U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

Overview of recent quarkonium results from the STAR collaboration

Rongrong Ma (BNL)

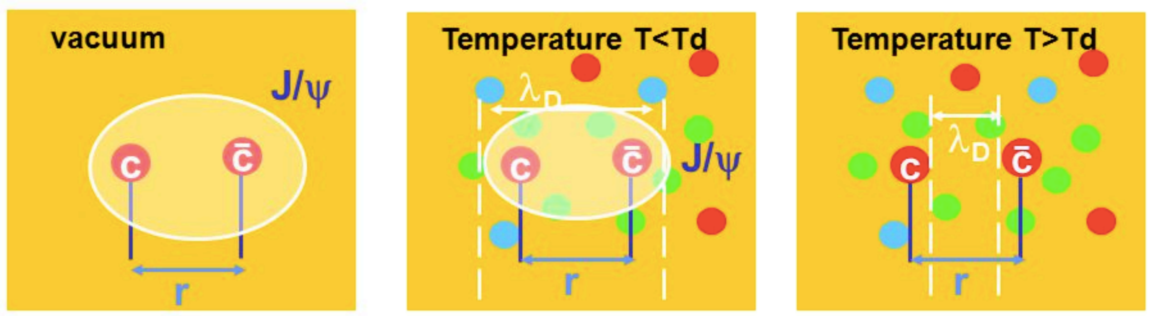
Workshop on Heavy Flavor Production in High Energy Collisions

Oct. 30 - Nov. 1, 2017, Lawrence Berkeley National Laboratory

The promise

- **Evidence of deconfinement**: quark-antiquark potential is color-screened by surrounding partons → *dissociation*
  - **J/ψ suppression was proposed as a direct proof of QGP formation**

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



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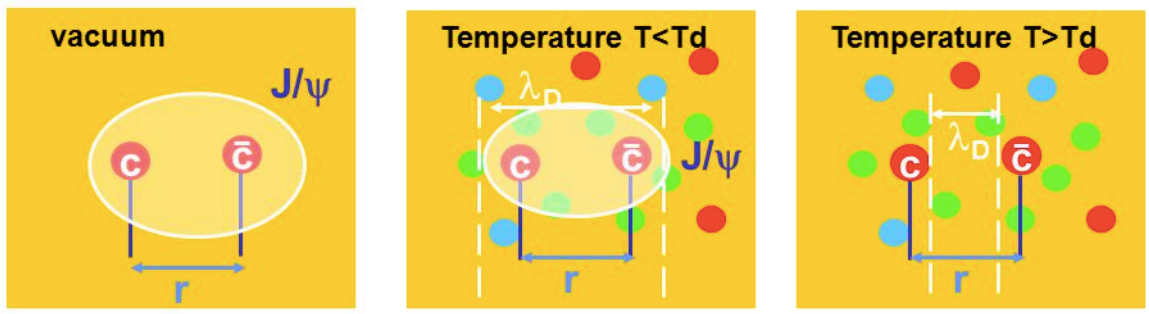
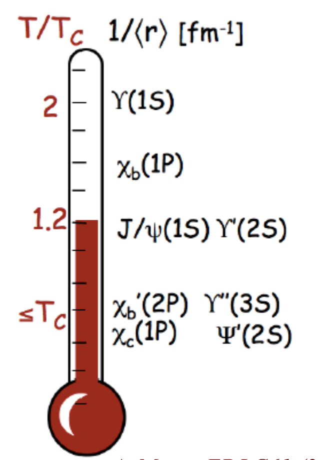


$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

- **Thermometer**: different quarkonium states of different binding energies dissociate at different temperatures → *sequential melting*

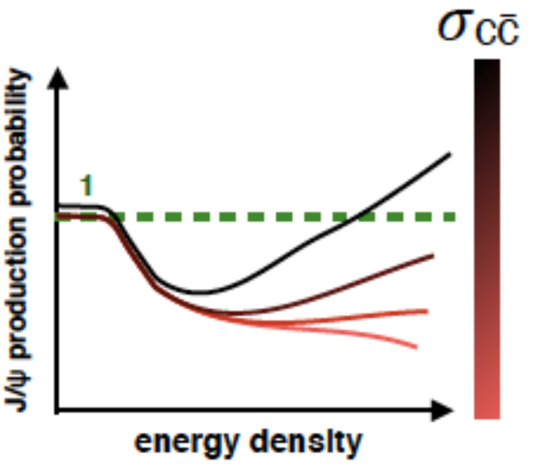


A. Mocsy EPJ C61 (2009) 705

Not so fast

Hot medium effects

- Regeneration
  - ~10 cc pairs/central event at 200 GeV
  - Much smaller effect for bb
- Medium-induced energy loss
  - Color-octet states
- Formation time



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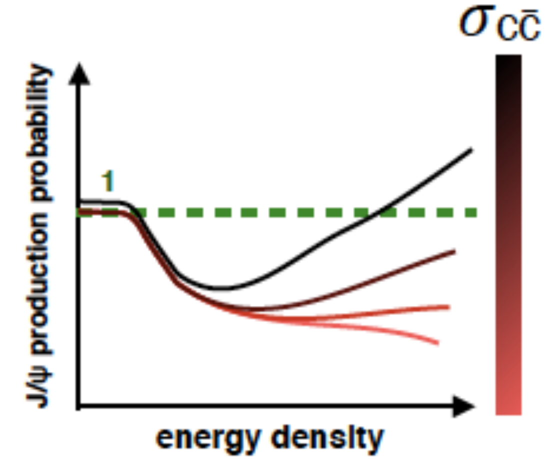
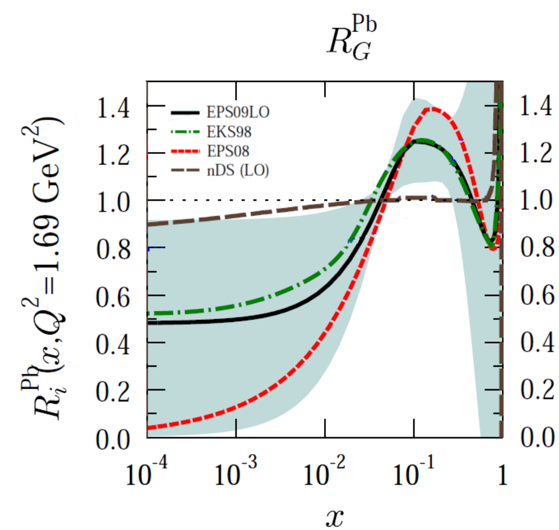


Cold nuclear matter effects (CNM)

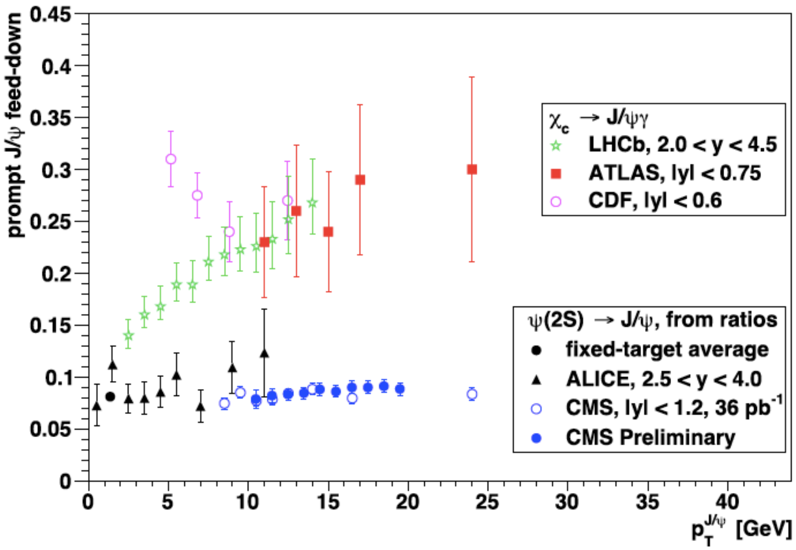
- Nuclear PDF: shadowing/anti-shadowing
- Coherent energy loss
- Nuclear absorption
- Interact with co-movers



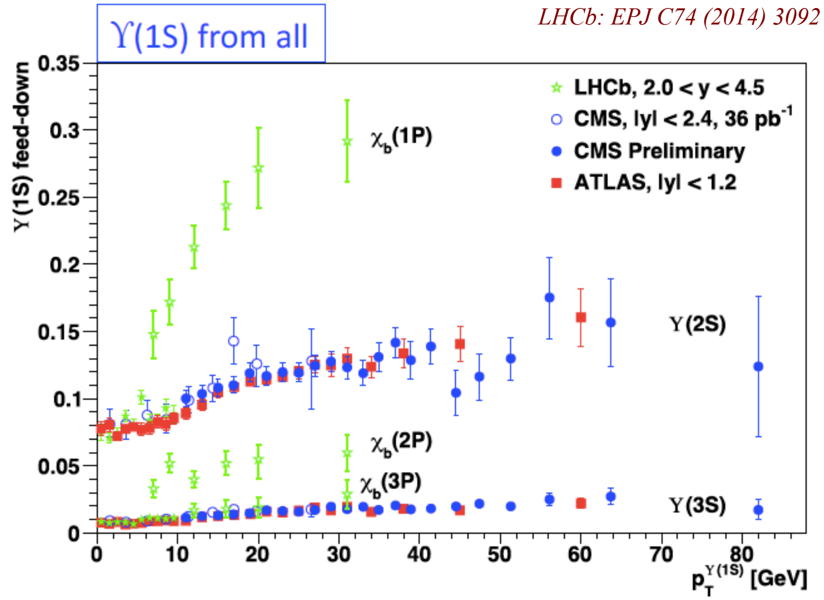
E.G. Ferreiro PRC 81 (2010) 064911

And the feed-down contribution

Woehri@Quarkonia'14



LHCb: EPJ C74 (2014) 3092

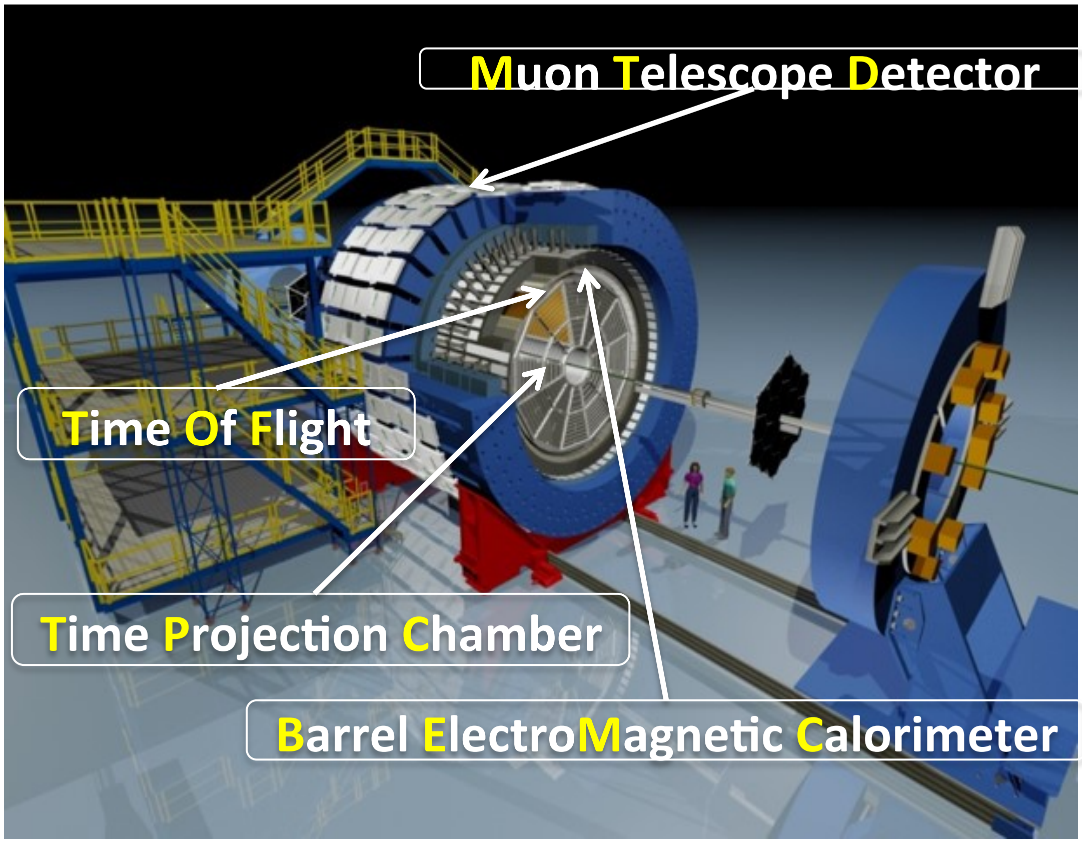


J/ψ feed-down	
χ_c	10-30% (vs. p_T)
$\psi(2S)$	~ 8%
B-hadron	0-50% (vs. p_T, $\sqrt{s}$)

