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Quarkonium Measurements @RHIC-STAR

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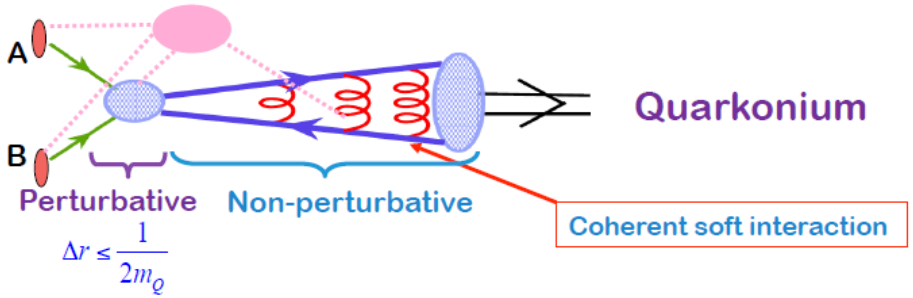
Outline

- Introduction
- J/ψ production in p+p collisions
  - p_T differential cross-section
  - Polarization
  - Yield vs. event activity
- Quarkonium production in Heavy-ion collisions
  - J/ψ R_{AA} vs p_T
  - J/ψ R_{AA} vs. centrality
  - Upsilon
- Summary

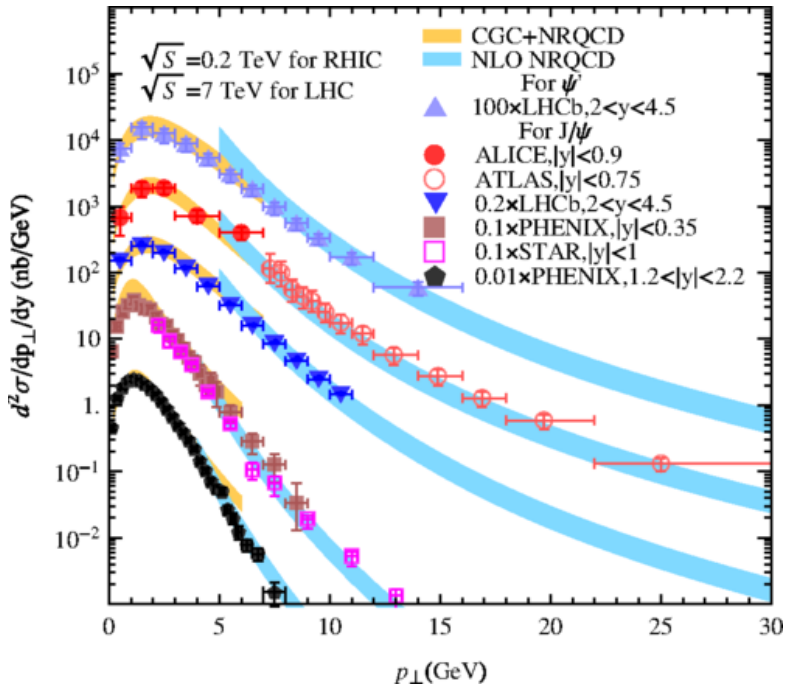
Quarkonium production mechanism in p+p

Jianwei Qiu, ECT workshop, 2016*



Approximation: on-shell pair + hadronization

$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_n \int dq^2 \left[\sigma_{AB\to[Q\bar{Q}](n)}(q^2)\right] F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$$



NRQCD factorization:

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \langle \mathcal{O}^H(n)\rangle$$

Matrix elements obtained from global fitting

CGC+NRQCD:

Gluon distribution described by CGC

STAR Data:
PRC80, 041902 (2009), PLB722, 55 (2013)

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

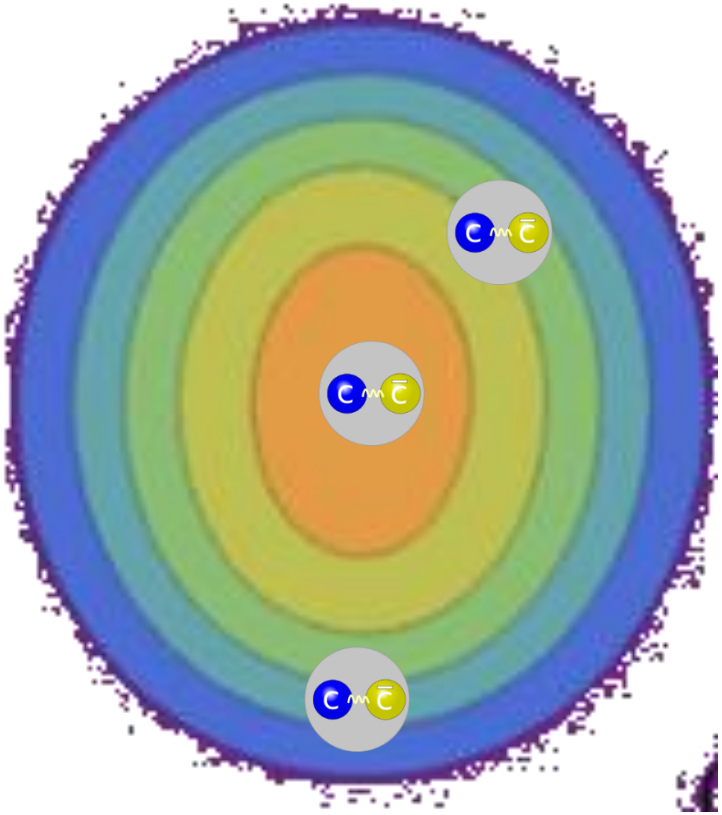
CGC+NRQCD:
Y.-Q. Ma and R. Venugopalan, PRL113, 192301 (2014)

Quarkonium in heavy-ion collisions

Hot nuclear matter effects (QGP effects)

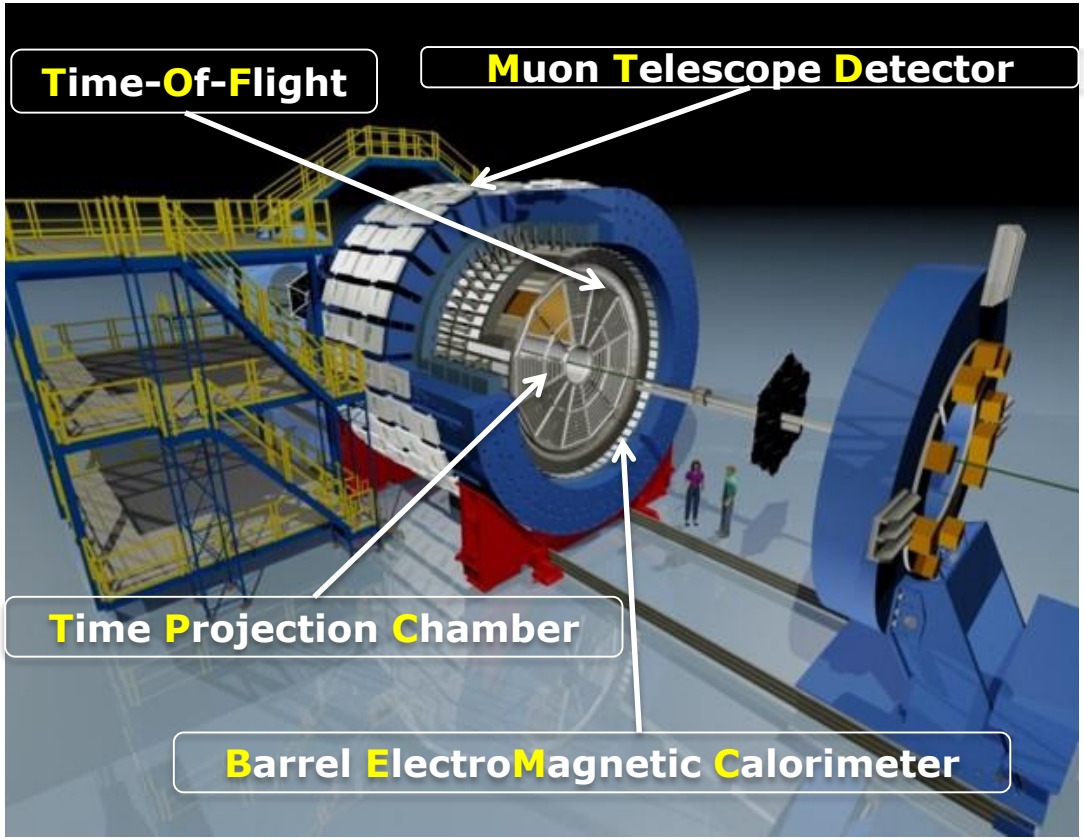
- Suppression due to color-screening
- Enhancement due to (re)generation

