J/ψ production at the STAR experiment

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Outline

- Motivation: QGP and quarkonia
- The STAR experiment at RHIC
- J/ψ production in p+p and polarization measurements
- J/ψ production and elliptic flow in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
- Energy dependence of J/ψ R_{AA}
- J/ψ in U+U collisions
- Outlook
- Conclusions

Quarkonia as a probe of QGP

- Large masses of c, b quarks
  - created during initial stages of collision
- Due to color screening of quark potential in QGP **quarkonium dissociation is expected**

Quarkonia family:
$\bar{c}$-c: J/ψ, ψ′, χ_c ...
$\bar{b}$-b: ϒ(1S), ϒ(2S), ϒ(3S) ...

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

- Suppression determined by medium temperature and binding energy.

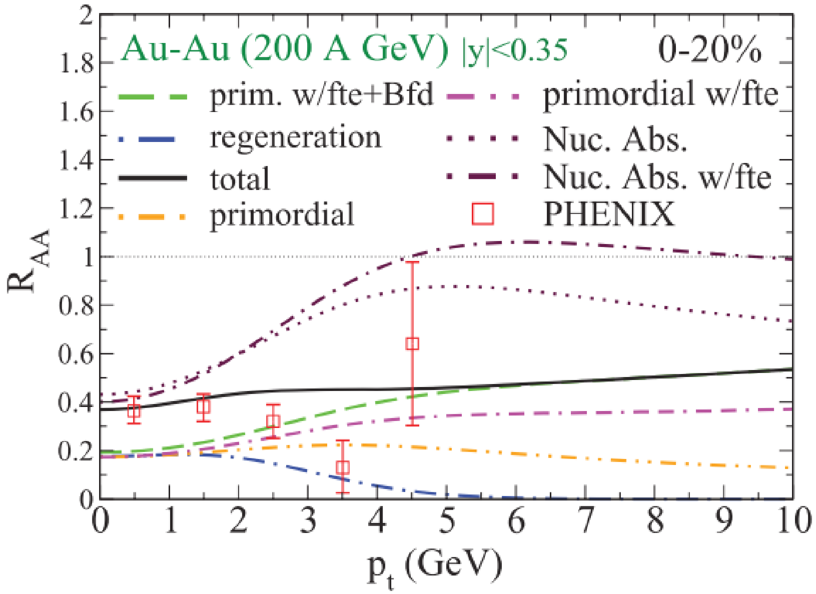
Sequential suppression of different quarkonia states is expected.

..see next STAR talk by R. Vertesi about ϒ.

Other effects

- Quarkonium production mechanism is not well understood.
- Observed yields are a mixture of direct production + feed-down
  - direct J/ψ (~60%) +feed-down ~30% χ_c & ~10% ψ′
  - B-meson decay
- Hot/dense medium effects
  - Coalescence from uncorrelated charm pairs.
- Suppression and enhancement in the "cold" nuclear medium
  - PDF modification in nucleus - shadowing , color glass condensate
  - Initial state energy loss
  - Nuclear absorption – break up of bound state precursor by collisions with passing nucleons
  - Dissociation by interaction with co-movers in final state

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



Measure J/ψ at different p_T, in different colliding systems, and collision energies.

Experimental approach - R_{AA}

- baseline - p+p
- cold nuclear matter effects - d+Au

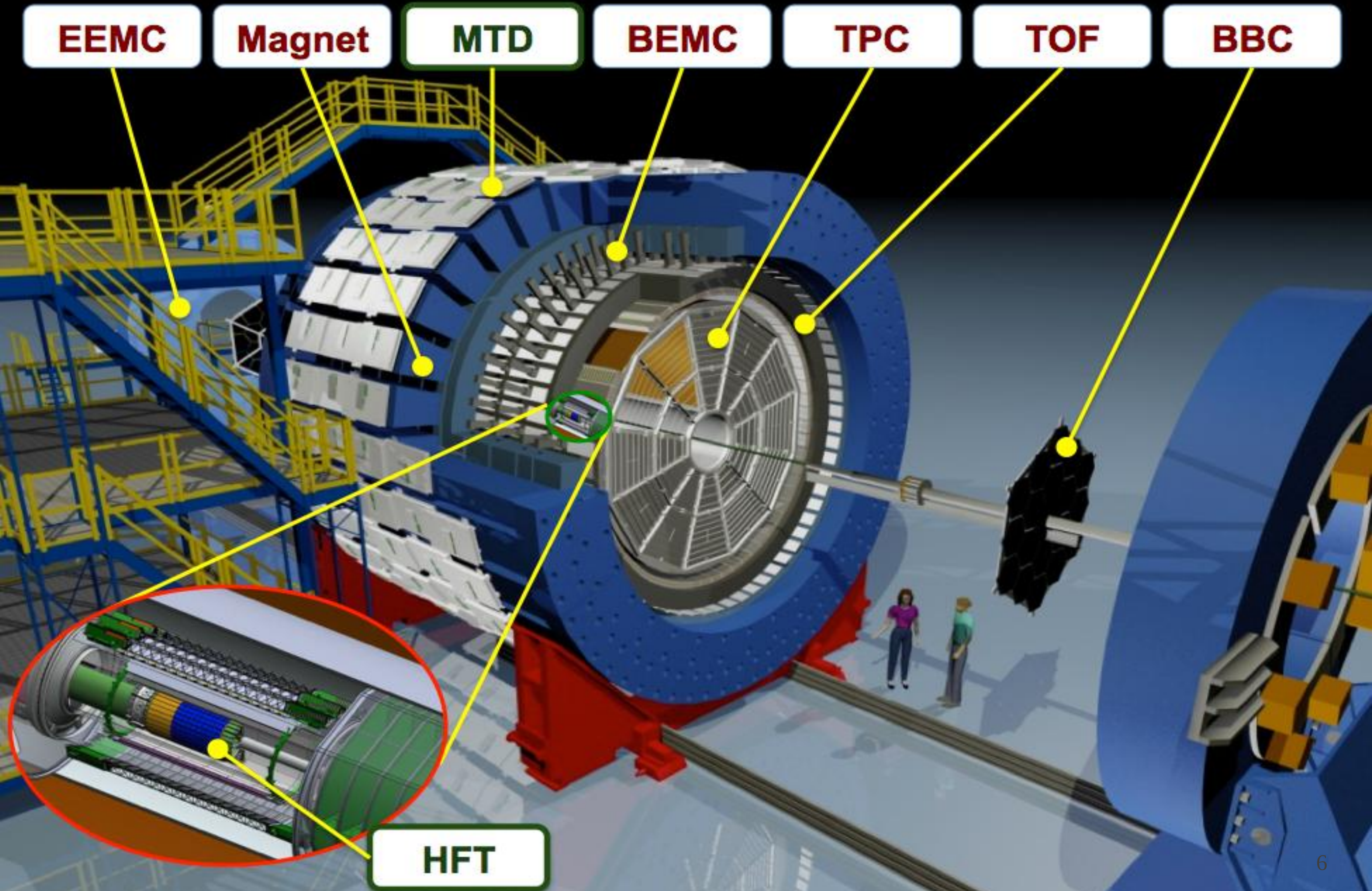
$$R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{dAu}}{dN/dy^{pp}}$$

- hot/dense medium effects - Au+Au

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}$$

R_{AA} = 1 for no modification of the production in the medium.

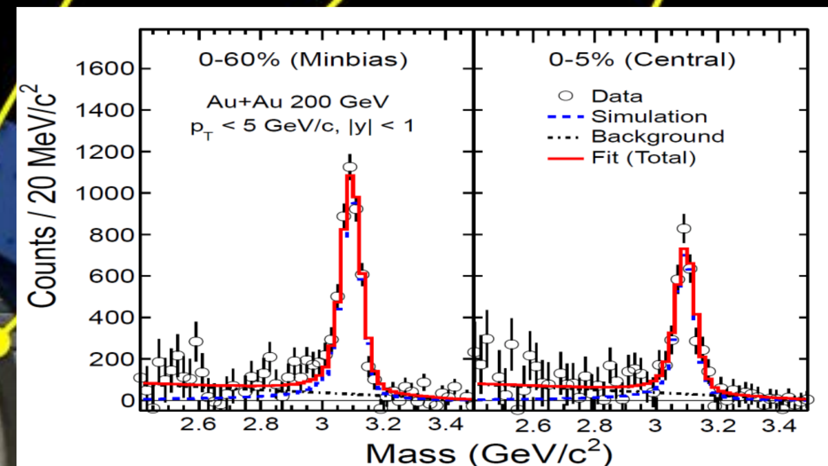
STAR experiment

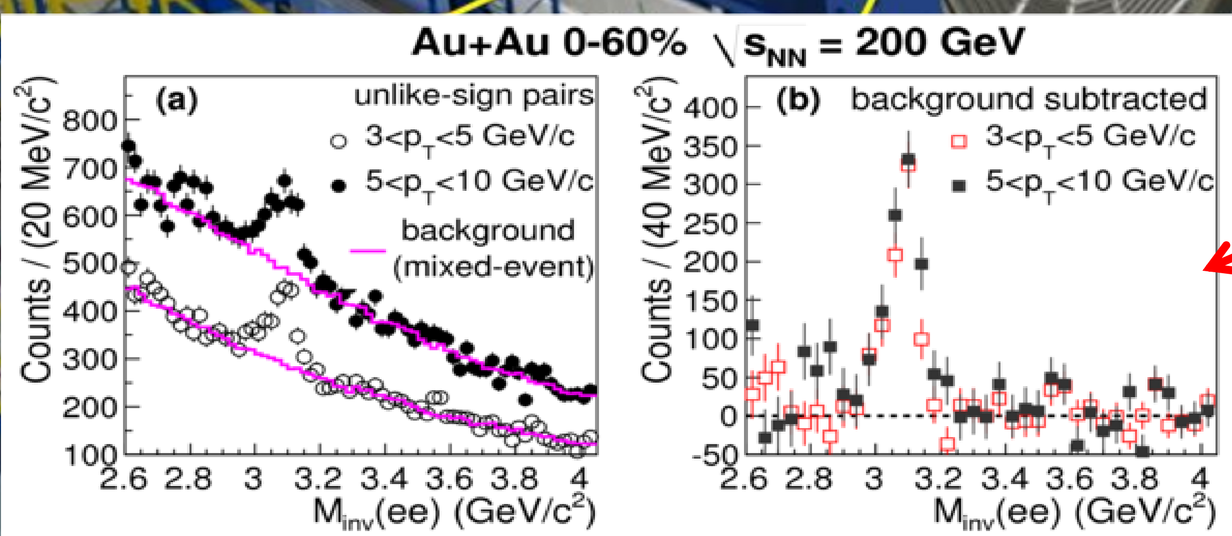


$J/\psi \rightarrow e^+e^-$ at STAR

EEMC | Magnet | MTD | BEMC | TPC | TOF | BBC

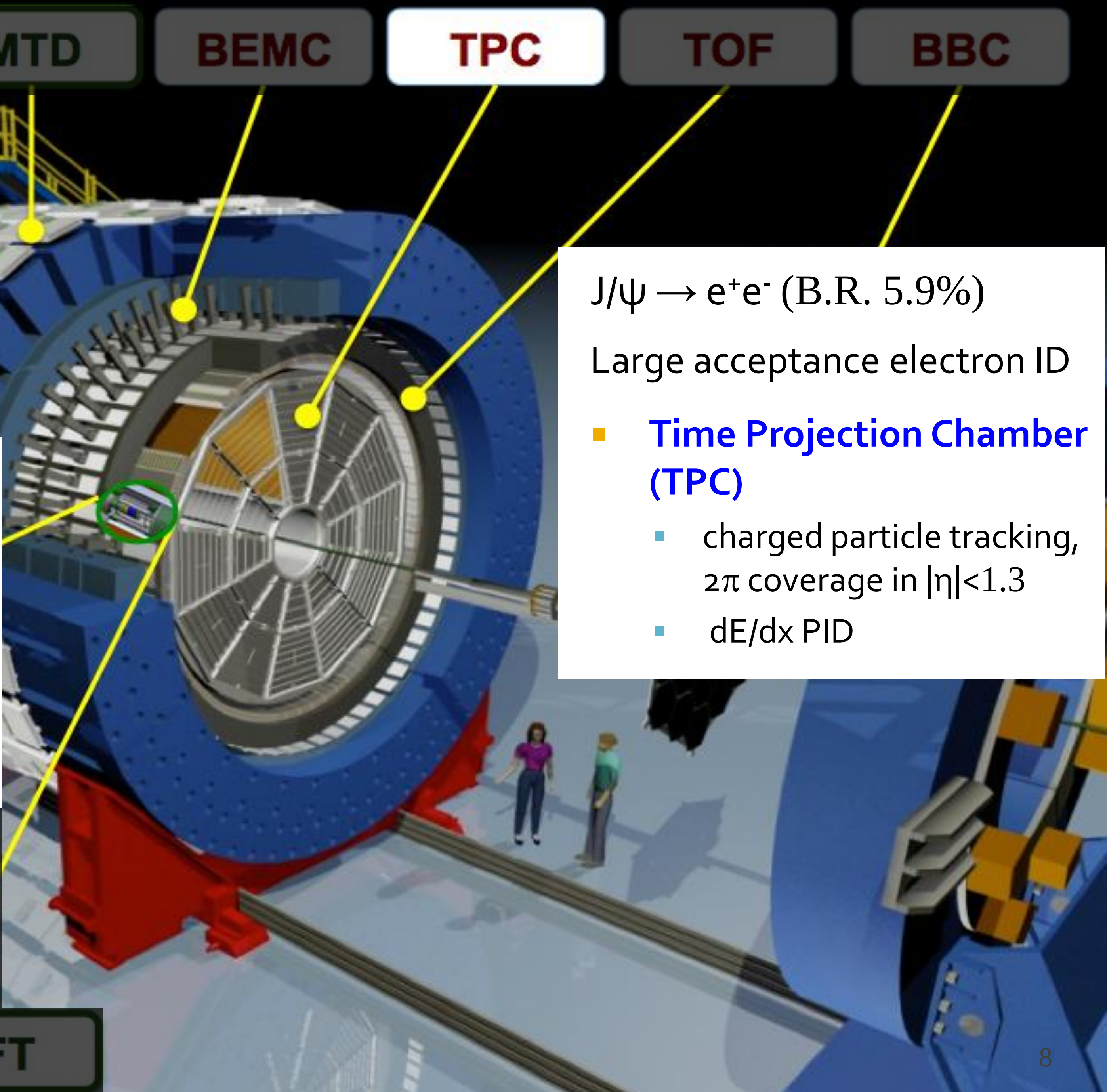
- $J/\psi \rightarrow e^+e^-$ (b.r. 5.9%) at midrapidity
- Electron identification at $|y|<1$
- Combinatorial background estimated by like-sign and mixed events techniques

