14. Zimányi
WINTER SCHOOL ON HEAVY ION PHYSICS
Dec. 1. - Dec. 5., Budapest, Hungary

Production of Quarkonia in Heavy Ion Collisions at STAR

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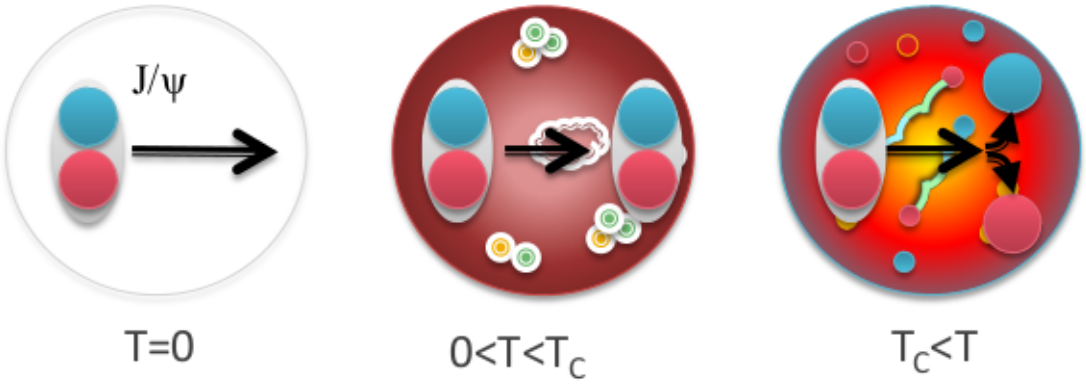
Academy of Sciences
of the Czech Republic

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Quarkonia in the sQGP

- Debye screening of heavy quark potential
  → Quarkonia are expected to dissociate

T. Matsui, H. Satz, Phys.Lett. B178, 416 (1986)



Charmonia $(c\bar{c})$:
J/Ψ, Ψ', χ_c

Bottomonia $(b\bar{b})$:
$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

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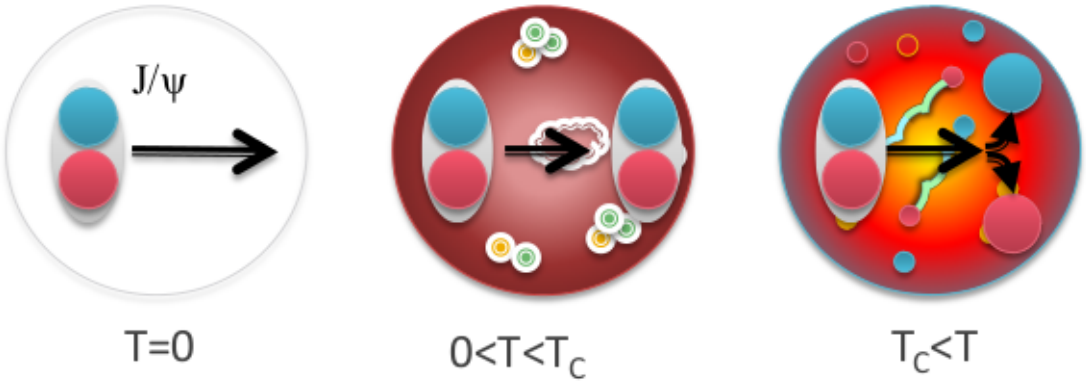

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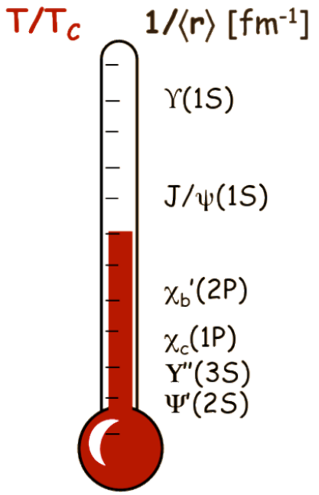

- Sequential melting: Different states dissociate at different temperatures

Á. Mócsy, P. Petreczky, Phys. Rev. D77, 014501 (2008)

Quarkonia may serve as sQGP thermometer

Complications…

- Feed-down
  - χ_c, ψ', B-meson decay to J/ψ
  - χ_b, Υ(2S), Υ(2S) to Υ(1S) …
- Cold nuclear matter effects
  - Nuclear shadowing (PDF modification in the nucleus)
  - Initial state energy loss
  - Co-mover absorption
- Hot/dense medium effects
  - Coalescence of uncorrelated charm and bottom pairs.

Model:
X. Zhao, R.Rapp, PRC82, 064905 (2010)

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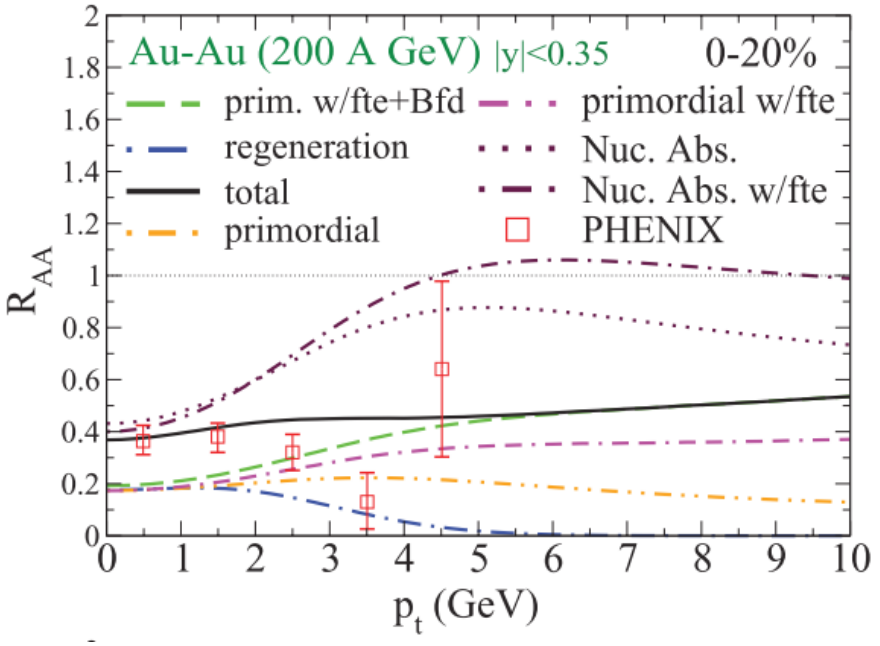

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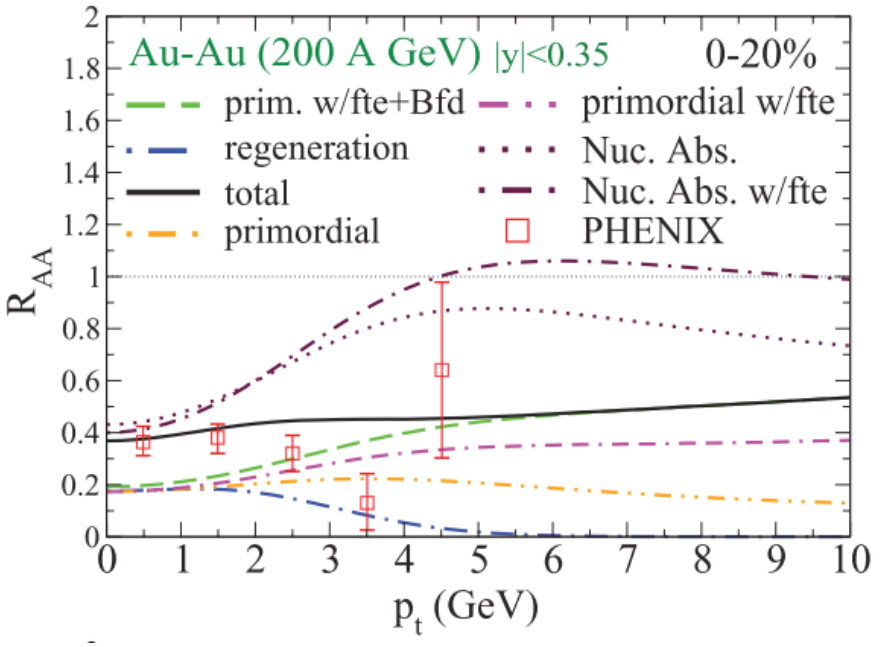


Contribution of different effects is not well understood

Measurements at STAR

- A wide variety of J/ψ measurements
  - Different species

    d+Au → cold nuclear matter (CNM) effects

    Au+Au, U+U → hot plasma effects, different energy densities

  - Energy scan

  → Change relative contributions

  - High-pT J/ψ

  →"turn off" regeneration and CNM effects

- Measure ϒ
  - Negligible recombination and co-mover absorption at RHIC energies

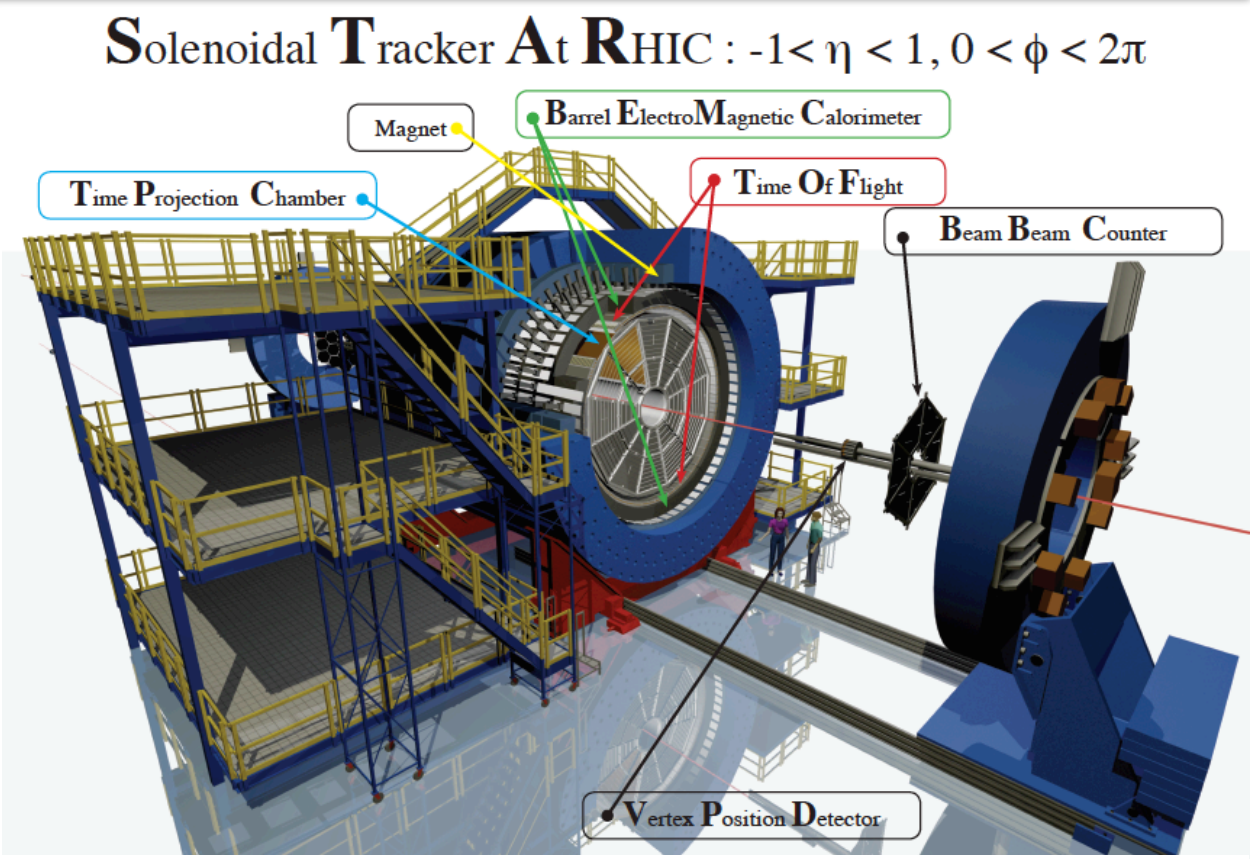
    ϒ states provide a cleaner probe at RHIC

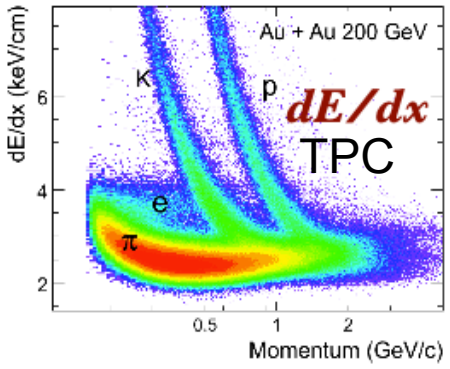
  - Difficult measurement: Low production rate

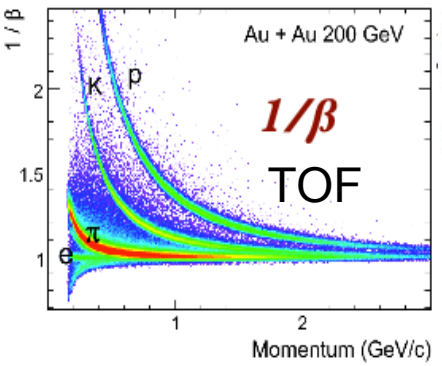
    Requires good acceptance and specific triggering

