J/ψ spin asymmetry measurements in p+p collisions at 200 and 510 GeV by the PHENIX experiment at RHIC

Alexandre Lebedev (ISU) for the PHENIX Collaboration

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Charmonium production in p+p collisions

Measurements of heavy quark bound states provide a good way to explore QCD.
Energy scale of the heavy 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.

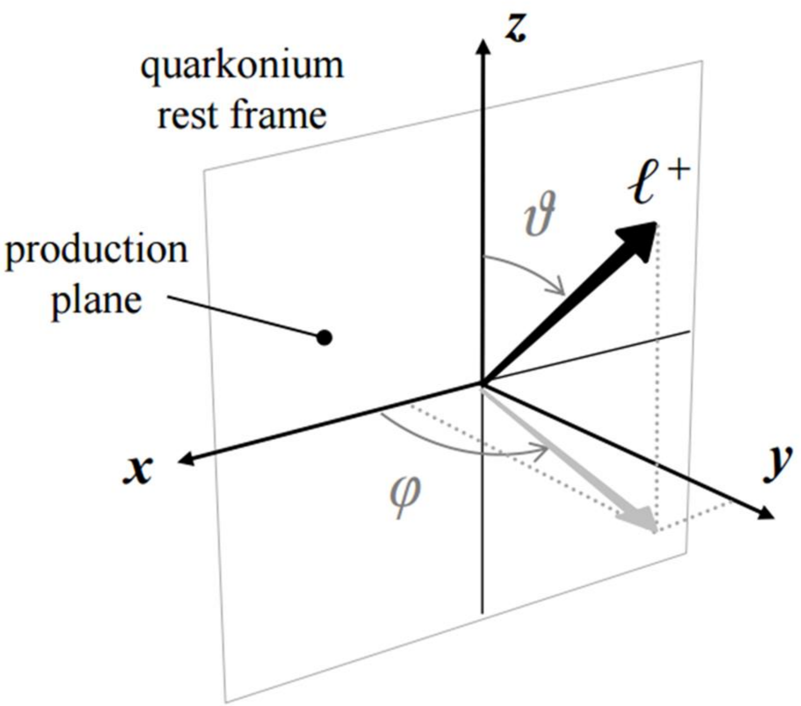
- J/ψ decays to lepton pairs with high branching ratio.
- copiously produced.

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

Describing finer details, like angular distribution (spin alignment) provide an additional handle on distinguishing production mechanisms.

Polarization introduction

We are looking at un-polarized 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:

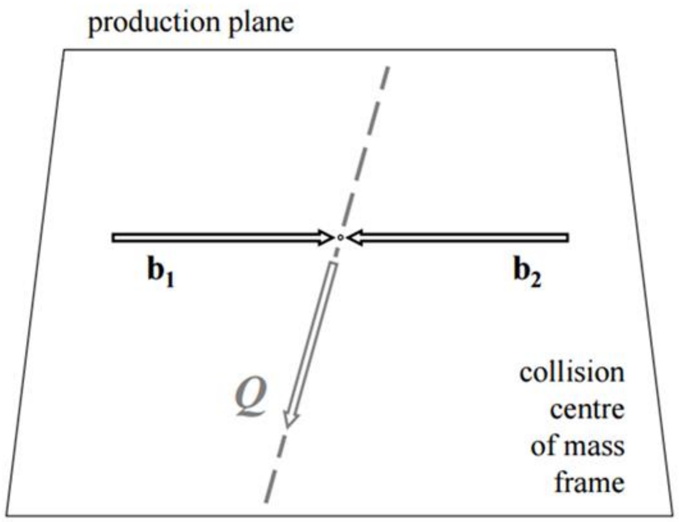
$$\frac{d\sigma}{d\cos\theta^*} = A(1 + \lambda\cos^2\theta^*)$$

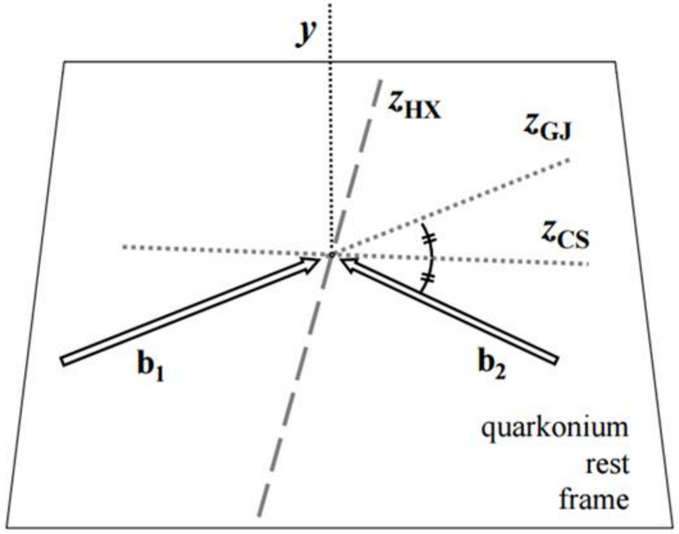
Different "polarization frames" can be used, depending on the goal of the study.

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*





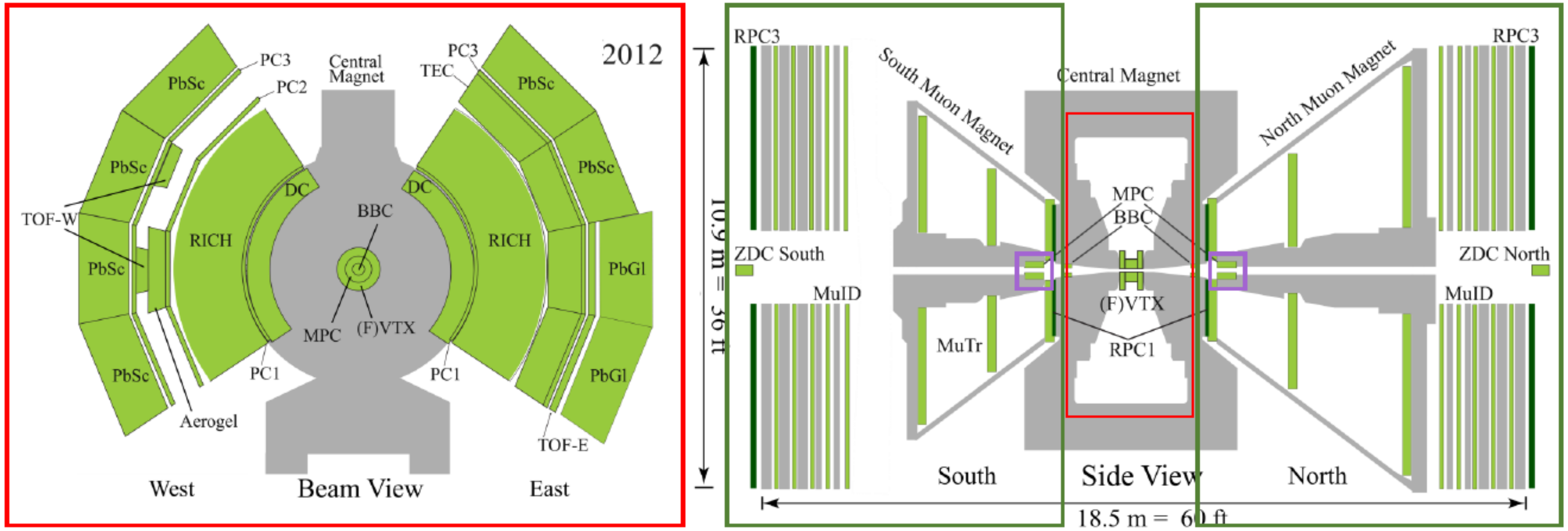
$$\frac{d\sigma}{d(\cos\vartheta)d\varphi} \propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi}\sin(2\vartheta)\cos\varphi + \lambda_\phi sin^2\vartheta\cos 2\varphi$$

