Flavor Physics and CP Violation 2012

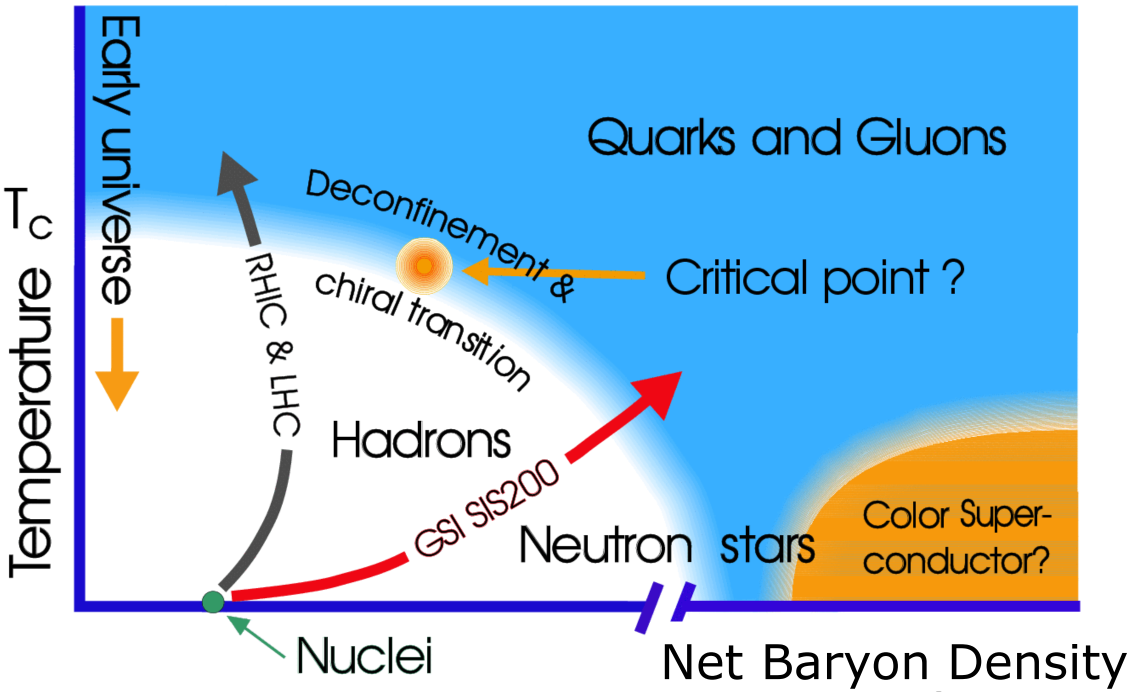
May 21-25, Hefei, Anhui, China

Hidden Heavy Flavor Production in Heavy-Ion Collisions

Zebo Tang (for the STAR Collaboration)

University of Science and Technology of China (USTC)

Explore QCD phase diagram

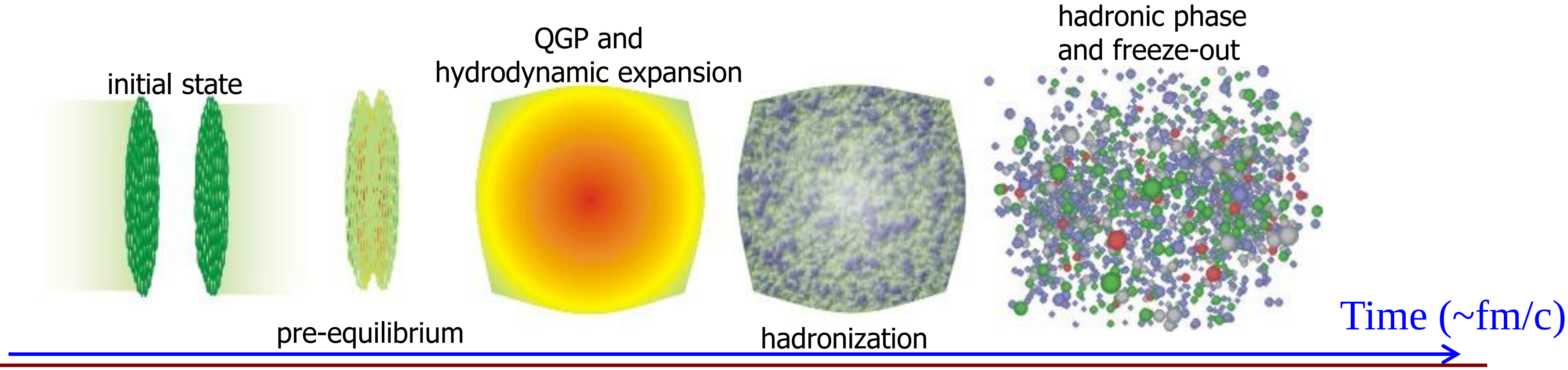


Relativistic Heavy-Ion collisions:

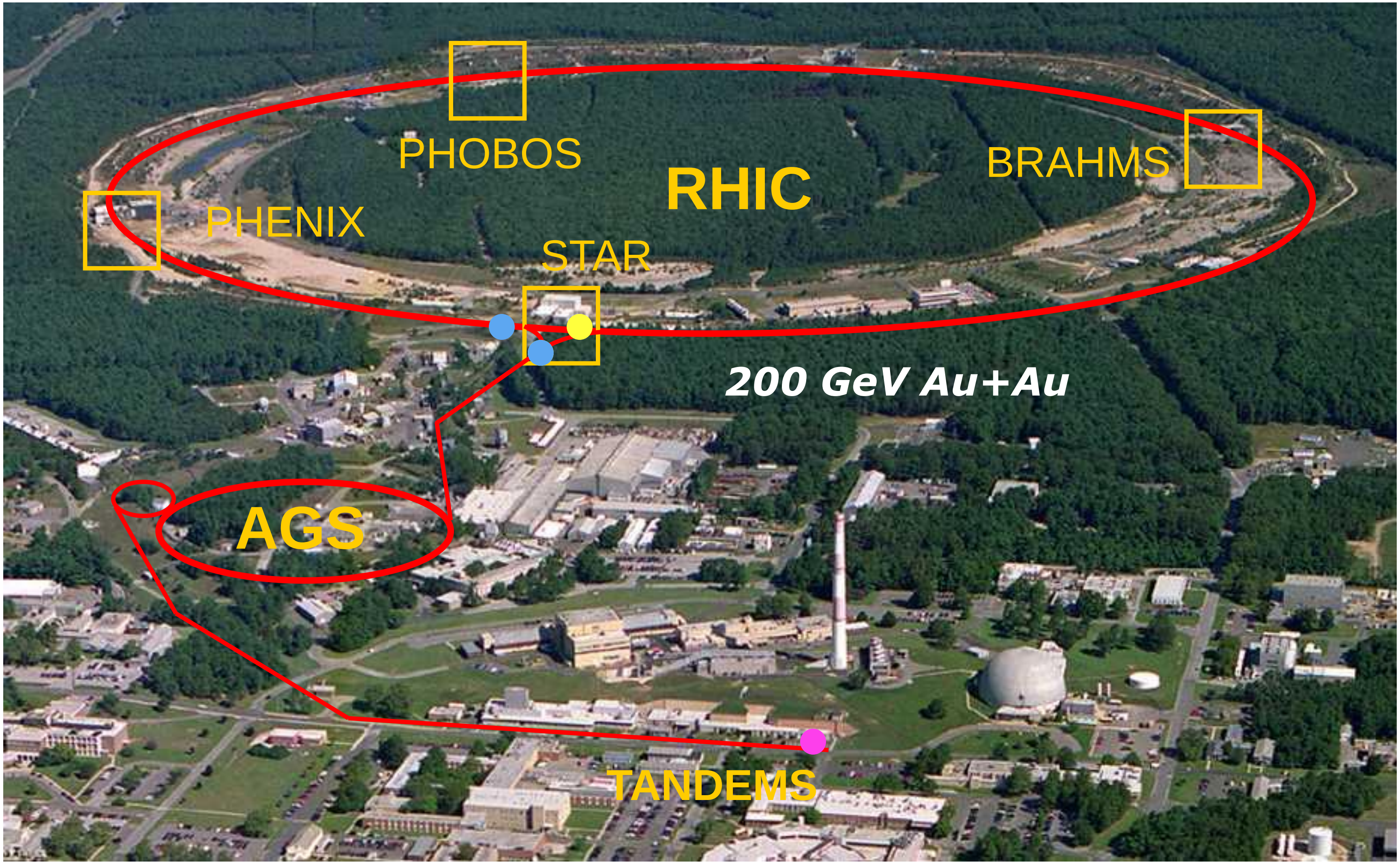
Search for deconfinement

Study the properties of the hot dense medium

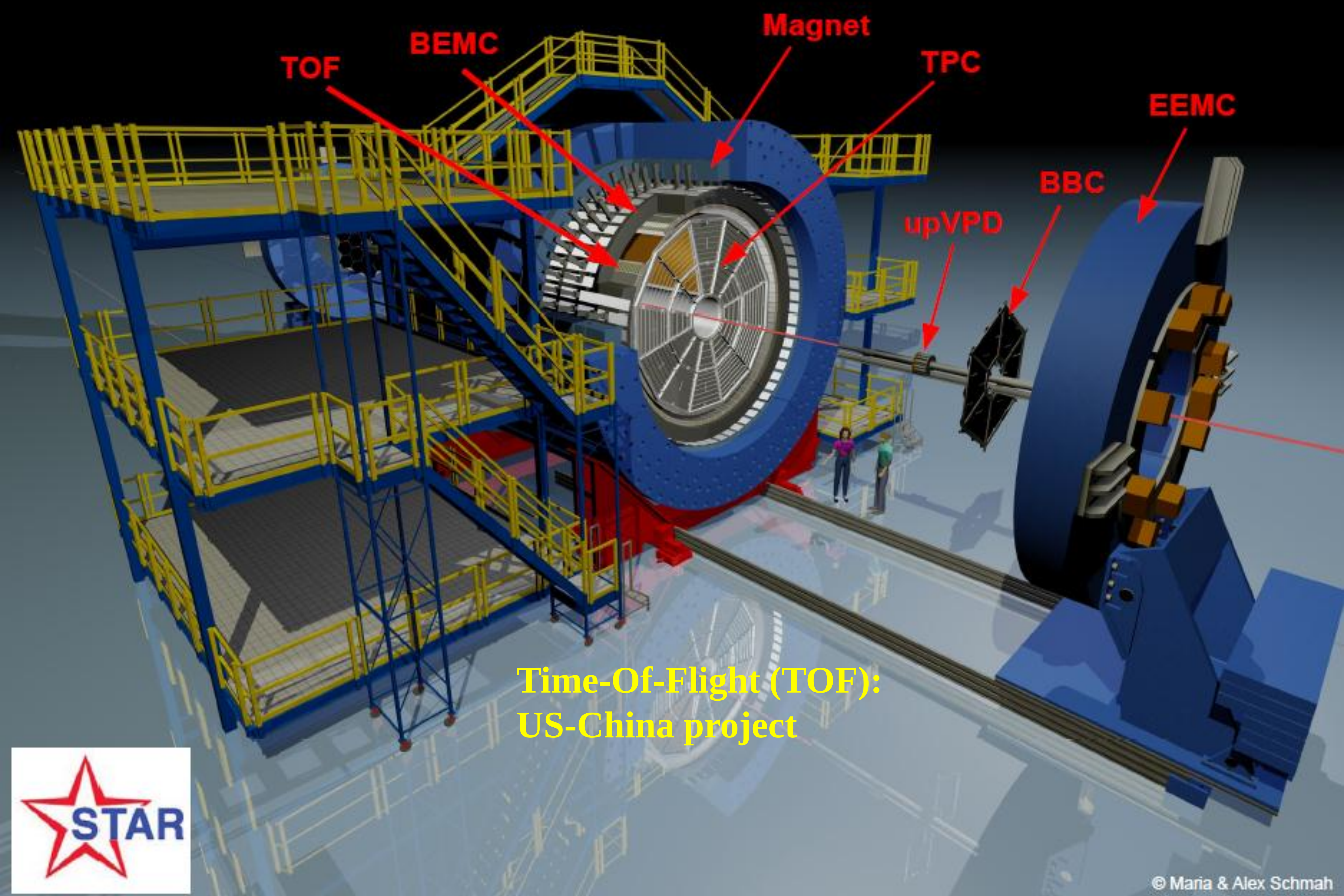
QCD at extreme condition



Relativistic Heavy Ion Collider (RHIC)



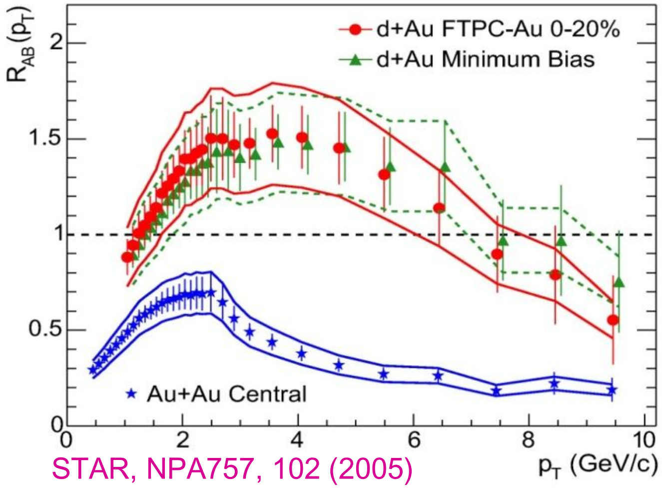
The Solenoid Tracker At RHIC (STAR)



Time-Of-Flight (TOF):
US-China project

Key observation in Heavy-Ion Collisions

Significant suppression for light hadrons

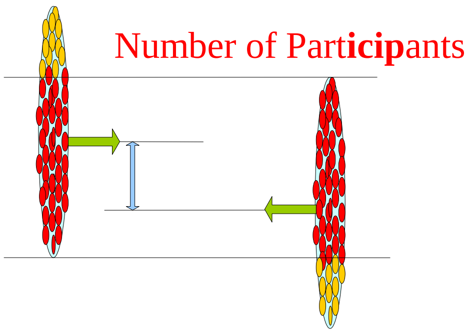


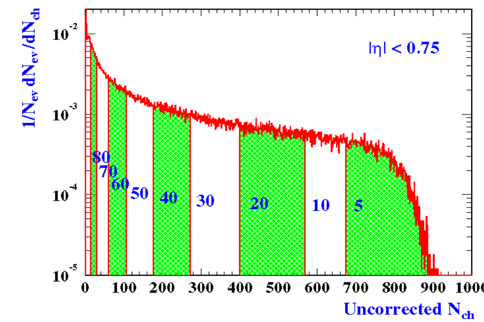
$$R_{AB}(p_T) = \frac{\frac{dN^2_{AB}}{dp_T d\eta} / N_{coll}}{\frac{dN^2_{pp}}{dp_T d\eta}}$$