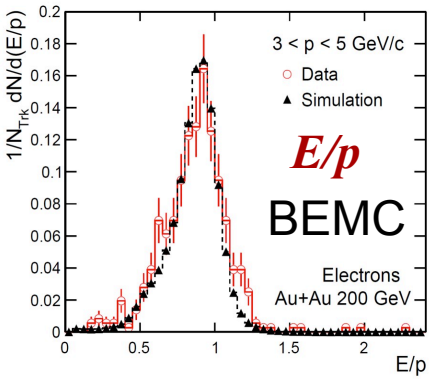
RHIC/STAR

- **Reconstruction:**
  - $J/\psi \rightarrow e^+e^-$ ($B_{ee} \sim 6\%$)
  - $\Upsilon \rightarrow e^+e^-$ ($B_{ee} \sim 2\%$)
- **TPC**
  - dE/dx PID
  - Large acceptance, uniform in a wide energy range
- **TOF**
  - PID using flight time
- **BEMC**
  - High-p_T trigger
  - PID using E/p and shower shape
- **VPD**
  - Minimum bias events







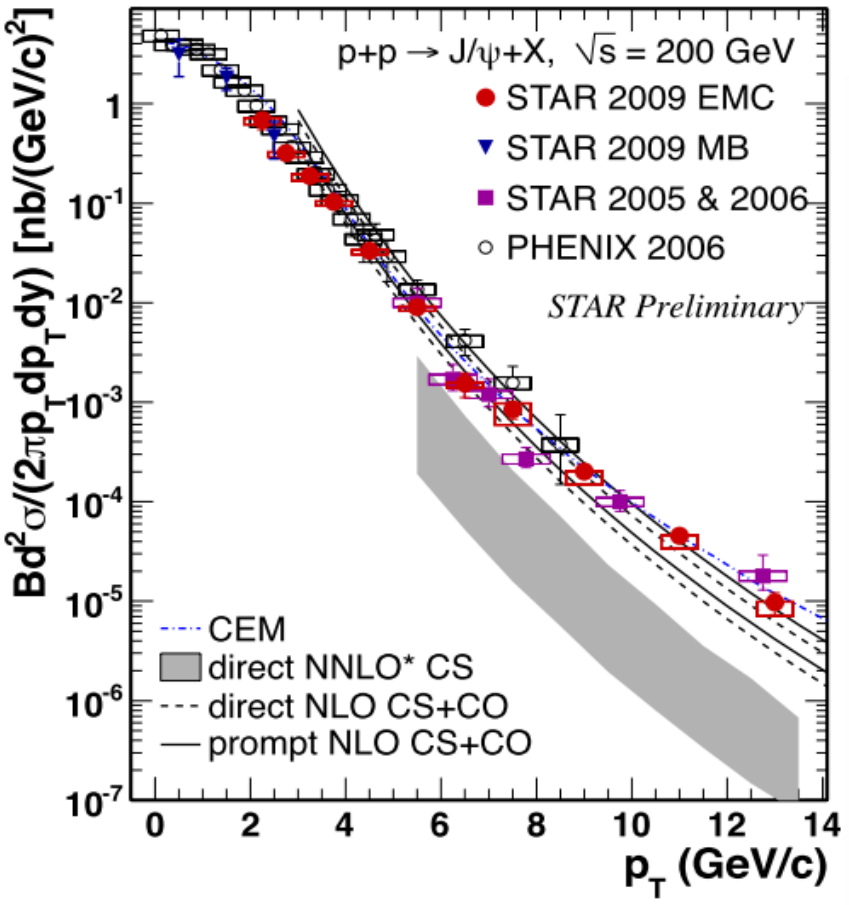


J/ψ spectra, p+p at 200 GeV

- STAR Data:
  - $0<p_T<14$ GeV/c in year 2009
  - Good agreement with PHENIX

STAR 2009 EMC : Phys. Lett. B 722 (2013) 55
STAR 2009 MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543
STAR 2005 & 2006: Phys. Rev. C80, 041902(R) (2009)
PHENIX 2006: Phys. Rev. D 85, 092004 (2012)

Inclusive J/ψ spectra:



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PHENIX 2006: Phys. Rev. D 85, 092004 (2012)

- Model comparison:
  - prompt NLO CS+CO: describes the data for p_T > 4 GeV/c
  - direct NNLO*CS: misses high- p_T part
  - Prompt CEM: reasonable description of spectra, but overpredicts the data at p_T~3 GeV/c

direct NNLO CS: P.Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008) and J.P.Lansberg private communication
NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, Phys. Rev. D 84, 51 114001 (2011) and priv. cor
CEM: A.D. Frawley, T Ullrich, R. Vogt, Pys. Rept. 462 (2008) 125, and R.Vogt priv. comm.

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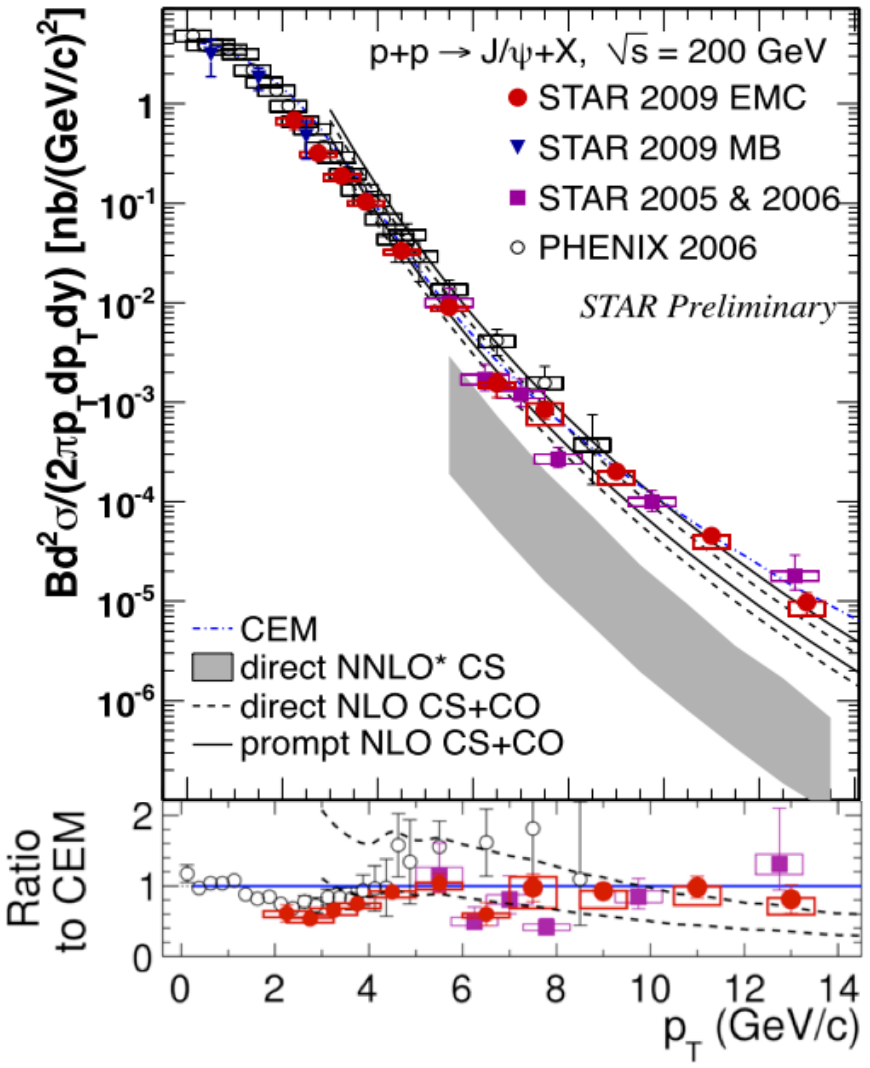


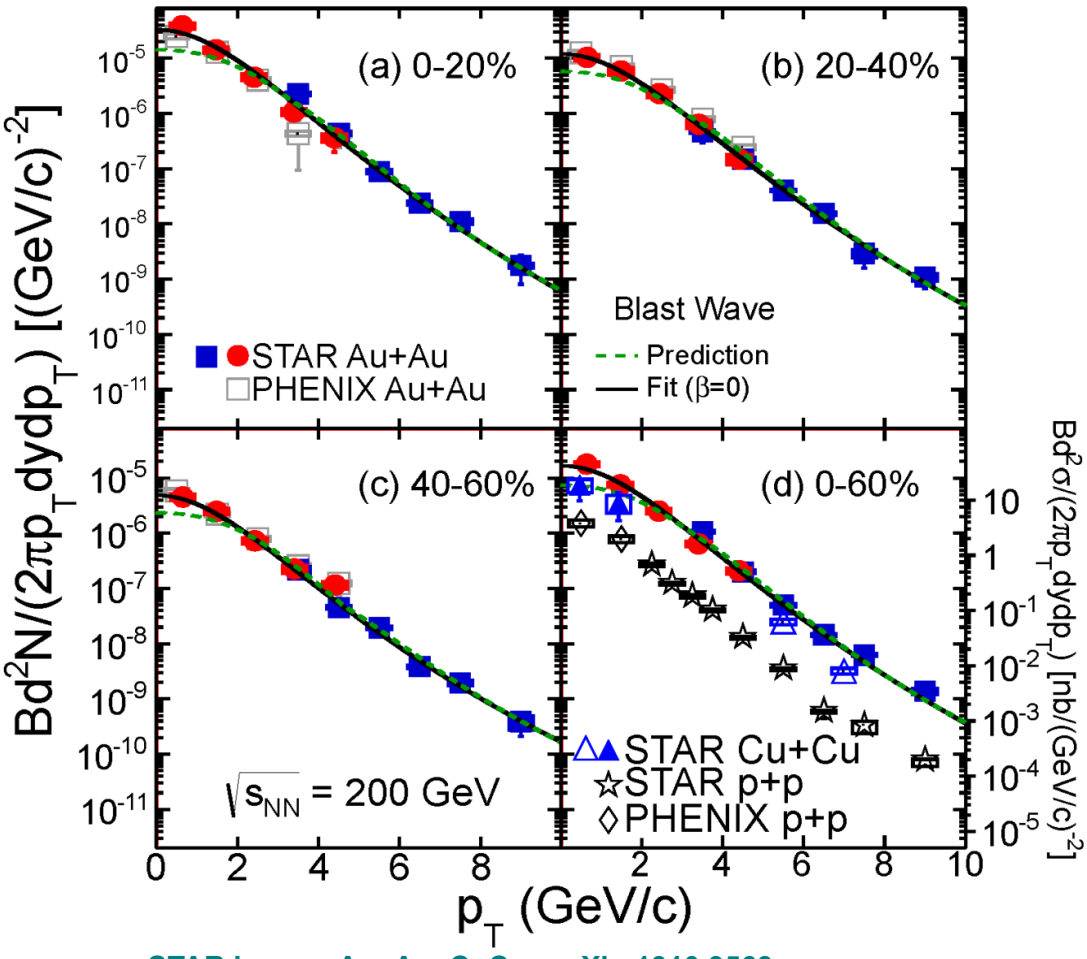
J/ψ spectra, Au+Au at 200 GeV

- J/ψ spectrum softer than Tsallis Blast-Wave model
  - Small radial flow?
  - Recombination at low p_T?

Tsallis Blast-Wave:

Hydro-inspired freezeout

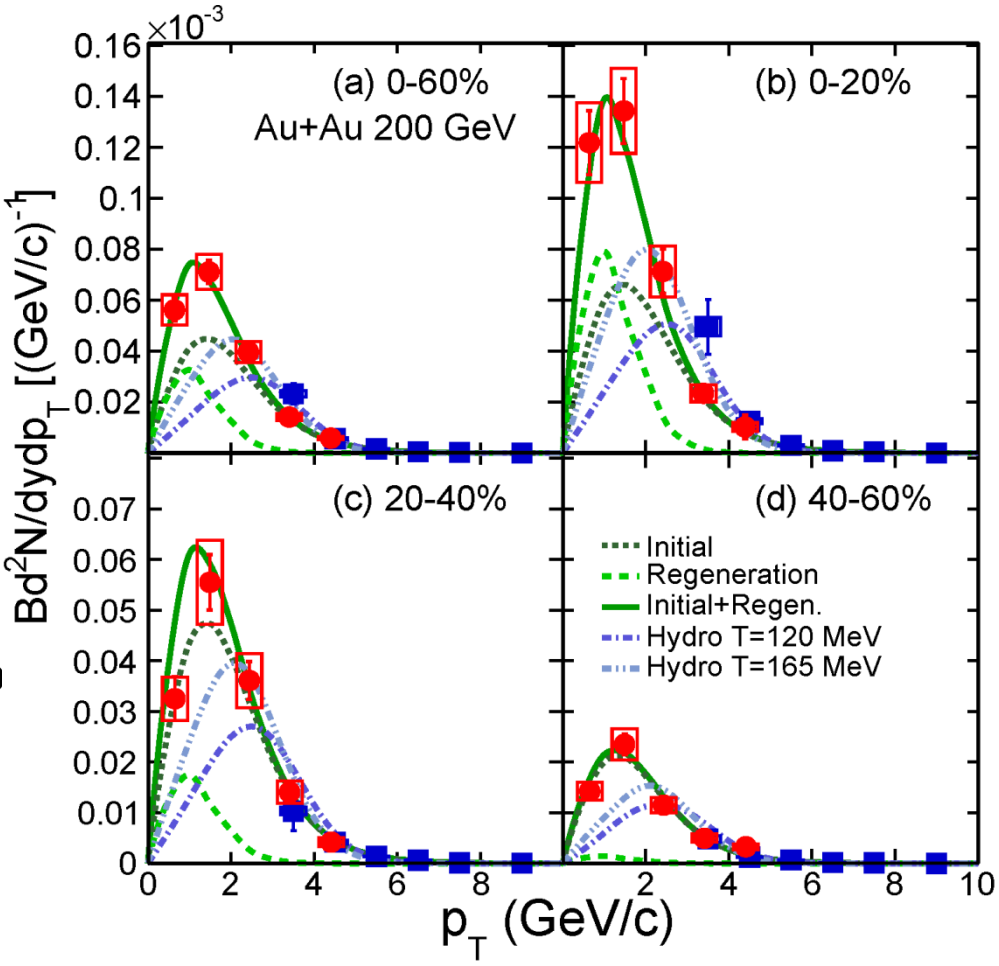
Particles produced according to a Lévy-distribution



