ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Heavy Quark Physics in Heavy-Ion collisions: experiments, phenomenology and theory

Production of Quarkonia in Heavy Ion Collisions at STAR

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for the STAR collaboration

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Academy of Sciences
of the Czech Republic

evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
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)

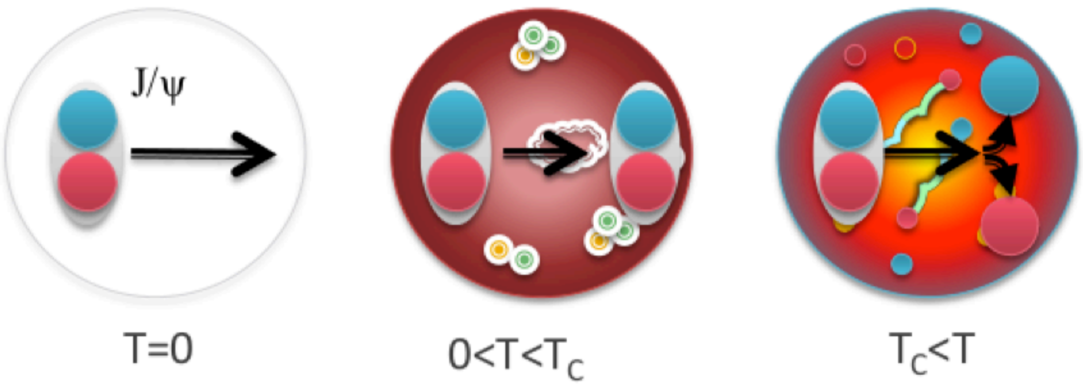

Illustration: A. Rothkopf

Charmonia ($c\bar{c}$):
J/Ψ, Ψ', χ_c

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

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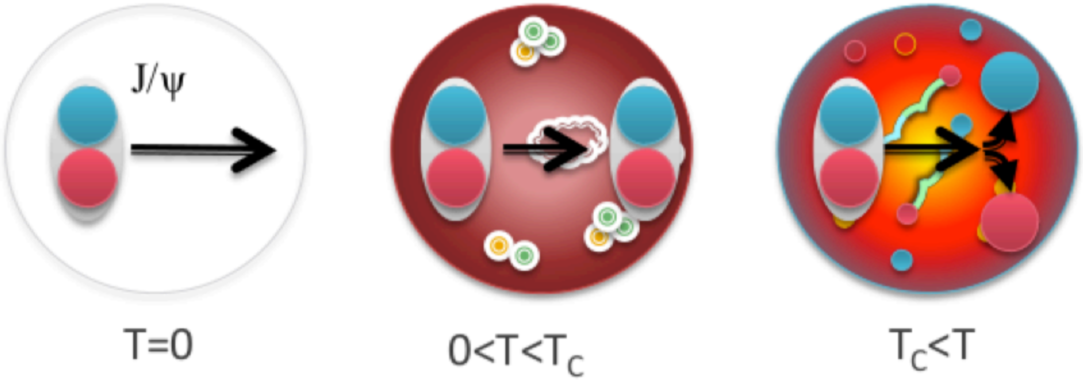

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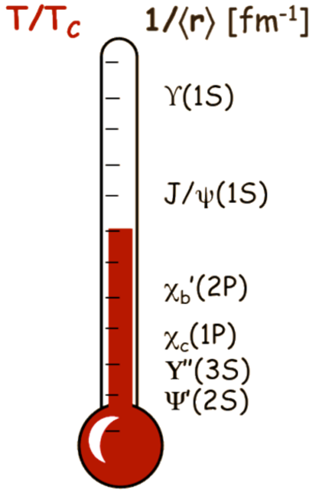


- Sequential melting: Different states dissociate at different temperatures

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

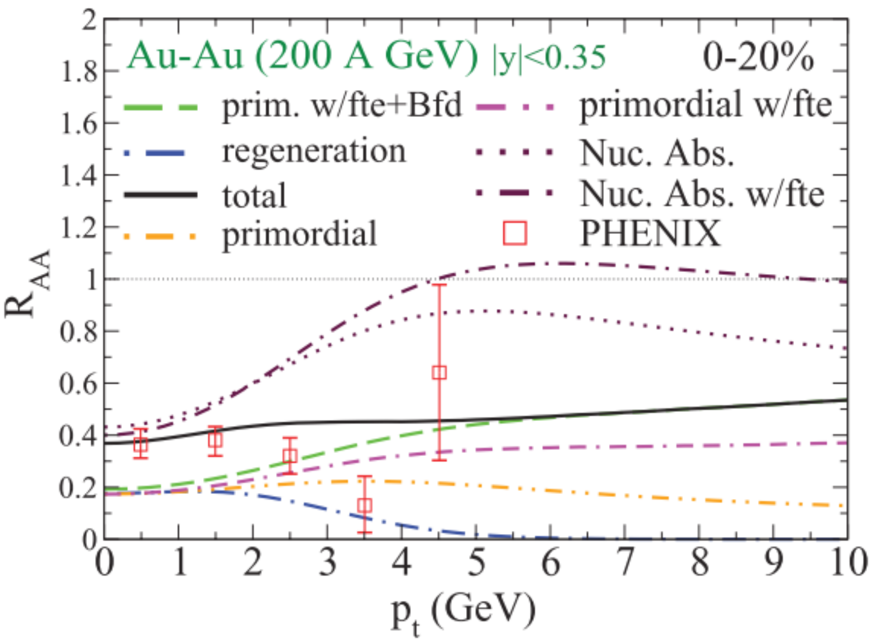
Quarkonia may serve as sQGP thermometer

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)

Data:
PHENIX, Nucl.Phys. A 774 (2006) 747



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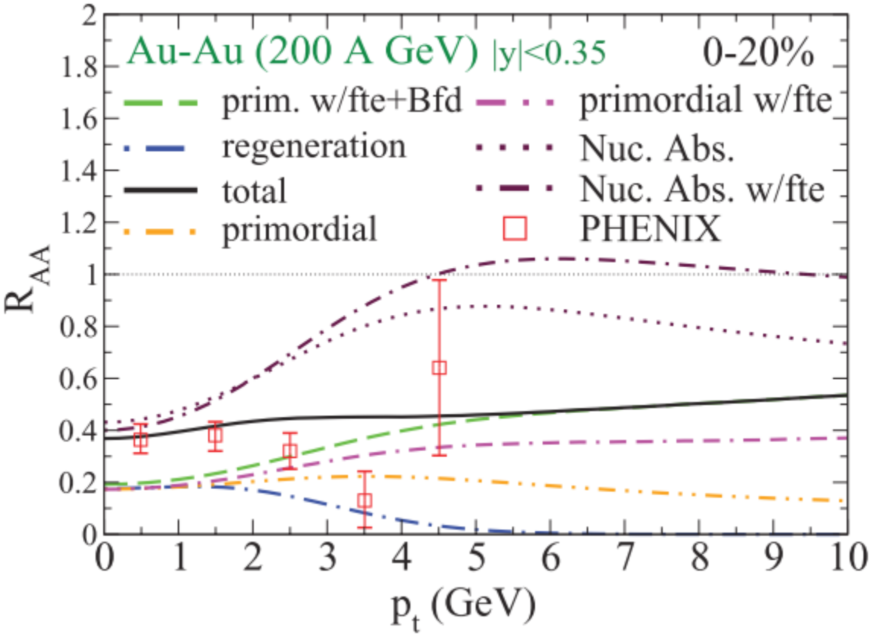


Contribution of different effects is not well understood

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-p_T J/ψ

  →"turn off" regeneration and CNM effects

- Measure ϒ
  - Predictions suggest negligible recombination and co-mover absorption at RHIC energies

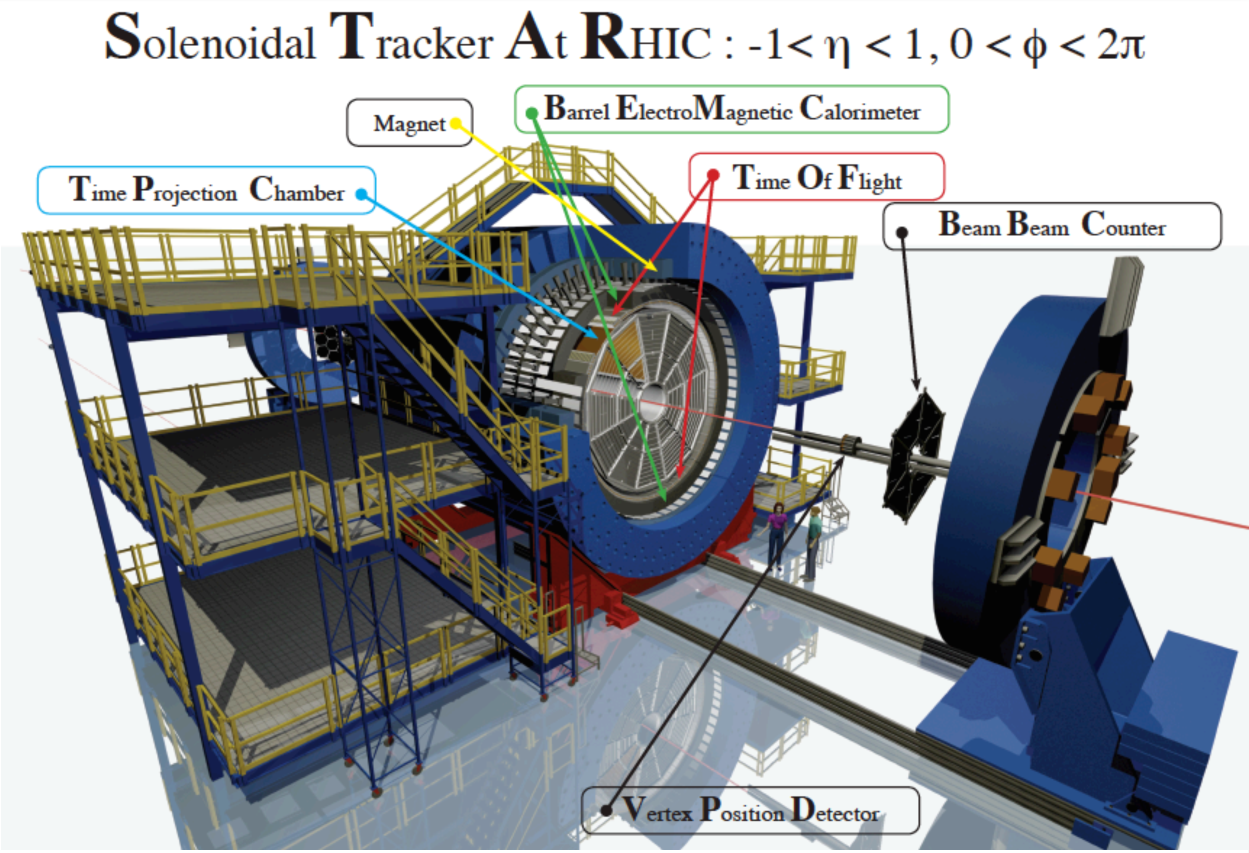
ϒ states provide a cleaner probe at RHIC

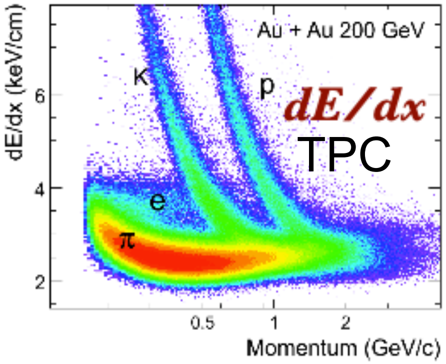
  - Difficult measurement: Low production rate
    Requires good acceptance and specific triggering

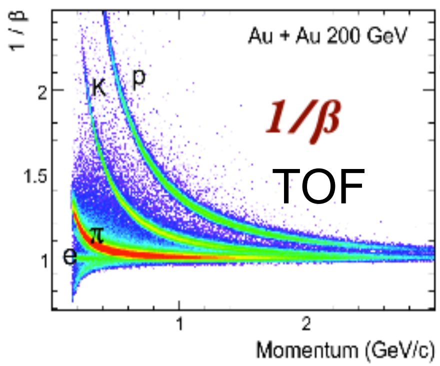
RHIC/STAR

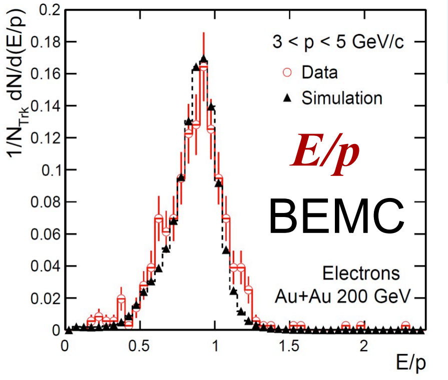
- Reconstruction:
  J/ψ → e^+e^- (B_{ee} ~ 6%)
  ϒ → e^+e^- (B_{ee} ~ 2.4%)
- TPC
  - dE/dx PID
  - Large acceptance, uniform in a wide energy range
- TOF
  - PID using flight time
- BEMC
  - High-p_T trigger
  - PID using E/p and shower shape
- VPD
  - Minimum bias events

