# Recent Measurements of Heavy Quarkonium Production in p+Au and p+p Collisions at STAR

In part supported by

Yanfang Liu, *for the STAR Collaboration*

*Texas A&M University*

# Outline

- J/ψ Production in Au+Au Collisions
  - J/ψ nuclear modification factor ($R_{AA}$) vs. $p_T$ and centrality
- J/ψ Production in p+Au Collisions
  - J/ψ $R_{pAu}$ in minimum-bias events
  - J/ψ yield in different centrality classes
- J/ψ and ϒ Productions in p+p Collisions
  - Event activity dependence of quarkonia production
  - J/ψ and ψ(2S) yields in 510 GeV p+p collisions
- Summary and Outlook

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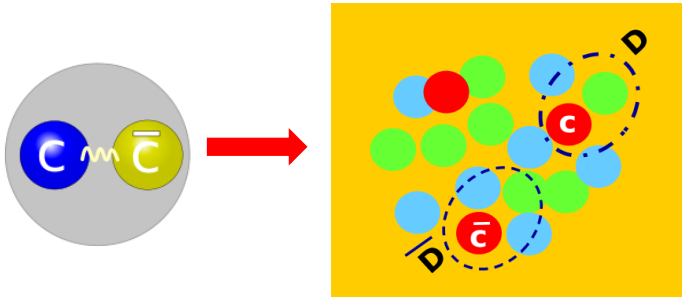
# Heavy Quarkonia as Probe of the QGP

- Lattice QCD predicts a transition between hadrons and the Quark-Gluon Plasma (QGP) when temperature/density is sufficiently high.

- Quarkonia are expected to be dissociated in the QGP due to the color screening effect. The resulting suppression is viewed as a signature of deconfinement. T. Matsui and H. Satz, PLB 178 (1986) 416

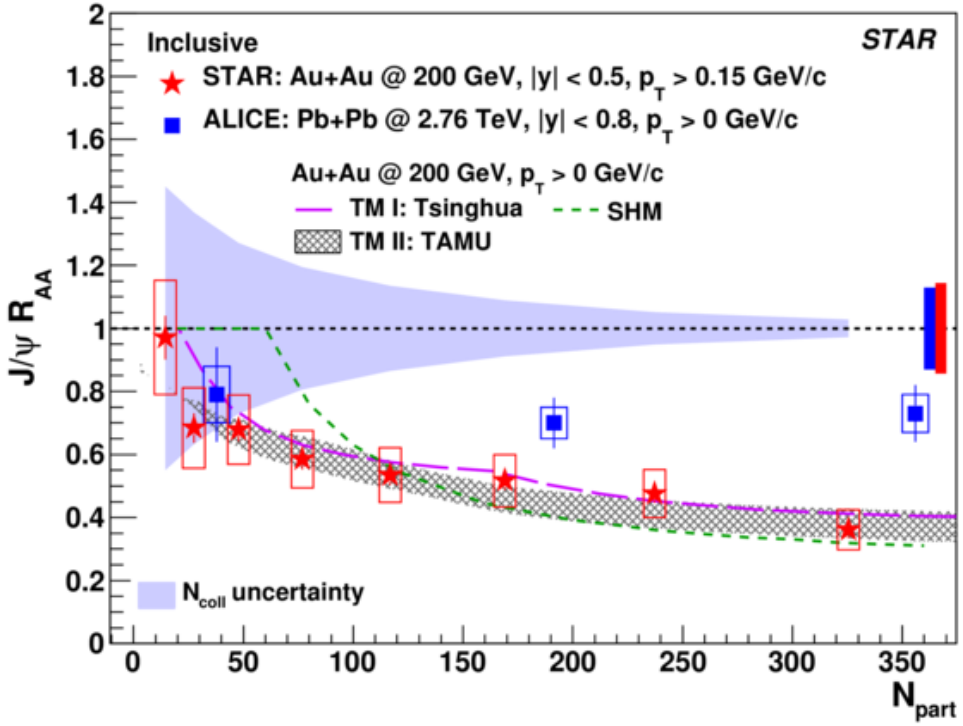


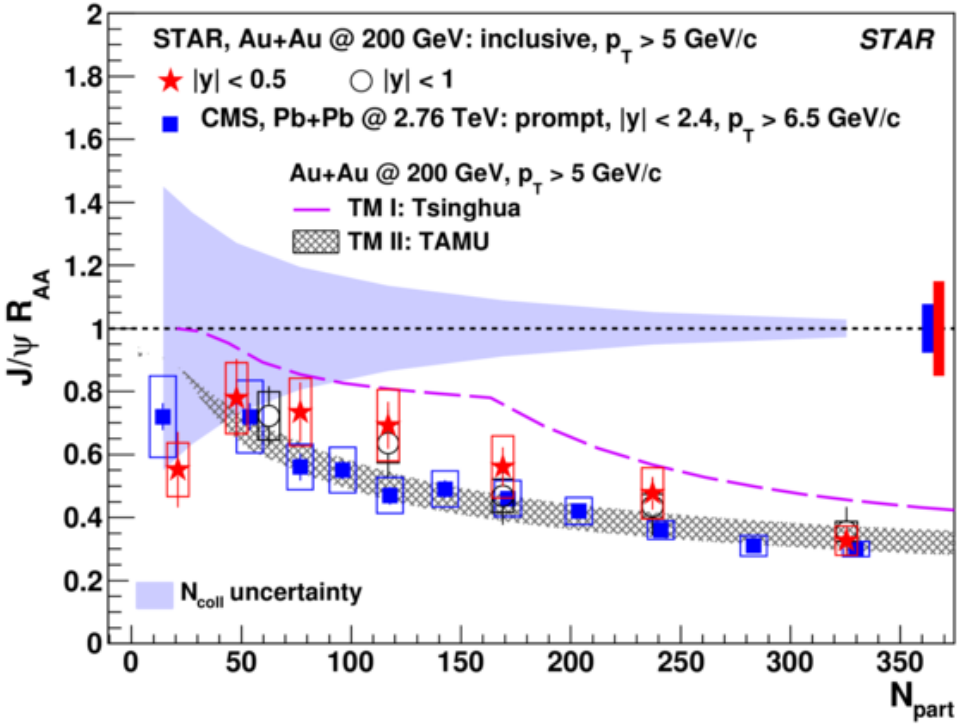

- Other effects could also play a role
  --- Regeneration
  --- Energy loss
  --- Cold nuclear matter effects (CNM)

# J/ψ Suppression: RHIC vs. LHC

J/ψ $R_{AA}$ as a function of $N_{part}$ in 200 GeV Au+Au and 2.76 TeV Pb+Pb collisions

STAR, PLB 797 (2019) 134917




Final

- **Low-$p_T$:** more suppressed at RHIC than at LHC in central collisions → smaller charm production cross-section at RHIC and thus smaller regeneration.
- **High-$p_T$:** J/ψ is strongly suppressed at both RHIC and LHC in (semi-)central collisions → Color Screening?