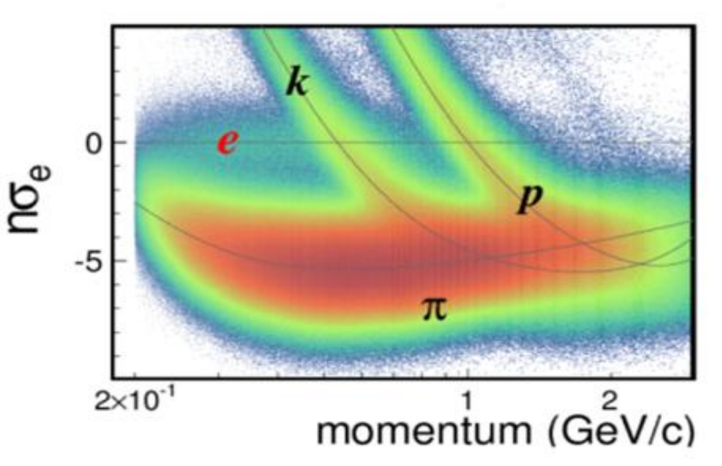




STAR low-p_T : arXiv:1310.3563
high-p_T : Phys.Lett. B722, 55 (2013)

Electron ID



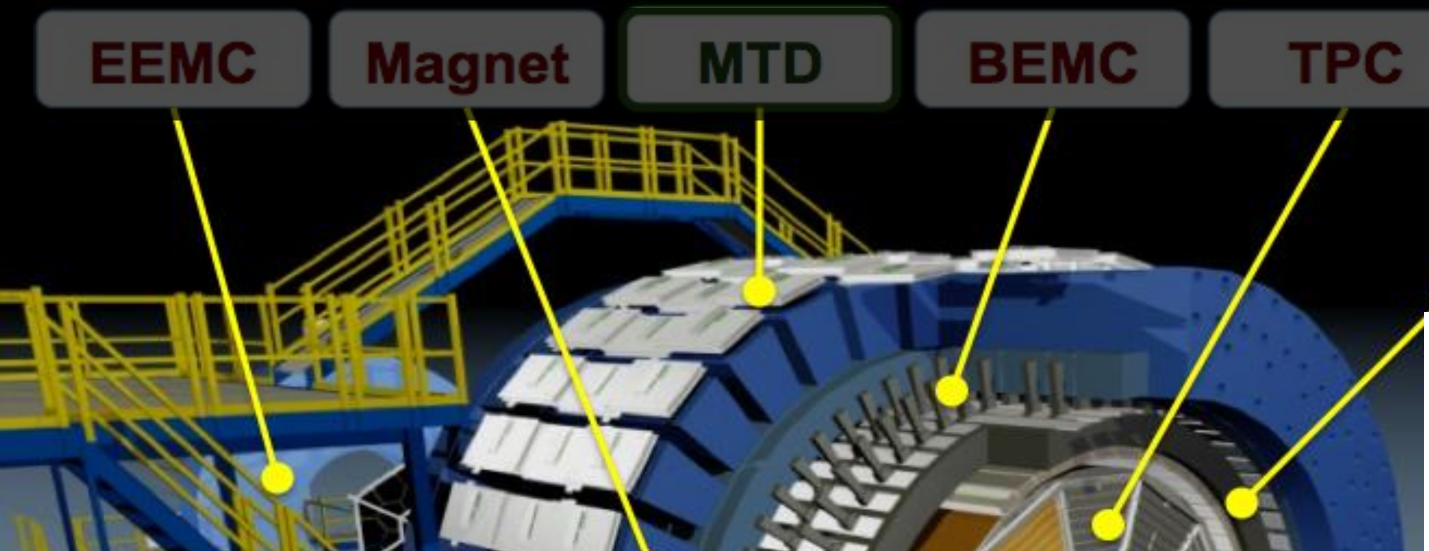


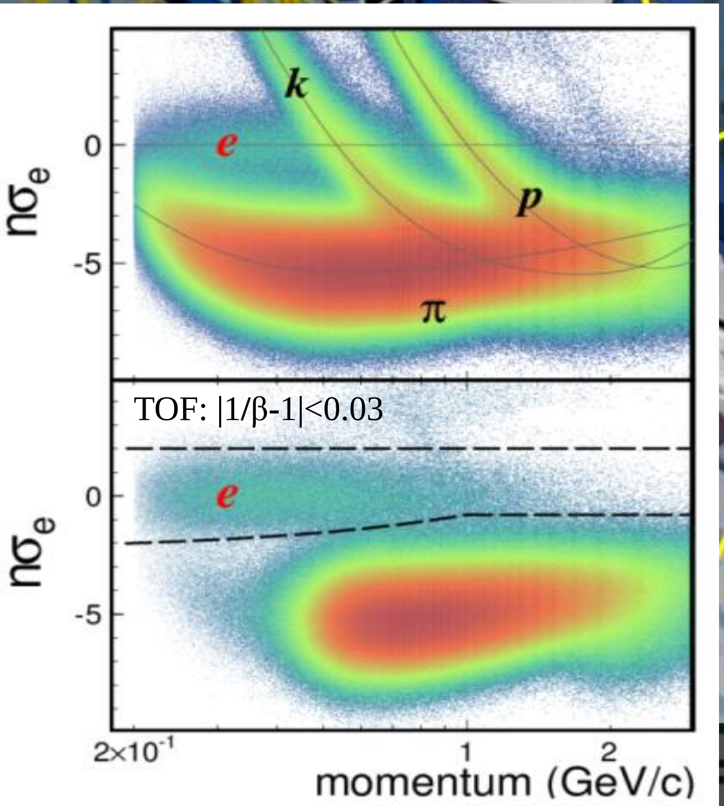
$J/\psi \rightarrow e^+e^-$ (B.R. 5.9%)

Large acceptance electron ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1.3$
  - dE/dx PID

Electron ID



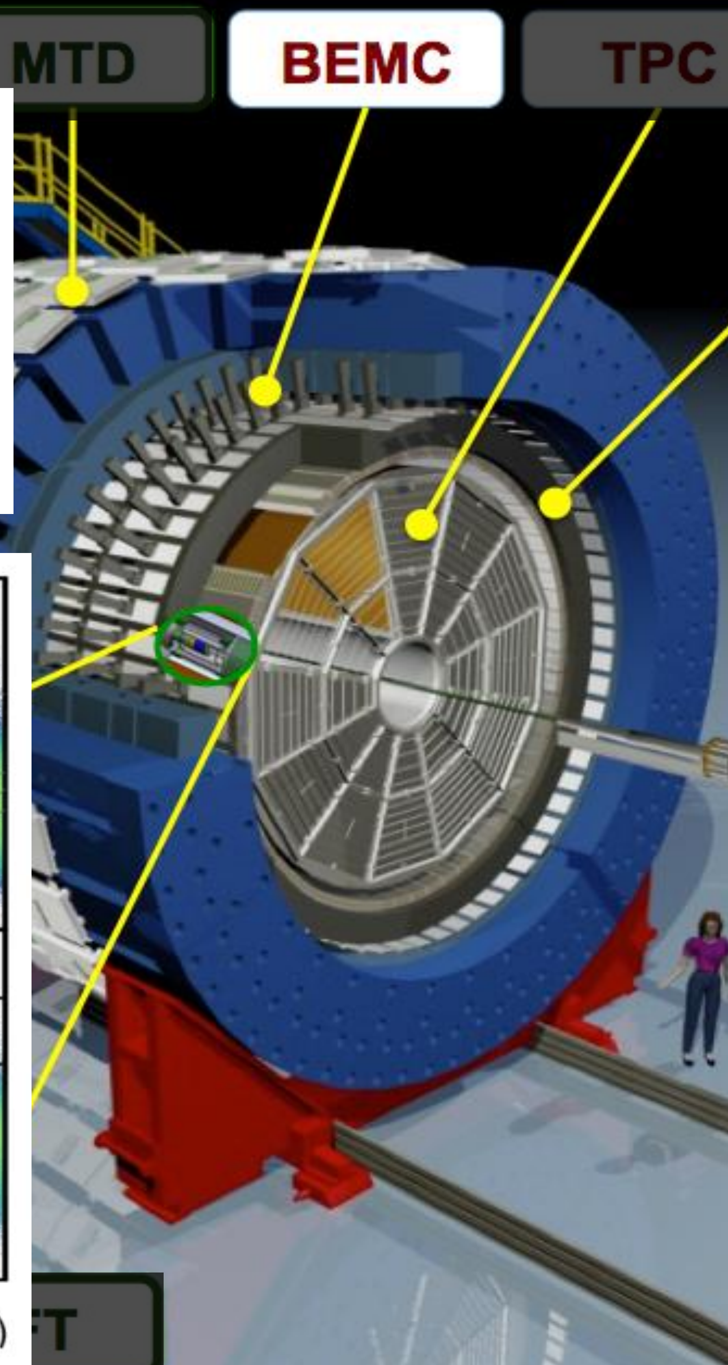


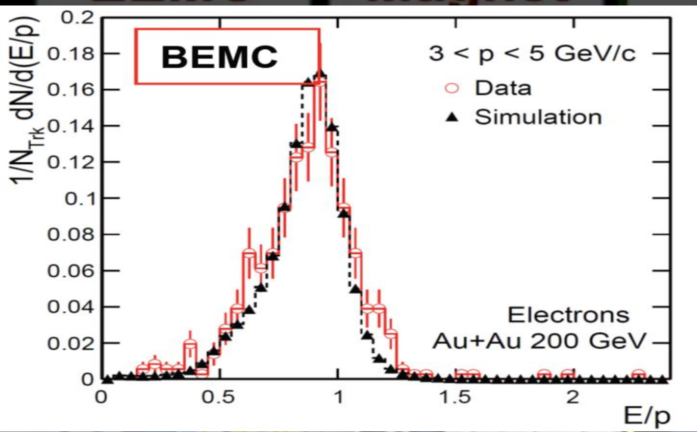
$J/\psi \rightarrow e^{+}e^{-}$ (B.R. 5.9%)

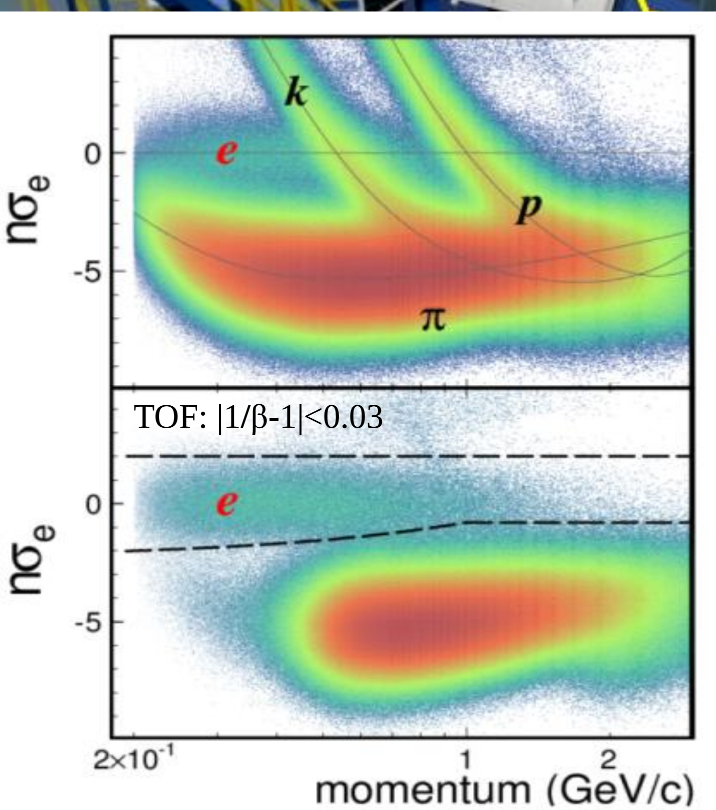
Large acceptance electron ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1.3$
  - dE/dx PID
- **Time Of Flight(TOF)**
  - Timing resolution <100 ps
  - $1/\beta$ PID
  - e purity >90%

Electron ID







$J/\psi \rightarrow e^+e^-$ (B.R. 5.9%)

Large acceptance electron ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in |η|<1.3
  - dE/dx PID
- **Time Of Flight(TOF)**
  - Timing resolution <100 ps
  - 1/β PID
  - e purity >90%
- **EM Calorimeter**
  - 2π coverage in |η|<1
  - Electron ID via E/p ~ 1
  - Triggering capability

J/ψ in p+p collisions

Why p+p collision?

