Measurements of quarkonium production in heavy-ion collisions at the STAR experiment

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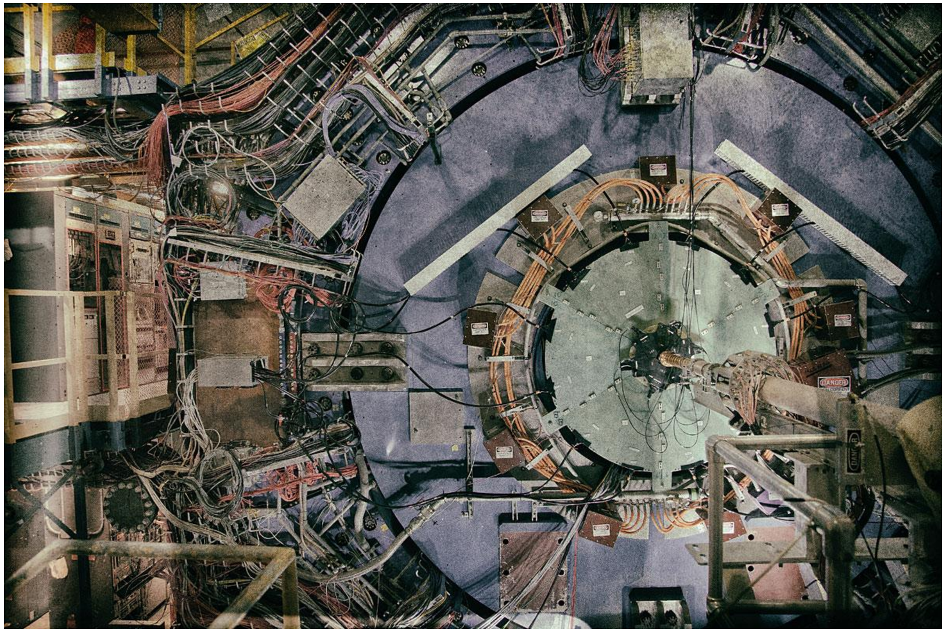
Outline

- Motivation
- Relativistic Heavy Ion Collider (RHIC)
- The STAR detector
- Measurements of charmonium production
- Measurements of bottomonium production
- Summary

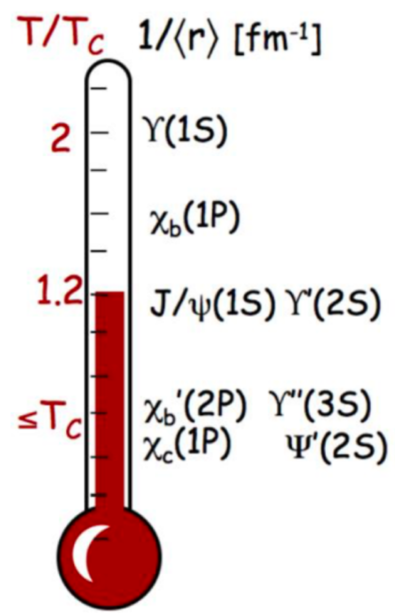


Study QGP using heavy flavor

- Heavy 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

- Quarkonium suppression is one of smoking guns of 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 temperature



A. Mocsy, EPJ C61 (2009) 705

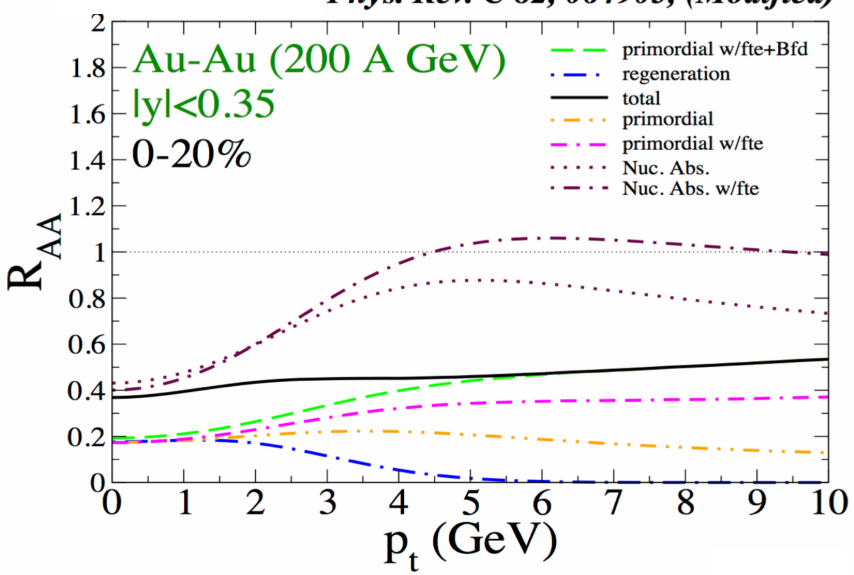
Illustration: A.Rothkopf

Study QGP using quarkonia

Interpretation of quarkonium suppression is not straightforward:

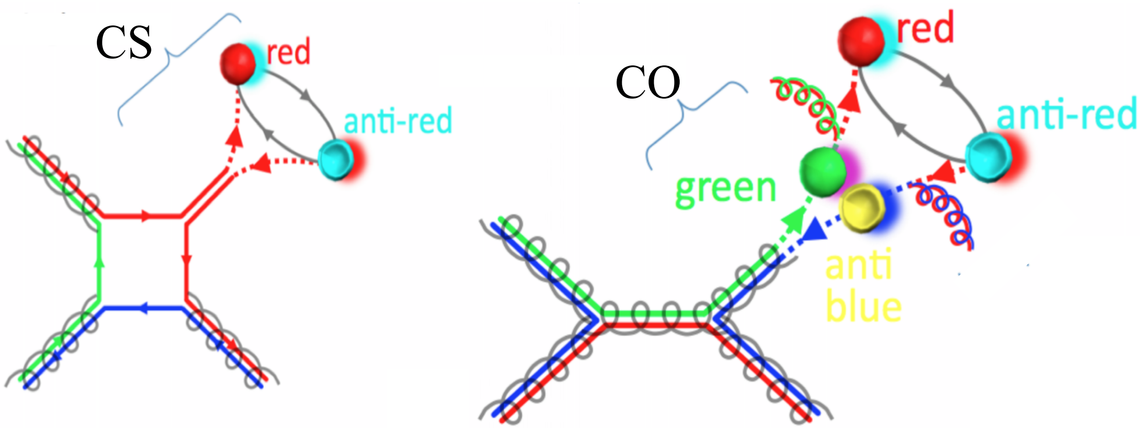
- Hot nuclear matter effects
  - Dissociation
  - Regeneration from deconfined quarks in the medium
  - Energy loss in the medium
  - Formation time effect
  - …
- Cold nuclear matter effects
  - Shadowing due to nuclear PDFs
  - Nuclear absorption
  - Parton energy loss
  - …
- Feed-down from excited states and B-hadrons

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

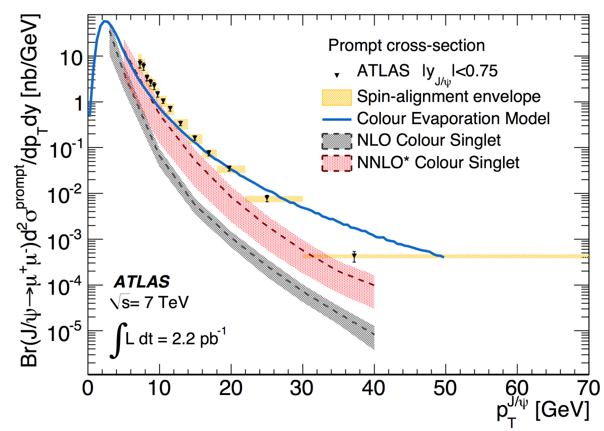


Quarkonium production mechanism

- The production mechanism of heavy quarkonium is not fully understood in hadron-hadron collision
- Some popular models on the market:
  - Color Singlet Model (CSM)
  - Non-relativistic QCD (NRQCD)
    - Also includes Color Octet Mechanism (COM)
    - + Color Glass Condensate effective theory (CGC) for low p_T
  - Color Evaporation Model (CEM) / Improved CEM
- Need to describe cross section and polarization simultaneously



