Quarkonium spin asymmetry measurements in p+p collisions by the PHENIX experiment at RHIC

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virtual Quarkonia as Tools 2021

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Motivation

Measurements of charm quark bound states provide a good way to explore QCD.
Charm quark mass is larger than the hadronization scale

⇨ NRQCD techniques can be used to provide theoretical access to hadronization.

J/ψ, a $c\bar{c}$ bound state with spin = 1 is especially convenient.

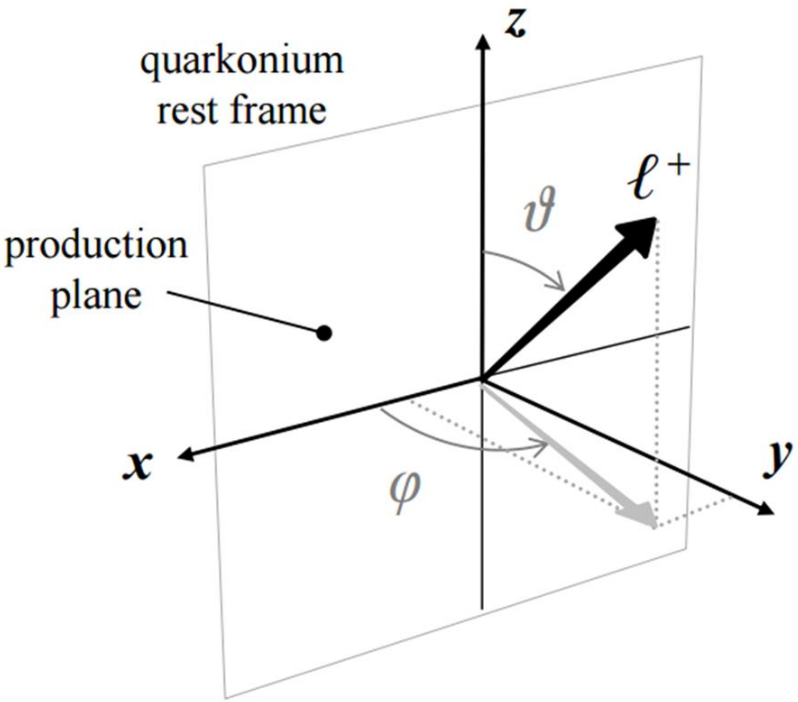
- J/ψ decays to lepton pairs with high branching ratio.
- copiously produced.

Many J/ψ production models describe well general features, like p_T or rapidity distributions.

Describing finer details, like angular distribution (spin alignment) can provide an additional handle on studying production and hadronization mechanisms.

J/ψ polarization introduction

We are studying unpolarized p+p collisions.
“Polarization” is not a good choice of words. “Spin alignment” is better.
We are looking at angular distribution of a positively charged decay lepton relative to a “polarization axis” in quarkonium rest frame.



$$\frac{dN}{d\cos\vartheta d\varphi} \propto$$
$$1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi + \lambda_\varphi \sin^2\vartheta\cos 2\varphi$$

Often shortened to:

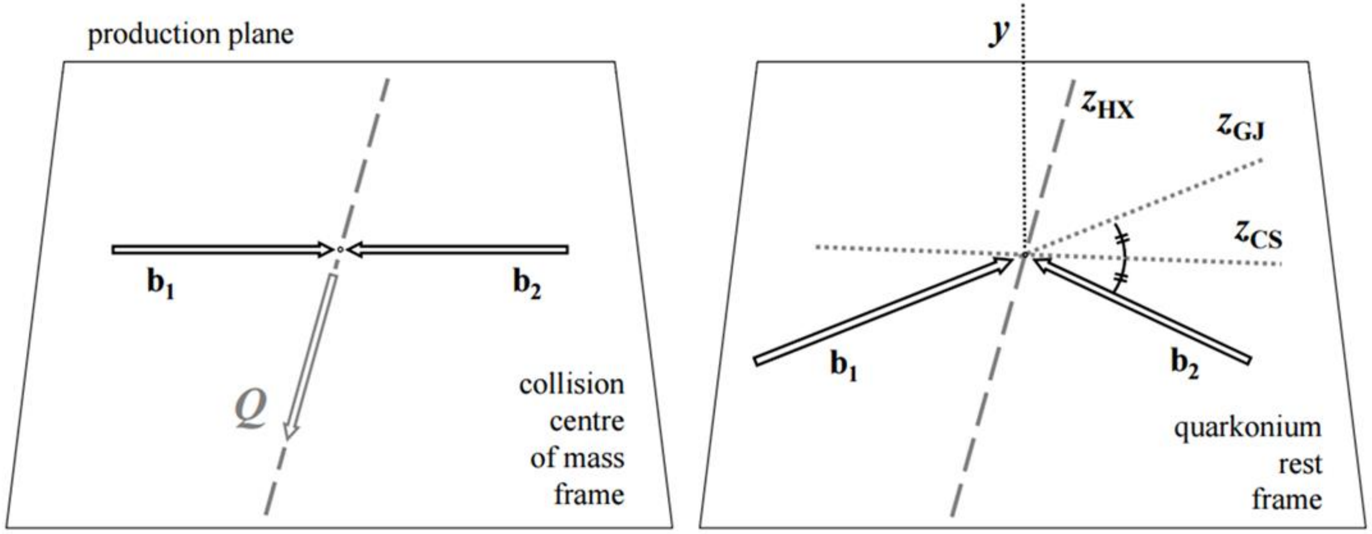
$$\frac{d\sigma}{d\cos\theta^*} = A(1 + \lambda\cos^2\theta^*),$$

Different “polarization frames” can be used, depending on the goal of the study.

Polarization frames: choosing Z-axis

Helicity (HX): J/ψ momentum in lab frame, explores final state effects
Gottfried-Jackson (GJ): beam particle momentum, fixed target experiments.
Collins-Soper (CS): bisector of two colliding beams.

- *Note the difference between parton momentum used in theory and proton momentum used in experiment*
- *Inclusive vs. direct production is also an important consideration*