- Baseline for heavy ion collisions

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}$$

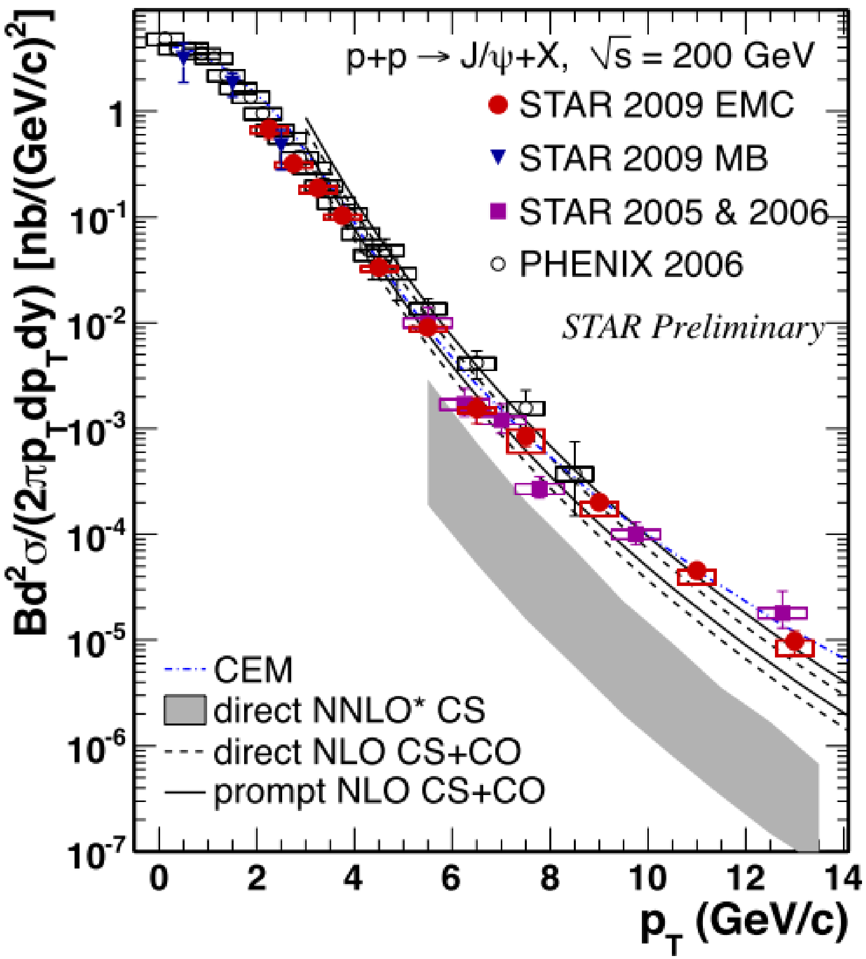
- Study quarkonium production mechanism
  - Heavy quarks are created in hard processes – calculable in pQCD
  - Soft processes forming quarkonia require models

J/ψ in p+p at 200GeV

- STAR – year 2009 data
  - Extending p_T to 0-14 GeV/c
  - Good agreement with PHENIX
- Comparison with J/ψ production models
  - prompt NLO CS+CO: model describes the data for $p_T > 4$ GeV/c
  - prompt CEM model can reasonably describe the p_T spectra (overpredicts the data at $p_T \sim 3$ GeV/c)
  - direct NNLO* CS model misses high- p_T part

Models predict different J/ψ polarizations …

Inclusive J/ψ spectra:



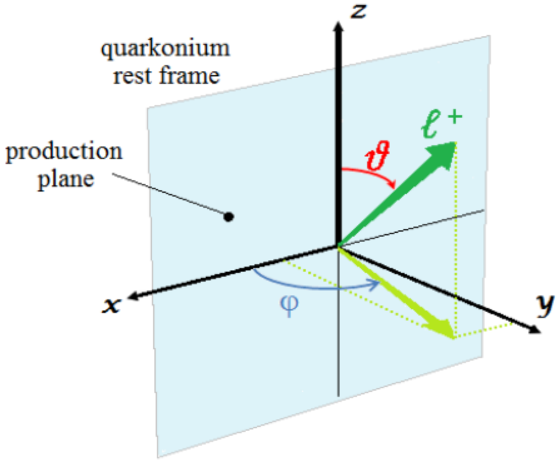
STAR EMC : Phys. Lett. B 722 (2013) 55
STAR MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543

STAR 2005&2006: Phys. Rev. C80, 041902(R) (2009)
PHENIX: Phys. Rev. D 85, 092004 (2012)
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. comm.
CEM: A.D. Frawley, T Ullrich, R. Vogt, Pys. Rept. 462 (2008) 125, and R.Vogt priv. comm.

Measuring J/ψ polarization

- Angular distribution of the decay lepton pair in the J/ψ rest frame – sensitive to polarization

$$\frac{d\sigma}{d(\cos\theta)d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi}\sin(2\theta)\cos\phi + \lambda_\phi \sin^2\theta\cos(2\phi)$$



Helicity frame - polarization(z)-axis chosen along J/ψ momentum direction in the J/ψ center of mass frame

θ - polar angle between momentum of a positive lepton and the polarization axis.

φ - corresponding azimuthal angle.

- Integrated over azimuthal angle

$$W(\cos\theta) \propto 1 + \lambda_\theta \cos^2\theta$$

λ_θ - polarization parameter

λ_θ = -1 longitudinal polarization
λ_θ = 0 no polarization
λ_θ = 1 transverse polarization

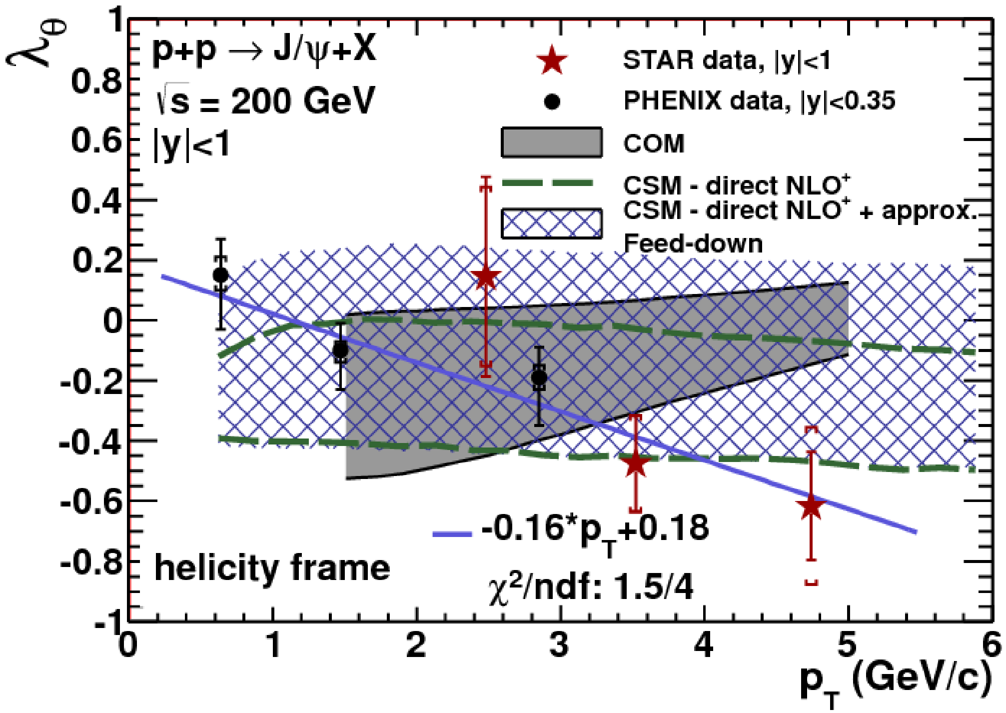
C. S. Lam, W.-K. Tung, Phys. Rev. D 18 (1978) 2447–2461

J/ψ polarization in p+p at 200 GeV

- Polarization parameter λ_θ
  - in helicity frame at $|y| < 1$ and $2 < p_T < 6$ GeV/c
- RHIC data indicate trend towards longitudinal polarization with increasing p_T
- Trend of data inconsistent with COM prediction
- 2011 500 GeV p+p data analyses underway - expected precision improvement

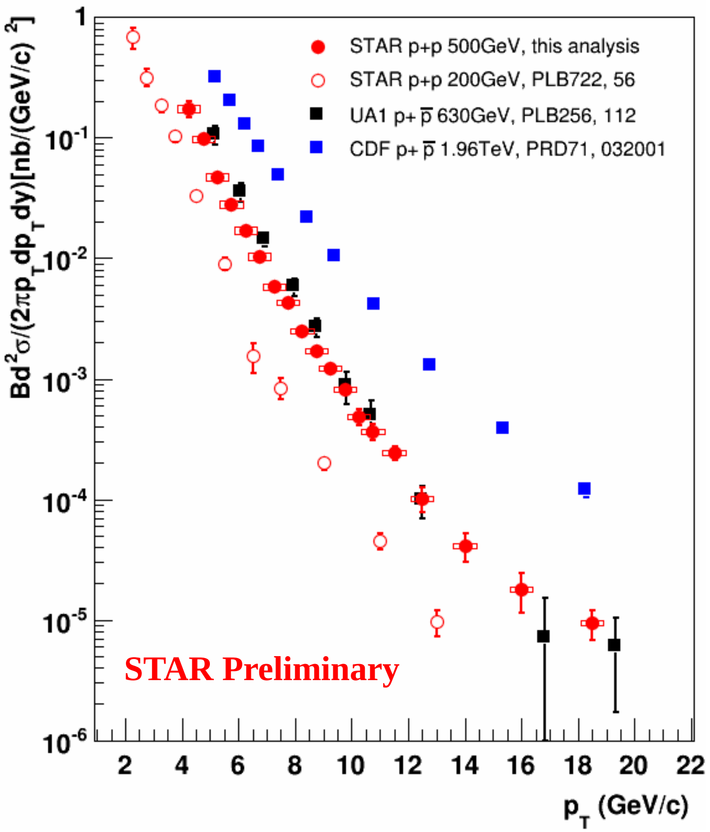
  ~1.8 pb^{-1} vs ~22 pb^{-1}

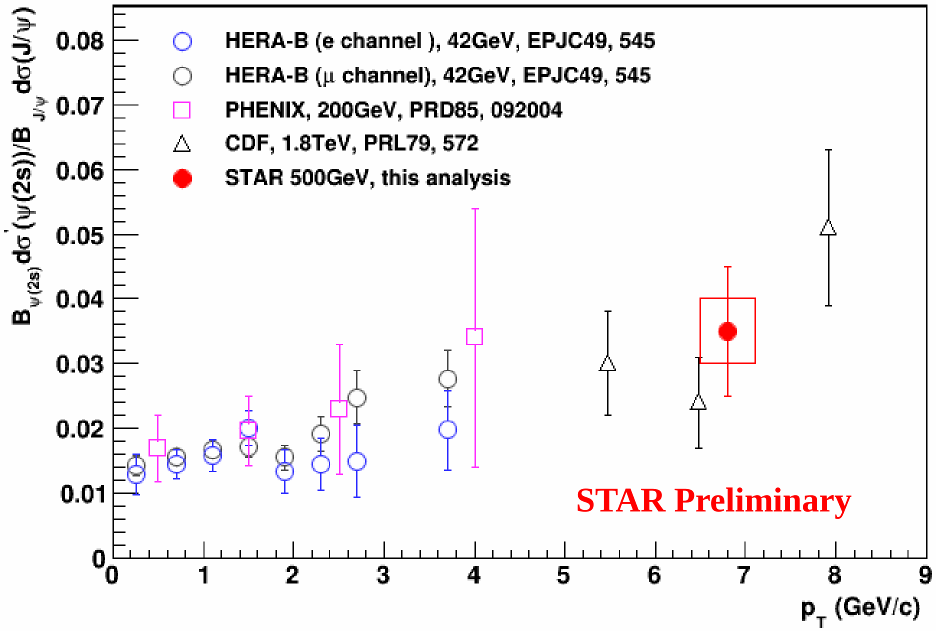
PHENIX: Phys. Rev. D 82, 012001 (2010)
COM: Phys. Rev. D 81, 014020 (2010)
CSM NLO $^+$: Phys. Lett. B, 695, 149 (2011) and private communication



STAR: arxiv: 1311.1621

J/ψ and ψ(2S) measurements in p+p 500 GeV

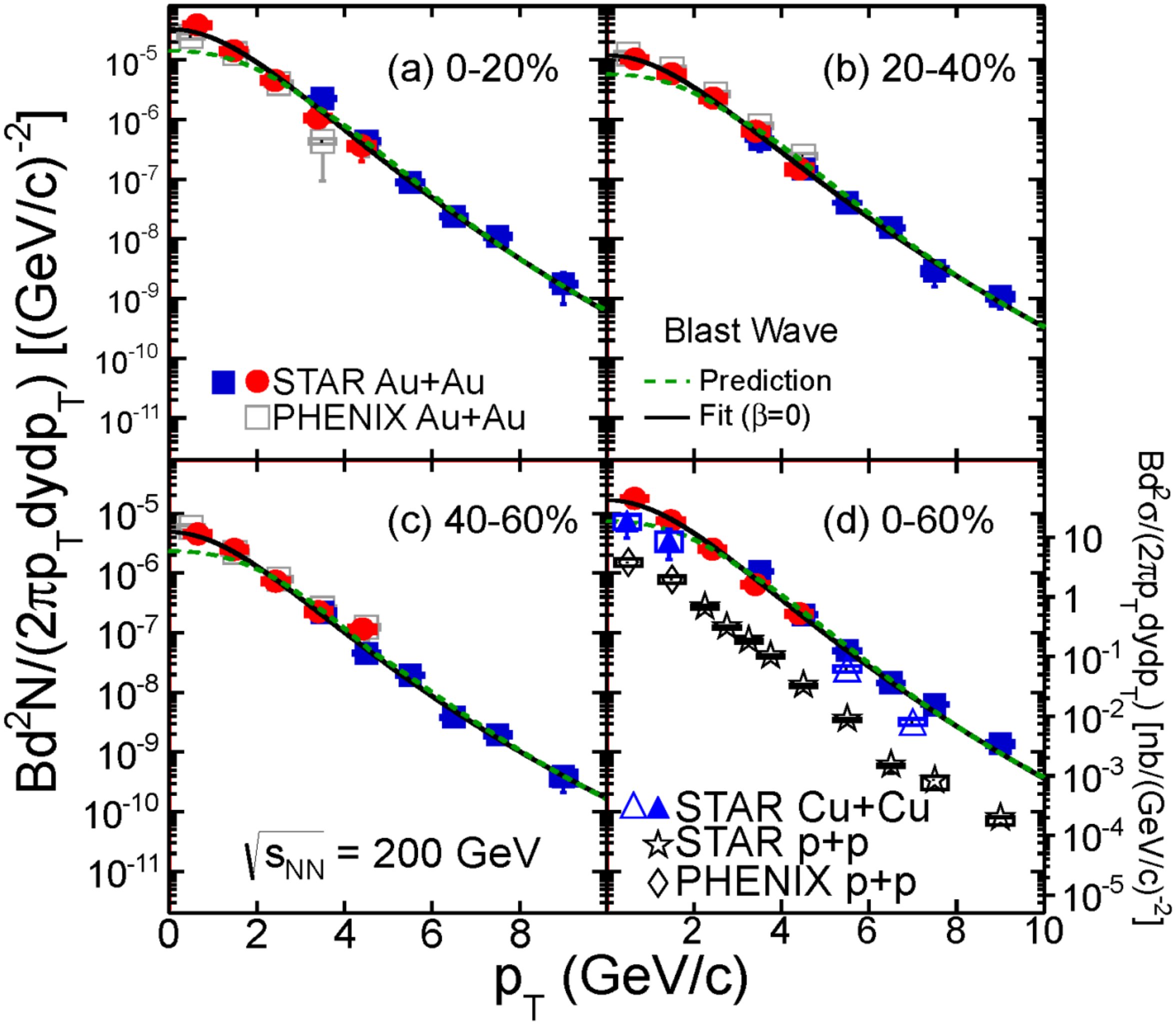




- J/ψ production measurements at highest RHIC collision energy up to 20 GeV/c
- First measurement of (ψ' / J/ψ) ratio in p+p at 500 GeV
  - Further test of charmonium production models
  - Constrain ψ' feed-down contribution to J/ψ
  - No collision energy dependence observed
  - Consistent with other experiments

J/ψ spectra in Au+Au at 200 GeV

- Large p_T range
  - Covers 0-10 GeV/c
- Tsallis Blast-Wave model (TBW) used for comparison
  - Hydro-inspired (blast-wave) freeze-out parametrization
  - Particle emission locally described by Levy distribution.
- J/ψ spectra softer at low p_T than the TBW prediction with the same freeze-out parameters as for light hadrons
  - Small radial flow?
  - Recombination at low p_T?