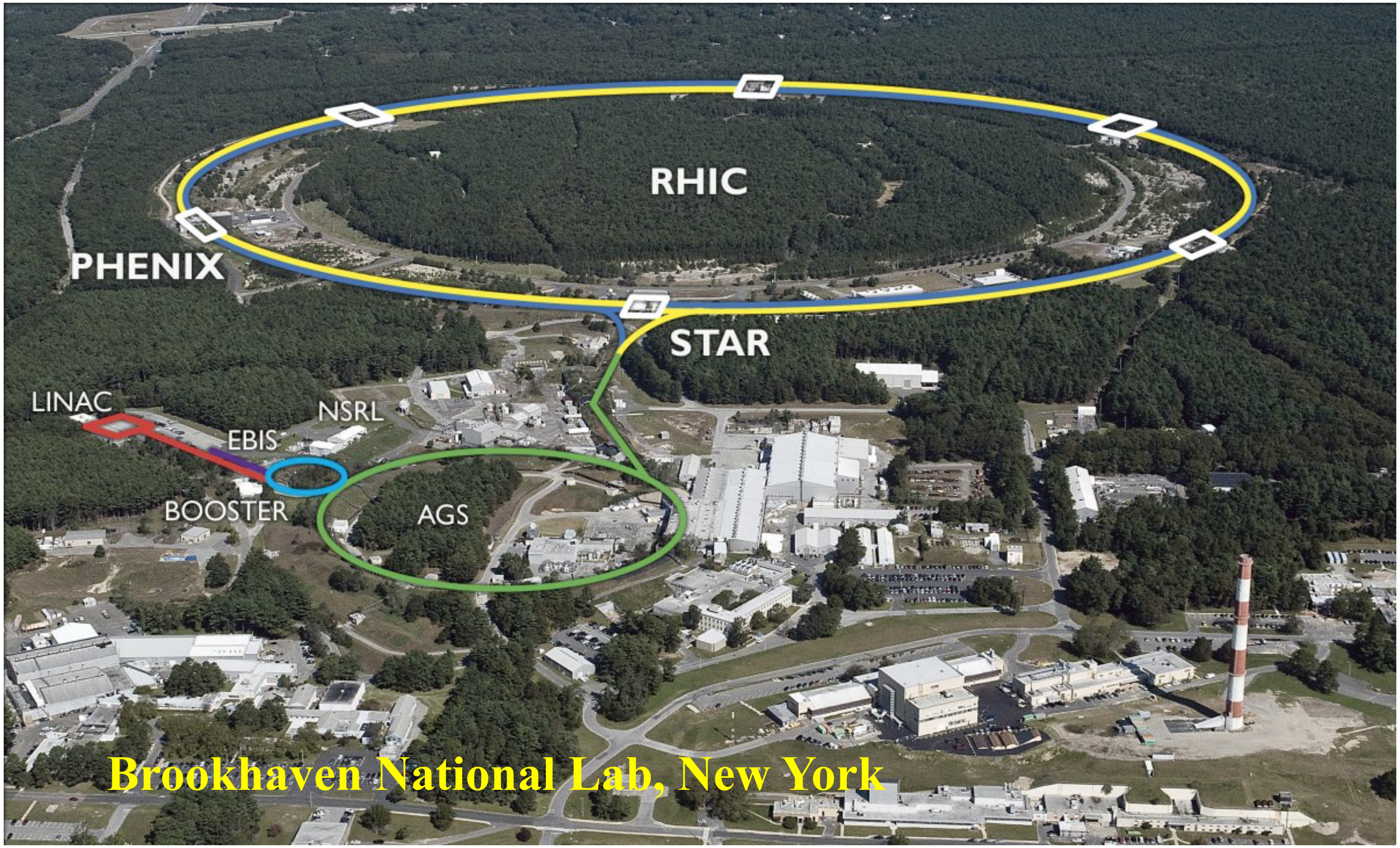
From Cristina Biino's Talk (FPCP2013)



Nucl. Phys. B 850 (2011) 387-444

Relativistic Heavy Ion Collider (RHIC)

- One of the most versatile particle colliders in the world!
  - Variety of colliding species: p+p, Au+Au, p+Au, d+Au, U+U, …
  - Different collision energies: 7.3 – 510 GeV

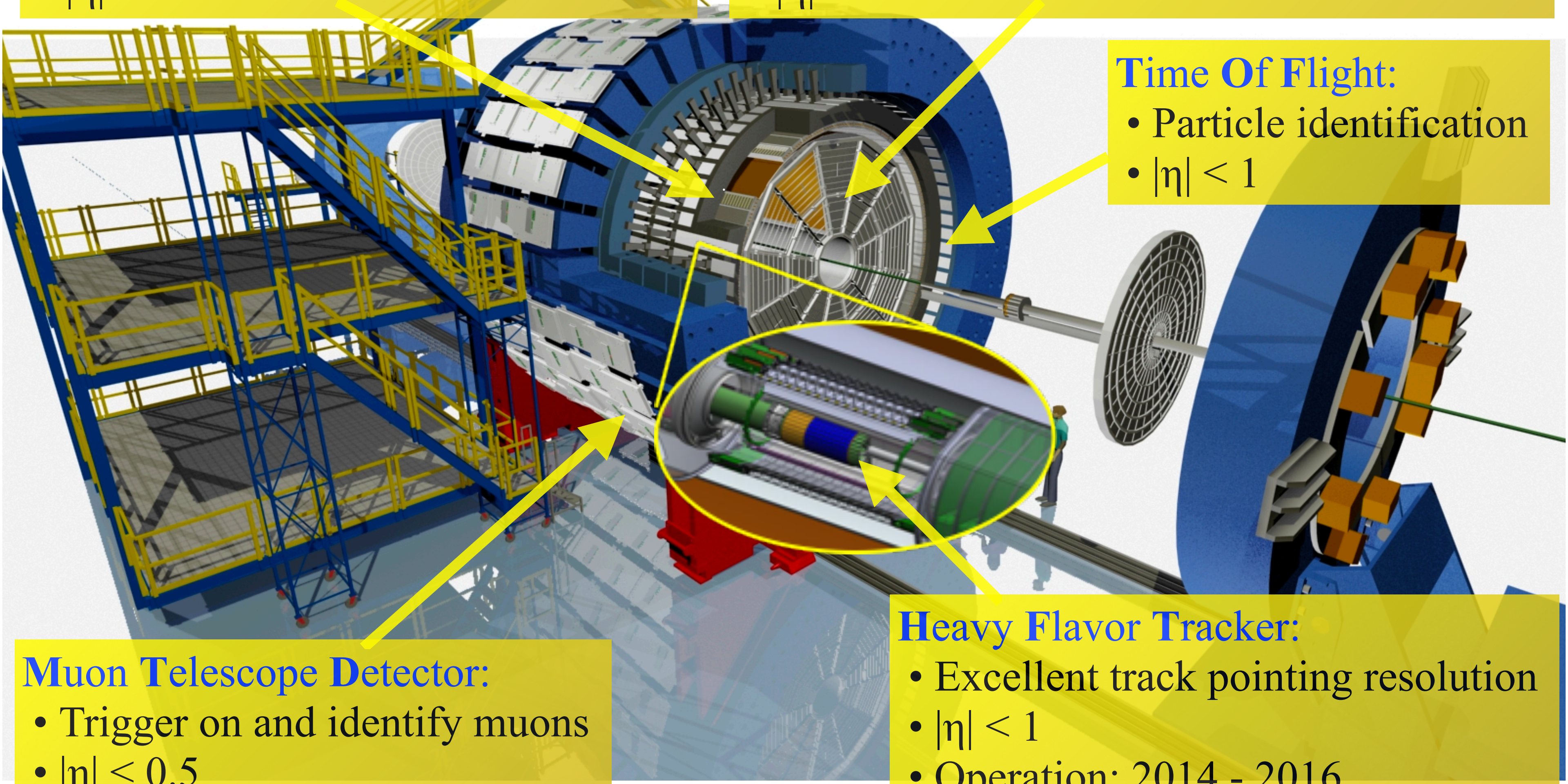


The STAR detector

Barrel ElectroMagnetic Calorimeter:
- Trigger on and identify electrons
- $|\eta| < 1$

Time Projection Chamber:
- Precise momentum and dE/dx measurement
- $|\eta| < 1$

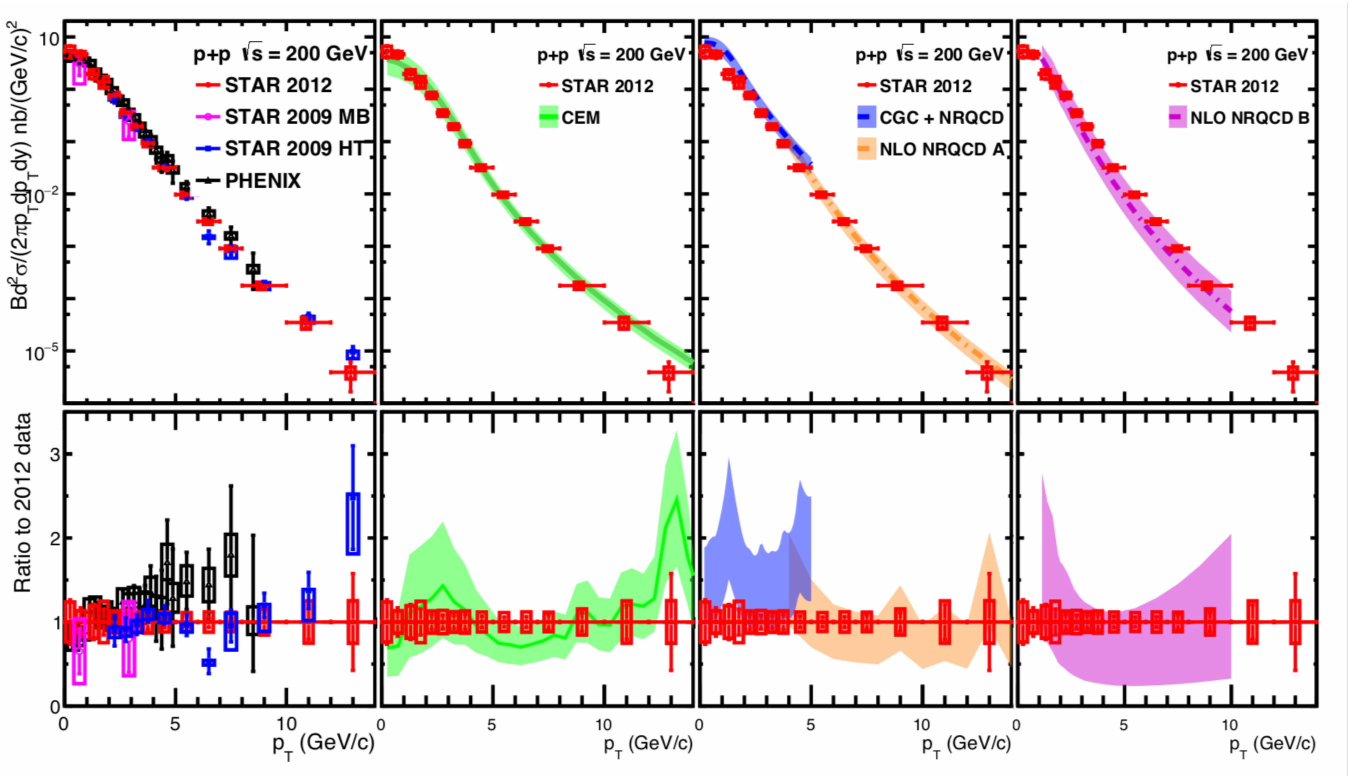
Time Of Flight:
- Particle identification
- $|\eta| < 1$



