Overview of recent Quarkonium results from STAR

2017 Quarkonia Working Group meeting @ Peking University, Beijing

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On behalf of the STAR Collaboration

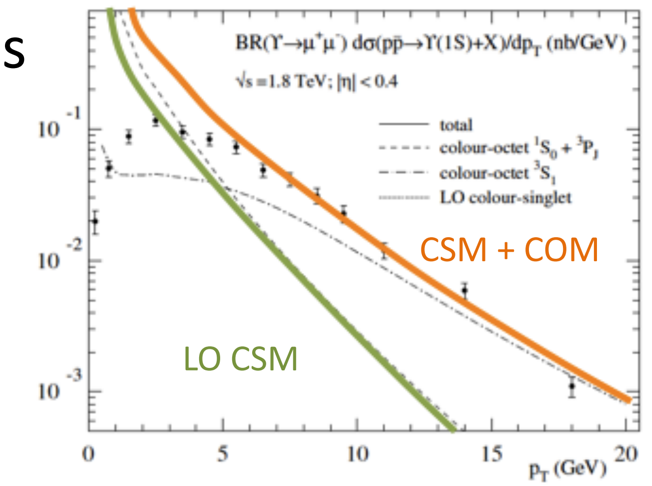
Outline

- Motivation
- Relativistic Heavy Ion Collider
- The STAR detector
- Physics measurements
  - Charmonium in p+p, p+A and A+A collisions
  - Bottomonium in p+p, p+A and A+A collisions
- Summary

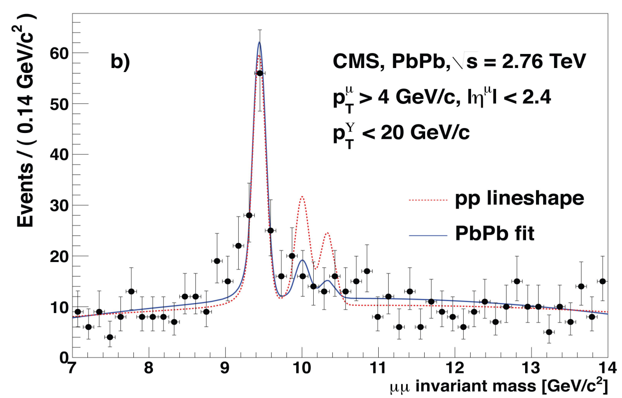
Motivation

- Quarkonium production mechanisms are still not fully understood in p+p collisions
- Some popular models on the market:
  - Color Singlet Model (CSM)
  - Color Octet Mechanism (COM) / NRQCD
  - Color Evaporation Model (CEM)
  - k_T factorization
  - …
- Studying the suppression of quarkonium states in heavy-ion collisions can provide deep insights into the properties of QCD and Quark-Gluon Plasma

CDF ϒ(1S) result



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



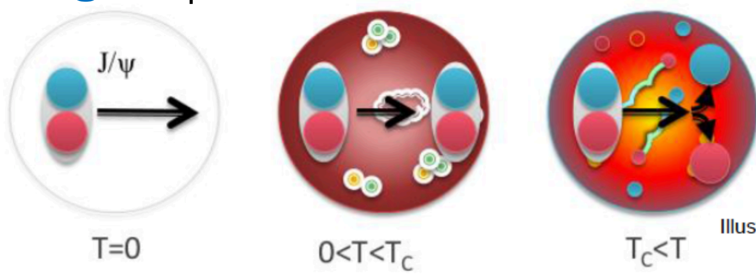
CMS Collaboration, Phys Rev Lett 107 052302,2011

Study QGP via J/ψ

- J/ψ suppression is one of smoking guns of QGP formation

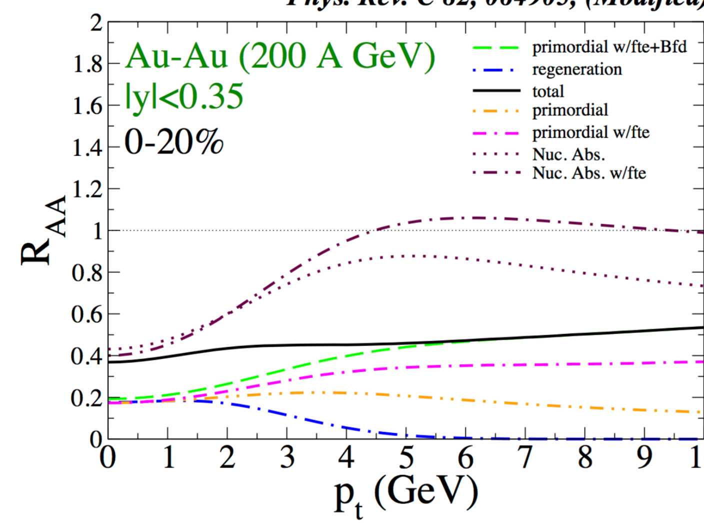
  (by T. Matsui and H. Satz PLB 178 (1986) 416)

  - **Color-screening**: J/ψ dissociates in the medium



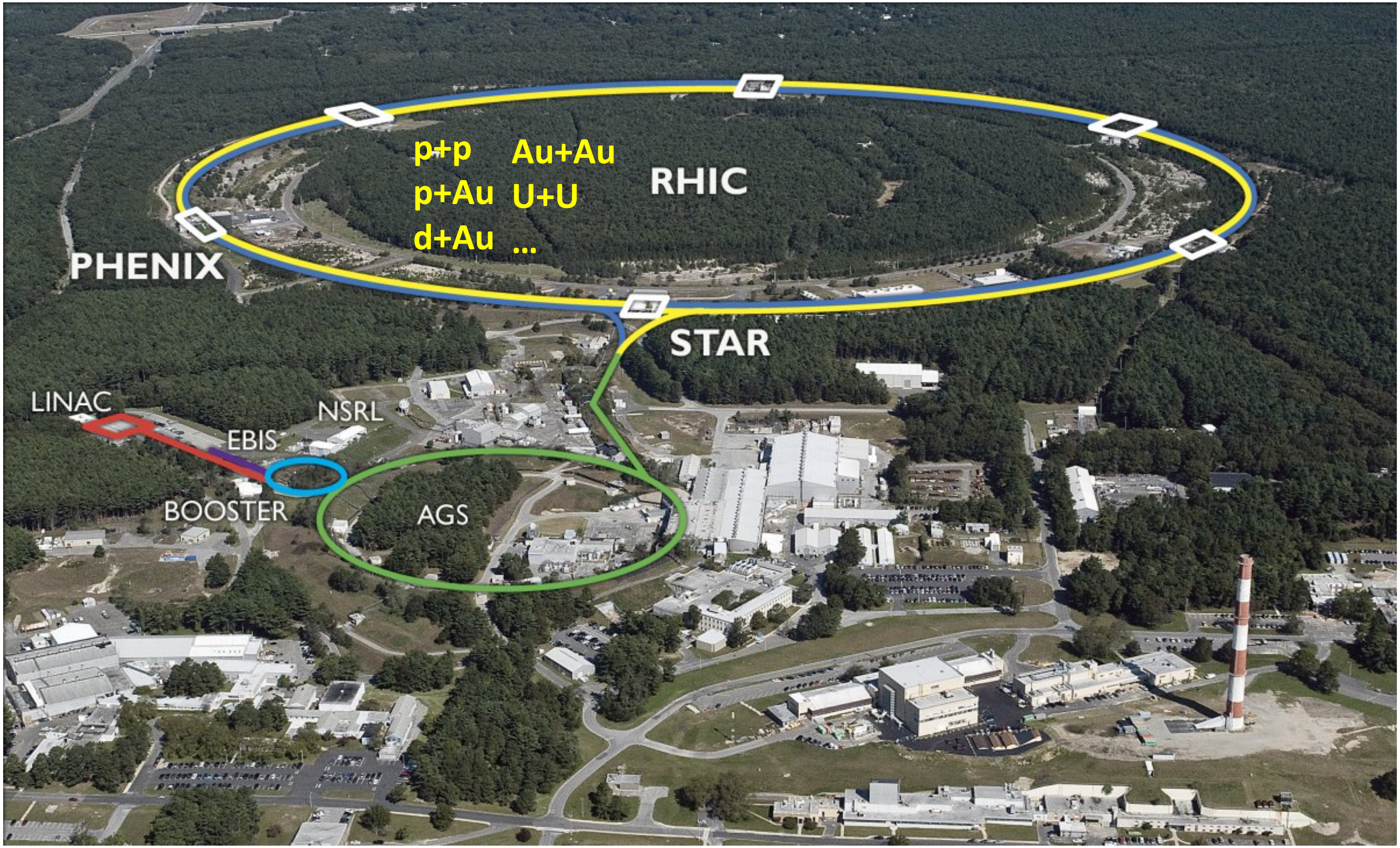
- But, interpretation of J/ψ suppression is complicated
  - ***Hot nuclear matter effects***
    - Dissociation
    - Regeneration from deconfined quarks
    - Medium-induced energy loss
    - Formation time effect
  - ***Cold nuclear matter effects***
  - ***Feed-down of excited charmonium states and B-hadrons***

Phys. Rev. C 82, 064905, (Modified)

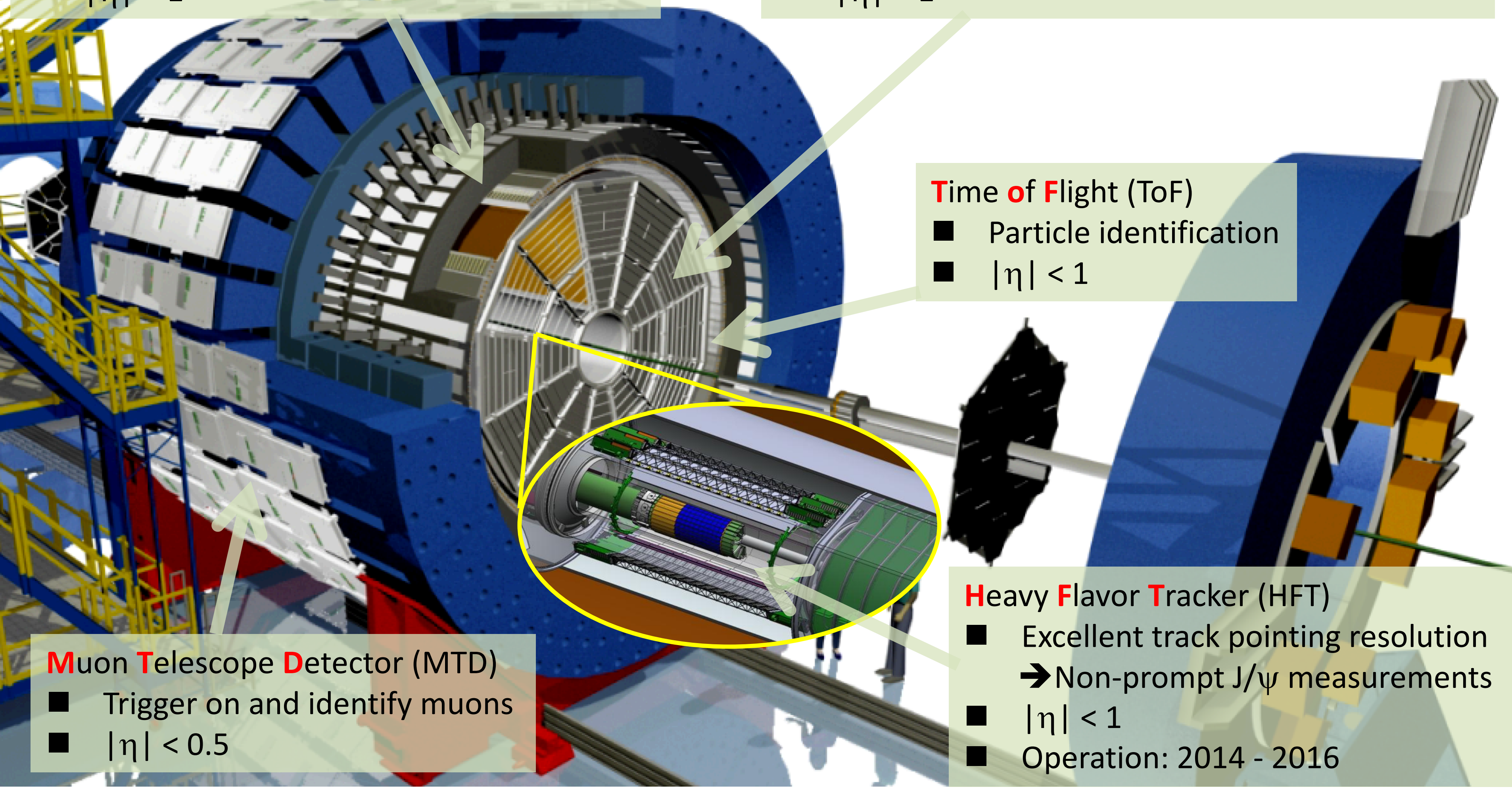


Relativistic Heavy-Ion Collider

- One of the most powerful heavy-ion colliders in the world!



