QUARK MATTER 2015

The XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

Measurements of Quarkonium Polarization and Production versus Charged-Particle Multiplicity in p+p Collisions at √s = 500 GeV in the STAR experiment

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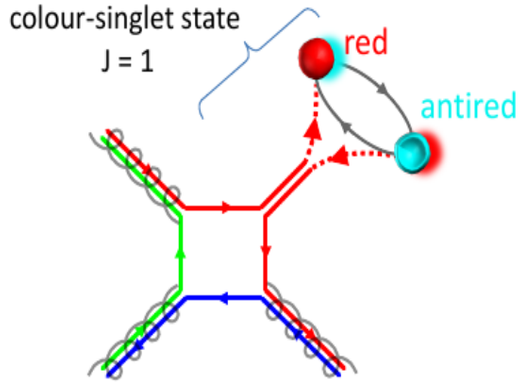
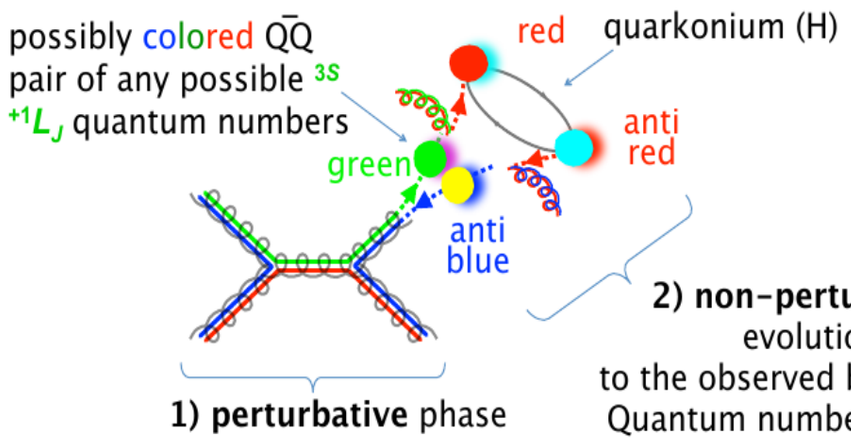
Quarkonia in p+p collisions

- ***Quarkonium Production mechanism*** in elementary collisions is not fully understood
  - ➔ Color singlet vs color octet intermediate state



+ analogous colour combinations



- ***Different models on the market:***
  - ✔ Color Singlet Model
  - ✔ Color Evaporation Model
  - ✔ NRQCD approach – applicable at high p_T
  - ✔ CGC+NRQCD – applicable at low p_T

- ***Feed-down***

  Inclusive J/ψ production:
  - prompt J/ψ
    - direct J/ψ (~60%), feed down from ψ(2S) (~10%) and χ_c (~30%) decays
  - non-prompt J/ψ: B-mesons feed-down (10-25% at 4-12 GeV/c, STAR: Phys. Lett. B722 (2013) 55)

➔ ***Measurements of quarkonium production and polarization - tests of different production models, help to understand QCD***

Quarkonia in the STAR Experiment

$J/\psi\,/\Upsilon \rightarrow e^+ e^-, \mu^+ \mu^-$

$0 < \varphi < 2\pi$

e: $|\eta| < 1$, μ: $|\eta| < 0.5$

- **VPD - minimum bias trigger**
- **TPC – tracking PID: dE/dx**
- **MTD – trigger on muon improve low-p_T J/ψ**
- **BEMC – PID: E/p trigger on electron high-p_T J/ψ**
- **TOF – time resolution < 100 ps PID: 1/β**

J/Ψ production in p+p 500 GeV

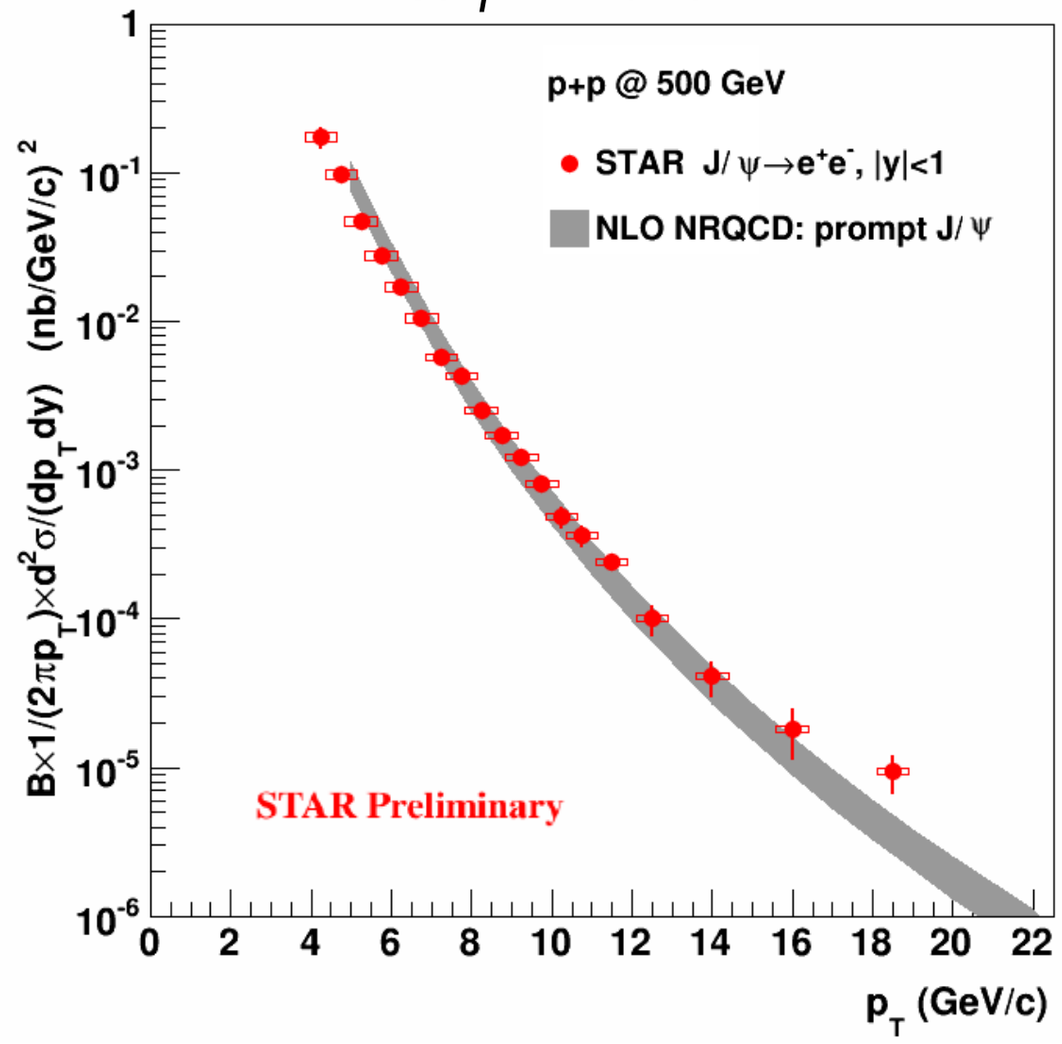
High-p_T J/ψ

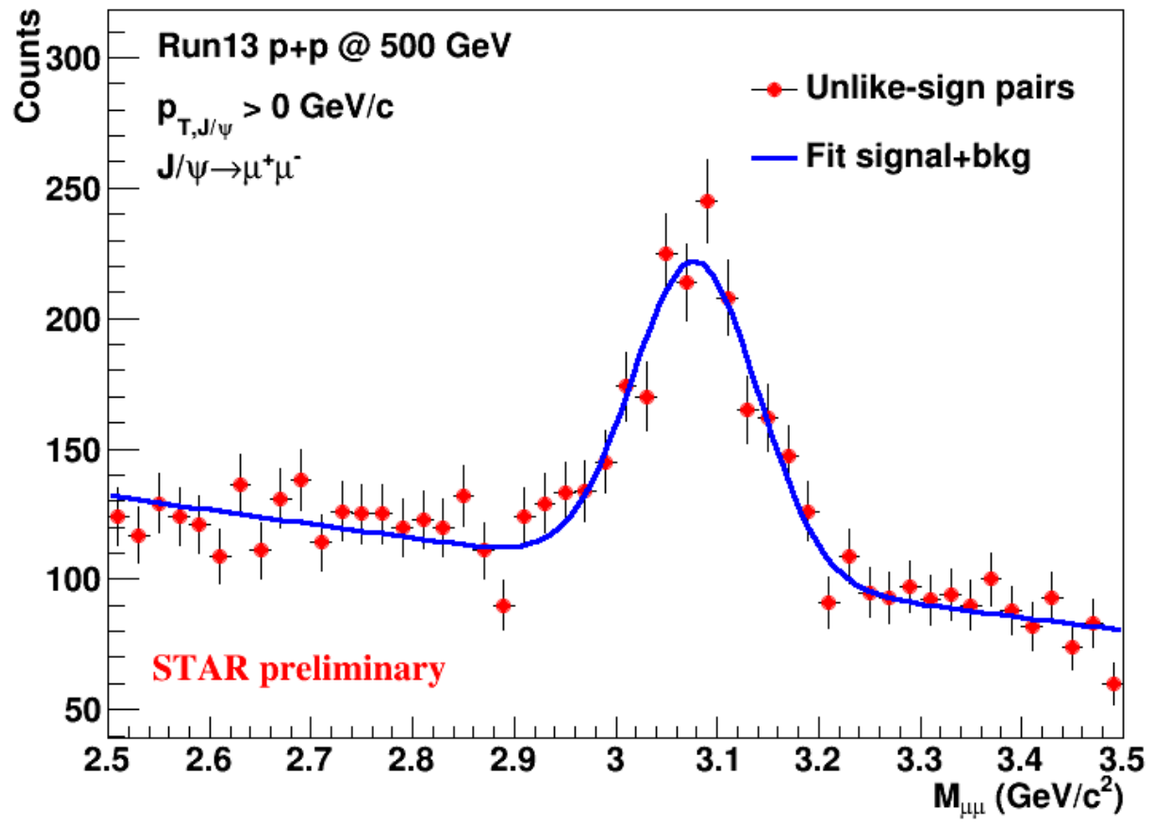
$J/\psi \rightarrow e^+ e^-$

inclusive J/ψ

Low-p_T J/ψ

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





- ✓ NLO NRQCD for prompt J/ψ describes the data well for $p_T > 4$ GeV/c

- ✓ Dimuon trigger – two hits in MTD
- ✓ More precise low-p_T J/ψ measurements

NLO NRQCD:
Phys.Rev.Lett. 106 (2011) 042002, Phys Rev. D84 (2011) 114001, JHEP 1505 (2015) 103 and private communication
Kuang-Ta Chao, Hao Han, Hua-Sheng Shao

J/Ψ x_T scaling in p+p collisions

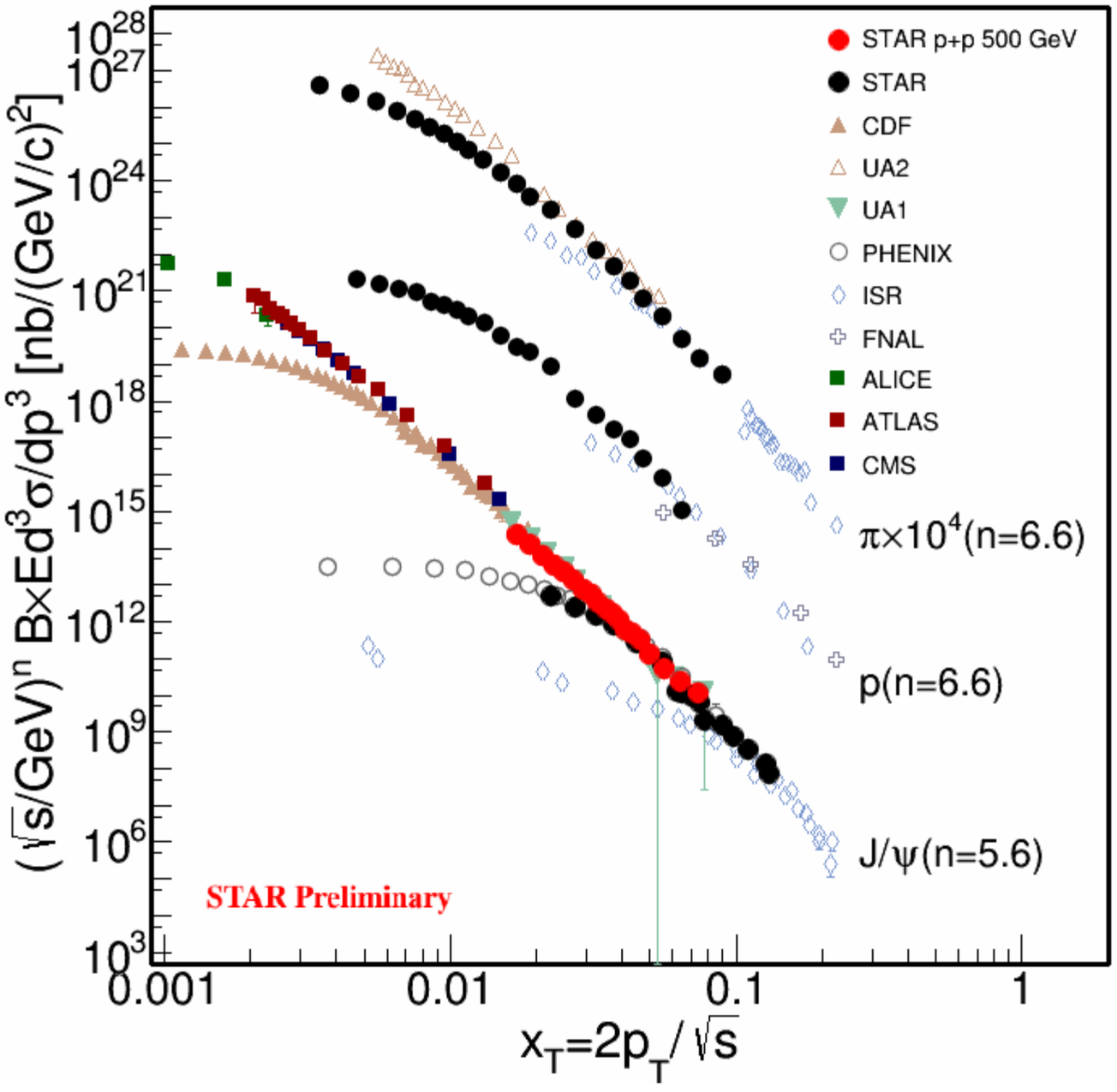
x_T scaling observed in STAR at 200 and 500 GeV

$$x_T = 2p_T/\sqrt{s}$$

$$\frac{d^2\sigma}{2\pi\, p_T\, dp_T\, dy} = g(x_T)/(\sqrt{s})^n$$

✓ p_T > 5 GeV/c – J/ψ production follows the x_T scaling of cross-section at mid-rapidity, with n ~ 5.6

