Quarkonium measurements in the STAR experiment

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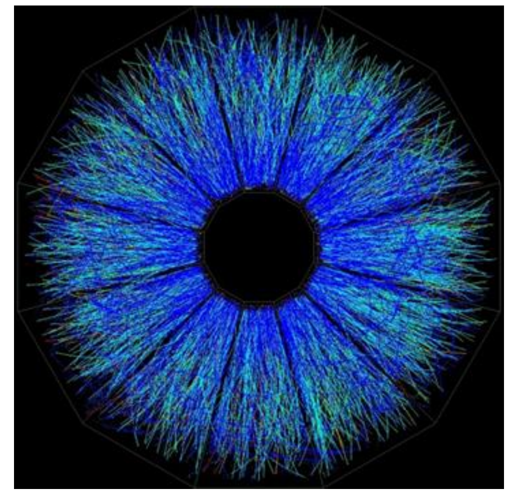

The 6-th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
Cape Town, November 4-8, 2013

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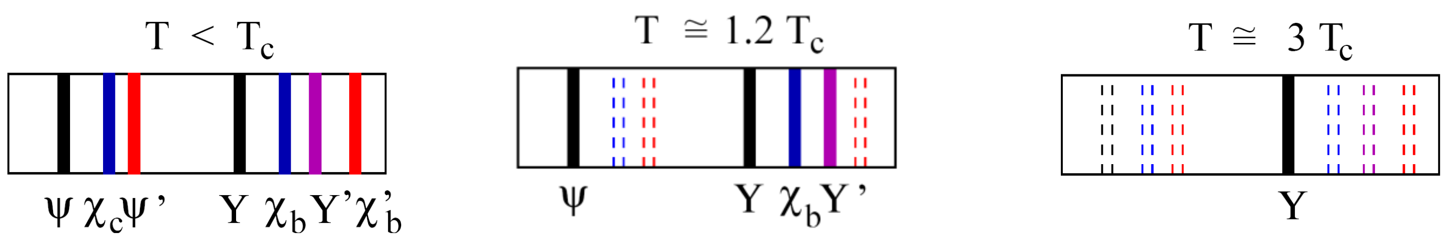
Outline

- Motivation.
- J/ψ measurements
  - p+p and d+Au 200GeV.
  - Au+Au 39, 62, 200 GeV, U+U 193 GeV.
- Upsilon measurements.
- Summary.

Quarkonium in nuclear matter

- Due to color screening of quark potential in QGP quarkonium dissociation is expected.
- Suppression of different states is determined by medium temperature and their binding energy - QGP thermometer.

H. Satz, Nucl. Phys. A (783):249-260(2007)



State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17
r_0 (fm)	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

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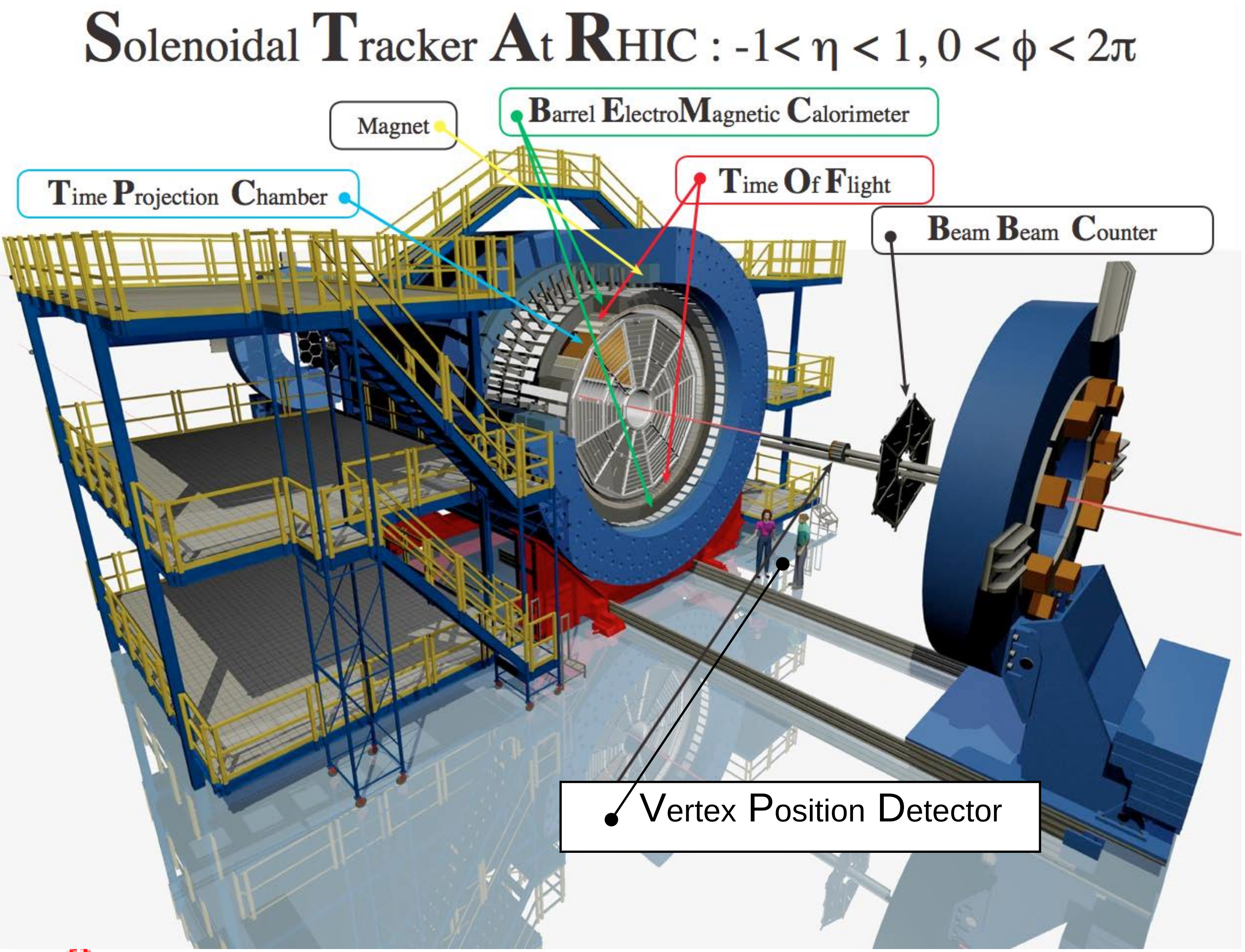
Other important effects

- Quarkonium production mechanism in p+p is not well understood.
  - Color-singlet vs. Color-octet?

- Observed yields are a mixture of direct production + feeddown
  - E.g. J/ψ = 0.6 J/ψ (Direct) + ~0.3 χ_c + ~0.1ψ'
  - Inclusive yields include also B $\rightarrow J/\psi+x$
- Suppression and enhancement in the “cold” nuclear medium
  - Nuclear Absorption, Gluon shadowing, initial state energy loss, Cronin effect and gluon saturation.
- Hot/dense medium effect
  - Recombination from uncorrelated charm pairs.

The STAR Detector



- VPD: minimum bias trigger.
- TPC: PID, tracking.
- TOF: PID.
- BEMC: PID, trigger.

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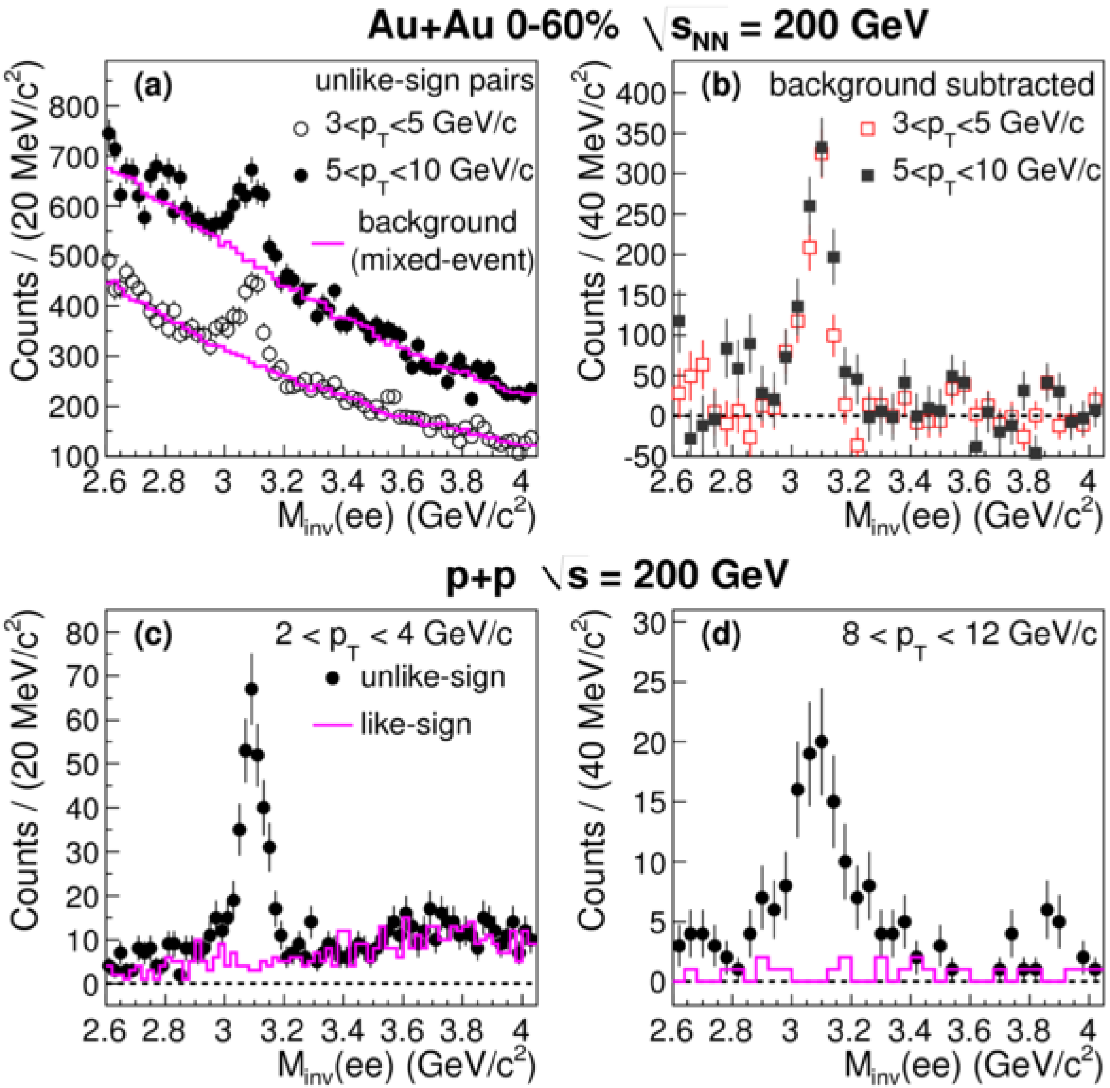
J/ψ –> e^+e^- signals



Phys.Lett. B722 (2013) 55

- Significantly reduced material in 2009 p+p and 2010 Au+Au collisions.
- Clear signal for high-p_T in both p+p and Au+Au 200 GeV collisions.