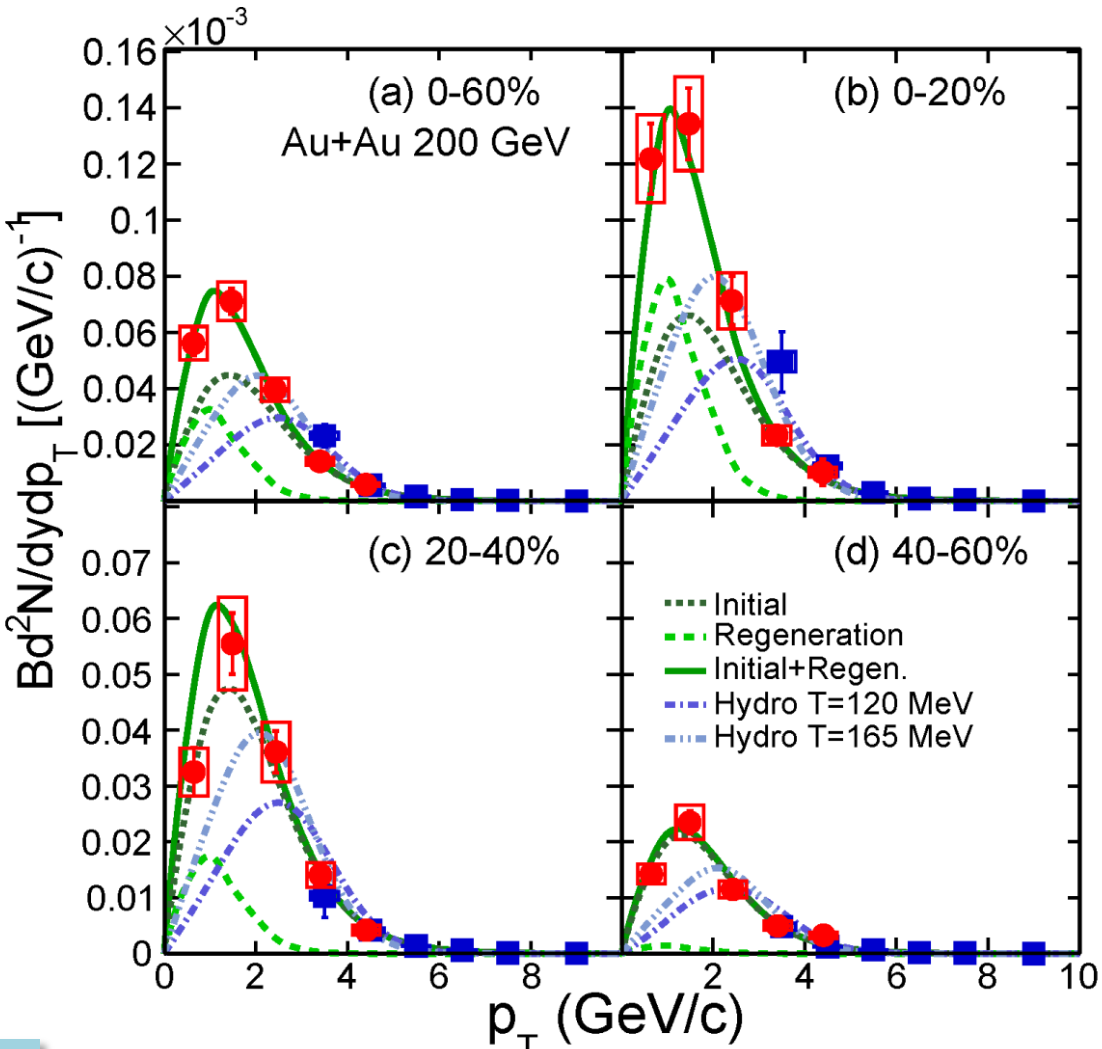
STAR low-p_T Au+Au, CuCu : arXiv:1310.3563
high-p_T Au+Au: Phys.Lett. B722, 55 (2013)
high-p_T Cu+Cu : Phys. Rev. C 80 (2009) 041902

Tsallis Blast-Wave model: Z.Tang et al., Chin.Phys.Lett. 30, 031201 (2013)
PHENIX: Phys. Rev. Lett. 98 (2007) 232301

J/ψ spectra in Au+Au at 200 GeV

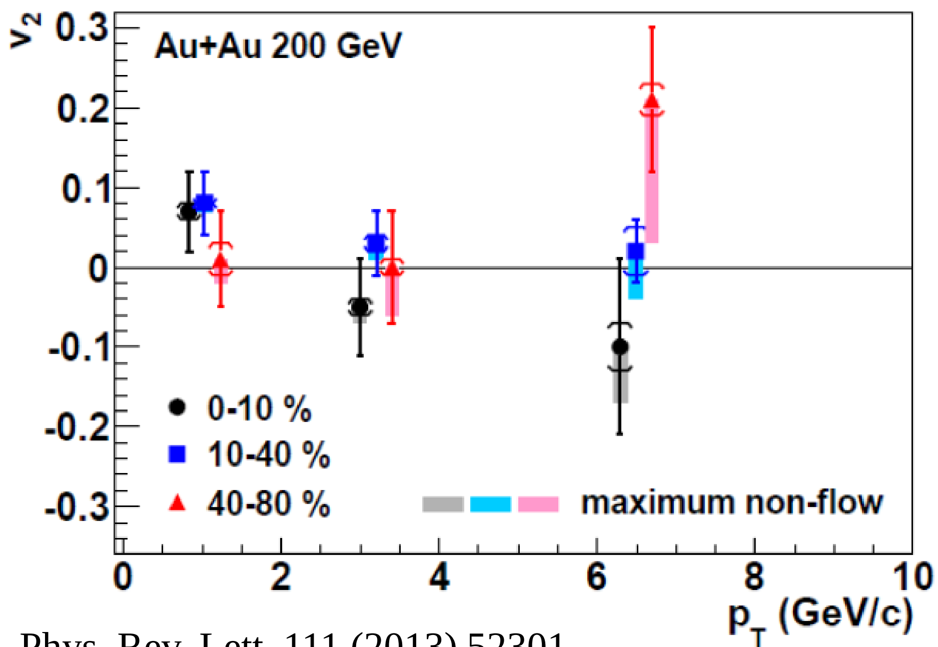
- **Viscous hydrodynamics**
  - J/ψ decoupling temperature of 120 and 165 MeV
  - fails to describe the low-p_T spectra
  - fails to describe the high-p_T v_2 (see next slide)
- **Y. Liu et al.**
  - model includes J/ψ suppression due to color screening and the statistical regeneration
  - peripheral: initial production dominates.
    central: regeneration becoming more significant at low p_T.

Coalescence of charm quarks is needed to describe the J/ψ production.