STAR low-p_T Au+Au, CuCu : arXiv:1310.3563
high-p_T Au+Au: Phys.Lett. B722, 55 (2013)
high-p_T Cu+Cu : Phys. Rev. C 80 (2009) 041902
PHENIX: Phys. Rev. Lett. 98 (2007) 232301
Tsallis B-W: Z.Tang et al., Chin.Phys.Lett. 30, 031201 (2013)

J/ψ spectra, Au+Au at 200 GeV

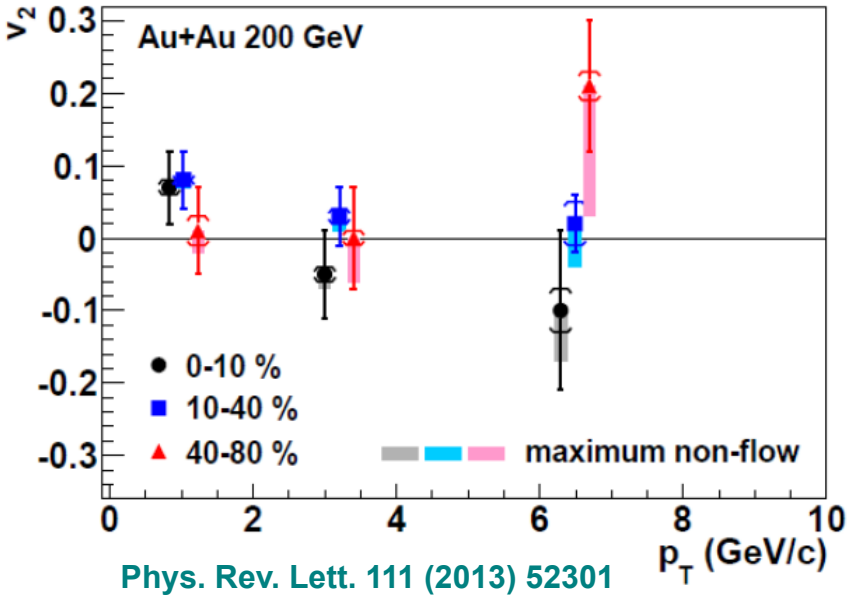
- J/ψ spectrum softer than Tsallis Blast-Wave model
  - Small radial flow?
  - Recombination at low p_T?
- **Viscous hydrodynamics**
  - J/ψ decouples at 120..165 MeV
  - fails at low-p_T
- **Y. Liu et al.**
  - Includes J/ψ suppression due to color screening
  - Includes statistical regeneration
  - peripheral: initial production dominates.
    central: regeneration becomes more significant at low p_T.



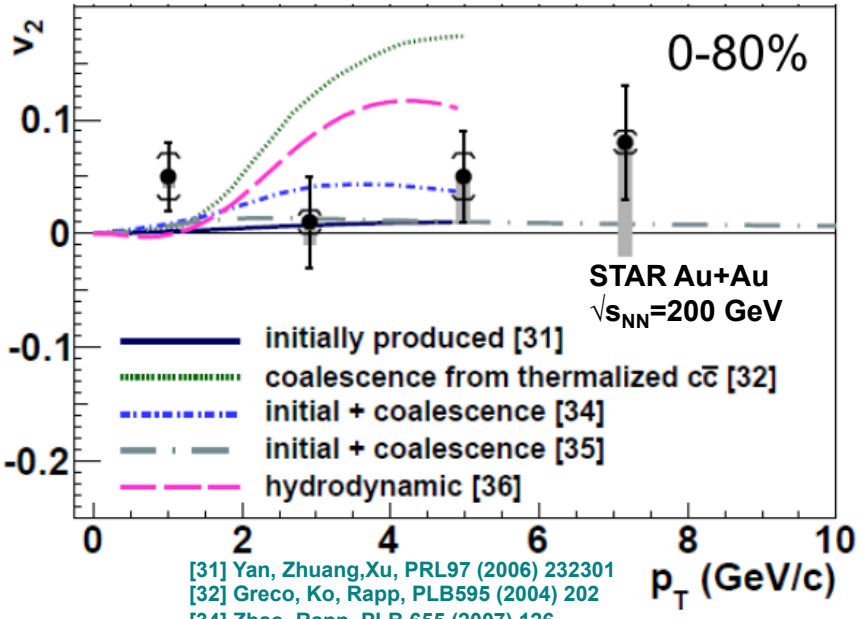
Y. Liu et al., Phys. Lett. B 678, 72 (2009)
U. W. Heinz and C. Shen (2011), private communication.

Coalescence of charm quarks is needed

Azimuthal anisotropy (v_2)



Phys. Rev. Lett. 111 (2013) 52301

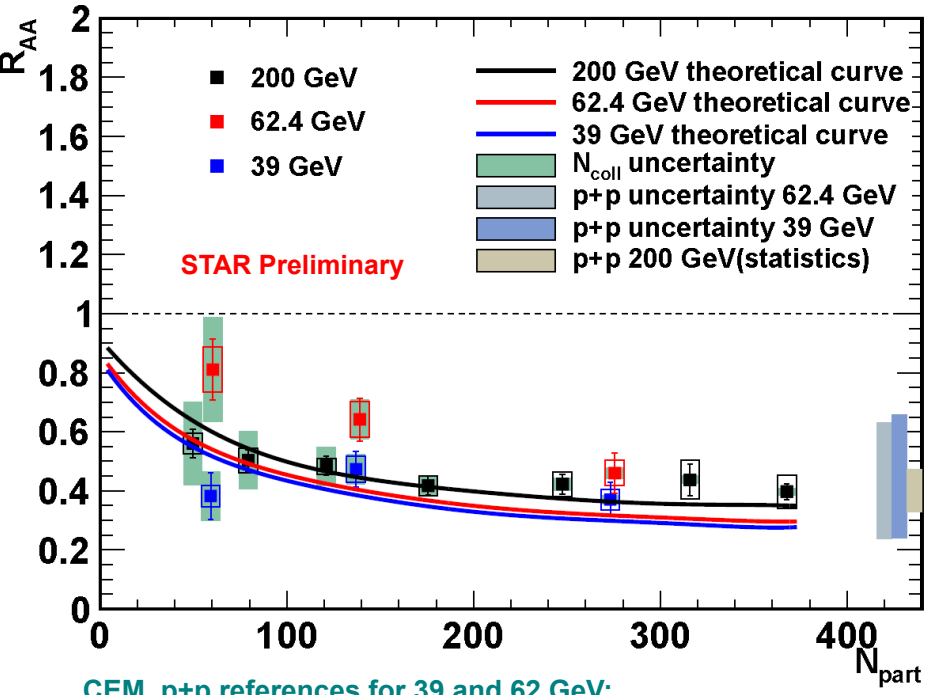


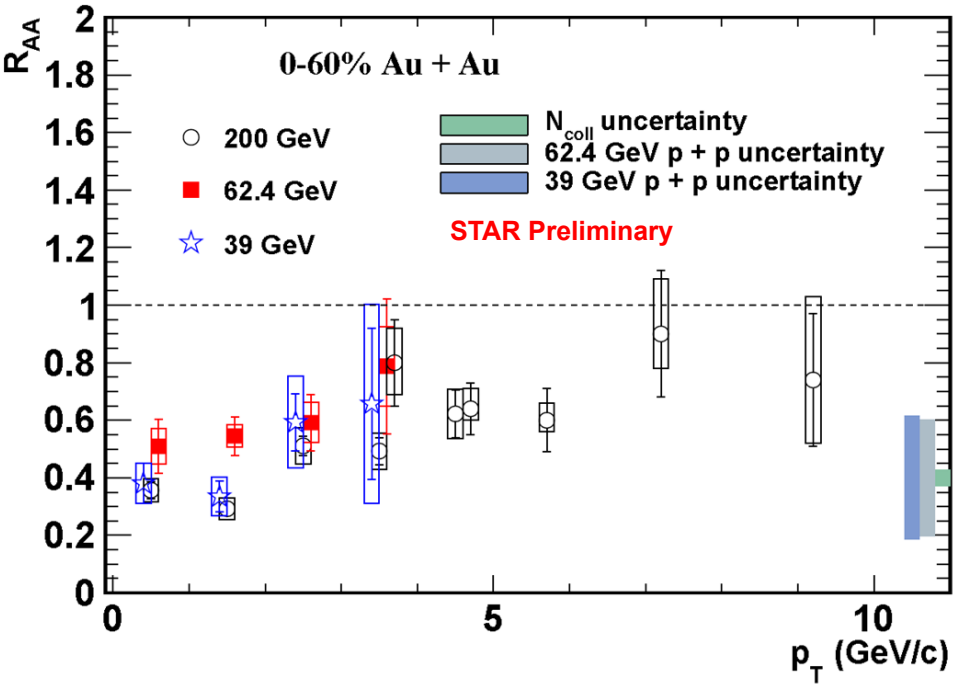
[31] Yan, Zhuang,Xu, PRL97 (2006) 232301
[32] Greco, Ko, Rapp, PLB595 (2004) 202
[34] Zhao, Rapp, PLB 655 (2007) 126
[35] Liu,Xu,Zhuang, NPA834 (2010) 317c
[36] Heinz, Chen (2012)

J/psi v_2 consistent with non-flow at at p_T>2 GeV/c

- Unique among hadrons!
- Regardless of centrality
- Thermalized charm quark coalescence does not dominate production

J/ψ R_{AA} vs. beam energy





CEM p+p references for 39 and 62 GeV:
Nelson, Vogt et al., PRC87, 014908 (2013)
Theory: Zhao, Rapp, PRC82, 064905 (2010)

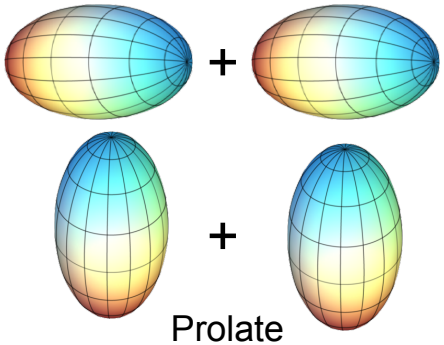
- Similar suppression in Au+Au at **200**, **62.4** and **39** GeV
  - p+p reference is based on CEM calculations
  - Large theoretical uncertainty
- Consistent with theoretical calculations
  - Does coalescence compensate for melting?

