Latest Results on Heavy Quarkonium Measurements in p+p, p+Au and Au+Au Collisions at STAR

13TH International Conference on Nucleus-Nucleus Collisions (NN2018)

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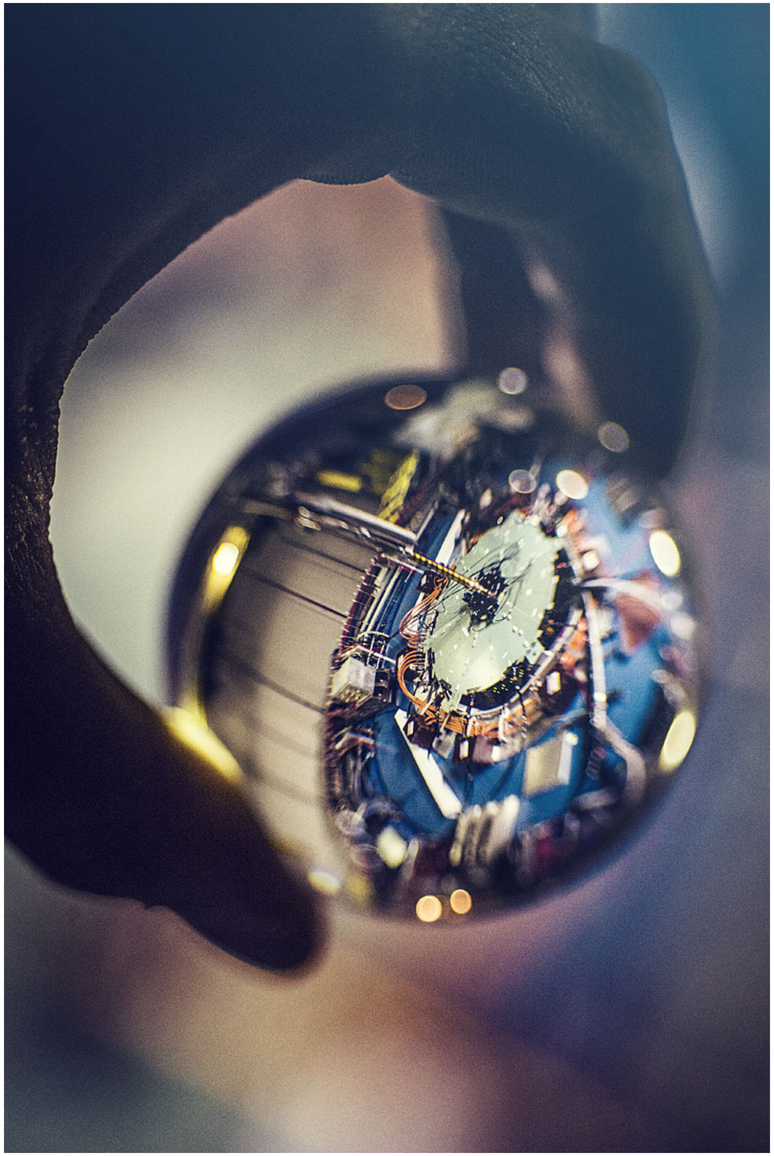
On behalf of the STAR Collaboration

Outline

- Motivation
- Relativistic Heavy Ion Collider
- The STAR detector
- Physics measurements
  - Charmonia
  - Bottomonia
- Summary

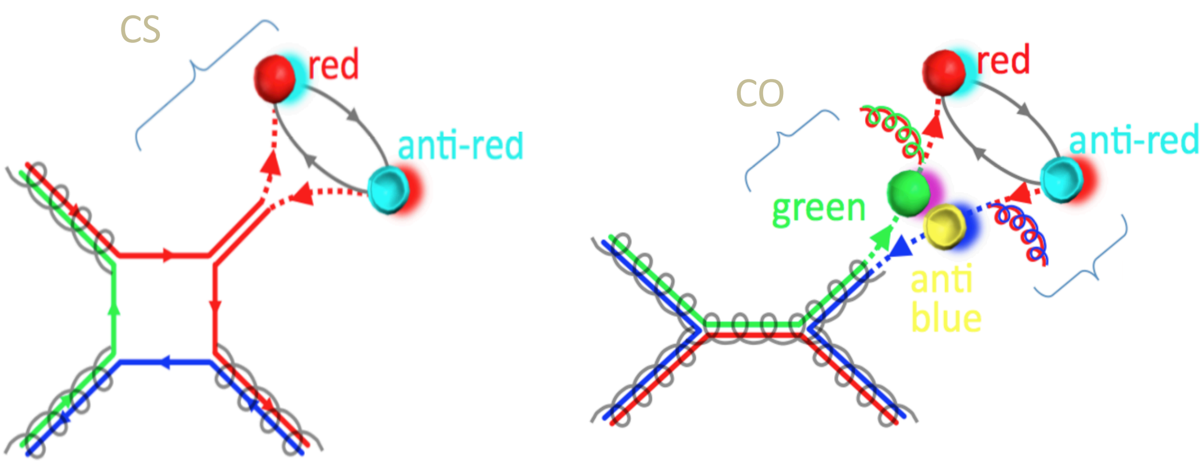


https://www.bnl.gov/photowalk/winners-2018.php

Motivation

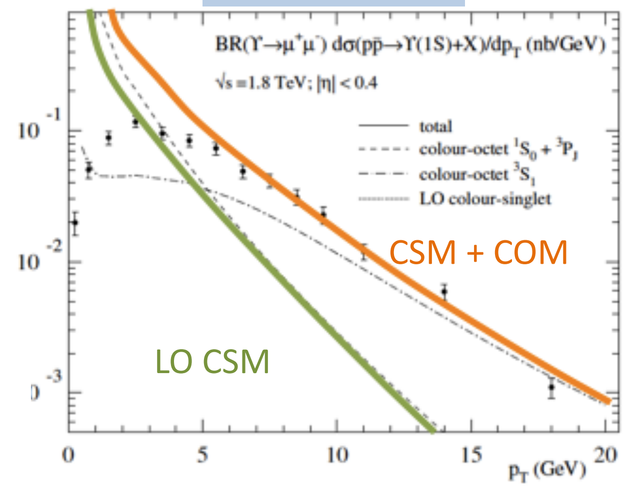
- Quarkonium production mechanism still not fully understood in hadron-hadron collisions
- Some popular models on the market:
  - **Color Singlet Model (CSM)** → The quantum numbers (spin, color) of the final and initial states are the same
  - **Color Octet Mechanism (COM) / NRQCD**
    - **+ Color Glass Condensate effective theory (CGC)**

    } The quantum numbers of the initial and final quark pairs can be different
  - **Color Evaporation Model (CEM) / Improved CEM**



From Cristina Biino's Talk (FPCP2013)

CDF Υ(1S) result

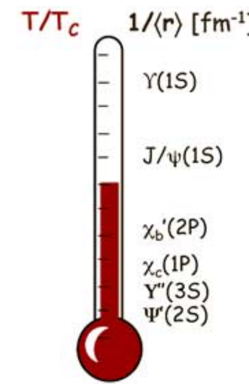


M. Kramer, Prog. Part. Nucl. Phys. 47, 141 (2001)

Study QGP via Heavy Flavor

- Heavy flavor quarks (open heavy flavor, quarkonia) are good probes for studying QGP in heavy-ion collisions
  - $m_{c,b} >> T_C, \Lambda_{QCD}, m_{u,d,s}$: produced dominantly by high-Q^2 scatterings in the early stage

    → **Good candidates to study the evolution of QGP**



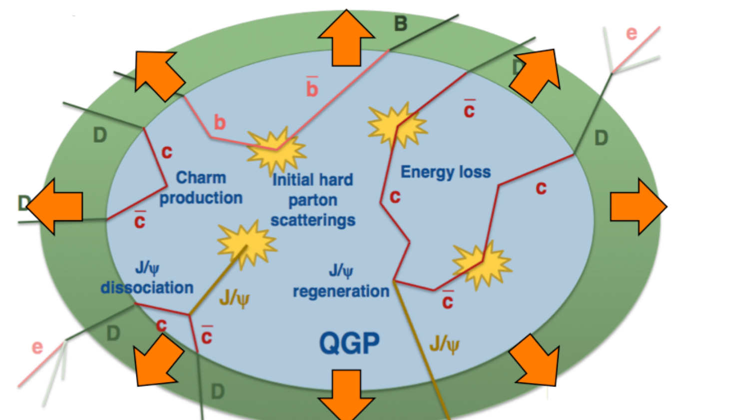
EPJ C61 (2009) 705

- Quarkonium suppression is one of the smoking guns for the QGP formation (by T. Matsui and H. Satz PLB 178 (1986) 416)

  → **Color-screening**: Quarkonium dissociates in the medium

- ***Sequential melting**: different states dissociate at different temperatures*

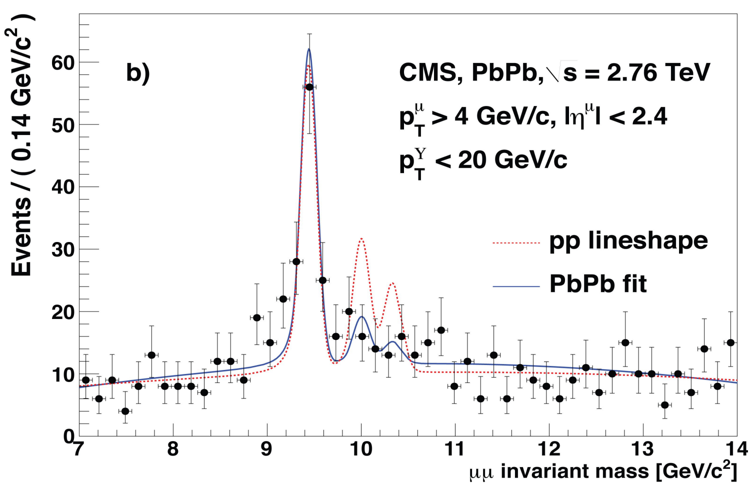
A. Rothkopf



https://indico.cern.ch/event/443462/images/6069-hf_cartoon1.png

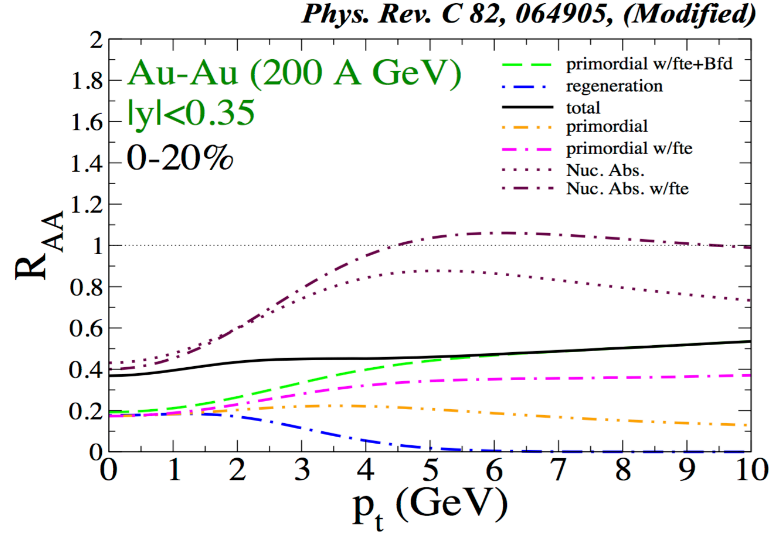
Study QGP via Quarkonium

- Interpretation of quarkonium 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 from excited states and B-hadrons***



