J/ψ production at the STAR experiment

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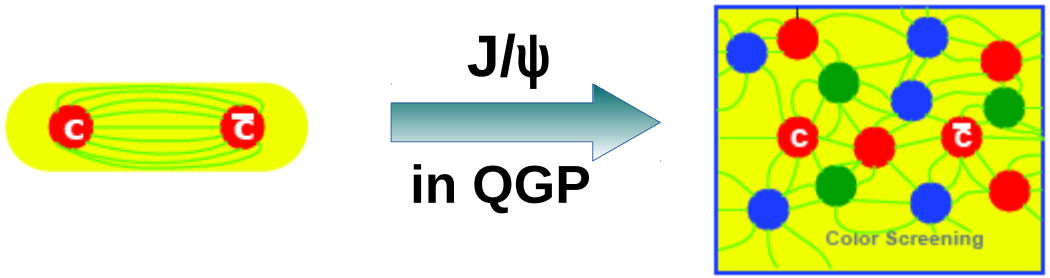
Why study quarkonia?

- **quarkonium suppression in heavy ion collision** due to color screening effect in Quark-Gluon Plasma (QGP)

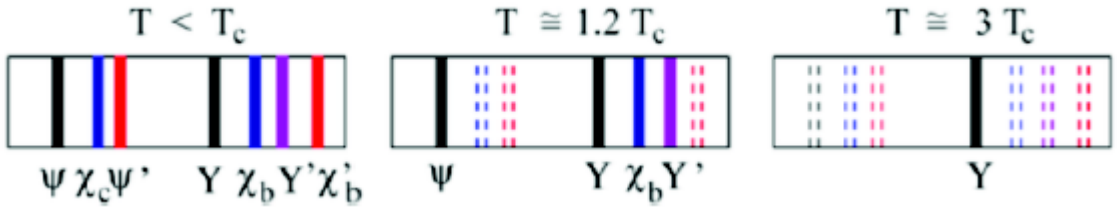
T. Matsui and H. Satz PLB 178 (1986) 416



- Low temparature
- High density
- High temperature

- **QGP thermometer** → different quarkonium states melt at different temperatures

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



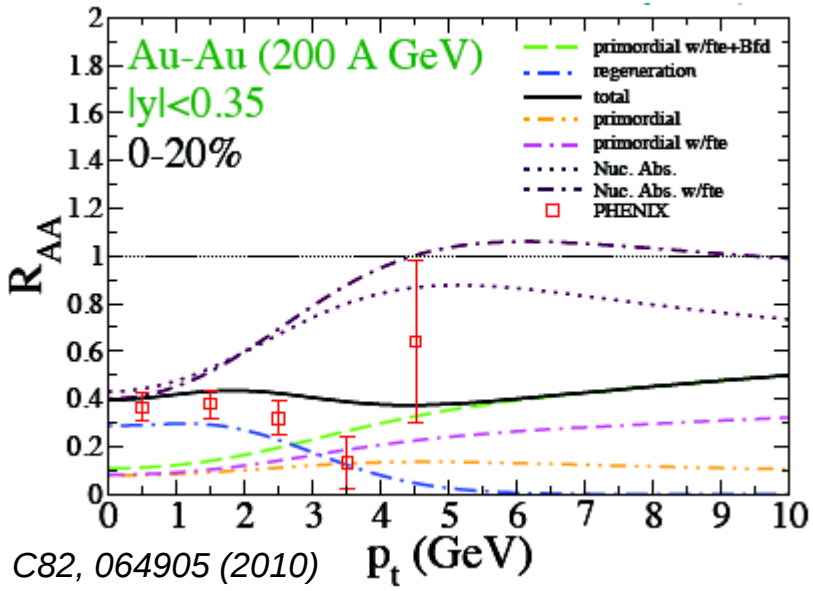
Quarkonium production

- quarkonium production mechanism in elementary collisions not fully understood

- observed J/ψ is a mixture of various production mechanisms:
  - **Prompt:** direct production (60%), decay of Ψ(2S) (10%) and χ_c (30%)
  - **Non-prompt:** B-mesons decay (up to 25% at 12 GeV/c)

Phys. Lett. B772(2013) 55

- suppression and enhancement of the quarkonium production due to the other effects:
  - **Cold Nuclear Matter Effects:**
    - (anti)shadowing
    - Cronin effect
    - Nuclear absorption
  - **Hot Nuclear Matter Effects:**
    - Regeneration



Phys. Rev. C82, 064905 (2010)

Nuclear modification factor R_{AA}

- **Modification of heavy quarkonium production** in nucleus+nucleus collisions (A+A) compared with p+p collisions is quantified by the nuclear modification factor :

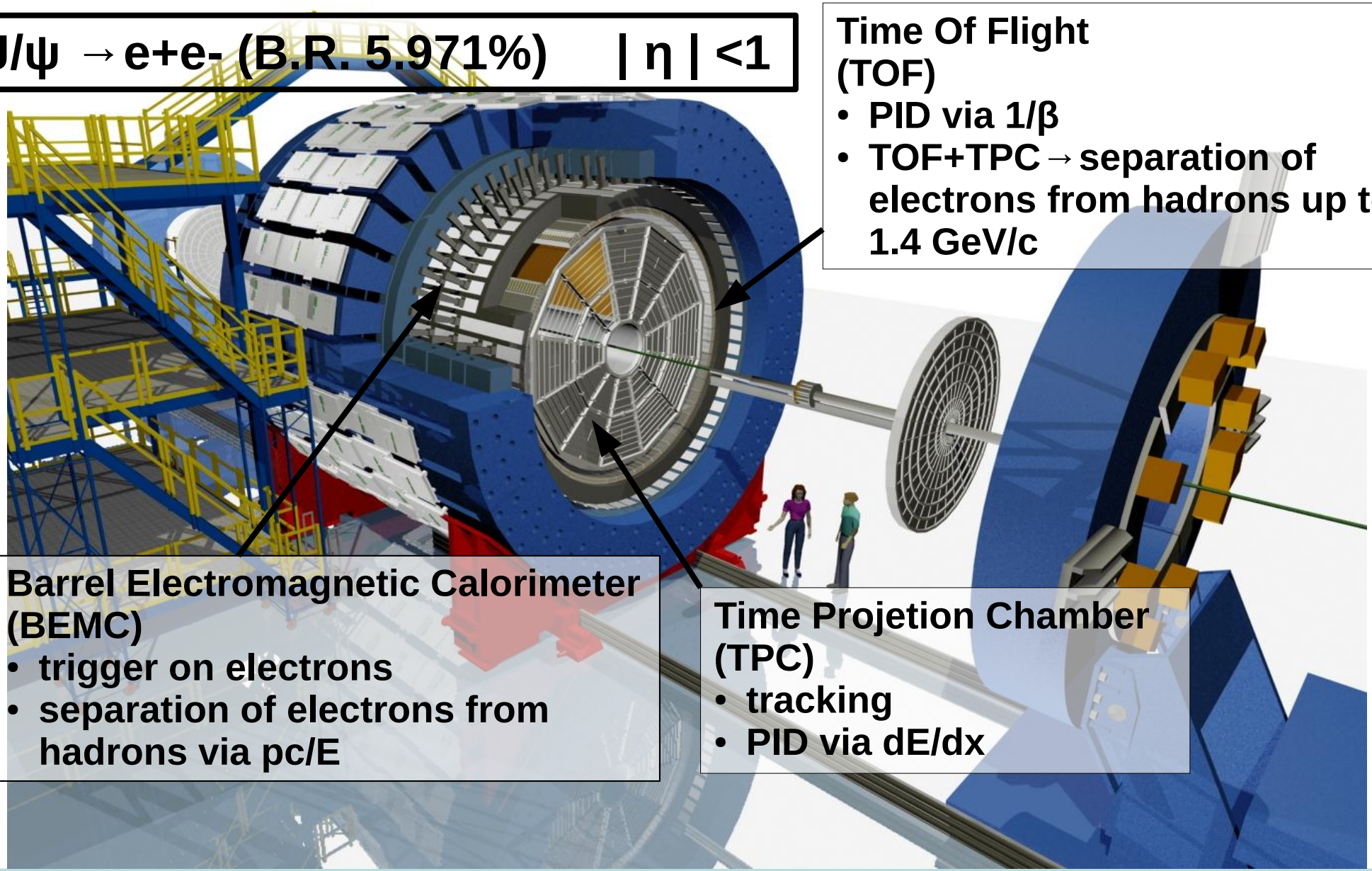
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T dy}{d^2 N_{pp} / dp_T dy}$$

$R_{AA} > 1$ …..enhancement
$R_{AA} = 1$ …..no medium effects
$R_{AA} < 1$ …..suppresion

- **p+p collision :** baseline for heavy ion collisions, study of quarkonium production mechanism
- **d+Au collision:** study of Cold Nuclear Matter effects
- **Au+Au, U+U collision :** study of hot/dense medium effects

The Solenoid Tracker At RHIC (STAR)