The STAR Detector



Barrel ElectroMagnetic Calorimeter (BEMC)
- Trigger on and identify electrons
- $|\eta| < 1$

Time Projection Chamber (TPC)
- Precise momentum and dE/dx measurements
- $|\eta| < 1$

Time of Flight (ToF)
- Particle identification
- $|\eta| < 1$

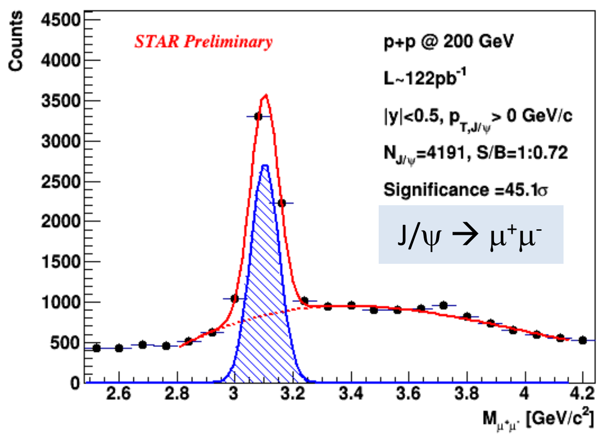
Muon Telescope Detector (MTD)
- Trigger on and identify muons
- $|\eta| < 0.5$

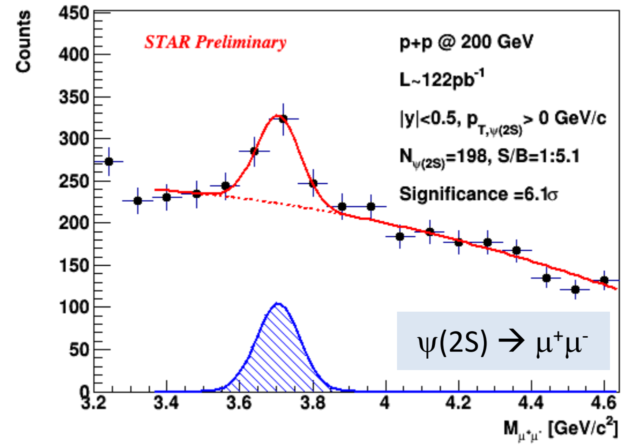
Heavy Flavor Tracker (HFT)
- Excellent track pointing resolution
  ➔Non-prompt J/ψ measurements
- $|\eta| < 1$
- Operation: 2014 - 2016

J/ψ & ψ(2S) in p+p @ 200 & 500 GeV

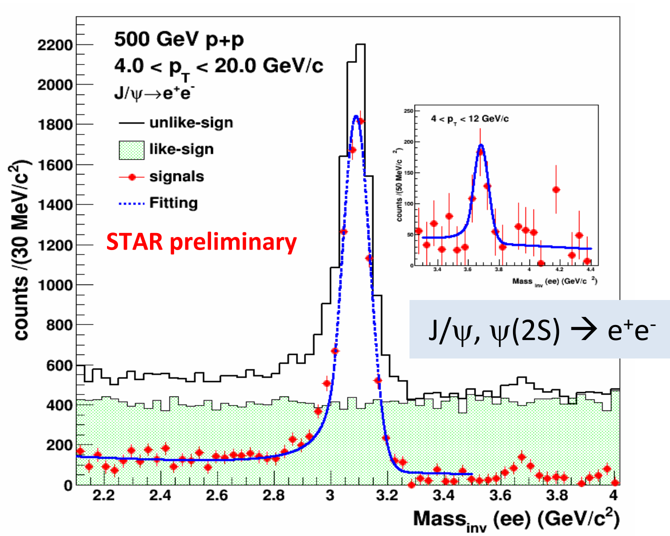
- Clear J/ψ and ψ(2S) signals from the ***dielectron*** and ***dimuon*** channels

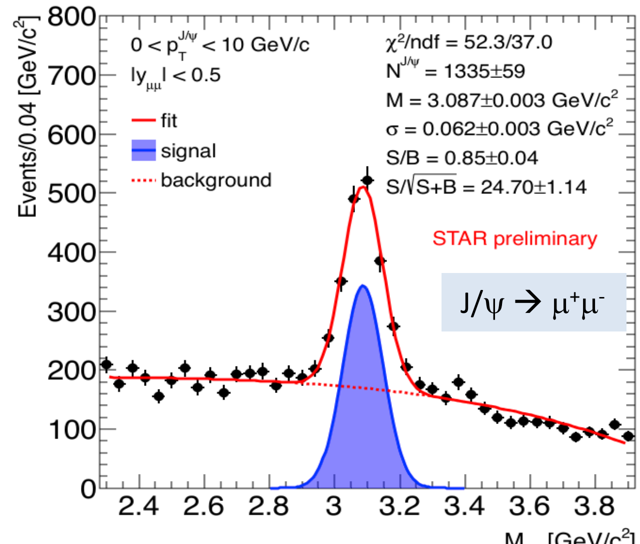
p+p @ 200 GeV





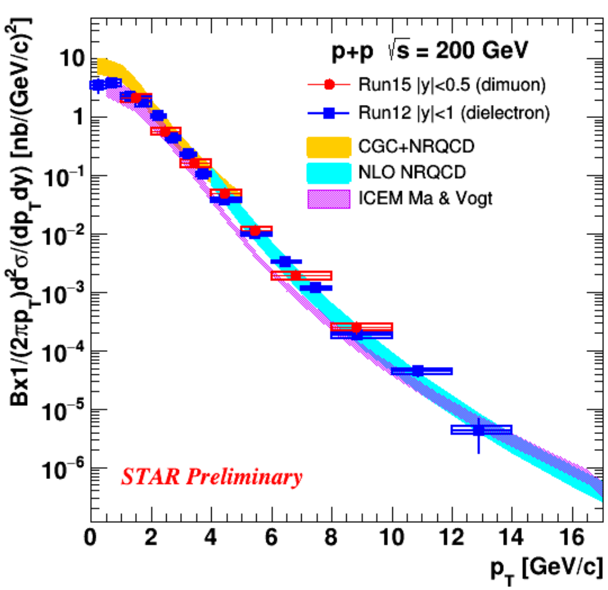
p+p @ 500 GeV

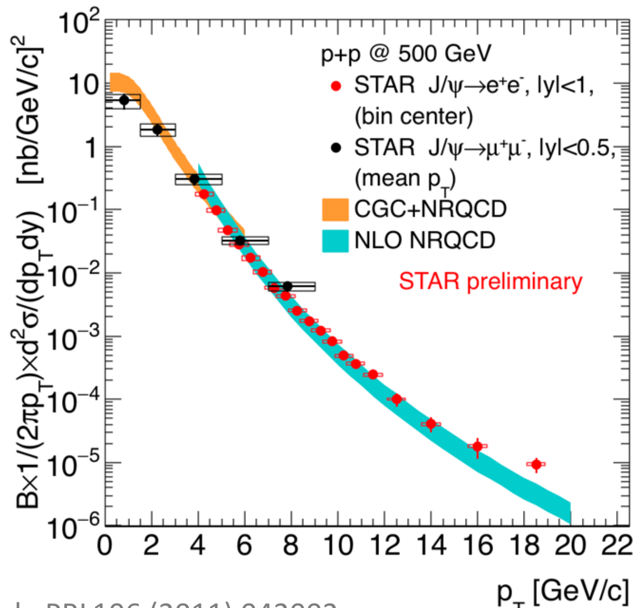


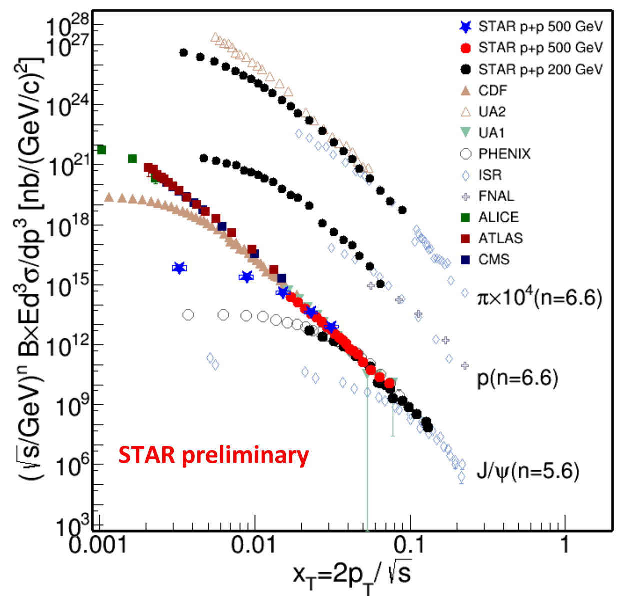


J/ψ Invariant Cross-Section in p+p Collisions

- Precision measurement of J/ψ production cross-section from 0 to 14 (20) GeV/c of $p_T^{J/\psi}$ for p+p @ 200 (500 GeV)
- Consistent with CGC+NRQCD & NLO NRQCD calculations (prompt J/ψ production) for both p+p @ 200 and 500 GeV
- ICEM (direct J/ψ production only) seems to underestimate in the intermediate p_T region
- The high-p_T J/ψ follows the x_T-scaling
  - Broken scaling at low x_T is due to soft processes