Frame-invariant parameters

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

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

The PHENIX Detector



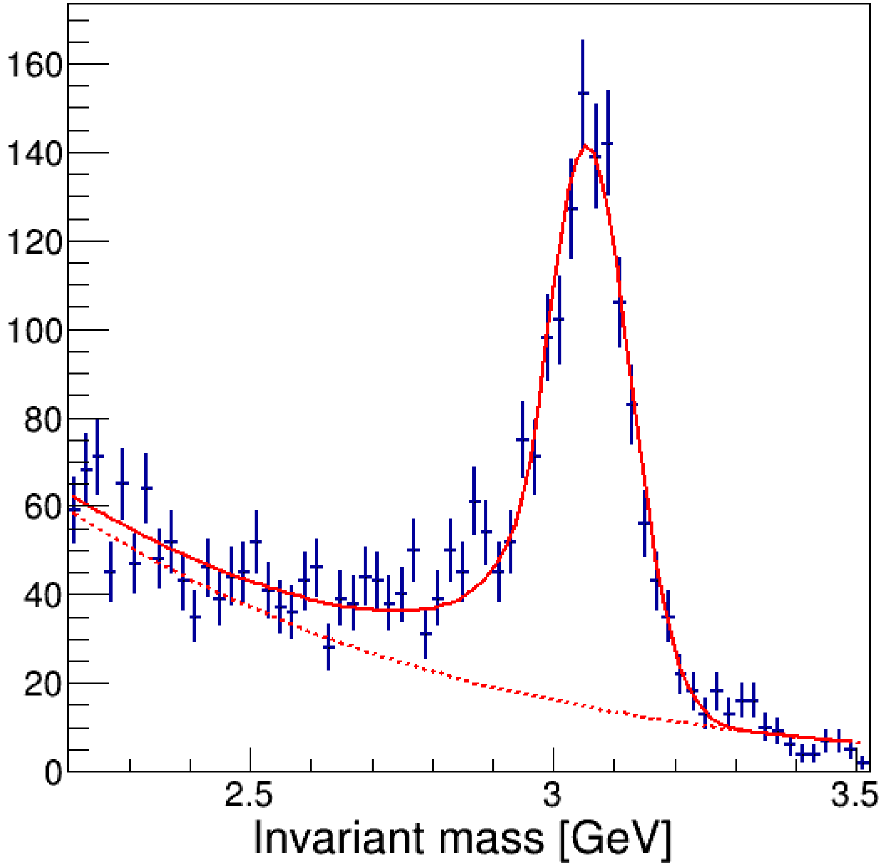
- **Central Arms** (|η| < 0.35, $\Delta\phi = \frac{\pi}{2} \times 2$)
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc

- **Muon Arms** (1.2 < |η| < 2.2 (S) or 2.4 (N), Δϕ = 2π)
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs

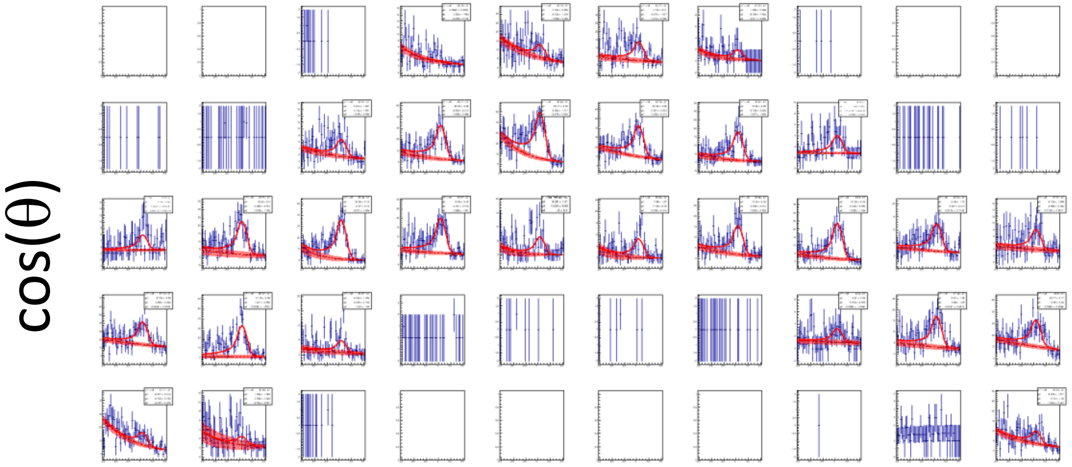
- **MPC/MPC-Ex** (3.1 < |η| < 3.8, Δϕ = 2π)
  - EMCal ($PbWO_4$) / Preshower by W + Si minipads