Solenoidal Tracker At RHIC : $-1 < \eta < 1$, $0 < \phi < 2\pi$







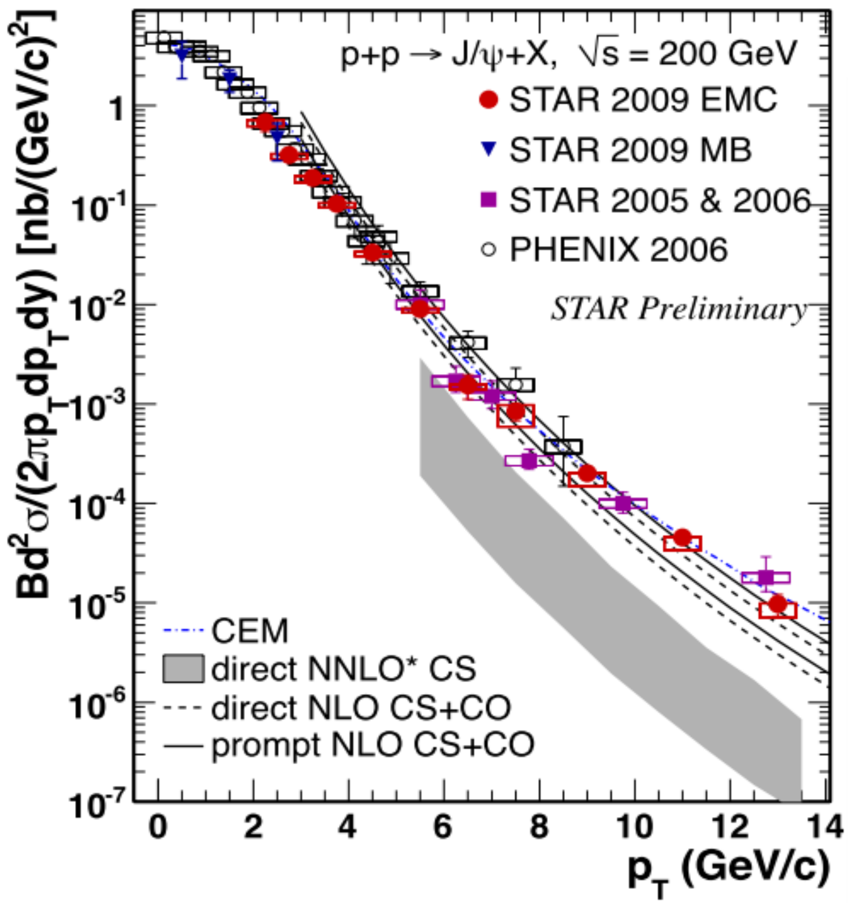


J/ψ spectra, p+p at 200 GeV

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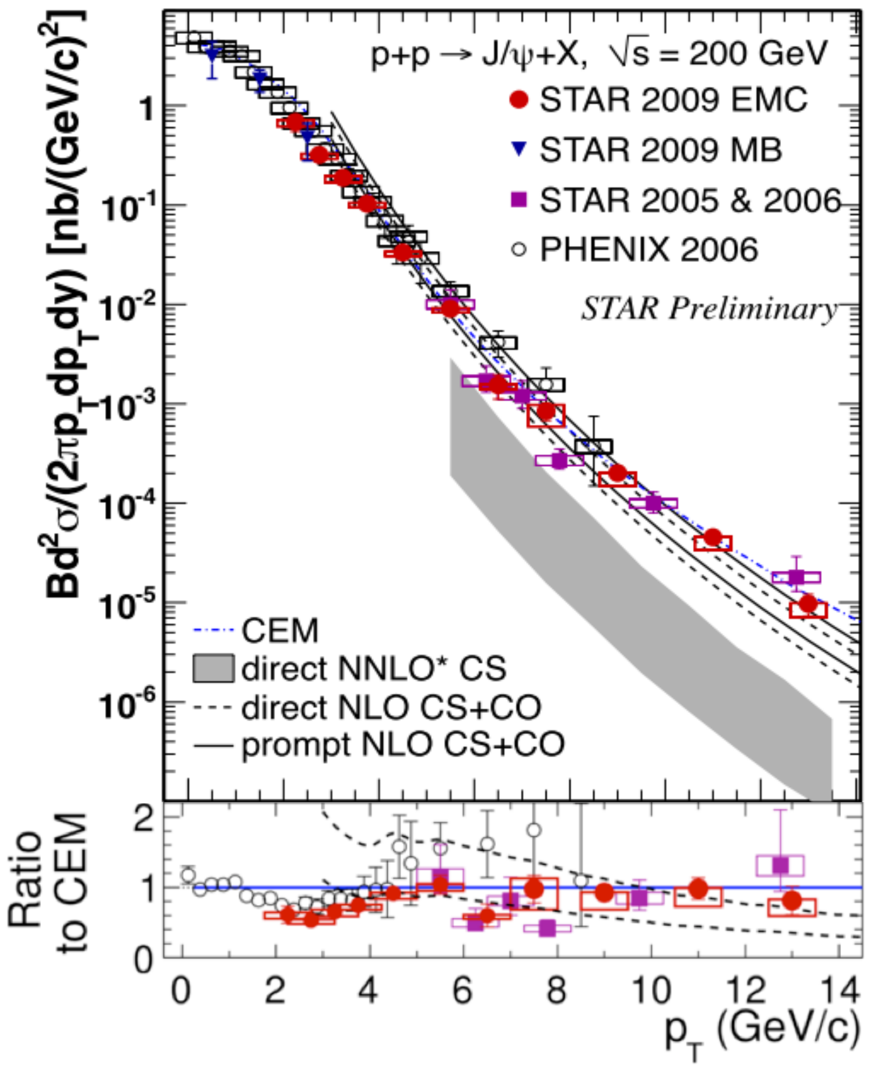
- Model comparison:
  - prompt NLO CS+CO: describes the data for p_T > 4 GeV/c
  - direct NNLO*CS: misses high- p_T part
  - Prompt CEM: reasonable description of spectra, but overpredicts the data at p_T~3 GeV/c

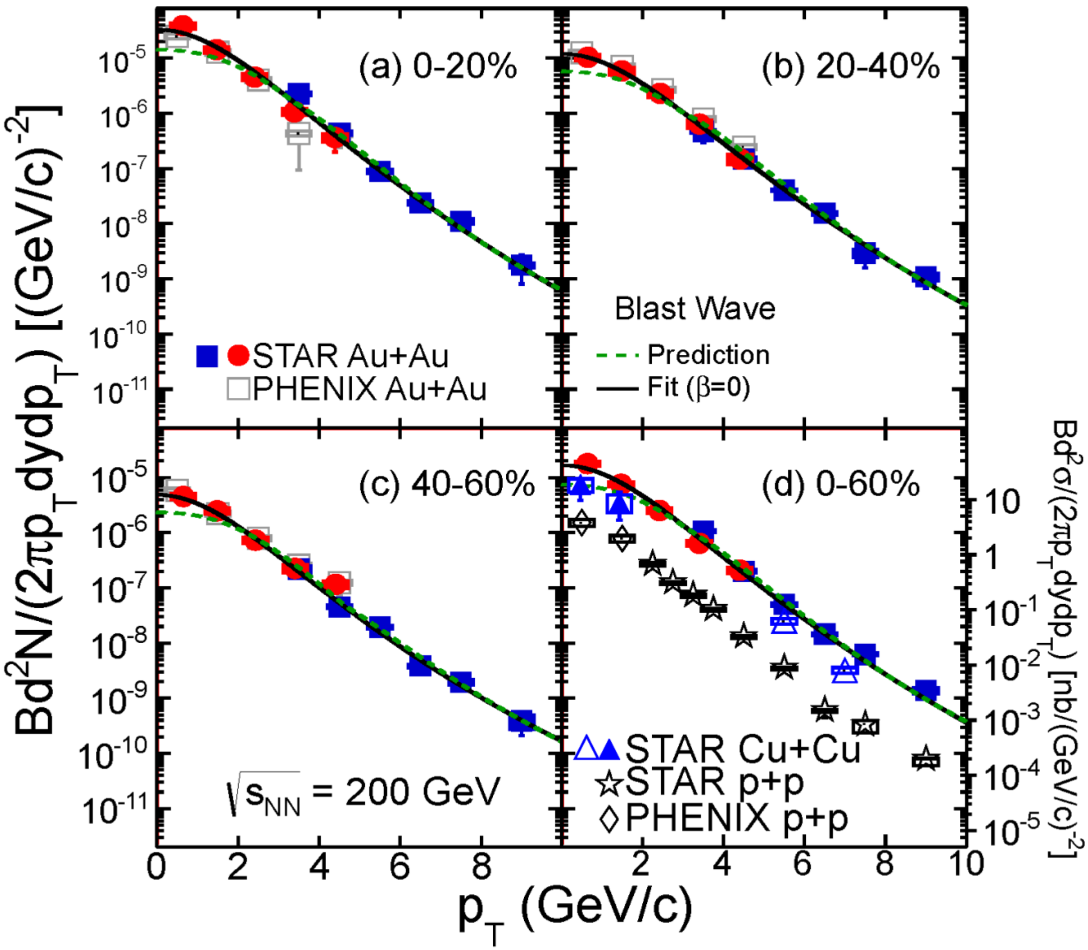
direct NNLO CS: P.Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008) and J.P.Lansberg private communication
NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, Phys. Rev. D 84, 51 114001 (2011) and priv. cor
CEM: A.D. Frawley, T Ullrich, R. Vogt, Pys. Rept. 462 (2008) 125, and R.Vogt priv. comm.

Inclusive J/ψ spectra:



J/ψ spectra, Au+Au at 200 GeV

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



Tsallis Blast-Wave:

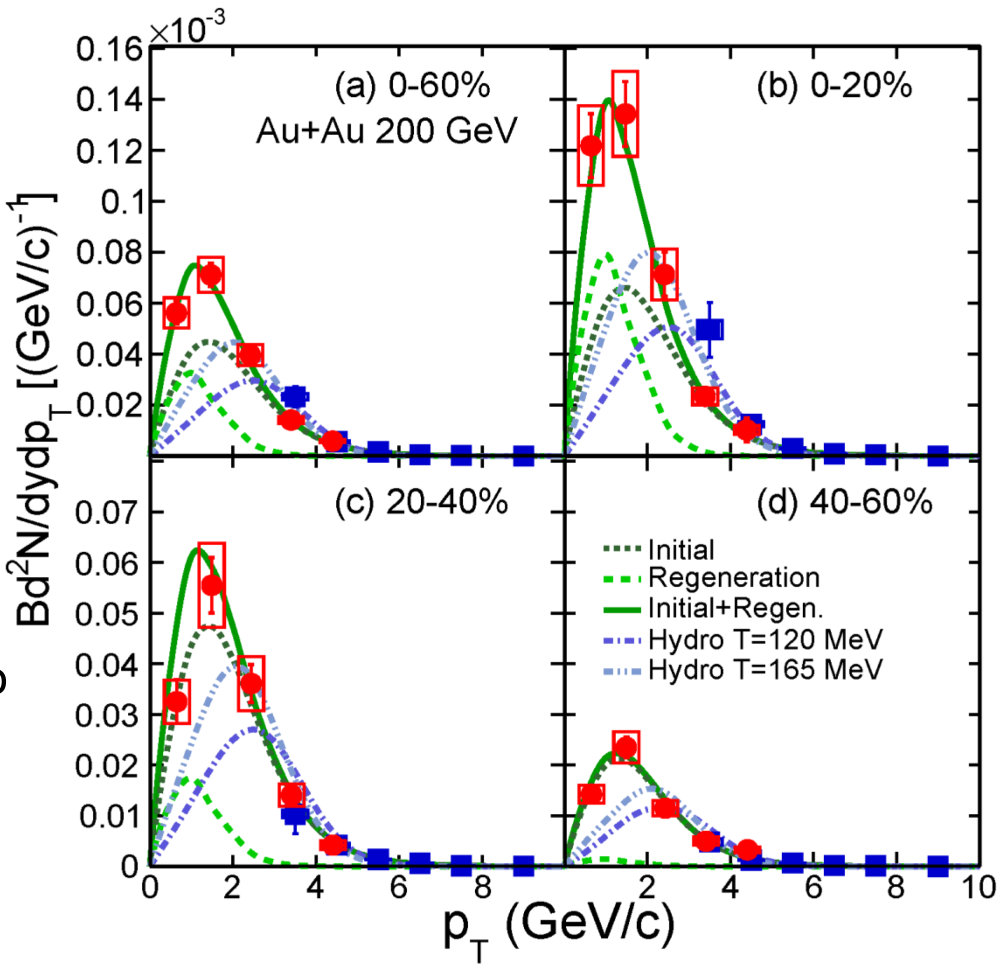
Hydro-inspired freezeout

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

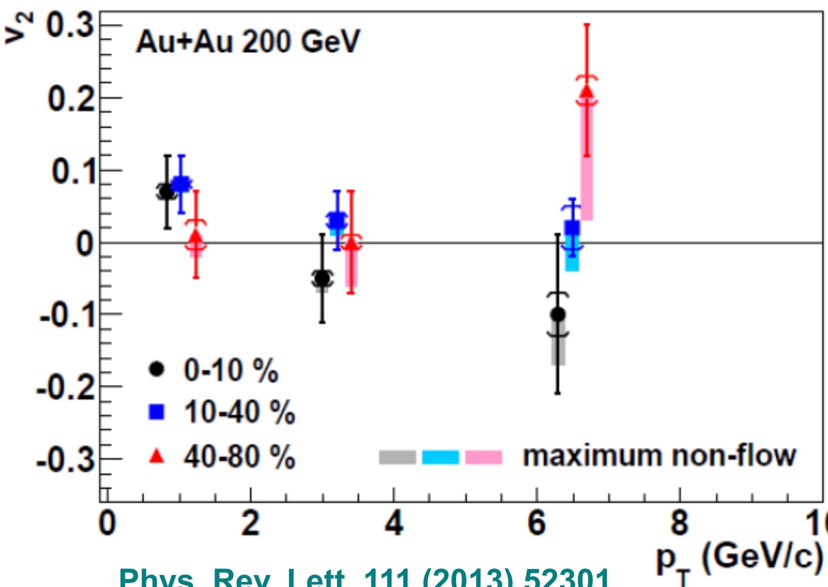
- J/ψ spectrum softer than Tsallis Blast-Wave prediction
  - Small radial flow?
  - Recombination at low p_T?
- **Viscous hydrodynamics**
  - J/ψ decouples at 120..165 MeV
  - fails at low-p_T
- **Y. Liu et al.**
  - Includes J/ψ suppression due to color screening
  - Includes statistical regeneration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



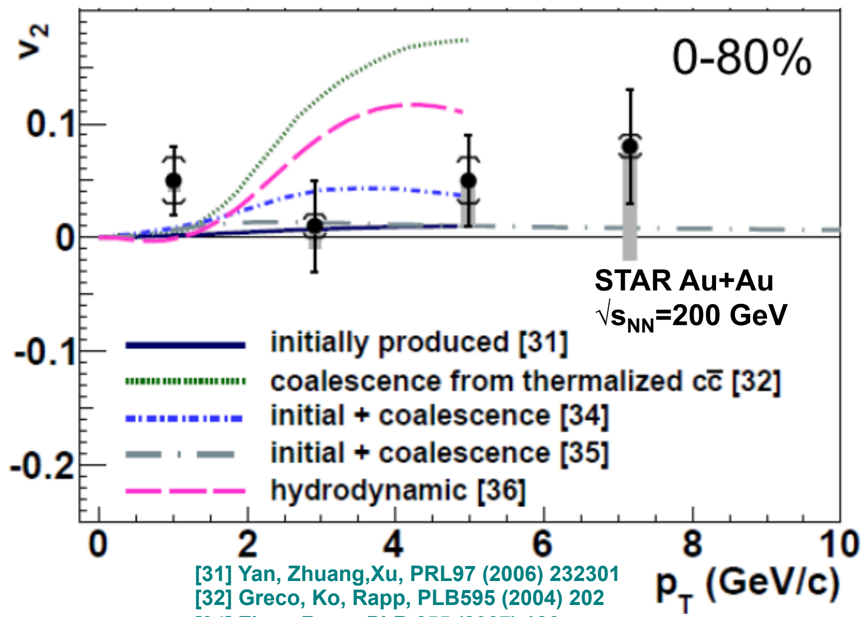
Y. Liu et al., Phys. Lett. B 678, 72 (2009)
U. W. Heinz and C. Shen (2011), private communication.

Coalescence of charm quarks is needed

Azimuthal anisotropy (v_2)



Phys. Rev. Lett. 111 (2013) 52301

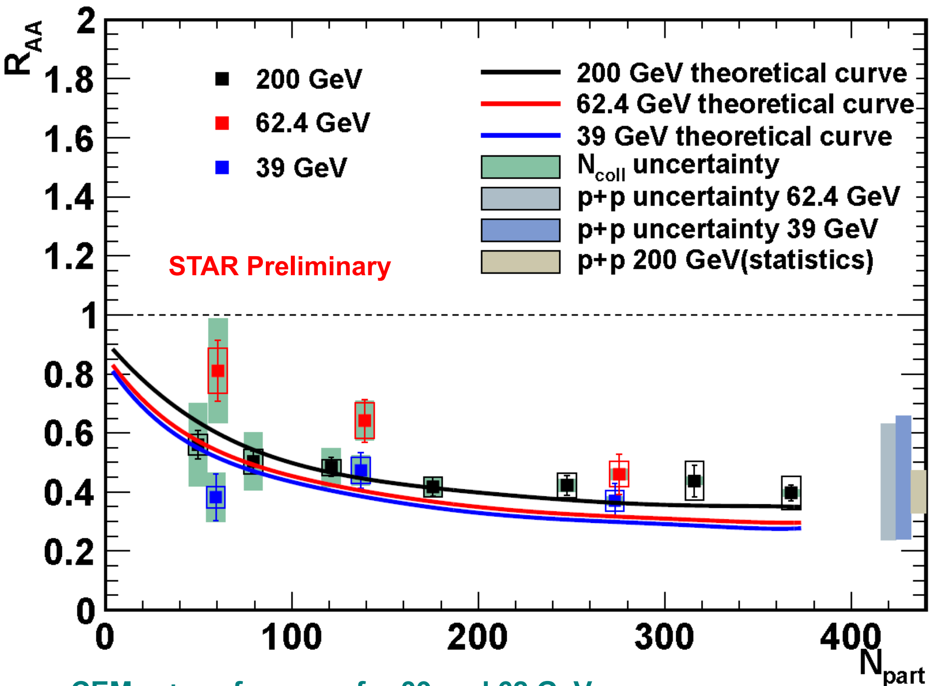


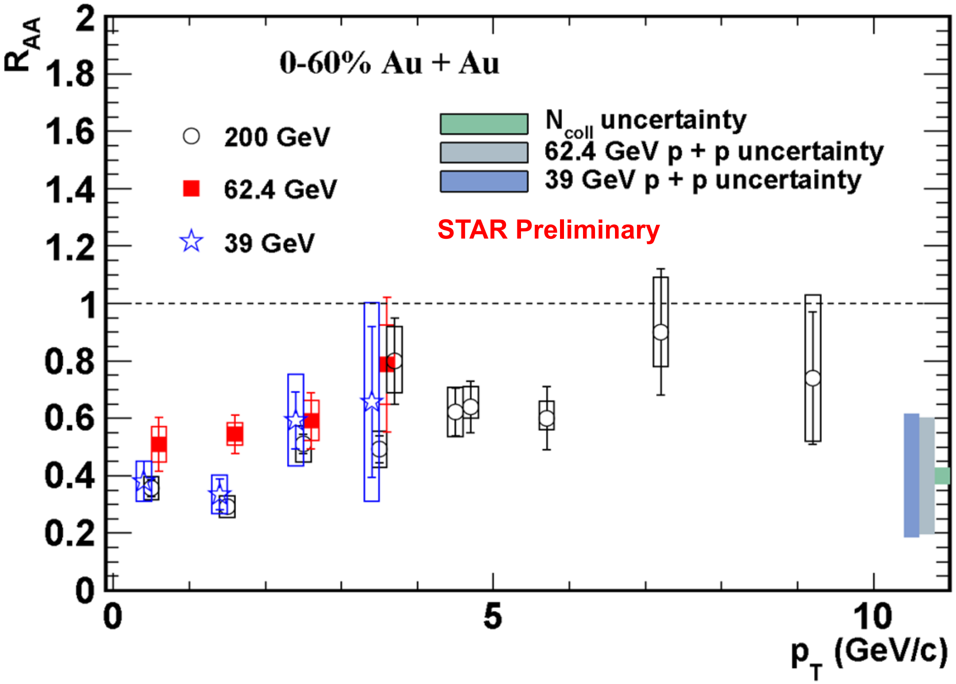
[31] Yan, Zhuang,Xu, PRL97 (2006) 232301
[32] Greco, Ko, Rapp, PLB595 (2004) 202
[34] Zhao, Rapp, PLB 655 (2007) 126
[35] Liu,Xu,Zhuang, NPA834 (2010) 317c
[36] Heinz, Chen (2012)

