Workshop on QCD Thermodynamics in High-Energy Collisions

26 July – 1 August, CCNU, Wuhan, China

Quarkonia measurements @ STAR

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Outline

J/ψ measurements in p+p collisions

- p_T spectra
- Polarization
- J/ψ yield vs. event activity
- Feed-down

Quarkonia measurements in heavy-ion collisions

- Results from 200 GeV Au+Au data
- Beam energy dependence
- System size dependence

Summary

J/ψ production in p+p collisions

J/ψ production mechanism in p+p collisions is not fully understood

- Color-singlet model
- Color-octet in NRQCD

Measurements on p_T spectra, polarization, associated production helps to understand QCD

Feed-down is an issue

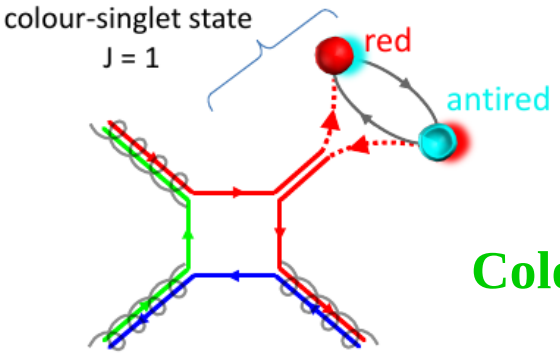
Inclusive J/ψ:

- Prompt J/ψ

Direct + feed-down from ψ (2S) and χ_c

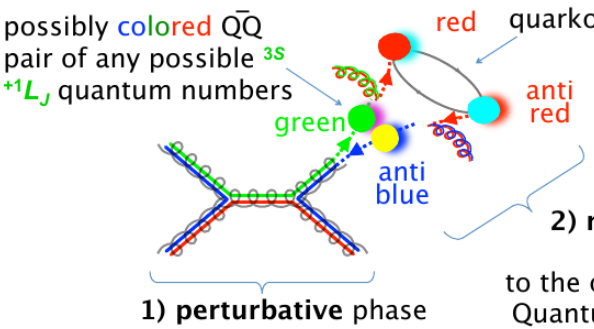
- Non-prompt J/ψ

Strong p_T dependence



Color-singlet

+ analogous colour combinations

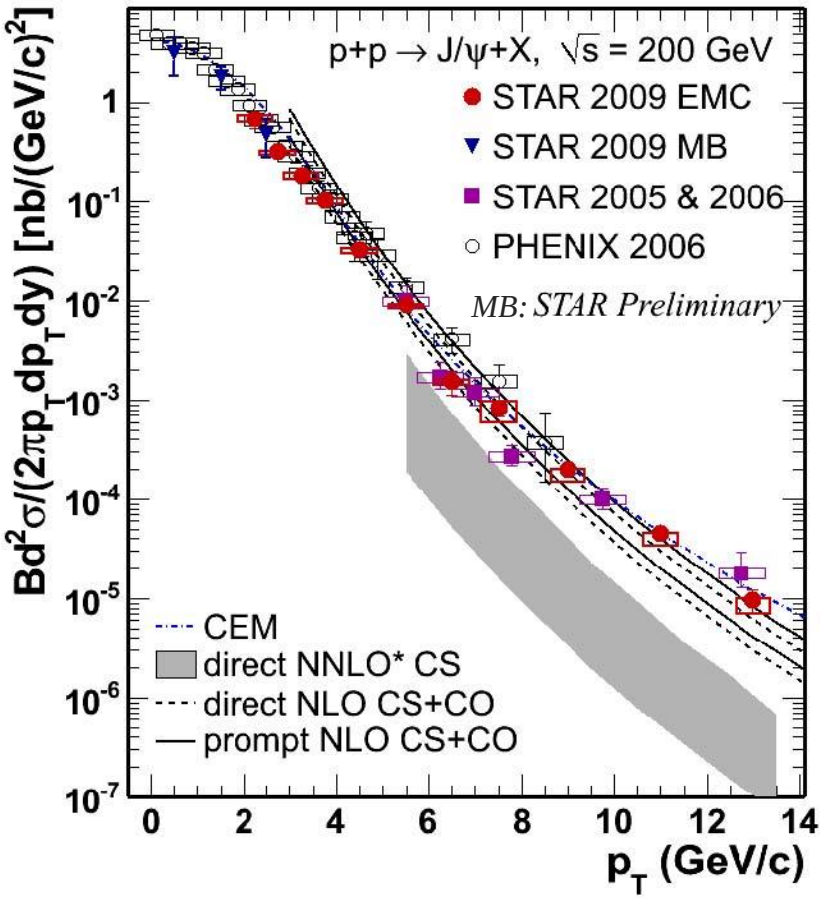


Color-Octet

$$d\sigma_H = \sum_\kappa d\hat{\sigma}^\kappa \langle \mathcal{O}_\kappa^H \rangle$$

Reference for heavy-ion collisions

J/ψ p_T spectra in p+p collisions



NNLO* CSM:
pQCD calculation, for direct only

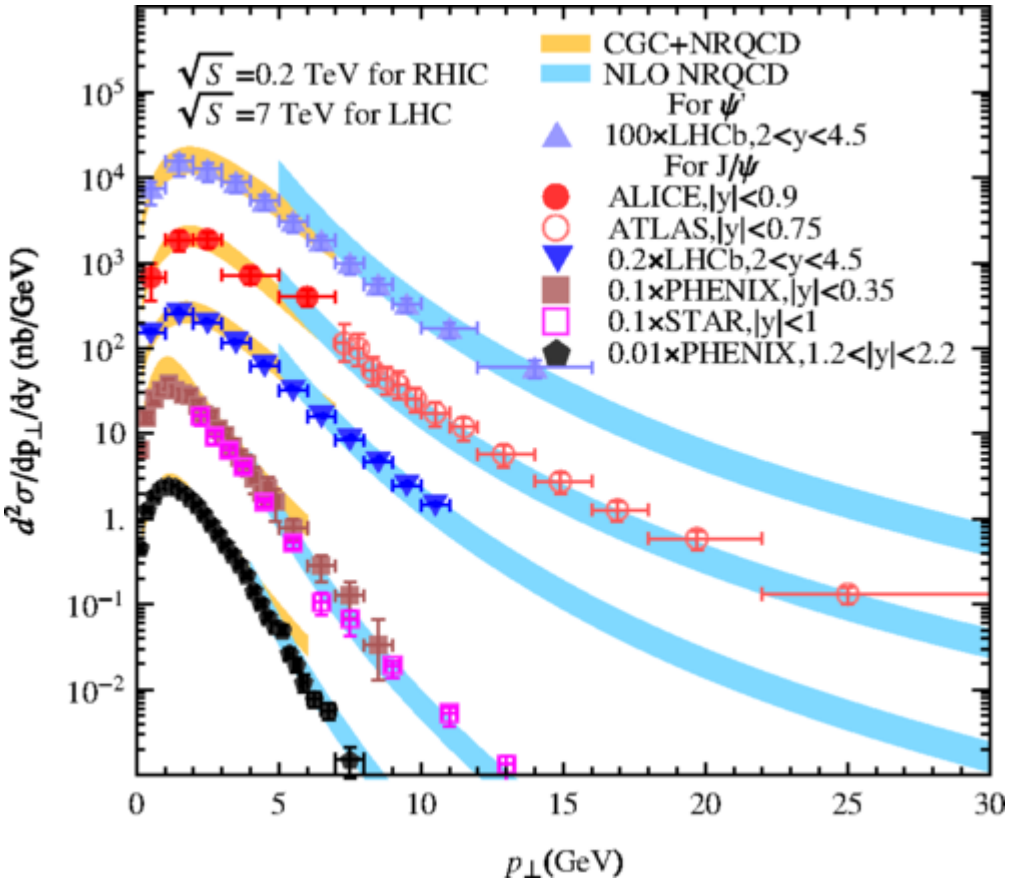
Misses high-p_T part

NRQCD:
Long-distance matrix elements from world-data fitting

Calculation at NLO available
Agrees with data well

STAR : PRC80, 041902 (2009), PLB722, 55 (2013)
PHENIX: PRD85, 092004 (2012)
direct NNLO CS: P.Artoisenet et al., PRL101, 152001 (2008) and private communication
NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, PRD 84, 114001 (2011) and private communication
CEM: A.D. Frawley, T Ullrich, R. Vogt, Phys. Rept. 462, 125 (2008) and R.Vogt private communication

CGC+NRQCD and NLO NRQCD



NLO NRQCD describes world data at high-p_T

CGC+NRQCD describes world data at low-p_T

New measurements to test?

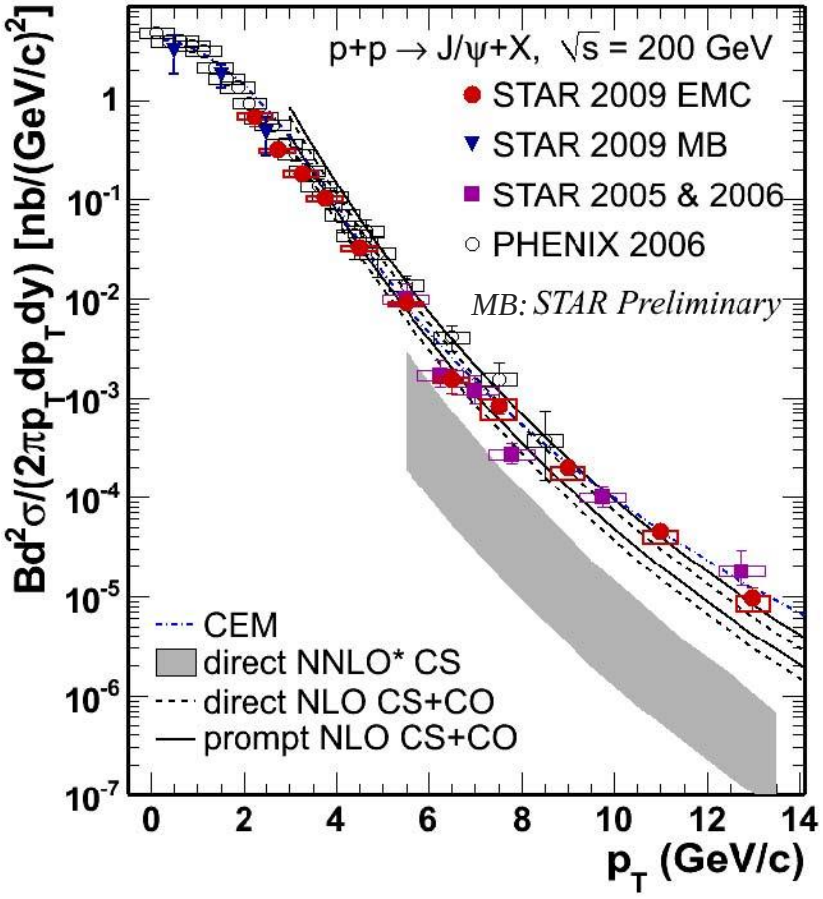
CGC+NRQCD:

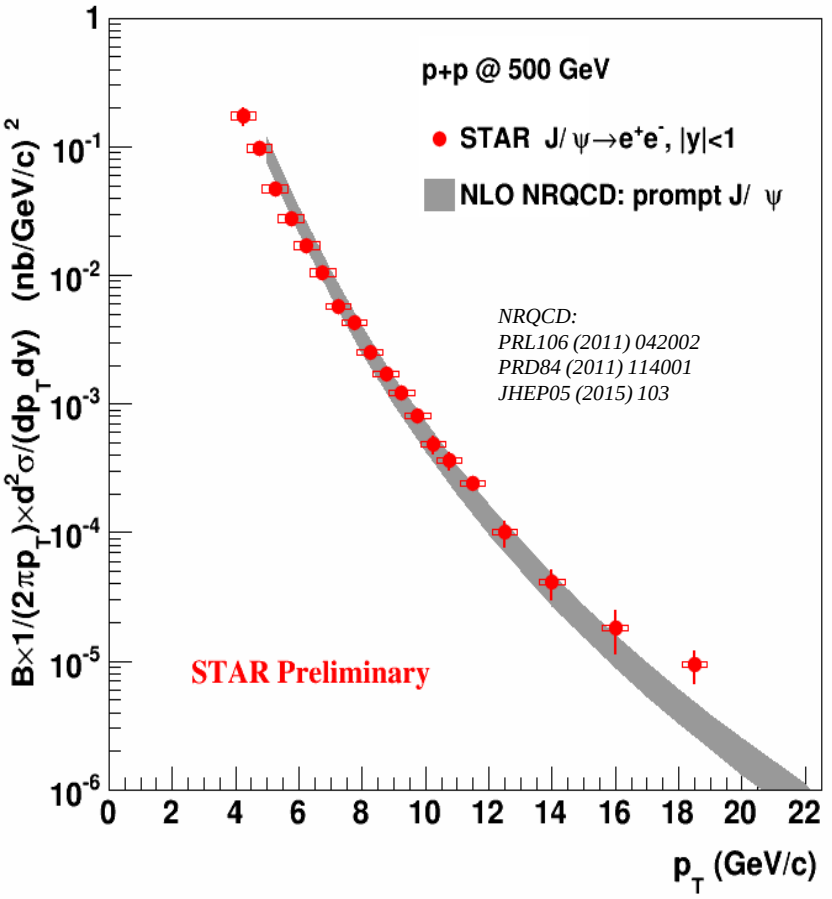
Y.-Q. Ma and R. Venugopalan, PRL113, 192301 (2014)