➔ x_T scaling breaking - transition from hard to soft process

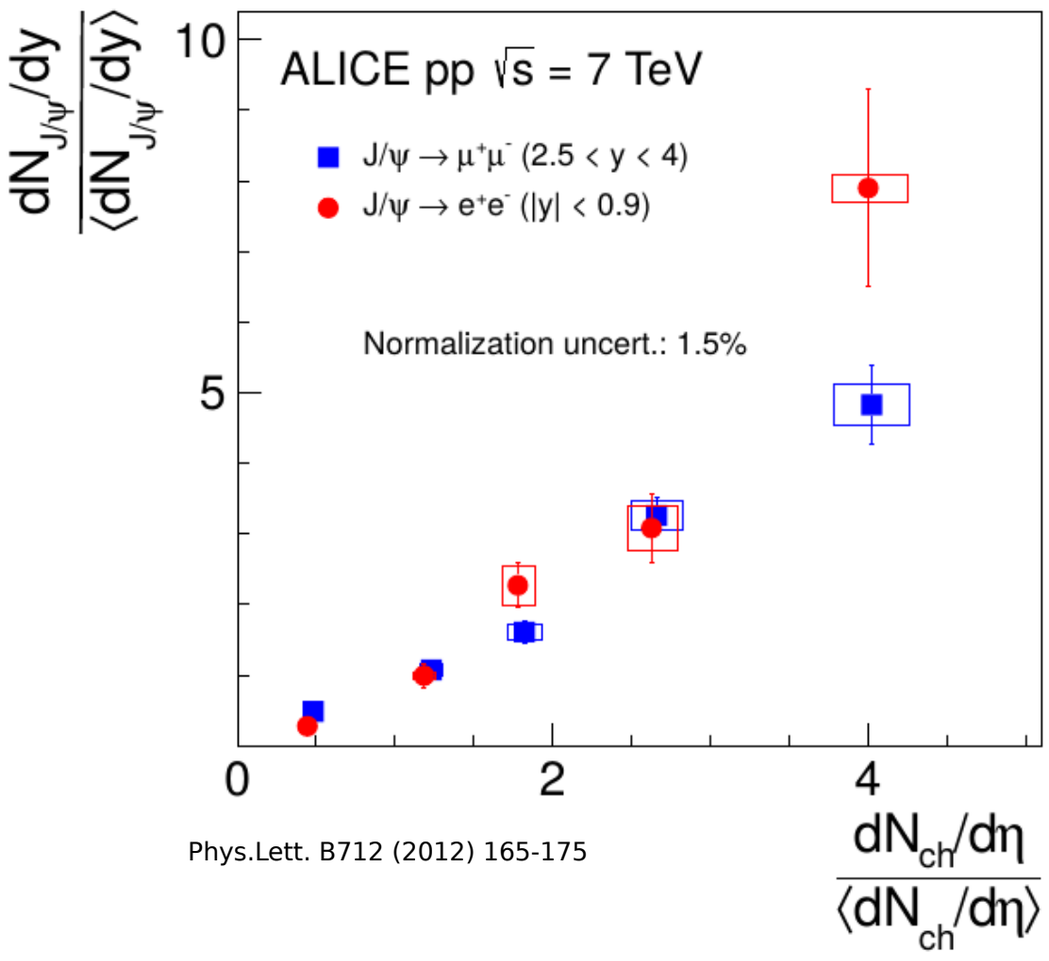


Phys. Rev. C 80, 041902 (2009)

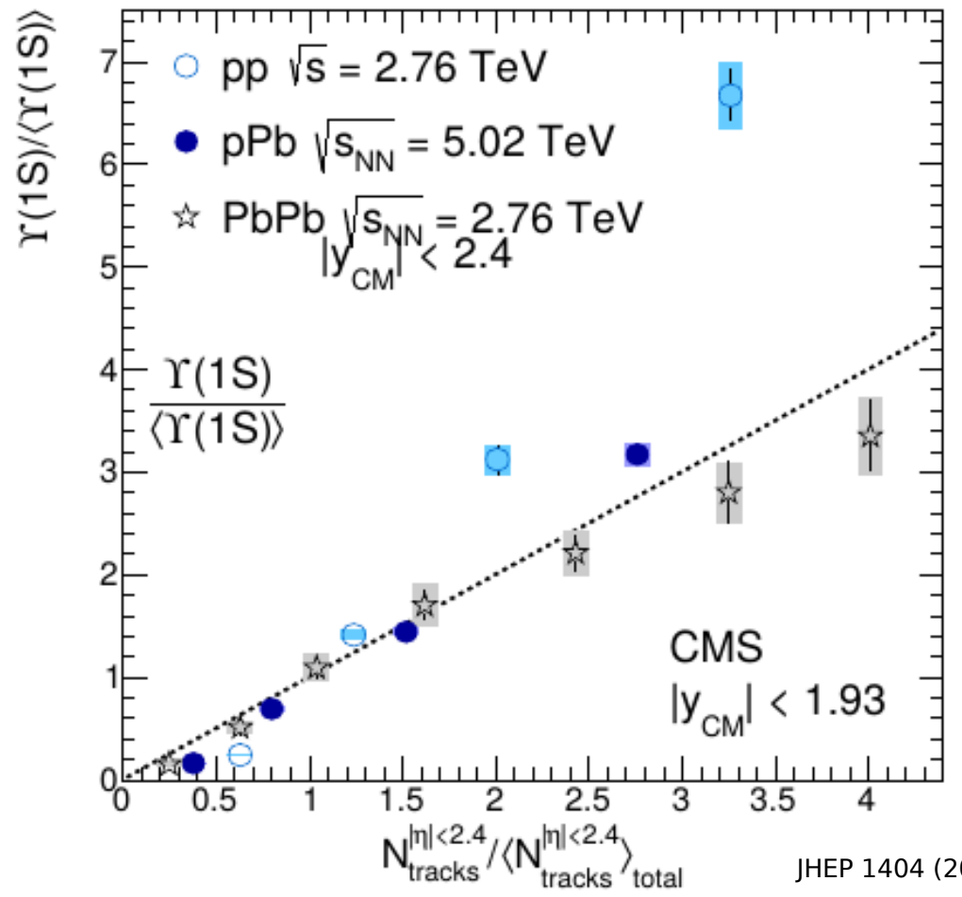
n – number of constituents taking an active role in hadron production

Quarkonium production vs. event activity

➔ In high energy proton-proton collisions Multi-Parton Interactions (MPI) may be important on a hard scale. At LHC correlation between quarkonium production and event activity has been observed.



Phys.Lett. B712 (2012) 165-175

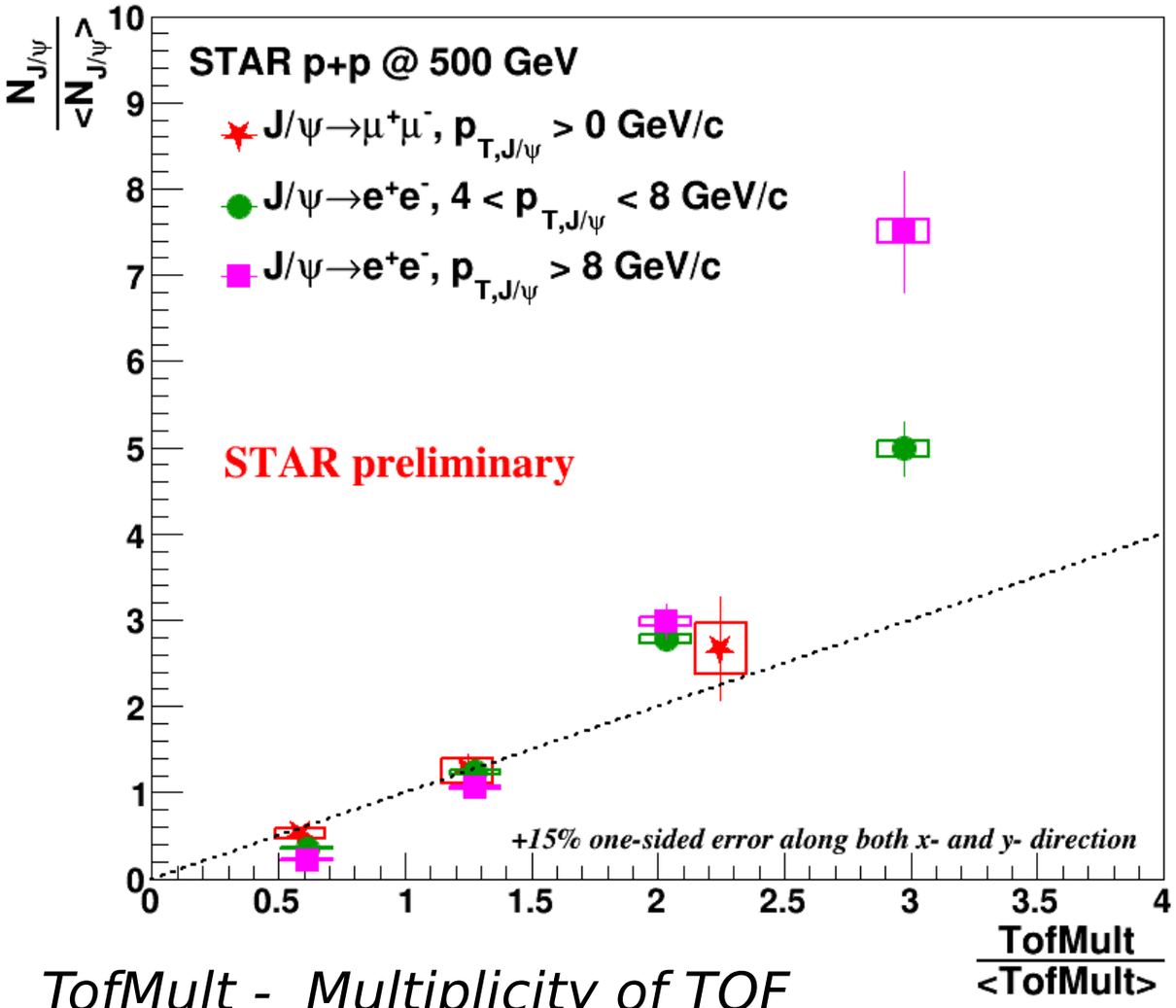


JHEP 1404 (2014) 103

➔ MPI? String screening? or ?