Muon Telescope Detector:
- Trigger on and identify muons
- $|\eta| < 0.5$

Heavy Flavor Tracker:
- Excellent track pointing resolution
- $|\eta| < 1$
- Operation: 2014 - 2016

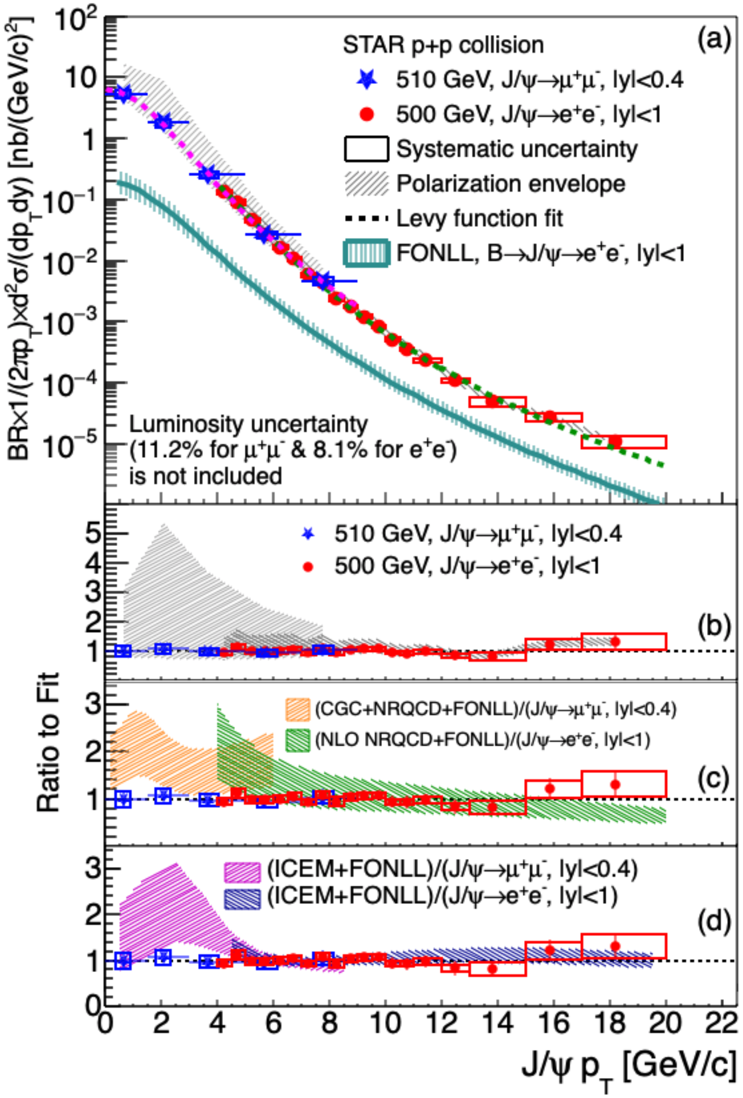
J/ψ cross-section in p+p collisions @ 200 GeV

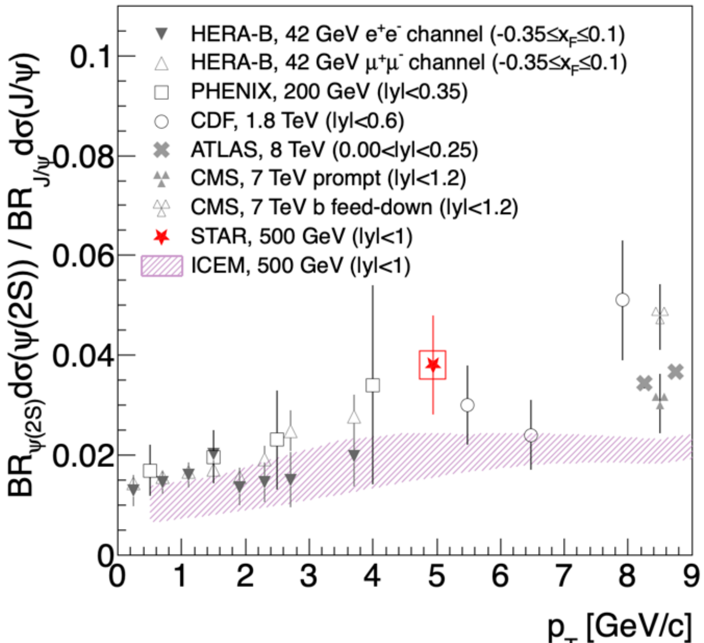


- Precise measurements of J/ψ cross-section covering J/ψ p_T from 0 to 14 GeV/c
- Consistent with CEM (direct production only) and NLO NRQCD (prompt production only) calculations
- CGC+NRQCD consistent, but data at lower edge of model uncertainty boundary

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 cross-section in p+p collisions @ 500 GeV



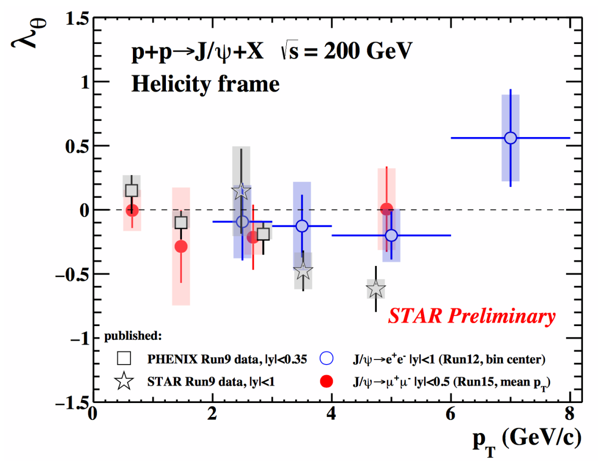


- Precise measurements of J/ψ cross-section covering J/ψ p_T from 0 to 20 GeV/c
- Consistent with CGC+NRQCD, NLO NRQCD, and ICEM calculations (B feed-down from FONLL included)
    - Models systematically above the data at low p_T, but within the polarization envelope
- ψ(2S) to J/ψ ratio follows the world trend