NLO NRQCD:

Y.-Q.Ma, K.Wang, and K.T.Chao, PRD 84, 114001 (2011)

J/ψ p_T spectra at 500GeV





STAR : PRC80, 041902 (2009), PLB722, 55 (2013)
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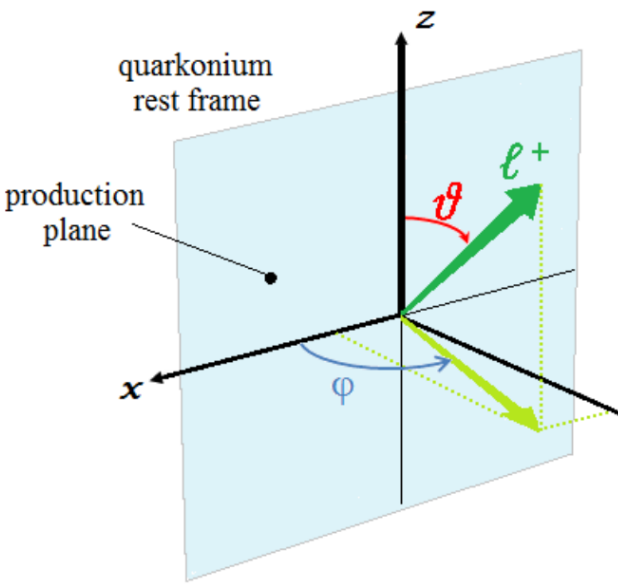
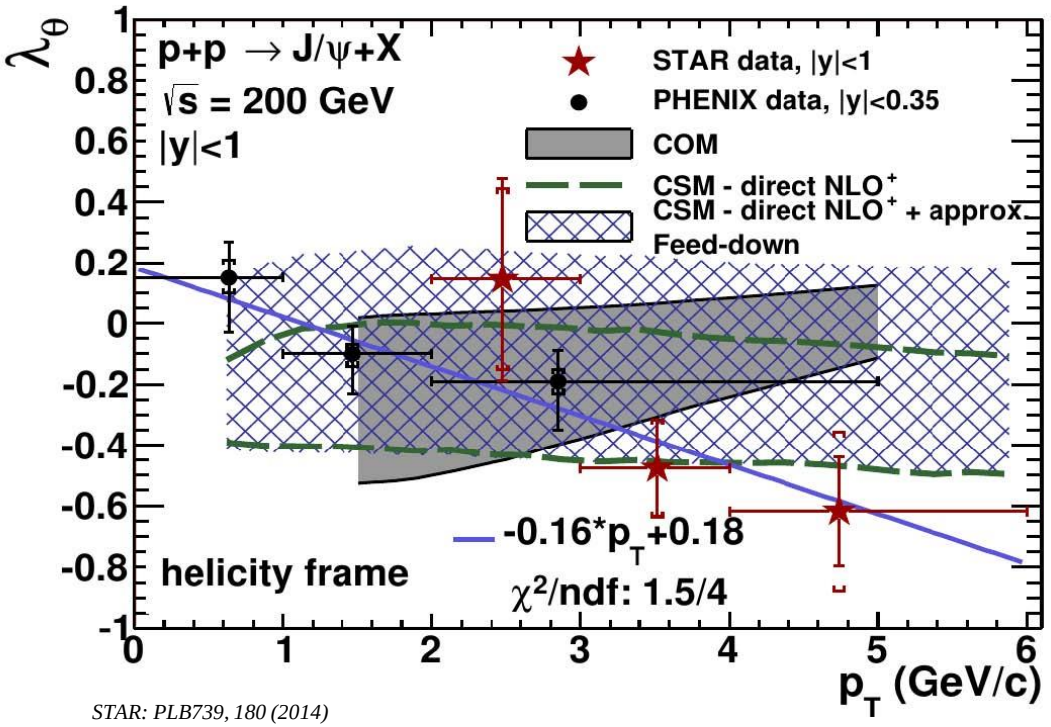
NRQCD describes 500GeV data

Measurement at low-p_T in progress

Polarization measurement at 200GeV



$d\sigma/d\cos\theta = 1 + \lambda_\theta \cos^2\theta$

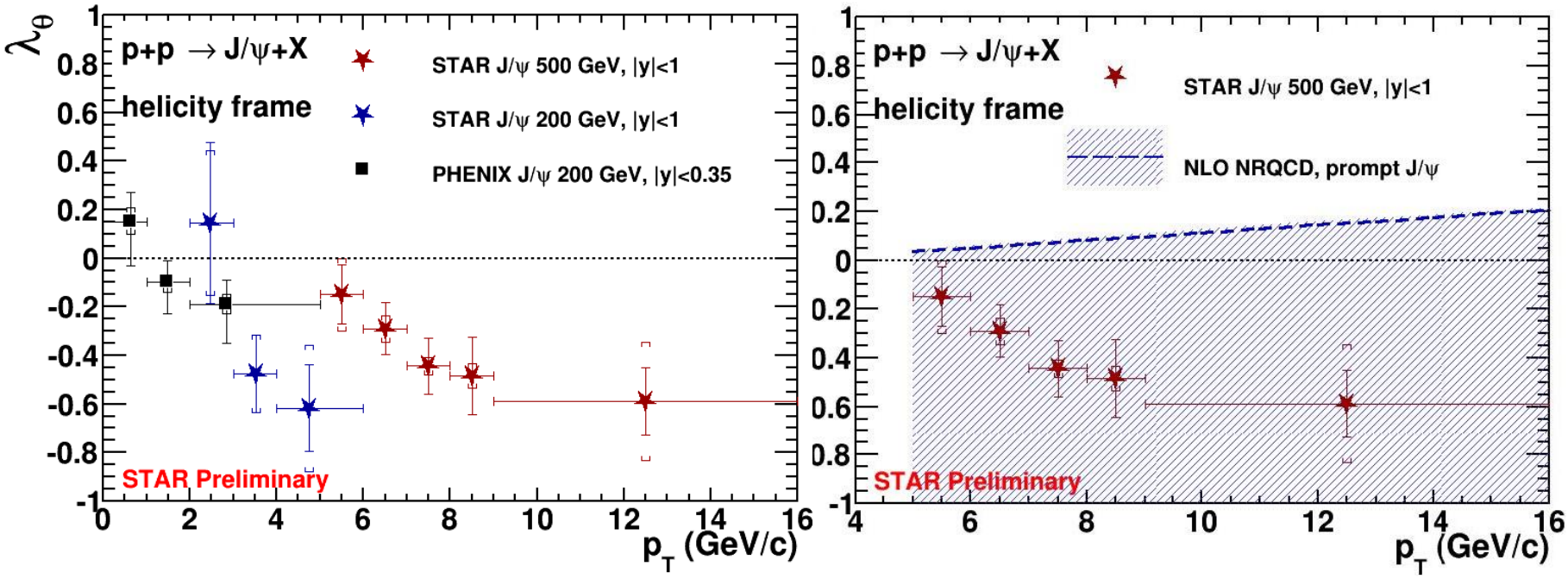


STAR: PLB739, 180 (2014)
PHENIX: Phys. Rev. D 82, 012001 (2010)
COM: Phys. Rev. D 81, 014020 (2010)
CSM NLO+: Phys. Lett. B, 695, 149 (2011) and private communication

Consistent with longitudinal polarization at intermediate p_T

Consistent with NLO$^+$ CSM calculation

Polarization measurement at 500GeV

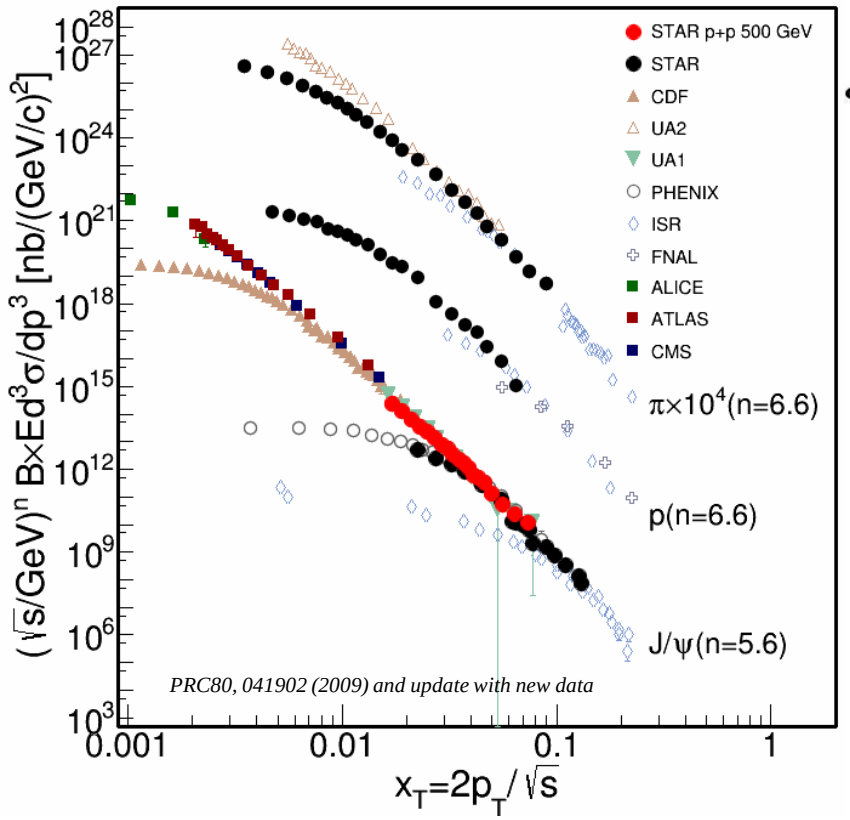


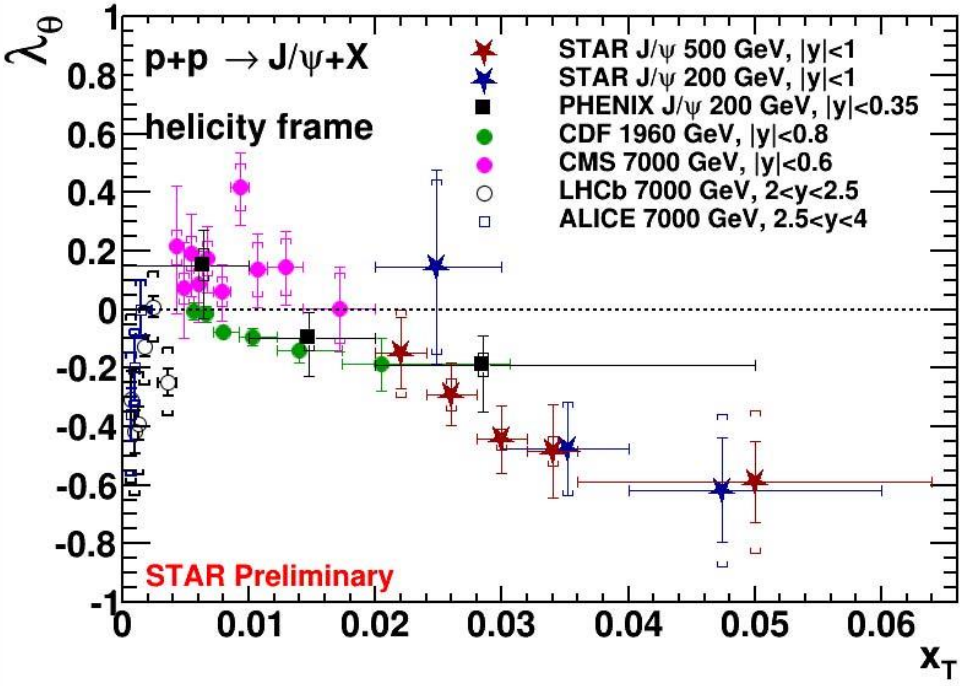
NLO NRQCD:
Phys. Rev. Lett. 108 (2012) 242004, Phys.Rev. D90 (2014) 1, 014002, Phys.Rev.Lett 112 (2014) 18, JHEP 1505 (2015) 103 and private communication