# J/ψ Suppression vs. $p_T$ in Au+Au Collisions

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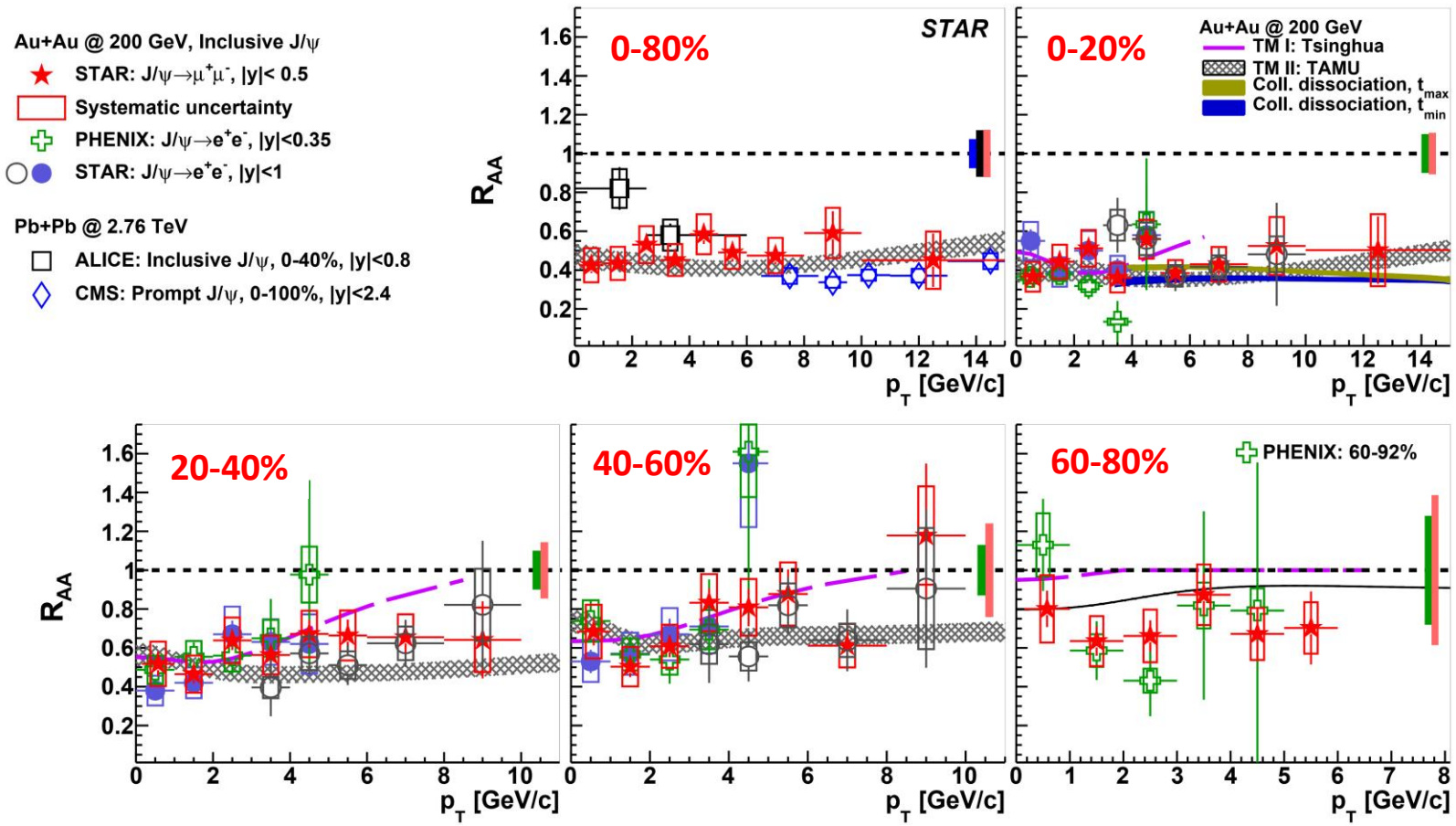
STAR, PLB 797 (2019) 134917




**First final results from MTD in Au+Au collisions**

- In central and semi-central collisions, J/ψ is suppressed from low to high $p_T$ with no strong $p_T$ dependence.
- Interplay of different effects
  - Dissociation: decreases with $p_T$ due to formation time effect
  - Regeneration: mostly at low $p_T$
  - Cold nuclear matter effects.
- Model calculations can describe data fairly well.

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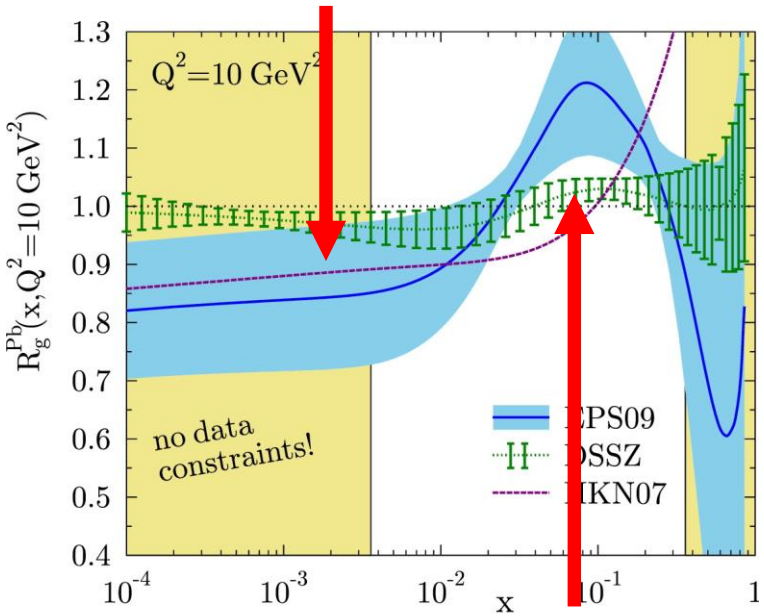
# Cold Nuclear Matter Effects

- Cold Nuclear Matter Effects
  - --- nPDF effect
  - --- Nuclear absorption effect
  - --- Comover absorption
  - --- Cronin effect
  - …

Modification of PDF distributions in a nucleus

- ➢ Shadowing: nPDF < proton PDF
- ➢ Anti-shadowing: nPDF > proton PDF

Shadowing




Anti-Shadowing

H. Paukkunen, Nucl. Phys. A 926 (2014) 24

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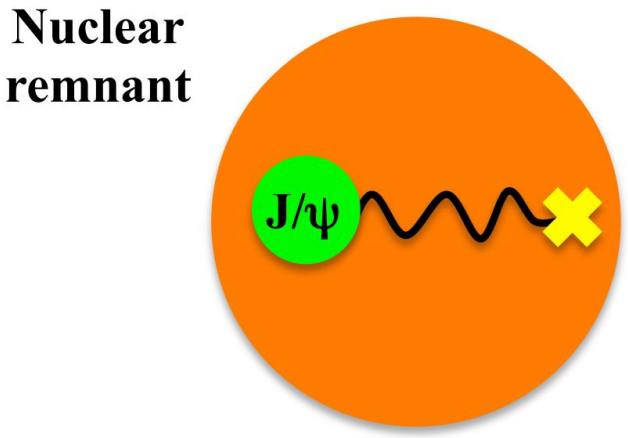
  - …