$R_{AA} \sim 1$, N-binary scaling,

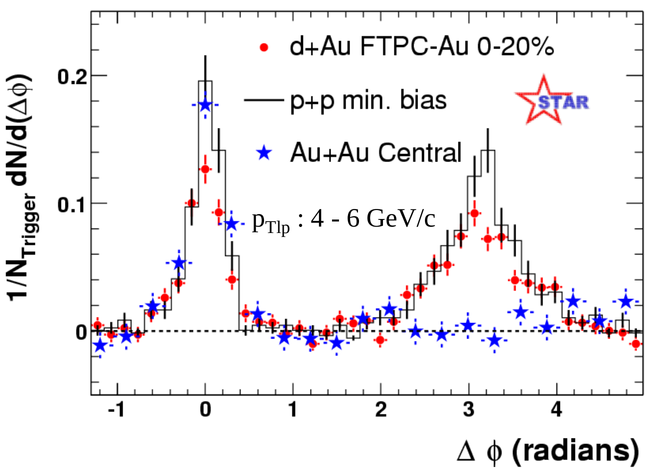
A+A is a superposition of nucleon-nucleon collisions

$R_{AA} \neq 1$, Medium modification





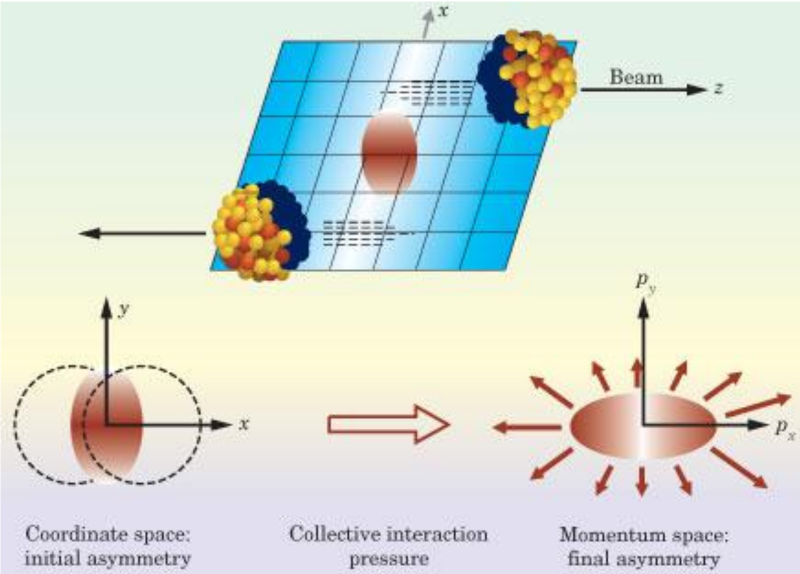
Away side yield modification

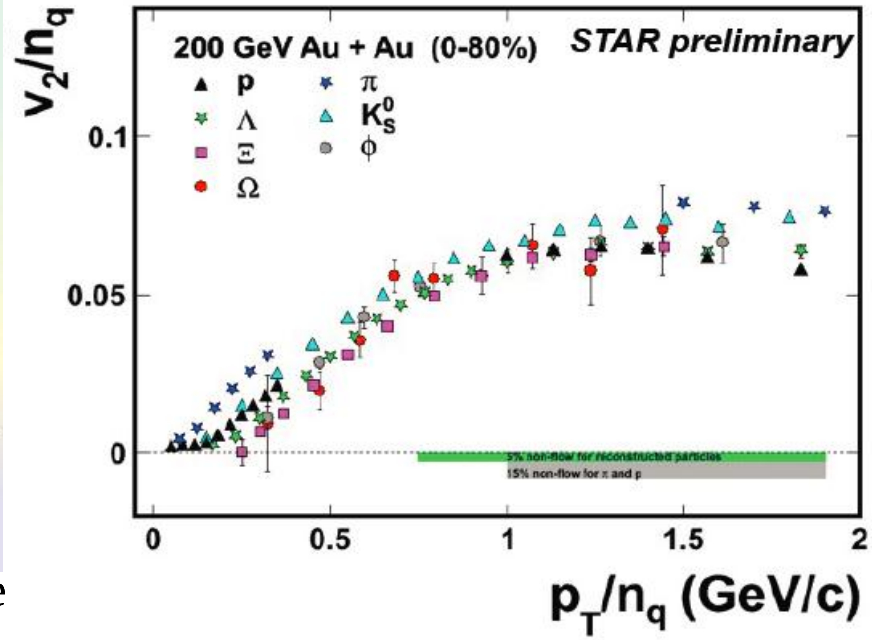


A *very* ***hot, dense*** and ***strongly interacting*** matter has been produced in relativistic heavy-ion collisions

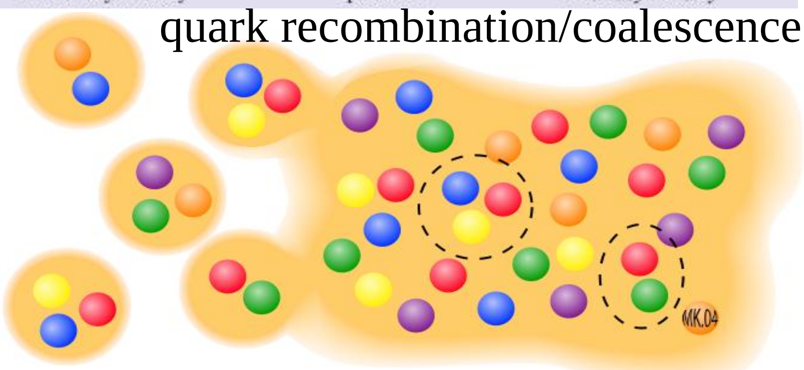
Phase transition to QGP?

Key observation in Heavy-Ion Collisions





quark recombination/coalescence



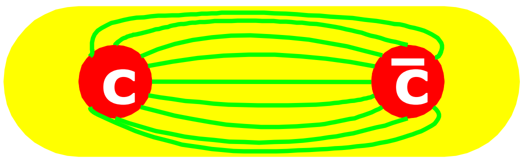
$$v_2^{hadron}(p_T^{hadron}) \approx n v_2^{quark}(n p_T^{quark})$$

$$p_T^{hadron} \approx n p_T^{quark}$$

For $p_T/n > 0.6$ GeV/c, v_2 scales with the number of quarks n, as predicted for hadron formation by quark coalescence

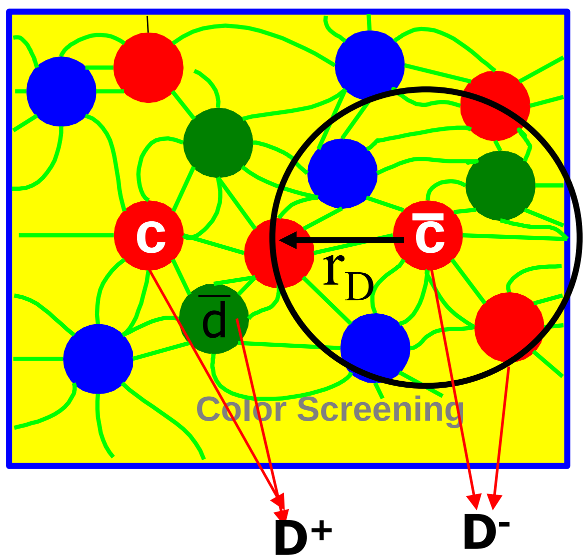
Partonic degree of freedom?
Deconfinement?

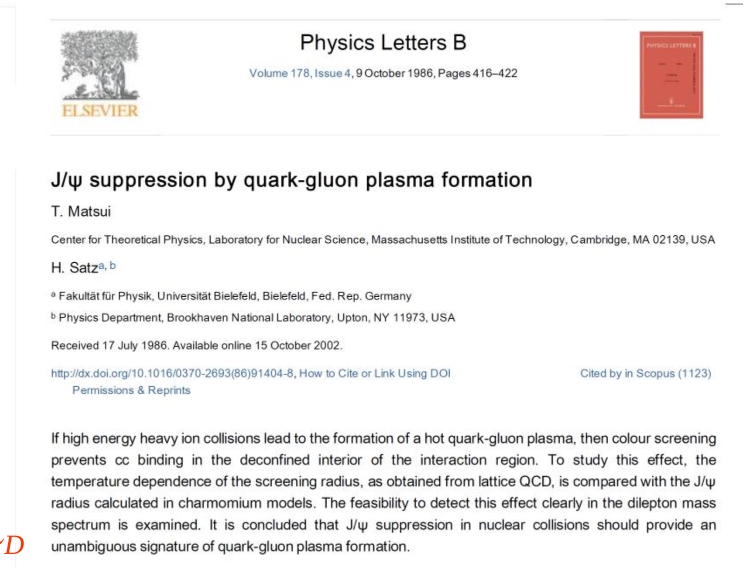
Quarkonium melting in QGP



$$V(r) = -\frac{\alpha}{r} + kr$$

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$





Physics Letters B
Volume 178, Issue 4, 9 October 1986, Pages 416–422

J/ψ suppression by quark-gluon plasma formation

T. Matsui

Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

H. Satz[a, b]

[a] Fakultät für Physik, Universität Bielefeld, Bielefeld, Fed. Rep. Germany

[b] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986. Available online 15 October 2002.

http://dx.doi.org/10.1016/0370-2693(86)91404-8, How to Cite or Link Using DOI Cited by in Scopus (1123)
Permissions & Reprints

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmomium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

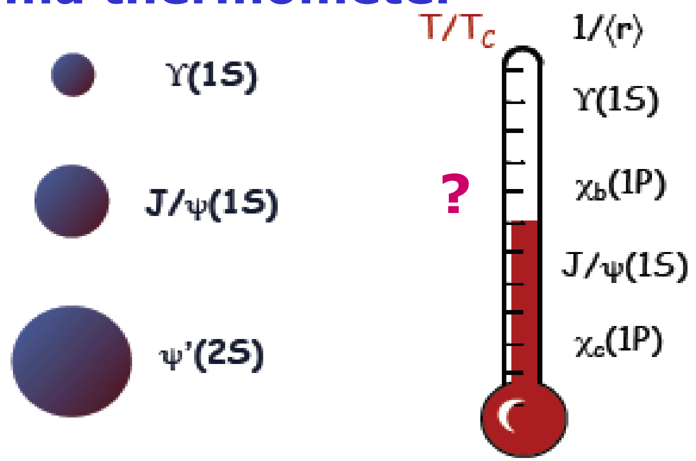
QGP Thermometer

$\lambda_D \propto 1/T$ Quarkonium dissociation temperatures – H. Satz, JPG (2006)

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

Model dependent

Plasma thermometer



Dissociation temperature depends on binding energy → QGP temperature

Life is not easy

Inclusive J/ψ includes:

- Direct production (~60%)
- Feeddown from ψ' (~10%)
- Feeddown from χ_c (~30%)
- Feeddown from B mesons (small for integrated, but strong p_T dependent)

Cold Nuclear Matter (CNM) effects:

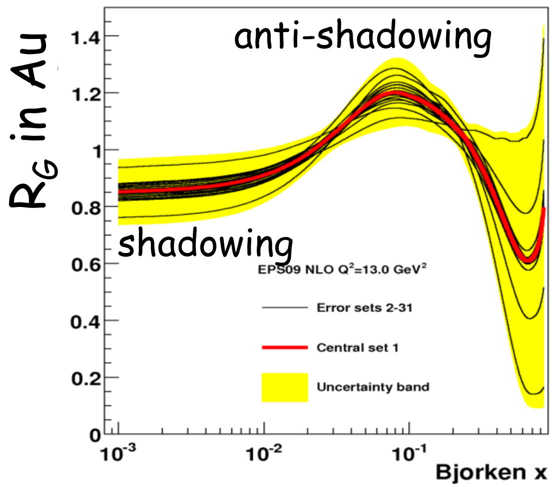
- Nuclear absorption
- PDF modification in nucleus
- Cronin effect
- Gluon saturation
- …

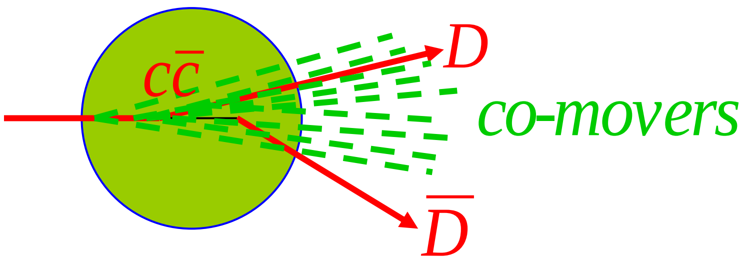
Hot Nuclear Matter effects:

- Color screening
- Recombination of uncorrelated c and cbar
- …

What are CNM effects

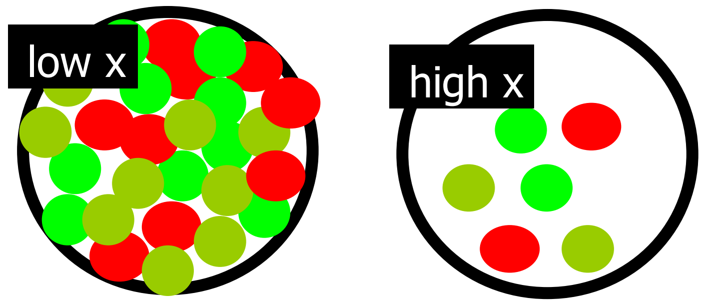
Traditional shadowing from fits to DIS or from coherence models

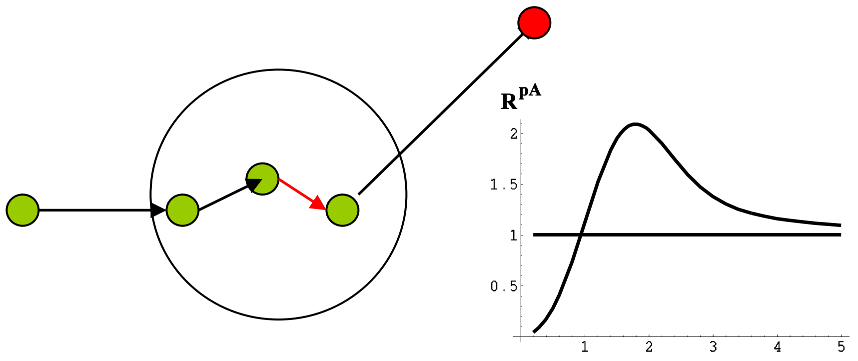




Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers

Gluon saturation from non-linear gluon interactions for the high density at small x - Amplified in a nucleus.