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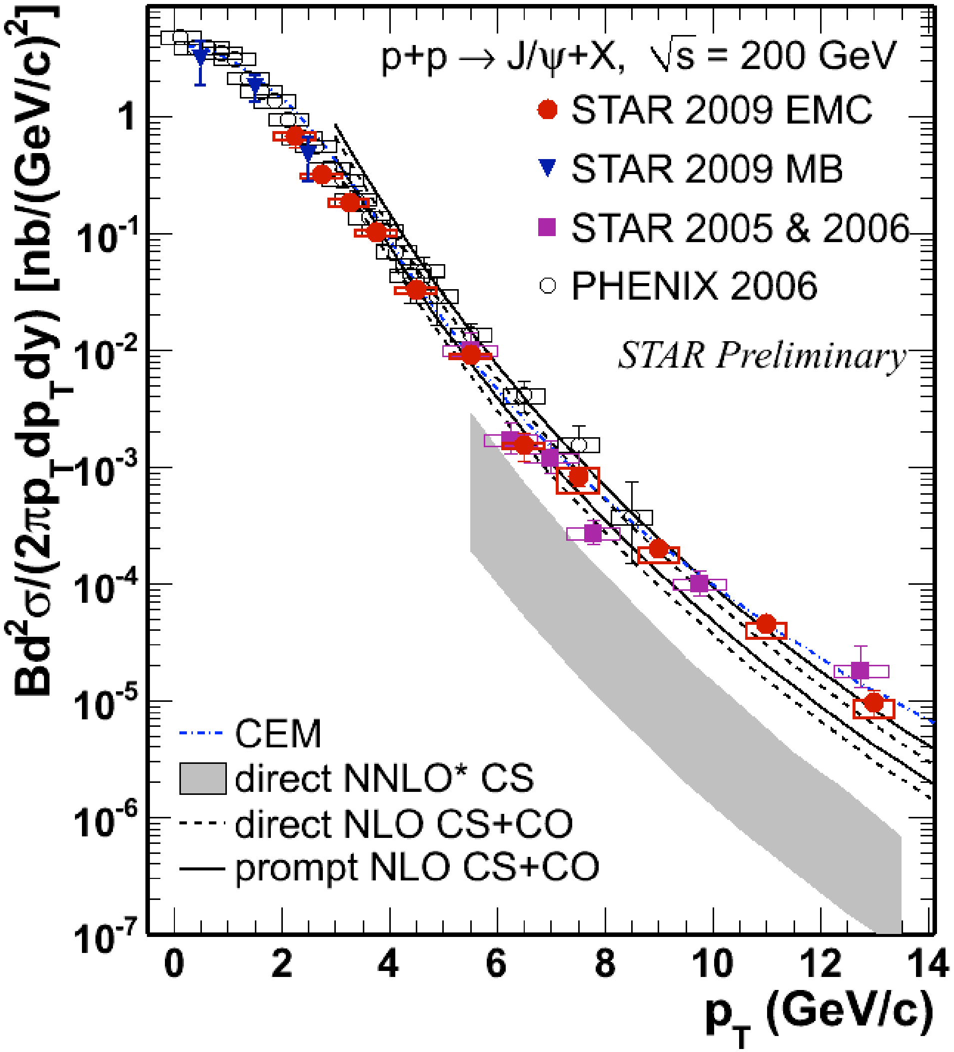
J/ψ in p+p 200 GeV



PHENIX: Phys. Rev. D82, 012001 (2010)
STAR 2005&2006: Phys. Rev. C80, 041902(R) (2009)
STAR 2009 EMC : Phys.Lett. B722 (2013)

- J/ψ p_T extended to 0-14 GeV/c.
- Prompt NLO CS+CO model describes the data.
- Prompt CEM model describes the high-p_T data.
- Direct NNLO* CS model underpredicts high-p_T part.

direct NNLO: 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. D84, 51 114001 (2011)
CEM:M. Bedjidian et al., hep-ph/0311048, and R.Vogt private communication

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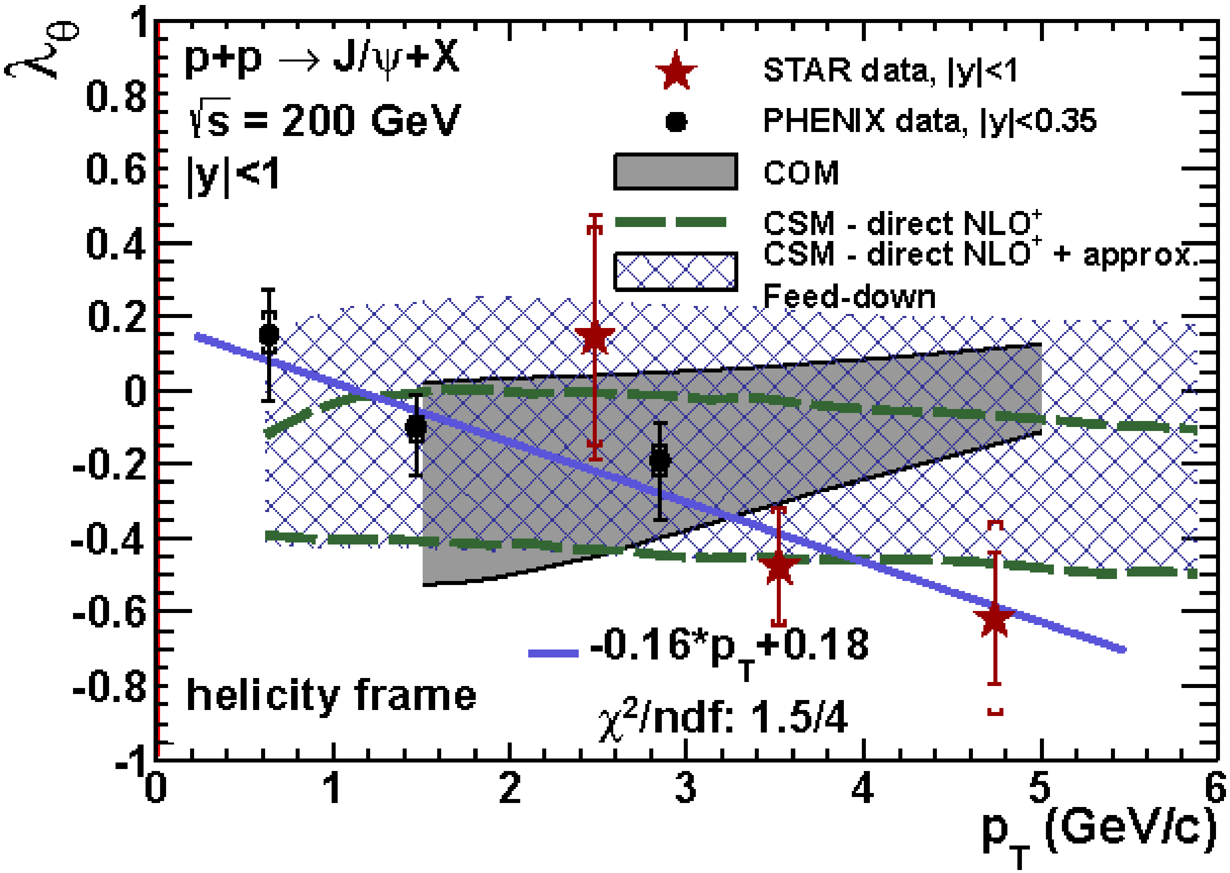
J/ψ polarization



- Polarization parameter λ_θ in helicity frame at $|y| < 1$ and $2 < p_T < 6$ GeV/c.
- λ_θ is consistent with NLO+ CSM.
- RHIC data indicates a trend towards longitudinal J/ψ polarization as p_T increases.
- More precise measurement from p+p 500 GeV expected.

PHENIX: Phys. Rev. D 82, 012001 (2010)
COM: Phys. Rev. D 81, 014020 (2010)
CSM NLO+: Phys. Lett. B, 695, 149 (2011)