Absorption of quarkonia by remnant of incident nuclei




Gavin et al., PRL 78 (1997) 1006
Capella et al., PLB 393 (1997) 431

# Cold Nuclear Matter Effects

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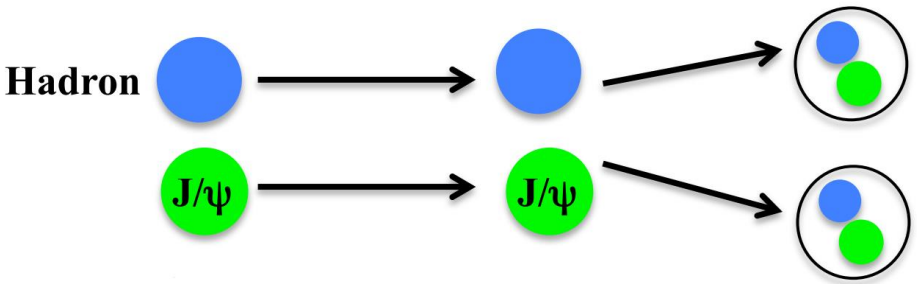
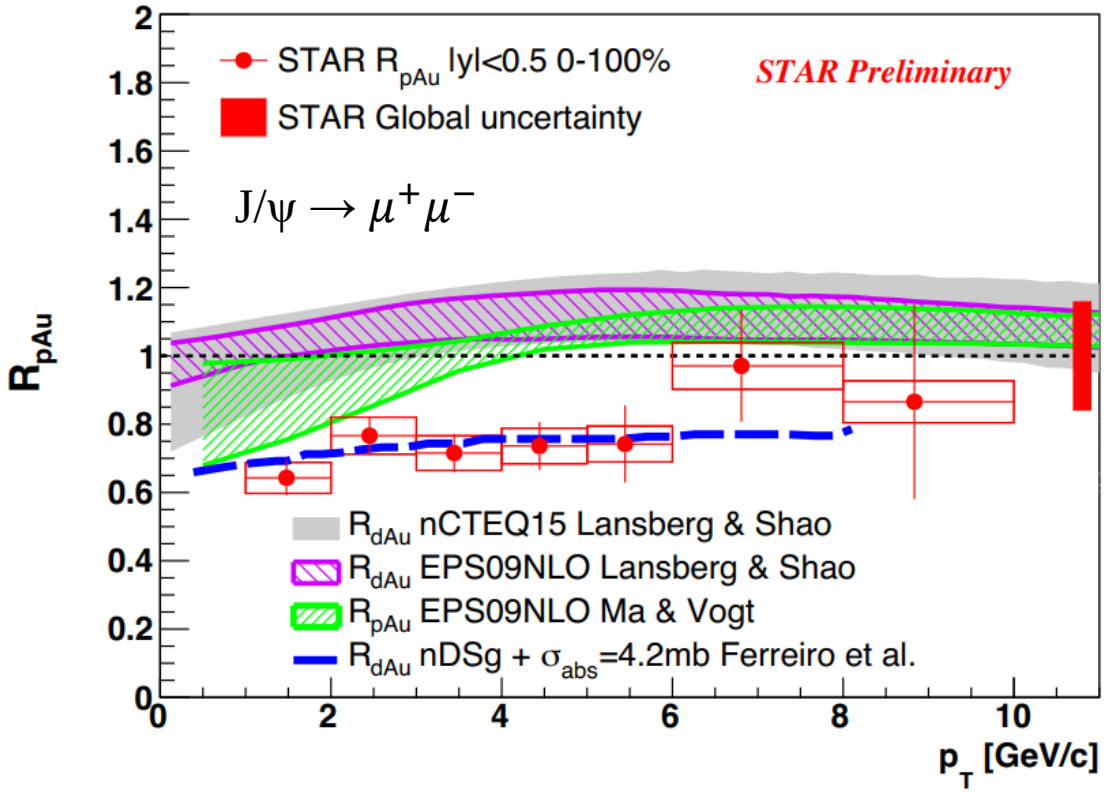
Break-up of quarkonia by comoving hadrons outside of nuclear remnant




Ferreiro et al., EPJC 61 (2009) 859
Ferreiro et al., PLB 680 (2009) 50
Ferreiro, et al., PRC 81 (2010) 064911

# J/ψ $R_{pAu}$ at 200 GeV




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

- $R_{pAu}$ is consistent with unity at high $p_T$ and is less than unity at low $p_T$
- Model calculations with nPDF effects only can touch data within uncertainties
- Additional nuclear absorption is favored by data, which could depend on centrality

# Centrality Determination in p+Au Collisions

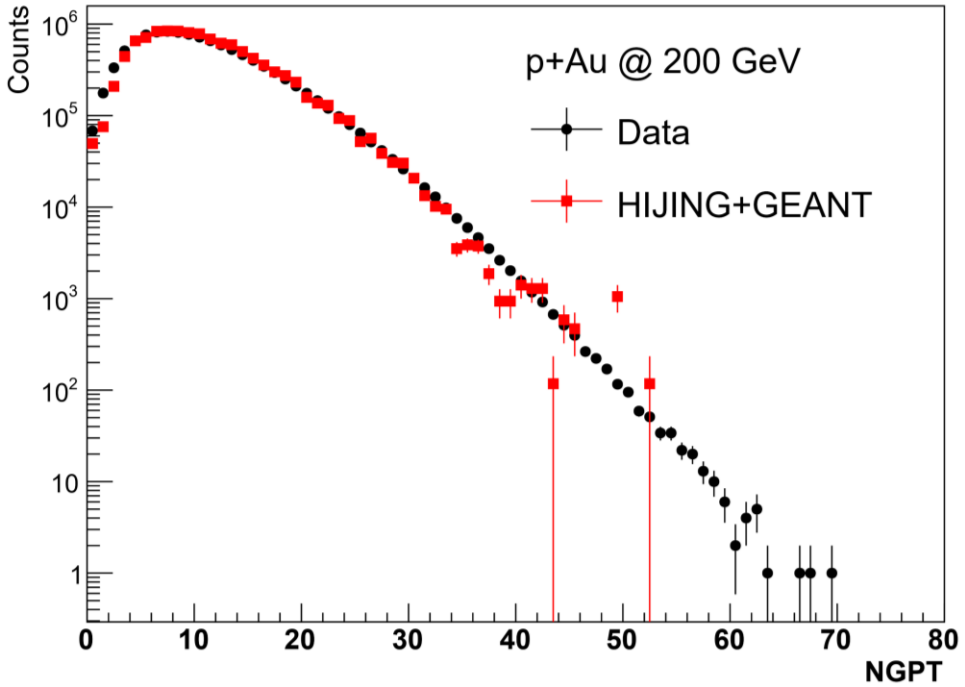
Use minimum-bias p+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV taken by STAR in 2015.

**Steps:**

1) Use the track multiplicity within $|\eta| < 1$, called **number of good primary tracks (NGPT)**, for centrality classification. Its distribution can be well described by HIJING+GEANT simulation.

The requirements for NGPT tracks are:

- **DCA < 1cm**
  --- closest distance between the track and the primary vertex
- $|\boldsymbol{\eta}| < \mathbf{1}$
  --- pseudo-rapidity
- **NHitsFit ≥ 10**
  --- number of TPC space points used for track reconstruction

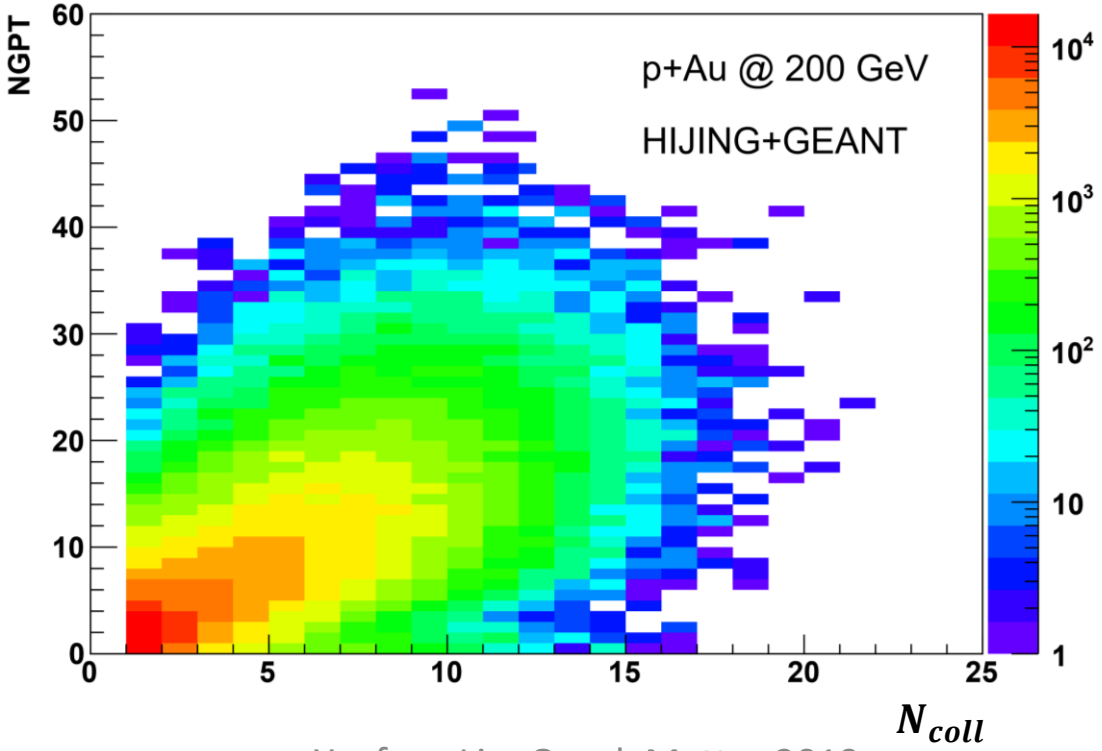


# Centrality Determination in p+Au Collisions

Use minimum-bias p+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV taken by STAR in 2015.

**Steps:**

2) Based on HIJING+GEANT simulation, the NGPT is seen to be correlated with the number of binary nucleon-nucleon collisions ($N_{\mathrm{coll}}$).