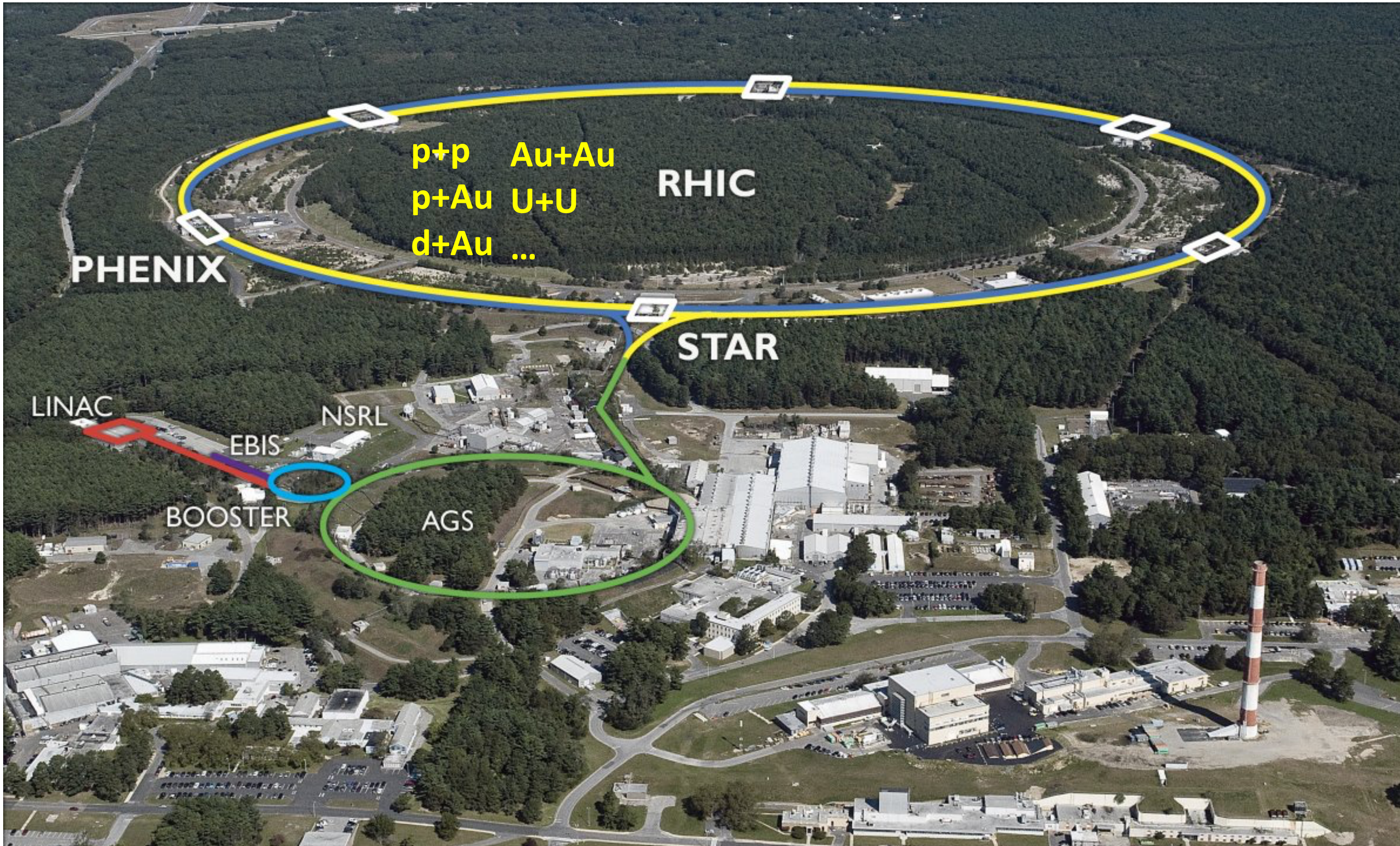
CMS Collaboration, Phys Rev Lett 107 052302,2011

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



Relativistic Heavy-Ion Collider (RHIC)

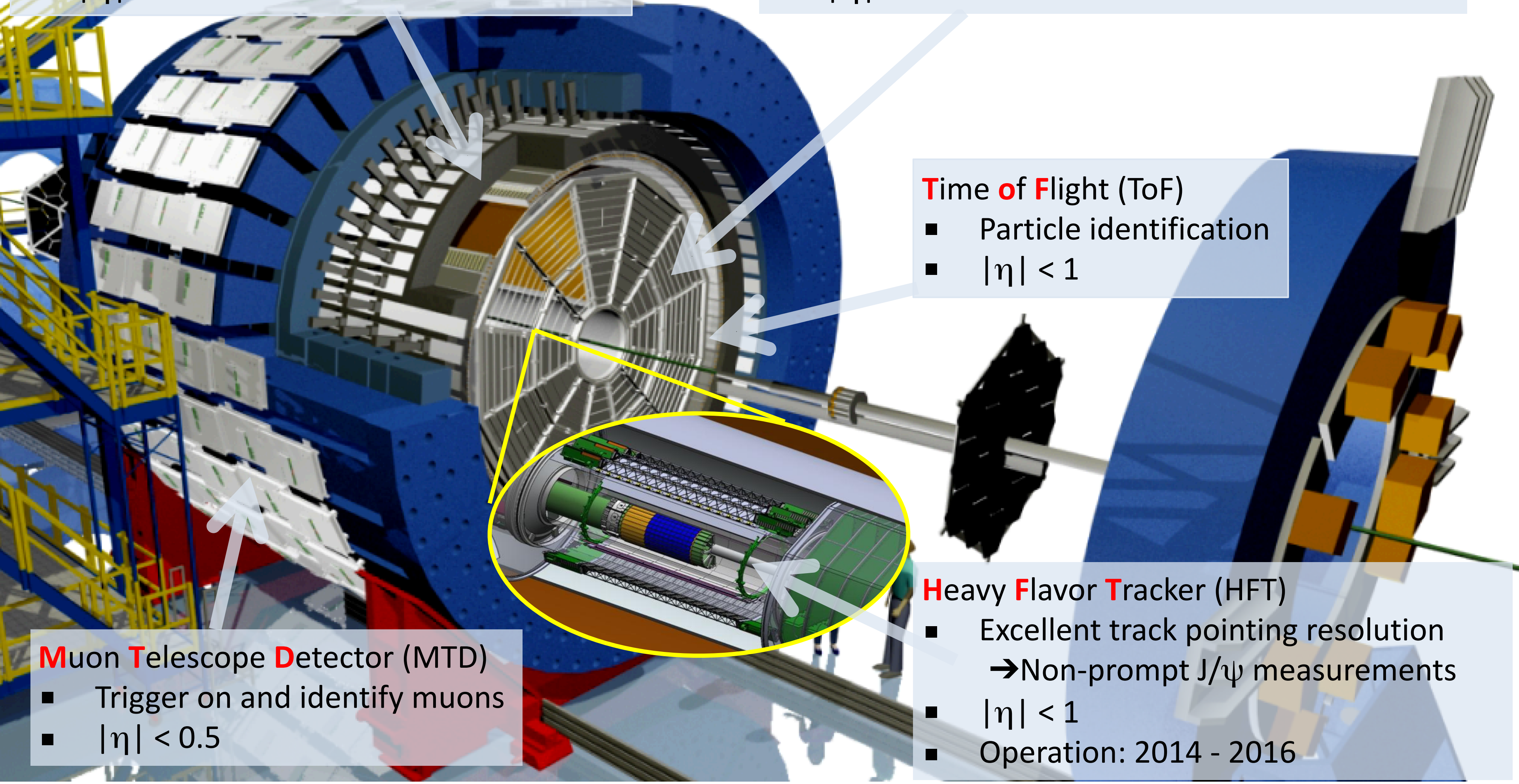
- The most versatile collider in the world!



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
- $|\eta| < 1$

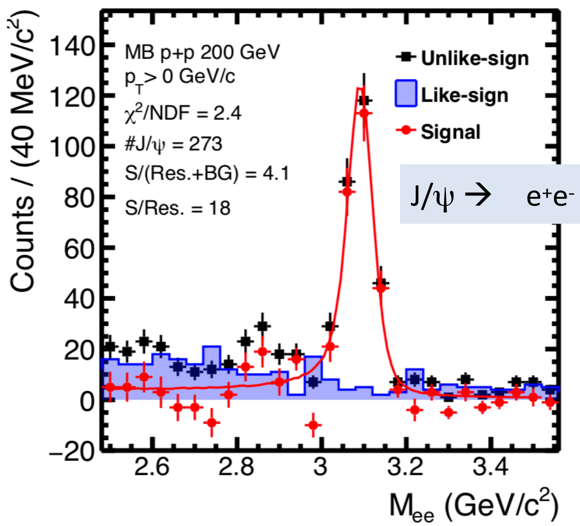
Muon Telescope Detector (MTD)
- Trigger on and identify muons
- $|\eta| < 0.5$

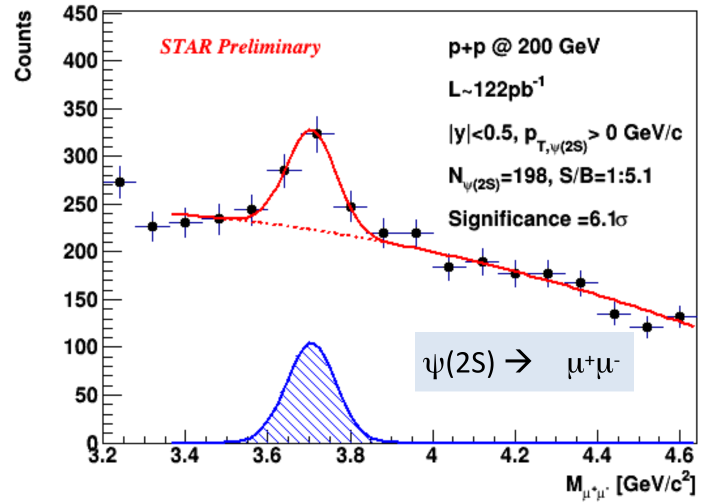
Heavy Flavor Tracker (HFT)
- Excellent track pointing resolution
  ➔Non-prompt J/ψ measurements
- $|\eta| < 1$
- Operation: 2014 - 2016

J/ψ & ψ(2S) in p+p @ 200 & 500 GeV

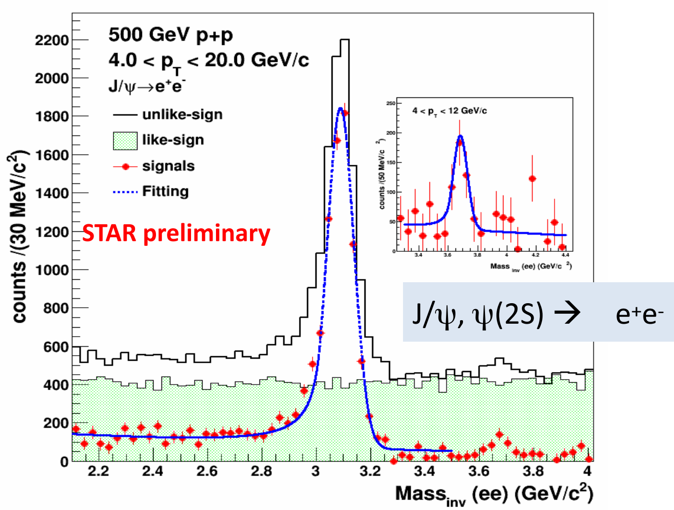
- J/ψ and ψ(2S) signals from the ***dielectron*** and ***dimuon*** channels