J/ψ → e+e- (B.R. 5.971%) | η | <1



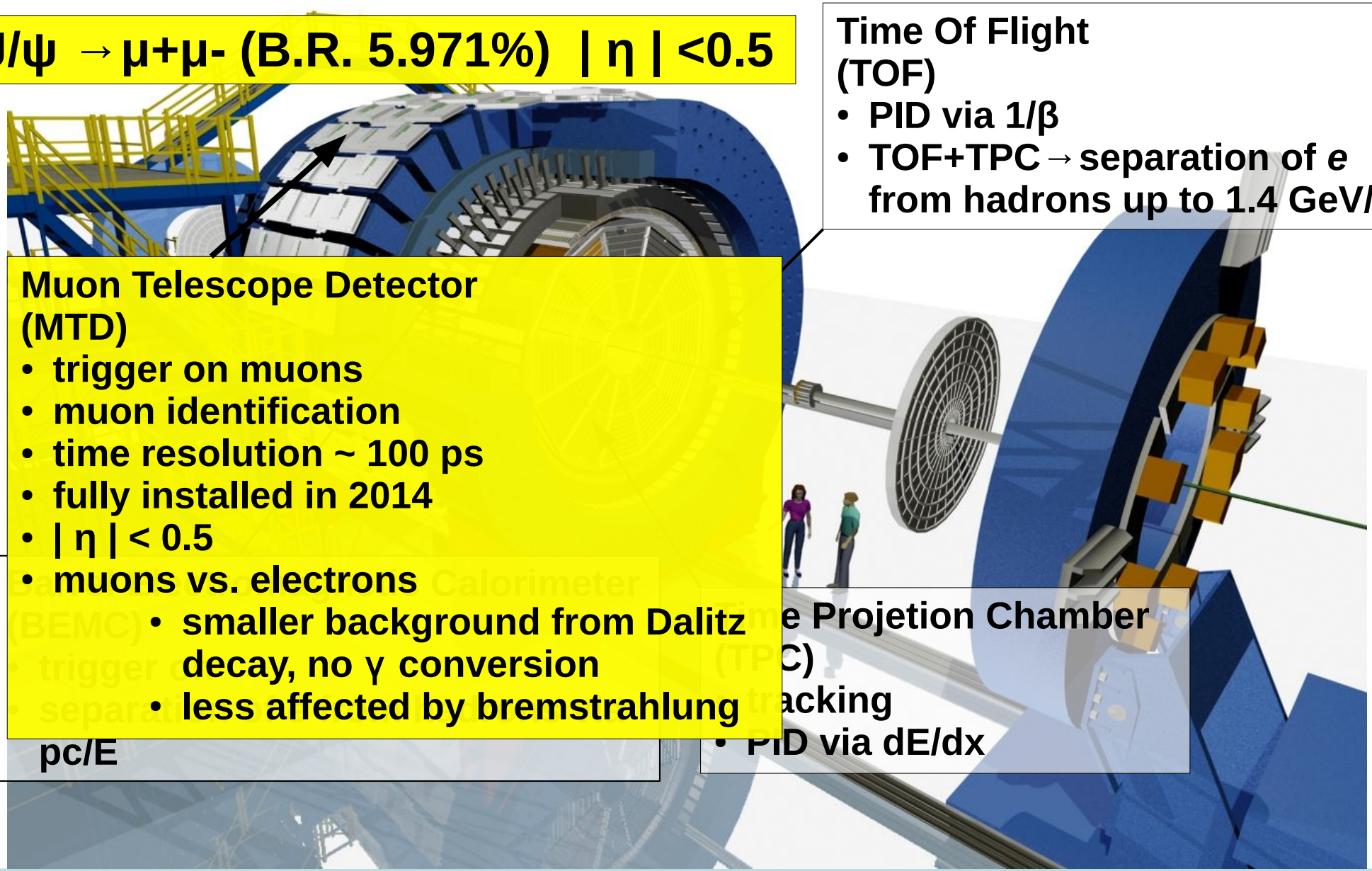
Time Of Flight (TOF)
- **PID via 1/β**
- **TOF+TPC → separation of electrons from hadrons up to 1.4 GeV/c**

Barrel Electromagnetic Calorimeter (BEMC)
- **trigger on electrons**
- **separation of electrons from hadrons via pc/E**

Time Projetion Chamber (TPC)
- **tracking**
- **PID via dE/dx**

The Solenoid Tracker At RHIC (STAR)

J/ψ → μ+μ- (B.R. 5.971%) | η | <0.5



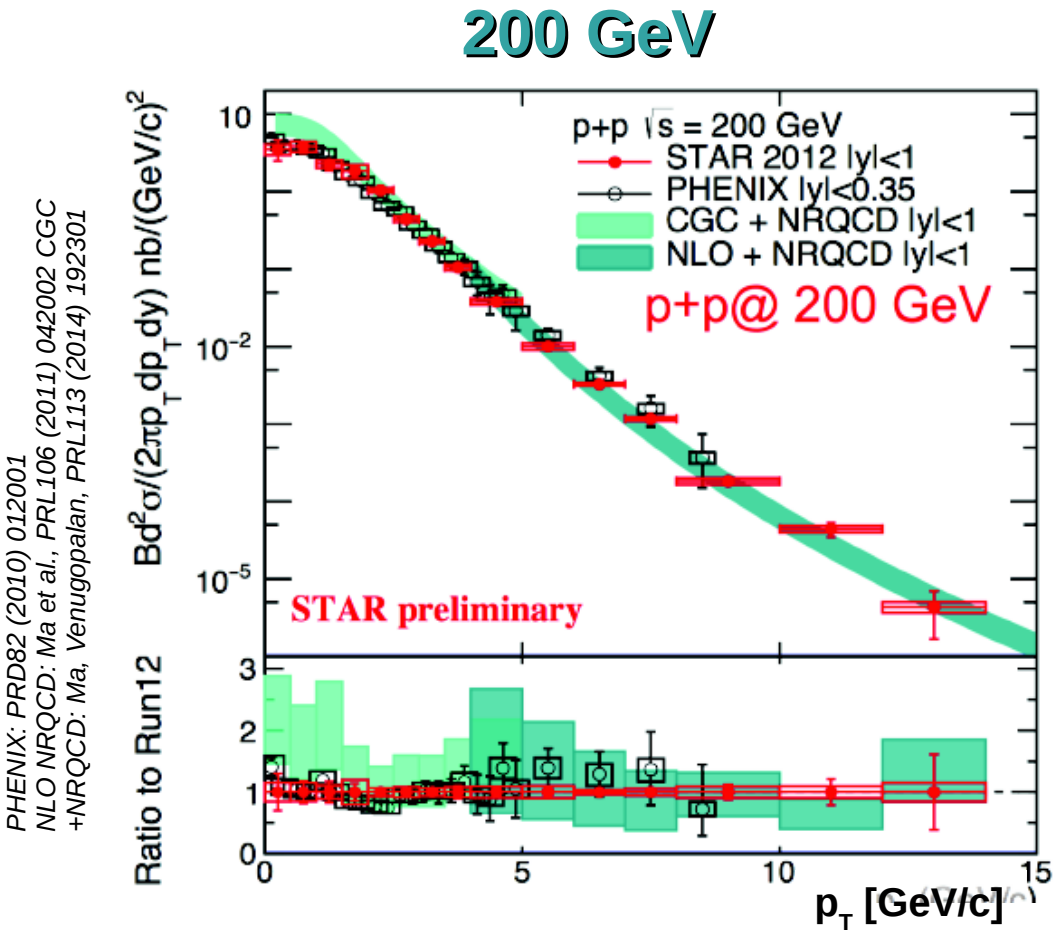
Time Of Flight (TOF)
- **PID via 1/β**
- **TOF+TPC → separation of *e* from hadrons up to 1.4 GeV/c**

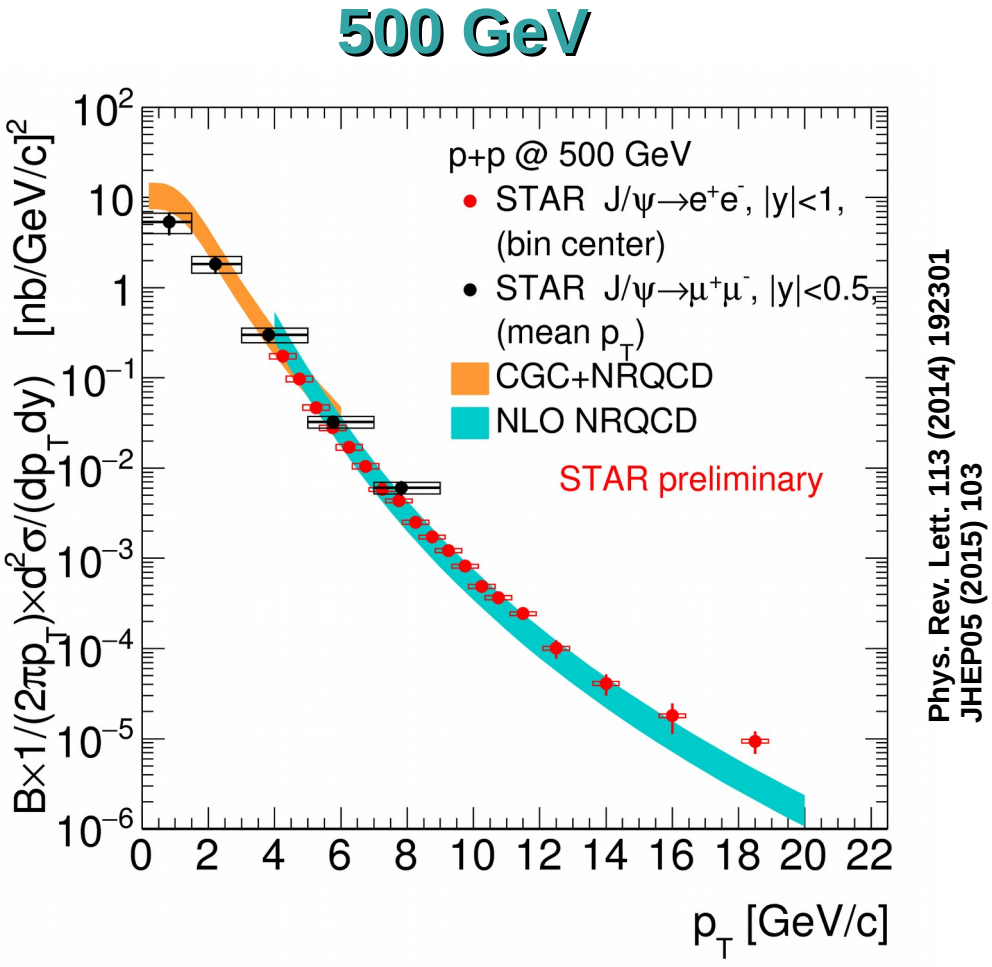
Muon Telescope Detector (MTD)
- **trigger on muons**
- **muon identification**
- **time resolution ~ 100 ps**
- **fully installed in 2014**
- **| η | < 0.5**
- **muons vs. electrons**
  - **smaller background from Dalitz decay, no γ conversion**
  - **less affected by bremstrahlung**