Analysis details

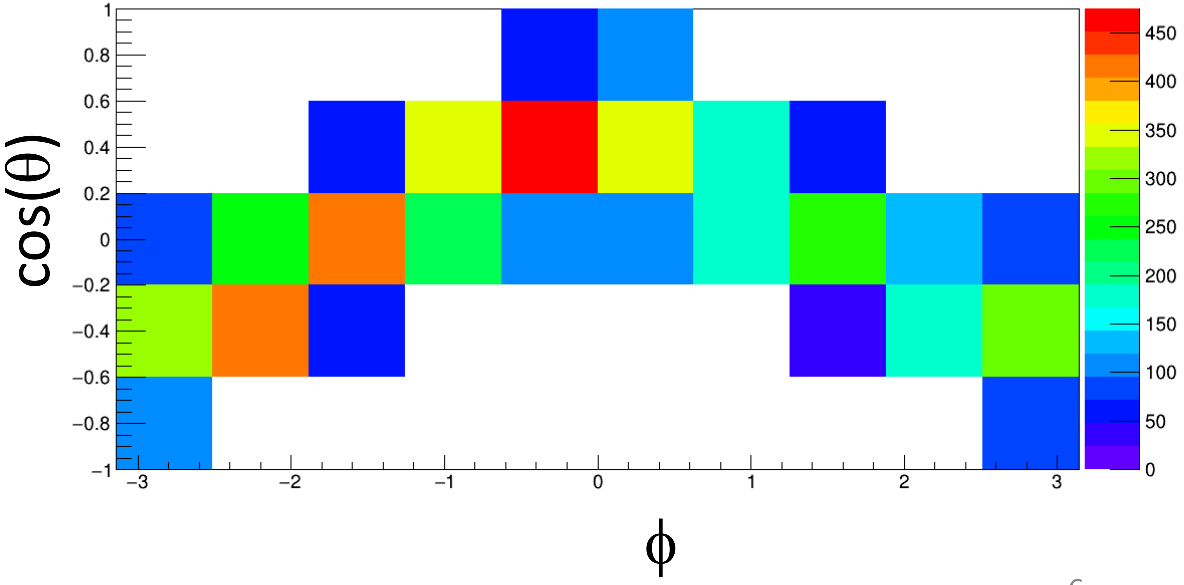
J/ψ are measured via invariant mass distribution of decay leptons.



Data

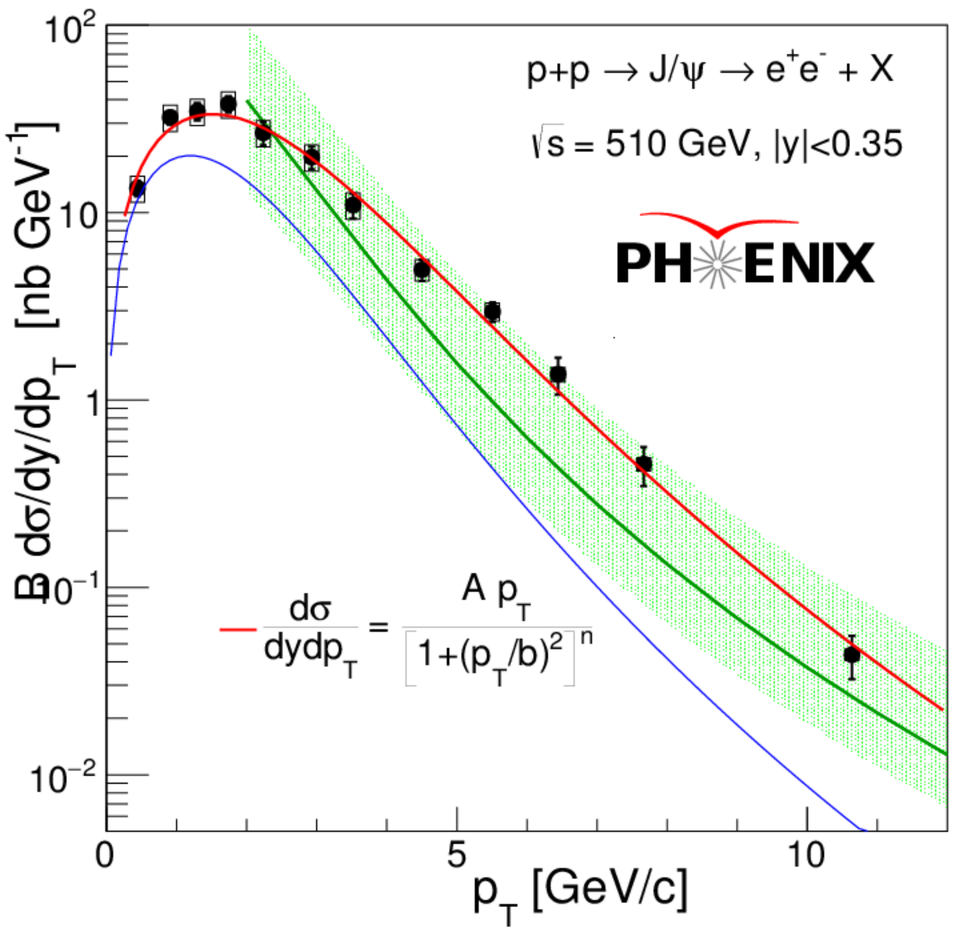


Simulation initially assumes unpolarized J/ψ



J/ψ p_T distribution at mid-rapidity

Phys. Rev. D 102 072008 (2020)



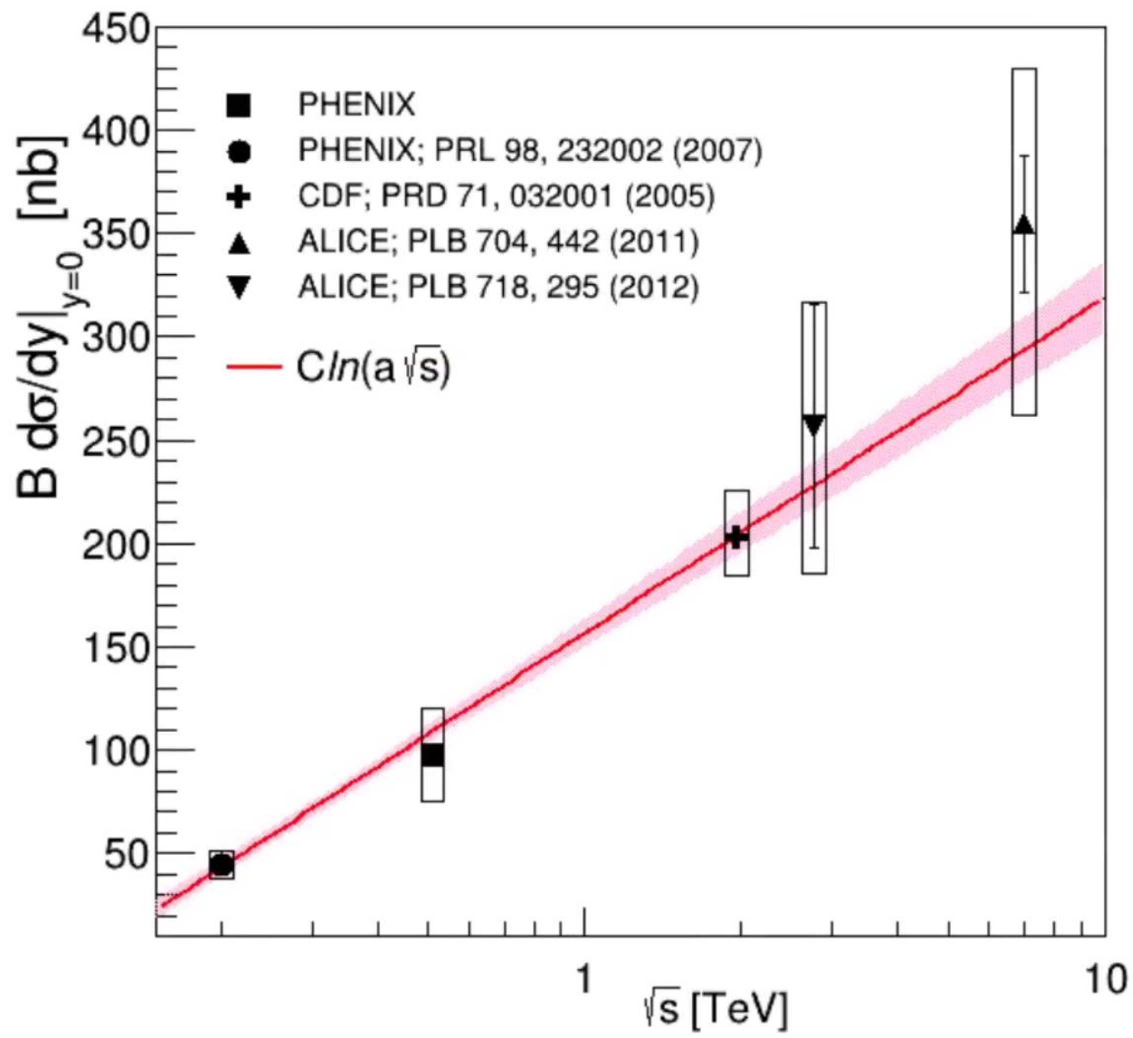
The shape of the J/ψ p_T distribution can strongly affect polarization acceptance due to limited PHENIX acceptance in ϕ