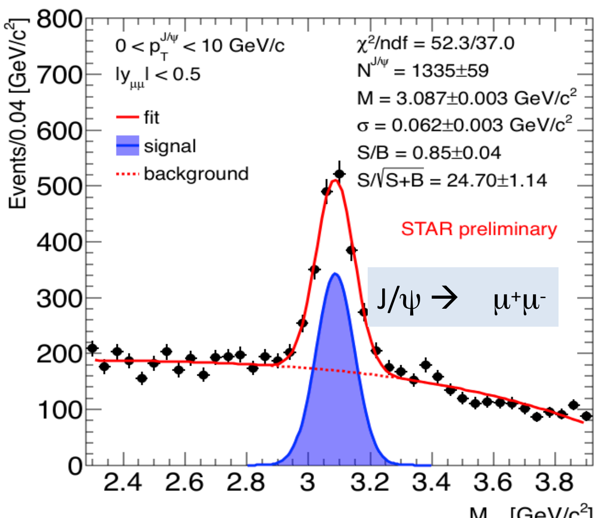
p+p @ 200 GeV





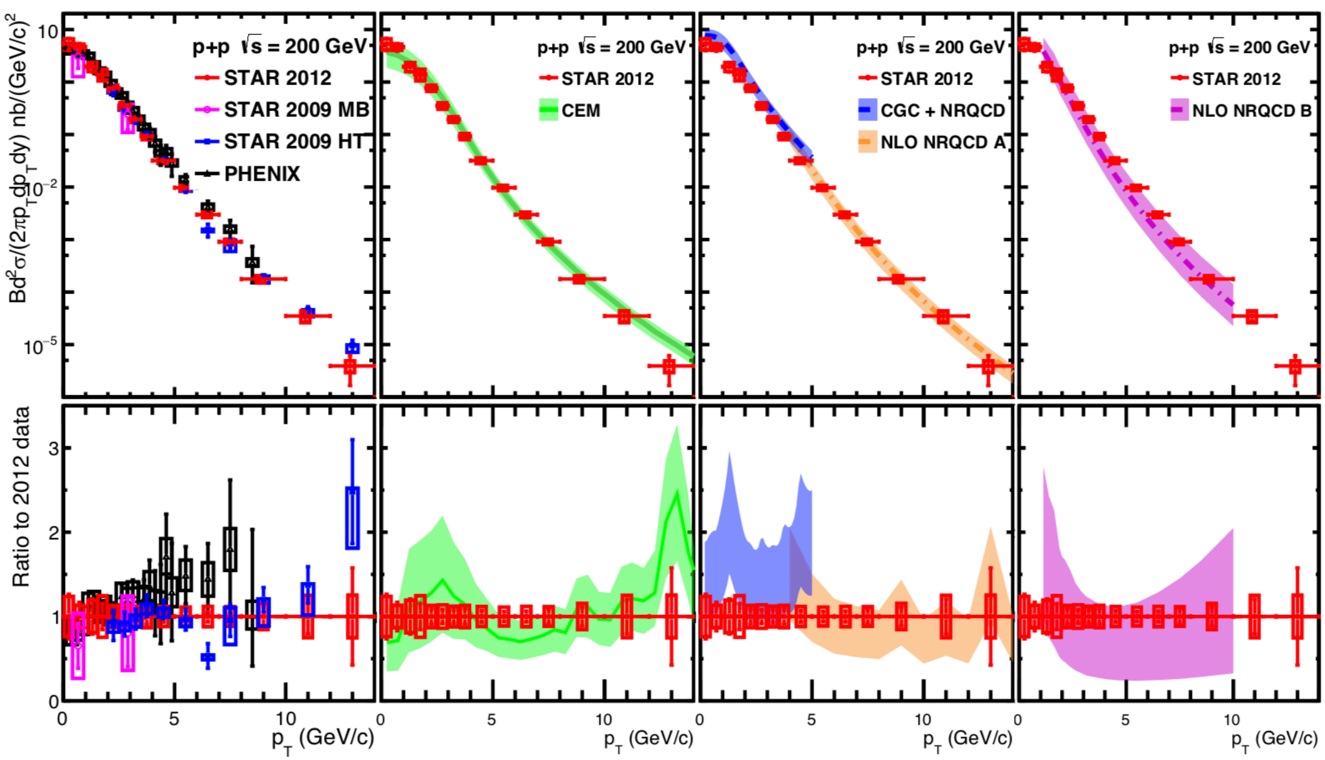
p+p @ 500 GeV





J/ψ Cross-Section in p+p Collisions @ 200 GeV

- Precision measurement of J/ψ production cross-section for $p_T^{J/\psi}$ from 0 to 14 GeV/c
- Consistent with CEM (direct J/ψ production only) and NLO NRQCD calculations (prompt J/ψ production)
- CGC+NRQCD seems to overestimate the data in the low p_T region

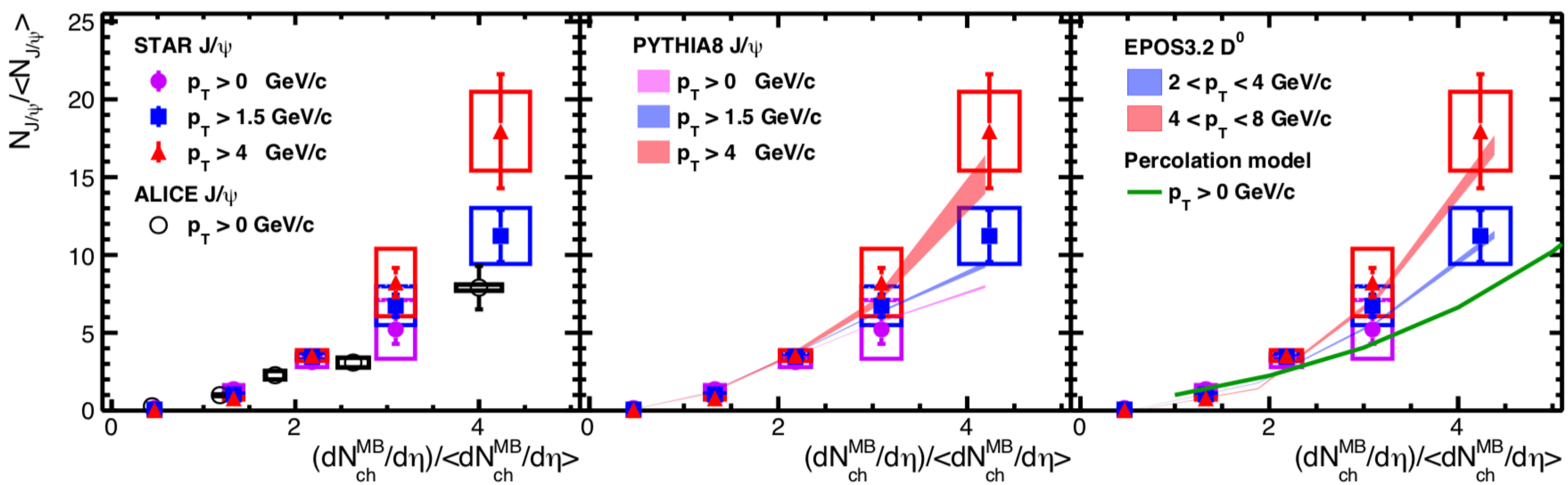


STAR 2012: PLB 786 (2018) 87-93
STAR 2009: PLB 722 (2013) 55; PRC 93 (2016) 064904
PHENIX: PRD 82 (2010) 012001
CEM: Phys. Rept. 462 (2008) 125; R. Vogt private communication (2009)
NLO+NRQCD A: PRD 84 (2011) 114001
CGC+NRQCD: PRL 113 (2014) 192301
NLO+NRQCD B: PRL 108 (2012) 172002

J/ψ vs. Event Activity in p+p Collisions @ 200 GeV

- Event activity = charged-particle multiplicity at mid-rapidity
- Relative J/ψ yield rises faster than a linear function
  - →Similar global trend at different collision energies, and similarly as for the D meson
- PYTHIA, EPOS3 and Percolation model can qualitatively describe the rising behavior

STAR 2012: PLB 786 (2018) 87-93



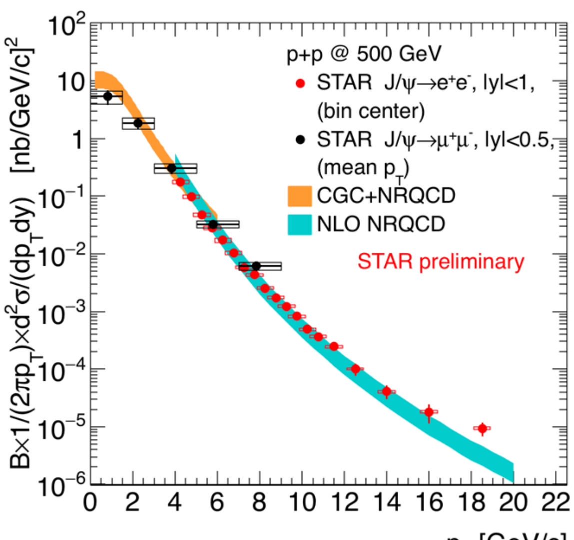
ALICE: JHEP 09 (2015) 148

Percolation model: Phys.Rev. C86 (2012) 034903

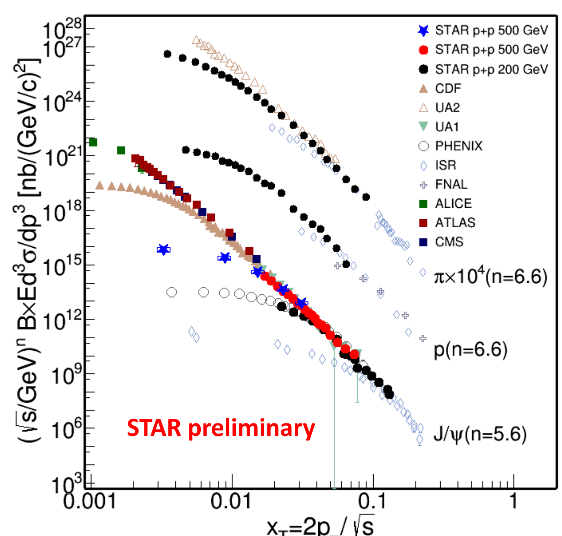
EPOS3.2: Phys. Rept. 350 (2001) 93.

