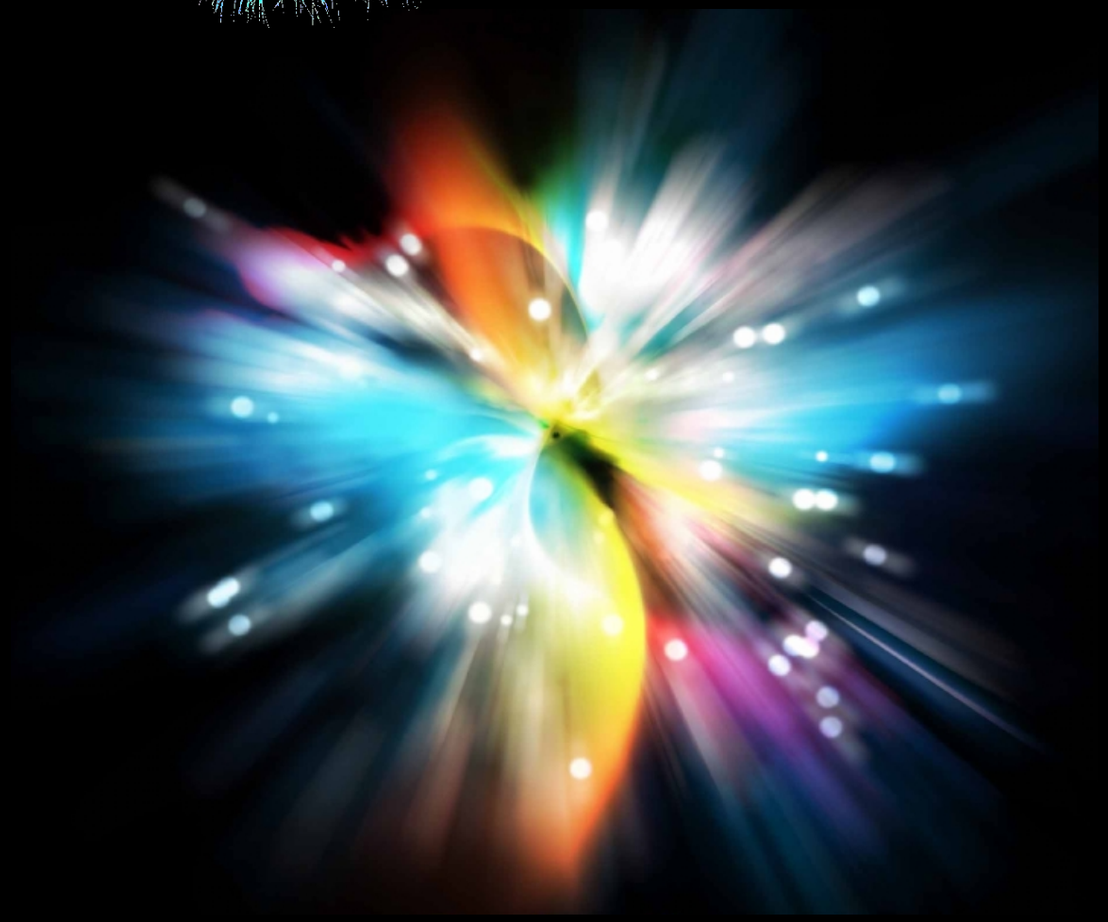
J/ψ and ψ(2S) measurements in p+p collisions at √s = 200 and 500 GeV with the STAR experiment



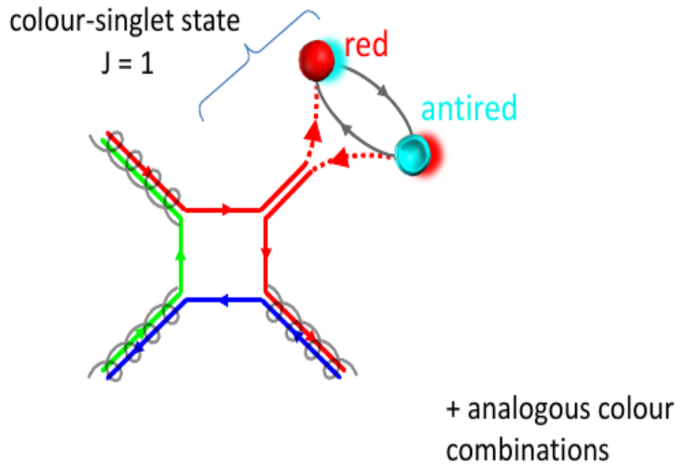
Barbara Trzeciak
for the STAR Collaboration
Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

Strangeness in Quark Matter 2015
6-11 July 2015
Dubna, Russia

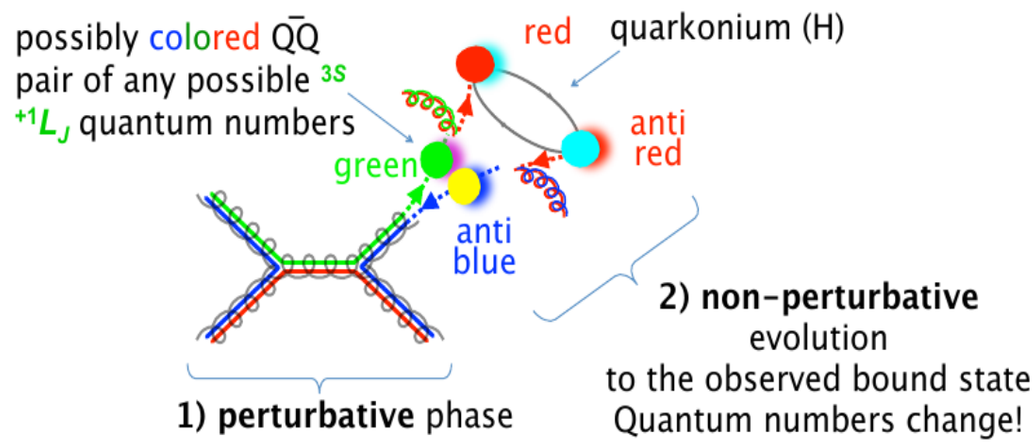
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Charmonia in p+p collisions

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



- ***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



  - ➔ ***Quarkonium measurements - tests of different production models, help to understand QCD***

- ***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)

Quarkonia in the STAR Experiment

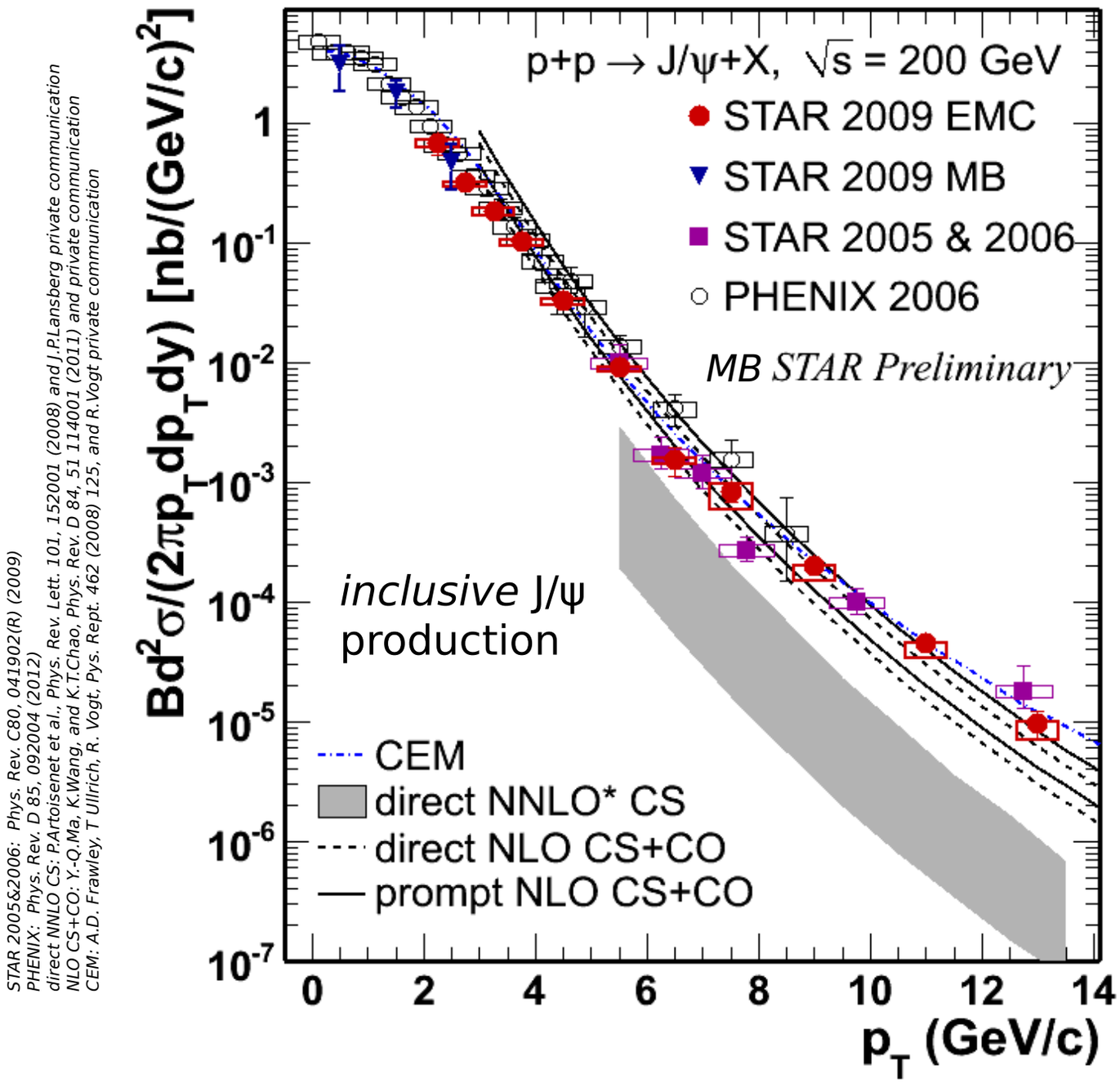
J/ψ / $\Upsilon \rightarrow e^+ e^-$, $\mu^+ \mu^-$

$|\eta| < 1, 0 < \varphi < 2\pi$

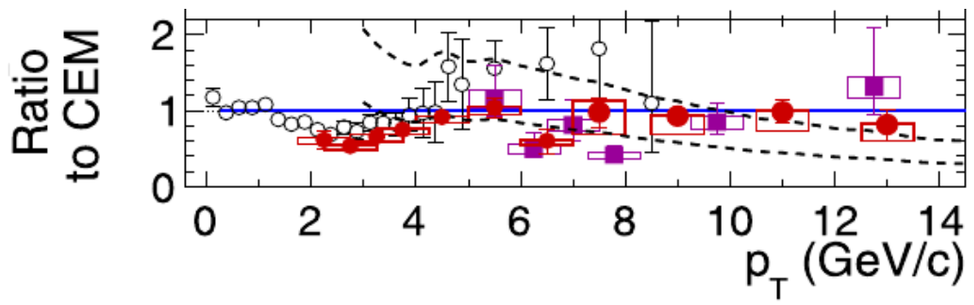
- **VPD - minimum bias trigger**
- **MTD – trigger on muon low-p_T J/ψ**
- **TPC – tracking, PID: dE/dx**
- **BEMC – PID: E/p trigger on electron high-p_T J/ψ**
- **TOF – time resolution < 100 ps PID: 1/β**