Probe the properties of QGP



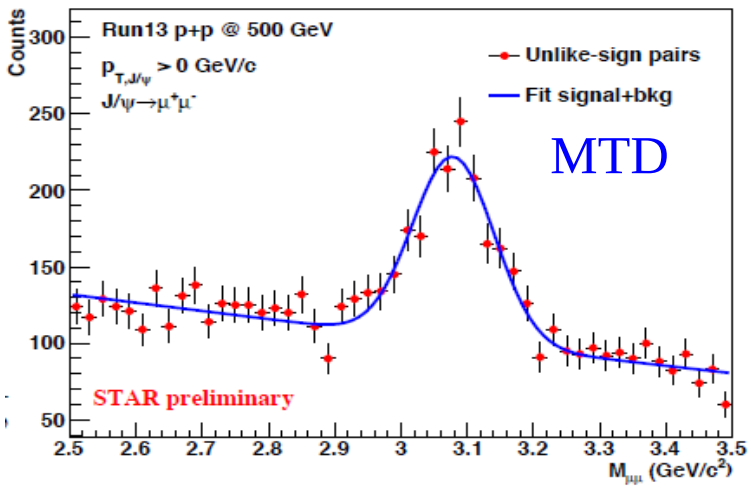
RHIC-STAR Experiment

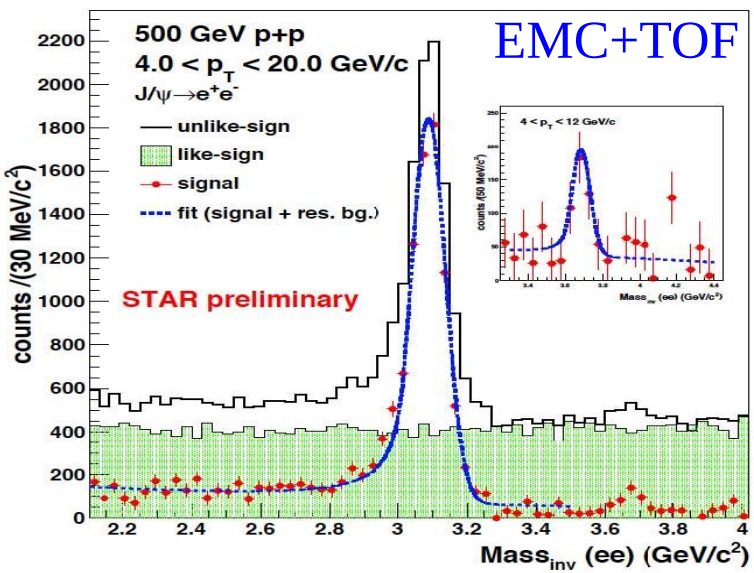
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$

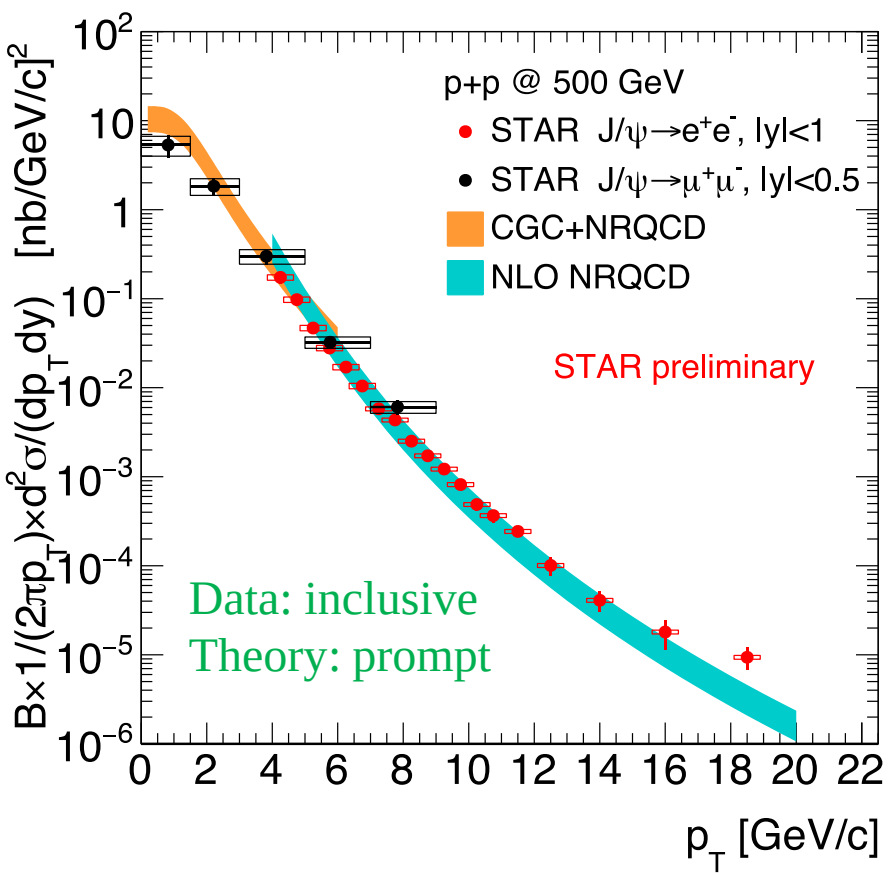


- **TPC**: precisely measure momentum and energy loss
- **TOF**: measure time-of-flight
  - **Installed 100% in 2010**
  - ***Precise timing for PID***
- **BEMC**: trigger on and identify electrons
- **MTD ($|\eta|<0.5$)** : trigger on and identify muons
  - **Installed 63% in 2013 and 100% in 2014** behind magnet
  - ***Precise timing measurement (σ~100 ps)***
  - ***Dimuon trigger for quarkonia***

J/ψ in 500 GeV p+p



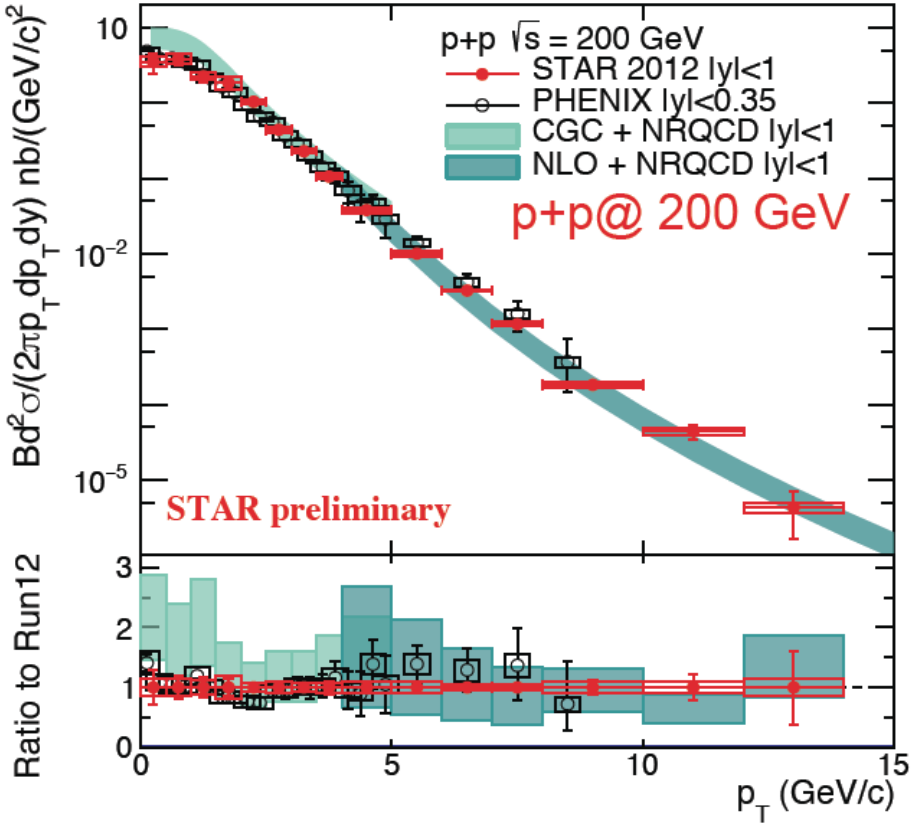




CGC+NRQDC and **NRQCD**

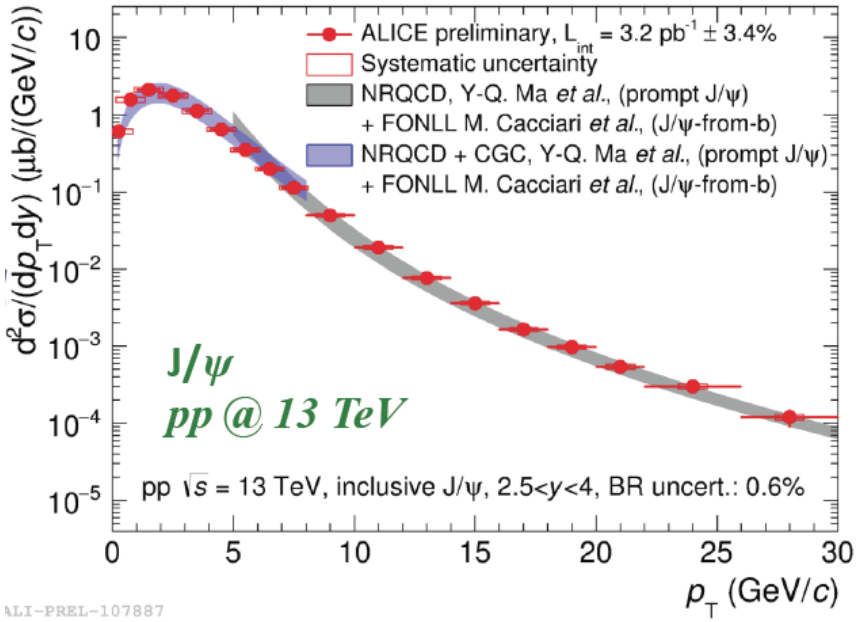
agree with the new data

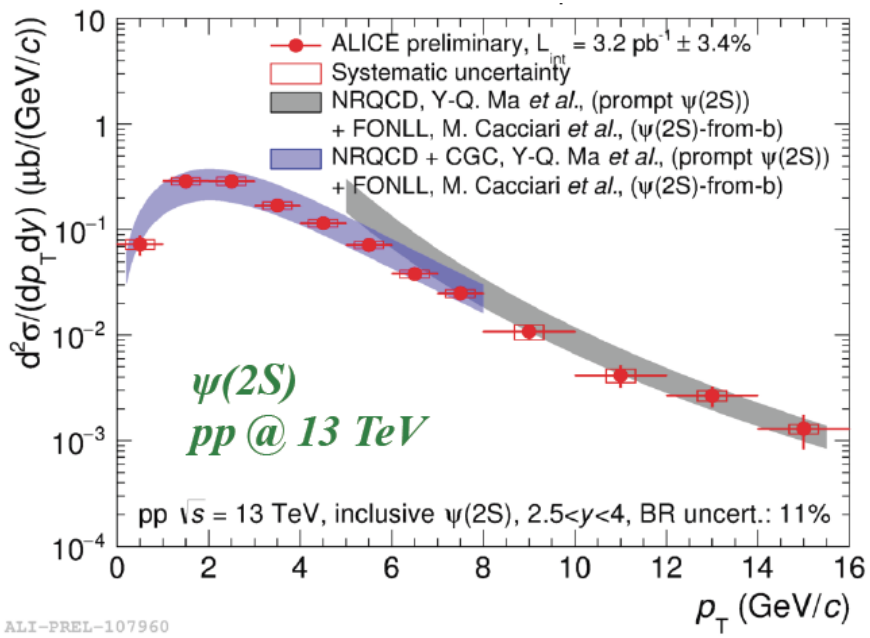
J/ψ in 200 GeV p+p (2012 data)