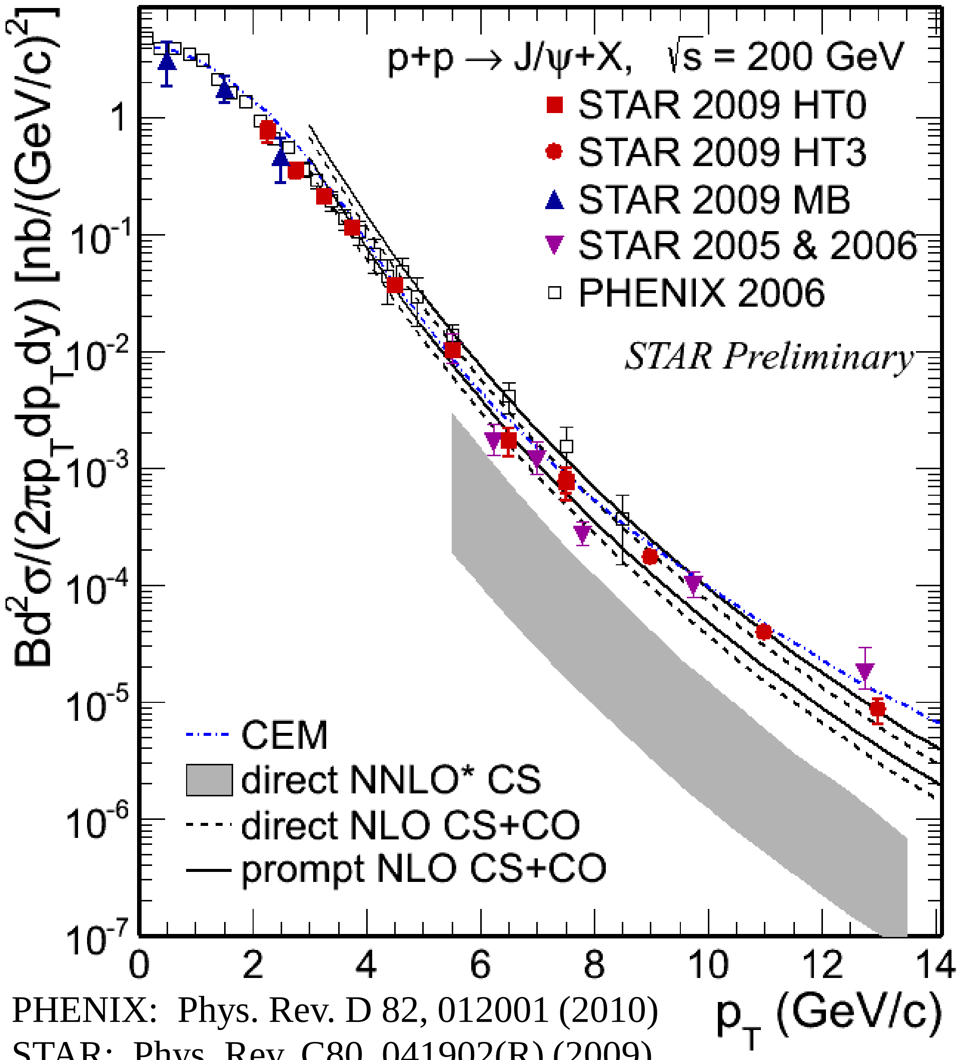




Initial multiple scattering, p_T broadening

Modifiled from Mike Leitch's slides

J/ψ production in p+p collisions



PHENIX: Phys. Rev. D 82, 012001 (2010)
STAR: Phys. Rev. C80, 041902(R) (2009)

Consistent between datasets/experiments

Color singlet model: direct NNLO still misses the high-p_T part

P. Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008), and J.P. Lansberg private communication.

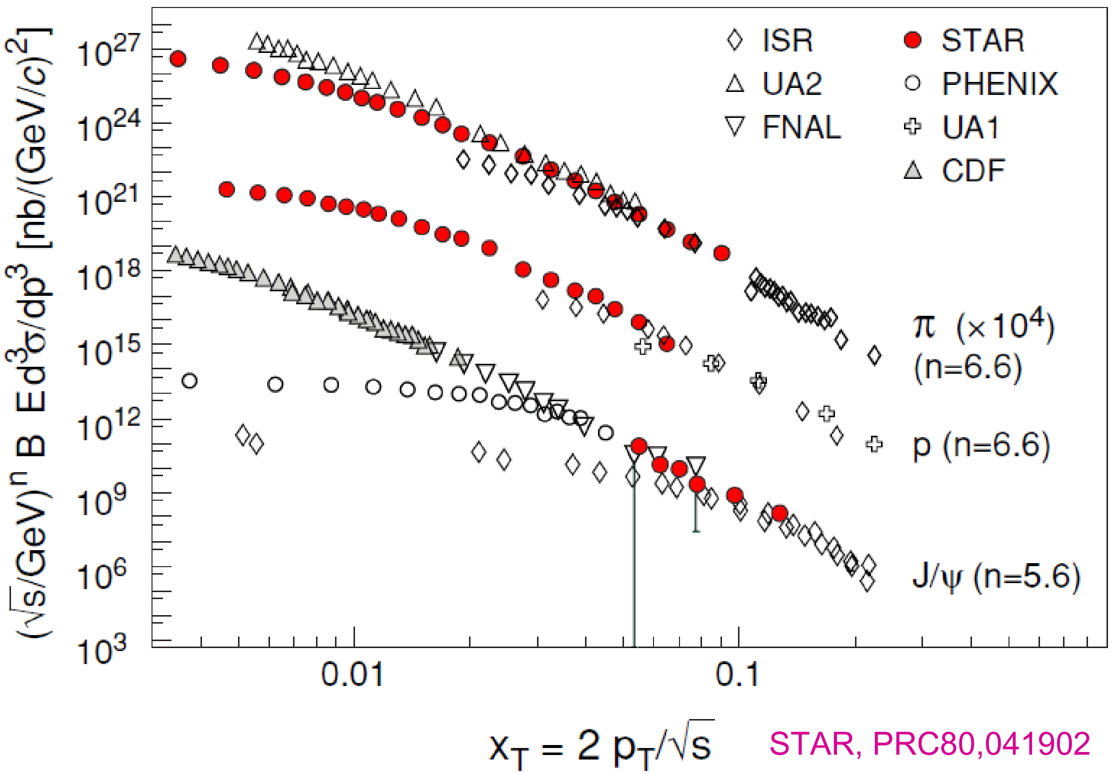
NLO CS+CO describes the data

Y.-Q. Ma, K. Wang, and K.-T. Chao, Phys. Rev. D84, 51 114001 (2011), and private communication

CEM can also reasonably explain the spectra down to ~1 GeV/c

M. Bedjidian et al., hep-ph/0311048, and R. Vogt private communication

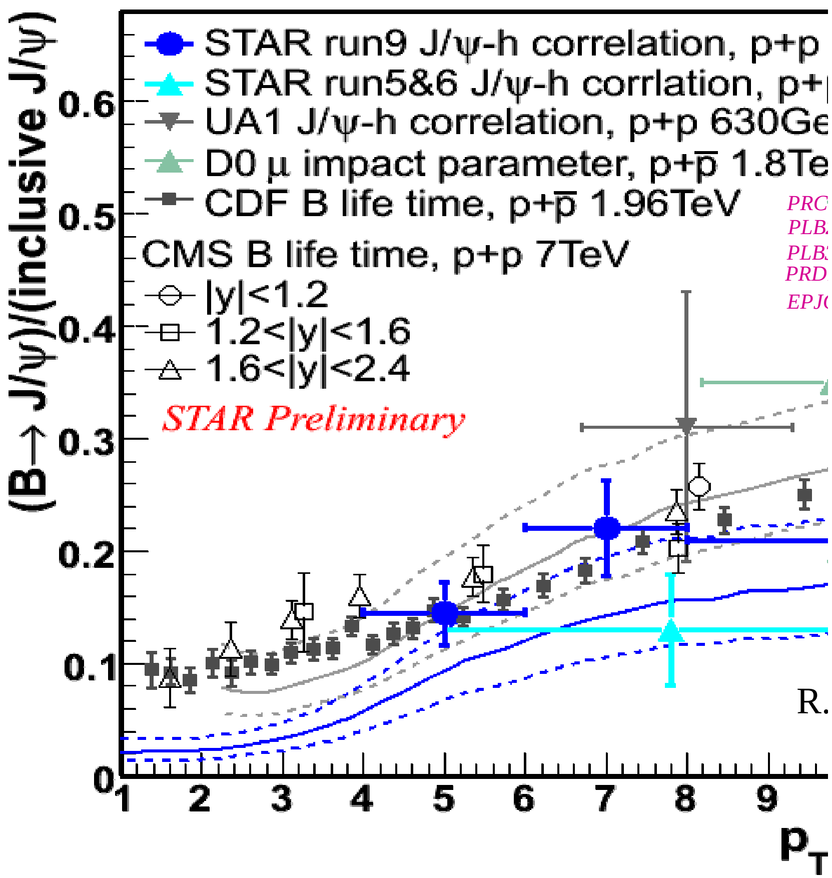
x_T scaling

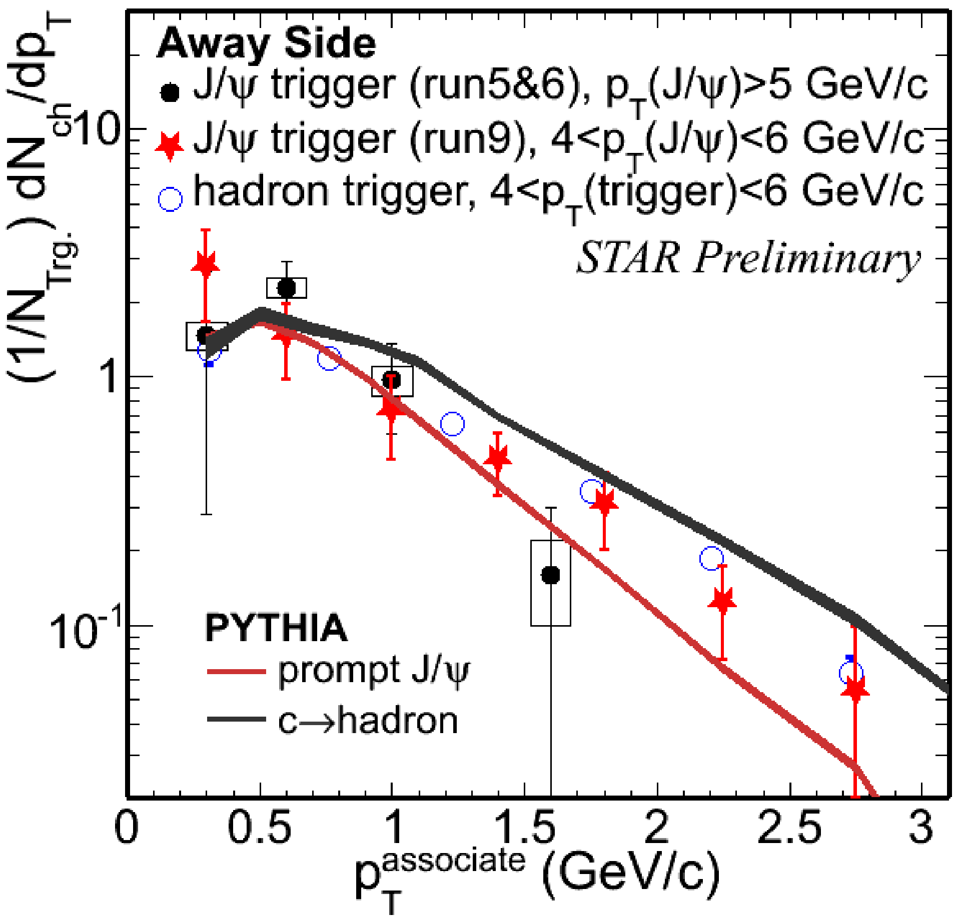


STAR, PRC80,041902

Soft processes affect low p_T J/ψ production

J/ψ production in p+p collisions



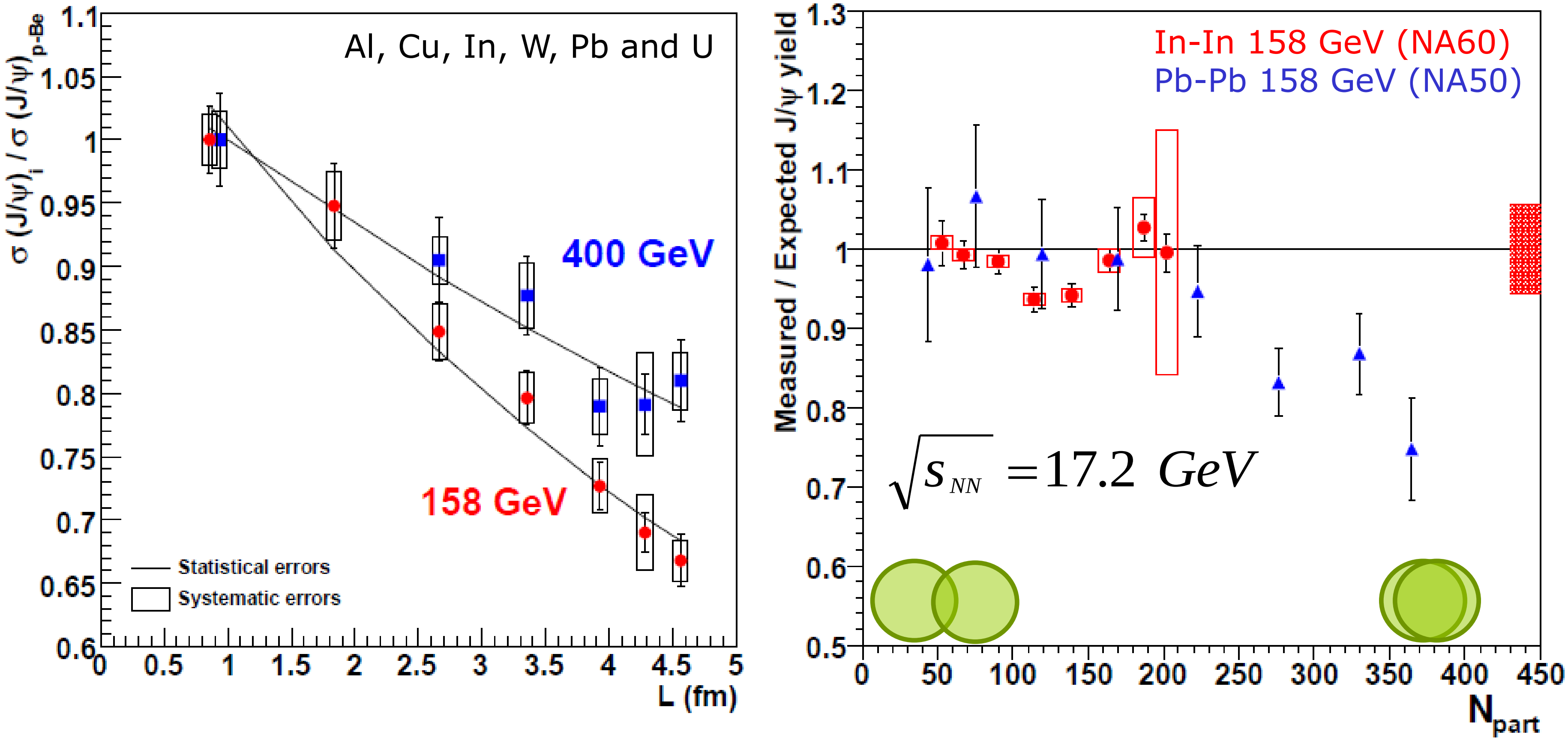


- Extracted from near side J/ψ-h correlation
- Consistent with previous results, 10-25%
- No significant beam energy dependence

Consistent with hadron-hadron correlation
➔away-side seems to come from gluon/light quark fragmentation