J/Ψ production vs. event activity

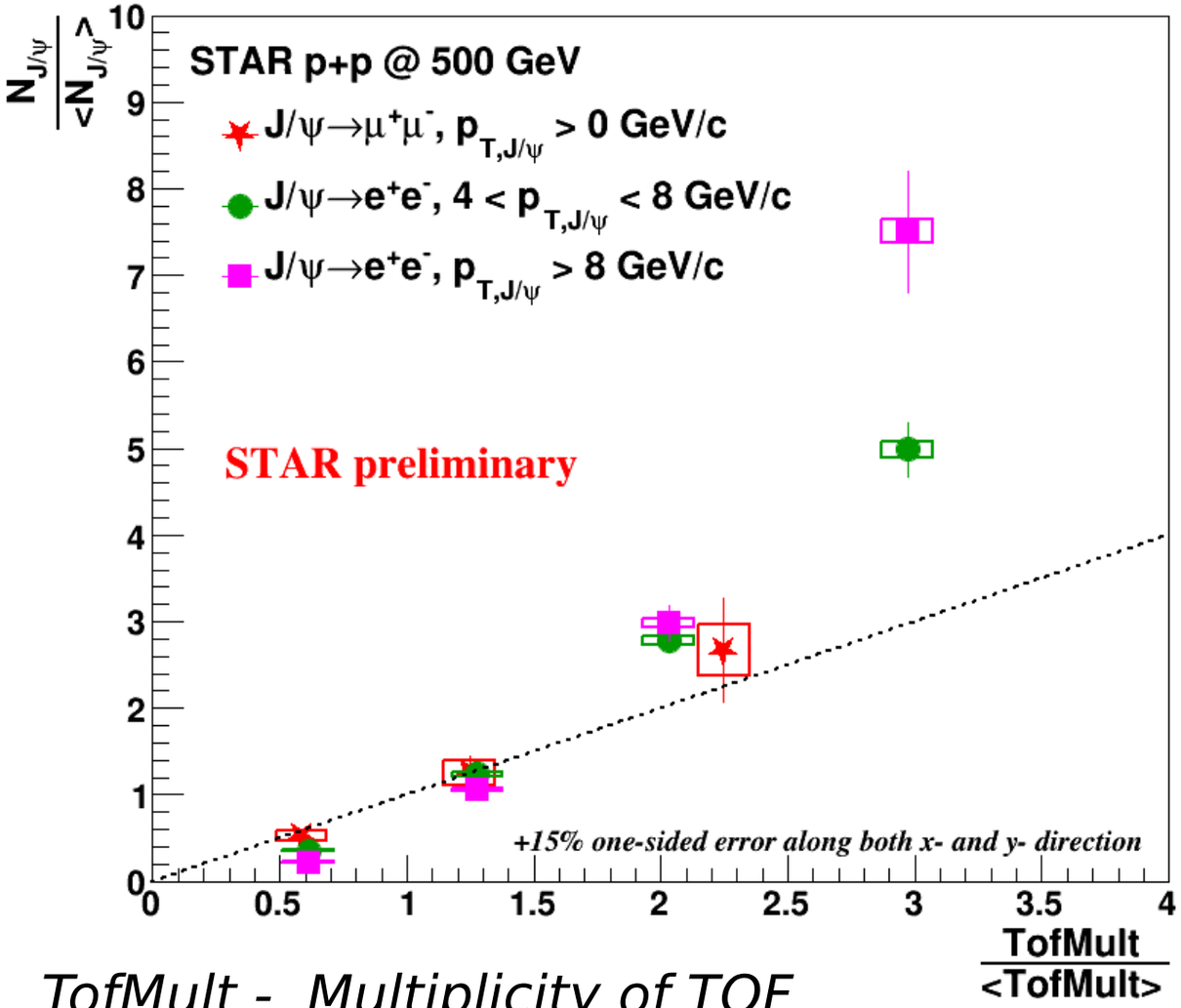
- STAR observes correlation between relative J/ψ yield and relative event multiplicity at 500 GeV
- At higher multiplicities stronger than linear growth at p_T > 4 GeV/c
  - Hint of p_T dependence



TofMult - Multiplicity of TOF matched tracks, $|\eta| < 0.9$

J/Ψ production vs. event activity

- STAR observes correlation between relative J/ψ yield and relative event multiplicity at 500 GeV
- At higher multiplicities stronger than linear growth at p_T > 4 GeV/c
  - Hint of p_T dependence
  - Similar trend at LHC for J/ψ and open charm production



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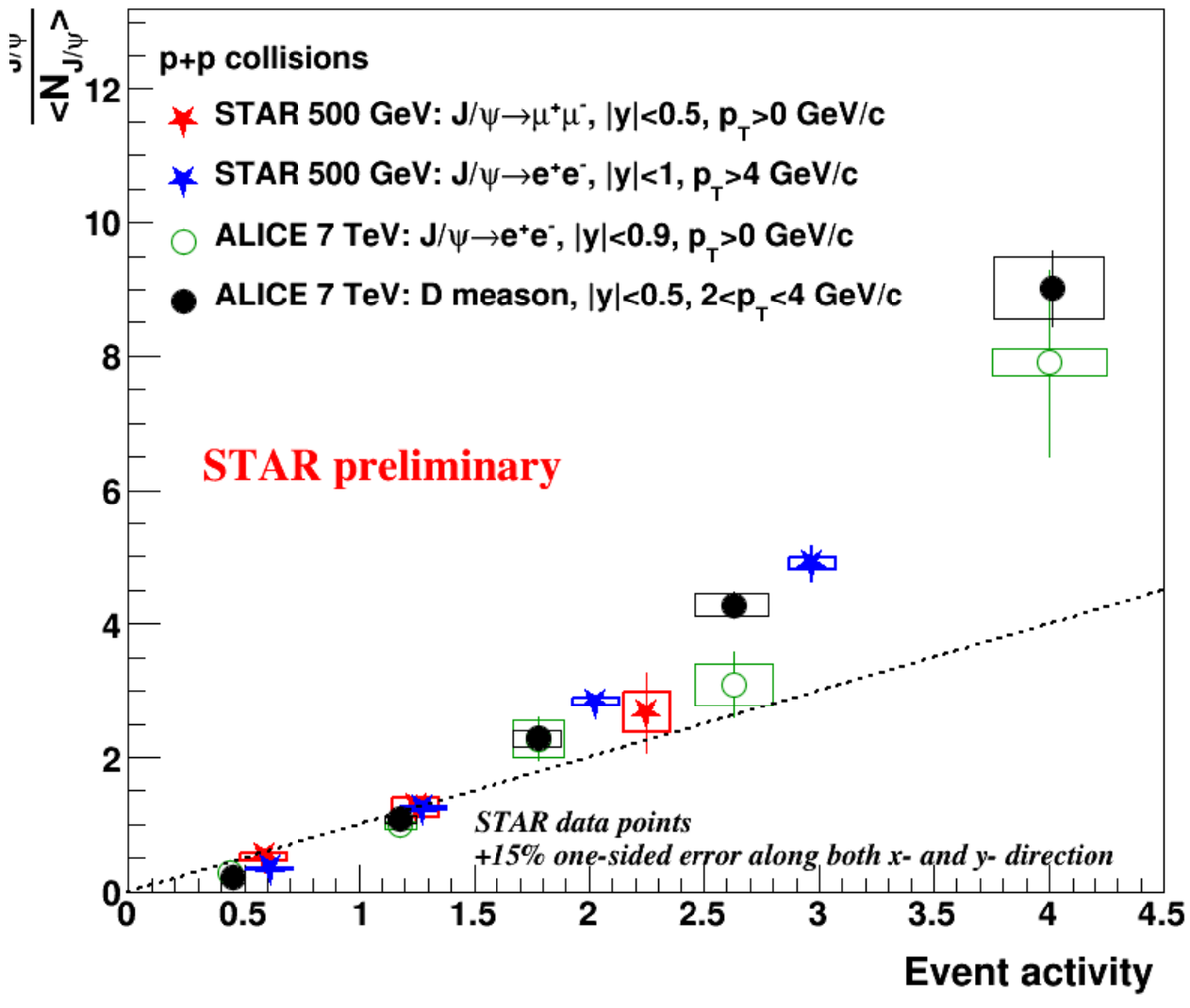
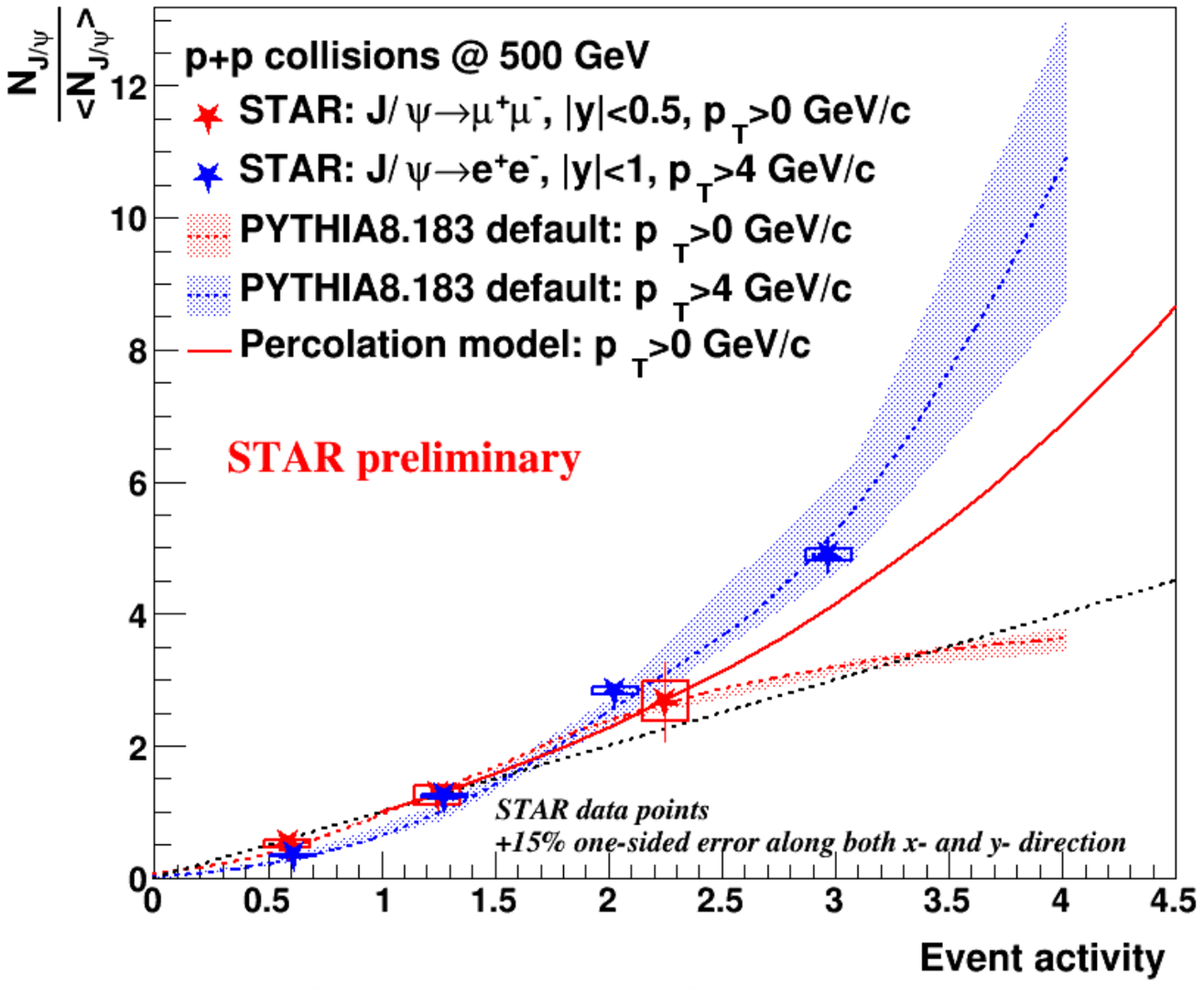


J/Ψ production vs. event activity - models

- Correlation between relative J/ψ yield and relative event multiplicity



- Possible explanations:
  - Multiple parton-parton interactions - *PYTHIA 8*
    - *Default Pythia tune, p_T dependence*
  - String screening - *percolation model* – quadratic dependence at high multiplicities
    - *PRC 86 (2012) 034903, and private communication*
  - Hadronic activity associated with J/ψ production

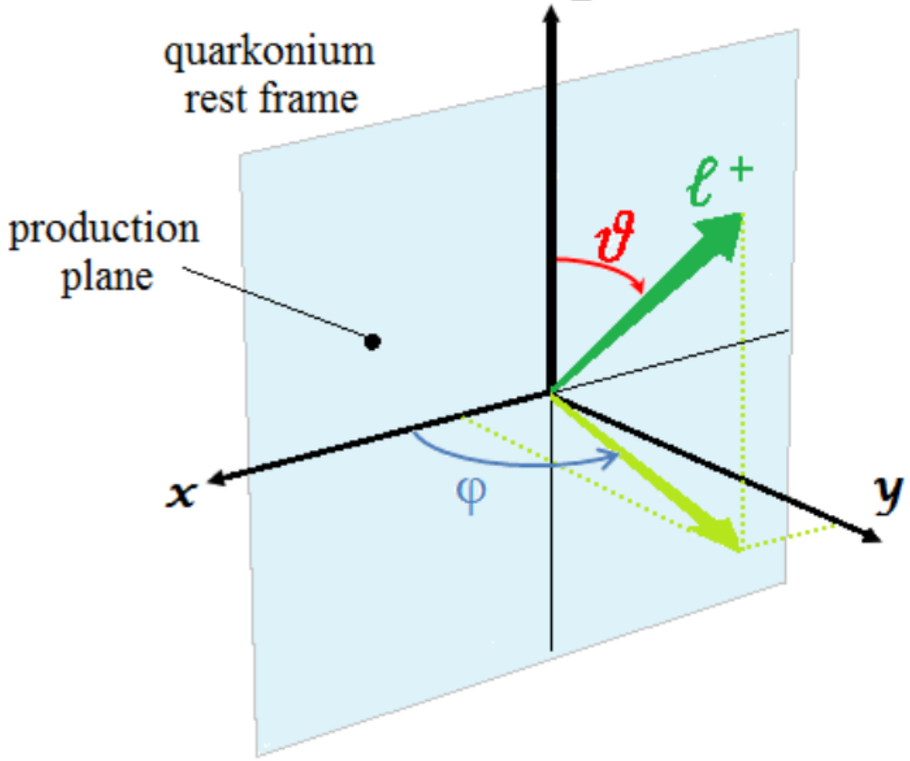
- Percolation Model and PYTHIA8 (in two p_T bins) can describe the observed correlation
- In order to distinguish between the models measurements need to be extended to higher event activity bins – *in progress*

J/Ψ polarization

- Polarization provides further constraints on J/ψ production models
  - Similar production cross-sections but different production mechanisms in competing theoretical approaches lead to different polarization
    - CSM vs different NRQCD calculations

J/ψ polarization can be analyzed via the angular distribution of the decay lepton pair:

