Recent Quarkonia Results from PHENIX Experiment

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PHENIX

Motivation

- Measurements of quarkonia provide an excellent opportunity to explore QCD.
  - In the case of J/ψ , the charm quark mass is larger than the hadronization scale ⇒ NRQCD techniques can be used to provide access to hadronization.
  - J/ψ is copiously produced and decays to lepton pairs with high branching ratio

- Many J/ψ production models describe general features well, like p_T or rapidity distributions at mid-rapidity, but not as well at forward rapidity.

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

J/ψ Polarization

The decay angular distribution of the positive lepton in the J/ψ rest frame is often parametrized as:

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

λ_θ, $\lambda_{\theta\phi}$ and λ_ϕ are related to the density matrix elements and depend on kinematical variables and the definition of coordinate system.

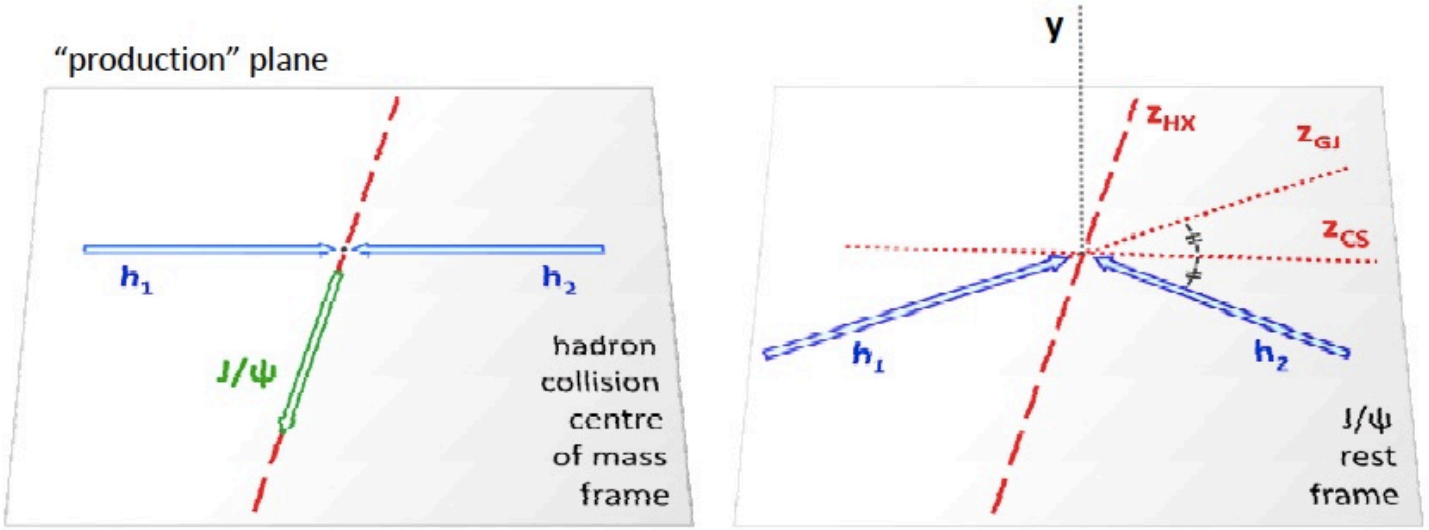
- Frame-invariant angular decay coefficient

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

  - It is sensitive to the maximum angular asymmetry, or polarization.