J/ψ v_2 consistent with non-flow 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



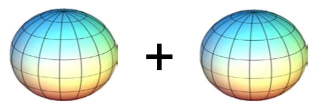


CEM p+p references for 39 and 62 GeV:
Nelson, Vogt et al., PRC87, 014908 (2013)
Theory: Zhao, Rapp, PRC82, 064905 (2010)

- 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?

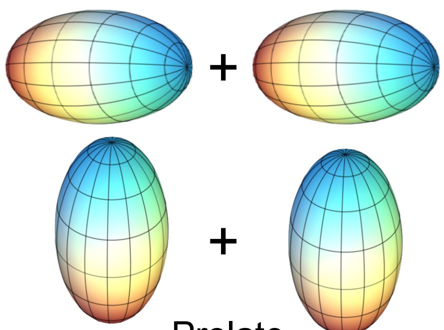
U+U: Higher energy densities

Au+Au Collisions

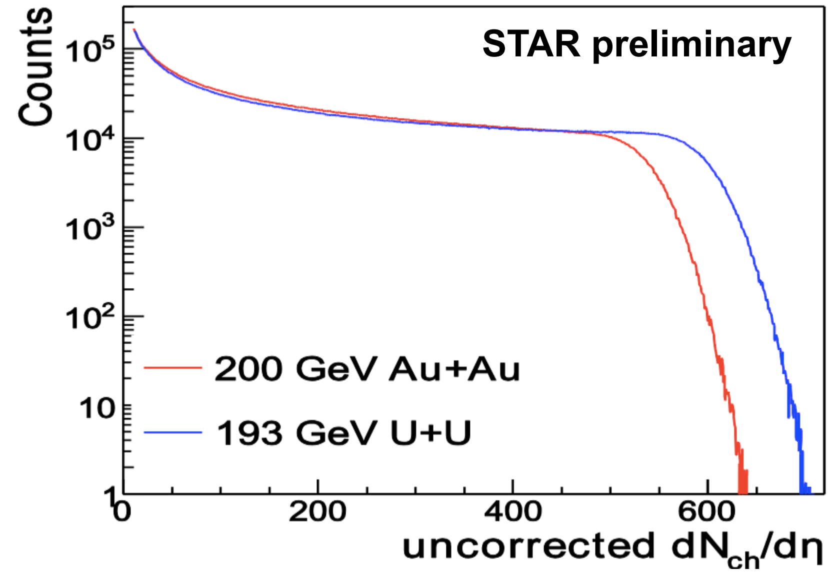


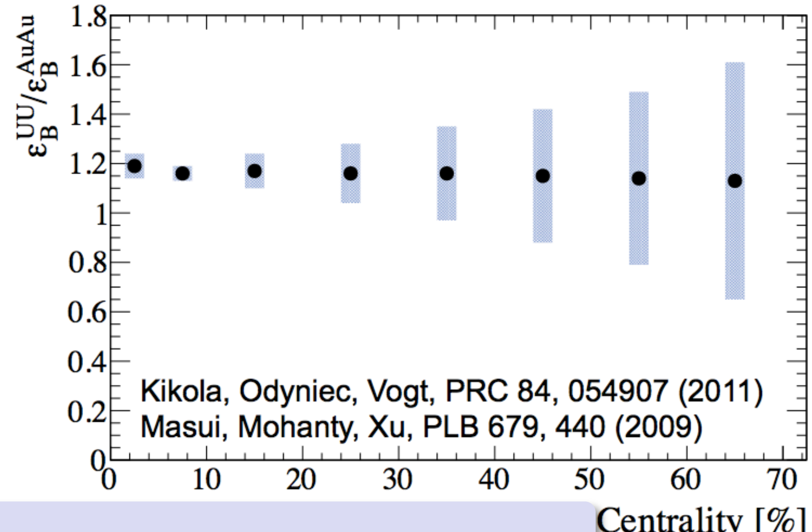
Oblate

U+U Collisions



Prolate



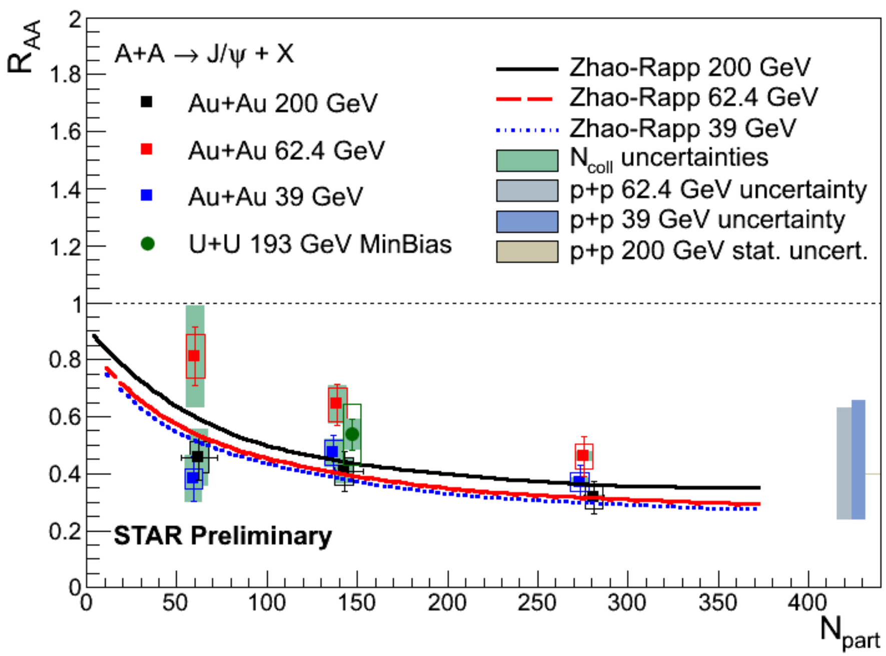


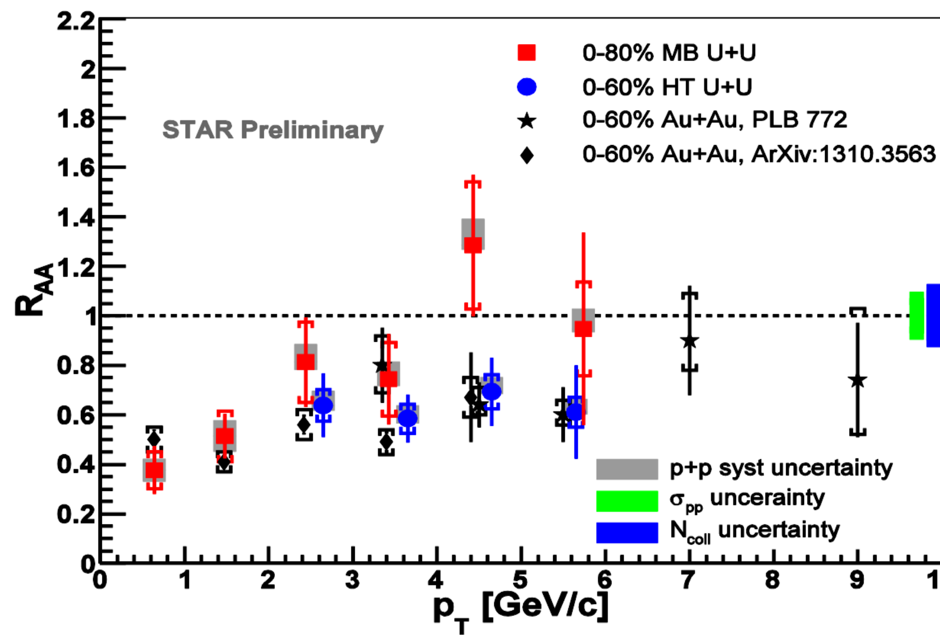
RHIC $\sqrt{s_{NN}}$=193 GeV U+U data (2012)

- 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



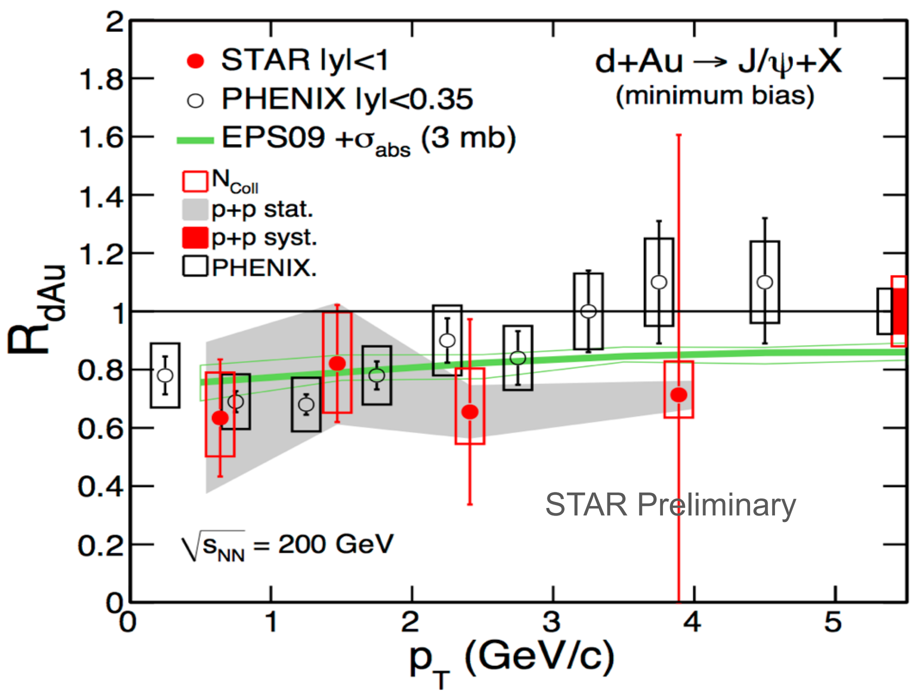


- Nuclear modification factor in U+U similar to Au+Au
  - Similar trend in transverse momentum

Note: 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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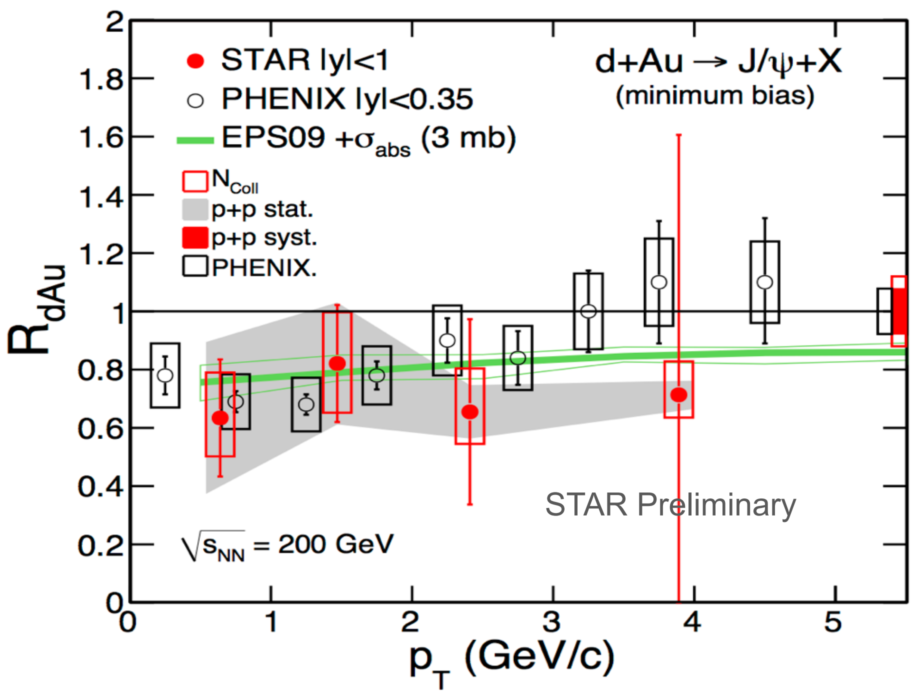

