Quarkonium Production at STAR

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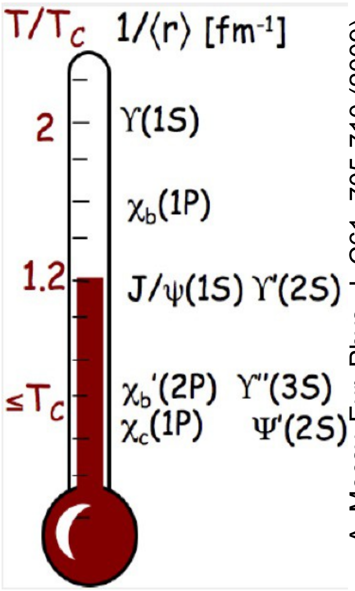
Outline

- Introduction
- Experiment
- Particle identification
- J/ψ production in p+p, d+Au, Au+Au at 200 GeV
  - *Spectra, elliptic flow, nuclear modification factor.*
- Υ production in p+p, d+Au, Au+Au at 200 GeV
  - *Cross section, nuclear modification factor.*
- Summary

Introduction

Charmonia: J/ψ, ψ', χ_c *Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b*

- Heavy quarks are created in the initial hard scattering
  → *exposed to the evolution of the system.*
- Expect a suppression of quarkonia in a QGP
  [T. Matsui and H. Satz, Phys Lett. B 178, 416 (1986).]
  → *color screening of heavy quark pair potential*
  → *unique probe of deconfined medium*
- Sequential melting of different states
  → *melting depends on binding energy and T_C*
  → *provides a thermometer of QGP*



A .Mocsy, Eur. Phys. J. C61, 705-710 (2009)

Introduction

However, there are complications to quarkonium production:

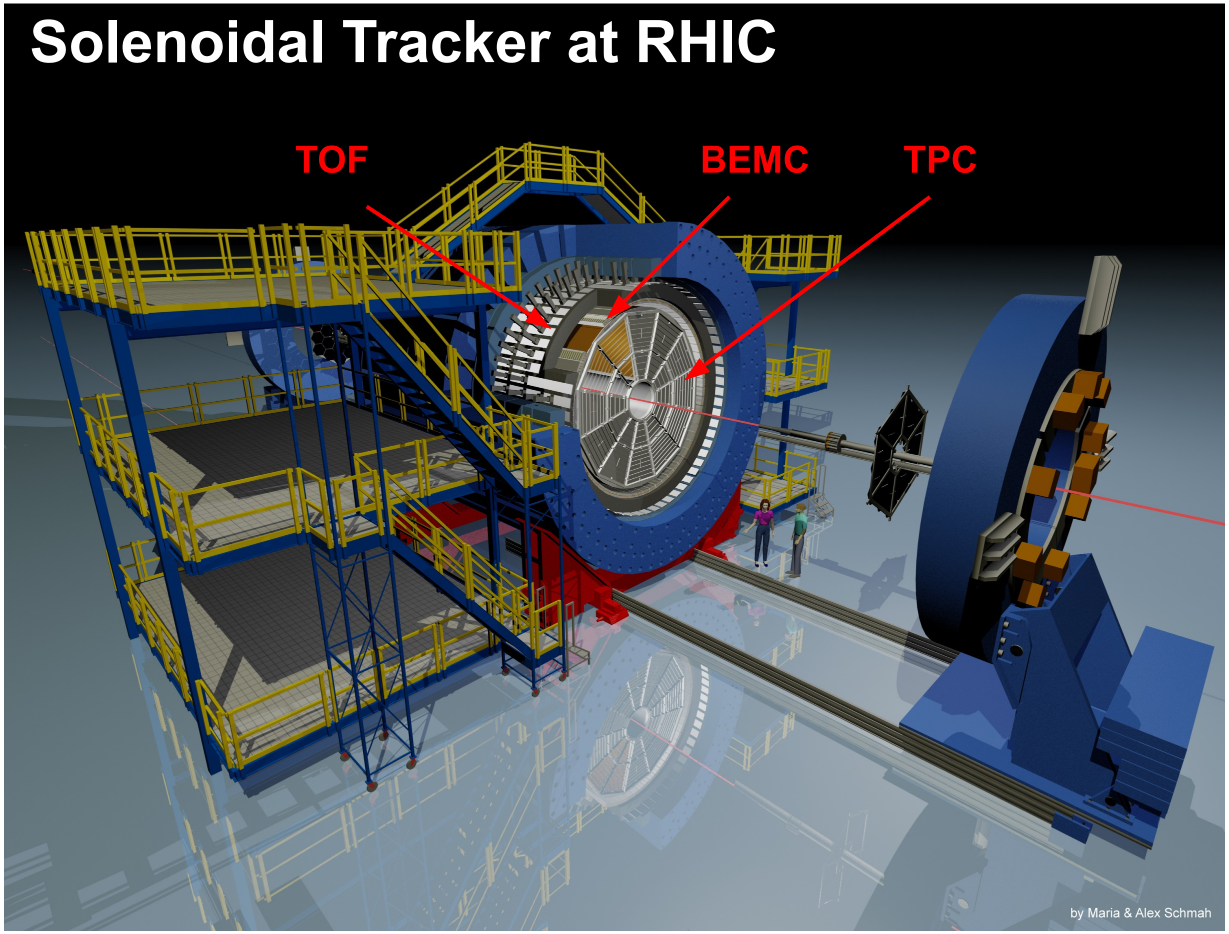
- *Production mechanism unclear;*
- *Modifications from Cold Nuclear Matter effects*
  → modification of nuclear PDFs (shadowing), nuclear absorption
- *Additional Hot Nuclear Matter effects*
  → regeneration in QGP
  → system size and formation time effects
  (high-p_T escape from suppression zone) [leakage]
- *Feed-down from resonances and decays*

→ Need to systematically study quarkonia production in p+p, d+Au, Au+Au collisions:

Measure p_T spectra, elliptic flow, nuclear modification factor to disentangle effects.

STAR Experiment

$J/\psi\,,\ \Upsilon \rightarrow e^{+}\,e^{-}$
(BR = 5.9%, 2.4%)



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

Time Projection Chamber:
Tracking $\rightarrow p_T,\ \eta,\ \phi$
dE/dx $\rightarrow$ PID

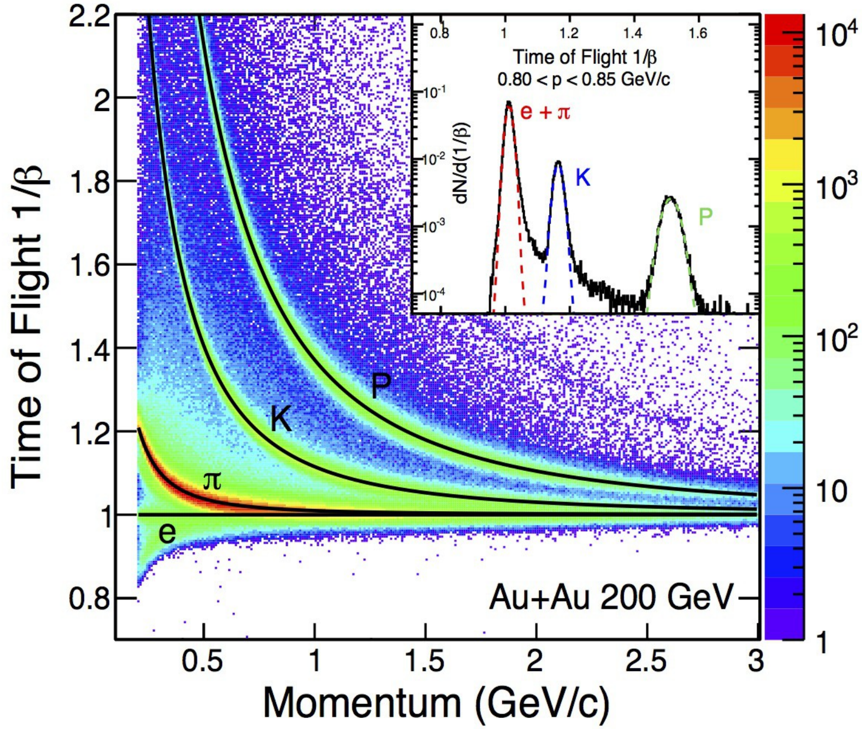
Time Of Flight:
Timing res. < 100 ps
$1/\beta \rightarrow$ PID