J/ψ suppression at SPS

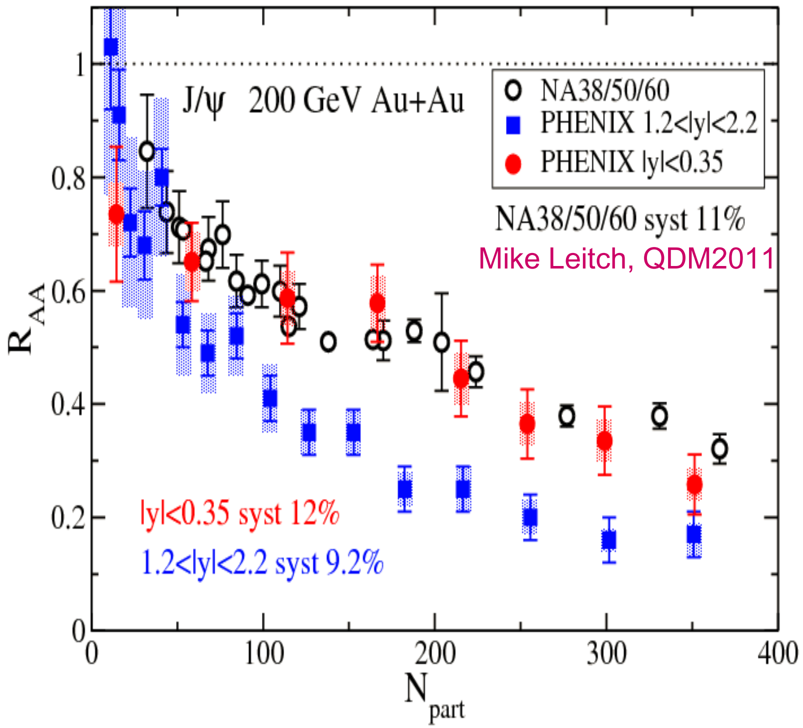
R. Arnaldi (NA60), NPA830:345c (2009), arXiv: 0907.5004

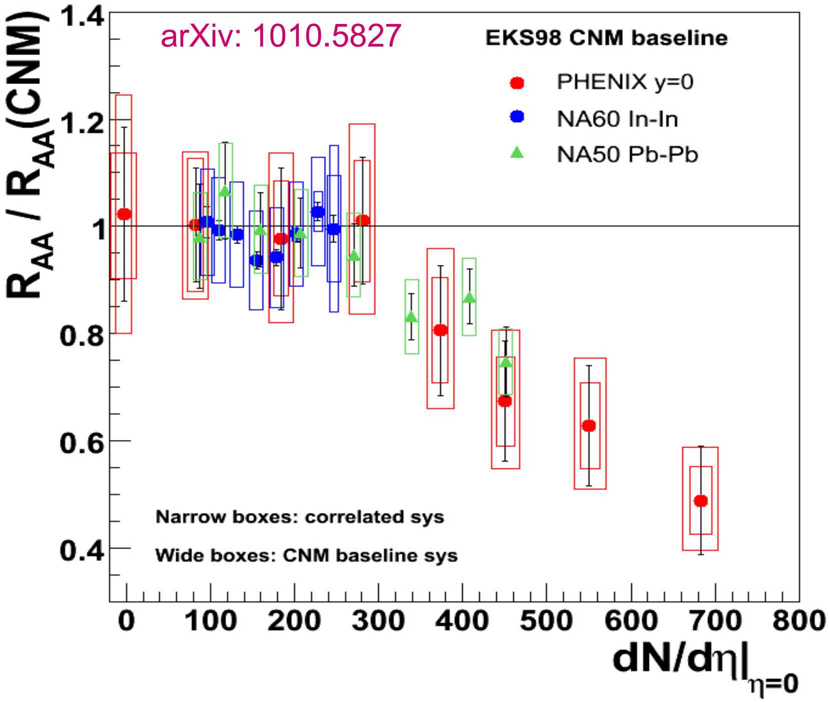


CNM effects extrapolated from pA collisions

Anomalous suppression observed in central Pb+Pb collisions at 17.2 GeV

J/ψ at RHIC





Mid-rapidity:

Similar suppression as SPS

Forward rapidity:

More suppression than in mid-rapidity

Similar anomalous suppression

Two Puzzles!!

Possible reasons

$T_D(\psi'$ and $\chi_c) < T_{SPS} < T_{RHIC} < T_D(J/\psi)$ + gluon saturation

Similar suppression at RHIC and SPS more suppression at forward

$T_D(\psi'$ and $\chi_c) < T_{SPS} < T_D(J/\psi) < T_{RHIC}$ + ccbar recombination

Recombination related to N^2_{cc}

More regeneration at RHIC than SPS

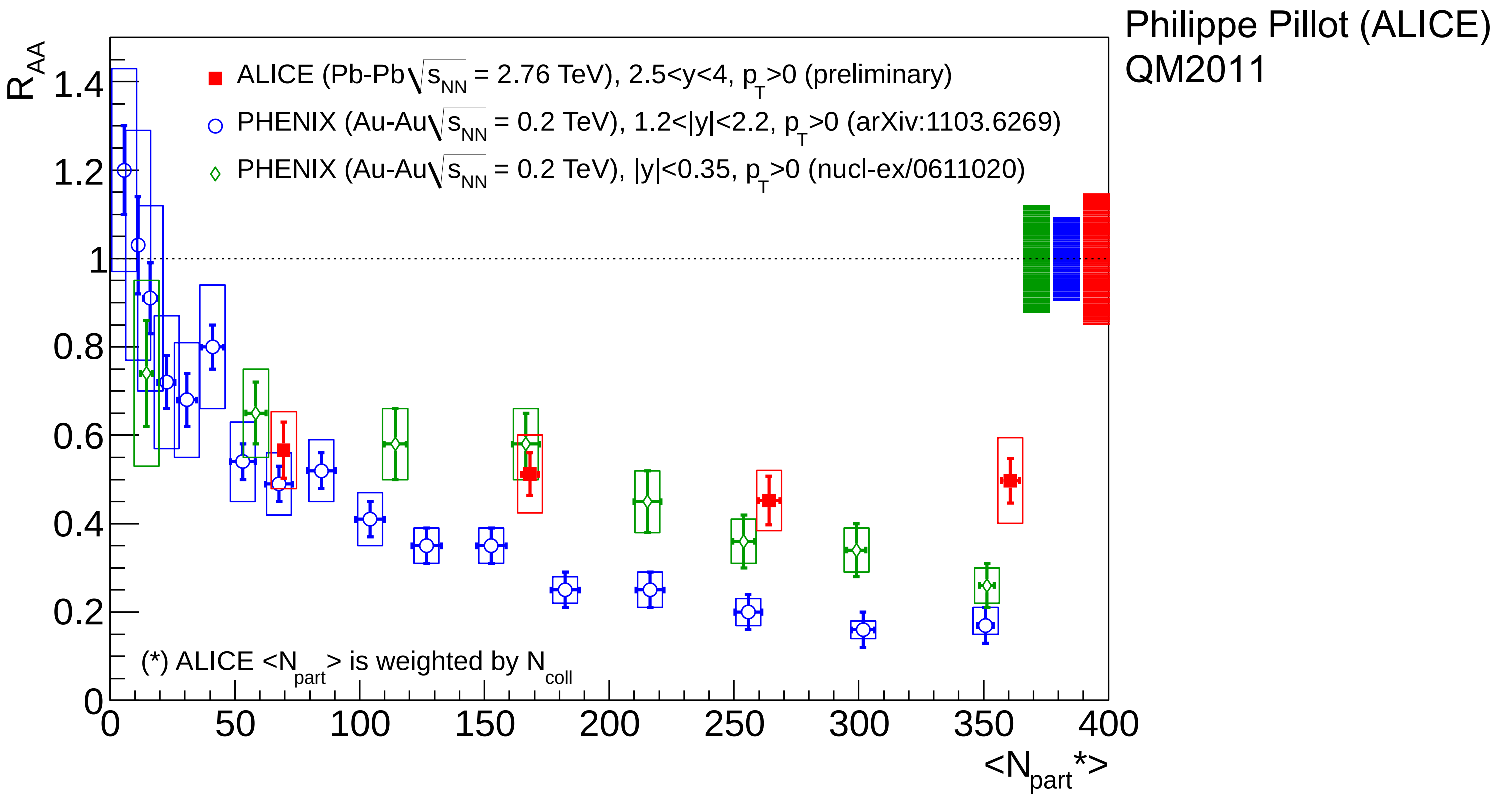
More regeneration at mid-rapidity than forward rapidity

Recombination dominated at low p_T, could be:

1. Indirectly measured through:
   - Beam energy dependence
   - p_T shape (softer)
   - collective flow (inherit from open charm)

2. Insignificant at high-p_T

J/ψ at LHC



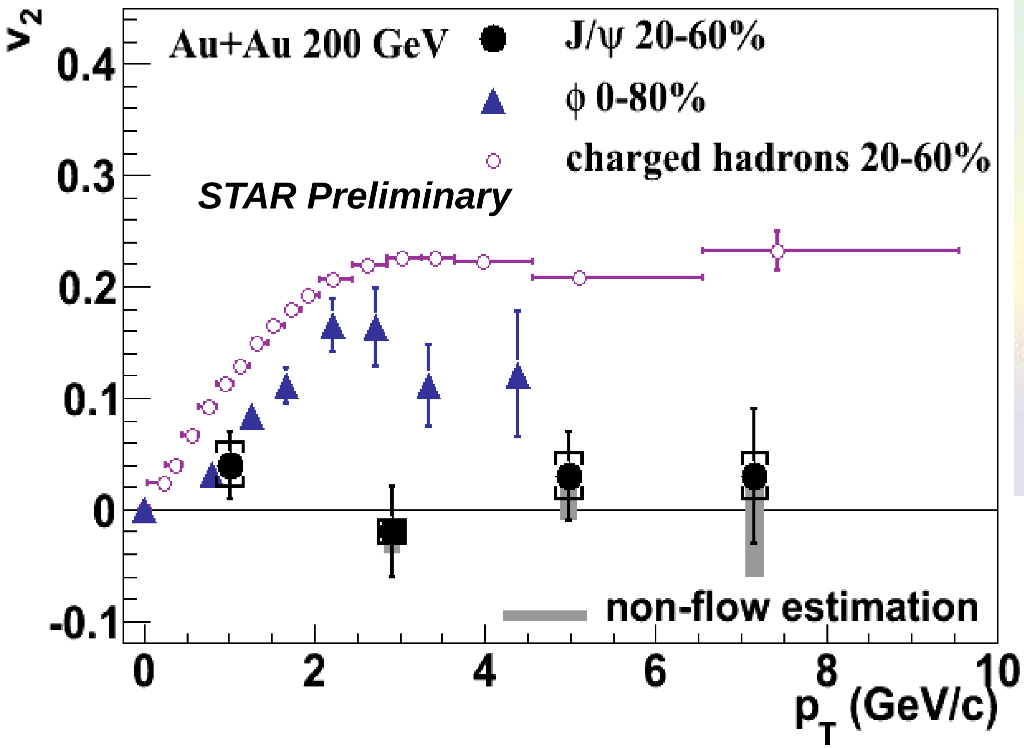
J/ψ R_{AA} in central collisions is larger at LHC in 2.5<y<4 than at RHIC in 1.2<|y|<2.2

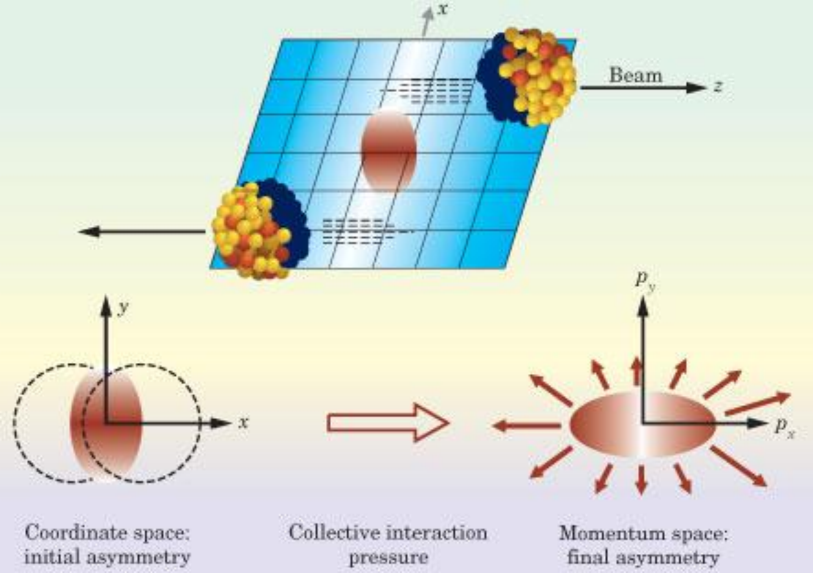
Shadowing is expected to be larger at LHC…?

Regeneration? Wider rapidity distribution?

J/ψ elliptic flow v_2

Hao Qiu, SQM2011





$$\frac{d^3N}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1+\sum_{i=1} 2v_i \cos(i\phi)\right]$$

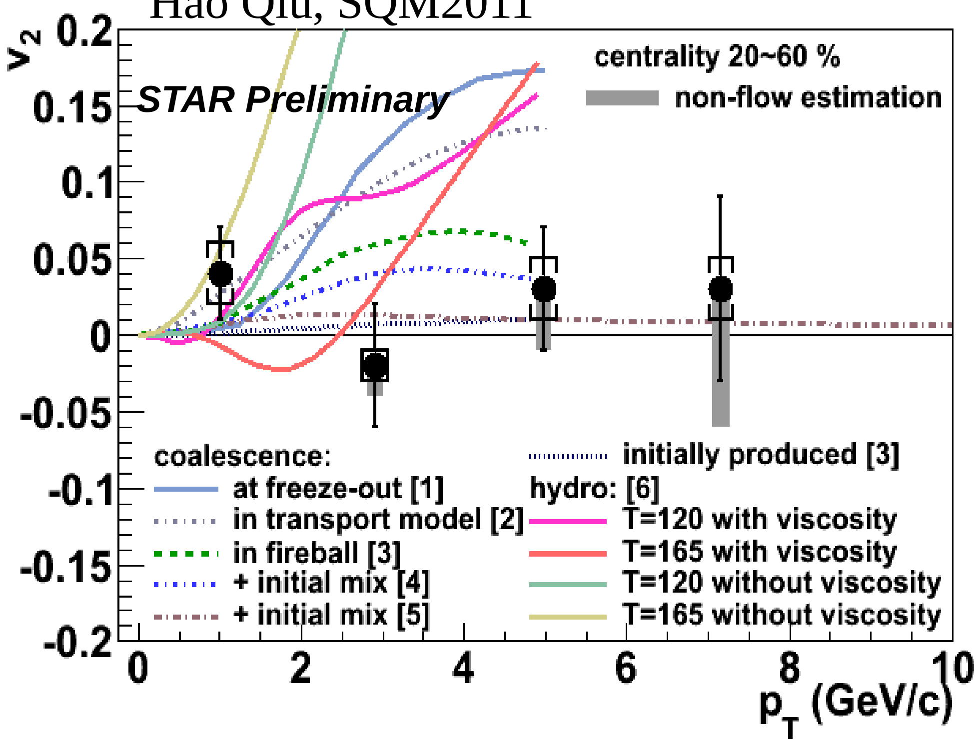
$$v_i = \langle \cos(i\phi) \rangle_{event}$$

v_2(hadron)>v_2(J/ψ)~0

1) Radial flow – integrated over whole evolution
2) Directed flow (v_1) – relatively early
3) Elliptic flow (v_2) – relatively early