appeared on arXiv today
arXiv 1311.1621

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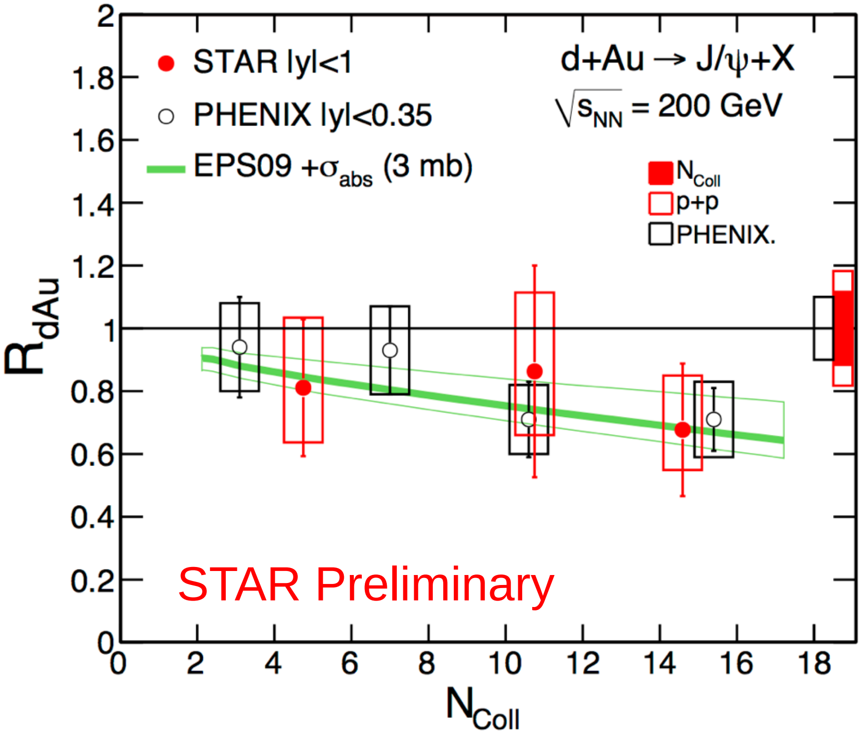
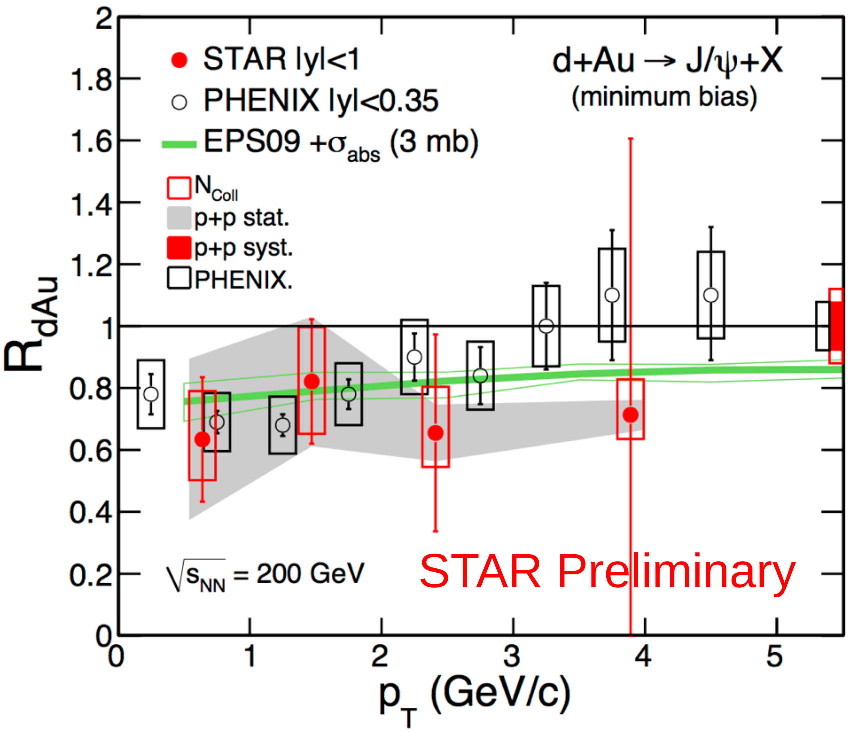
J/ψ in d+Au 200 GeV





E.Eskola, H.Paukkunenea and C.Salgo, Nucl. Phys. A 830, 599 (2009) R.Vogt, Phys. Rev. C 81, 044903 (2010)

- Cold nuclear effects are important to interpret the heavy ion results.
- Good agreement with model predictions using EPS09 nPDF parametrization for the shadowing, and J/ψ nuclear absorption cross section.
- $\sigma_{abs}^{J/\psi} = 2.8^{+3.5}_{-2.6}(stat.)^{+4.0}_{-2.8}(syst.)^{+1.8}_{-1.1}(EPS09)mb$ fit to the data.

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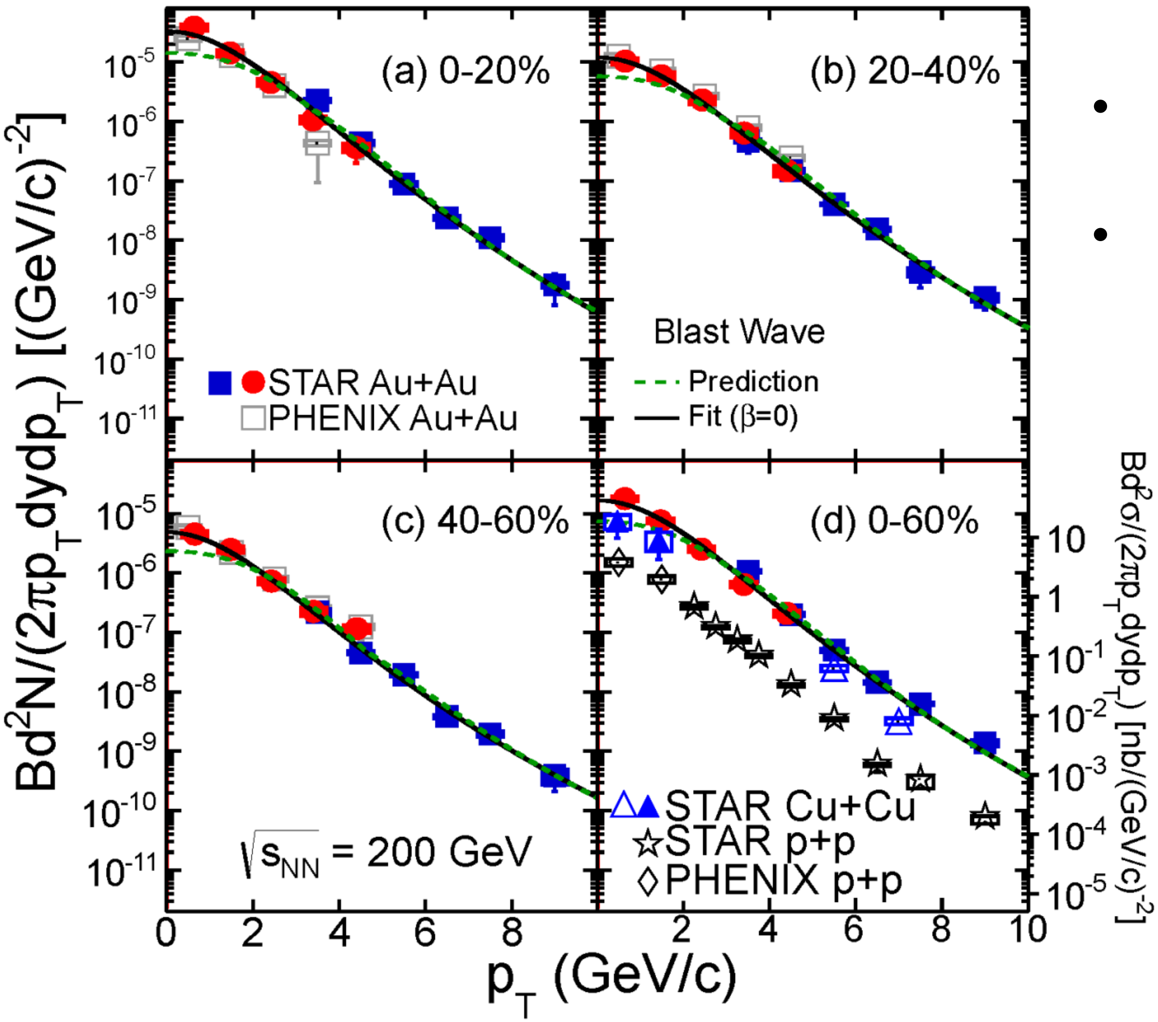
J/ψ spectra in 200 GeV Au+Au collisions



- Large p_T range of 0- 10 GeV/c.
- J/ψ spectra significantly softer at low p_T than the prediction from light hadrons.
  - Recombination at low p_T?
  - Small radial flow?

STAR low-p_T **arXiv:1310.3563** high-p_T : Phys.Lett. B722 (2013)
Tsallis Blast-Wave model: Z.Tang *et al.*, Chin.Phys.Lett. 30 (2013)

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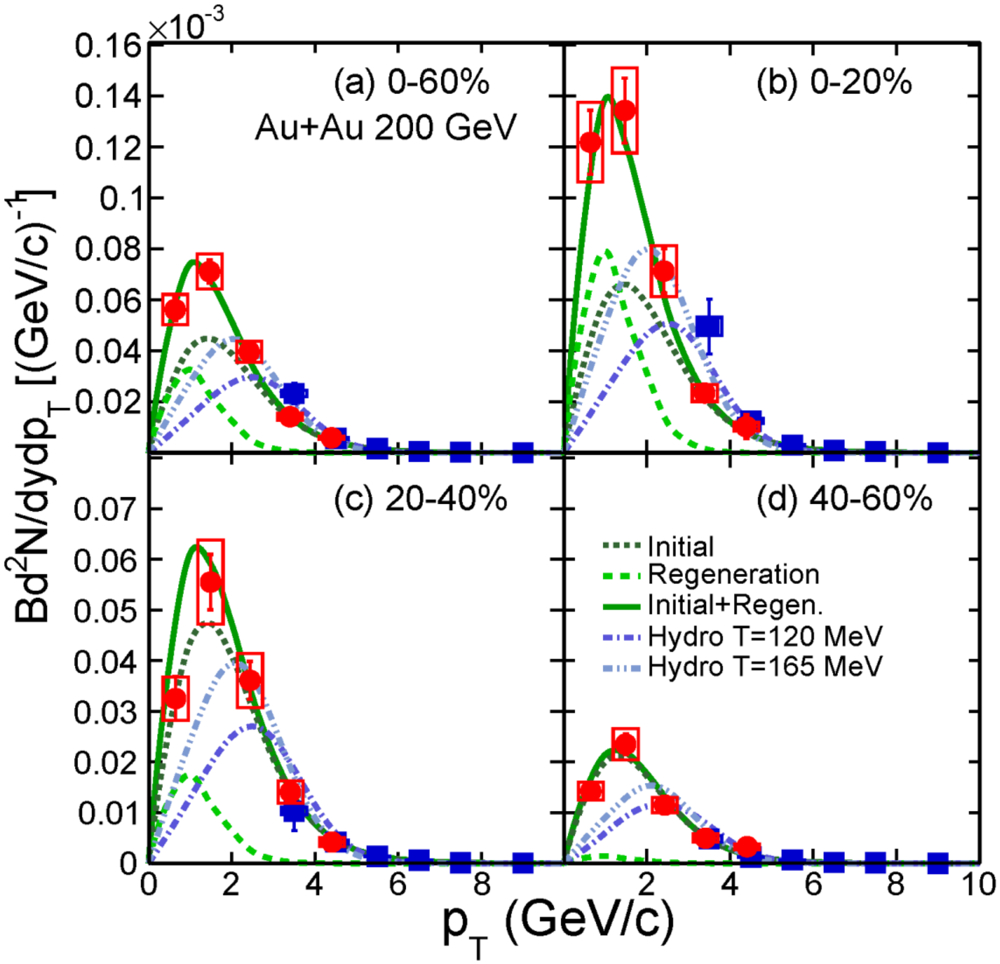
J/ψ spectra in 200GeV Au+Au collisions



- **Viscous hydrodynamics**
  J/ψ decoupling temperature of T = 120 MeV and T = 165 MeV fails to describe low-p_T data (predicts large flow).