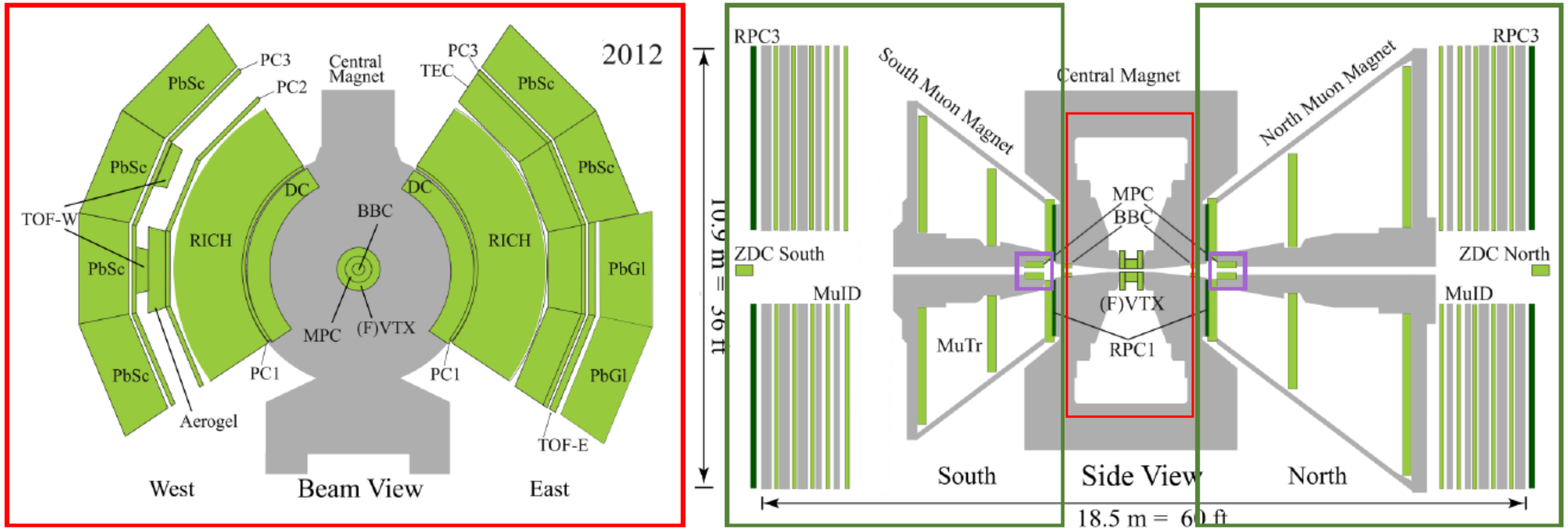
$$\frac{d\sigma}{d(\cos\vartheta)d\varphi} \propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi}\sin(2\vartheta)\cos\varphi + \lambda_\phi sin^2\vartheta\cos 2\varphi$$

Frame-invariant parameters

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

$$F = \frac{1 + \lambda_\theta + 2\lambda_\phi}{3 - \lambda_\theta}$$

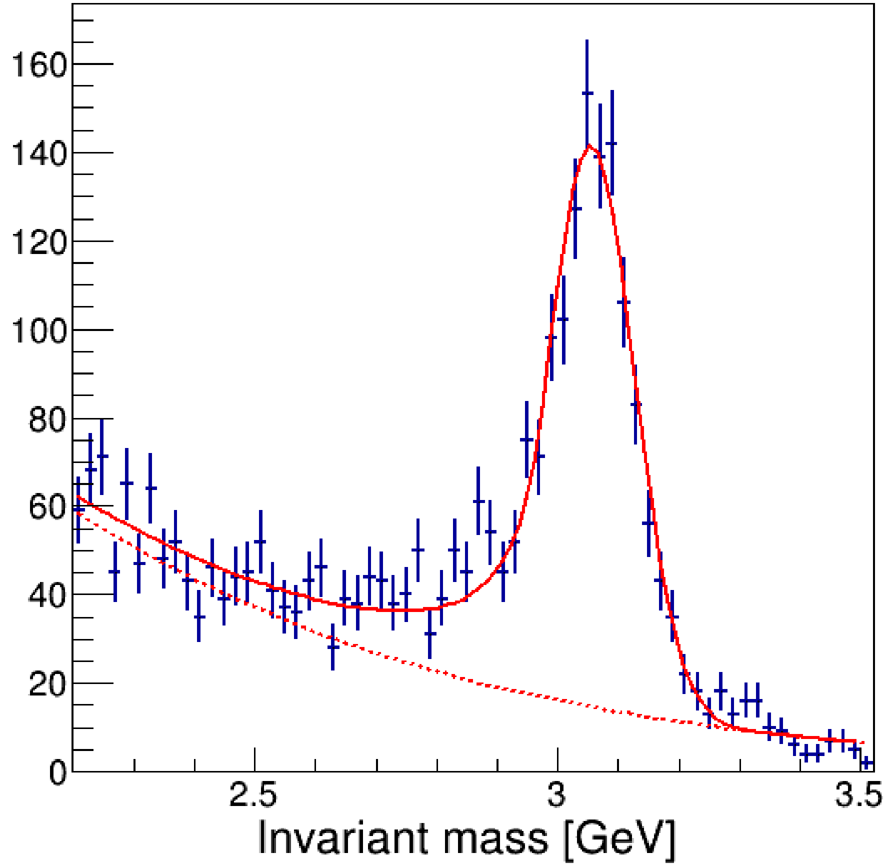
The PHENIX Detector



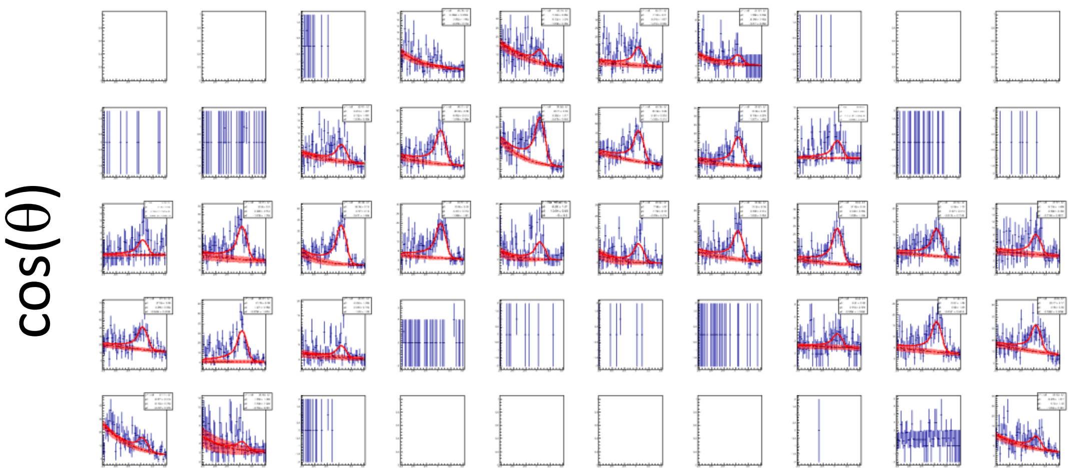
- **Central Arms** (|η| < 0.35, $\Delta\phi = \frac{\pi}{2} \times 2$)
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc
- **Muon Arms** (1.2 < |η| < 2.2 (S) or 2.4 (N), $\Delta\phi = 2\pi$)
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs
- **MPC/MPC-Ex** (3.1 < |η| < 3.8, $\Delta\phi = 2\pi$)
  - EMCal ($PbWO_4$) / Preshower by W + Si minipads