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



- **θ** - polar angle between momentum of a positive lepton in the J/ψ rest frame and the polarization axis *z*
- **φ** - corresponding azimuthal angle

Polarization z axis:

- ***Helicity (HX) frame*:** along the J/ψ momentum in the center of mass of the colliding beams
- ***Collins-Soper (CS) frame*:** bisector of the angle formed by one beam direction and the opposite direction of the other beam in the J/ψ rest frame

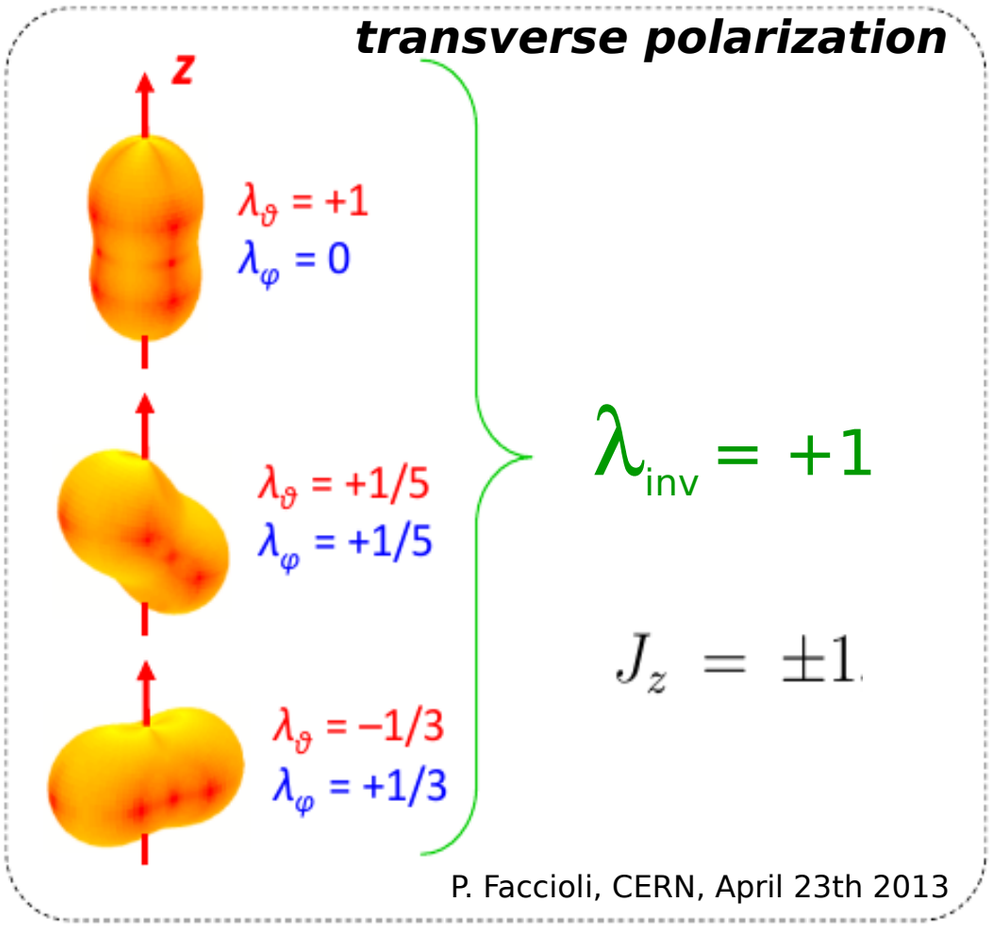
Polarization parameters

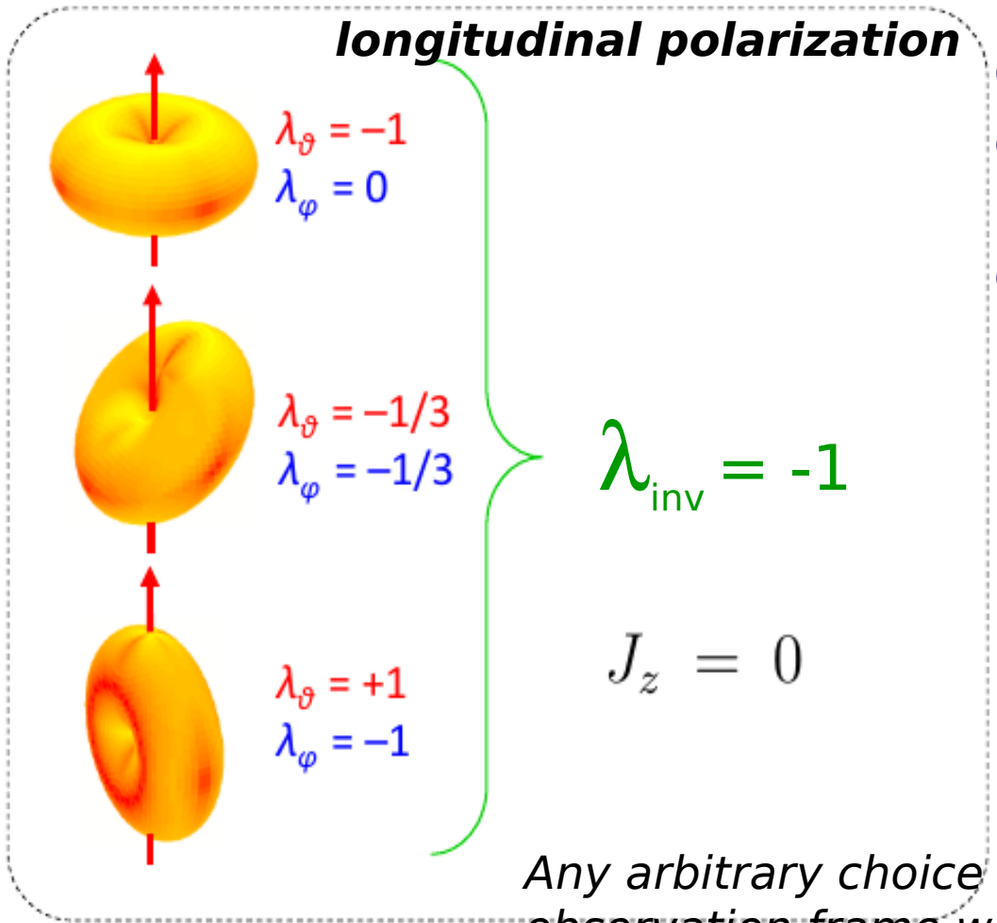
- The angular distribution, integrated over

  azimuthal angle: $W(\cos\theta) \propto 1 + \lambda_\theta \cos^2\theta$

  polar angle: $W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta}\cos 2\varphi$

- *Frame invariant quantity:* $\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\varphi}{1-\lambda_\varphi}$





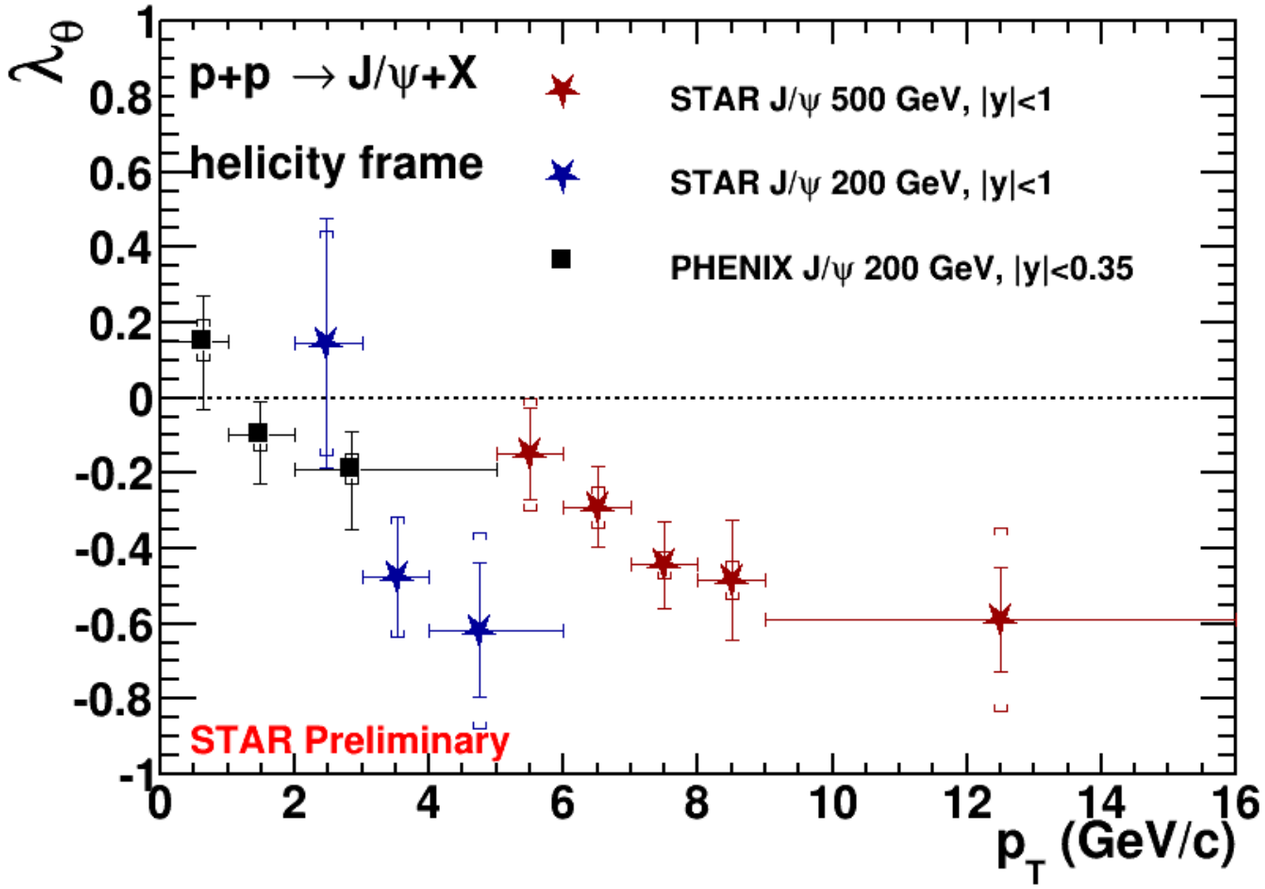
Good cross-check on measurements performed in different frames

Any arbitrary choice of the experimental observation frame will give the same value of this quantity