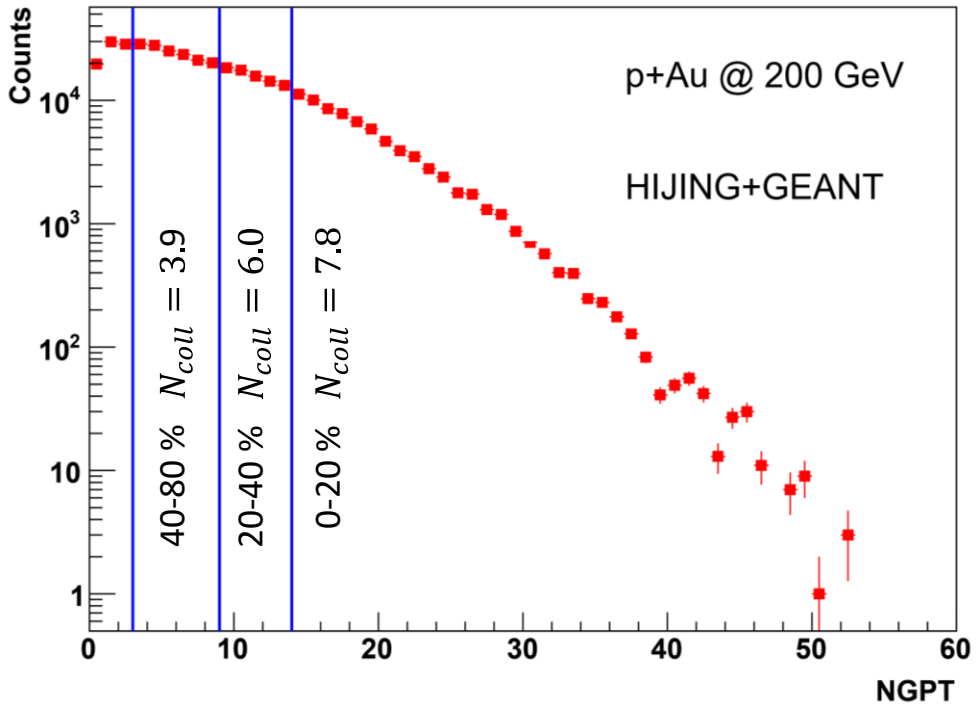


# Centrality Determination in p+Au Collisions

Use minimum-bias p+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV taken by STAR in 2015.

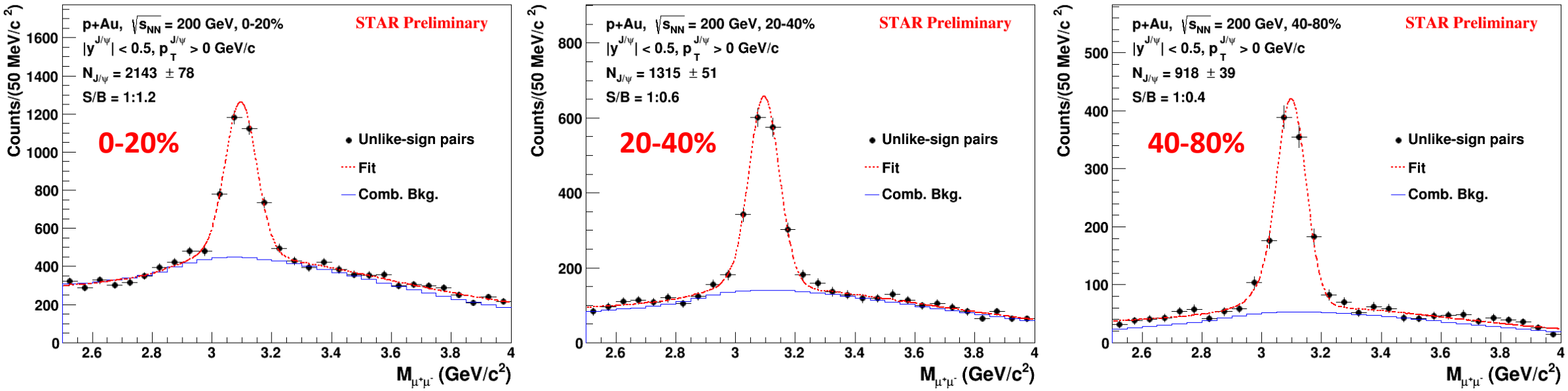
**Steps:**

3) The boundaries of different NGPT centrality classes are determined, and the corresponding $\langle N_{\mathrm{coll}} \rangle$ values are calculated.




| Centrality Classes | $\langle N_{\mathrm{coll}} \rangle$ |
|---|---|
| 0-20% | 7.8 |
| 20-40% | 6.0 |
| 40-80% | 3.9 |

# J/ψ Signal in Different p+Au Centralities




- Good J/ψ signal in different p+Au centrality bins
- $R_{pAu}$ and study of correlation between self-normalized yield and event activity are underway

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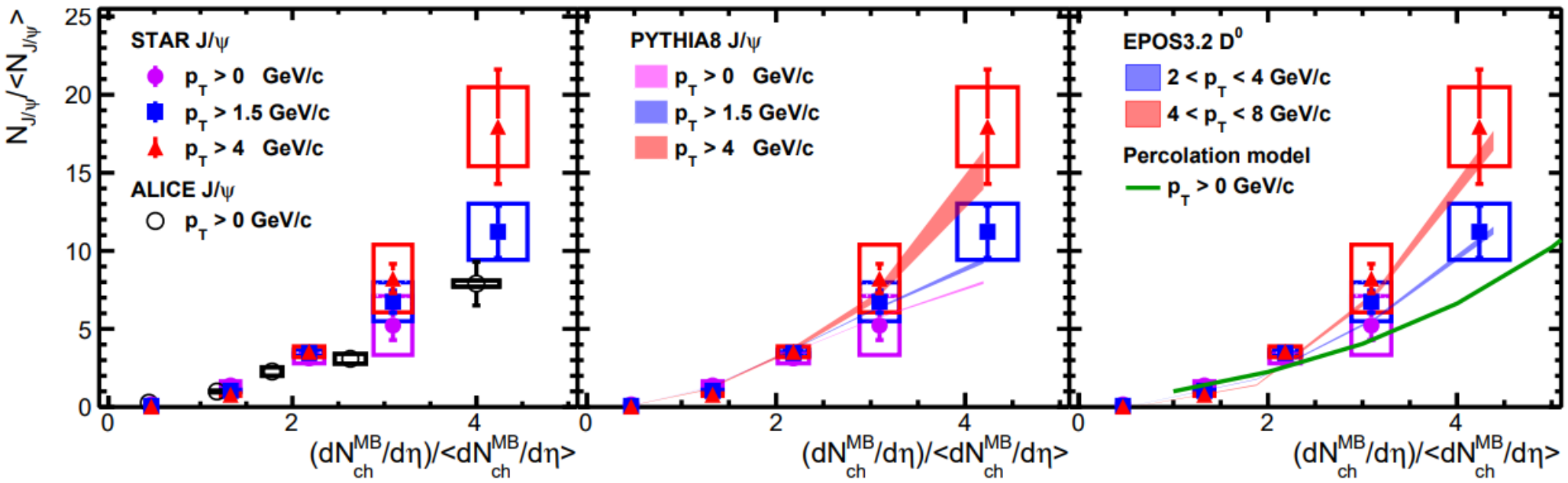
# J/ψ Yield vs. Event Activity in p+p @ 200 GeV