Barrel Electromagnetic Calorimeter:
Tower $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$

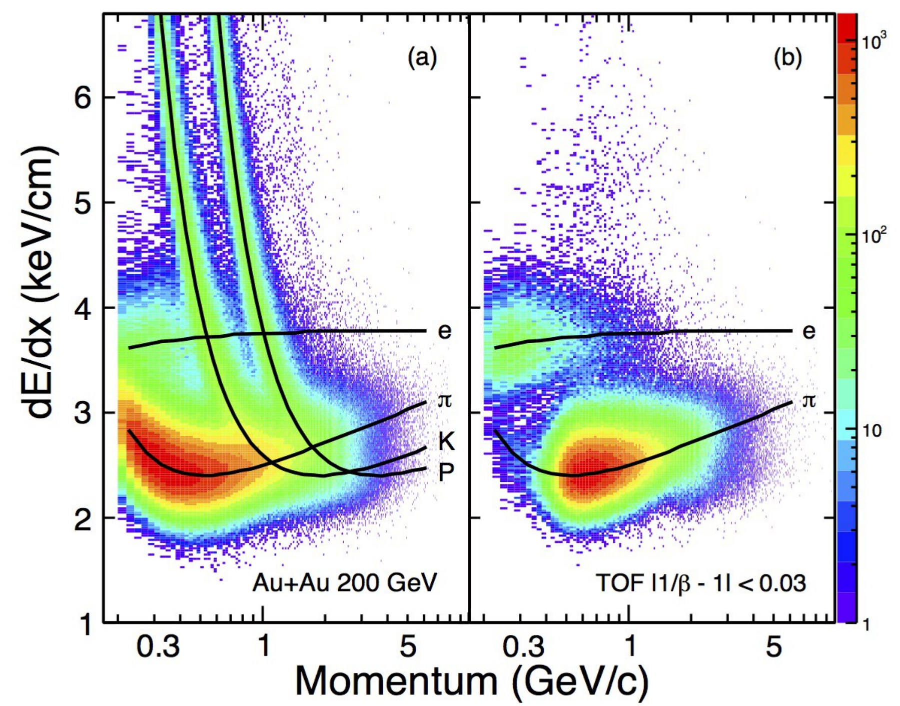
Large acceptance, excellent particle identification, fast DAQ!

Particle Identification: low p_T

Time of Flight
($1/\beta \sim 1$ for electrons)



Time Projection
Chamber dE/dx

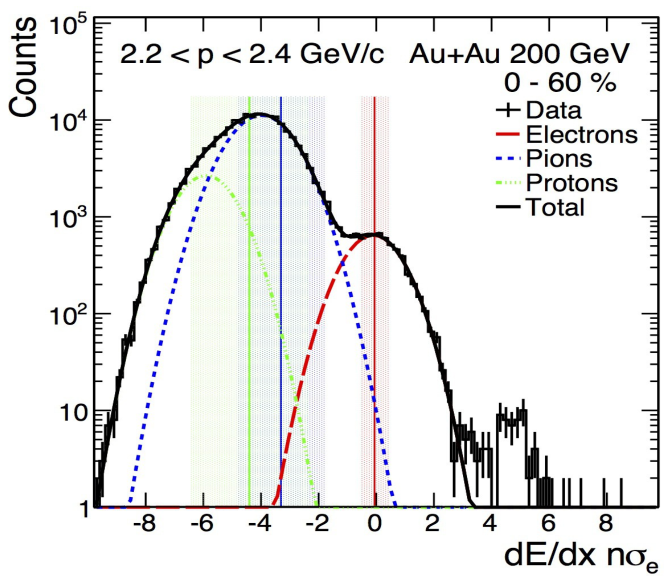


TPC: momentum reconstruction, good separation of electrons from pions using dE/dx.
TOF: good separation of electrons from heavier hadrons for p < 1.5 GeV/c using $1/\beta$.

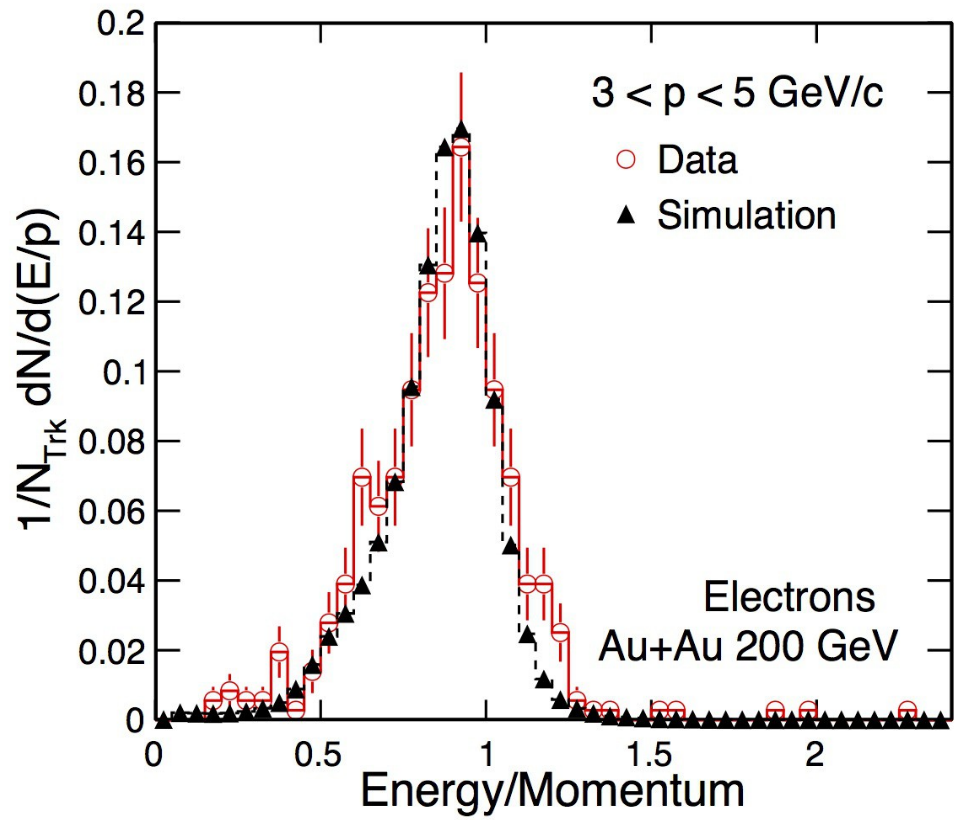
Particle Identification: high p_T

dE/dx normalized to electrons.

$$n\sigma_e = \log\left(\frac{dE/dx|_{\text{measured}}}{dE/dx|_{\text{Bethe-Bloch}}}\right)/\sigma$$



BEMC energy to momentum ratio E/p.



BEMC energy E, TPC momentum p, E/p ~ 1 for electrons.
Good electron-hadron separation in E/p for p > 1.5 GeV/c.