P. Faccioli, et al., Eur. Phys. J. C 69, 657 (2010)

J/Ψ polarization in p+p 200 and 500 GeV

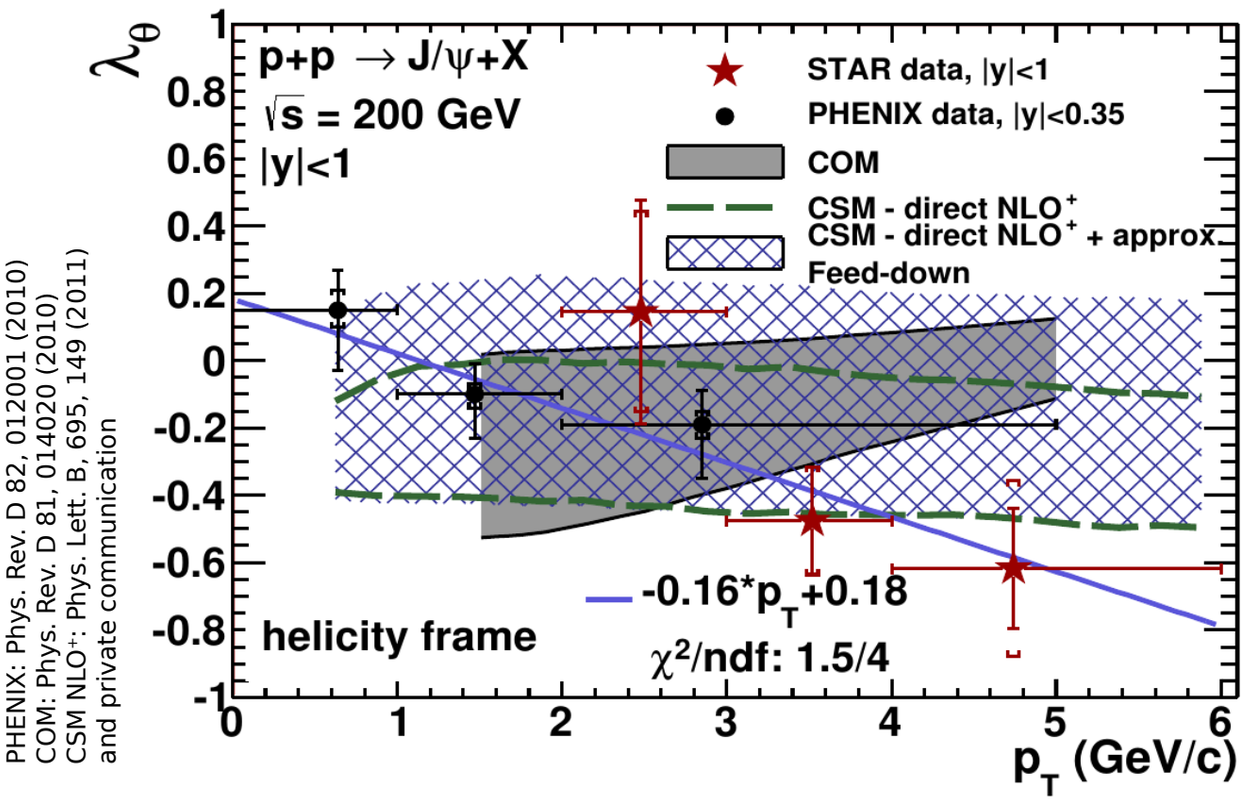
λ_θ parameter in HX frame

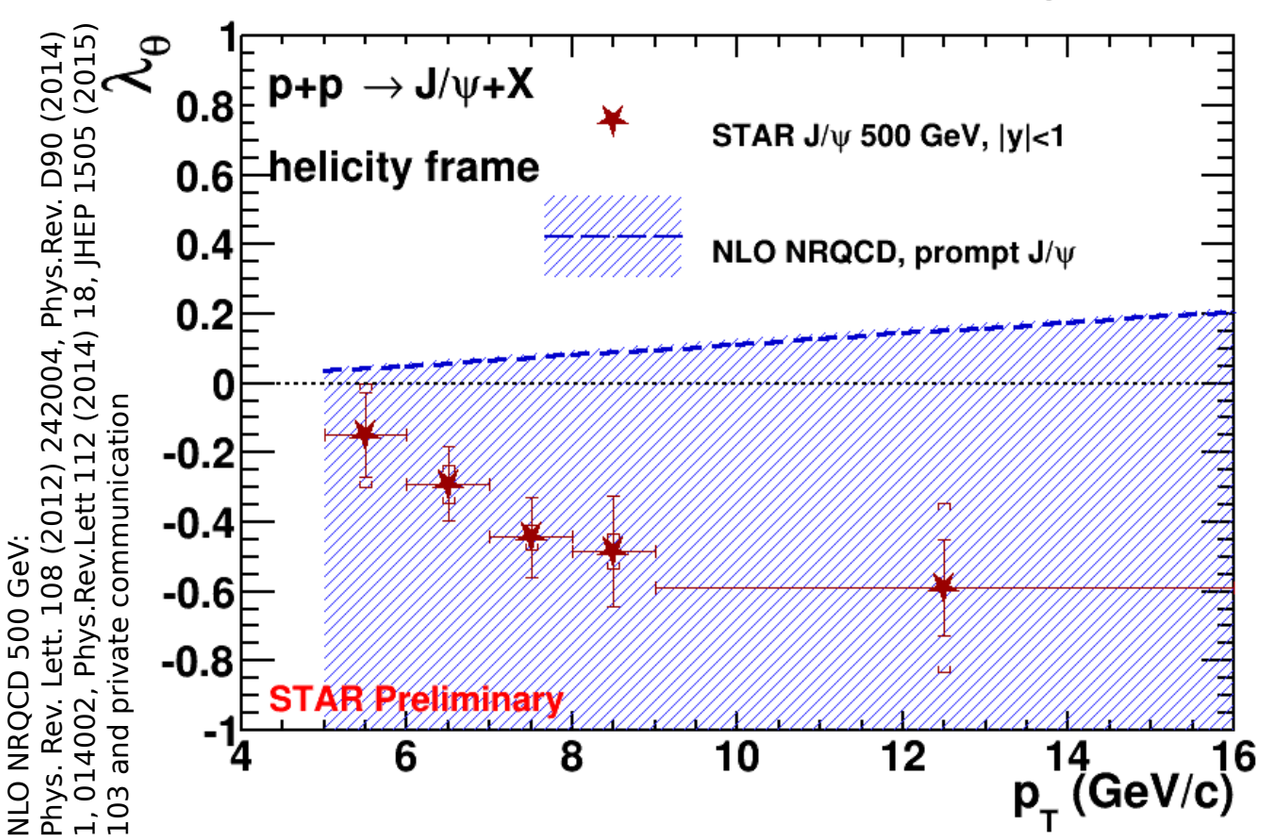


- Similar trend observed in 500 and 200 GeV p+p collisions
- RHIC data indicate trend towards longitudinal polarization with increasing p_T
- Measurement extended to higher p_T range, $5 < p_T < 16$ GeV/c, with new 500 GeV data

PHENIX: Phys. Rev. D 82, 012001 (2010)
STAR 200 GeV: Phys.Lett. B739 (2014) 180

J/Ψ polarization vs model predictions





λ_θ parameter in HX frame

200 GeV

STAR:Phys.Lett. B739 (2014) 180

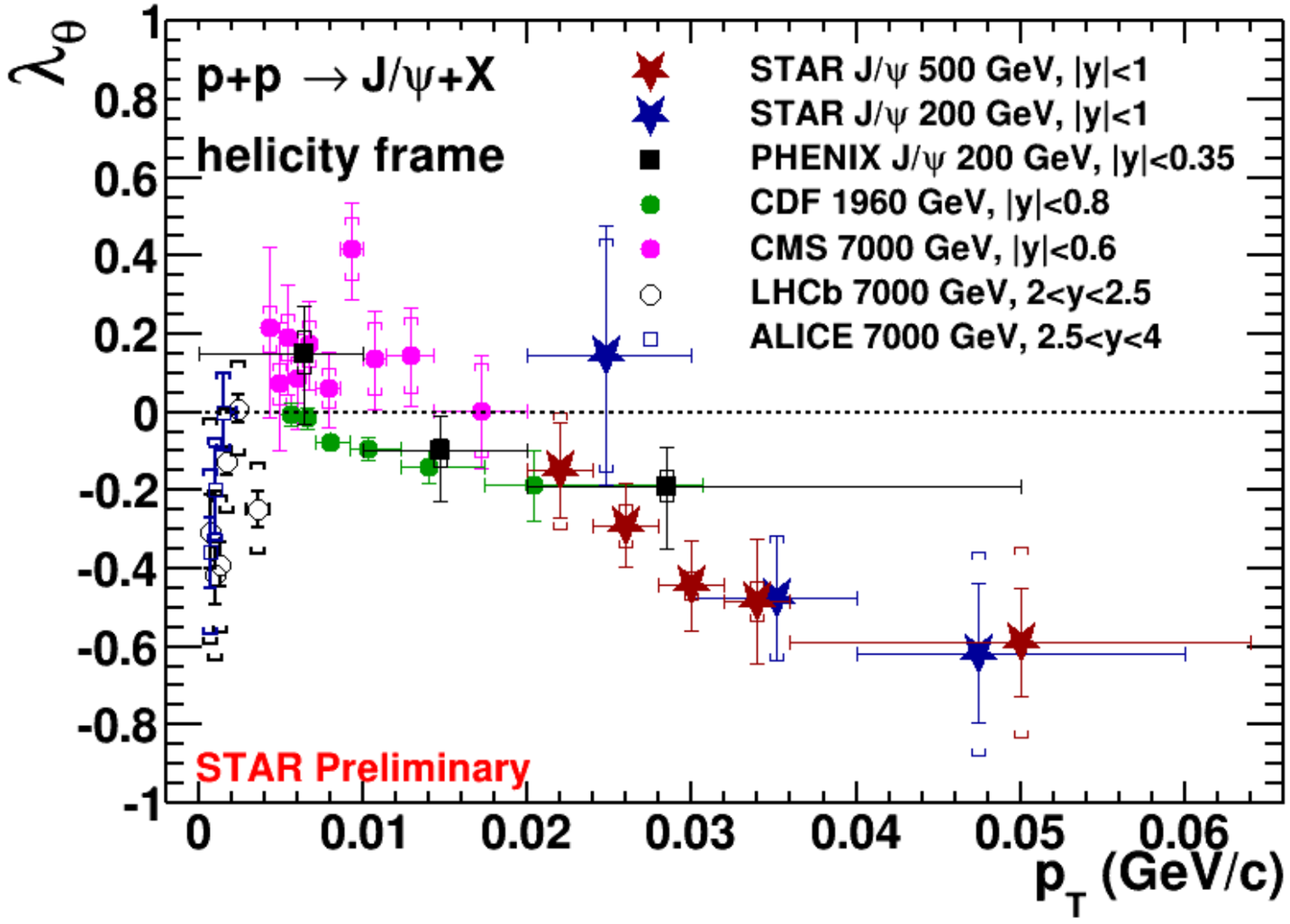
- ✓ Consistency with NLO+ CSM prediction

500 GeV

- ✓ Lower value of λ_θ not constrained within the NLO NRQCD calculations for prompt J/ψ
- ✓ STAR data can help to constrain color-octet Long-Distance Matrix Elements for the NLO NRQCD
- ➔ Predictions that can describe cross-sections well have little prediction power for the polarization – *input from data needed*

x_T dependence of λ_θ

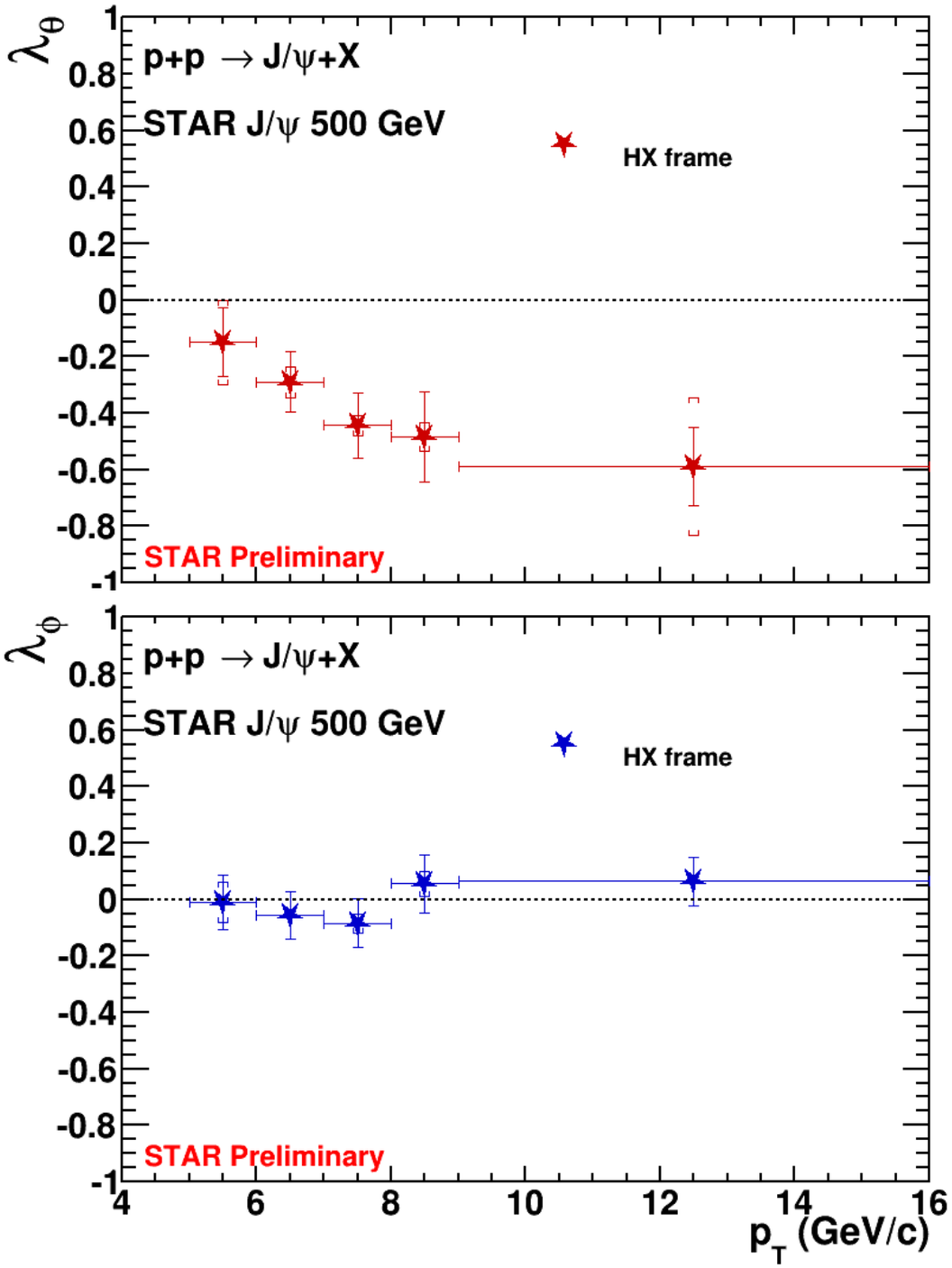
λ_θ parameter in HX frame

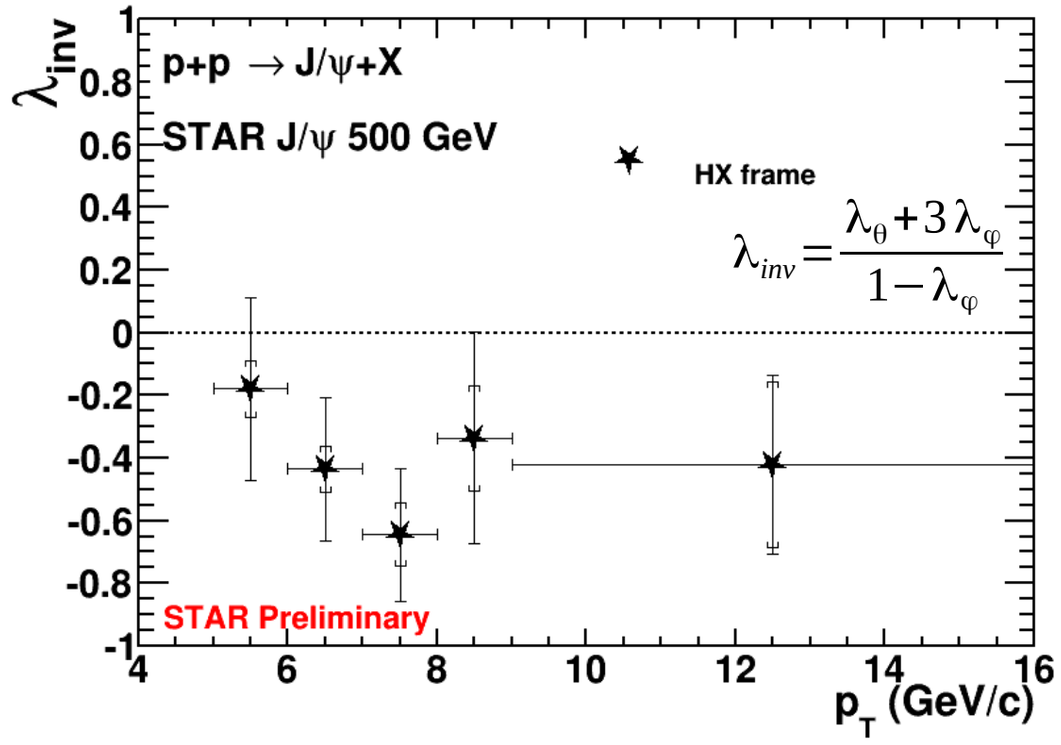


$$x_T = 2p_T/\sqrt{s}$$

- Common trend towards strong negative values with increasing x_T
- x_T scaling of cross-section at p_T > 5 GeV/c