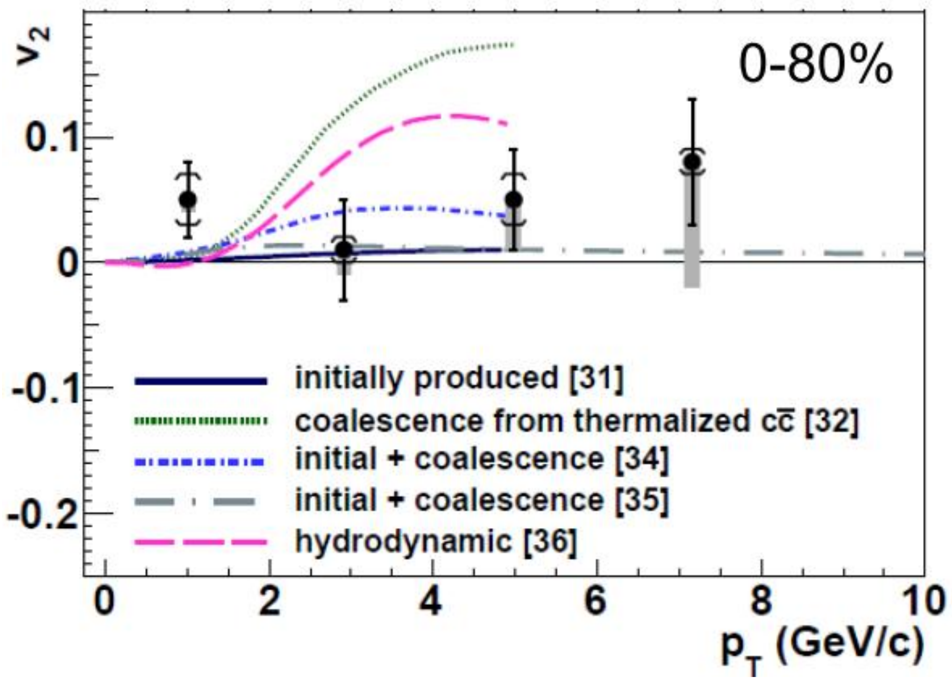


Y. Liu et al., Phys. Lett. B 678, 72 (2009)
U. W. Heinz and C. Shen (2011), private communication.

J/ψ elliptic flow



Phys. Rev. Lett. 111 (2013) 52301

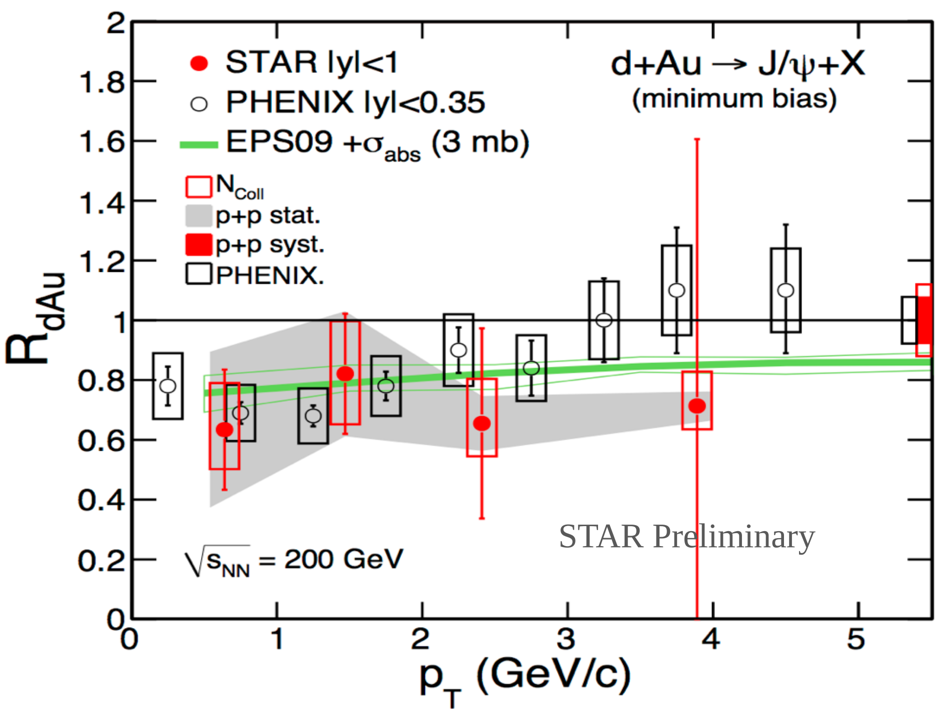


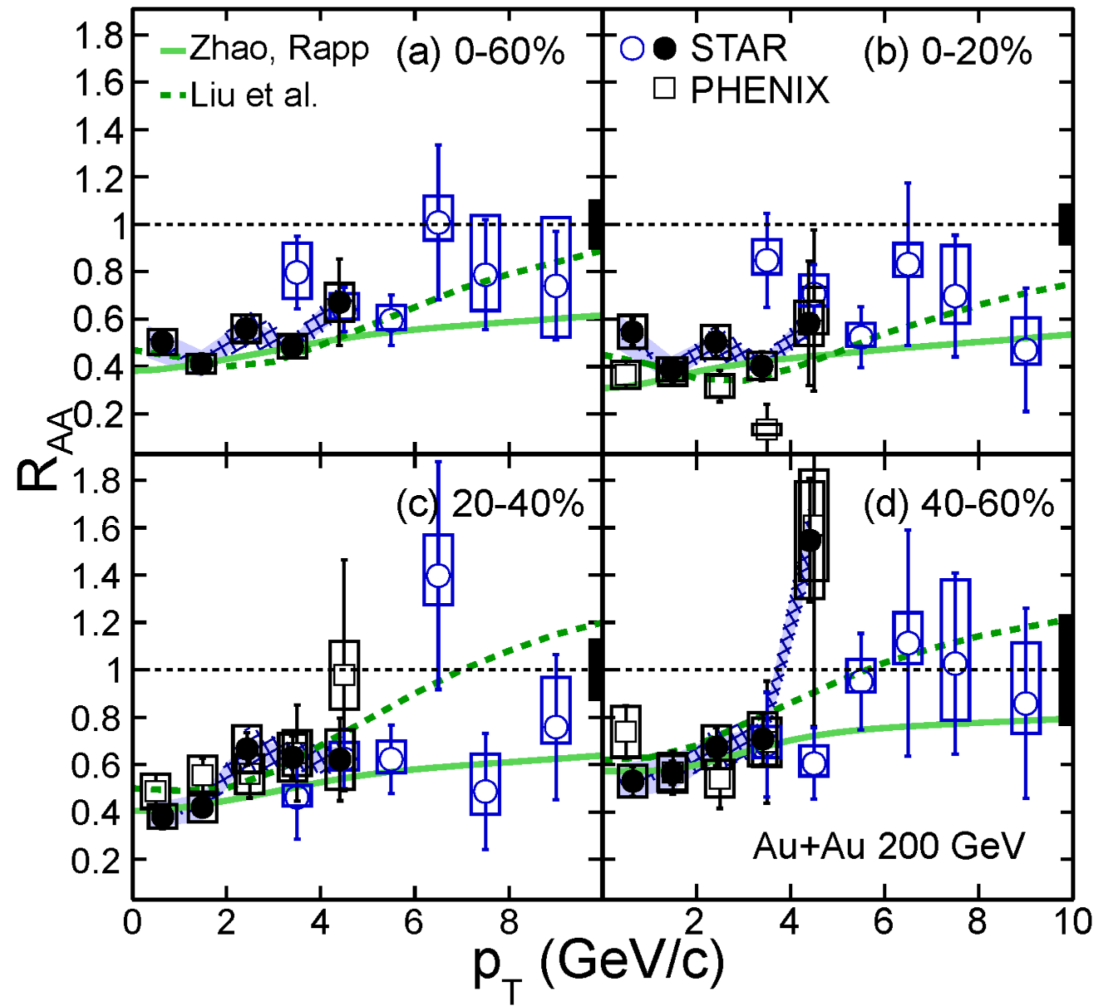
[31] L. Yan, P. Zhuang, N. Xu, PRL 97 (2006), 232301.
[32] V. Greco, C.M. Ko, R. Rapp, PLB 595, 202.
[34] X. Zhao, R. Rapp, arXiv:0806.1239 (2008)
[35] Y. Liu, N. Xu, P. Zhuang, Nucl. Phy. A, 834, 317.
[36] U. Heinz, C. Shen, private communication.

- Consistent with zero (p_T > 2 GeV/c)
- The only hadron so far that does not appear to flow at RHIC energies.

Disfavors coalescence from thermalized charm quarks at high p_T.

Message from d+Au





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

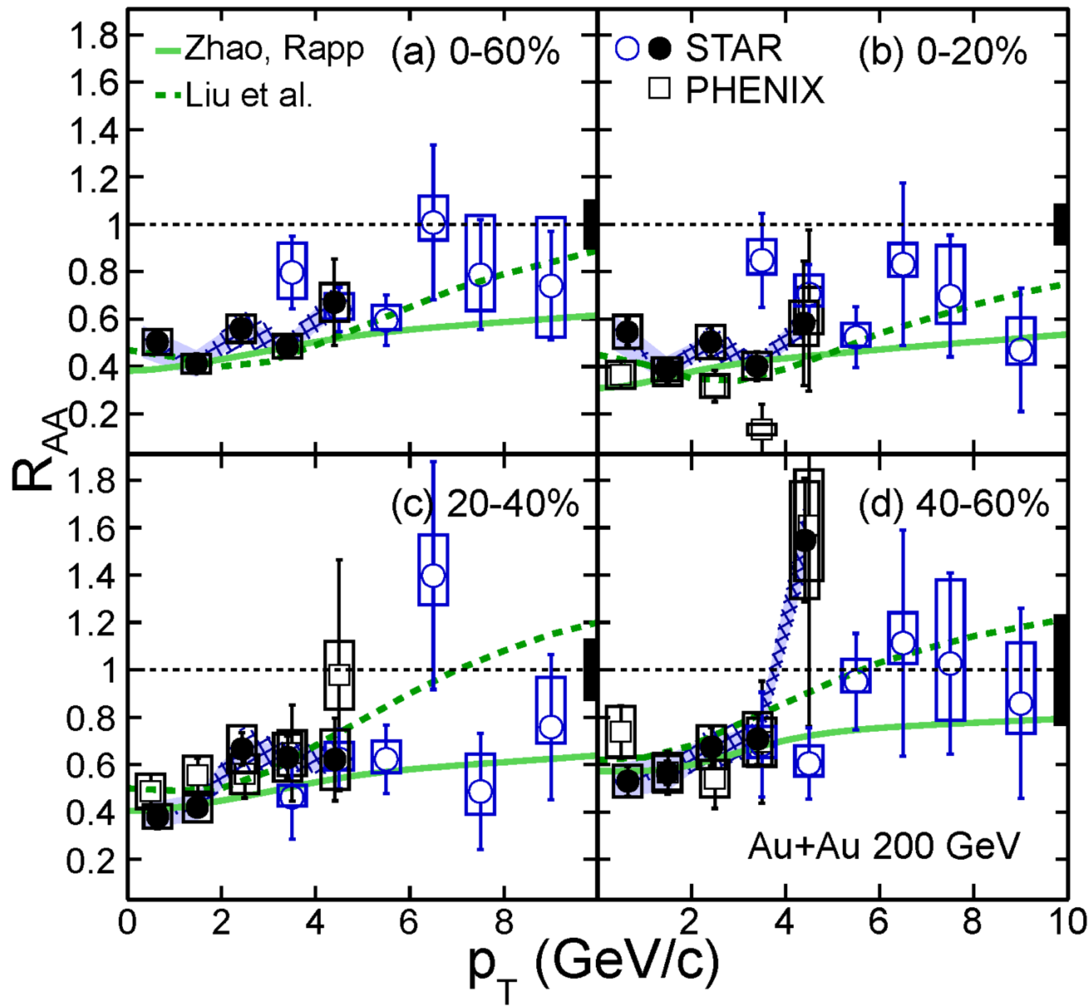
> High- p_T J/ψ carry cleaner signal with less CNM influence.

d+Au:
STAR: J.Phys.Conf.Ser. 455 (2013) 012038
PHENIX: Phys. Rev. C 87, 034904 (2013)
Model: E.Eskola, H.Paukkunenea and C.Salgo, Nucl. Phys. A 830, 599 (2009)

J/ψ suppression in Au+Au at 200 GeV

Nuclear modification factor:

- Larger suppression at low-p_T at all centralities
- Suppression decreasing towards high-p_T
  - Consistent with unity at high p_T (semi-)peripheral collisions
  - Remaining suppression at high-p_T in central collisions
- Agreement with theory
  - Includes effects of coalescence
  - Zhao and Rapp : additional effects of formation-time effect and B hadron feed-down



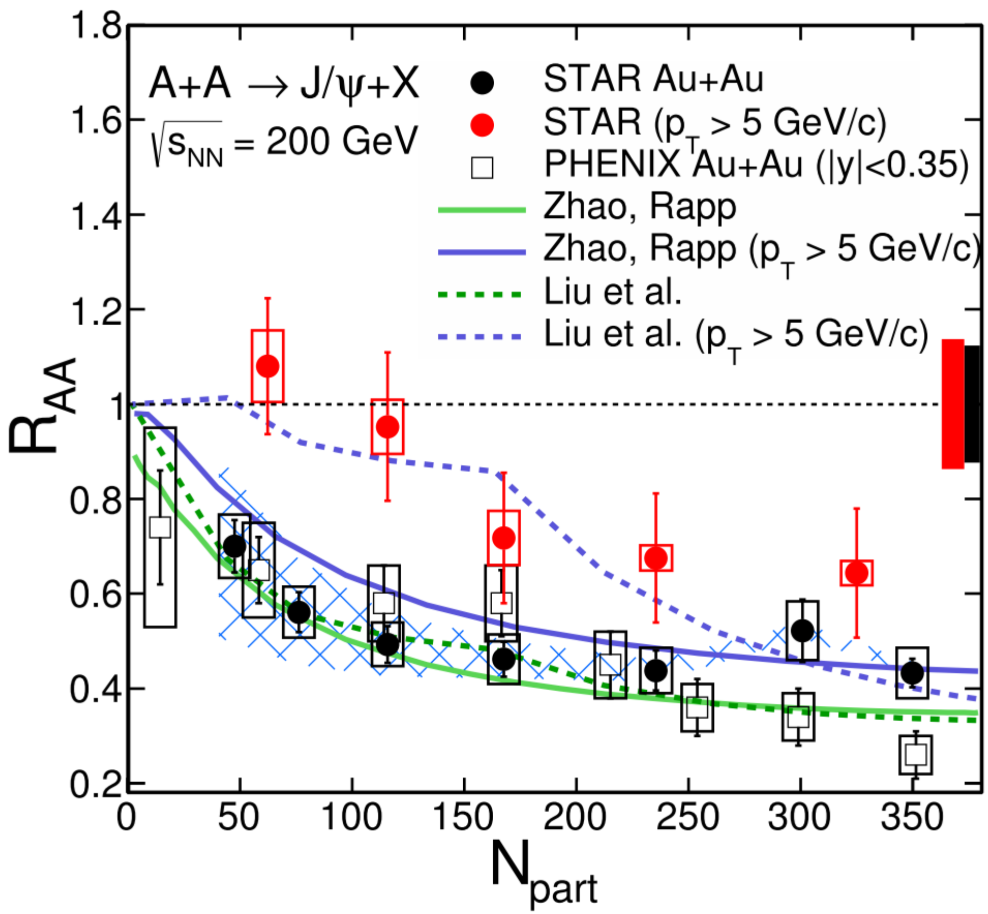
STAR low-p_T : arXiv:1310.3563
high-p_T : Phys.Lett. B722, 55 (2013)

Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010)
PLB 664, 253 (2008)

J/ψ supression: high-p_T vs low-p_T

System size (N_{part}) dependence

- Suppression grows with the size of the system
- J/ψ in central collisions suppressed even at high p_T
- Models including initial production and recombination reasonably describe the J/ψ in our measured p_T region
- High p_T data less suppressed than low p_T
  - No recombination in this region
  - No CNM effects (from d+Au)

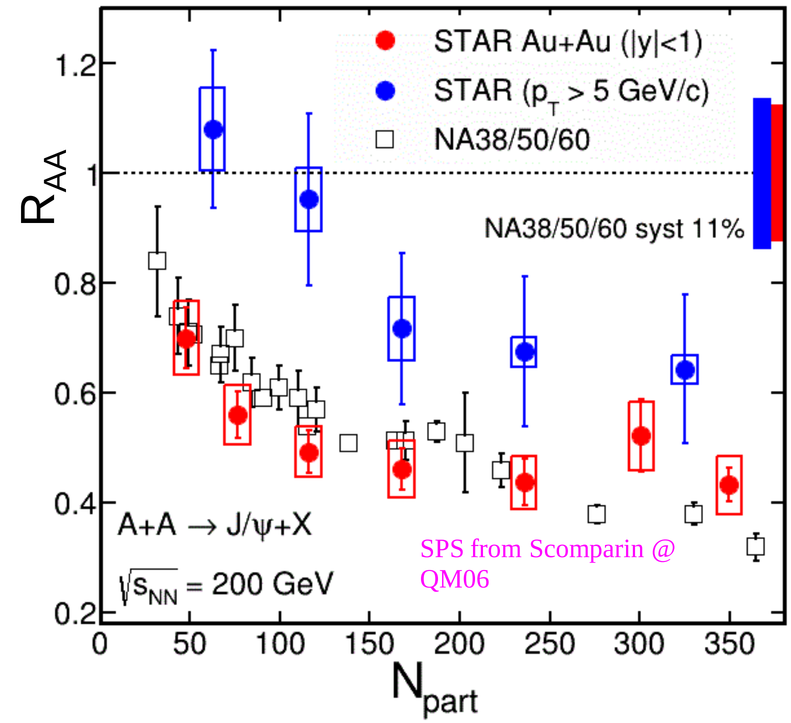


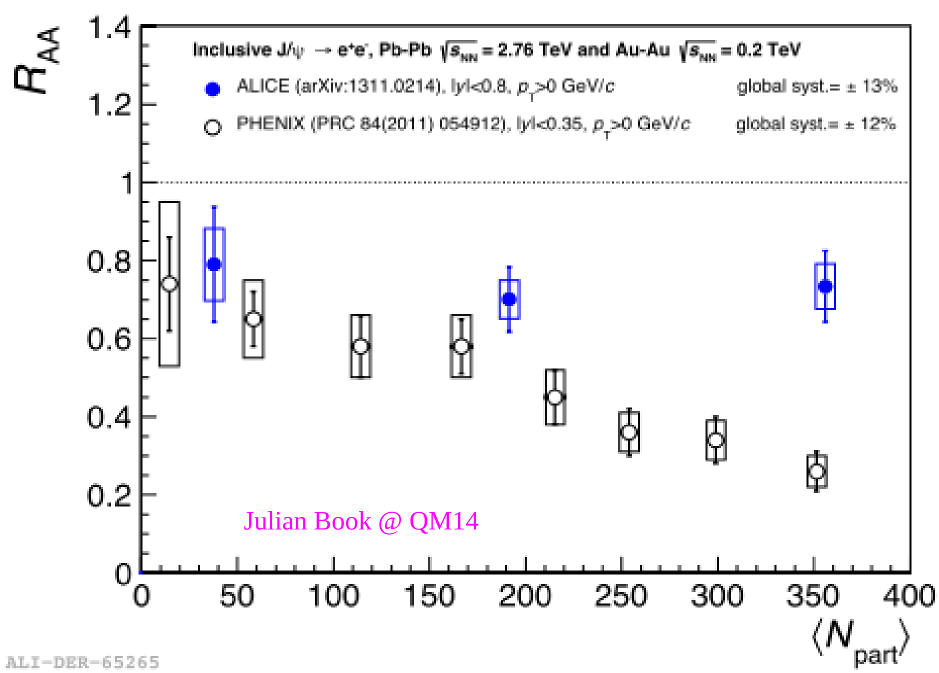
J/ψ suppression in Au+Au at high- p_T is a manifestation of the QGP effects.

