Quarkonium production in proton-proton collisions at the STAR experiment

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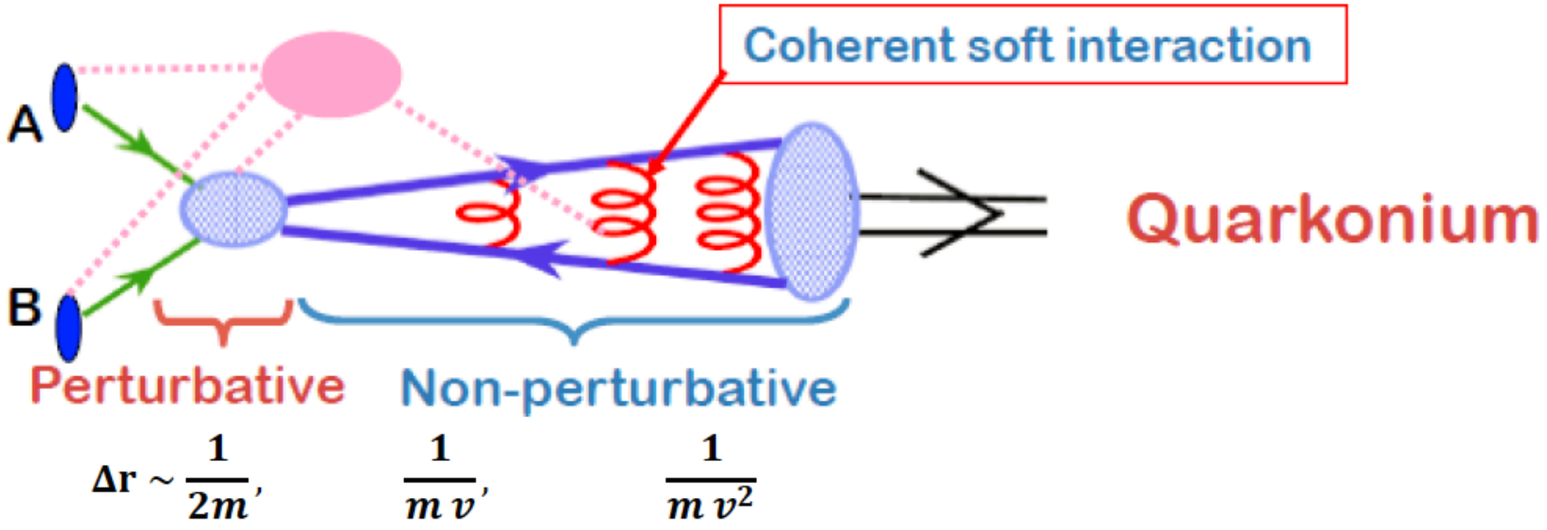
Outline

- **Motivation**
- **STAR experiment**
- **Charmonium production in p+p collisions**
- **Υ production in p+p collisions**
- **Summary**

Quarkonium in p+p collisions

- Heavy quarkonium is a non-relativistic QCD system(v^2<<1): the simplest system in QCD.

Production of the $Q\bar{Q}$ (large momentum transfer) → evolution of the $Q\bar{Q}$ pair into quarkonium (small dynamical scale)



- Difficulty:Involving both perturbative and non-perturbative processes

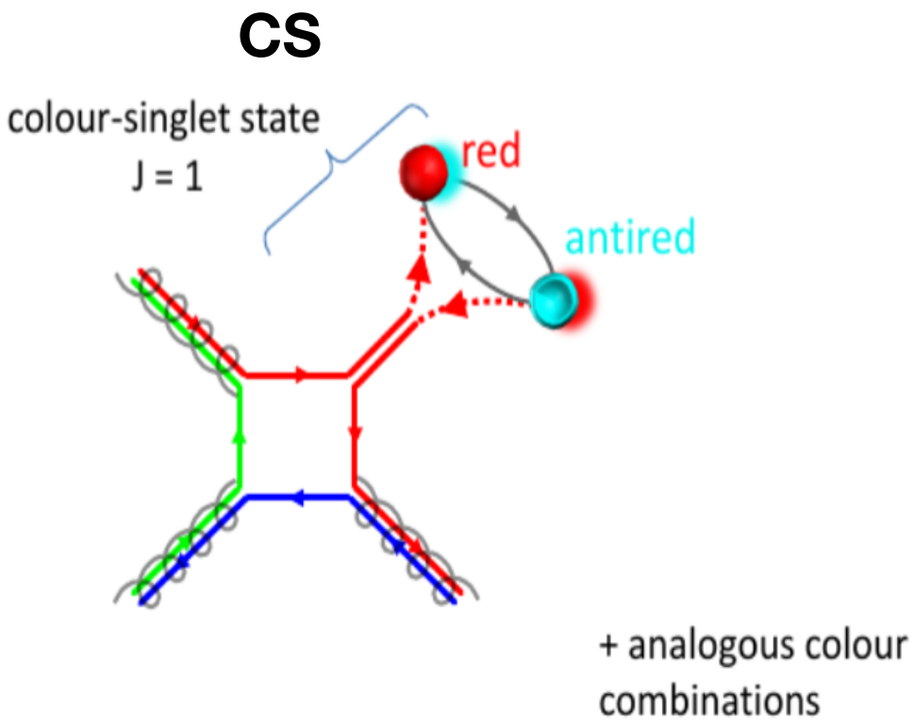
Quarkonium: An ideal test ground of QCD!!

Production mechanism

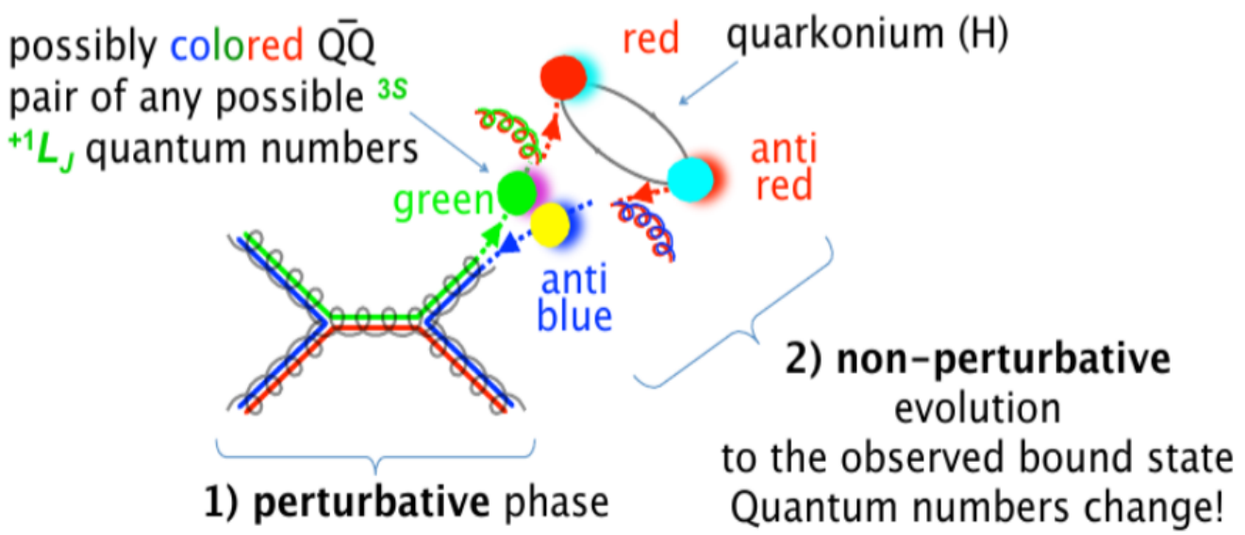
Models differ in the treatment of hadronization:

- Improved color evaporation model
- Color singlet model
- NRQCD approach (CGC+NRQCD at low p_T)

CS



CO

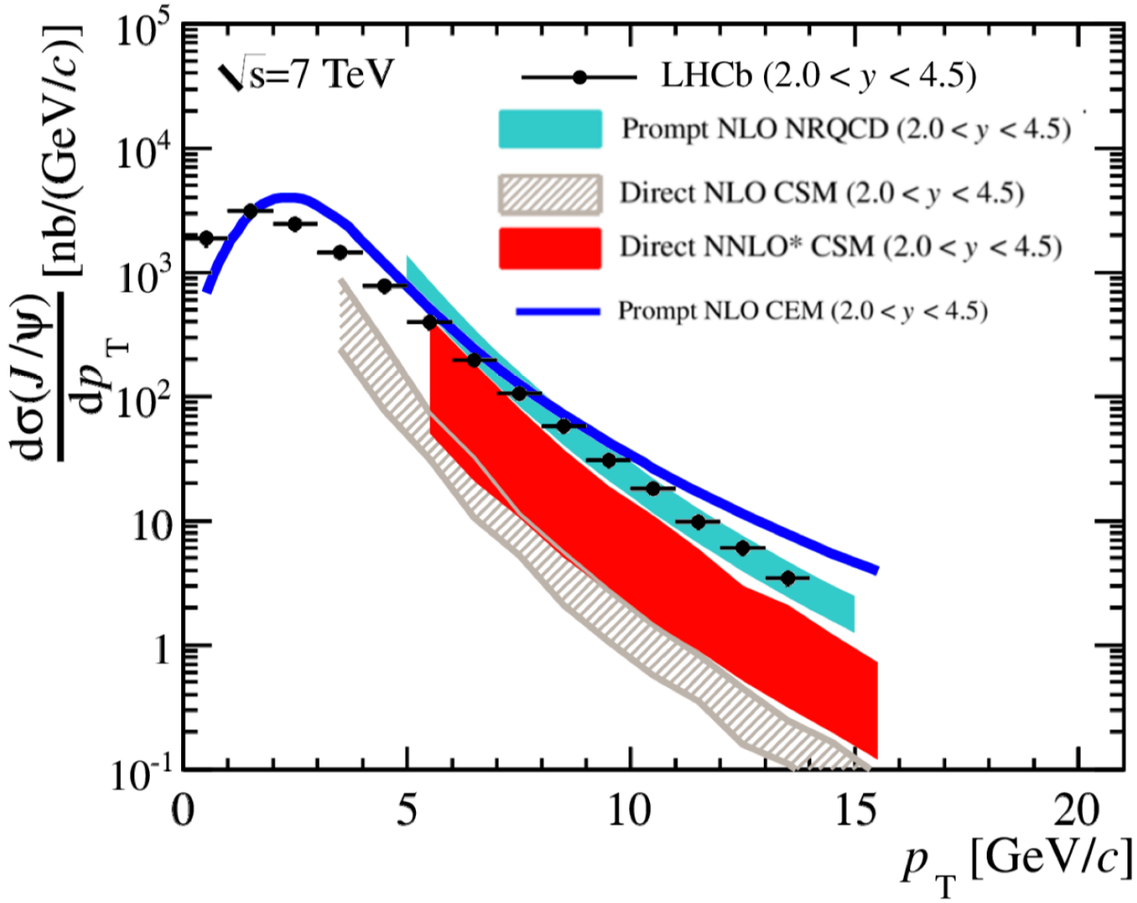


[P. Faccioli, Polarization in LHC physics, Course on Physics at the LHC 2014]