[arXiv:1905.06075] submitted to PRD

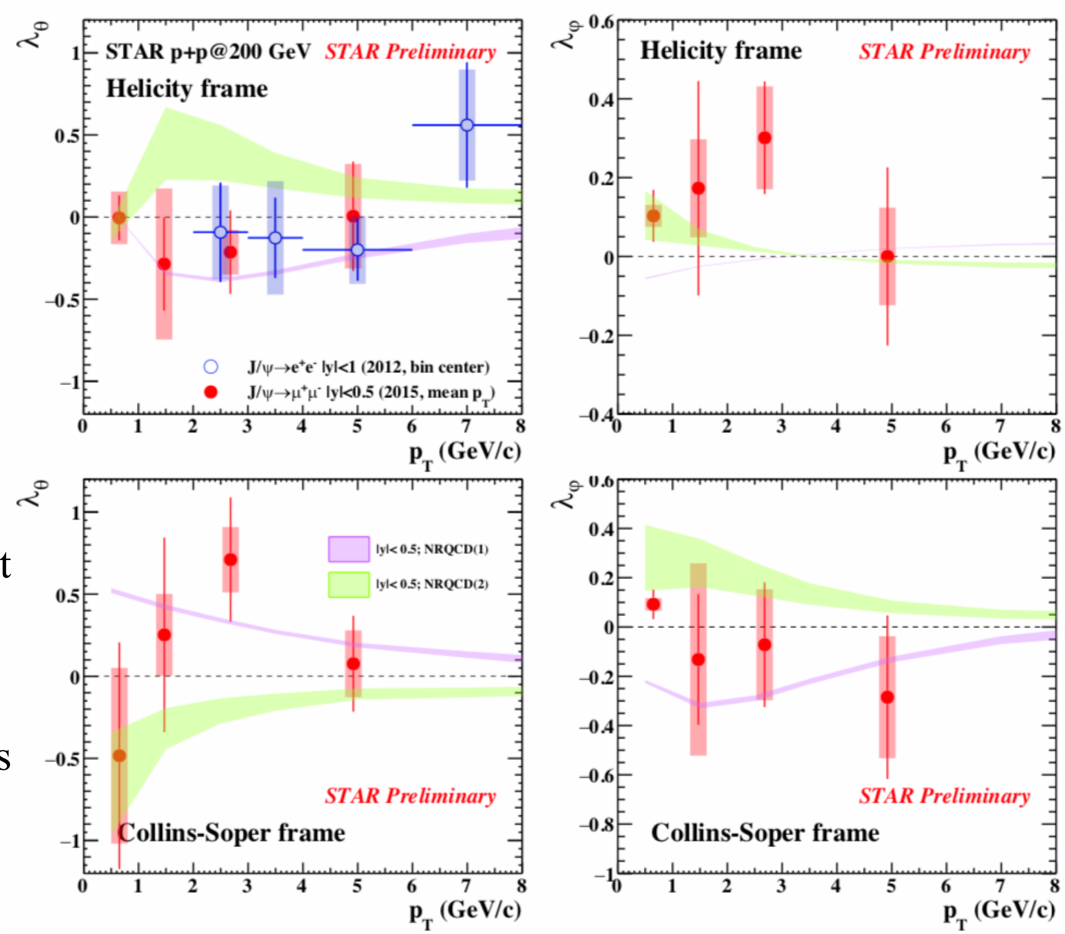
J/ψ polarization measurements

- First measurement of J/ψ polarization in both Helicity (HX) and Collins-Soper (CS) frame from STAR via dimuon decay channel in p+p collisions at 200 GeV



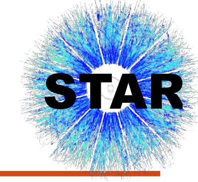
STAR 2009: Phys. Lett. B739 (2014) 180–188
PHENIX: Phys. Rev. D 95, 092003

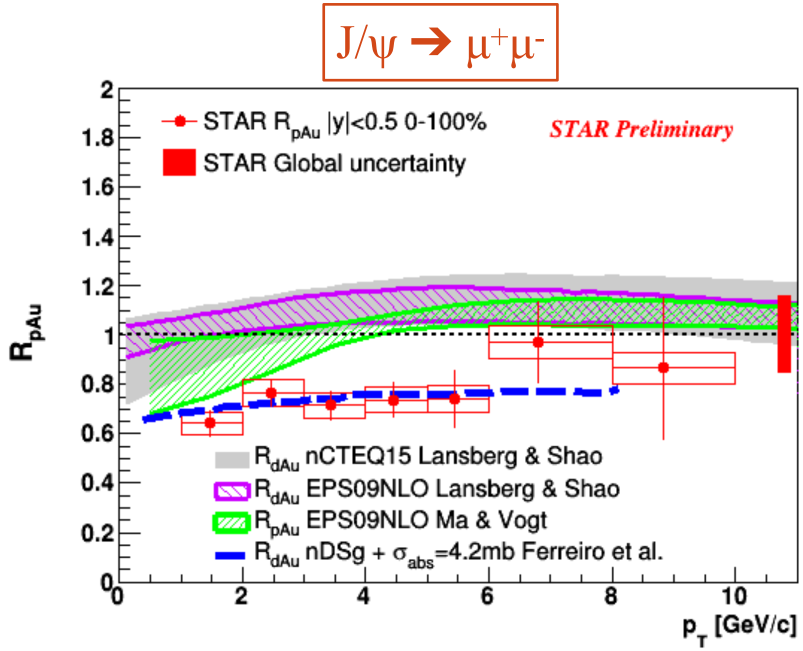
- λ_θ consistent with previous measurements at STAR and PHENIX
- Both λ_θ and λ_φ are consistent with zero within uncertainty
- NRQCD calculations with two different sets of Long Distance Matrix Elements (LDMEs) - consistent with data within uncertainties
    - Measurements at low p_T can be used to constrain the LDMEs

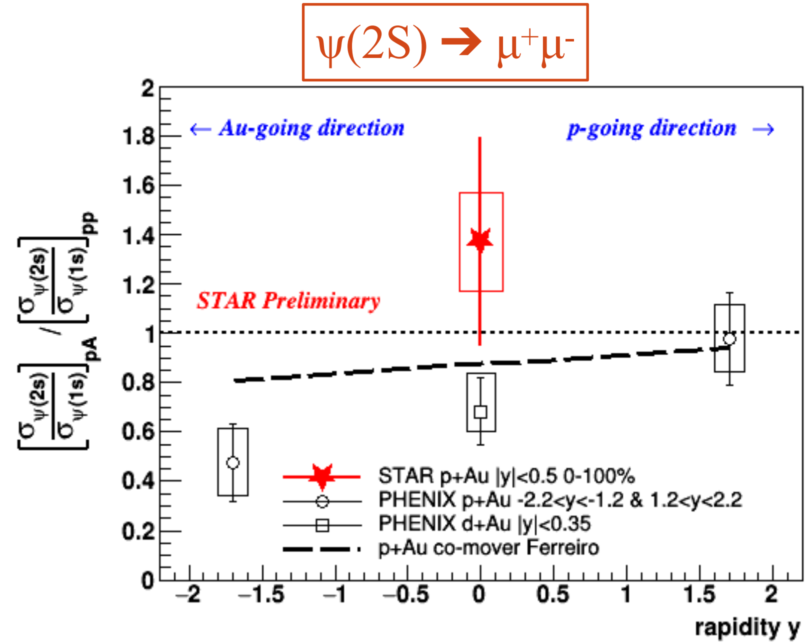


NRQCD1: Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Phys. Rev. Lett 110 (2013) 042002

Charmonia production in p+Au @ 200 GeV



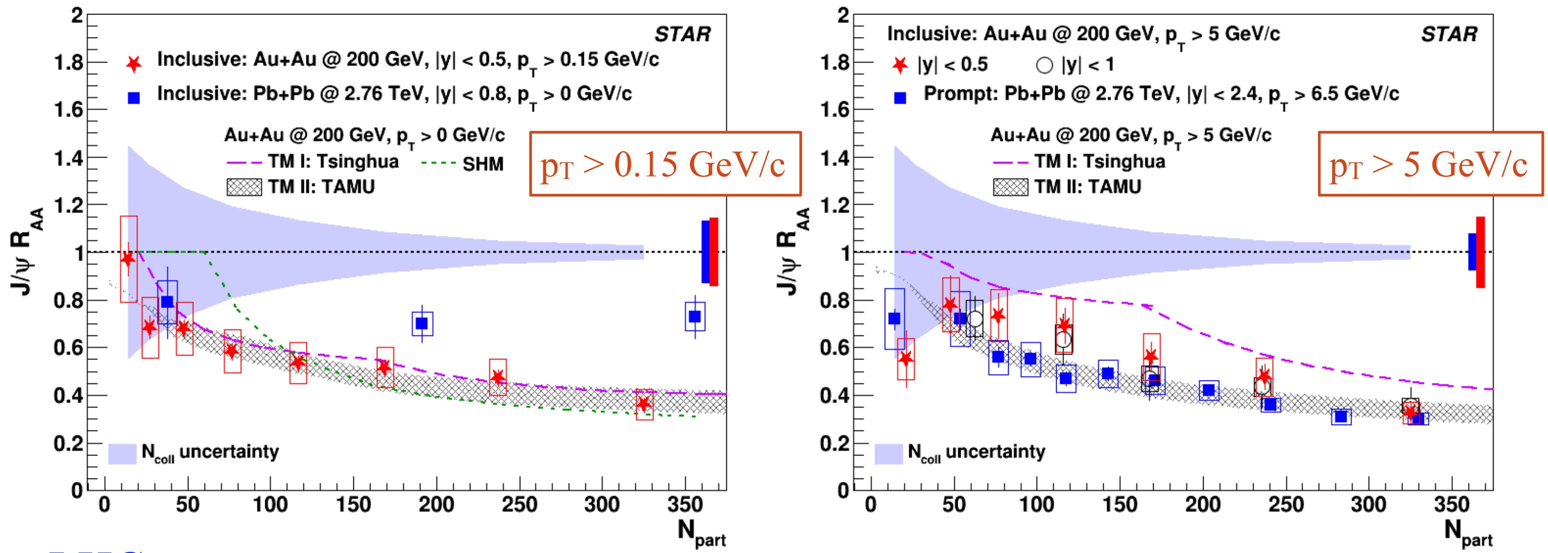




- The model calculation with additional nuclear absorption on top of nuclear PDF effects can describe the J/ψ R_{pAu} data
- First STAR ψ(2S) to J/ψ double ratio measurement between p+Au and p+p at mid-rapidity at RHIC: 1.37 ±0.42(stat.) ±0.19(syst.)