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. √s at mid-rapidity



B dσ/dy(y=0) = 97.6 ± 3.6 (stat) ± 5.1 (sys)
± 9.8 (global)
± 19.5 (mult. coll.) nb

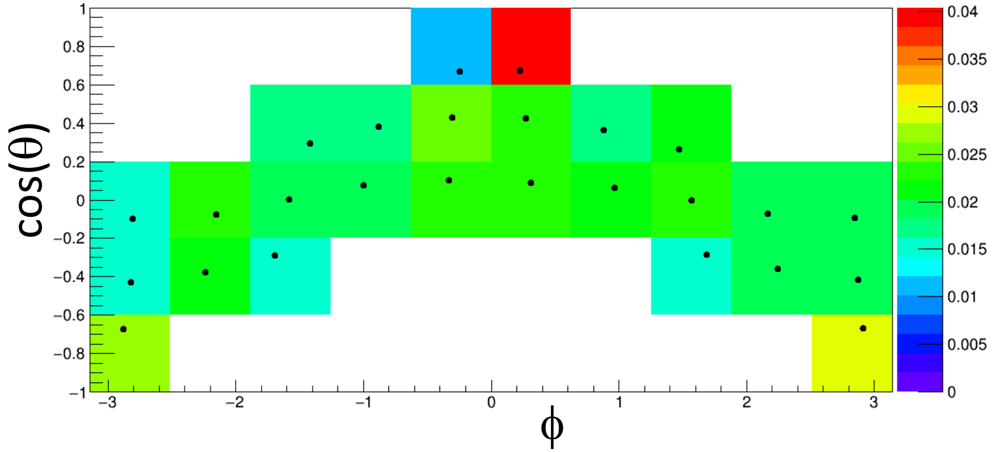
Simple log dependence allows to predict J/ψ yield at any $\sqrt{s}$

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

Cross-section at forward rapidity measurement is difficult to due to minimum J/ψ p_T requirement.

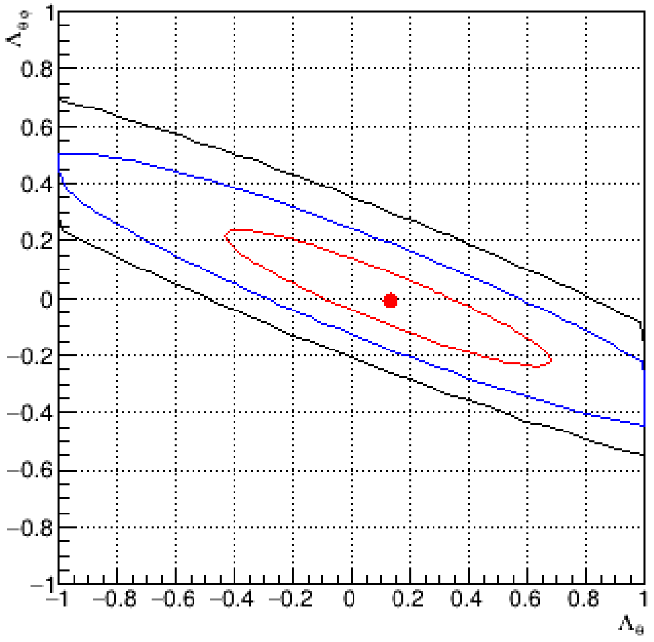
More analysis details

acceptance corrected distribution

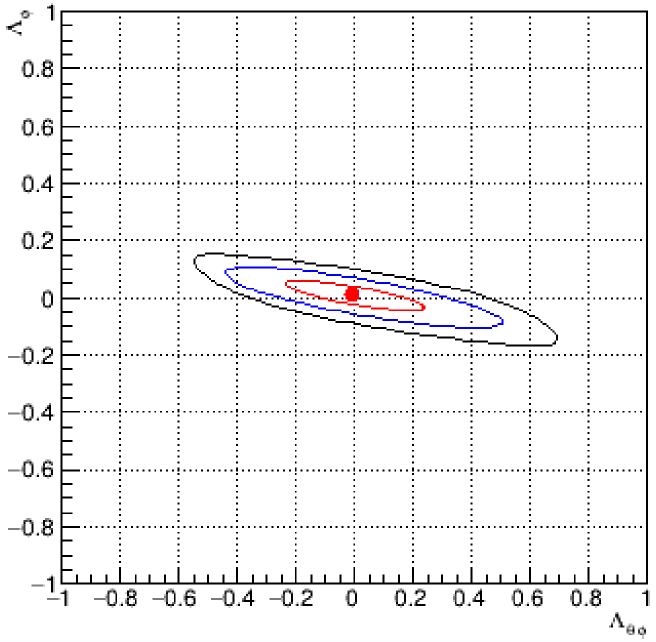


$$\frac{dN}{d\cos\vartheta d\varphi} \propto$$
$$1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi + \lambda_\varphi \sin^2\vartheta\cos 2\varphi$$