STAR, PLB 786 (2018) 87

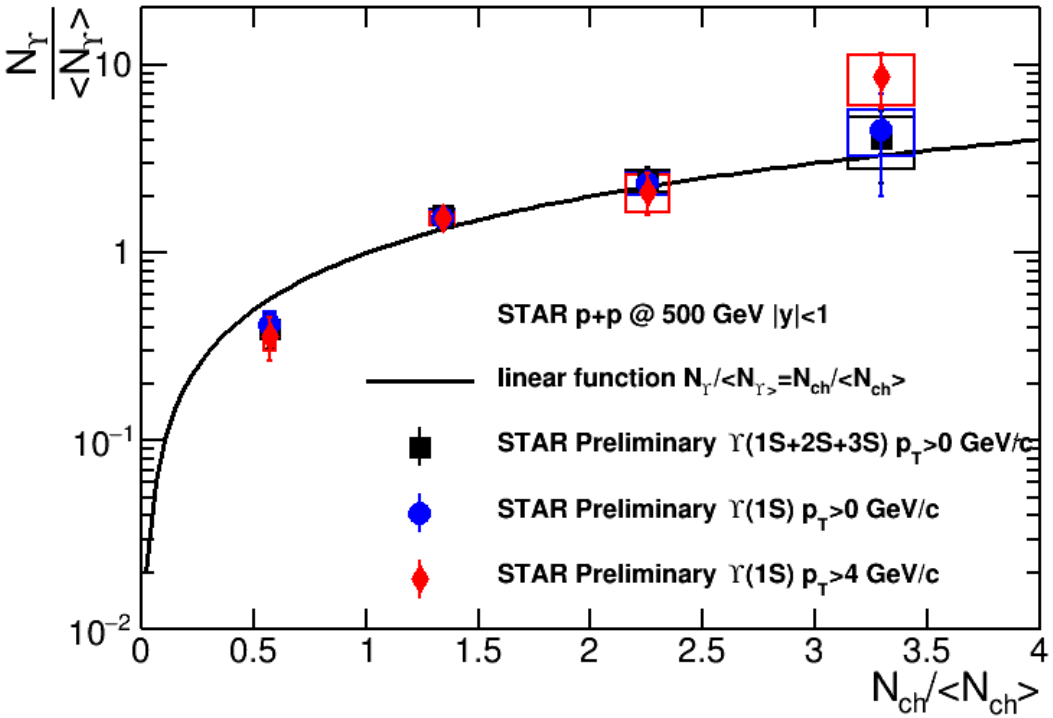
Final

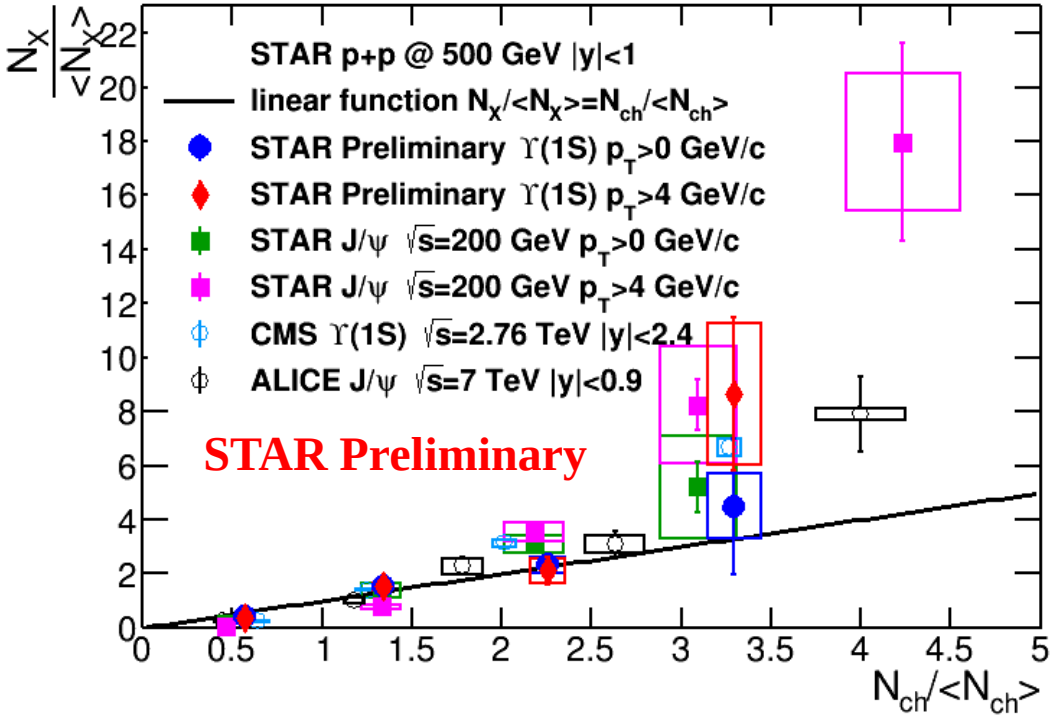



- Stronger-than-linear rise of J/ψ yield vs. mid-rapidity activity, especially at high $p_T$
- Possible scenarios:
  - Quarkonium produced in multi-parton interactions (MPI): PYTHIA8 and EPOS
  - String percolation
  - Color glass condensate (CGC)/saturation

