The 16th International Workshop on Heavy Quarkonium at IISER Mohali

Quarkonium Production in p+p Collisions Measured by the STAR

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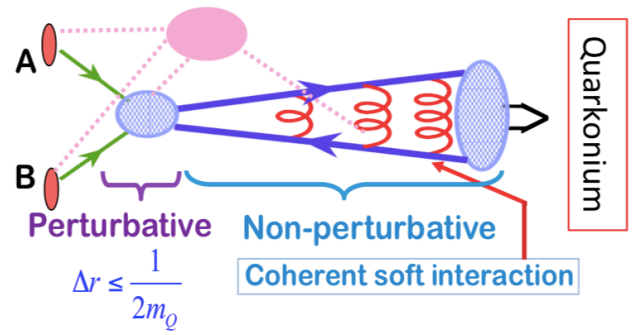
Outline

- Introduction
- The STAR Detector
- Results
  - J/ψ Production (Charm)
  - ϒ Production (Bottom)
- Summary

Quarkonium Measurement in p+p

- Understanding production mechanism in p+p.
  - Heavy quarks are primarily produced in initial hard scatterings (Perturbative QCD)
  - Formation of quarkonia state happens over long distances (Non-perturbative QCD)

E. G. Ferreiro, SQM19



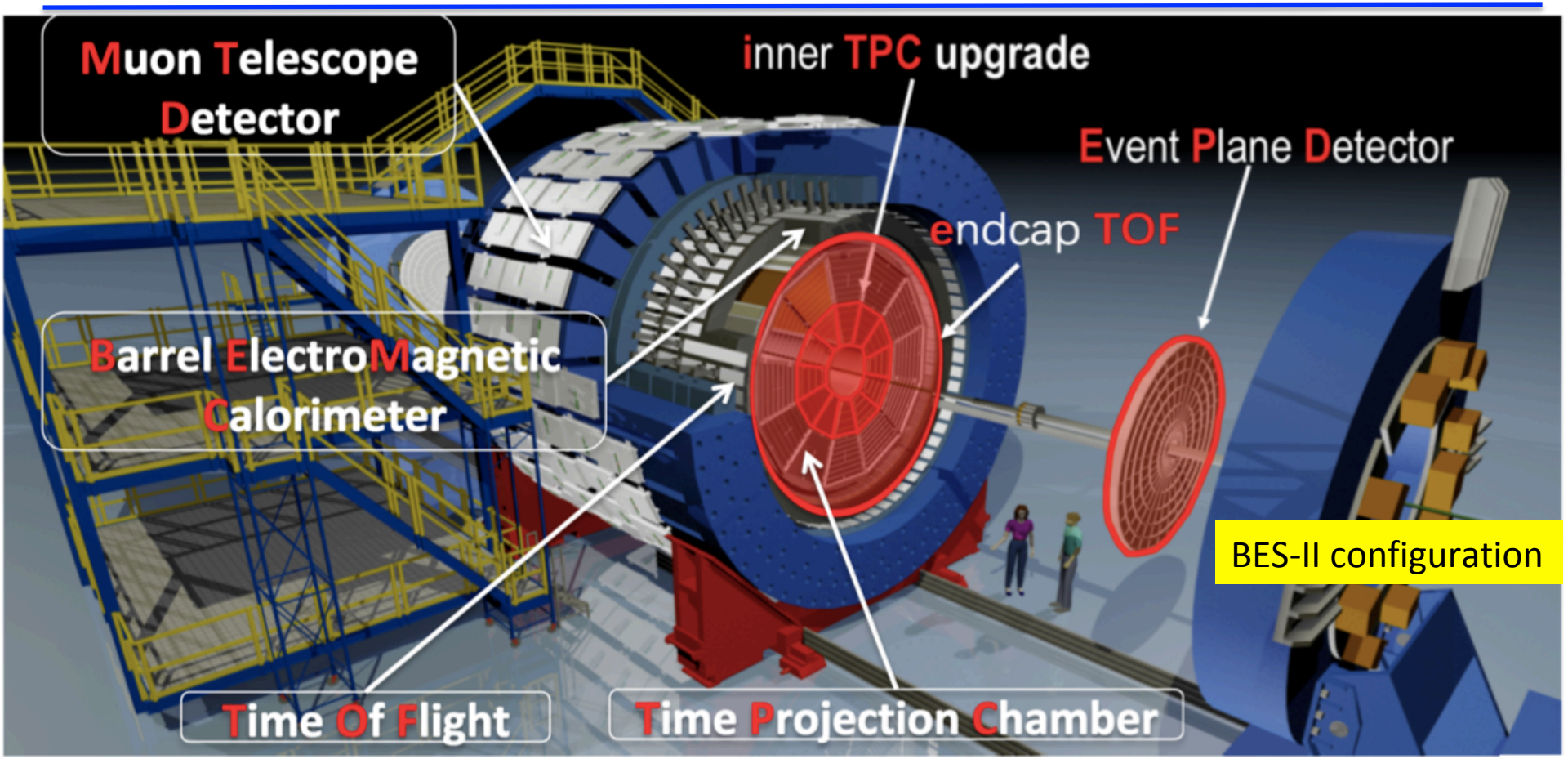
  - Evolution of heavy-quark pair into quarkonium states is usually parameterized by phenomenological models

- Color-Evaporation Model (CEM) Phys. Rept. 462, 125 (2008)
  All pairs with invariant mass less than open heavy flavor threshold forms quarkonium states
- Non- Relativistic Quantum Chromodynamics (NRQCD) PRL 106, 042002 (2011)
  Based on effective field theory where formation of quarkonium state is dependent on long-distance matrix elements (LDMEs)

- Baseline of Heavy-ion Measurements.

See Nihar Sahoo's talk for STAR heavy-ion results

The STAR Experiment



TPC : Tracking (momentum measurement, particle identification) ($|\eta| < 1.5$, $0 < \varphi < 2\pi$)

TOF : Particle identification at high p_T ($|\eta| < 1$, $0 < \varphi < 2\pi$)

BEMC : Triggering and identification of high-p_T electrons ($|\eta| < 1$, $0 < \varphi < 2\pi$)

MTD : Triggering and identification of muons ($|\eta| < 0.5$, 45% in φ)