Similar trend observed in 200 and 500GeV

Data can help to constrain NRQCD calculation

x_T scaling behaviors

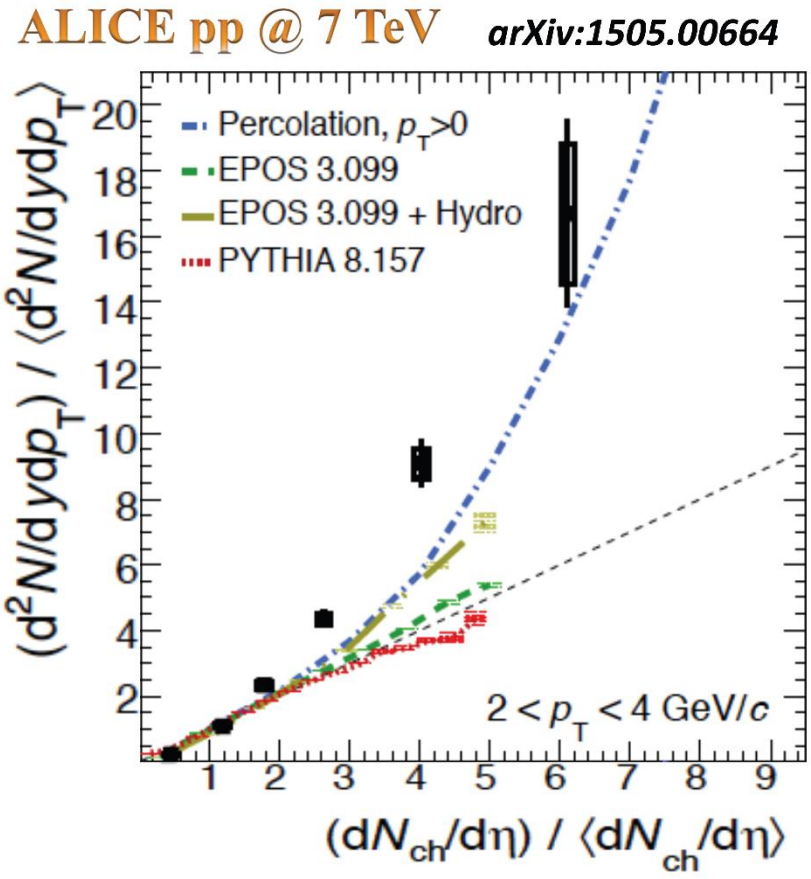




Both p_T spectra and polarization follows x_T scaling

Production at low-p_T affected by soft processes

J/ψ yield vs. event activity



- Faster increase of open charm than charged hadron observed at LHC
- Similar trend for inclusive J/ψ

Models:

PYTHIA8

- Linear increase thanks to Multi-Parton-Interaction (MPI)
- Underestimate yield at large multiplicity

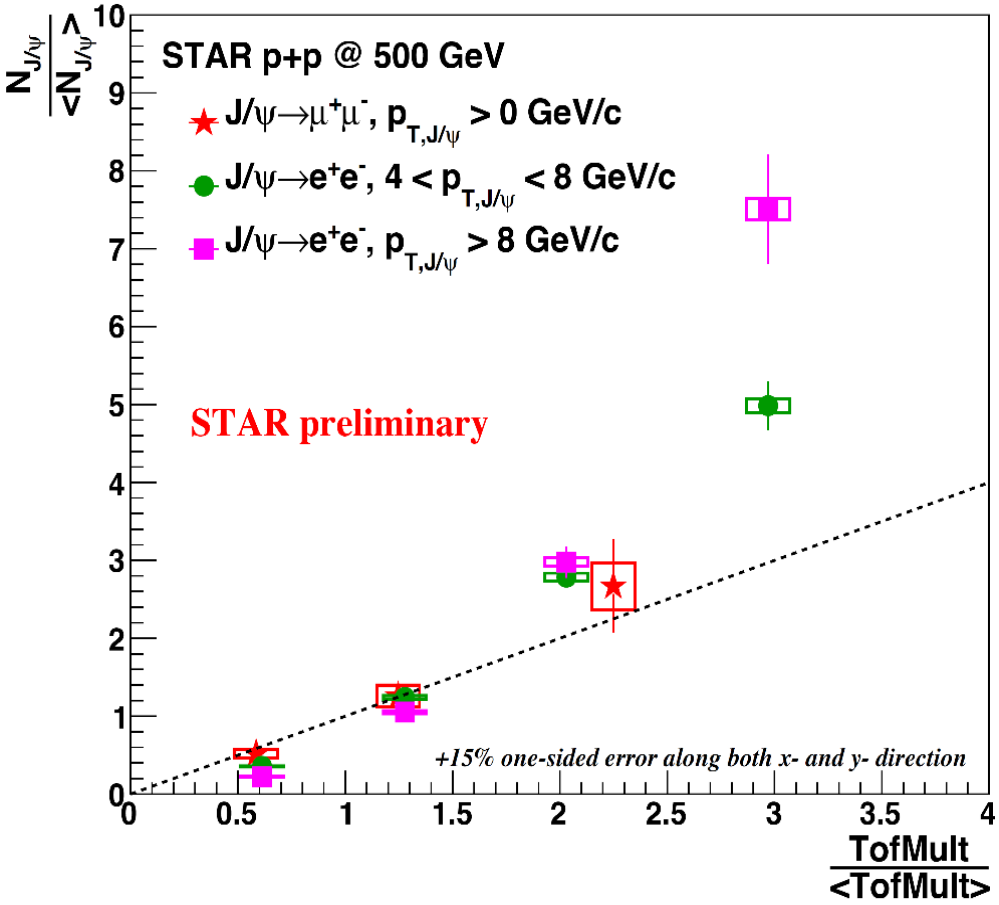
Percolation

- Reduction of effective number of color sources due to coherence at high density

EPOS

- Linear increase due to #MPI
- Stronger increase due to hydro. evolution

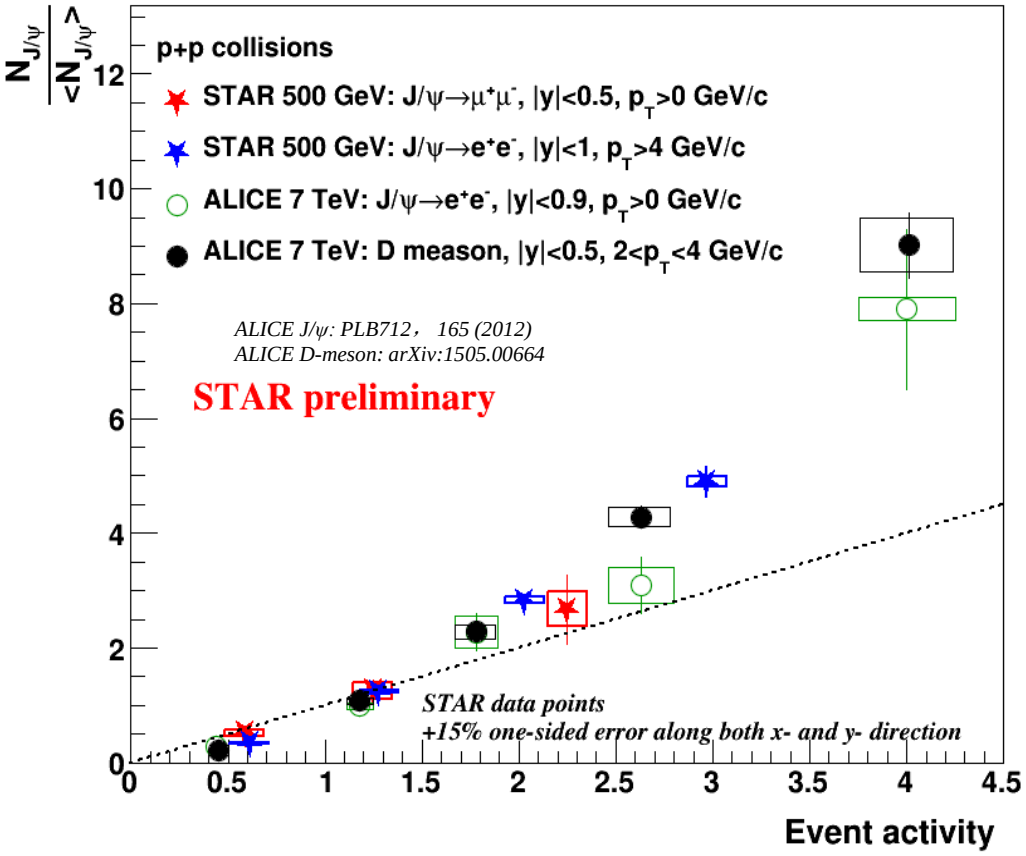
J/ψ yield vs. event activity at 500GeV



Stronger-than-linear increase observed at RHIC as well

Different trends for J/ψ with different p_T

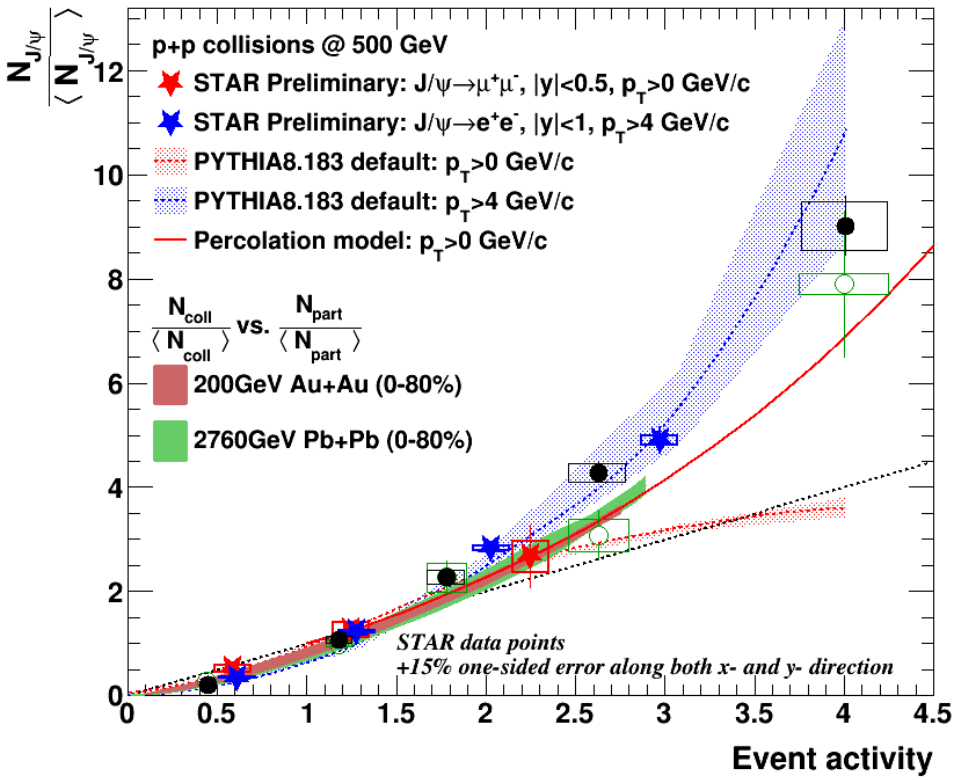
Compare to LHC



Similar dependence between：

- RHIC vs. LHC
- J/ψ vs. D

Compare to models



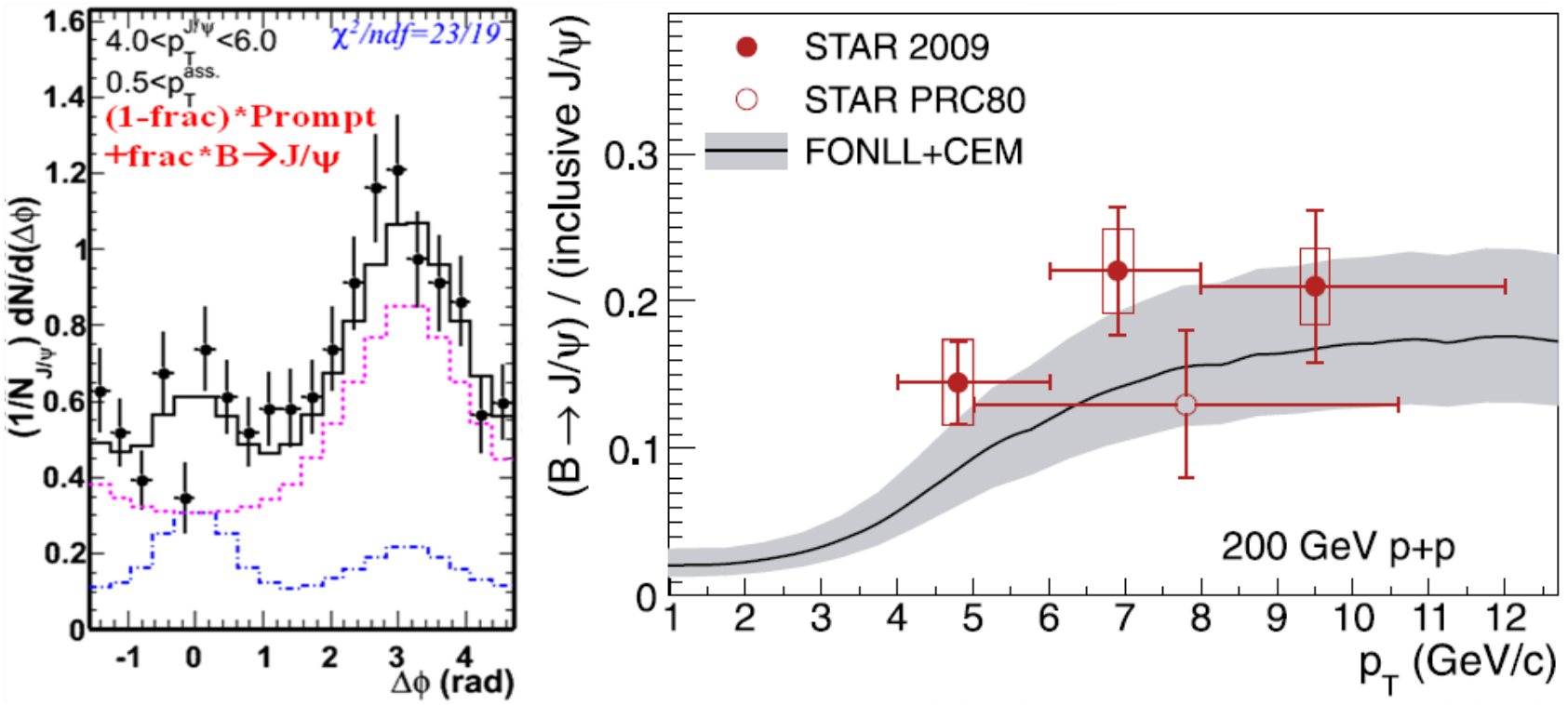
Both PYTHIA8 and percolation model describe data

Test with larger multiplicity bins is important

N_{coll} vs. N_{part} in heavy-ion collisions has similar trend

What a coincidence?!