Analysis details

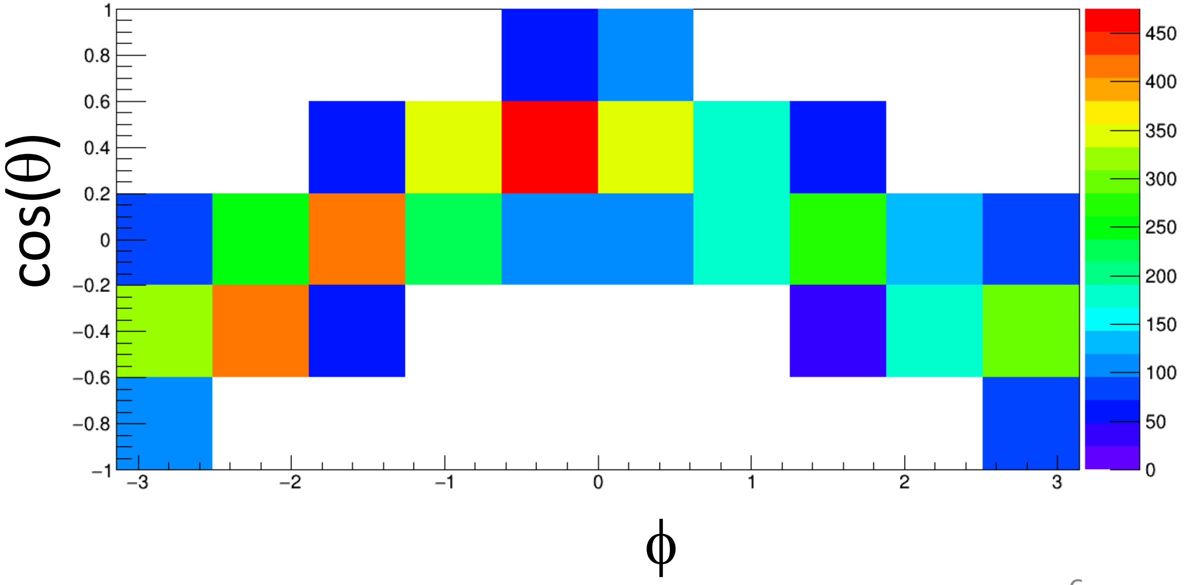
J/ψ are measured via invariant mass distribution of decay leptons.



Data

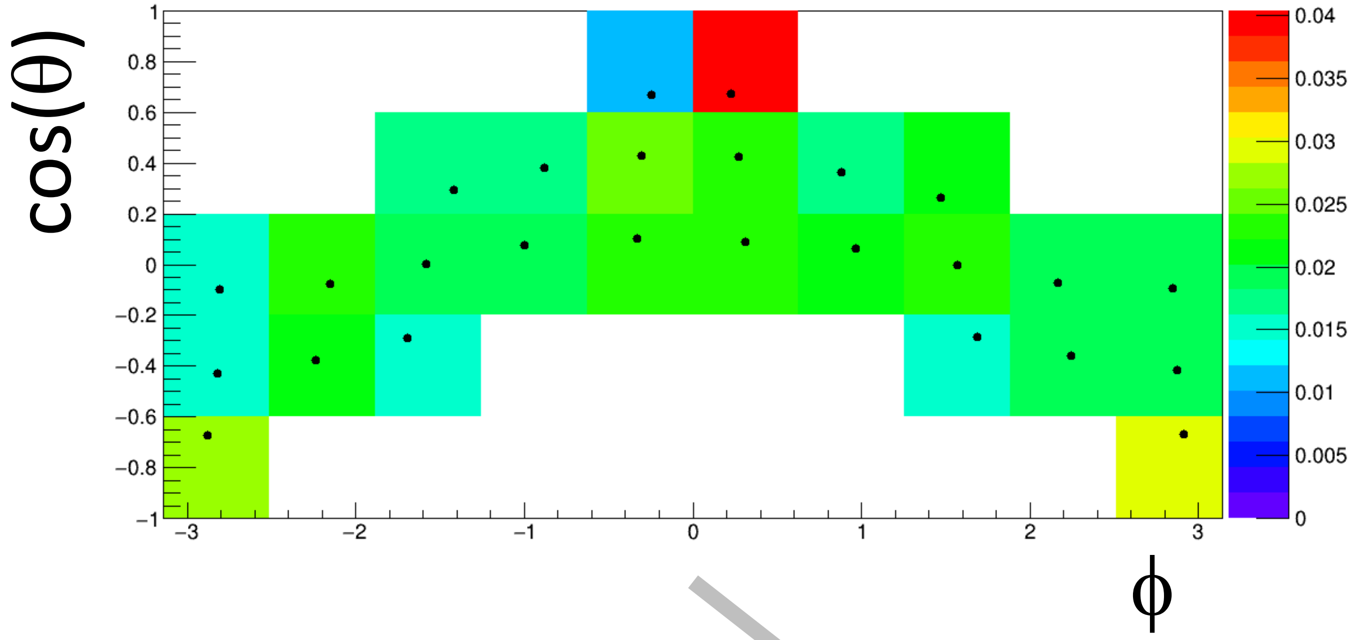


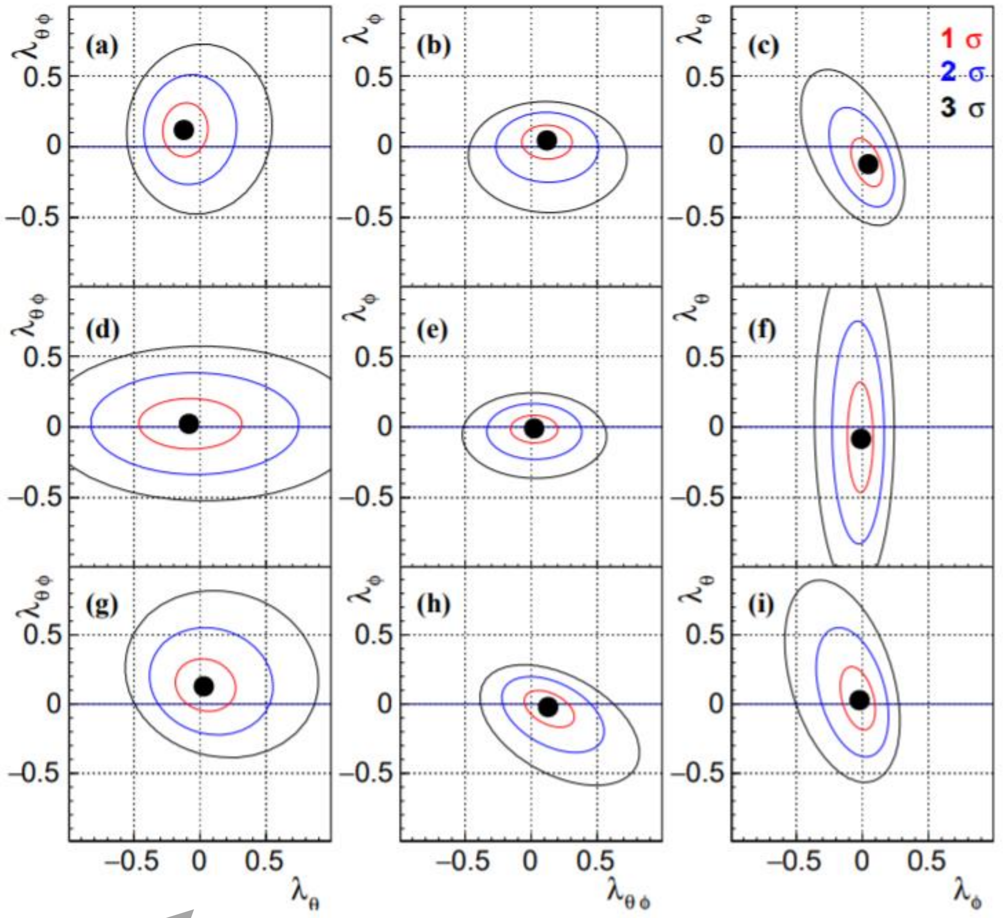
Simulation initially assumes unpolarized J/ψ