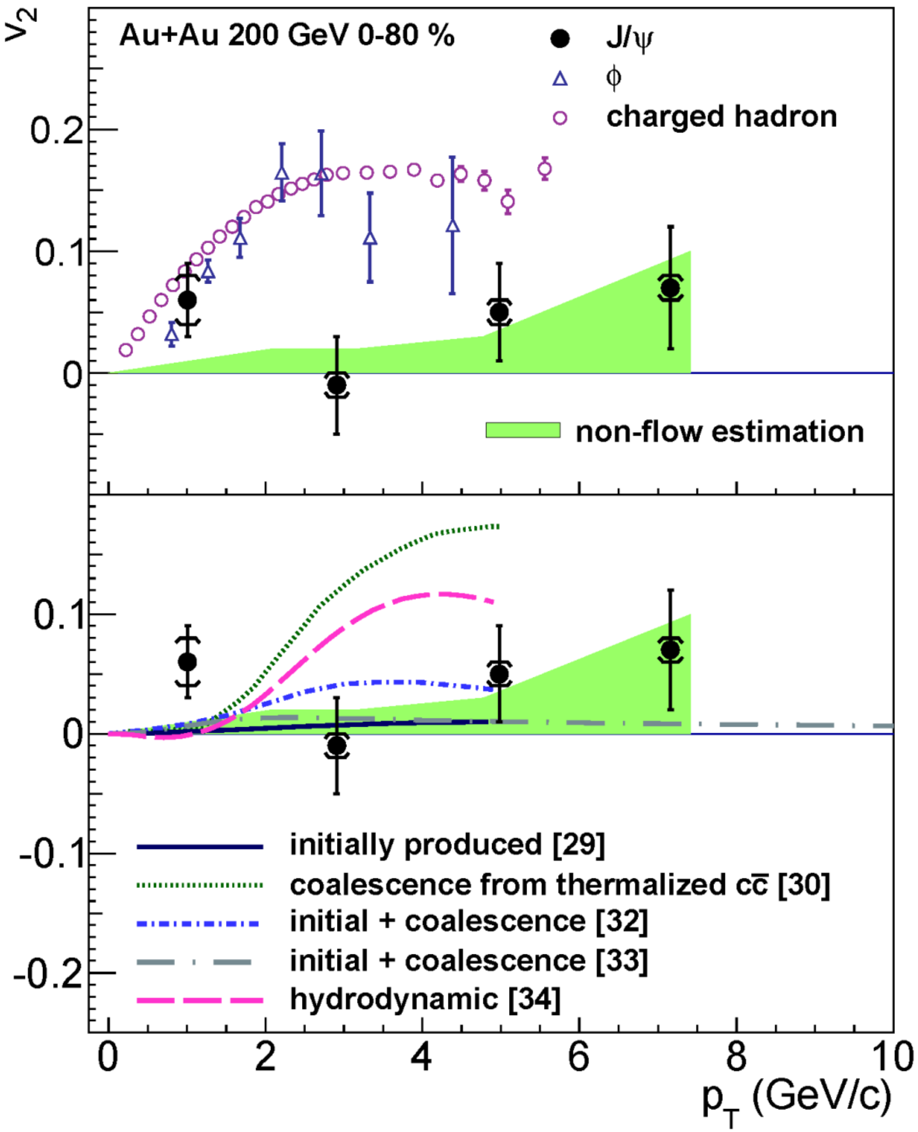
- **Y. Liu et al .**
  model includes J/ψ suppression due to color screening and the statistical regeneration + B meson feed-down and formation-time effects describes the data well.

peripheral: initial production dominates.
central: regeneration becoming more significant at low p_T.

STAR arXiv:1310.3563 high-p_T : Phys.Lett. B722 (2013)
Y. Liu et al., Phys. Lett. B 678, 72 (2009)
U. W. Heinz and C. Shen (2011), private communication.

J/ψ elliptic flow v_2

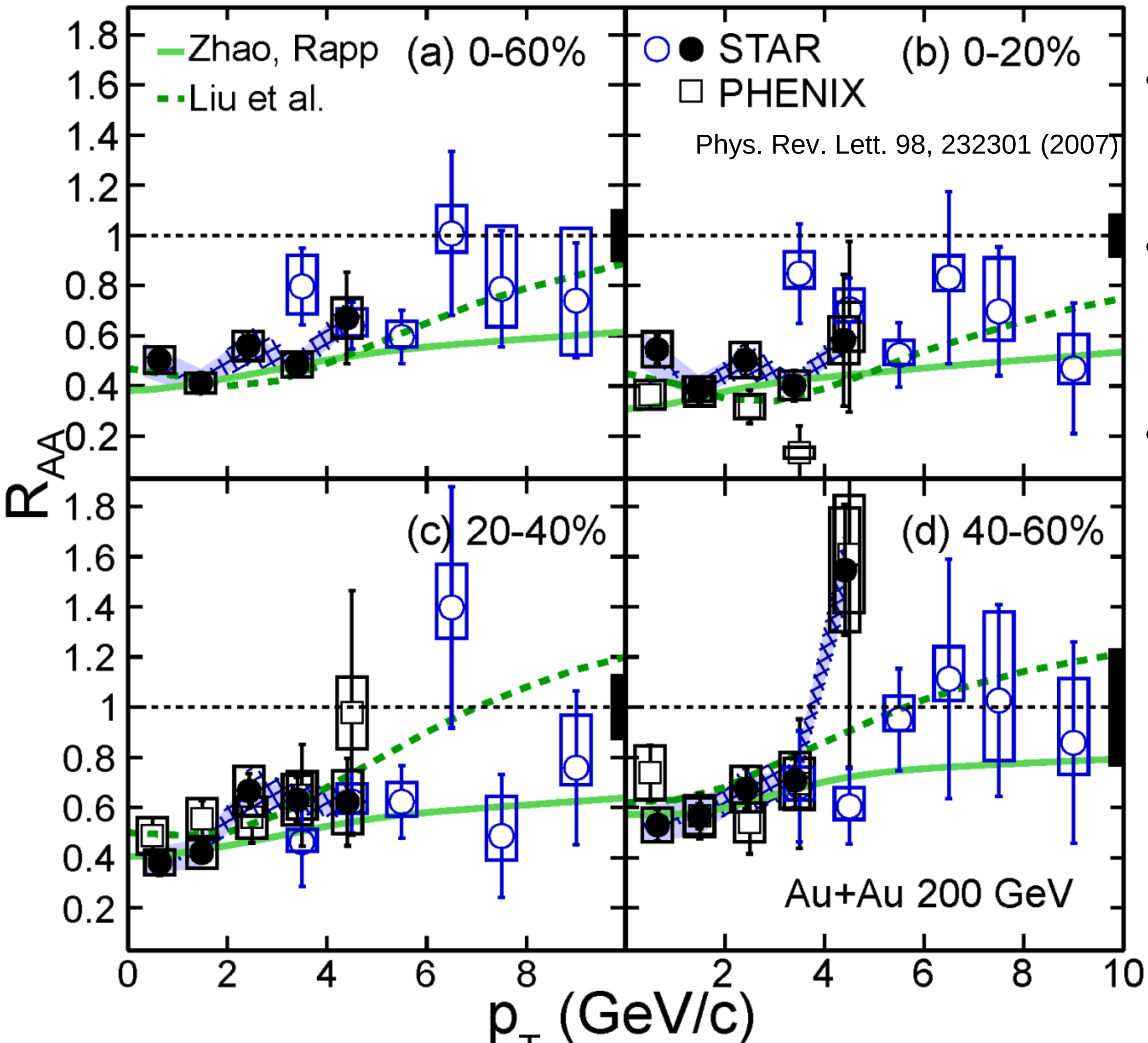
Phys. Rev. Lett. 111 (2013) 52301



- Consistent with zero (p_T > 2 GeV/c), first hadron that does not flow.
- Disfavor coalescence from thermalized charm quarks at high p_T.

[29] L. Yan, P. Zhuang, N. Xu, PRL 97 (2006), 232301.
[30] V. Greco, C.M. Ko, R. Rapp, PLB 595, 202.
[32] X. Zhao, R. Rapp, arXiv:0806.1239 (2008)
[33] Y. Liu, N. Xu, P. Zhuang, Nucl. Phy. A, 834, 317.
[34] U. Heinz, C. Shen, priviate communication.

Nuclear modification factor vs. p_T



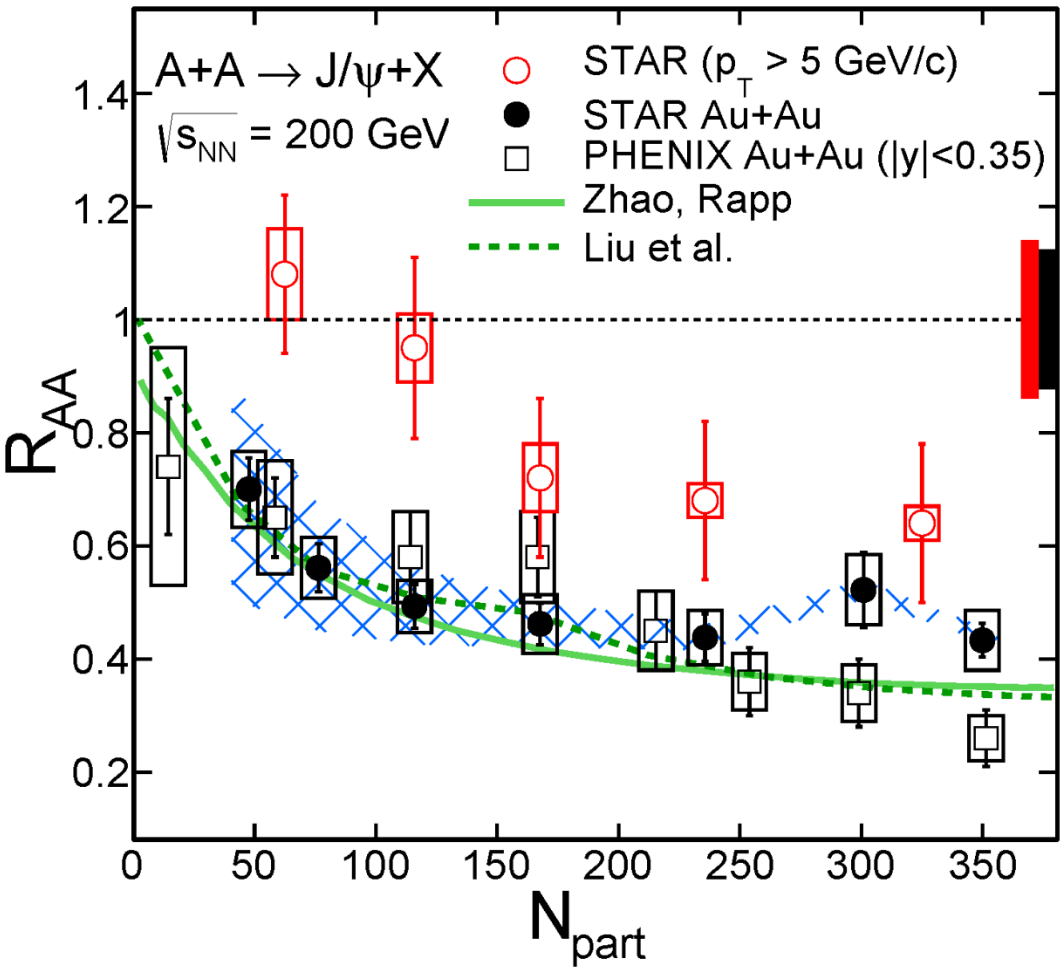
- Increase from low p_T to high p_T.
- Consistent with unity at high p_T in peripheral col.
- More suppression in central than in peripheral even at high p_T.