B→J/ψ feed-down

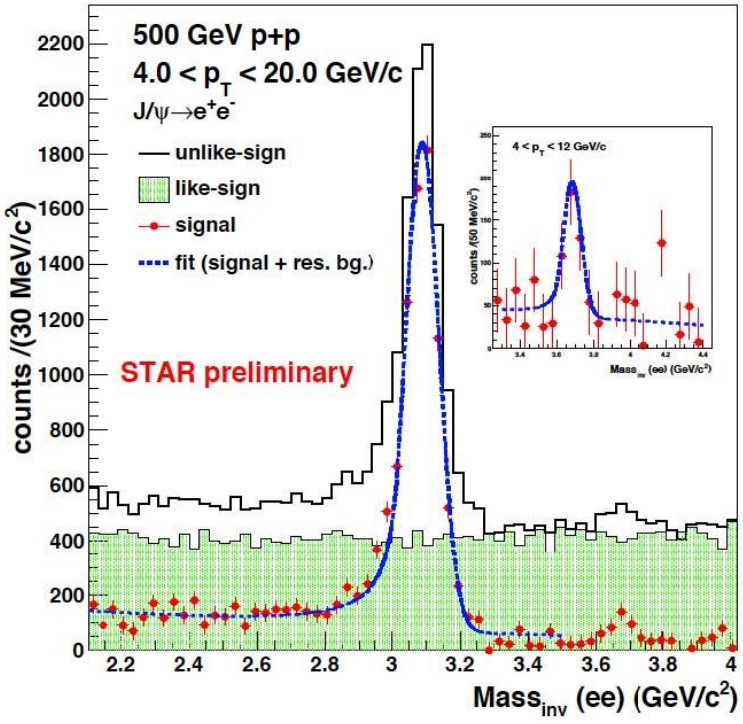


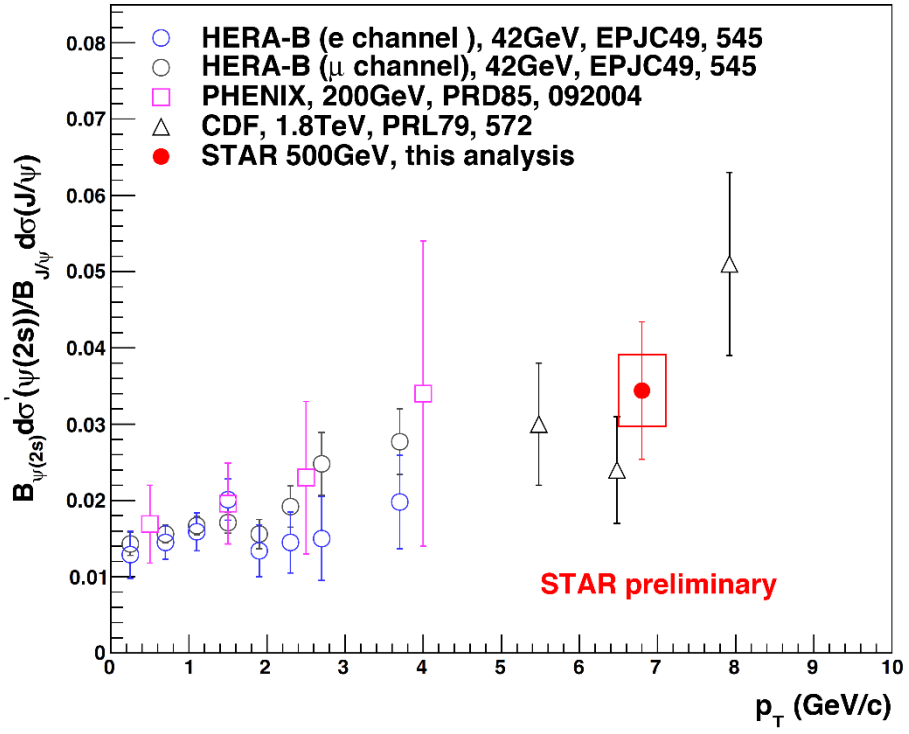
Extract B→J/ψ feed-down through J/ψ-hadron correlation

~10-25% at p_T>4 GeV/c at RHIC

Consistent with FONLL+CEM model calculation

ψ(2S) feed-down





Di-electron invariant mass in p+p collisions at 500GeV

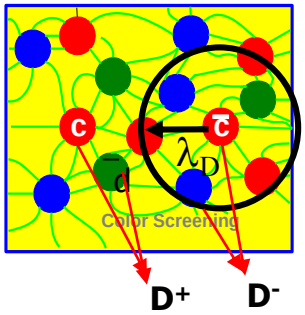
Follows world data trend with p_T

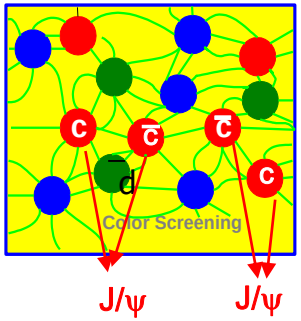
No obvious energy dependence

J/ψ production in heavy-ion collisions

- Modification in the hot, dense matter (QGP effects)
  - Suppression due to color-screening
  - Enhancement due to recombination

A+A

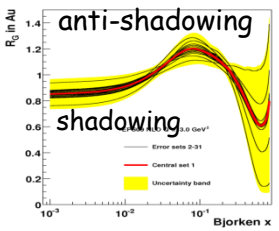


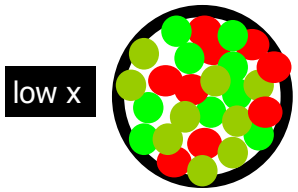


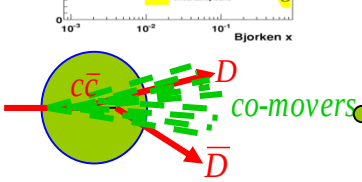
- Modification in the cold nuclear matter (CNM effects)
  - Gluon (anti-)shadowing
  - Gluon saturation
  - Absorption
  - Cronin effect