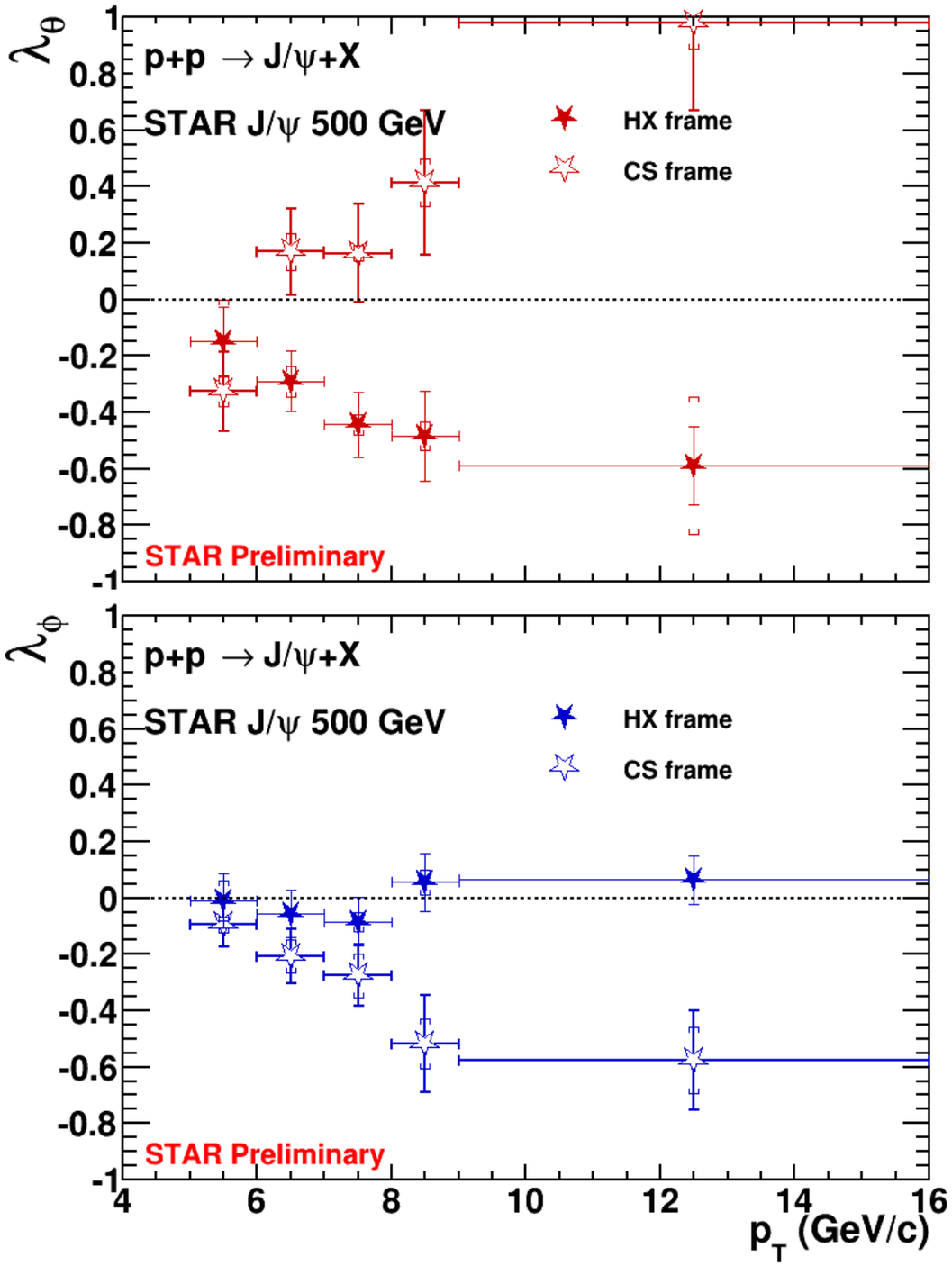
λ_φ and λ_{inv} parameters in HX frame

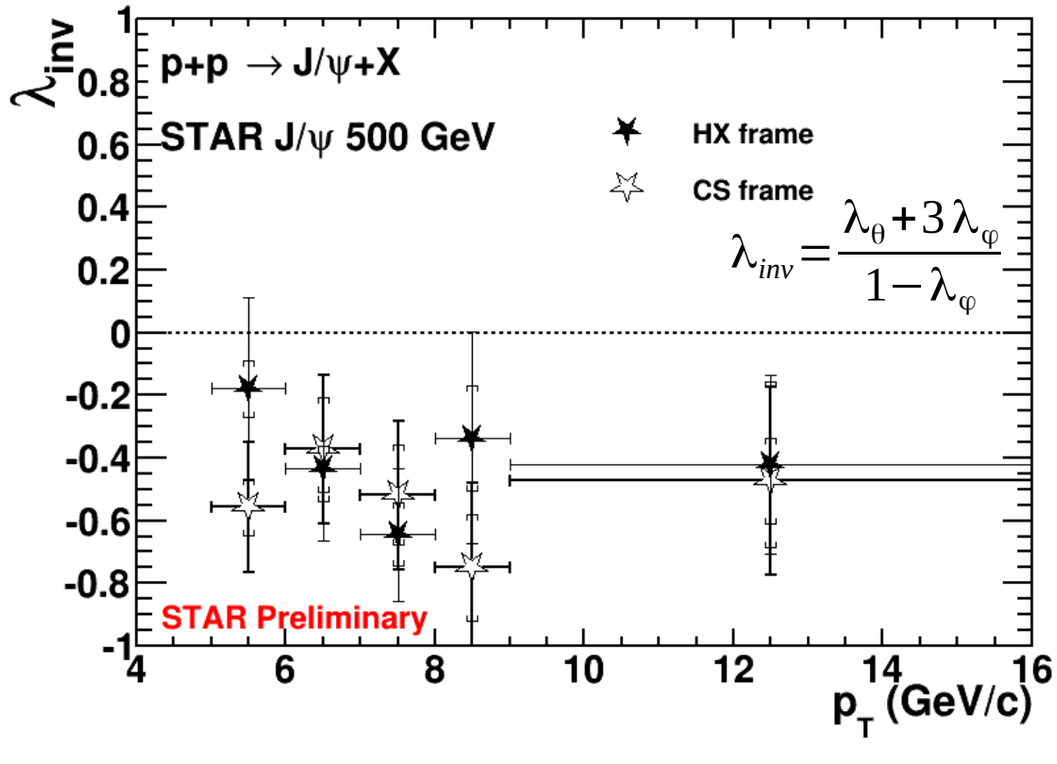




- No strong azimuthal anisotropy observed in the HX frame
- Negative values of the frame invariant λ_{inv} parameter

J/Ψ polarization in CS frame





- Different values of the λ_θ and λ_ϕ polarization parameters in the CS frame
- Frame invariant parameters, λ_{inv}, consistent in both frames
- Trend towards longitudinal polarization with increasing p_T

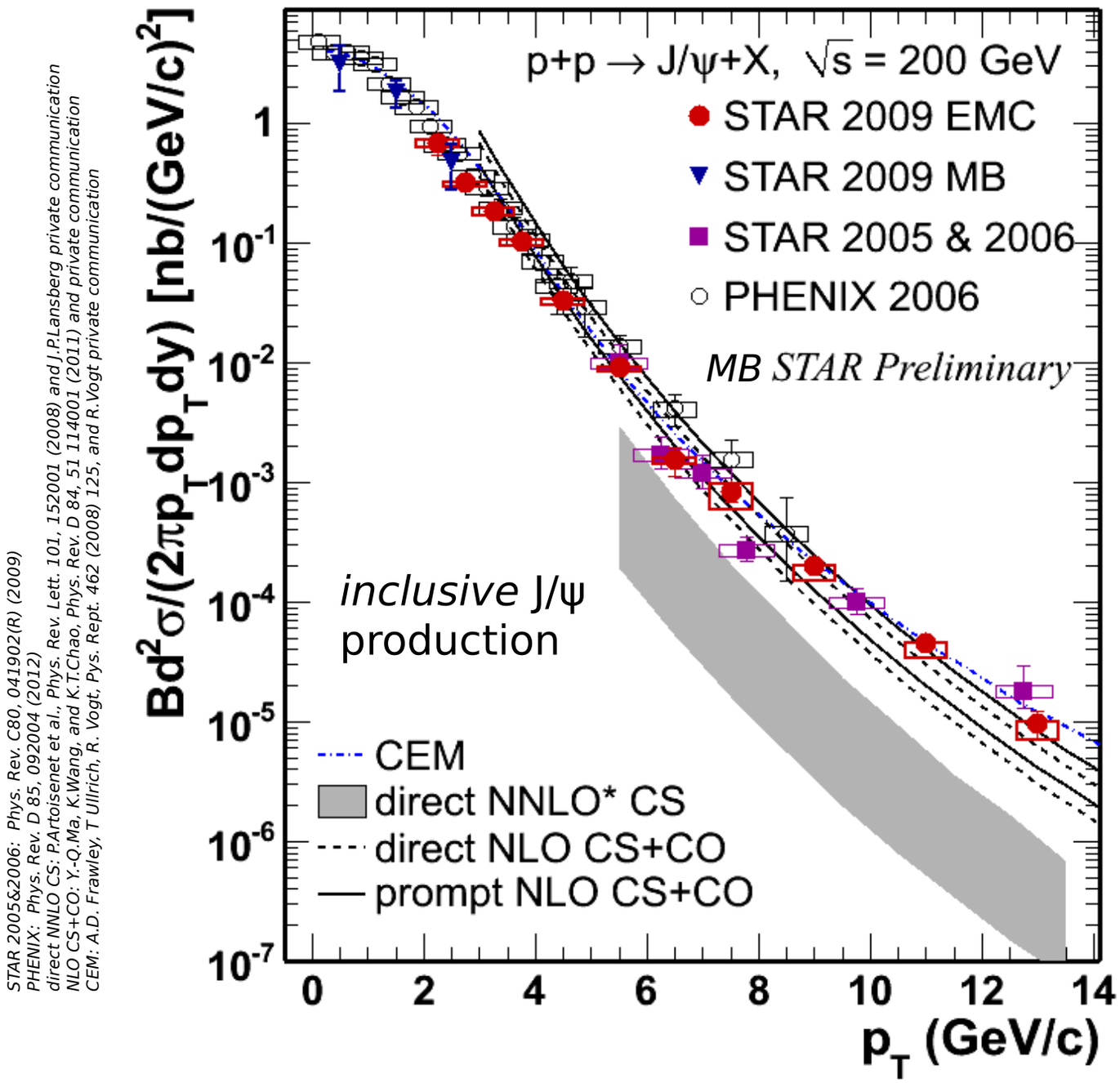
Summary

- J/ψ p_T spectra at $\sqrt{s}$ = 200 and 500 GeV measured, can be described well by NRQCD predictions
- Increase of relative J/ψ yield with relative charged-particle multiplicity in p+p at $\sqrt{s}$ = 500 GeV
  - Stronger than linear rise at higher multiplicities at $p_T > 4$ GeV/c
  - PYTHIA8 and Percolation Model can describe the observed increase
  - Similar trend as observed at LHC
- Longitudinal J/ψ polarization in HX frame at $\sqrt{s}$ = 200 and 500 GeV
  - No strong azimuthal anisotropy observed
  - x_T dependence of λ_θ observed
- Frame invariant parameters agree in HX and CS frames at $\sqrt{s}$ = 500 GeV
- Data will help to constrain J/ψ production models
- ϒ analysis of cross-section at 500 GeV and relative yield vs event activity in progress – *see Leszek Kosarzewski poster 0613*

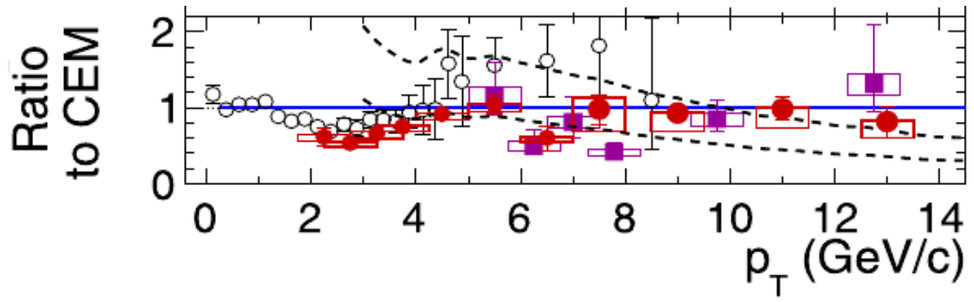
Thank you !