U+U: Higher energy densities

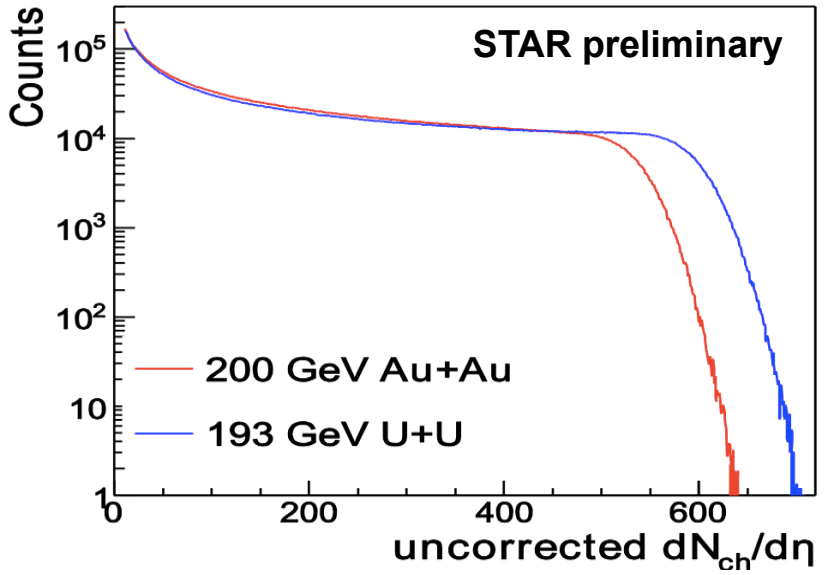
Au+Au Collisions

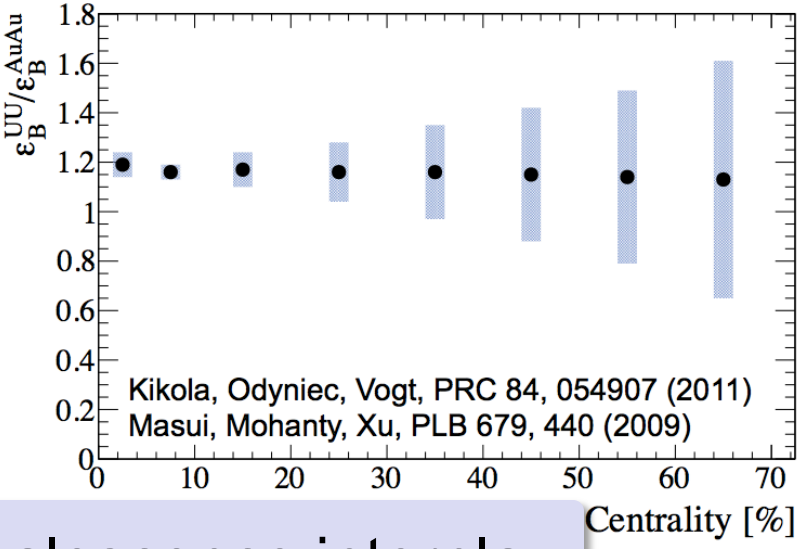
Oblate

U+U Collisions



Prolate



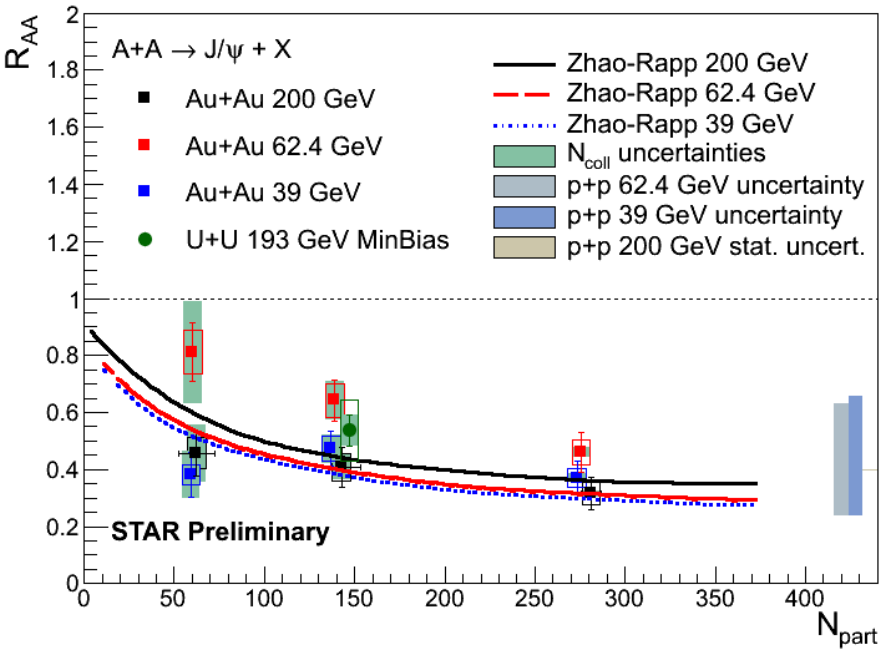


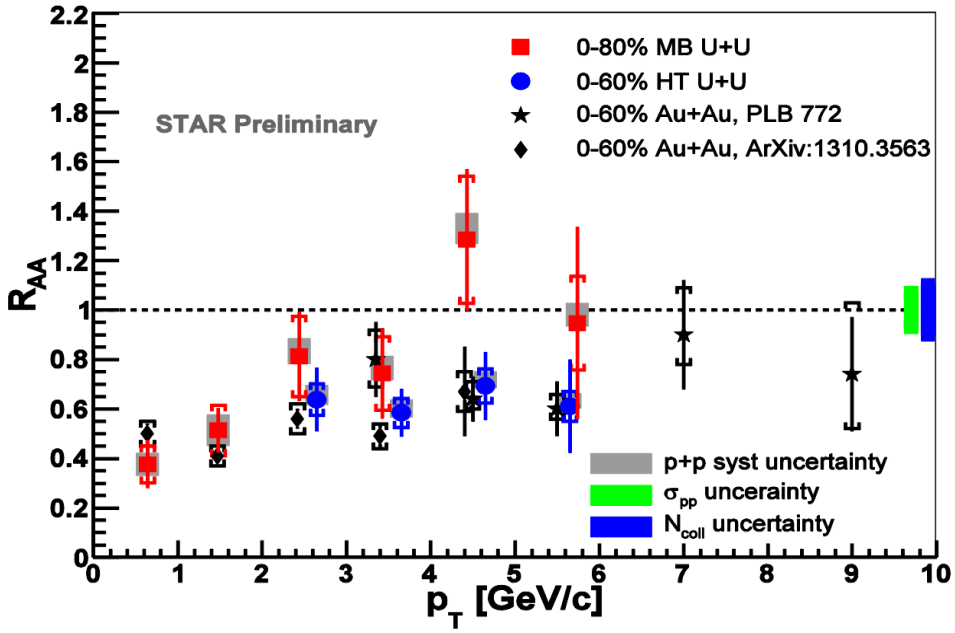
RHIC $\sqrt{s_{NN}}$=193 GeV U+U data (2012)

- Reach higher N_{part} than in Au+Au
- Provide higher energy density

Further test of dissociation-coalescence interplay

J/ψ R_{AA} in 193 GeV U+U



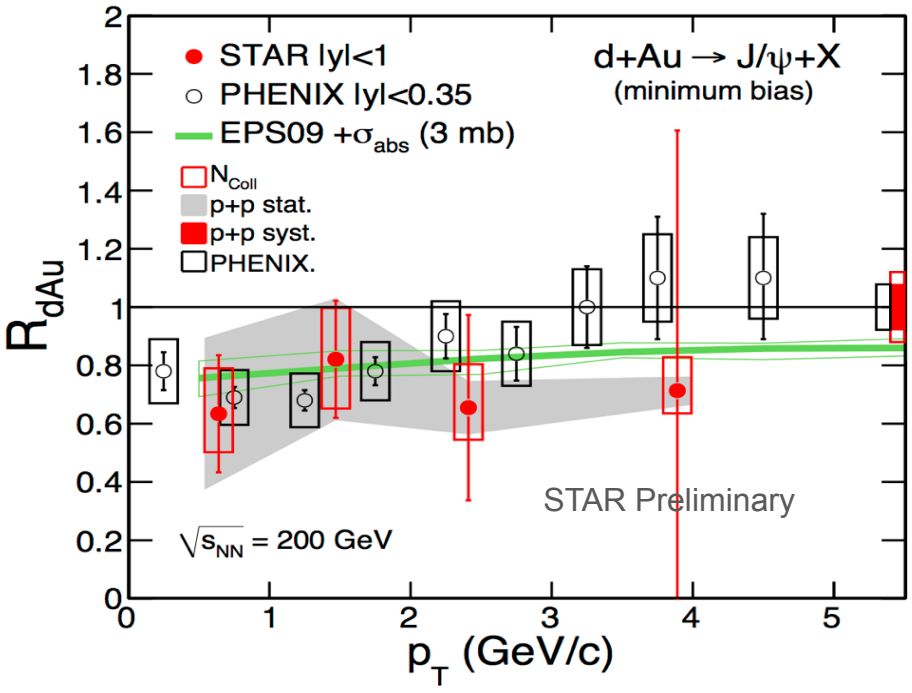


- Nuclear modification factor in U+U similar to Au+Au
  - p+p reference is 200 GeV

Motivation for high-p_T J/ψ

- d+Au → study of cold nuclear matter effects
- $R_{dAu} \approx 1$ for high p_T

  → CNM effects are small at high-p_T



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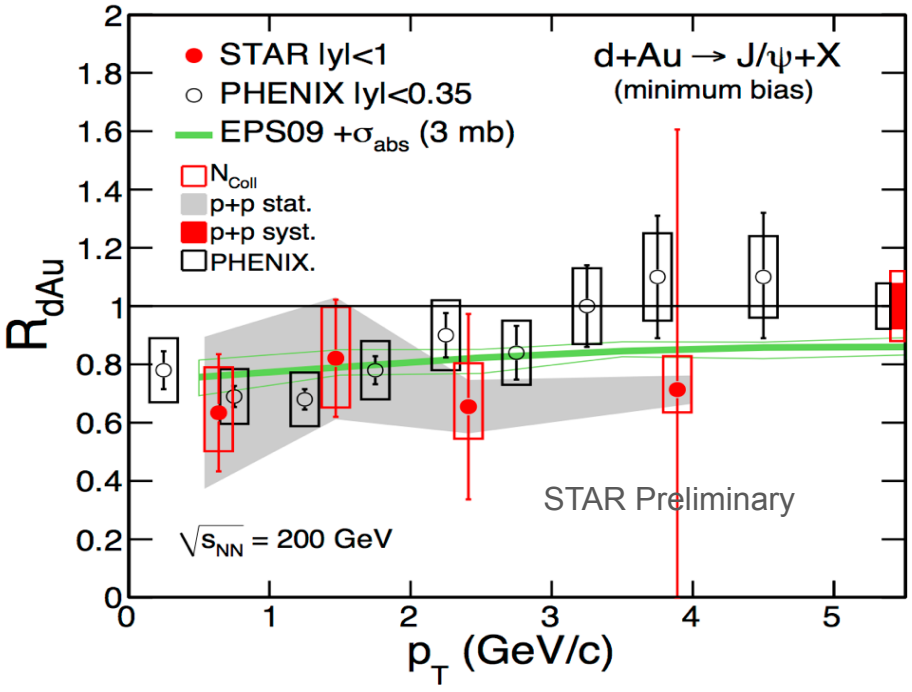

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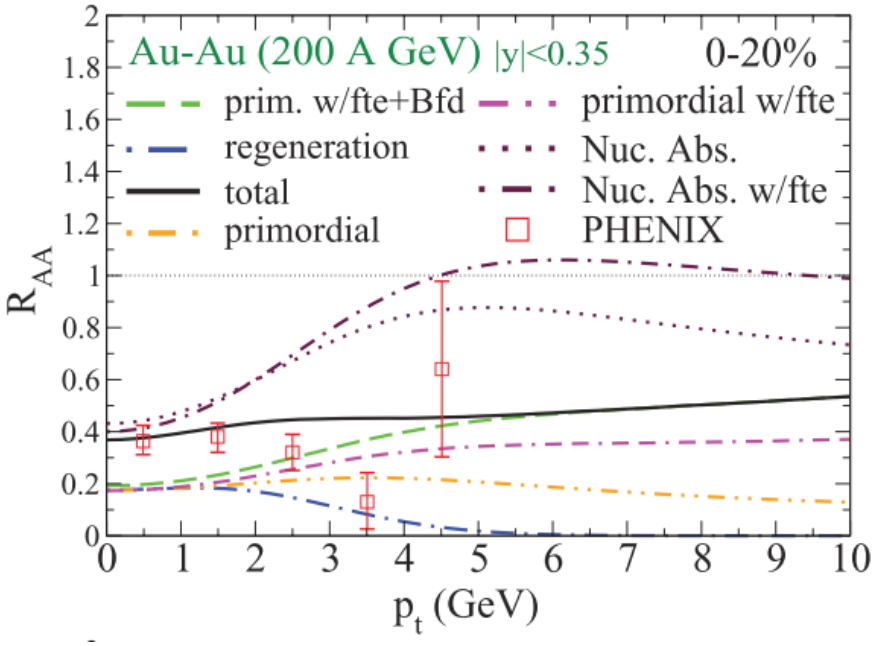
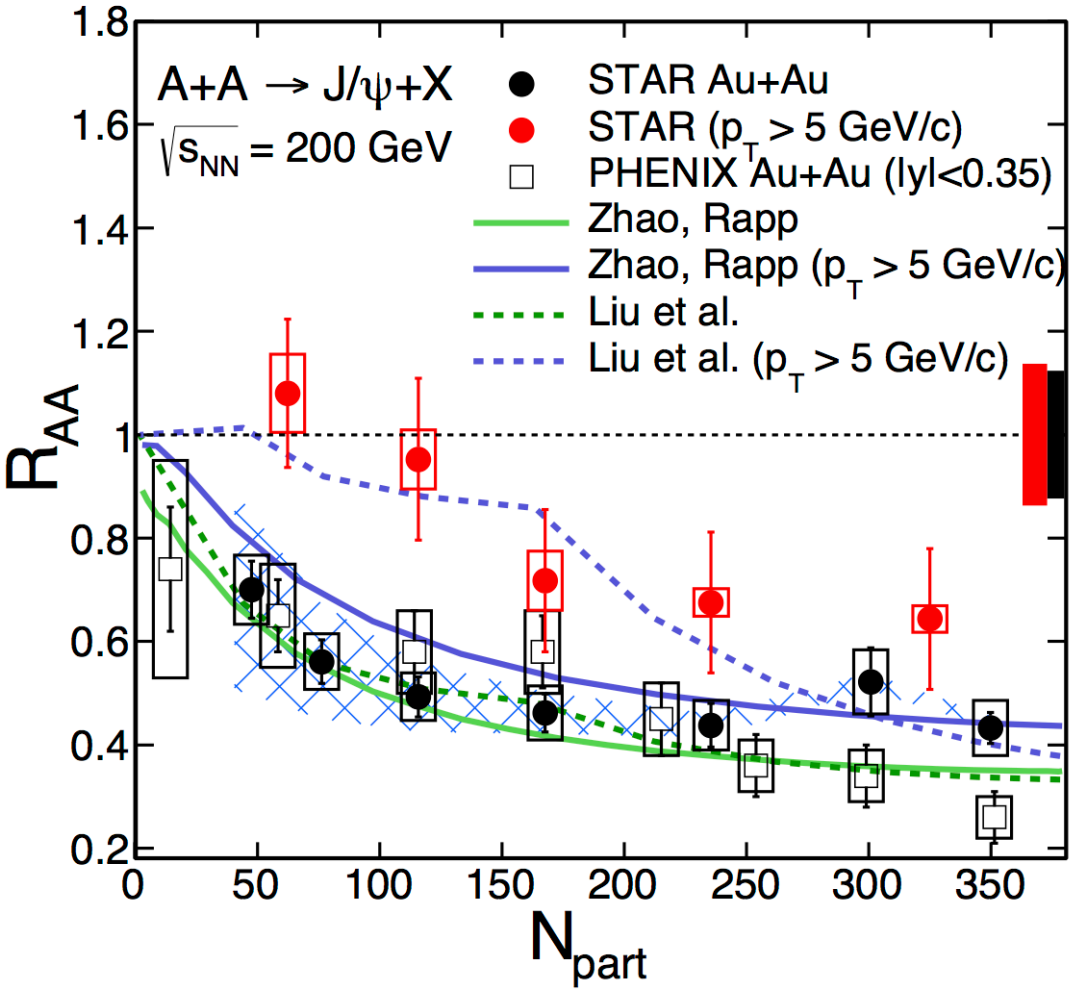


- Much less regeneration

High-p_T J/ψ in Au+Au



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- Suppression of high-p_T J/ψ in central collisions