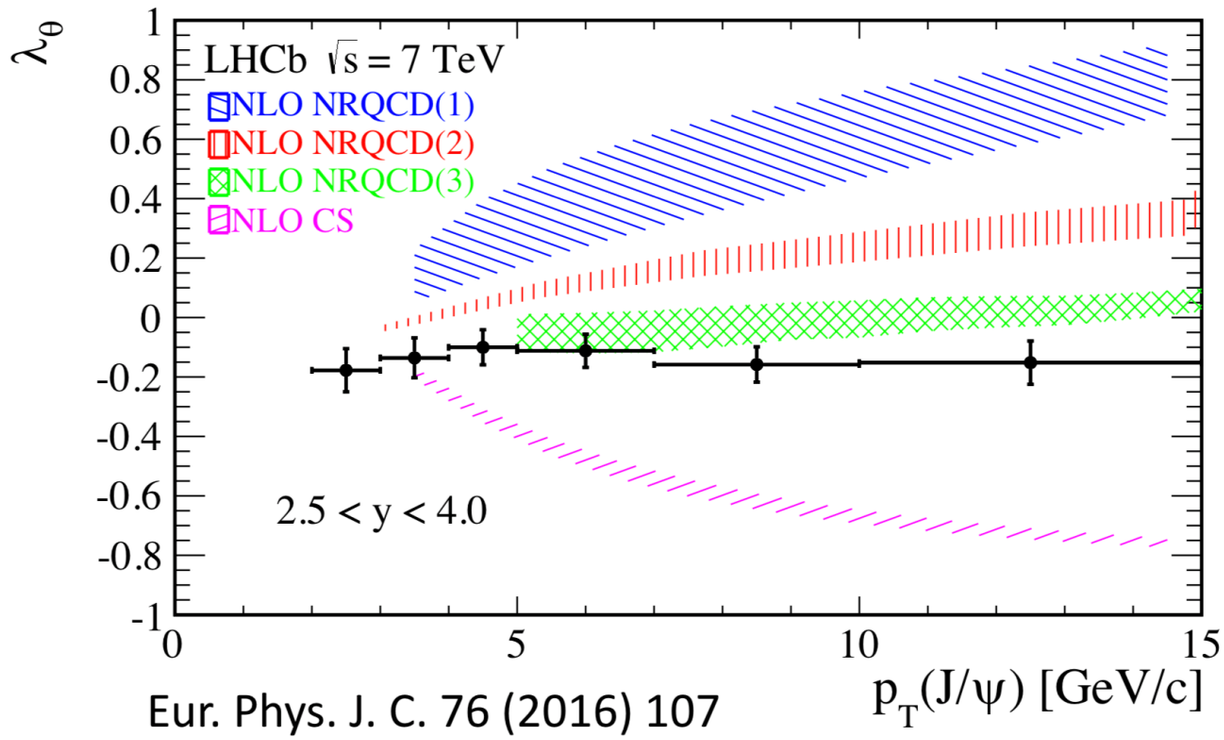
Observables

Quarkonium production mechanism in elementary collisions is not fully understood

Cross-section



Polarization



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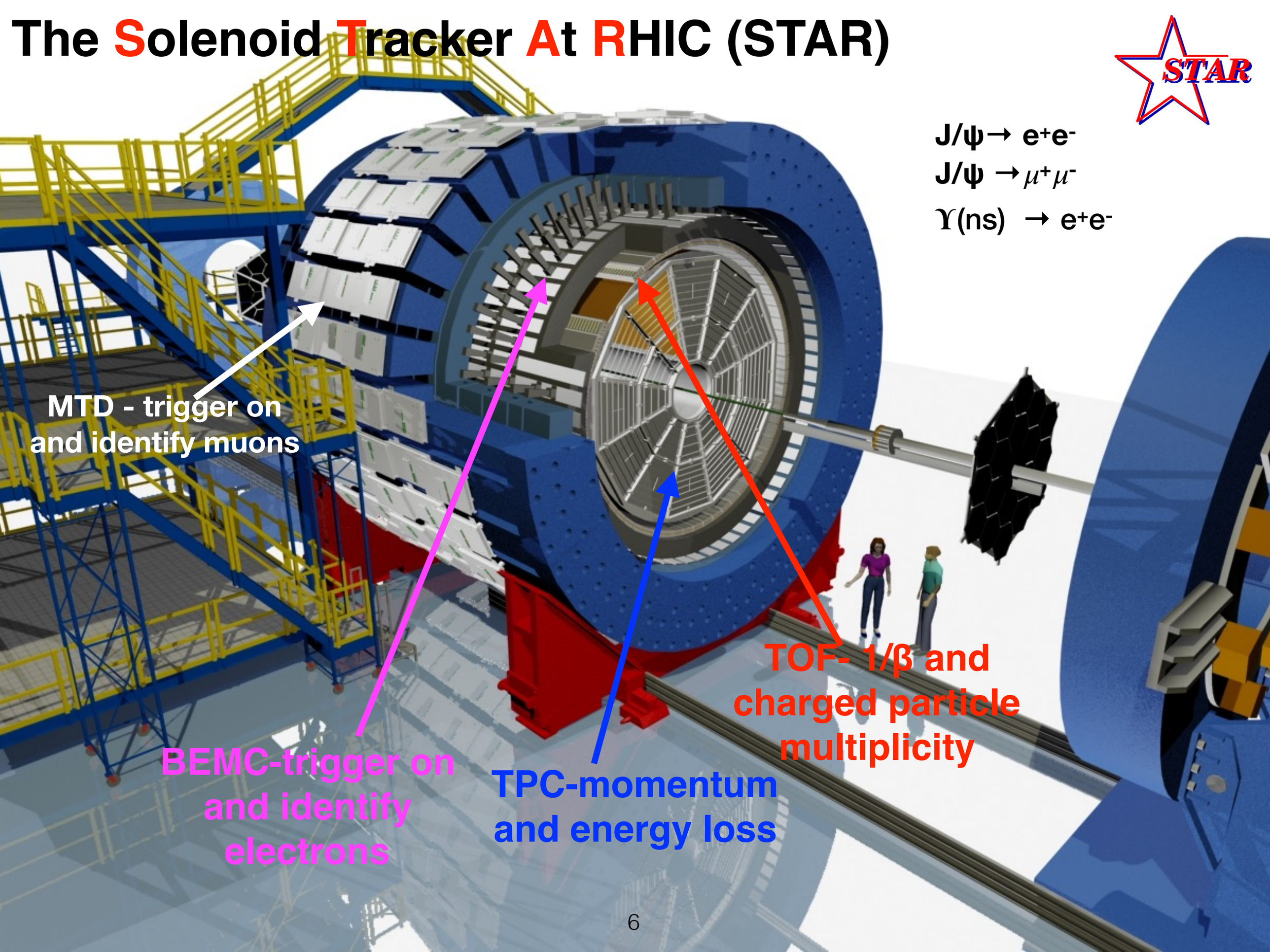
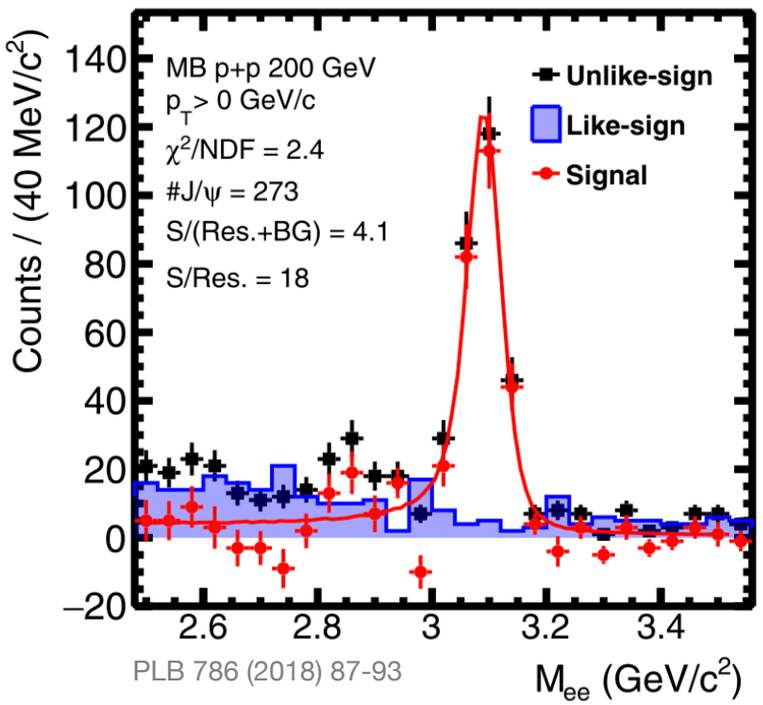
No consistent descriptions of cross section and polarization

The Solenoid Tracker At RHIC (STAR)