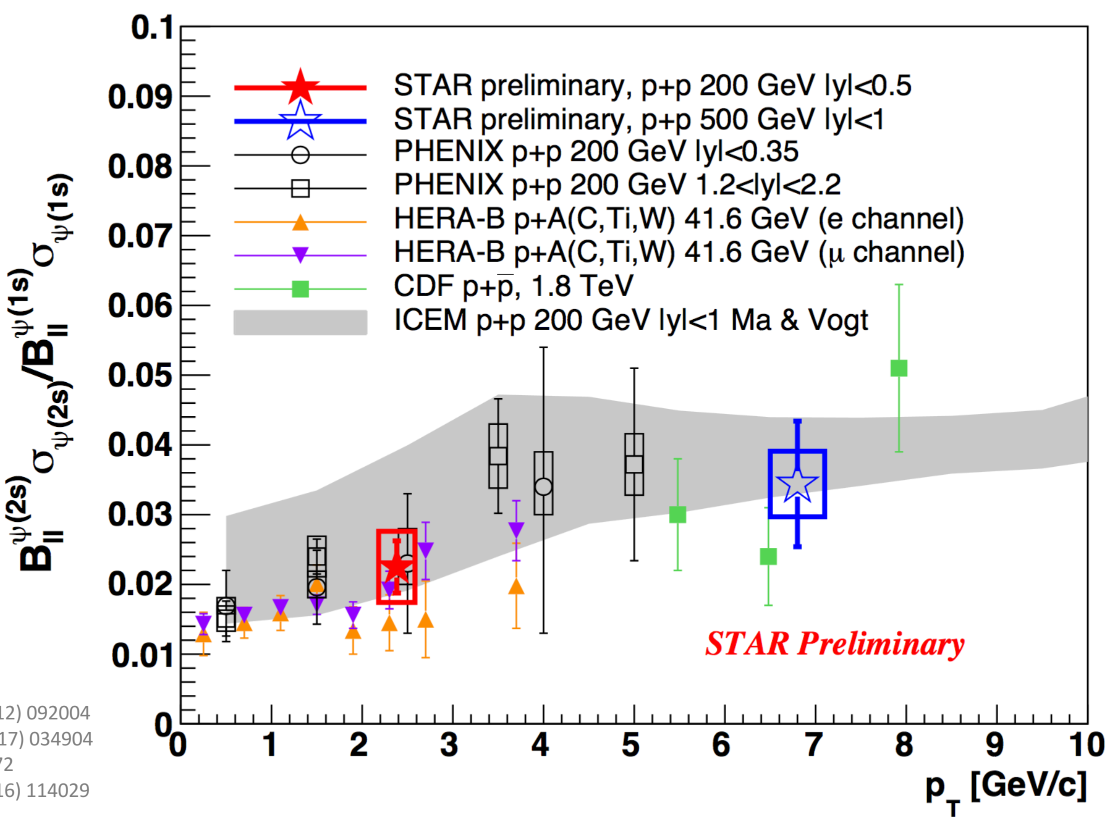
NLO NRQCD: Ma et al., PRL106 (2011) 042002
CGC+NRQCD: Ma, Venugopalan, PRL**113** (2014) 192301

PRC **80** (2009) 041902

ψ(2S) to J/ψ Ratio

- To help determine the feed-down contribution of ψ(2S) to J/ψ
- Result from STAR is consistent with other experiments for both 200 & 500 GeV

➔ **No obvious collision energy dependence**



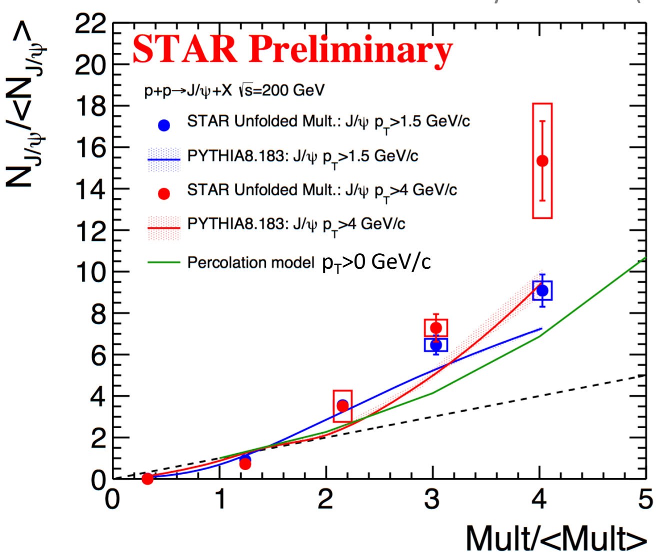
HERA-B, EPJC**49**,
545PHENIX mid y, PRD**85** (2012) 092004
PHENIX forward y, PRC**95** (2017) 034904
CDF, 1.8 TeV, PRL**79** (1997) 572
ICEM, Ma & Vogt, PRD**94** (2016) 114029

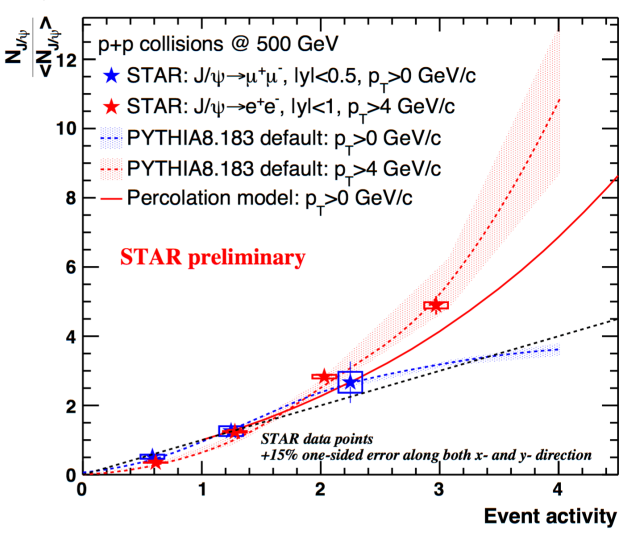
J/ψ Yield vs. Event Activity

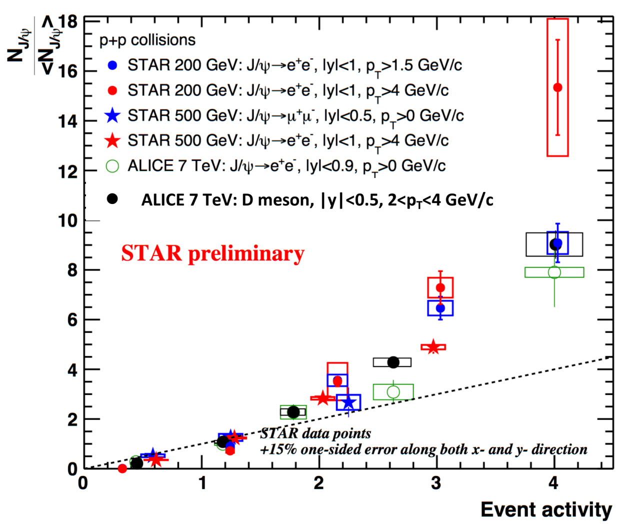
- Event activity = charged-particle multiplicity
- Relative J/ψ yield rises faster than a linear function
  - ➔ Similar global trend at different collision energies and as for the D meson
- PYTHIA and Percolation model can qualitatively describe the rising behavior