J/ψ elliptic flow v_2

Hao Qiu, SQM2011

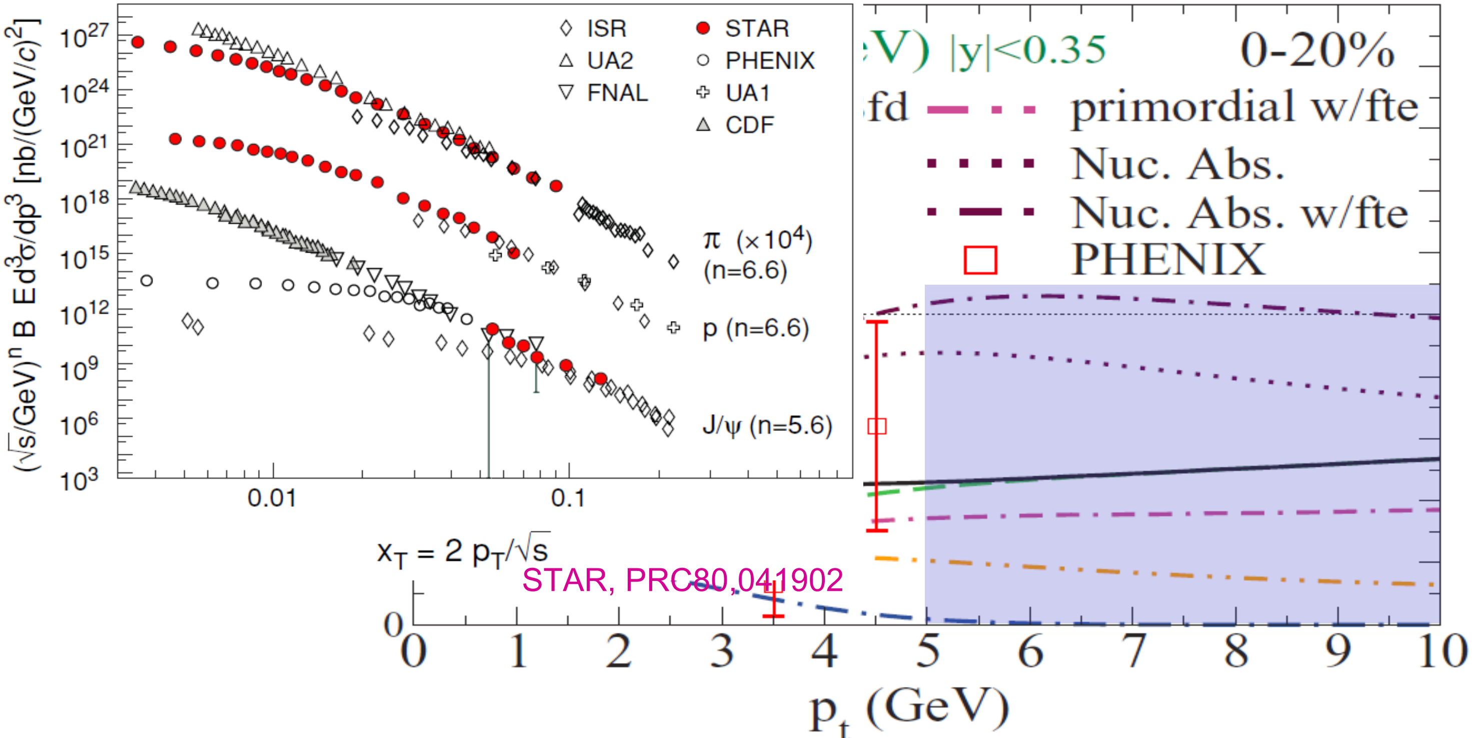


Models		P-value
Initially produced	1.8/3	6.2e-1
Coalescence at freezeout	22.6/3	4.9e-5
Coalescence In transport	13.9/3	3.0e-3
Coalescence In transport	4.8/3	1.8e-1
Coalescence +initial mix	2.9/3	4.0e-1
Coalescence +initial mix	1.8/4	7.7e-1
Hydro T=120 w/viscosity	16.5/3	9.2e-4
Hydro T=165w/ viscosity	14.9/3	1.9e-03
Hydro T=120 w/o viscosity	191.6/3	2.7e-41
Hydro T=165w/o viscosity	237.3/3	0.0

[1] V. Greco, C.M. Ko, R. Rapp, PLB 595, 202. (MB)
[2] L. Ravagli, R. Rapp, PLB 655, 126. (MB)
[3] L. Yan, P. Zhuang, N. Xu, PRL 97, 232301. (b=7.8fm)
[4] X. Zhao, R. Rapp, 24th WWND, 2008. (20-40%)
[5] Y. Liu, N. Xu, P. Zhuang, Nucl. Phy. A, 834, 317. (b=7.8)
[6] U. Heinz, C. Shen, priviate communication. (20-60%)

Disfavors the case that J/ψ with p_T > 2 GeV/c is produced dominantly by coalescence from thermalized charm and anti-charm quarks.

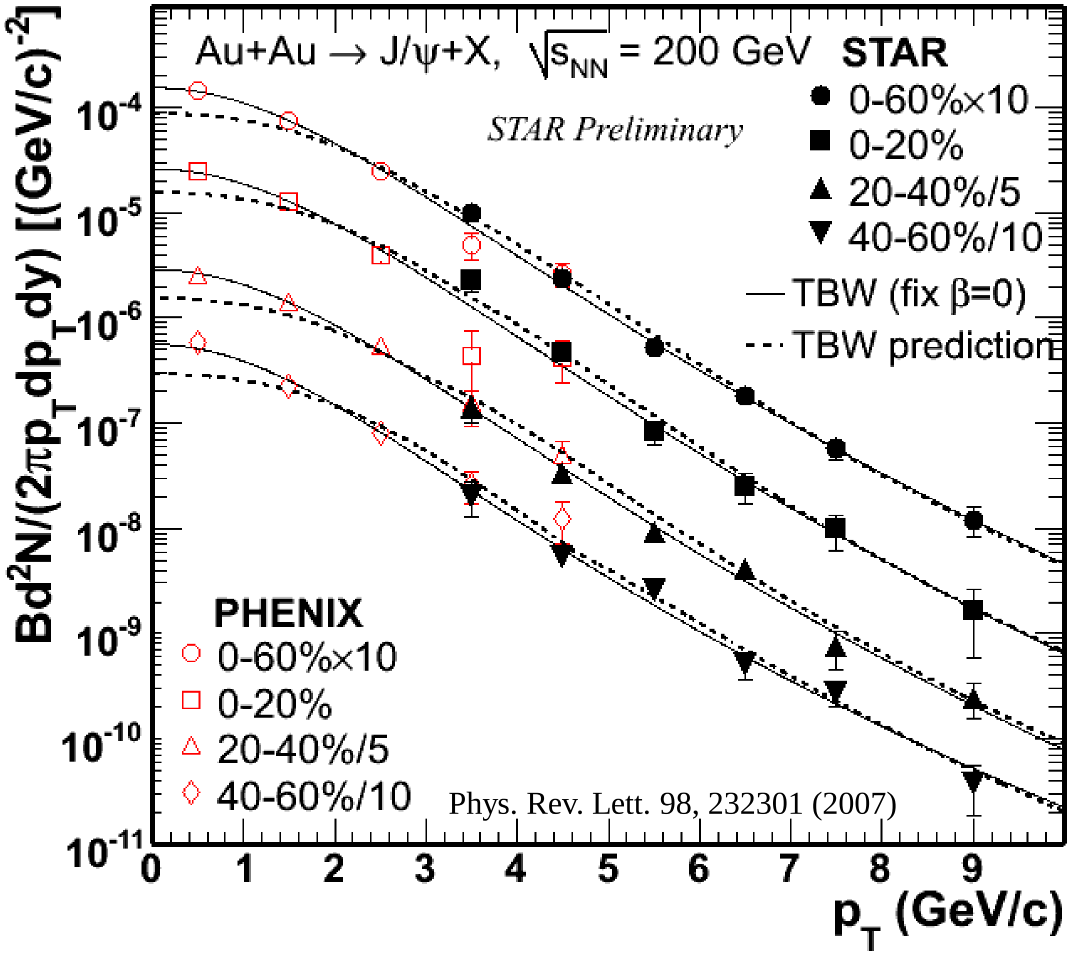
High-p_T J/ψ provides a cleaner probe



X. Zhao and R. Rapp, PRC82, 064905

- Nuclear absorption and life time (Cold Nuclear Matter effects) R_{AA}~0.5 at low p_T, increase to unity at 5 GeV/c
- Regeneration and radial flow only affect low p_T
- Low-p_T J/ψ deviates from x_T-scaling, soft process affects

J/ψ spectra in 200GeV Au+Au collisions



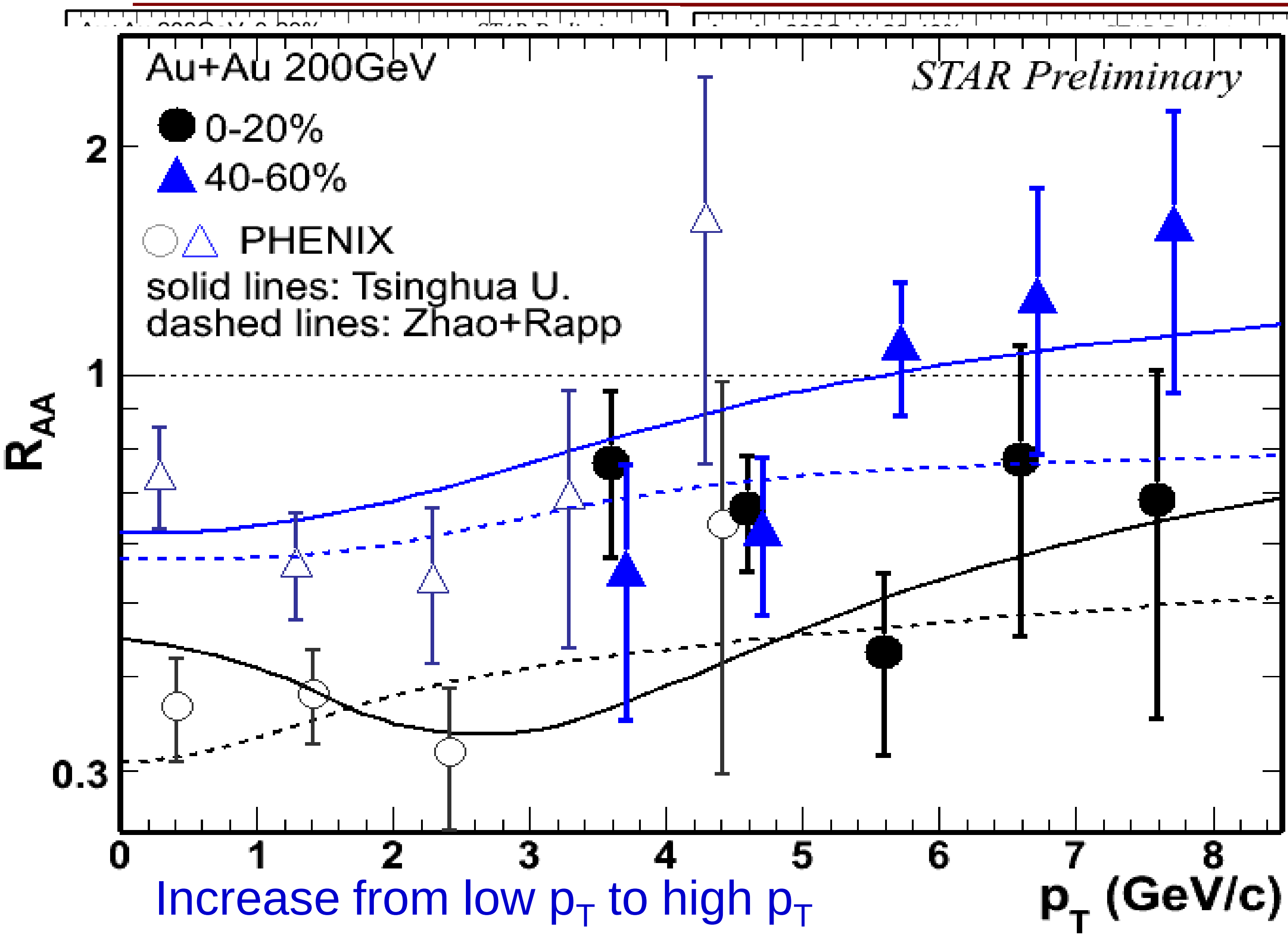
Good agreement between STAR and PHENIX

Significantly extend the p_T range to 10 GeV/c

J/ψ spectra significantly softer than the prediction from light hadrons
→ Much smaller radial flow?
→ Regeneration at low p_T?

Tsallis Blast-Wave model: ZBT *et al*., arXiv:1101.1912; JPG 37, 085104 (2010)

R_{AA} vs. p_T



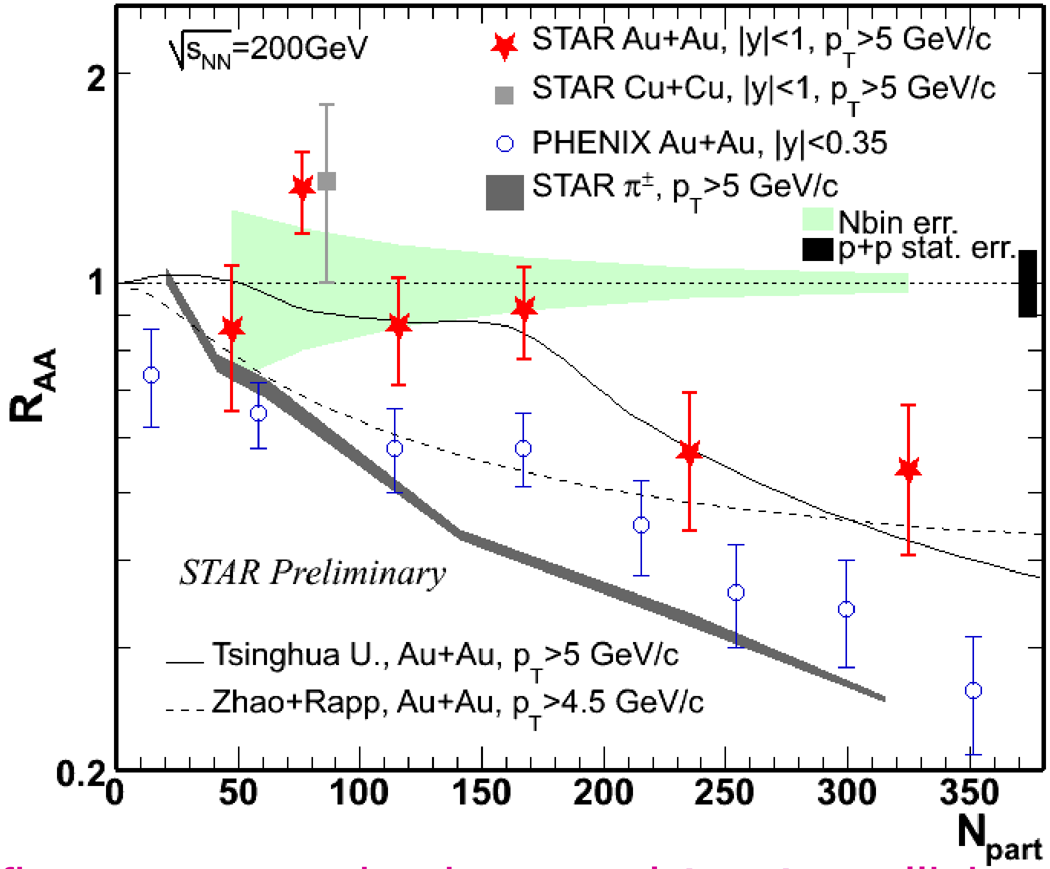
STAR CuCu: PRC80, 014922(R)
PHENIX: PRL98, 232301