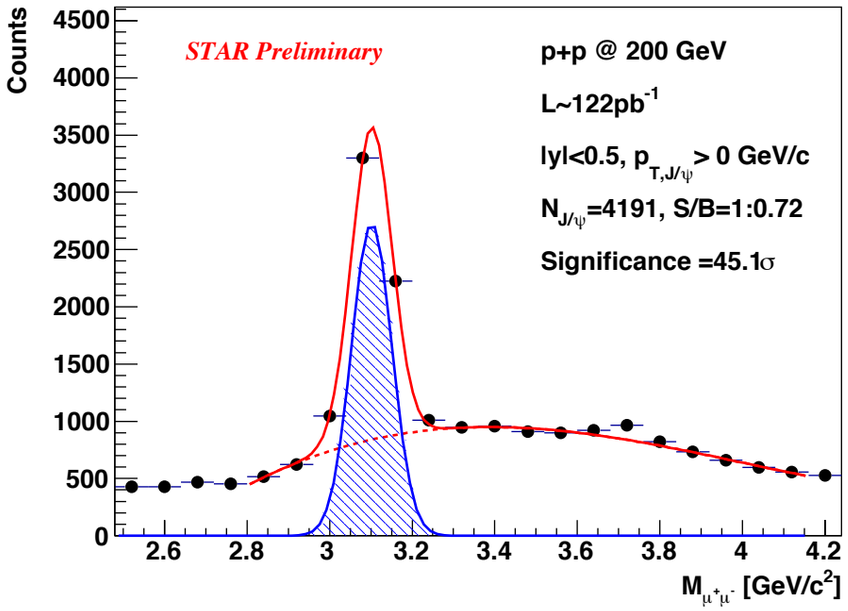
J/ψ and ψ(2S) in p+p at 200 &500 GeV

J/ψ → e^+e^-

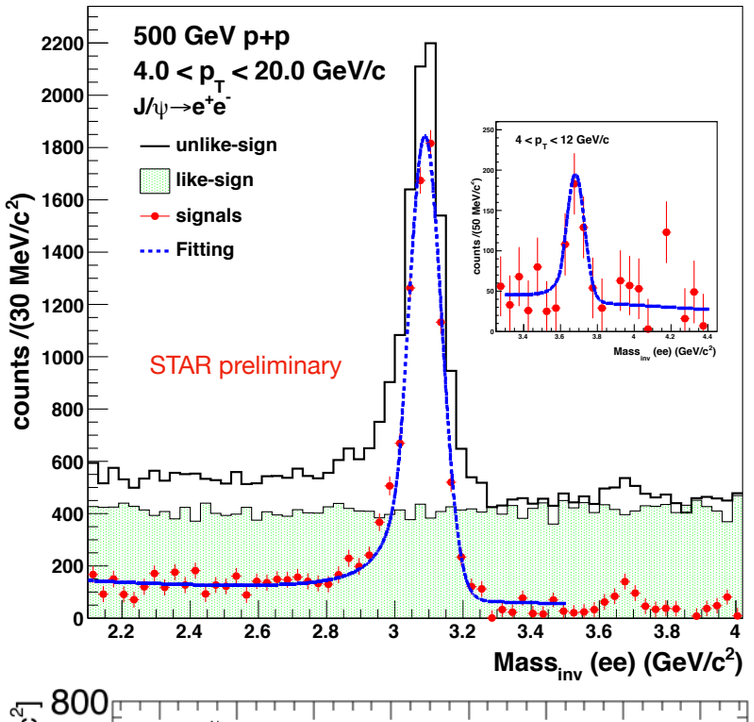


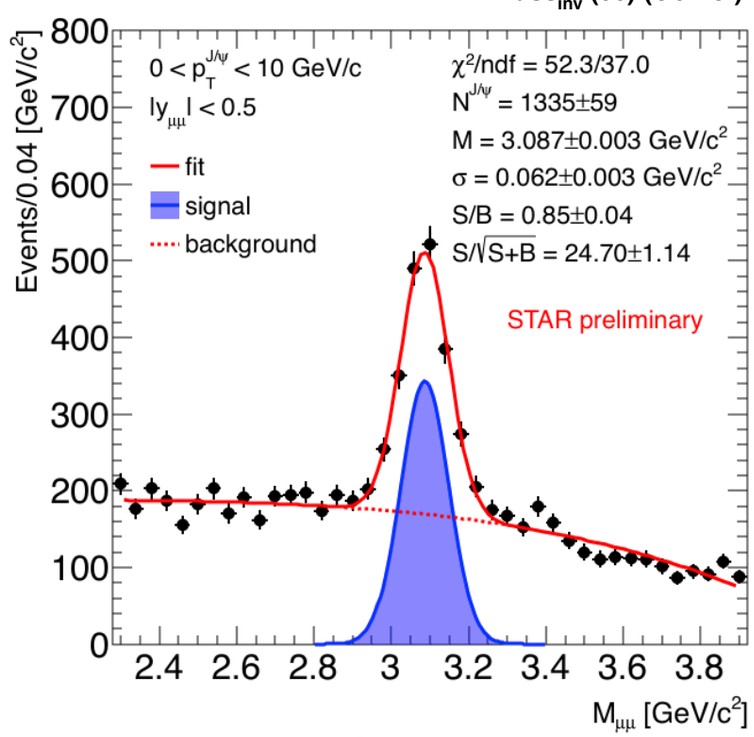
PLB 786 (2018) 87-93

J/ψ → $\mu^+\mu^-$



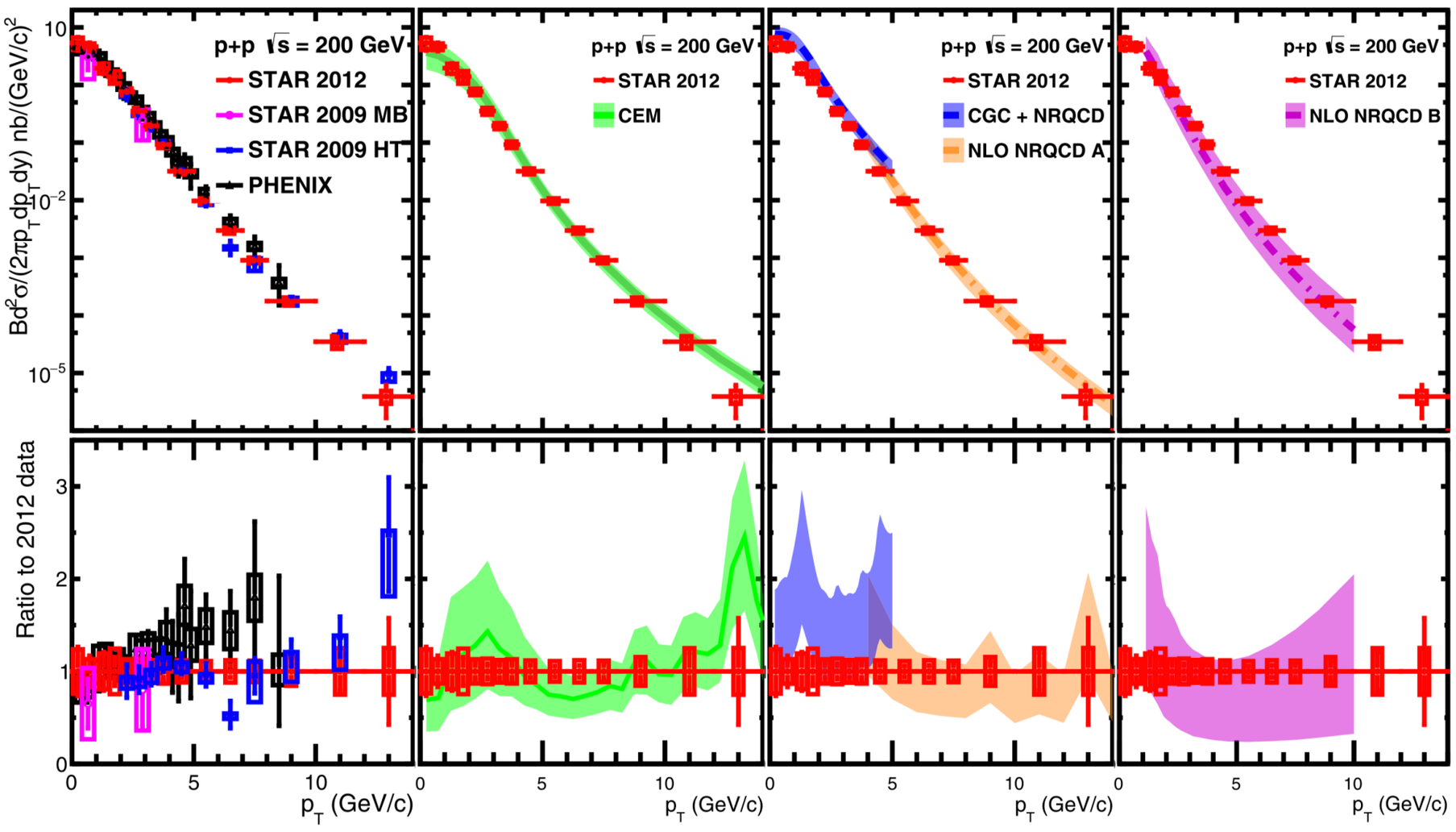
p+p at √s = 200 GeV





p+p at √s = 500 GeV

Inclusive J/ψ cross section at 200 GeV



STAR 2012: PLB 786 (2018) 87-93 STAR 2009: PLB 722 (2013) 55; PRC 93 (2016) 064904

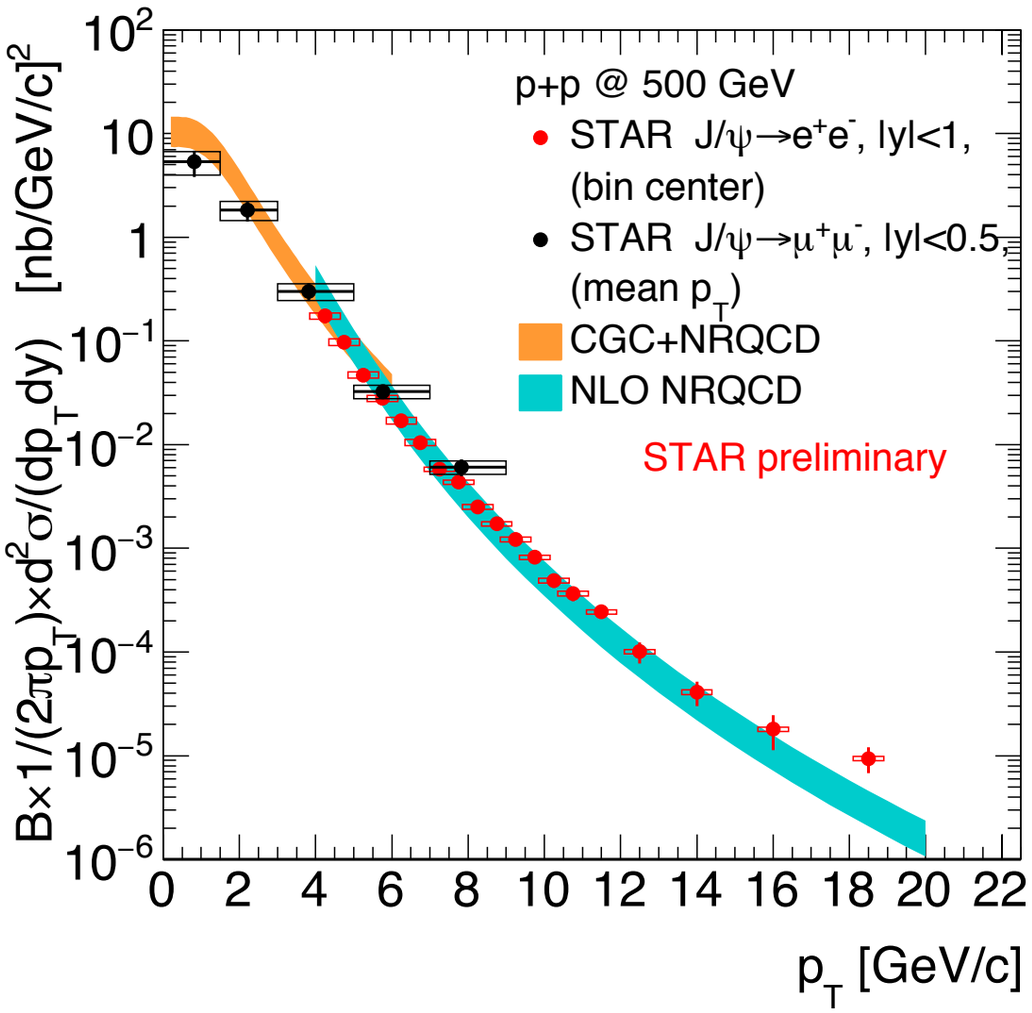
PHENIX: PRD 82 (2010) 012001

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

- Both CEM model (direct J/ψ) and NLO NRQCD calculations (prompt J/ψ) describe the data reasonably well in the relevant p_T ranges