More analysis details

acceptance corrected distribution

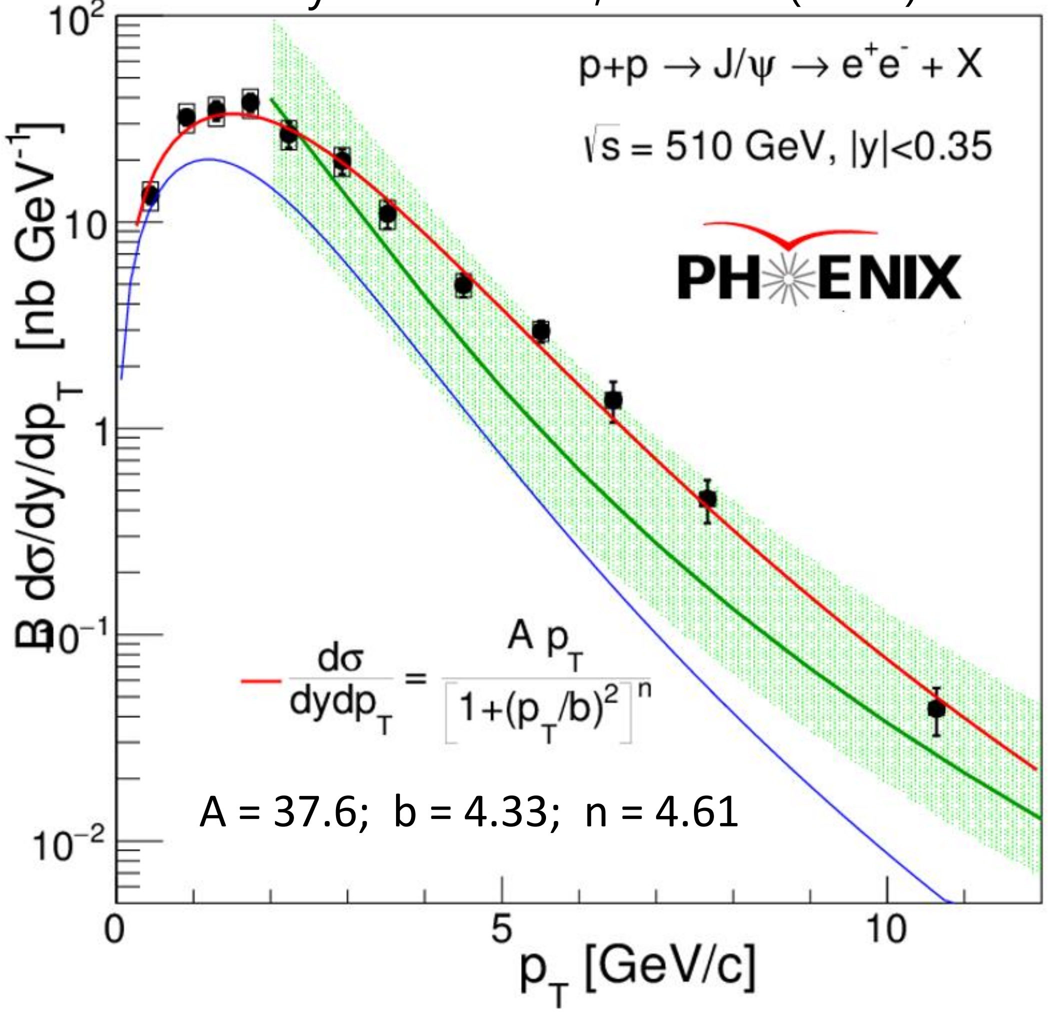




$$\frac{dN}{d\Omega} \approx 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin^2\theta \cos 2\phi + \lambda_\phi \sin 2\theta \cos\phi,$$

J/ψ p_T distribution at mid-rapidity

Phys. Rev. D 102, 072008 (2020)



The shape of the J/ψ p_T distribution can strongly affect polarization acceptance due to limited PHENIX acceptance in ϕ

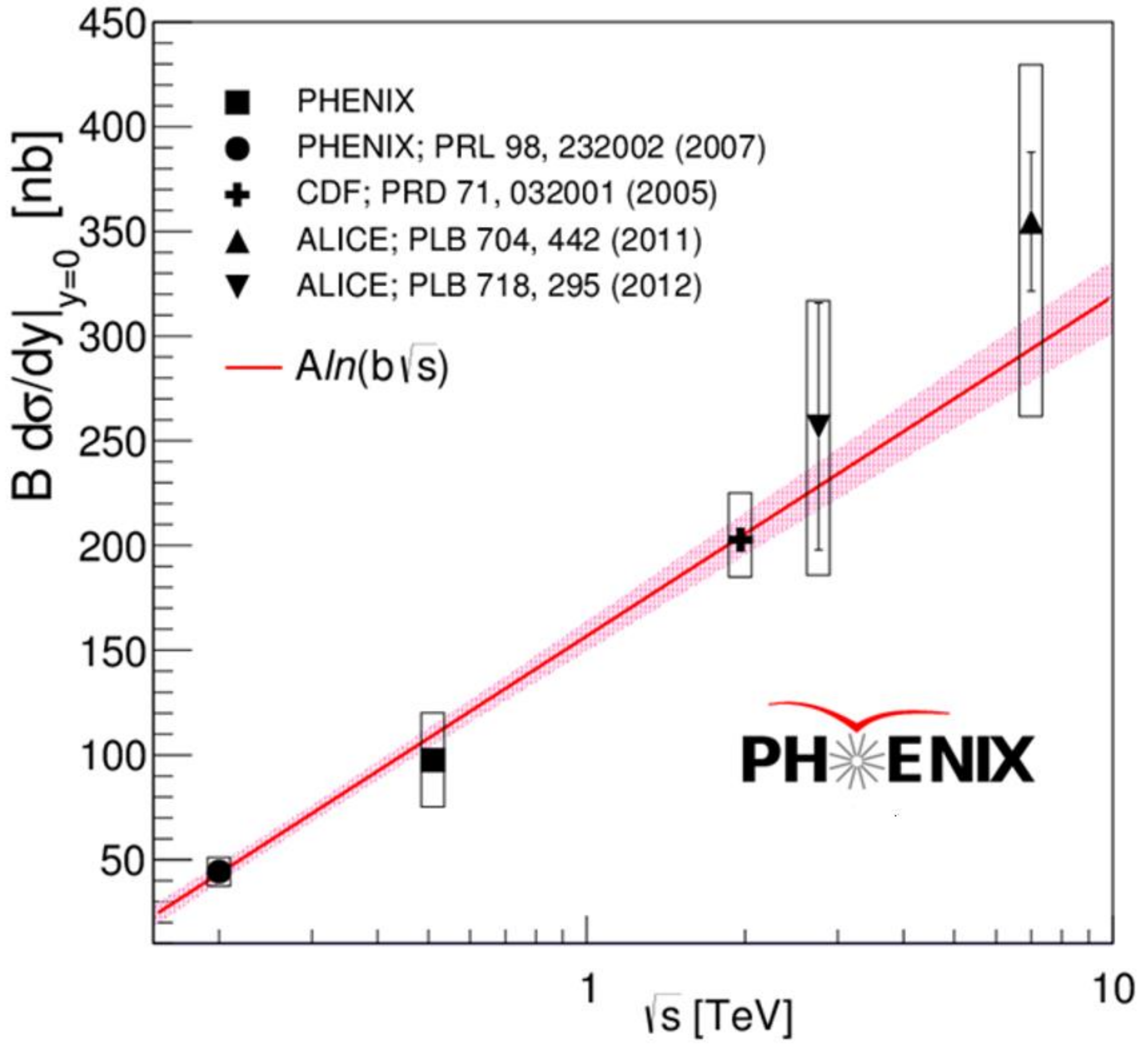
Blue: fit to J/ψ p_T distribution in p+p at 200 GeV (PHENIX, PRL 98, 232002 (2007))