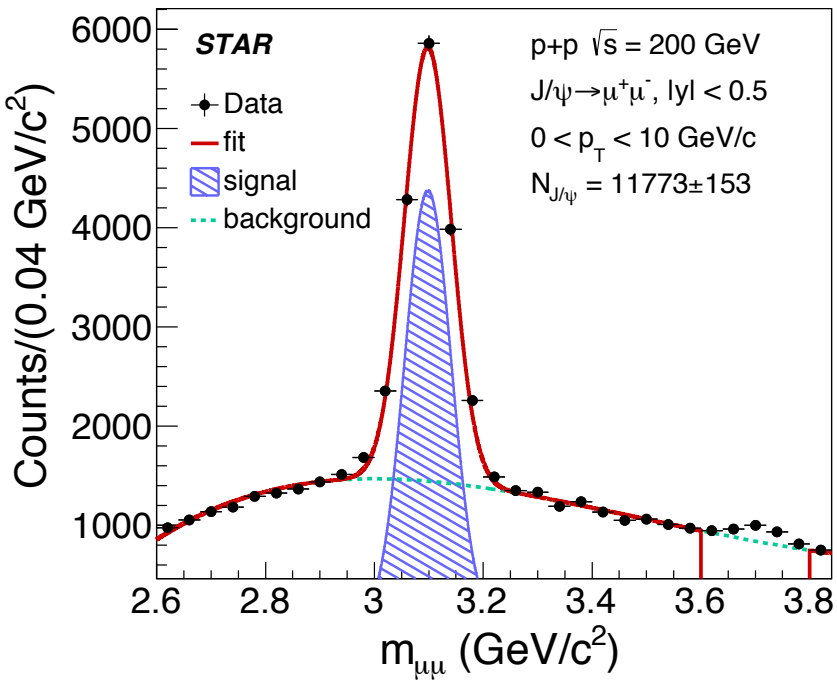
J/ψ ($c\bar{c}$) Production

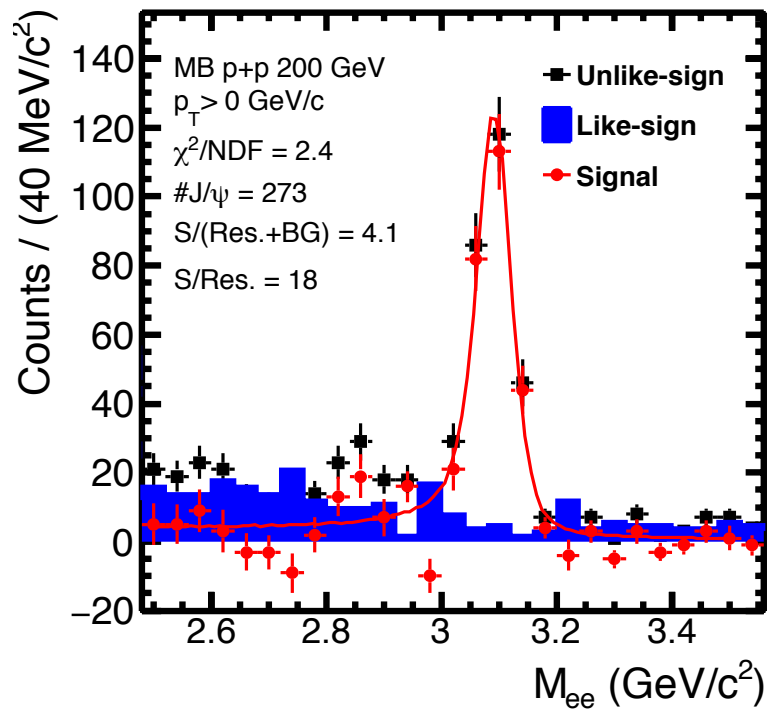
J/Ψ Reconstruction

p+p, √s = 200 GeV

$$J/\psi -> \mu^+ + \mu^-(BR = 5.9\%)$$

$$J/\psi -> e^+ + e^-(BR = 5.9\%)$$





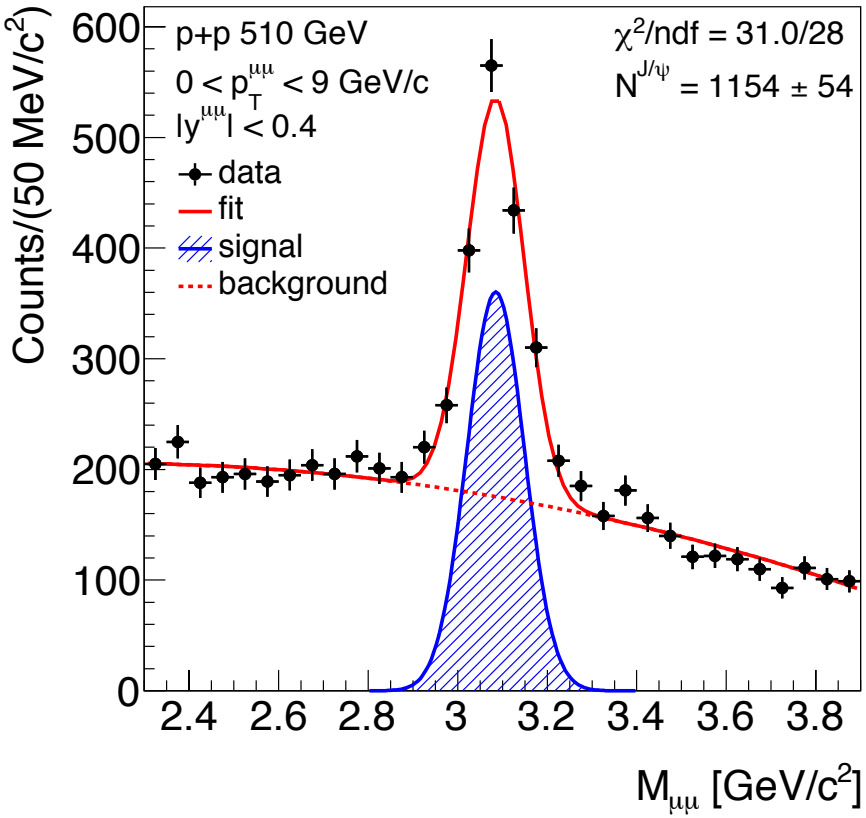
J/Ψ are reconstructed in both di-muon and di-electron decay channel

STAR: PLB 786, 87 (2018)