pc/E

e Projetion Chamber C)
acking
- **PID via dE/dx**

J/ψ p_T spectra in p+p collisions



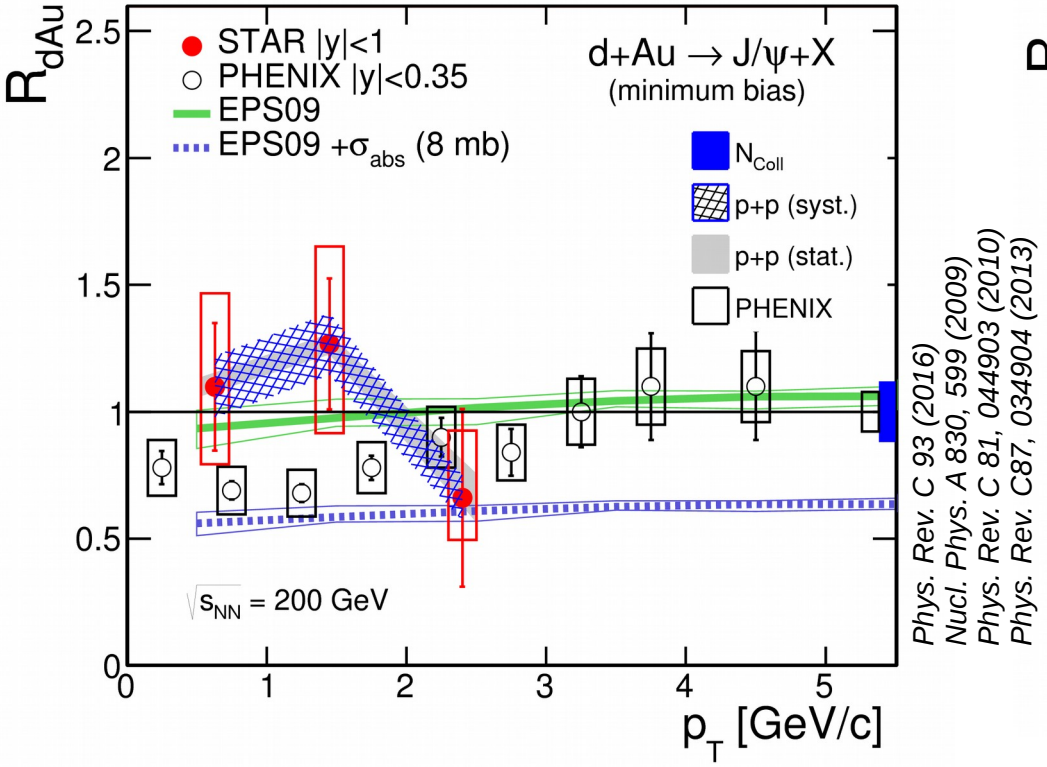


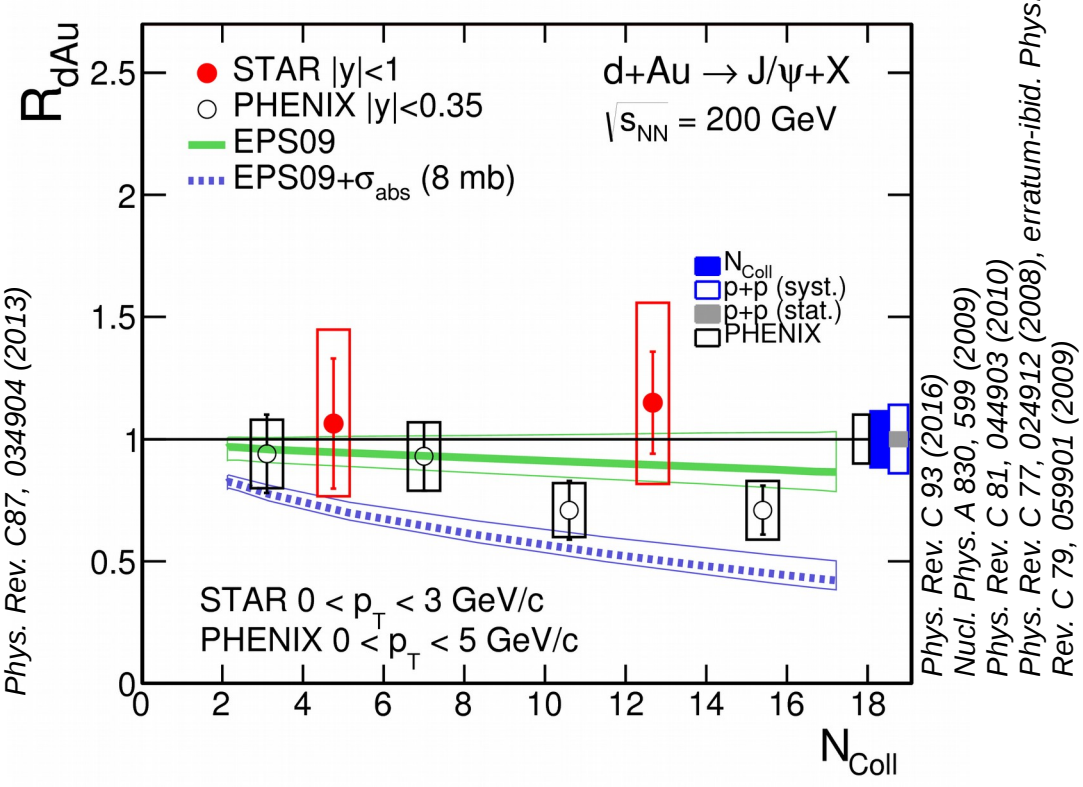
PHENIX: PRD82 (2010) 012001
NLO NRQCD: Ma et al., PRL106 (2011) 042002 CGC
+NRQCD: Ma, Venugopalan, PRL113 (2014) 192301

Phys. Rev. Lett. 113 (2014) 192301
JHEP05 (2015) 103

- CGC+NRQCD (low p_T) and NLO NRQCD (high p_T) together can describe the data well both at 200 GeV and 500 GeV