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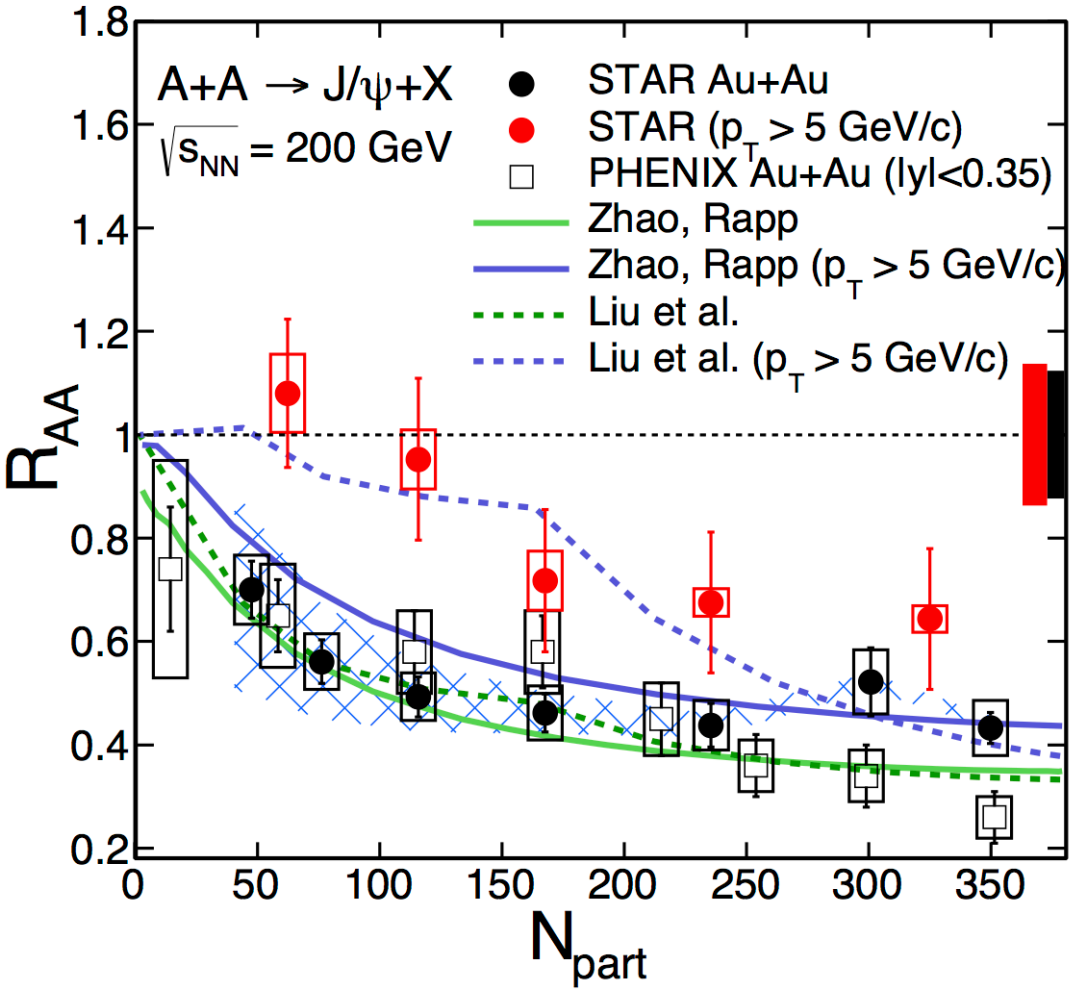

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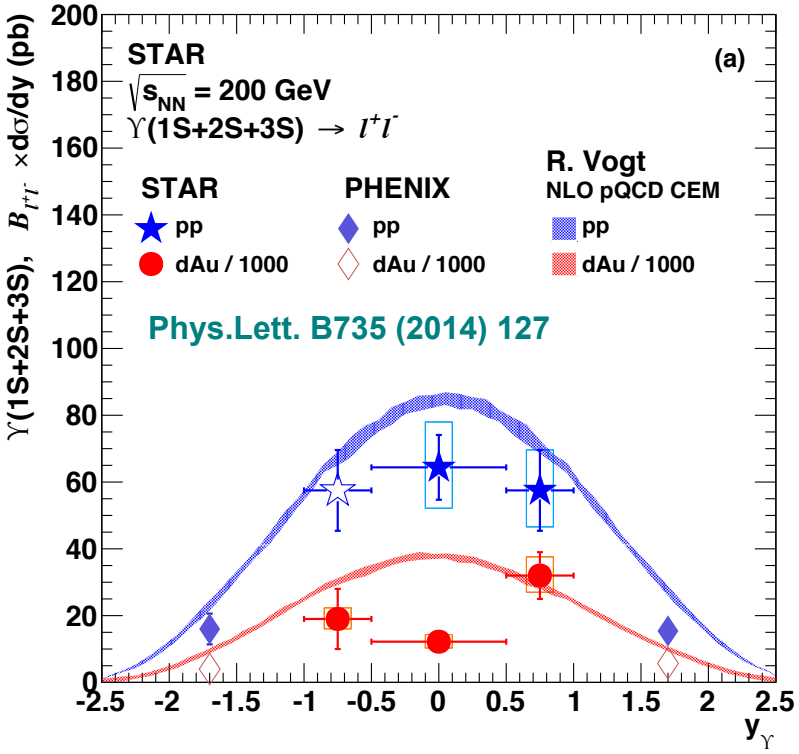
High-p_T J/ψ suppression is clearly an sQGP effect

Υ in p+p – baseline



- p+p Υ cross section vs. y, compared to pQCD predictions

  R. Vogt, Phys. Rep. 462125, 2008

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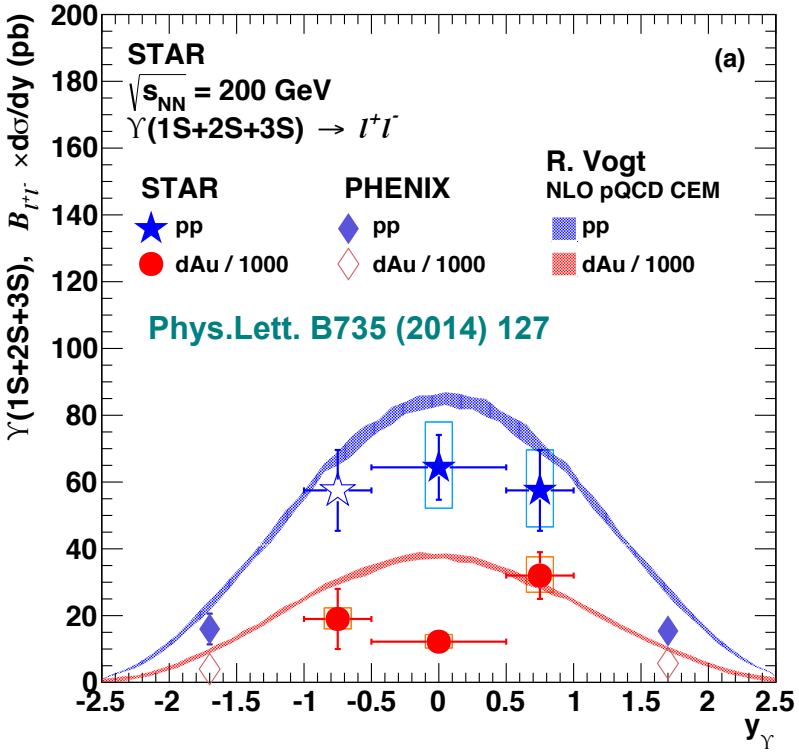

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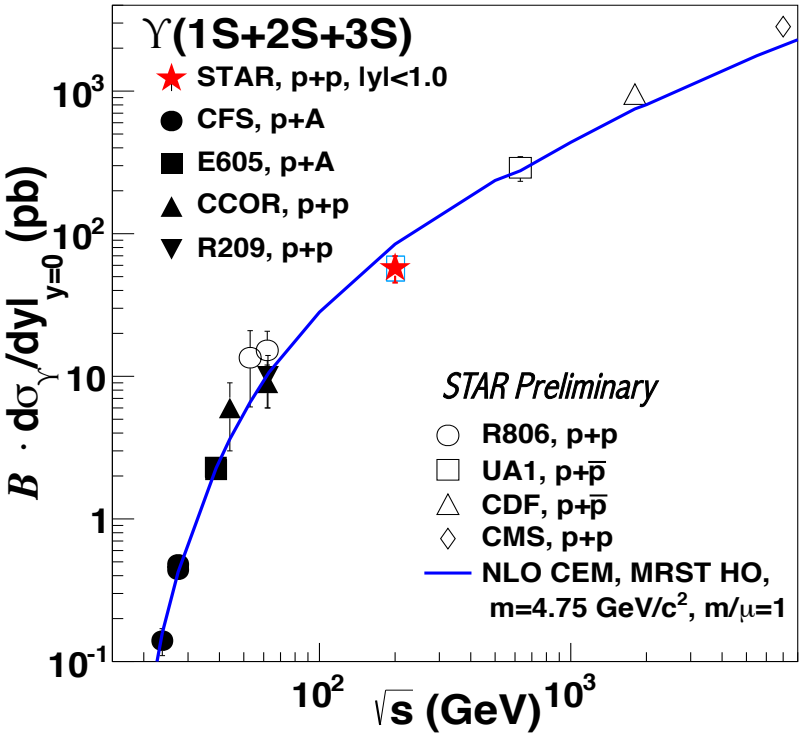
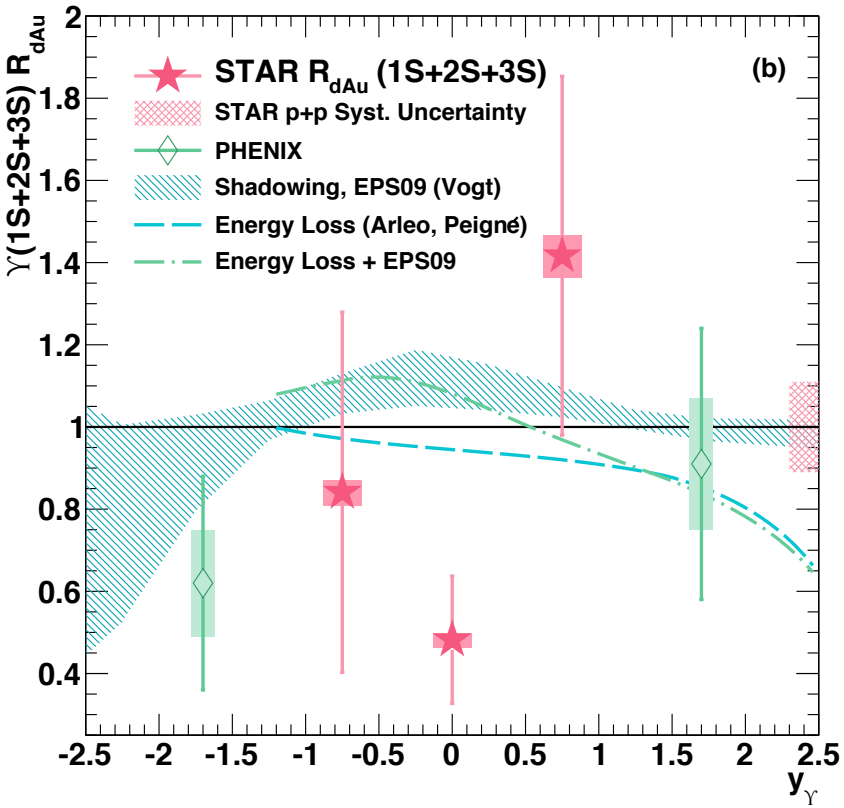


- p+p Υ cross section, compared to world data trend

→ Leszek Kosarzewski's talk on Υ in p+p 500 GeV

Υ R_{dAu} – CNM effects



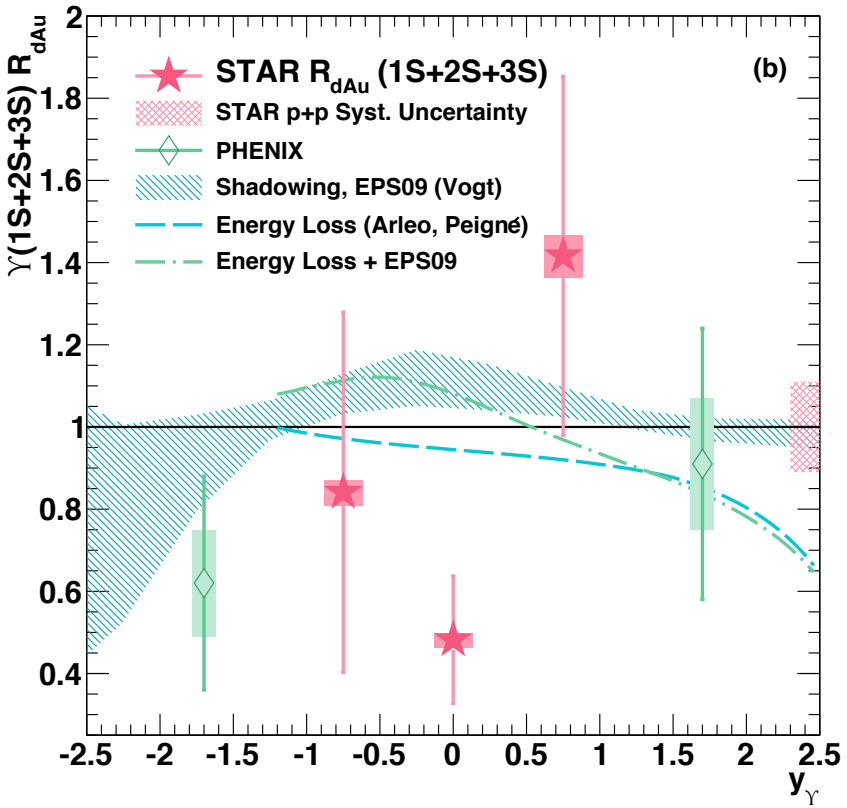
Phys.Lett. B735 (2014) 127

- Models include
  - Gluon nPDF (Anti)shadowing
  - Initial parton energy loss
- Indication of suppression at mid-rapidity beyond models