Results

Results from quarkonium production at STAR have been obtained in p+p, d+Au, and Au+Au collisions

- *Production in p+p collisions*
  → understand production mechanism
  → provide baseline for heavy ion collisions
- *Production in d+Au*
  → constrain modification from cold nuclear matter effects
- *Production in Au+Au*
  → constrain modifications from hot nuclear matter effects

J/ψ in p+p at 200 GeV

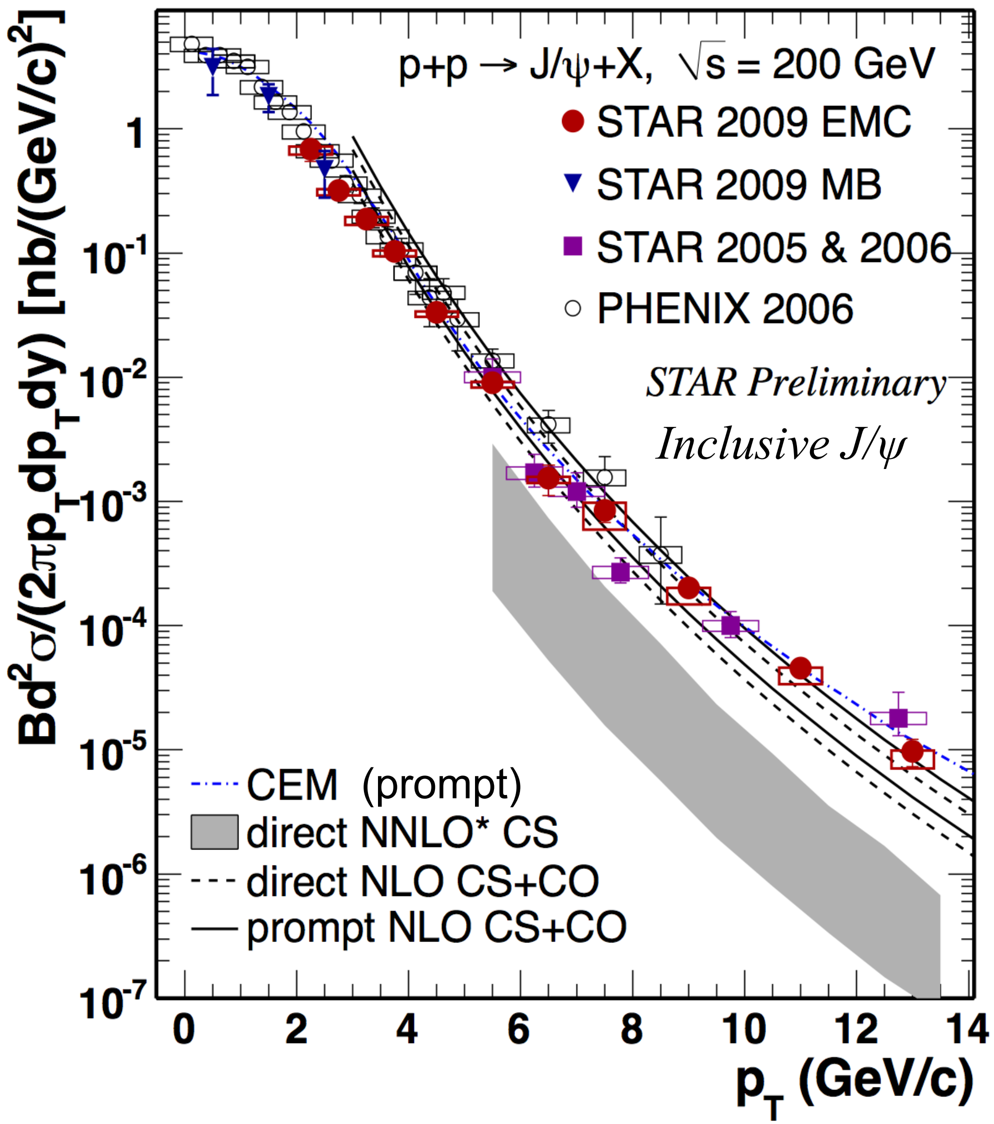
Look at p_T spectrum in p+p to understand production mechanism.

· Color singlet model: direct NNLO* still misses high-p_T;

· NLO CS+CO: describes data reasonably well at high p_T;

· Color Evaporation Model: describes the data reasonably well across the p_T range

[No B feed-down in models]



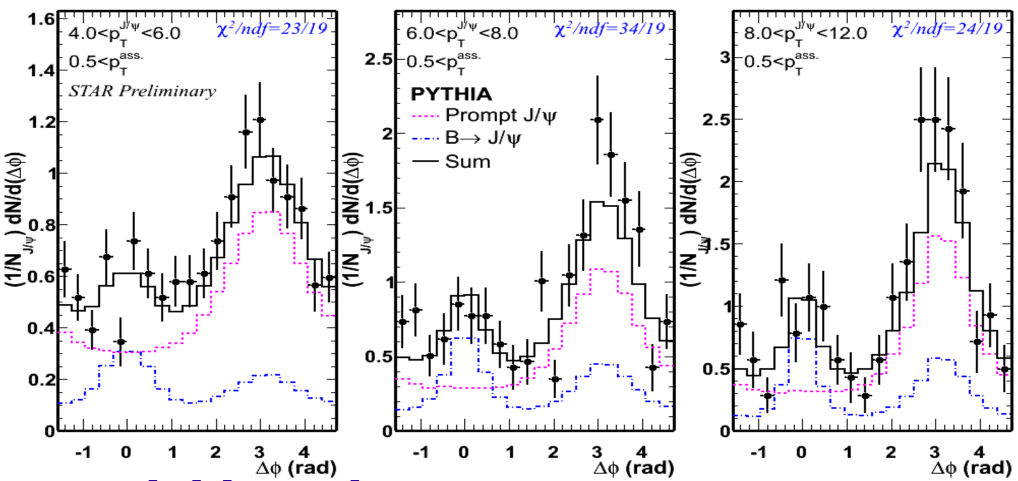
STAR: Phys. Rev. C80, 041902(R) (2009); Arxiv:1208.2736;
PHENIX: Phys. Rev. D 82, 012001 (2010)
NNLO* CS: Phys. Rev. Lett. 101, 152001 (2008)
NLO CS+CO: Phys. Rev. D84, 51 114001 (2011)
CEM: hep-ph/0311048, and R.Vogt private communication

$B \rightarrow J/\psi$ (incl.) decays

J/ψ-hadron azimuthal correlations

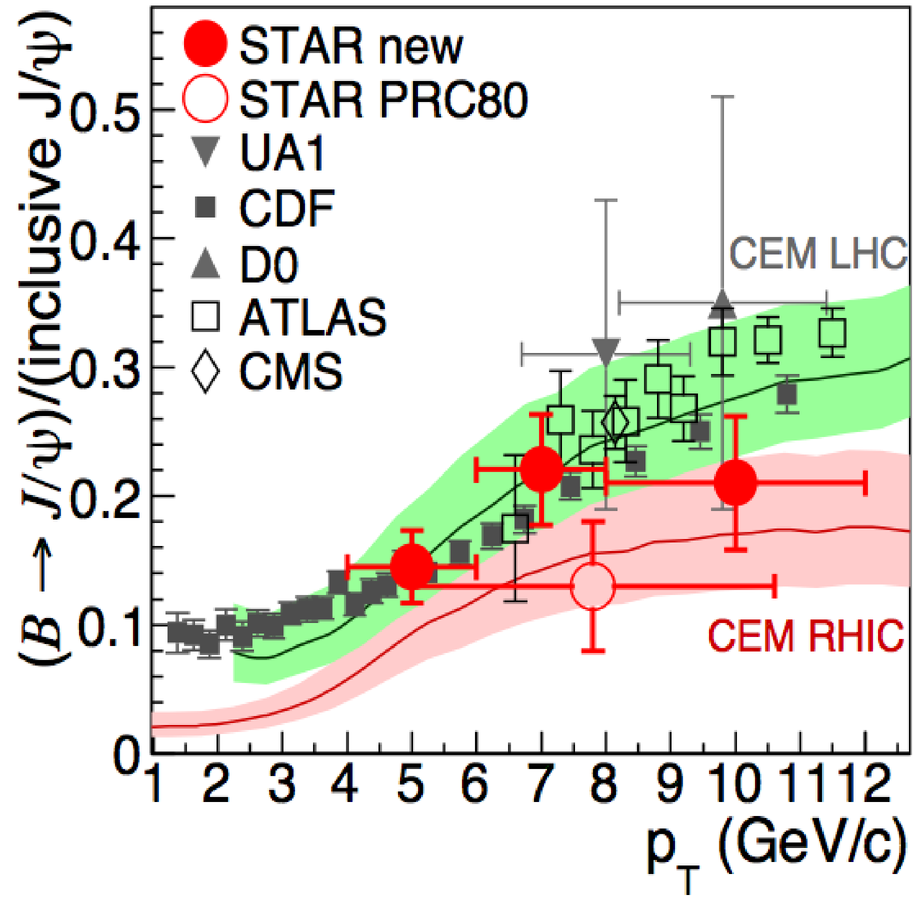
Separate prompt J/ψ from $B \rightarrow J/\psi$ feed-down:

- $J/\psi_{Total} = J/\psi_{Prompt} + J/\psi_{B \rightarrow J/\psi}$



Model based extraction using PYTHIA

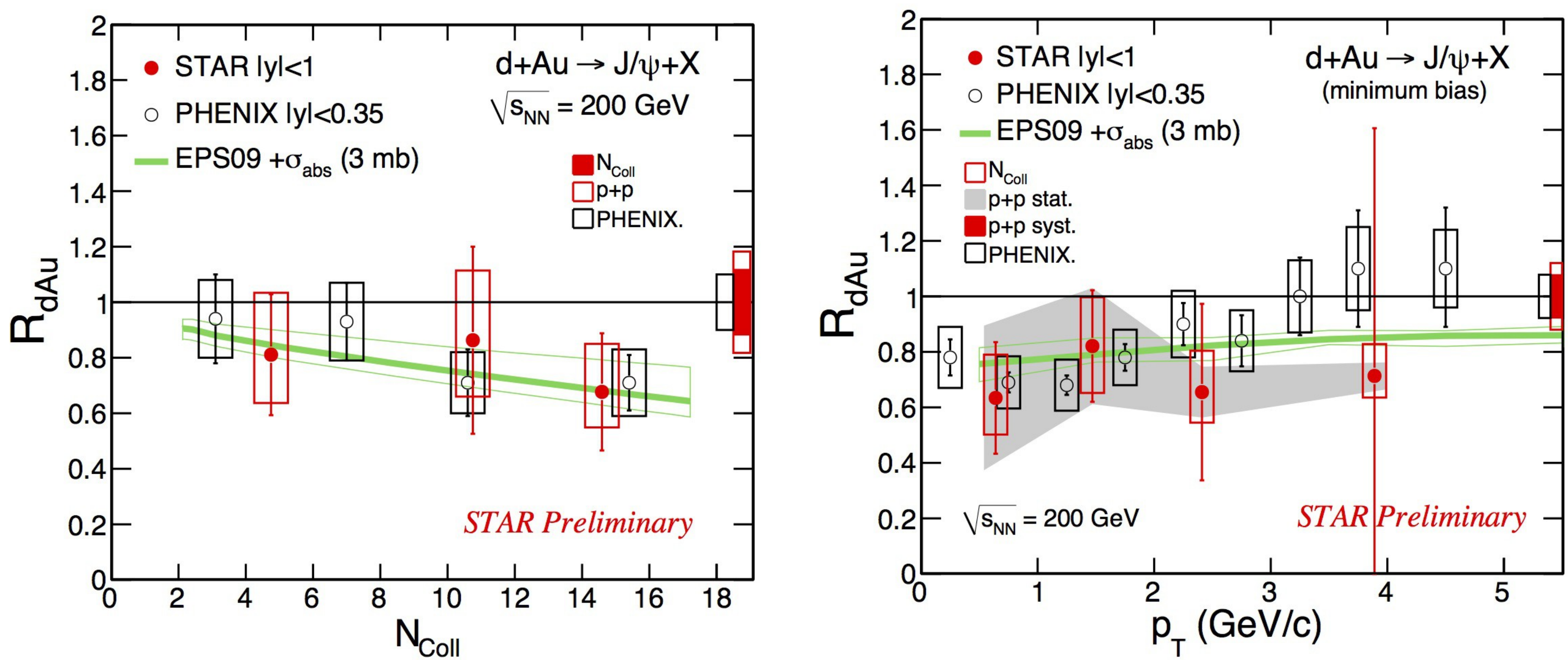
Arxiv:1208.2736;



Contribution from $B \rightarrow J/\psi$ decay ~ 10 – 25 % in p+p collisions at 200 GeV

J/ψ in d+Au at 200 GeV

J/ψ in d+Au collisions used to constrain CNM effects.



Suppression in central d+Au collisions, however large uncertainties.

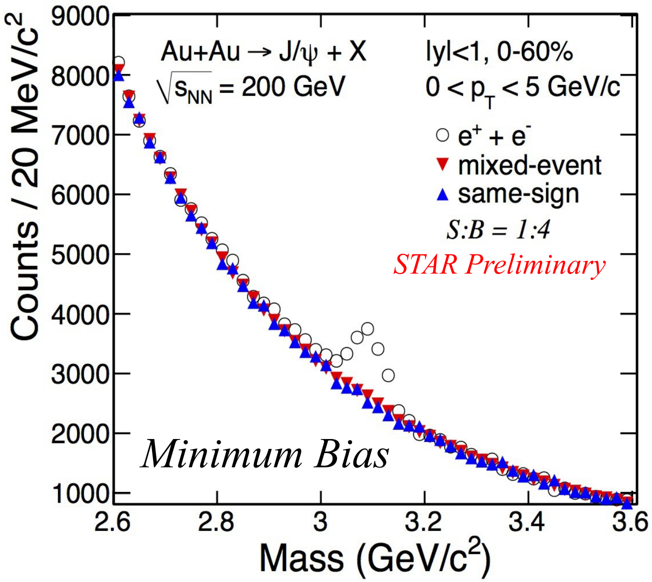
EPS09 nPDFs + absorption cross section (fit to STAR data):

$$\sigma_{abs} = 2.8\ ^{+3.5}_{-2.6}\ \text{(stat.)}\ ^{+4.0}_{-2.8}\ \text{(syst.)}\ ^{+1.8}_{-1.1}\ \text{(EPS09)}$$

EPS09, Nucl. Phys. A 830, 599 (2009) R. Vogt, Phys. Rev. C 81, 044903 (2010)

More data required for precise measurement!

J/ψ in Au+Au at 200 GeV

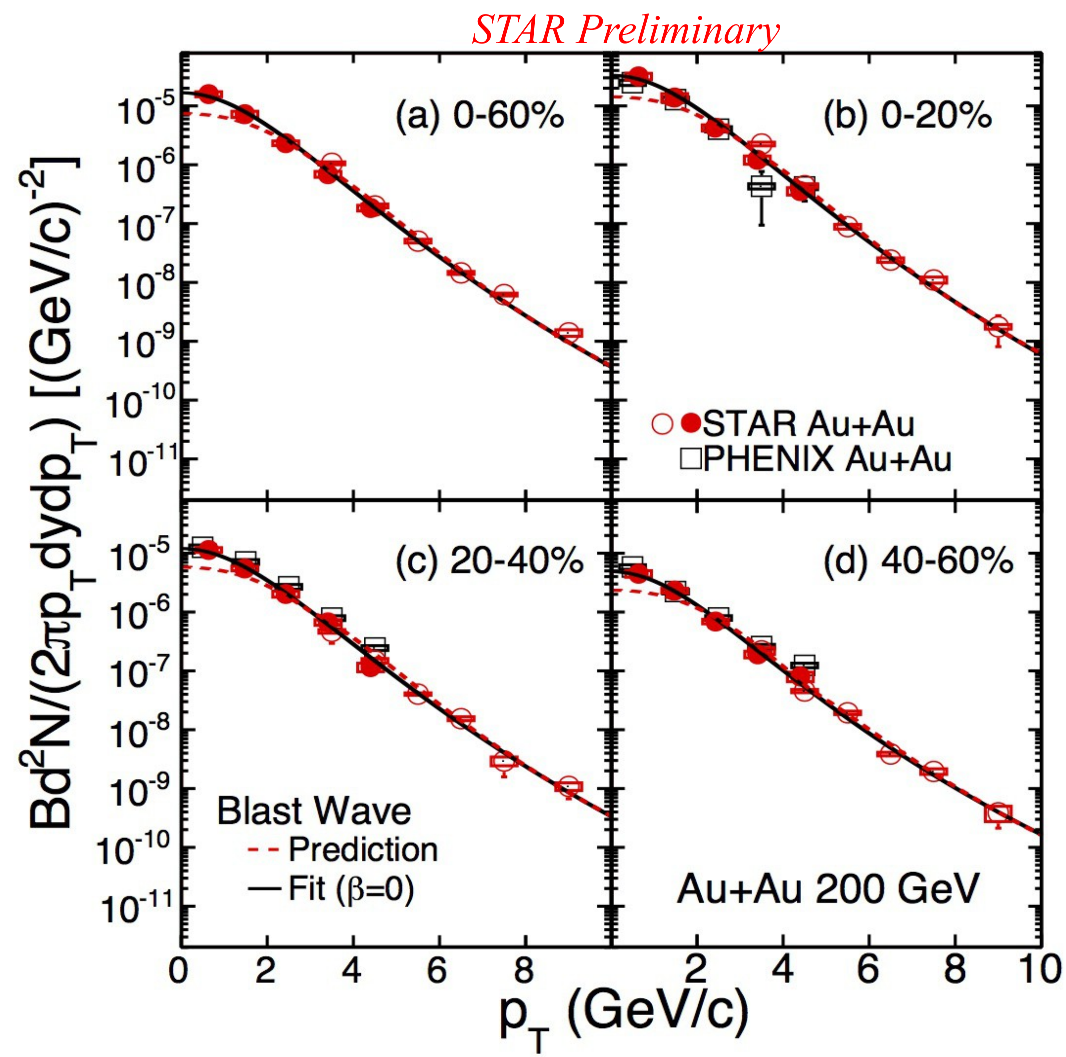


STAR p_T spectrum extended to $0 < p_T < 10$ GeV/c.