EPS09+NLO: Ma & Vogt, Private comm
nCTEQ, EPS09+NLO: Lansberg Shao, EPJC77 (20
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} in Au+Au @ 200 GeV



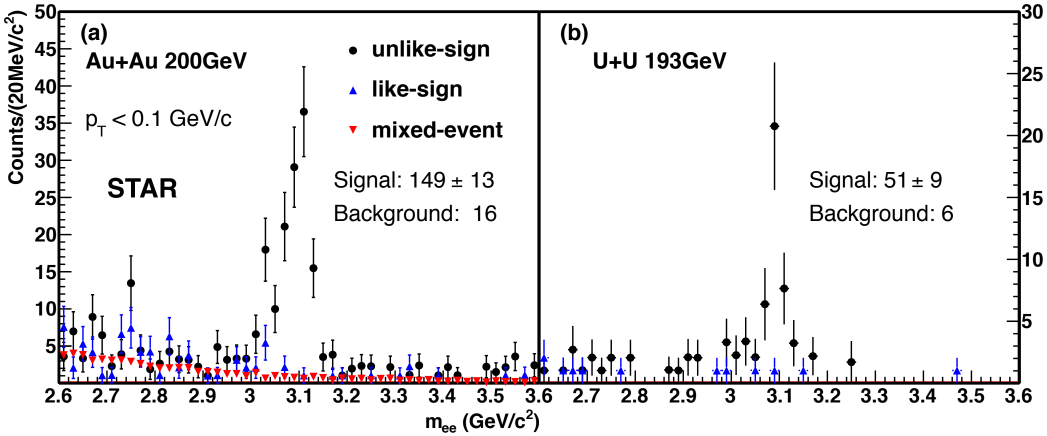
- RHIC vs. LHC
  - Larger suppression in central collisions at RHIC for p_T > 0.15 GeV/c
    - Possibly due to less regeneration at RHIC
  - Indication of smaller suppression at RHIC for p_T > 5 GeV/c
    - Hint at higher dissociation rate at LHC because of higher temperature

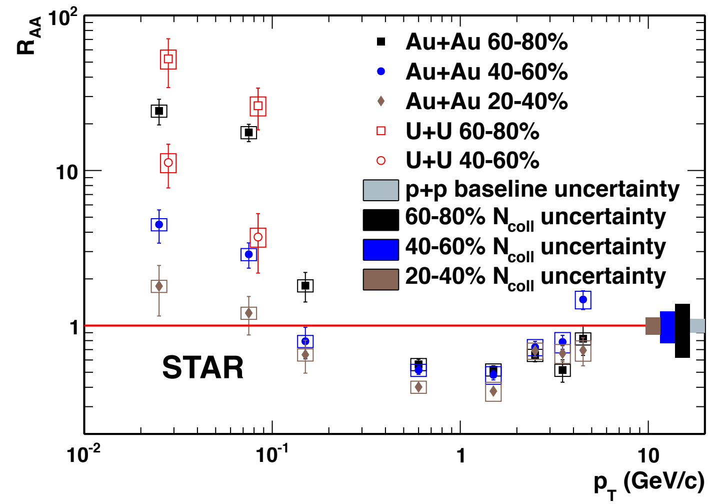
STAR: [arXiv:1905.13669] submitted to PLB
ALICE : JHEP 07 (2015) 051
CMS: Eur. Phys. J. C77 (2017) 252

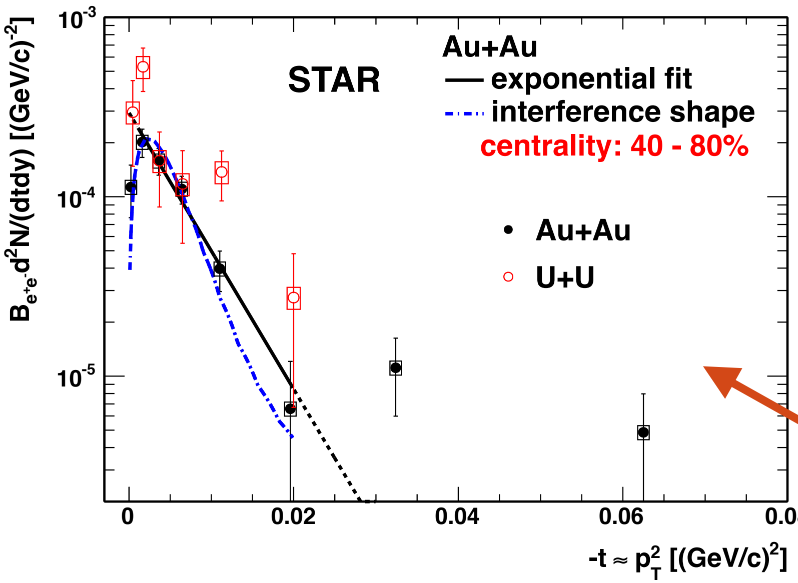
- Data vs. transport models (dissociation + regeneration effects)
  - For p_T > 0.15 GeV/c: both models can describe the centrality dependence at RHIC
  - For p_T > 5 GeV/c: there is tension among data and models

Transport model:
Model I: Y. Liu, Z. Qu, P. Zhuang PLB 678 (2009) 72
Model II: X. Zhao, R. Rapp PRC 82 (2010) 064905

Excess of J/ψ at very low p_T in Au+Au and U+U







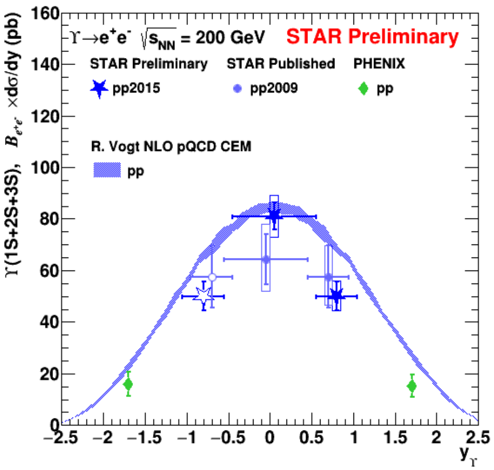
- First measurement of J/ψ production at very low p_T in Au+Au @ 200 GeV and U+U @ 193 GeV
- Strong enhancement of J/ψ yield at $p_T < 0.1$ GeV/c in peripheral and semi-peripheral collisions after subtracting the expected yield from hadronic interaction
- The nature of enhancement indicates the excess is from coherent photon-nucleus interactions
- No significant difference between Au+Au and U+U collisions

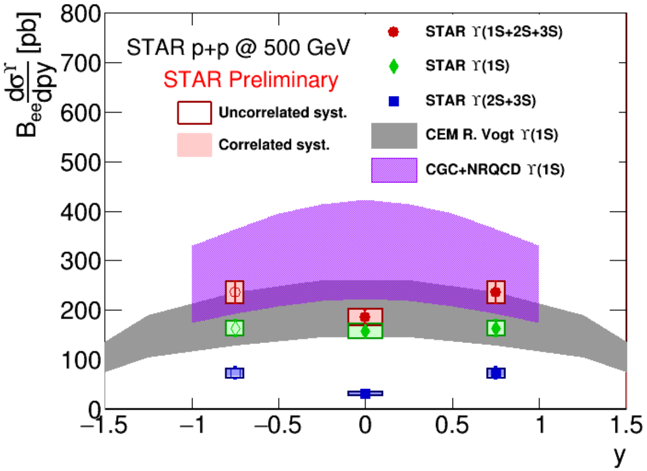
[arXiv:1904.11658] submitted to PRL

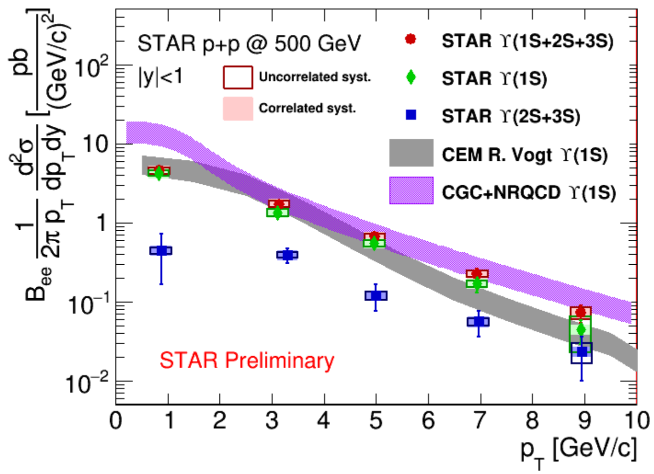
Υ cross-section in p+p @ 200 and 500 GeV

p+p @ 200 GeV

p+p @ 500 GeV







CEM for 200 GeV: Phys. Rept. 462(2008)125
CEM for 500 GeV: Phys.Rev.C 92 034909(2015)
CGC+NRQCD: Phys.Rev.D 94, 014028(2016)
Phys.Rev.Lett. 113, 192301(2014)