J/ψ Cross-Section in p+p Collisions @ 500 GeV

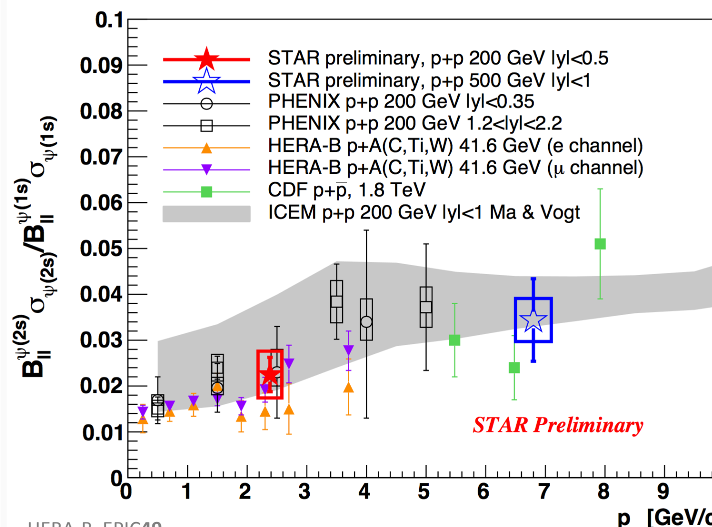
- Precision measurement of J/ψ production cross-section for $p_T^{J/\psi}$ from 0 to 20 GeV/c
- Consistent with CGC+NRQCD & NLO NRQCD calculations (prompt J/ψ)
- The high-p_T J/ψ follows the x_T-scaling
  - Broken scaling at low x_T is due to soft processes
- ψ(2S) to J/ψ ratios in p+p @ 200 & 500 GeV follow the world trend



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



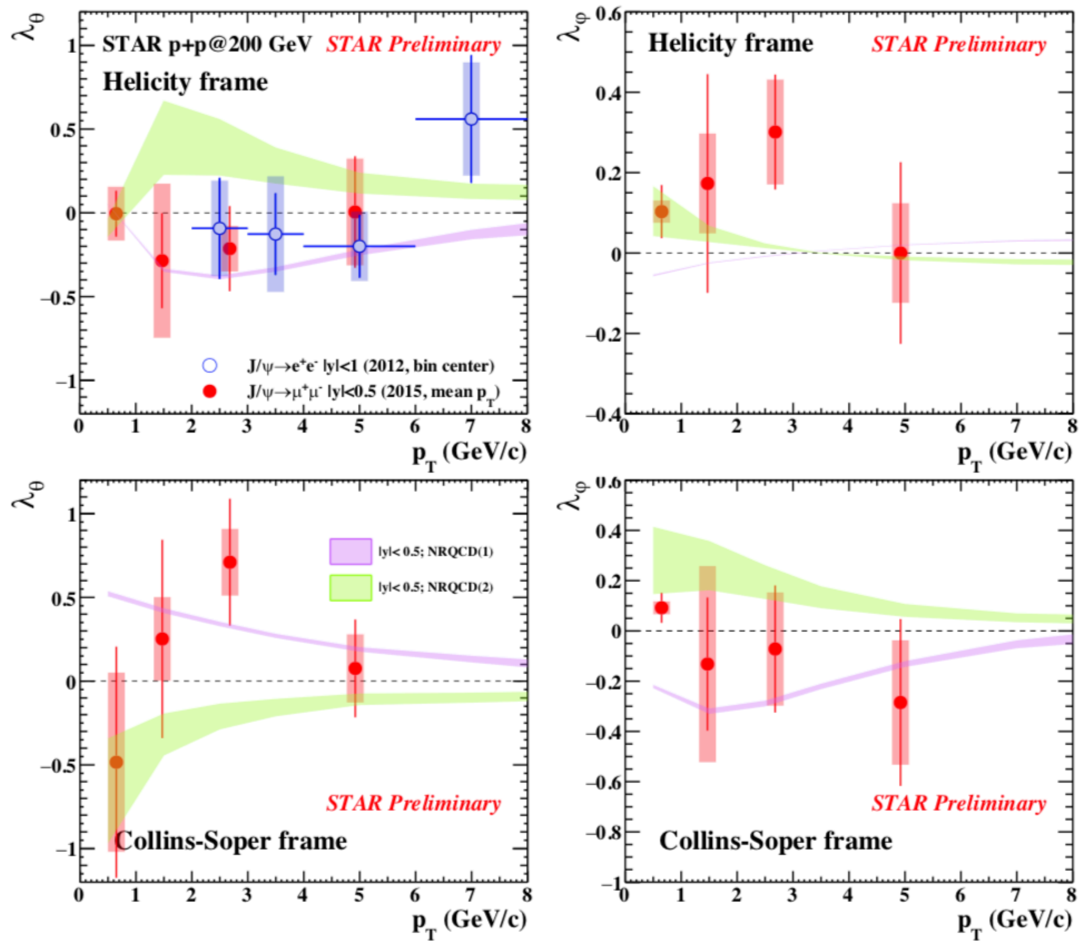
PRC **80** (2009) 041902



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 Polarization Measurement

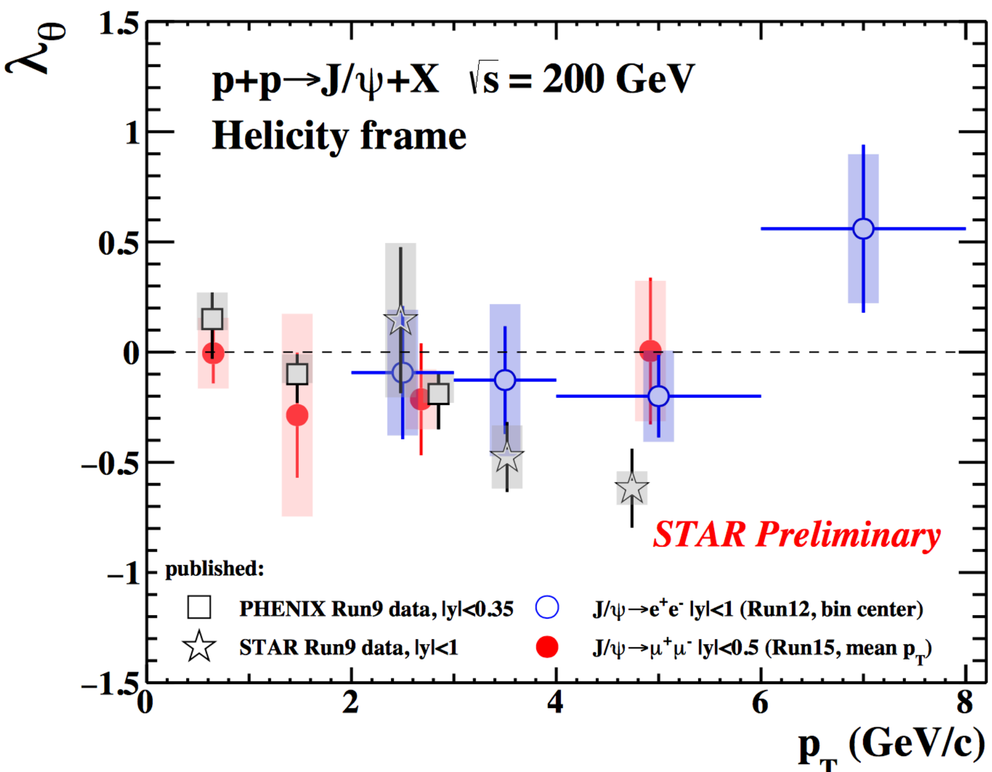
- First STAR J/ψ polarization measurements in Helicity (HX) and Collins-Soper (CS) frames from the ***dimuon*** channel in p+p collisions @ 200 GeV
- Both λ_θ and λ_ϕ are consistent with **ZERO** within uncertainties
- NRQCD prediction can qualitatively describe data
- Possible to distinguish different NRQCD predictions with improved precision at low p_T

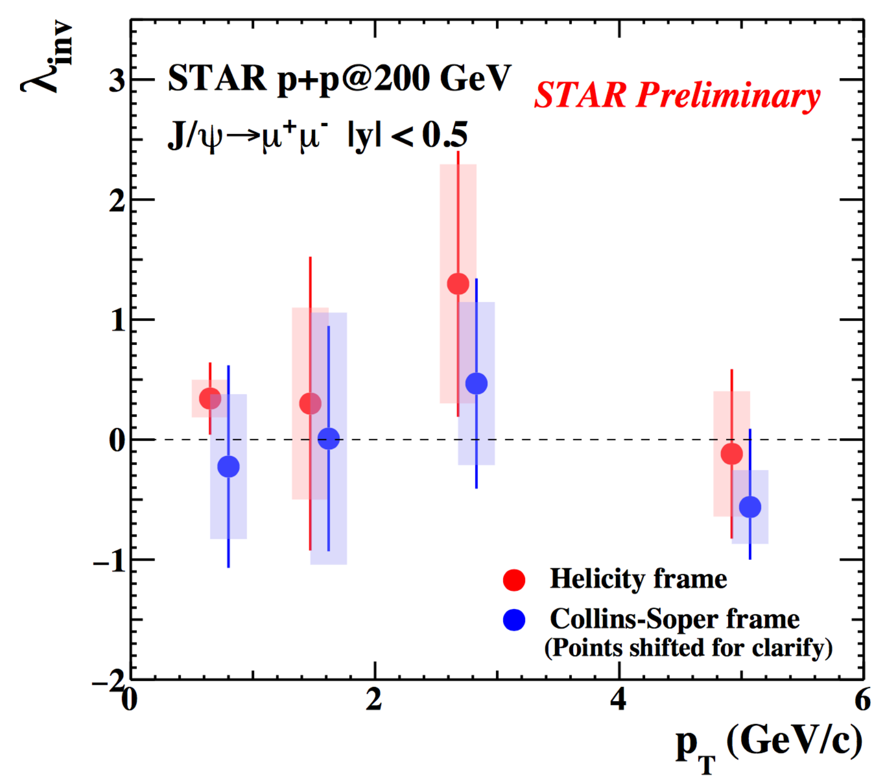


NRQCD1: Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Phys. Rev. Lett 110 (2013) 042002