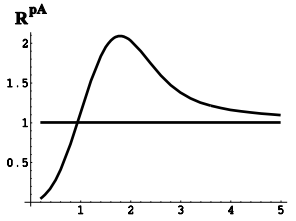
p(d)+A

A+A

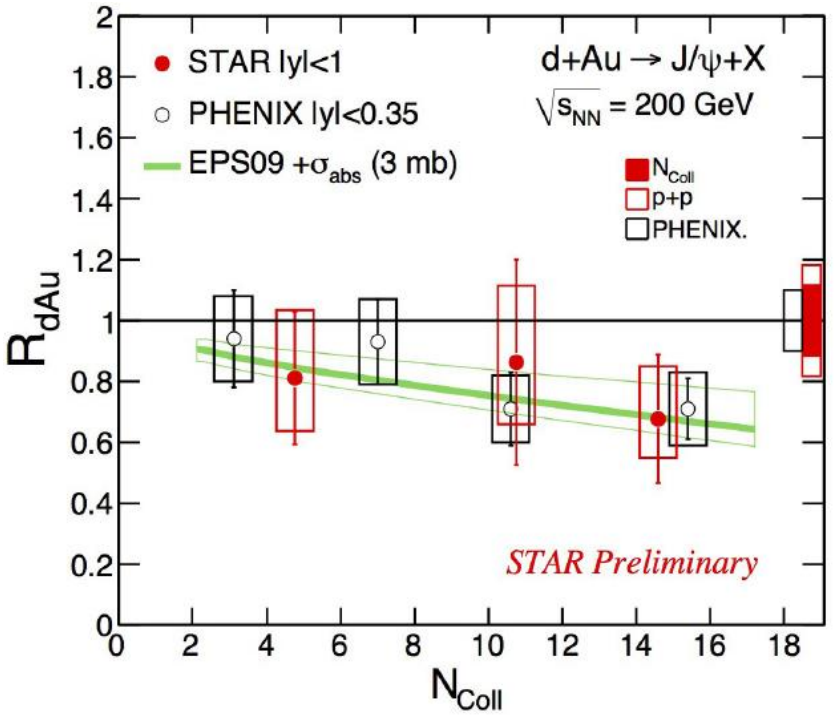


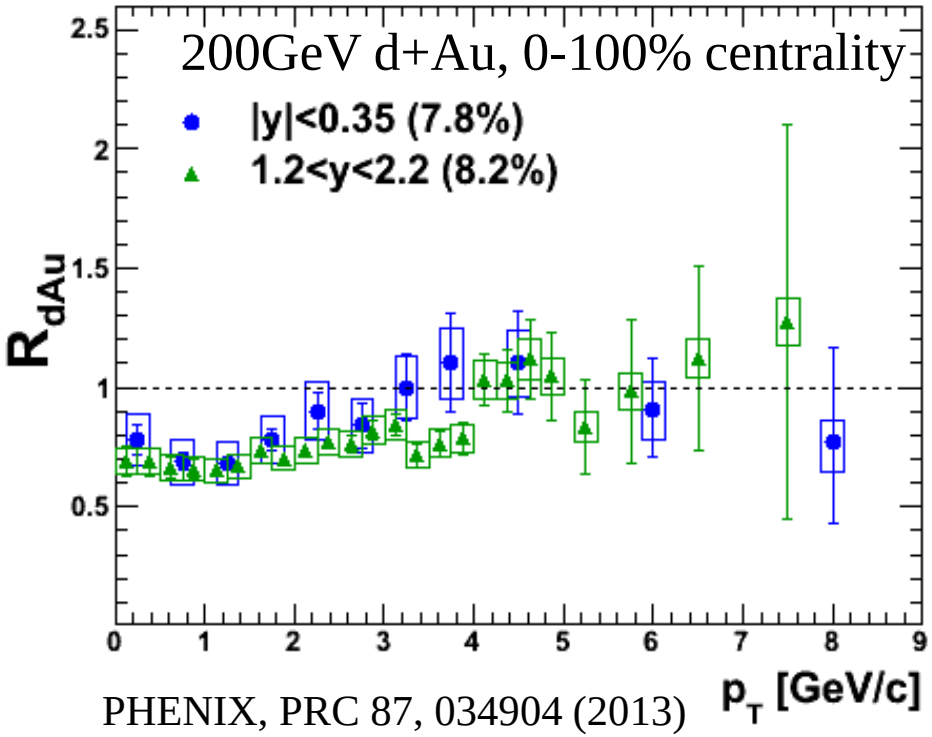






J/ψ suppression in d+Au



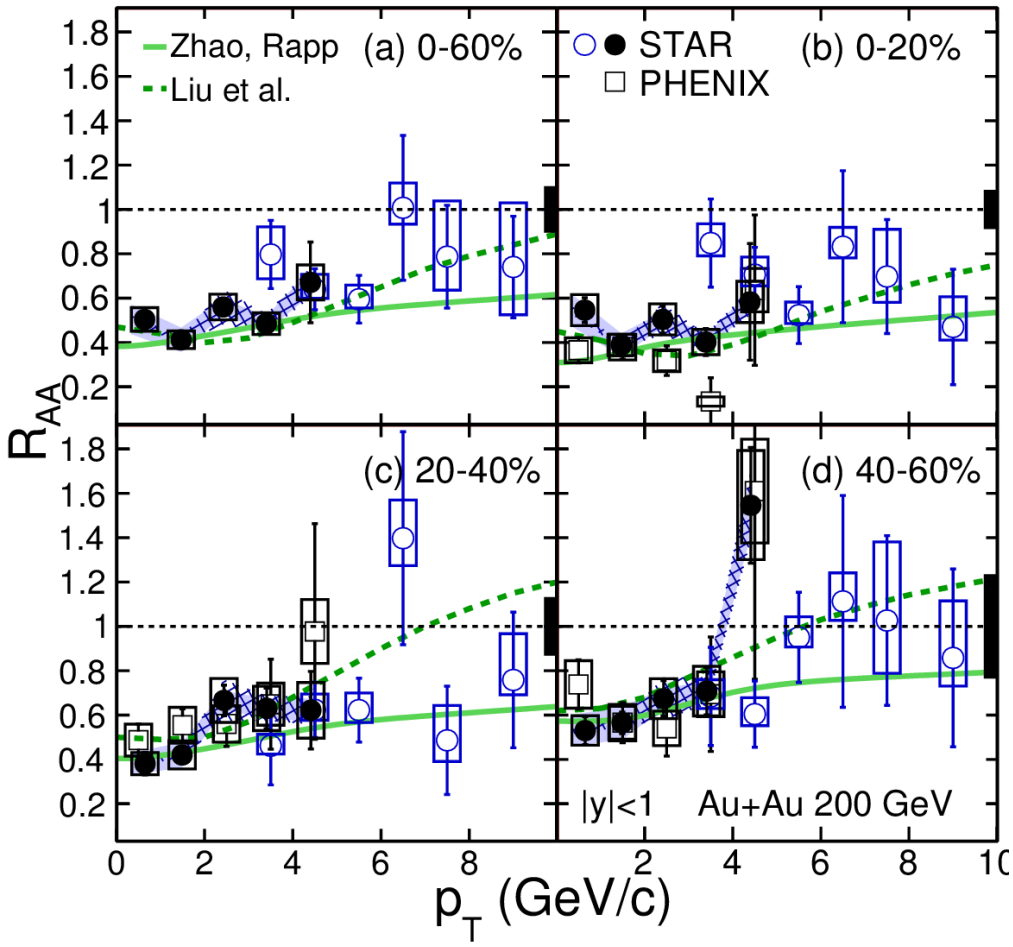


PHENIX, PRC 87, 034904 (2013)

Significant suppression in central d+Au, mainly at low-p_T

Consistent with no suppression at p_T>4 GeV/c

J/ψ suppression in 200GeV Au+Au



Less suppression at high p_T in all centralities

- Reduced CNM and recombination contributions

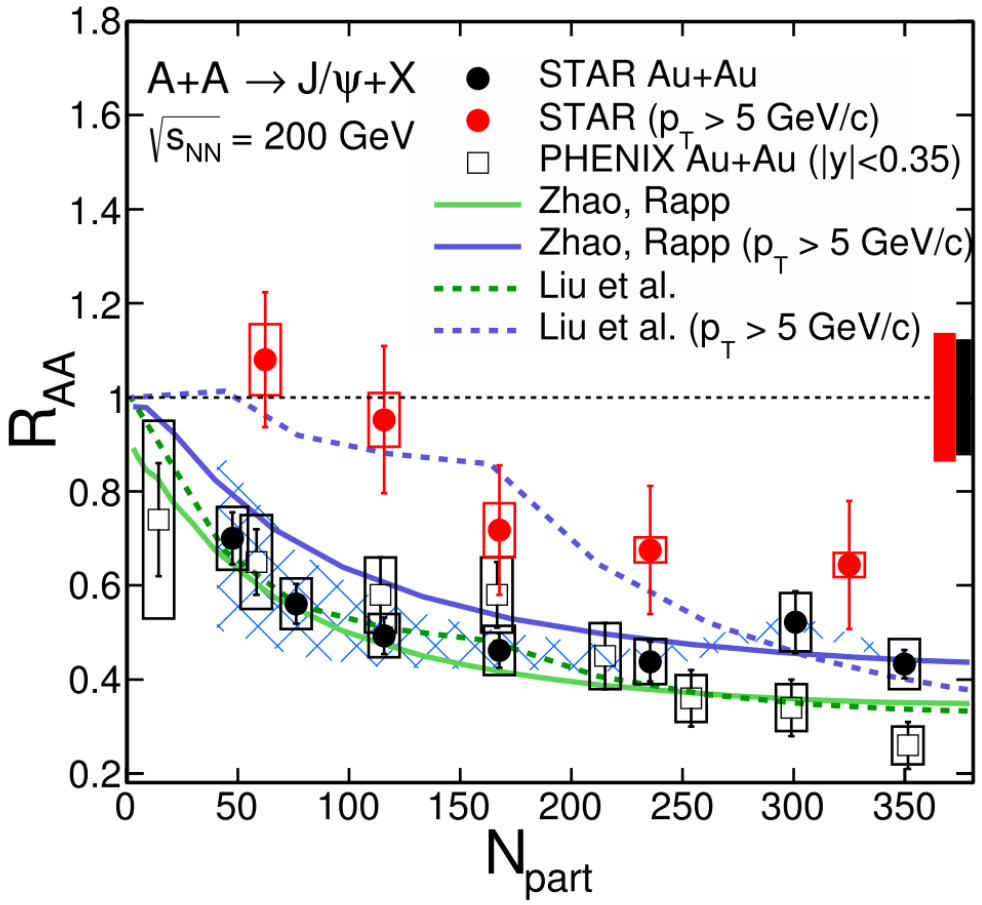
Agree with theoretical calculations with QGP effects included

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

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

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

Centrality dependence



Less suppression at high p_T in all centralities

High-p_T data consistent with unity in peripheral, significant suppression in central → May indicate QGP

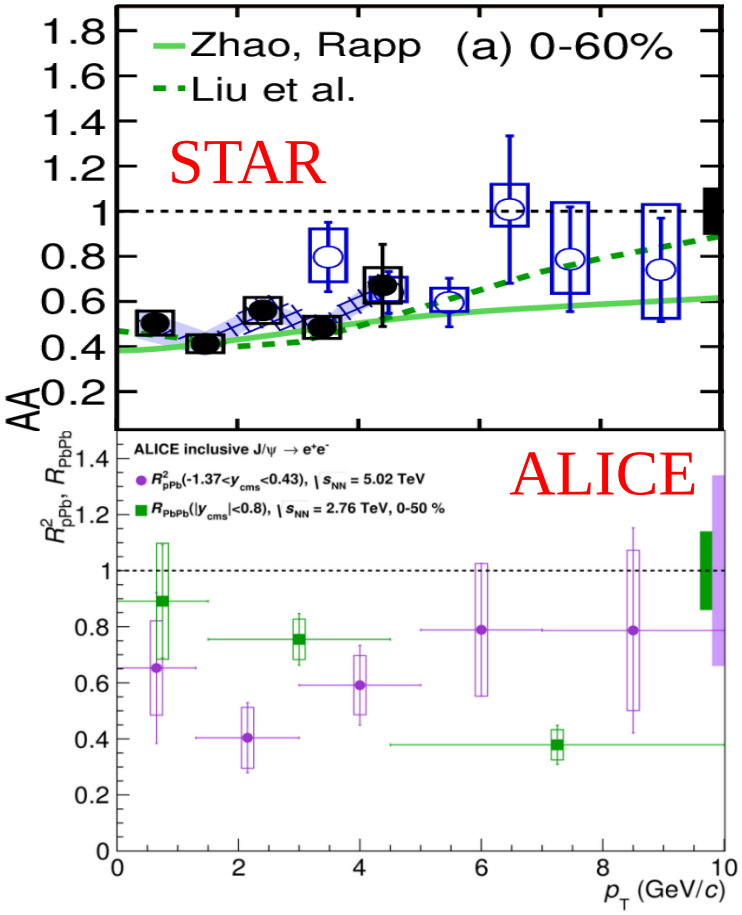
Models including color-screening and recombination describe data

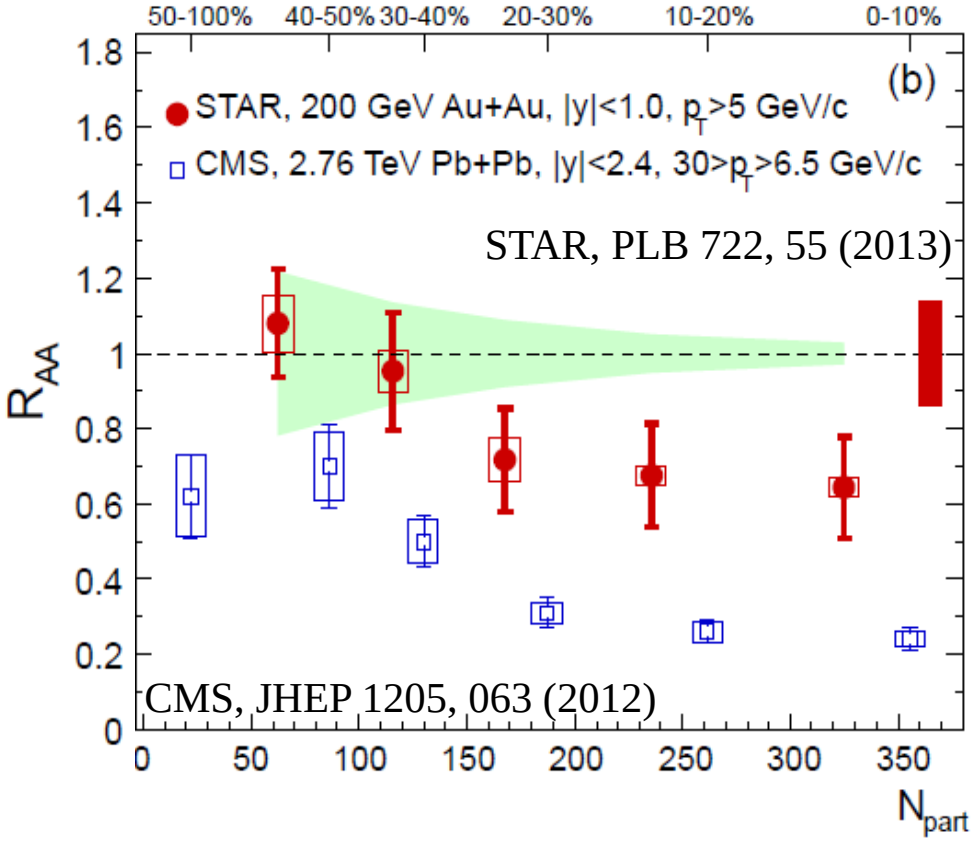
STAR: PLB 722, 55 (2013), PRC 90, 024906 (2014)