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

The Solenoid Tracker At RHIC

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

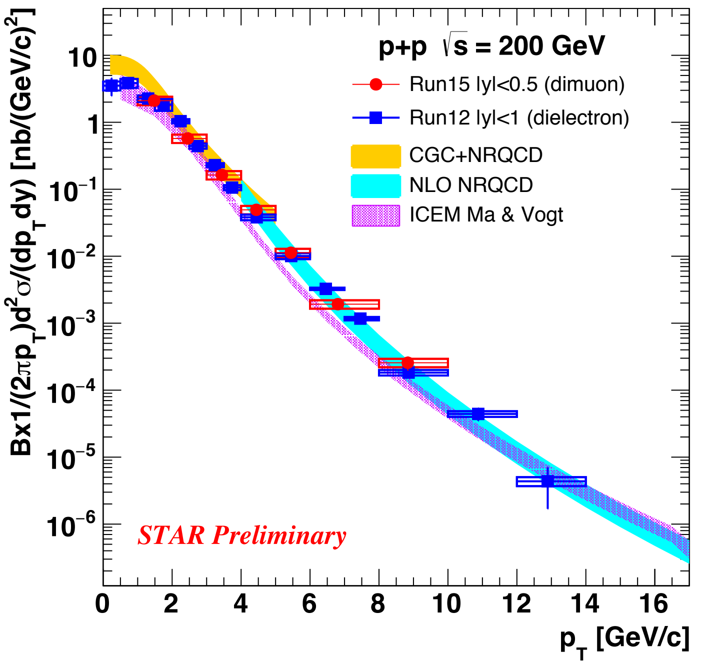


- **TPC**: measure momentum and energy loss
- **TOF**: measure particles' flight time to enhance PID at low p_T
- **BEMC**: trigger on and identify high-p_T electrons
- **MTD**: trigger on and identify muons
  - $|\eta| < 0.5$, $\varphi \sim 45\%$
  - $p_T >\sim 1.0$ GeV/c
  - Less bremsstrahlung

Charmonium

Inclusive J/ψ in p+p collisions

CGC+NRQCD: Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD: Shao et al., JHEP 05 (2015) 103
ICEM: Ma & Vogt, PRD 94 (2016) 114029



- p+p: inclusive J/ψ cross-section measured in $0 < p_T < 14$ GeV/c
  - CGC+NRQCD & NLO NRQCD (prompt) agree with data above 1 GeV/c
  - Improved CEM (direct) is below data in 3.5 – 12 GeV/c
  - *B-hadron feed-down needs to be taken into account*

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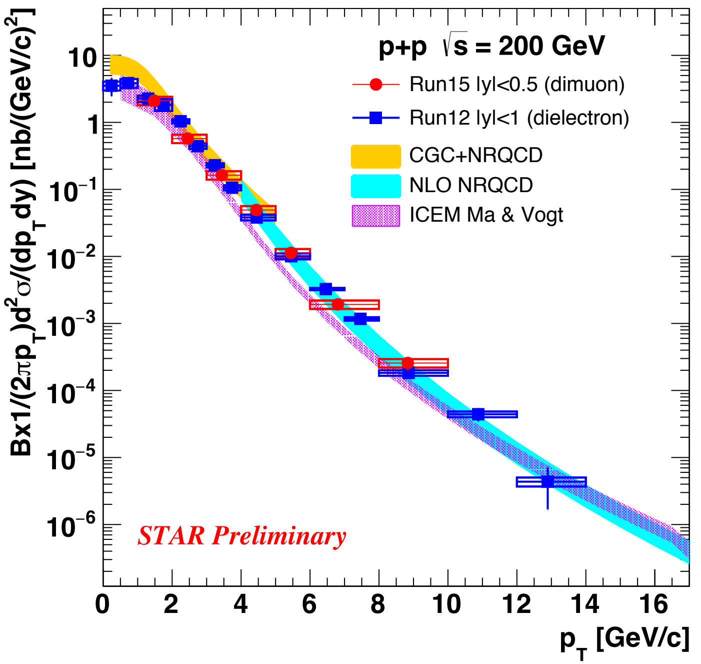

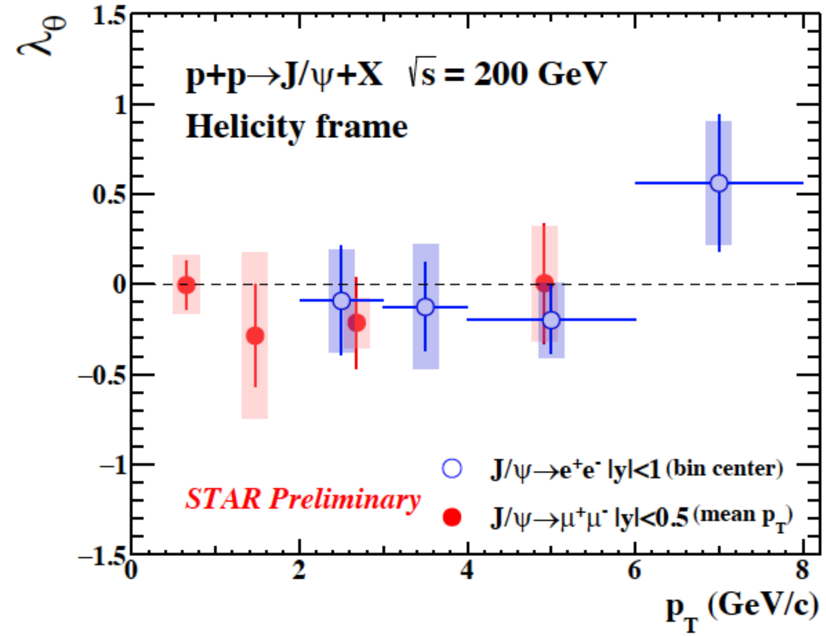

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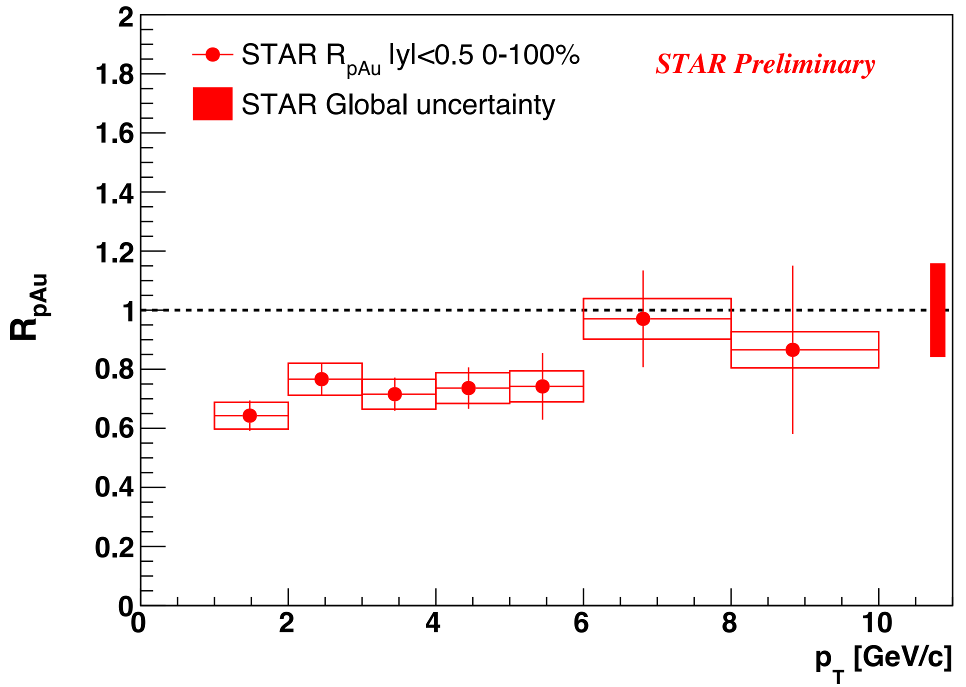
  - Improved CEM (direct) is below data in 3.5 – 12 GeV/c
  - *B-hadron feed-down needs to be taken into account*
- λ_θ in Helicity frame is consistent with 0 within $0 < p_T < 8$ GeV/c

Inclusive J/ψ R_{pAu} at 200 GeV



$$R_{pAu} = \frac{\sigma_{inel}^{pp}}{\langle N_{coll} \rangle} \frac{d^2 N_{pAu} / dydp_T}{d^2 \sigma_{pp} / dydp_T}$$