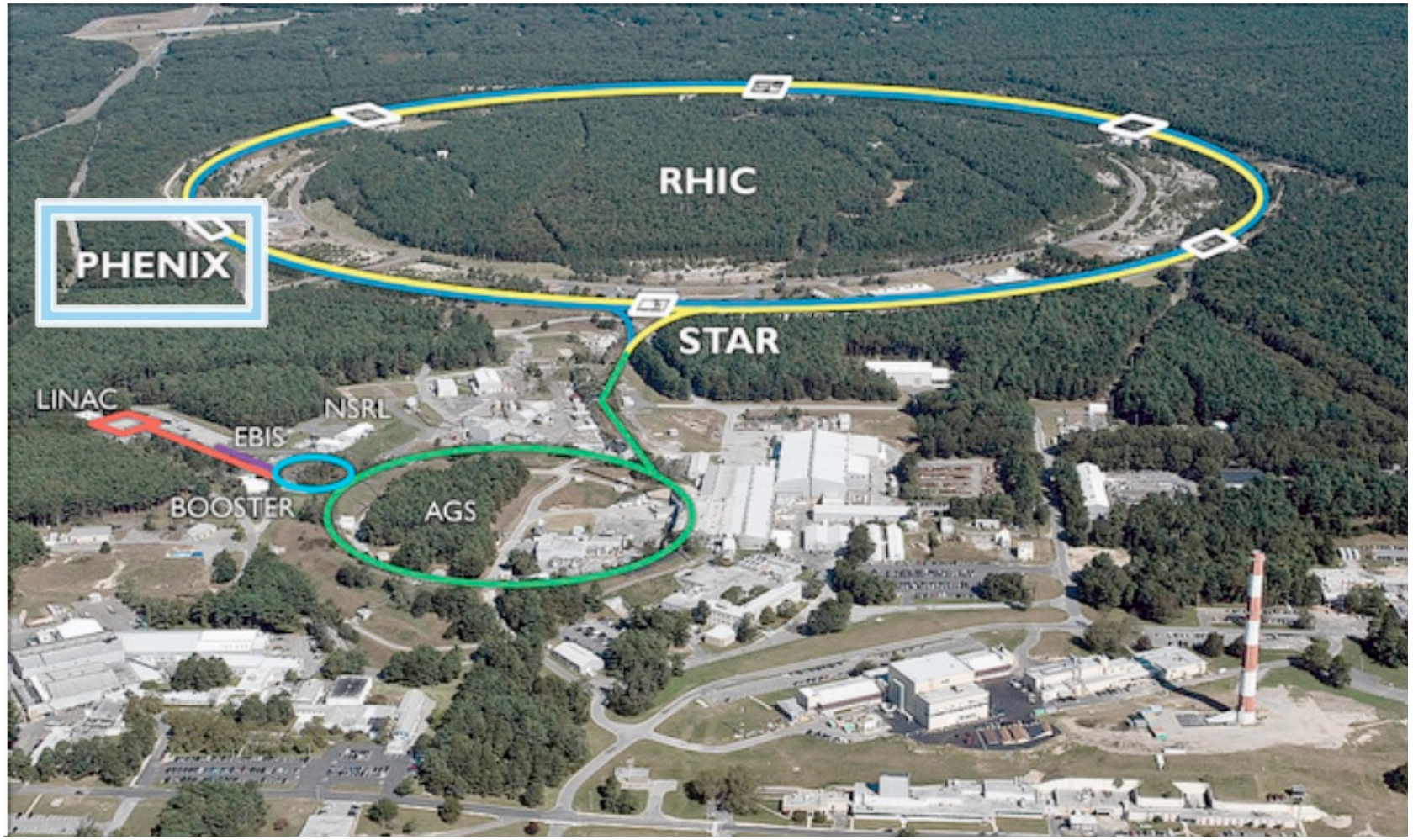
Reference Systems

- The decay angular distribution is usually reported in one of 3 systems of axes, differing in the definition of the polarization axis ($\hat{z}$):
  - **Helicity** (HX): J/ψ momentum in lab frame (traditionally used in collider experiments)
  - **Gottfried-Jackson** (GJ): direction of h_1 or h_2 in J/ψ rest frame (typically used in fixed target experiments)
  - **Collins-Soper** (CS): bisector between h_1 and (-) h_2 directions in J/ψ rest frame (widely used in Drell-Yan measurements)



❖ $\tilde{\lambda}$ is sensitive to the maximum angular asymmetry, or polarization, independent of the $\hat{z}$-axis orientation of the reference frame.

The Relativistic Heavy Ion Collider (RHIC)



- RHIC is an extremely versatile machine, located at Brookhaven National Lab (BNL), that has collided a variety of collision species at various energies
- PHENIX finished its last run in 2016.

