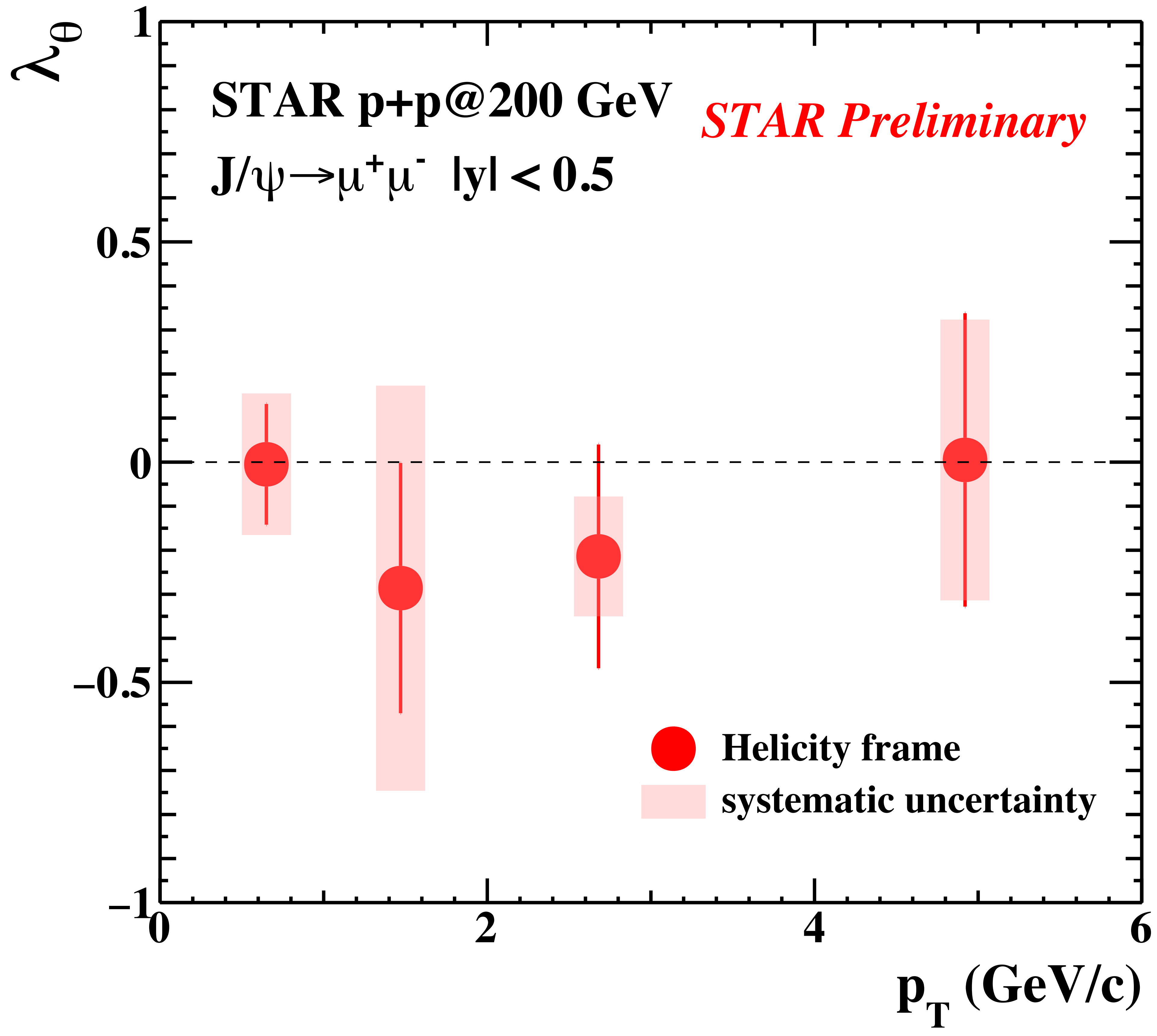
Inclusive J/ψ in p+p@200 GeV



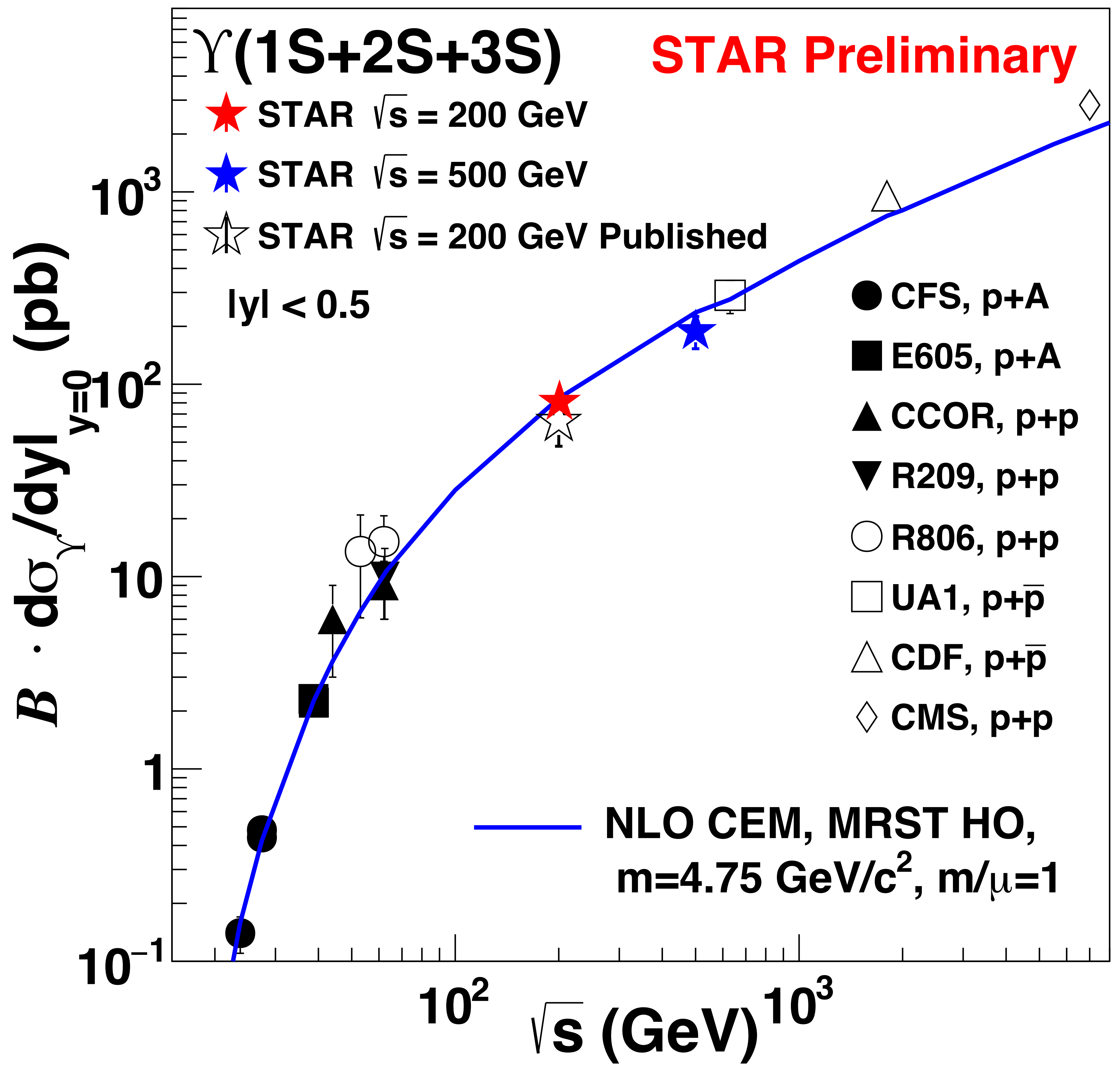
Run12, STAR, PLB 786 (2018) 87
CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029
S. Digal, P. Petreczky & H. Satz, PRD 64 (2001) 094015

- **Inclusive J/ψ cross-section is measured in $0 < p_T < 14$ GeV/c**
  - **Feed-down contribution from excited charmonium states is about 40%**
  - **Feed-down contribution from bottom hadrons is predicted to be approximately ~10-25% in $4 < p_T < 14$ GeV/c**
- **CGC+NRQCD (prompt J/ψ) calculations are consistent with the data within uncertainties. However, the data are close to the lower uncertainty boundary of the theoretical calculation**
- **NLO NRQCD (prompt J/ψ) describes the data reasonably well in $4 < p_T < 14$ GeV/c**
- **Improved CEM model (direct J/ψ) describes data well at low p_T, but underpredicts data in 3.5 – 10 GeV/c**