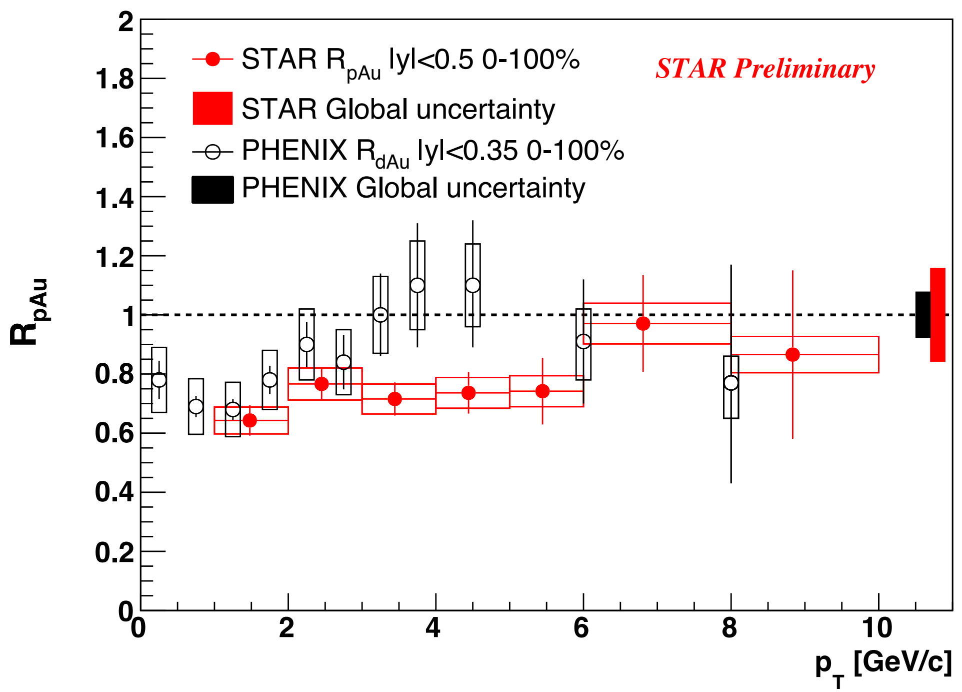
← **Global Uncertainty**

Luminosity p+p
N_{coll}
Trigger efficiency
Tracking efficiency

- $R_{pAu} \sim 1$ at high p_T and is less than unity at low p_T

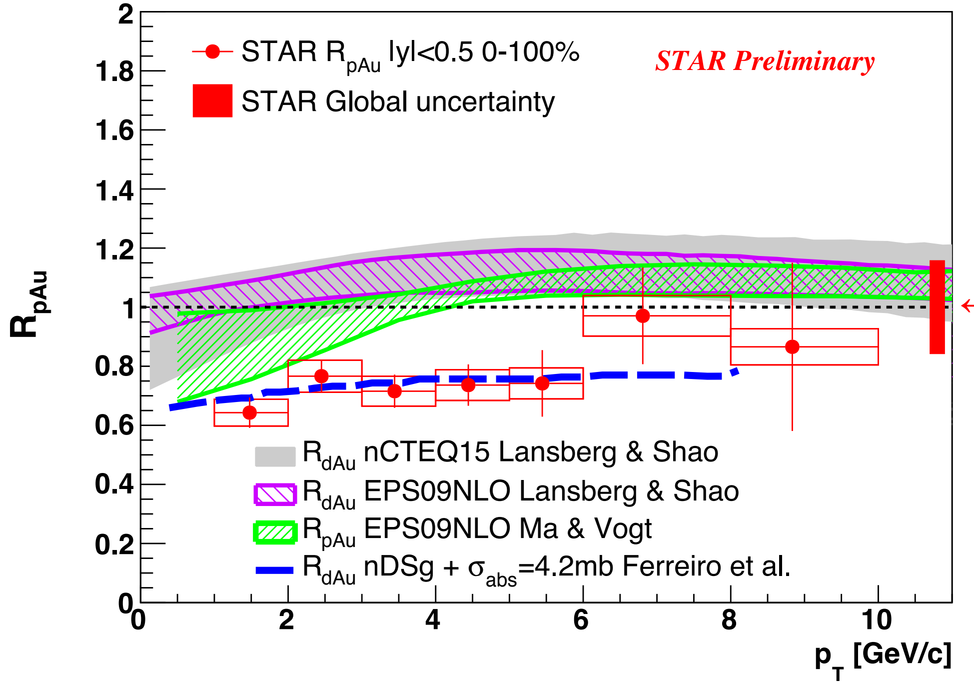
Inclusive J/ψ: R_{pAu} vs. R_{dAu}

PHENIX, PRC 87 (2012) 034903



- R_{pAu} is consistent with R_{dAu} within uncertainties
  - There seems to be tension at 3.5 – 5 GeV/c (1.4σ)

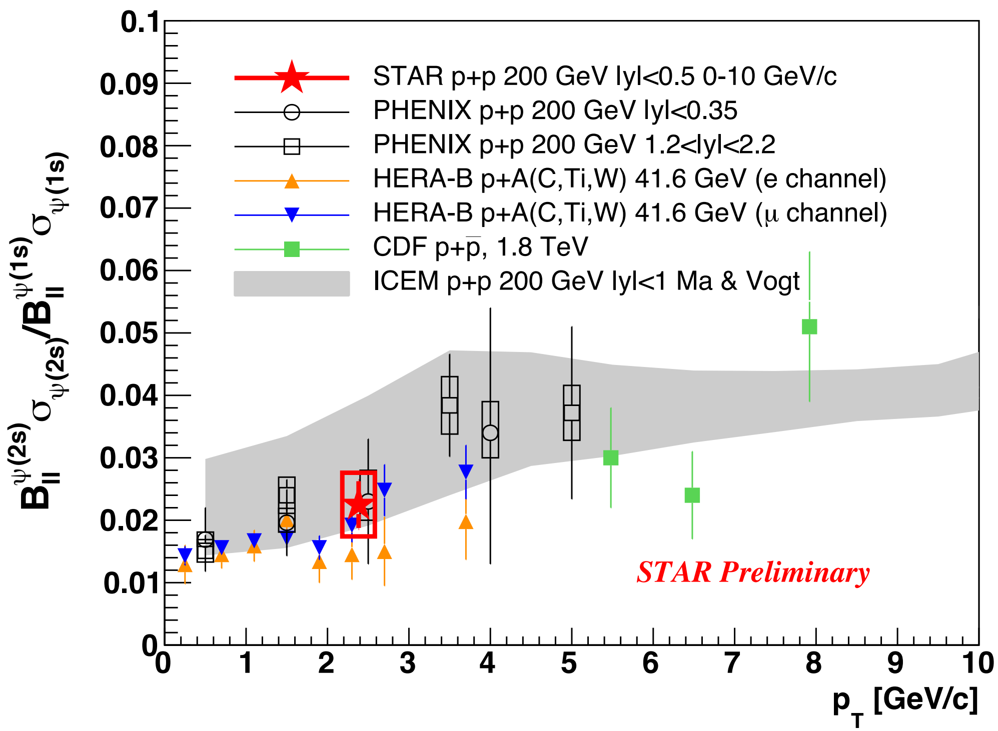
Inclusive J/ψ R_{pAu}: data vs. model



EPS09+NLO: Ma & Vogt, Private Comm.
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

- **Data seem to favor additional nuclear absorption on top of nuclear PDF effects**
- However, models with only nPDF are not fully ruled out given the relatively large global uncertainty on data

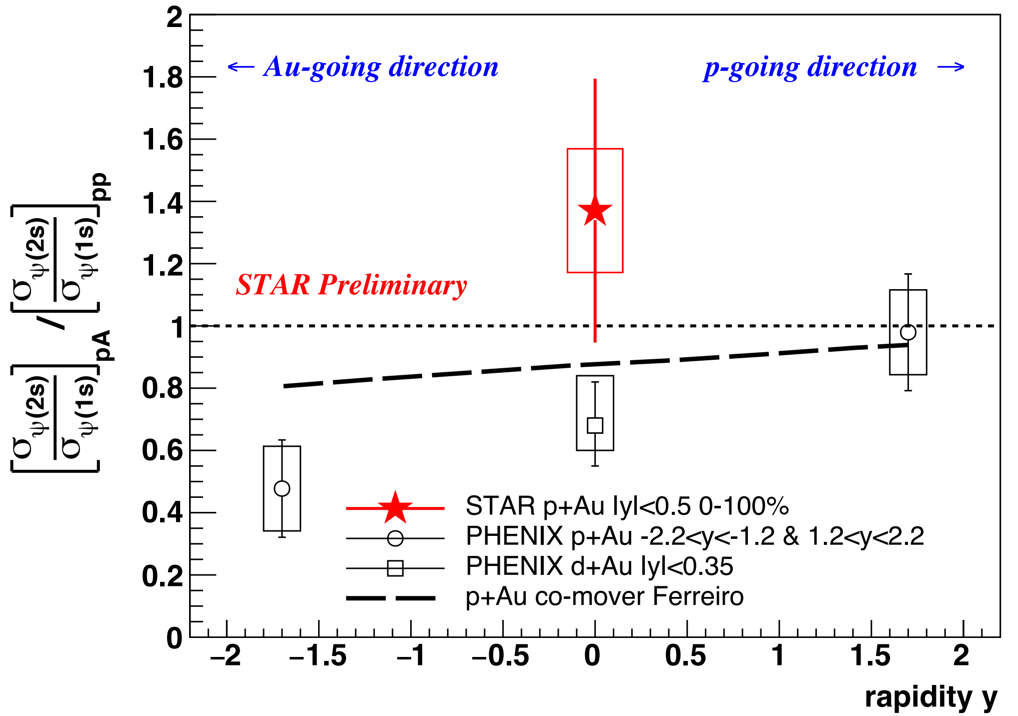
ψ(2S)/J/ψ ratio in 200 GeV p+p



HERA-B, EPJC49, 545
PHENIX mid y, PRD85 (2012) 092004
PHENIX forward y, arXiv:1609.06550 (Accepted by PRC)
CDF, 1.8TeV, PRL79 (1997) 572
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- Recently measured ψ(2S)/J/ψ ratio in 200 GeV p+p collisions is consistent with world-wide data
- The ICEM model describes the increasing trend

ψ(2S)/J/ψ double ratio between p+p and p+Au



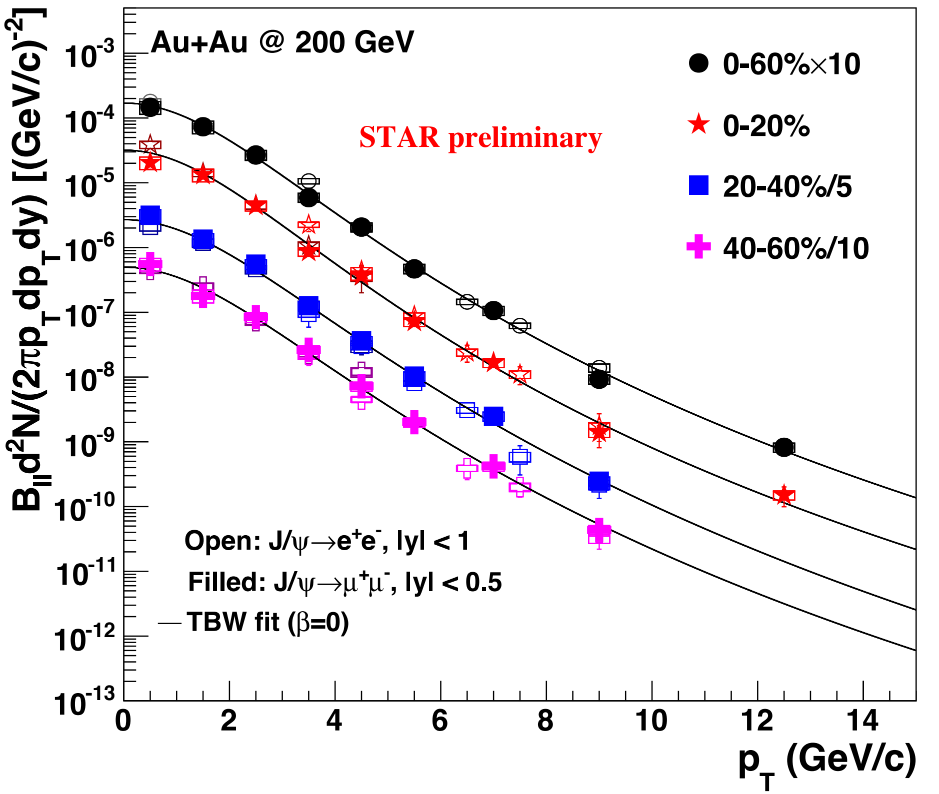
PHENIX p+Au, arXiv:1609.06550 (Accepted by PRC)
PHENIX d+Au, PRL111 (2013) 202301

Co-mover calculation, Ferreiro (2016) private communication
Calculation based on PLB749 (2015) 98-103

- First $[\sigma_{\psi(2S)} / \sigma_{J/\psi(2S)}]_{pAu} / [\sigma_{\psi(2S)} / \sigma_{J/\psi(2S)}]_{pp}$ measurement at mid-rapdity at RHIC