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

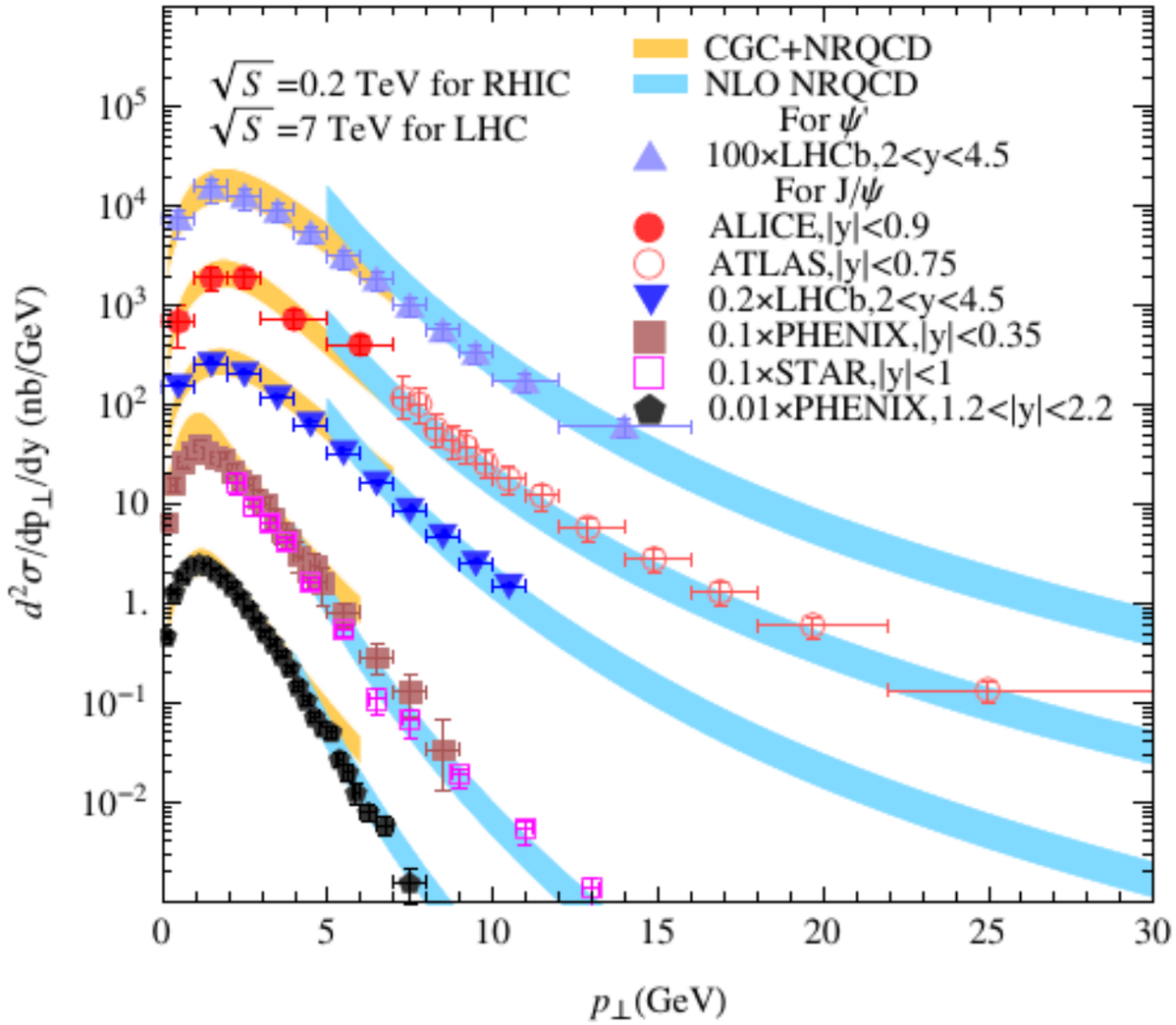


- ✓ *NLO NRQCD*, prompt production, describes the data for p_T > 4 GeV/c

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

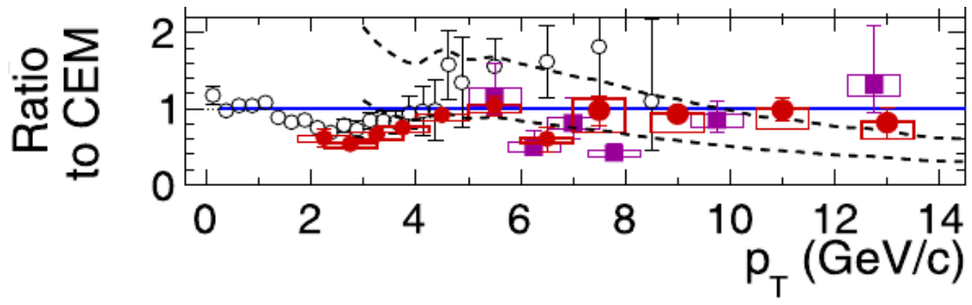
J/Ψ p_T spectrum in p+p 200 GeV

- Test of different production models



Phys. Rev. Lett. 113 (2014) 192301

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

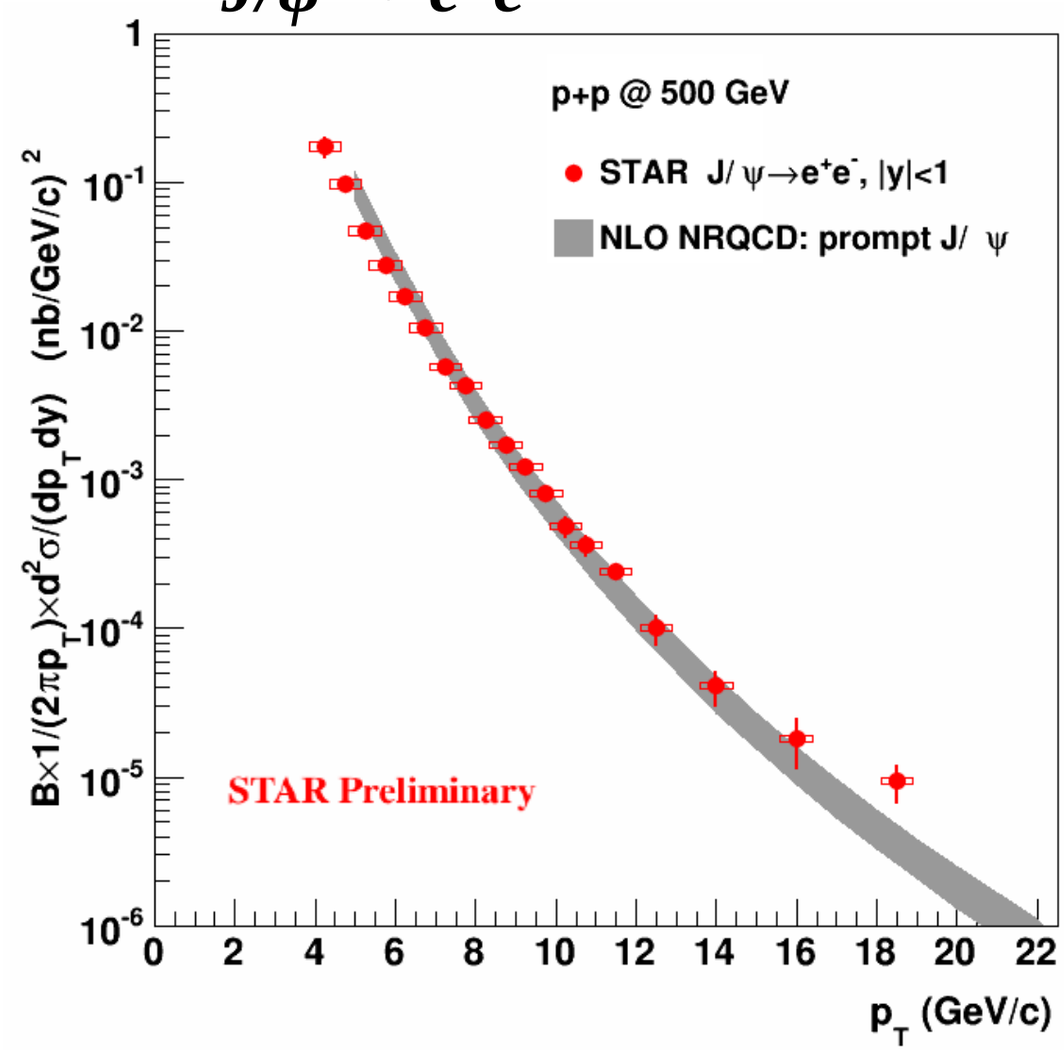


- ✓ *NLO NRQCD*, prompt production, describes the data for $p_T > 4$ GeV/c
- ✓ *CGC + NRQCD*, describes the data in the full p_T range

J/Ψ production in p+p 500 GeV

High-p_T J/ψ

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

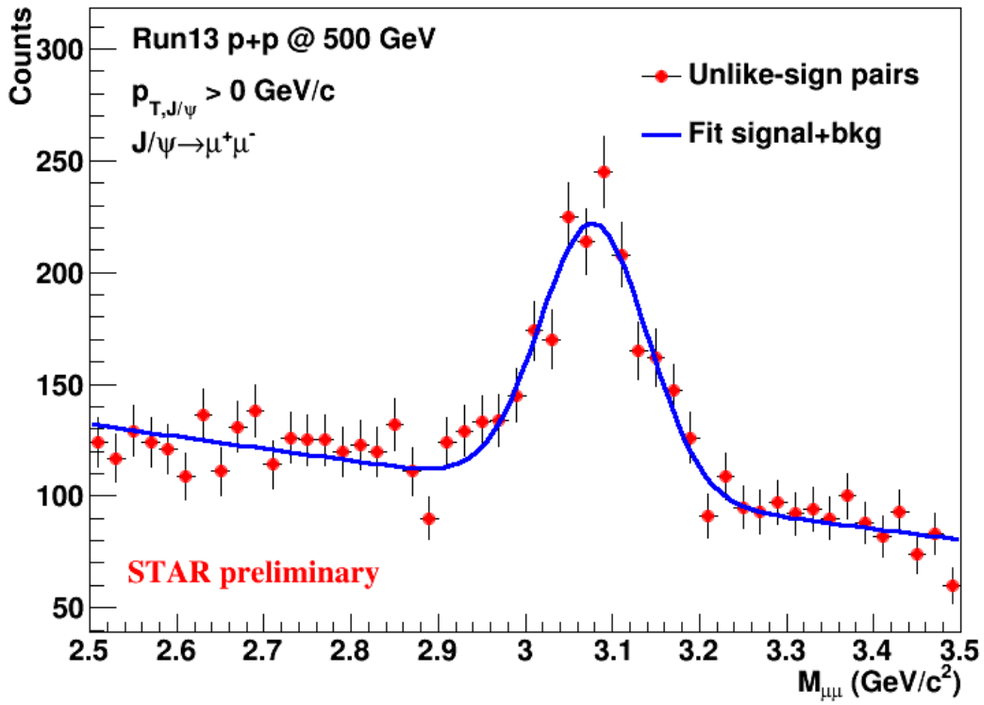


✓ NLO NRQCD describes the data well for $p_T > 4$ GeV/c

Low-p_T J/ψ accessible via dimuon channel, thanks to MTD

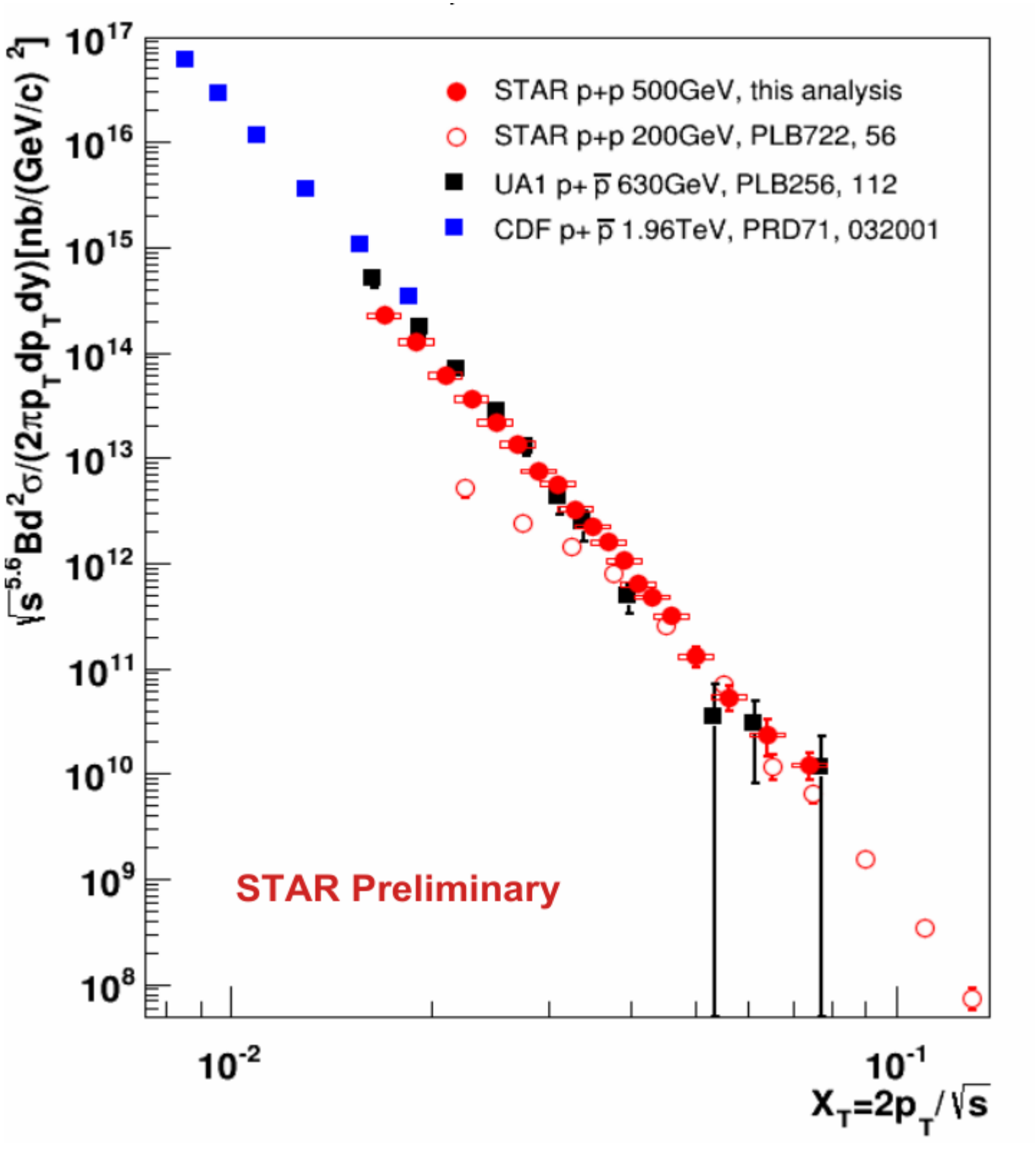
- special dimuon trigger – two hits in MTD

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



NLO NRQCD:
Phys.Rev.Lett. 106 (2011) 042002, Phys Rev. D84 (2011) 114001, JHEP 1505 (2015) 103
And private communication