J/ψ polarization in p+p Collisions



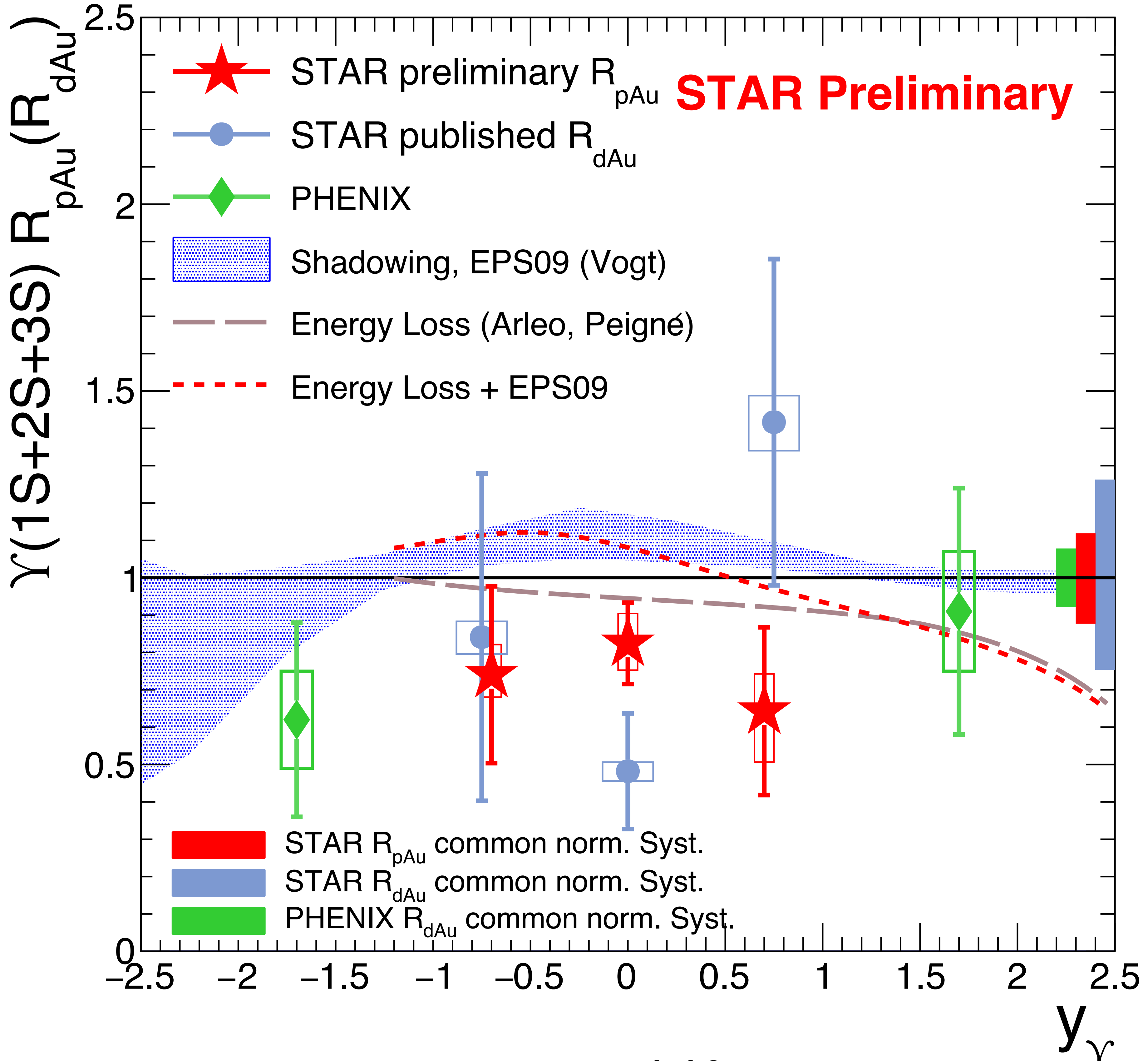
Υ cross-section in p+p collisions



p+p@200 GeV: $\sigma = 81 \pm 5(\text{stat.}) \pm 8(\text{syst.})$ pb

- Baseline for p+A and A+A collisions with improved precision
- Consistent with the Color Evaporation Model (CEM) prediction

Υ(1S+2S+3S) R_{pAu} at 200 GeV



p+Au@200 GeV: $R_{pAu} = 0.82 \pm 0.10(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{syst.}) \pm 0.10\,(\text{global})$

- **Indicates CNM effects**
- **Additional suppression mechanism beyond nPDF effects seems to be needed**