- New data consistent with PHENIX and STAR previous results, but with better precision
- Described by CGC+NRQCD and NRQCD, small tension at low-p_T

Charmonium in p+p at 13 TeV

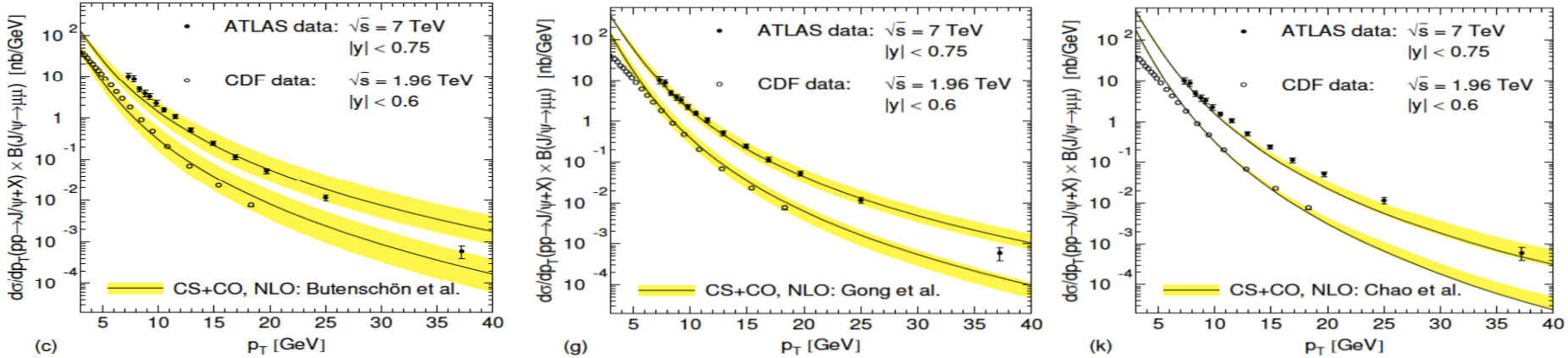




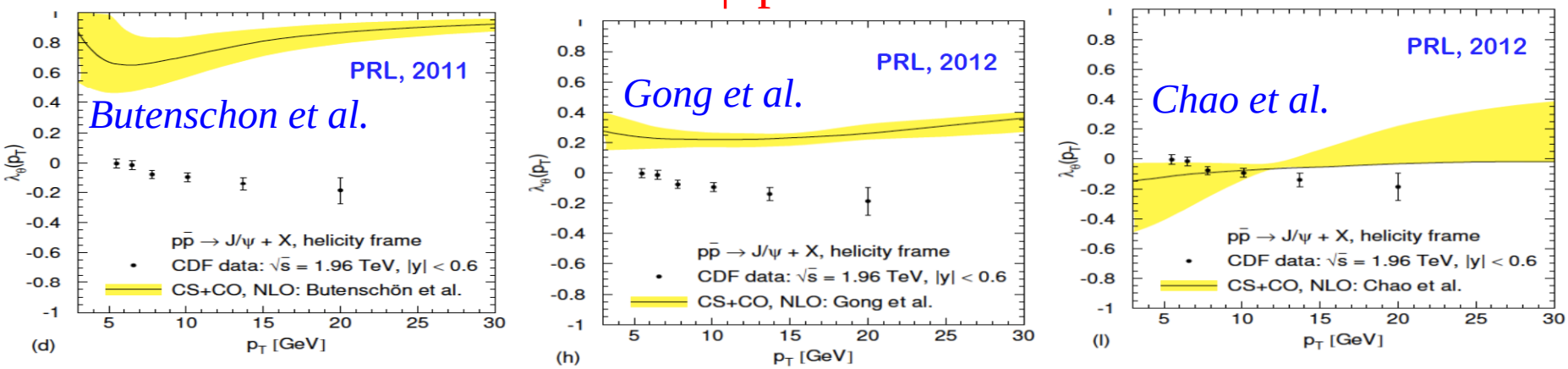
LHC new data described by CGC+NRQCD and NRQCD