1.37 ± 0.42(stat) ± 0.19(sys)

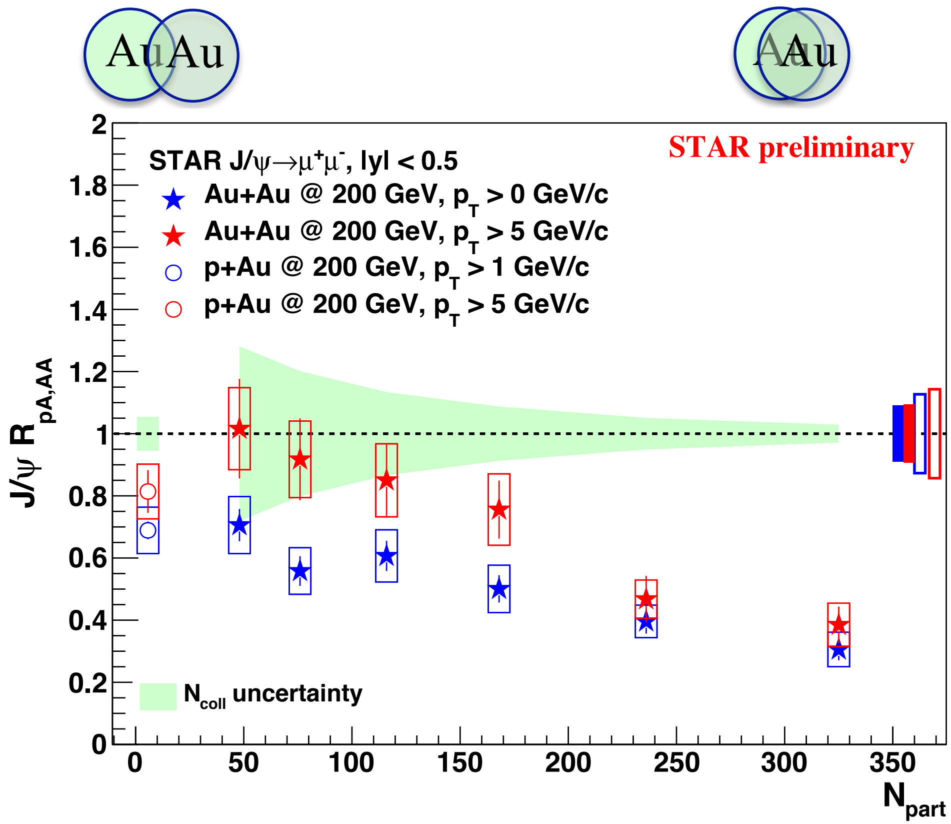
J/ψ yield in 200 GeV Au+Au collisions



Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

- Mid-rapidity J/ψ yield measured via the di-muon channel for 0–15 GeV/c
- Consistent with the published di-electron results over the entire kinematic range

J/ψ R_{AA} vs. centrality

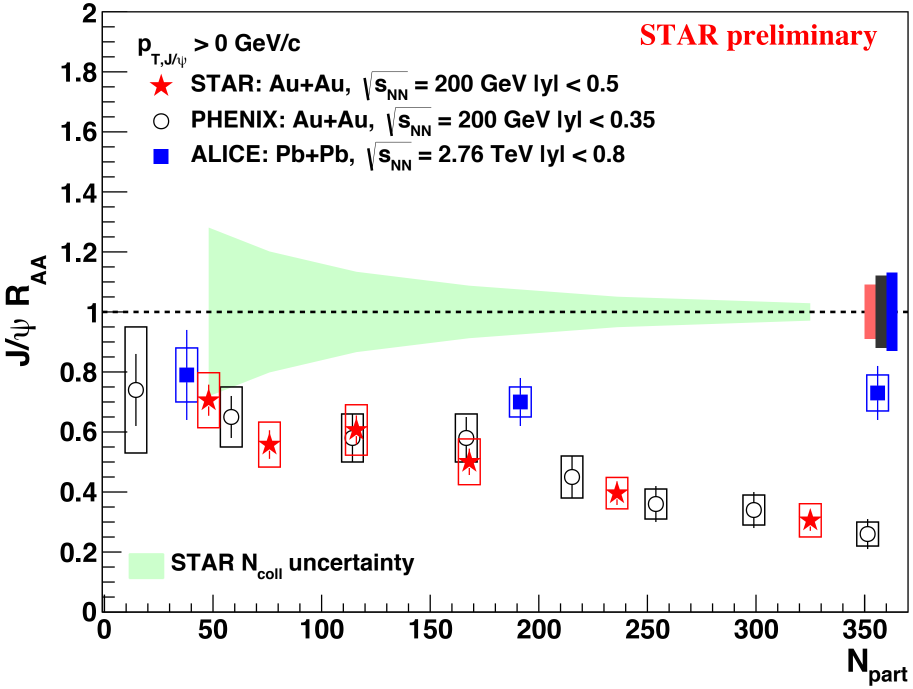


- Central collisions: significant suppression for $p_T > 5$ GeV/c → **dissociation in effect**
- Peripheral collisions: R_{AA} of J/ψ for $p_T > 0$ GeV/c is less than 1→ consistent with cold nuclear matter (CNM) effects

J/ψ R_{AA}: RHIC vs. LHC

p_T > 0 GeV/c

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



- p_T > 0 GeV/c: more suppressed at RHIC in central events → **smaller regeneration contribution due to smaller charm cross-section**

J/ψ R_{AA}: RHIC vs. LHC

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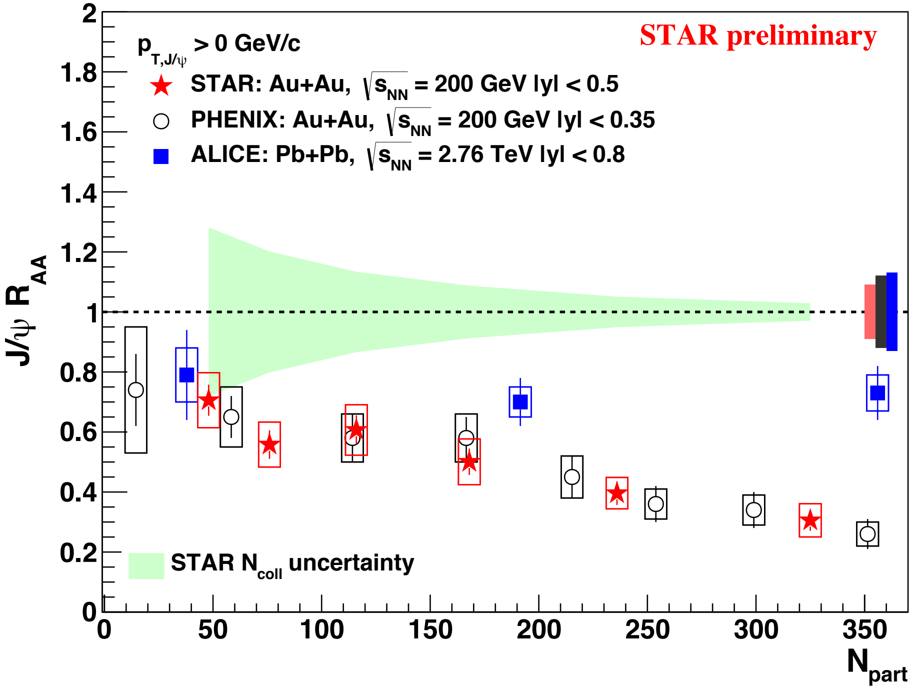
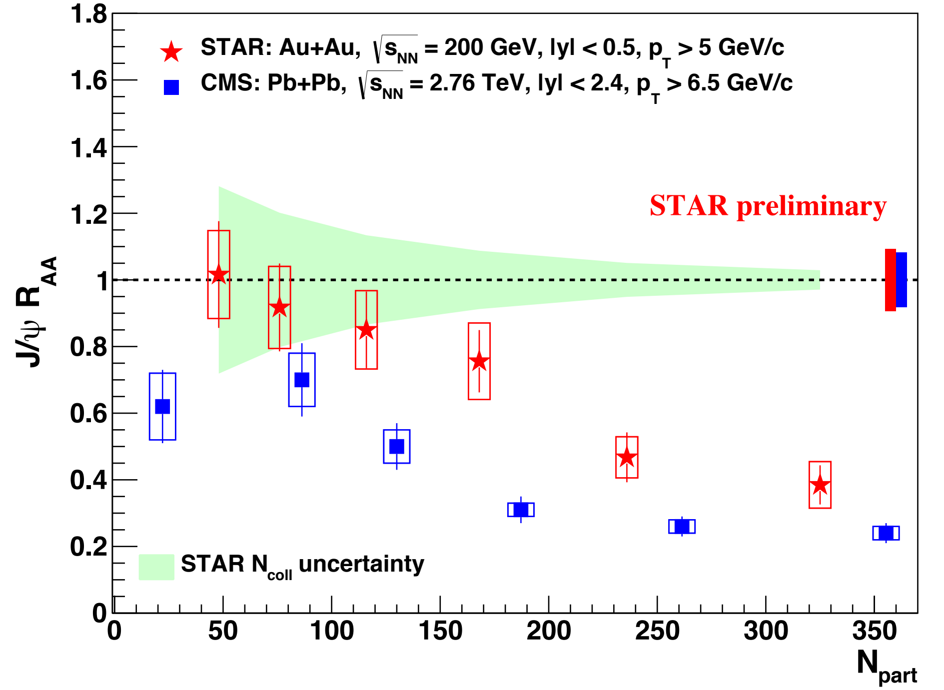


p_T > 5 GeV/c

CMS: JHEP 05 (2012) 063



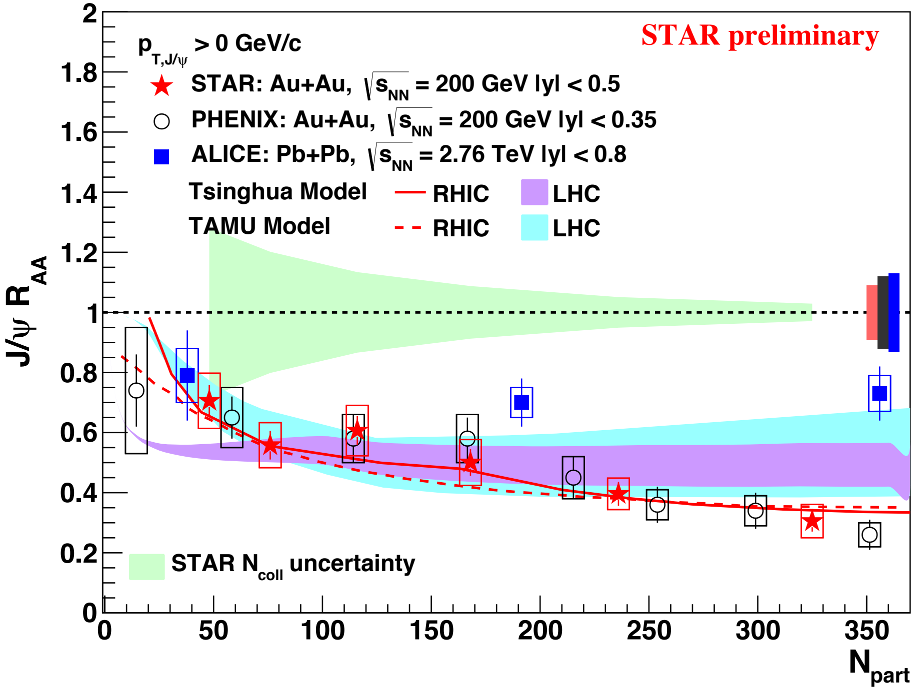
- p_T > 0 GeV/c: more suppressed at RHIC in central events → **smaller regeneration contribution due to smaller charm cross-section**
- p_T > 5 GeV/c: less suppressed at RHIC in all centralities → **smaller dissociation rate due to lower temperature**