J/Ψ x_T scaling



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

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

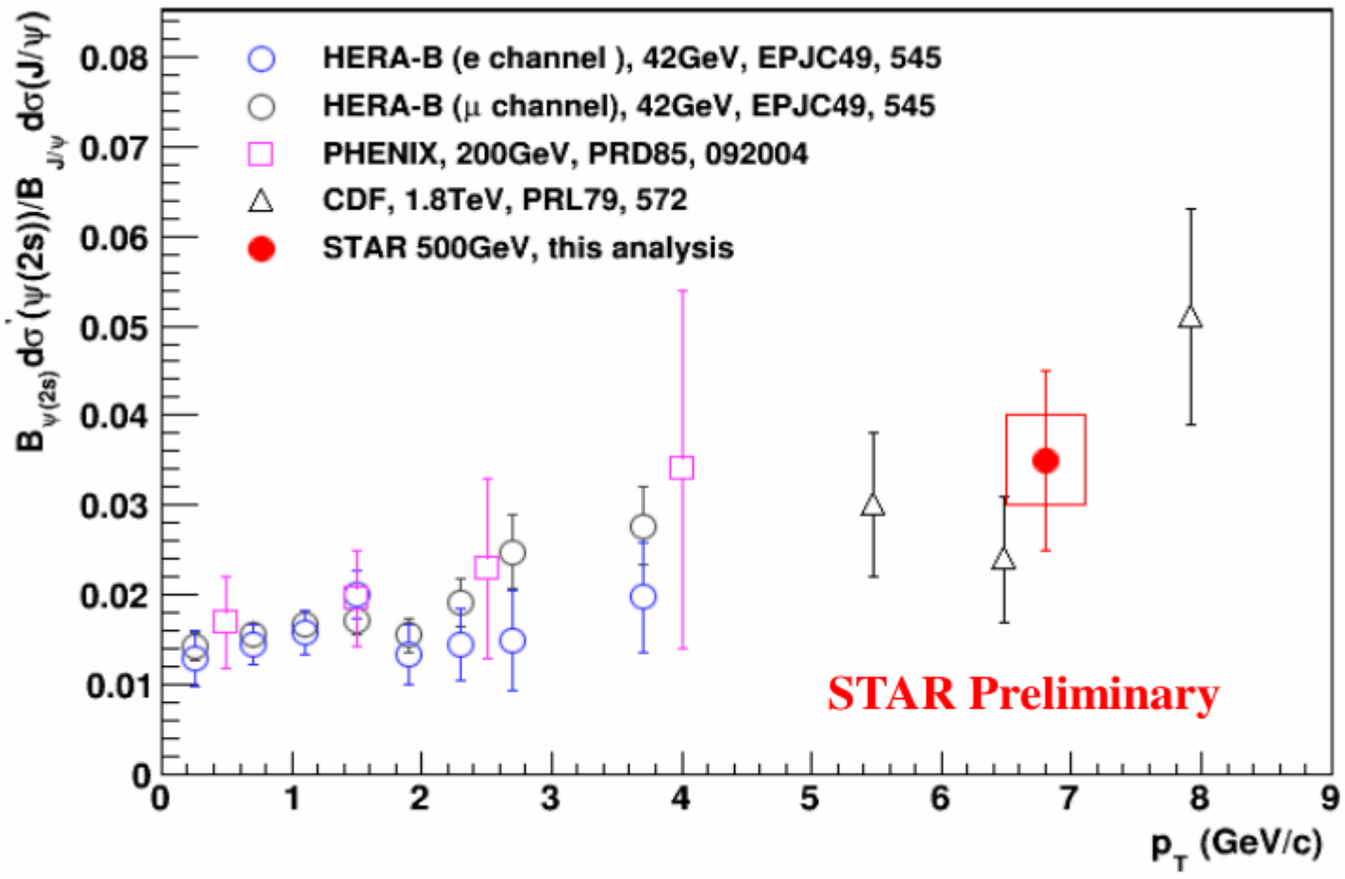
✓ p_T > 5 GeV/c – J/ψ production follows the x_T scaling of cross-section at mid-rapidity, with n ~ 5.6
(Phys. Rev. C 80, 041902 (2009))

➔ x_T scaling breaking - transition from hard to soft process

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

Ψ(2S) in p+p 500 GeV

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



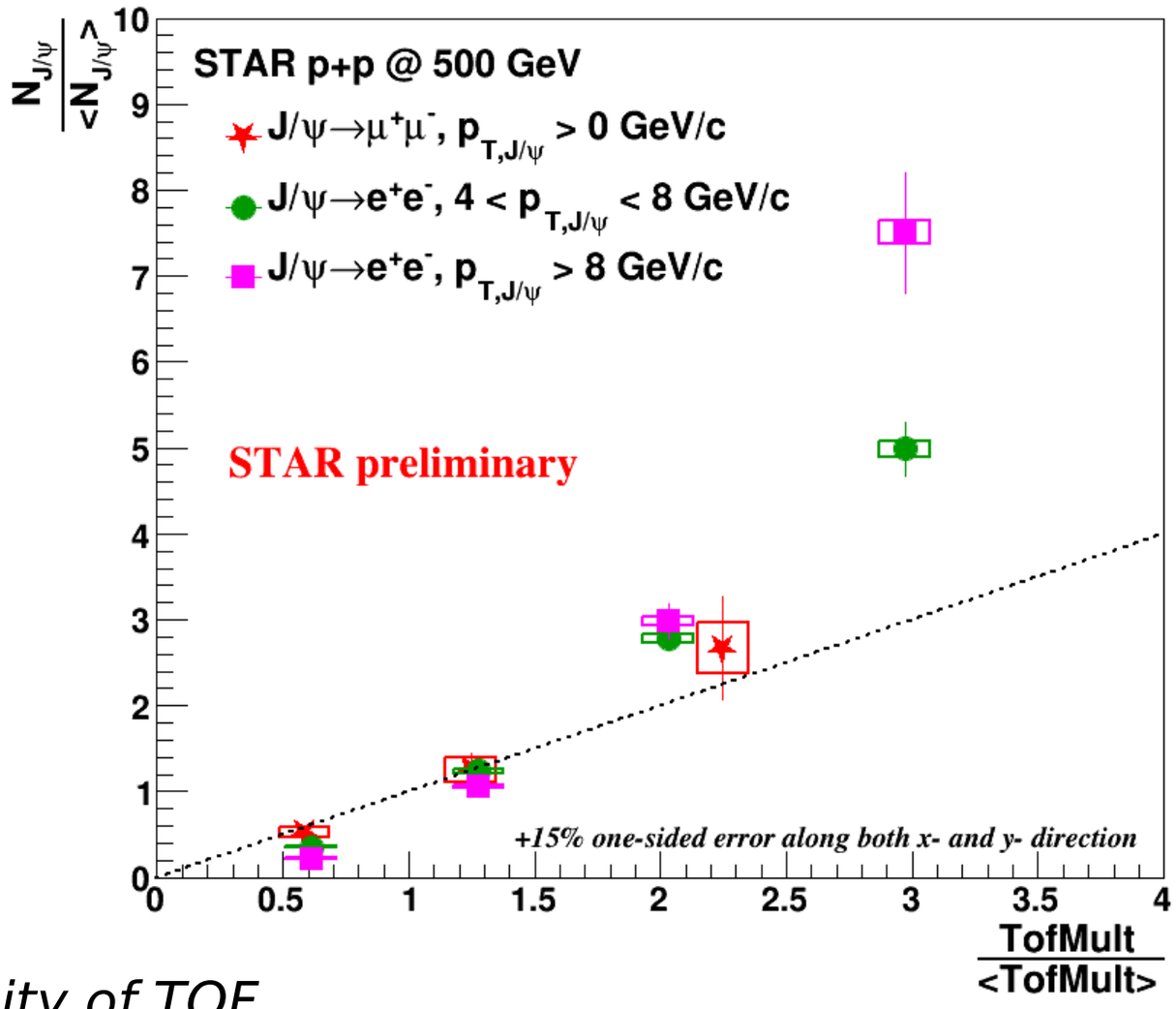
✓ First measurement of (ψ(2S) / J/ψ) ratio in p+p at 500 GeV

➔ Consistent with other experiments

➔ No collision energy dependence observed

J/Ψ production vs. event activity

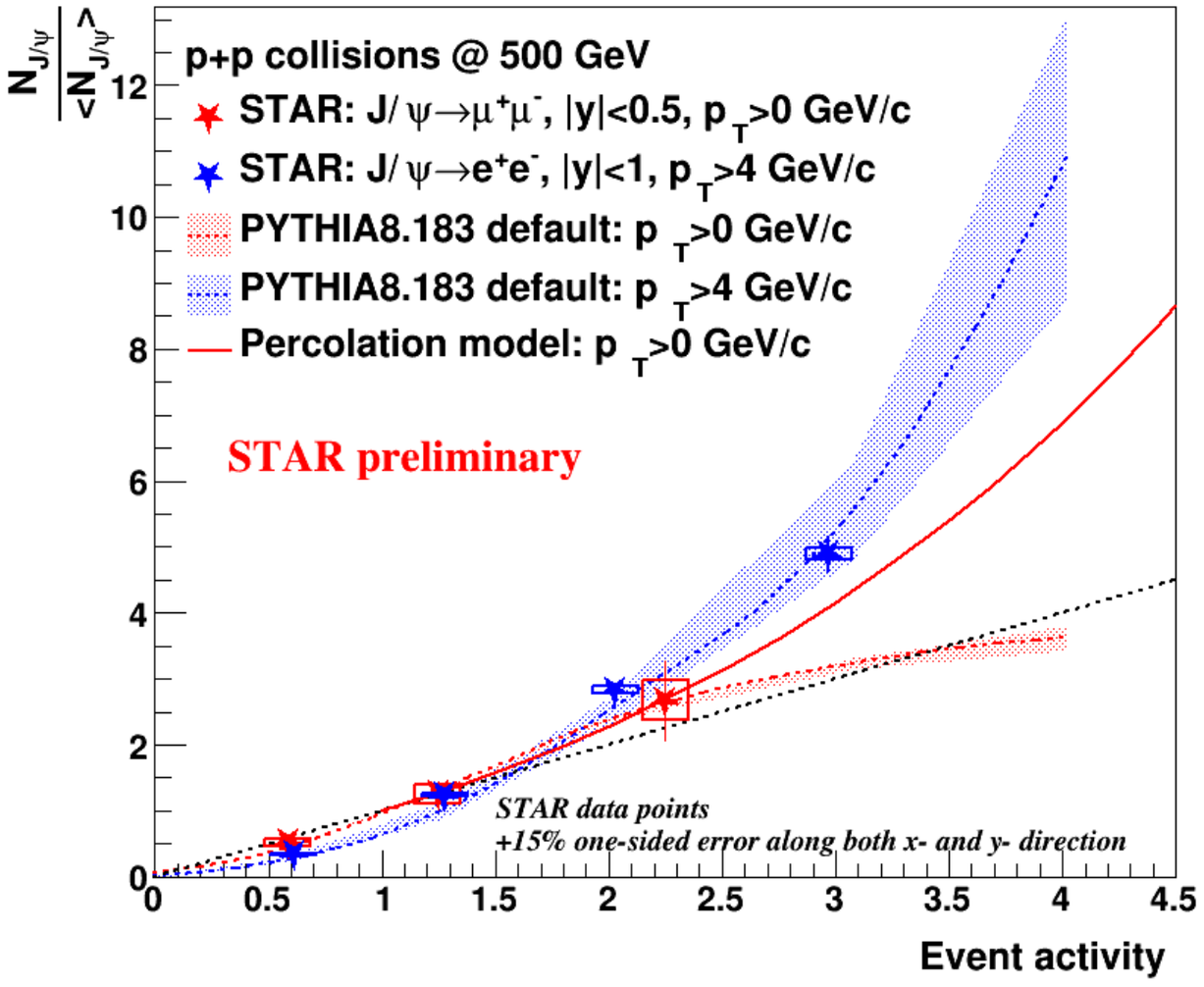
- Correlation between relative J/ψ yield and relative event multiplicity
- At higher multiplicities stronger than linear growth at p_T > 4 GeV/c
  - Similar trend at LHC for J/ψ and open charm production
  - Hint of p_T dependence



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

J/Ψ production vs. event activity - models

- Correlation between relative J/ψ yield and relative event multiplicity
- At higher multiplicities stronger than linear growth at p_T > 4 GeV/c



- 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

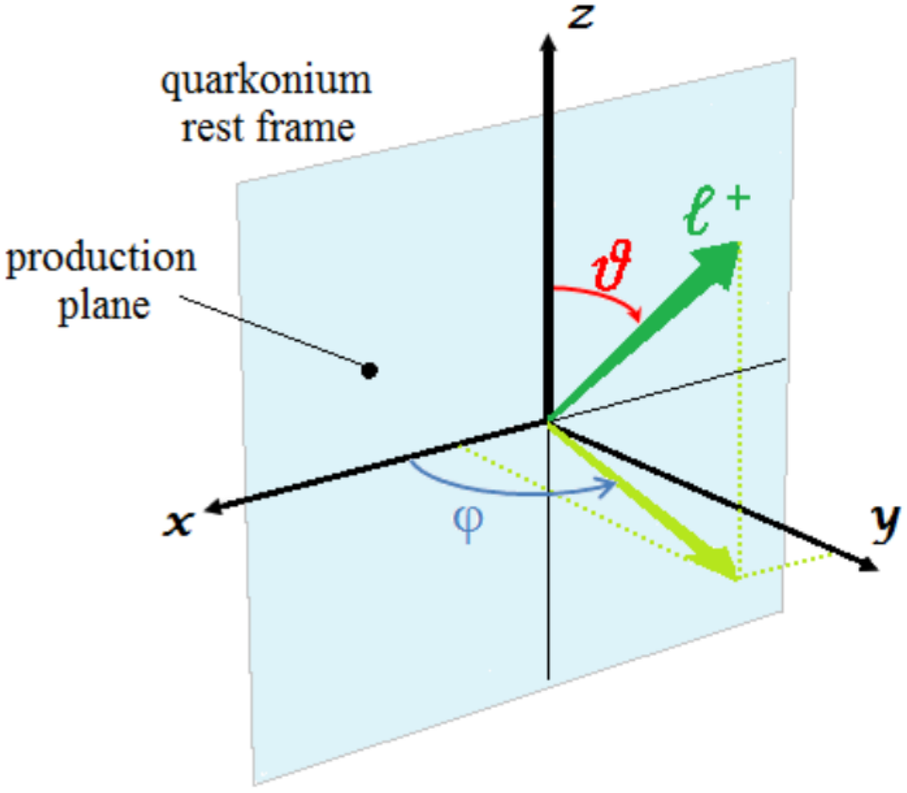
✔ PYTHIA 8 and Percolation model can qualitatively describe the observed increase

J/Ψ polarization

- Further constraints for J/ψ production models
  - Different production mechanisms in competing theoretical approaches lead to different expected polarization

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 frame
- ***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