Yunpeng Liu, Zhen Qu, Nu Xu and Pengfei Zhuang, PLB 678:72 (2009) and private comminication

Xingbo Zhao and Ralf Rapp, PRC 82,064905(2010) and private communication

Increase from low p_T to high p_T
Consistent with unity at high p_T in (semi-) peripheral collisions
More suppression in central than in peripheral even at high p_T

R_{AA} vs. Npart



Yunpeng Liu, Zhen Qu, Nu Xu and Pengfei Zhuang, PLB 678:72 (2009) and private comminication

Xingbo Zhao and Ralf Rapp, PRC 82,064905(2010) and private communication

STAR Pion: Yichun Xu at QM2009

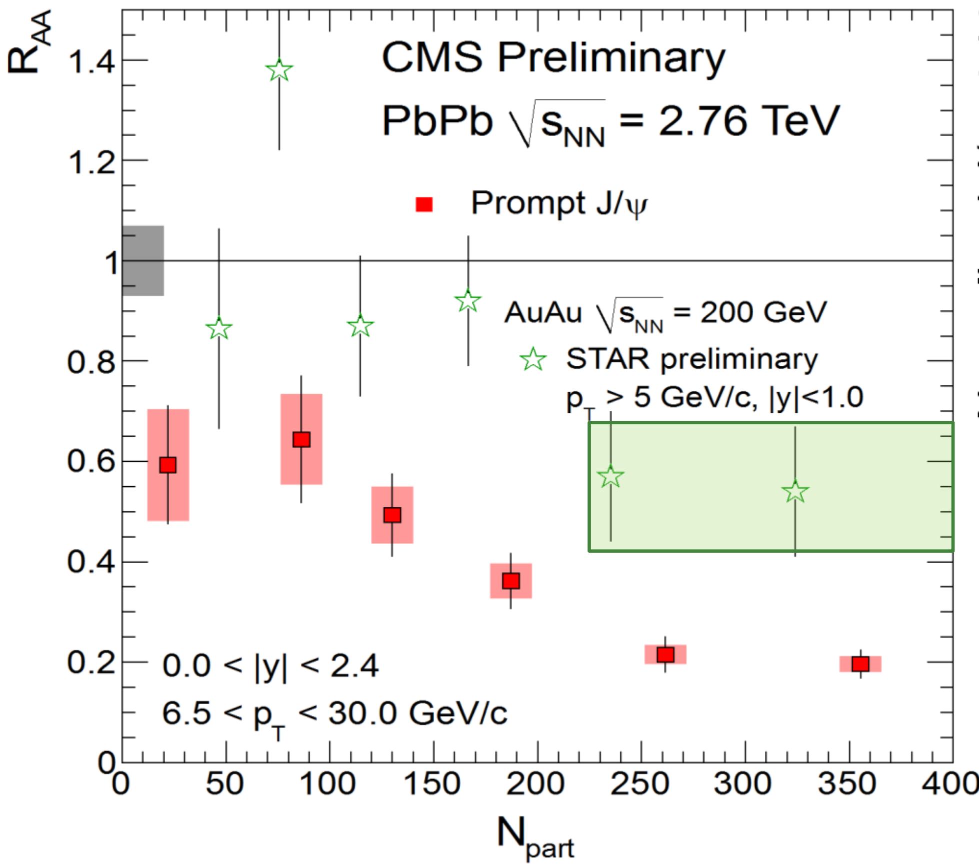
Significant suppression in central Au+Au collisions for high-p_T J/ψ

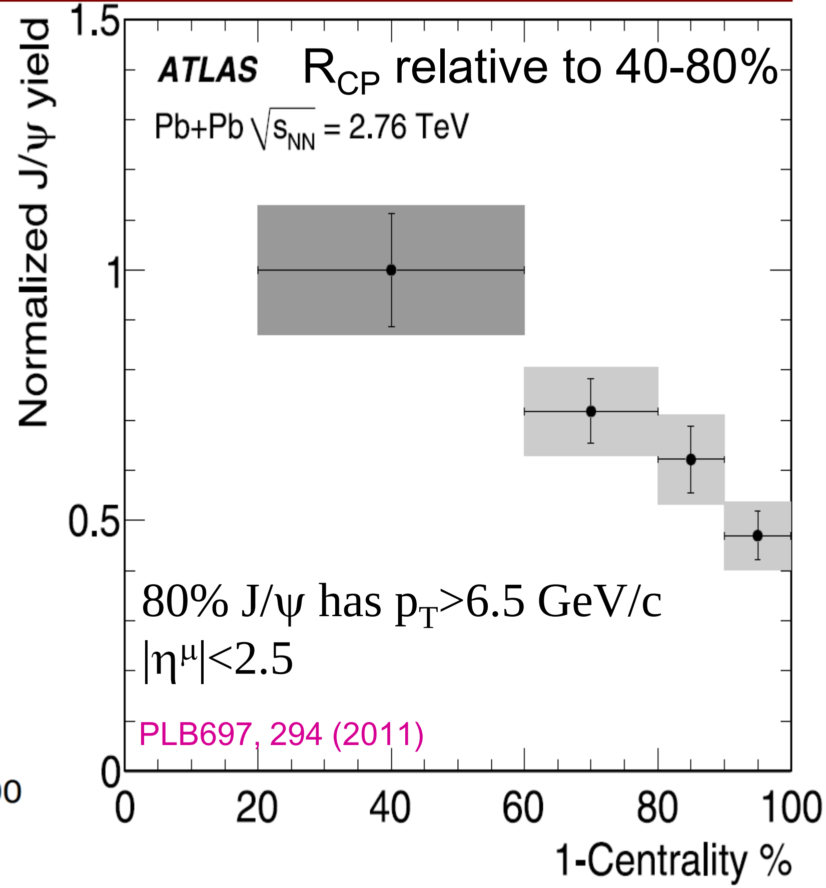
Trend is different from high-p_T pion, not dominantly from color-octet?

Systematically higher at high p_T in all centralities

Consistent with two models including color screening effects

Compare to LHC





Stronger suppression at CMS than STAR

R_{CP}~1/3 for CMS, 0.45 for ATLAS and 0.5 for STAR,

Similar at RHIC and LHC if take the uncertainty into account

CNM and regeneration is less important at high p_T at RHIC. ➔ Is it true for LHC?

Upsilon in heavy-ion collisions

$\lambda_D \propto 1/T$ Quarkonium dissociation temperatures – H. Satz, JPG (2006)

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

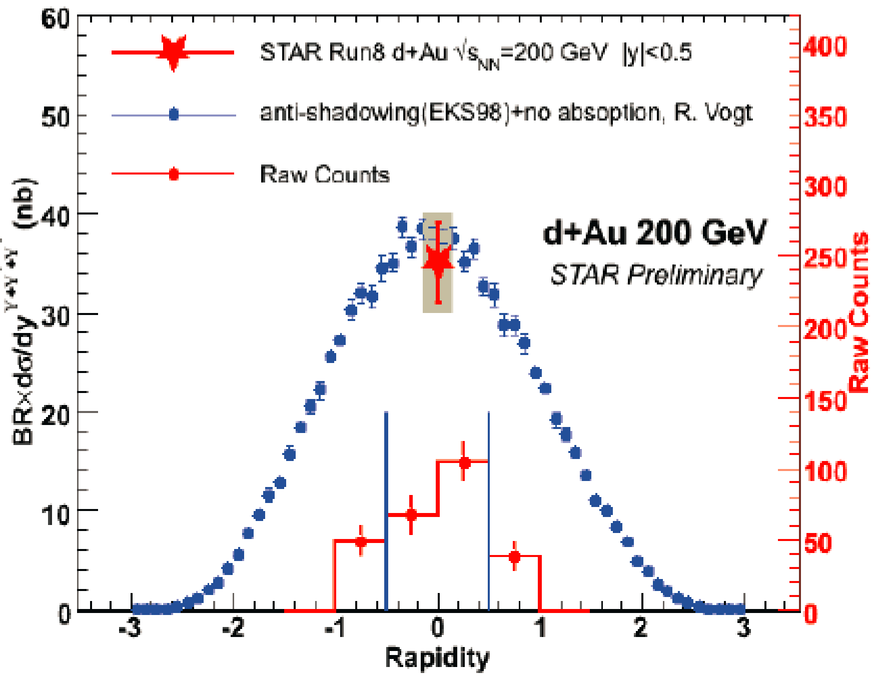
Model dependent

Size (for Upsilon(1S)) is smaller → absorption is smaller
Hadronic co-mover absorption is negligible
Recombination is negligible (at least at RHIC)
More robust theoretical calculations

Lower production rate
Also have significant feeddown from excited states
PDF modification is still there (different from J/ψ due to Q^2)
Cronin effect maybe still there

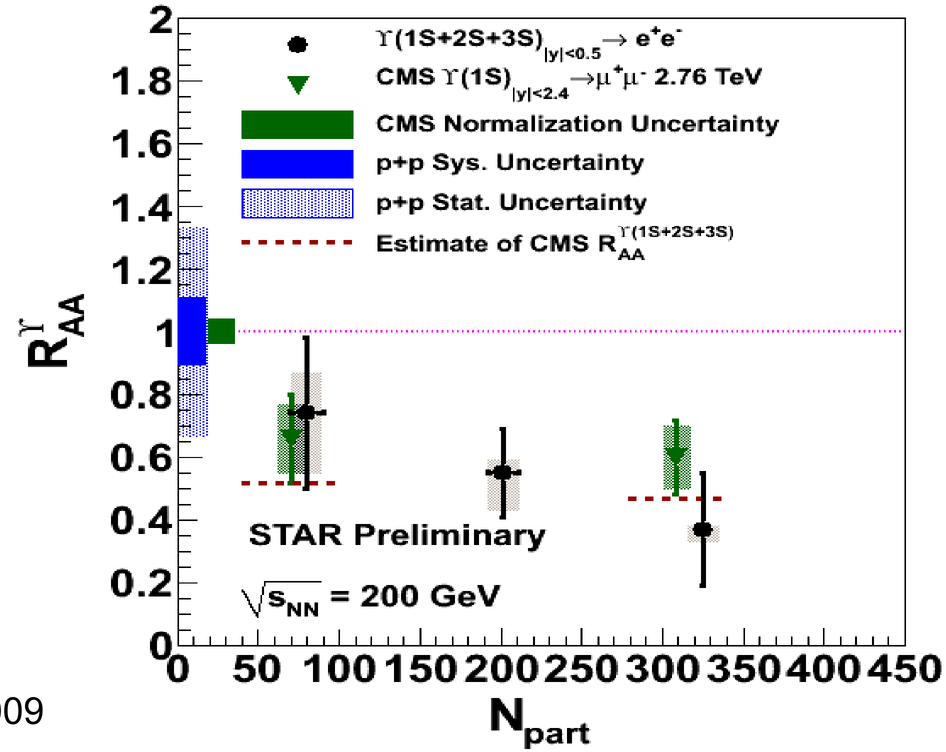
Upsilon at STAR

200GeV d+Au



Haidong Liu, QM2009

200GeV Au+Au

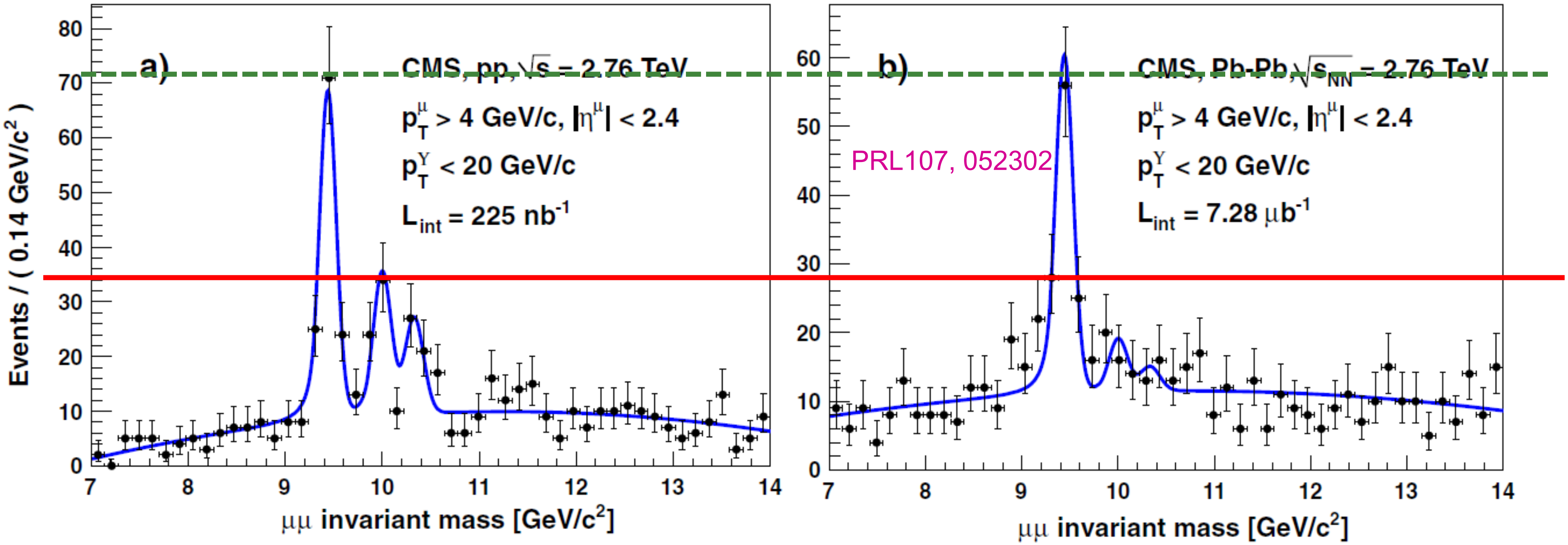


$R_{AA} = 0.78 \pm 0.28 \pm 0.20$

Consistent with pQCD and minimal shadowing effects

Suppression consistent with melting of excited states: **Deconfinement?**

Upsilon suppression at CMS



$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\text{Pb-Pb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15}(\text{stat}) \pm 0.03(\text{syst})$$

Initial state CNM effects cancel out (at least to first order)