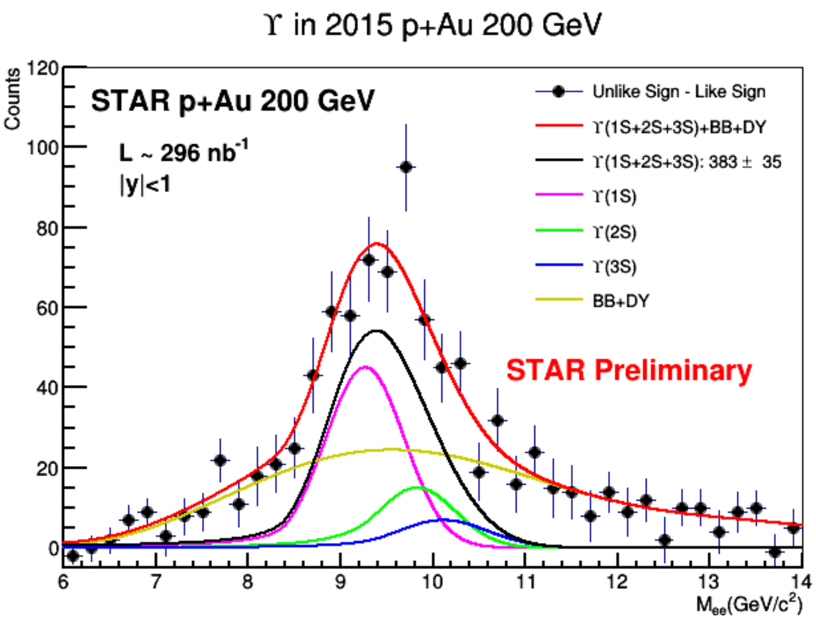
- Cross-section vs. rapidity:
  - Flatter spectrum at 500 GeV compared to 200 GeV
  - Small dip at mid-rapidity for *Υ*(2S+3S) (~2σ from flat) at 500 GeV
  - STAR data slightly narrower than CEM at 200 GeV
  - CEM for *Υ*(1S) (inclusive production) consistent with data at 500 GeV
  - CGC+NRQCD predictions for *Υ*(1S) (direct production) are above the data
- Cross-section vs. p_T at 500 GeV:
  - CEM for *Υ*(1S) (inclusive production) reasonably describes the data
  - CGC+NRQCD predictions for *Υ*(1S) (direct production) are above the data especially at low p_T

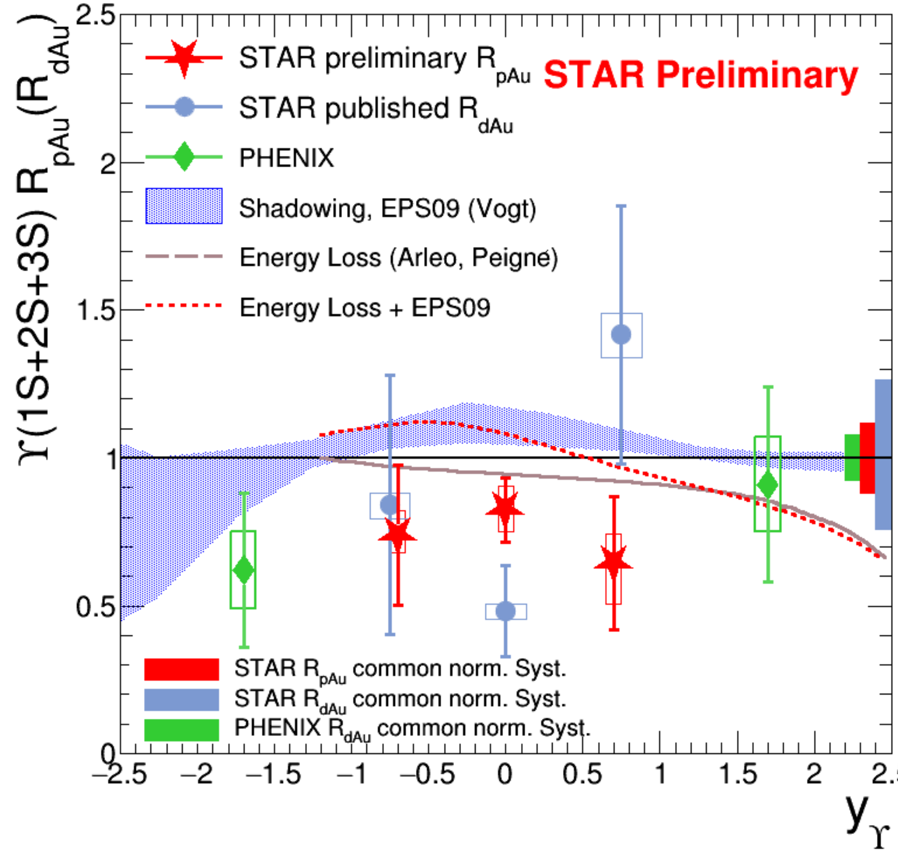
Υ in p+Au @ 200 GeV

- R_{pAu} is useful for quantifying the cold nuclear matter (CNM) effects

$$0.82 \pm 0.10\ (\text{stat.})\ ^{+0.08}_{-0.07}\ (\text{syst.})\ \pm 0.10\ (\text{global})$$

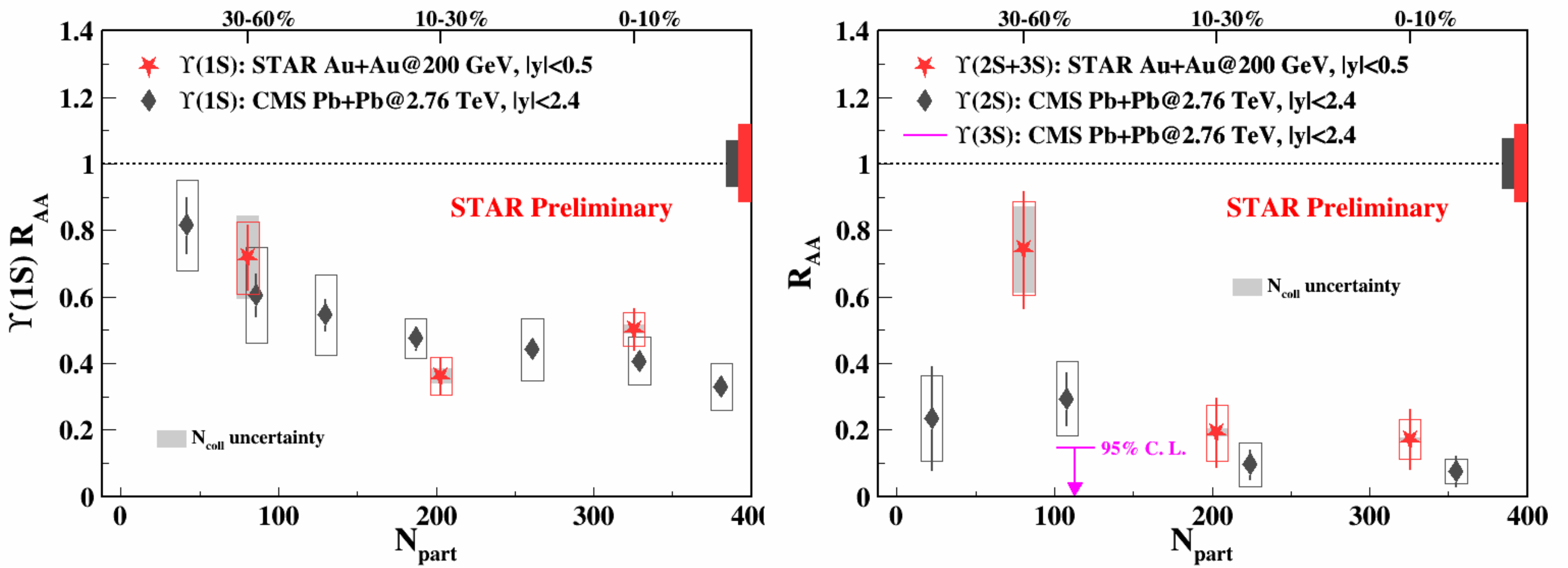
- Discrepancy between data and model indicates the suppression may not only be due to the nuclear PDFs





STAR R_{dAu}: J.Phys.Lett.B 735(2014)127
PHENIX R_{dAu}: Phys. Rev. C 87, 044909
Theory: JHEP 03, 122(2013)

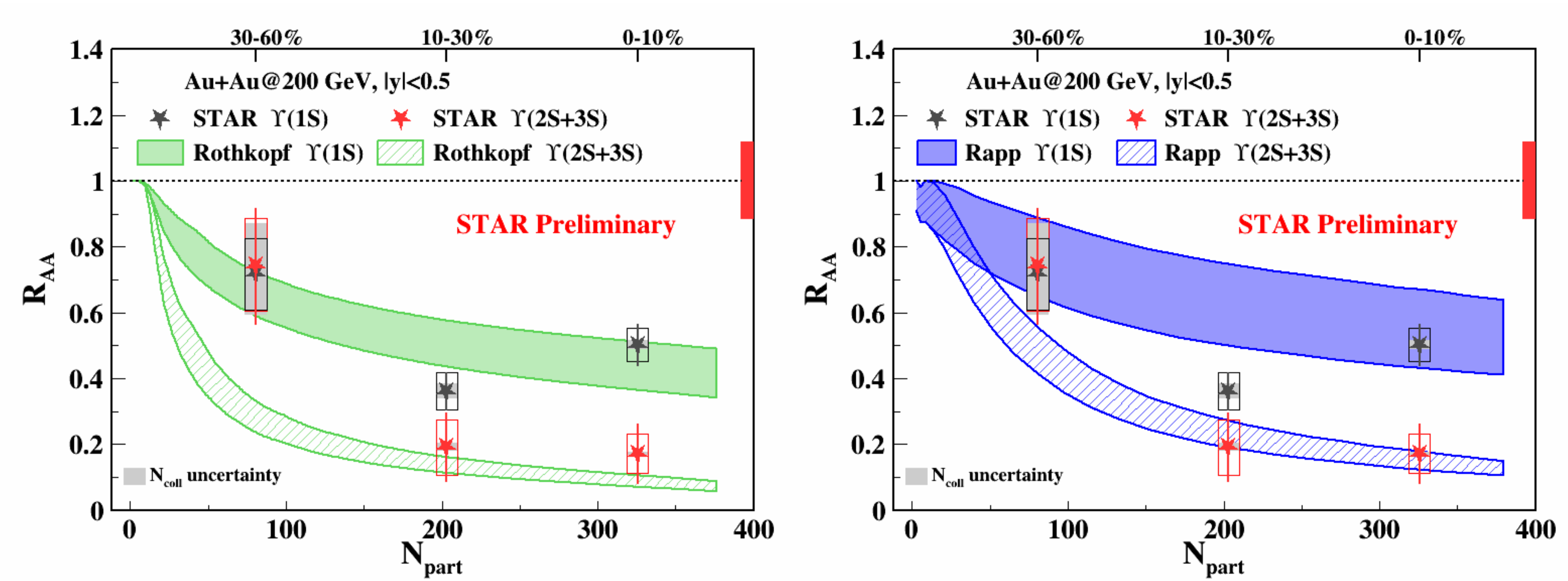
Υ R_{AA} vs. N_{part} in Au+Au @ 200 GeV