J/ψ Polarization

J/ψ p_T spectra

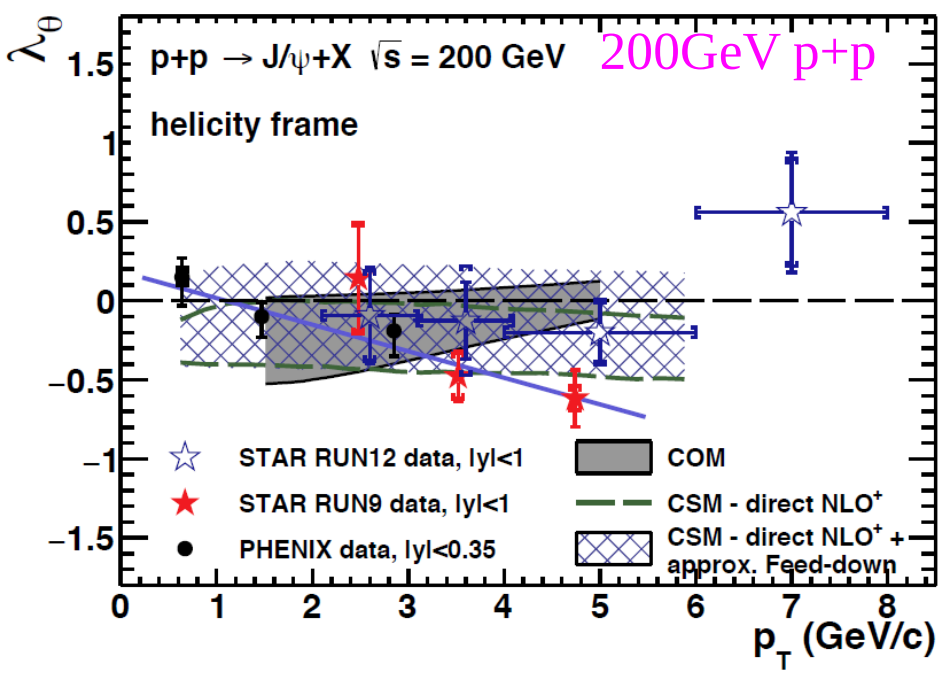


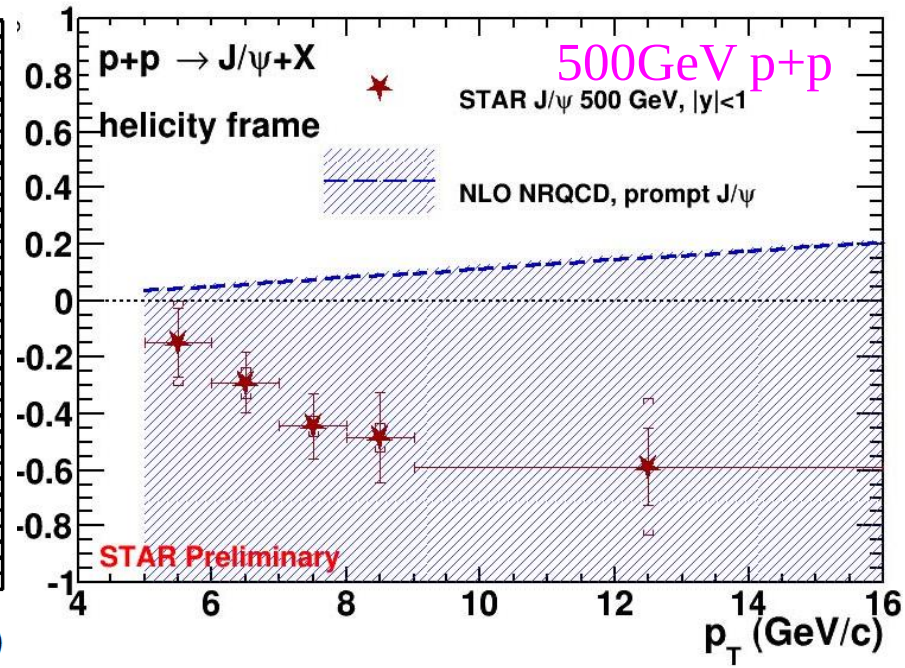
J/ψ polarization



J/ψ polarization: more constraints for the production mechanism models

J/ψ polarization at RHIC-STAR

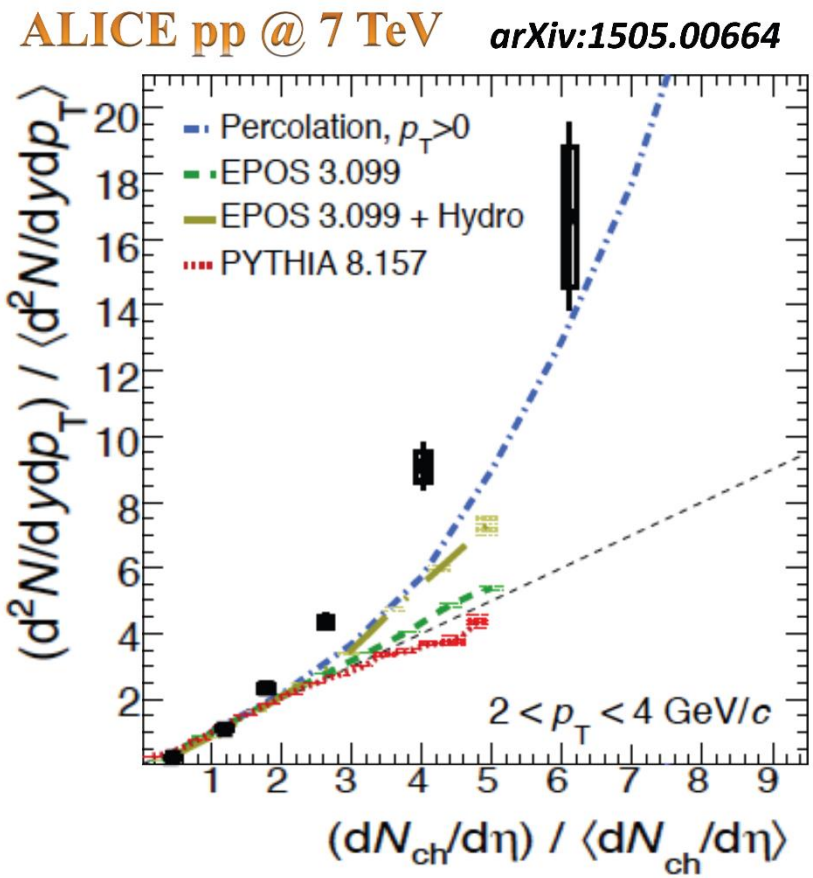




NLO NRQCD:
Phys. Rev. Lett. 108 (2012) 242004, Phys.Rev. D90 (2014) 1, 014002, Phys.Rev.Lett 112 (2014) 18, JHEP 1505 (2015) 103 and private communication

- Towards to longitudinal polarization at moderate p_T
- Similar trend observed in 200 and 500GeV
- Data can help to constrain theoretical calculations

Hard process vs. Soft process



- 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

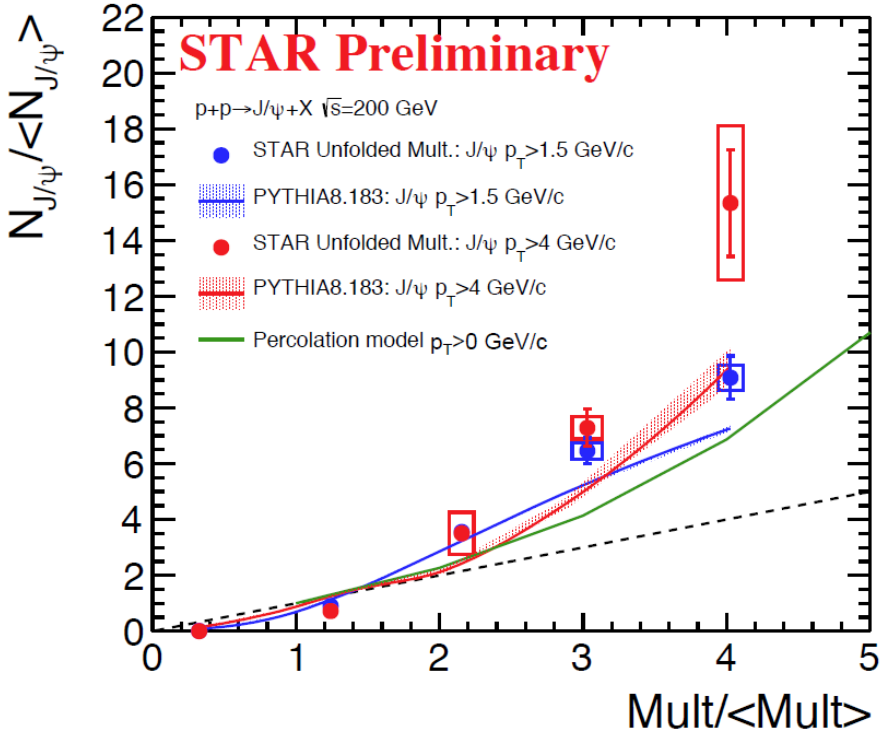
- Reduction of effective number of color sources due to coherence at high density

EPOS

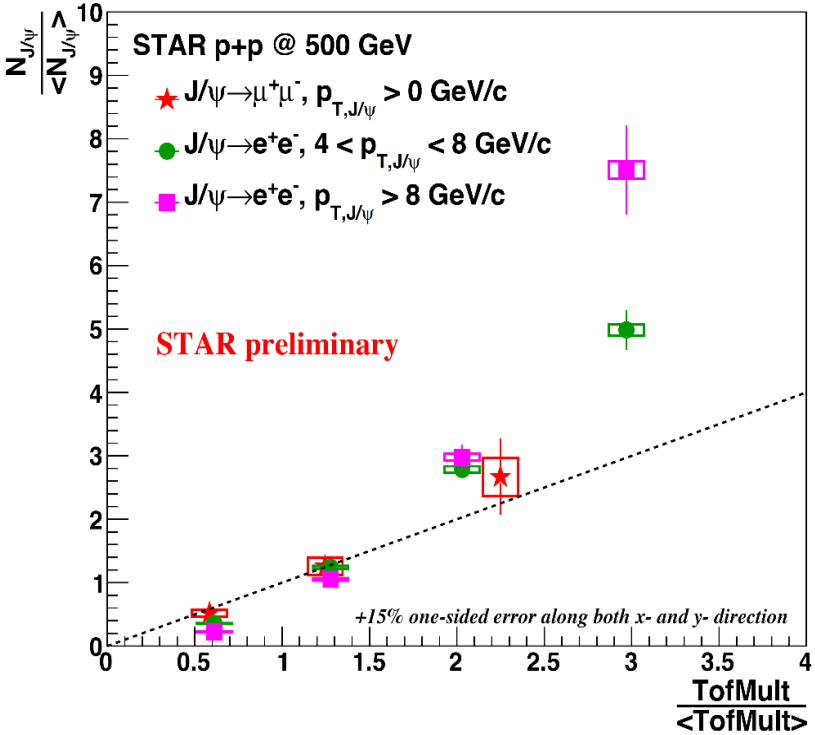
- Linear increase due to #MPI
- Stronger increase due to hydro. evolution

J/ψ vs. Event activity @ RHIC-STAR

200 GeV p+p

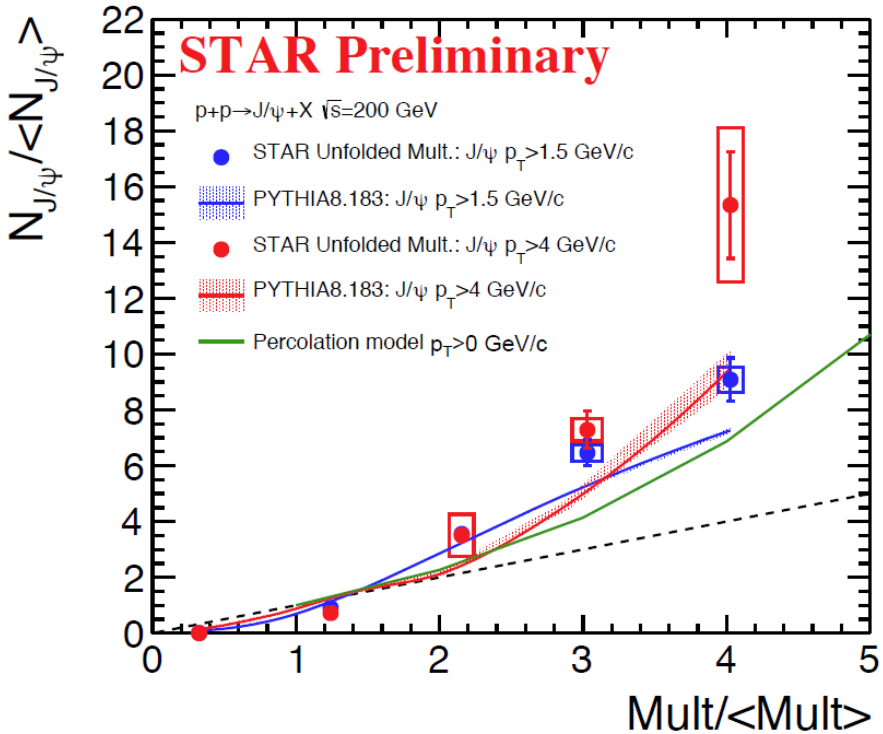


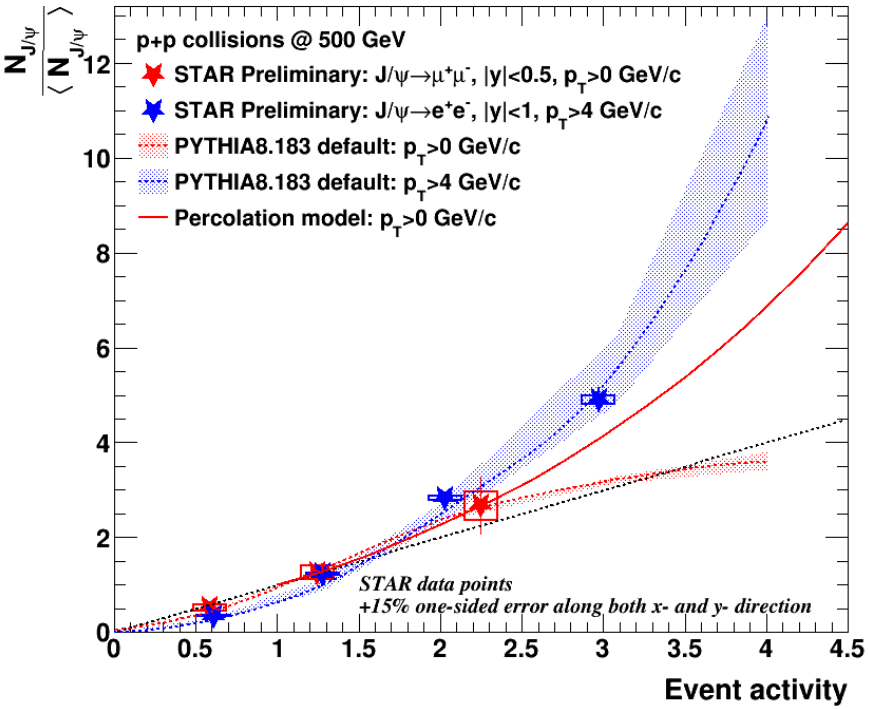
500 GeV p+p



- Stronger-than-linear growth for J/ψ at both energies
- Different trends for low and high-p_T