Data vs. transport model

Transport model:
Tsinghua at RHIC: PLB 678 (2009) 72
Tsinghua at LHC: PRC 89 (2014) 054911
TAMU at RHIC: PRC 82 (2010) 064905
TAMU at LHC: NPA 859 (2011) 114

p_T > 0 GeV/c

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



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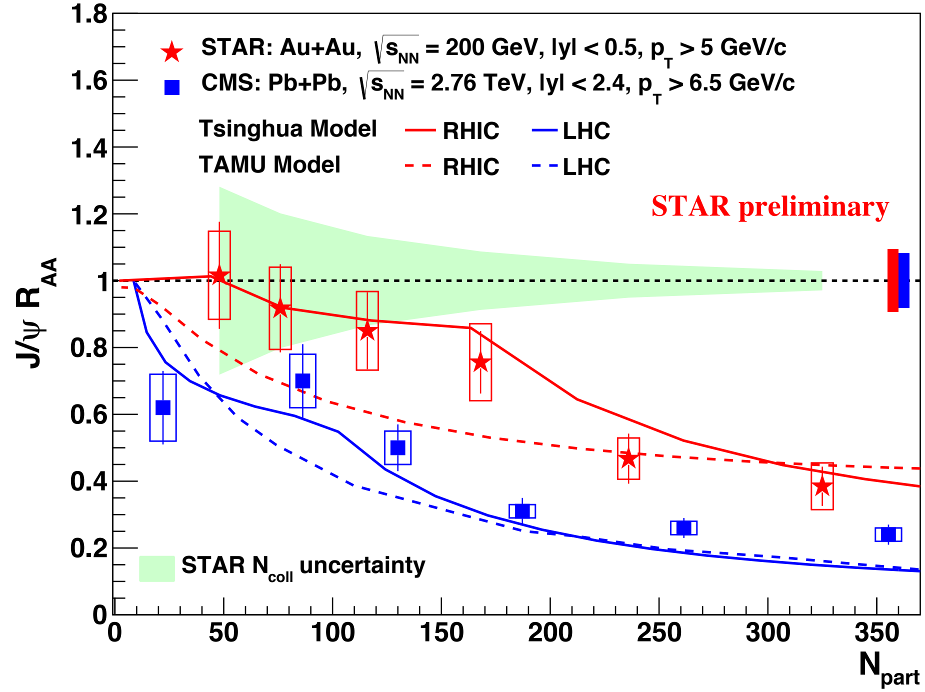
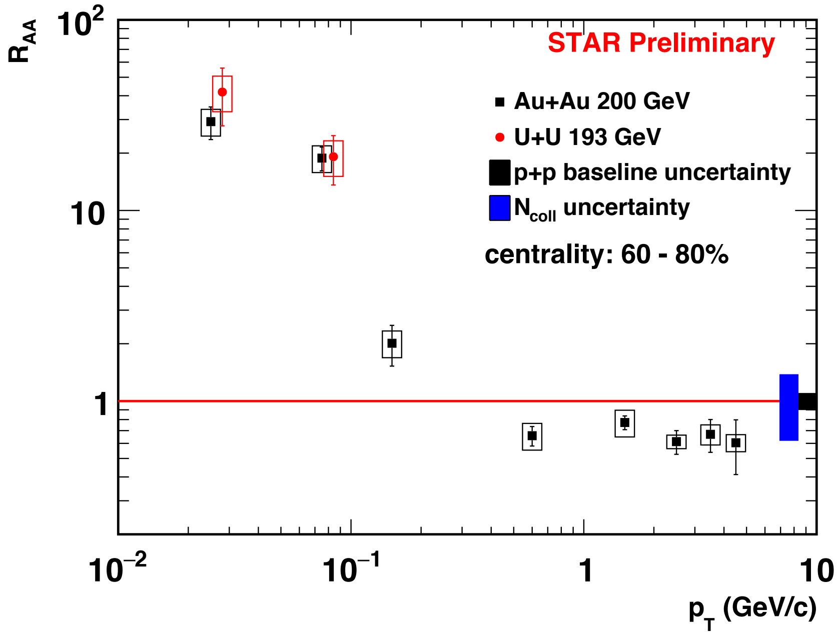
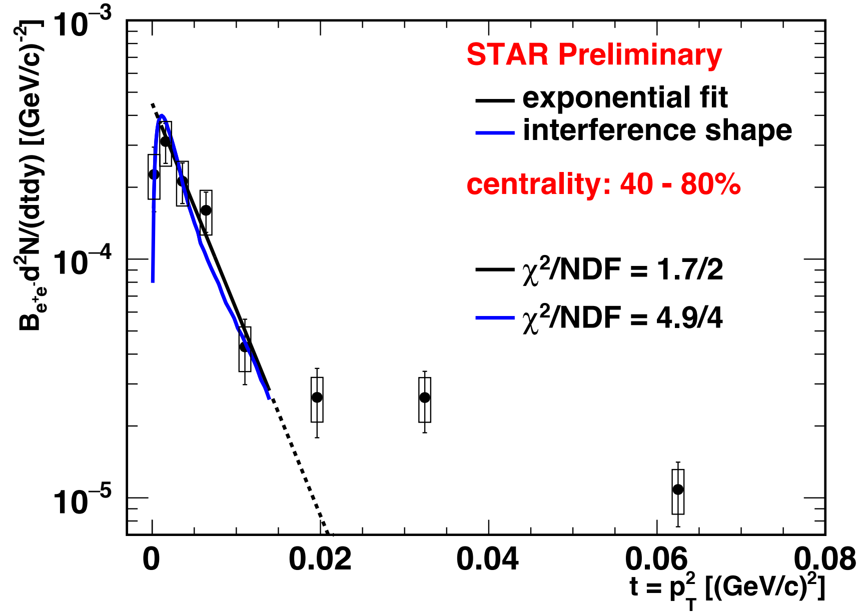


- p_T > 0 GeV/c: both models can describe centrality dependence at RHIC, but tends to overestimate suppression at LHC
- p_T > 5 GeV/c: there is tension among models and data
- Other models on the market: SHM, co-mover …

PBM, J. Stachel, PLB 490 (2000) 196, and PLB 652 (2007) 659
E.G. Ferreiro, PLB 731 (2014) 57–63

Excess of low-p_T J/ψ



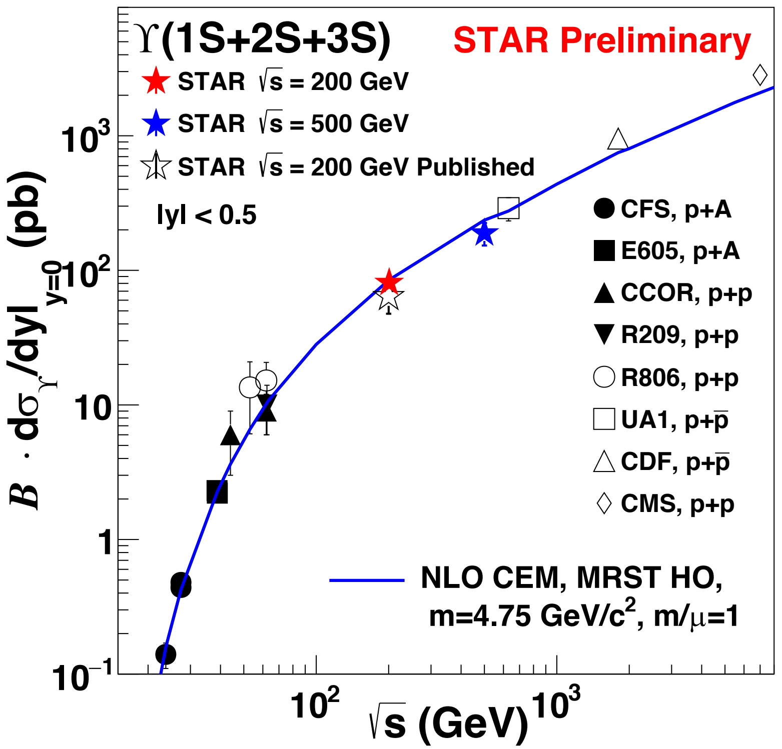


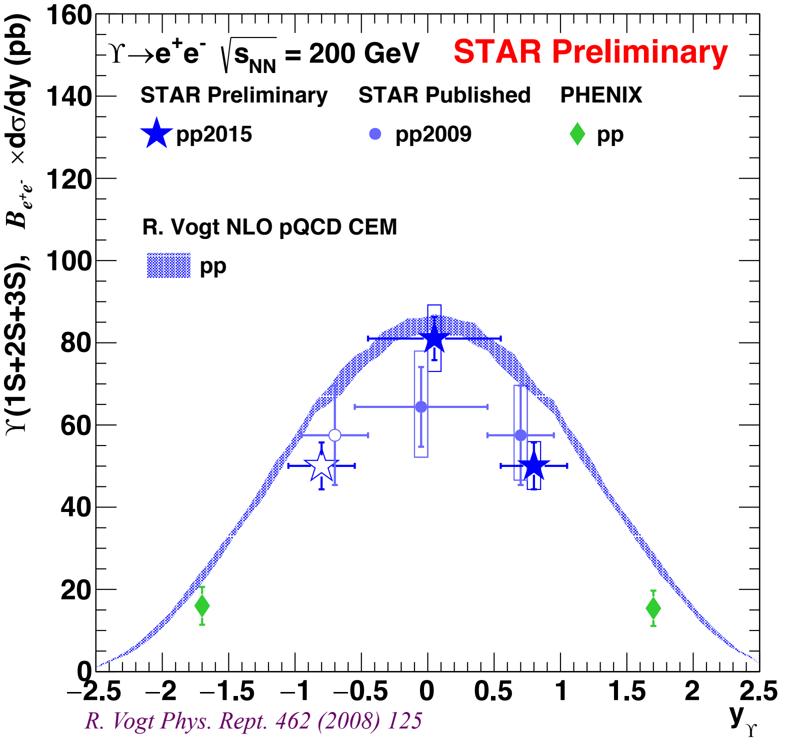
- Huge excess of J/ψ yield at low p_T in peripheral Au+Au collisions.
- *Exhibit characteristics of coherent photon-nuclear production.*
  - Slope: fit w/o first data point: 199 ± 31 $(GeV/c)^{-2}$; STARLIGHT: 196 $(GeV/c)^{-2}$
- Can be used to probe hot medium. However, theoretical calculations are challenging.