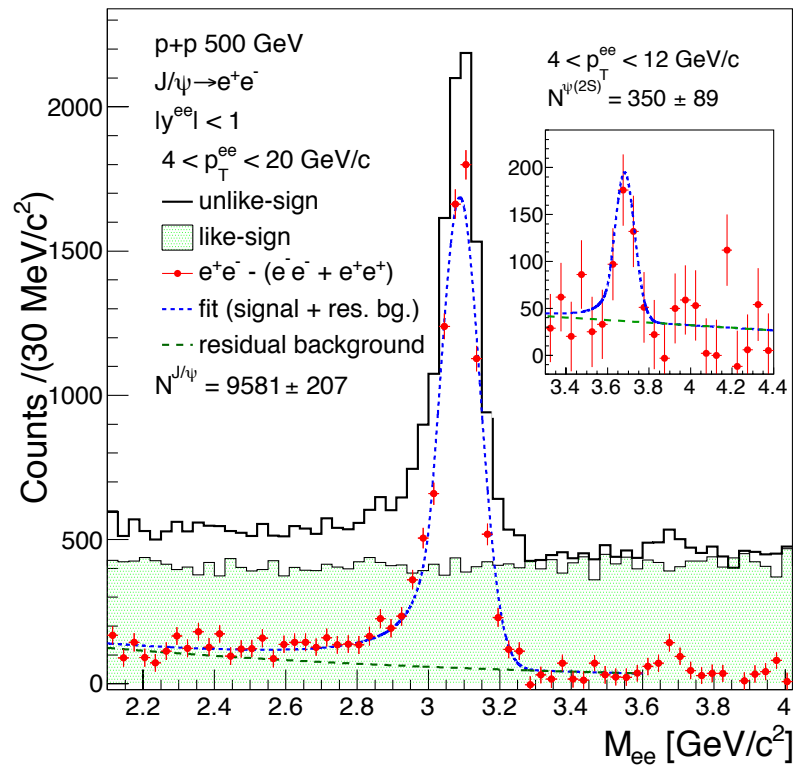
J/Ψ Reconstruction

p+p, √s = 500 GeV

$$J/\psi -> \mu^+ + \mu^-(BR = 5.9\%)$$



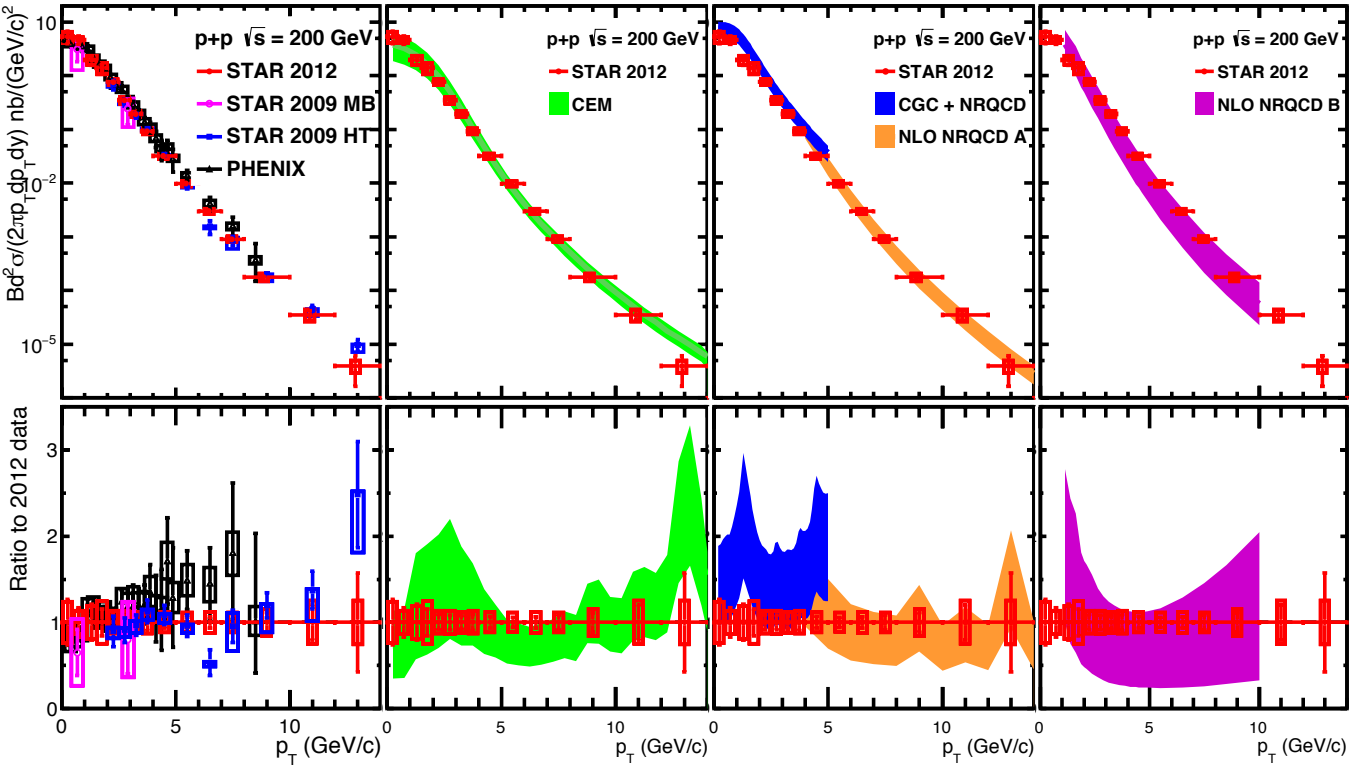
$$J/\psi -> e^+ + e^-(BR = 5.9\%)$$



J/Ψ are reconstructed in both di-muon and di-electron decay channel

STAR: PRD 100, 52009 (2019)

J/ψ Cross-Section in p+p at 200 GeV



Available model

CEM: Color Evaporation Model

Phys. Rept. 462, 125 (2008)

NRQCD : Non-relativistic QCD approach

PRL 113, 192301 (2014)

PRL 106, 042002 (2011)

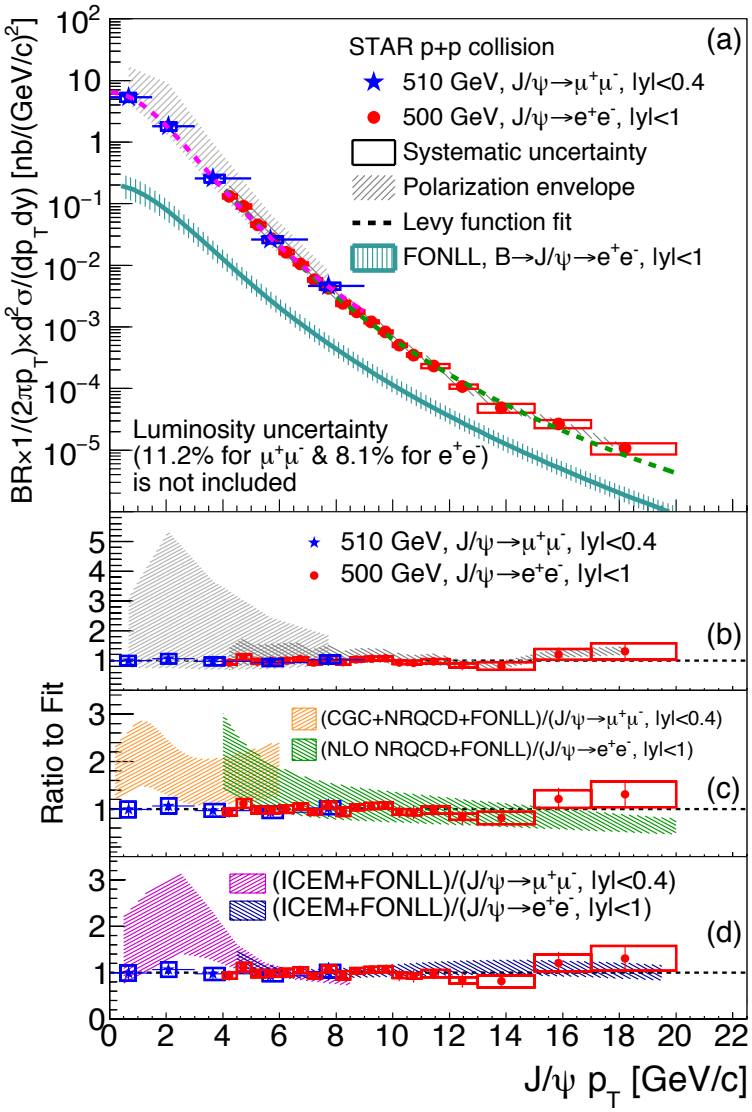
PRL 108,172002 (2012)

- Precise measurement than before, consistent with PHENIX
- All models give reasonable description for the data

STAR: PLB **786**, 87 (2018)

PHENIX : PRD 82, 012001 (2010)

J/ψ Cross-Section in p+p at 500 GeV



- Precise measurement of J/Ψ cross-section up to p_T =20 GeV/c
- Low p_T reach is extended through di-muon channel
- All models give reasonable description for the data, mainly at high p_T

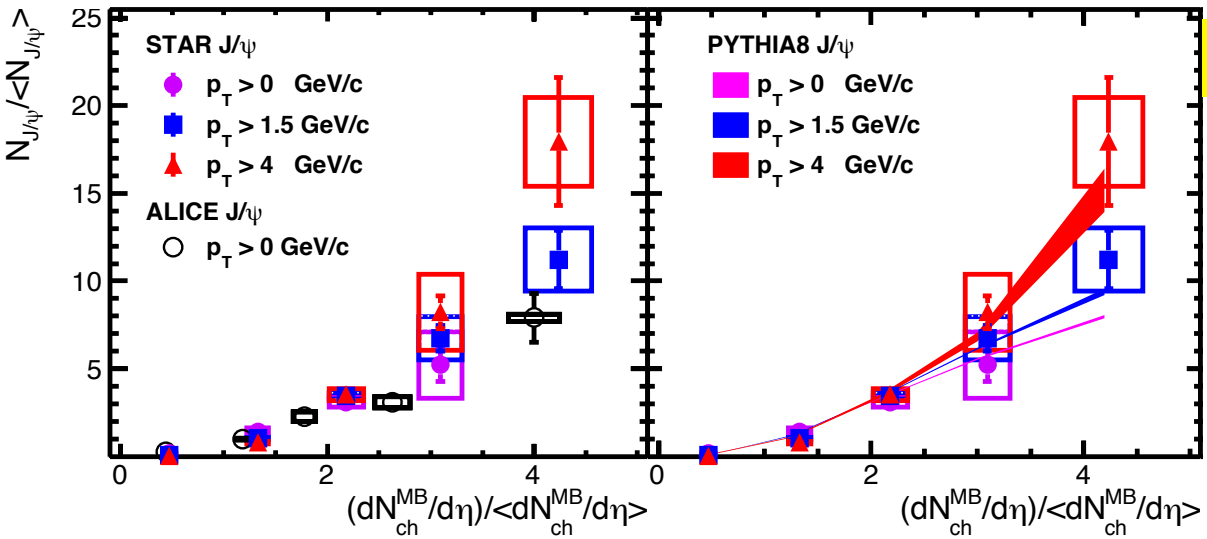
Available model

NRQCD : PRL 106, 042002 (2011)
PRL 113, 192301 (2014)

ICEM: Phys. Rept. 462, 125 (2008)