ALICE: JHEP 09 (2015) 148
Percolation model: Phys.Rev. C86 (2012) 034903

* p_T > 0.2 GeV/c for tracks

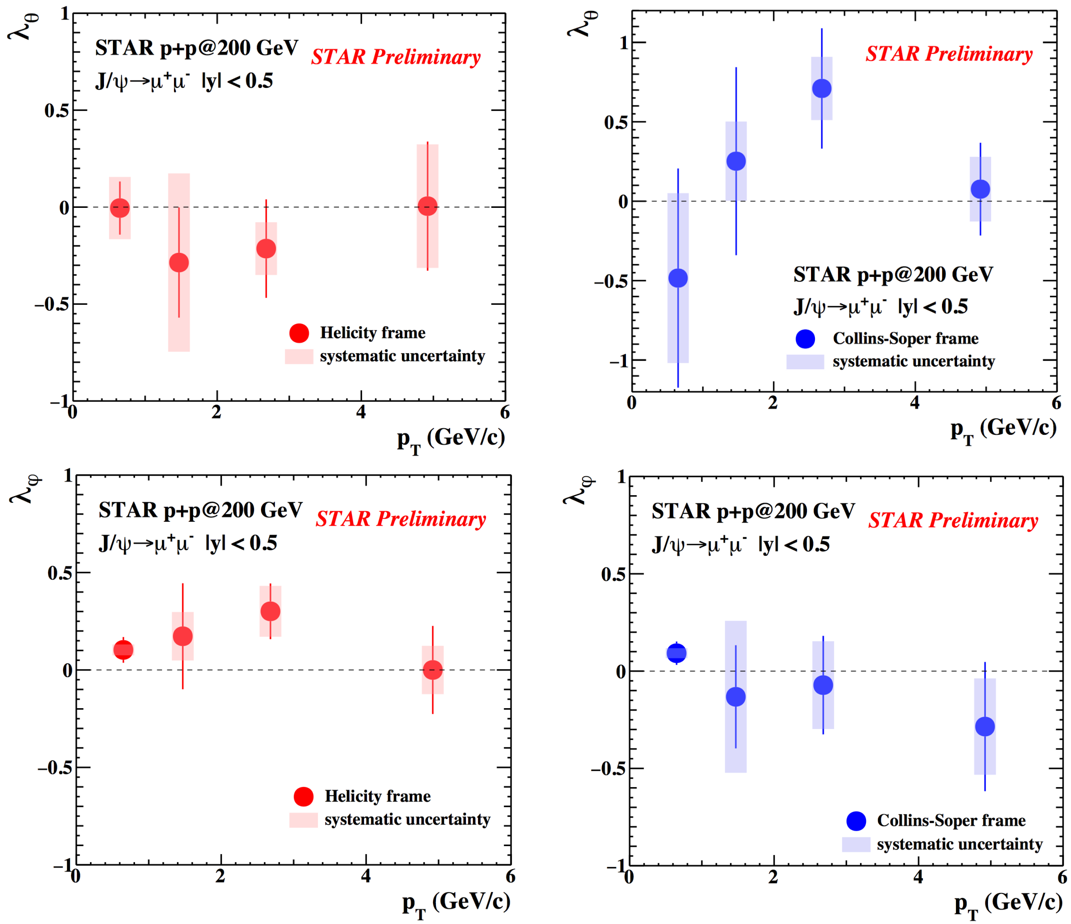






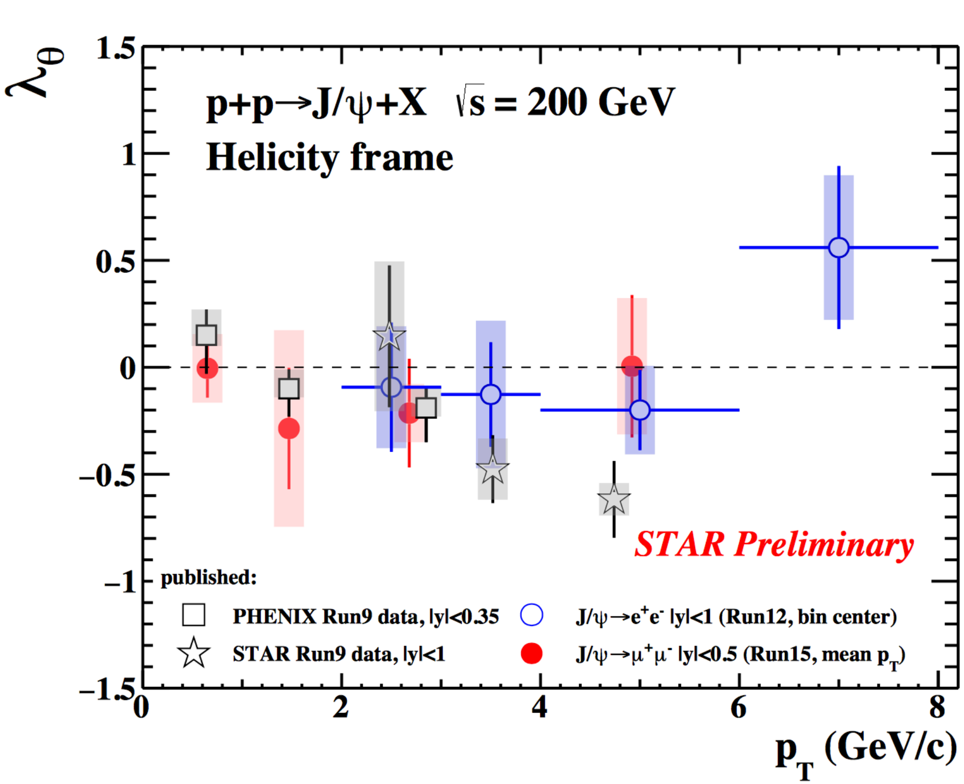
J/ψ Polarization Measurement

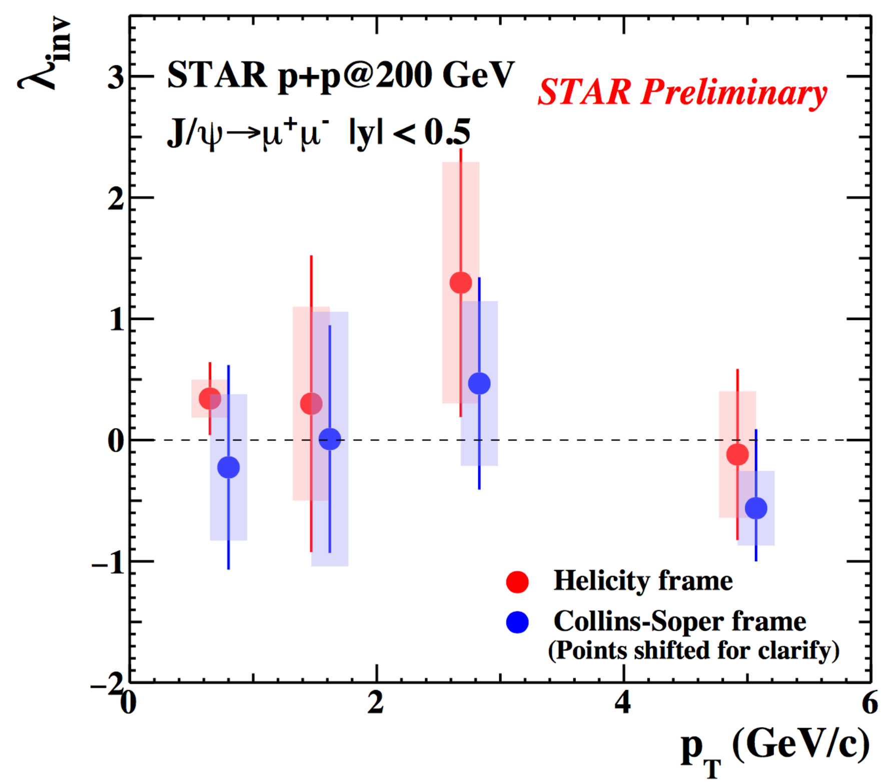
- First J/ψ polarization measurements in HX and CS frame from ***dimuon*** channel in p+p collisions @ 200 GeV
- Both λ_θ and λ_ϕ are consistent with **ZERO** within uncertainties



J/ψ Polarization Measurement

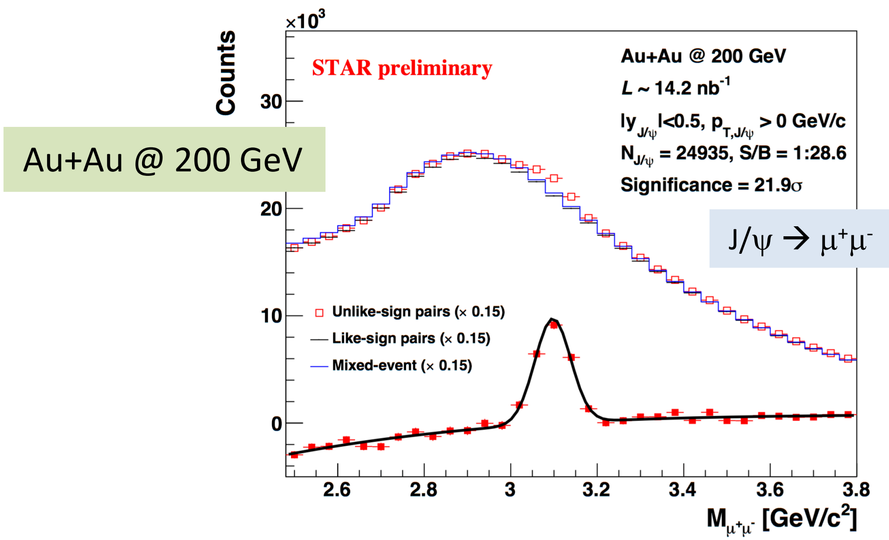
- Consistent with the previous measurements from STAR and PHENIX
- Frame invariant quantity: $\lambda_{inv} = \dfrac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$
  - Good cross-check on measurements performed in different frames

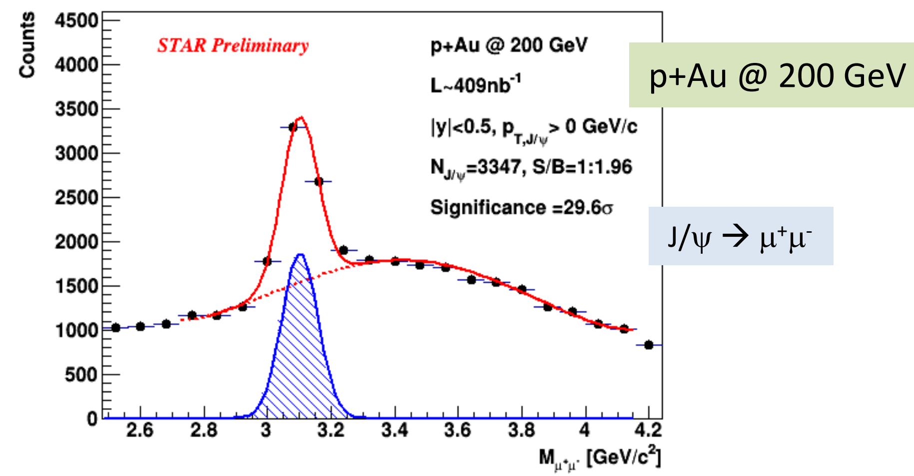


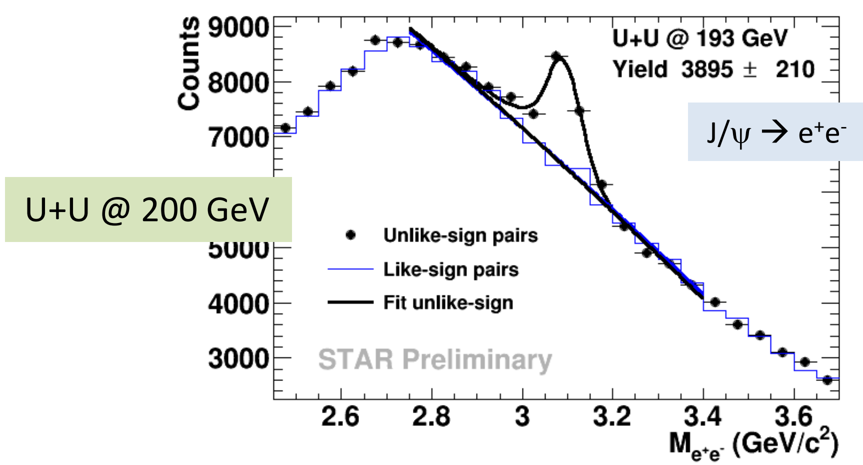


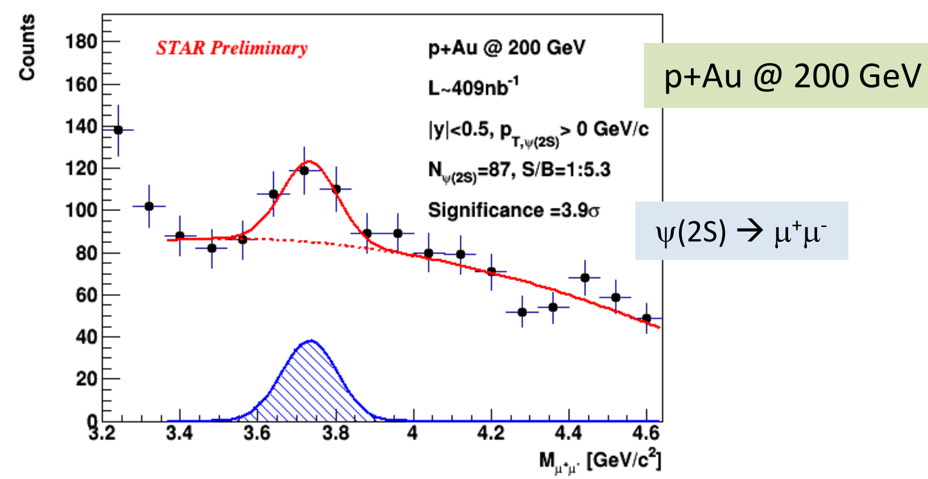
J/ψ & ψ(2S) in A+A & p+A @ 200 GeV

- Clear J/ψ and ψ(2S) signals in Au+Au, U+U and p+Au collisions





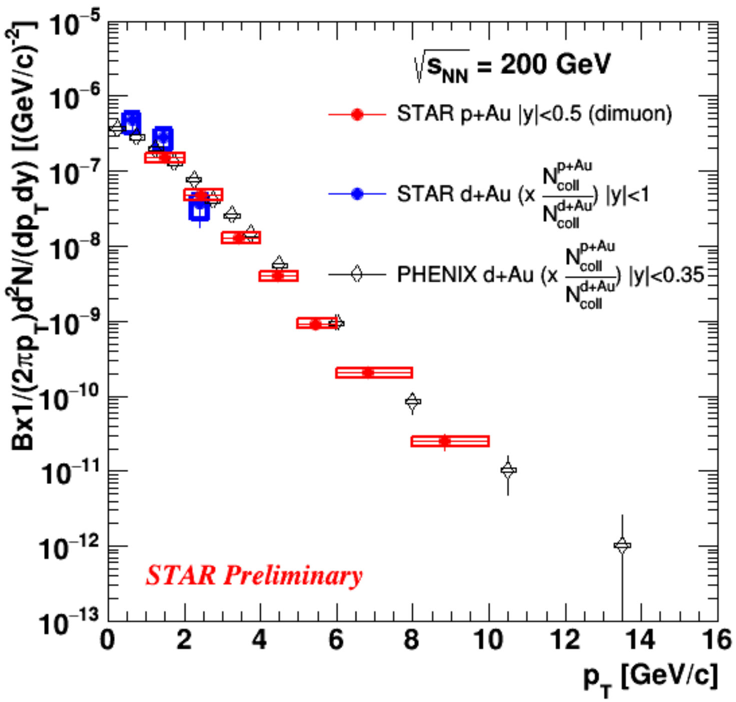


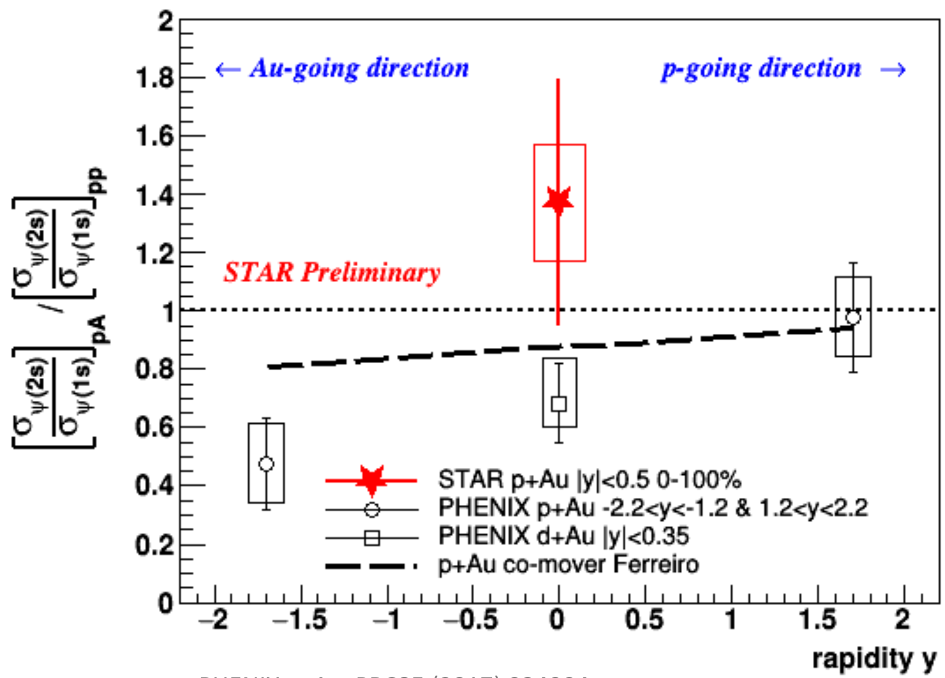


Invariant Yields and Double Ratio in p+Au

- Precision measurements of J/ψ invariant yield for p+Au
- First ψ(2S) to J/ψ double ratio measurement from STAR between p+p and p+Au at midrapdity at RHIC:

1.37 ±0.42(stat.) ±0.19(syst.)