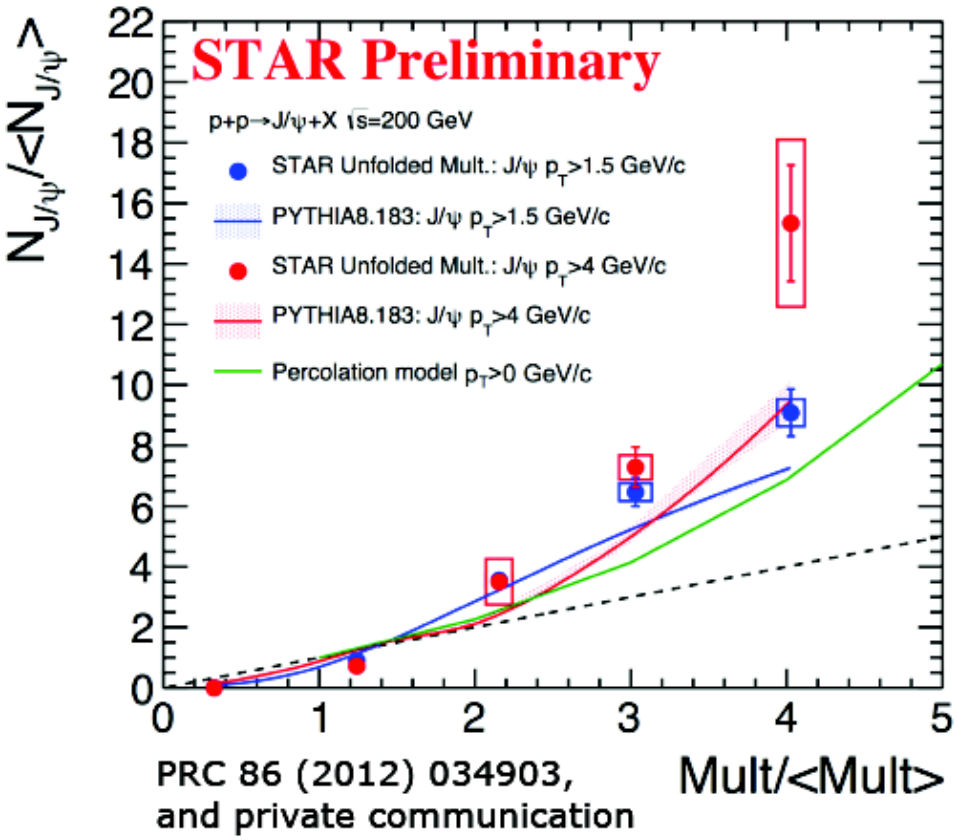
J/ψ in d+Au collisions

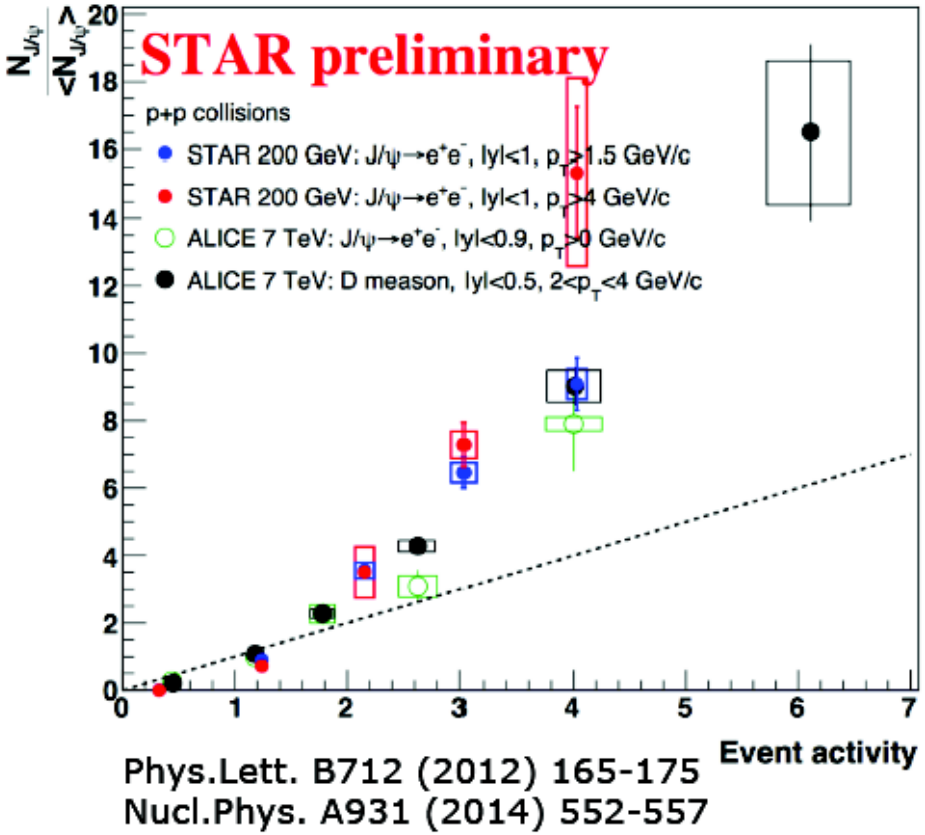




- study of Cold Nuclear Matter (CNM) effects
- $R_{dAu} \approx 1$ (no suppresion) for high p_T ⇒ **influence of CNM effects is small**
- PHENIX low p_T results ⇒ indication of sizable CNM effects
- STAR results consistent with PHENIX results and EPS09 model within large uncertainties.

J/ψ production vs. event activity



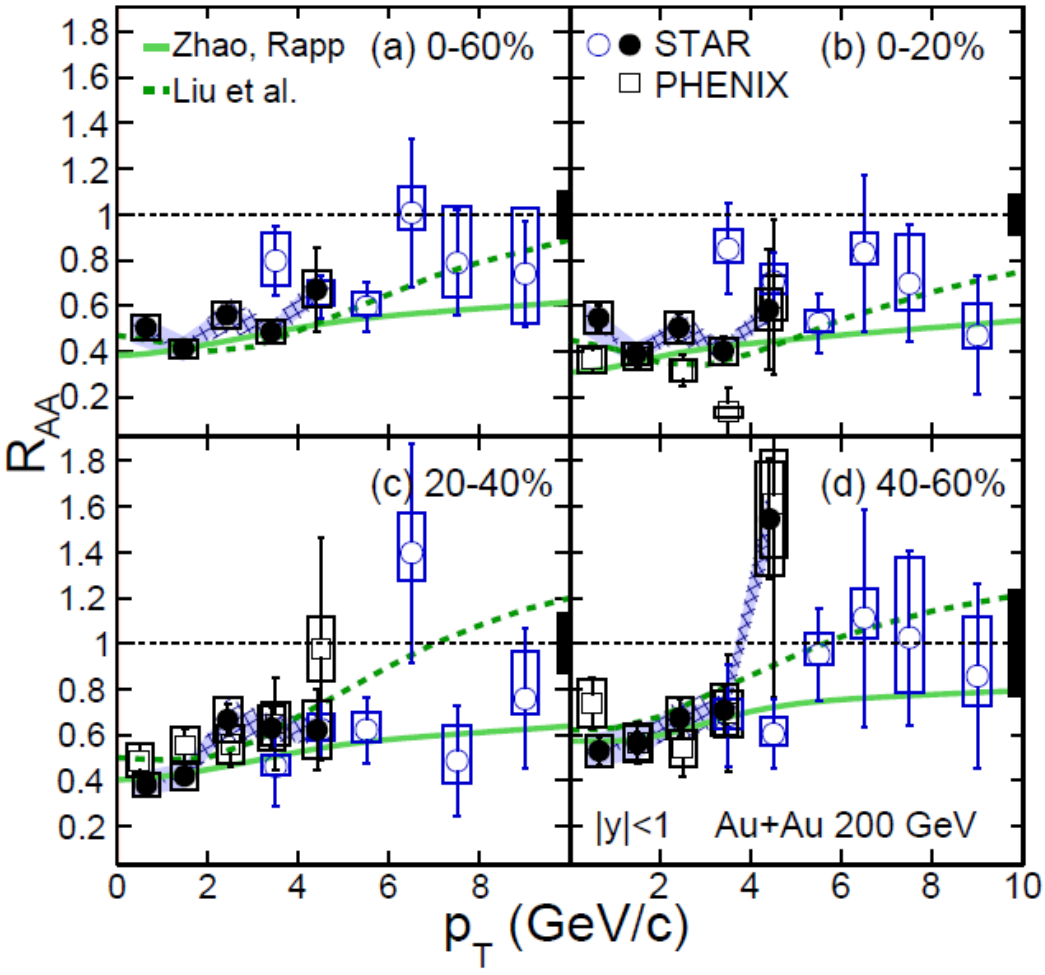


- stronger-than-linear growth for relative J/ψ yield ➡ soft and hard processes are correlated
- PYTHIA8 and Percolation model reproduce trends in data well
- hint of different trends for low and high pT J/ψ
- similar trend at LHC and RHIC

J/ψ suppresion in Au+Au collisions

e+e- channel

- **larger suppression at low p_T** than at high p_T at all centralities
- suppression decreasing towards high p_T
  - consistent with unity at high p_T in semi/peripheral collisions
  - remaining suppression at high p_T in central collisions
- **model calculations** (including color screening, regeneration, B feed-down and formation time effect) **can qualitatively describe the data**



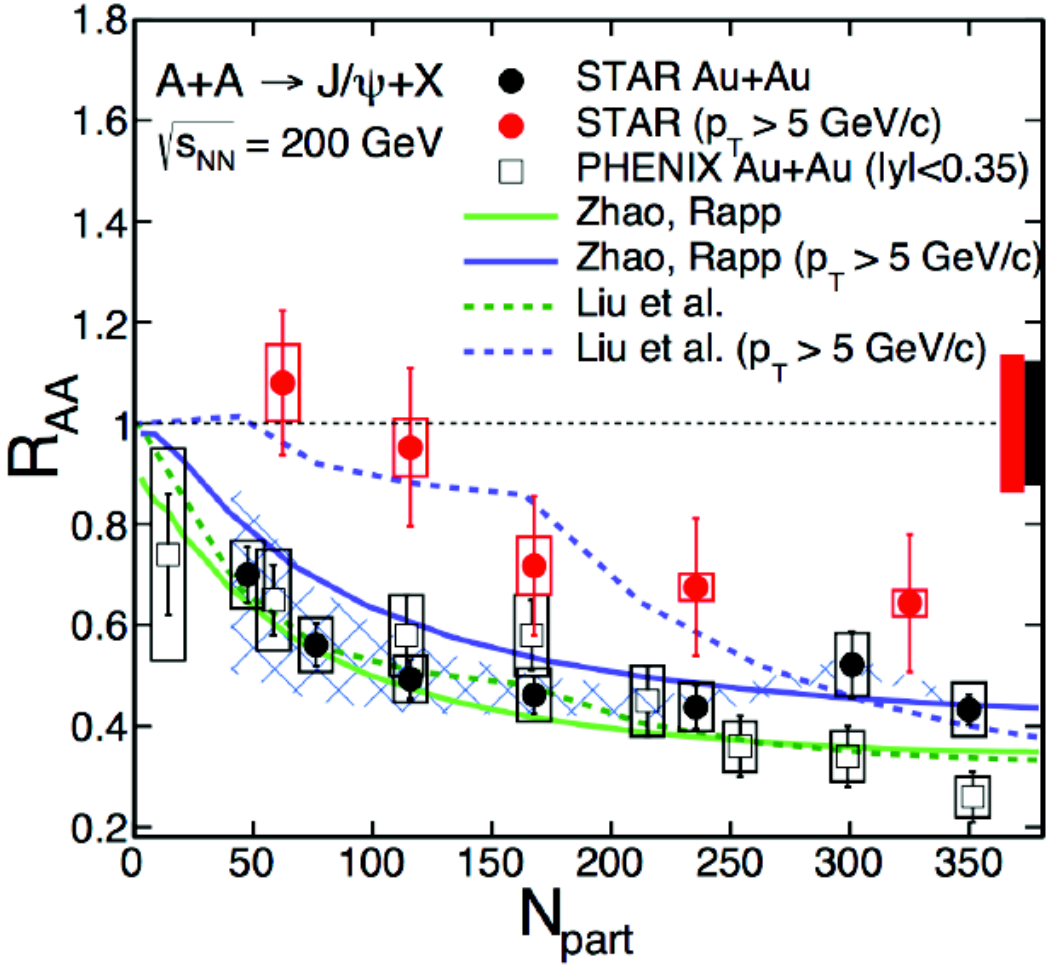
Phys. Rev. C 90 (2014) 24906
Phys. Rev. Lett. 98, 232301 (2007)
Phys. Lett. B722, 55 (2013)

J/ψ in Au+Au collisions

e+e- channel

- **suppression increases** with centrality
- **high p_T data less suppressed** than low p_T
  - no recombination
  - no CNM effects (from d+Au collision)
- models including initial production and recombination can qualitatively describe the data
- suppression of high-p_T J/ψ in central Au+Au collisions

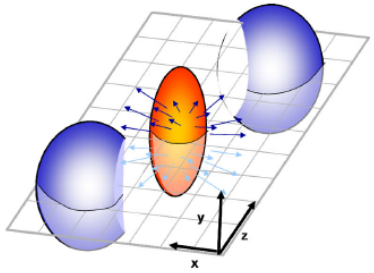
→ **clear QGP effect**



arXiv:1310.3563
PLB 678, 72 (2009)
PLB 664, 253 (2008)

Phys.Lett. B722, 55 (2013)
PRC 82, 064905(2010)
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