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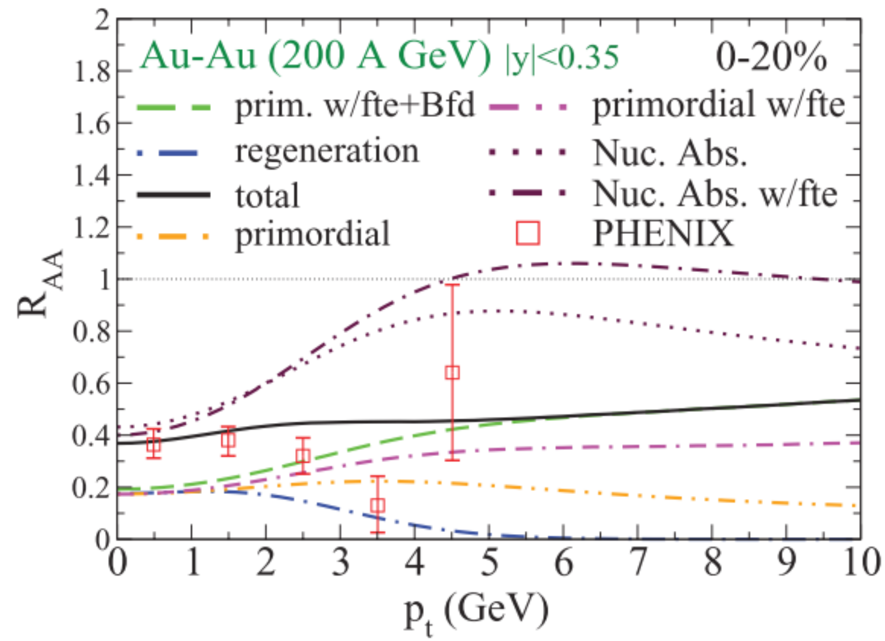
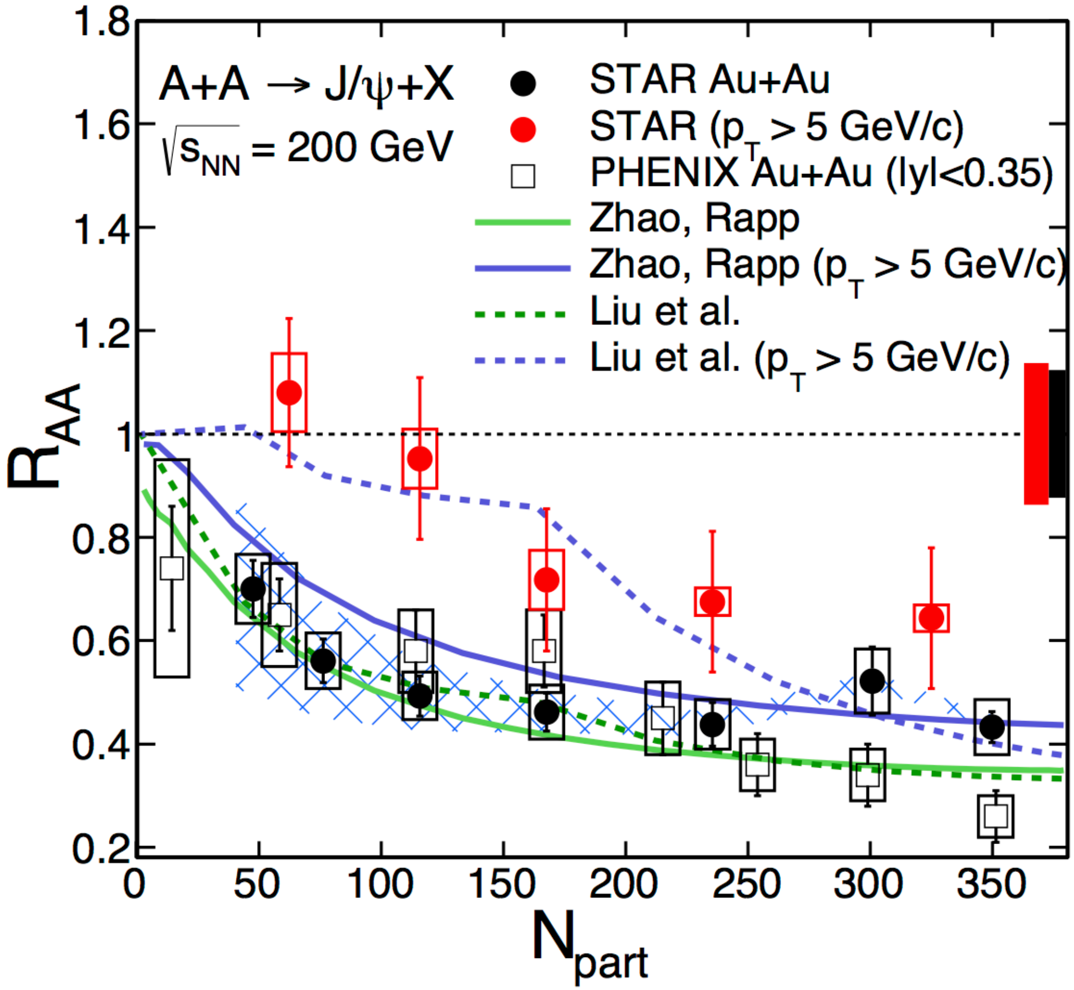


- Much less regeneration

High-p_T J/ψ in Au+Au



- CNM effects are small
- Less regeneration
- Suppression of high-p_T J/ψ in central collisions

STAR low-p_T : arXiv:1310.3563
STAR high-p_T : PLB722, 55 (2013)
Liu et al., PLB 678, 72 (2009)
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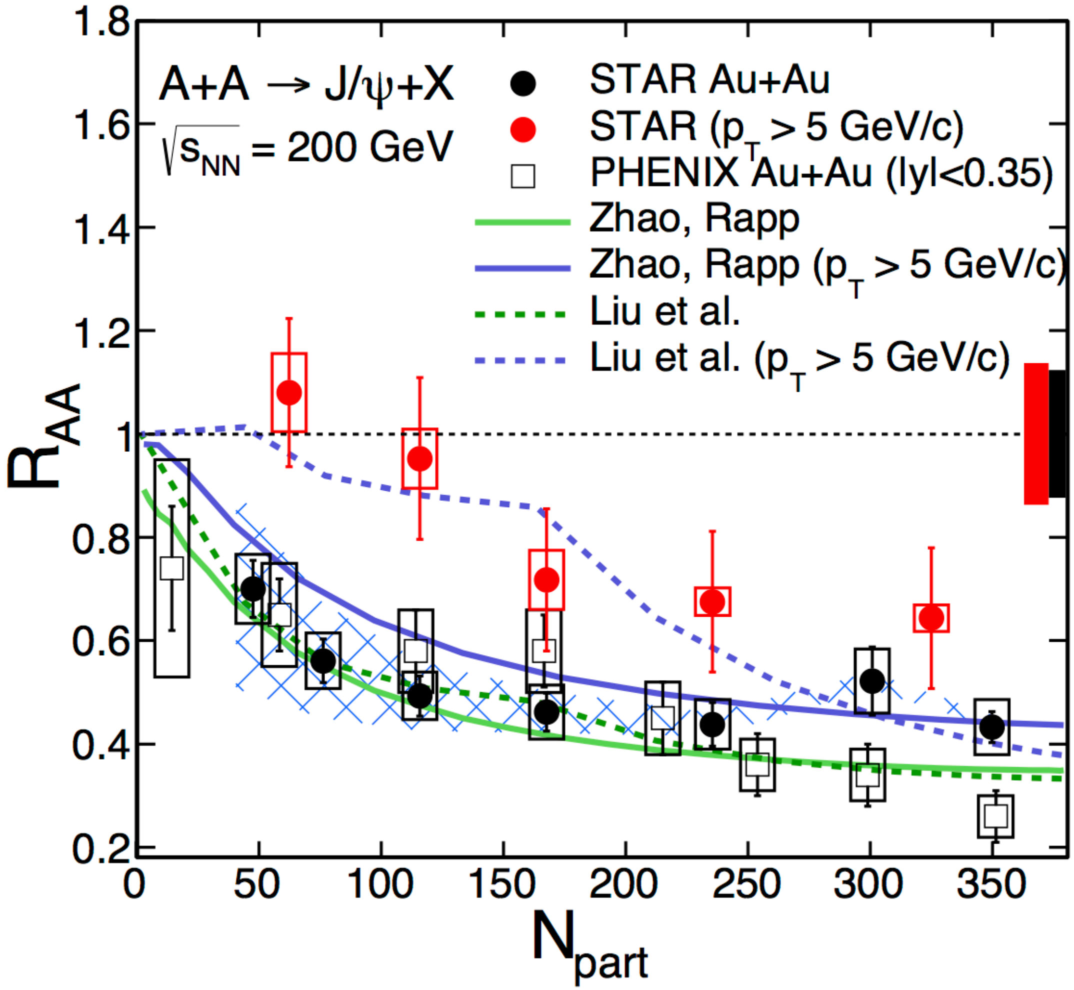
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

High-p_T J/ψ in Au+Au



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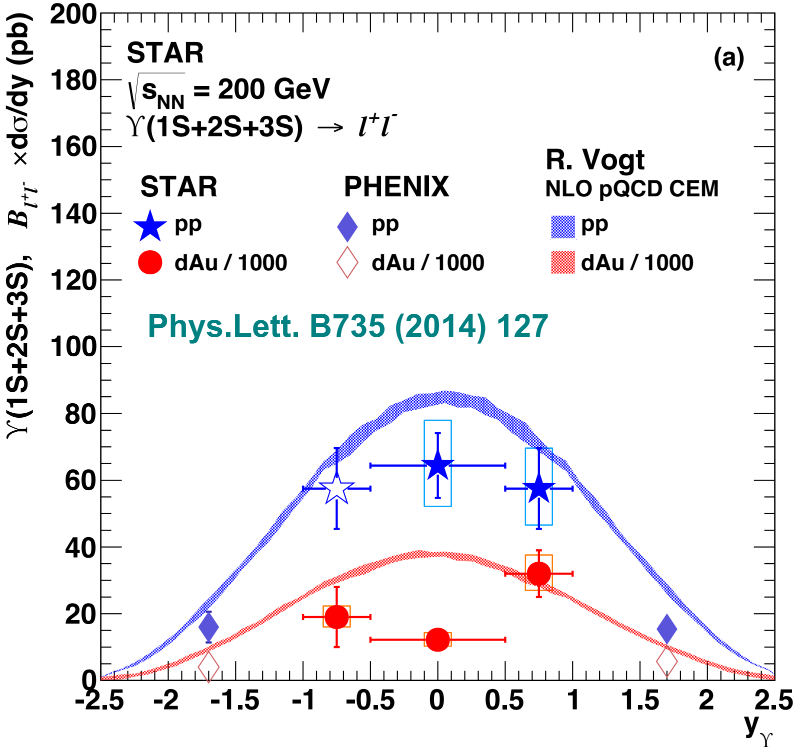
High-p_T J/ψ suppression is clearly an sQGP effect

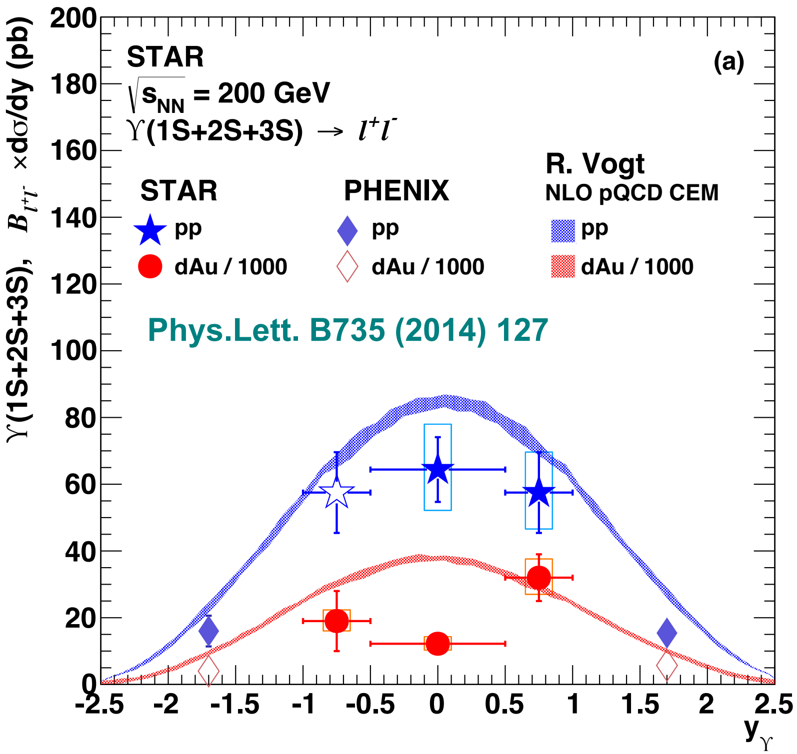
Υ in p+p – baseline



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

R. Vogt, Phys. Rep. 462125, 2008

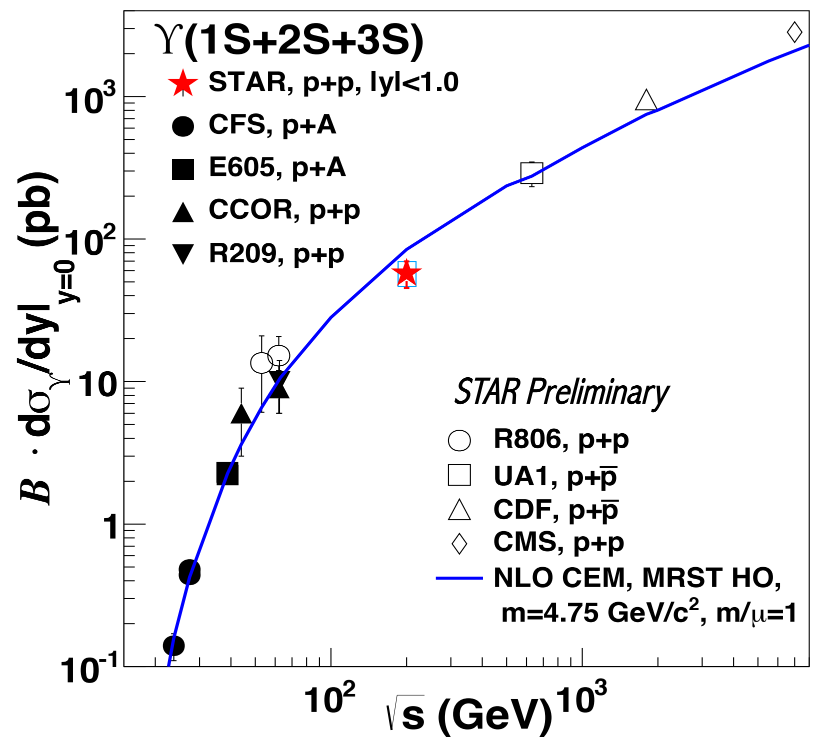
ϒ in p+p – baseline and pQCD test



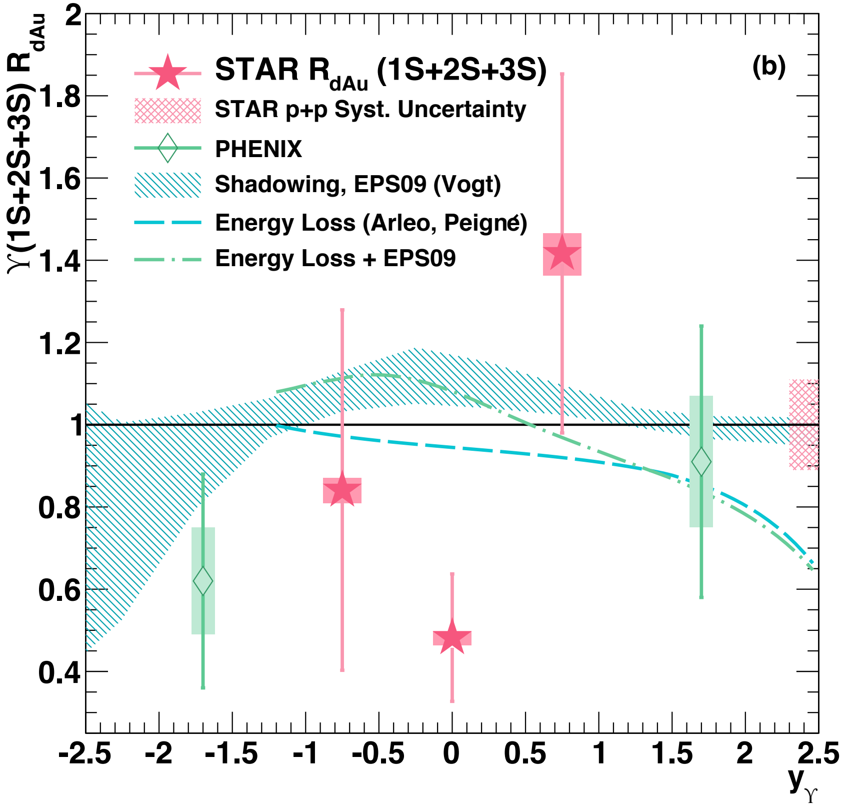
- p+p ϒ cross section vs. y, compared to pQCD predictions