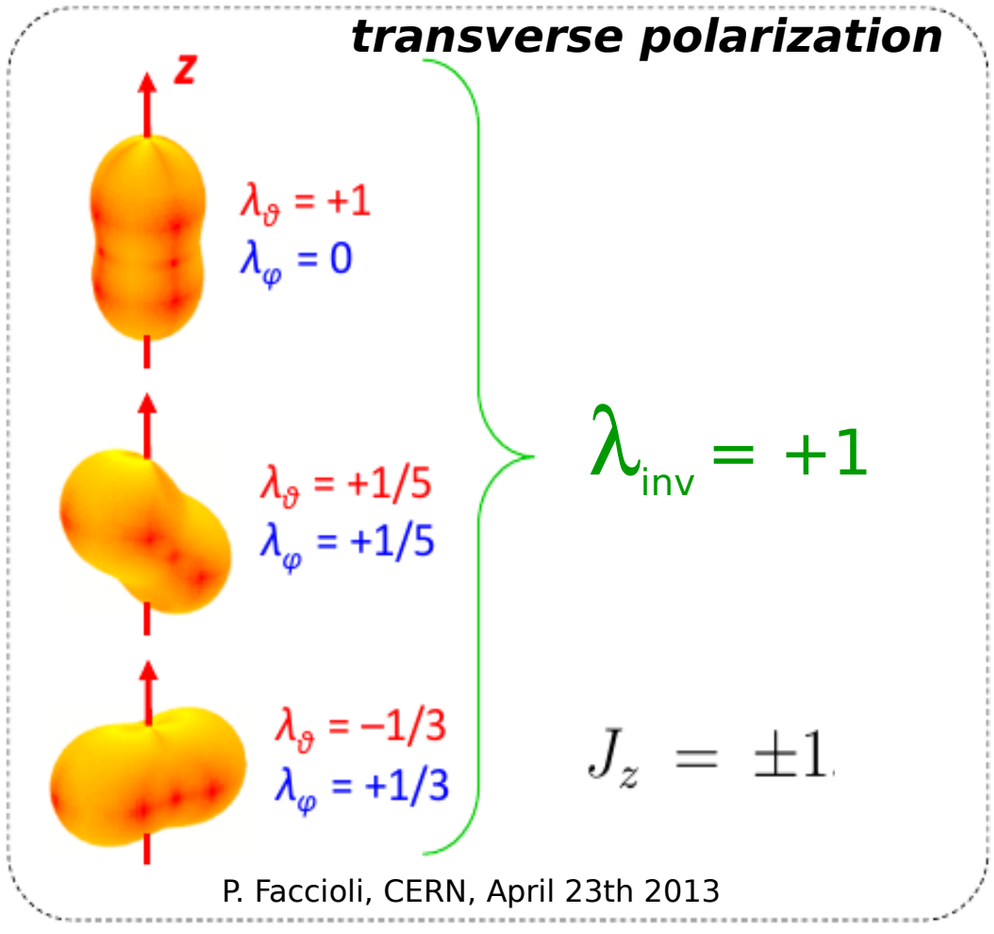
  azimuthal angle:

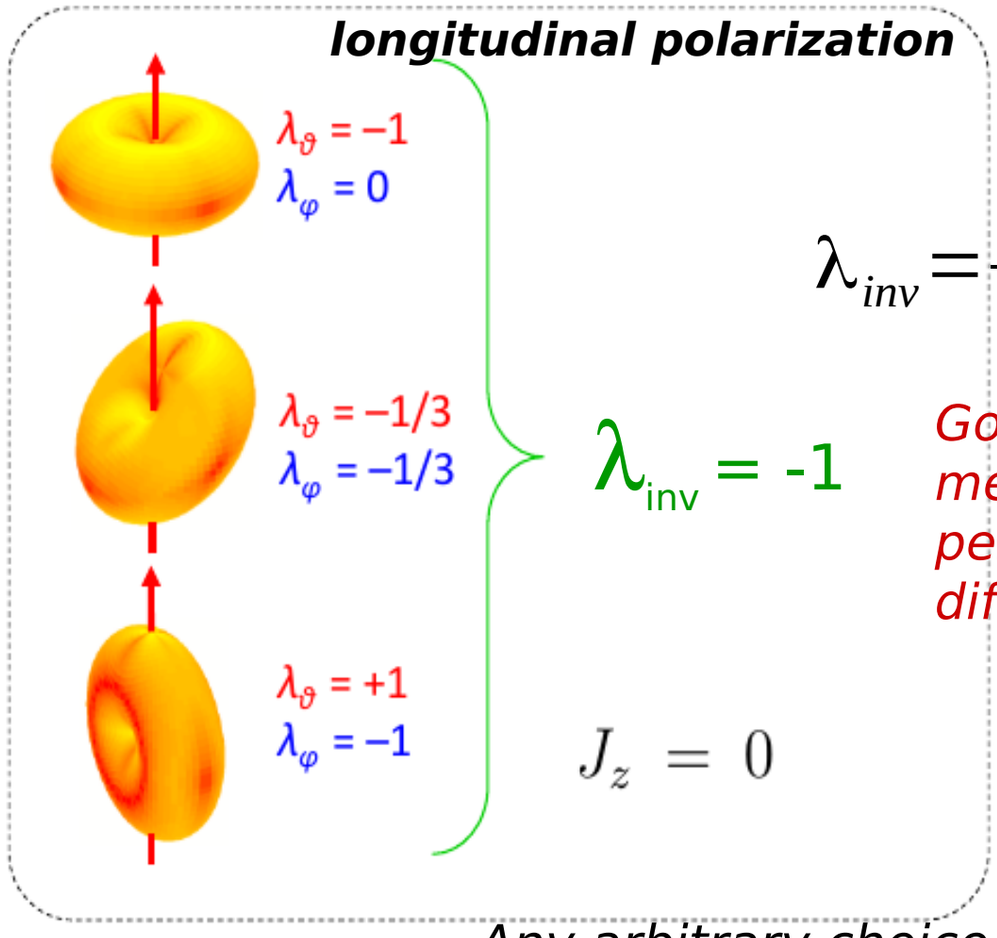
$$W(\cos\theta) \propto 1 + \lambda_\theta \cos^2\theta$$

  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 of measurements performed in different frames

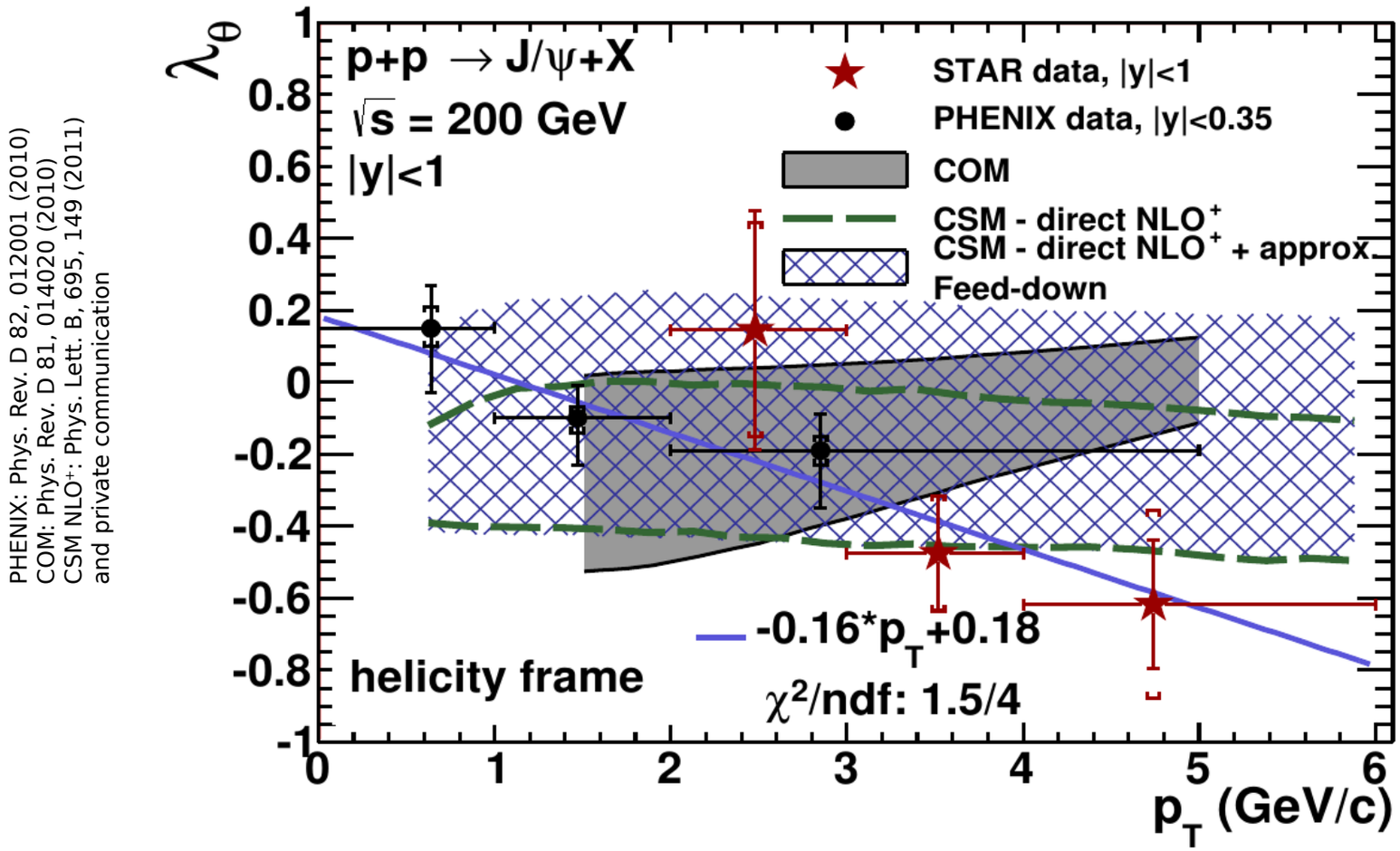
P. Faccioli, CERN, April 23th 2013

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 GeV

- First J/ψ polarization measurement at STAR
  - ✓ λ_θ parameter measured in the HX frame, $2 < p_T < 6$ GeV/c

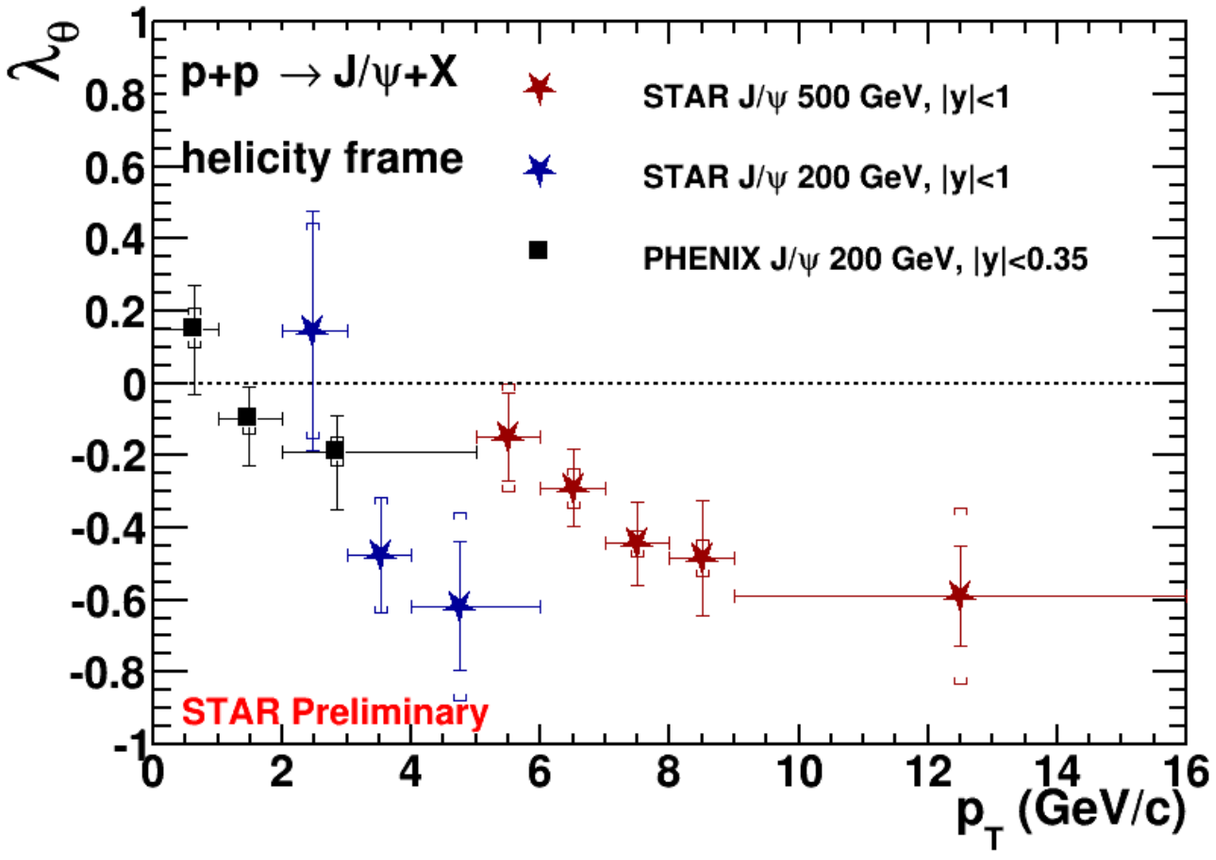


Phys.Lett. B739 (2014) 180

- ✓ RHIC data indicate trend towards longitudinal polarization with increasing p_T
- ✓ The result is consistent with NLO+ CSM