R_{dAu}=0.48 ± 0.14(stat) ± 0.07(syst) ± 0.02 (pp stat) ± 0.06 (pp syst)

|y|<0.5

Υ R_{dAu} – CNM effects



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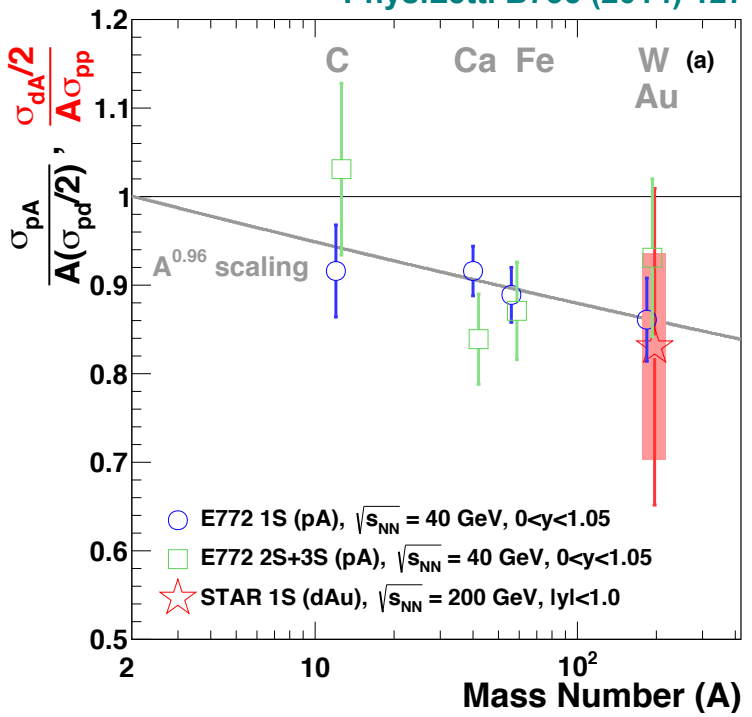
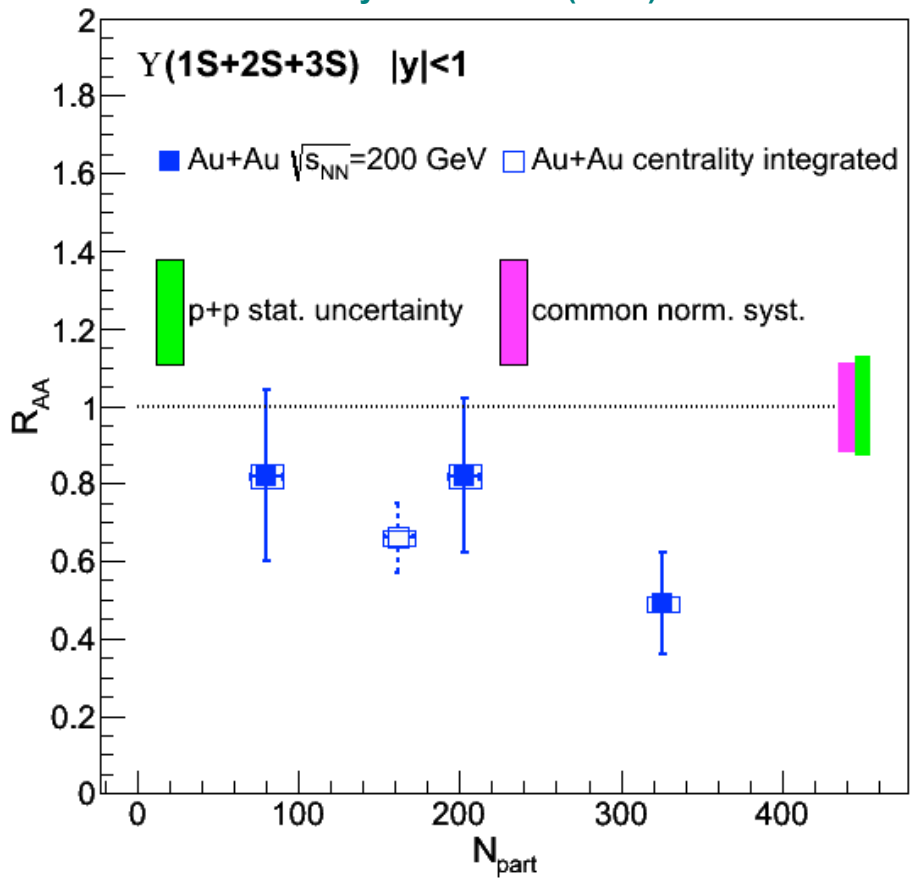


- STAR data consistent with E772

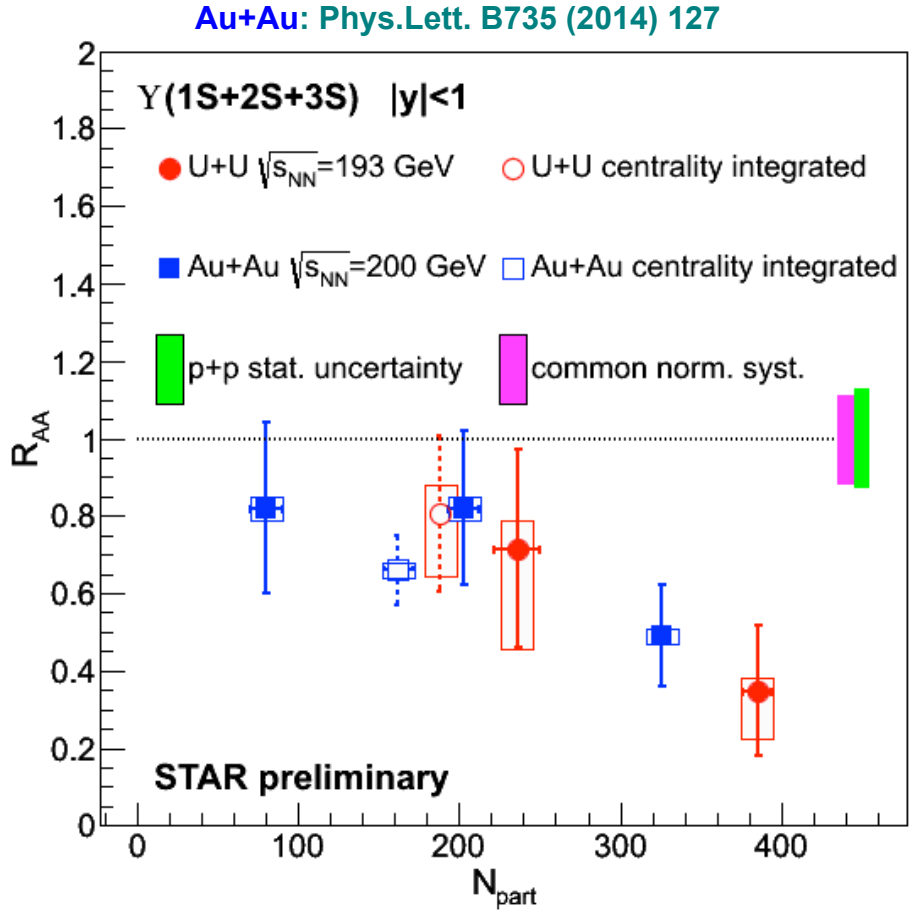
Υ R_{AA}



Au+Au data

- Peripheral data at |y|<1 is consistent with no suppression
- Significant suppression in central data

Υ R_{AA}

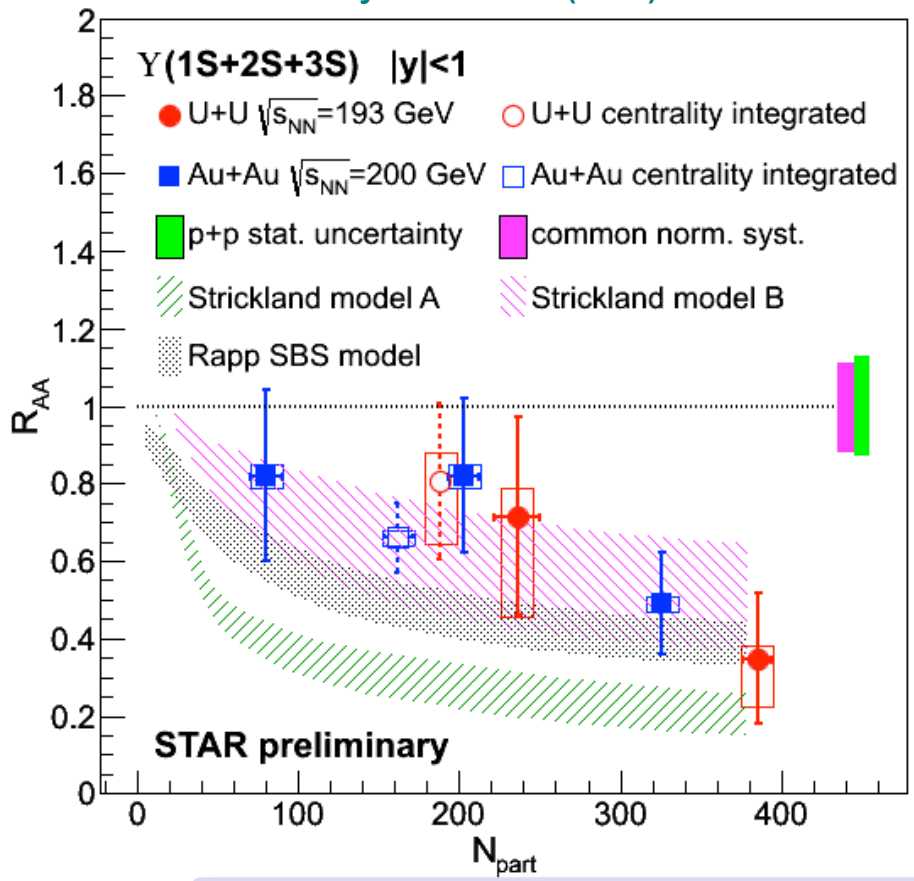


Au+Au and U+U data

- Peripheral data at |y|<1 is consistent with no suppression
- Significant suppression in central data

Trend in U+U follows and extends trend in Au+Au

Υ R_{AA} – data vs. models



Model calculations:

- Strong binding scenario, CNM effects included
  Emerick, Zhao, Rapp, Eur. Phys. J A48, 72 (2012)
- Potential model based on heavy quark internal energy 'B' assumes **428 < T < 443 MeV**
  Strickland, Bazov, Nucl. Phys. A879, 25 (2012)
- Potential model based on heavy quark free energy 'A' disfavored

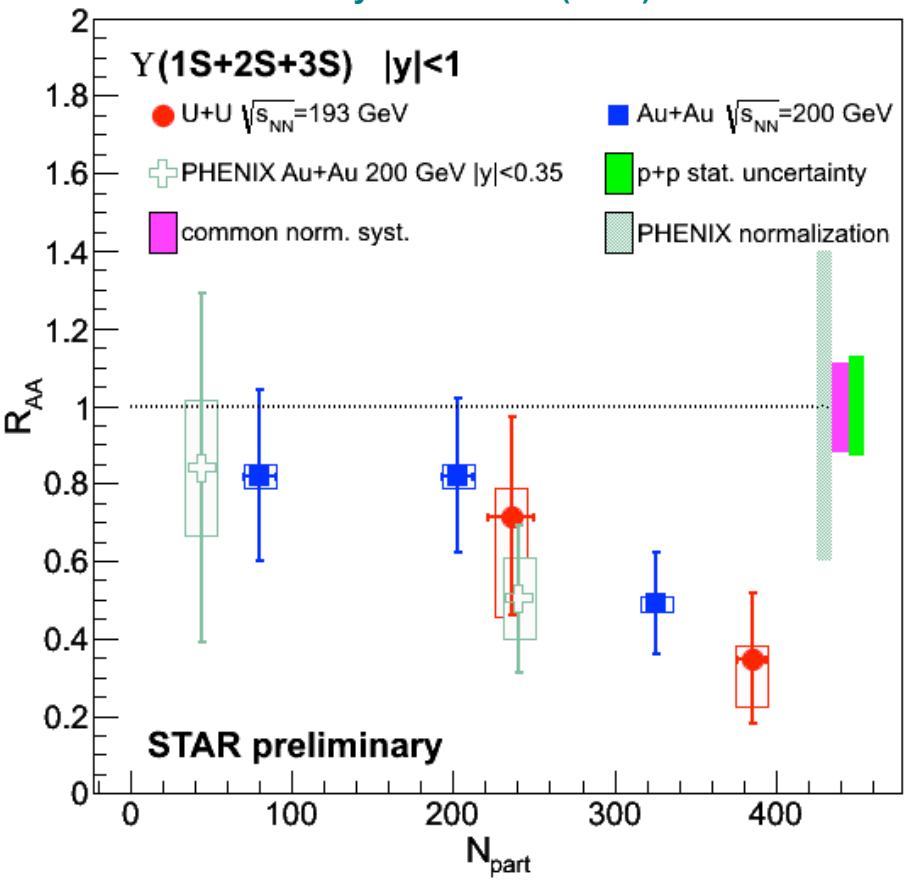
Suppression indicates Υ melting in colored medium