# ϒ Yield vs. Event Activity in p+p @ 500 GeV

Leszek Kosarzewski
Poster No. HF30

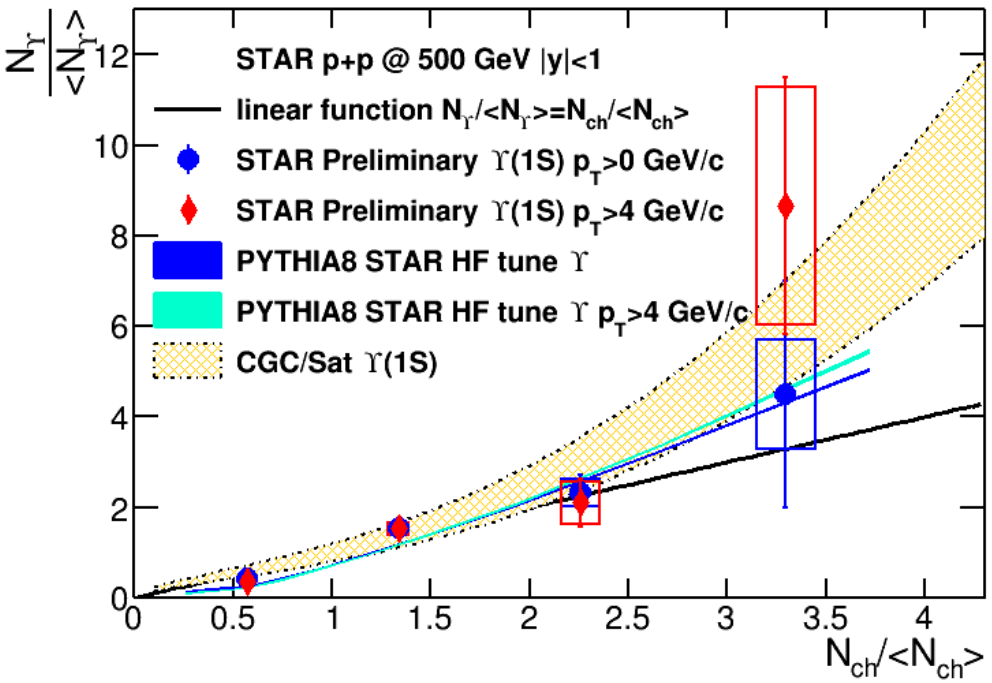


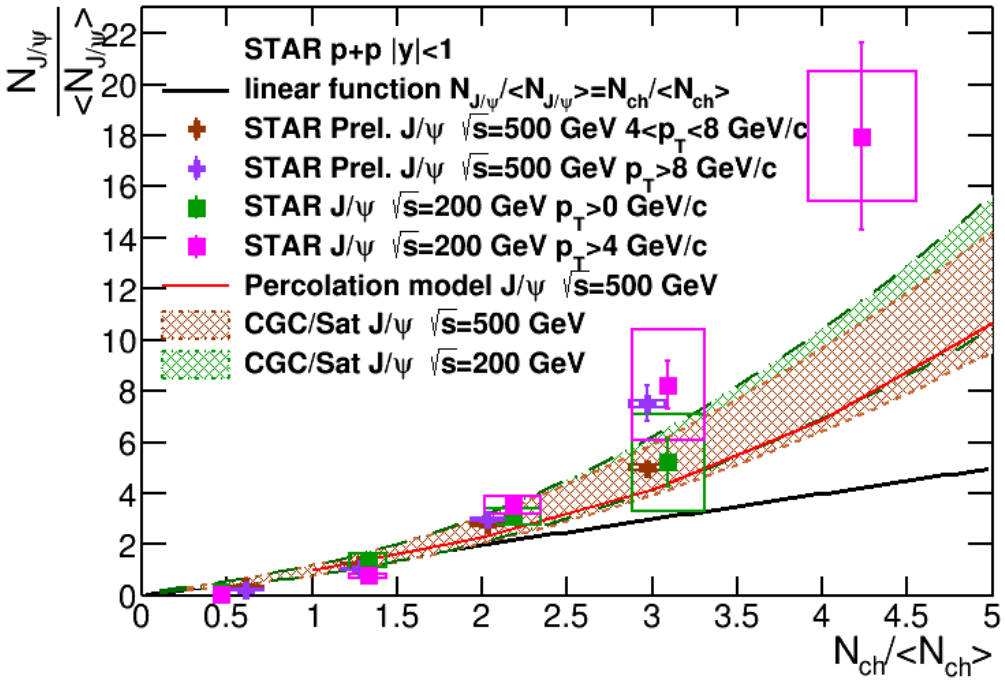




CMS, JHEP 04 (2014) 103
ALICE, PLB 712 (2012) 165
STAR, PLB 786 (2018) 87

- Faster-than-linear rise for ϒ(1S)
- Similar trends observed for J/ψ and ϒ at RHIC and LHC

# ϒ(1S) and J/ψ Event Activity: Data vs. Models



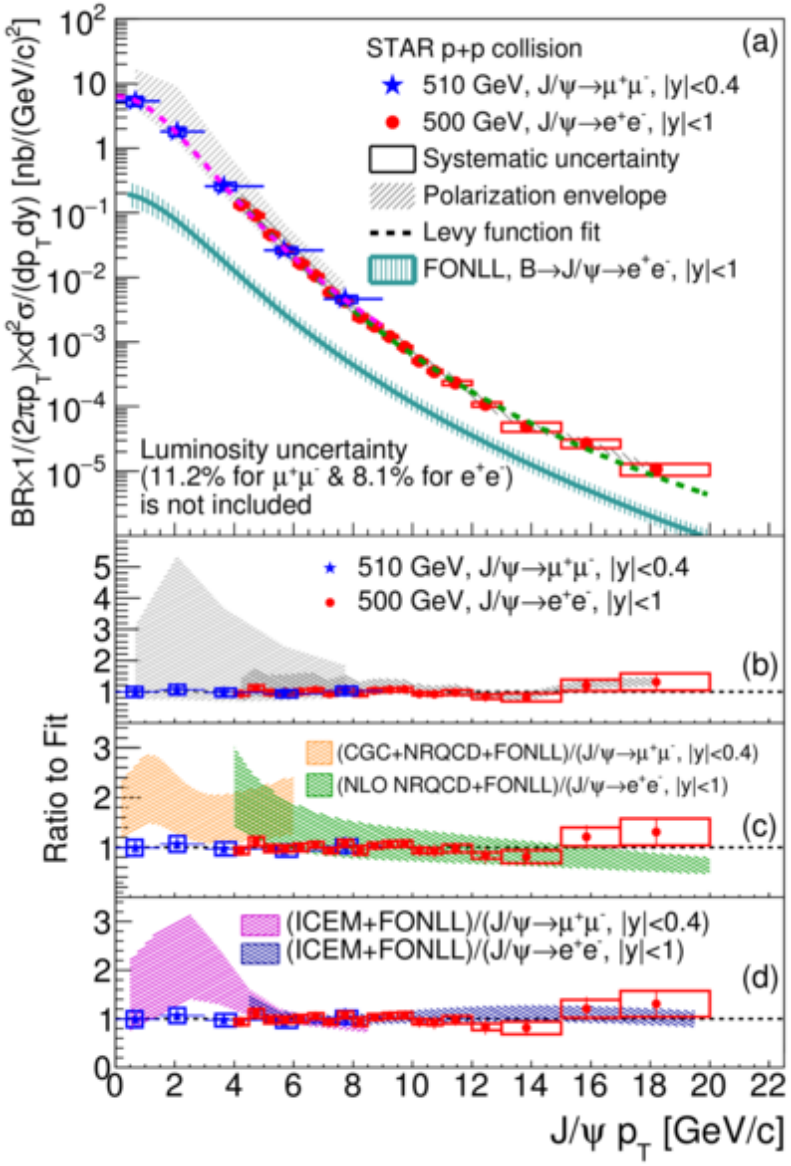

- Both PYTHIA8 with MPI and Percolation Model qualitatively describe data trend
- CGC/Saturation consistent with both J/ψ and ϒ measurements at low and high $p_T$
- More precise measurements at high multiplicity needed in order to distinguish between models

E. Levin, et al., EPJC 79 (2019) 376
E, Ferreiro, et al., PRC 86 (2012) 034903

# J/ψ Cross-Section in p+p @ 500/510 GeV

STAR, PRD 100 (2019) 52009

Final



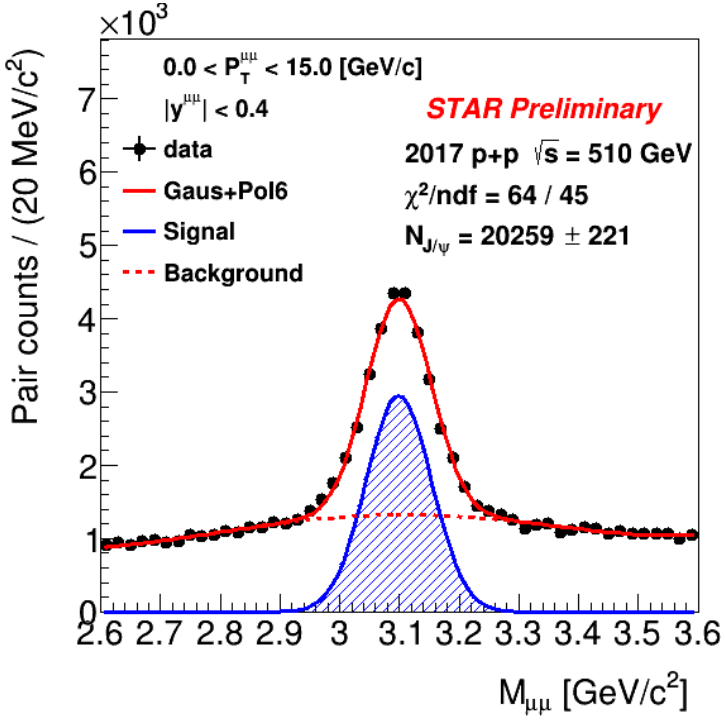

- Inclusive J/ψ cross-section combining dimuon channel at low $p_T$ and dielectron channel at high $p_T$
- Several models on the market
  - Improved color evaporation model (ICEM)
  - NLO non-relativistic QCD (NRQCD), applicable at high $p_T$
  - CGC+NRQCD at low $p_T$
- ICEM and NRQCD calculations are compared to data with b-hadron feed-down contributions from FONLL added
  - Low $p_T$: ICEM and CGC+NRQCD over-predict data assuming zero polarization
  - High $p_T$: ICEM and NLO NRQCD are consistent with data

# New J/ψ and ψ(2S) in p+p @ 510 GeV

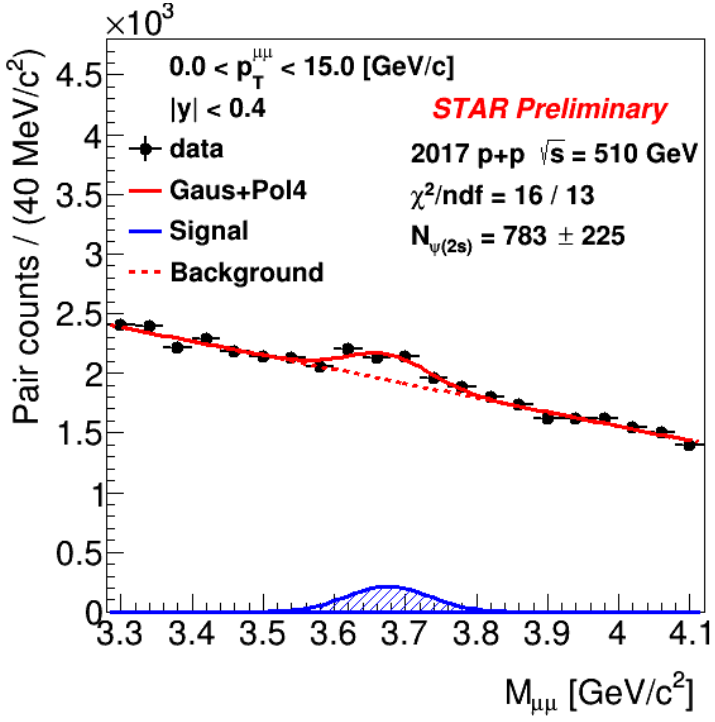
Chan-Jui Feng
Poster No. HF35

- J/ψ and ψ(2S) signal through the dimuon channel using 2017 data
  - About a factor of 8.5 more statistics compared to published 2013 result