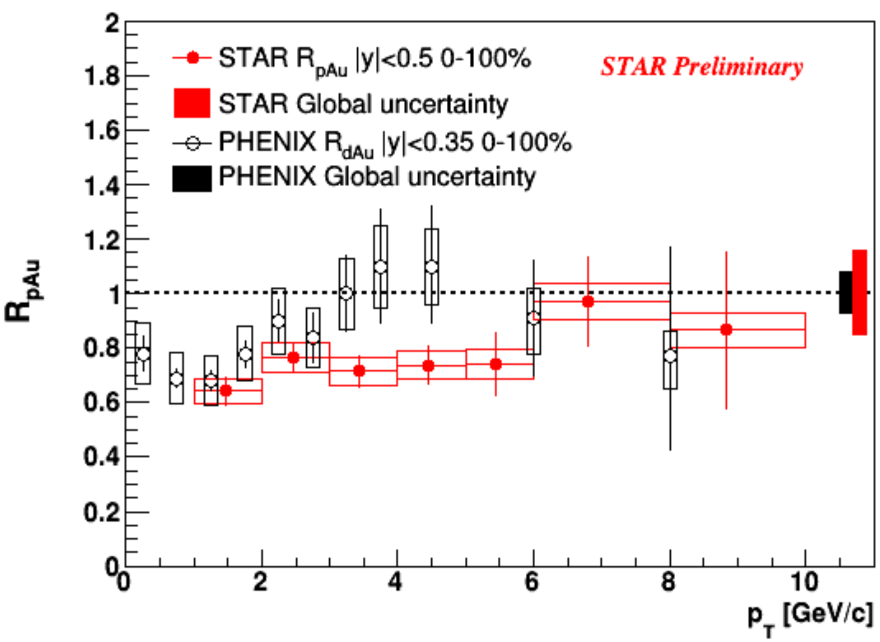




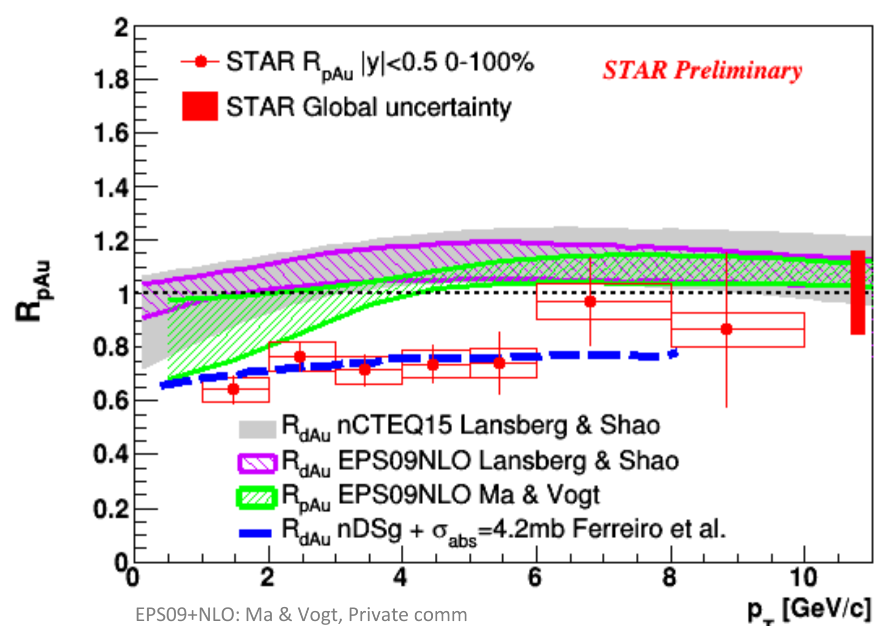
PHENIX p+Au, PRC**95** (2017) 034904
PHENIX d+Au, PRL**111** (2013) 202301
Co-mover calculation, Ferreiro, private comm.

J/ψ R_{pAu} vs. p_T

- R_{pAu} from STAR has similar trend as $\mathbf{R_{dAu}}$ from PHENIX
  - ➔ With a small tension at $3.5 < p_T < 5$ GeV/c (~ 1.4σ).
- The model calculation with additional nuclear absorption on top of nuclear PDF effects can qualitatively describe the data



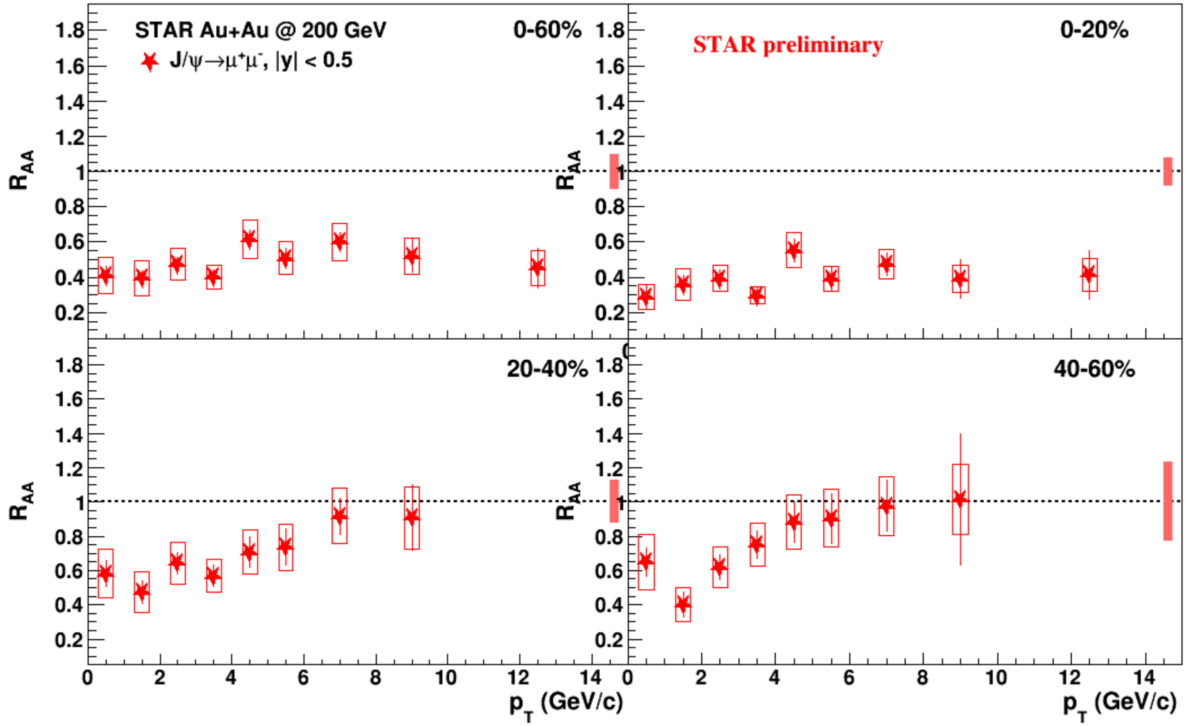
PHENIX, PRC87 (2012) 034903



EPS09+NLO: Ma & Vogt, Private comm
nCTEQ, EPS09+NLO: Lansberg Shao, EPJC**77** (2017) 1
Comp. Phys. Comm.**198**(2016) 238-259
Comp. Phys. Comm.**184**(2013) 2562-2570
Ferreriro et al., Few Body Syst.**53**(2012) 27

J/ψ R_{AA} vs. p_T

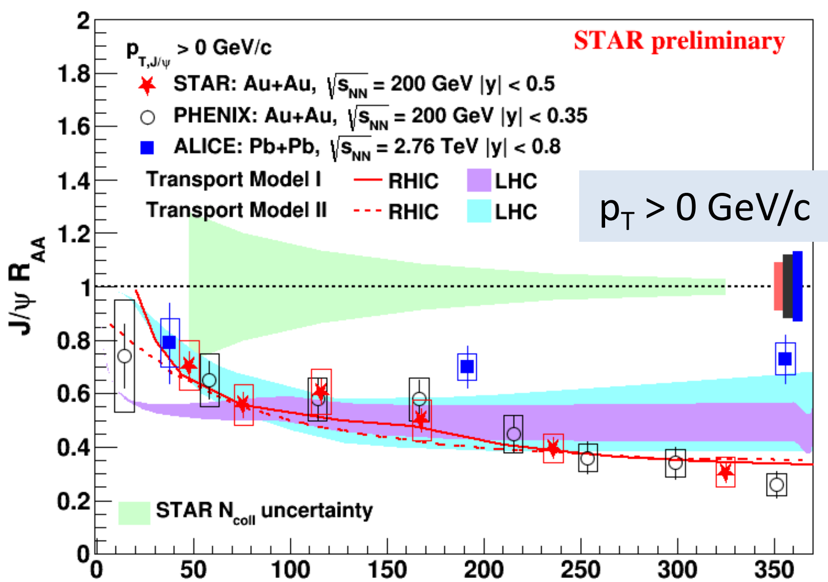
- No obvious p_T dependence in R_{AA} in 0 - 20% centrality bin
- Rising R_{AA} with p_T in 20 - 40% and 40 - 60% centrality bins
- Suppression at low p_T: dissociation, Cold Nuclear Matter (CNM) effect, regeneration
- Rising trend at high p_T could be due to formation time effects, B-hadron feed-down
- Strong suppression at high p_T in central collisions is a clear sign of dissociation since regeneration contribution and CNM effects are small



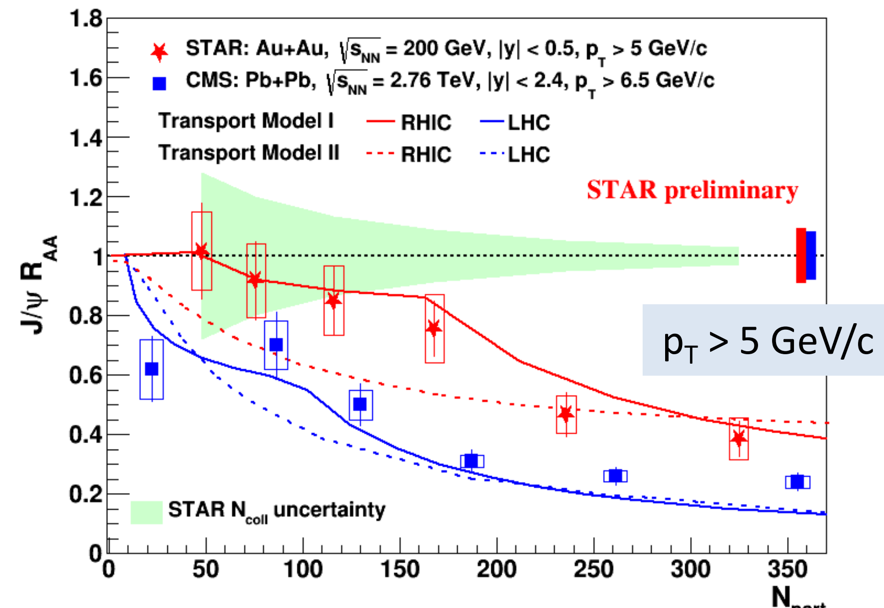
J/ψ R_{AA} vs. N_{part}

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

- RHIC vs. LHC
  - p_T > 0 GeV/c: less suppressed in central collisions at the LHC
    ➔ larger regeneration contribution due to higher charm quark cross-section
  - p_T > 5 GeV/c: more suppressed in central collisions at the LHC
    ➔ larger dissociation rate due to higher medium temperature
- Data vs. transport models (dissociation + regeneration effects)
  - p_T > 0 GeV/c: both models can describe the centrality dependence at RHIC, but tend to overestimate suppression at LHC
  - p_T > 5 GeV/c: there is tension among data and models