R. Vogt, Phys. Rep. 462125, 2008

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



Υ R_{dAu} – CNM effects



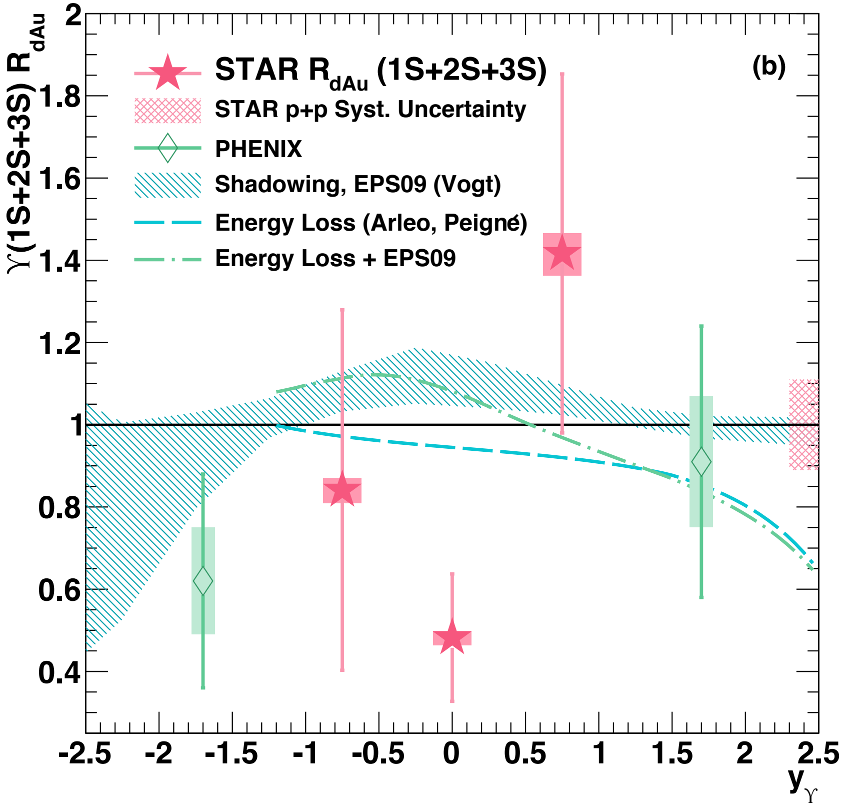
Phys.Lett. B735 (2014) 127

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

$R_{dAu} = 0.48 \pm 0.14(stat) \pm 0.07(syst) \pm 0.02(pp\ stat) \pm 0.06(pp\ syst)$

$|y|<0.5$

Υ R_{dAu} – CNM effects



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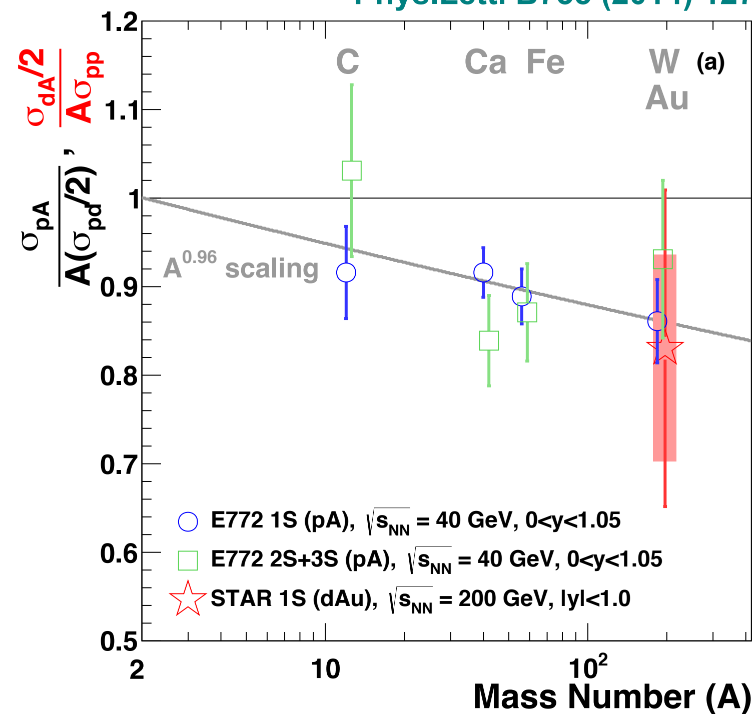
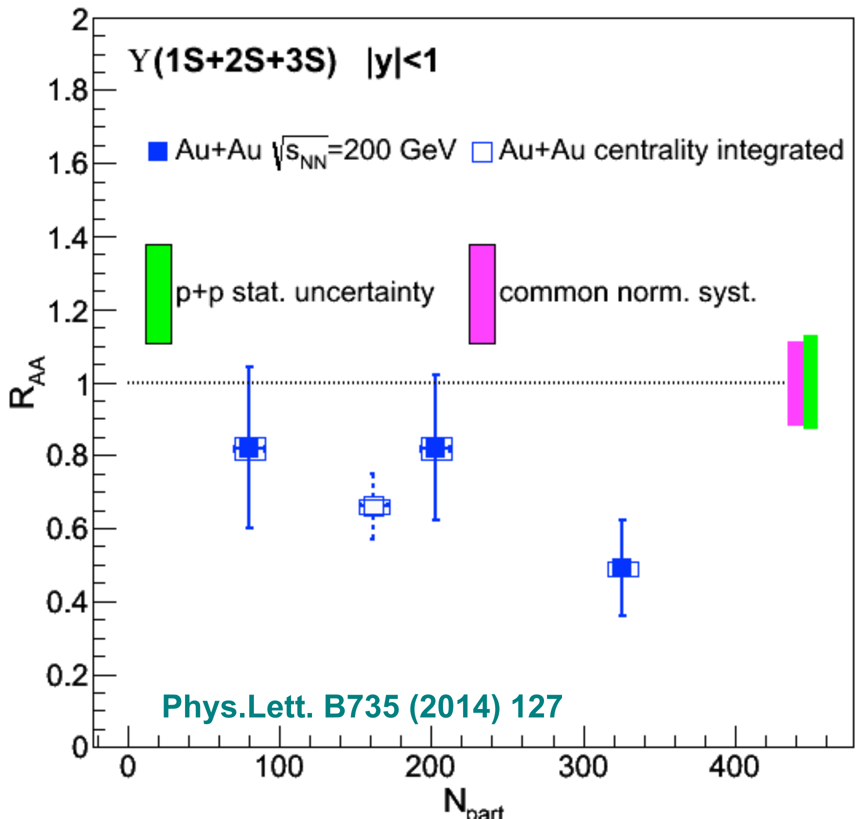
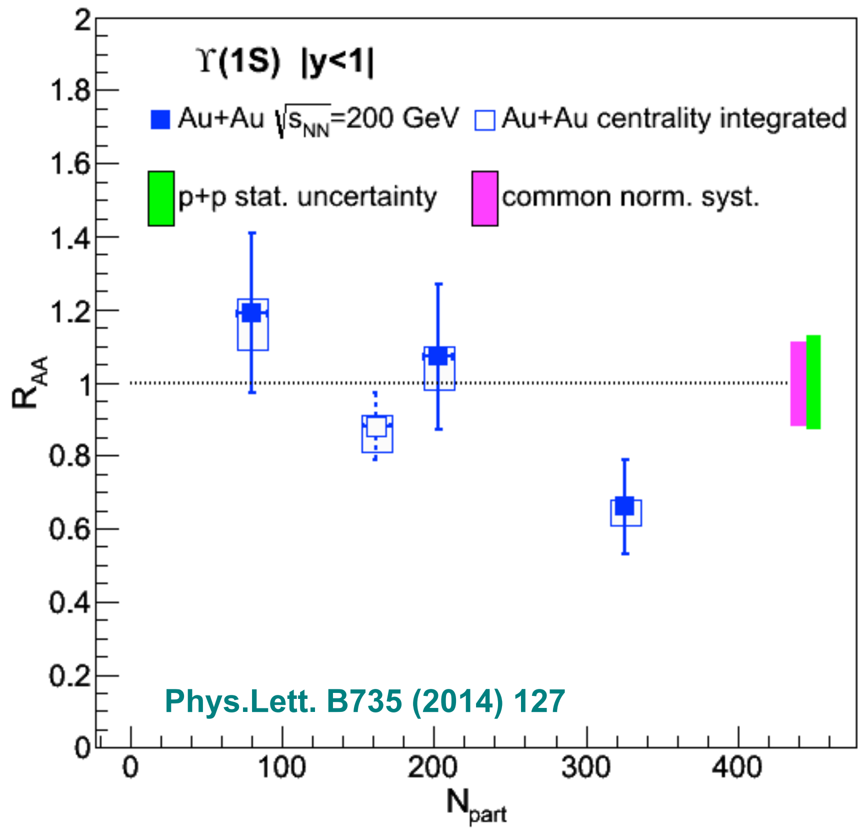


- STAR data consistent with E772 despite difference in energy

R_{AA} : ϒ(1S+2S+3S) and ϒ(1S)

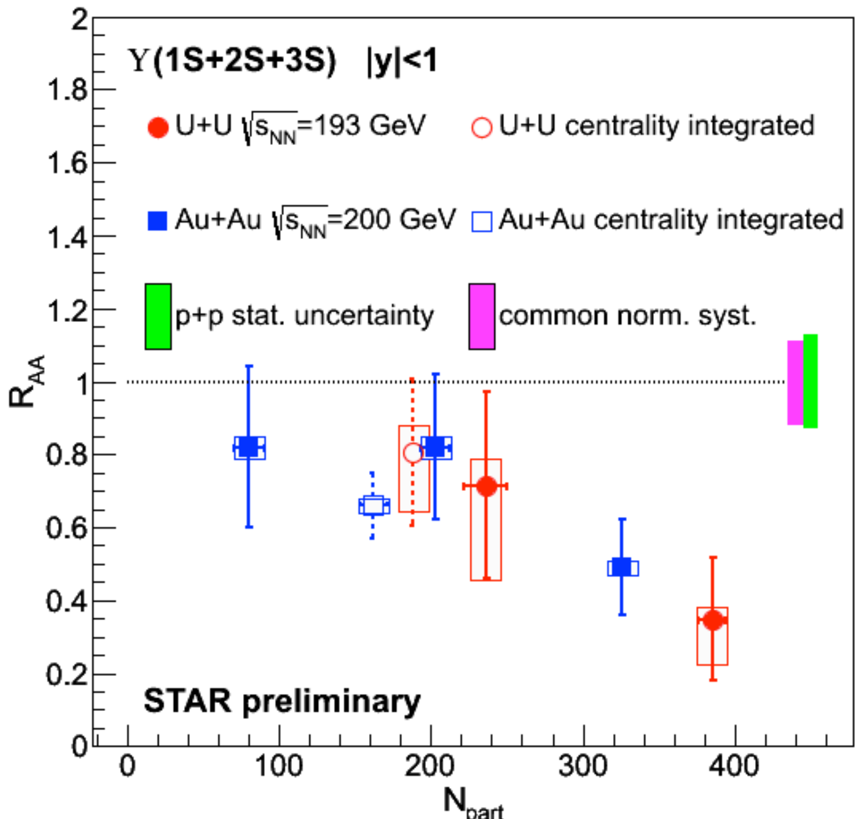


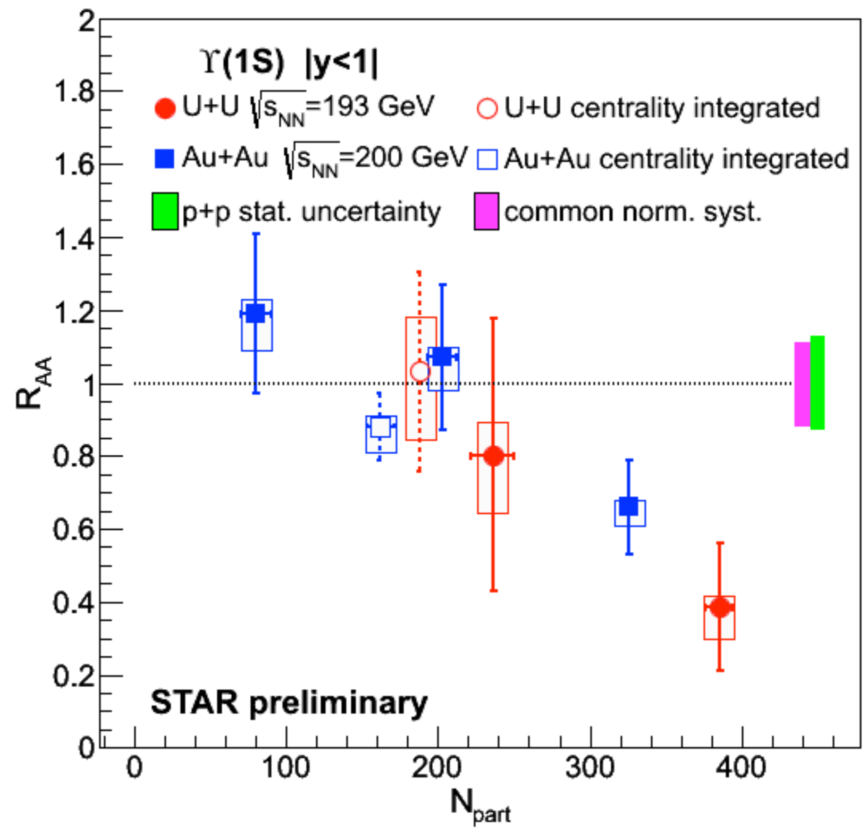


- Peripheral ϒ:
  consistent with no suppression
- Central ϒ:
  significant suppression

- Central ϒ(1S):
  indication of a suppression

ϒ R_{AA} : Au+Au vs. U+U



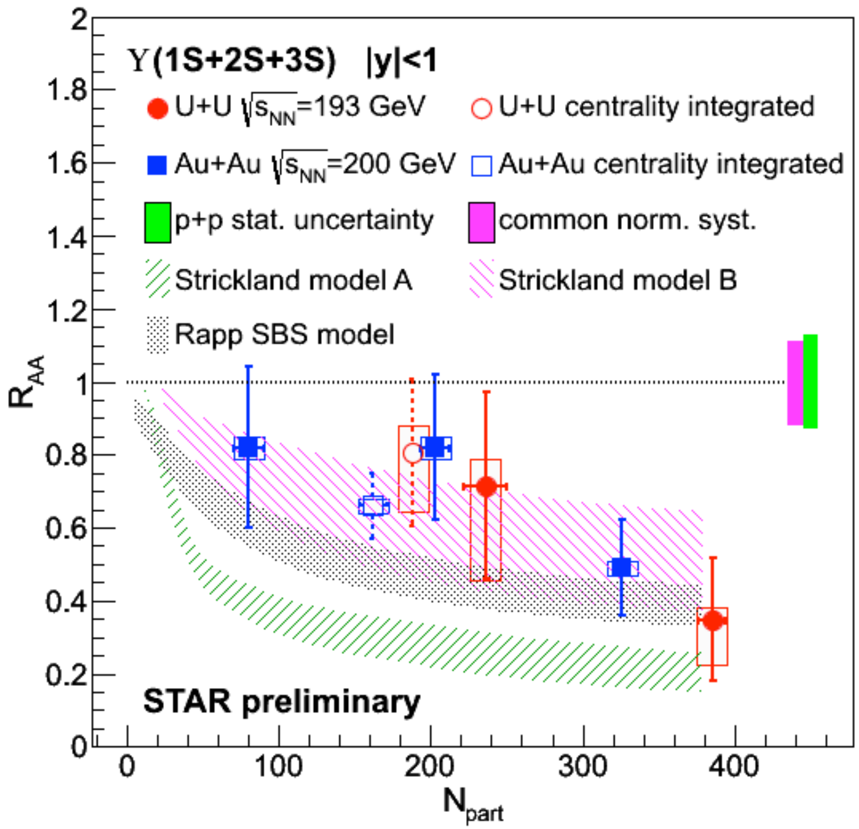


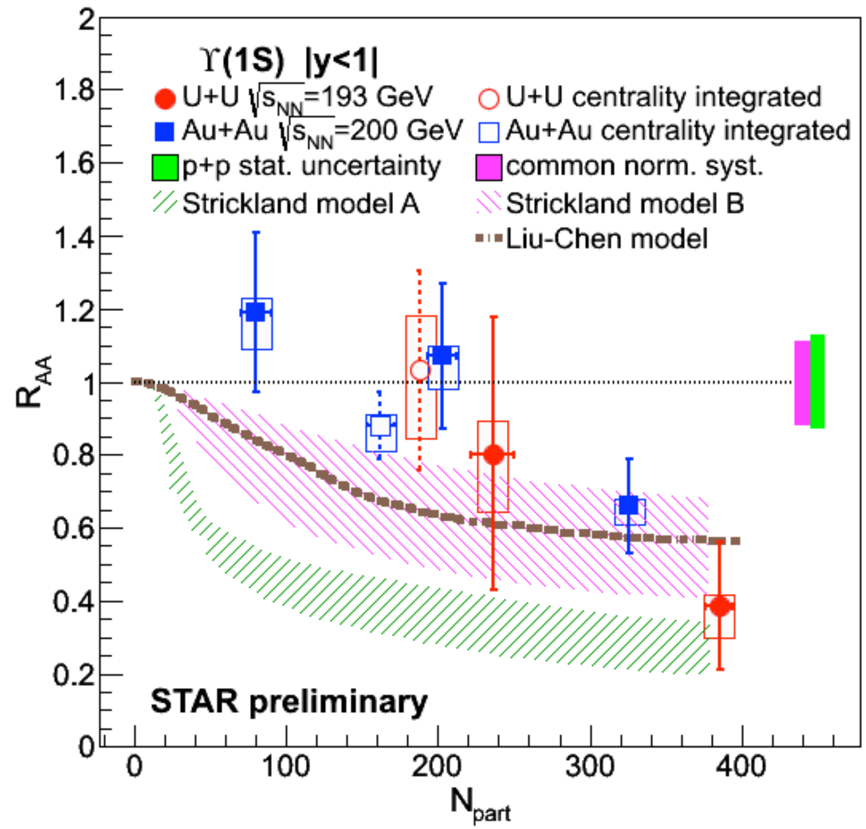
- Peripheral ϒ:
  consistent with no suppression
- Central ϒ:
  significant suppression