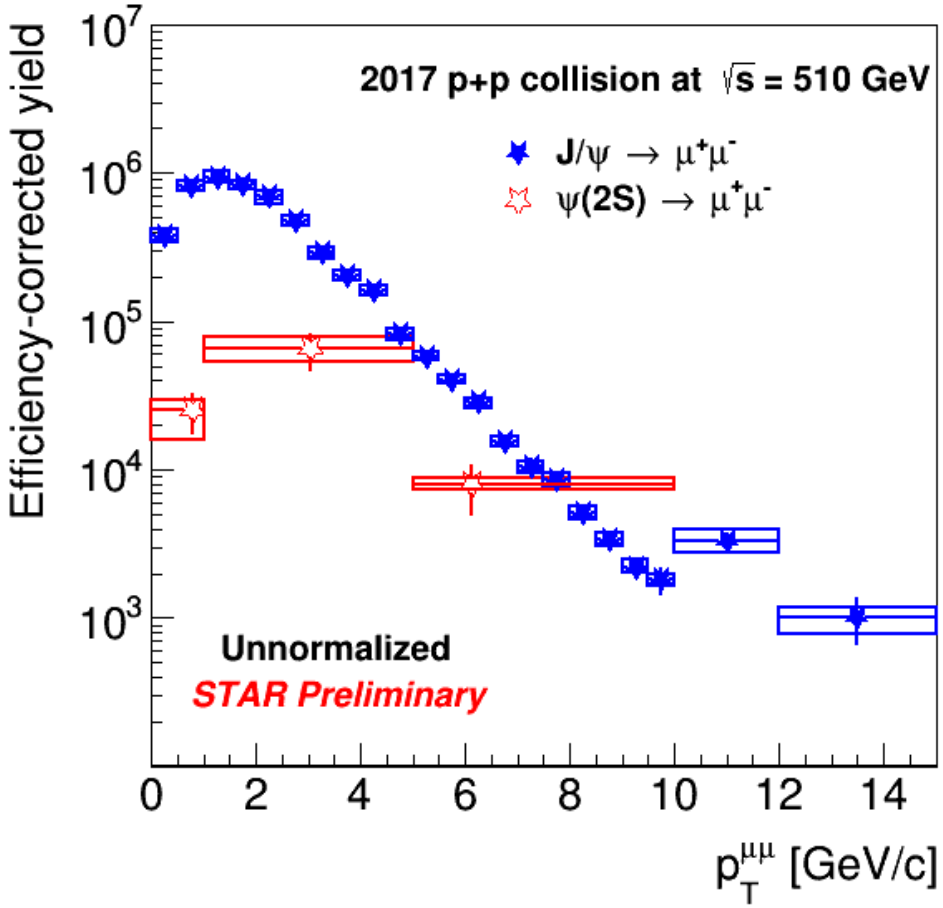
$J/\psi \rightarrow \mu^+\mu^-$

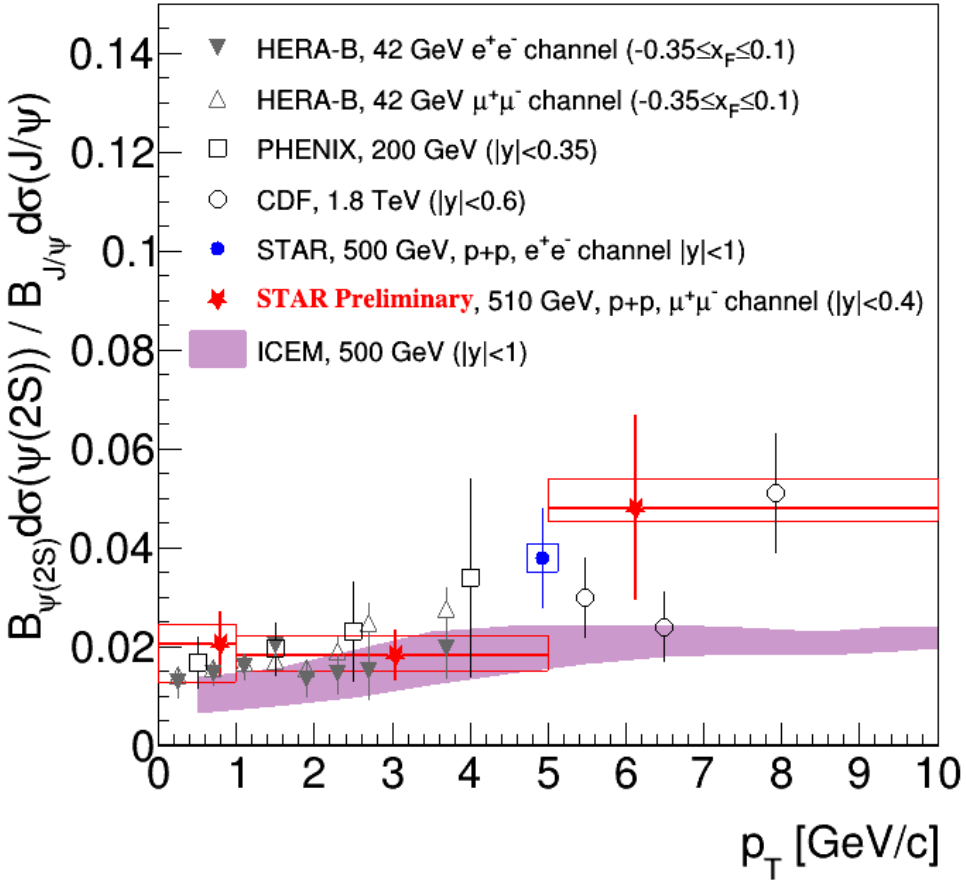



$\psi(2S) \rightarrow \mu^+\mu^-$



# Corrected J/ψ and ψ(2S) Yields and Their Ratio



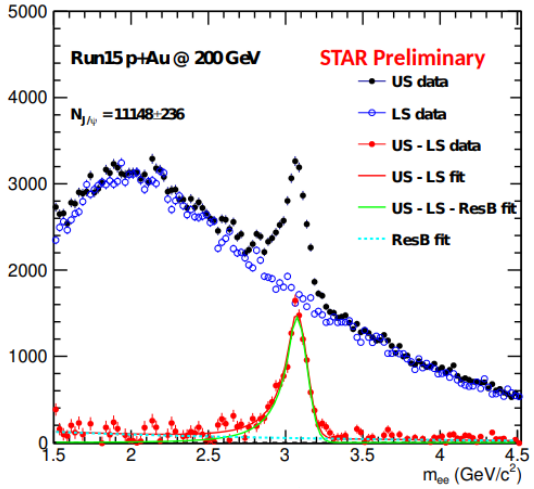




- More differential J/ψ measurement at low $p_T$ with improved precision, and extends to higher $p_T$
- First ψ(2S) to J/ψ ratio vs. $p_T$ from STAR
- Results follow the world-data trend and ICEM prediction