Green: theory prediction based on full NRQCD at NLO with leading relativistic corrections including CS and CO states.

M. Butenschoen and B. A. Kniehl,
Mod. Phys. Lett. A 28, 1350027 (2013)
Phys. Rev. Lett, 108, 172002 (2012)

J/ψ cross-section vs. $\sqrt{s}$ at mid-rapidity

Phys. Rev. D 102, 072008 (2020)



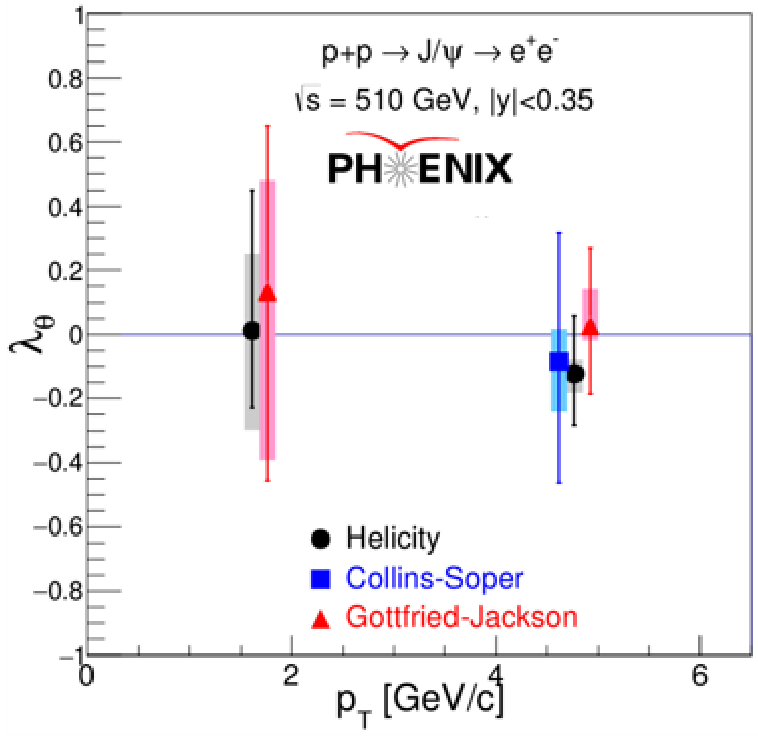
$B\,d\sigma/dy(y=0) = 97.6 \pm 3.6\,(\text{stat}) \pm 5.1\,(\text{sys})$
$\pm 9.8\,(\text{global})$
$\pm 19.5\,(\text{mult. coll.})$ nb

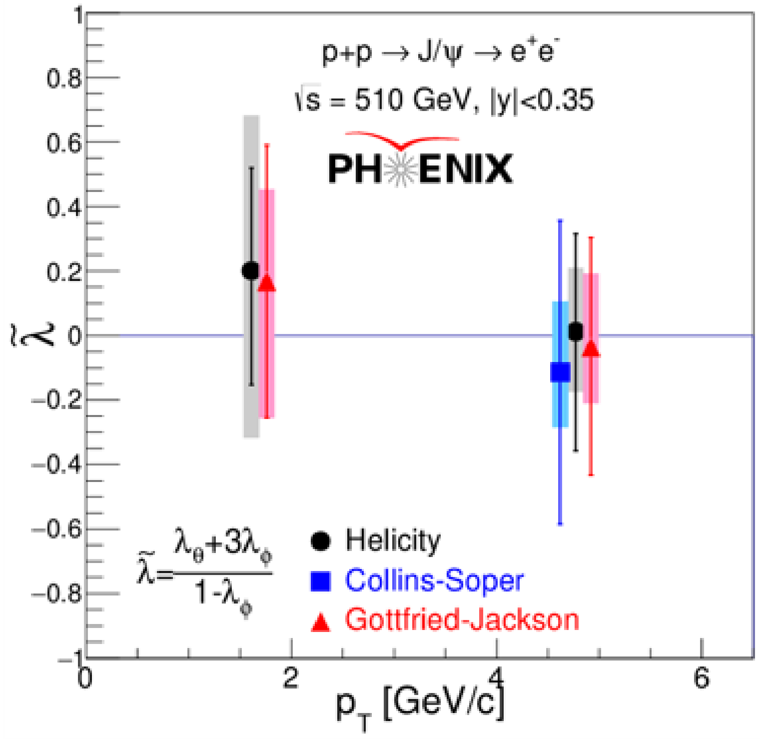
Simple log dependence allows to predict J/ψ yield at any $\sqrt{s}$