Softer spectra as compared to Blast Wave for lighter hadrons.

→ Regeneration at low-p_T?

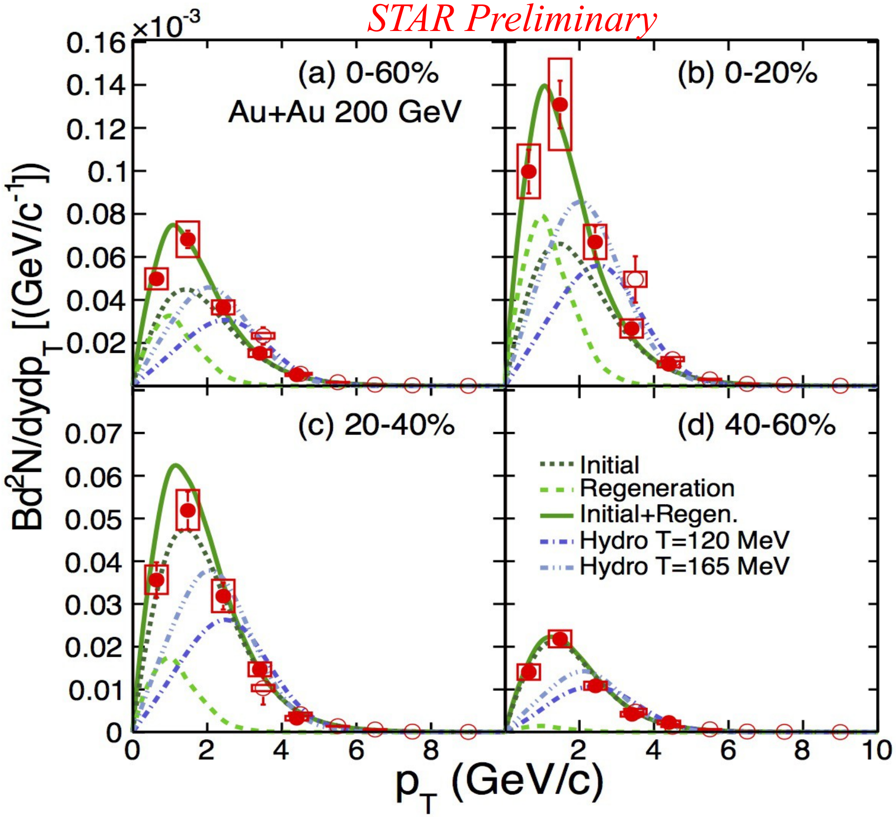
→ Smaller radial flow?

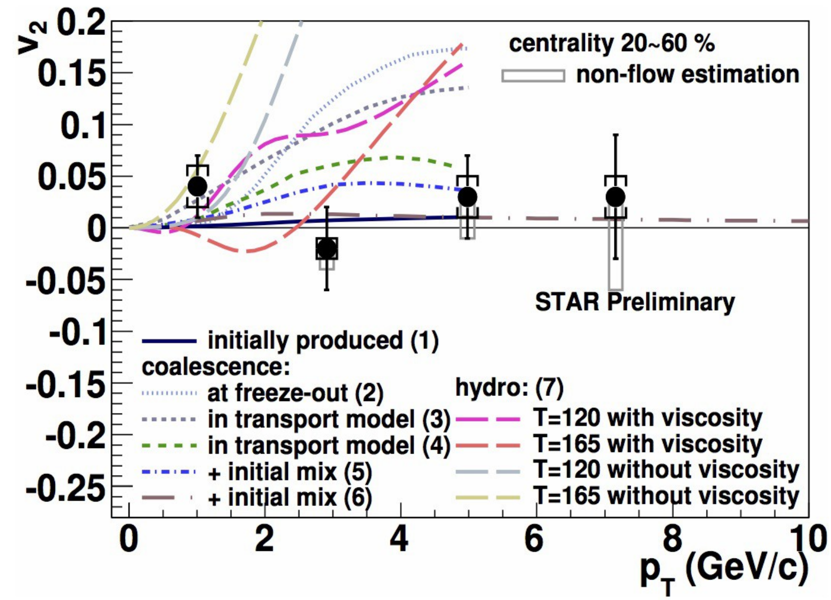


STAR: Arxiv:1208.2736, Arxiv:1111.6944v2
PHENIX: Phs.Rev.Lett.98:232301,2007
Tsallis Blast-Wave model: arXiv:1101.1912, JPG 37, 08194 (2010)

J/ψ in Au+Au at 200 GeV

J/ψ from recombination of thermalized charm quarks expected to acquire flow and populate low p_T → *Look at J/ψ p_T spectrum and v_2*





J/ψ v_2 consistent with zero within errors. Disfavor regeneration from thermalized charm quarks in 20-60%.

→ Good agreement with initial + regeneration.

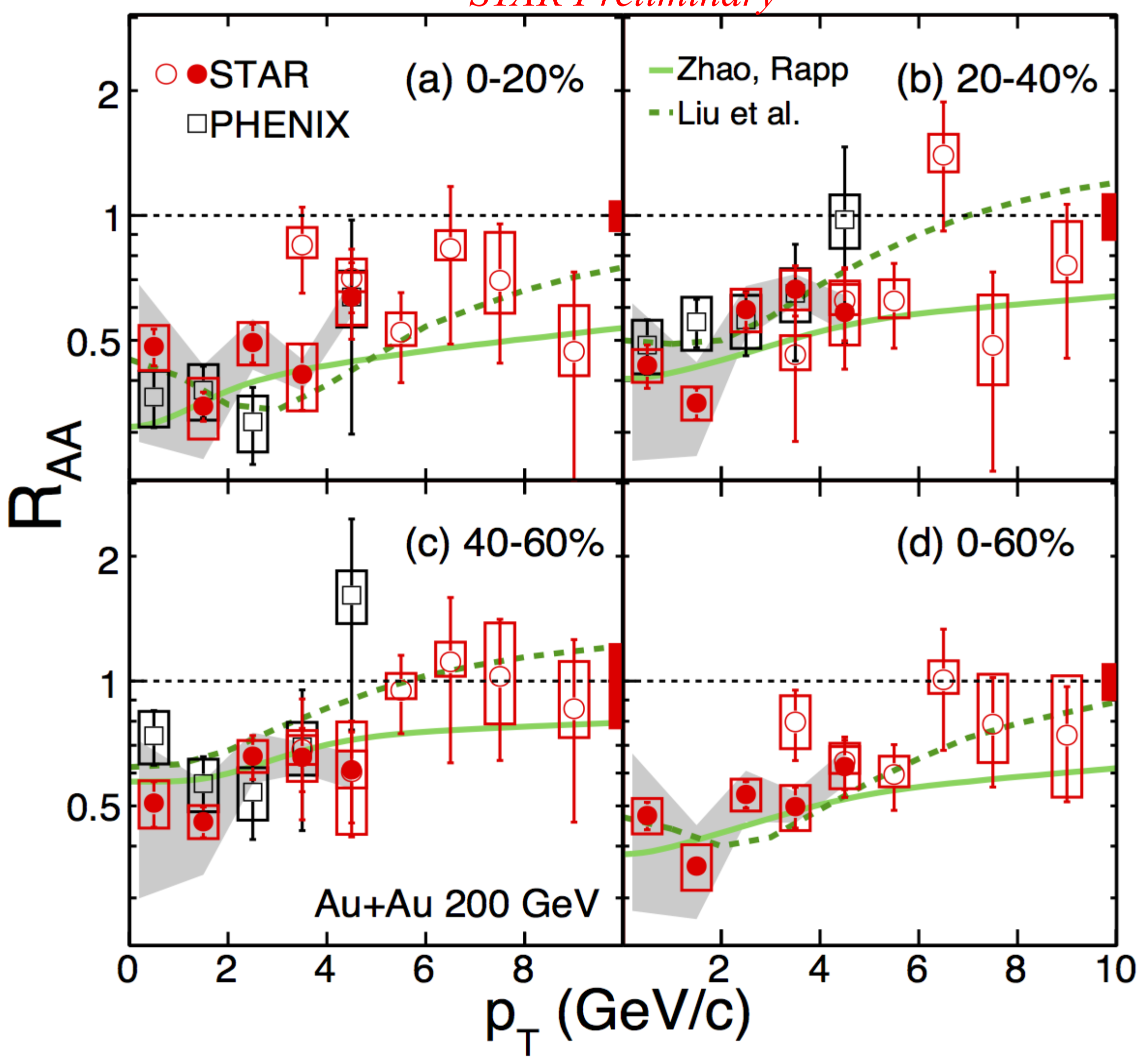
→ Regeneration expected to be significant in 0-20%.