STAR : PRD 100 (2019) 52009

J/ψ Production Vs Event Activity



p+p, √s = 200 GeV

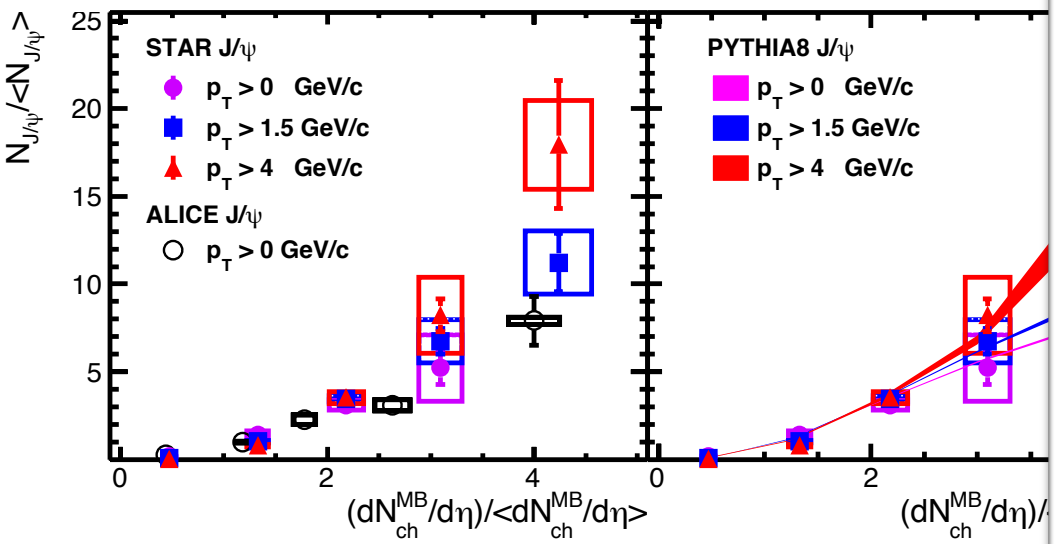
- Correlation between soft and hard processes
- Stronger-than-linear growth in high mult. events
- Similar trend at RHIC and LHC

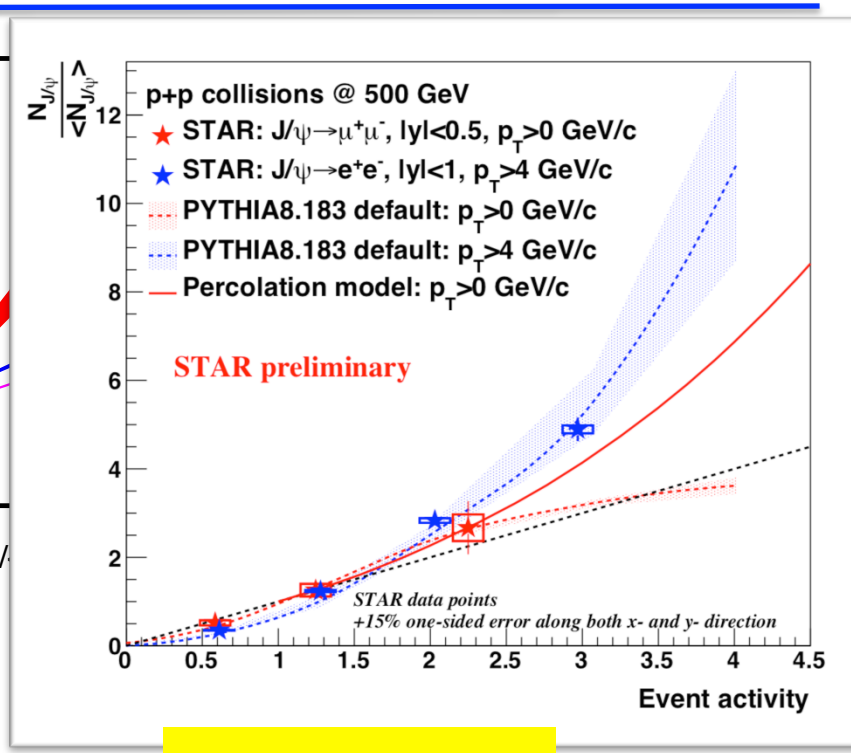
STAR: PLB 786 (2018) 87

ALICE : PLB 712 (2012) 165-175

Percolation: PRC 86 (2012) 034903

J/ψ Production Vs Event Activity





p+p, √s = 500 GeV

- Correlation between soft and hard processes
- Stronger-than-linear growth in high mult. events
- Similar trend at RHIC and LHC
- Available model explain data,