J/ψ elliptic flow



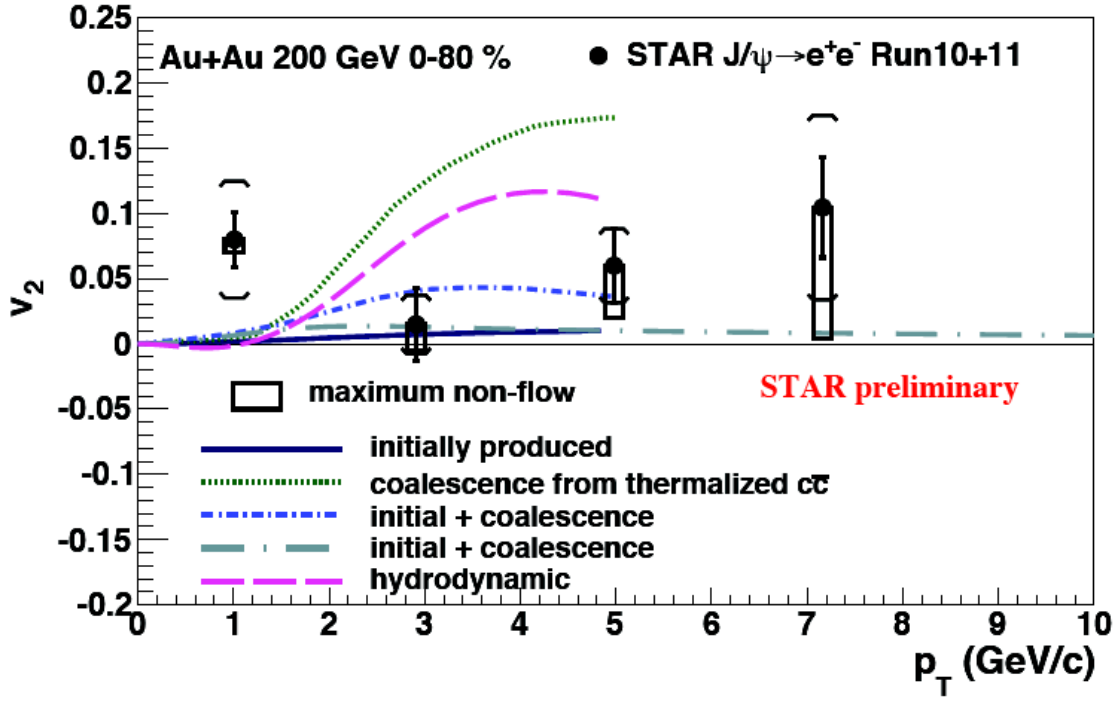
e+e- channel

STAR, PRL 111 (2013) 052301
PRL 97 (2006) 232301
PLB 595 (2004) 202
ArXiv: 0806.1239
Phys. Lett. B655, 126 (2007)
NPA 834 (2010) 317
U.W. Heinz and C. Shen, (private communication)

- measure the second-order Fourier coefficient (v_2)

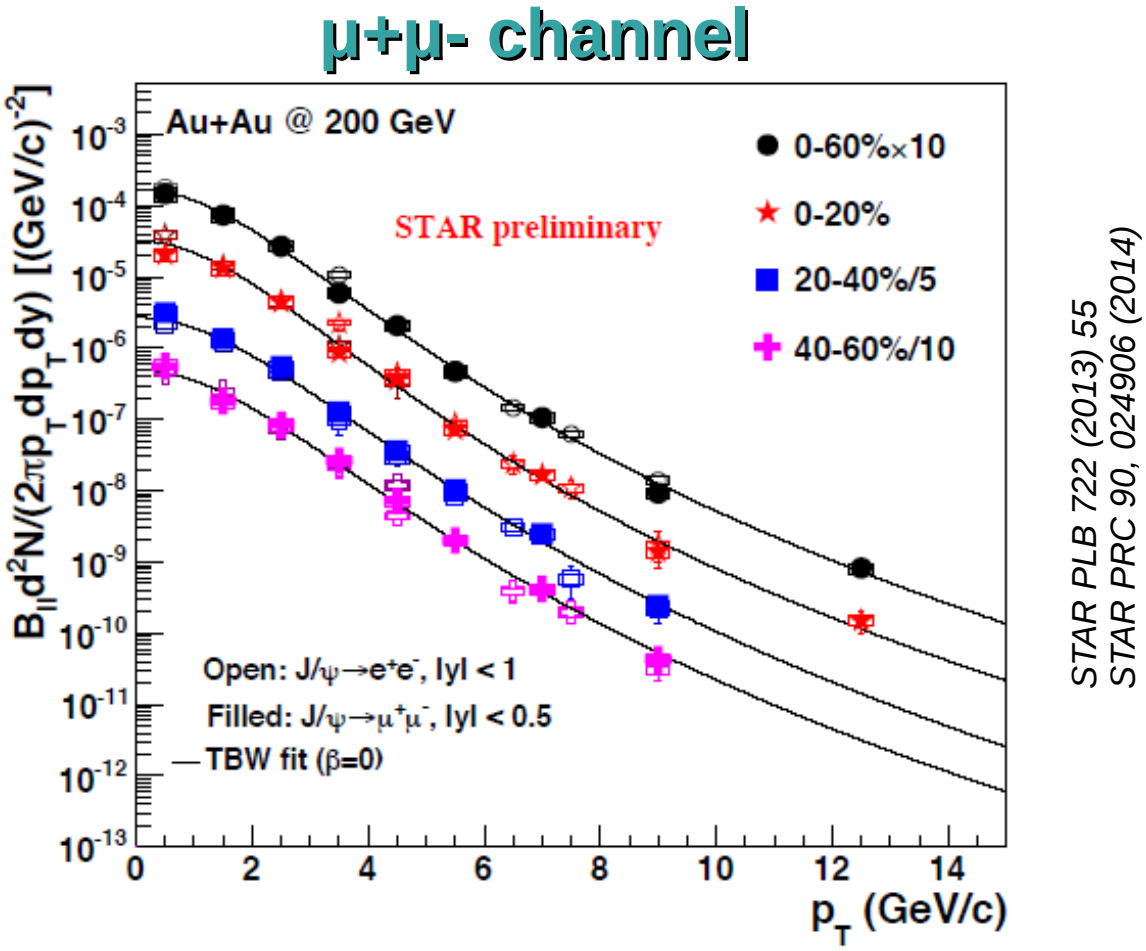
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right)$$

- **primordial:** little or zero v_2
- **regenerated:** inherit v_2 from constituent charm quarks
- for p_T above 2 GeV/c, v_2 is consistent with zero



disfavor the scenario that J/ψ with p_T > 2 GeV/c are produced dominantly by coalescence of fully thermalized charm quarks

J/ψ p_T spectrum in Au+Au collisions

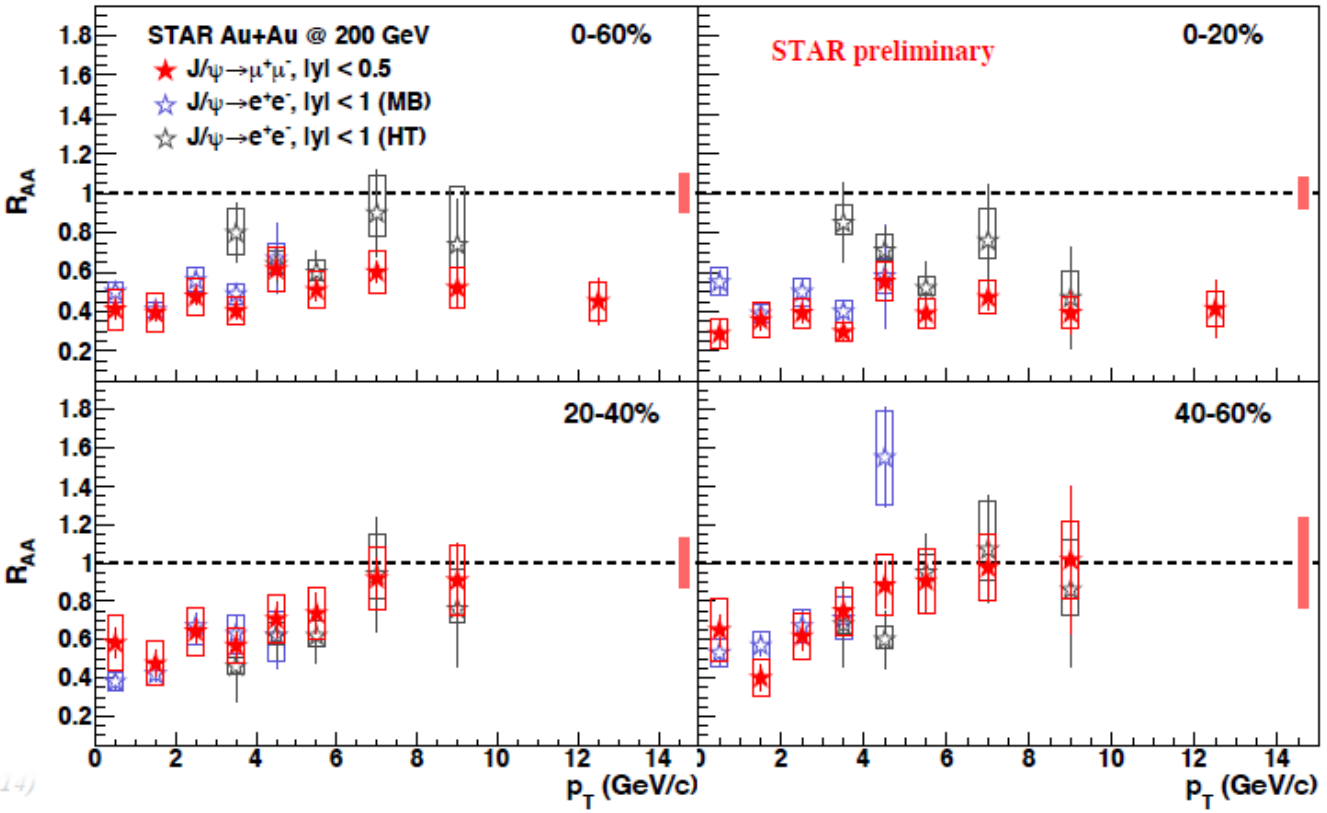


STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

- **first mid-rapidity measurement of J/ψ yield in Au+Au collisions via dimuon channel for 0 < p_T < 15 GeV/c**
- consistent with the published dielectron results