Nuclear absorption partially cancel out

Summary

Quarkonium is a unique probe to study the QGP

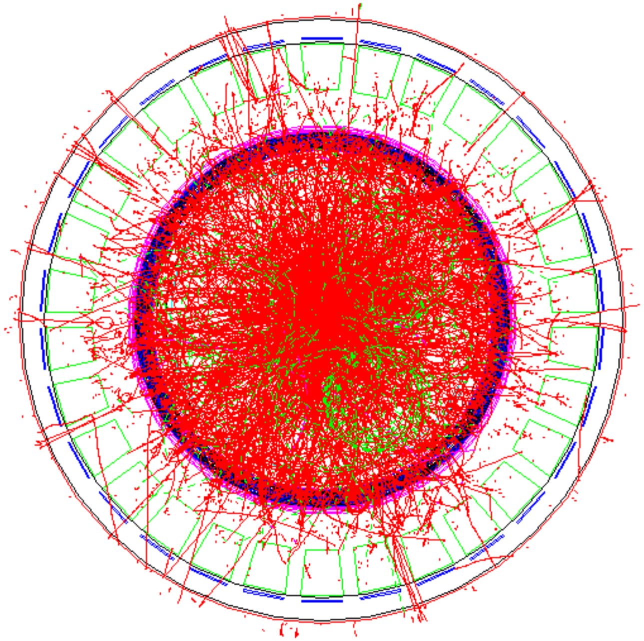
J/ψ :

- Similar suppression at SPS and RHIC, stronger at forward
- J/ψ v_2 consistent with 0 at RHIC
- Less suppression at LHC for J/ψ at forward rapidity
- High-p_T J/ψ suppressed in central collisions at RHIC and LHC, stronger at LHC

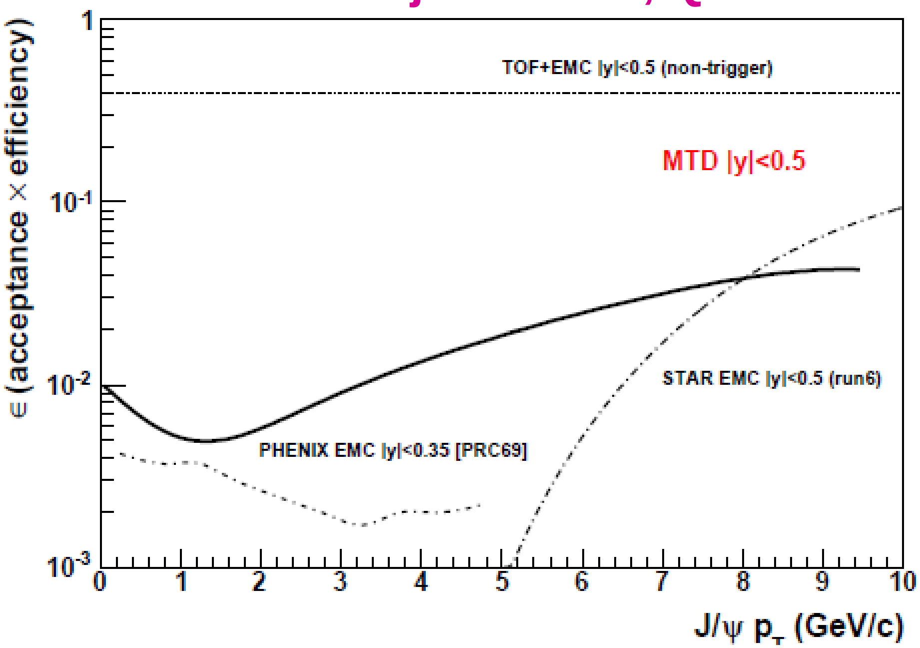
Upsilon:

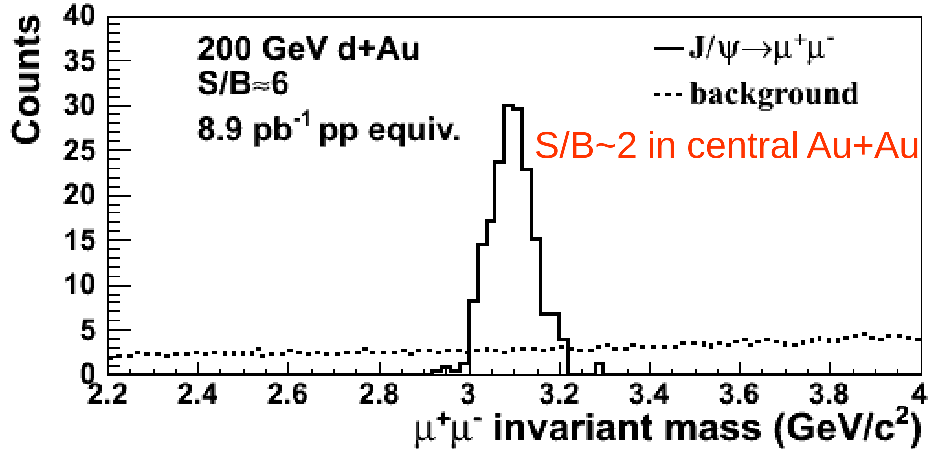
- Consistent with pQCD and minimal shadowing in 200 GeV d+Au
- Significant suppression in central heavy-ion collisions, consistent with melting of excited states
- Similar at RHIC and LHC
- Significant Upsilon(2S+3S)/Upsilon(1S) suppression in Pb+Pb at LHC

Muon Telescope Detector (MTD)



Lijuan Ruan, QM2011





Advantages over electrons

no γ conversion

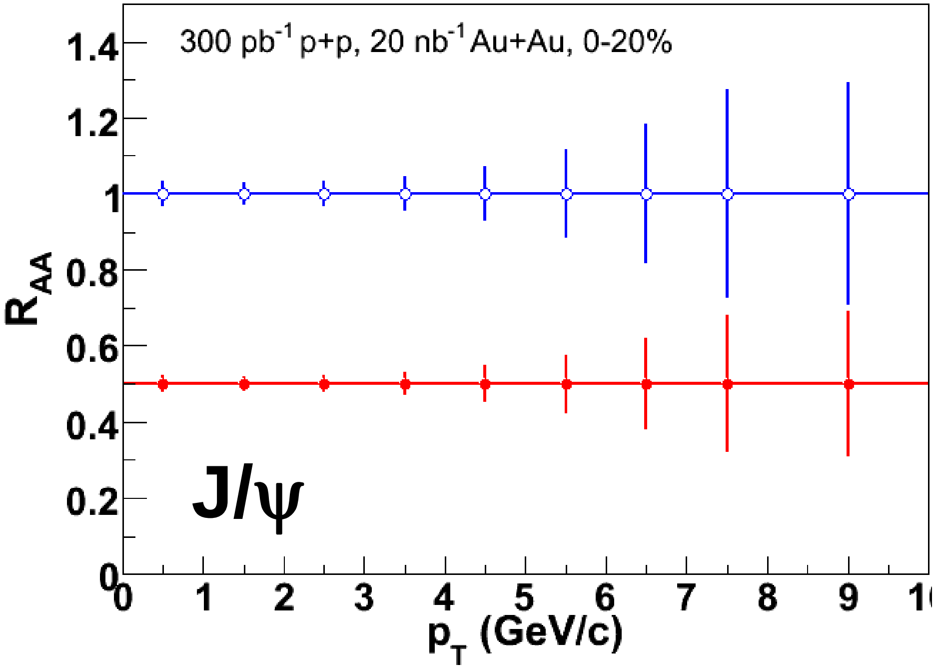
much less Dalitz decay contribution

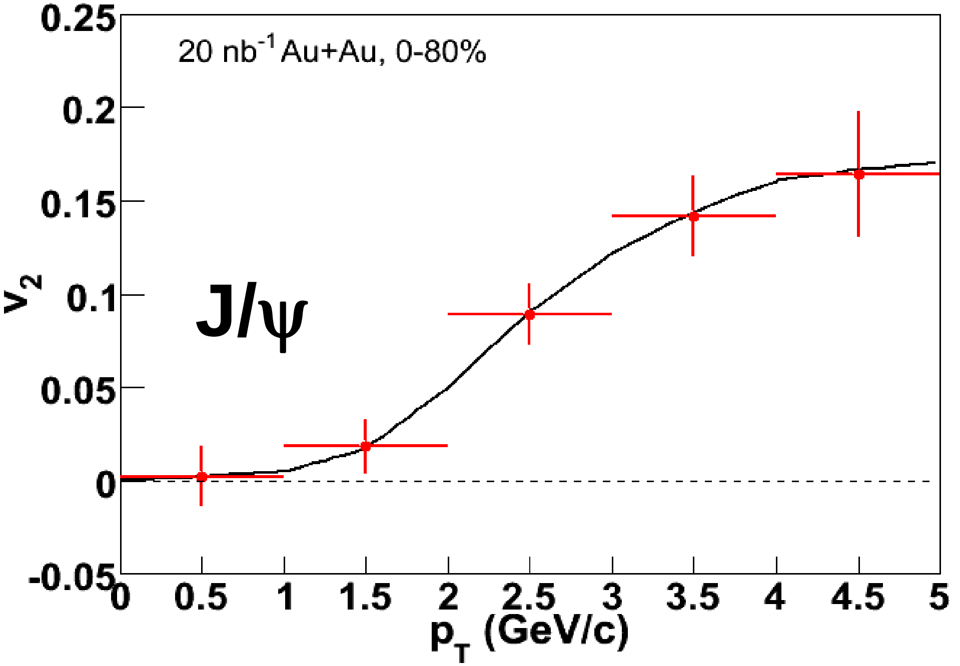
less affected by radiative losses in the materials

Trigger capability for low to high p_T J/ψ in central Au+Au collisions

High μ/hadron enhancement

J/ψ with MTD projection





Charmonium production mechanism

- **Color singlet model (CSM), LO**

  underpredicted CDF data by order of magnitude
- **Color octet model (COM), LO**

  good agreement with CDF cross section

  disagreement with CDF polarization

- **CSM*, NLO**

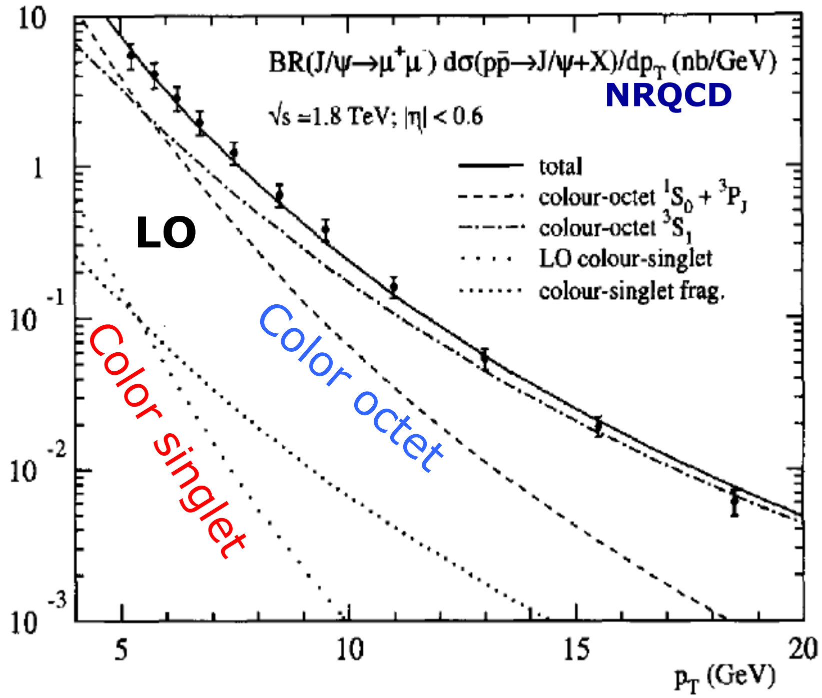
  better agreement

  NNLO* applicable at p_T>5-7 GeV/c
- **COM***

  improvement of polarization,

  NLO will come, valid at p_T>3 GeV/c
- **CSM+s-channel cut**

  valid at low p_T



Decay feeddown (CDF):

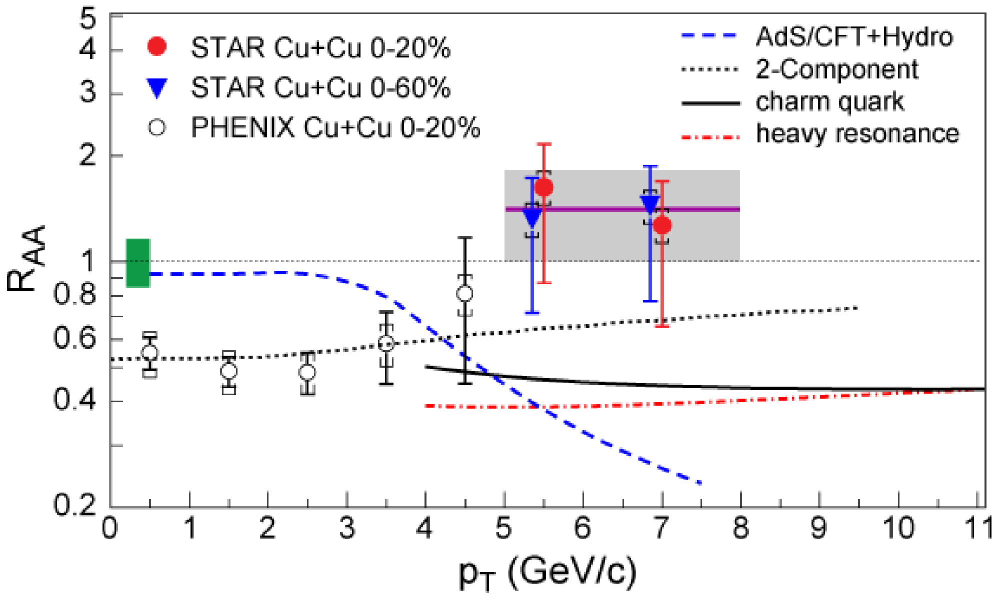
ψ(2s): 7%-15%, slightly increase with p_T

$\chi_{c0,1,2}$: ~30%, slightly decrease with p_T

B: Strong p_T dependence

Know your reference!