W. Zha, arXiv:1705.01460

Bottomonium

Υ cross-section in p+p collisions

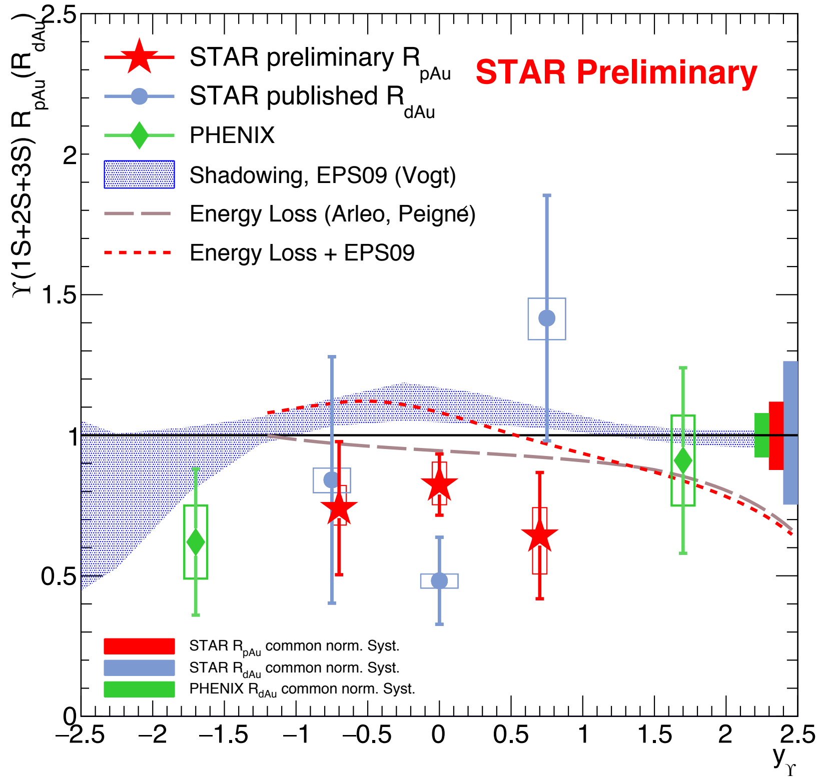




- p+p @ 200 and 500 GeV: Υ cross-sections follow world-wide data trend predicted by CEM
- p+p @ 200 GeV: Υ cross-section exhibit narrower rapidity distribution than NLO CEM calculation

Improved p+p reference for p+Au and Au+Au studies

Υ(1S+2S+3S) R_{pAu} at 200 GeV



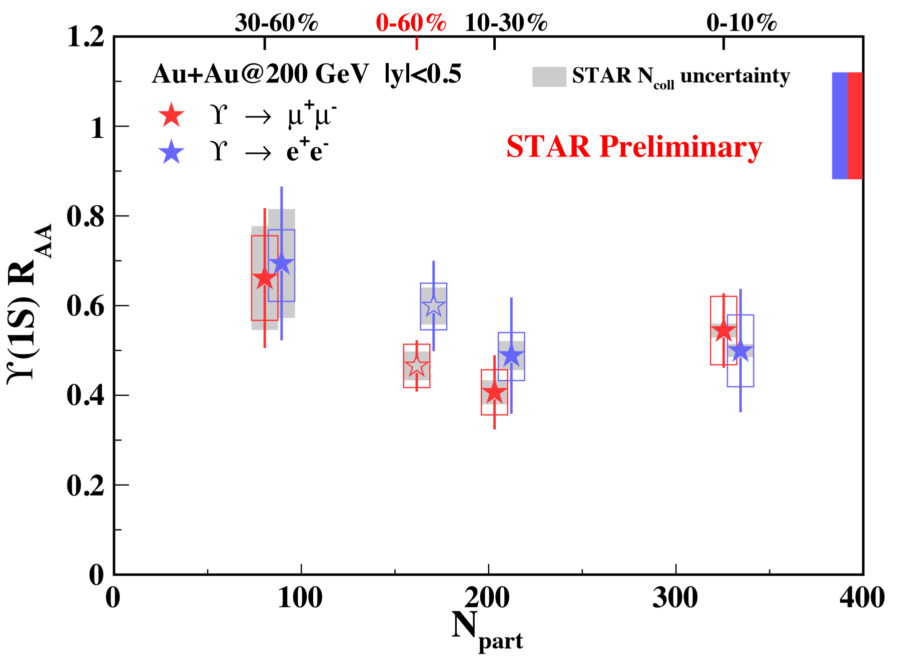
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

STAR: PLB 735 (2014) 127
PHENIX: PRC 87 (2013) 044909

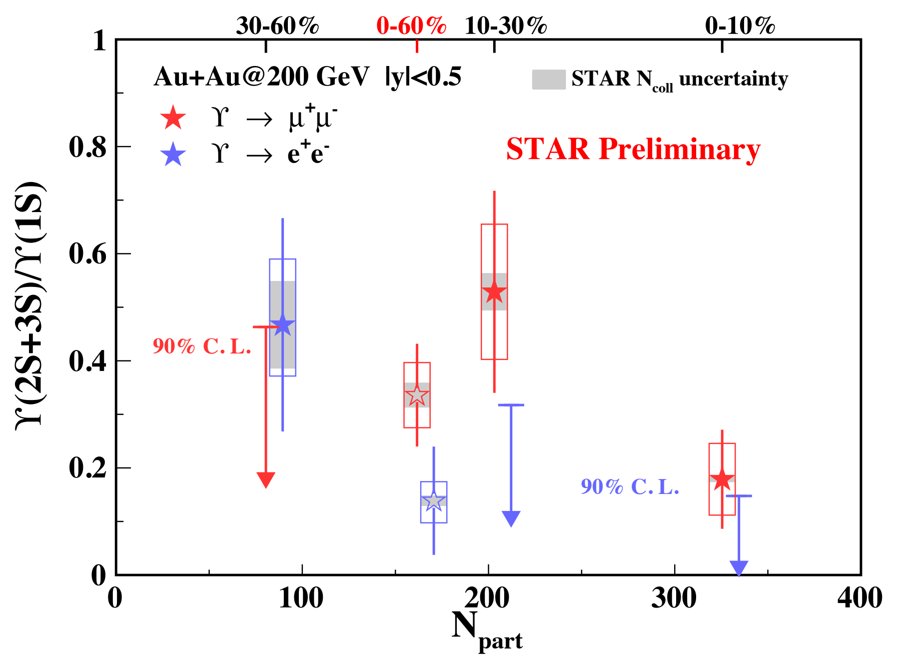
- **CNM: indication of Υ(1S+2S+3S) suppression in p+Au collisions**
  - $R_{pAu} = 0.82 \pm 0.10(stat) + 0.08(syst) - 0.07(syst) \pm 0.10(global)$
  - A factor of two better precision than R_{dAu} measurement
- Additional suppression mechanism seems needed beyond nPDF effects

Consistency check

Υ(1S) R_{AA}



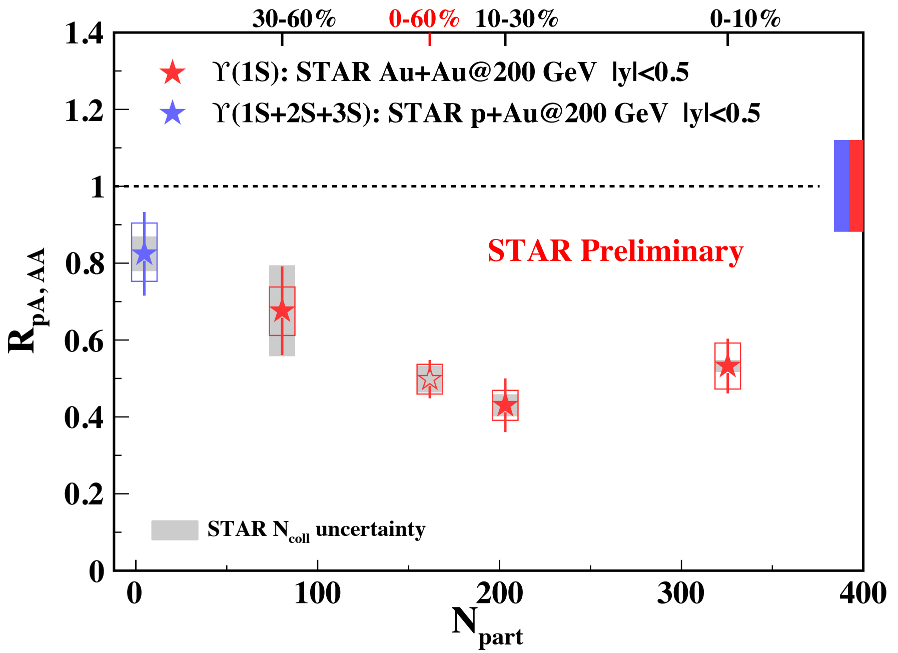
Υ(2S+3S)/Υ (1S)



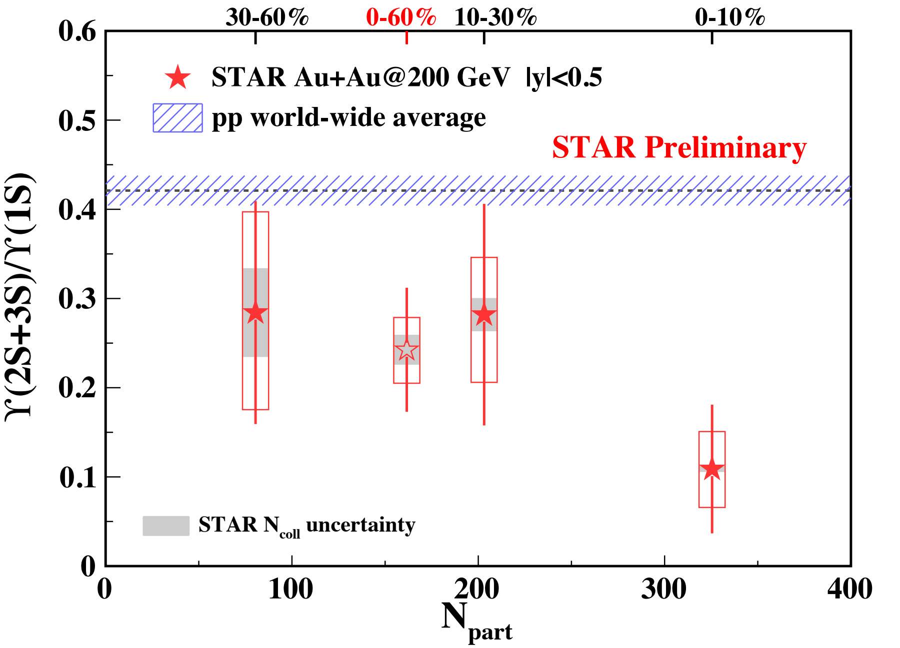
- Di-muon: 2014 data; di-electron: 2011 data
- Consistent results from the two channels → Combine

Υ suppression at RHIC

Υ(1S) R_{AA}



Υ(2S+3S)/Υ(1S)

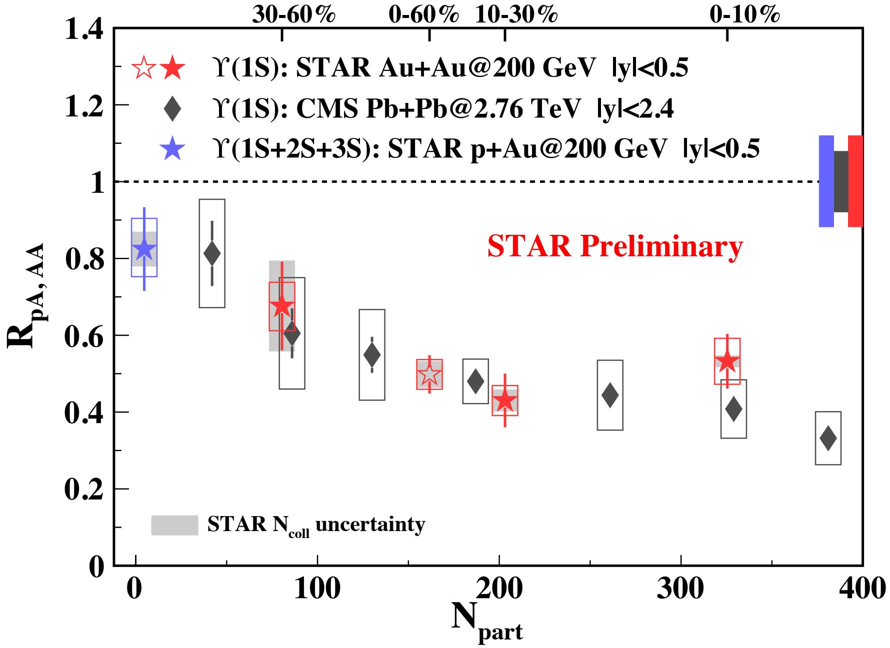


World-wide p+p: W. Zha, et. al, PRC 88 (2013) 067901

- **Υ(1S) is suppressed**
  - Indication of more suppression with increasing centrality
  - *Is direct Υ(1S) suppressed?*
- **Central: Υ(2S+3S) is more suppressed → sequential melting**