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

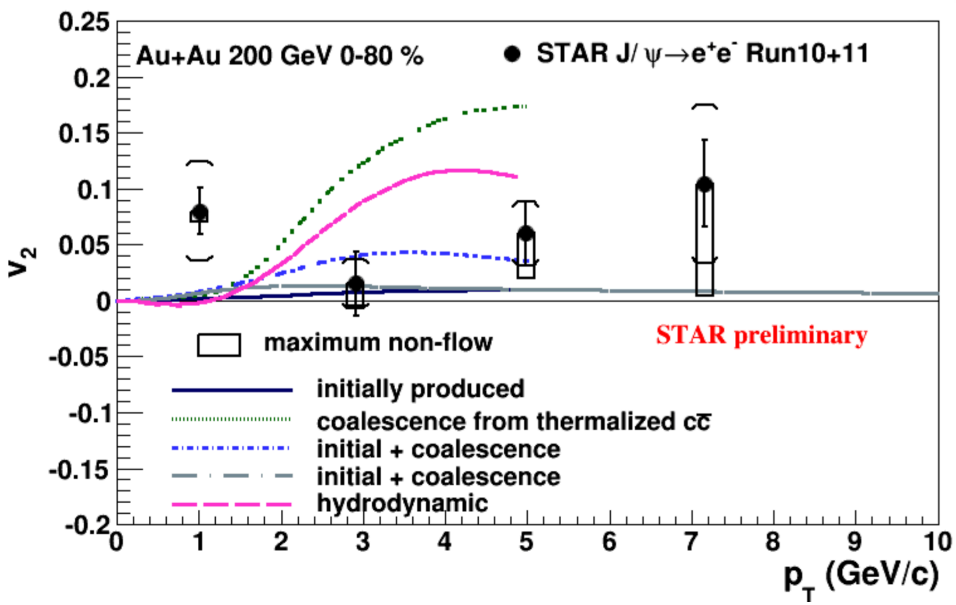


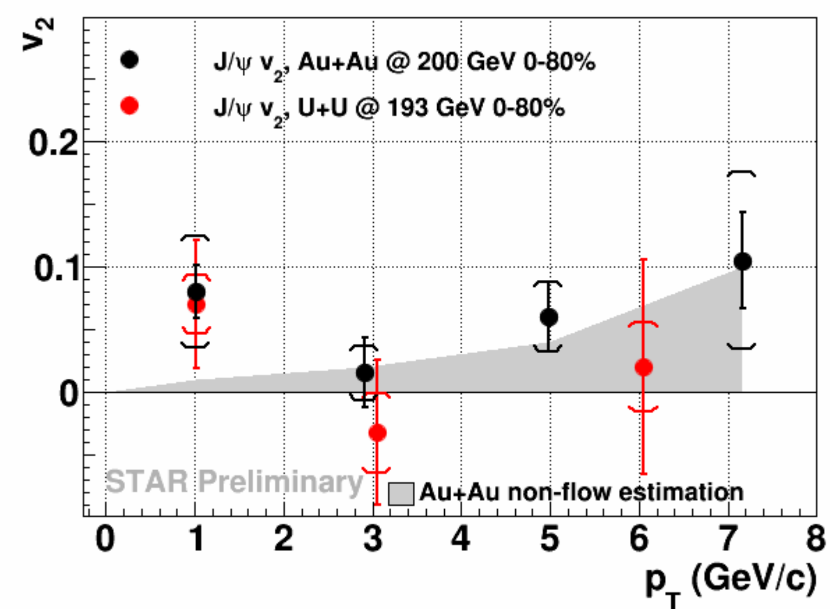
CMS: JHEP 05 (2012) 063

J/ψ Elliptic Flow (v_2)

STAR Run10, PRL 111 (2013) 052301
L. Yan, P. Zhuang, and N. Xu, PRL 97 (2006) 232301
V. Greco, C.M. Ko, and R. Rapp, PLB 595 (2004) 202
X. Zhao and R. Rapp, arXiv: 0806.1239
Y. Liu, N. Xu and P. Zhuang, NPA 834 (2010) 317
U.W. Heinz and C. Shen, (private communication)

- Two main production mechanisms for J/ψ:
  - Primordial at low p_T: close to zero v_2
  - Regenerated: inherit v_2 from constituent charm quarks
- The first measurement of J/ψ v_2 in U+U collisions
  - ➔ U+U and Au+Au results are consistent within uncertainties.
- For p_T above 2 GeV/c, v_2 is consistent with zero
  - ➔ Contribution of regenerated J/ψ is likely small (need more statistics)



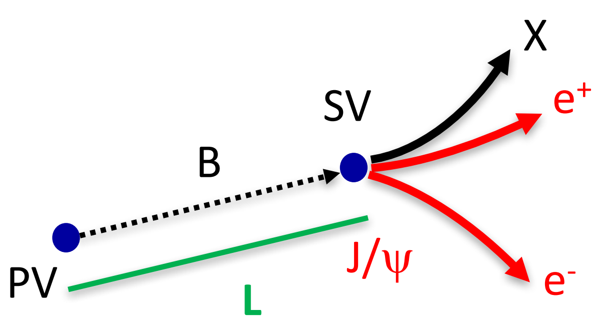


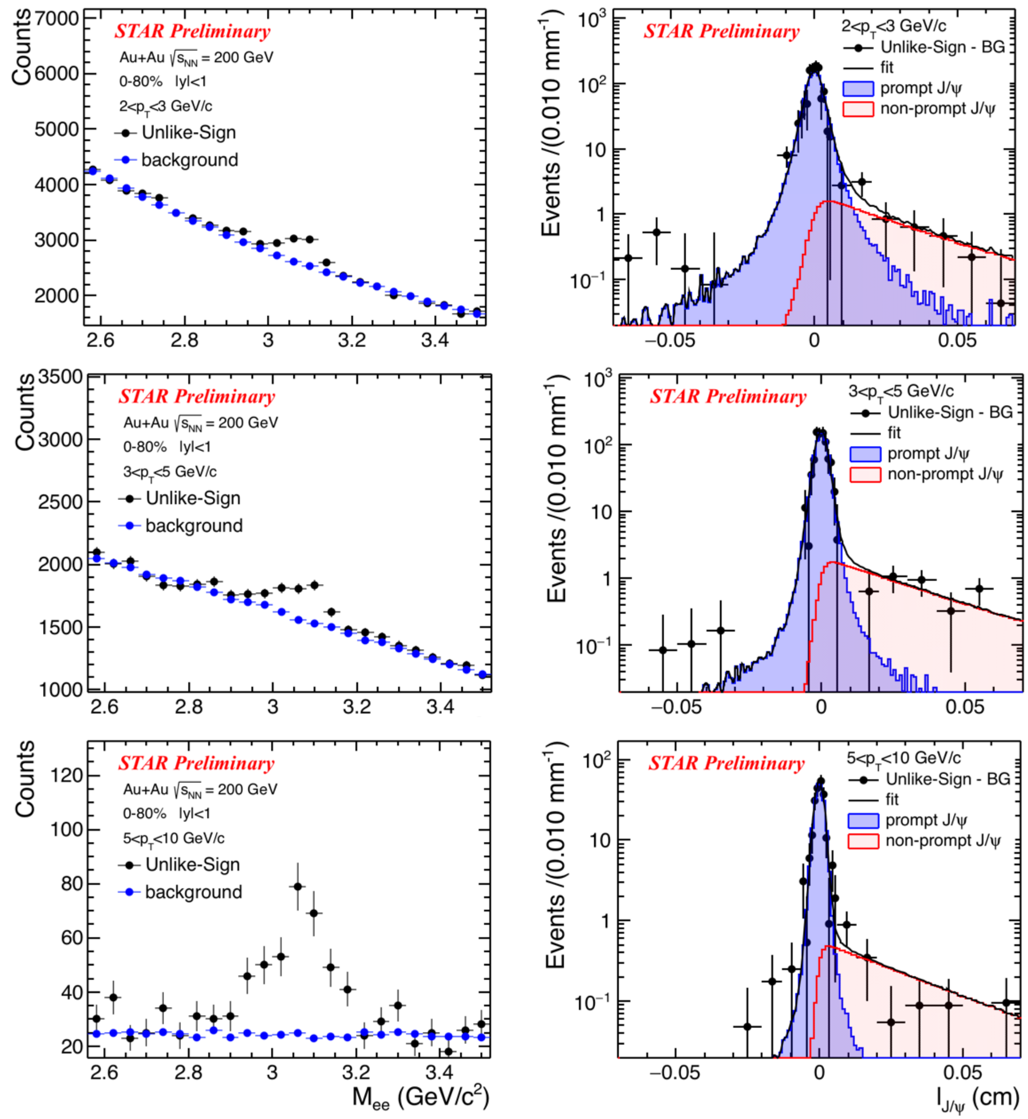
Extract Non-prompt J/ψ Fraction

- Fit the distribution of the pseudo proper decay length with templates to extract non-prompt J/ψ fraction

- Pseudo proper decay length:

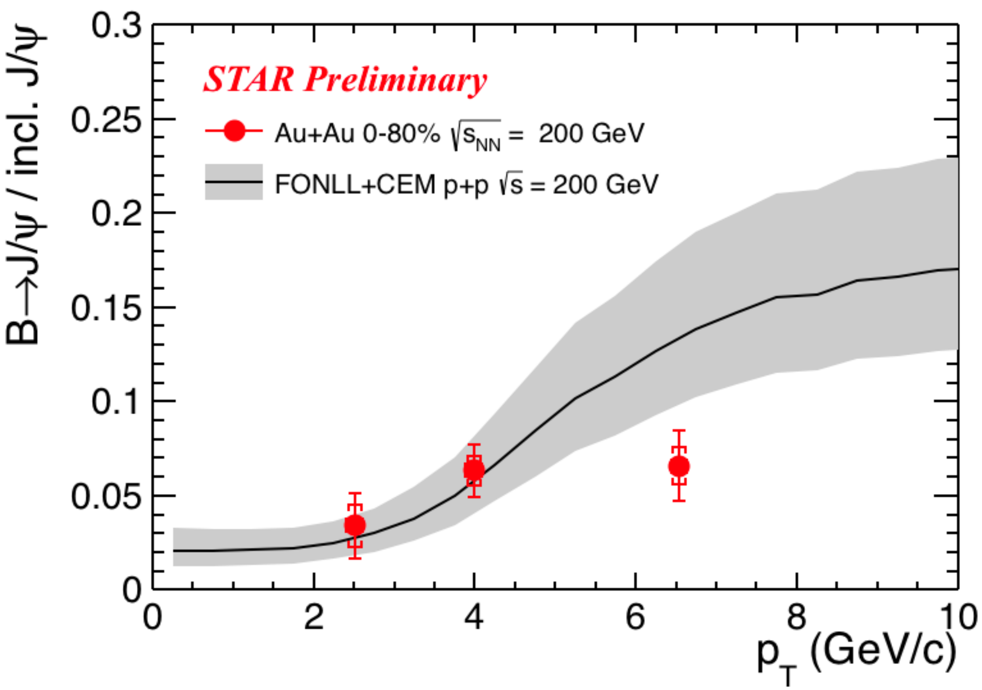
$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|\vec{p}|/c}\cdot M_{J/\psi}$$