- CGC+NRQCD calculation are close to the upper uncertainty boundary of data in the low-p_T region ($p_T < 5$ GeV/c)

Inclusive J/ψ cross section at 500 GeV

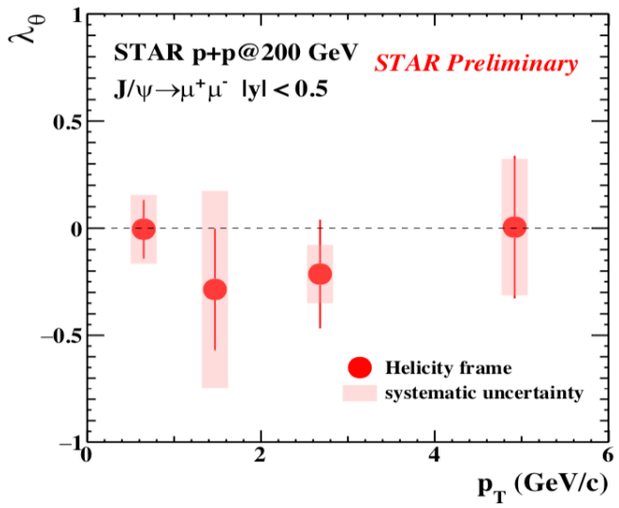


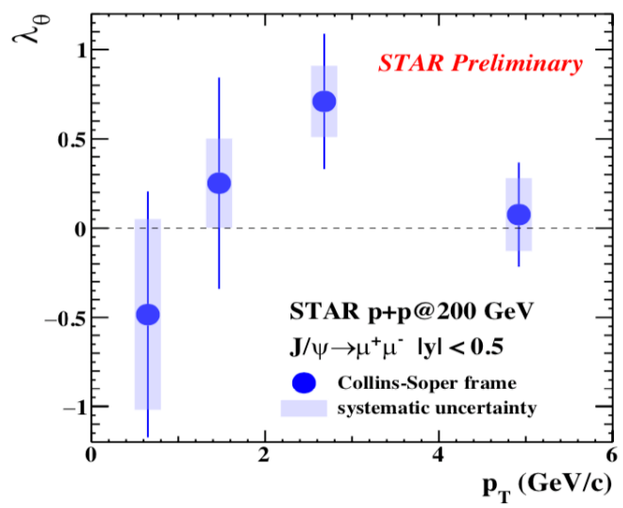
NLO NRQCD: Phys. Rev. Lett. 106, 042002 (2011)

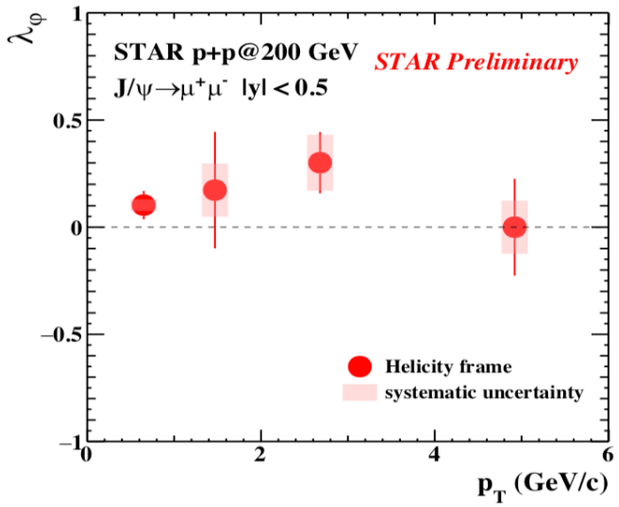
CGC+NRQCD: Phys. Rev. Lett. 113, 192301 (2014)

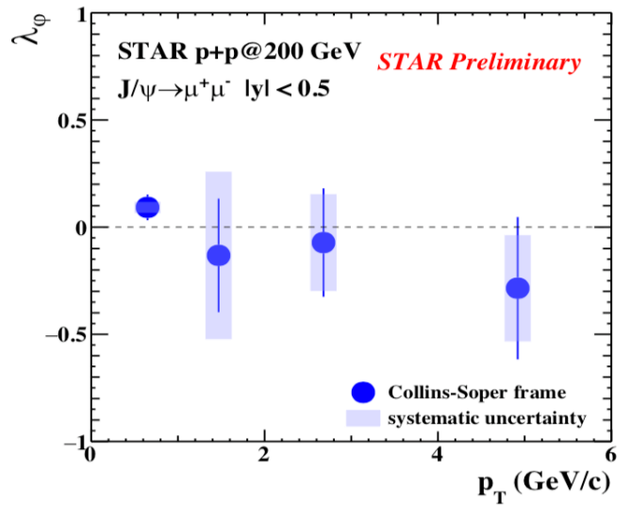
- Precision measurement within large dynamic range
  - J/ψ production cross-section for p_T from 0 to 20 GeV/c
- Measurements consistent with CGC+NRQCD & NLO NRQCD calculations
  - Calculations only take prompt J/ψ production into account