J/Ψ polarization in p+p 500 GeV

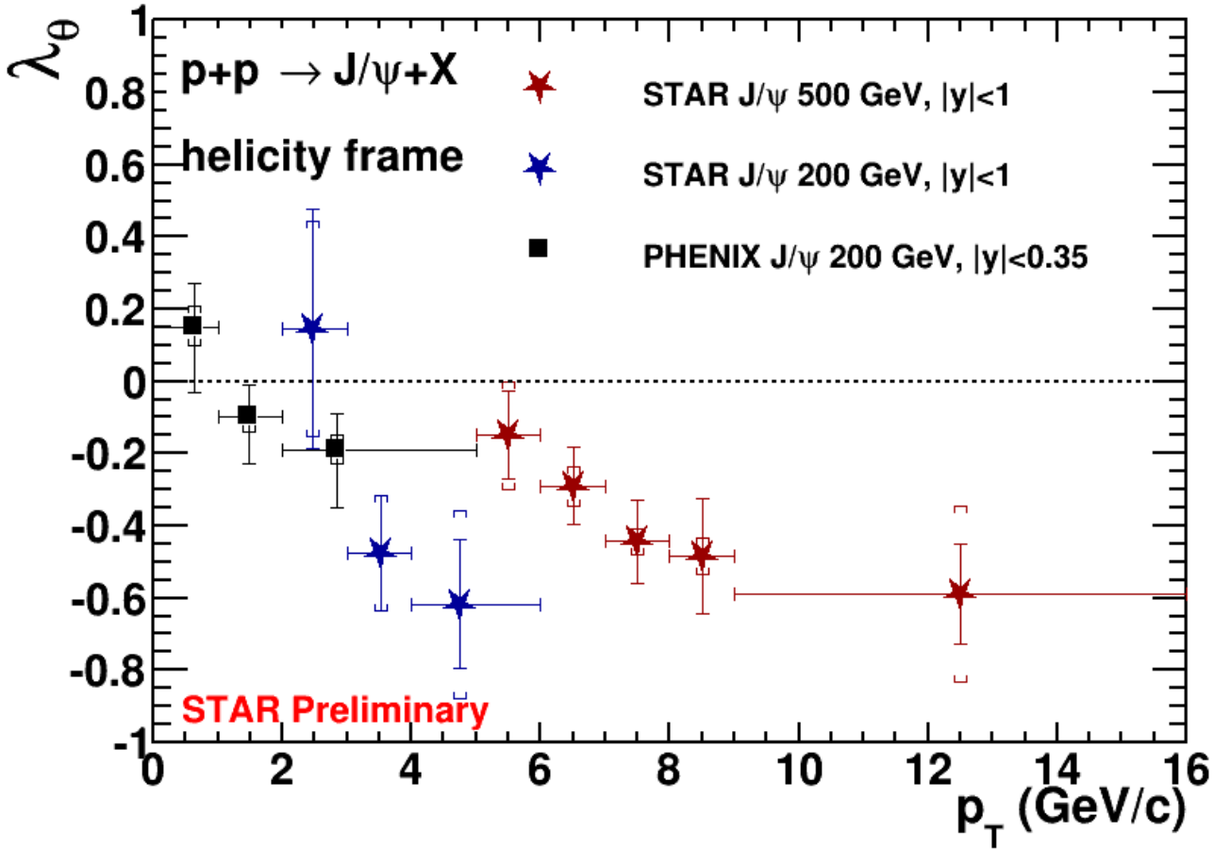
λ_θ parameter in HX frame



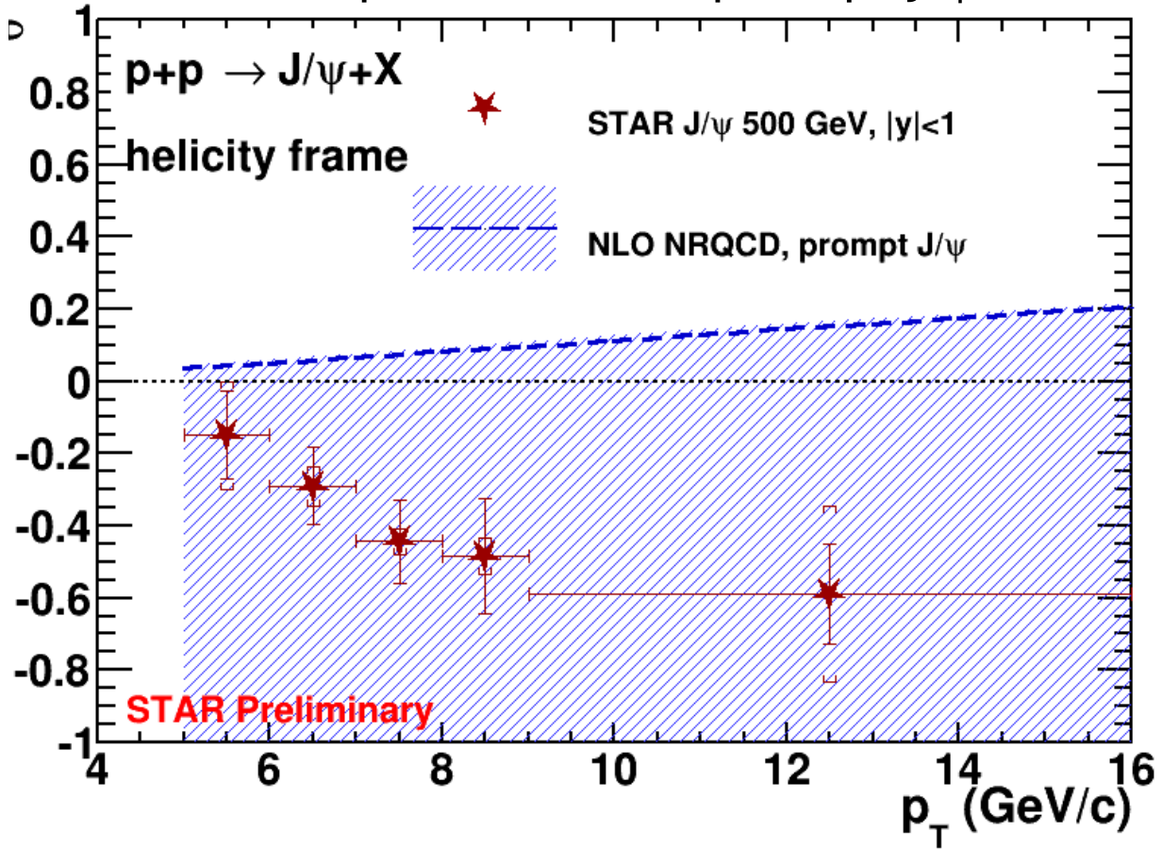
- Similar trend observed in 500 and 200 GeV p+p collisions
- Measurement extended to higher p_T range, $5 < p_T < 16$ GeV/c

J/Ψ polarization in p+p 500 GeV

λ_θ parameter in HX frame



data vs NLO NRQCD prediction for prompt J/ψ

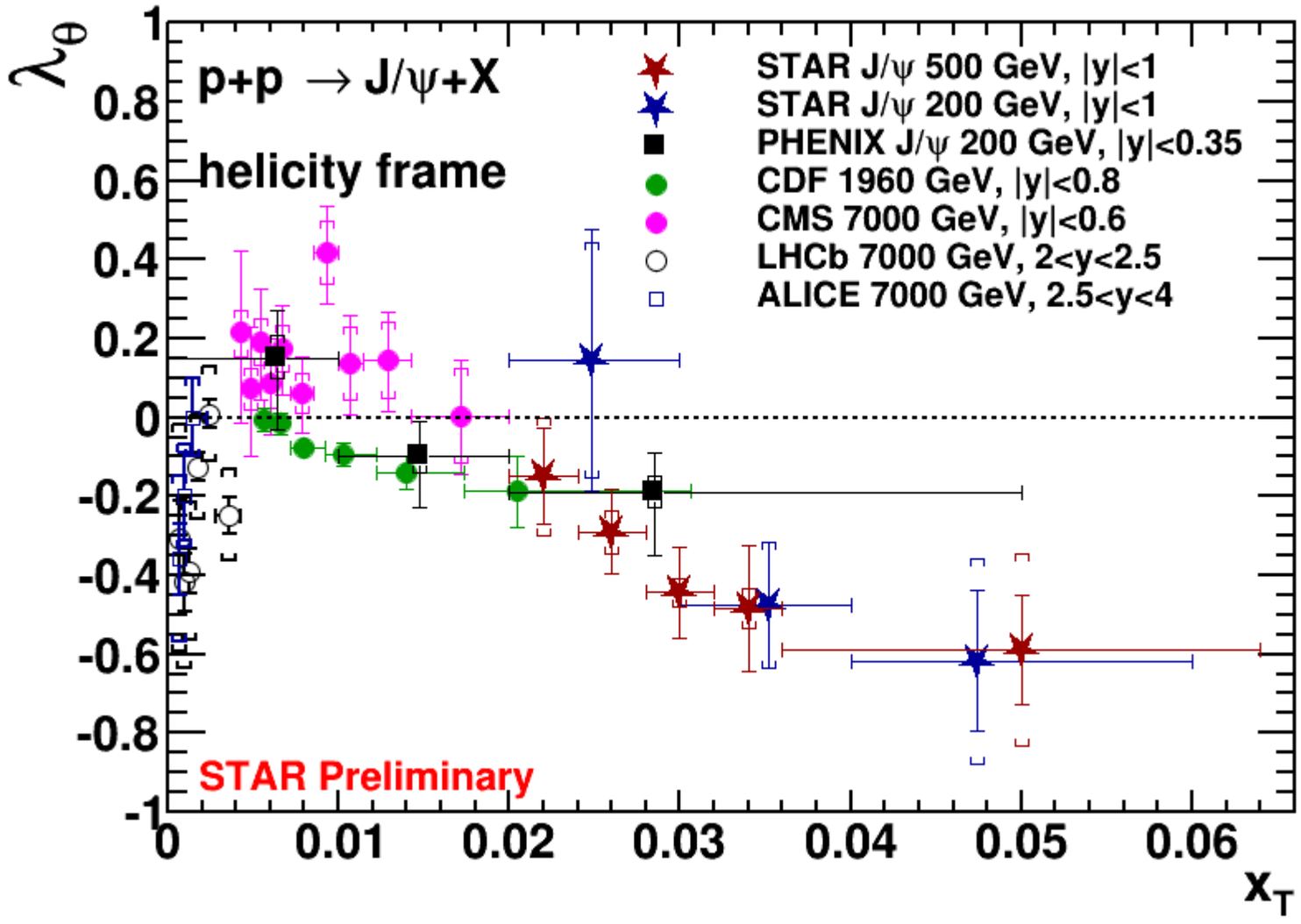


- Similar trend observed in 500 and 200 GeV p+p collisions
- Measurement extended to higher p_T range, $5 < p_T < 16$ GeV/c
- Data can help to constrain color-octet Long-Distance Matrix Elements

NLO NRQCD:
Phys. Rev. Lett. 108 (2012) 242004, Phys.Rev. D90 (2014) 1, 014002, Phys.Rev.Lett 112 (2014) 18, JHEP 1505 (2015) 103
And private communication