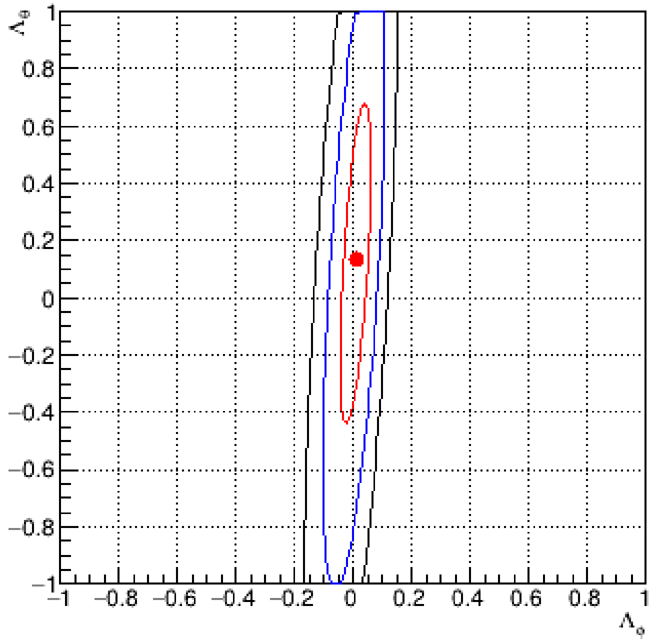
Fit contours for $\Lambda_{\theta\phi}$ vs Λ_θ



Fit contours for Λ_ϕ vs $\Lambda_{\theta\phi}$



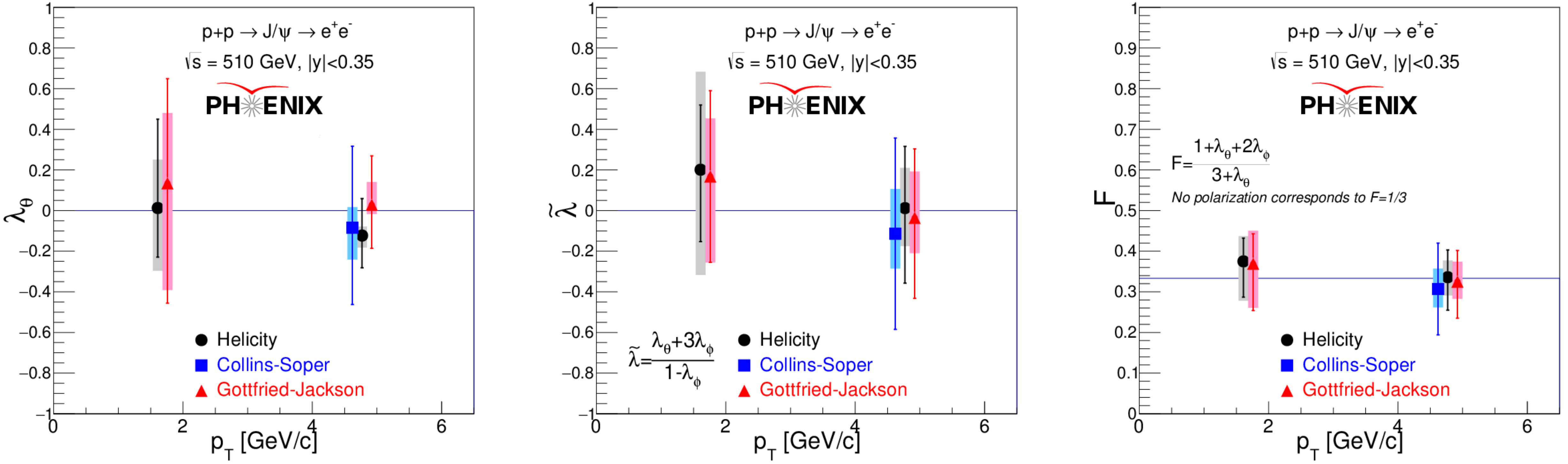
Fit contours for Λ_θ vs Λ_ϕ



Polarization vs. p_T at mid-rapidity.

Phys Rev D 102 072008 (2020)