J/Ψ p_T spectrum in p+p 200 GeV

- Test of different production models



- ✓ *NNLO* CS,* direct production, misses high-p_T part
- ✓ *CEM*, prompt production, can reasonably well describe the p_T spectra

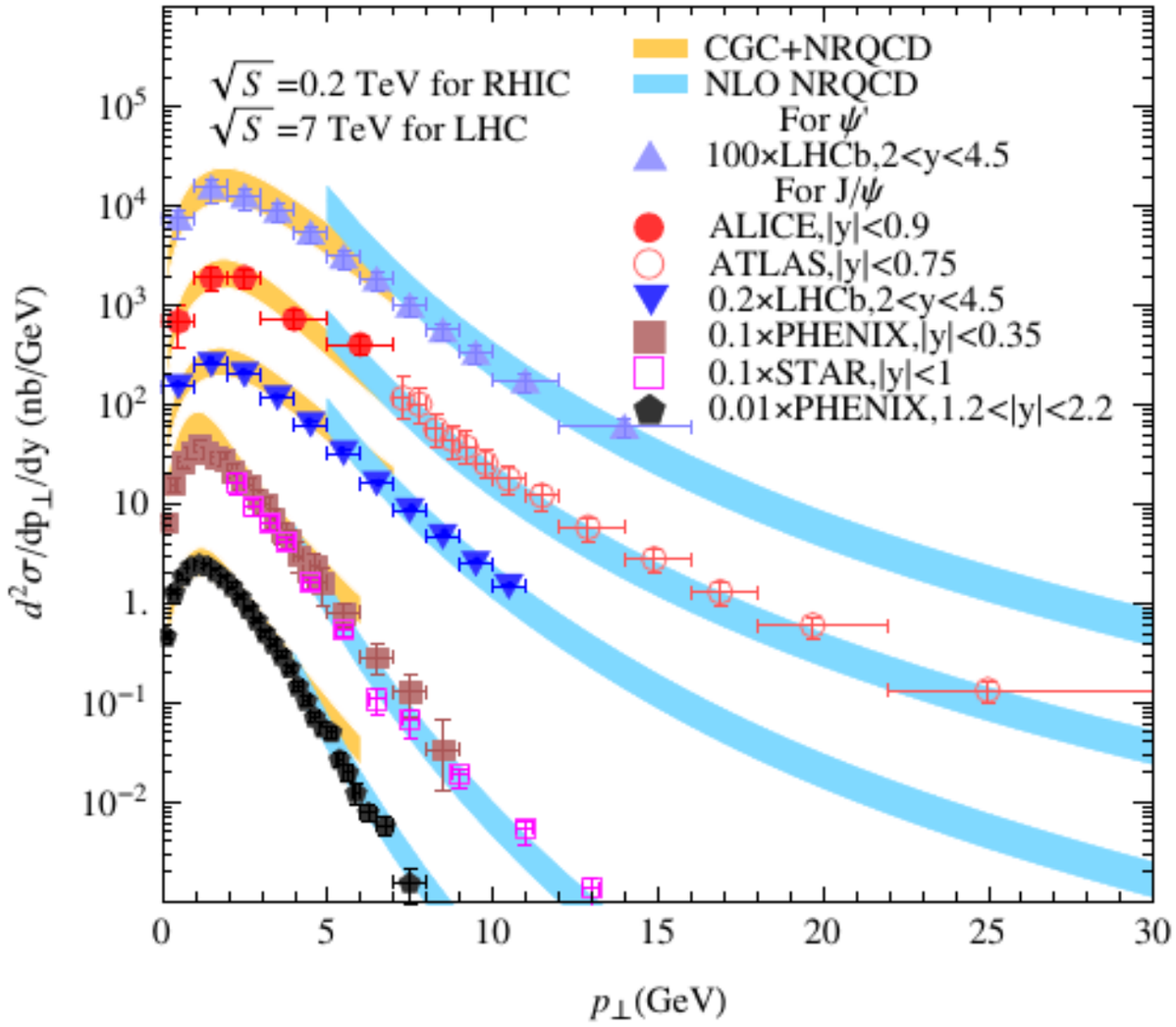


- ✓ *NLO NRQCD*, prompt production, describes the data for p_T > 4 GeV/c

STAR EMC : Phys. Lett. B 722 (2013) 55
STAR MB: Acta Phys. Polonica B Vol.5, No 2 (2012), 543

J/Ψ p_T spectrum in p+p 200 GeV

- Test of different production models



Phys. Rev. Lett. 113 (2014) 192301

- ✓ *NNLO* CS,* direct production, misses high-p_T part
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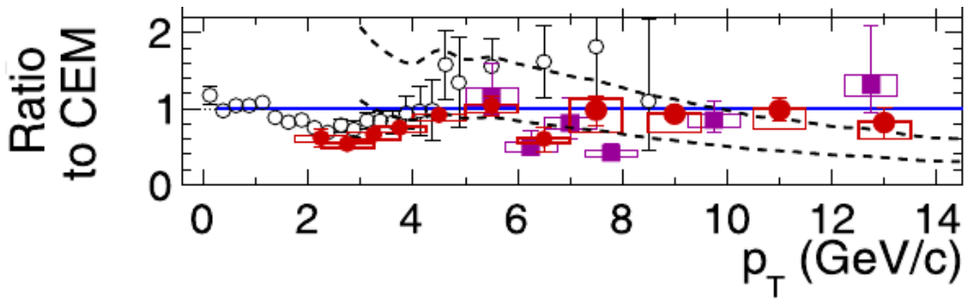
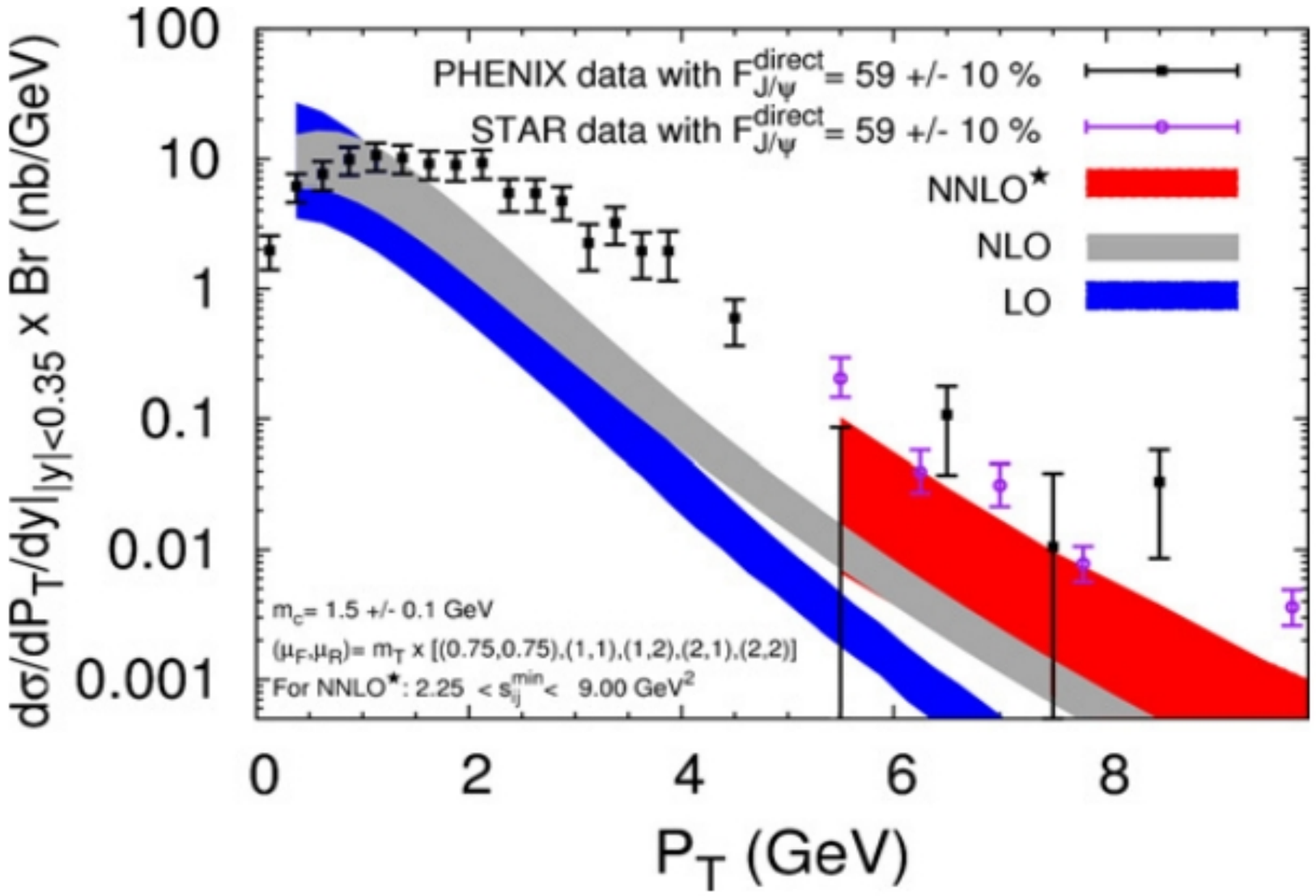


- ✓ *NLO NRQCD*, prompt production, describes the data for p_T > 4 GeV/c
- ✓ *CGC + NRQCD*, describes the data in the full p_T range