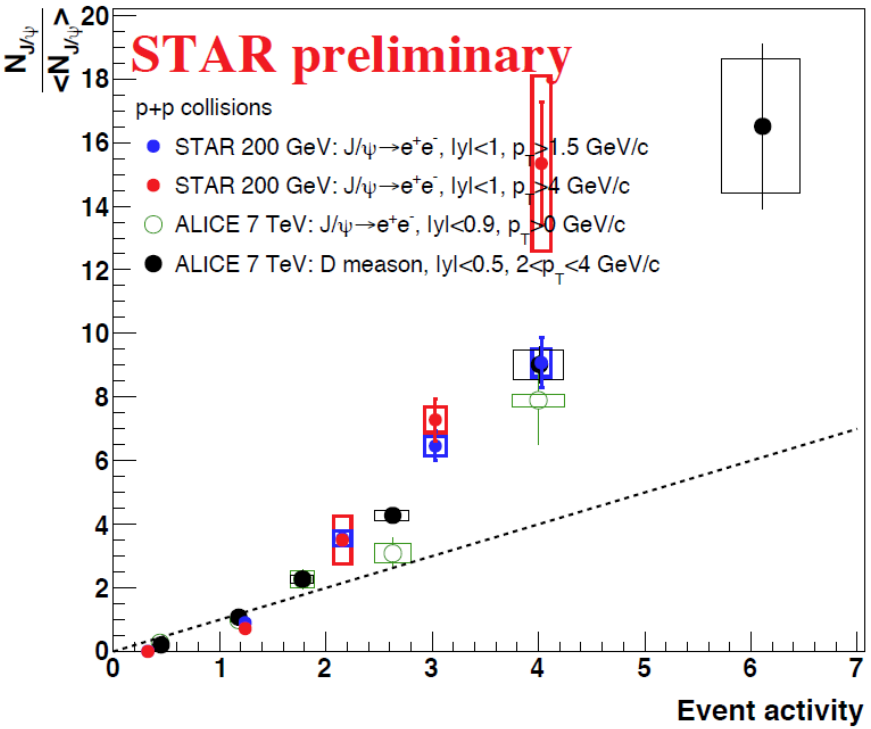
Compare to Model

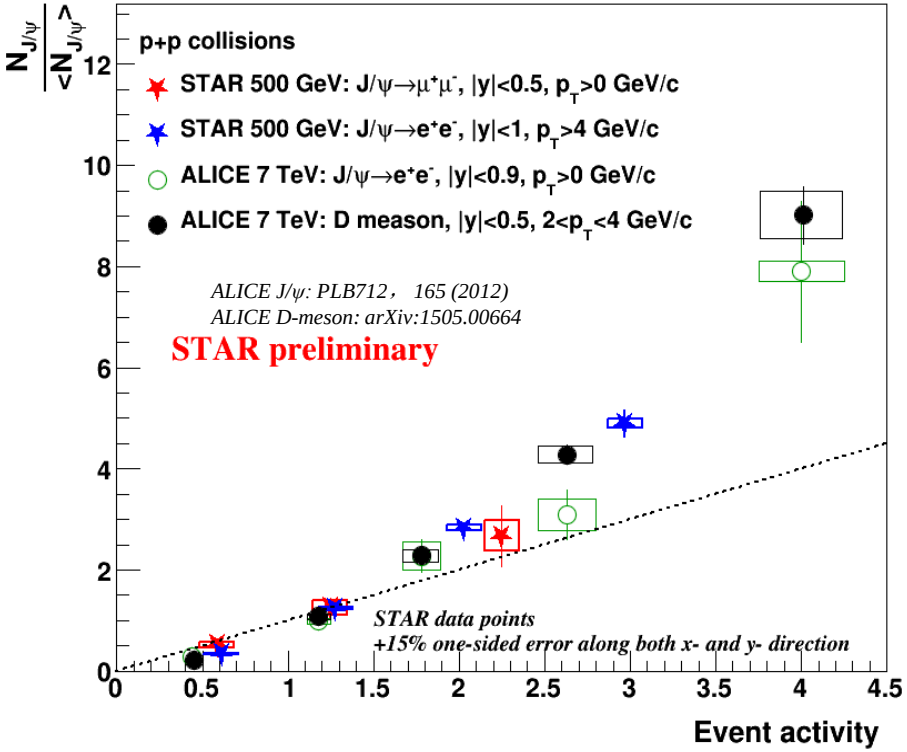




- Both PYTHIA8 and percolation model reproduce trend qualitatively
- Pushing to higher multiplicity bin for 500GeV data

Compare to LHC data



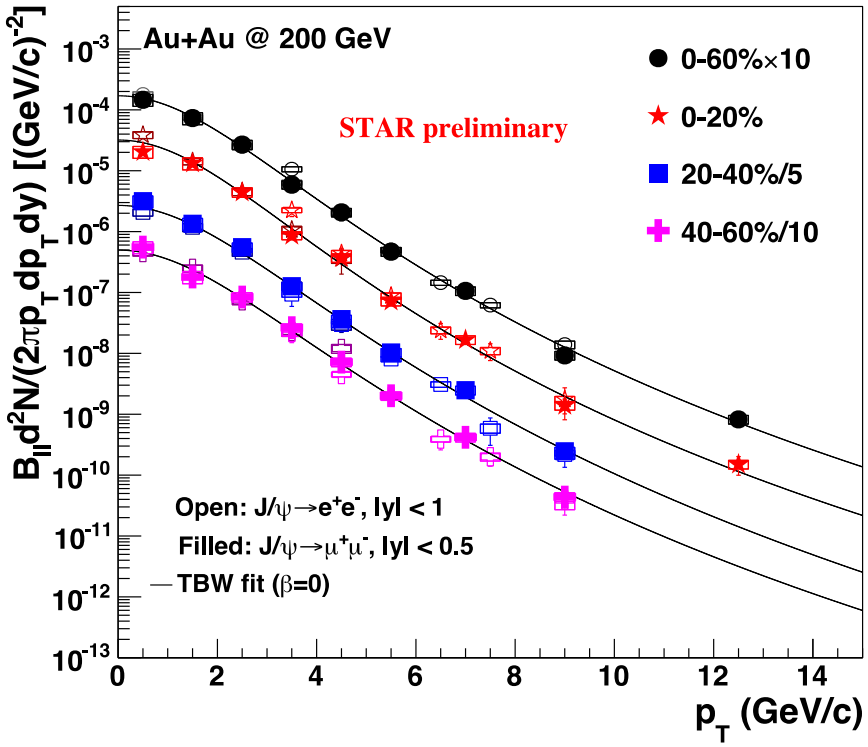


Similar trends from 200GeV, 500GeV to 7 TeV

Seminar trend as D mesons

Challenge for model (like EPOS+Hydro.) to explain

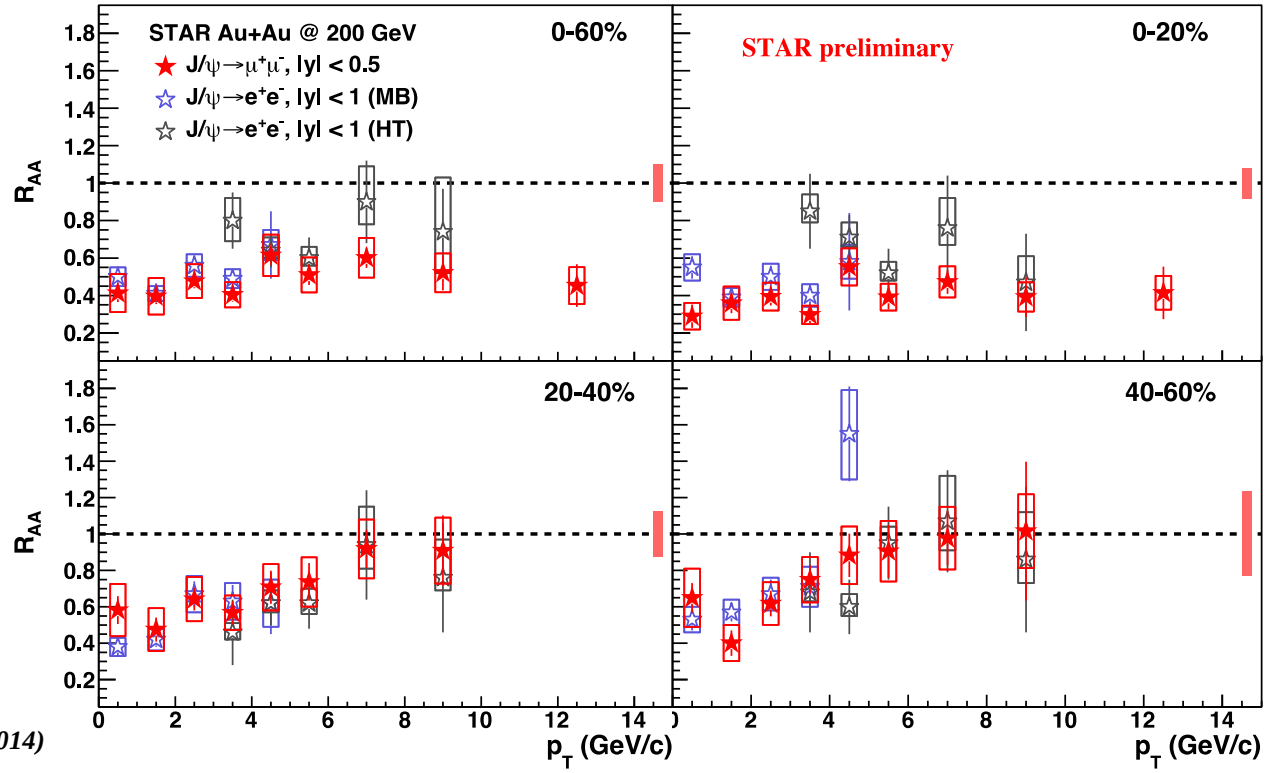
J/ψ p_T spectra in 200 GeV Au+Au



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

- **First mid-rapidity measurement of J/ψ yield in Au+Au collisions via the di-muon channel for $0 < p_T < 15$ GeV/c**
- Consistent with the published di-electron results using Run10 data over the entire kinematic range.