Liu et al.., PLB 678:72 (2009) and private comminication

Zhao and Rapp, PRC 82,064905(2010) PLB 664, 253 (2008).

STAR low-p_T arXiv:1310.3563 high-pT : Phys.Lett. B722 (2013)

R_{AA} vs. Npart



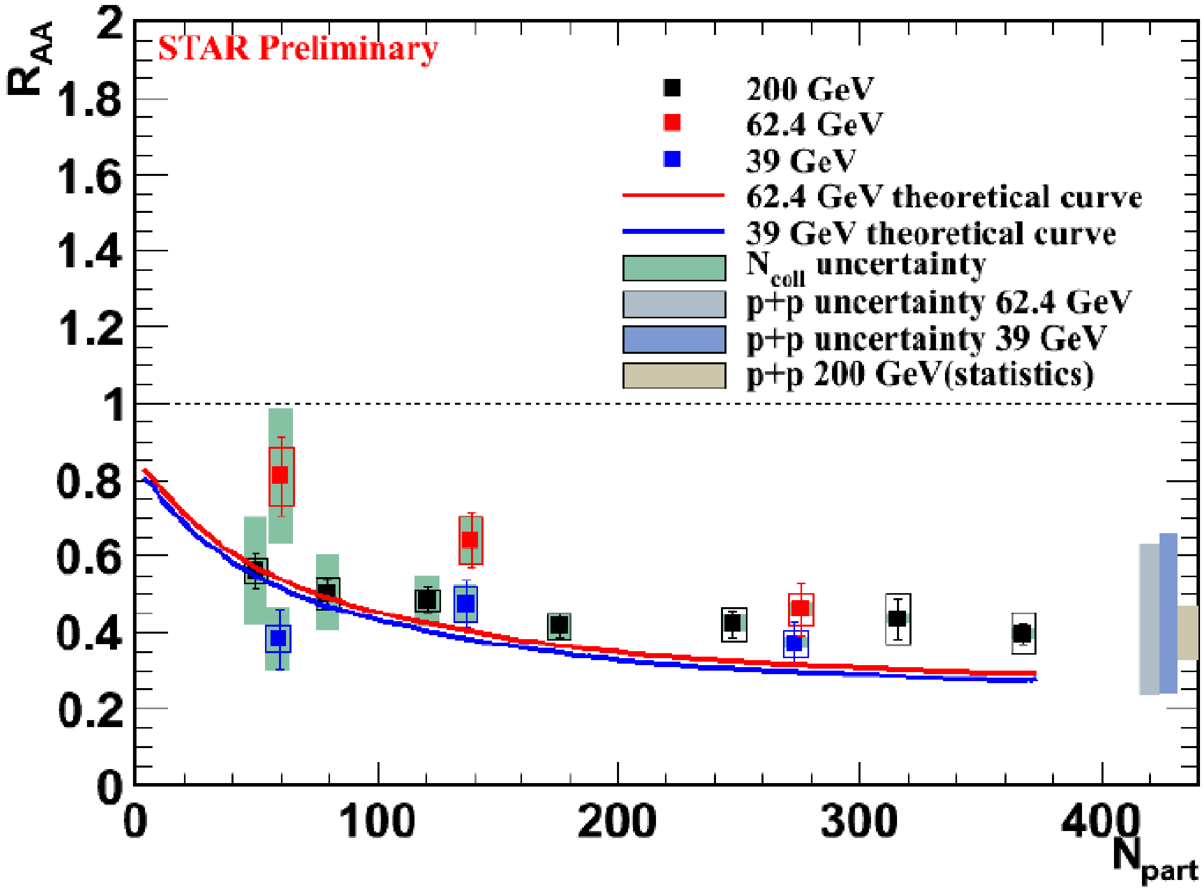
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

Y. Liu, et al., PLB 678:72 (2009)
X. Zhao and R.Rapp, PRC 82, 064905(2010)

STAR low-p_T **arXiv:1310.3563**
STAR high-p_T Phys.Lett. B722 (2013)

- R_{AA} for p_T < 5 GeV/c: Low-p_T data agrees with both models.
- R_{AA} for p_T > 5 GeV/c: High-p_T data less suppressed than low-p_T.
- More suppression in central than in peripheral even at high p_T.

J/ψ suppression at RHIC low energy

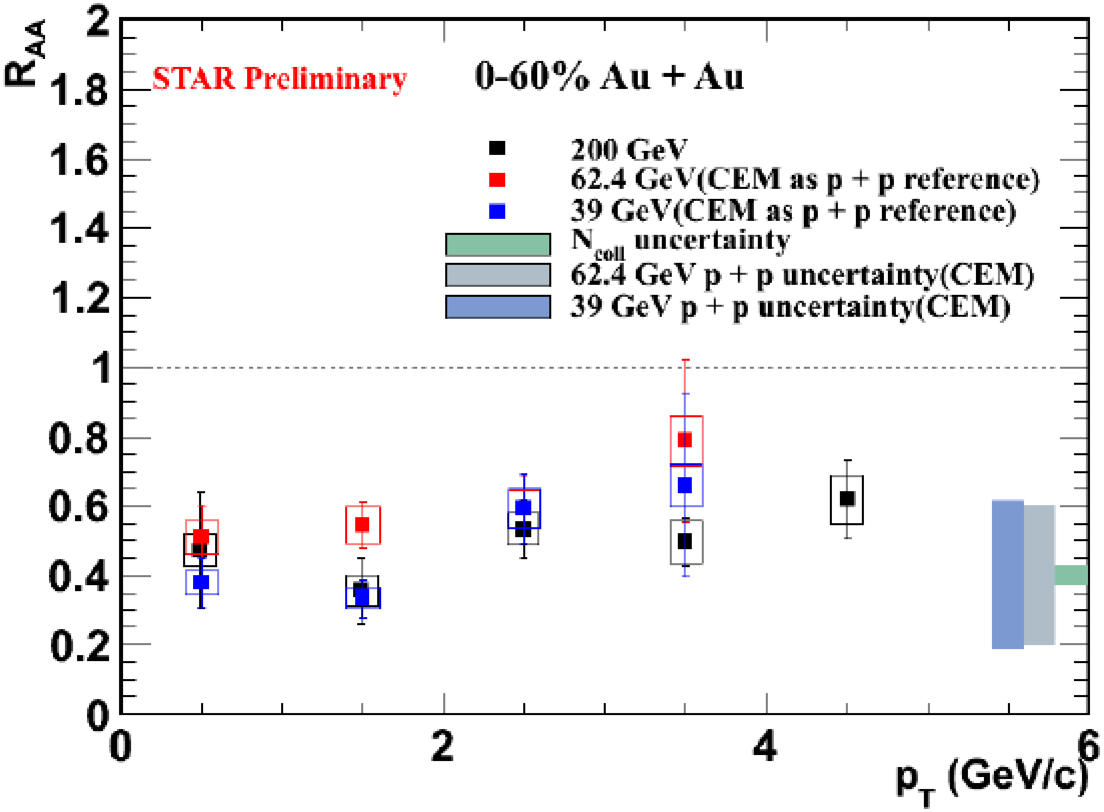


p+p references for 39 and 62 GeV: CEM
R. Nelson, R. Vogt et al, arXiv:1210.4610

Theoretical curves:
Xingbo Zhao, Ralf Rapp PRC82, 064905 (2010)

- Similar suppression from 39 – 200 GeV.
- Consistent with theoretical calculation within uncertainties.