Υ(1S): RHIC vs. LHC

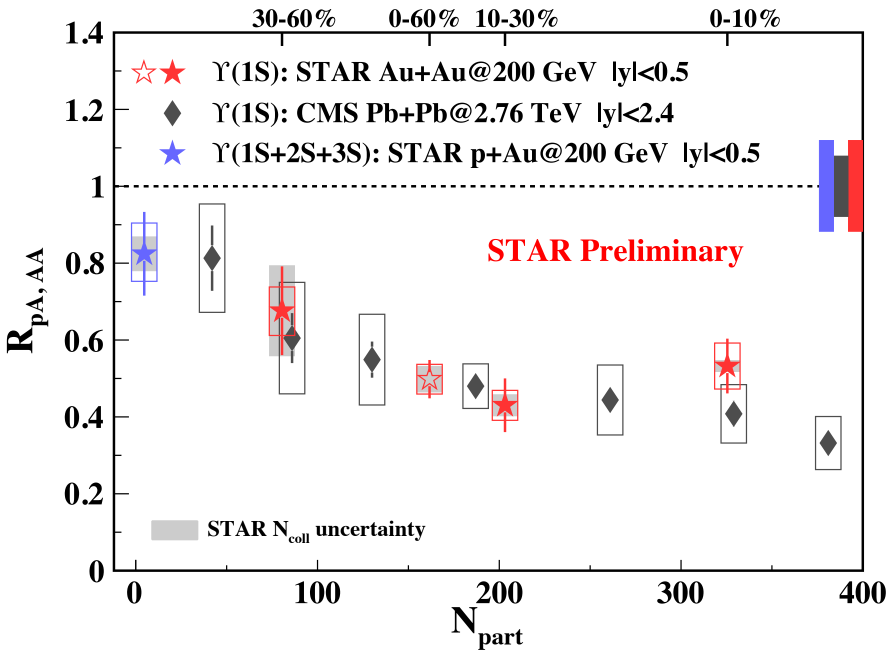
CMS: arXiv:1611.01510



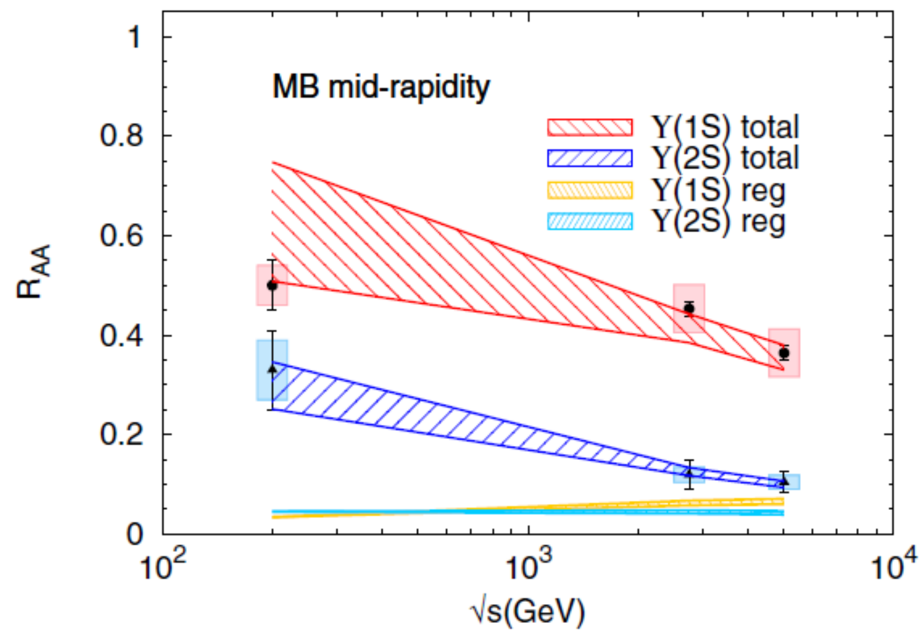
- Υ(1S) suppression: **similar at RHIC and LHC**

Υ(1S): model comparison

CMS: arXiv:1611.01510

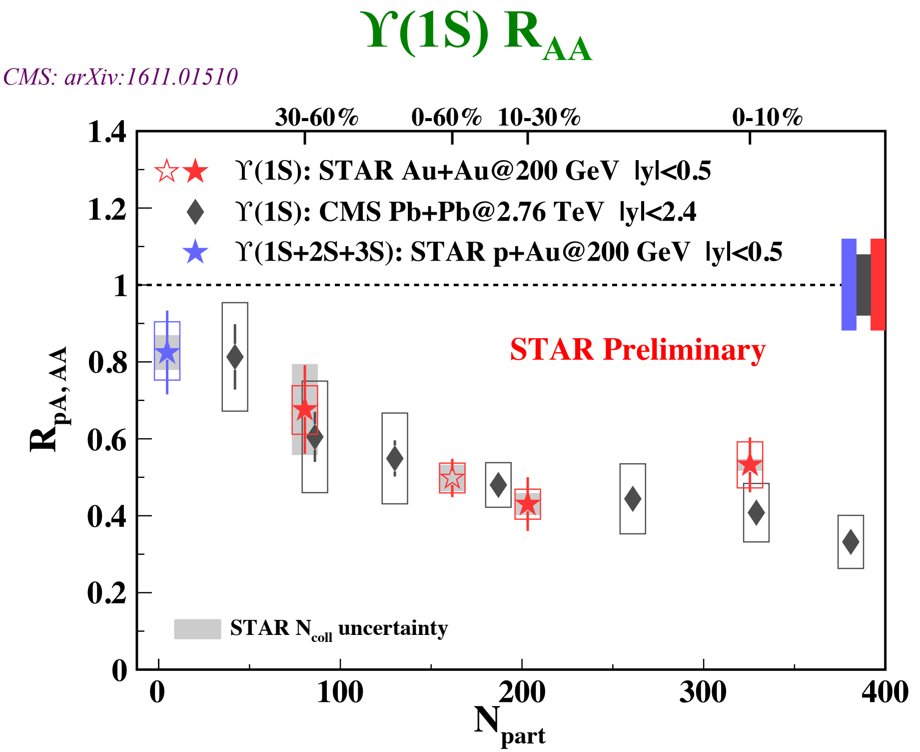


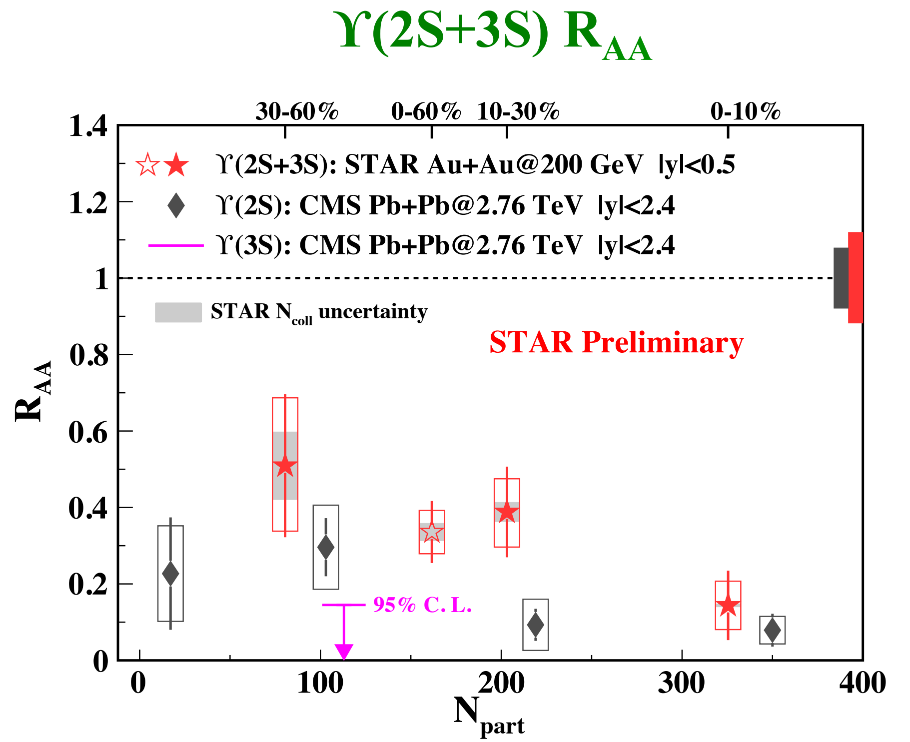
(R. Rapp Monday)



- Υ(1S) suppression: **similar at RHIC and LHC**
- Ralf model: seems consistent with Υ(1S) suppression by including CNM and regeneration
  - Regeneration plays an important role for excited states.