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

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

Compare to LHC

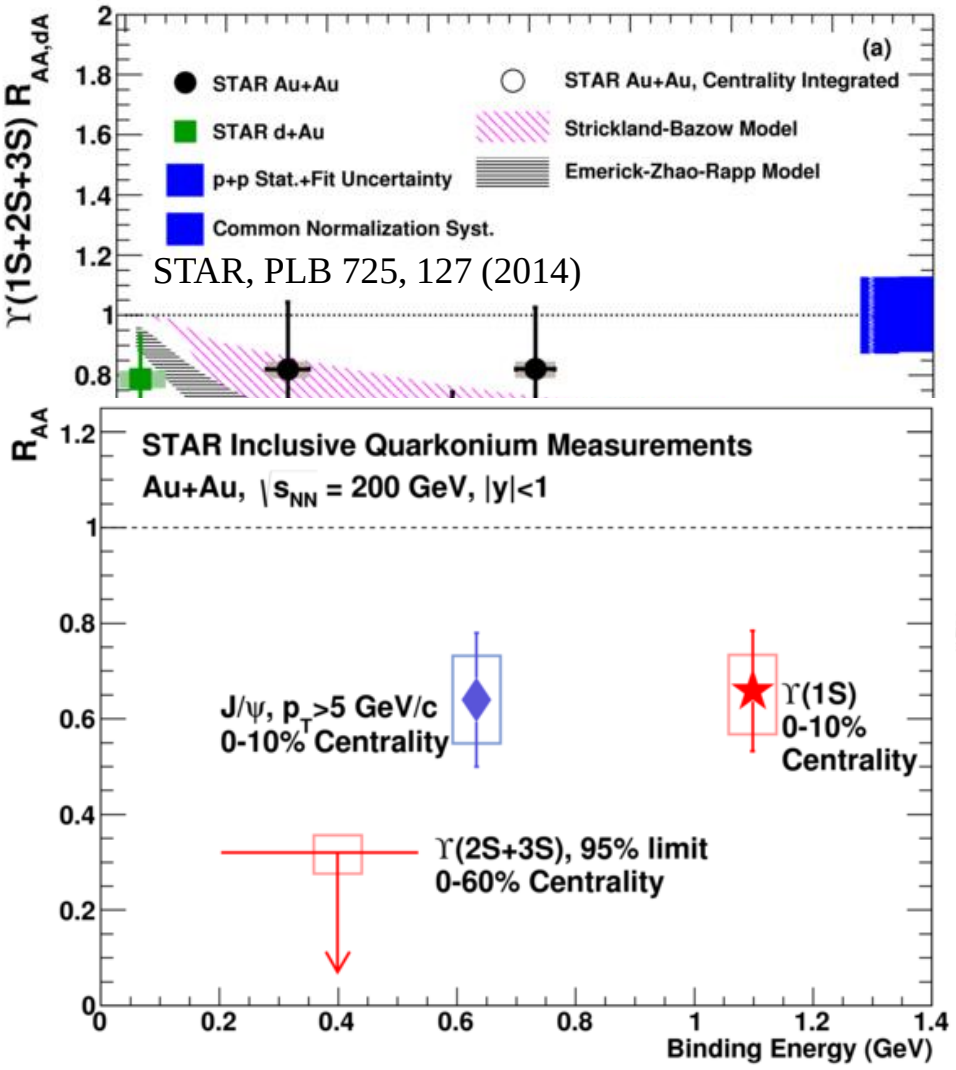




Different trend with p_T at RHIC and LHC

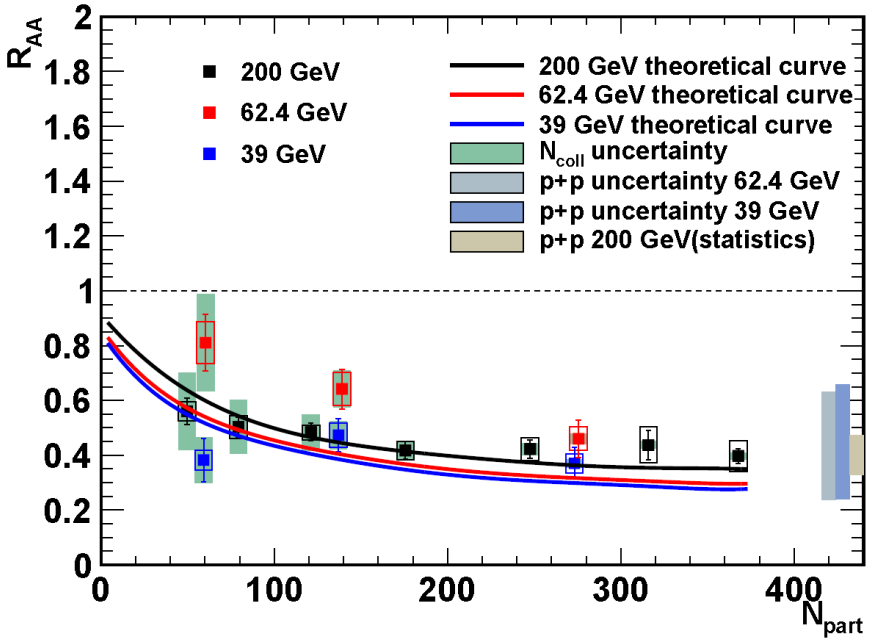
More suppression at LHC than at RHIC at high-p_T

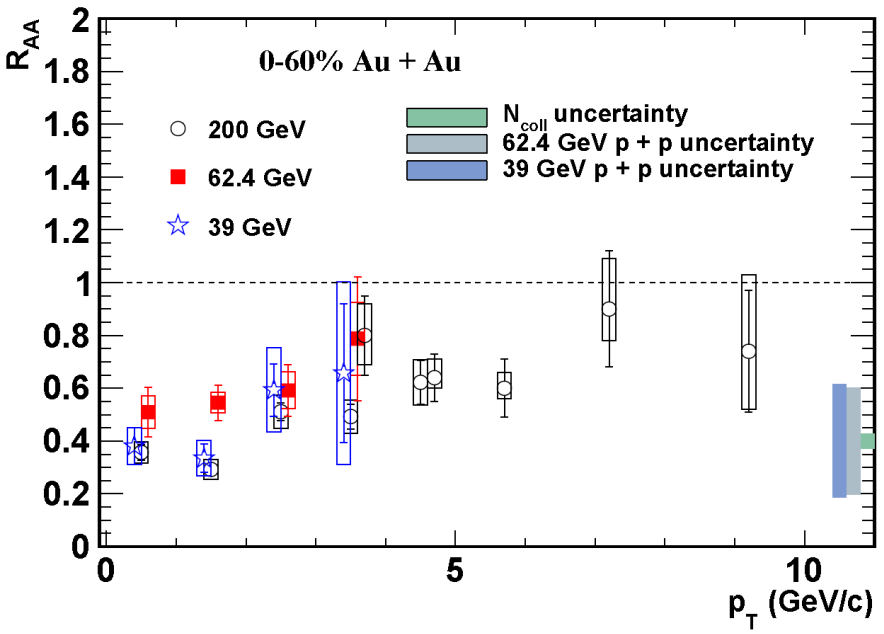
Upsilon measurement in 200GeV Au+Au



- Similar suppression from d+Au to mid-central Au+Au
- Stronger suppression in central collisions
- Agree with model based on lattice QCD calculation of melting in hot medium
- R_{AA}~0.6 for high-p_T J/ψ and Upsilon(1S)
- Stronger suppression for excited Upsilons

J/ψ in Beam Energy Scan





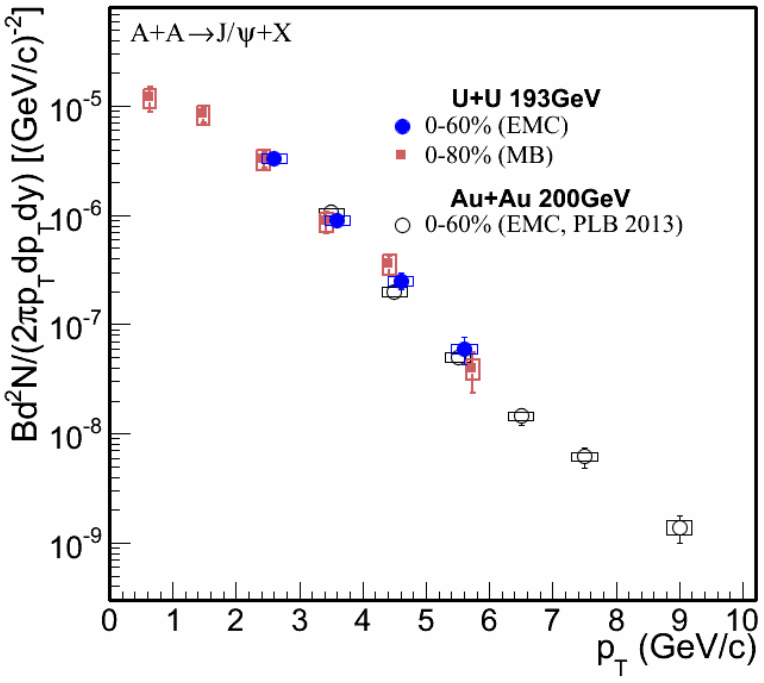
Similar suppression in Au+Au at 39, 62 and 200 GeV

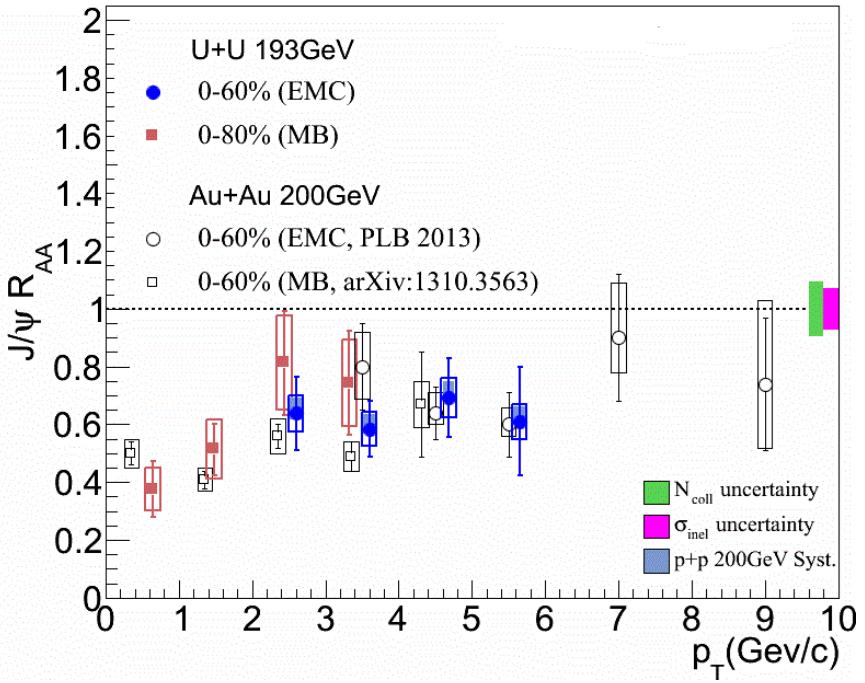
- p+p reference from CEM, large uncertainty
- Developed a interpolation method to improve (W. Zha et al., arXiv: 1506.08985)

Theoretical calculations predict weak energy dependence as well

- Compensation of various medium effects

J/ψ in U+U collisions

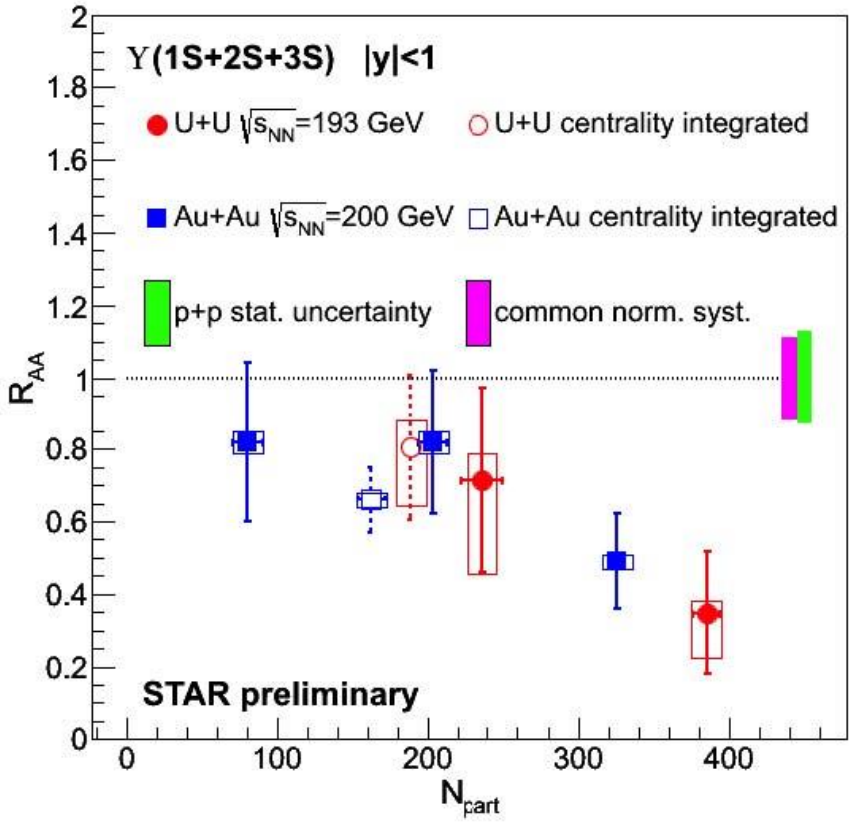


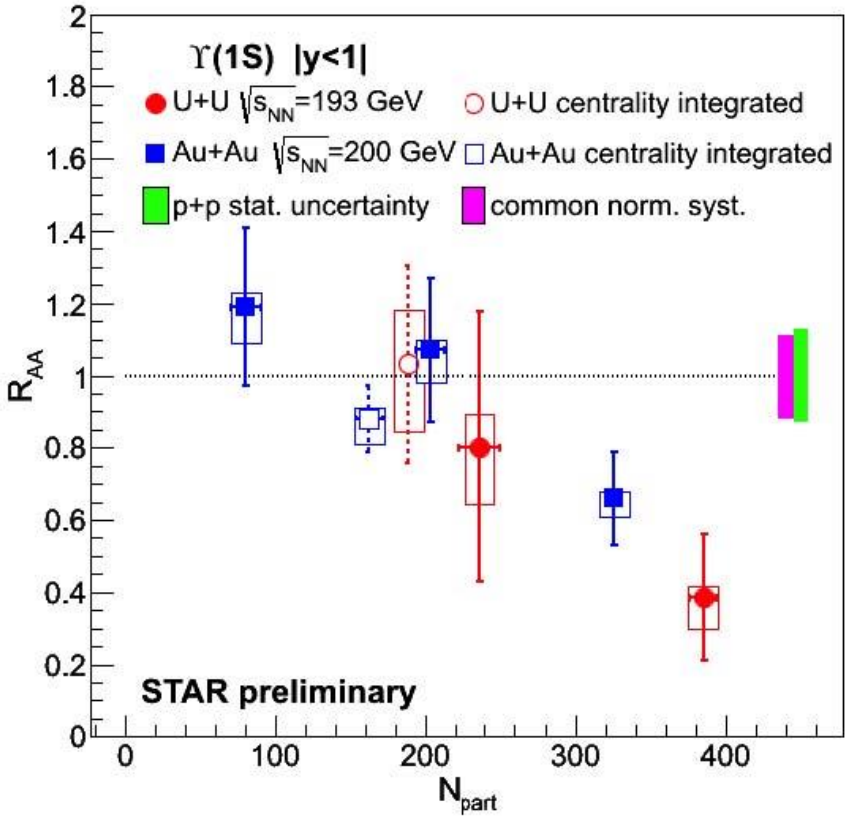


Baseline: J/ψ measurements in p+p 200 GeV.