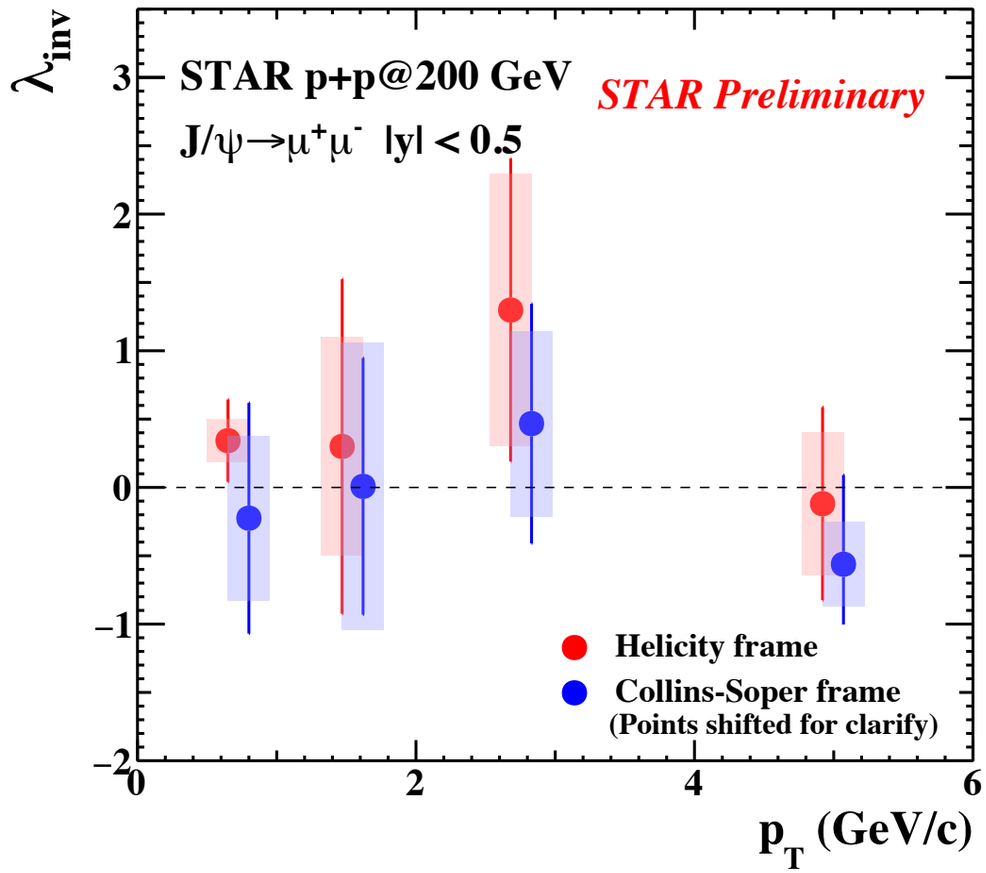
Inclusive J/ψ polarization at 200 GeV







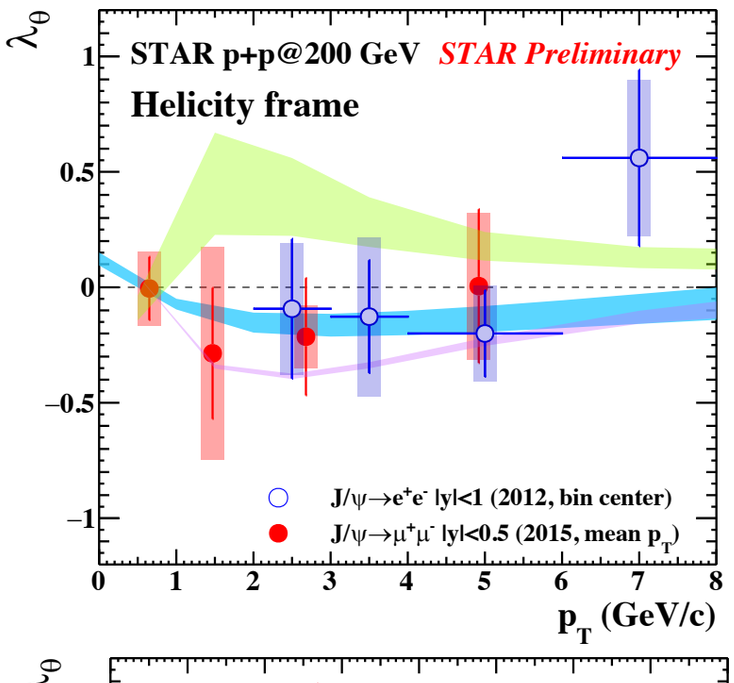


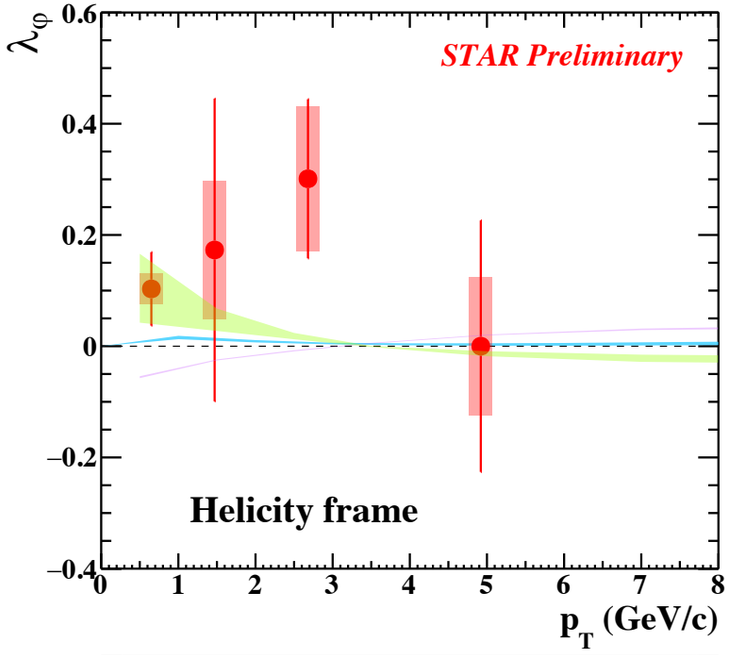


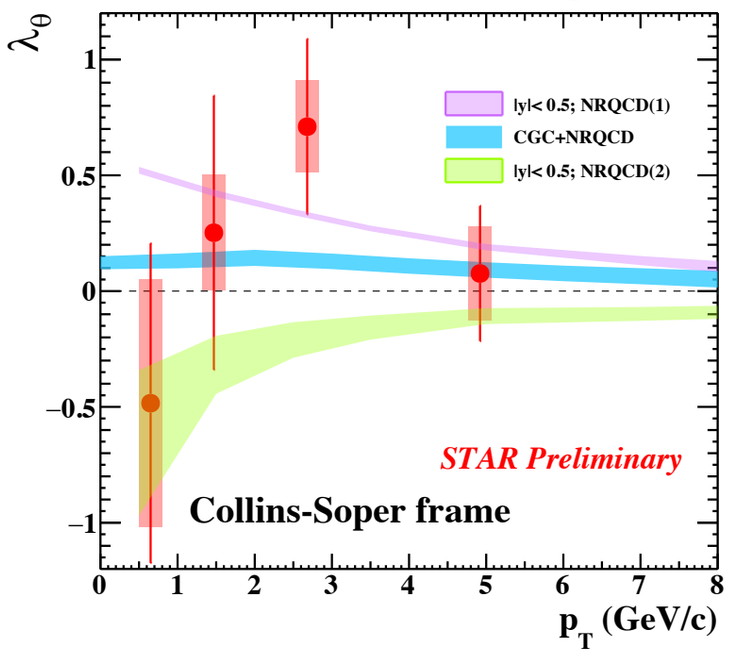
- λ_θ and λ_φ are consistent with 0 in both HX and CS frames
- Frame invariant quantity: $\lambda_{inv} = \dfrac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}$

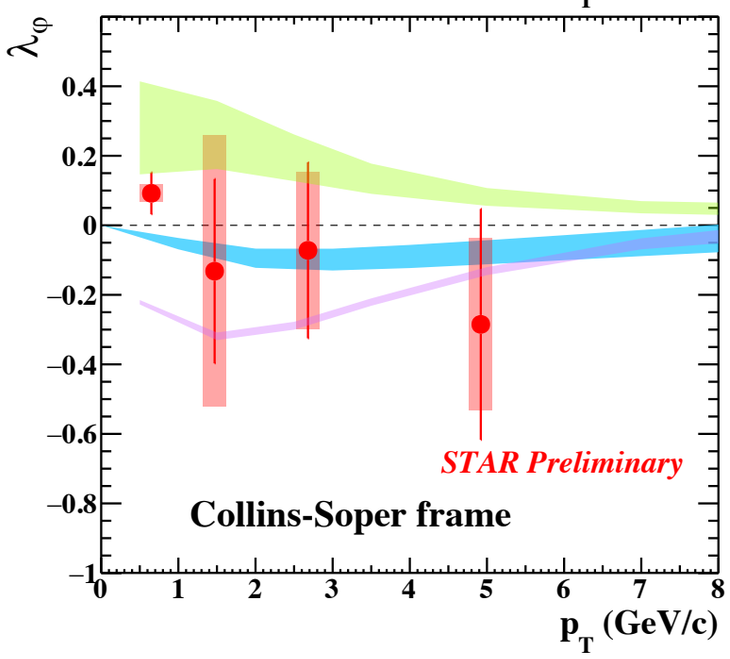
  →Good cross-check on measurements performed in different frames
- λ_{inv} as a function of p_T are consistent between HX and CS frames

J/ψ polarization-model comparison









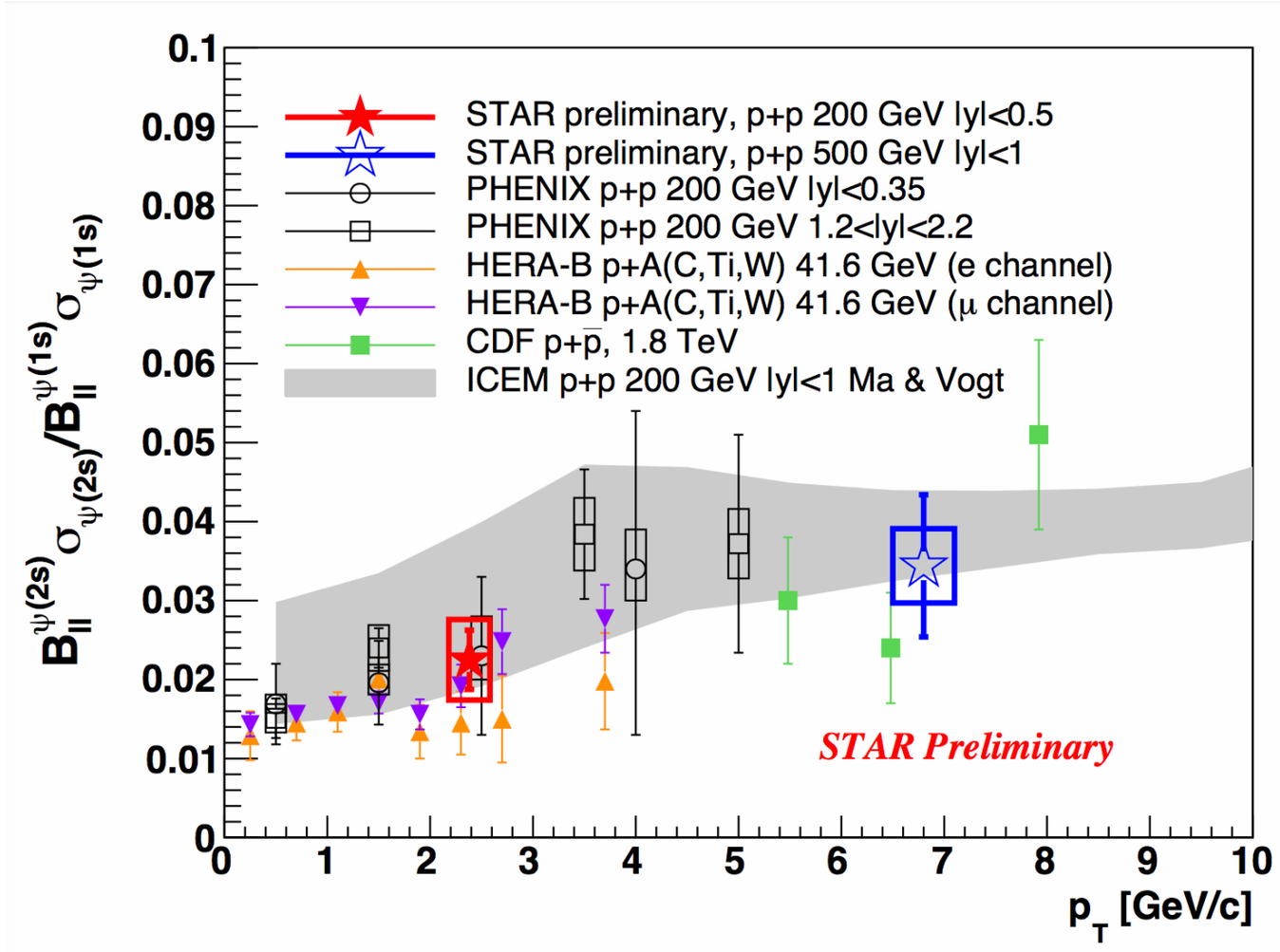
NRQCD1: Phys. Rev. Lett 114 (2015) 092006