ϒ(2S+3S): RHIC vs. LHC

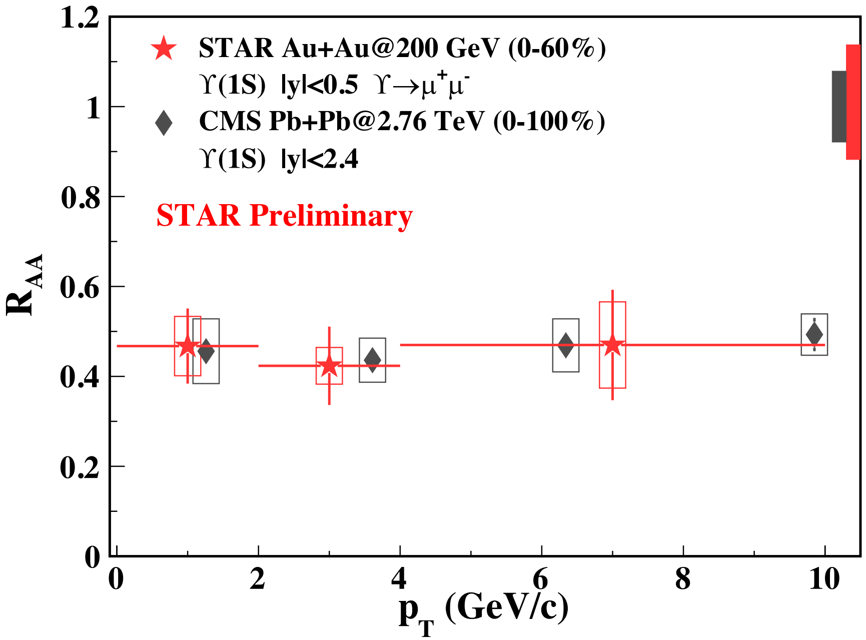




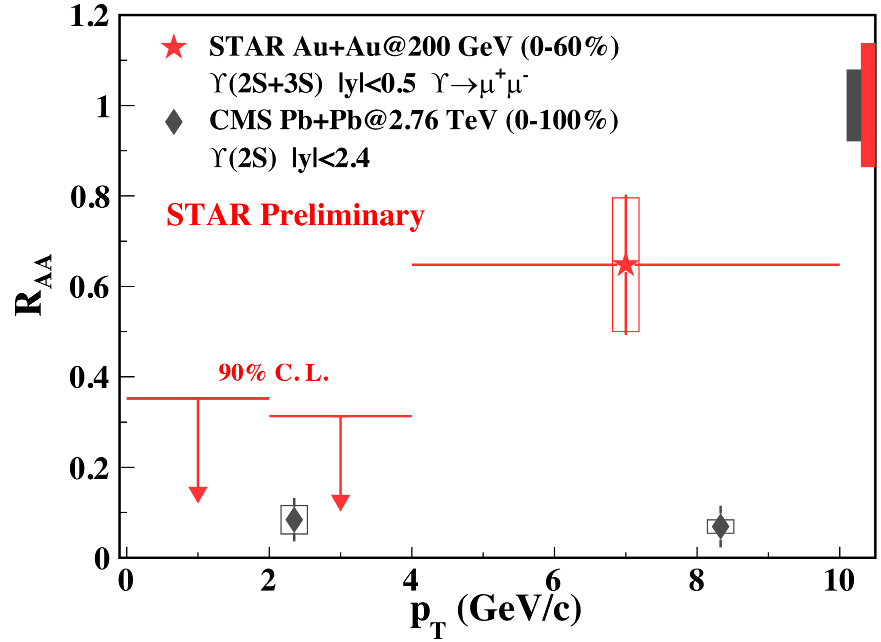
- ϒ(1S) suppression: **similar at RHIC and LHC**
- ϒ(2S+3S): **hint of less suppression at RHIC than at the LHC**

Υ R_{AA} vs. p_T

Υ(1S)



Υ(2S+3S)



- Υ(1S): no obvious dependence on p_T; similar to CMS
- Υ(2S+3S): hint of less suppression at high p_T

Summary

- p+p/Au collisions
  - p+p: models describe cross-section reasonably well (e.g. CEM, NRQCD, etc)
  - p+Au: quarkonia $R_{pAu} < 1$; additional suppression mechanisms are supported by data, even though nPDF effects only cannot be fully ruled out yet.

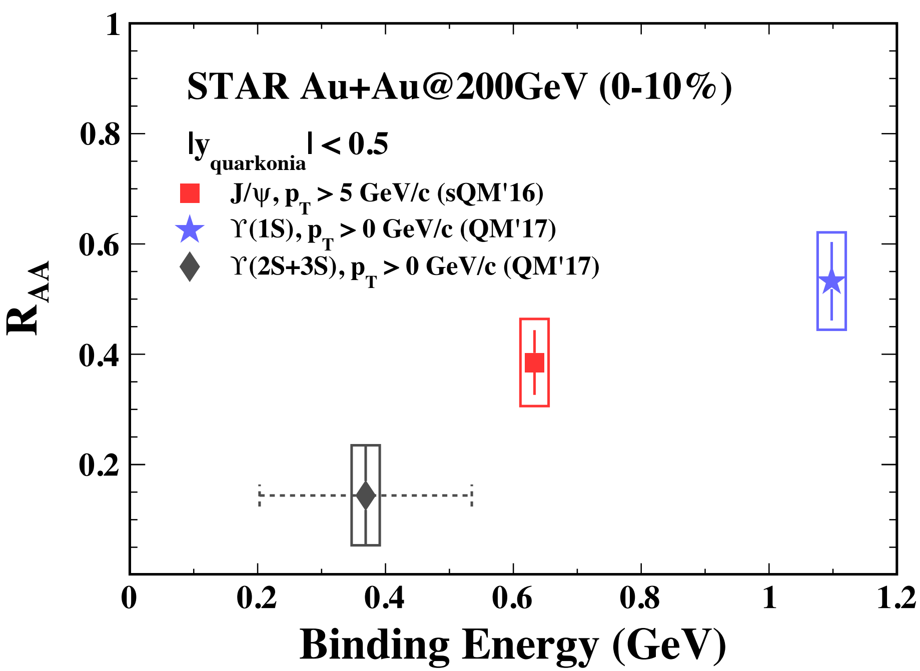
- Au+Au collisions
  - J/ψ $R_{AA} << 1$ for $p_T > 5$ GeV/c → **dissociation in effect**
  - 0-10%: Υ(2S+3S) R_{AA} < Υ(1S) R_{AA} → **sequential melting**
  - Υ(1S) R_{AA}: RHIC ≈ LHC. Model including CNM and regeneration seems consistent with data
  - Low-p_T J/ψ: a new probe to QGP?

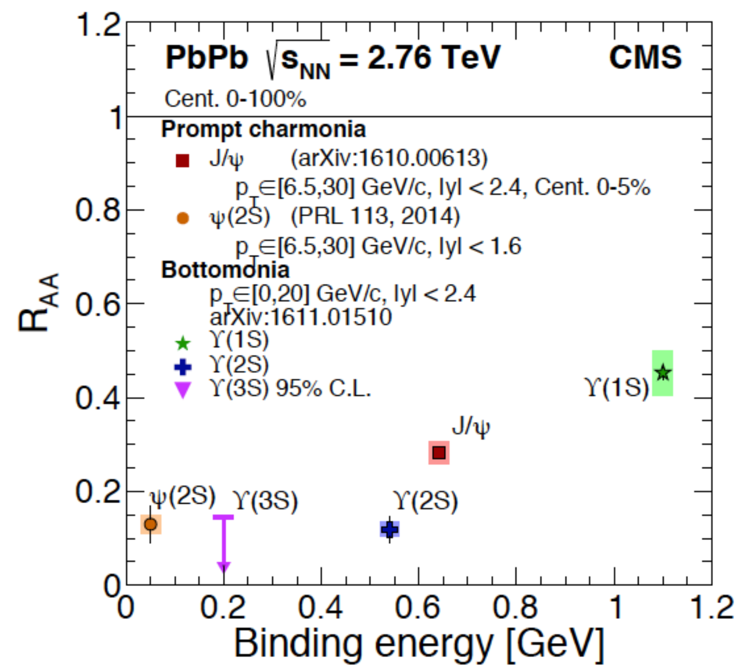
- Outlook: 2x Au+Au data on tape for Υ analyses at STAR

Have we fulfilled the promise?

Have we fulfilled the promise?

(Cautiously optimistic) YES

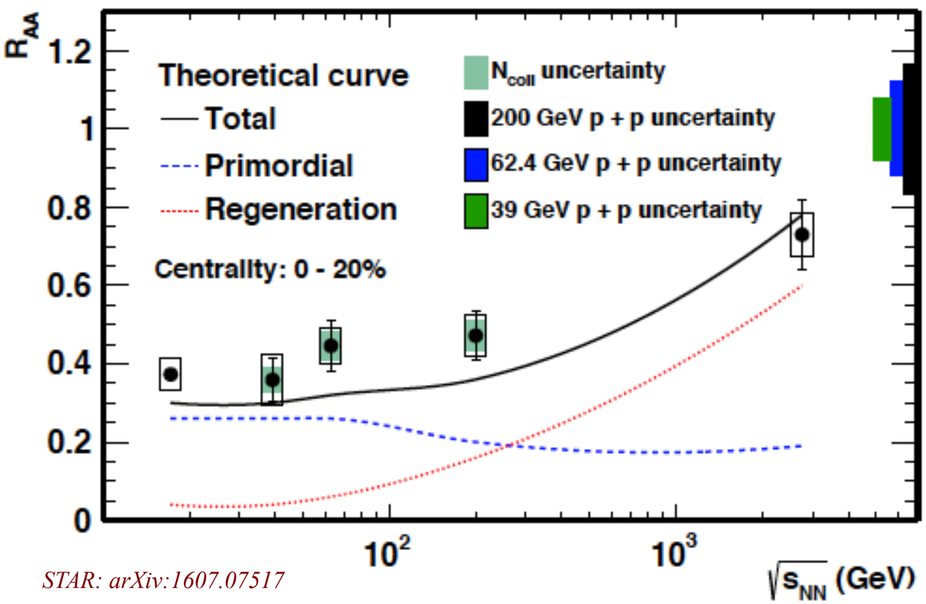




- Other effects (CNM, regeneration, etc) also play important roles.
- The "cloud": do we understand quarkonium production in pp?

Backup

"Dissociation + Regeneration" Picture



STAR: arXiv:1607.07517

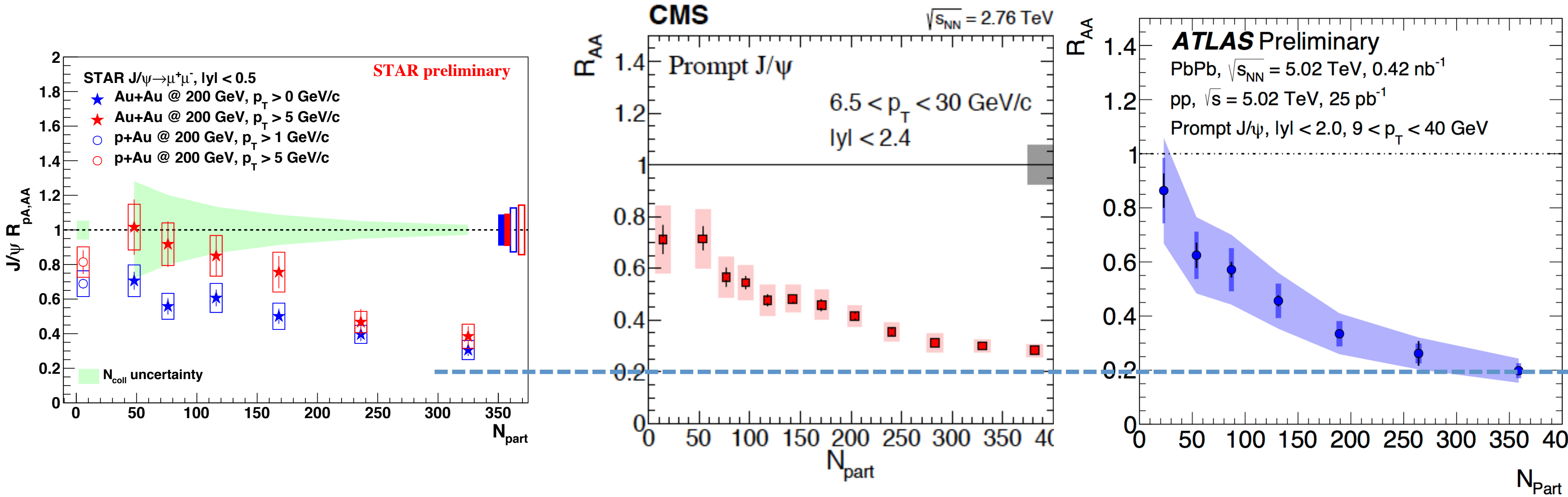
- Pretty successfully in describing the J/ψ production over a vast range of collision energy.

- More differential measurements to test the picture

	Dissociation	Regeneration	Shadowing
√s ↑	↑	↑	↑
p_T ↑	↓	↓	↓
y ↑	↓	↓	↑

J/ψ: High p_T, Mid-Rapidity

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



- ➢ Decreasing R_{AA} towards central collisions in all collision energies
- ➢ R_{AA}(5.02 TeV) <~ R_{AA}(2.76 TeV) <~ R_{AA}(0.2 TeV)

→ Dissociation in effect

CMS: arXiv:1610.00613
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