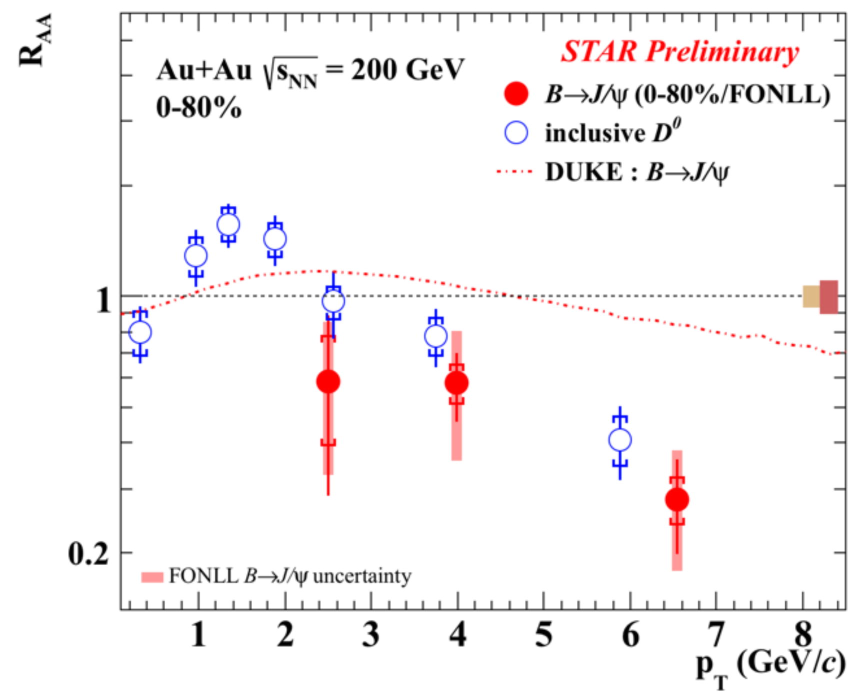




Non-prompt J/ψ Fraction and R_{AA}

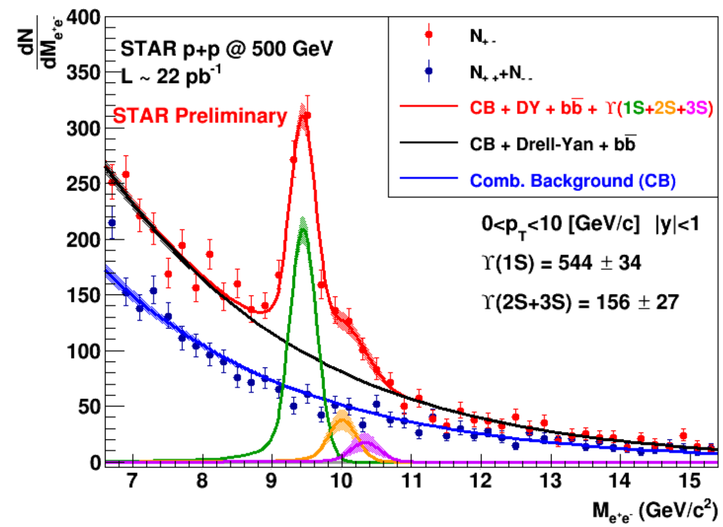
- $$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(Data)}{f_{p+p}^{B\to J/\psi}(Theory)} R_{AA}^{inc.J/\psi}(Data)$$
- Observe strong suppression of B → J/ψ at high p_T (> 5 GeV/c)
- Consistent with inclusive D^0 R_{AA}

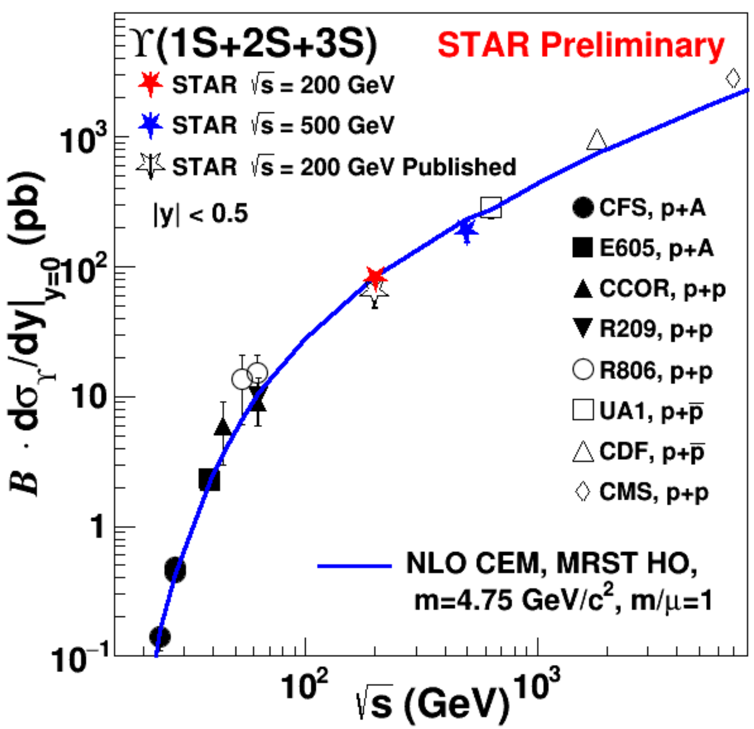


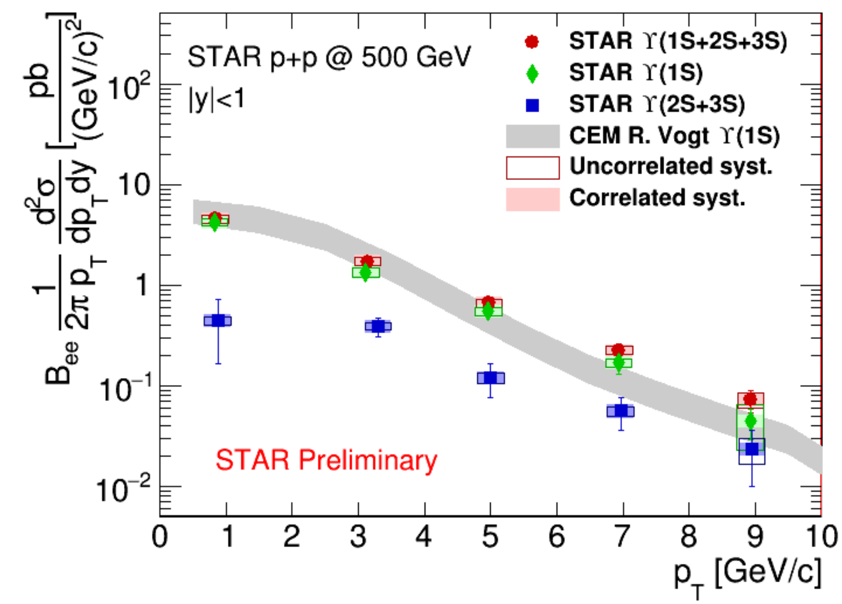


Υ in p+p @ 200 & 500 GeV

- Precision measurements of Υ(1S+2S+3S) production cross-sections from 0 to 10 GeV/c of p_T^{Υ}
- Consistent with CEM prediction
- $\sigma^{\Upsilon(1S+2S+3S)}$ = 81 ± 5(stat.) ± 8(syst.) pb for p+p @ 200 GeV

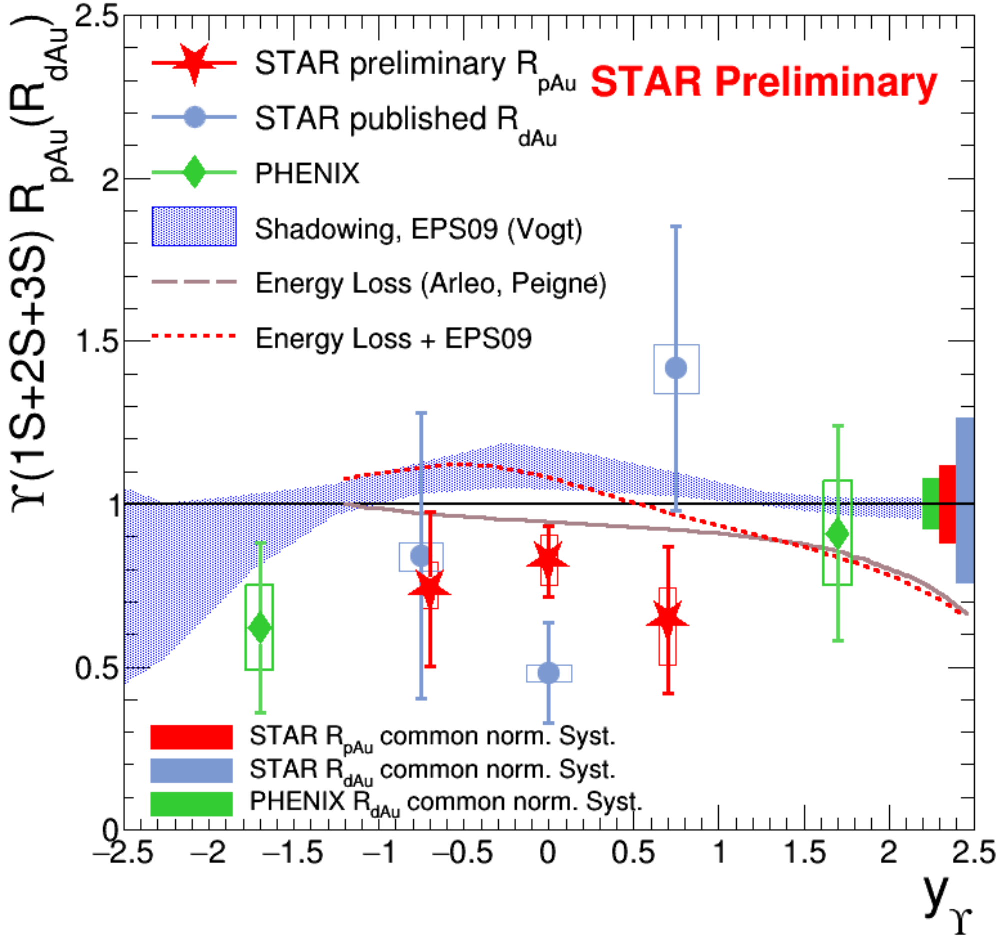






Υ in p+Au @ 200 GeV

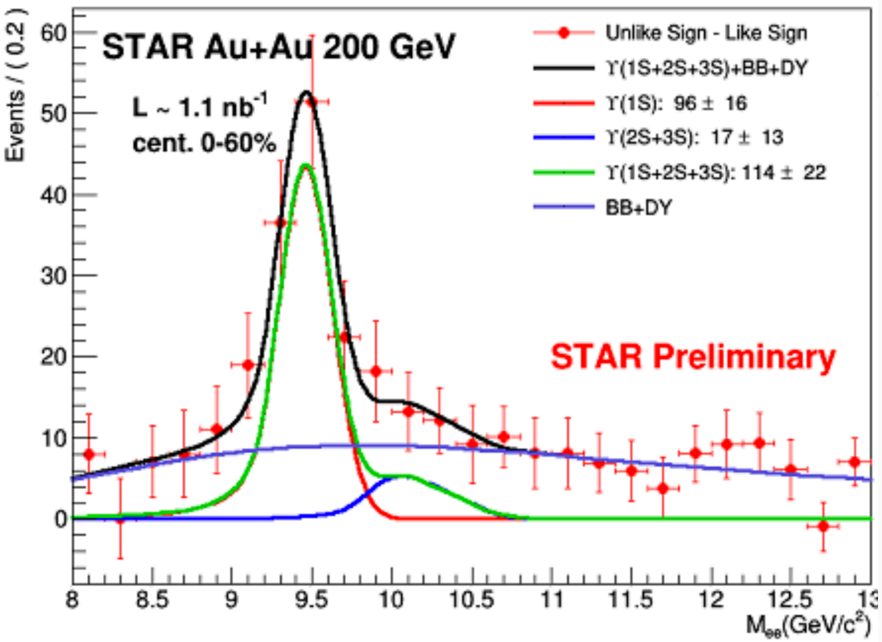
- R_{pAu} = 0.82 ± 0.10 (stat.) $^{+0.08}_{-0.07}$ (syst.) ±0.10 (global)
  - ➔ Quantify CNM effects