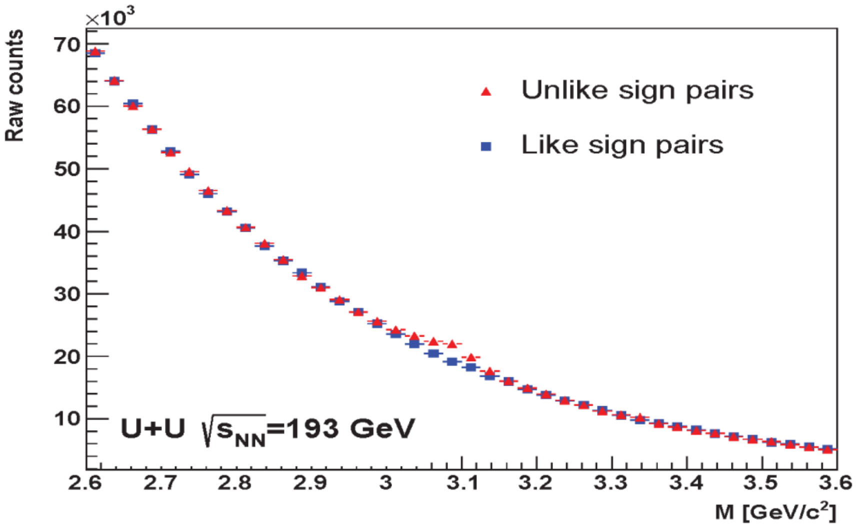
J/ψ suppression at RHIC low energy

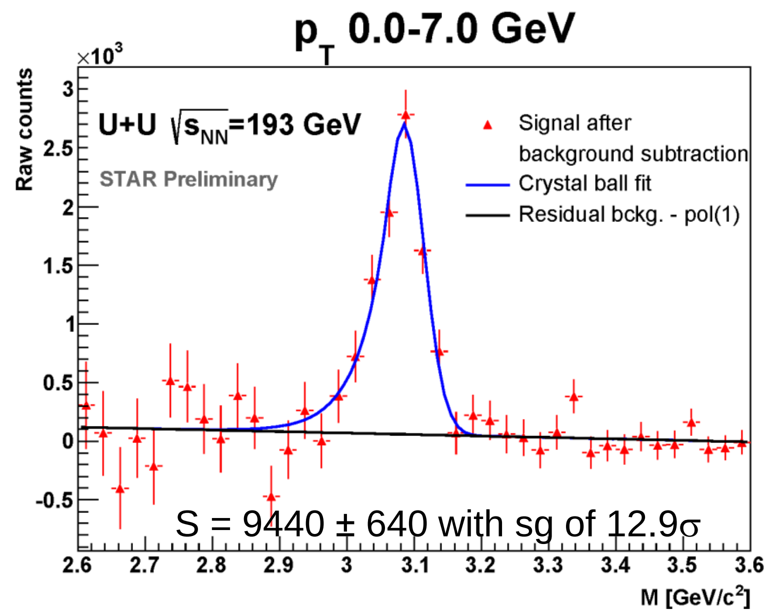


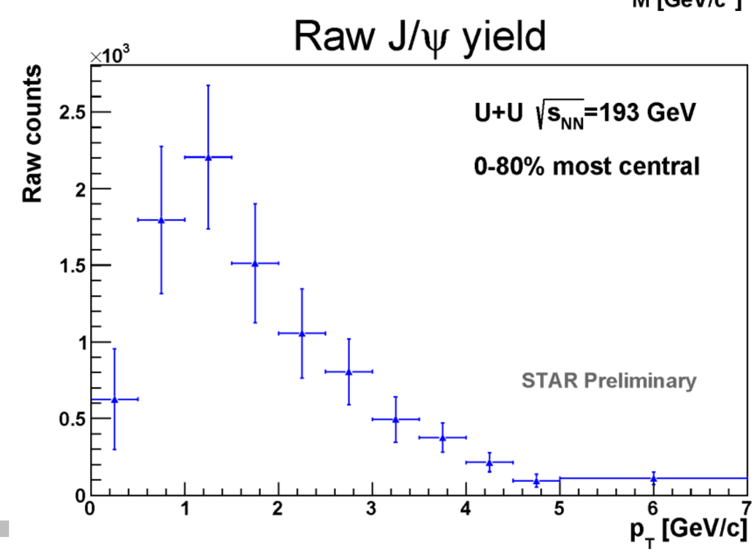
- Strong suppression at low-p_T.
- No significant beam-energy dependence within uncertainties.

J/ψ production in U+U 193 GeV

OTA KUKRAL poster







- Higher achievable energy density in U+U collisions.
- Run 2012 MB data

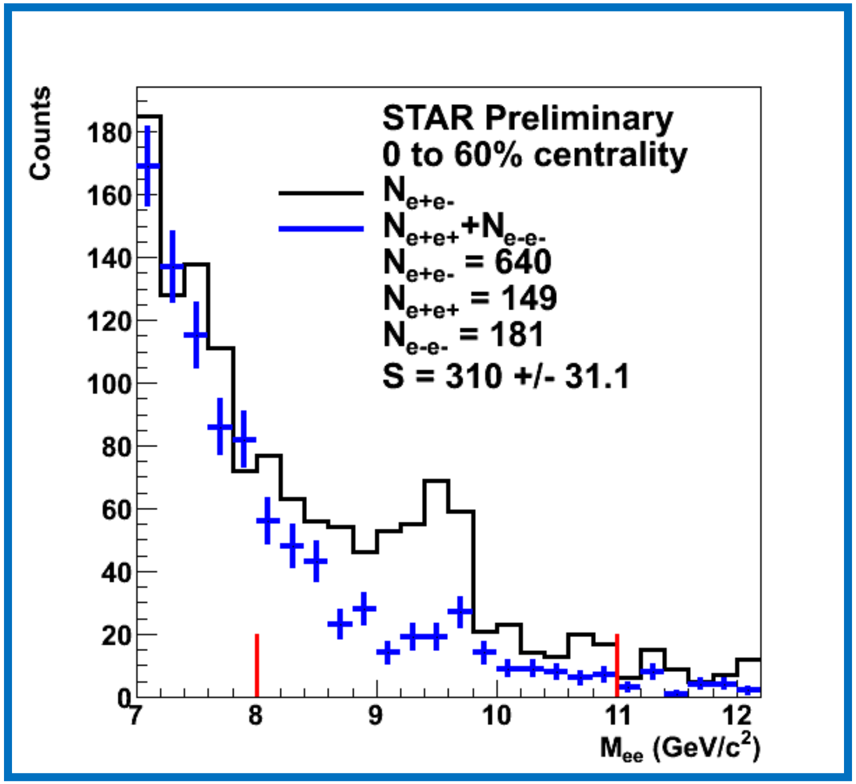
  $J/\psi \rightarrow e^+e^-$ TPC+TOF+BEMC.

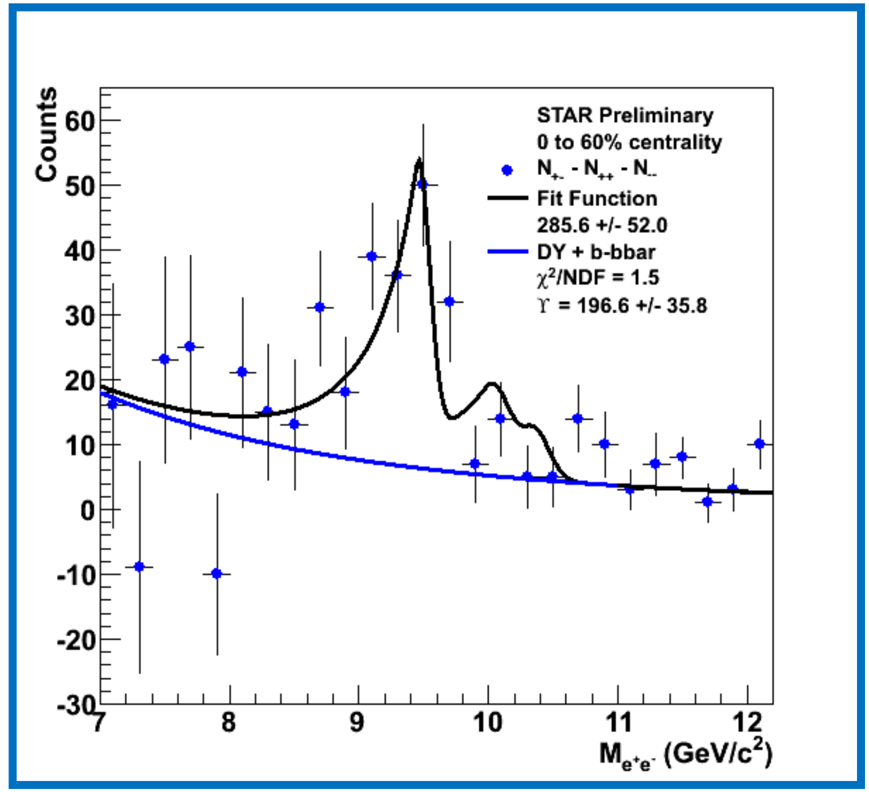
- Corrections of the signal underway.
- HT trigger events could extend the range even more.

Upsilons
a cleaner probe of the QGP

- Recombination effects
  - J/ψ : Evidence for large effects.
  - Υ: Expecting negligible contribution.
    - $\sigma_{c\bar{c}}$ @ RHIC: $797 \pm 210\ ^{+208}_{-295}$ μb. (PRD 86, 072013(2012))
    - $\sigma_{b\bar{b}}$ @ RHIC: ~ 1.34 – 1.84 μb (PRD 83 (2011) 052006)
- Co-mover absorption effects
  - $\Upsilon(1S)$: tightly bound, larger kinematic threshold.
    - Expect σ ~ 0.2 mb, 5-10 times smaller than for J/ψ
      - Lin & Ko, PLB 503 (2001) 104

Υ Signal in Au+Au 200 GeV





Raw yield of $\Upsilon \to e^+e^-$ with $|y|<0.5$ = 196.6 ±35.8 = N_{+-} - N_{--} - N_{++} - ∫DY+$b\bar{b}$

$$\text{Drell-Yan}+b\bar{b} = \frac{A}{\left(1+\frac{m}{m_0}\right)^n}$$

n = 4.59, m_0 = 2.7

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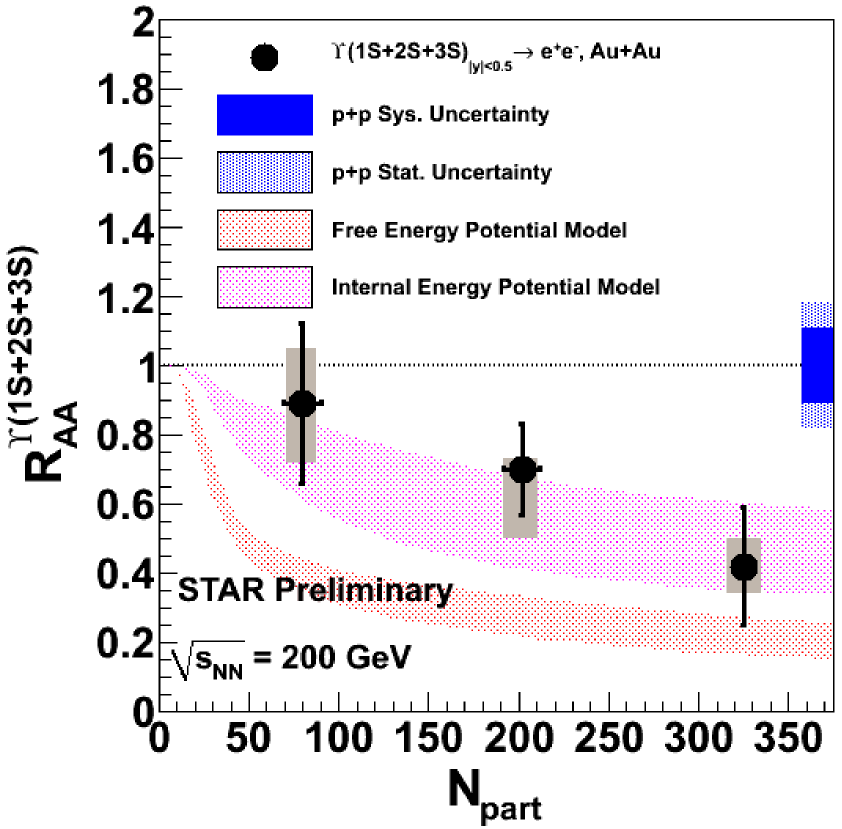
Nuclear modification factor