(1) (4) Phys. Rev. Lett. 97, 232301 (2006)
(2) Phys. Lett. B595, 202 (2004)
(3) Phys. Lett. B655, 126 (2008)
(5) X.Zhao, R.Rapp, 24th WWND (2008)
(6) Nucl. Phys. A834, 317 (2010)
(7) U.Heinz, C. Shen, private communication Phys. Lett B. 678, 72 (2009).

J/ψ in Au+Au at 200 GeV

J/ψ nuclear modification factor R_{AA} versus p_T.

STAR Preliminary



Good agreement with theory (initial + regeneration).

Suppression for pT < 5 GeV/c → color screening

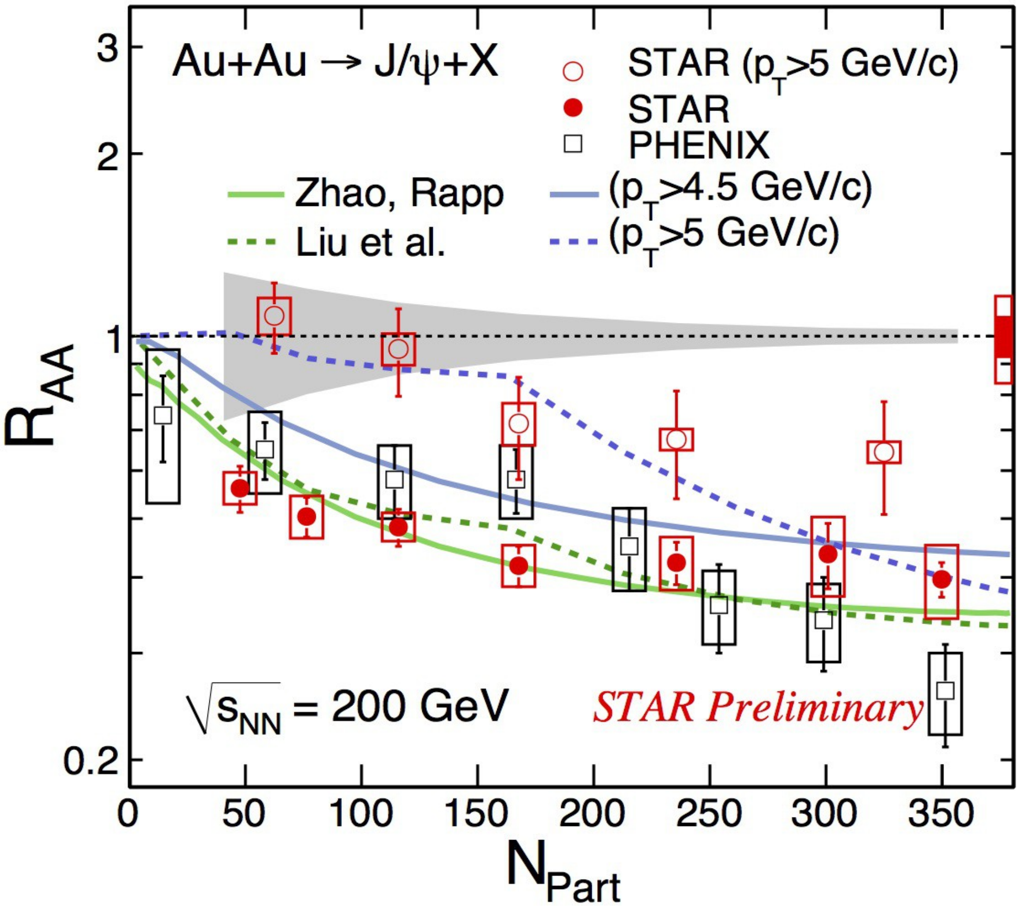
Increase of R_{AA} with p_T
[R_{AA} ~ 1 for pT > 5 GeV/c in 40-60%]
→ formation time effects?

Expect an increase in R_{AA} at low p_T in central events from regeneration.

STAR: Arxiv:1208.2736, Arxiv:1111.6944v2
PHENIX: Phs.Rev.Lett.98:232301,2007
Zhao, Rapp: Phys. Rev. C 82, 064905 (2010)
Liu et. al: Phys. Lett B. 678, 72 (2009).

J/ψ in Au+Au at 200 GeV

J/ψ nuclear modification factor R_{AA} versus N_{part}.



STAR: Arxiv:1208.2736, Arxiv:1111.6944v2
PHENIX: Phs.Rev.Lett.98:232301,2007
Zhao, Rapp: Phys. Rev. C 82, 064905 (2010)
Liu et. al: Phys. Lett B. 678, 72 (2009).

Good agreement with theory (initial + regeneration).

→ Zhao, Rapp under-estimate R_{AA} at high-p_T

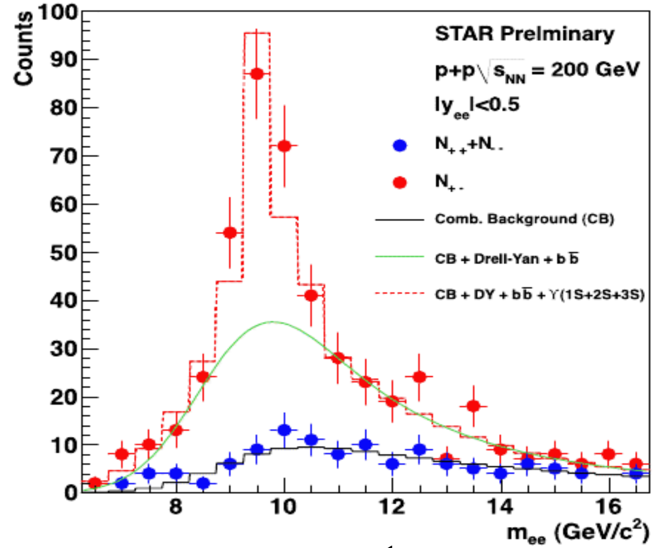
Significant suppression in central events

→ high p_T is less sensitive to regeneration, cold nuclear effects.