J/Ψ production mechanism - CSM

- Comparison of CSM to RHIC data

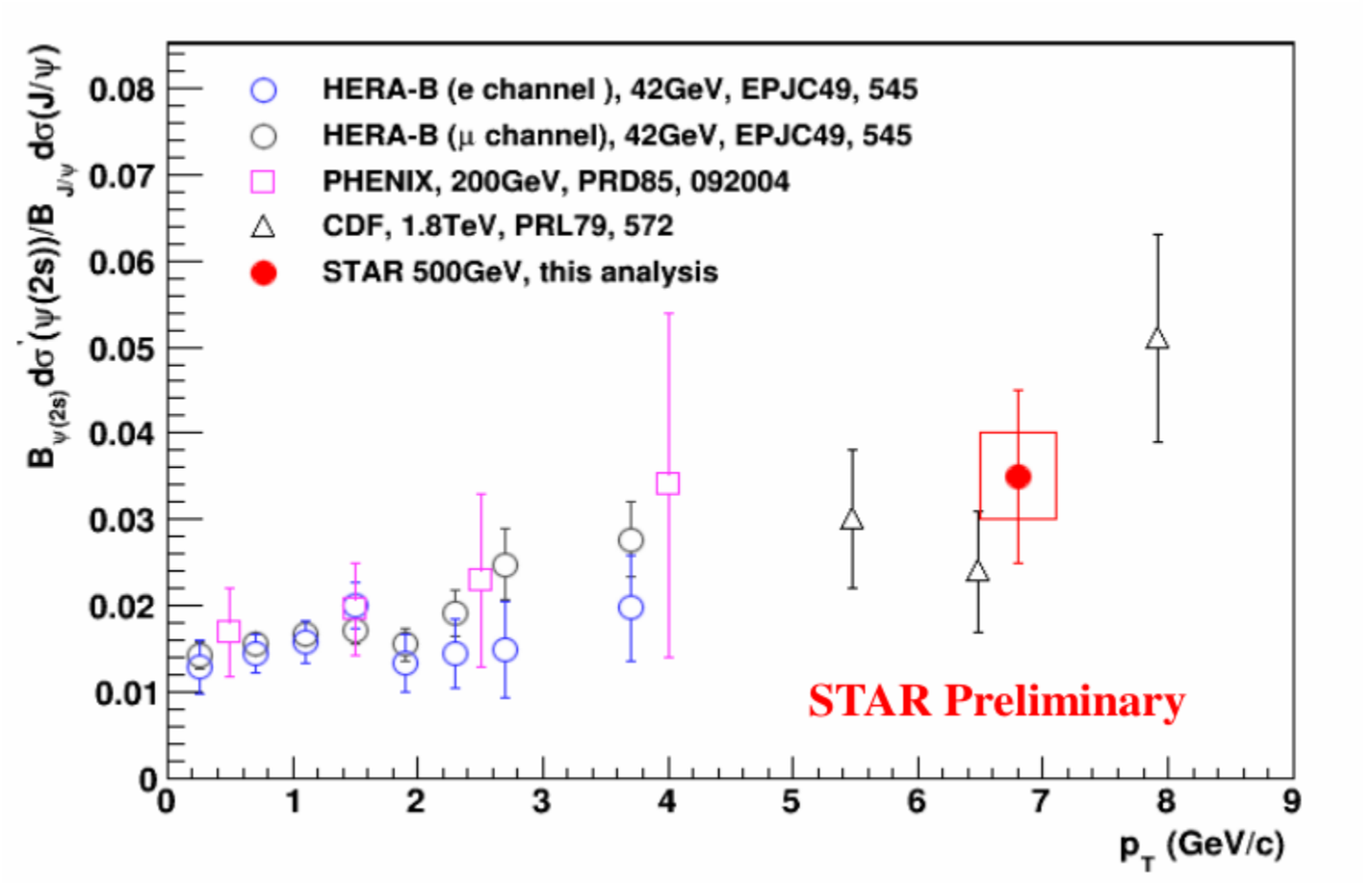


(a) central

J.P. Lansberg, Phys.Lett.B 695 (2011) 149

Ψ(2S) in p+p 500 GeV

- Constrain ψ(2S) feed-down contribution to inclusive J/ψ production



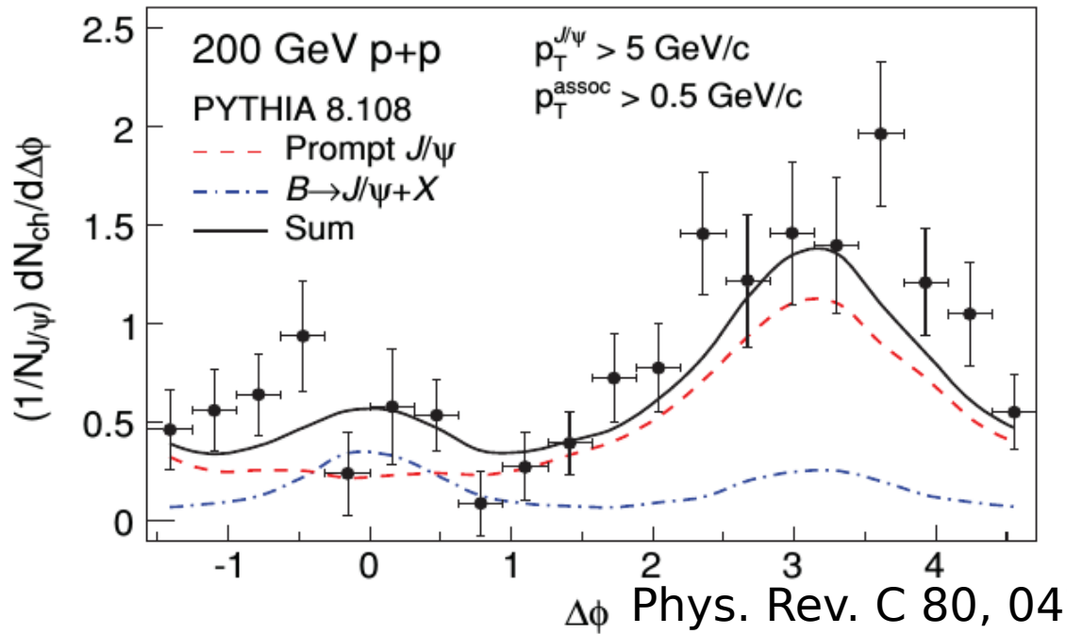
✓ First measurement of (ψ(2S) / J/ψ) ratio in p+p at 500 GeV

➔ Consistent with other experiments

➔ No collision energy dependence observed

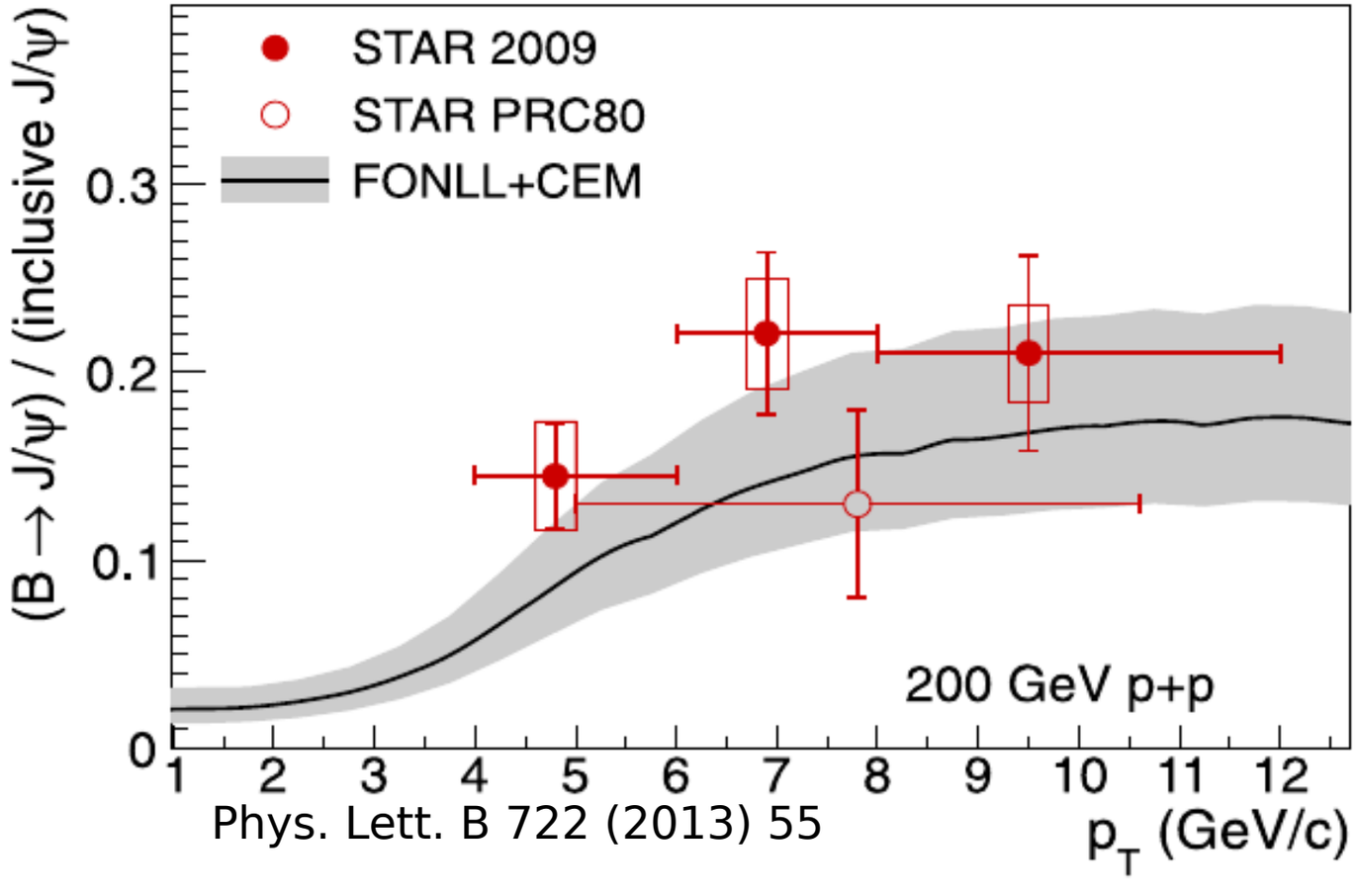
B -> J/Ψ fraction in p+p 200 GeV

- ✓ Measurement based on azimuthal angular correlations between high-p_T J/ψ and charged hadrons



Phys. Rev. C 80, 041902 (2009)

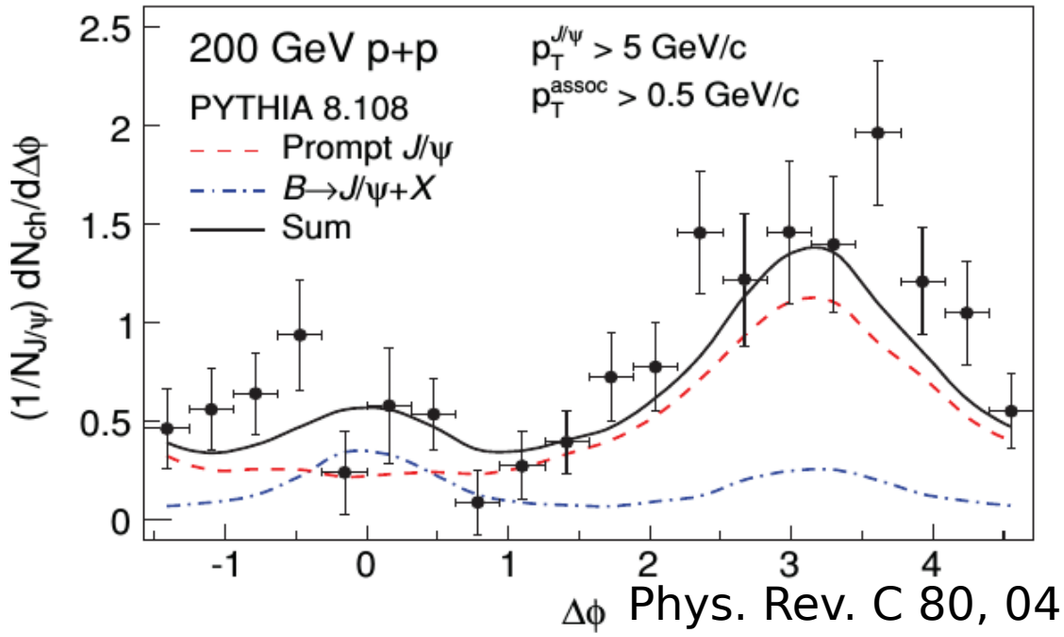
- ➔ B-hadron feed-down contribution: 10-25%, in the range $4 < p_T < 12$ GeV/c
- ➔ Agreement with FONLL + CEM prediction



Phys. Lett. B 722 (2013) 55

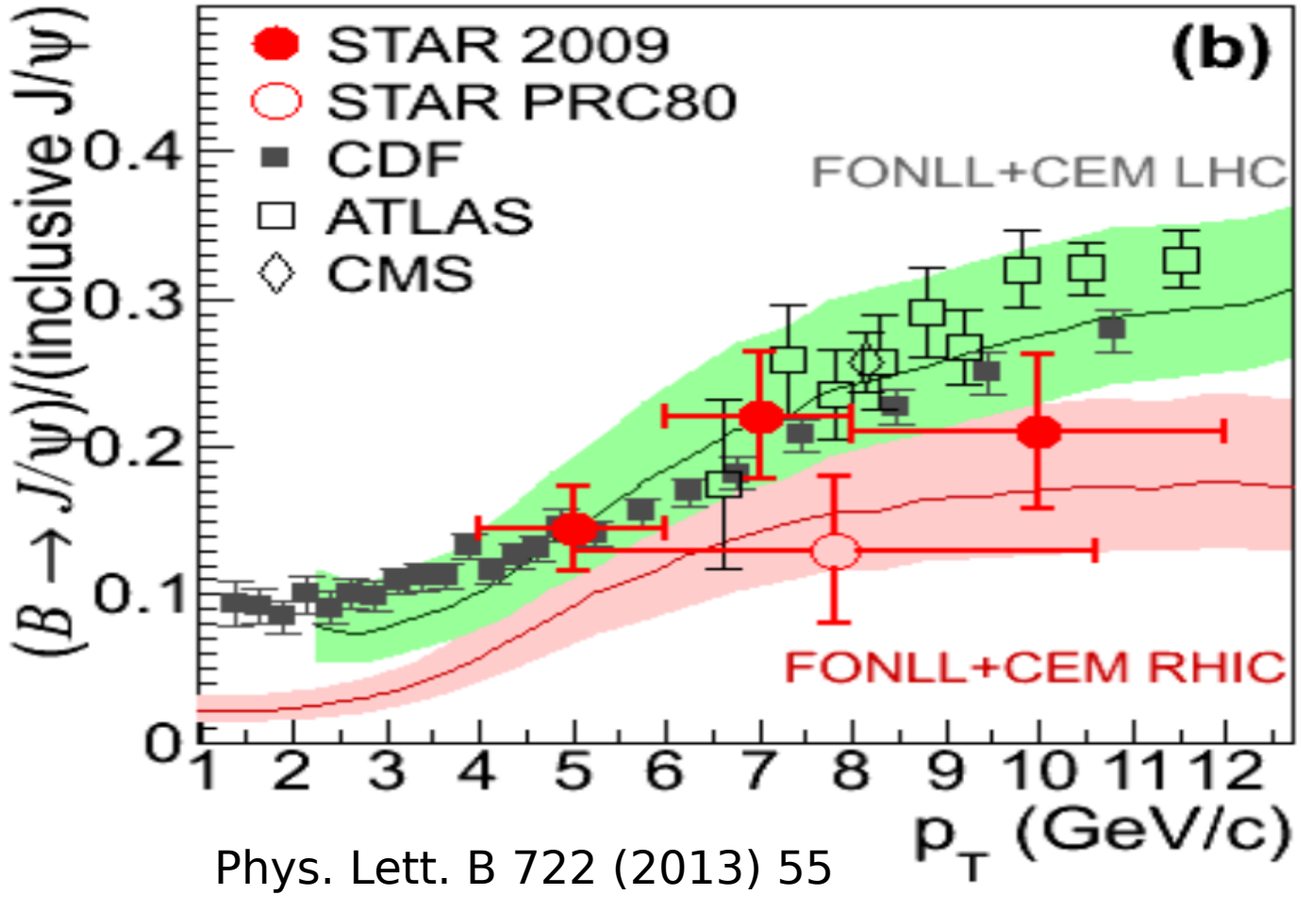
B -> J/Ψ fraction in p+p 200 GeV

- ✓ Measurement based on azimuthal angular correlation between high-p_T J/ψ and charged hadrons



Phys. Rev. C 80, 041902 (2009)

- ➔ B-hadron feed-down contribution: 10-25%, in the range $4 < p_T < 12$ GeV/c
- ➔ Agreement with FONLL + CEM prediction and with measurements from other experiments



Phys. Lett. B 722 (2013) 55