STAR low-p_T : arXiv:1310.3563
high-p_T : Phys.Lett. B722, 55 (2013)
Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010)
PLB 664, 253 (2008)
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

J/ψ R_{AA} – energy dependence

- Similar suppression at RHIC and SPS
  - Canceling influence of melting and regeneration?
- LHC: suppression is reduced at low-p_T
  - Suggests dominance of regeneration production mechanism at the LHC.





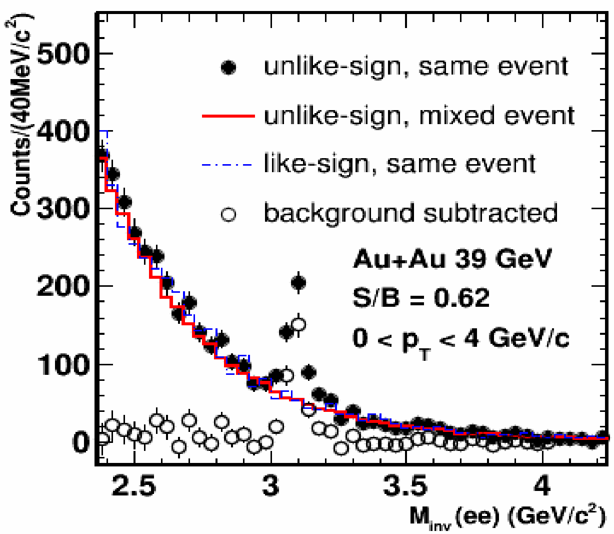
RHIC Beam Energy Scan (BES) program: a unique tool to study the interplay of CNM, screening, and regeneration effects

STAR low-p_T : arXiv:1310.3563
high-p_T : Phys.Lett. B722, 55 (2013)
ALICE: PLB 743 (2014) 314-327

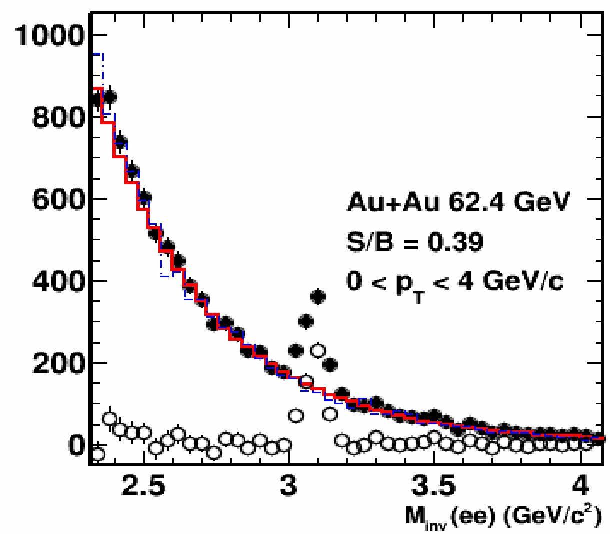
J/ψ at Beam Energy Scan (BES)

- J/ψ observed at 200, 62.4 , and 39 GeV
- 62.4 and 39 GeV data from Run10
- Signal up to p_T 4 GeV/c for 39 and 62.4 GeV

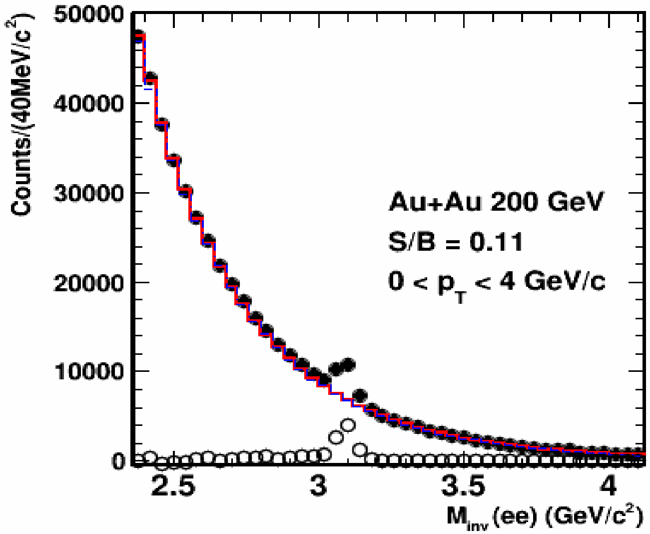
39 GeV



62.4 GeV

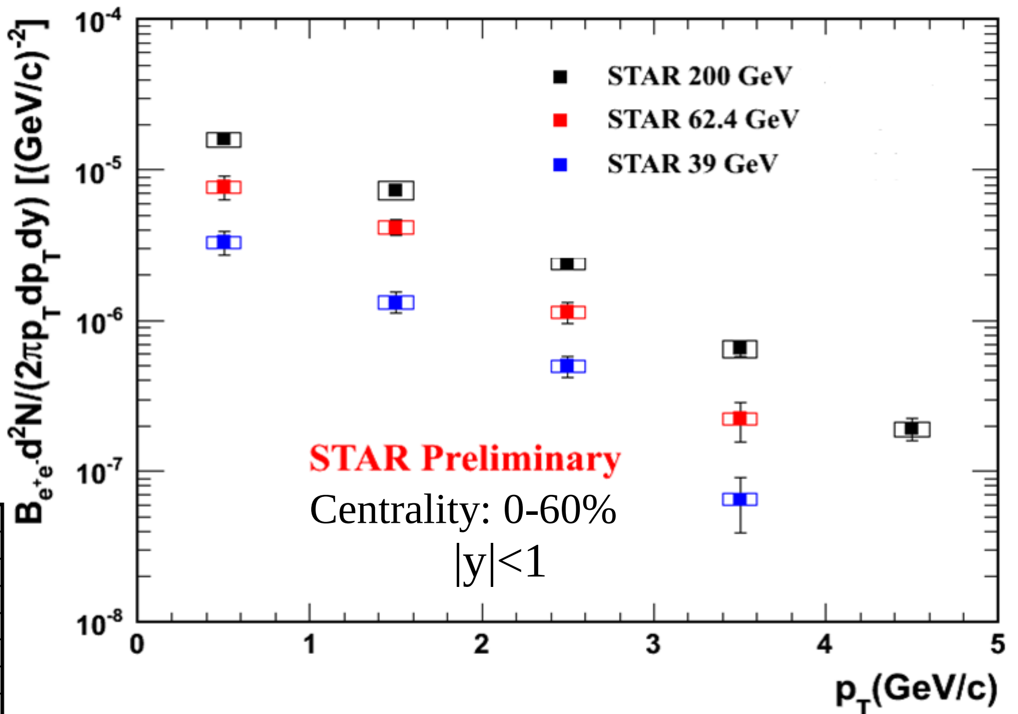


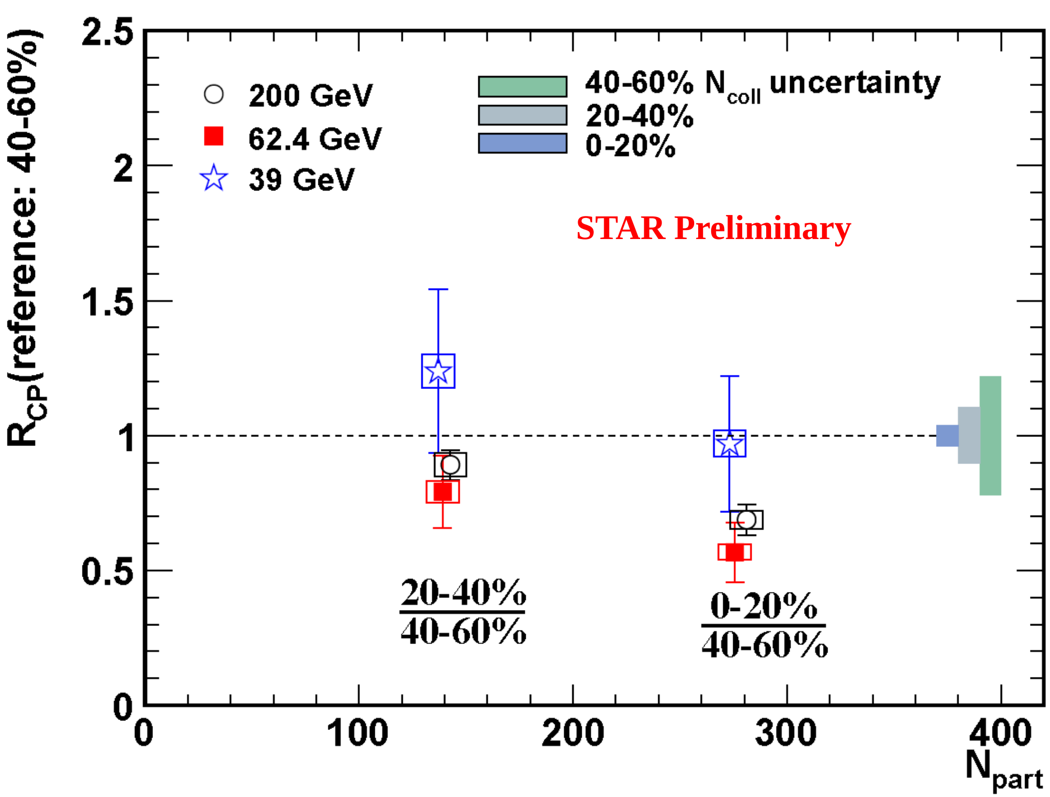
200 GeV



J/ψ in Au+Au-energy dependence

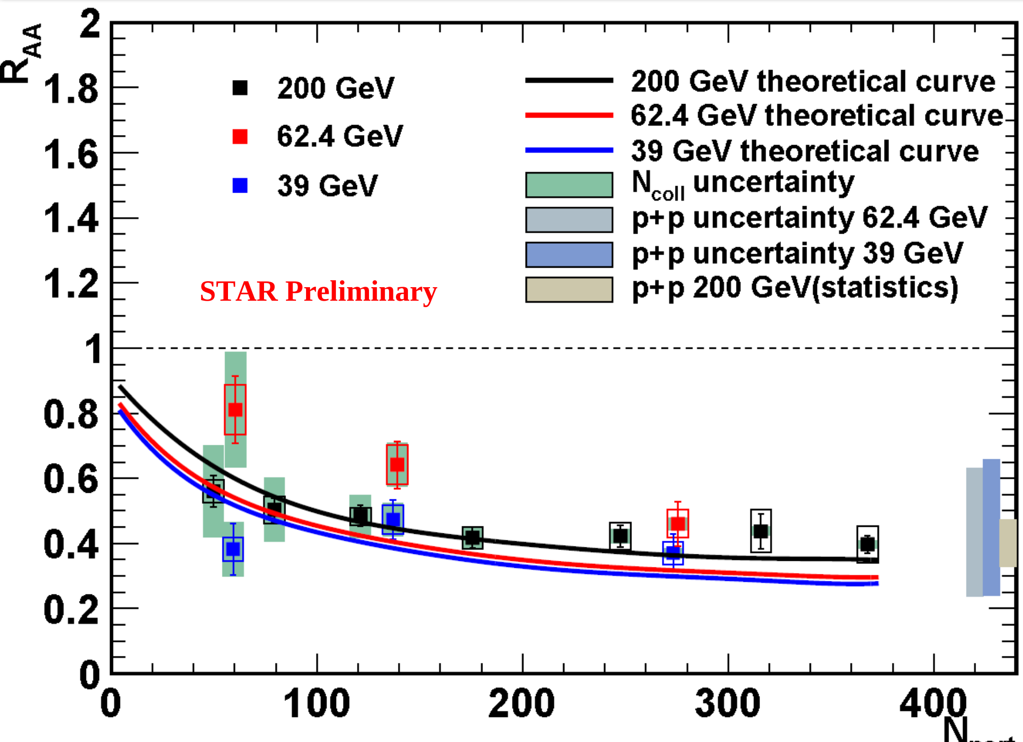
- Measured J/ψ spectra at 200, 62.4 and 39 GeV

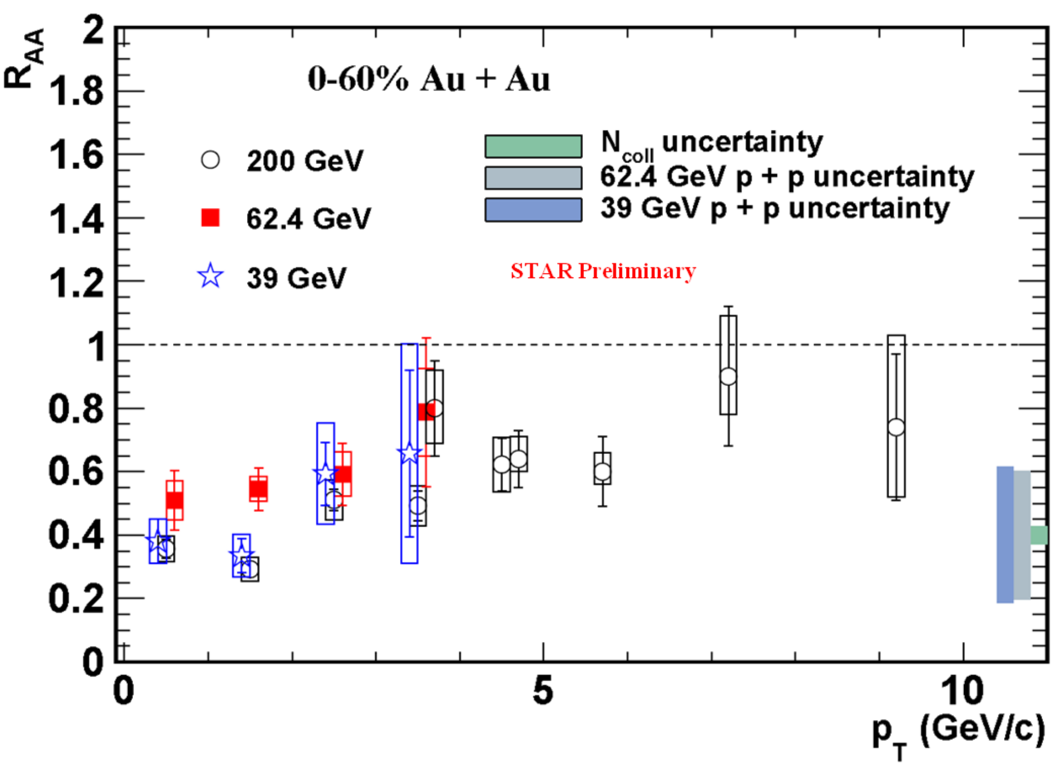




- No p+p reference data at 62.4 and 39 GeV
  - Using R_{CP} -ratio of central to peripheral
- Significant suppression in central Au + Au collisions at 62.4 GeV, similar as at 200 GeV.