- Central ϒ(1S):
  significant suppression

New U+U data confirms and extends Au+Au trend

Υ R_{AA} : data vs. models





Strickland, Bazov, Nucl.Phys.A 879, 25 (2012)

- No CNM effects, 428<T<443 MeV
- Potential model ‘B’ based on **heavy quark internal energy**
- Potential model ‘A’ based on heavy quark free energy (disfavored)

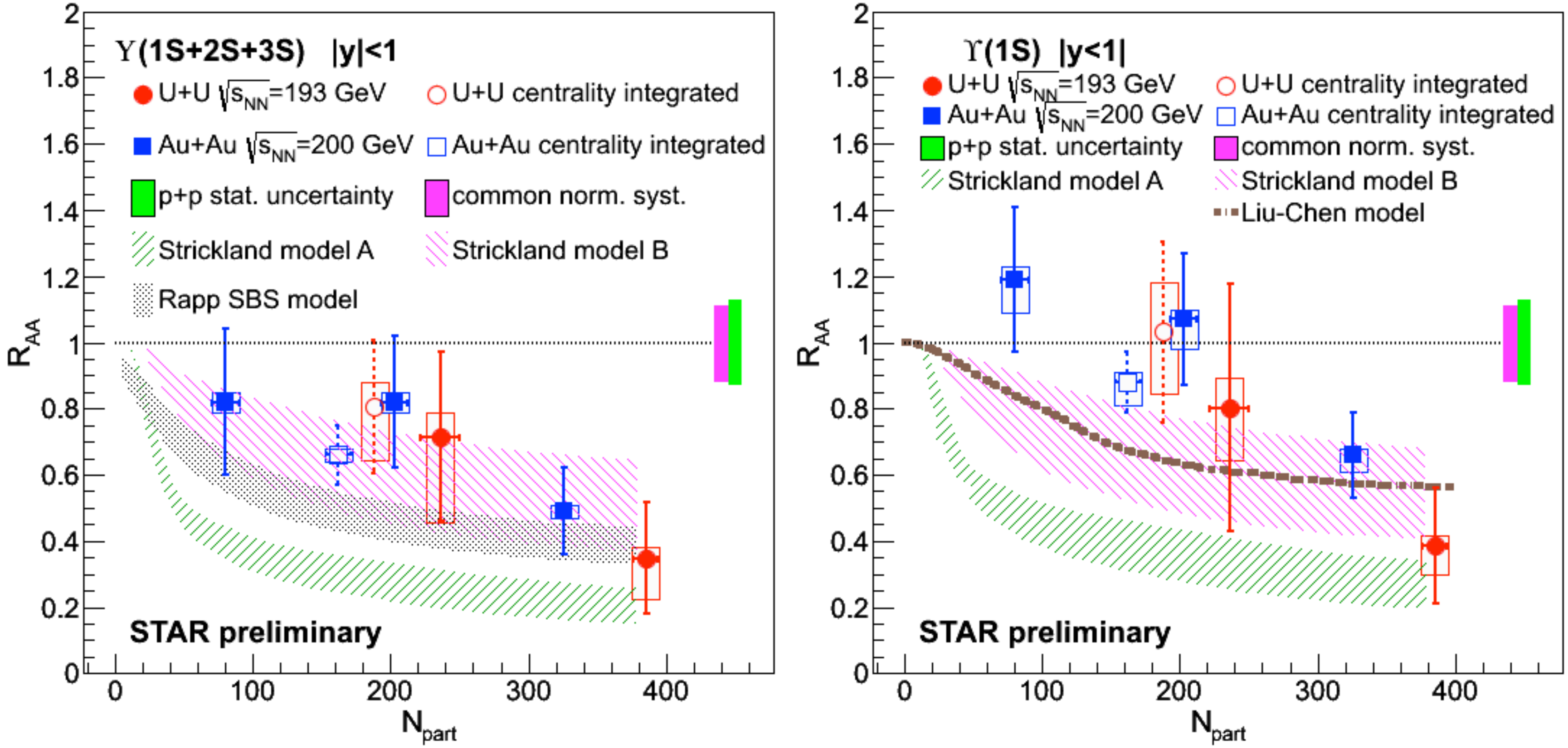
Liu, Chen, Xu, Zhuang, Phys.Lett.B 697, 32 (2011)

- Potential model, no CNM effects
- T=340 MeV, only excited states dissociate

Emerick, Zhao, Rapp, Eur.Phys.J A48, 72 (2012)

- **CNM effects** included
- Strong binding scenario

Υ R_{AA} : data vs. models

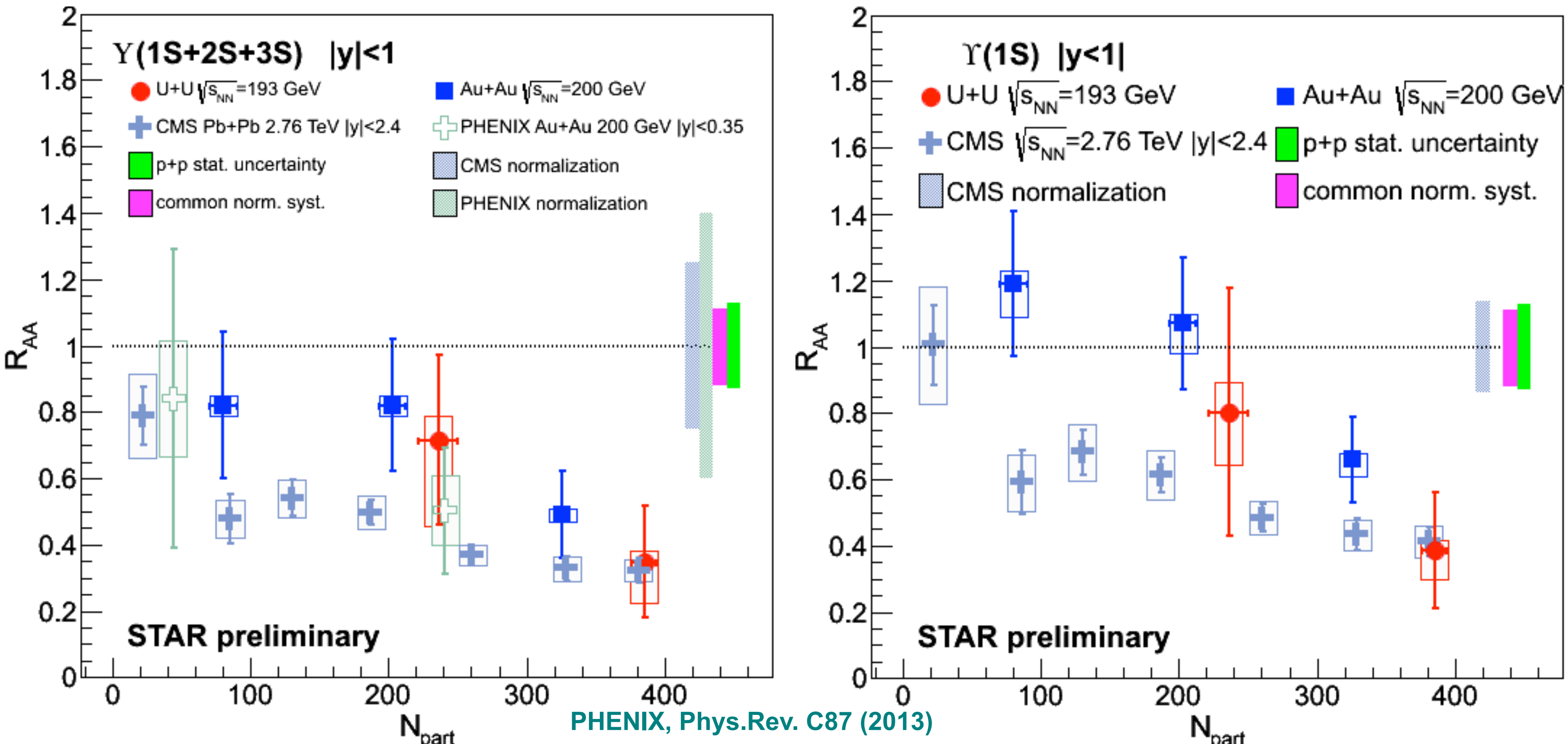


Suppression indicates Υ melting in a deconfined medium

However: CNM effects have to be understood

→ **RHIC 2015 p+Au run**

Υ R_{AA} : RHIC & LHC comparison



PHENIX, Phys.Rev. C87 (2013)
CMS, Phys. Rev. Lett 109 (2012) 222301

- LHC and RHIC suppressions are comparable at high N_{part}
- N_{part} dependence of Υ suppression appears weaker at the LHC

Is suppression driven by energy density?

→*Note the uncertainties and y-range, however*

Excited ϒ states in Au+Au

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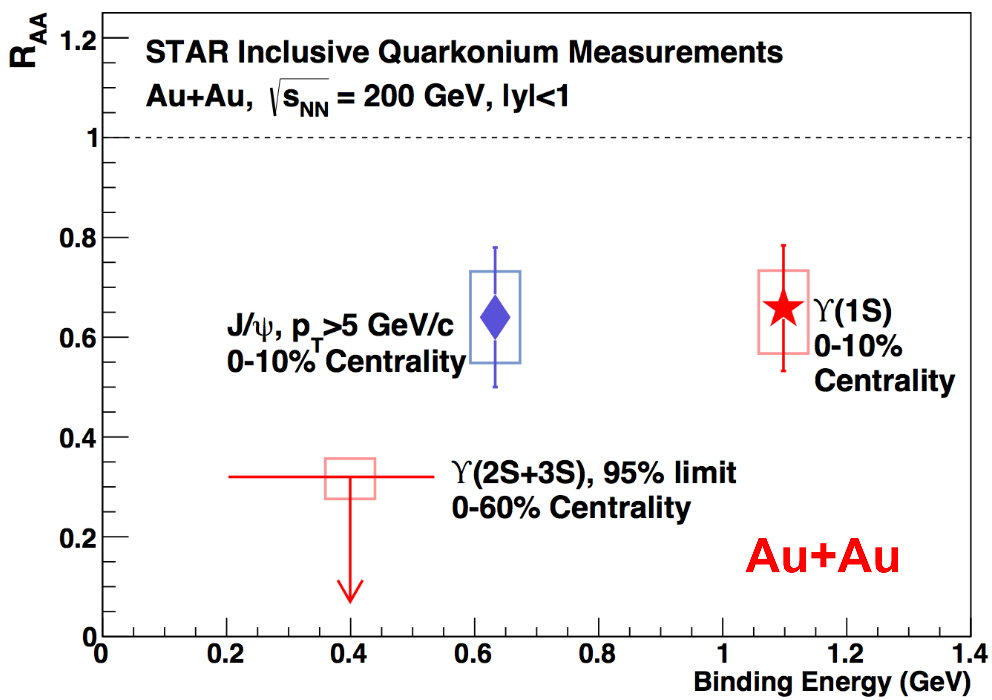

Central Au+Au:

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

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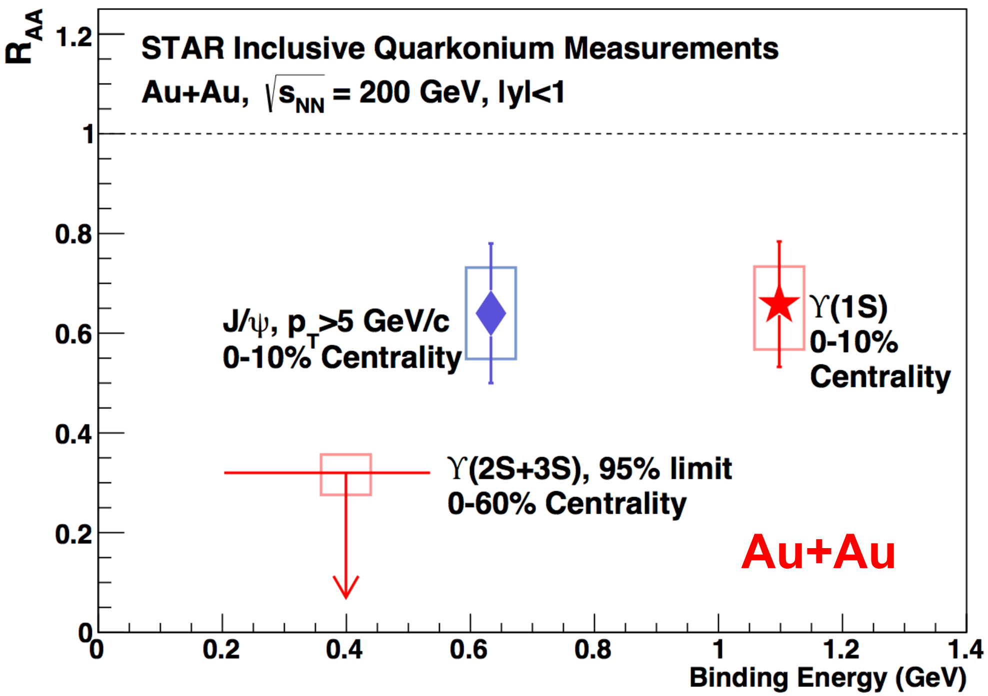