However: CNM effects need further study

→ **Upcoming p+Au run at RHIC in 2015**

Υ R_{AA} – RHIC comparison

Au+Au: Phys.Lett. B735 (2014) 127

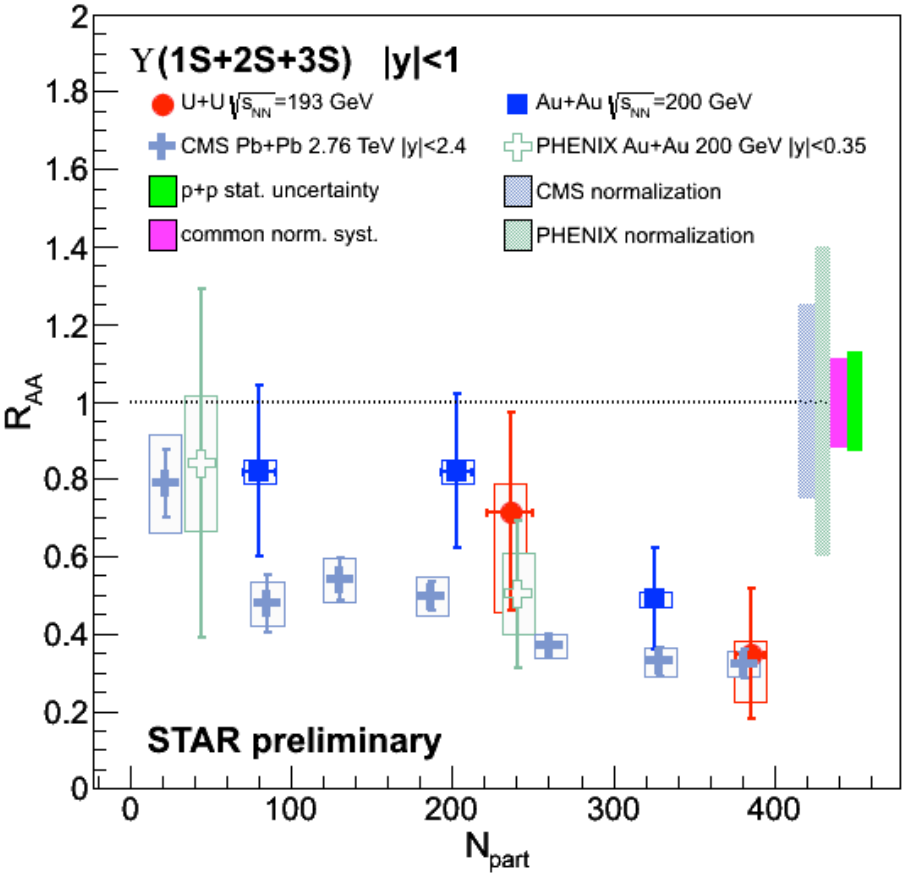


PHENIX Collaboration, arXiv:1404.2246

- STAR vs. PHENIX: data are consistent

Υ R_{AA} – RHIC & LHC comparison

Au+Au: Phys.Lett. B735 (2014) 127



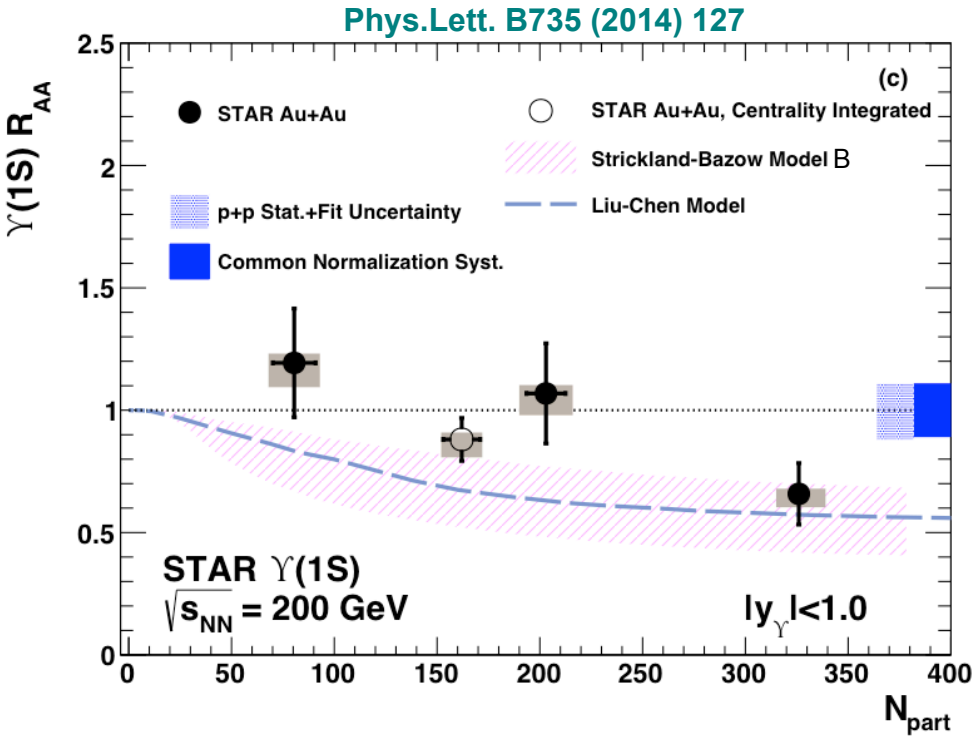
PHENIX Collaboration, arXiv:1404.2246
CMS Collaboration, PRL 109 (2012) 222301

- STAR vs. PHENIX: data are consistent
- RHIC vs. LHC:
  - N_{part} dependence of Υ suppression is weaker at LHC
  - At the highest N_{part} LHC and RHIC suppressions are comparable

→ is suppression driven by the energy density?

Note the uncertainties, however

Υ(1S) R_{AA} in Au+Au

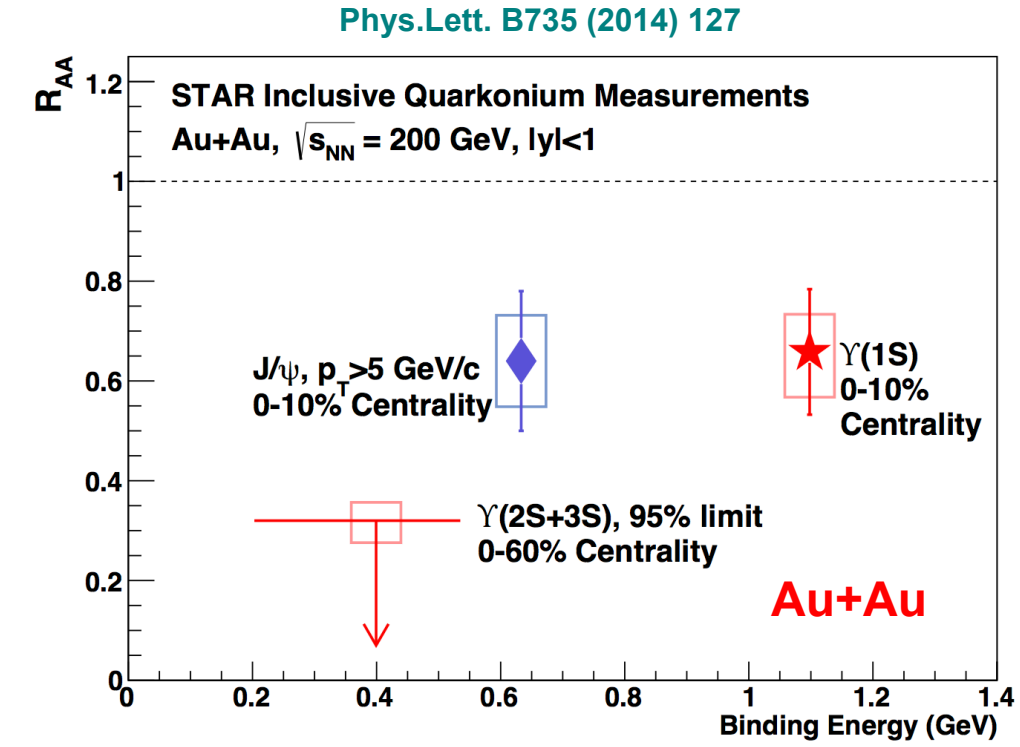


Model calculations

- Strickland-Bazov model B: Hot and cold effects
  Nucl. Phys. A879, 25 (2012)
- Liu-Chen model: Dissociation of Quarkonium No CNM effects
  Phys. Lett. B697 (2011) 32

- Υ(1S) R_{AA} is consistent with unity in peripheral and mid-central Au+Au
- Indication of suppression consistent with model calculation in central Au+Au

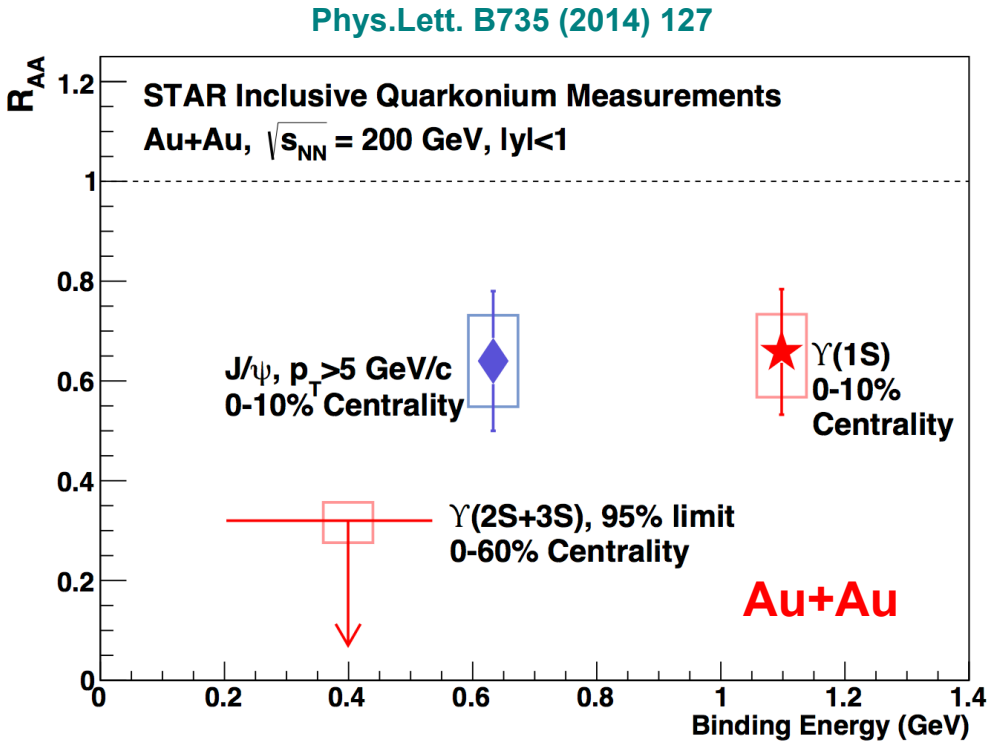
Excited ϒ states in Au+Au



Central Au+Au:

- Excited states ϒ(2S) and ϒ(3S) consistent with complete melting
- ϒ(1S) suppression is similar to high-p_T J/ψ

Excited ϒ states in Au+Au



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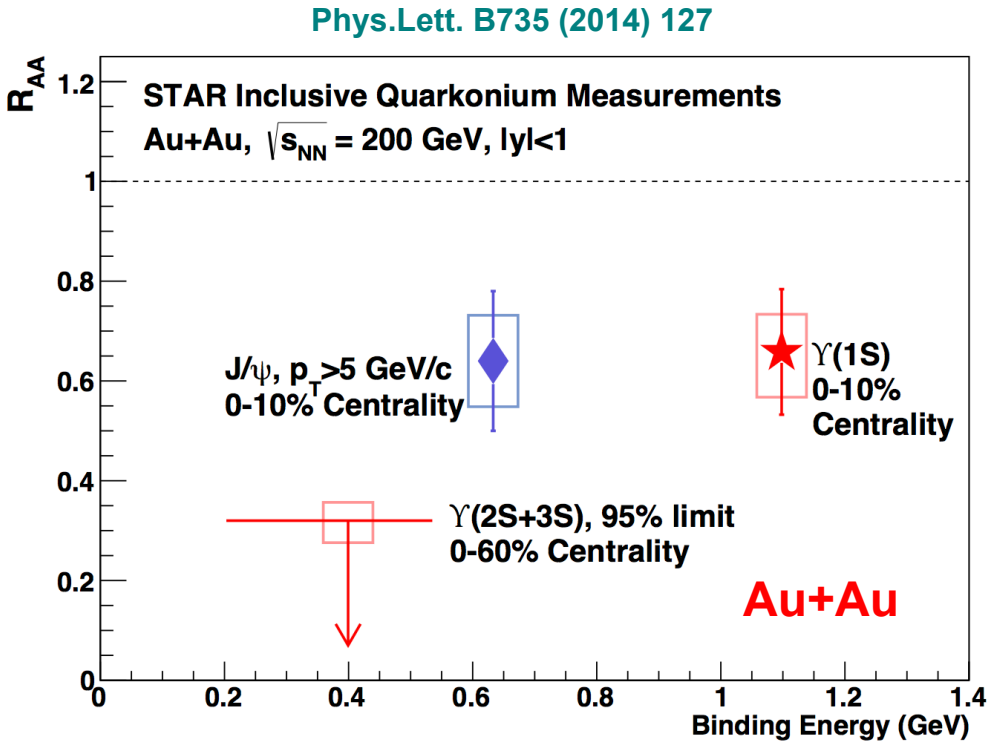
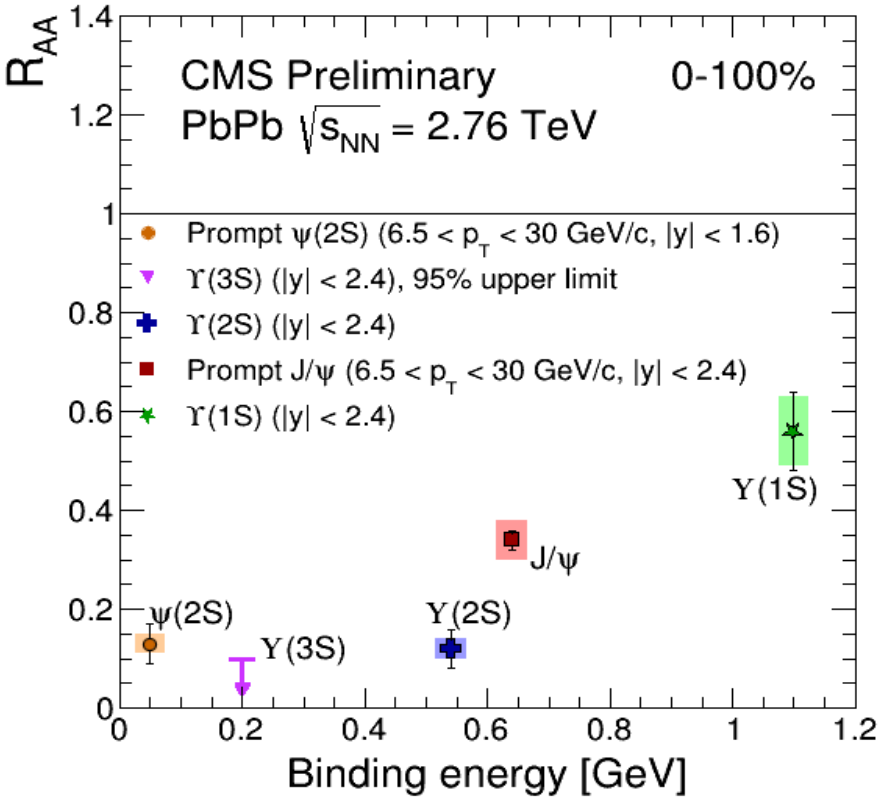
ϒ suppression pattern supports sequential melting