- Suppression increasing with centrality
- *Υ*(2S+3S) is more suppressed than *Υ*(1S) in central collision
  - sequential melting
- RHIC vs. LHC:
  - Similar suppression in RHIC and LHC for *Υ*(1S)
  - Smaller suppression for *Υ*(2S+3S) in 30-60% central collisions at RHIC than at LHC

CMS: Phys. Lett. B 770 (2017) 357–379

Υ R_{AA} vs. N_{part} compared to models



- Kroupaa, **Rothkopf**, Strickland:
  - no regeneration and CNM effects
- De, He, **Rapp**:
  - include both regeneration and CNM effects
- Both models agree with STAR Υ(1S) measurement
- Rothkopf's model underestimates Υ(2S+3S) data in 30-60%

Rothkopf: PRD 97, 016017 (2018)
Rapp: PRC 96, 054901 (2017)

Summary

- J/ψ production in p+p , p+Au, and Au+Au:
  - Inclusive J/ψ production cross-section for p+p @ 200 GeV and 500 GeV can be reasonably described by CEM, CGC+NRQCD, and NLO NRQCD
  - Both λ_θ and λ_φ for J/ψ in p+p @ 200 GeV are consistent with no polarization in HX and CS frames
  - J/ψ R_{pAu} can be qualitatively described by model calculation with additional nuclear absorption on top of nuclear PDF effects
  - J/ψ suppression in central Au+Au collisions is larger at RHIC than at LHC at low p_T but is smaller at high p_T
  - J/ψ R_{AA} can be reasonably described by the models at low p_T, but with a tension at high p_T
  - Excess of J/ψ observed at very low p_T in peripheral Au+Au and U+U collisions which may come from coherent photon-nucleus interactions
- *Υ* production in p+p , p+Au, and Au+Au:
  - *Υ*(1S) cross-section in p+p @ 500 GeV can be described by CEM (inclusive production) but is overestimated by the CGC+NRQCD predictions (direct production) at low p_T
  - The CNM effects on *Υ* production is quantized by R_{pAu}: $0.82 \pm 0.10(\text{stat.})\ ^{+0.08}_{-0.07}(\text{syst.}) \pm 0.10(\text{global})$
  - Inclusive *Υ*(1S) at RHIC are strongly suppressed in semi-central and central Au+Au collisions
  - *Υ* R_{AA} measurement in central Au+Au collisions indicates sequential melting of bottomonium family

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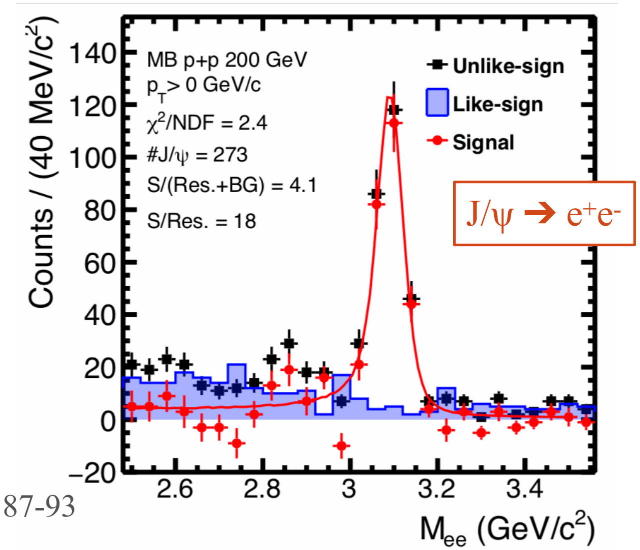
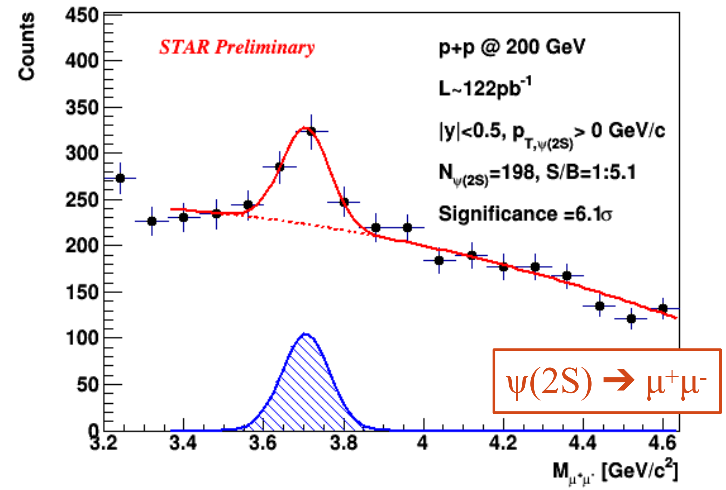
Backup