J/ψ suppresion in Au+Au collisions

μ+μ- channel



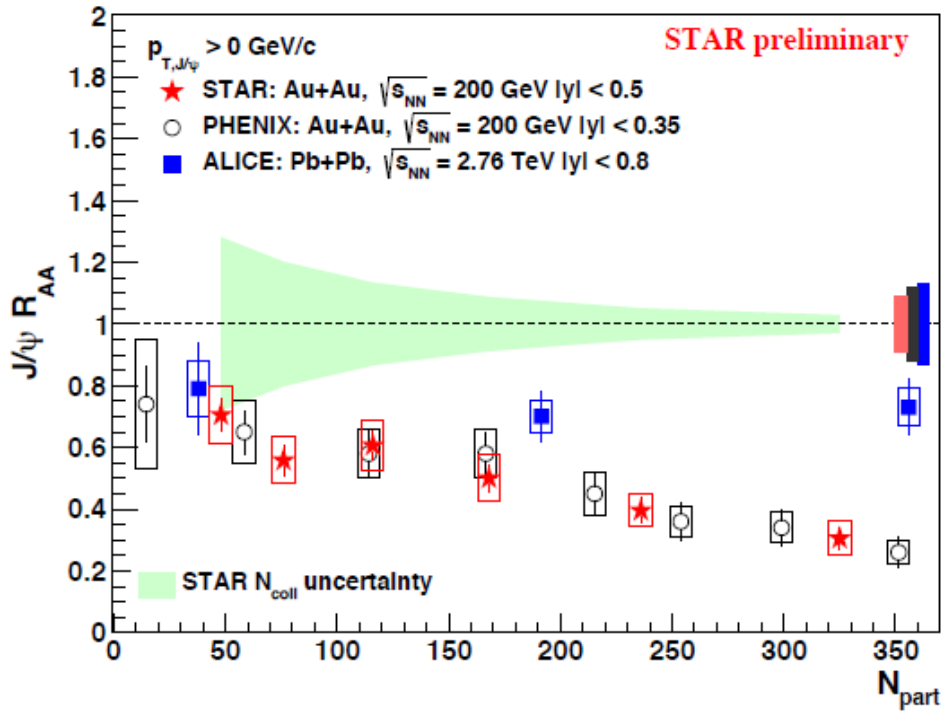
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

- **consistent with dielectron channel** results within uncertainties in all centralities
- strong suppression at low p_T: dissociation, regeneration, CNM effects
- less suppression at higher p_T : dissociation, longer formation time

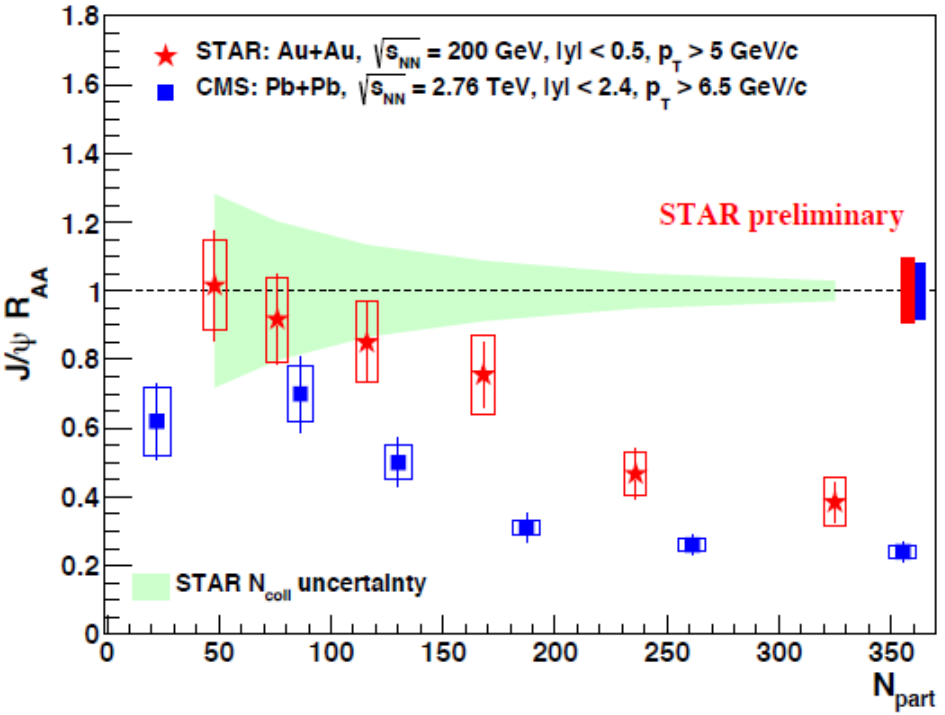
Centrality dependence: RHIC vs LHC

μ+μ- channel

p_T > 0 GeV/c



p_T > 5 GeV/c



ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301

CMS: JHEP 05 (2012) 063

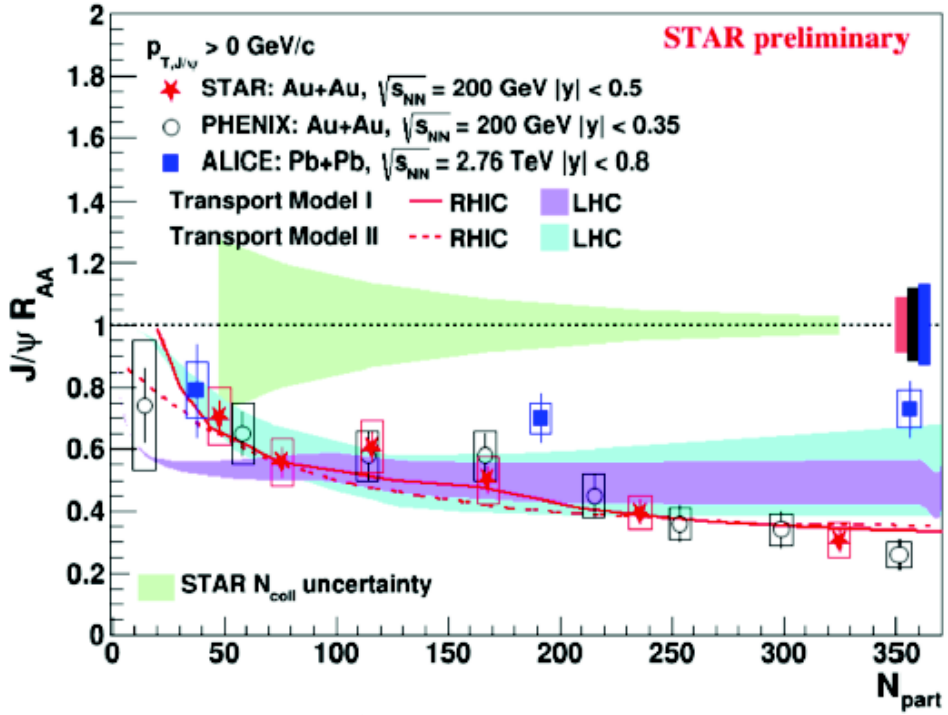
- STAR data are consistent with PHENIX but have better statistical precision
- p_T > 0 GeV/c : more suppressed at RHIC than at LHC in central collisions
- p_T > 5 GeV/c : less suppressed at RHIC than at LHC in all centralities

Transport models: RHIC vs LHC

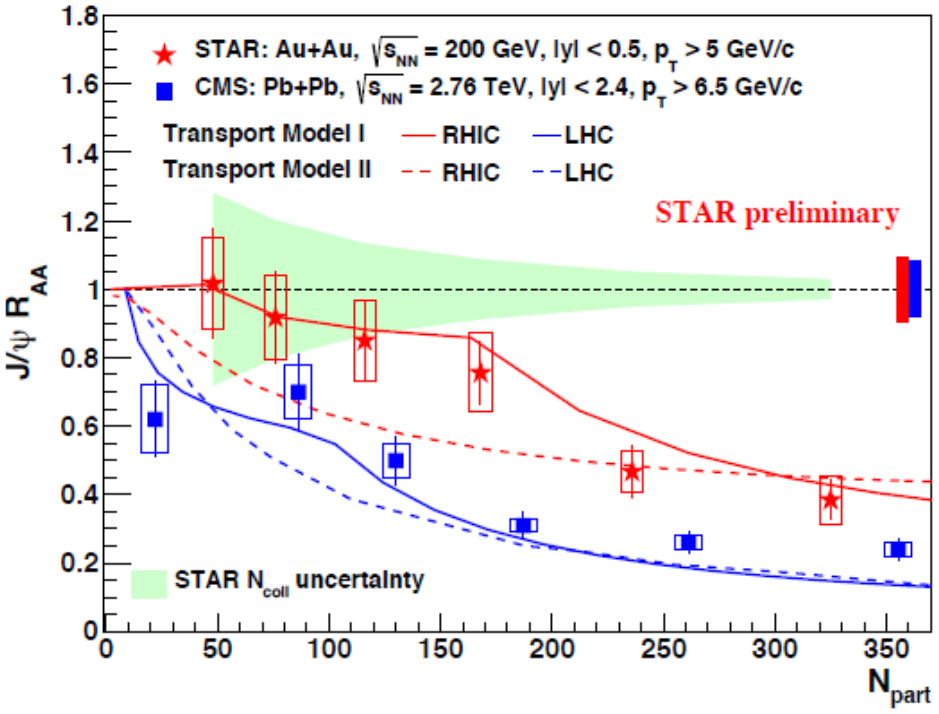
μ+μ- channel

Model I at RHIC:Y. Liu et al. - PLB 678 (2009) 72
Model I at LHC: K. Zhou et al. - PRC 89 (2014) 054911
Model II at RHIC: X. Zhao and R. Rapp - PRC 82 (2010) 064905
Model II at LHC: E. Scomparin - NPA 859 (2011) 114

p_T > 0 GeV/c



p_T > 5 GeV/c



ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301

CMS: JHEP 05 (2012) 063

- p_T > 0 GeV/c : both transpost models including **dissociation and recombination effects** qualitatively describe centrality dependence at RHIC, but tends to overestimate suppression at LHC
- p_T > 5 GeV/c : there is tension among transport models and data