Similar suppression pattern as in Au+Au 200 GeV

Upsilon in U+U collisions





Similar suppression pattern as in Au+Au 200 GeV

Summary

J/ψ measurements in p+p collisions

- p_T spectra agree with NRQCD at high p_T and CGC+NRQCD at low p_T
- Theoretical uncertainty on polarization is large
- Both p_T spectra and polarization follows x_T scaling at high p_T
- J/ψ yield vs. event activity provides a new tool

Quarkonia measurements in heavy-ion collisions

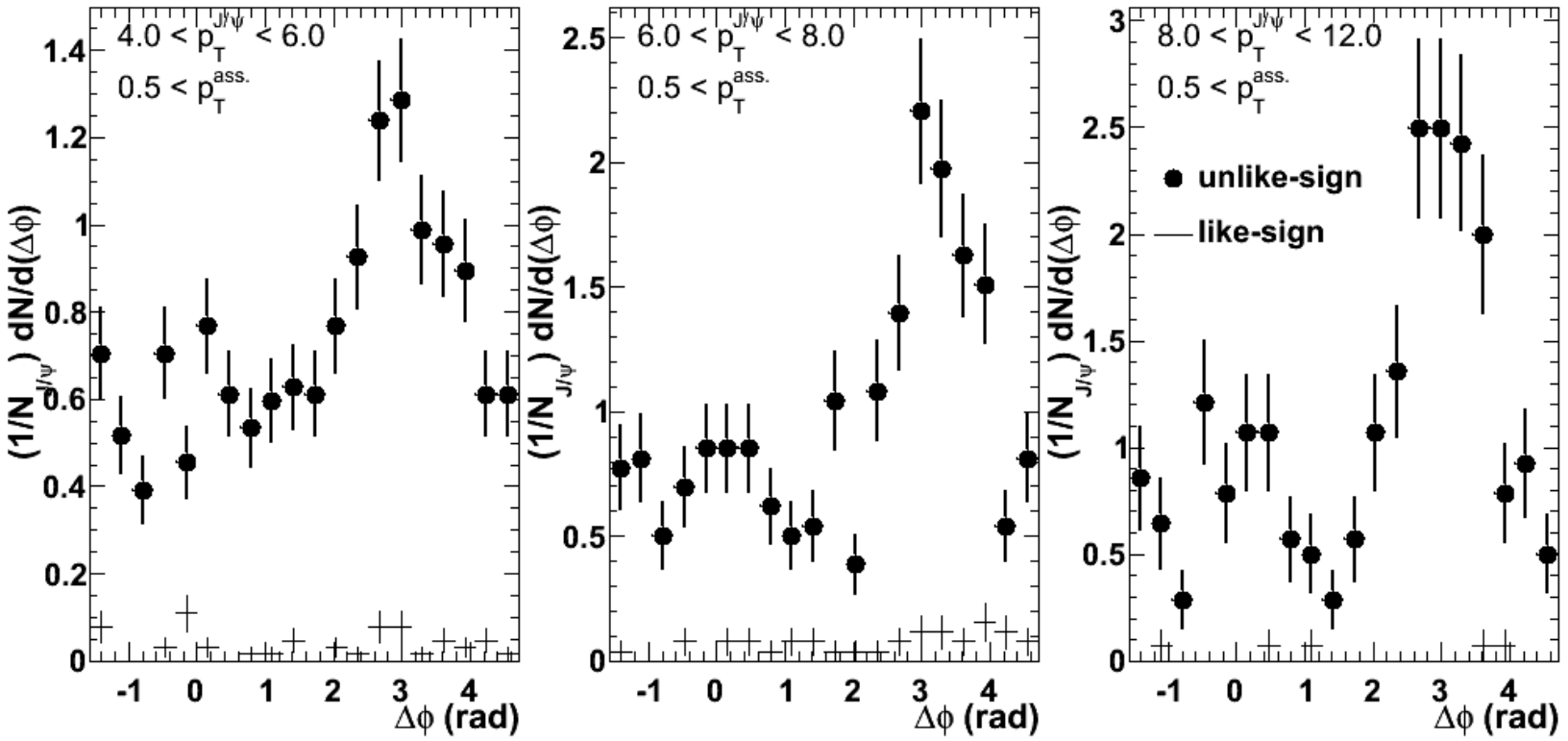
- Suppression of high-p_T J/ψ and Upsilon observed in central Au+Au
- Consistent with theoretical calculations including QGP effects
- No obvious beam energy and system size dependence

Thanks

Backup slides

J/ψ-hadron angular correlation

400 J/ψ with p_T>4 GeV/c and 3.0<M<3.2 GeV/c^2, **S:B=22:1**

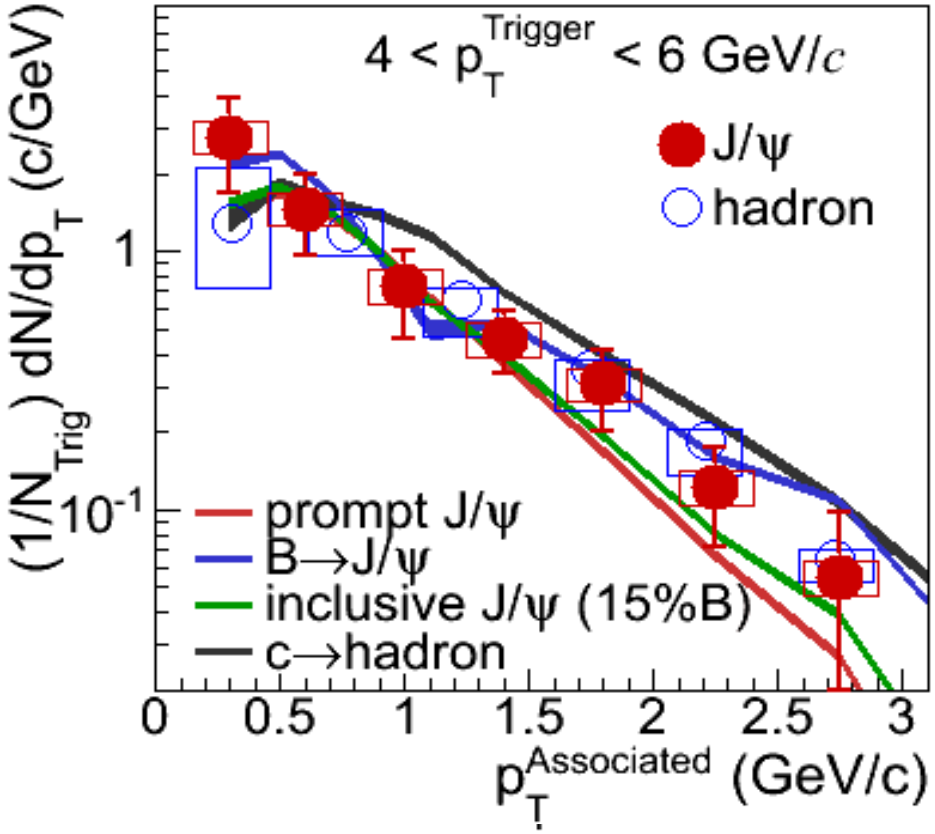


$$C_{J/\psi}(\Delta\phi) = [(D_{e^{\pm}e^{\mp}-h}(\Delta\phi) - (D_{e^{\pm}e^{\pm}-h}(\Delta\phi)]/(N_{e^{\pm}e^{\mp}} - N_{e^{\pm}e^{\mp}})$$

No significant near-side correlation

Strong away-side correlation

Away-side hadron p_T spectra



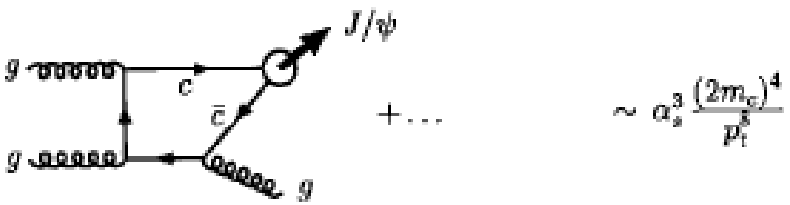
Consistent with hadron-hadron correlation

Consistent with PYTHIA8 simulation

Away-side parton

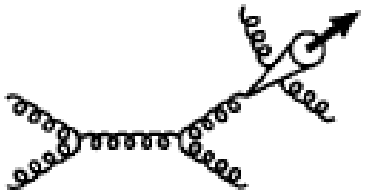
Color-Singlet

(a) leading-order colour-singlet: $g + g \to c\bar{c}[^3S_1^{(1)}] + g$



$+\ldots \quad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

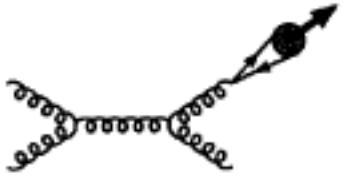
(b) colour-singlet fragmentation: $g + g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



$+\ldots \quad \sim \alpha_s^5 \frac{1}{p_t^4}$

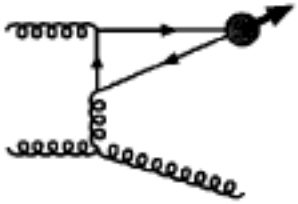
Color-Octet

(c) colour-octet fragmentation: $g + g \to c\bar{c}[^3S_1^{(8)}] + g$



$+\ldots \quad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

(d) colour-octet t-channel gluon exchange: $g + g \to c\bar{c}[^1S_0^{(8)}, ^3P_J^{(8)}] + g$



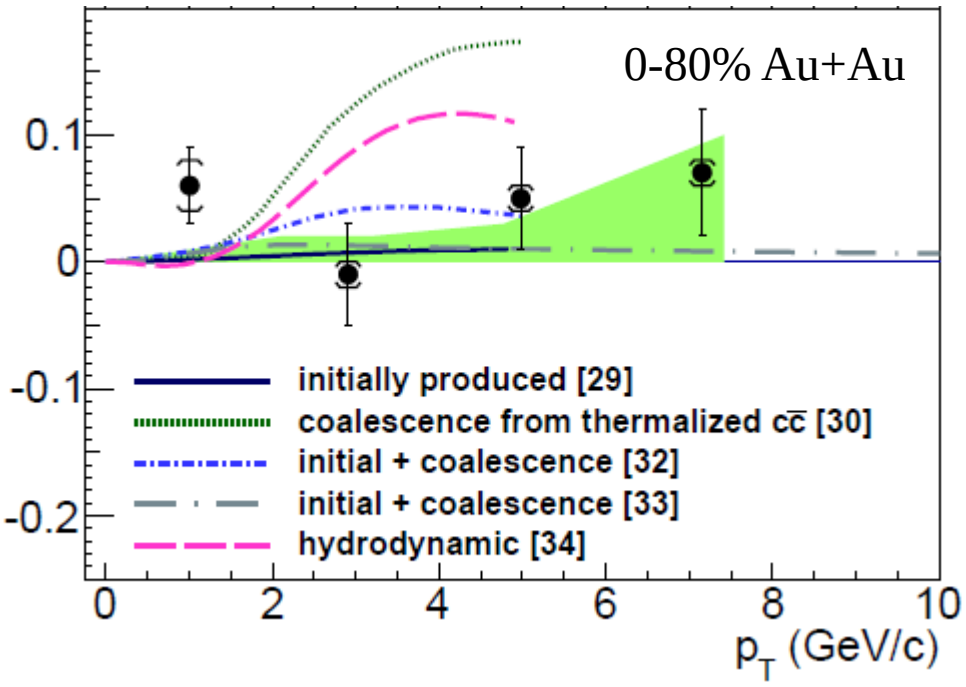
$+\ldots \quad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

K. Kramer, Prog. Part. Nucl. Phys. 47, 141 (2001)

There is always a gluon jet on the away side

Gluon jet tag?