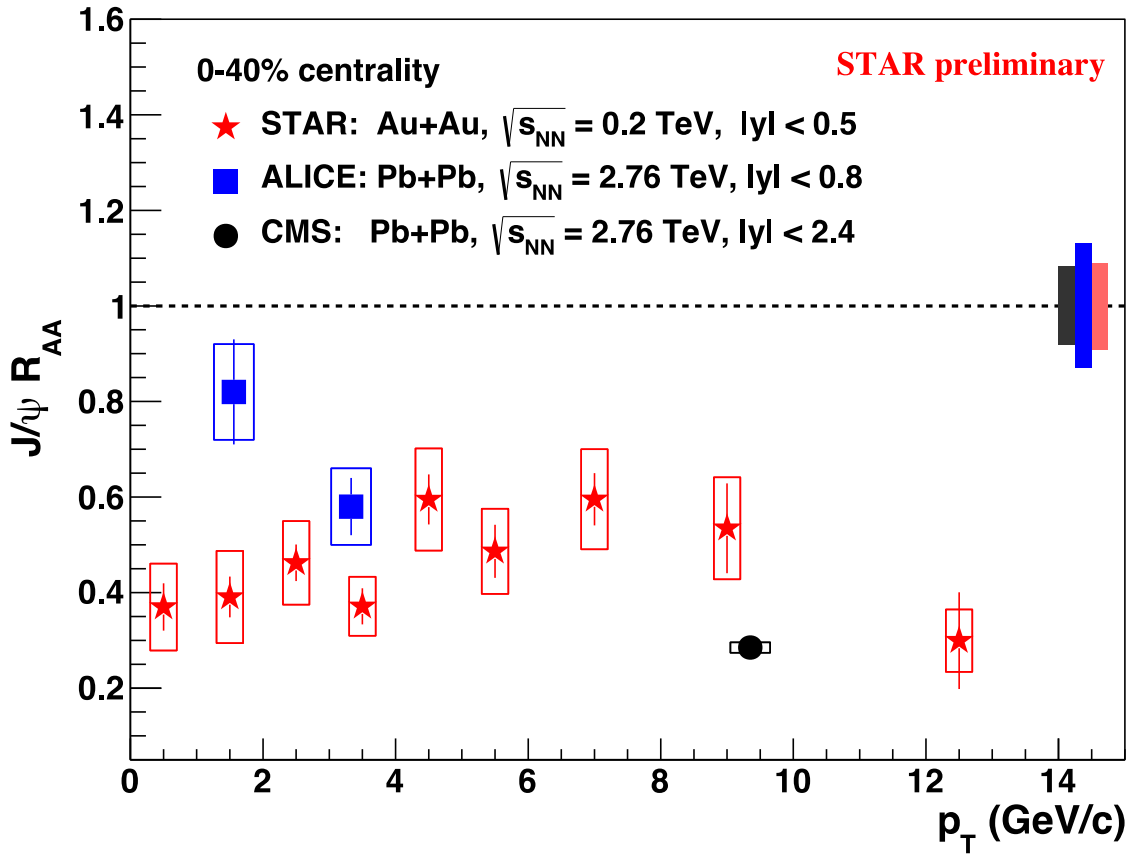
R_{AA} vs. p_T



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

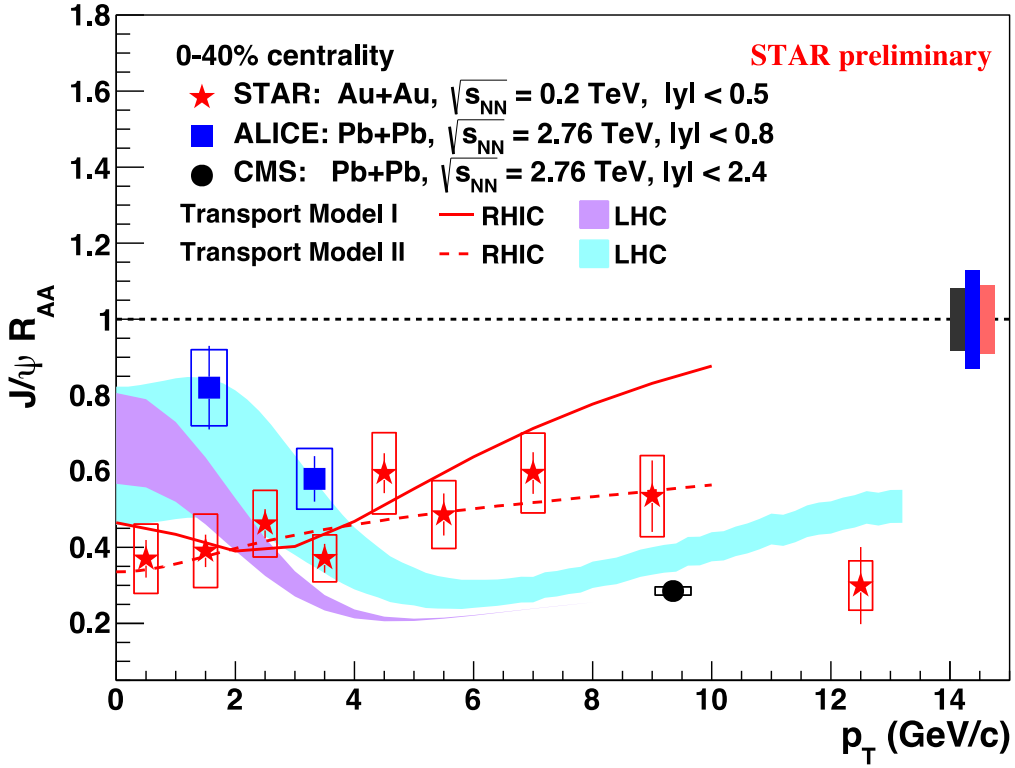
- **Consistent with di-electron channel results for the entire p_T range within uncertainties in all centralities**

Compare to LHC



- Less suppressed at LHC in low-p_T → **larger regeneration contribution due to higher charm cross-section**
- More suppressed at LHC in high-p_T → **larger dissociation rate due to higher temperature and shadowing effect**

Compare to transport models



Model I : Tsinghua Group
Model II : TAMU Group

ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063

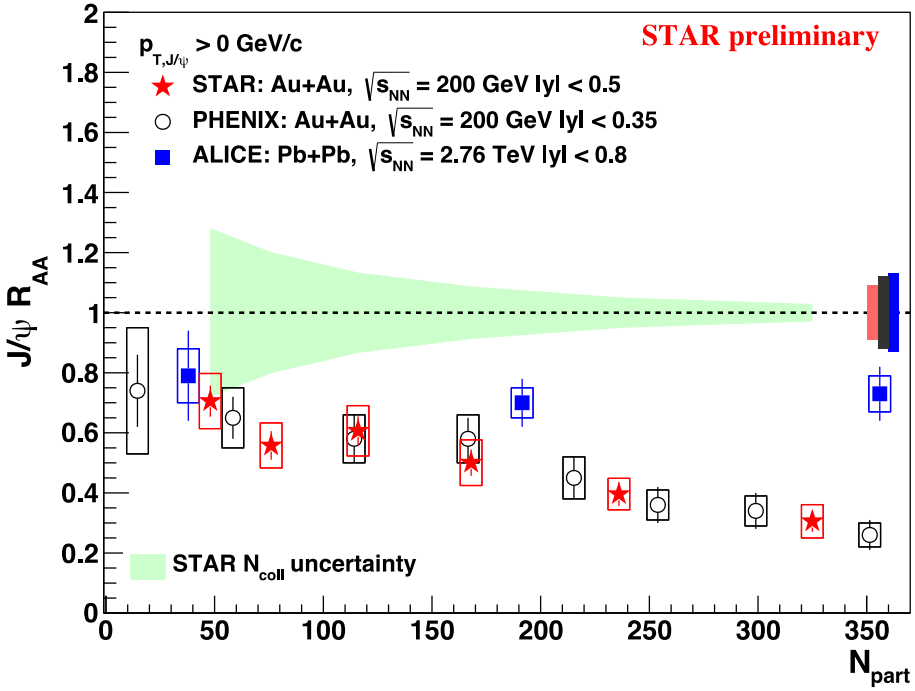
Transport model:
Model I at RHIC: PLB 678 (2009) 72
Model I at LHC: PRC 89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

- Transport models including **dissociation and regeneration effects** qualitatively describe p_T dependence shape