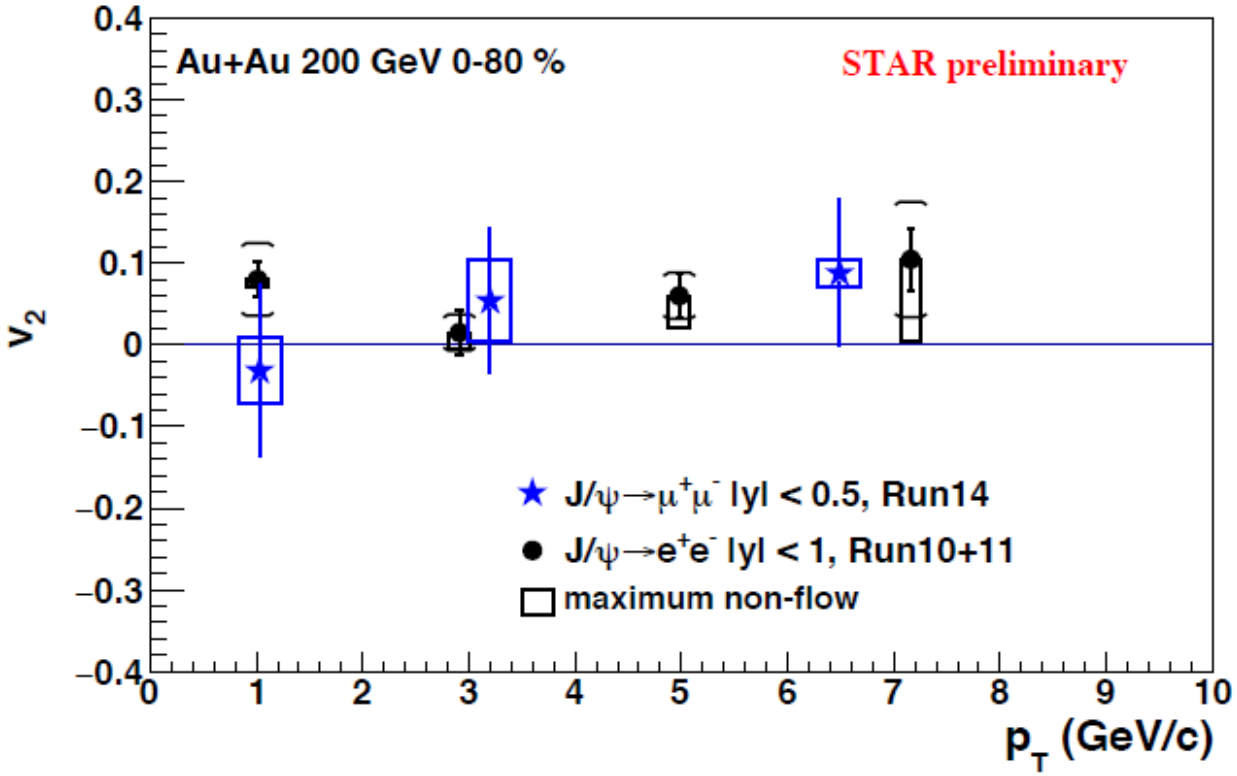
J/ψ elliptic flow

μ+μ- channel

- measure the second-order Fourier coefficient (v_2)
- **primordial:** little or zero v_2
- **regenerated:** inherit v_2 from constituent charm quarks

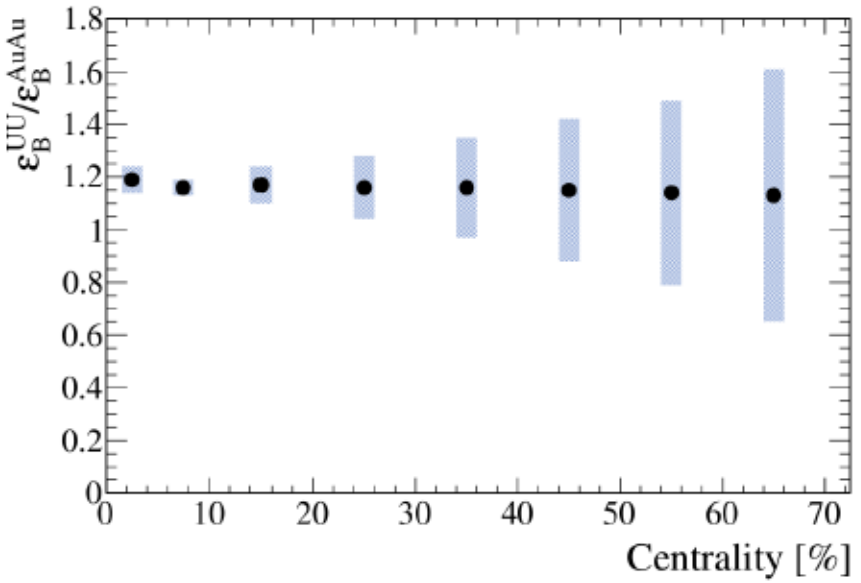
- first measurement of J/ψ v_2 in di-muon channel

- results are consistent with di-electron channel within large error bars

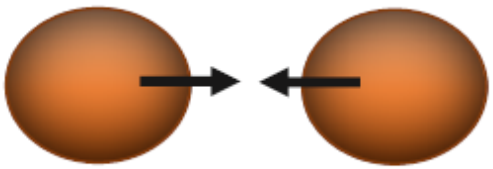


J/ψ in U+U collisions

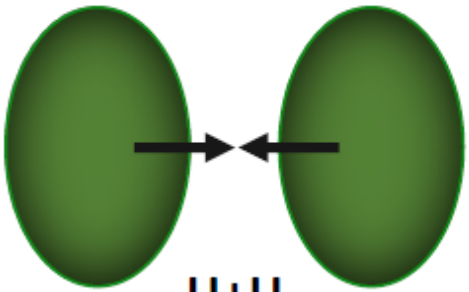
- U nuclei are non-spherical and larger than Au nuclei
- in U+U collisions the energy density of the created medium is expected to be higher (20% “side+side”, up to 30% “tip+tip”) than in Au+Au collisions
- central U+U collisions → energy density is the highest → good tool for studying the QGP



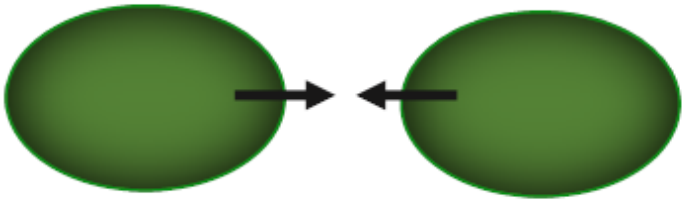
Phys. Rev., C 84. 054907 (2011)