Excited Υ states – LHC comparison

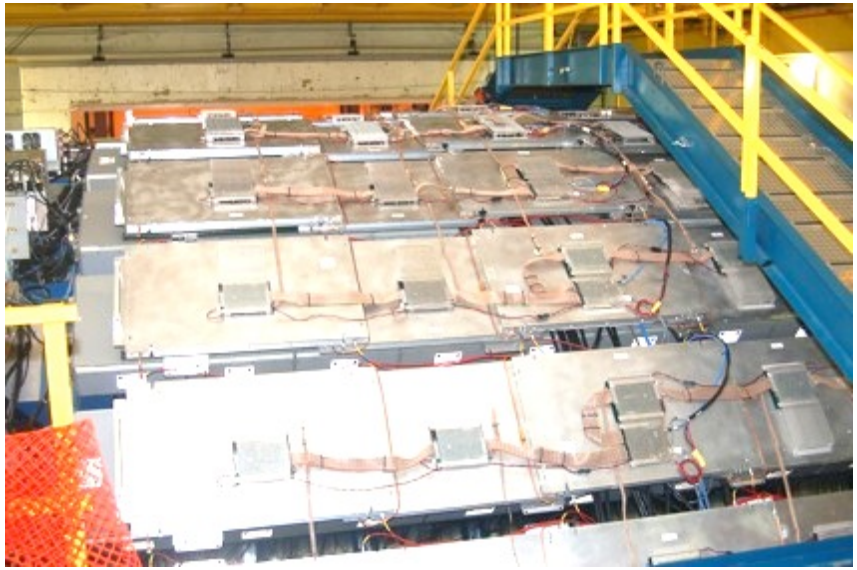




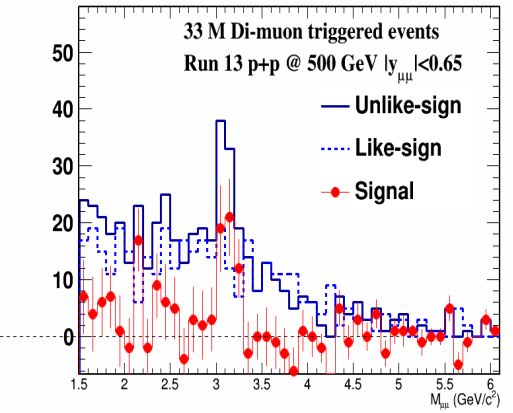
- RHIC $\sqrt{s_{NN}}$=200 GeV Au+Au and LHC $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb collisions: Similar suppression of central Υ(1S)

Outlook: Muon Telescope Detector

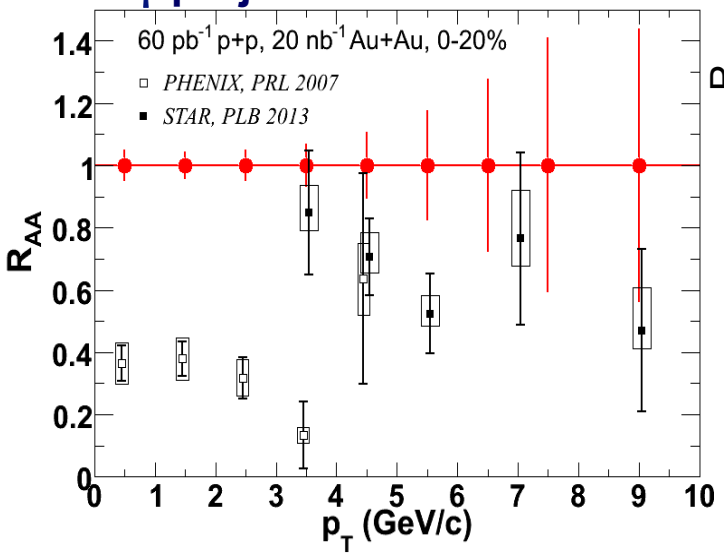
- $J/\psi/\Upsilon \rightarrow \mu^+\mu^-$ (BR ~ 6%)
  - No γ conversion
  - Less Bremsstrahlung → better resolution
  - Less contribution from Dalitz decays
  - Trigger capability for J/ψ in central A+A collisions



Reconstructed J/ψ peak



J/ψ projected stat. errors



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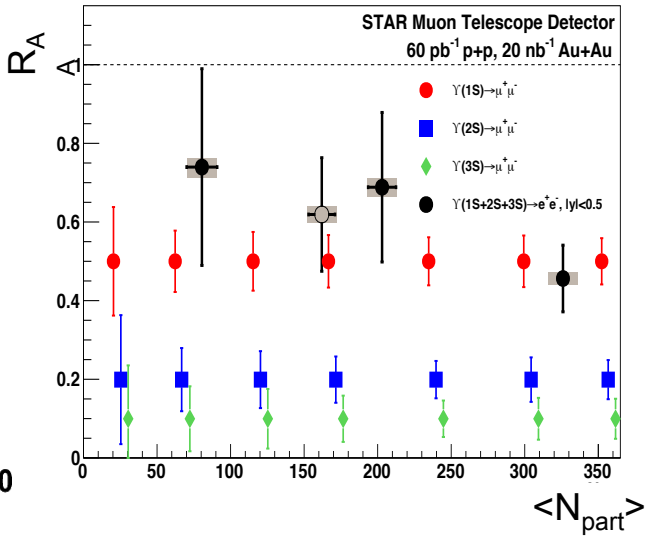

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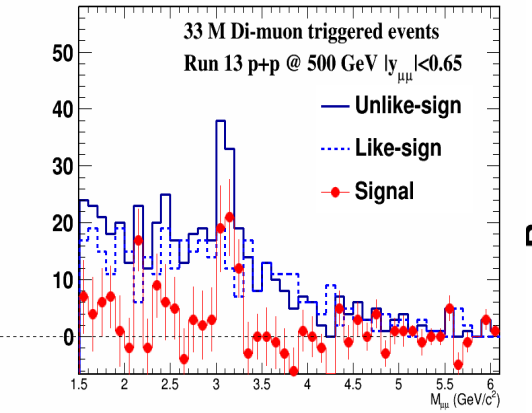
Run14 data was taken with MTD fully operational

Reconstructed J/ψ peak



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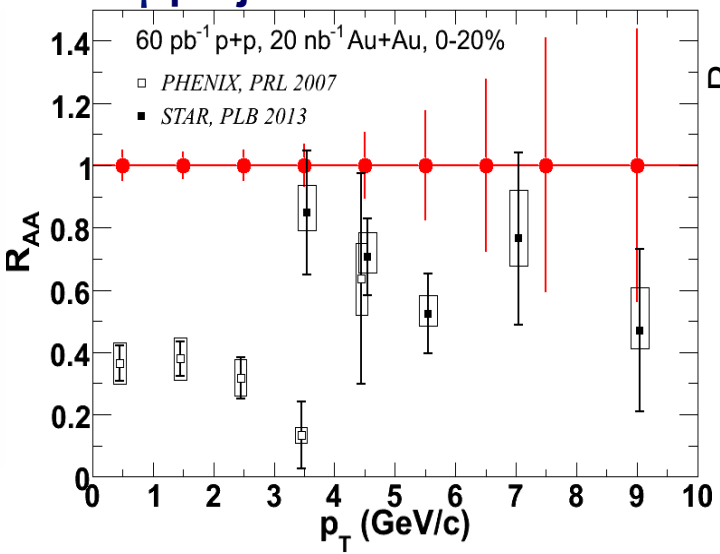
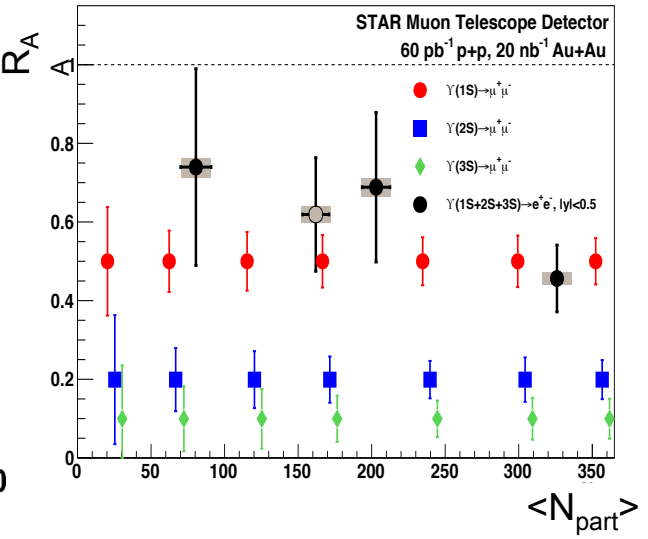


Υ projected stat. errors



Summary

- J/ψ suppression similar in central 39, 62.4 and 200 GeV collisions
- No strong collective behavior of J/ψ observed (v_2, radial flow)
  → *thermalized $c\bar{c}$-coalescence not dominant in production*
- Significant suppression of high-p_T J/ψ and similar Υ(1S) suppression in central A+A collisions
- Υ(2S) and Υ(3S) suppression is stronger than Υ(1S)
  → *clear signal of a deconfined medium*
- Υ(nS) suppression in most central collisions similar to LHC
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Stay tuned for new great results with MTD

Thank You!

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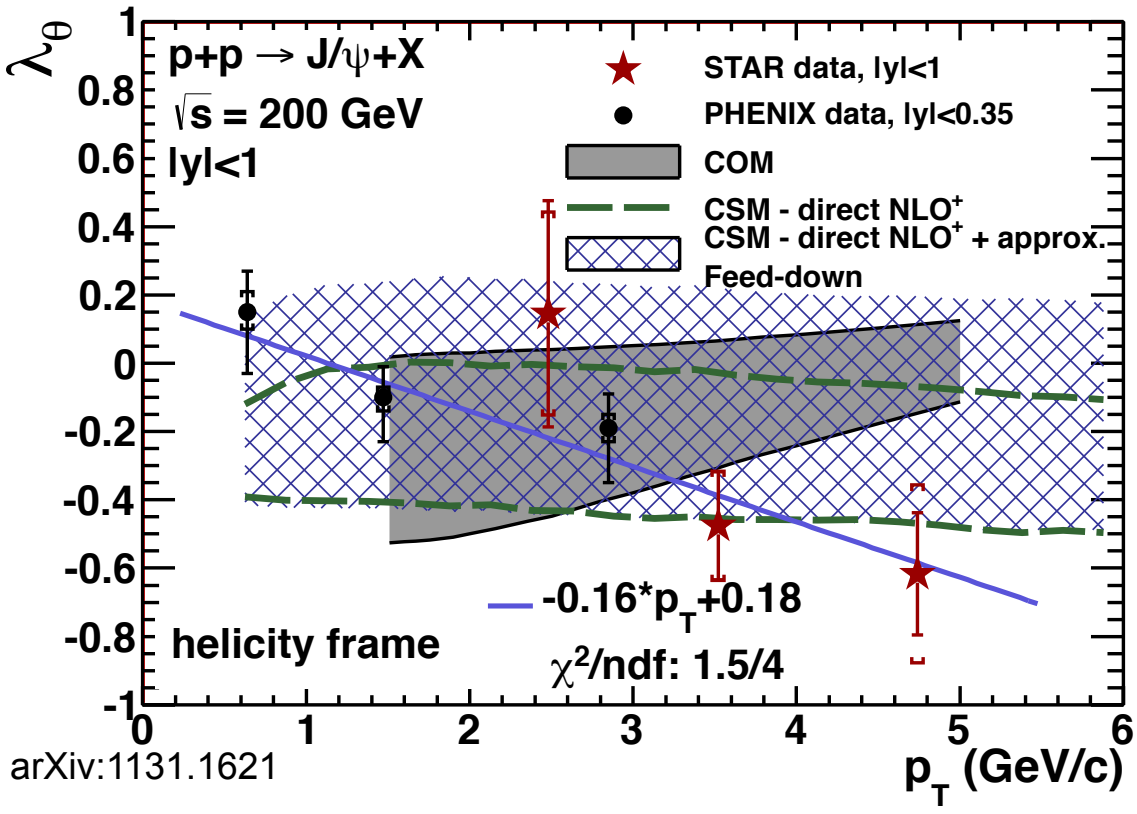
University of Zagreb, Zagreb, HR-10002, Croatia

STAR Collaboration

J/ψ in p+p – polarization



- 2<pT<6 GeV/c
- STAR+PHENIX consistent with NLO +CSM
  - Higher statistics needed to discriminate
- p+p 500 GeV results will improve precision for future CNM calculations