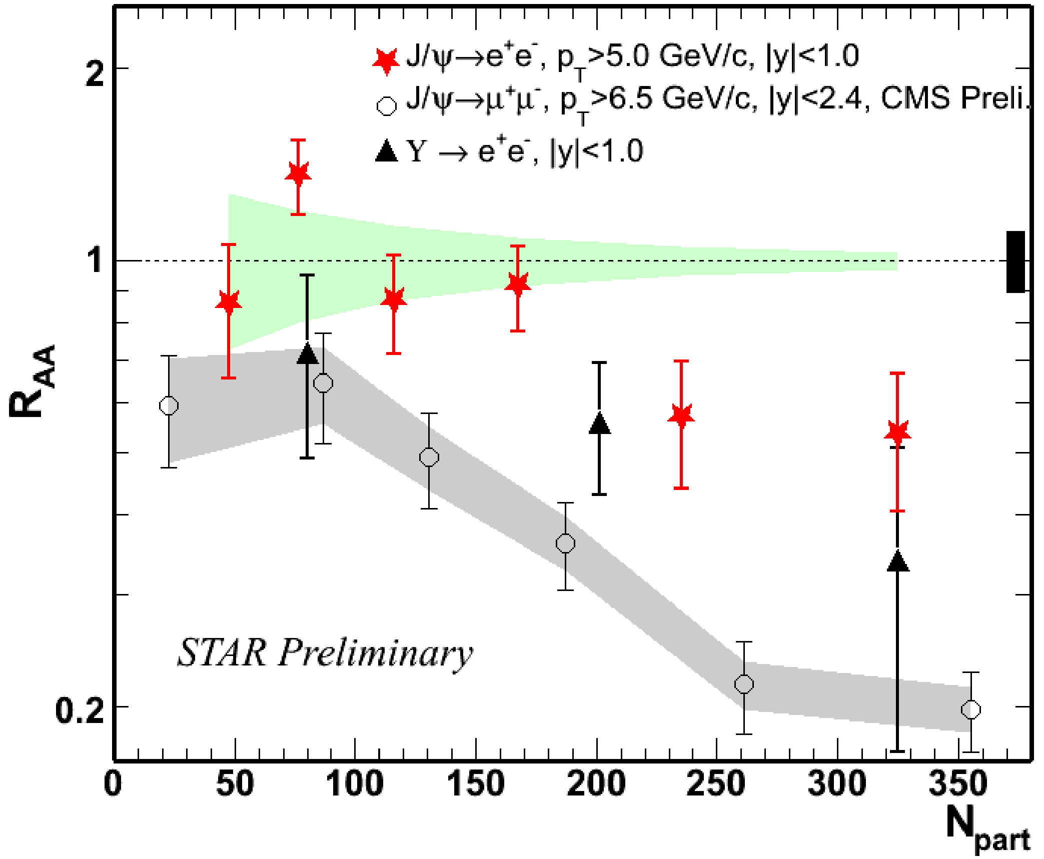
R_{AA} at high p_T



- Consistent with no suppression at high p_T:
  $R_{AA}(p_T>5$ GeV/c) = 1.4± 0.4±0.2
- Indicates R_{AA} increase from low p_T to high p_T

- **How does production mechanism (CS vs. CO) affect energy loss?**
- **Contrast to AdS/CFT+ Hydro prediction**
  (H. Liu, K. Rajagopal and U.A. Wiedemann PRL 98, 182301(2007), T. Gunji, JPG 35, 104137(2008))
- **Good jobs:**
  - **two-component model**, leakage and B feeddown is important
    (R. Rapp, X. Zhao, arXiv:0806.1239)
  - **transport+hydro**, from initial produced instead of regenerated
    (Y.Liu, Zhen Qu, N. Xu and P. Zhuang, arXiv:0901.2757)

Compare to J/ψ

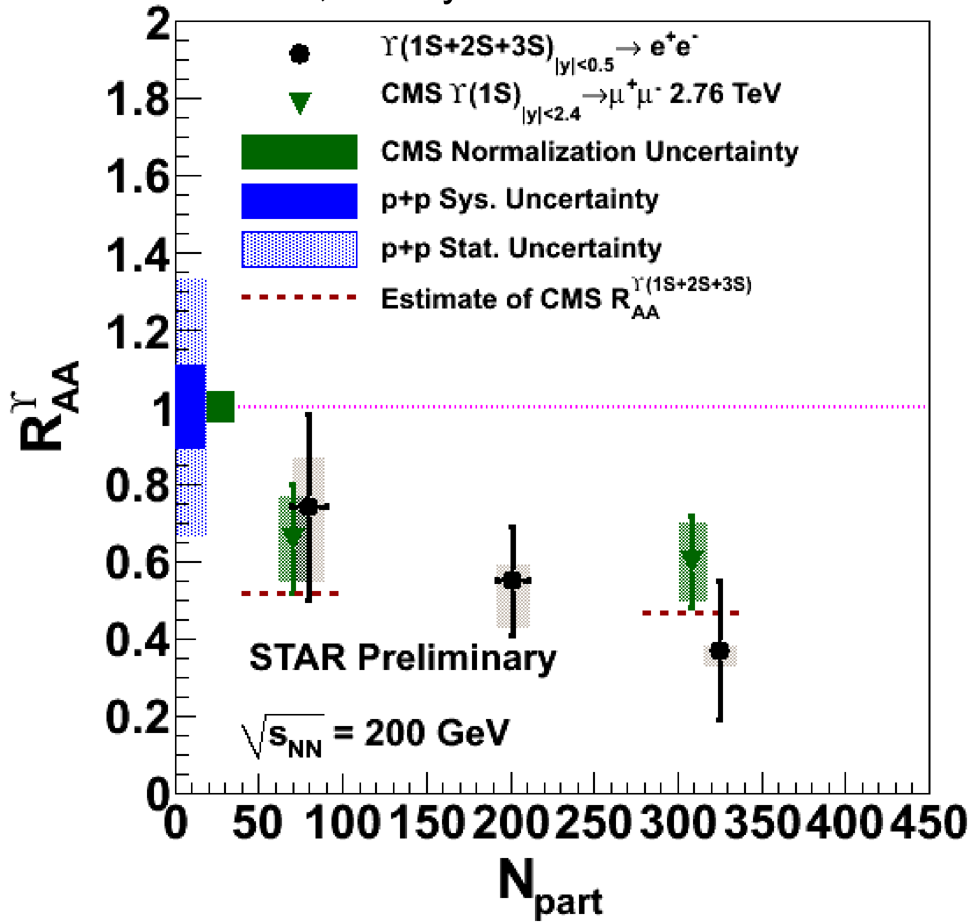


All suppressed in central heavy-ion collisions!!

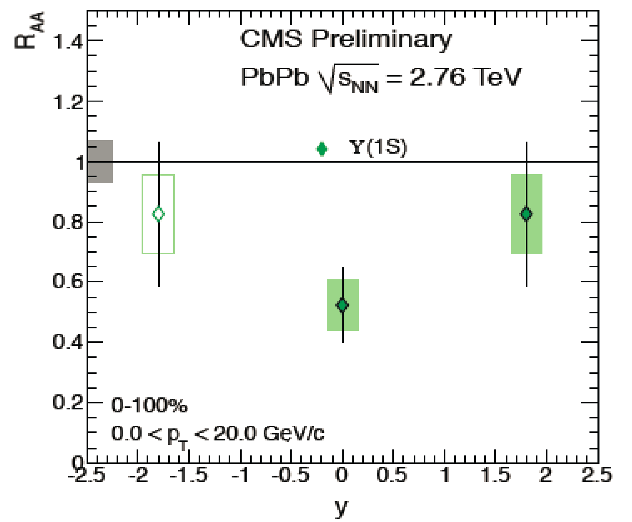
Similar suppression for STAR high-p_T J/ψ and Upsilon

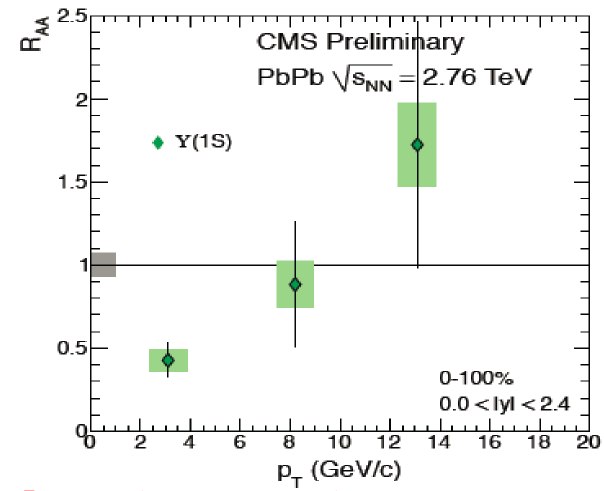
Upsilon suppression at LHC-CMS

Rosi Reed, Heavy Quarkonium 2011



Zhen Hu, QM2011

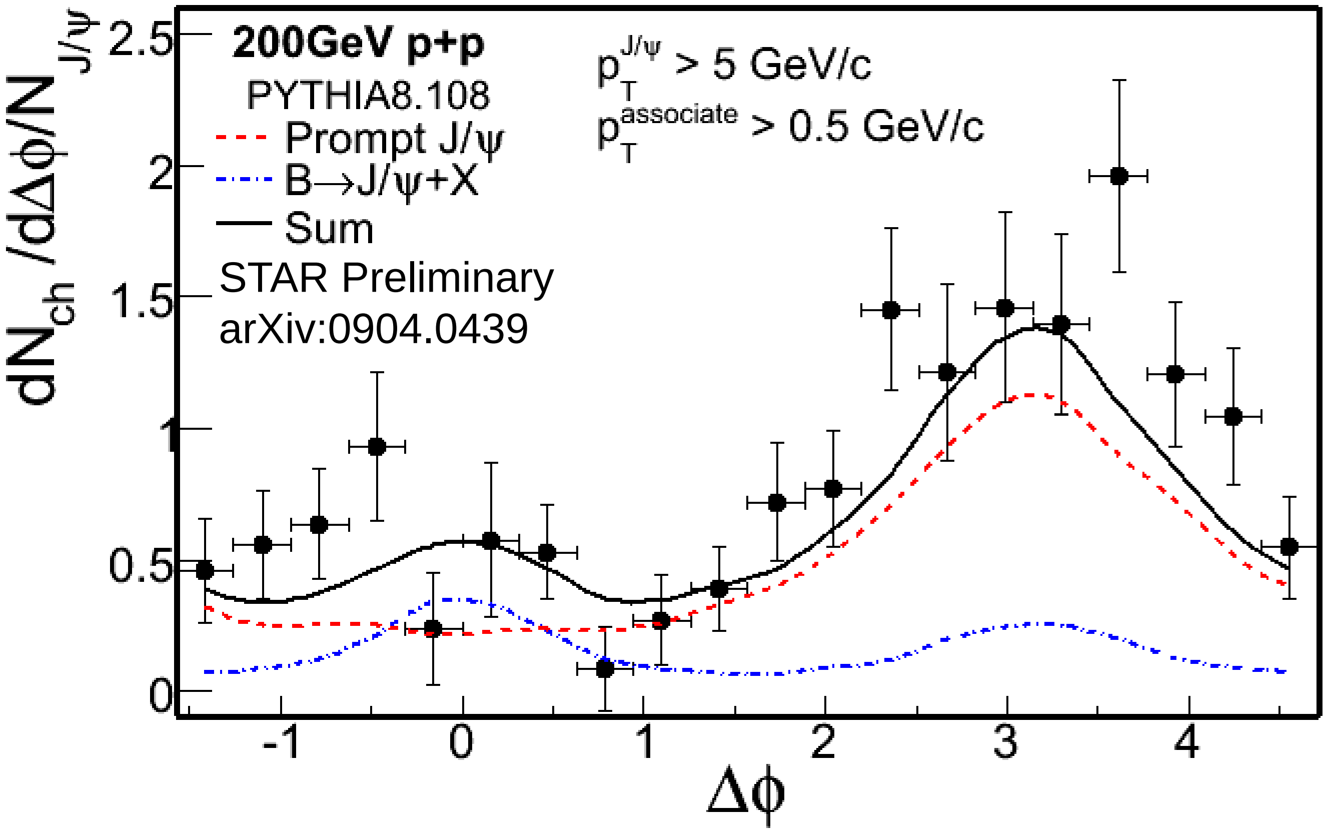




Similar suppression

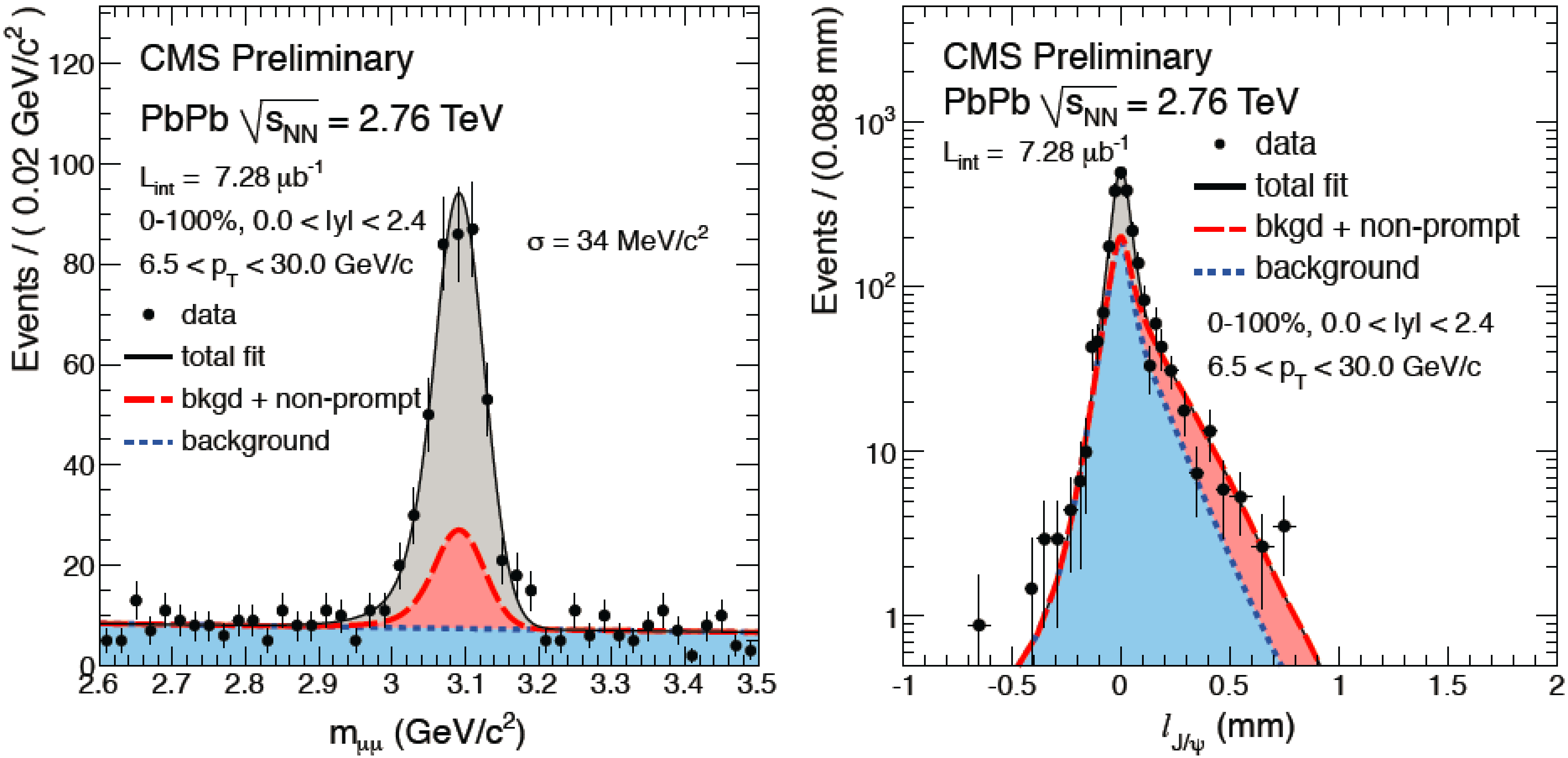
Seems to increase with rapidity and p_T (at LHC)

B→J/ψ



No significant near side correlation
B contribution (13 ± 5) %
Little room for parton fragmentation

Prompt vs. non-prompt J/ψ in PbPb



First time that prompt and non-prompt J/ψ have been separated in heavy ion collisions