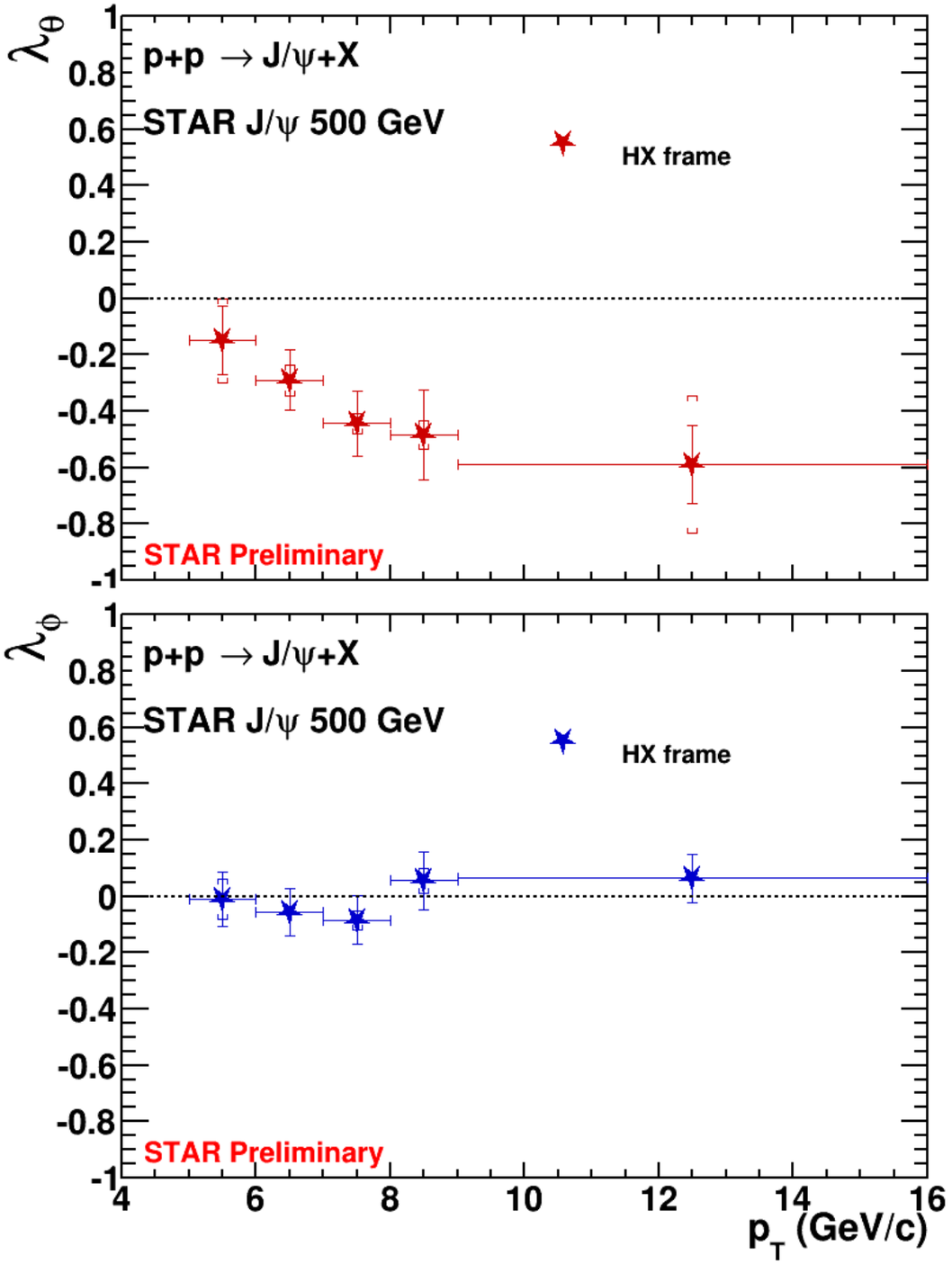
x_T dependence of λ_θ

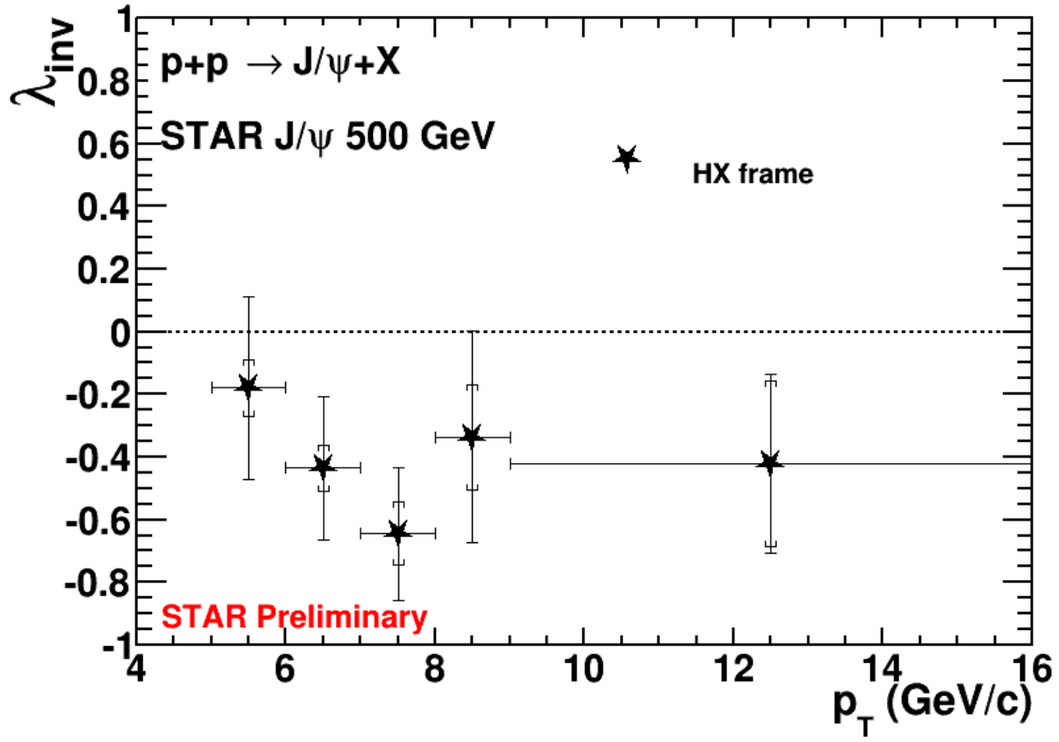
λ_θ parameter in HX frame



- Common trend towards strong negative values with increasing x_T

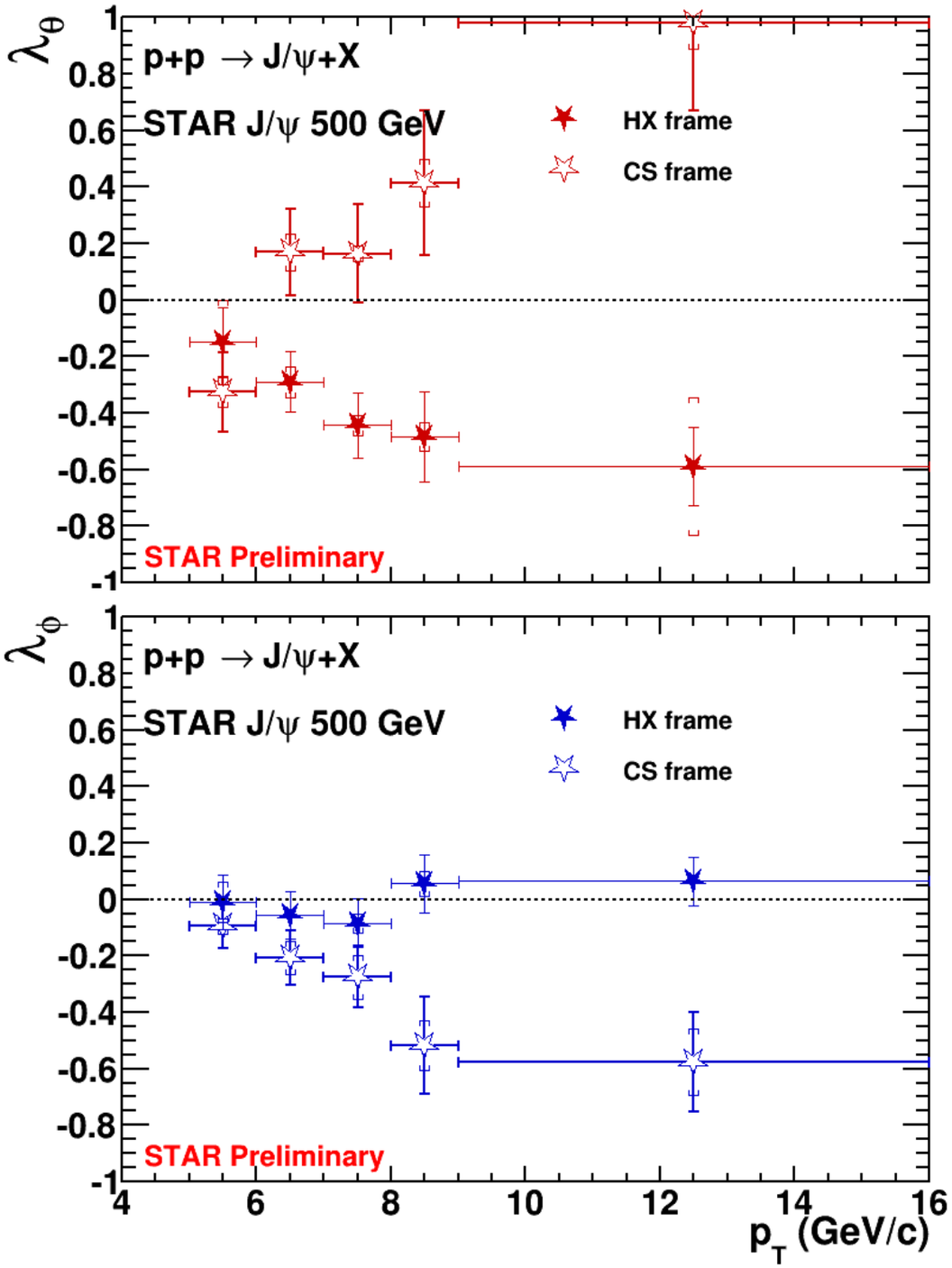
λ_φ and λ_{inv} parameters, HX frame

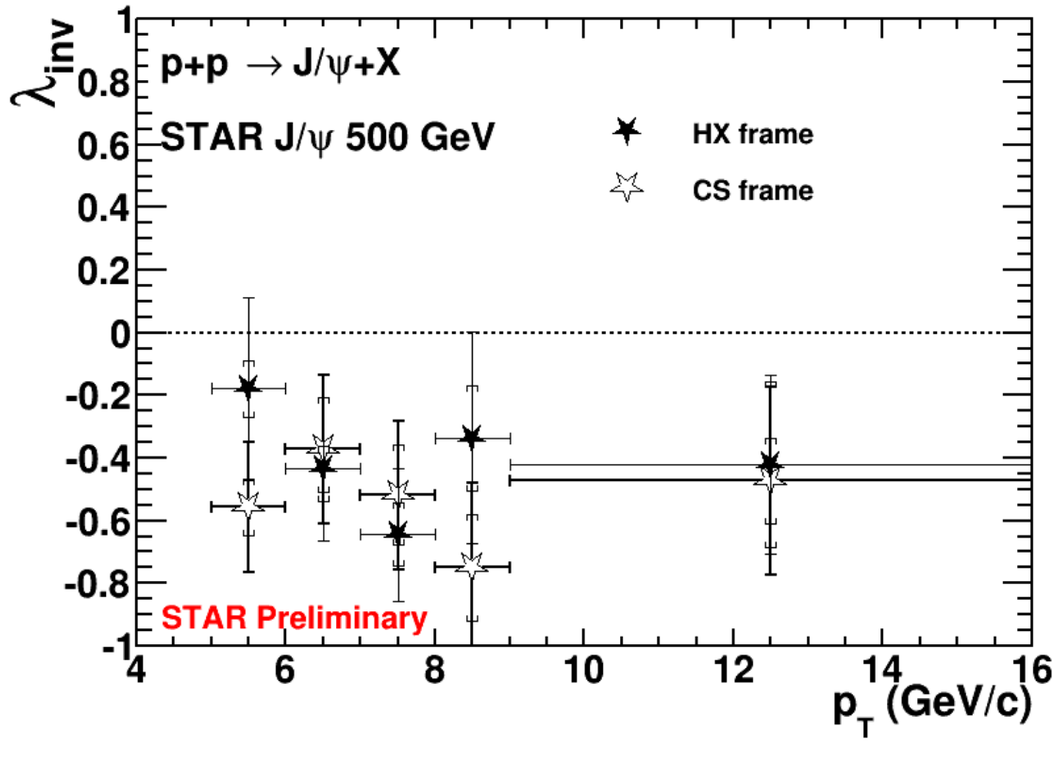




- No strong azimuthal anisotropy observed in the HX frame
- Negative values of the frame invariant λ_{inv} parameter
- Trend towards longitudinal polarization with increasing p_T

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

Summary

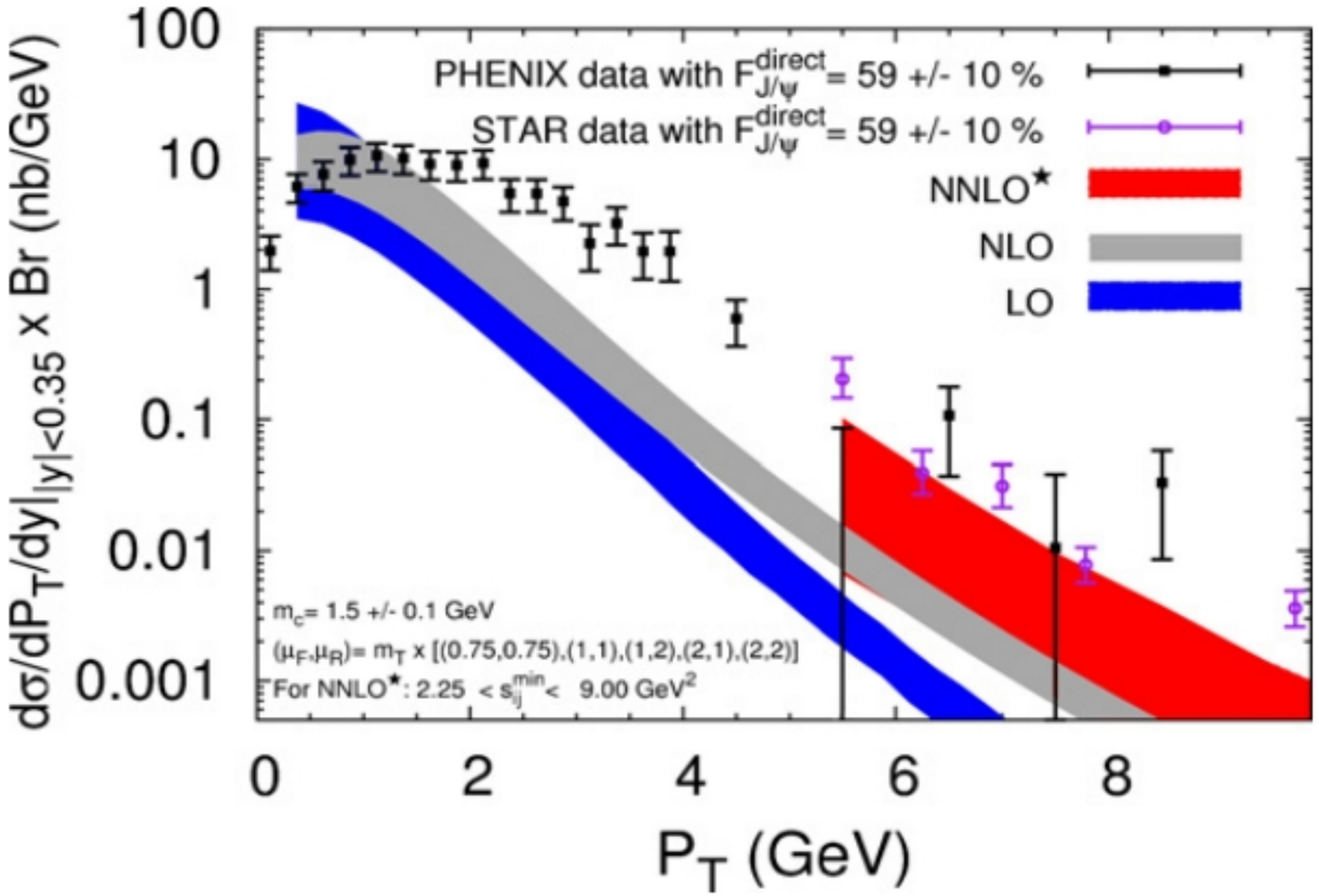
- ✔ J/ψ p_T spectra at $\sqrt{s}$ = 200 and 500 GeV described well by NRQCD prediction
- ✔ Increase of relative J/ψ yield with relative charged-particle multiplicity in p+p at $\sqrt{s}$ = 500 GeV
  - ➔ Stronger than linear rise at higher multiplicities at p_T > 4 GeV/c
  - ➔ PYTHIA8 and Percolation model can qualitatively describe the observed increase
- ✔ 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
- ➔ Different values of the λ_θ and λ_ϕ polarization parameters in CS frame
- ➔ Frame invariant parameters agree in both frames

Czech Technical University in Prague
Faculty of Nuclear Science and Physical Engineering
Project „ Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague “
CZ.1.07/2.3.00/30.0034

Thank you !