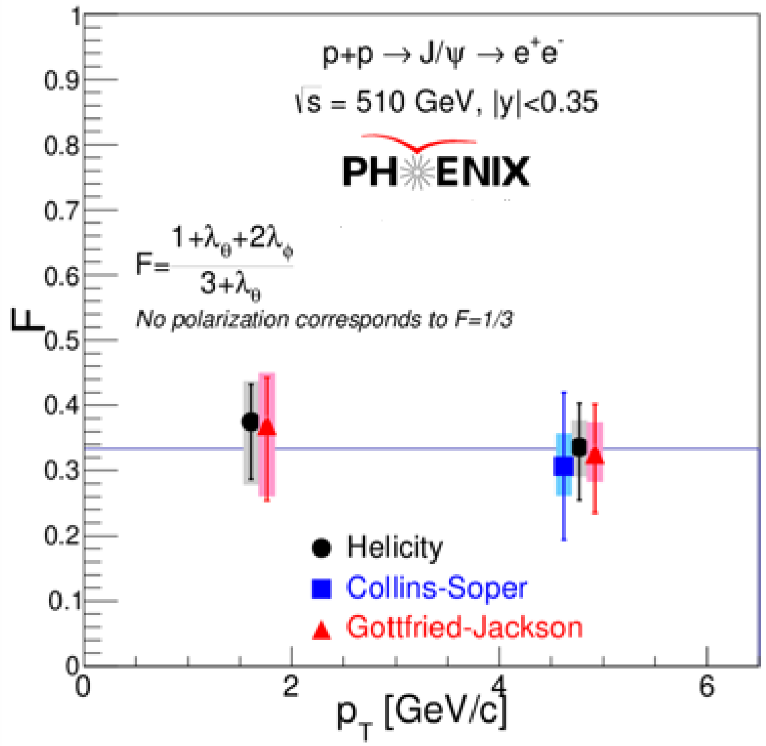
A = 70.4 nb; b = 9.27 TeV^{-1}

No cross-section at forward rapidity due to minimum J/ψ p_T

Polarization vs. p_T at mid-rapidity.





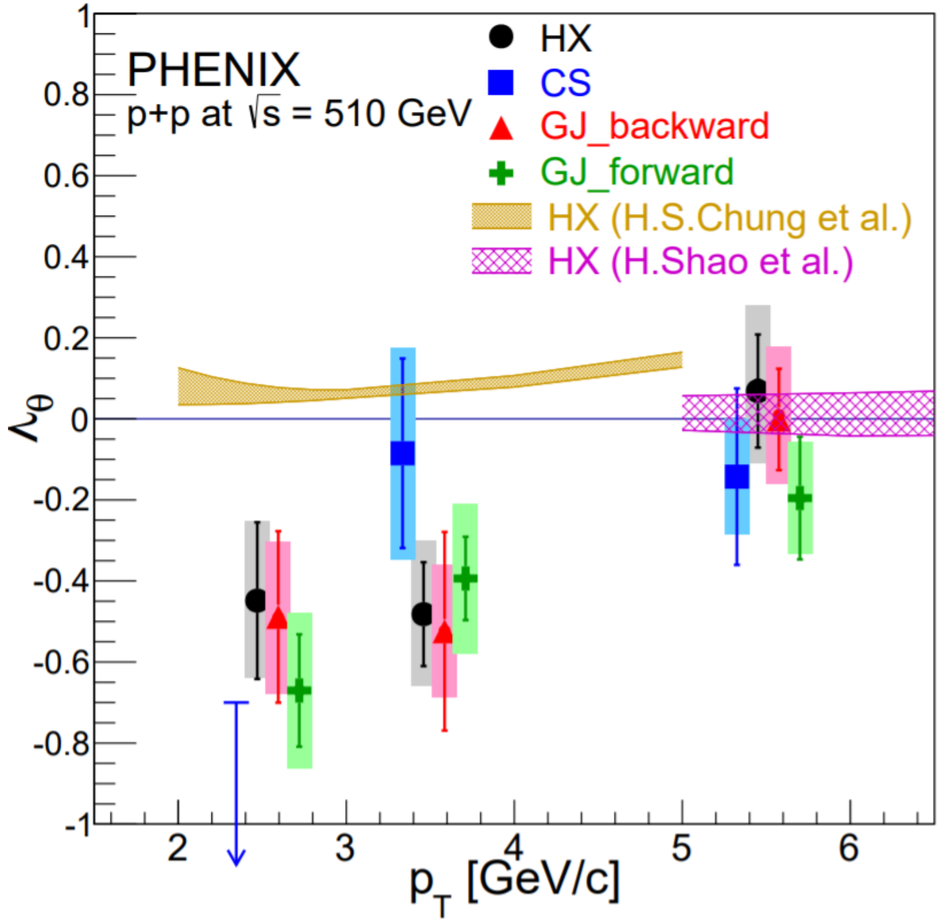


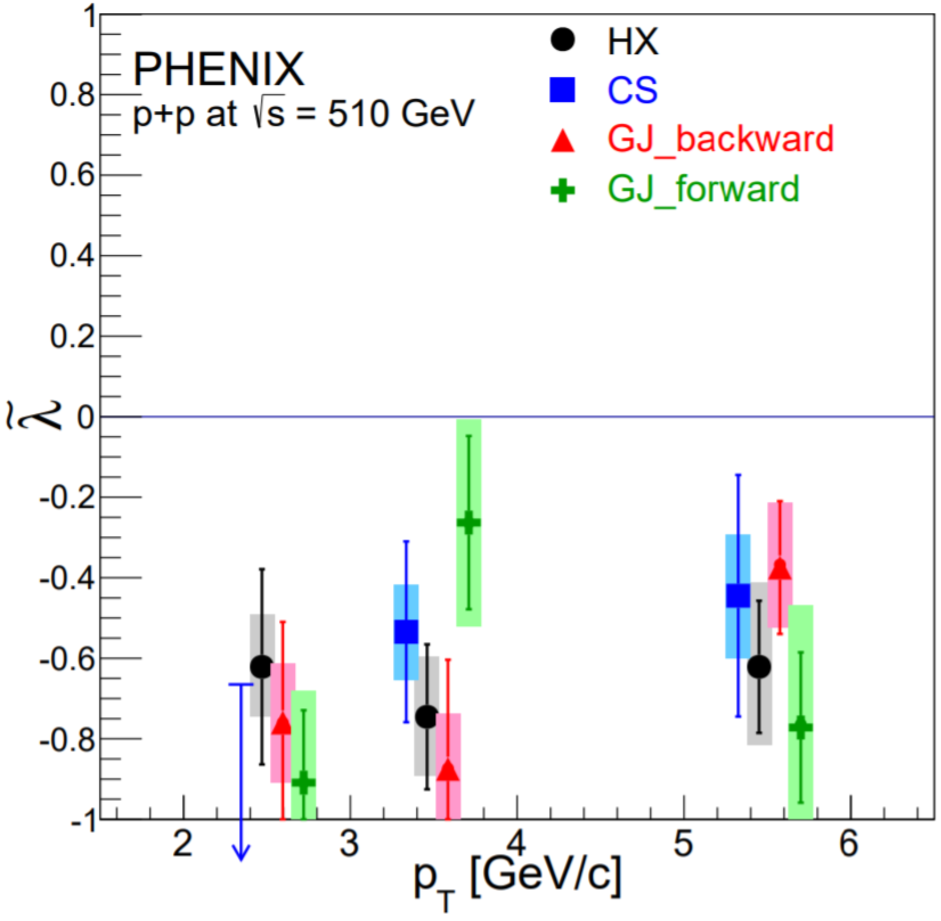
Consistent with no J/ψ polarization.
C-S frame measurement at low p_T impossible due to poor acceptance.

Polarization vs. p_T at forward rapidity.