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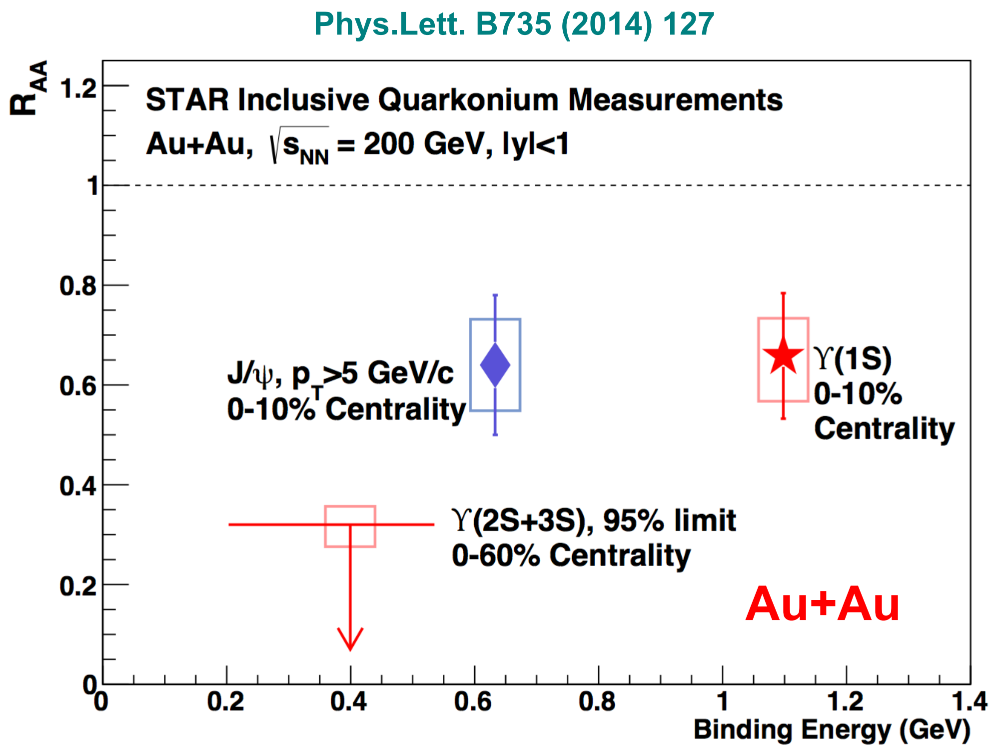
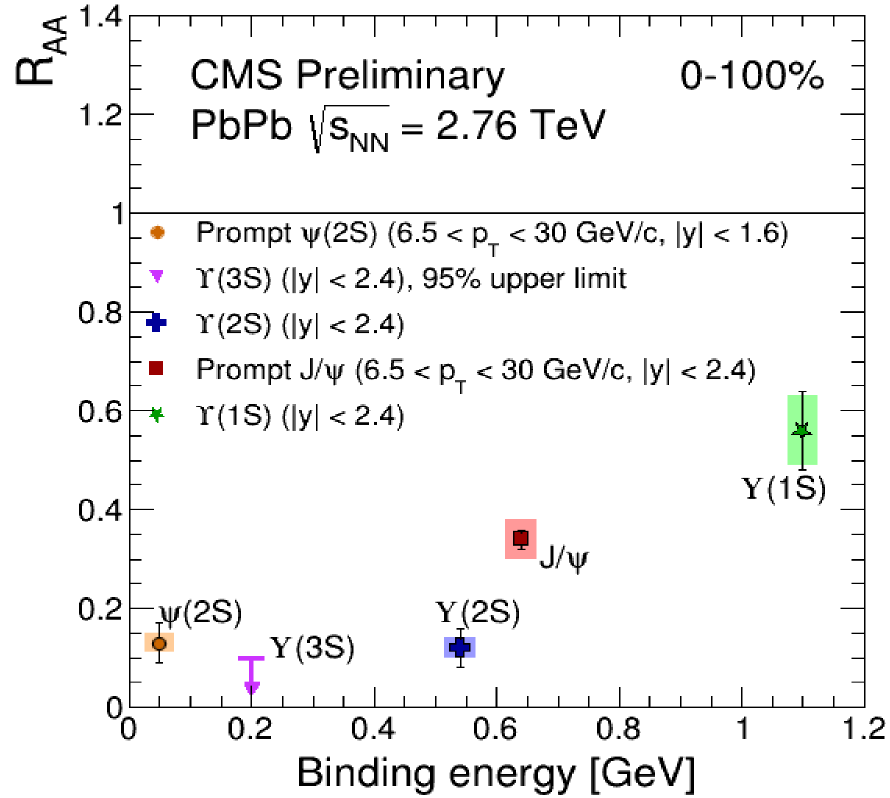
ϒ suppression pattern supports sequential melting

Excited ϒ states – LHC comparison



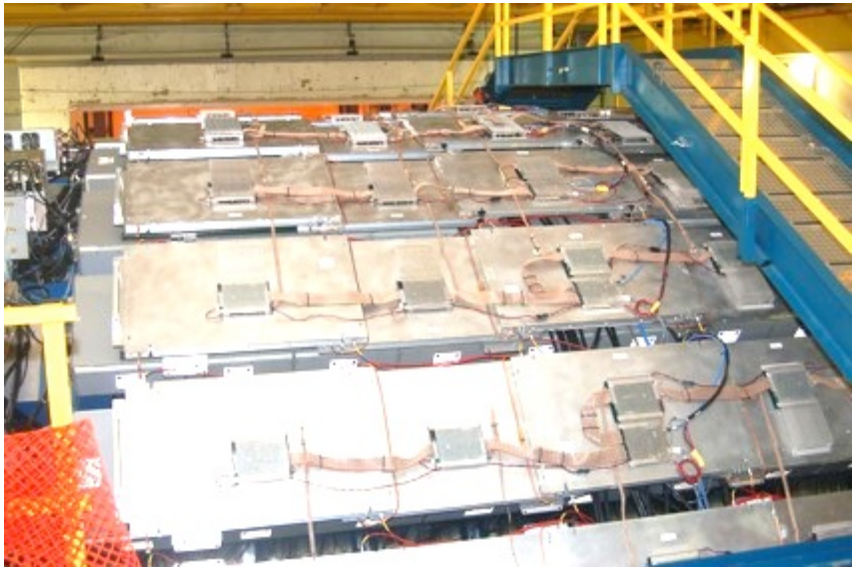


- RHIC $\sqrt{s_{NN}}$=200 GeV Au+Au and LHC $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb collisions: Similar suppression of central ϒ(1S)

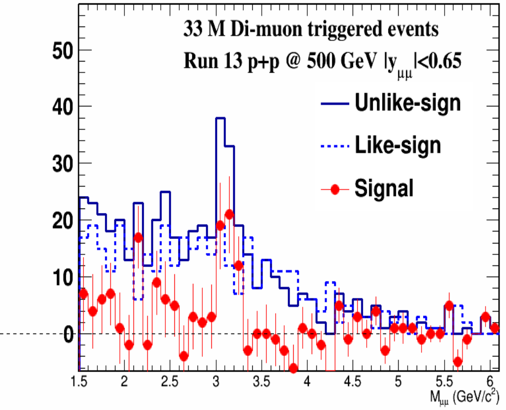
Outlook: Muon Telescope Detector

$J/\psi \to \mu^+\mu^-$(BR~6%), $\Upsilon \to \mu^+\mu^-$(BR~2.5%)

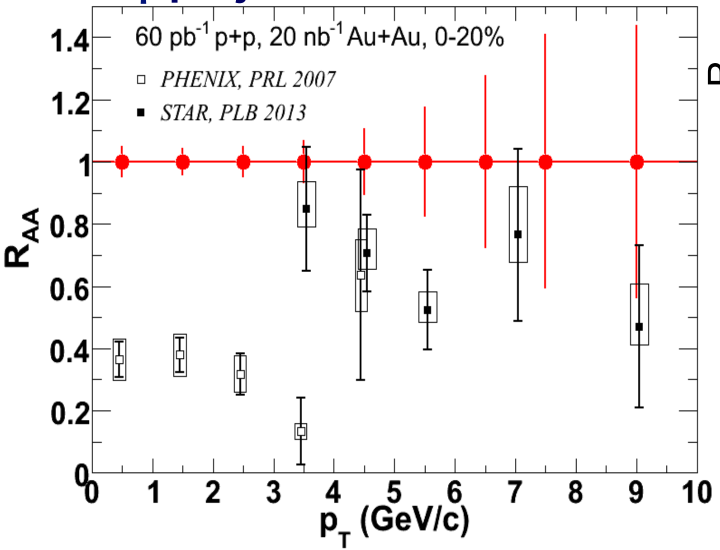
- No γ conversion
- Less Bremsstrahlung → better resolution
- Less contribution from Dalitz decays
- Trigger capability for J/ψ in central A+A collisions



Reconstructed J/ψ peak



J/ψ projected stat. errors



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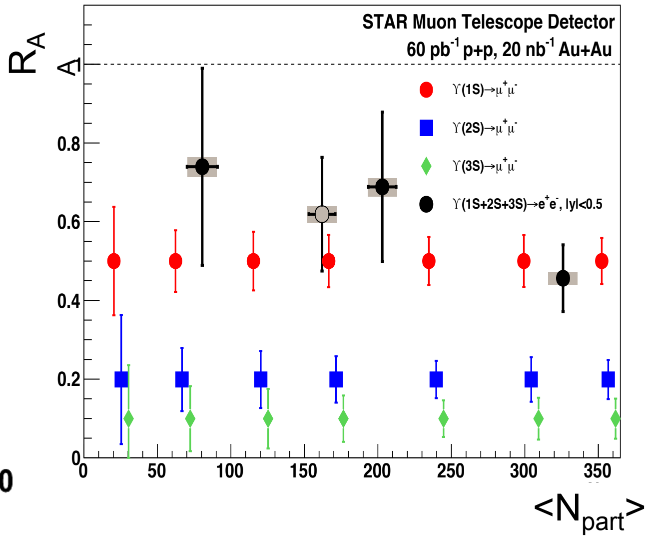

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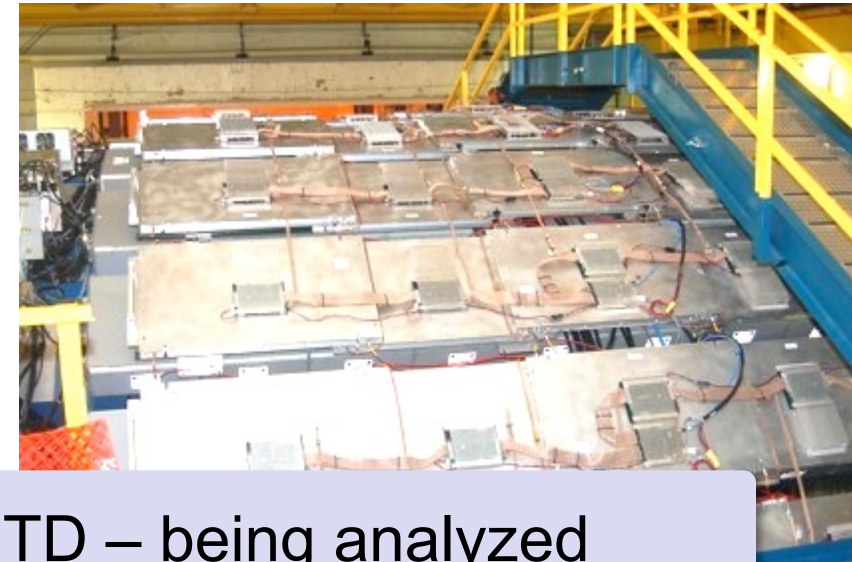
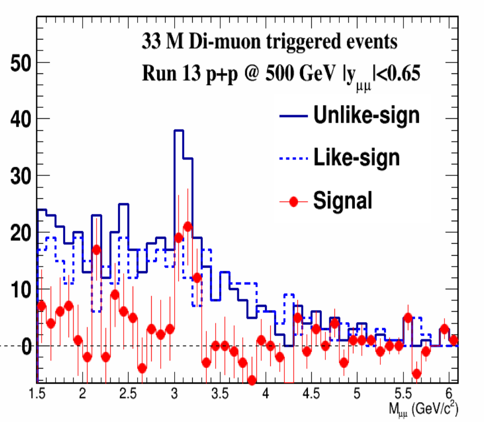


Run14 data with full MTD – being analyzed

Reconstructed J/ψ peak



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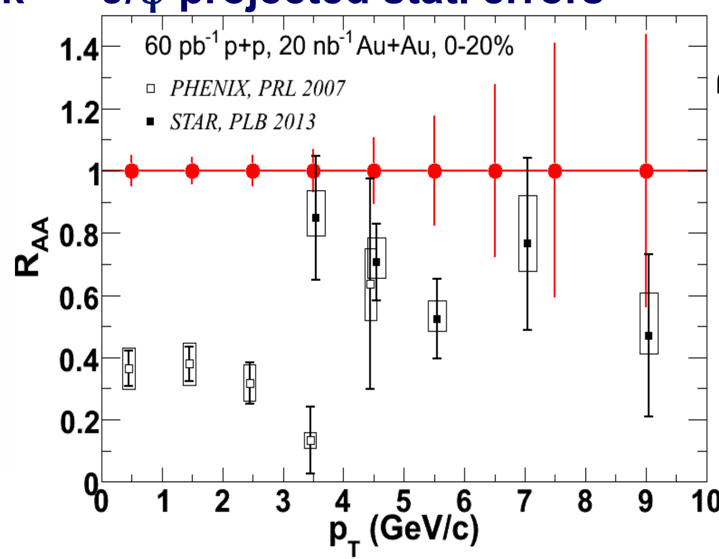

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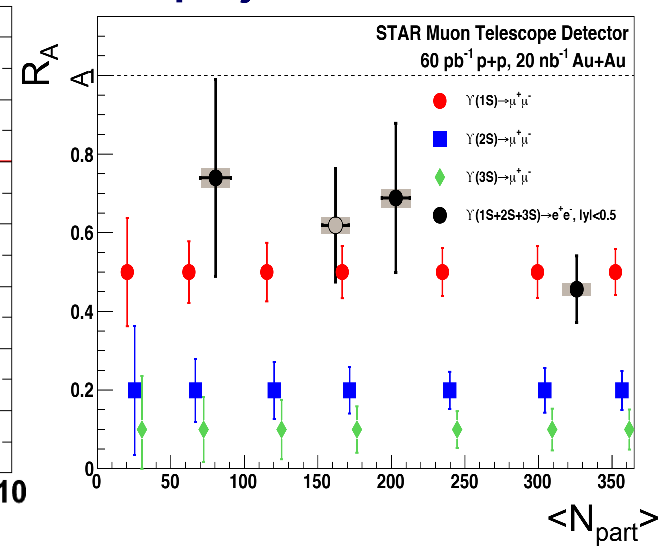

Summary

J/ψ BES: similar suppression in central 39, 62.4 and 200 GeV data

→ *attests to the role of regeneration*

Collective behavior of J/ψ: no strong v_2, radial flow observed

→ *thermalized $c\bar{c}$-coalescence not dominant in production*

Hot medium effects: 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 melting in a deconfined medium*
- ϒ suppression in most central collisions similar to LHC

CNM effects: ϒ suppression in d+Au has to be understood

U+U measurements: similar suppression patterns to Au+Au

- Suppression of central ϒ(1S) confirmed

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Stay tuned for new great results with MTD

Thank You!