J/Ψ production mechanism - CSM

- Comparison of CSM to RHIC data

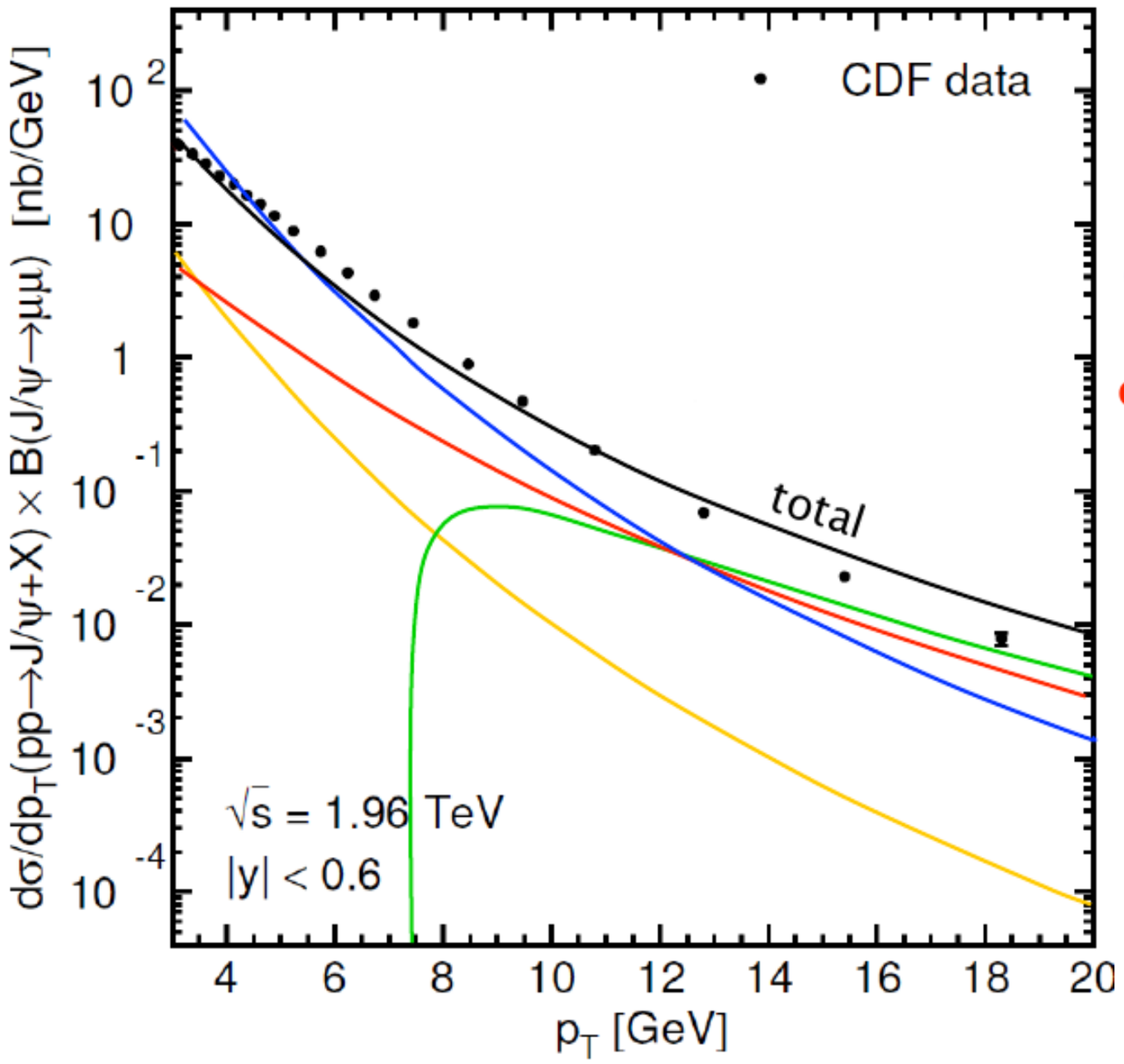


(a) central

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

J/Ψ production mechanism - NRQCD

Each color singlet and octet term has a specific polarization associated



C. Lourenço et al., Hard Probes 2013

colour-singlet $^3S_1$

$\lambda_\theta = +1$ at LO to $\lambda_\theta = -1$ at NLO

tiny fraction of the total cross section

octet $^1S_0$ → $\lambda_\theta = 0$ at LO, NLO

octet $^3S_1$ → $\lambda_\theta = +1$ at LO, NLO at high p_T

octet ^3P_J → $\lambda_\theta >> +\bar{1}$ at NLO at LO it is 0

Dominance of the $^3S_1$ and ^3P_J octet terms

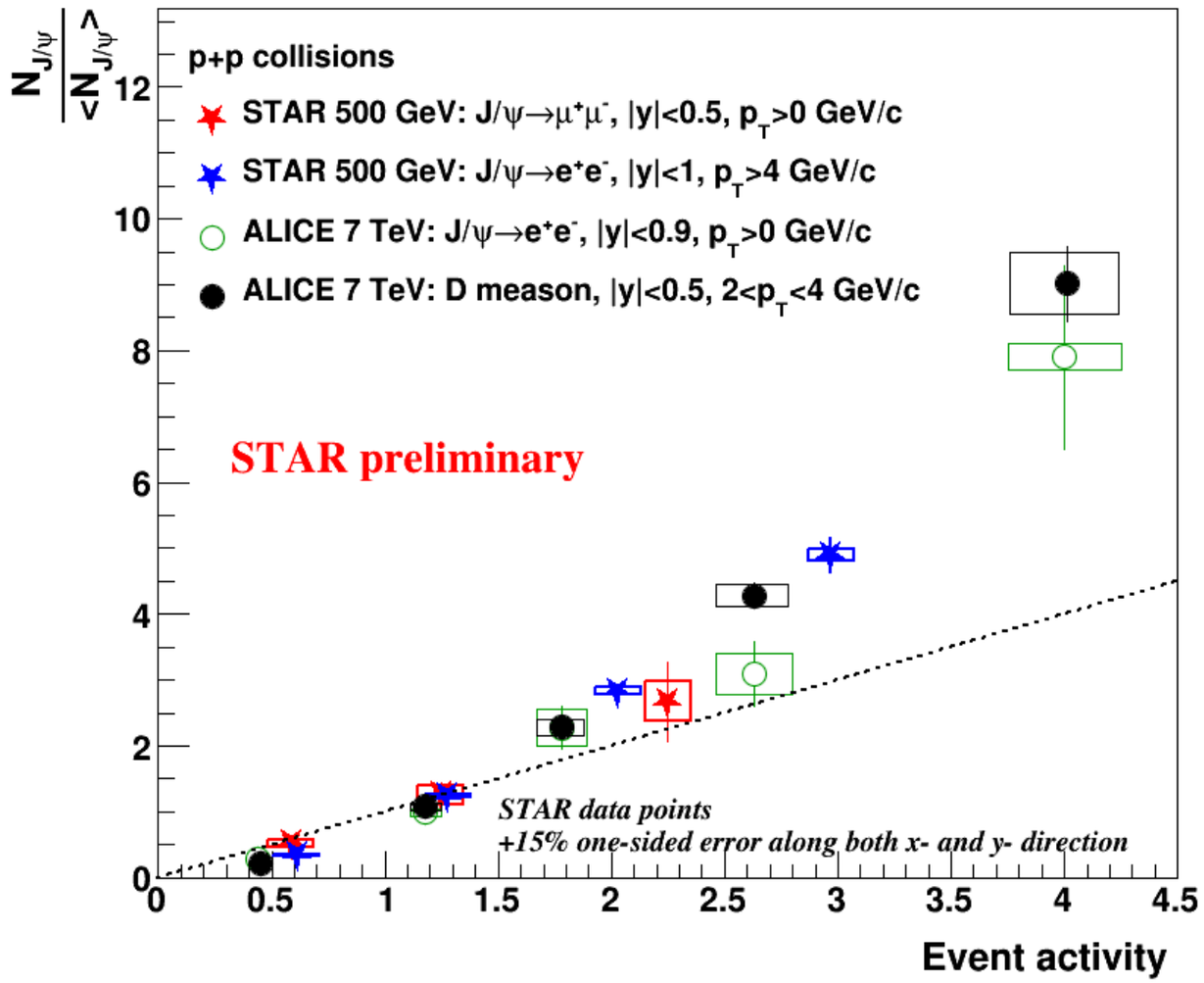
→ $\lambda_\theta \approx +1$,

for high-p_T S-wave quarkonia

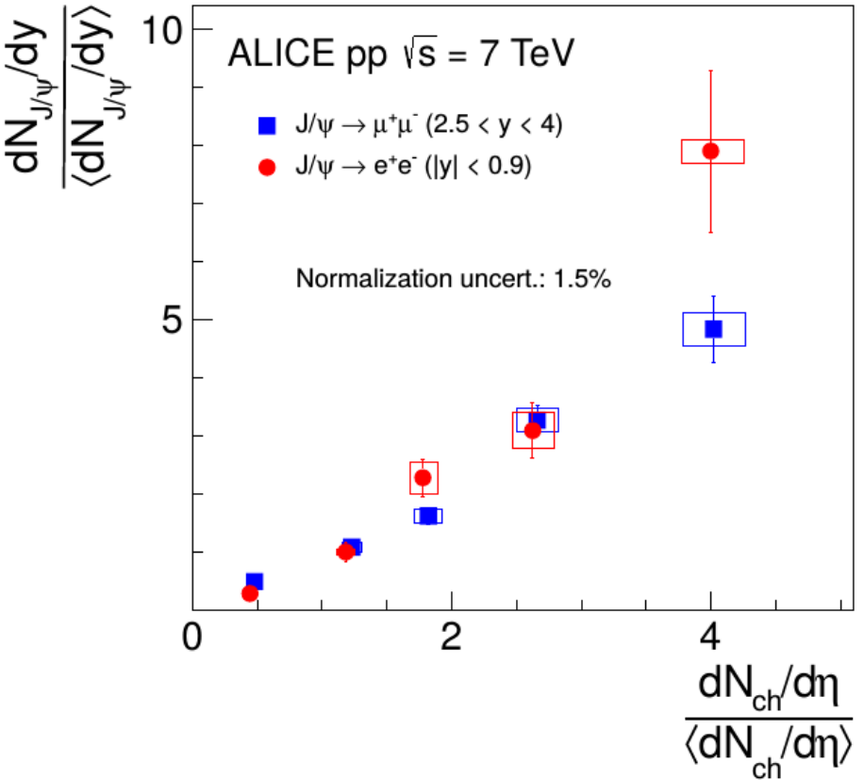
Color-octet contributions have fixed shape but adjustable normalizations (LDMEs)

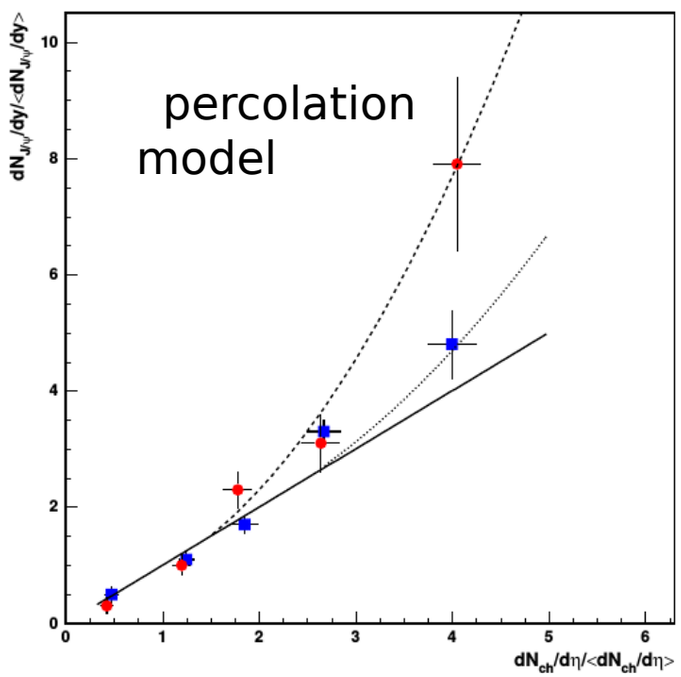
J/Ψ production vs. event activity

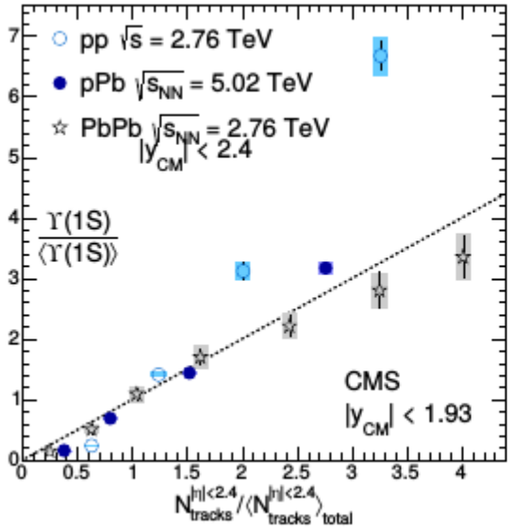
- Correlation between relative J/ψ yield and relative event multiplicity
- At higher multiplicities stronger than linear growth
  - Similar trend at LHC for J/ψ and open charm production
  - Hint of p_T dependence