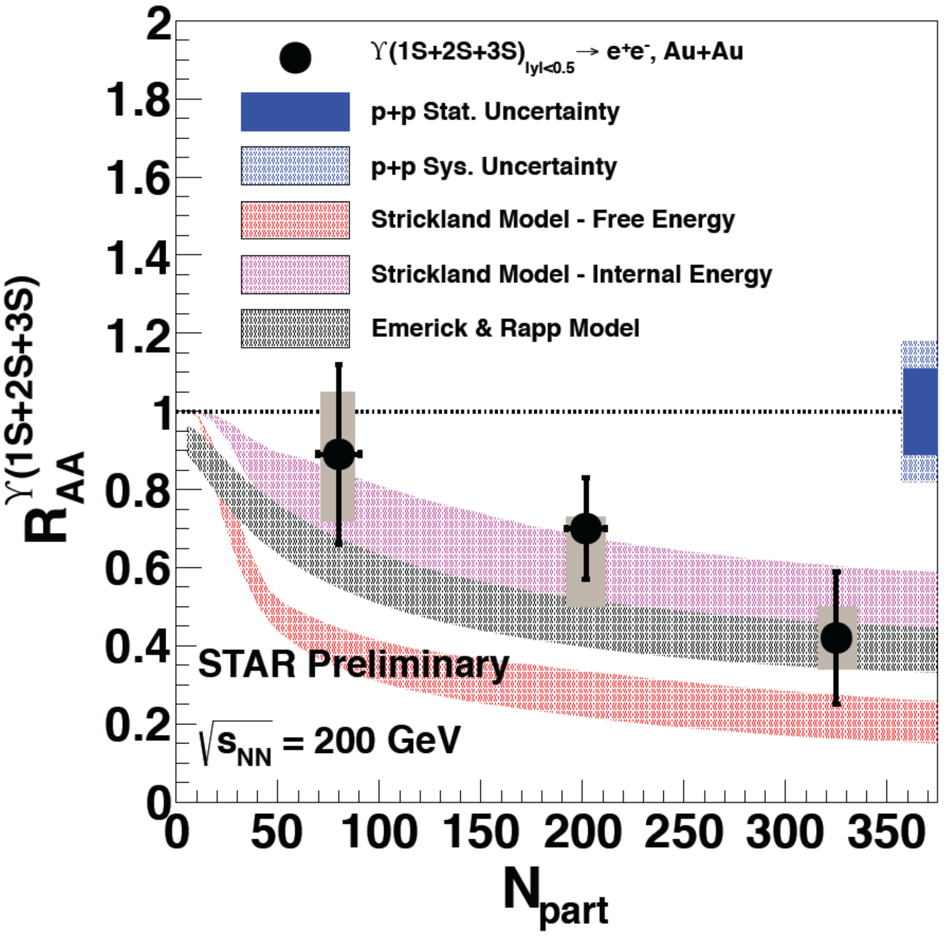
- Suppression of Υ(1S+2S+3S) in central Au+Au observed.
- Incorporating lattice-based potentials, including real and imaginary parts
  - A: Free energy
    - Disfavored.
  - B: Internal energy
    - Consistent with data vs. N_{part}
- Includes sequential melting and feed-down contributions
  - ~50% feed-down from χ_b.
- Dynamical expansion, variations in initial conditions (T_0, η/S)
  - Models uncertainty bands include :
    - $428 < T_0 < 442$ MeV at RHIC
    - for $3 > 4\pi\eta/S > 1$



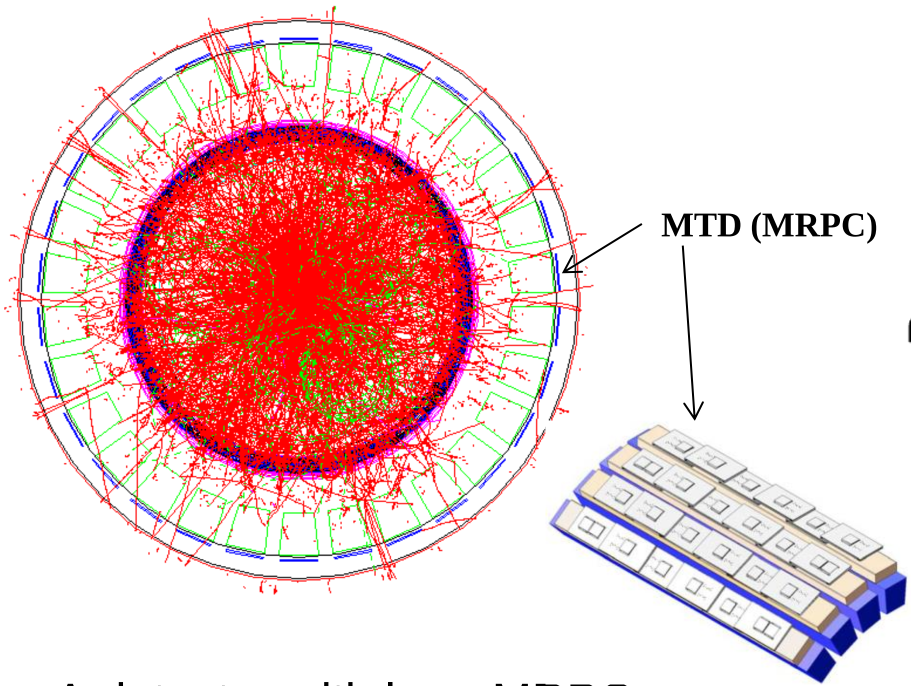
Model: M. Strickland, PRL 107, 132301 (2011).

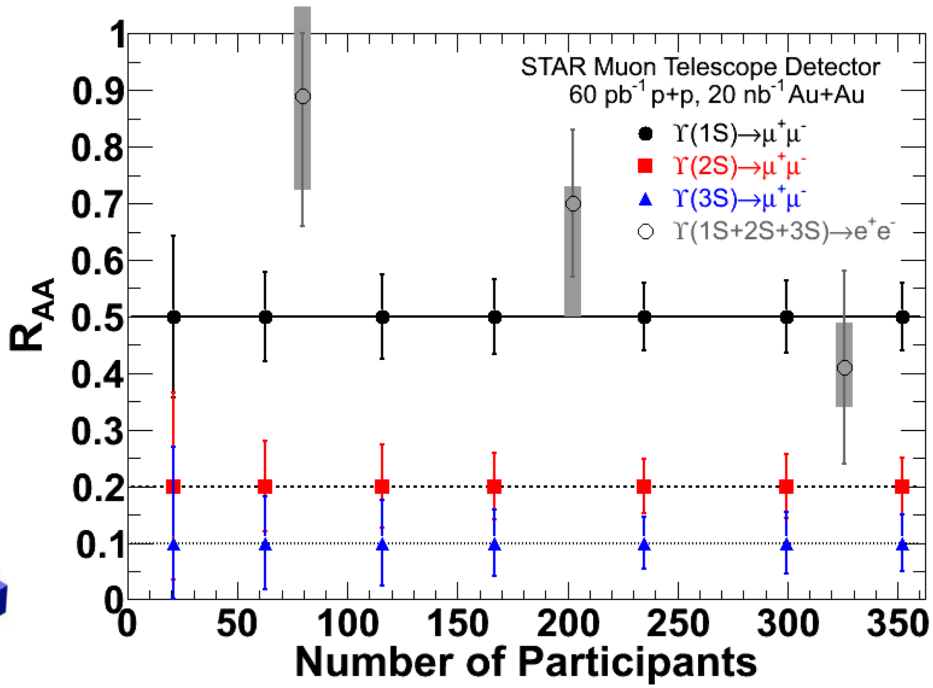
Υ in Au+Au 200 GeV, R_{AA}

- Rapp et al., EPJ A 48 (2012) 72
  - Kinetic theory + fireball.
  - T_0 = 330 MeV
  - "Weak Binding" (shown)
    - Binding energy changes with T
    - Bound state mass : constant
    - In-medium open-bottom threshold is reduced
    - Motivated by Lattice QCD
  - "Strong binding" (not shown)
    - Bound states stay with constant mass and binding energy