J/ψ Polarization Measurement

- λ_θ 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

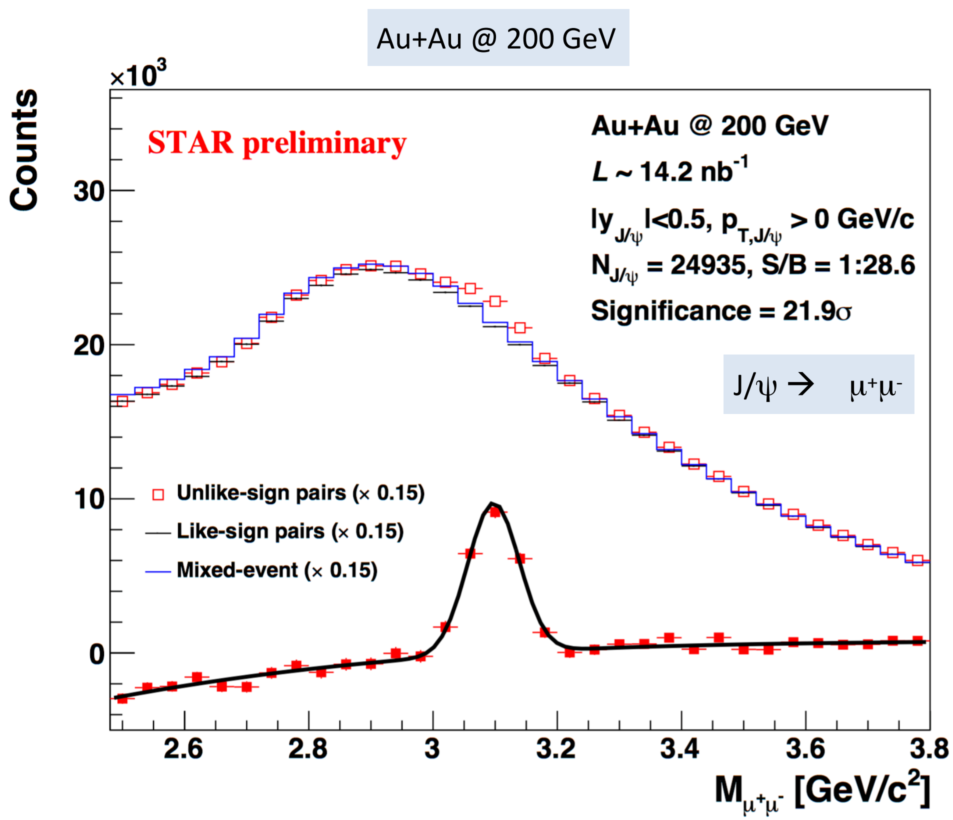


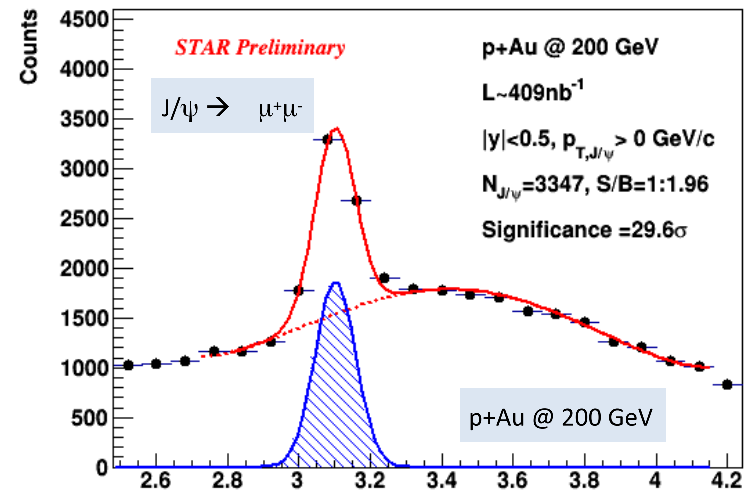


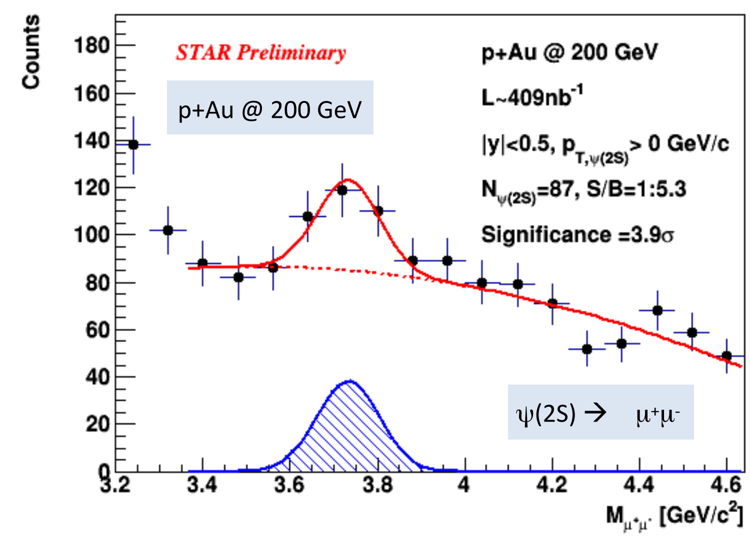
STAR Run 9: Phys. Lett. B739 (2014) 180–188
PHENIX: Phys. Rev. D **95**, 092003

J/ψ & ψ(2S) in p+A & Au+Au @ 200 GeV

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



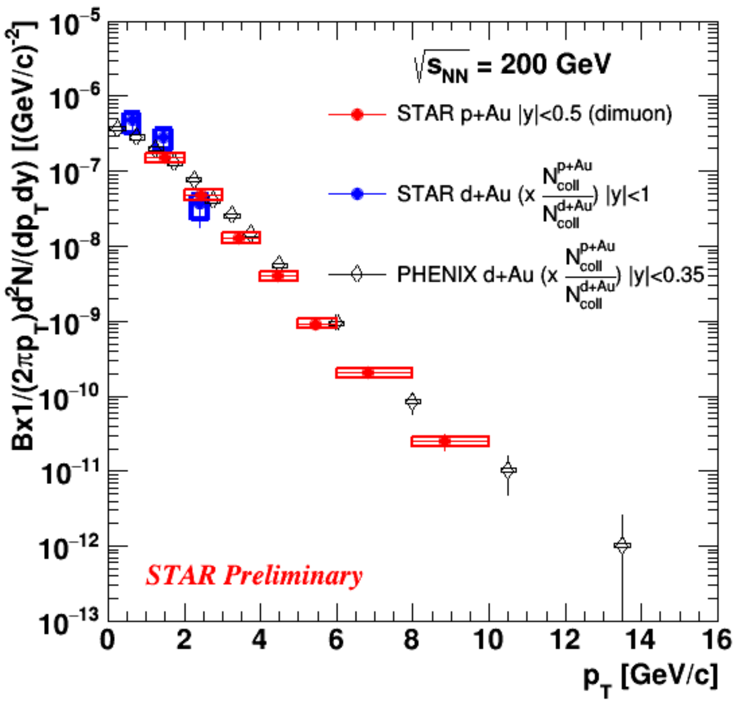


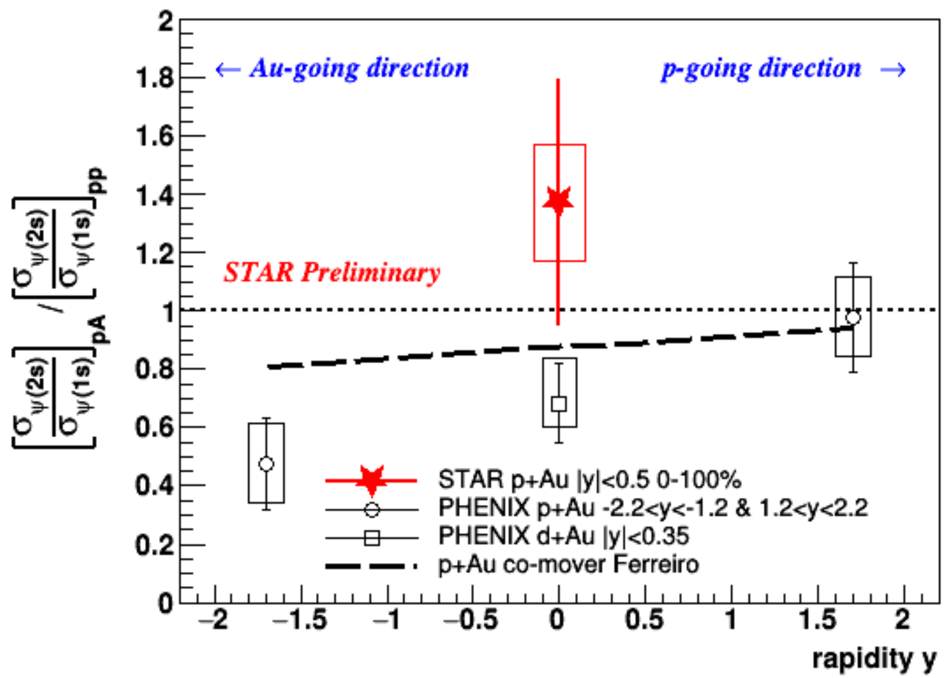


Invariant Yields and Double Ratio in p+Au

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

1.37 ±0.42(stat.) ±0.19(syst.)

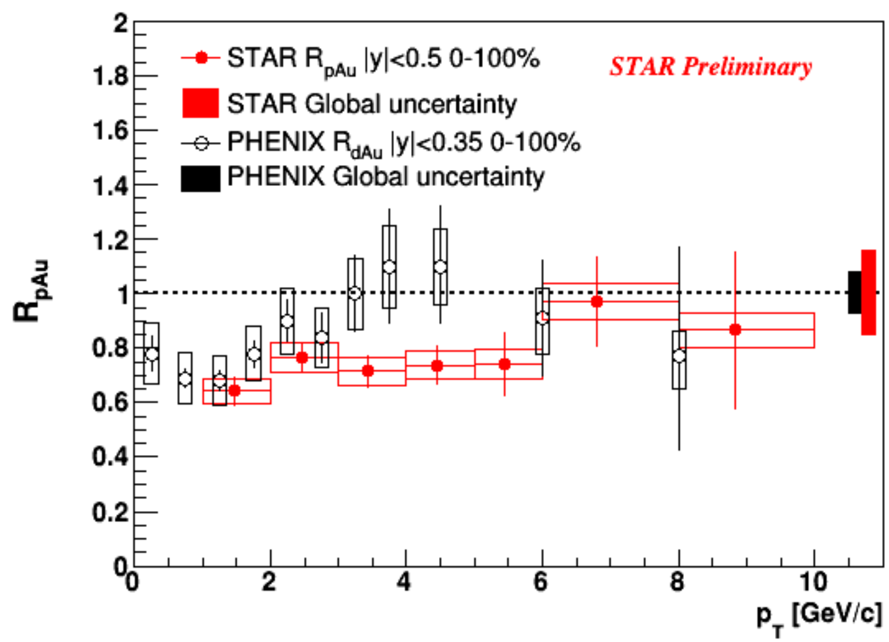




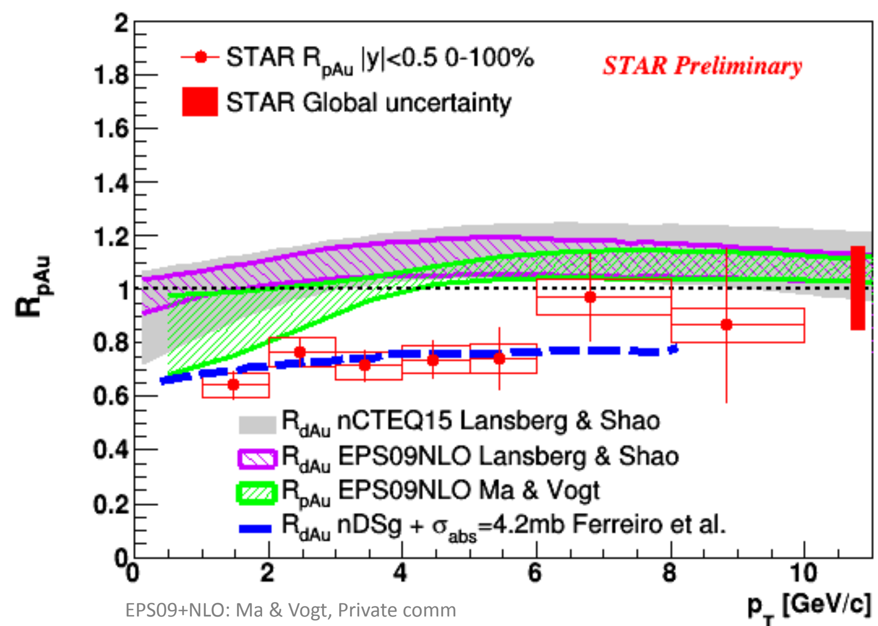
PHENIX p+Au, PRC**95** (2017) 034904
PHENIX d+Au, PRL**111** (2013) 202301
Co-mover calculation, Ferreiro, private comm.