R_{AA} vs. centrality

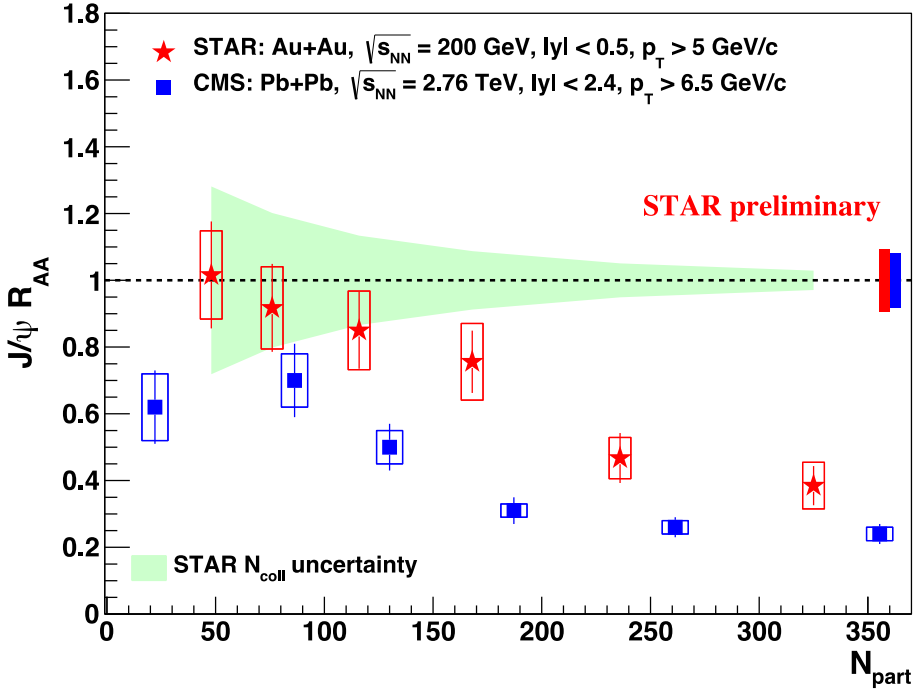
p_T > 0 GeV/c

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



p_T > 5 GeV/c

CMS: JHEP 05 (2012) 063

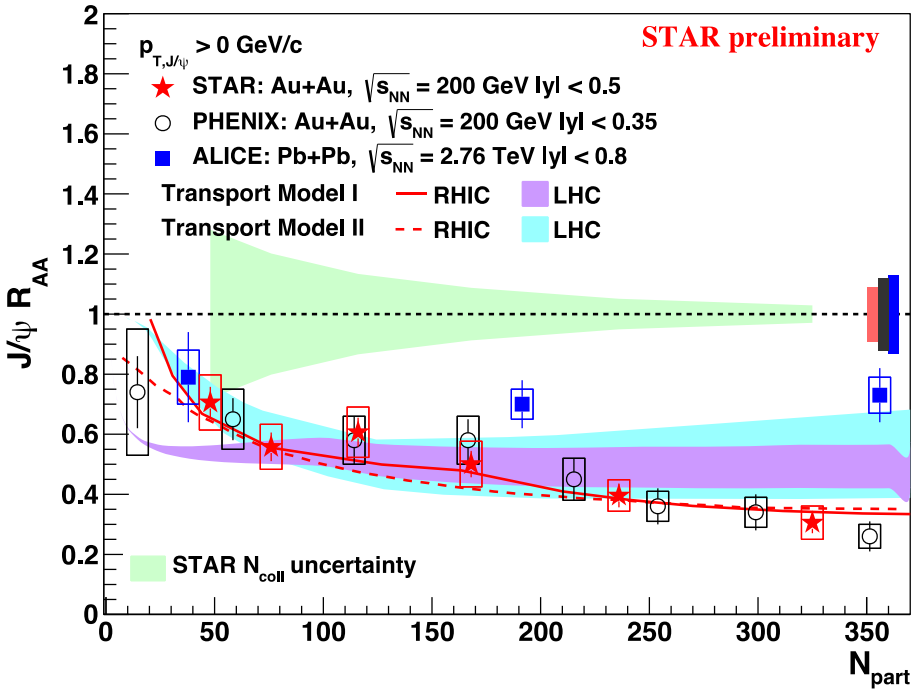


- STAR data are consistent with PHENIX with better statistical precision for p_T > 0 GeV/c
- Low p_T: more suppressed at RHIC in central collisions
- High p_T : less suppressed at RHIC in all centralities

Compare to transport models

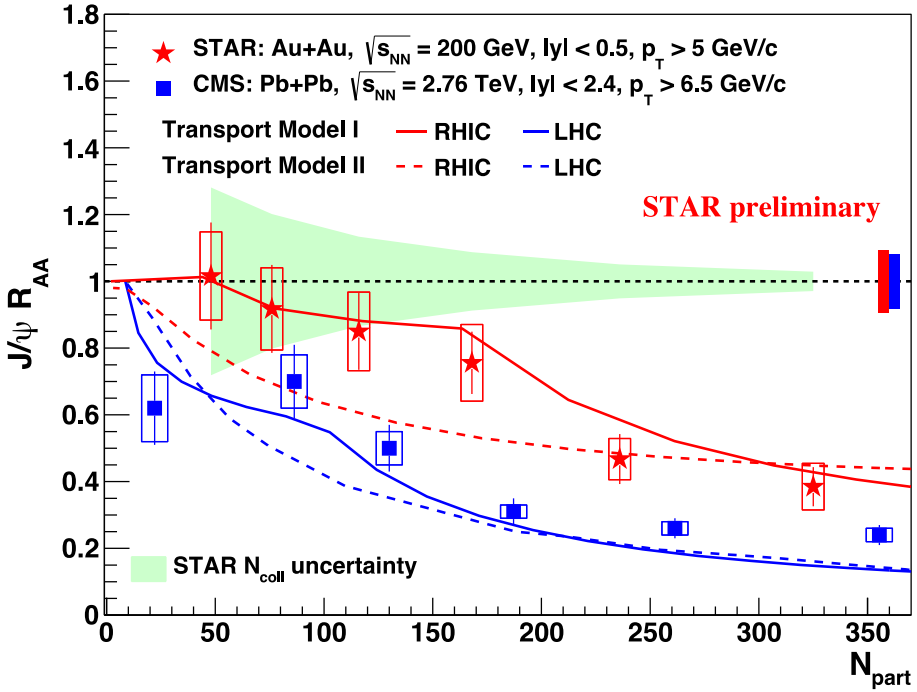
p_T > 0 GeV/c

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



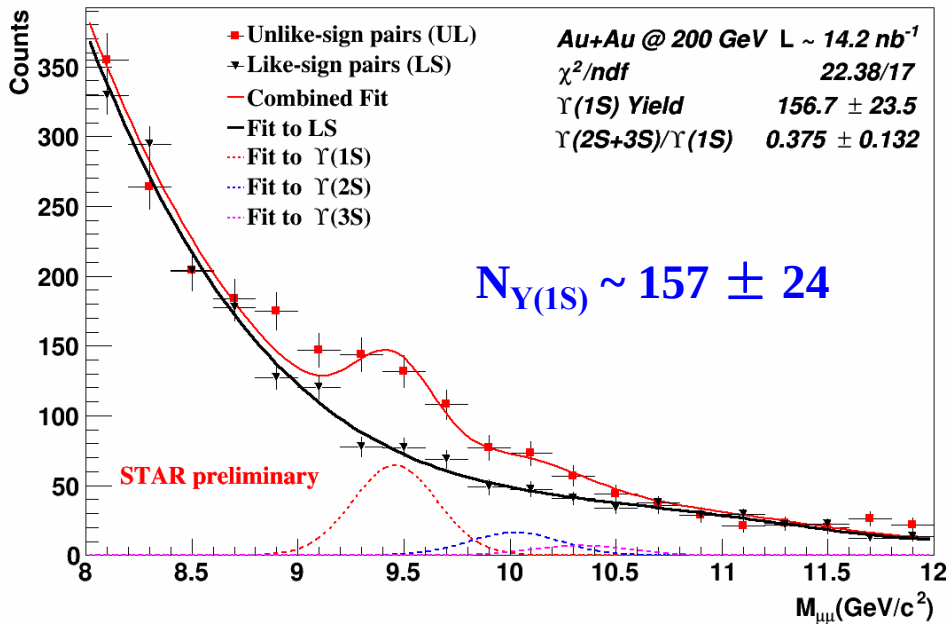
p_T > 5 GeV/c

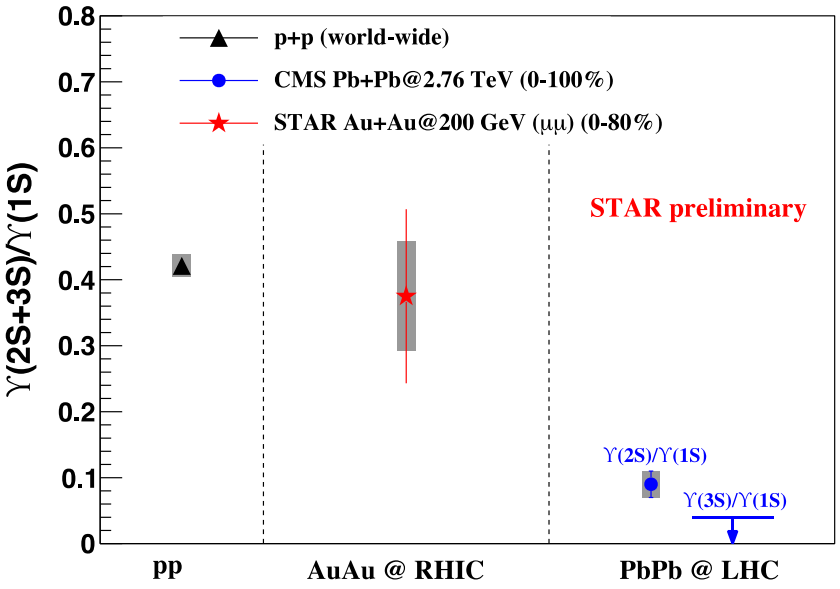
CMS: JHEP 05 (2012) 063



- Low p_T: both models can describe centrality dependence at RHIC, but tends to overestimate suppression at LHC
- High p_T: there is tension among models and data