  - measurement in larger multiplicity bins is important

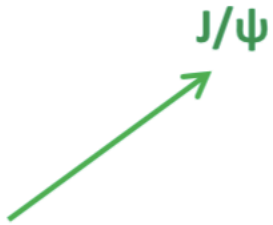
STAR: PLB 786 (2018) 87

ALICE : PLB 712 (2012) 165-175

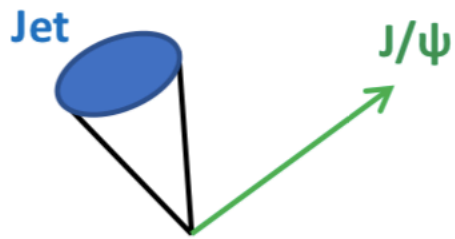
Percolation: PRC 86 (2012) 034903

J/ψ ($c\bar{c}$) Production Associated with Jet

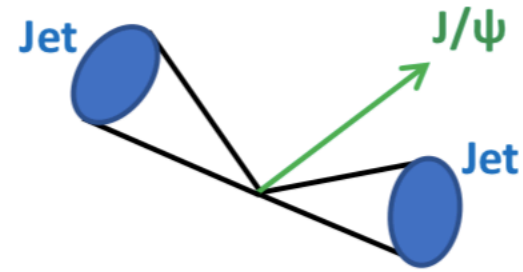
J/ψ Production Associated with Jet



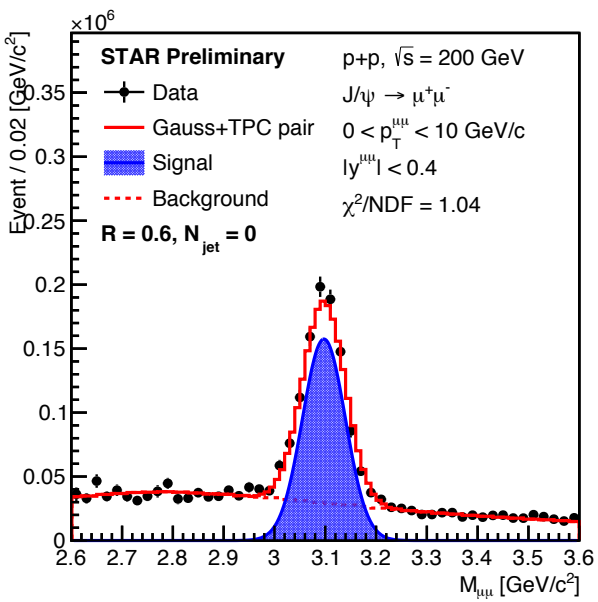
• J/ψ with 0 jet

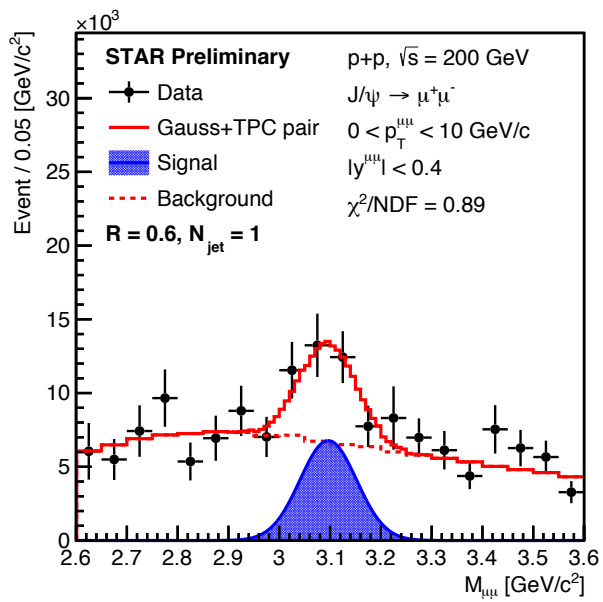


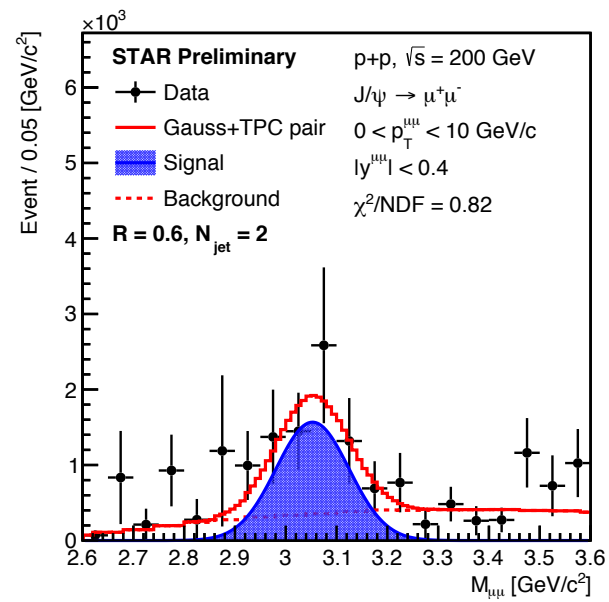
• J/ψ with one jet



• J/ψ with two jets

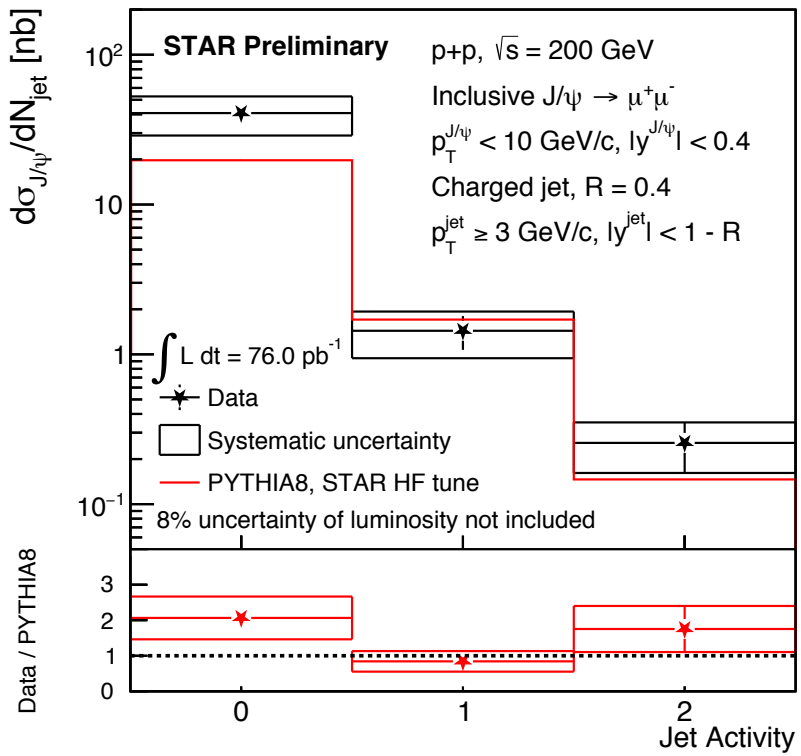


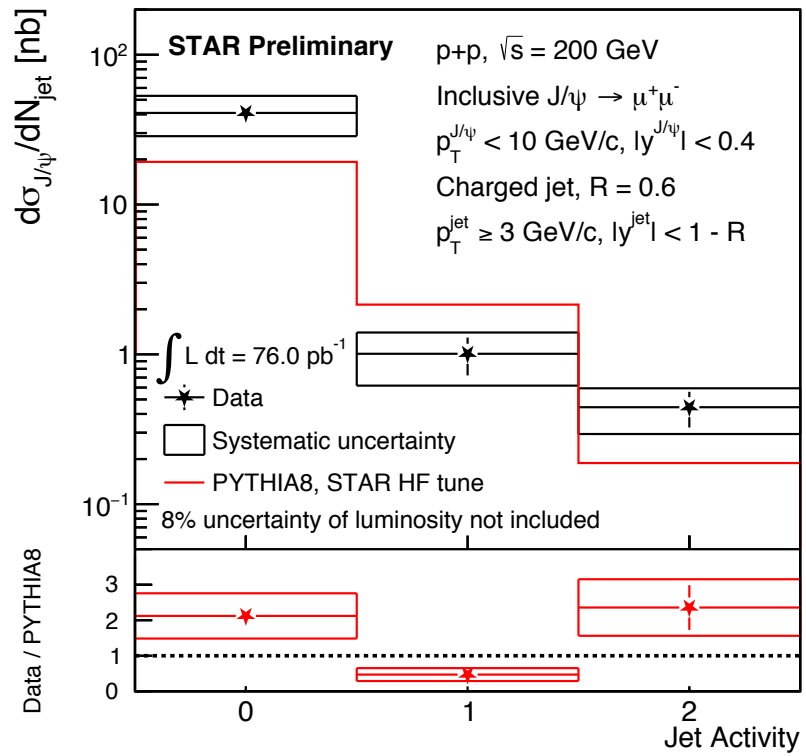




Reconstructed J/ψ in different jet activity categories (left to right: $N_{jet} = 0$ to $N_{jet} = 2$)

J/ψ Production Vs Jet Activity

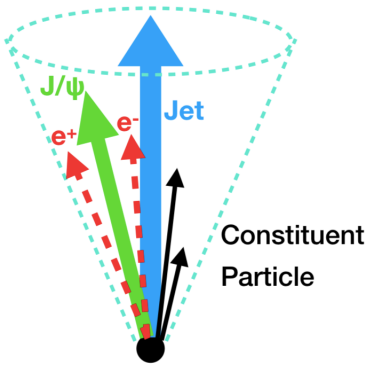


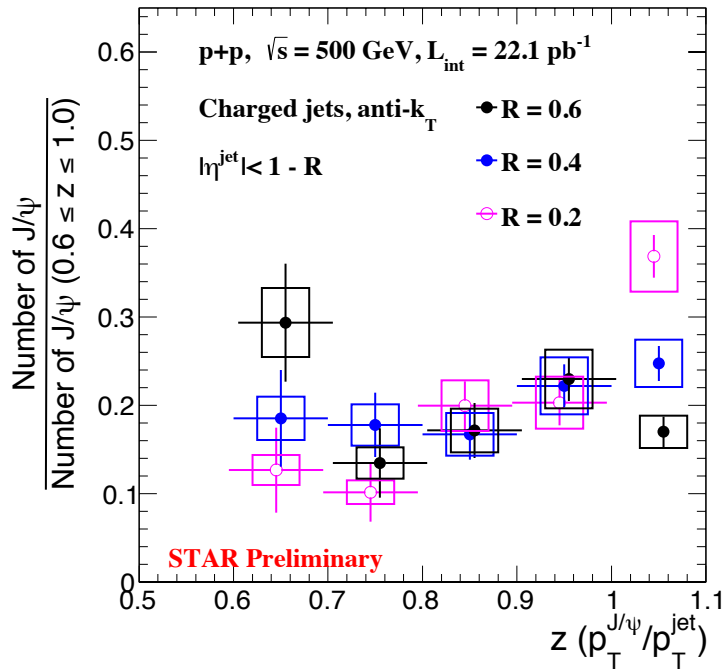


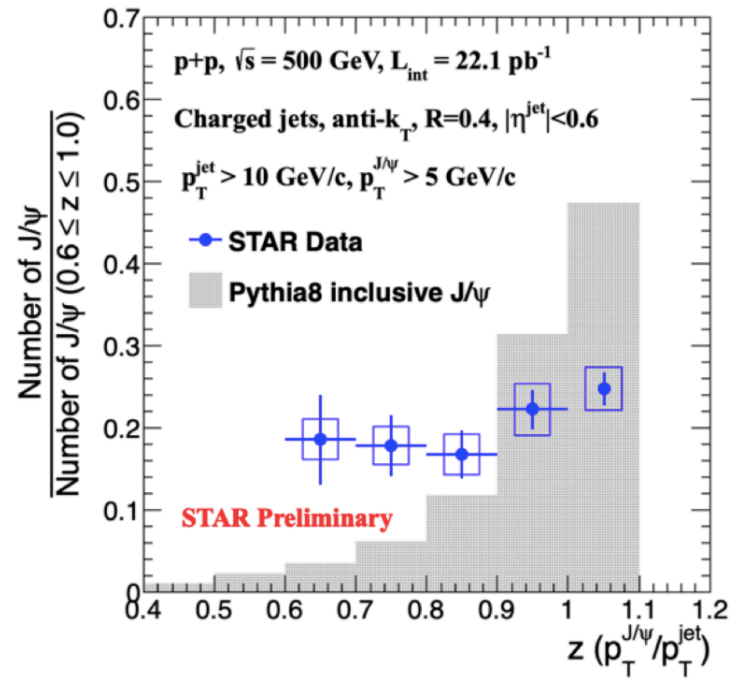
- Production cross section of J/ψ as a function of jet activity (number of jets per event)
- Inconsistency in shape between PYTHIA and data mainly for R = 0.6 (p-value = 0.01)

arXiv: 2110.09447

J/ψ Production in Jets







- First measurement of J/ψ production in jets at RHIC
- Unlike PYTHIA, no significant z dependence observed within uncertainties for z <1
- Provide further constrain on models