# Summary and Outlook

- Au+Au
  - Strong suppression of J/ψ at high $p_T$ → dissociation in medium
  - Weak dependence of J/ψ $R_{AA}$ on $p_T$ seen in all centrality classes
- p+Au
  - In MB events, suppression at low $p_T$, and consistent with unity at high $p_T$
  - Significant J/ψ signal in different centrality classes. Centrality and multiplicity dependent studies are underway
- p+p
  - J/ψ and ϒ at RHIC follow similar faster-than-linear trend as at LHC
  - New J/ψ and ψ(2S) measurements will further help constrain models
- Outlook
  - More statistics from 2017 p+p (10×) and 2015 p+Au for the dielectron channel

Ziyue Zhang
Poster No. SS26



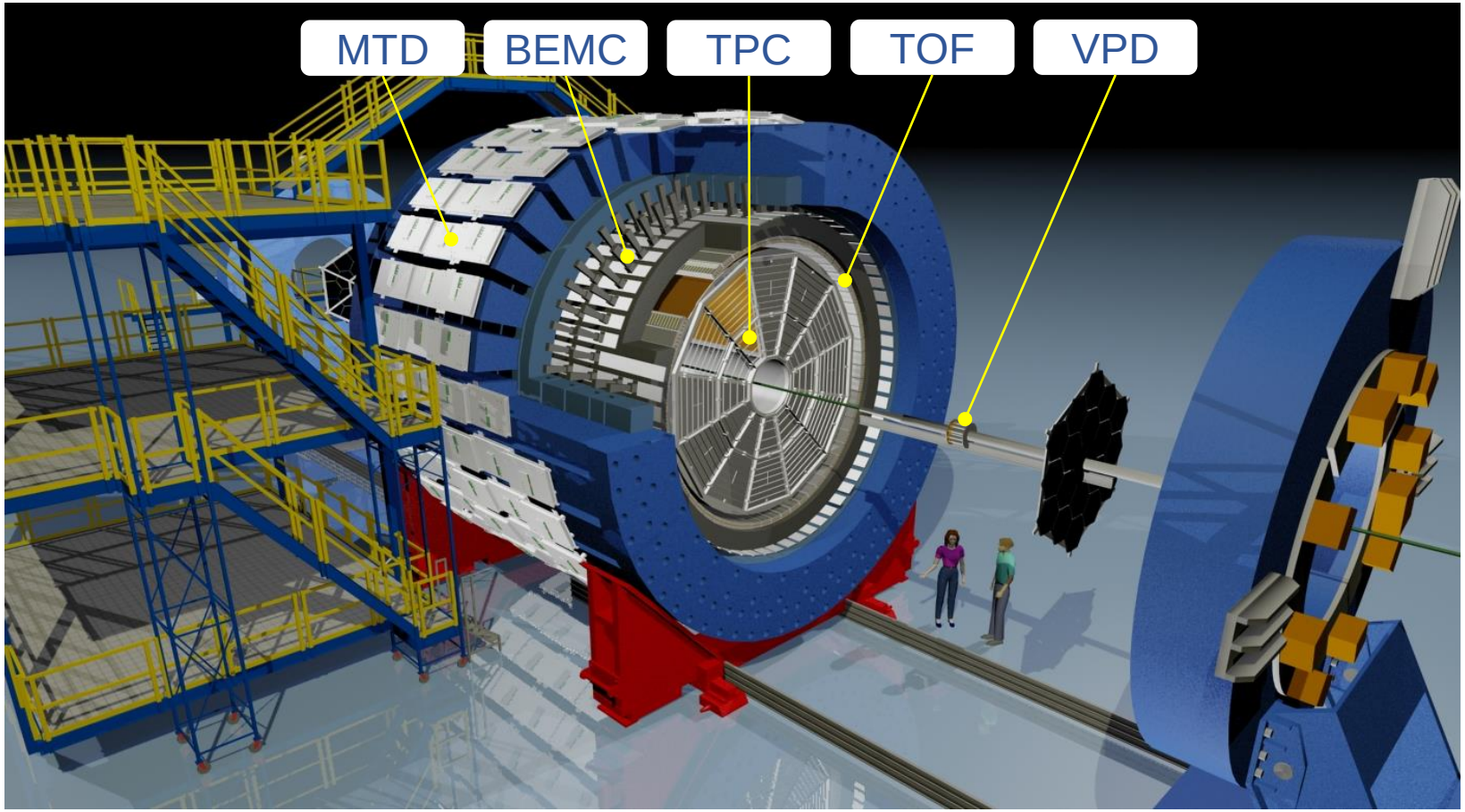
# Back Up

# The Solenoid Tracker At RHIC (STAR)

**TPC**
**T**ime **P**rojection **C**hamber measures tracking for particle momenta and energy loss for particle identification. Covers $|\eta| \leq 1.0$

**TOF**
**T**ime **O**f **F**light detector measures particles' flight time for particle identification. Covers $|\eta| \leq 1.0$

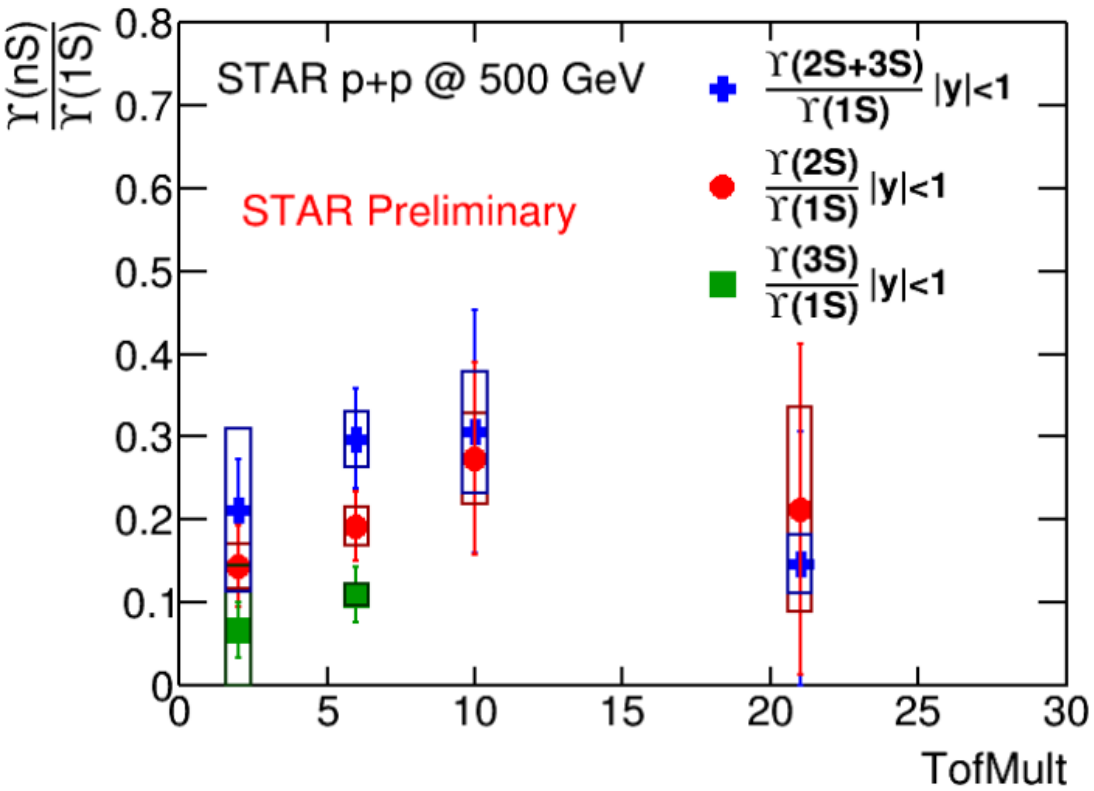
**BEMC**
**B**arrel **E**lectro-**M**agnetic **C**alorimeter triggers on and identifies high-$p_T$ electrons. Covers $|\eta| \leq 1.0$




**MTD**
**M**uon **T**elescope **D**etector triggers on and identifies muons. Covers $|\eta| \leq 0.5$ and 45% in $0 \leq \phi < 2\pi$

**VPD**
**V**ertex **P**osition **D**etectors provide main minimum-bias trigger, the event start time and the primary collision vertex location. Covers $4.24 \leq |\eta| \leq 5.1$

# ϒ(nS)/ϒ(1S) vs. Multiplicity




- No significant dependence on event multiplicity