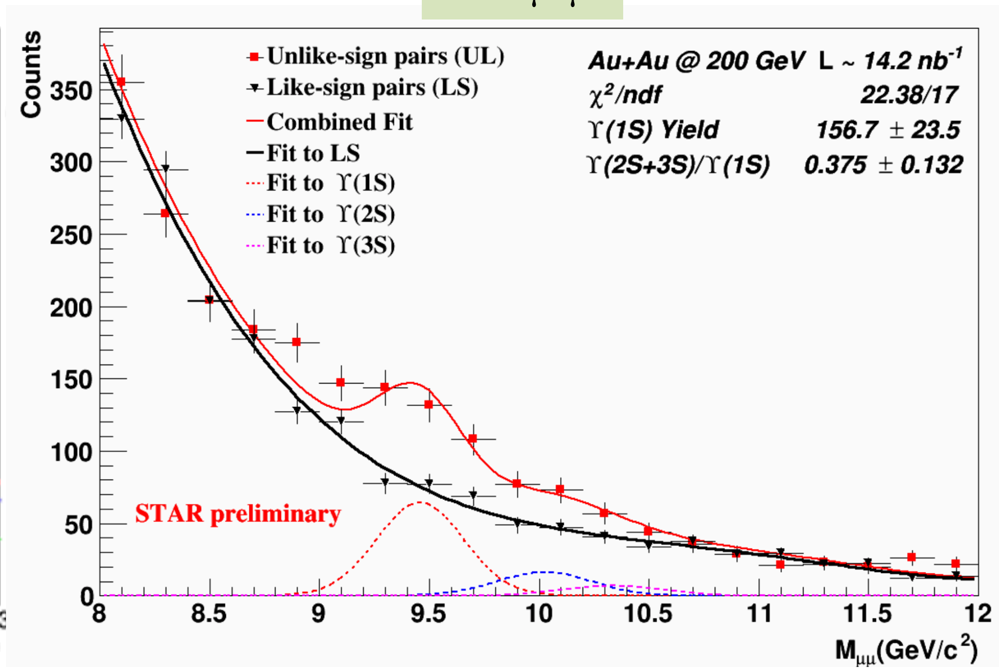
Υ in Au+Au @ 200 GeV

- Clear Υ(1S, 2S, 3S) signals in Au+Au collisions
  - ➔ First Υ(1S, 2S, 3S) → $\mu^+\mu^-$ signal from STAR

$\Upsilon \rightarrow e^+e^-$

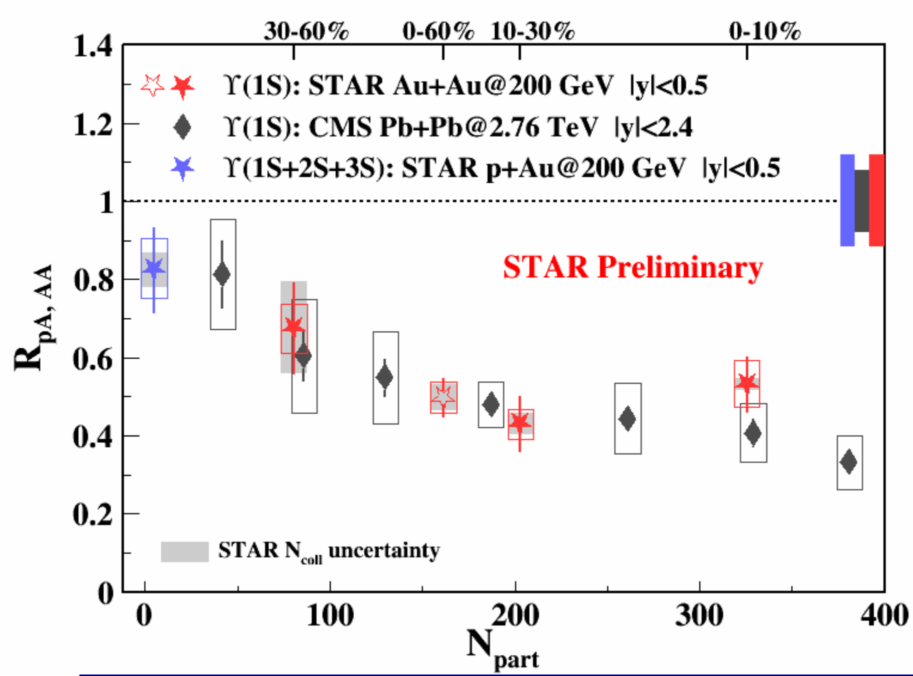


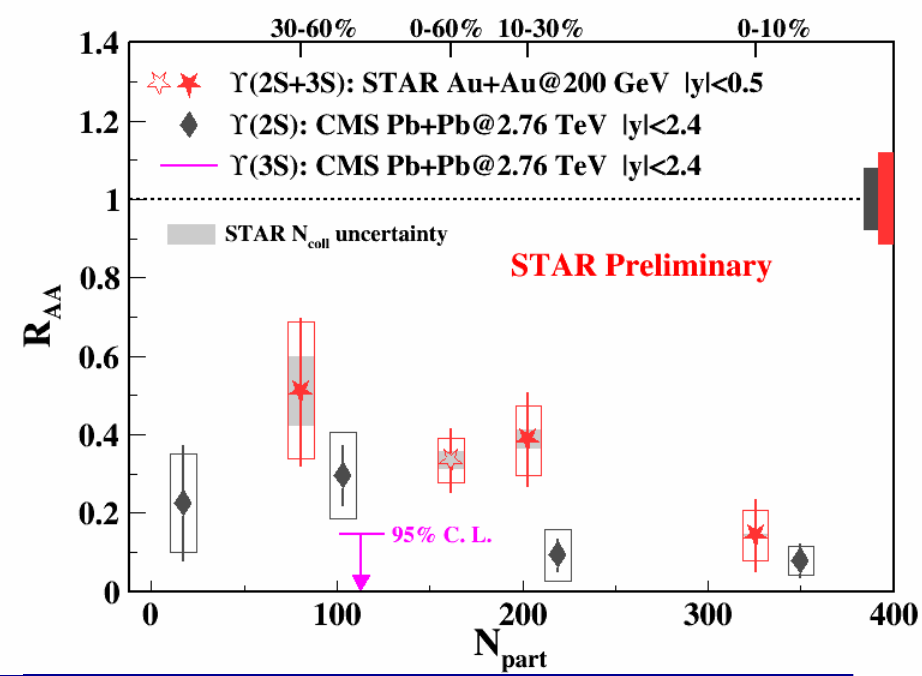
$\Upsilon \rightarrow \mu^+\mu^-$



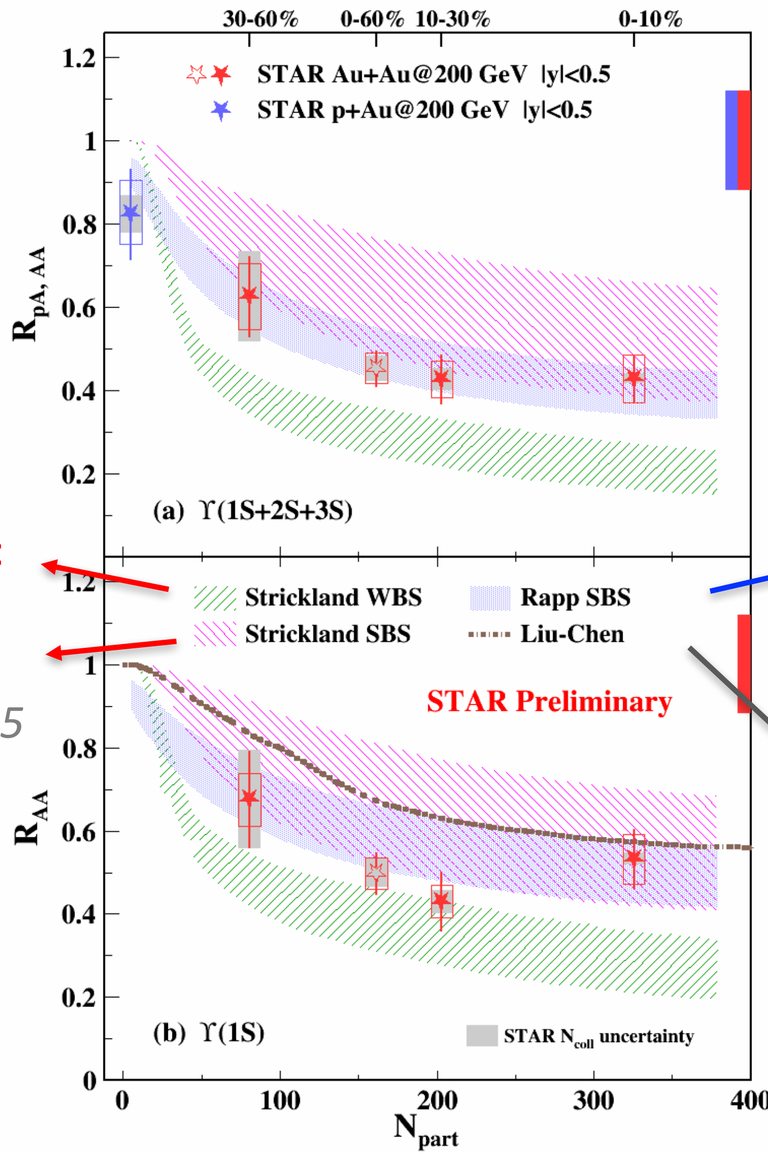
Υ R_{AA} vs. N_{part}

- Stronger suppression in central collisions in both RHIC and LHC
- Υ(2S+3S) is more suppressed than Υ(1S), in central collisions
  - ➔ **Sequential melting**
- RHIC vs. LHC:
  - Υ(1S): similar suppression as the CMS measurement
  - Υ(2S+3S): hint of less suppression at RHIC than at LHC





Υ R_{AA} vs. Models



- WBS (Weakly Binding Scenario):
  - Slow dissociation-potential based on free energy
- SBS (Strongly Binding Scenario):
  - Fast dissociation-potential based on internal energy

Strickland, Bazov:
No CNM,
no regeneration
NPA 879 (2012) 25

Emerick, Zhao, Rapp:
Includes CNM, SBS case
EPJ A48 (2012) 72

Data seem to favor SBS scenario

Liu, Chen, Xu, Zhuang:
Dissociation only for excited states, suppression of ground state due to feed- down, SBS.
PLB 697 (2011) 32

Summary

- **J/ψ production in p+p, Au+Au, p+Au and U+U**
  - Inclusive J/ψ production cross-sections for p+p @ 200 and 500 GeV can be described by CGC + NRQCD and NLO NRQCD predictions for prompt J/ψ production, while ICEM for direct J/ψ production underestimates the data in the intermediate p_T region
  - J/ψ yield vs. N_{ch} in p+p increases faster than a linear function
  - Both λ_θ and λ_ϕ for J/ψ in p+p are consistent with 0 in HX and CS frames
  - J/ψ R_{pAu} can be described by the model calculation with additional nuclear absorption on top of nuclear PDF effects
  - J/ψ v_2 in U+U and Au+Au collisions are consistent within uncertainties
  - The first measurements of non-prompt J/ψ in Au+Au from STAR: strong suppression of B → J/ψ at high p_T (> 5 GeV/c)

- **Υ production in p+p, Au+Au and p+Au**
  - Υ(1S+2S+3S) production cross-section in p+p consistent with CEM prediction
  - R_{AA} measurement indicates sequential melting in bottomonium system
  - Data seem to favor the models with Strongly Binding Scenario

- **Stay tuned for more quarkonium results from STAR in the next few years!**