J/ψ R_{pAu} vs. p_T

- R_{pAu} from STAR has similar trend as 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



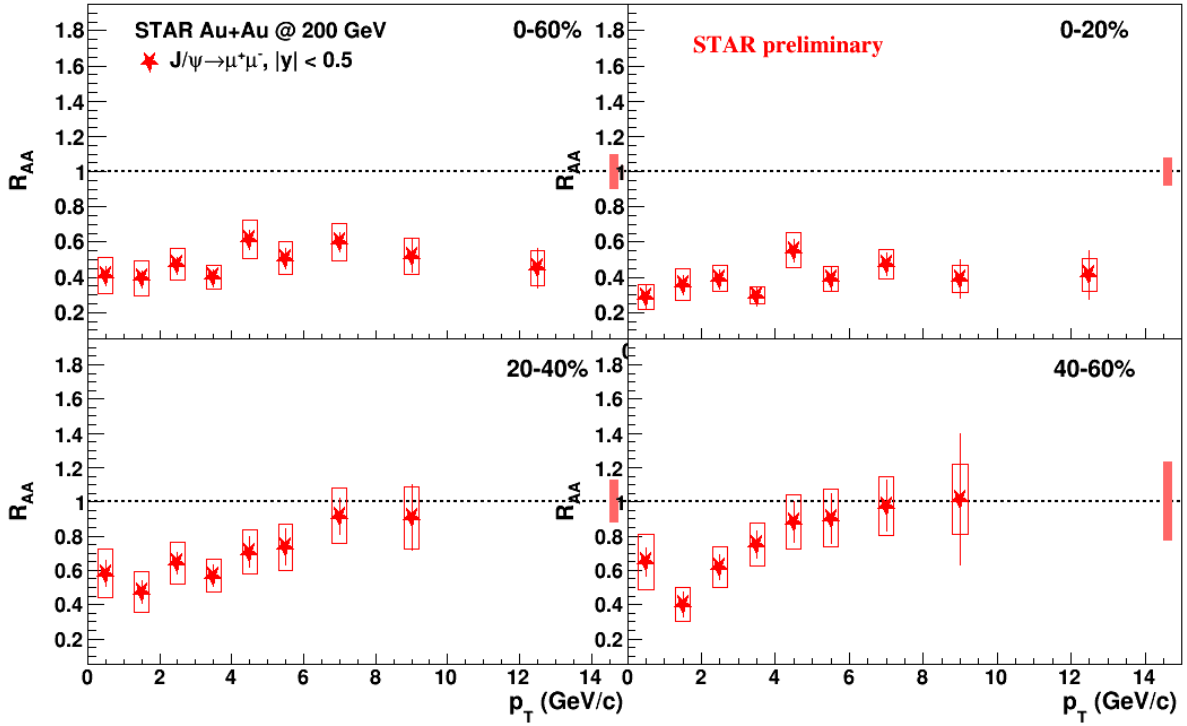
PHENIX, PRC87 (2012) 034903



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
Ferreiro et al., Few Body Syst.**53**(2012) 27

J/ψ R_{AA} vs. p_T

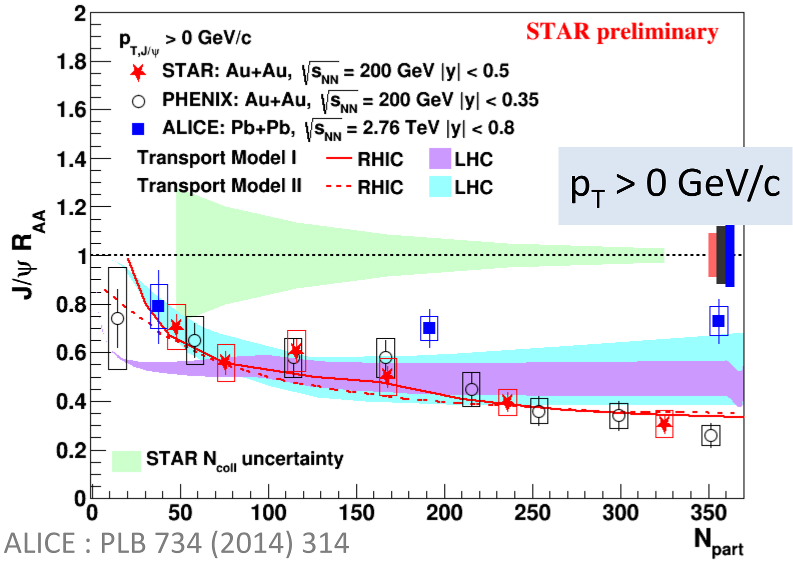
- No obvious p_T dependence in R_{AA} in 0 - 20% centrality bin
- Rising R_{AA} with p_T in 20 - 40% and 40 - 60% centrality bins
  - Rising trend at high p_T could be due to formation time effects, B-hadron feed-down
- Suppression at low p_T: dissociation, Cold Nuclear Matter (CNM) effects, regeneration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



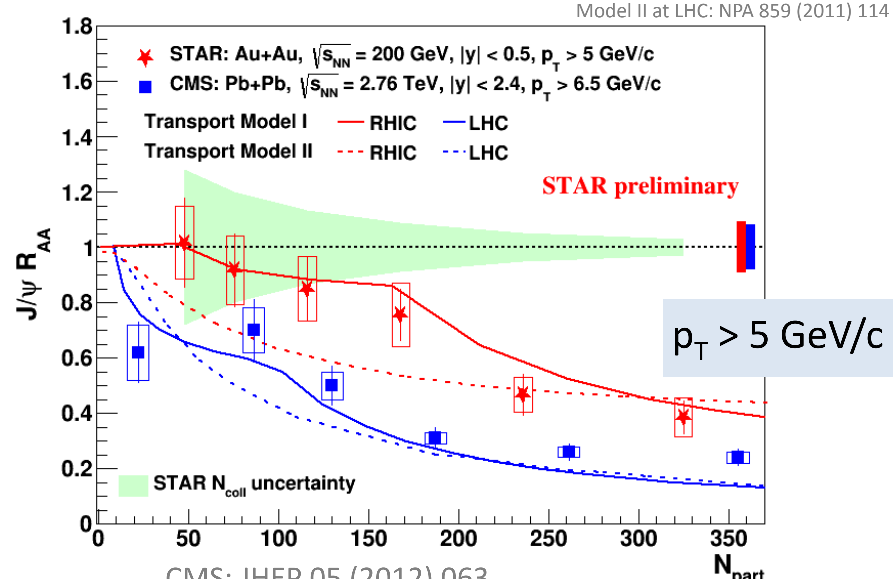
J/ψ R_{AA} vs. N_{part}

- RHIC vs. LHC
  - $p_T > 0$ GeV/c: at RHIC suppression increases with centrality, for central collision larger suppression compared to LHC
    - ➔Larger contribution from regeneration at LHC
  - $p_T > 5$ GeV/c: less suppression in central collisions at RHIC compared to LHC
    - ➔Larger dissociation rate at LHC
- 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

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



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



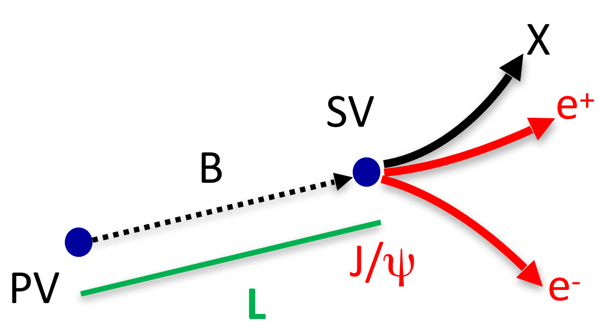
CMS: JHEP 05 (2012) 063

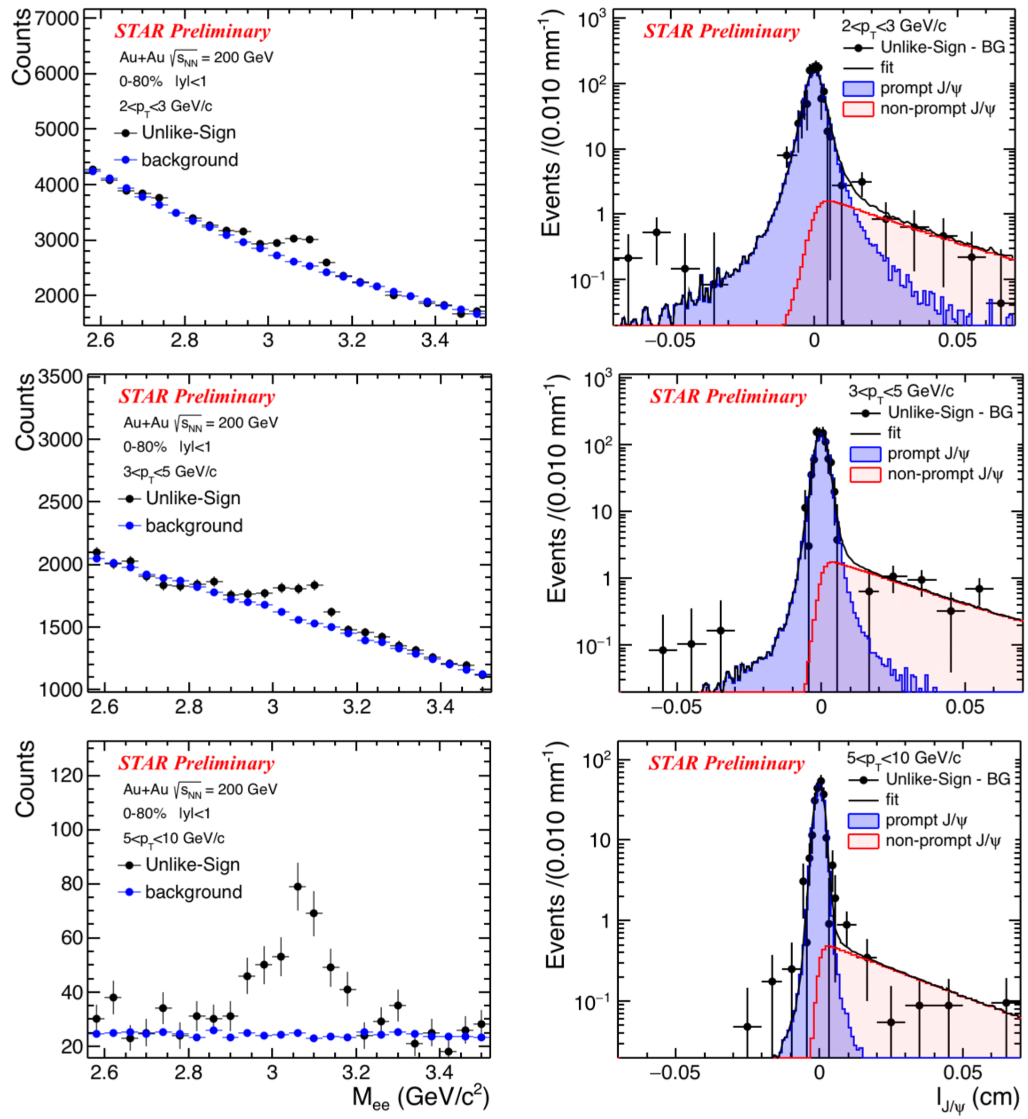
Extract Non-prompt J/ψ Fraction

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

- Pseudo proper decay length:

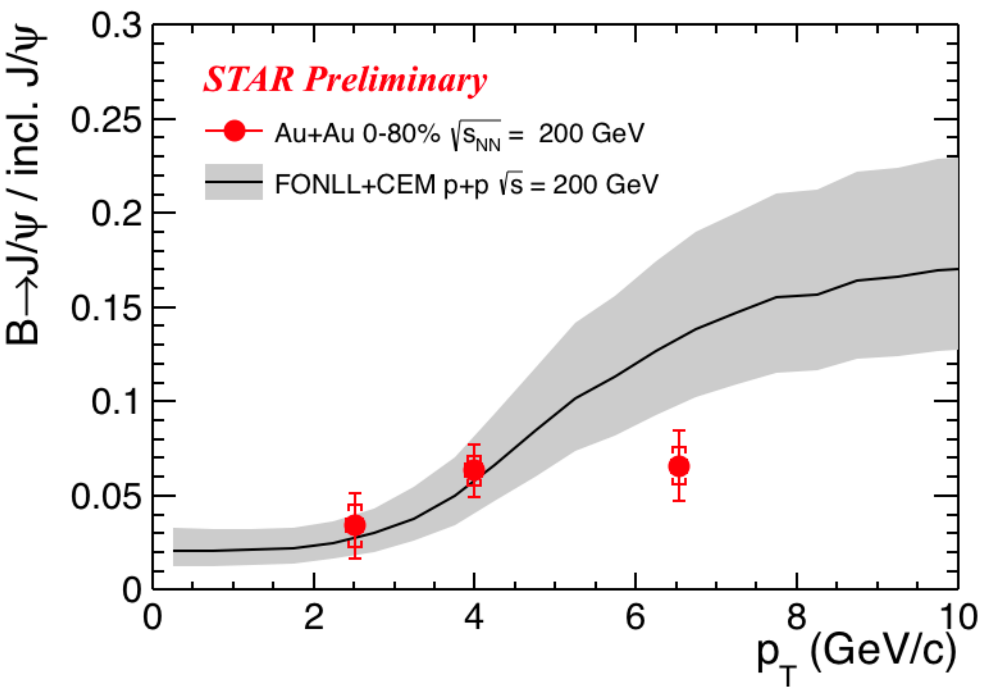
$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|\vec{p}|/c}\cdot M_{J/\psi}$$