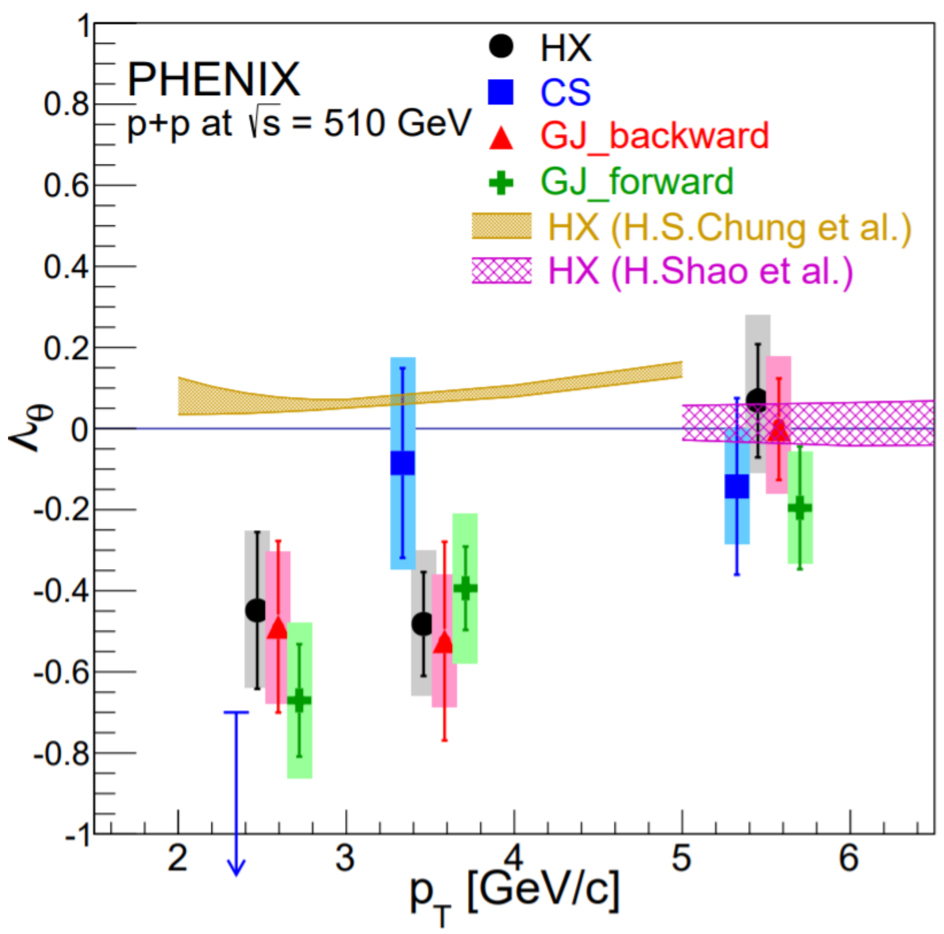
Consistent with no J/ψ polarization

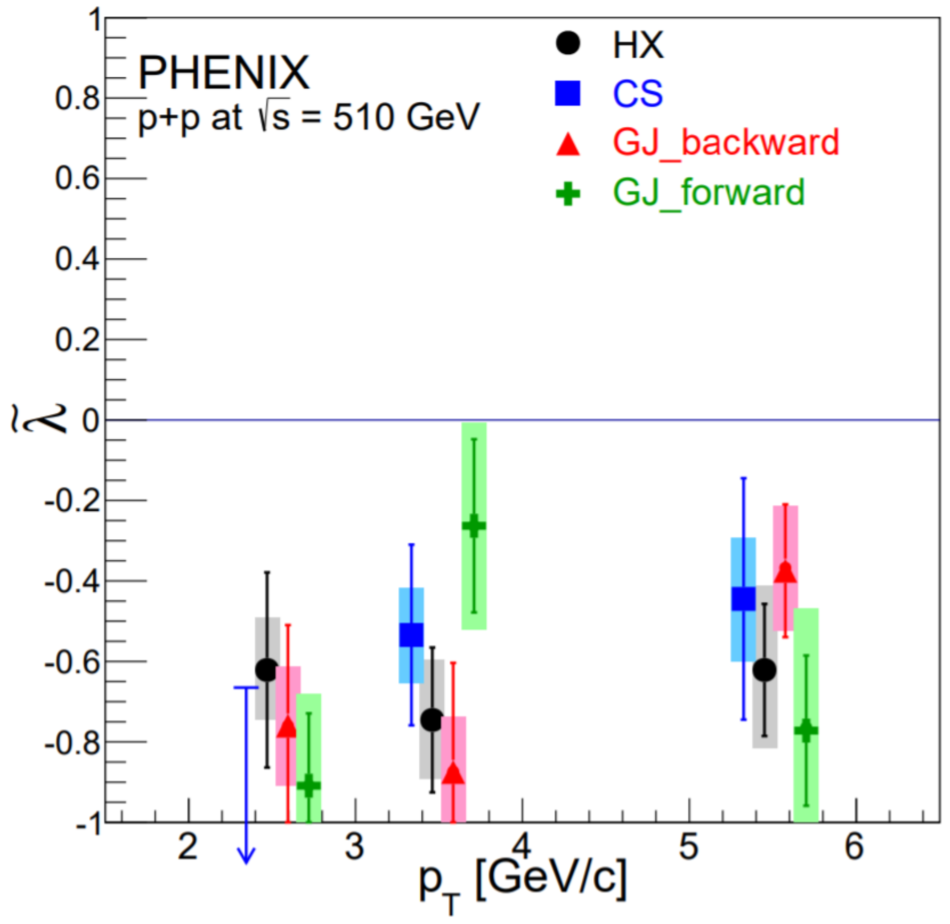


Polarization vs. p_T at forward rapidity.

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

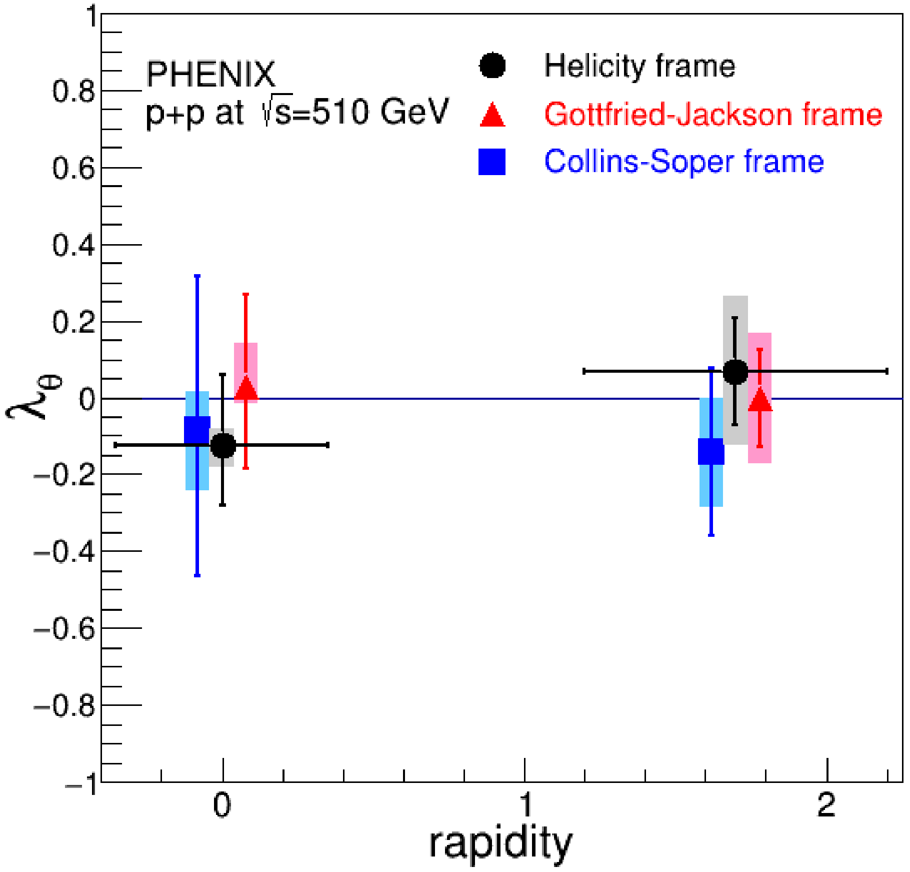
NRQCD predictions in Helicity frame based on
H.S.Chung et al., Phys. Rev. D 401 83, 037501 (2011)
H.-S.Shao et al., J. High Energy Phys. 05 (2015) 103