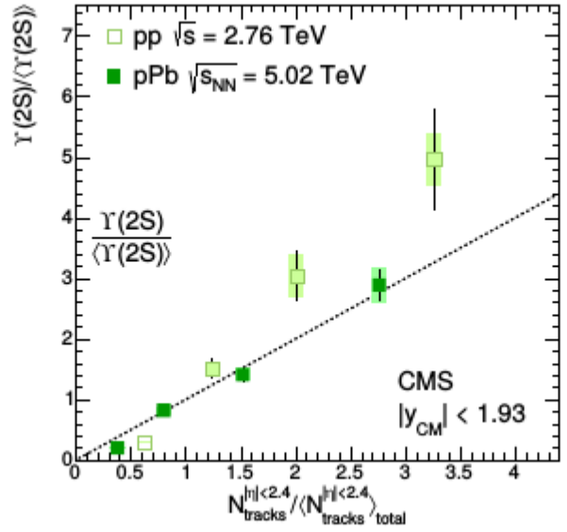


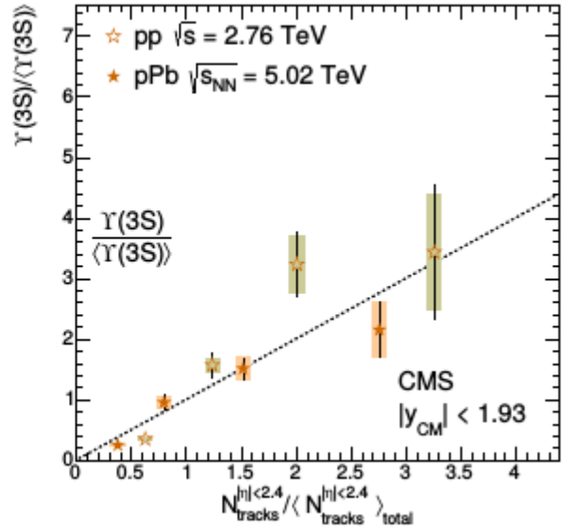
J/Ψ production vs. event activity, LHC

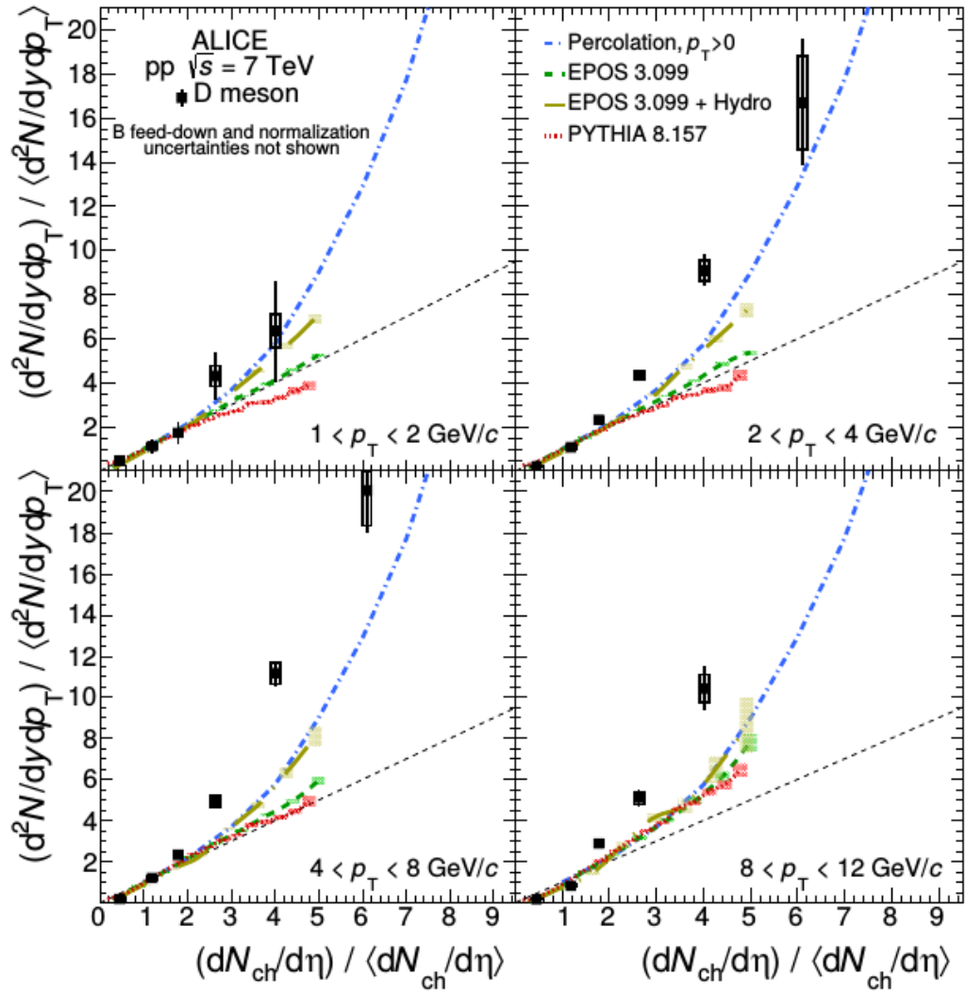






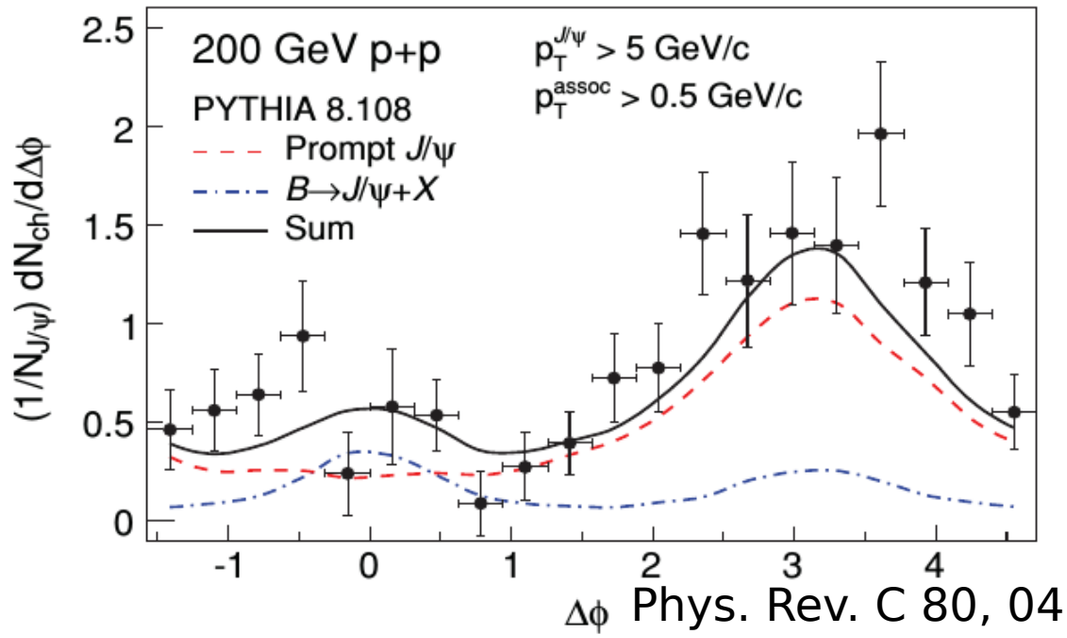






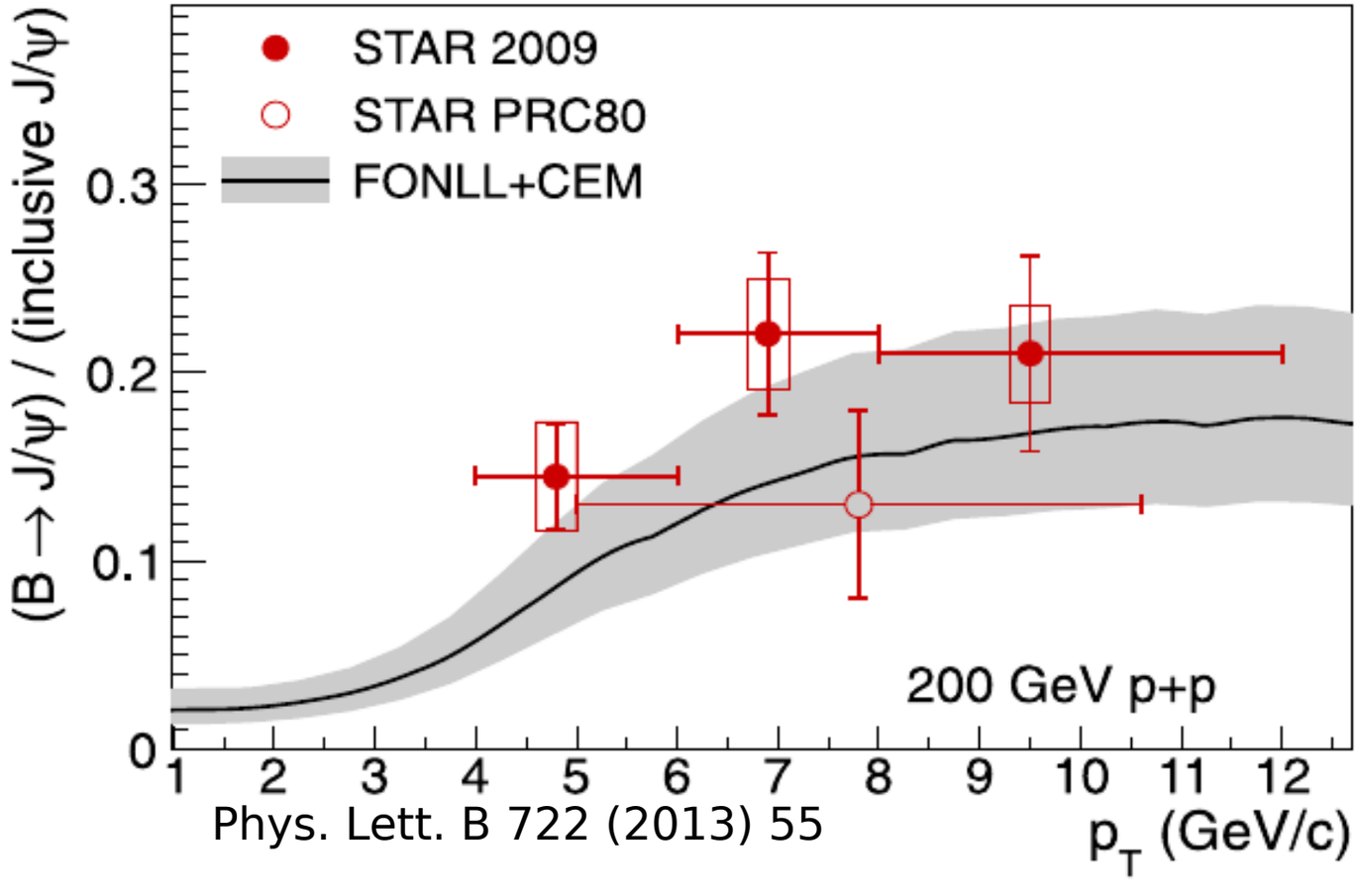
B -> J/Ψ fraction in p+p 200 GeV

- ✓ 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

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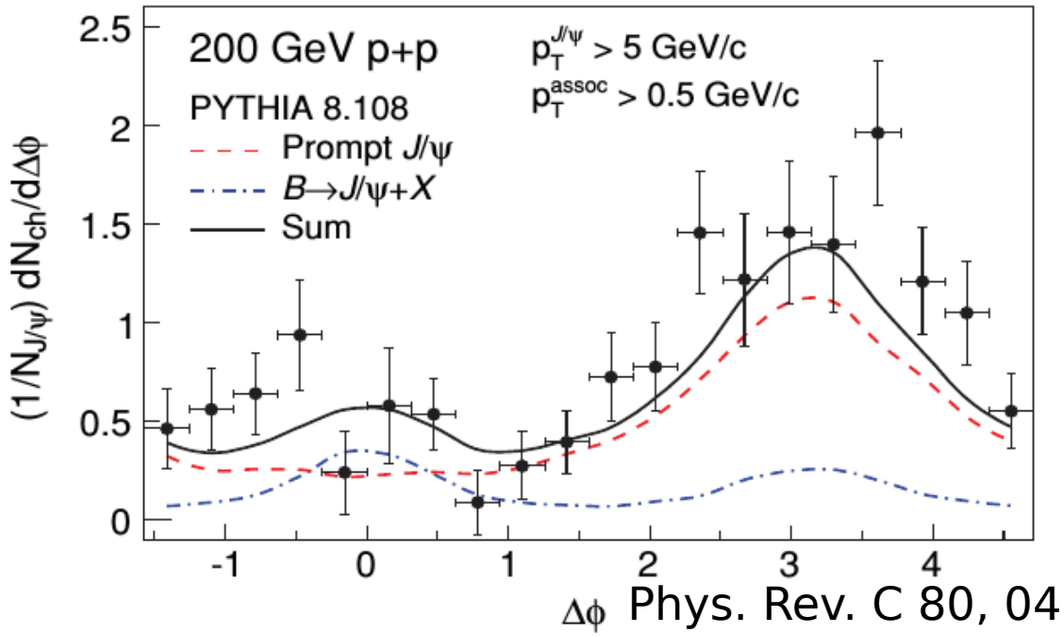
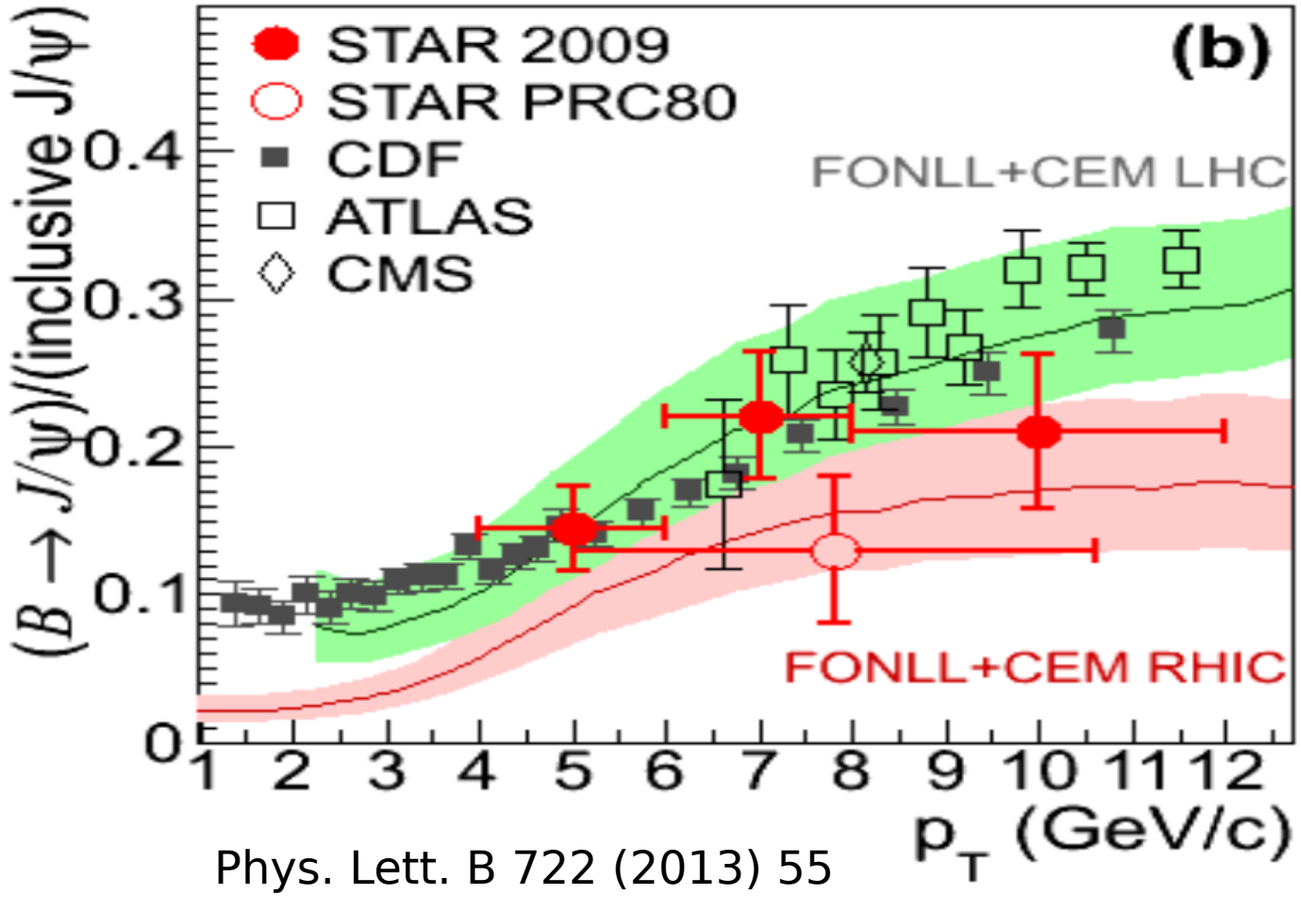


Phys. Rev. C 80, 041902 (2009)

- ➔ 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

Quarkonia in the STAR Experiment

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

$|\eta| < 1$, $0 < \varphi < 2\pi$