NRQCD2: Phys. Rev. Lett 110 (2013) 042002

CGC+NRQCD： JHEP12 (2018) 057

- NRQCD calculations with two different sets of Long Distance Matrix Elements (LDMEs) and CGC+NRQCD calculation are all consistent with data within uncertainties

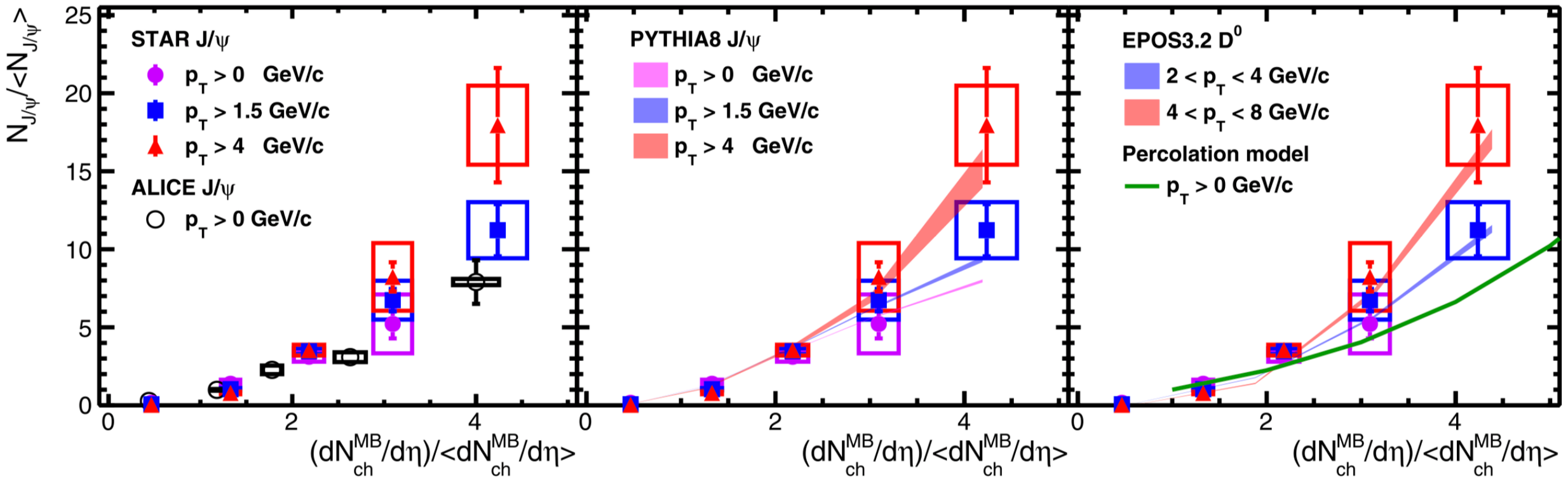
ψ(2S)/J/ψ cross section ratio



- Measured ψ(2S)/J/ψ ratio in both 200 & 500 GeV are consistent with world-wide data
- The ICEM model can qualitatively describe the measurement

J/ψ production vs. n_{ch} in 200 GeV

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



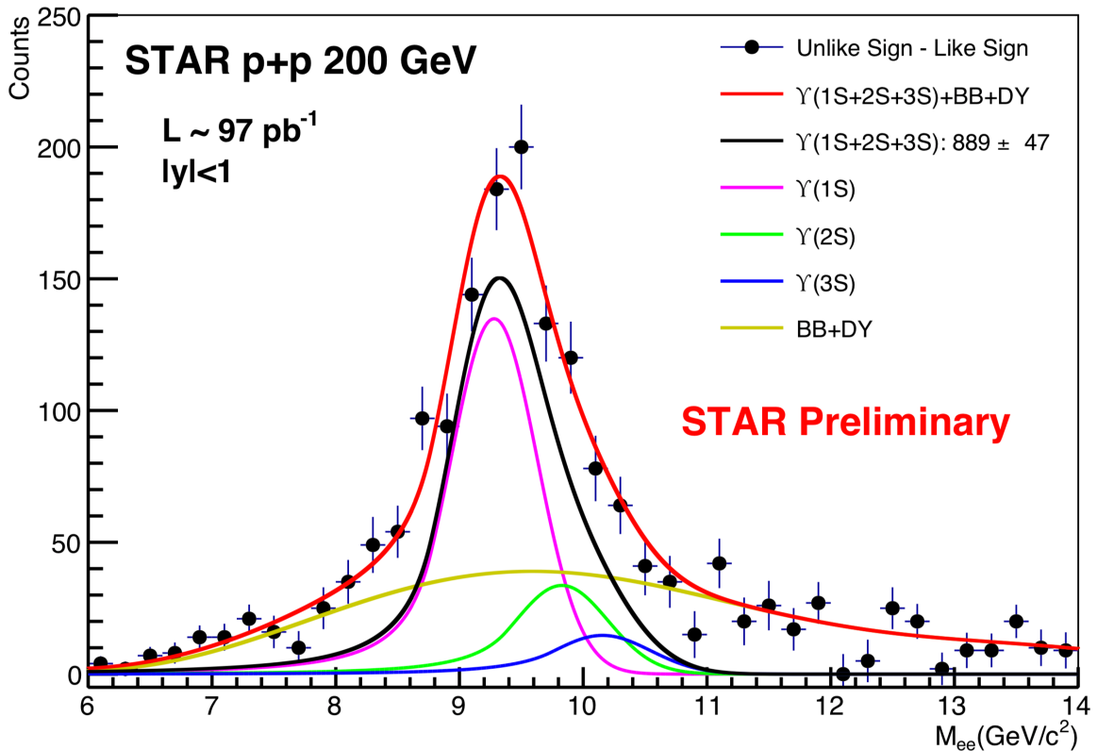
STAR: PLB 786 (2018) 87-93
ALICE: JHEP 09 (2015) 148

Percolation: Ferreiro, Pajares PRC 86 (2012) 034903

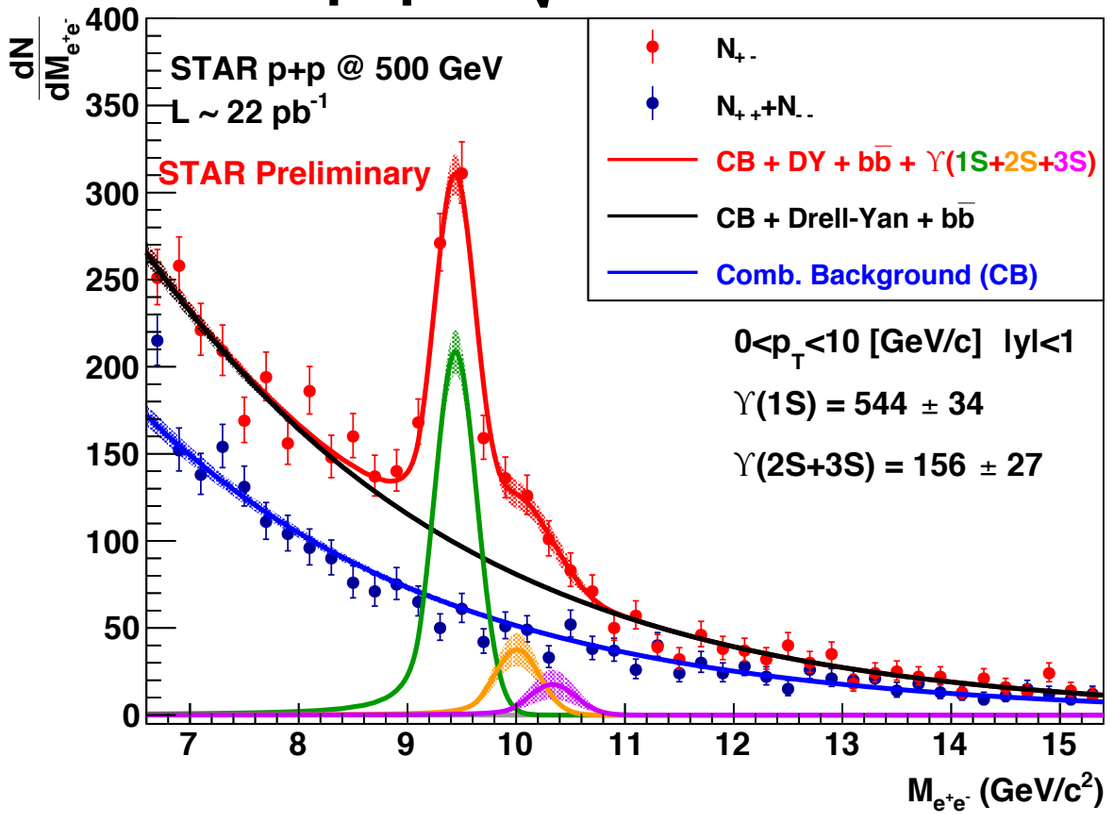
- A strong increase in J/ψ relative yields with n_{ch} is observed, which seems to be stronger at high p_T (> 4 GeV/c)
- Similar trend at LHC's measurement → weak dependence of the underlying mechanism on collision energy
- PYTHIA8, EPOS3 and Percolation model can qualitatively describe the rising behavior