J/ψ ellptic flow in 200GeV Au+Au



At p_T > 2 GeV/c:

- Consistent with 0
- Disfavor the case of dominantly produced by thermalized charm quarks coalescence

STAR, PRL in press

theoretical calculation	χ^2/NDF	p-value
initially produced [29]	3.7 / 3	2.9×10^{-1}
coalescence from thermalized $c\bar{c}$ [30]	21.1 / 3	1.0×10^{-4}
initial + coalescence [32]	3.7 / 3	3.0×10^{-1}
initial + coalescence [33]	4.9 / 4	3.0×10^{-1}
hydrodynamic [34]	10.1 / 3	1.7×10^{-2}

J/psi radial flow

Tsallis Blast-Wave model: ZBT *et al*., CPL 30, 031201 (2013); JPG 37, 085104 (2010)

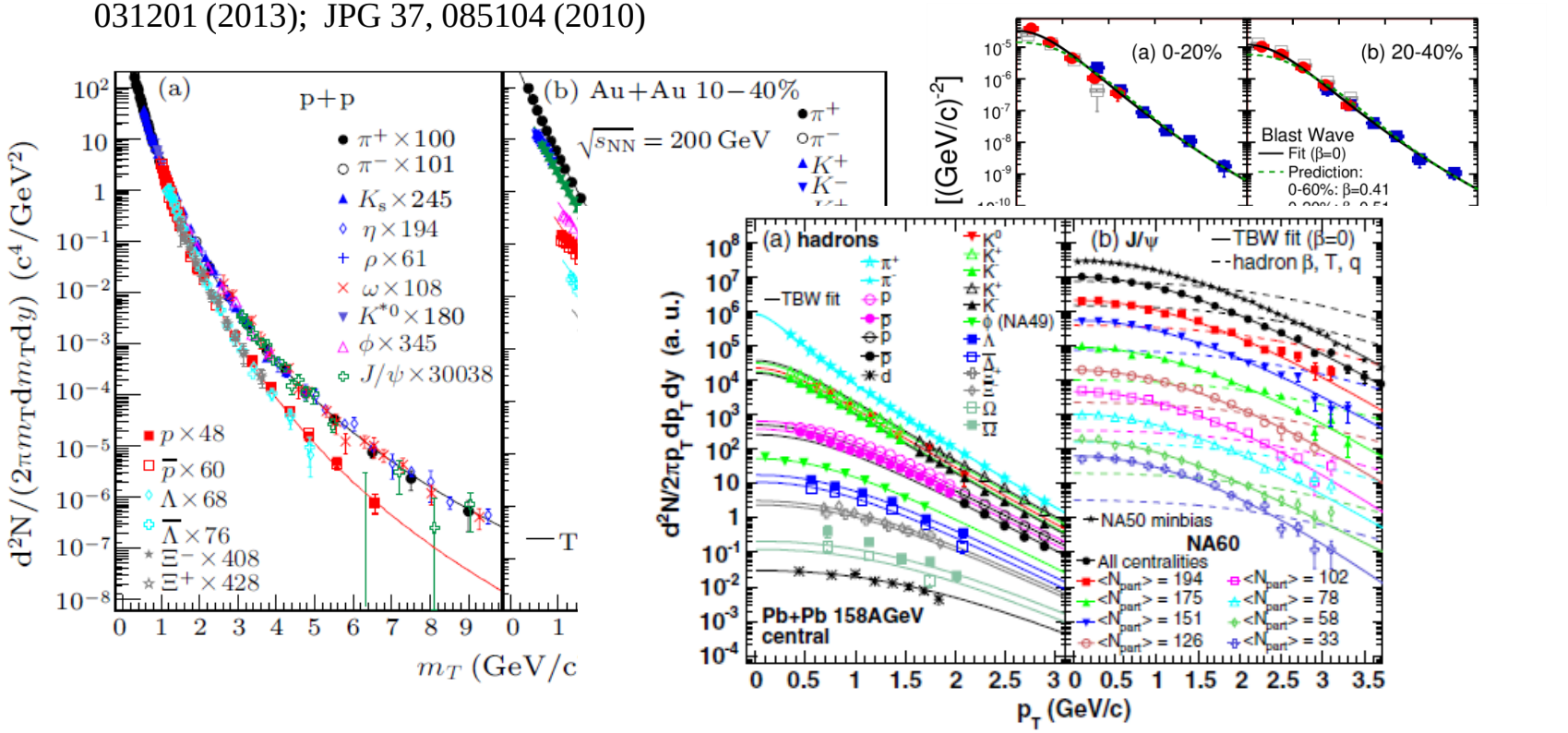
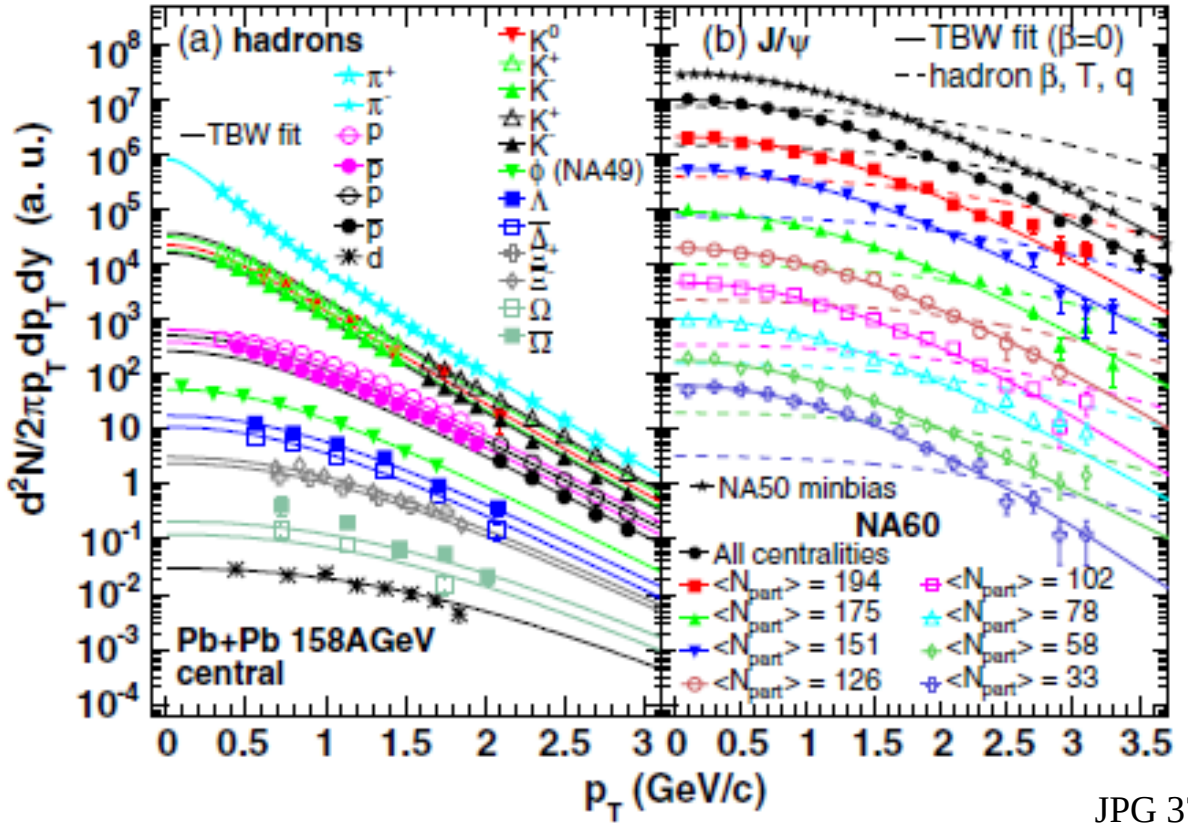


Figure 2. Identified particle spectra in central Pb+Pb collisions at the beam energy of 158 A GeV from the fixed-target experiments at SPS. Left panel: spectra of light hadrons and strange hadrons. The solid curves are results from the TBW fit. Right panel: J/ψ spectra, the dashed line is the TBW prediction using parameters from the fit to other hadrons, and the solid curve is a TBW fit to J/ψ alone.

No sign of radial flow at SPS either



JPG 37, 085104 (2010)

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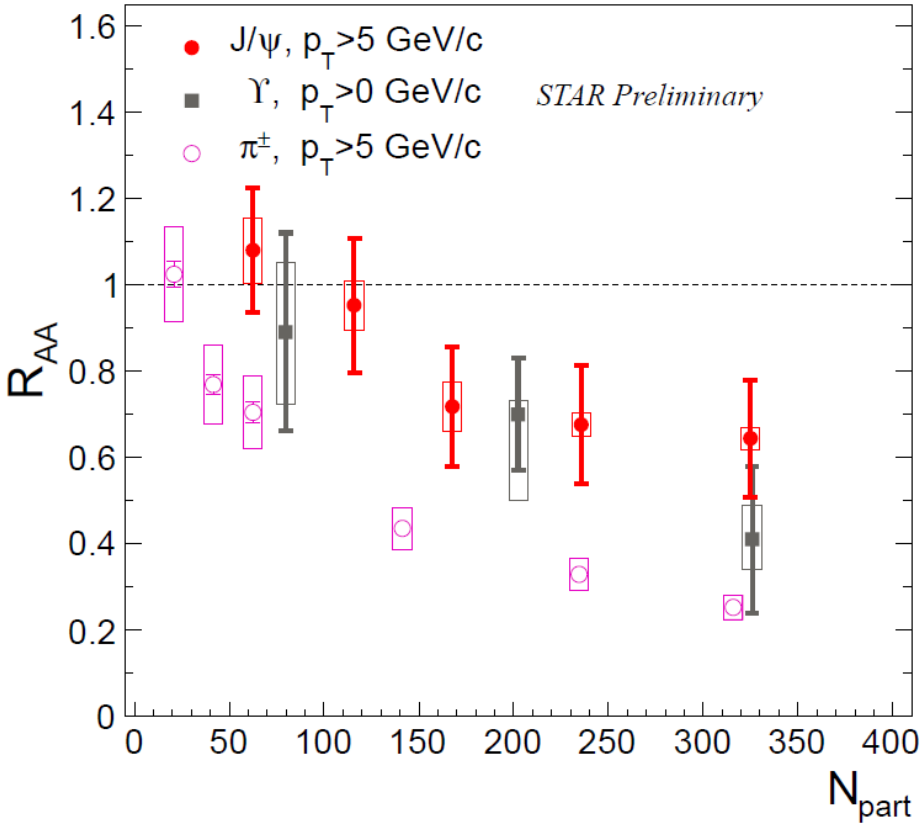
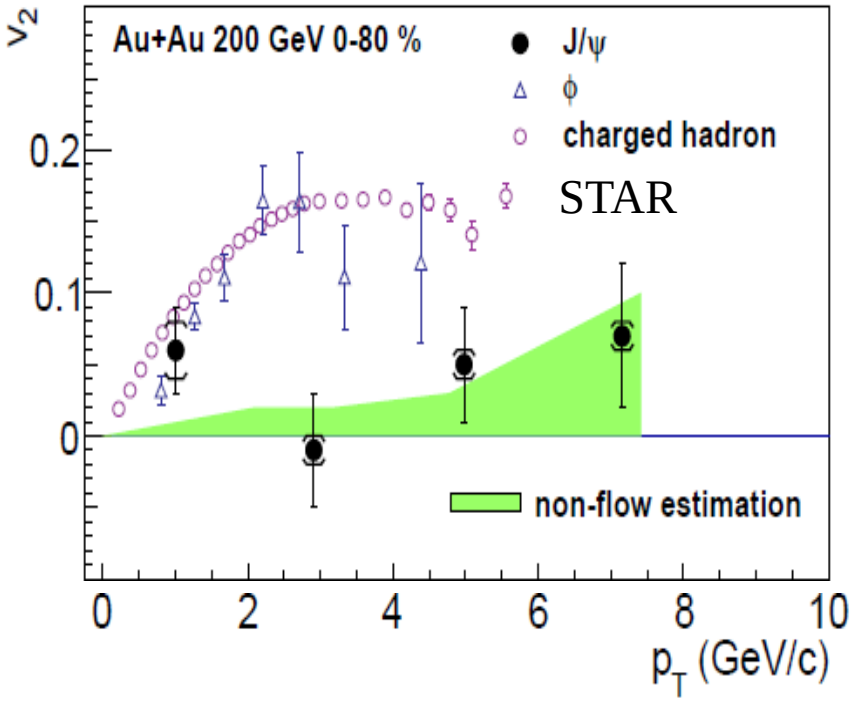
Quarkonium is a unique probe of QGP





Similar suppression for high-p_T J/ψ and Upsilon

J/ψ R_{AA} and v_2 very different from other hadrons

Empirically, J/ψ is the only measured hadron at RHIC with significant suppression in R_{AA}, but no elliptic flow and radial flow