Data: A. Adare et al. (PHENIX Collaboration), Phys. Rev. D95, 092003 (2017)

NRQCD predictions in Helicity frame based on
H.S.Chung et al., Phys. Rev. D 401 83, 037501 (2011)
H.-S.Shao et al., J. High Energy Phys. 05 (2015) 103

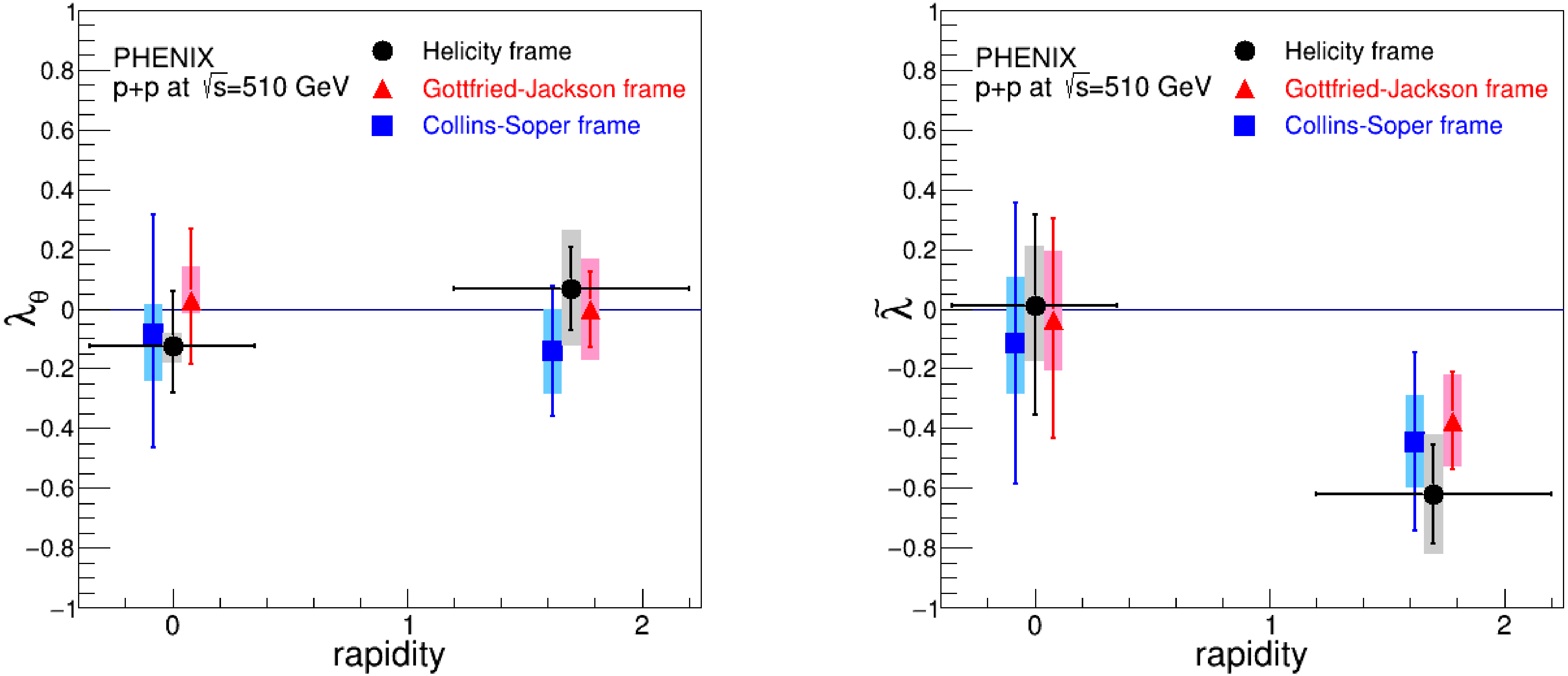




Polarization vs. rapidity

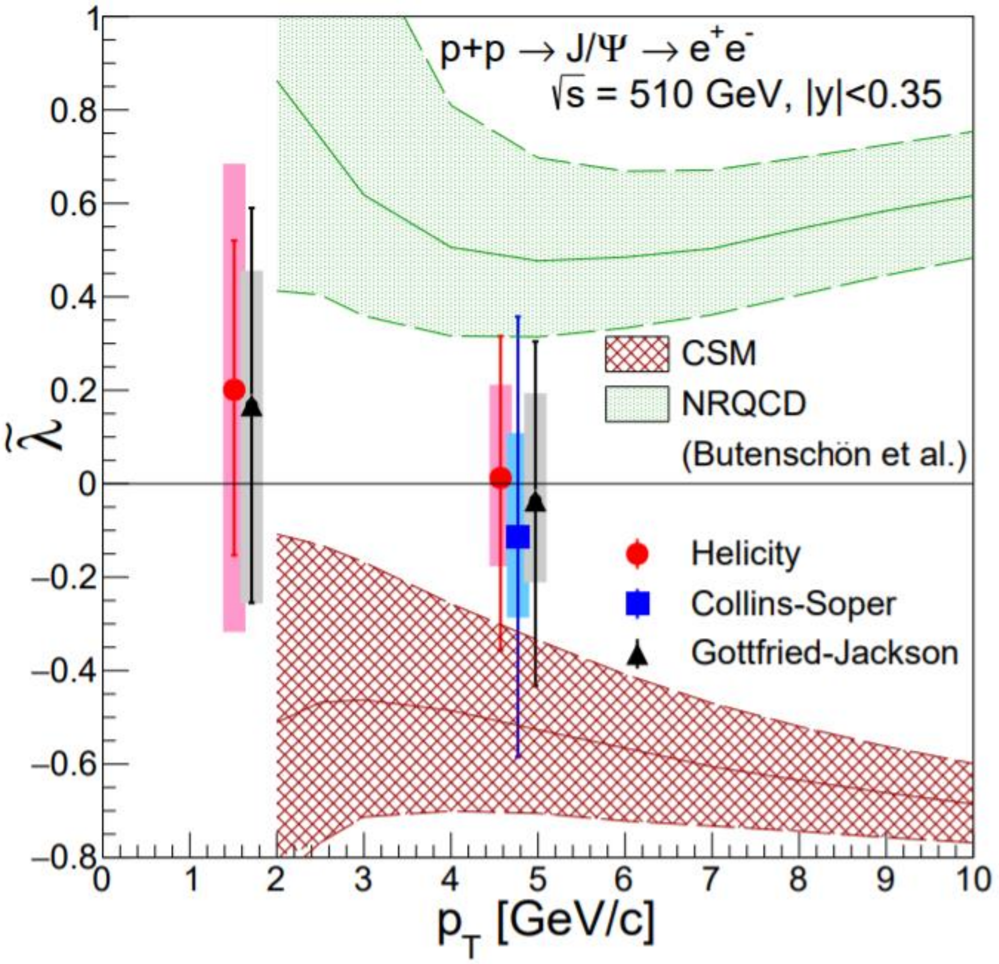
p_T range 3-10 GeV at midrapidity, 4-10 GeV at forward rapidity