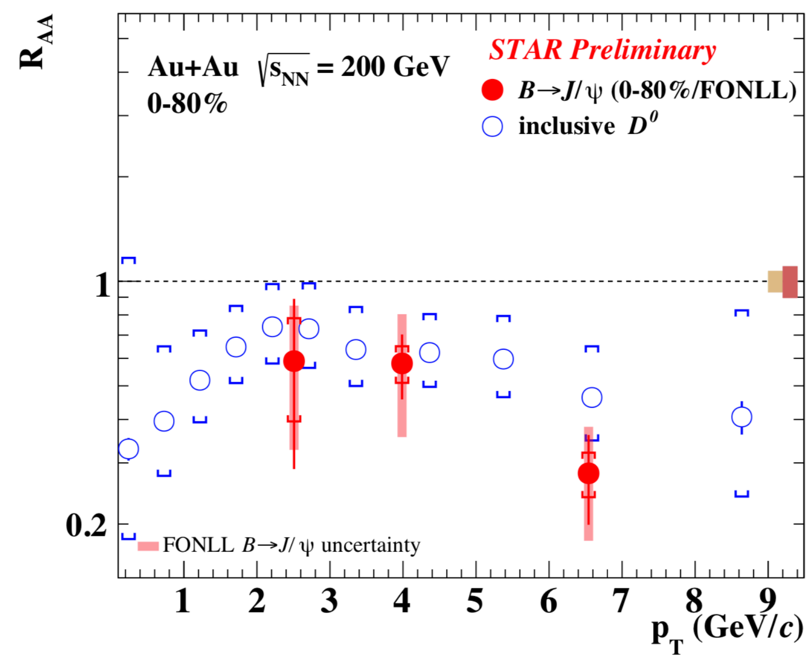




Non-prompt J/ψ Fraction and R_{AA}

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

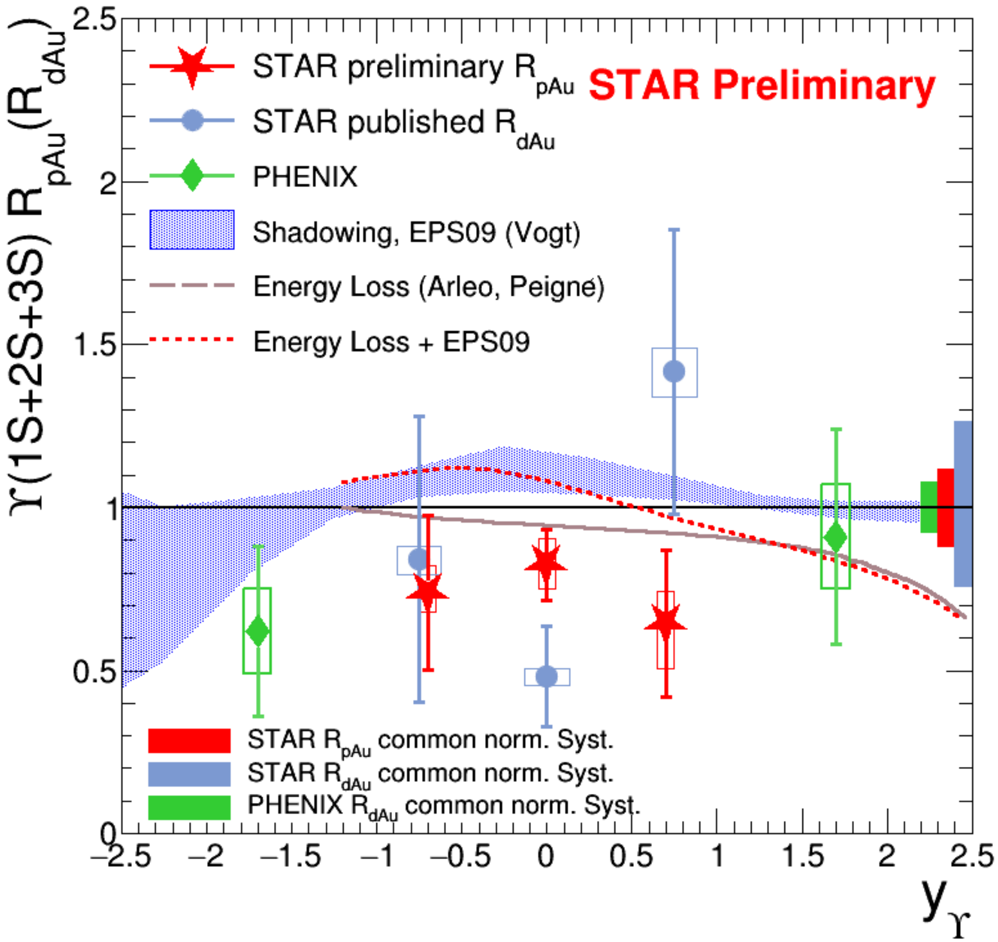




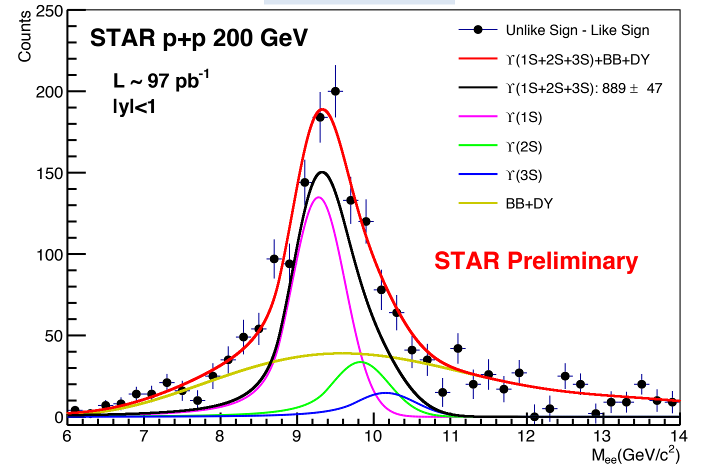
Υ in p+Au @ 200 GeV

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

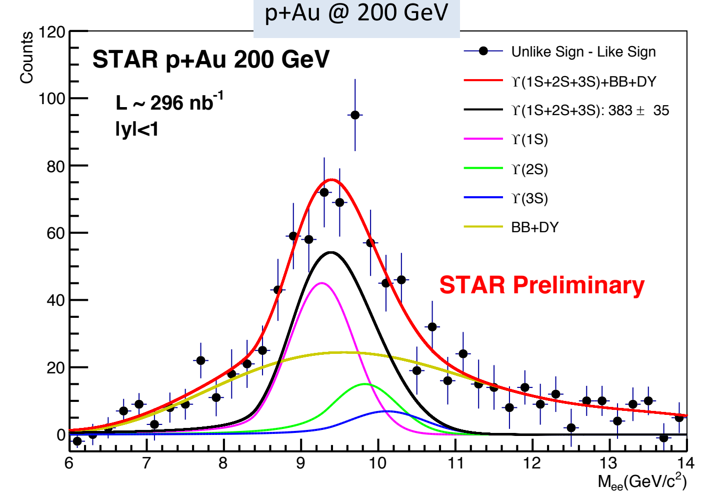
→Quantify CNM effects



p+p @ 200 GeV



p+Au @ 200 GeV

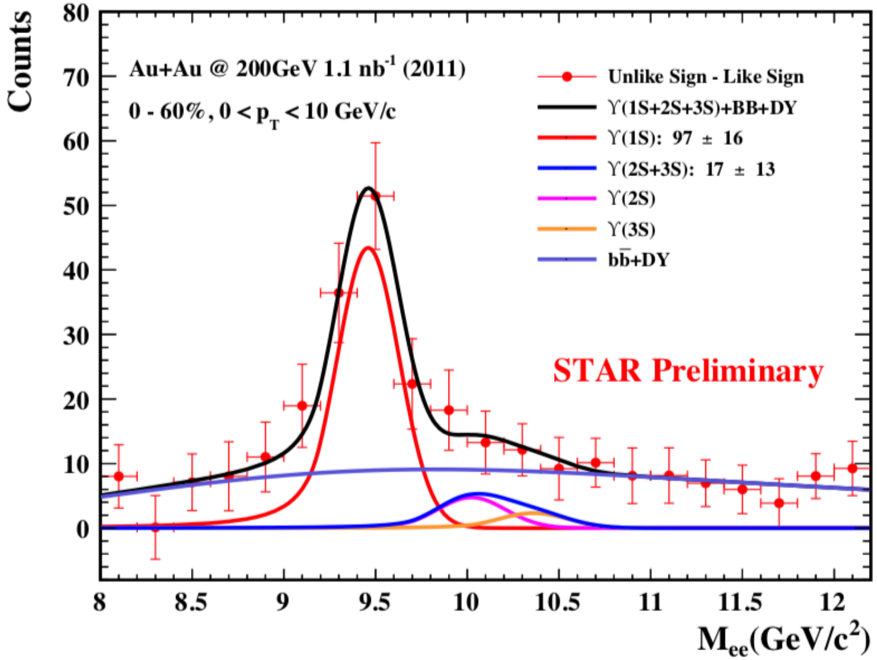


Υ in Au+Au @ 200 GeV

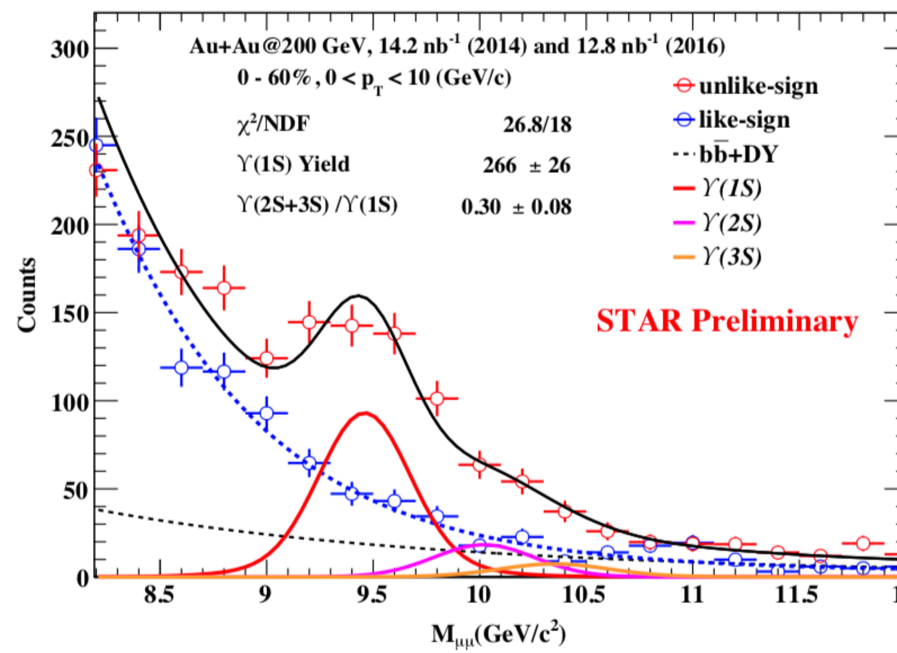
- Clear Υ(1S, 2S, 3S) signals in Au+Au collisions

  →First Υ(1S, 2S, 3S) → $\mu^+\mu^-$ measurement at STAR

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

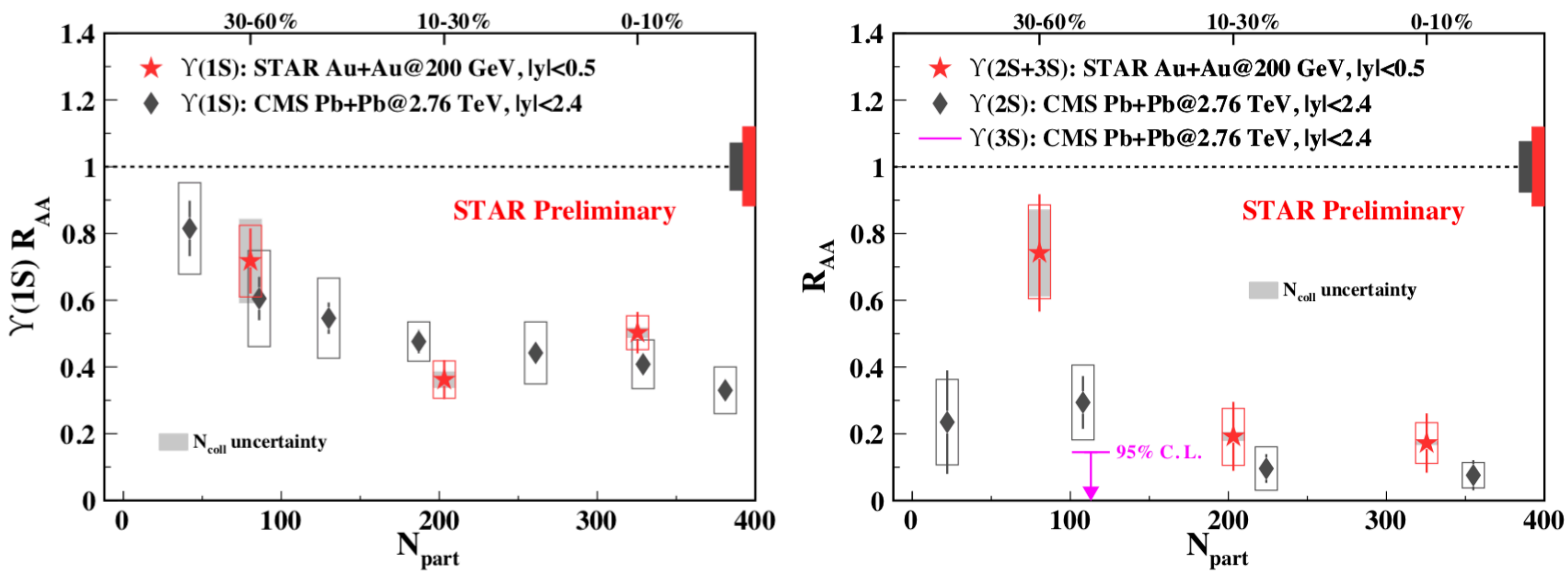


$\Upsilon \rightarrow \mu^+\mu^-$



Υ R_{AA} vs. N_{part}

- Suppression increasing with centrality
- 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

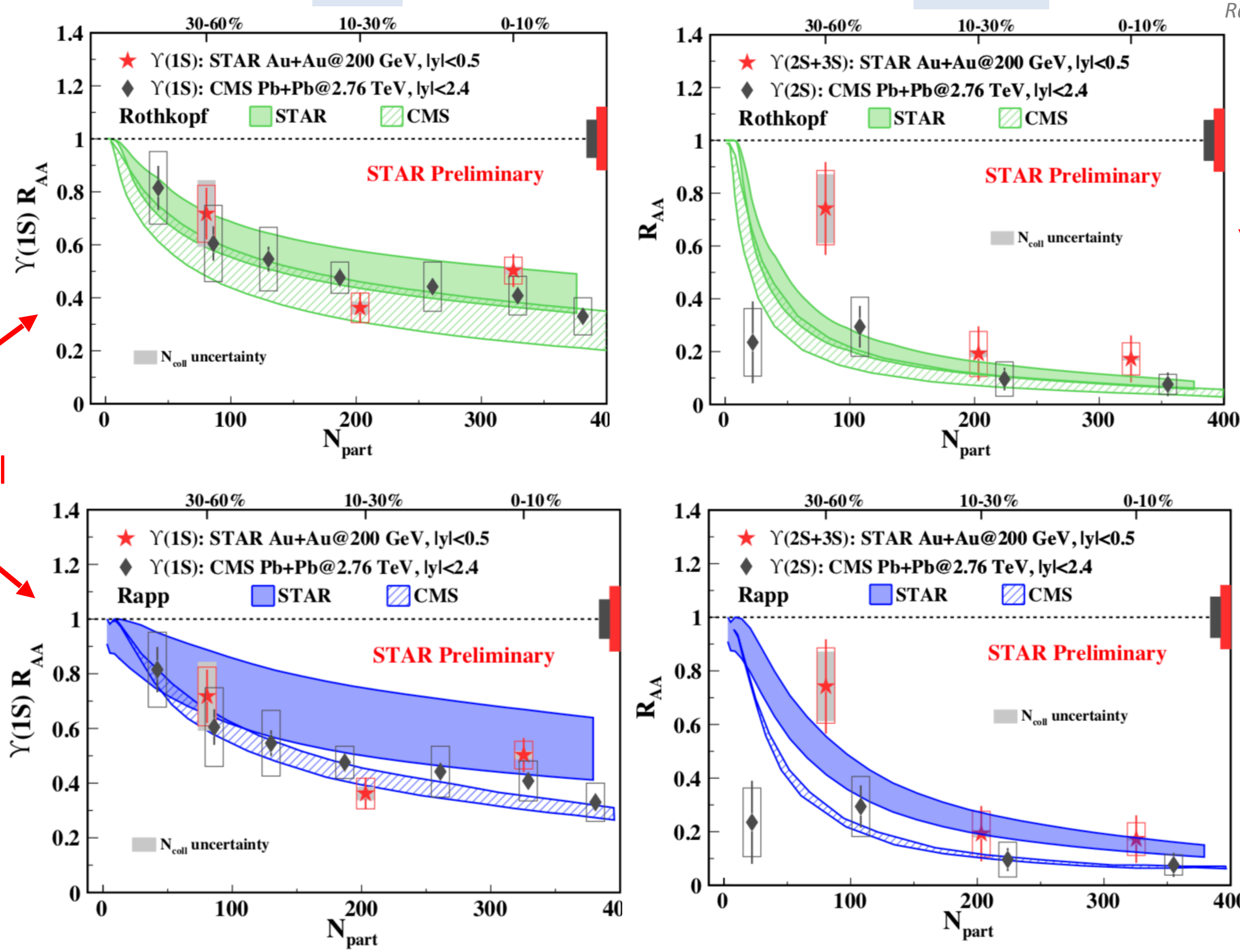


CMS: Phys. Lett. B 770 (2017) 357–379

Υ R_{AA} vs. Models

CMS: PLB 770, 357 (2017)
Rothkopf: PRD 97, 016017 (2018)
Rapp: PRC 96, 054901 (2017)

Υ(1S) Υ(2S+3S)



Both Rothkopf's and Rapp's model can describe Υ(1S)

Rapp's model can describe Υ(2S+3S), but Rothkopf's model slightly Underestimates data in 30-60%

Rothkopf: using a lattice QCD vetted, complex-valued, heavy-quark potential embedded in a realistic, hydrodynamically evolving medium background

Rapp: using temperature-dependent binding energies and pertinent reaction rates, B-meson resonance states in the equilibrium limit near the hadronization temperature, and a lattice-QCD based equation of state for the bulk medium

Summary

- **J/ψ production in p+p , p+Au, and Au+Au**
  - Inclusive J/ψ production cross-section for p+p @ 200 GeV can be described by CEM (direct J/ψ) and NLO NRQCD (prompt J/ψ), while CGC+NRQCD overestimates the data in the low p_T region
  - Inclusive J/ψ production cross-section for p+p @ 500 GeV can be described by CGC+NRQCD and NLO NRQCD (prompt J/ψ)
  - J/ψ yields in p+p grow faster than linearly with N_{ch}
  - 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
  - Strong J/ψ suppression at high p_T in central collisions indicates dissociation effect in the QGP
  - The first measurements of non-prompt J/ψ in Au+Au from STAR: strong suppression of $B \rightarrow J/\psi$ at high p_T (> 5 GeV/c)
- **Υ production in p+p, p+Au and Au+Au**
  - Υ R_{pAu} measurement can quantify the CNM effect
  - Υ R_{AA} measurement indicates sequential melting of bottomonium family
  - Inclusive Υ(1S) at RHIC are strongly suppressed in semi-central and central collisions