J/ψ and ψ(2S) in p+p @ 200 and 500 GeV

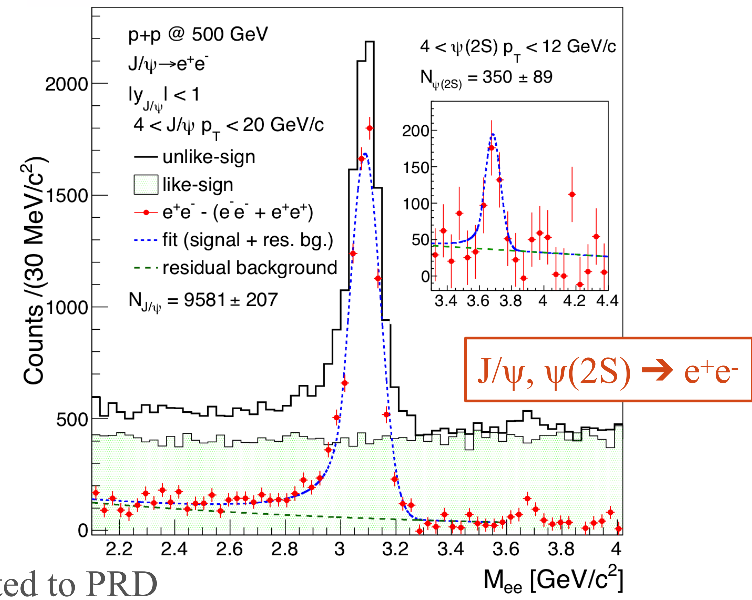
p+p @ 200 GeV

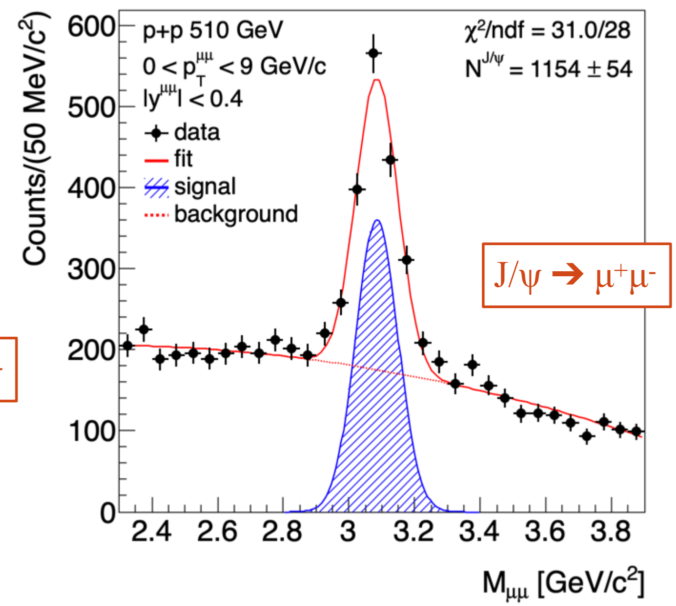


PLB 786 (2018) 87-93



p+p @ 500 GeV



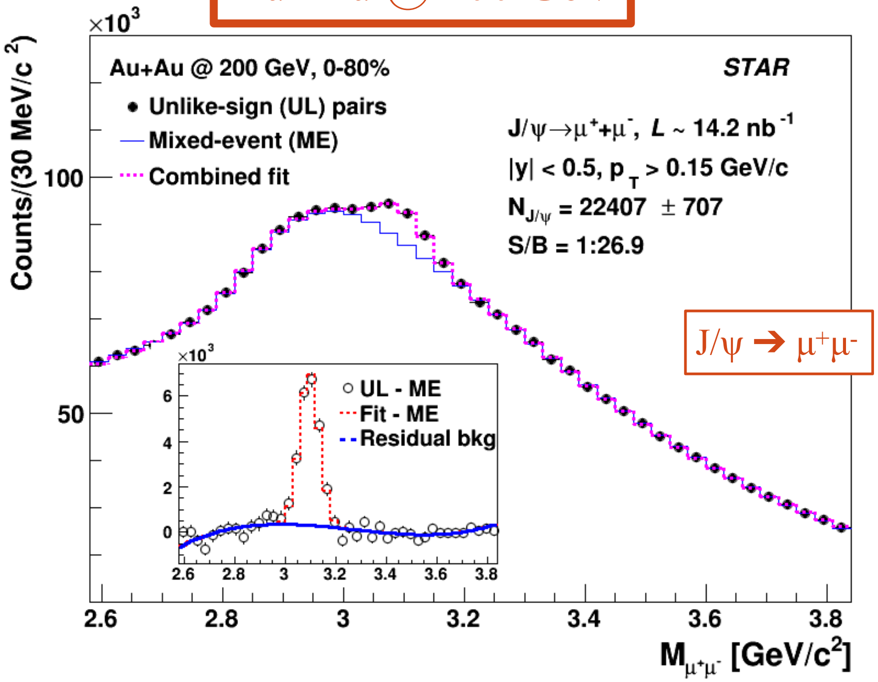


[arXiv:1905.06075] submitted to PRD

J/ψ and ψ(2S) in p+Au and Au+Au @ 200 GeV

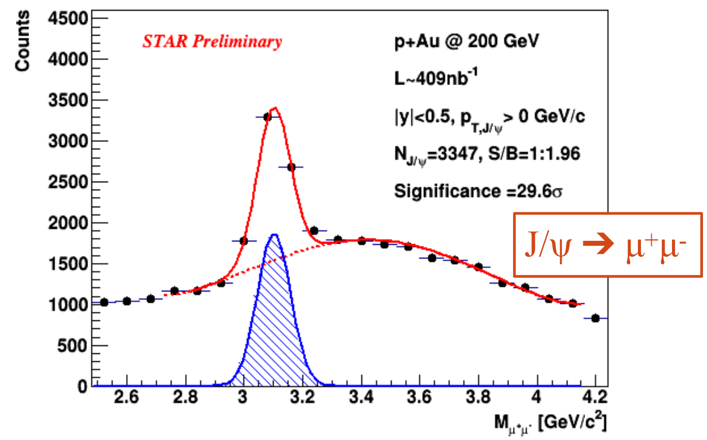
- Clear J/ψ signals in p+Au and Au+Au collisions and ψ(2S) signals in p+Au collisions

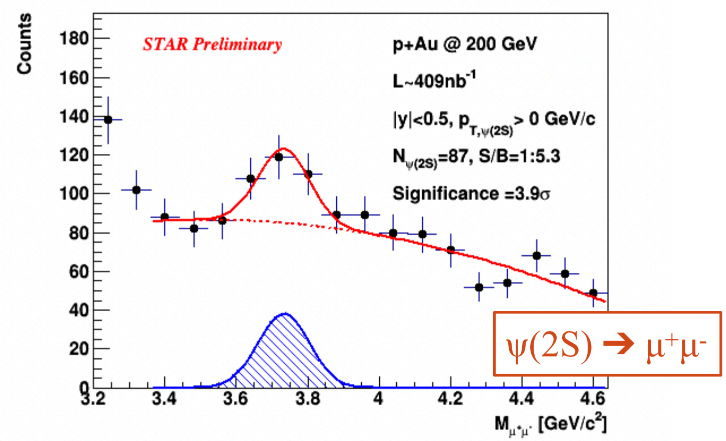
Au+Au @ 200 GeV



[arXiv:1905.13669] submitted to PLB

p+Au @ 200 GeV

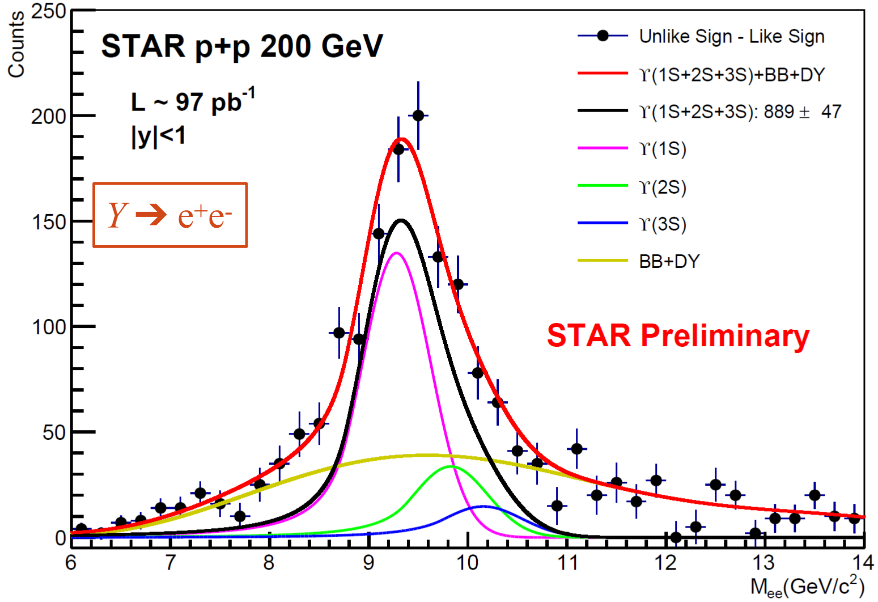




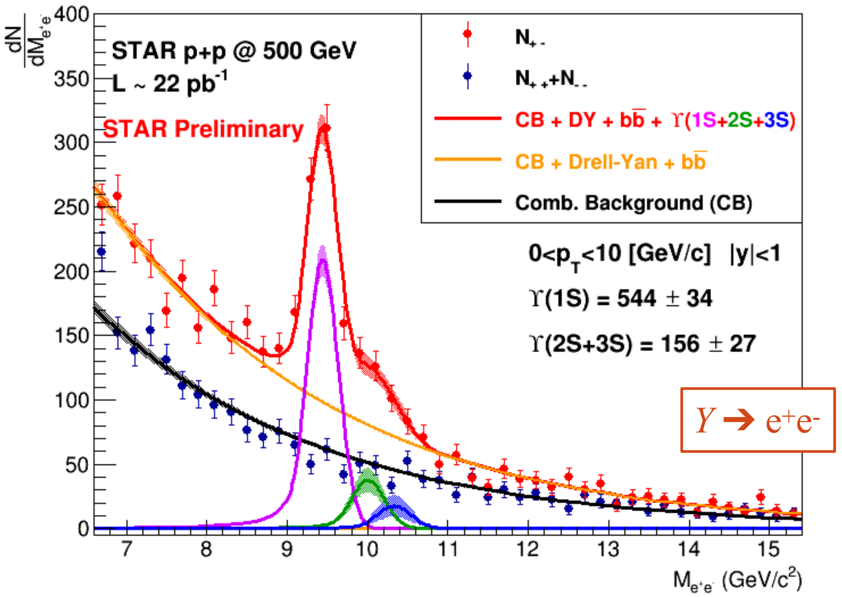
Υ in p+p @ 200 and 500 GeV

- Clear *Υ* signals in p+p collisions at both 200 GeV and 500 GeV

p+p @ 200 GeV



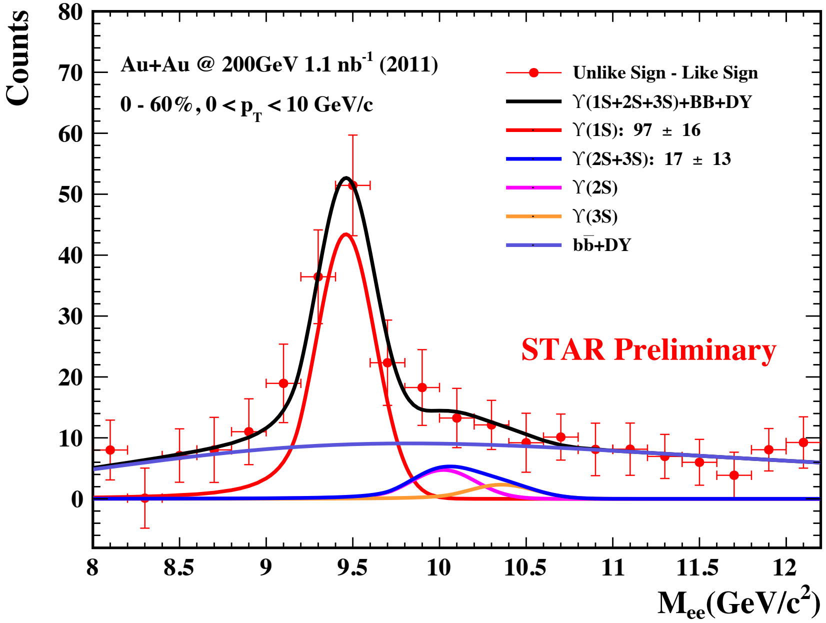
p+p @ 500 GeV



Υ in Au+Au @ 200 GeV

- Clear *Υ*(1S, 2S, 3S) signals in Au+Au collisions
- First *Υ*(1S, 2S, 3S) signals from dimuon decay channel measured by STAR

Υ ➔ e^+e^-



Υ ➔ $\mu^+\mu^-$