Energy dependence of J/ψ R_{AA}





CEM p+p references for 39 and 62 GeV:
Nelson, Vogt et al., PRC87, 014908 (2013)

Theoretical R_{AA} curves:
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
  - Almost compensating interplay of melting and coalescence

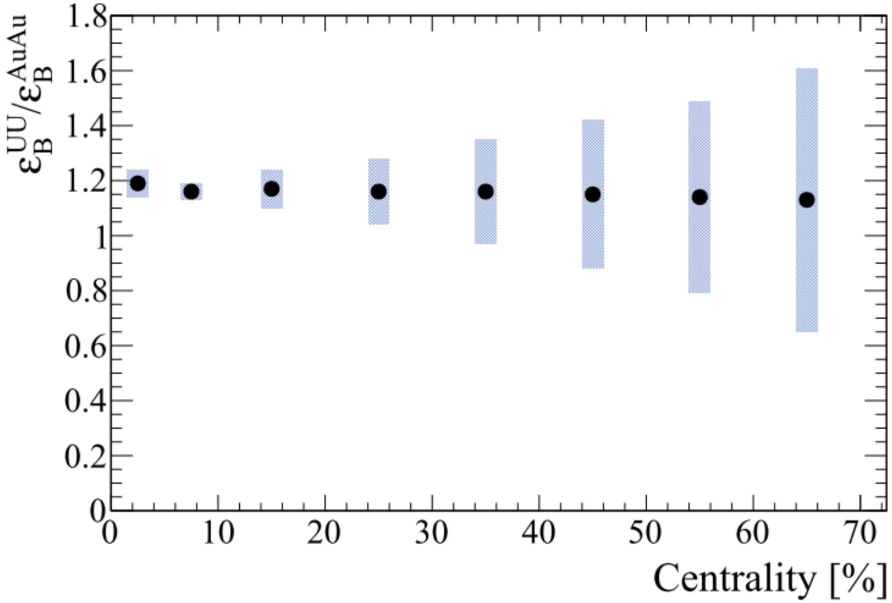
U+U collisions at 193 GeV

- Uranium nucleus is larger than Au and non-spherical
- U+U collisions provide higher energy density then Au+Au
  - Tip-to-tip collisions - highest energy density
- Larger number of binary collisions
  - Increased charm production and coalescence

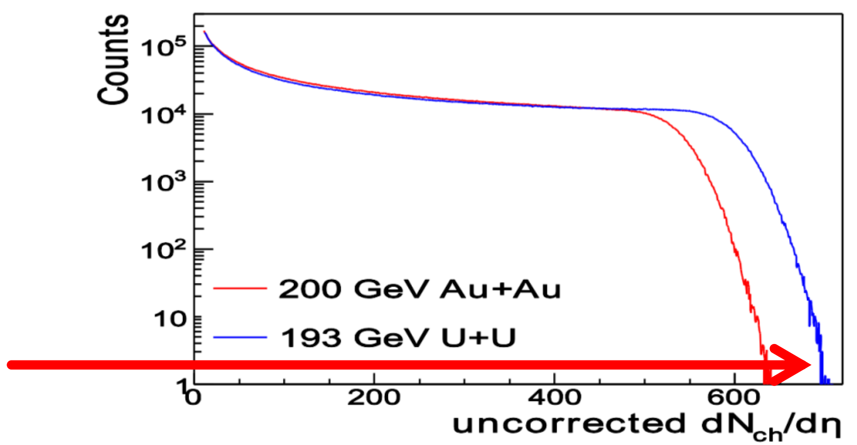
$$N_{stat}^{J/\psi} \propto N_c^2$$

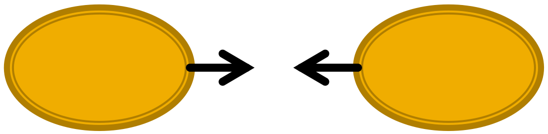
- These two effects go in opposite directions

U+U collisions: study of interplay between color screening and coalescence



Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907

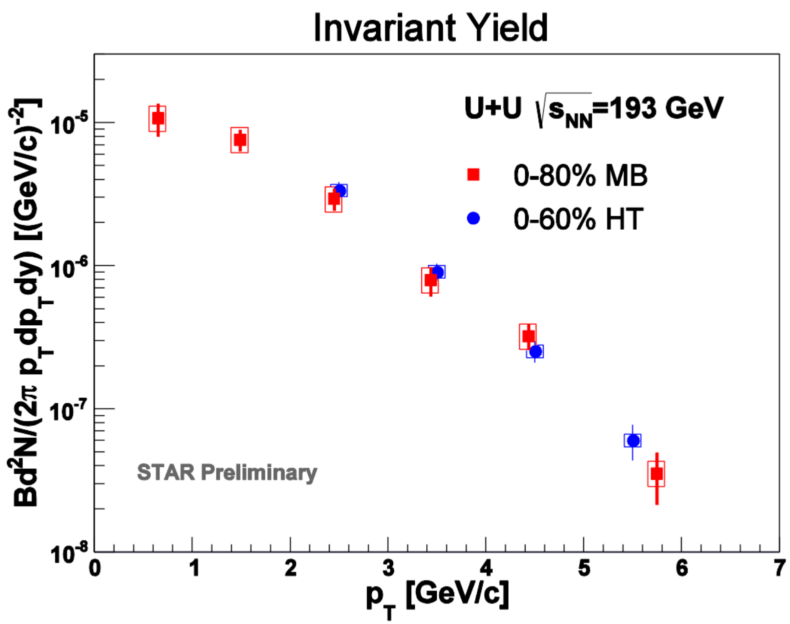


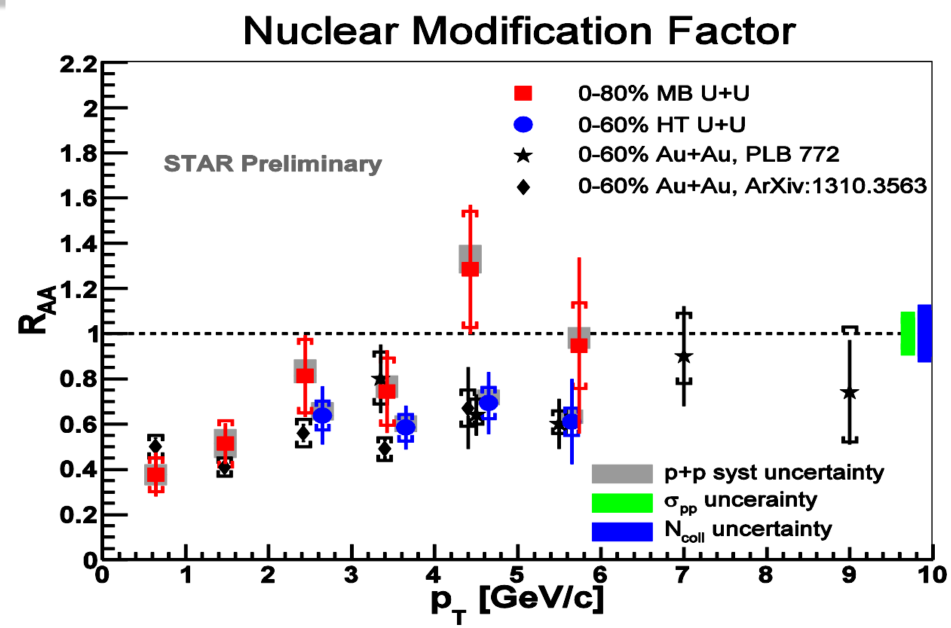


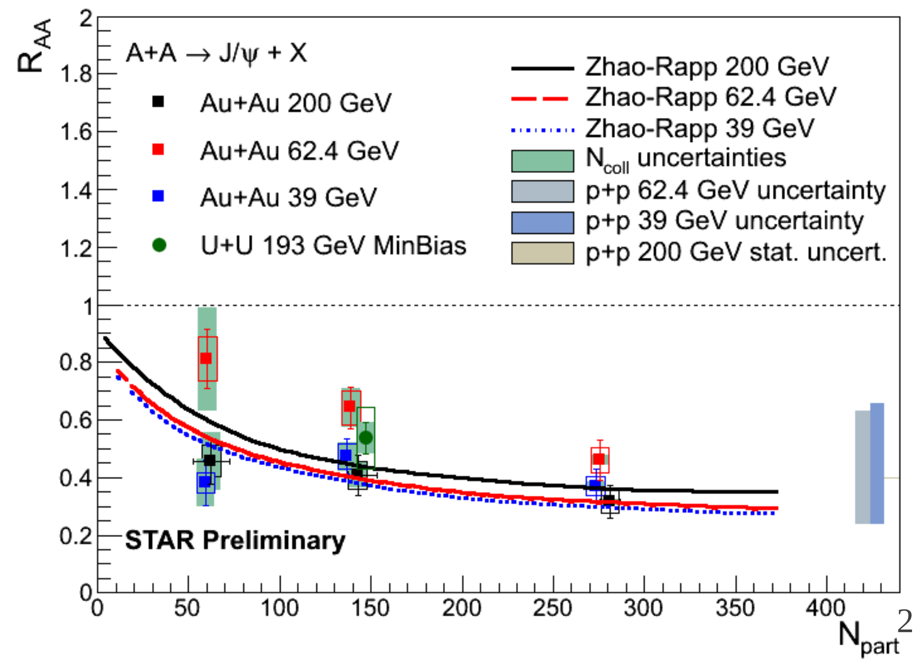
Tip-to-tip collision

STAR Collaboration: arXiv 1310.3563 (2013)

J/ψ R_{AA} in U+U



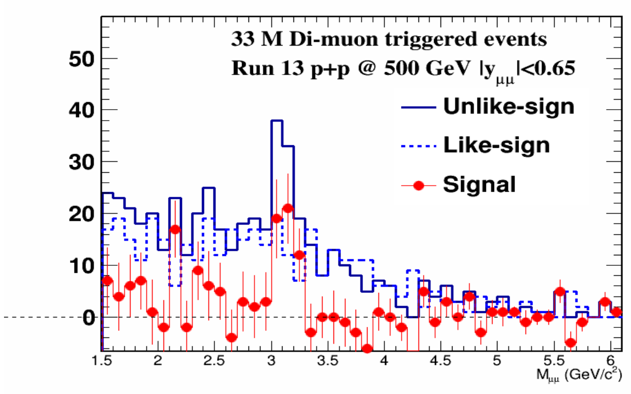




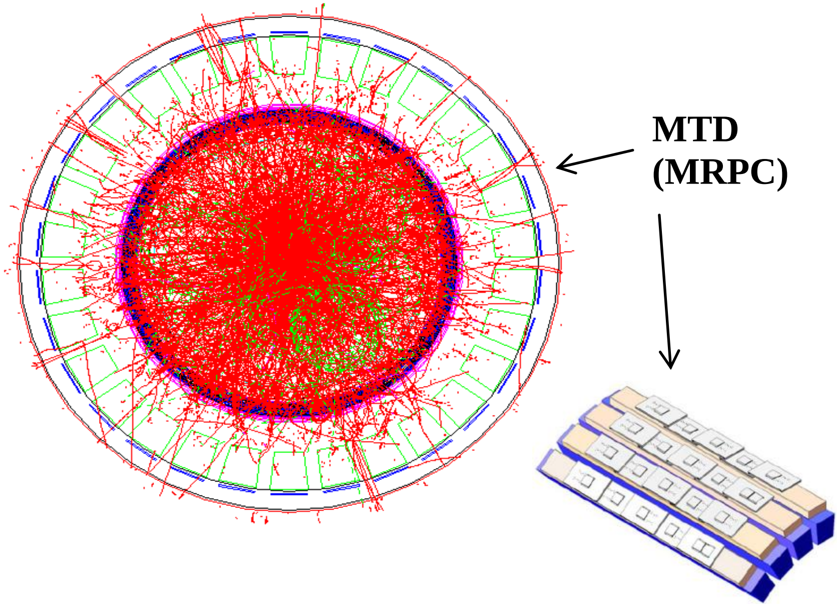
- Nuclear modification factor as a function of p_T similar to Au+Au
  - p+p reference from 200 GeV used