Upsilon





- **Signs of ϒ (2S+3S) from the di-muon channel**
  - Challenging for di-electron channel due to Bremsstrahlung
- Hint of less melting of ϒ(2S+3S) at RHIC than at LHC

Summary

J/ψ production in p+p collisions:

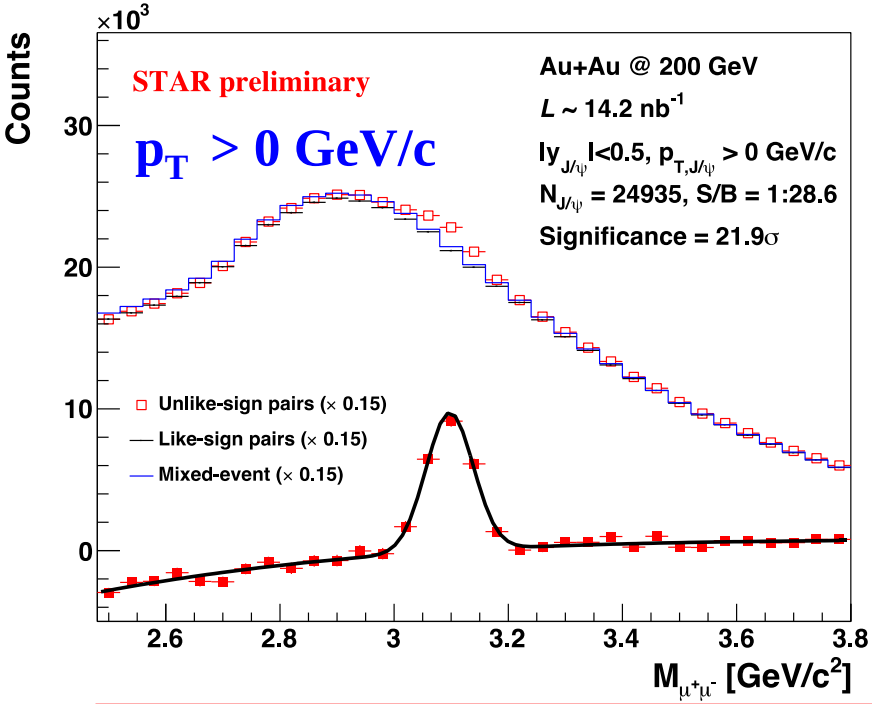
- p_T spectra in p+p collisions well understood (CGC, NRQCD)
- Polarization more sensitive to different theoretical treatments
- Yield vs. event activity provides a new tool

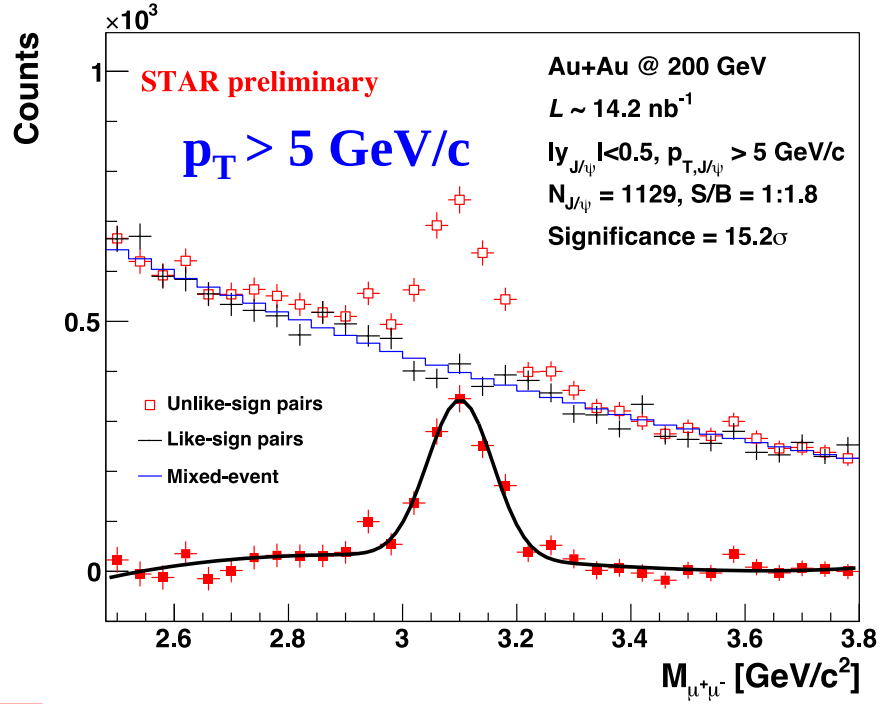
Quarkonium production in heavy-ion collisions:

- Consistent with dissociation+regeneration picture for J/ψ
- Details in transport models matter
- Hints of less melting of ϒ(2S+3S) at RHIC than LHC observed

Thanks

J/ψ signals from MTD in Au+Au

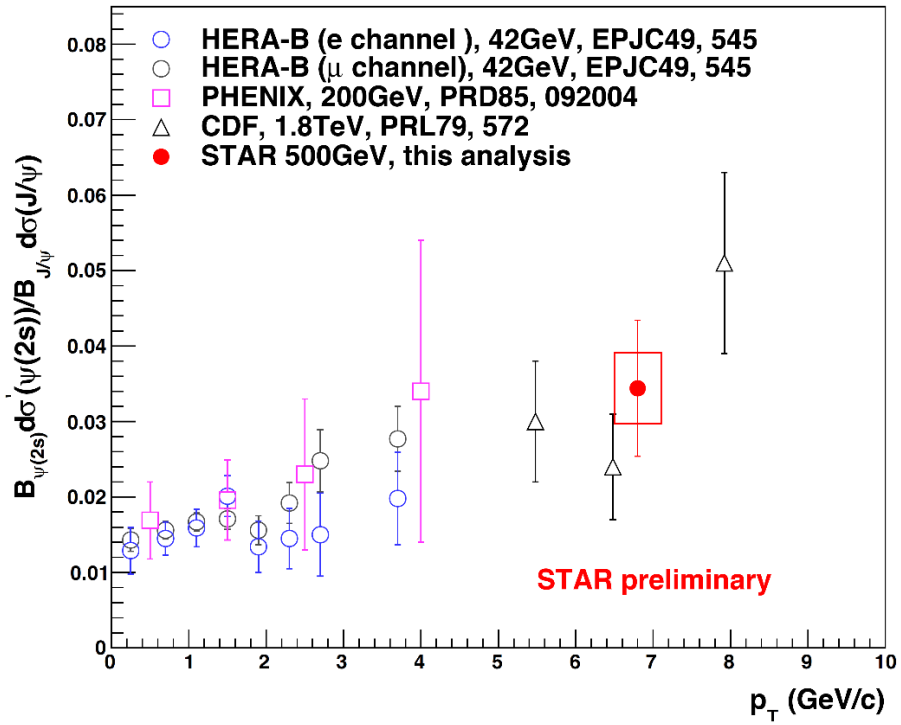




No bremsstrahlung tail
N ~ 25000
S/B ratio & Significance
S/B = 1:29, ~ 22σ @ p_T > 0 GeV/c
S/B = 1:1.8, ~ 15σ @ p_T > 5 GeV/c

- Full statistics from 2014 Au+Au 200 GeV run
- Similar statistics from 2016 run waiting for reconstruction

ψ(2s) Feeddown



- ψ(2S) to J/ψ ratio increases with p_T, consistent with world data
- No collisions energy dependence seen with current precision
- (0.032±0.010) * 6%/0.8% * 61% ~ (15±5)% feeddown contribution at $4<p_T<12$ GeV/c

J/ψ polarization in Au+Au

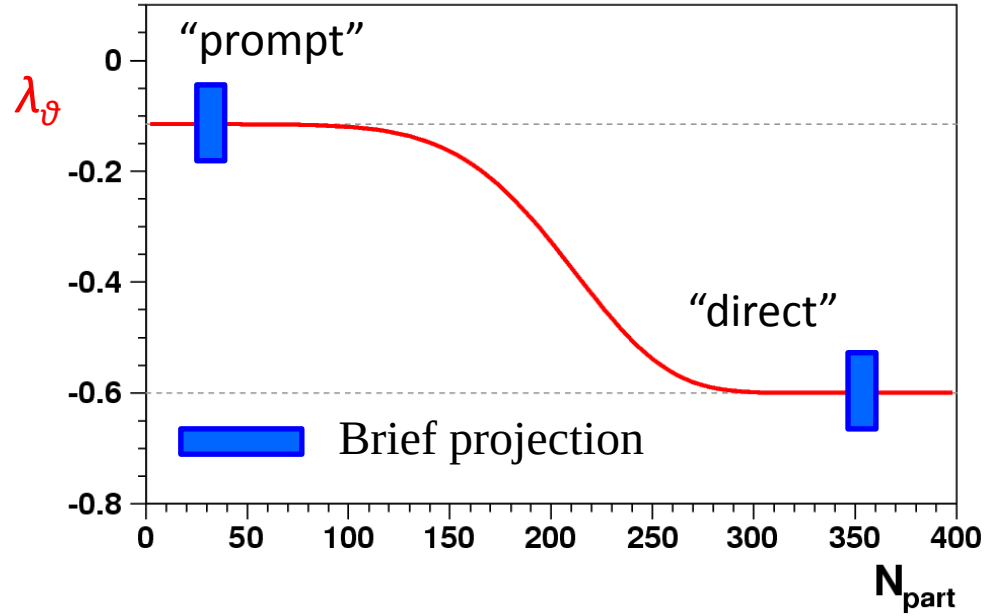
J/ψ polarization in heavy-ion collisions

- Screening of non-perturbative physics?

  PRC 68, 061902 (2003)

- (Chiral) Magnetic effect?
- Sequential suppression?

- Polarization parameters should be modified by hot, dense medium



Curve from Joao Seixas, workshop AFTER@ECT

- Analysis is ongoing
- Centrality dependence seen in 2011 data
- 2014+2016 data will significantly improve