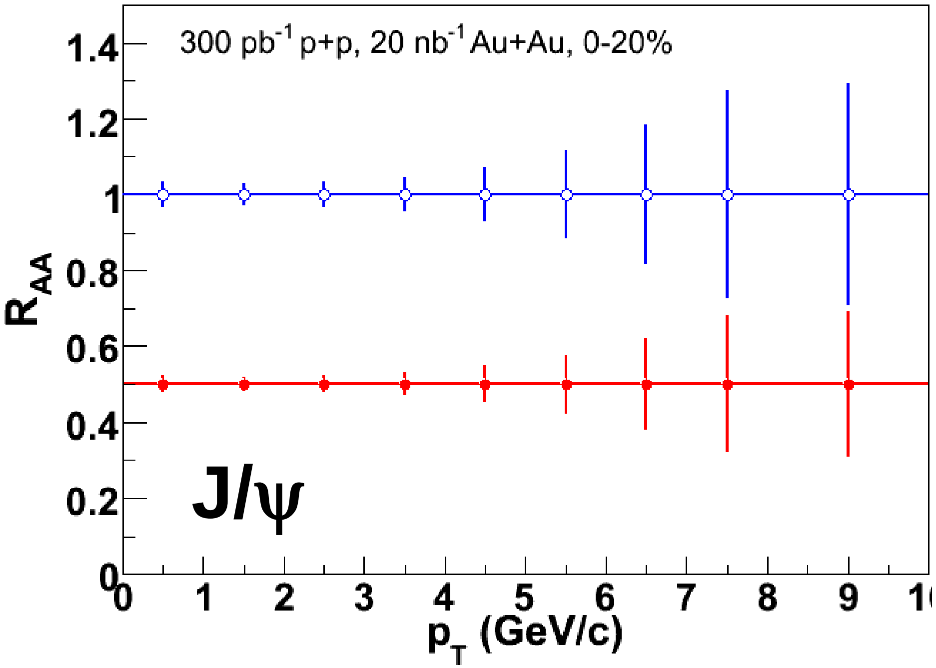
ϒ with STAR MTD

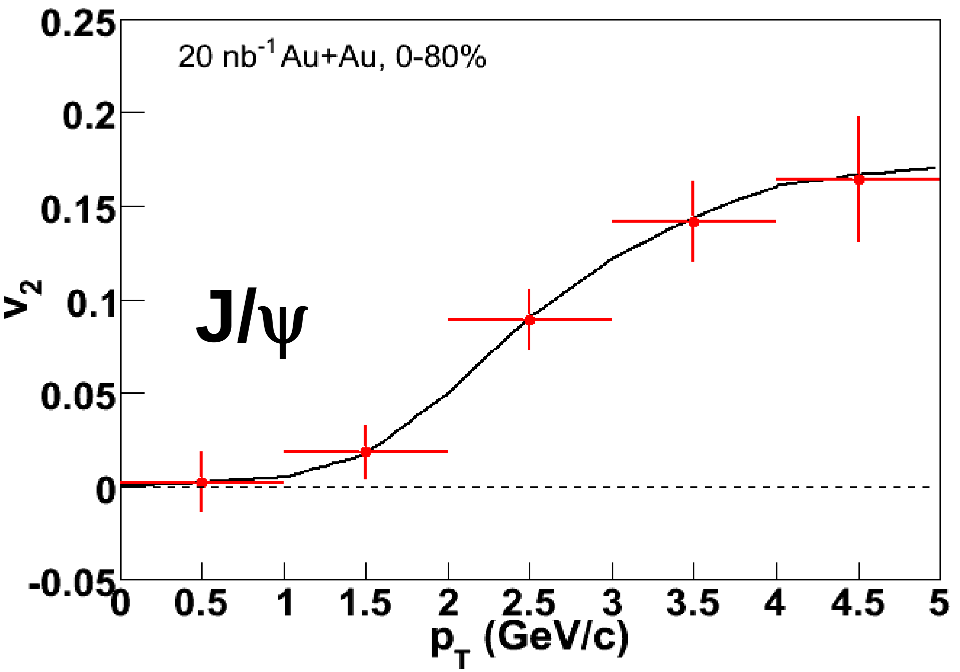




- A detector with long-MRPCs
  - Covers the whole iron bars and leave the gaps in between uncovered.
  - Acceptance: 45% at |η|<0.5
  - 122 modules, 1464 readout strips, 2928 readout channels
- Long-MRPC detector technology, electronics same as used in STAR-TOF
- Run 2012 -- 10%; 2013 – 60%+; 2014 – 100%: ϒ via μ+μ-

J/ψ with MTD projection





Advantages over electrons

- no γ conversion, much less Dalitz decay contribution.
- less affected by radiative losses in the materials.

- Trigger capability for low to high p_T J/ψ in central Au+Au collisions.
- High μ/hadron enhancement.

STAR

Summary

- **J/ψ in p+p 200GeV**
  - NLO CS+CO and CEM describe the data.
  - Indication of longitudinal J/ψ polarization as p_T increases .
- **J/ψ in d+Au 200GeV**
  - R_{dAu} consistent with the model using EPS09+ $\sigma_{abs J/\psi}$ (3 mb).
- **J/ψ in Au+Au 200GeV**
  - Suppression observed; it increases with collision centrality and decreases with p_T.
  - v_2 consistent with no flow; disfavors the production dominantly by coalescence from thermalized (anti-)charm quarks for $p_T > 2$ GeV/c.
- **J/ψ in Au+Au 39GeV and 62GeV**
  - Similar centrality and p_T dependence like 200 GeV within uncertainty.
- **J/ψ in U+U 193GeV**
  - Strong signal observed for p_T 0-7 GeV/c
- **Upsilon in Au+Au 200GeV**
  - Increasing of ϒ suppression vs. centrality.
  - R_{AA} consistent with suppression of feed down from excited states only (~50%).
- **Heavy flavor tracker** and **Muon telescope detector** upgrades.
  - Significant improvement of STAR quarkonium measurements.

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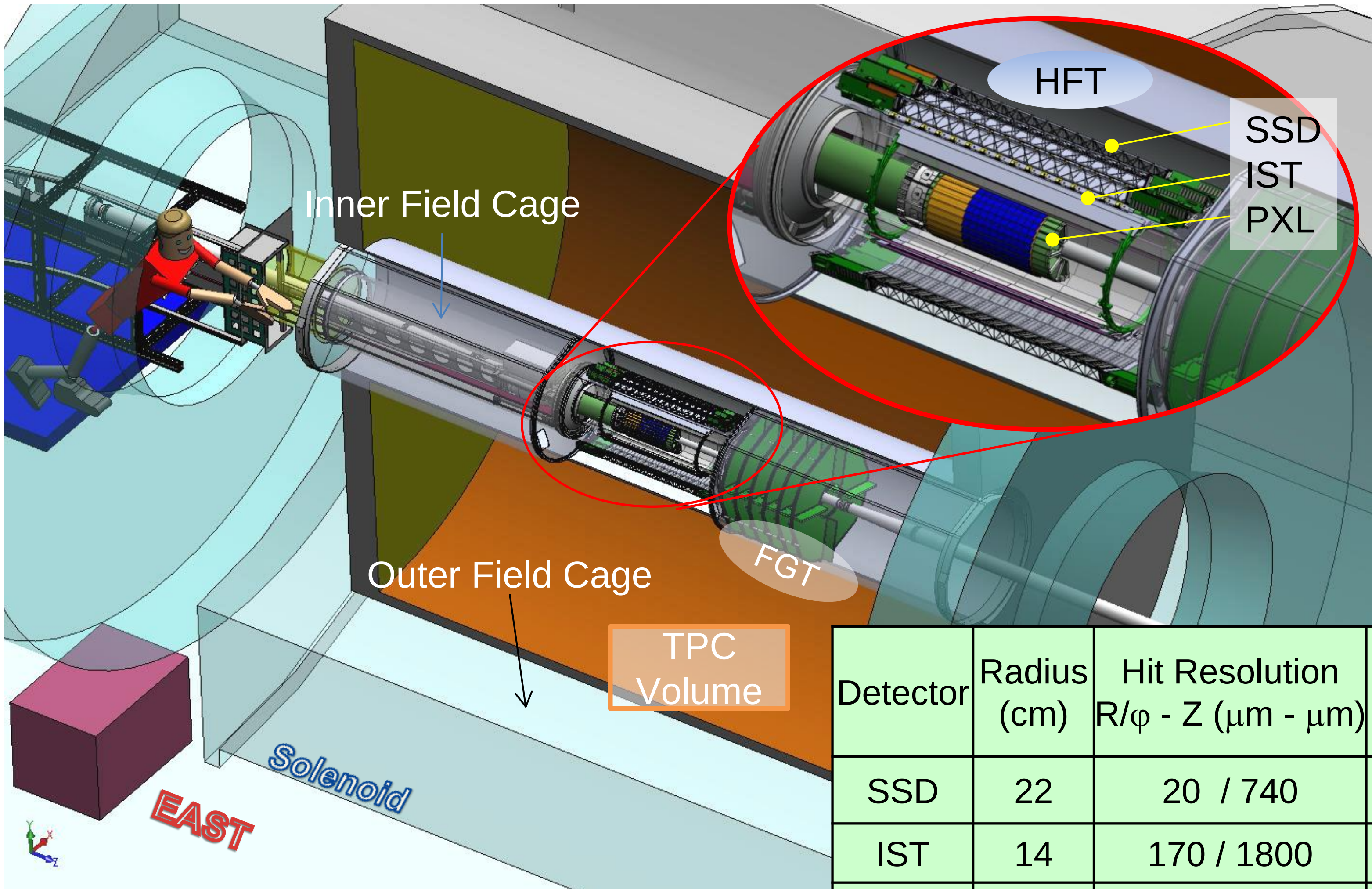
Heavy Flavor Tracker

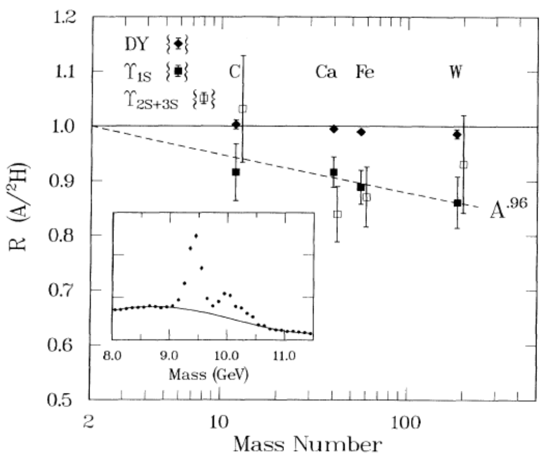


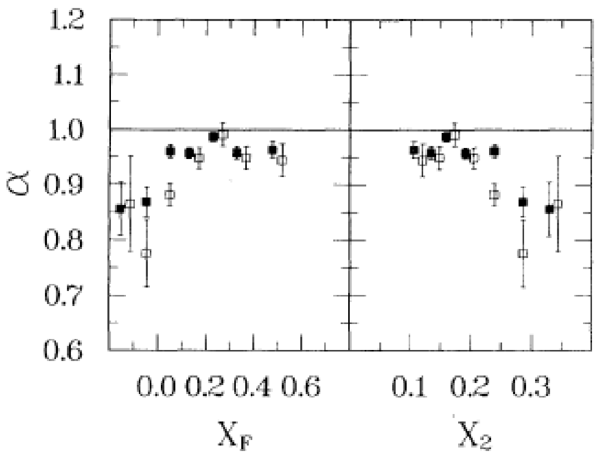
Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Radiation length
SSD	22	20 / 740	1% X_0
IST	14	170 / 1800	<1.5% X_0
PIXEL	8	12 / 12	~0.4% X_0
	2.5	12 / 12	~0.4% X_0

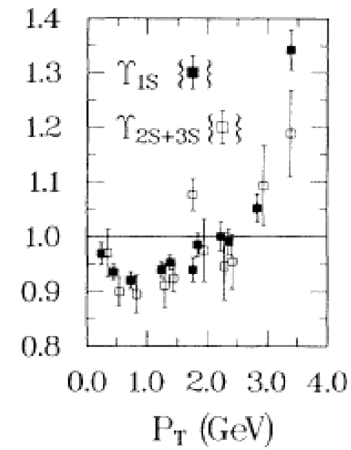
HFT will help to study non-prompt $B \rightarrow J/\psi + X$

Cold Nuclear Matter Effects

- ϒ : CNM effects established by E776 (√s=38.8 GeV):
  - Magnitude and A dep: ϒ(1S)=ϒ(2S+3S). α can be as low as ~ 0.8.







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ϒ in Au+Au 200 GeV, Centrality