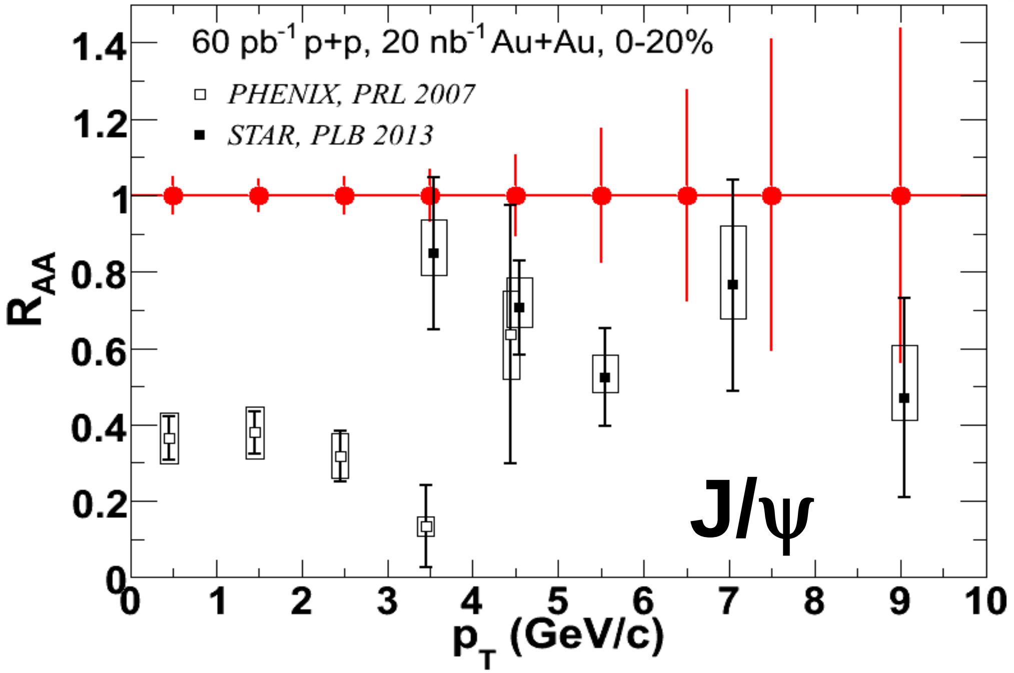
Muon Telescope Detector (MTD)

- $J/\psi \rightarrow \mu^+\mu^-$ (B.R. 5.9%)
  - No γ conversion, less contribution from Dalitz decays
  - Trigger capability for J/ψ in central A+A collisions



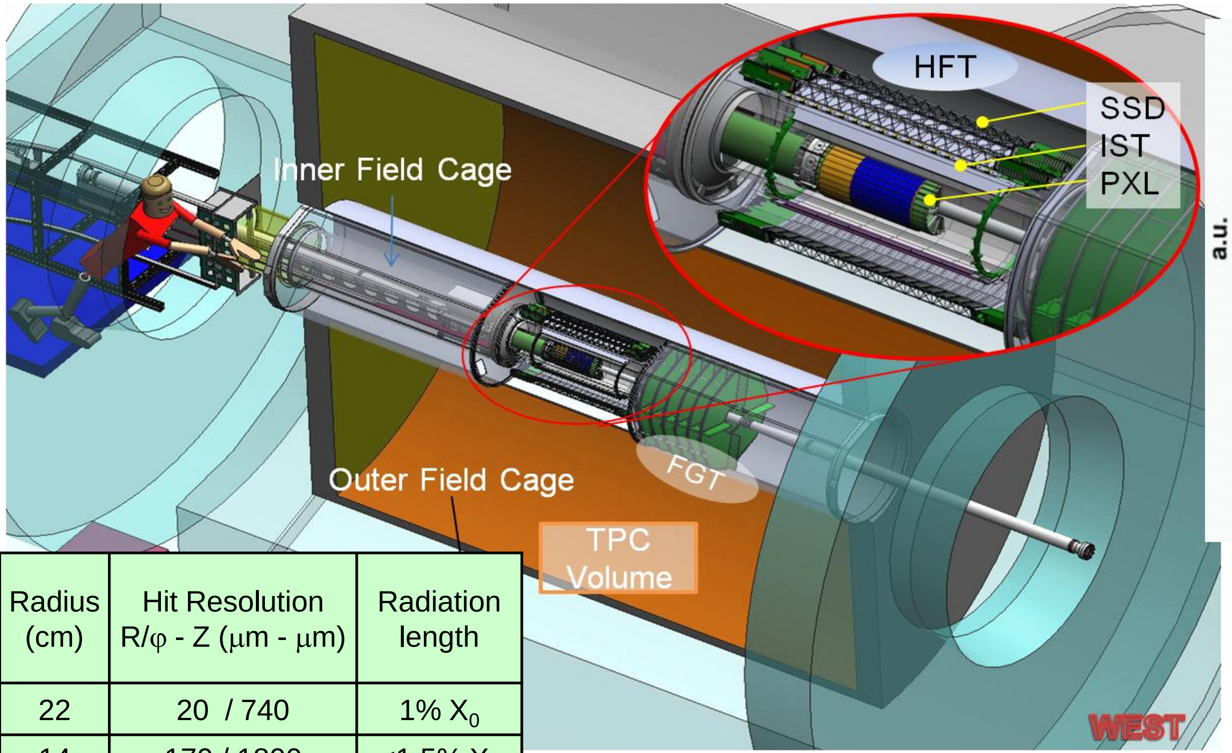
..see next talk by Robert Vertesi…



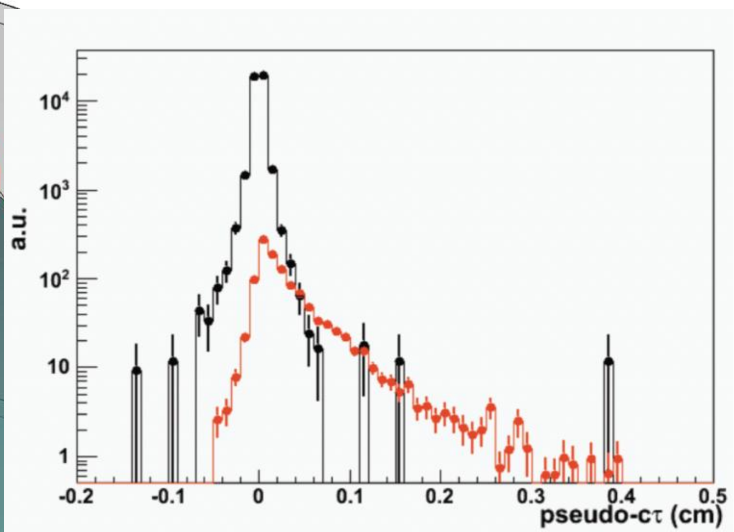


Heavy Flavor Tracker (HFT)

- Inner tracking system - precise pointing resolution
- Separation of prompt and non-prompt J/ψ (B → J/ψ + X; cτ ≈ 500 μm)
- Installed for year 2014



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



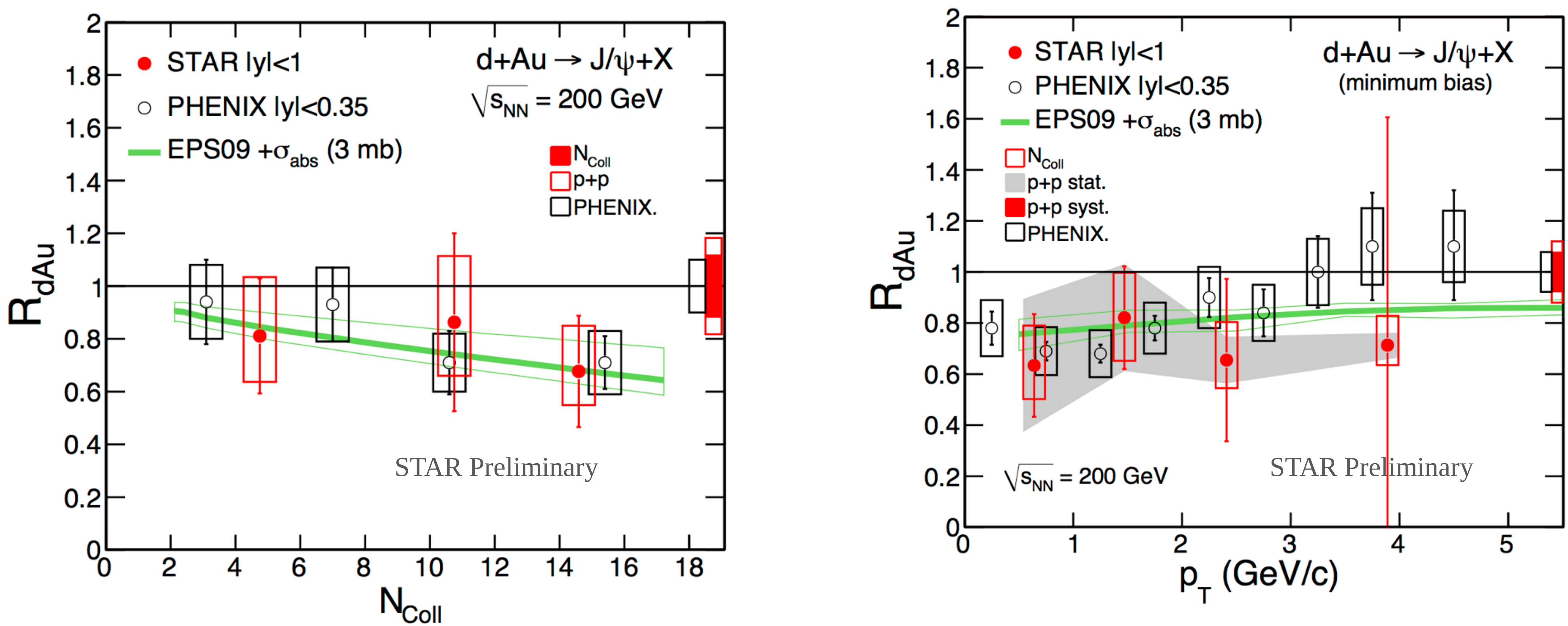
Simulation of separation of prompt and non-prompt J/ψ using HFT

Summary and outlook

- J/ψ in p+p 200GeV
  - NLO CS+CO and CEM models describe J/ψ p_T
  - p_T polarization trend different from COM prediction
- J/ψ in p+p 500 GeV
  - First measurement of ψ (2S) - consistent with previous measurements at different energies
- J/ψ in Au+Au at 200 GeV
  - Significant suppression – increases with centrality and decreases with p_T
  - Elliptic flow consistent with zero (p_T>2 GeV/c) - disfavors coalescence from thermalized (anti-)charm quarks for p_T > 2 GeV/c
- J/ψ in Au+Au at 39 GeV and 62.4 GeV and U+U collisions at 193 GeV
  - Similar suppression as in Au+Au 200 GeV within uncertainties
  - Consistent with interplay of melting and regeneration
- Outlook
  - Polarization measurements in p+p at 500 GeV
  - Muon Telescope Detector: J/ψ → $\mu^+\mu^-$
  - Heavy Flavor Tracker: separation of prompt and non-prompt J/ψ

Backup slides

Message from J/ψ in d+Au 200 GeV

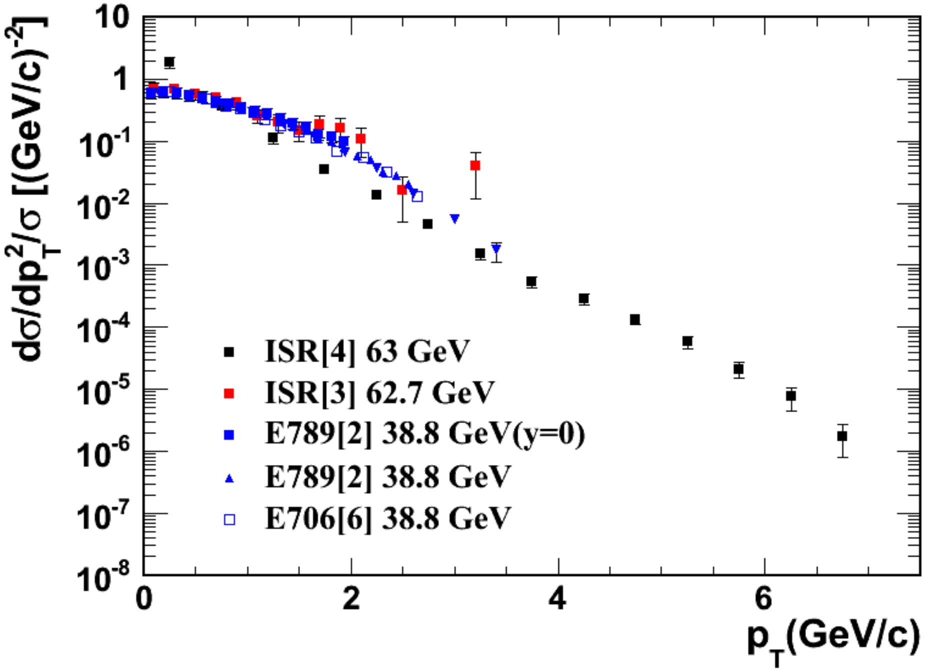


- Cold nuclear effects important for interpreting Au+Au results.
- R_{dAu} consistent with model calculations
  - shadowing from EPS09 nPDF
  - nuclear absorption: $\sigma_{abs}^{J/\psi} = 3mb$

d+Au:
STAR: J.Phys.Conf.Ser. 455 (2013) 012038
PHENIX: Phys. Rev. C 87, 034904 (2013)
Model: E.Eskola, H.Paukkunenea and C.Salgo, Nucl. Phys. A 830, 599 (2009)
R.Vogt, Phys. Rev. C 81, 044903 (2010)

Measurements of J/ψ cross section in 39 and 63 GeV p + p collisions

Experiment	Reaction	Energy (GeV)	Cross section (y=0) (nb/nucleon)
E771[1]	p + Si	38.8	202±17
E789 [2]	p + Au	38.8	170±30
ISR [3]	p + p	62.7	172±15
ISR [4]	p + p	63	250±56



[1] T. Alexopoulos et al, Phys. Rev. D55, 3927 (1997)
[2] M.H. Schub et al., Phys. Rev. D 62, 1307 (1995)
[3] A.G. Clark et al., Nucl. Phys. B 142, 29 (1978)
[4] C. Kourkounelis et al., Phys. Lett. 91B, 481 (1980)
[5] R. Nelson, R. Vogt et al, arXiv:1210.4610v1
[6] A. Gribushin (E706) et al., Phys. Rev. D 62, 012001 (2000).

- Experimental results on cross section and p_T shape are inconsistent. We use Color Evaporation Model estimations as our p + p references for 39 and 62.4 GeV.
- CEM describes the p_T and y distributions in 200 GeV p + p collisions[5].