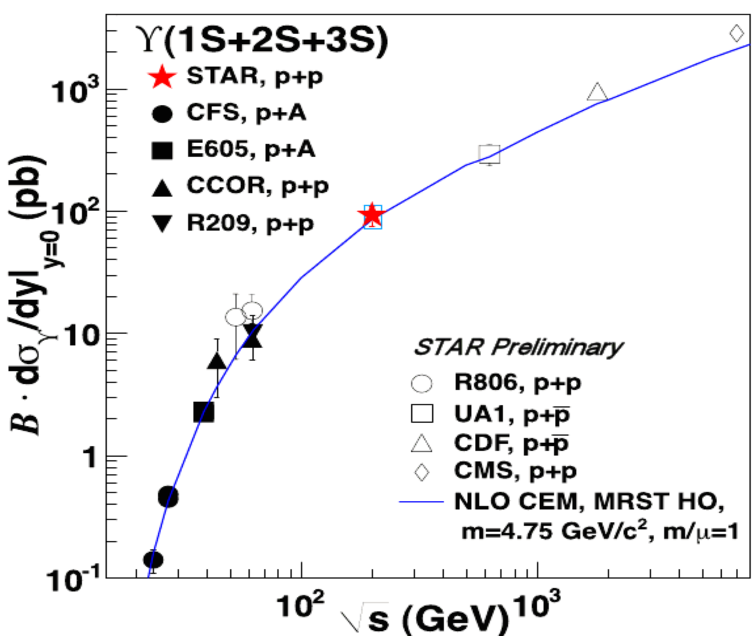
Less suppression at high p_T compared to low pT

→ formation time effects?

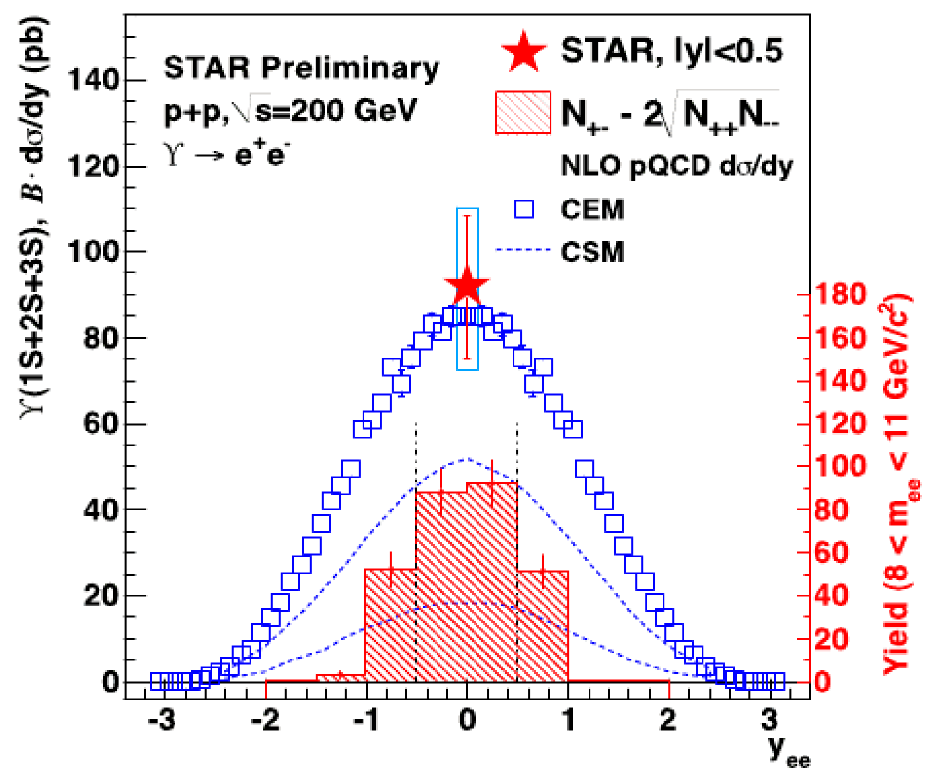
ϒ in p+p at 200 GeV



L dt = 19.7 pb^{-1}



ϒ(1S+2S+3S) → e$^+$ + e$^-$



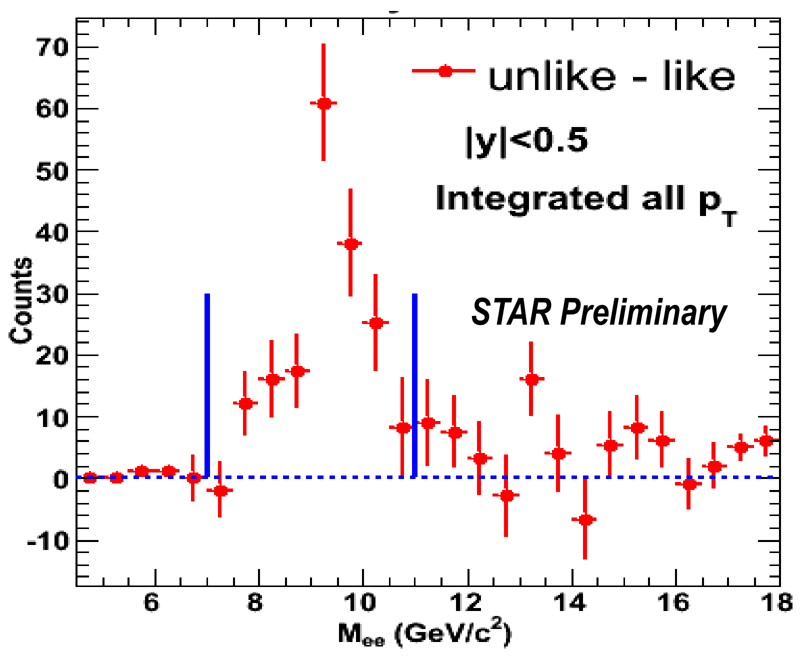
CEM: R. Vogt, Phys. Rep. 462125, 2008
CSM: J.P. Lansberg and S. Brodsky, PRD 81, 051502, 2010

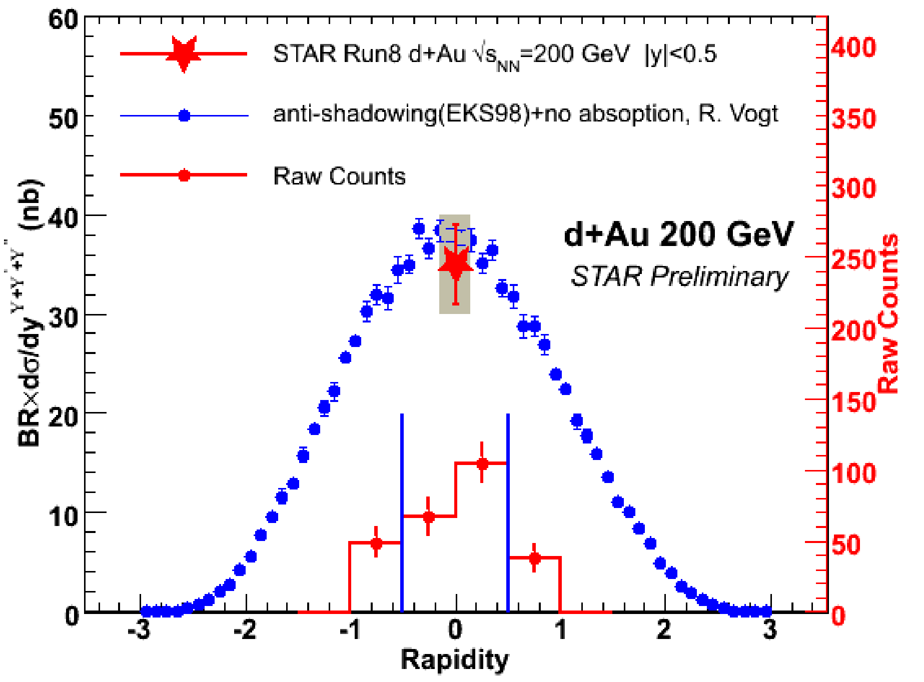
$$\sum_{n=1} \mathcal{B}(n\mathrm{S}) \times \sigma(n\mathrm{S}) = 91.8 \pm 16.6 \pm 19 \text{ pb}$$

Good agreement with NLO CEM and world data trend.

ϒ in d+Au at 200 GeV

ϒ is heavier than J/ψ, less sensitive to nuclear absorption.





Good agreement with anti-shadowing (EKS98) and no ϒ nuclear absorption.

$$R_{dAu} = 0.78 \pm 0.28 \pm 0.20$$

Drell-Yan and $b\bar{b}$ not subtracted.
Published 2006 p+p cross section used as baseline (~114 pb).