J/ψ ($c\bar{c}$) Polarization

Polarization Measurement

- **Measure the spin-alignment of vector meson with respect to a chosen direction.**
- **Polarization can be measured through the angular distribution of the daughter particle**

$$\frac{\partial^2 N}{\partial \cos\theta \partial\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi$$

$(\lambda_\theta , \lambda_\phi , \lambda_{\theta\phi})$ = (0,0,0) -> No polarization
$(\lambda_\theta , \lambda_\phi , \lambda_{\theta\phi})$ = (-1,0,0) -> longitudinal polarization
$(\lambda_\theta , \lambda_\phi , \lambda_{\theta\phi})$ = (+1,0,0) -> transverse polarization

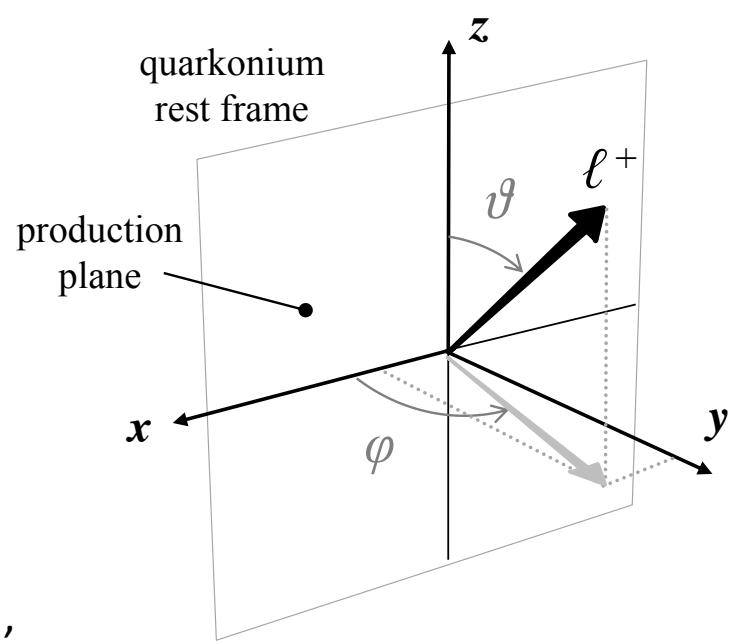


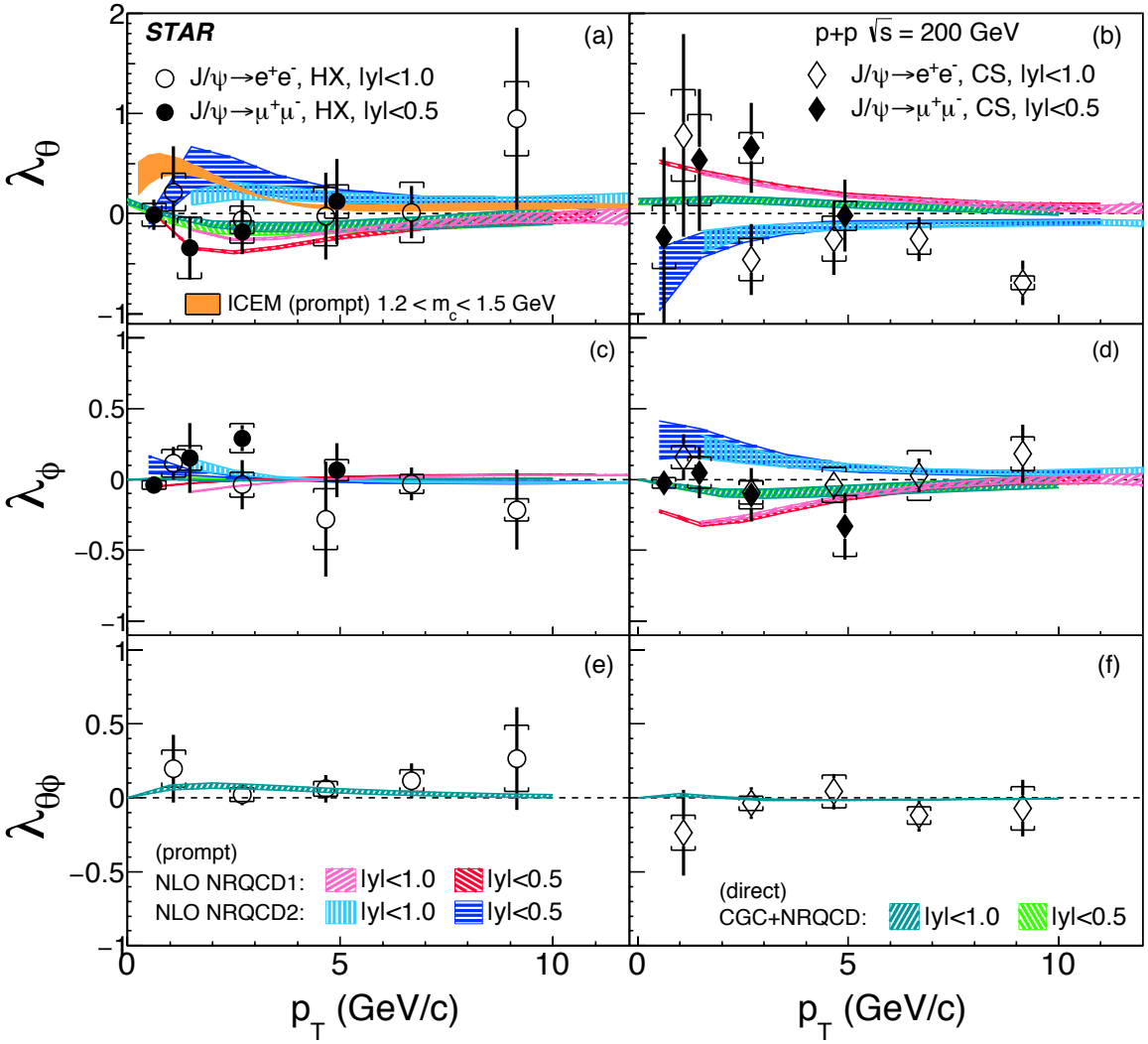
Image taken from
EPJC 69, 657-673(2010)

Polarization axis :

Helicity (HX) Frame:
Direction of vector meson in the collision center of mass frame

Collins-Soper (CS) Frame: the bisector of the angle between the beam and the opposite of the other beam, in the vector meson rest frame

J/ψ Polarization Measurement



HX frame (left) ---- CS Frame (right)

- The inclusive J/ψ's do not exhibit significant transverse or longitudinal polarization
- No significant p_T dependence
- Available model explain data within the measured uncertainties

ICEM: PRD 98 (2018) 114029.

NLO+NRQCD: PRL 110 (2013) 042002

CGC+NRQCD: JHEP 12 (2018) 057.