Υ signals in p+p at 200 & 500 GeV

p+p at $\sqrt{s}$ = 200 GeV



p+p at $\sqrt{s}$ = 500 GeV



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

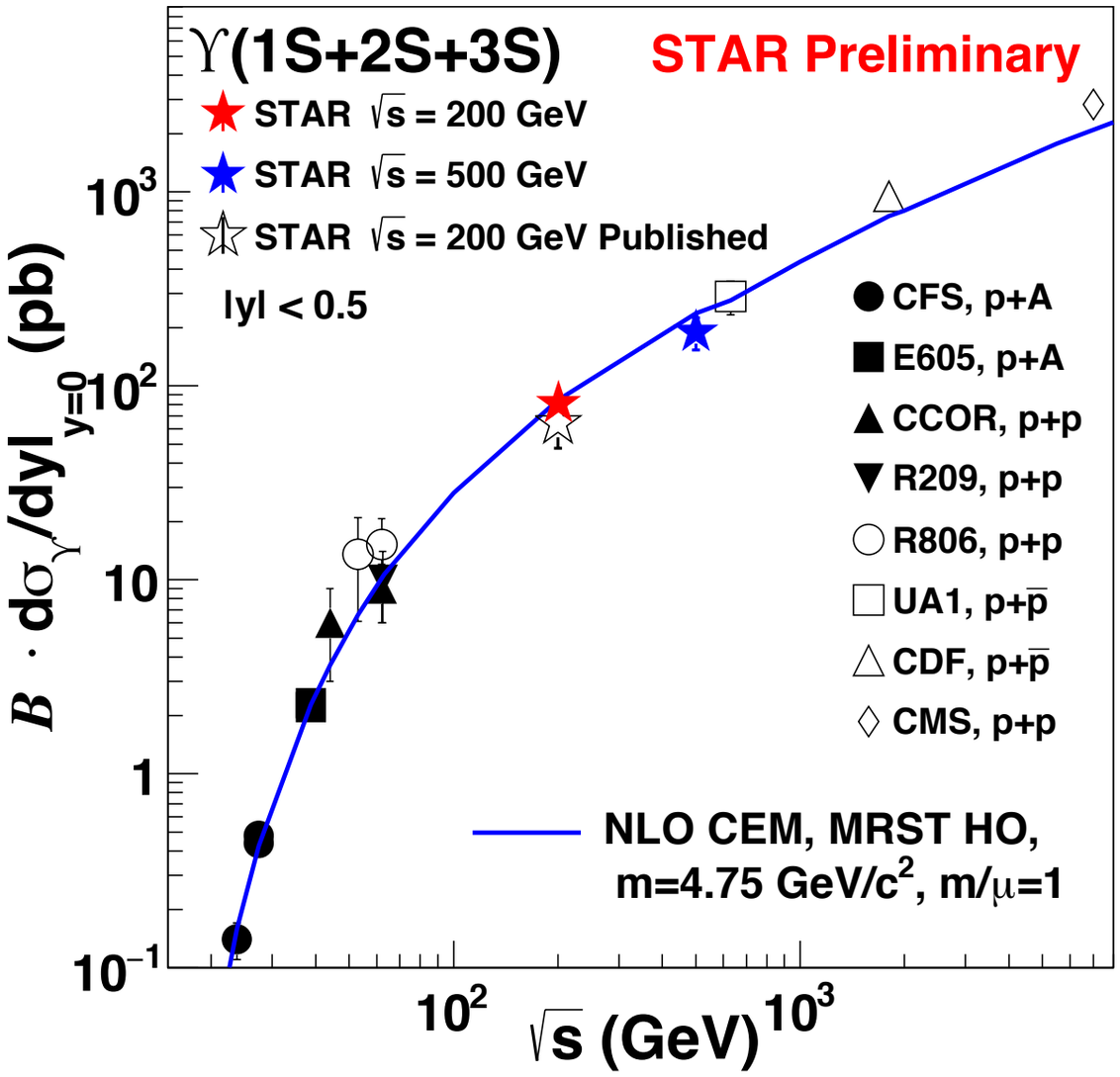
Υ signal shape:

- 3 Crystal-ball functions - Geant simulation of STAR detector

Residual background:

- $b\bar{b}$ and Drell-Yan correlated background - Pythia

Υ cross section in p+p



STAR: [Phys.Lett.B 735,127–137(2014)]
CDF: [Phys.Rev.Lett. 88,161802(2002)]
CMS: [Phys.Rev.D 83,112004(2010)]
CFS: [Phys.Rev.Lett. 39,1240-1242(1977)]
[Phys.Rev.Lett. 41,684–687(1978)]
[Phys.Rev.Lett. 42,486–489(1979)]
[Phys.Rev.Lett. 55,1962–1964(1985)]
E605: [Phys.Rev.D 43,2815–2835(1991)]
[Phys.Rev.D 39,3516(1989)]
CCOR: [Phys.Lett.B 87,398–402(1979)]
E866: [Phys.Rev.Lett. 100,062301(2008)] ISR
[Phys.Lett.B 91,481-486(1980)]

- p+p at √s = 200 GeV (2015 data):

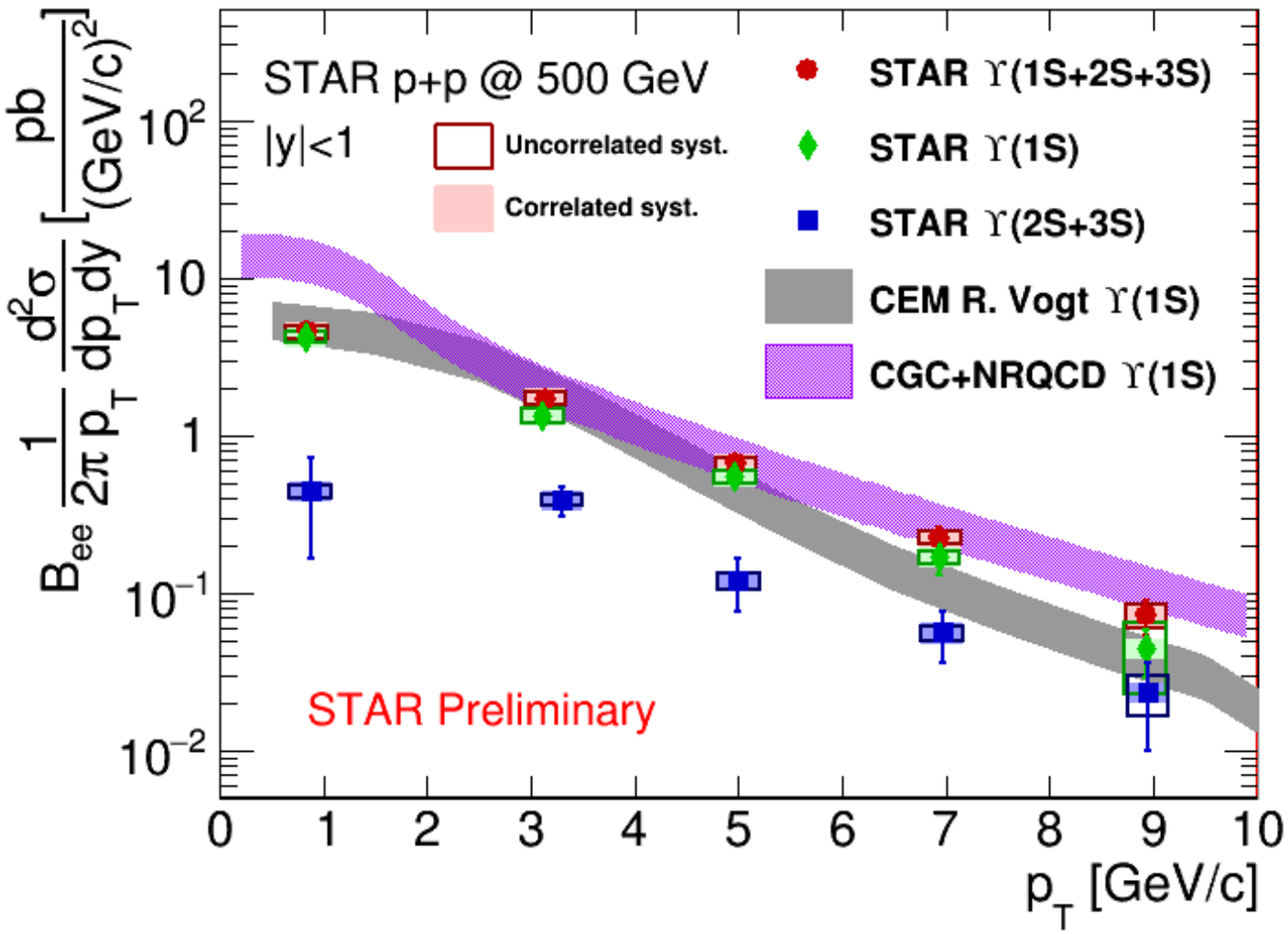
$$81 \pm 5(stat.) \pm 8(syst.)pb$$

- p+p at √s = 500 GeV (2011 data):

$$186 \pm 14(stat.) \pm 33(syst.)pb$$

- Measurements in p+p collisions at 200 and 500 GeV
  - Follow the world data trend
  - Consistent with CEM prediction
- Baseline for measurements in 200 GeV p+Au and Au+Au collisions

Υ differential cross section



CEM: Phys.Rev.C 92 034909(2015)