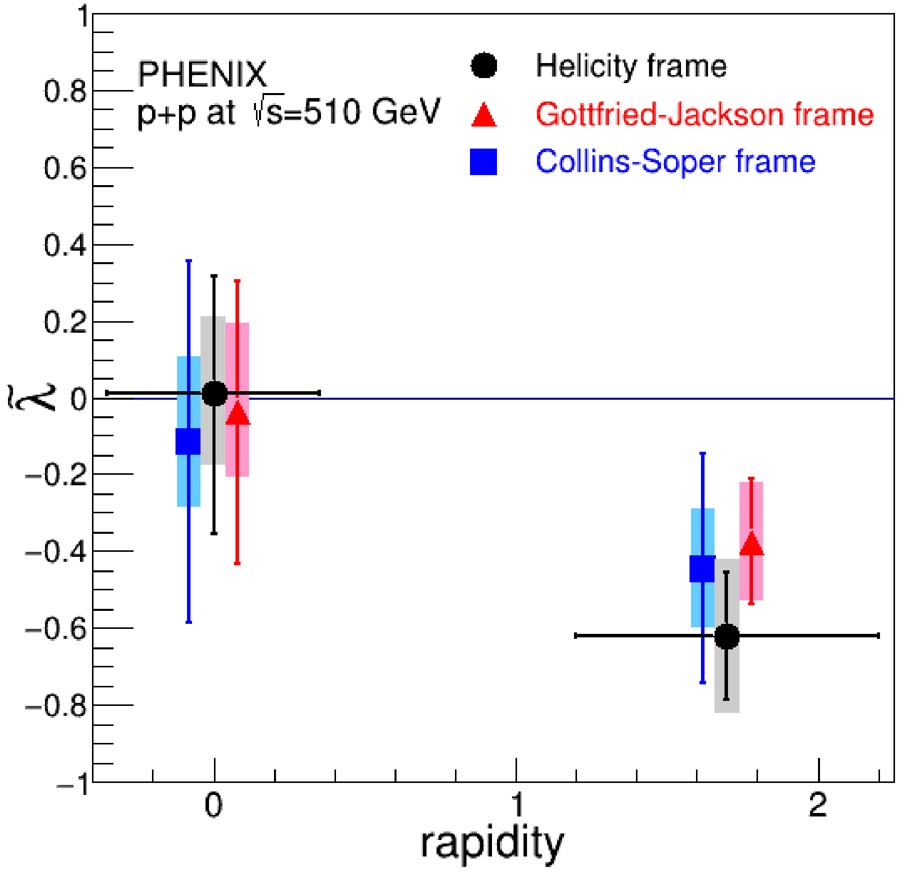




Polarization vs. rapidity

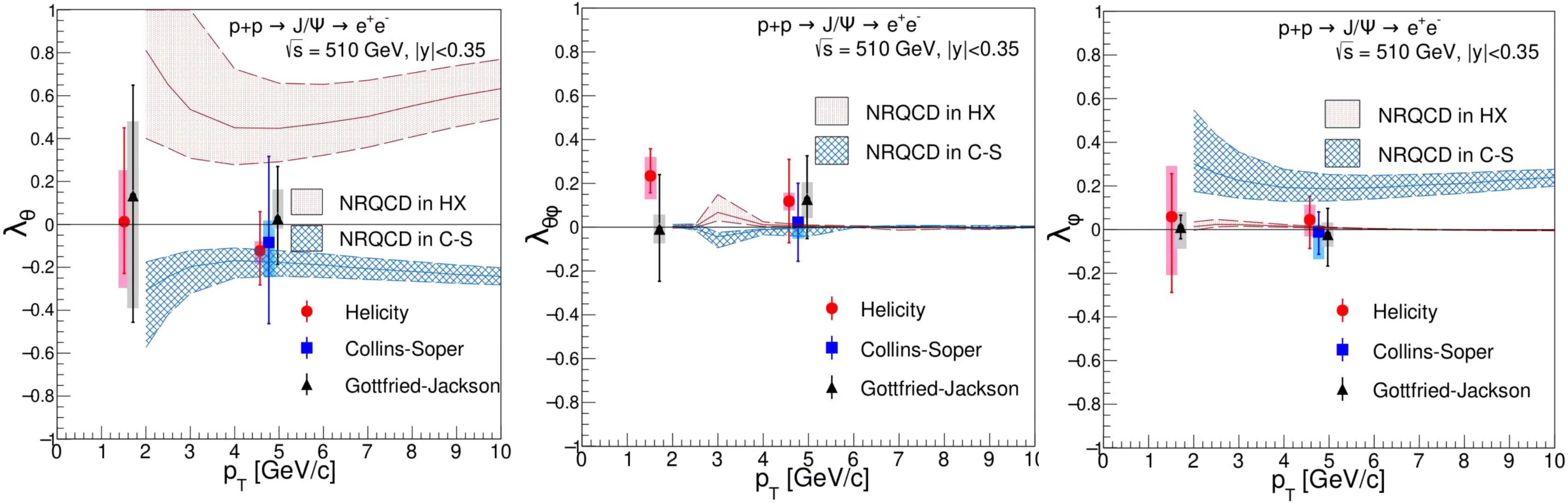
p_T range 3-10 GeV at midrapidity, 4-10 GeV at forward rapidity