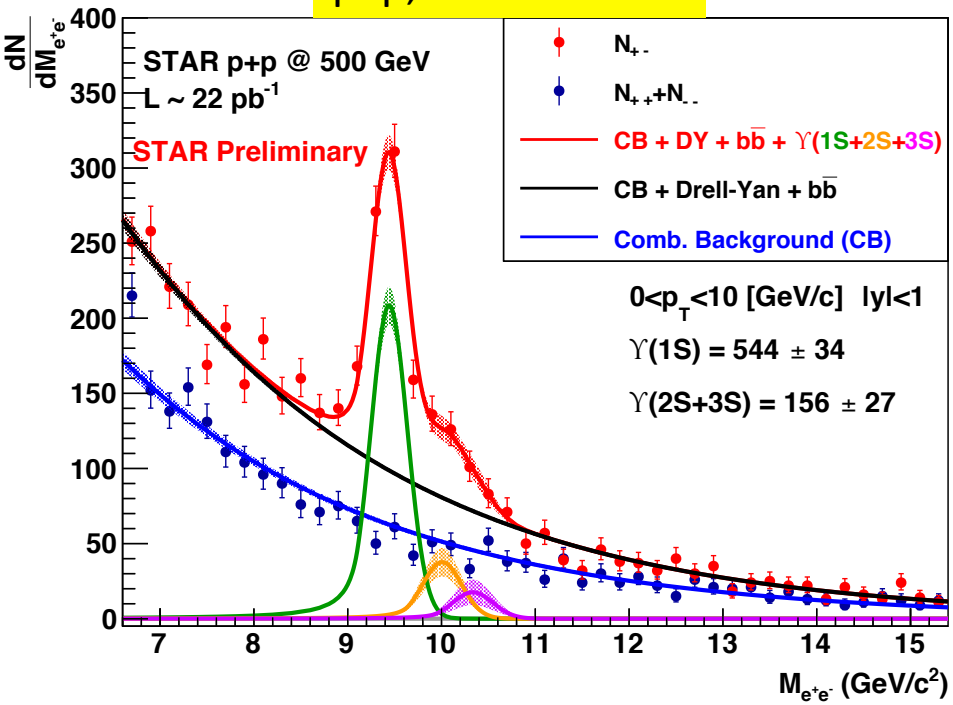
STAR: PRD 102 (2020) 92009

Upsilon($b\bar{b}$) Production

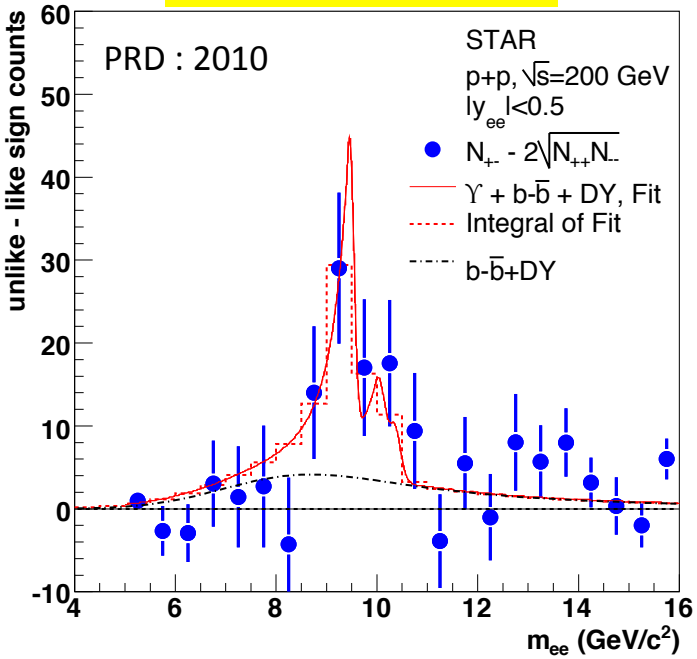
Upsilon Reconstruction in p+p at 500 GeV

$$\Upsilon -> e^{+} + e^{-} [BR = 2.3(1S), 1.9(2S), 2.1(3S)]$$

p+p, √s = 500 GeV



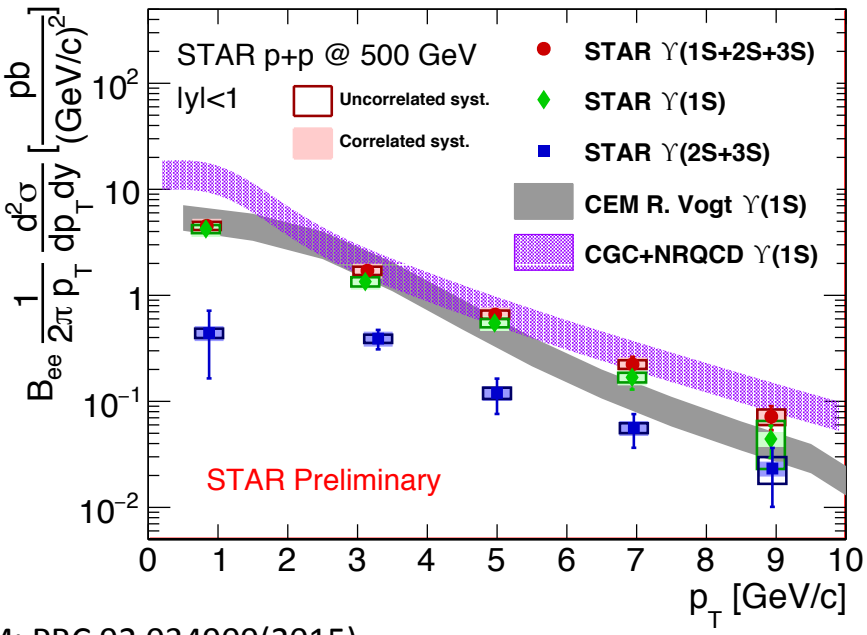
p+p, √s = 200 GeV

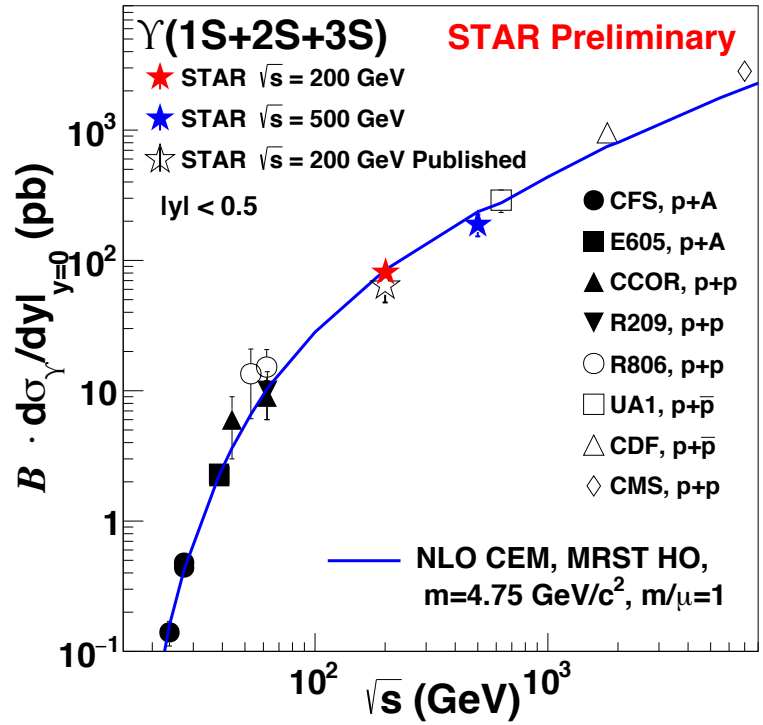


Upsilon are reconstructed in di-electron decay channel in p+p 500 GeV, more precise compared to published result in p+p 200 GeV