Υ in Au+Au at 200 GeV

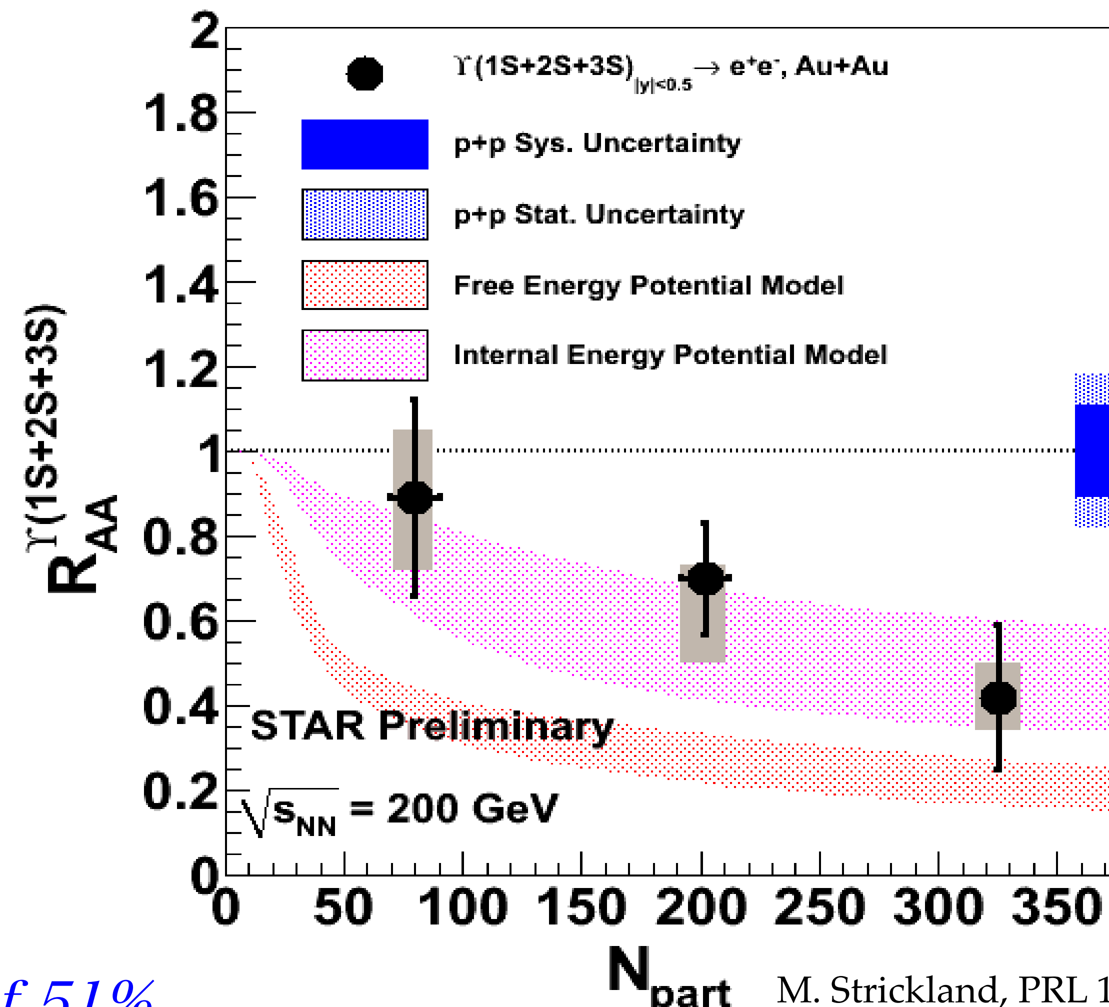
Υ nuclear modification factor R_{AA} versus N_{part}

Suppression increases with increasing centrality
→ color screening

Lattice-based potentials
→ Disfavors free energy
→ Consistent with internal energy

Calculations include melting and feed down (χ_b ~50%)

Consistent with complete melting of higher states Υ(2S+3S)
→ assumes a direct fraction of 51%



M. Strickland, PRL 107, 132301 (2011).

Summary

In p+p collisions:

- J/ψ p_T spectrum extended to $0 < p_T < 14$ GeV/c;
- $B \rightarrow J/\psi$ feed-down calculated at 10-25%;
- High statistics Υ cross section consistent with NLO CEM.

In d+Au collisions:

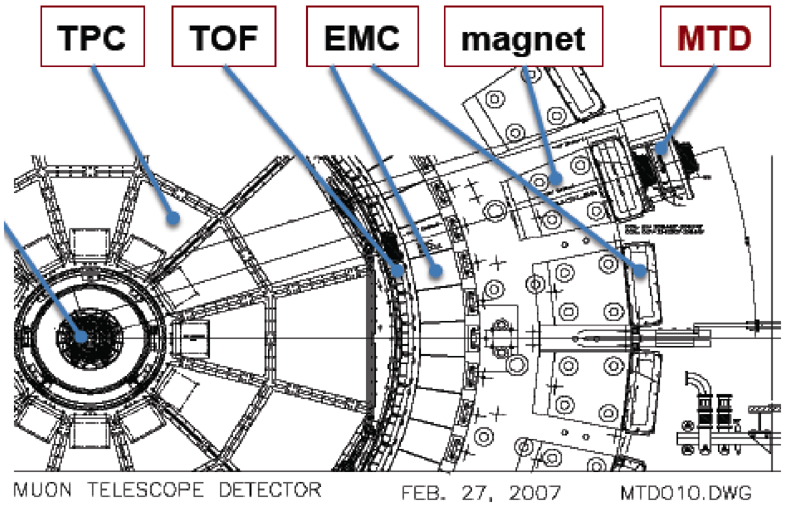
- Suppression of J/ψ in central events;
- J/ψ R_{dA} fitted with EPS09 shadowing + absorption, J/ψ absorption cross section σ_{abs} extracted;
- Υ R_{dA} consistent with EKS98 anti-shadowing + no abs.

In Au+Au collisions:

- J/ψ p_T spectrum softer than TBW from light hadrons, disfavors hydro, good agreement with initial+regeneration;
- J/ψ v_2 consistent with zero, favors initial (initial+regen.);
- J/ψ R_{AA} suppressed in central events, decreasing at high p_T and in peripheral collisions, agrees with initial+regen.;
- Υ suppressed in central events, good agreement with lattice-based internal energy potential.

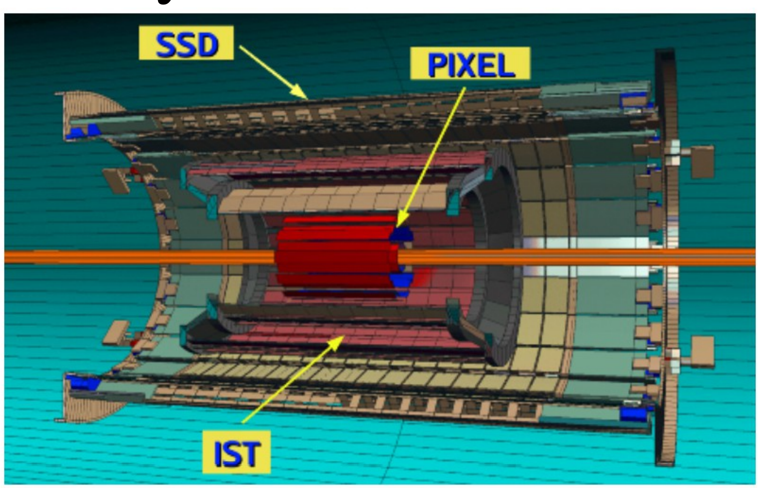
Future

Muon Telescope Detector



MRPC technology (similar to TOF)
Acceptance ~ 45% ($|\eta| < 0.5$)
118 modules, 1416 readout strips,
2832 readout channels
No photon conversion
Less Dalitz decay
→ J/ψ trigger across pT range in central Au+Au collisions

Heavy Flavor Tracker



Pixel and silicon strip detector:
PXL: 2 layers of CMOS pixel detectors (2.5, 8 cm)
IST: low mass silicon strip sensor (14 cm)
SSD: double-sided silicon strip detector (22 cm)
Constrain $B \rightarrow J/\psi$ feed-down