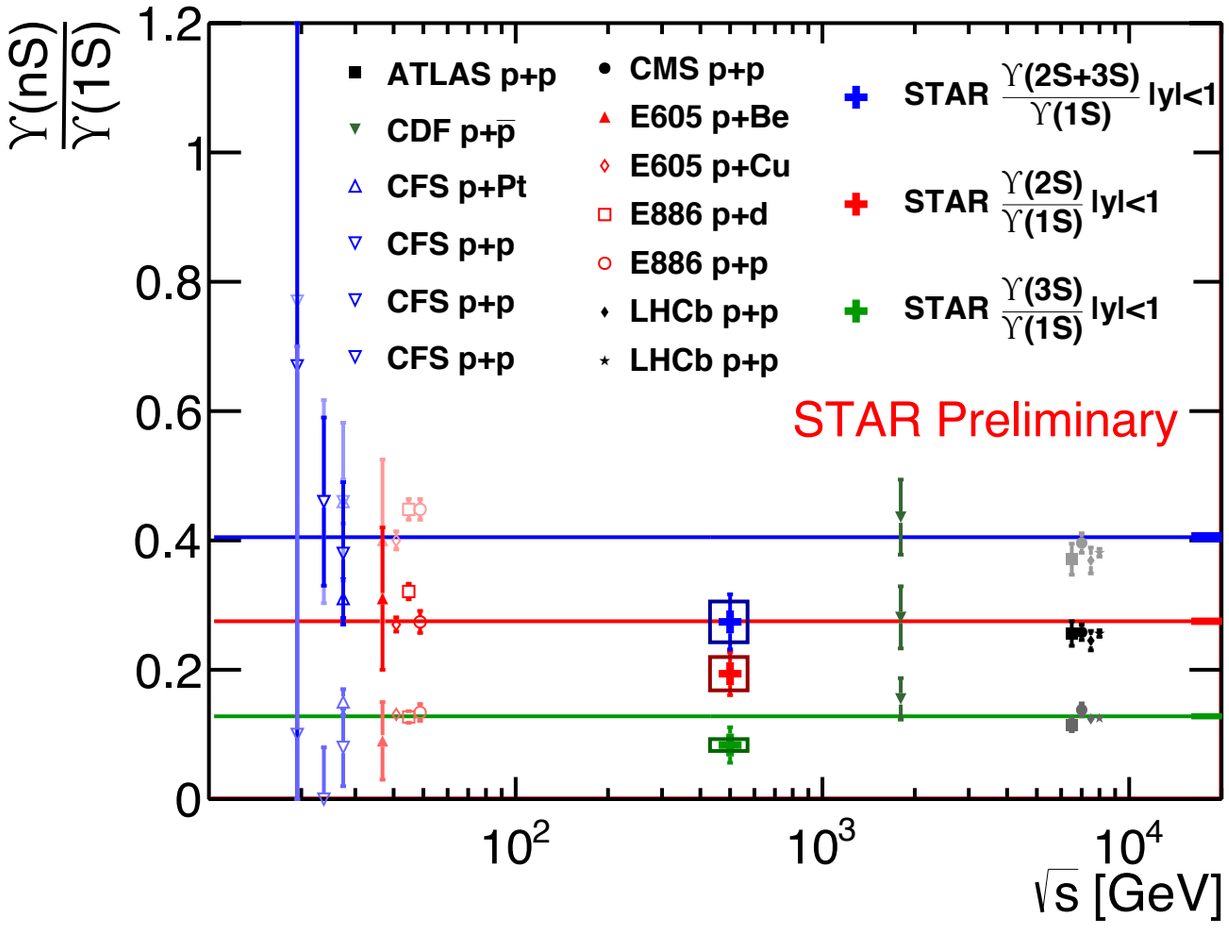
CGC+NRQCD:

Phys.Rev.D 94, 014028(2016)

Phys.Rev.Lett. 113, 192301(2014)

- CEM prediction of inclusive Υ(1S) describes measurement
- CGC+NRQCD calculation of direct Υ(1S) are above the inclusive Υ(1S) measurement
  - According to the authors: additional correction is needed for the lowest p_T bin (feed-down et.al)

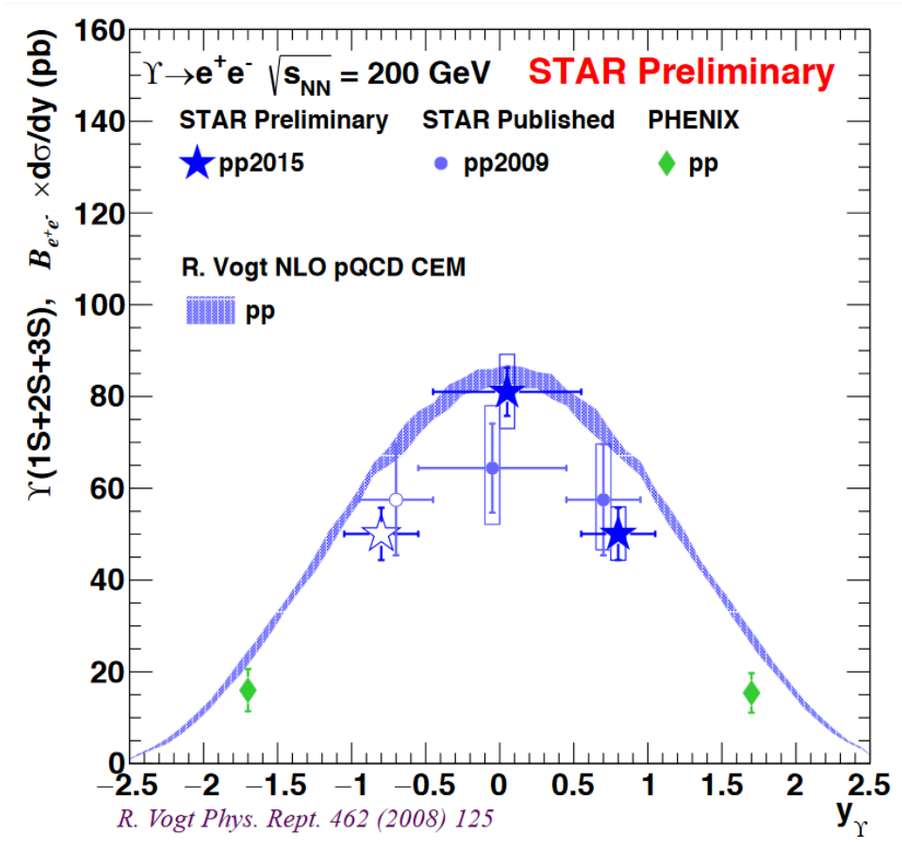
Cross section ratios: Υ(nS)/Υ(1S)

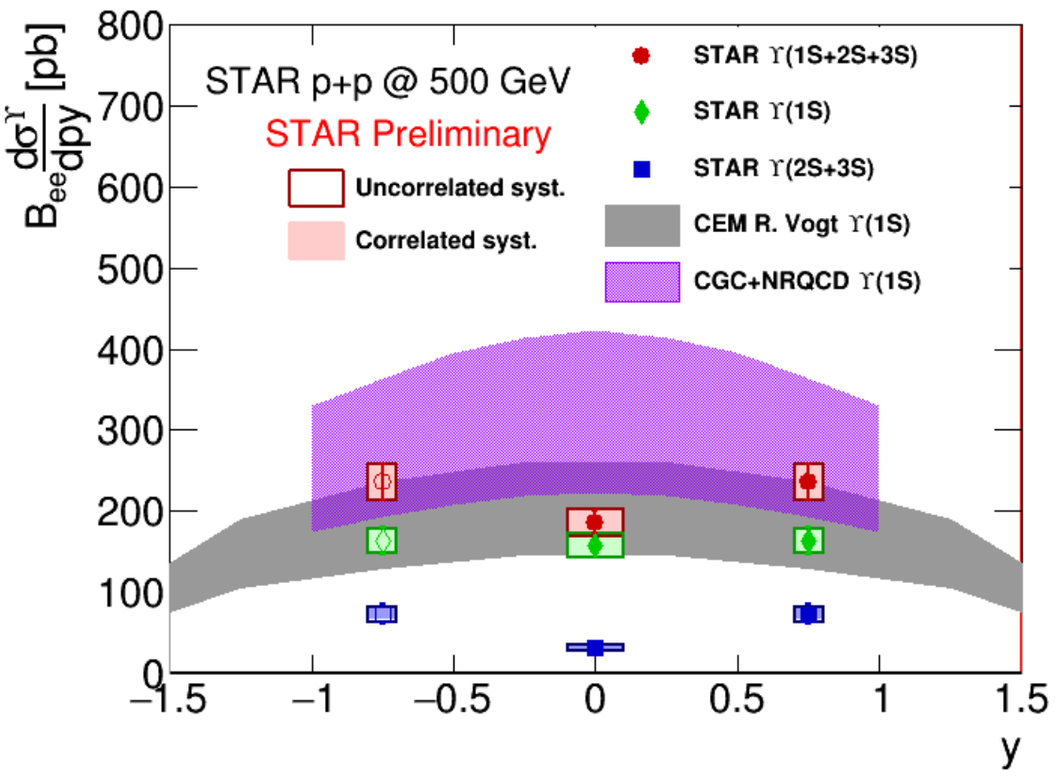


Phys. Rev. C 88, 067901(2013)

- Cross section rations are slightly below (2σ) world data average

Υ rapidity in p+p at 200 & 500 GeV





Open circle and star are mirror image points

p+p @ 200 GeV:

- Narrower rapidity distribution than NLO CEM calculation

p+p @ 500 GeV:

- Flatter rapidity spectrum at $\sqrt{s}$ = 500 GeV compared to 200 GeV
- Indication (~ 2σ) of dip at mid-rapidity for Υ(2S +3S)
- CEM model consistent with measurement for Υ(1S)
- CGC+NRQCD (direct) overestimates measurement (inclusive)

Summary

J/ψ production:

- Inclusive J/ψ production cross-section for p+p at $\sqrt{s}$ = 200 GeV and 500 GeV can be described by CEM (direct J/ψ) and NLO NRQCD (prompt J/ψ) model calculations,
  - CGC+NRQCD seems to overestimate the data at 200 GeV
- Both λ_θ and λ_φ forJ/ψ in p+p are consistent with 0 in HX and CS frames
- J/ψ yields in p+p grow faster than linearly with n_{ch}

Υ production:

- The Υ(1S+2S+3S) total cross-section at $\sqrt{s}$ = 200 GeV and 500 GeV can be reasonably well described by NLO CEM calculation
- The p_T-differential Υ(1S) spectra can also be described by NLO CEM calculations
- Flatter rapidity distribution for Υ at $\sqrt{s}$ = 500 GeV than at 200 GeV