STAR : PRD **82** (2010) 12004

Upsilon cross section in p+p collisions





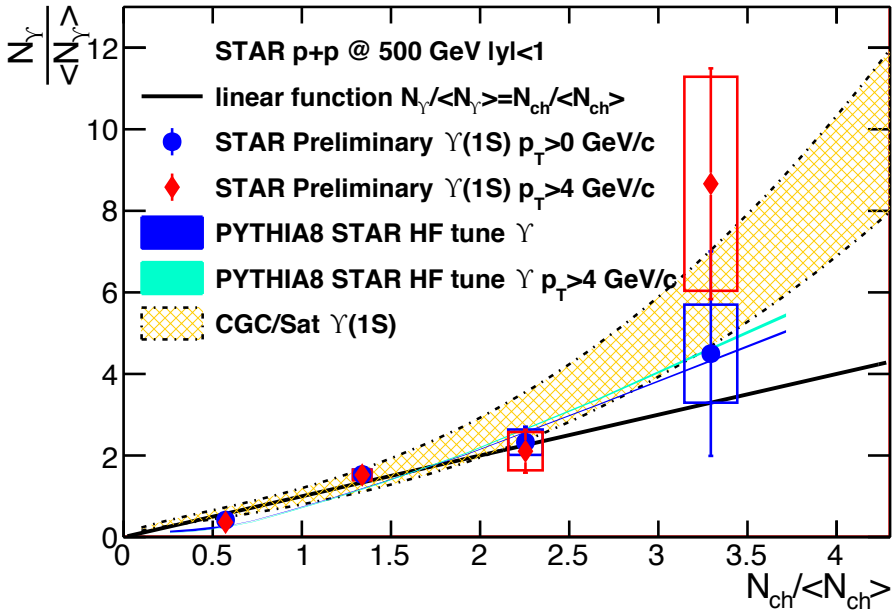
CEM: PRC 92 034909(2015)

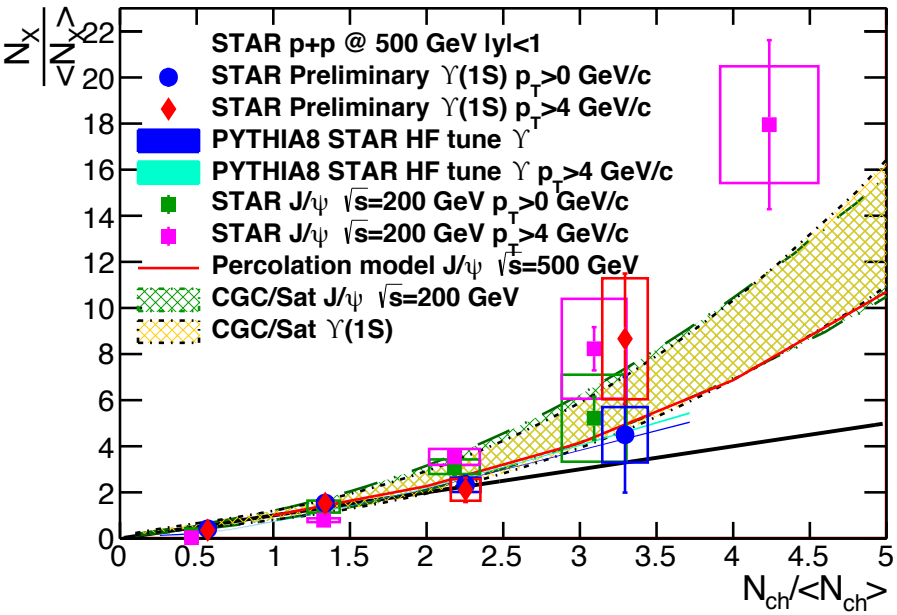
CGC+NRQCD: PRL 113, 192301(2014)

- Spectra for Y(1S) and Y(2S+3S)
- Models agree with data reasonably well, CGC+NRQCD model seems to over predicts at low pT

- STAR results follow the world data trend
- Consistent with the Color Evaporation Model calculation

Upsilon Production Vs Event Activity





CGC/Sat: EPJC 97(5) 376(2019)

- Stronger-than-linear growth in high mult. events
- PYTHIA, CGC model reproduce the trend in the data
- Upsilon shows similar trend like J/ψ when plotted against event activity

Summary

The recent results on quarkonium production in p+p collisions from STAR are presented

J/ψ <u>Production:</u>

- Precise and more differential measurement of J/ψ cross-section.
- J/ψ do not exhibit significant polarization

<u>ϒ Production:</u>

- More precise measurement at √s = 500 GeV compared to published results at 200 GeV.
- Upsilon cross section (186± 14(stat) ± 33(sys) pb) at 500 GeV follow world data trend predicted by Color Evaporation Model

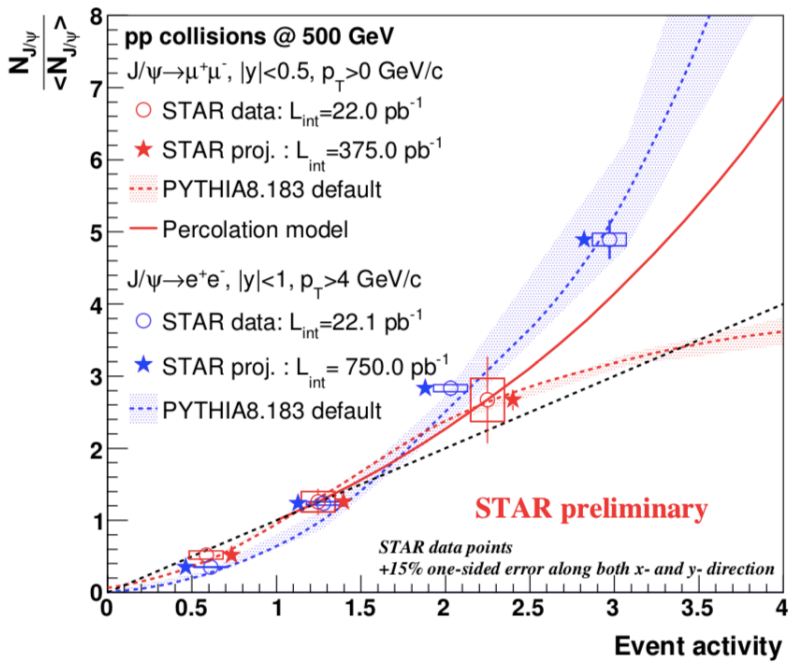
Current measurement along with model calculation could provide better understanding on quarkonium production mechanism in p+p collisions

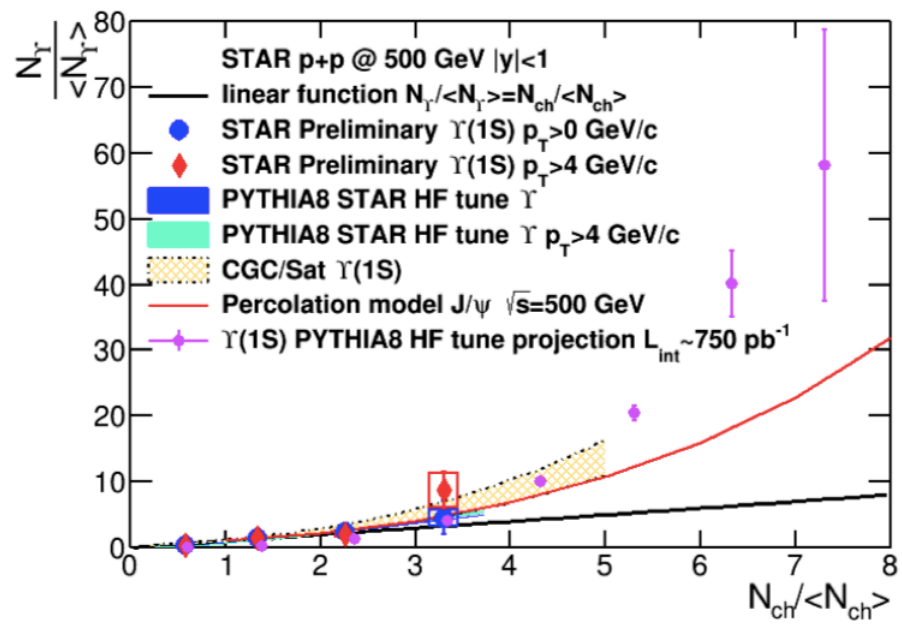
Outlook

New results to be available soon using Run 17 and 22 data in p+p @ 510 GeV

Integrated luminosity ~ 750 pb^{-1} for BHT e and ~ 375 $pb^{-1}$for di-muon triggers

Projection for J/ψ and Y in p+p using 2017+2022 data






Thank you!