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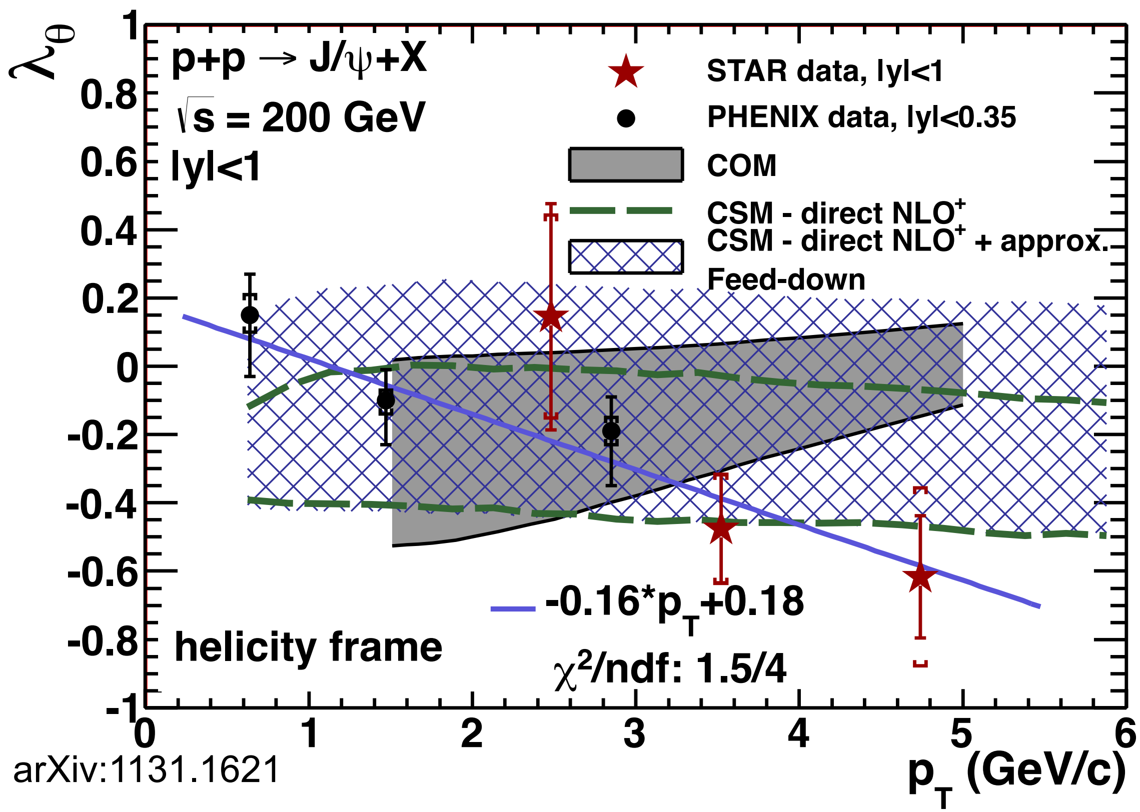
STAR Collaboration

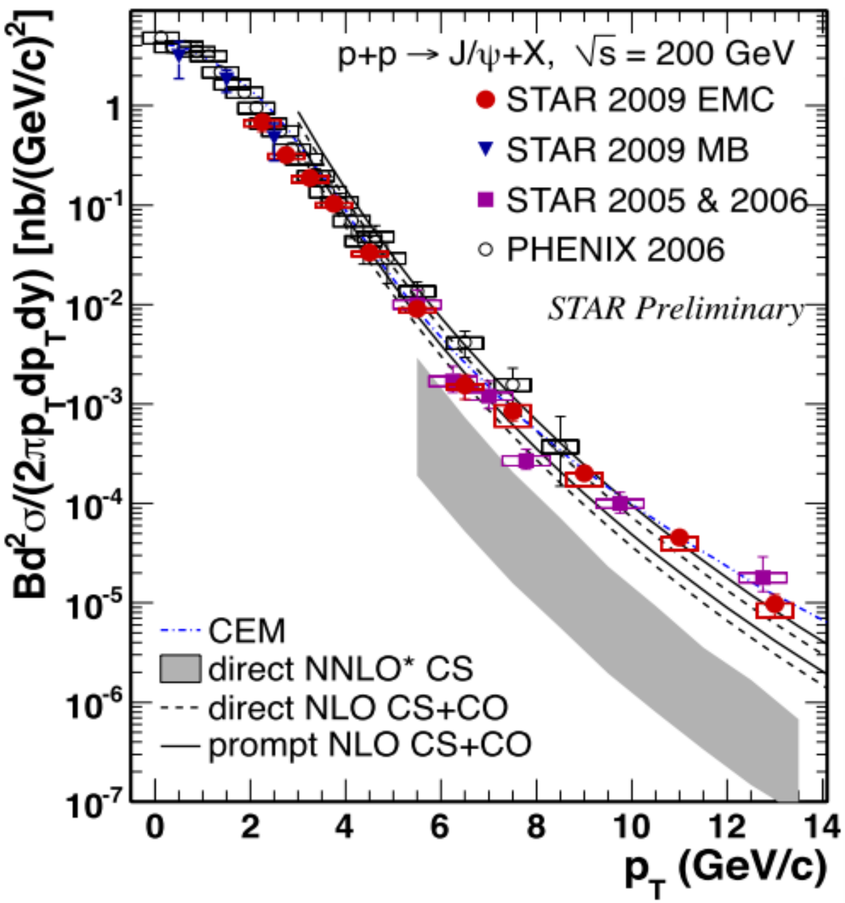
J/ψ in p+p – polarization

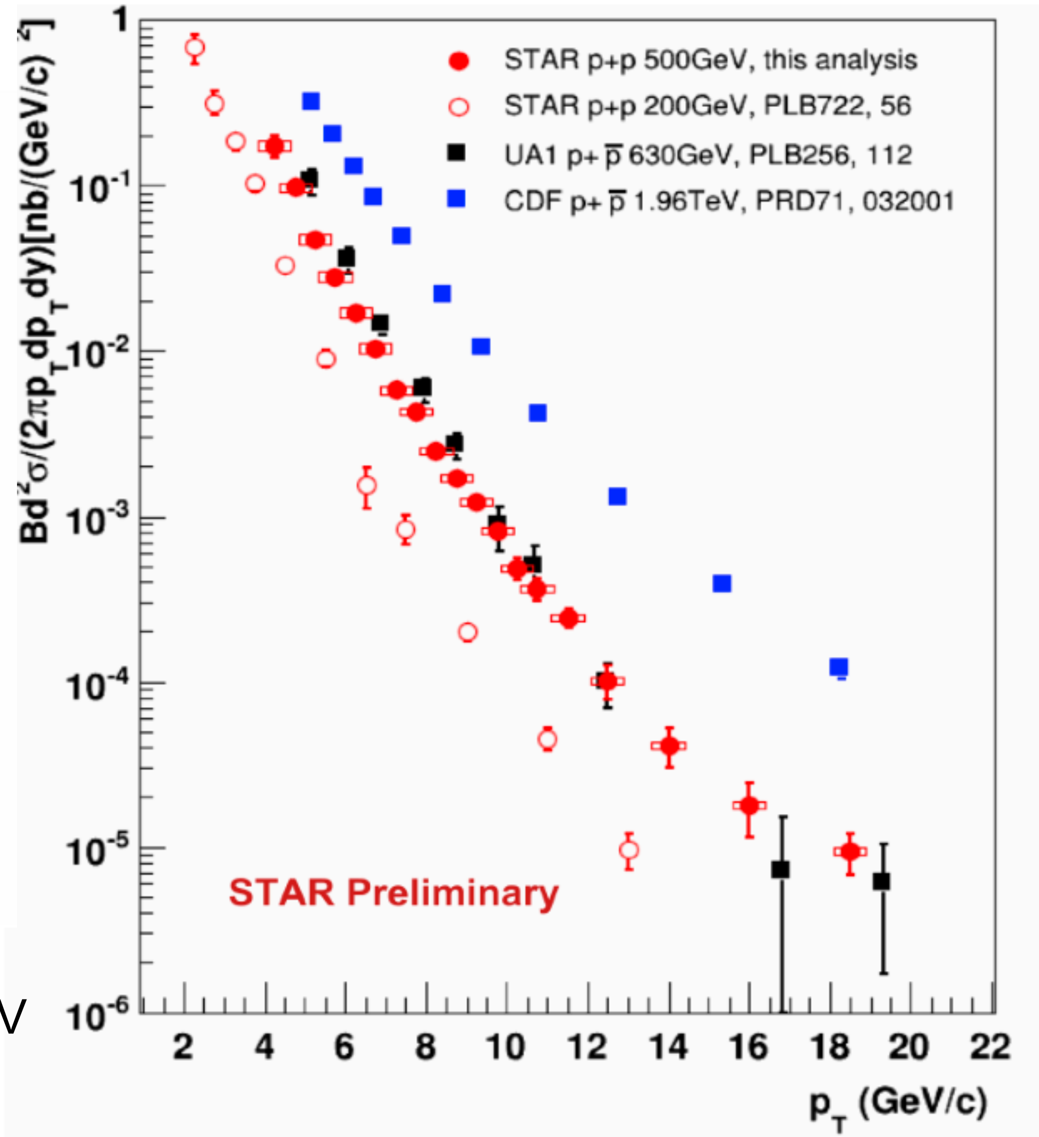


arXiv:1131.1621

- 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

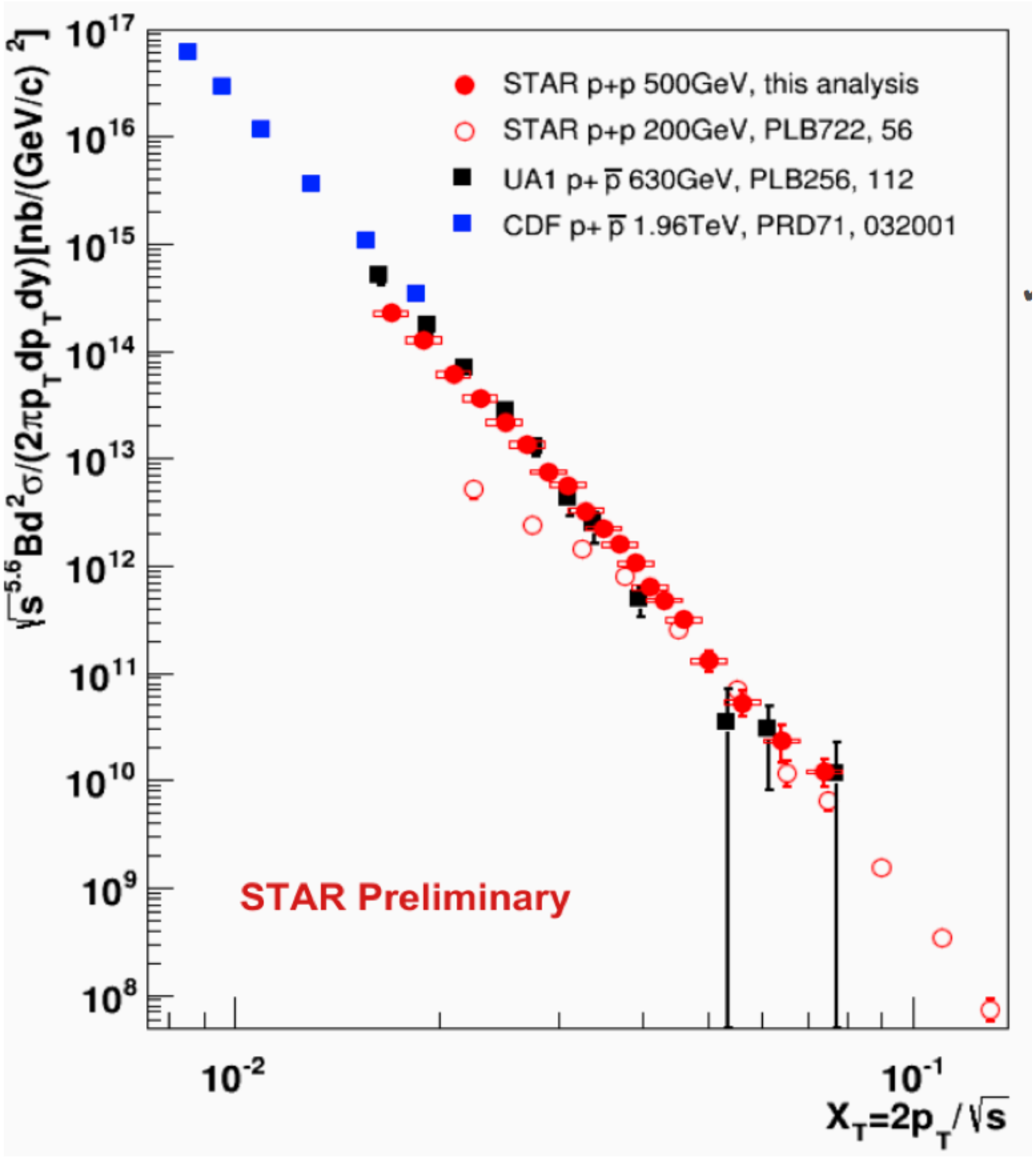
J/ψ spectra, p+p at 500 GeV





- Precise measurements at 500 GeV
- up to p_T=20 GeV

J/ψ x_T-scaling



$$\frac{d^2\sigma}{2\pi\, p_T\, dp_T\, dy} = g(x_T)/(\sqrt{s})^n$$

200 GeV:

- high-p_T x_T-scaling with

  n = 5.6 ± 0.2

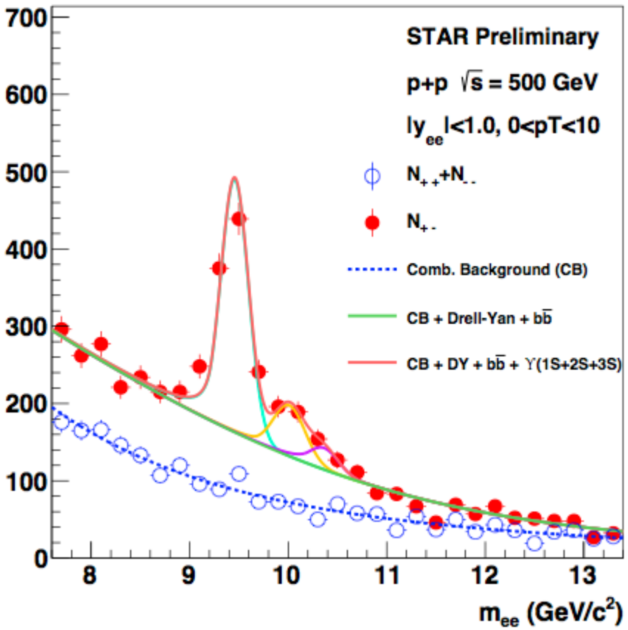
Phys. Rev. C 80, 041902 (2009)

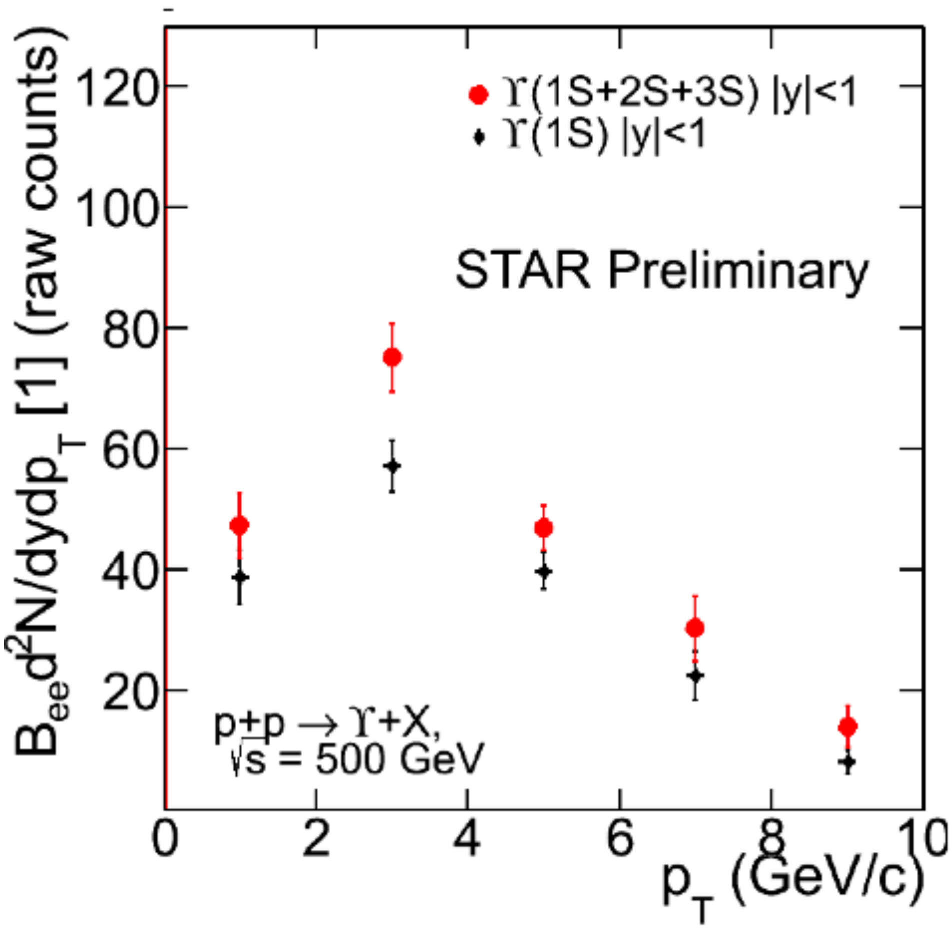
- Breaking of scaling: transition to soft processes

500 GeV:

- x_T-scaling present down to lower p_T

Upsilons in p+p 500 GeV





- Precise measurements
- Uncorrected spectra so far