Phys. Rev. D 102, 072008 (2020)



Some theory comparisons

Phys. Rev. D 102, 072008 (2020)

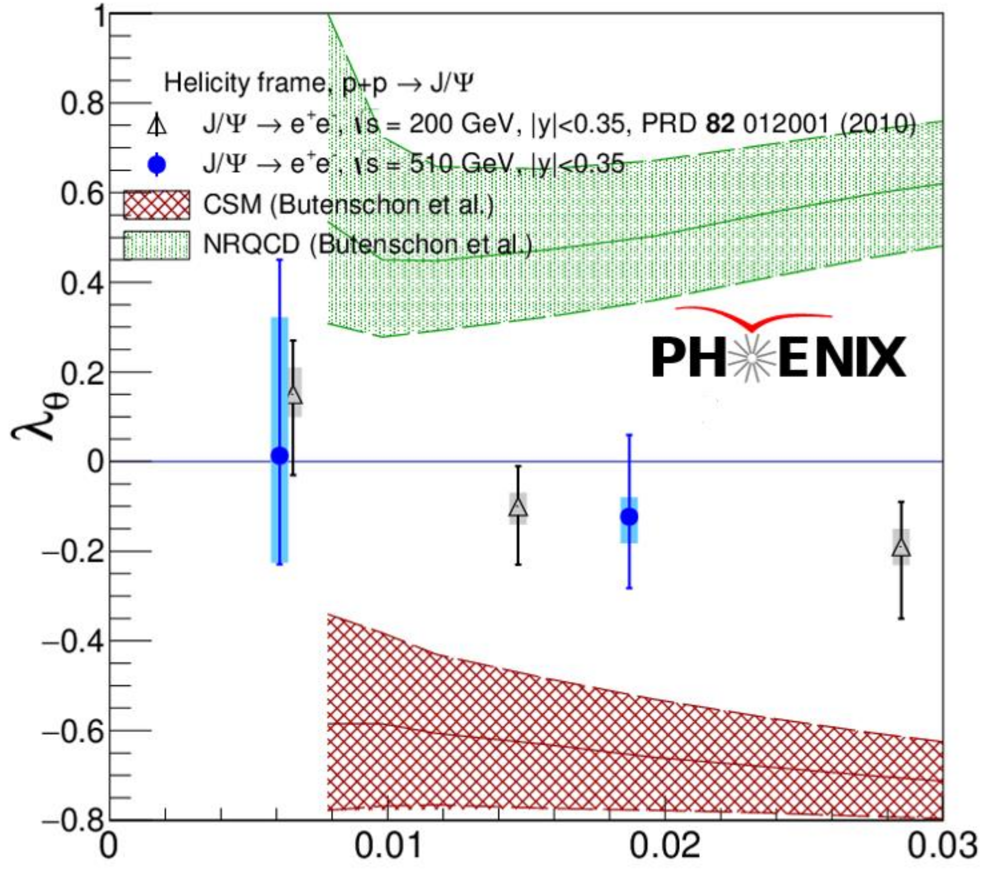


Predictions in Helicity frame based on M. Butenschoen and B. A. Kniehl, Mod. Phys. Lett. A **28**, 1350027 (2013) and Phys. Rev. Lett. **108**, 172002 (2012)

NRQCD and CSM ($v \rightarrow 0$ limit of NRQCD) give qualitatively different predictions for strong polarization.

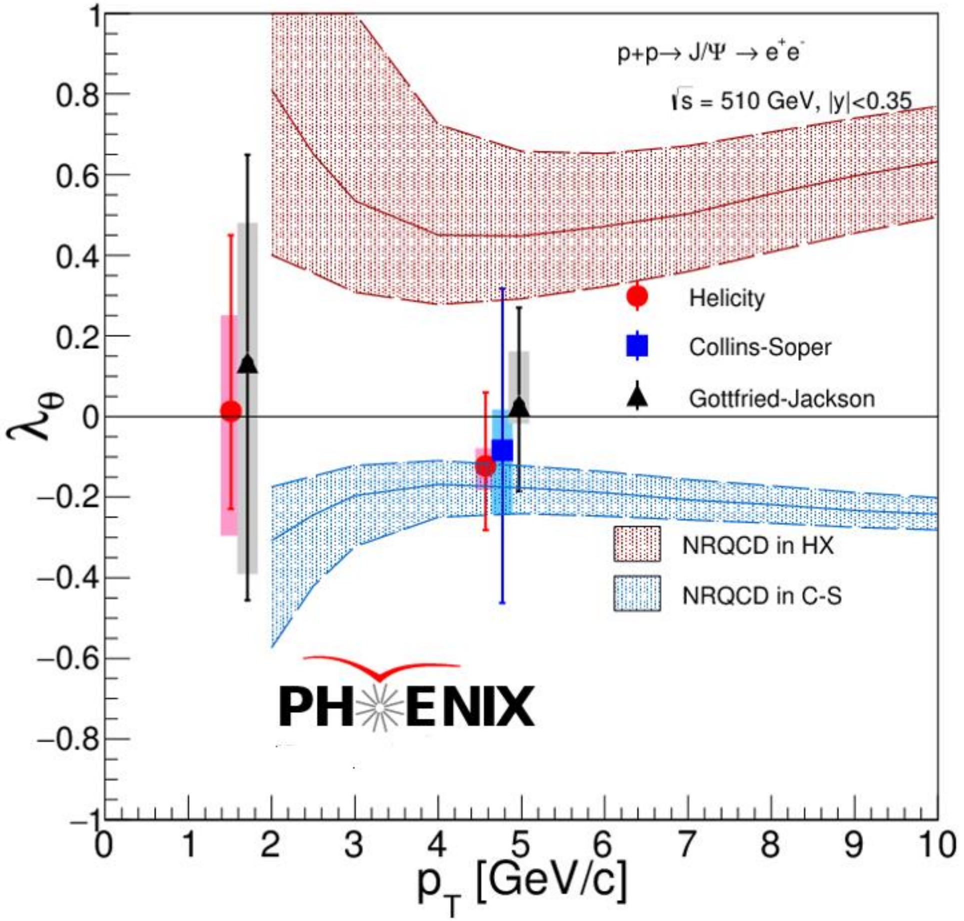
More theory comparisons

Phys. Rev. D 102, 072008 (2020)



$$x_T = \frac{2pT}{\sqrt{s}}$$

NRQCD for different frames



Theory is consistent with data in CS frame, but disagree in HX

Conclusions

- The PHENIX experiment has measured J/ψ polarization in p+p collisions at 200 and 510 GeV both at mid- and forward rapidity.
  - Results are consistent with no polarization at mid-rapidity
  - Indication of negative polarization at forward rapidity with some p_T dependence.
  - Various NRQCD-based predictions can not describe the full set of data.

- PHENIX has measured J/ψ p_T distributions and production cross-section in p+p collisions.
  - Significant difference in shape between $\sqrt{s}$ = 200 and 510 GeV
  - Cross-section's $\sqrt{s}$ dependence follows simple logarithmic law.