Au+Au

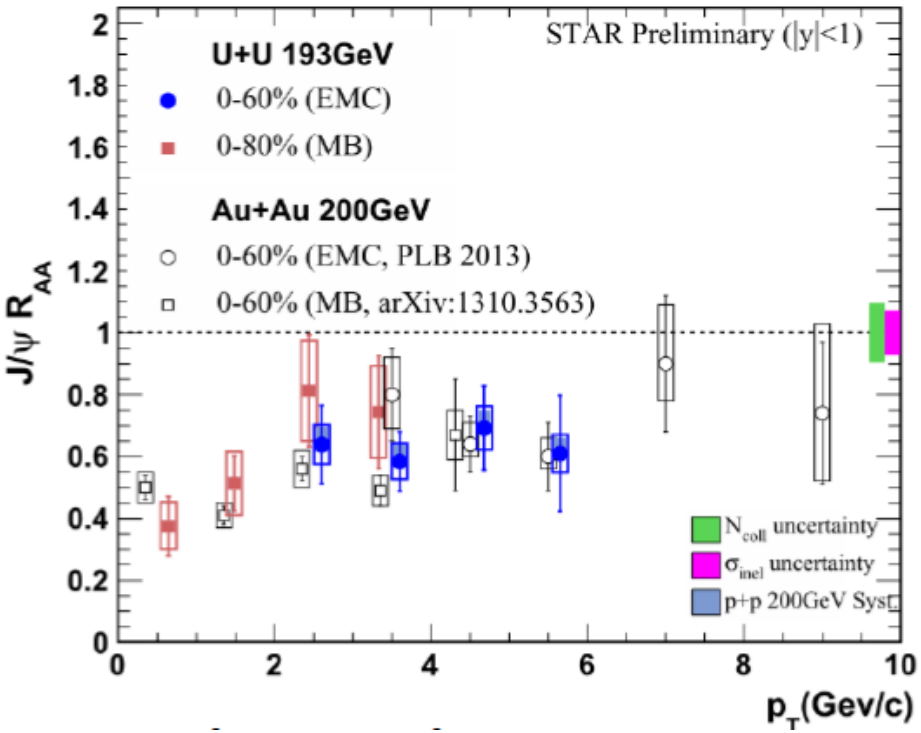


U+U
side+side



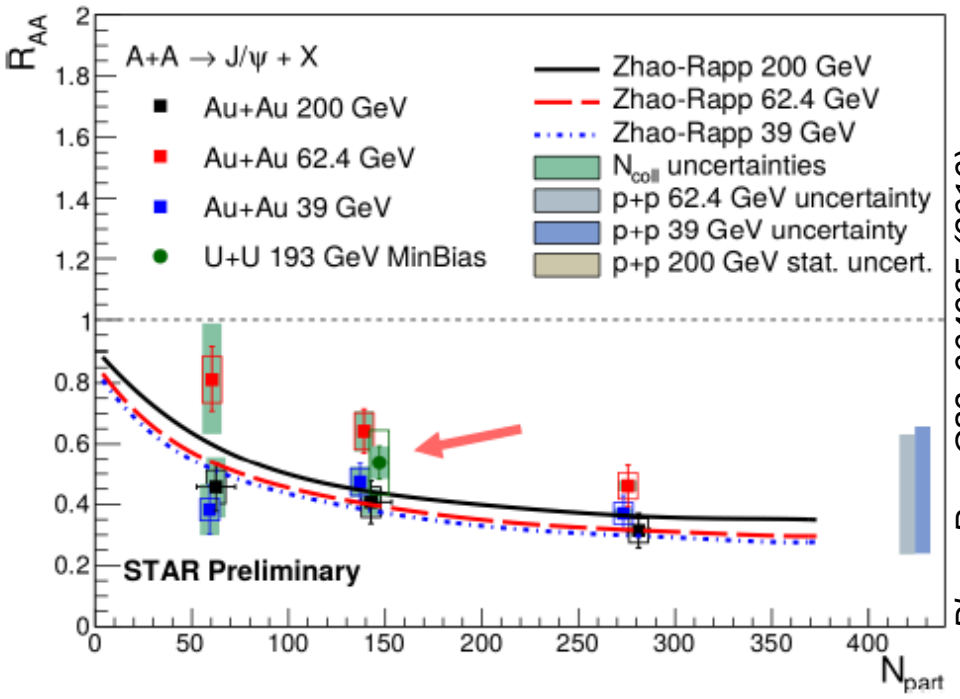
U+U
tip+tip

J/ψ in U+U collisions



- suppression of J/ψ production in U+U collision at 193 GeV **is similar** to that observed in Au+Au collision at 200 GeV

Nucl. Phys. A931, 596 (2014)



Phys. Rev. C82, 064905 (2010)
Phys. Rev. C87, 014908 (2013)

- U+U MB data **is consistent** with Au+Au results at similar N_{part}
- **no significant energy dependence** observed in Au+Au collisions at 39, 62.4 and 200 GeV

Summary

- **J/ψ production in p+p 200 GeV and 500 GeV collisions:**
  - p_T spectra described well by CGC+NRQCD and NLO NRQCD calculations
- **J/ψ production in d+Au collisions:**
  - high p_T → influence of CNM effects is small
  - low p_T → indication of sizable CNM effects
- **J/ψ production vs. event multiplicity** shows correlation between soft and hard processes → similar trend at RHIC and LHC
- **J/ψ production in Au+Au collisions:**
  - significant suppression – increases with centrality and decreases with p_T → clear QGP signal
  - different models including color screening and regeneration can qualitatively describe the data
  - di-muon data consistent with di-electron data
- **collective behavior of J/ψ:** v_2 consistent with zero for $p_T > 2$ GeV/c → contribution from coalescence of fully thermalized charm quarks is small
- **J/ψ production in U+U collisions:**
  - similar suppression patterns to Au+Au collisions

Thank you!

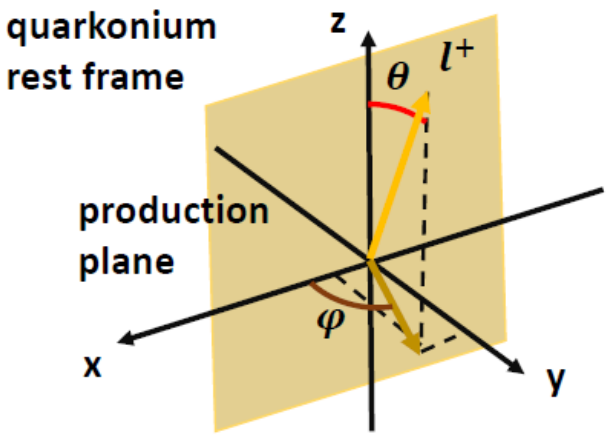
BACK UP

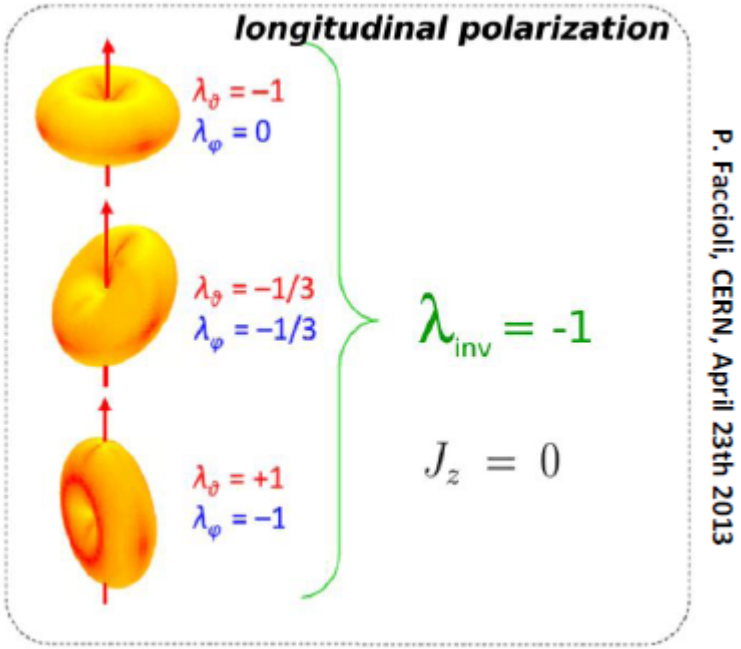
J/ψ polarization

- study via the angular distribution of the decay lepton pair (J/ψ → e+e-)

$$\frac{d^2\sigma}{d\cos\theta\, d\varphi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$

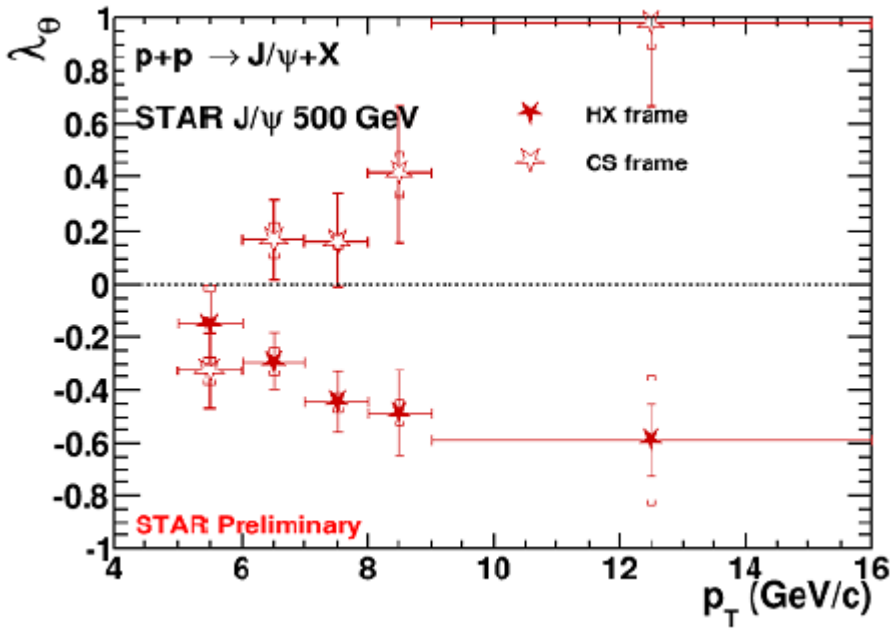
- **Helicity (HX) frame**: z along $p_{J/\psi}$ in collision center of mass
- **Collins-Soper (CS) frame**: z along bisector of the angle formed by one beam direction and the opposite direction of the other beam in the J/ψ rest frame
- longitudinal polarization observed at high p_T

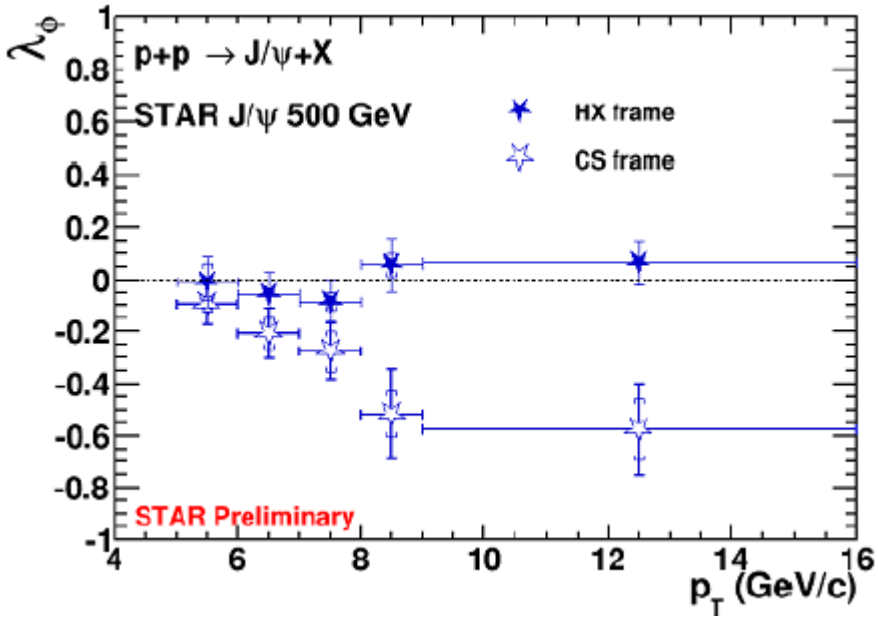




J/ψ polarization

$$\frac{d^2\sigma}{d\cos\theta\, d\varphi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$





- towards longitudinal polarization with increasing p_T

Very low p_T J/ψ excess

- observed excess of very low p_T J/ψ in peripheral collisions
- features consistent with coherent photo-nucleus interaction