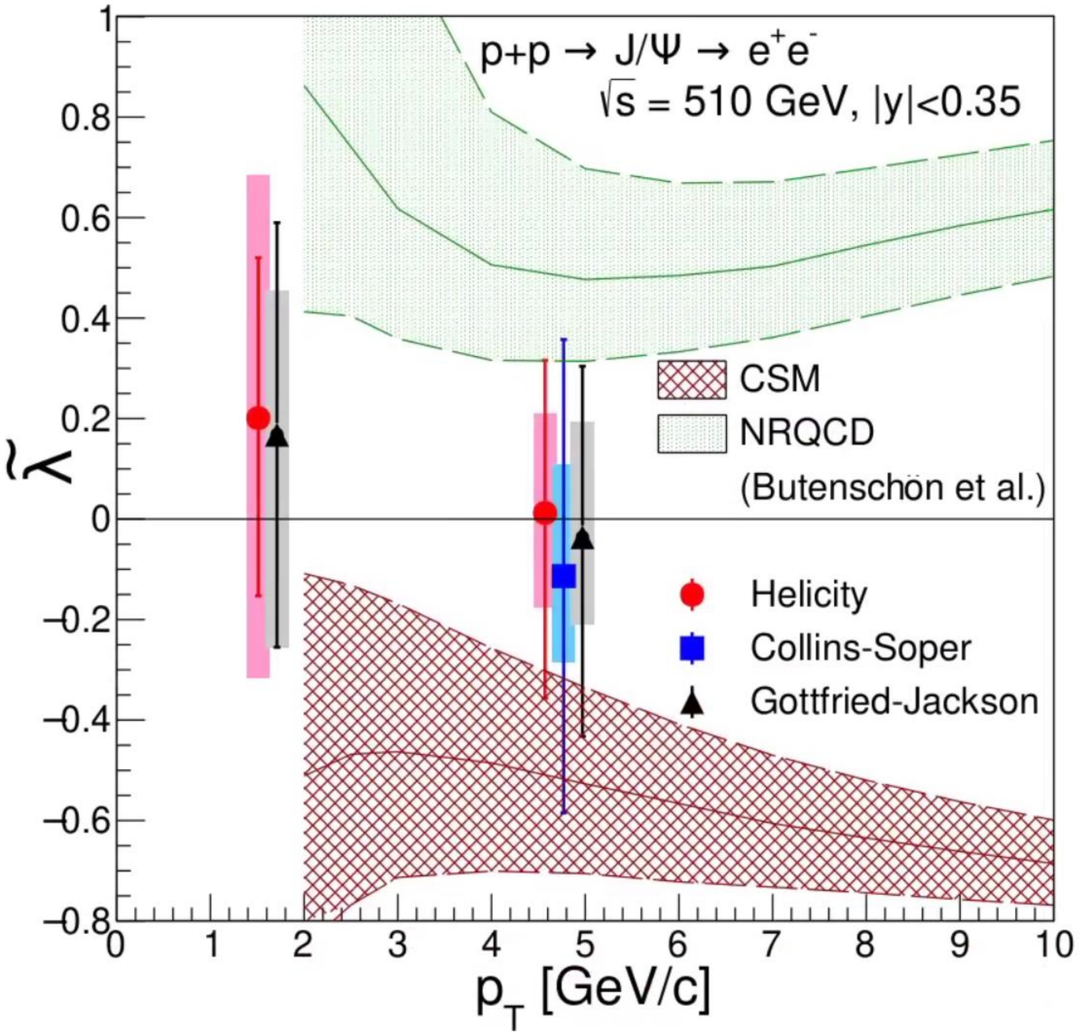
Theory predictions

PHENIX data: Phys Rev D 102 072008 (2020)



Full NRQCD at NLO with leading relativistic corrections including CS and CO.
M. Butenshoen and B.A. Kniehl, Phys Rev. Lett. 108, 172002 (2012)

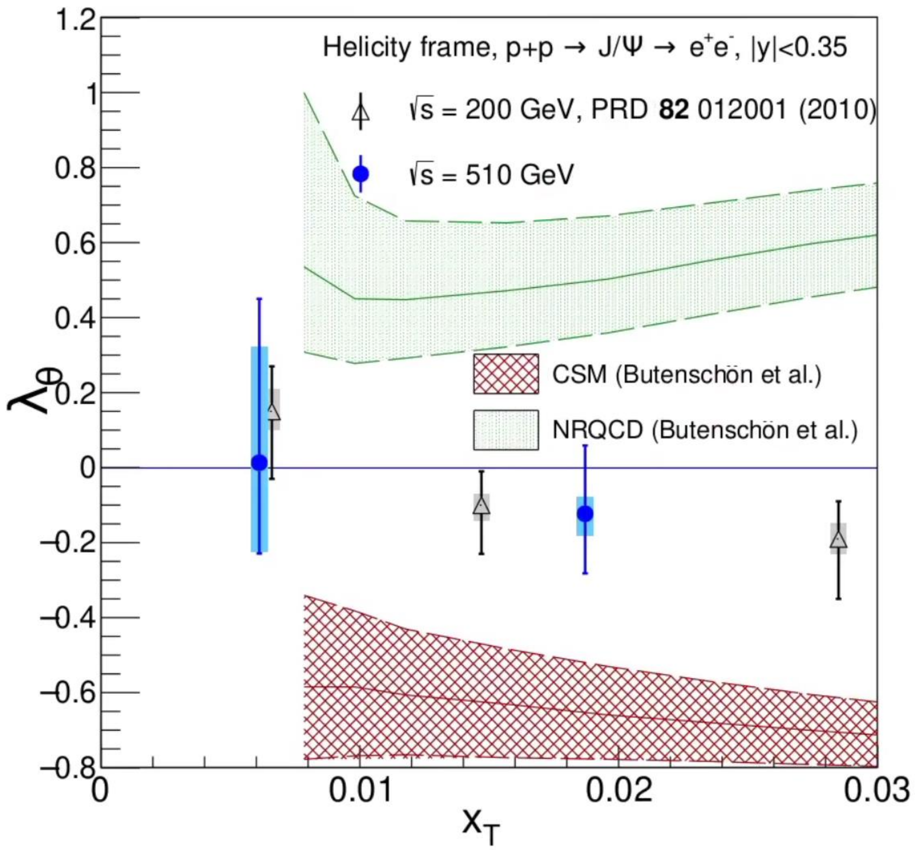
Different models comparizon



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)

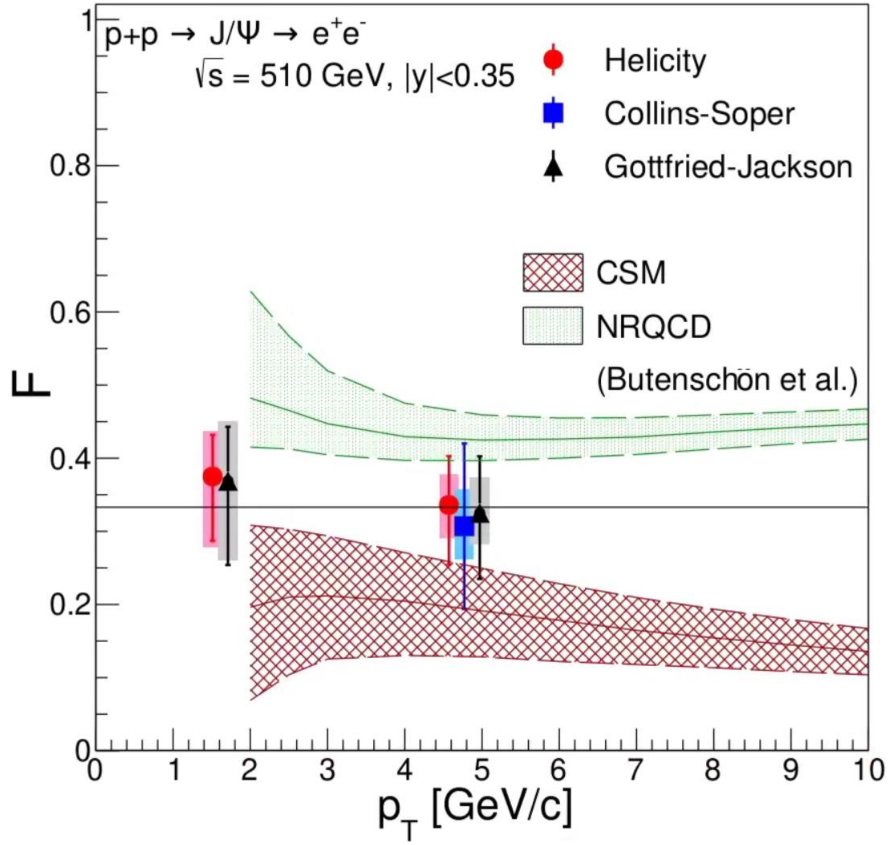
NRQCD with CS+CO and CSM give qualitatively different predictions for strong polarization.

More model comparisons



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

Same model (NRQCD with CO+CS) but 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.

PHENIX