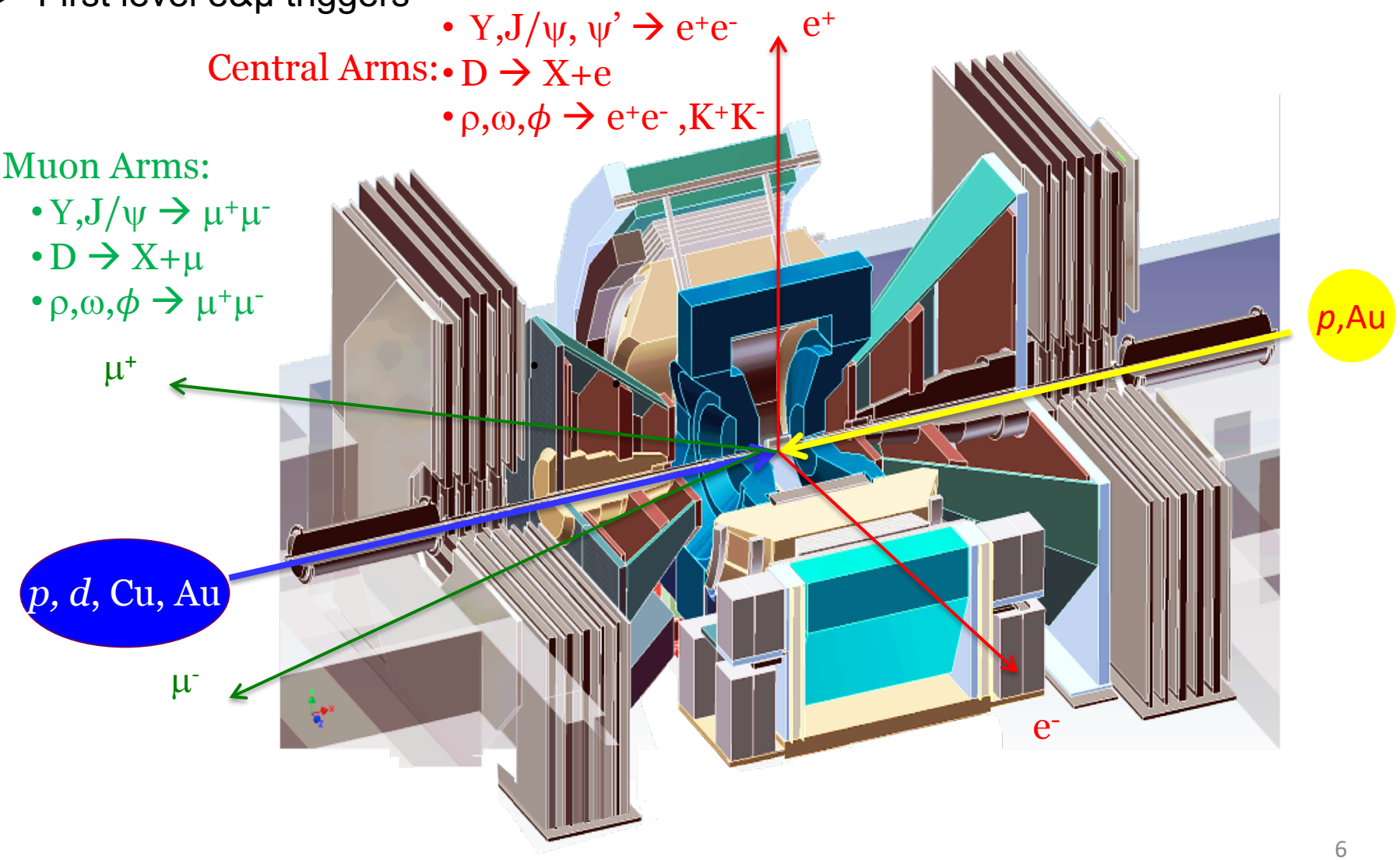
The PHENIX Detector

PHENIX: optimized to measure leptons: rapidity coverage: 1.2<|y|<2.2 & |y|<0.35

- High-rate capability with emphasis on mass resolution & particle ID
- First level e&μ triggers

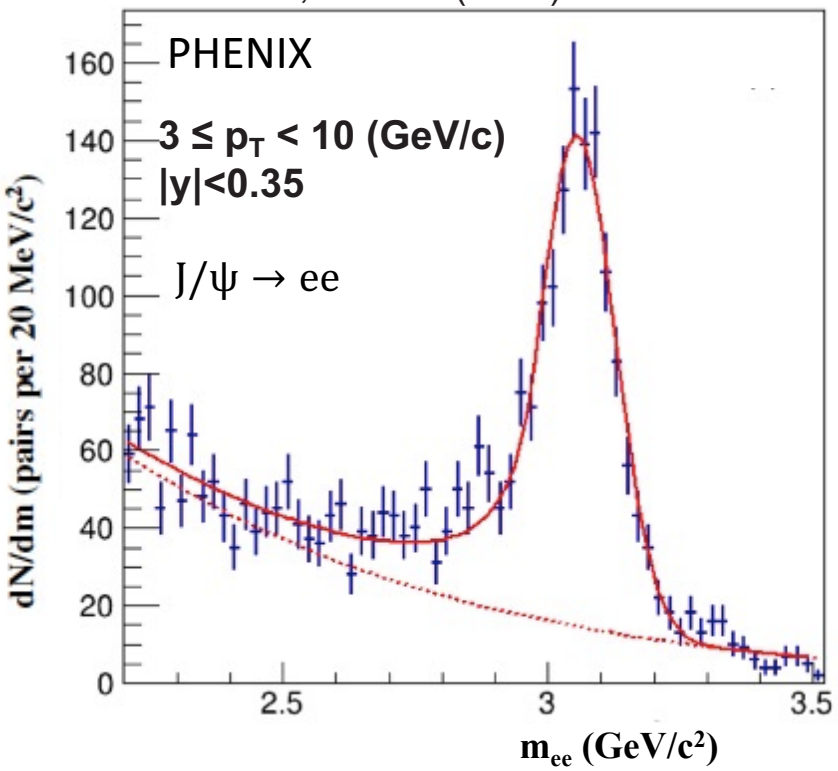
Central Arms:
- Υ,J/ψ, ψ' → e^+e^-
- D → X+e
- ρ,ω,ϕ → e^+e^- ,K^+K^-

Muon Arms:
- Υ,J/ψ → $\mu^+\mu^-$
- D → X+μ
- ρ,ω,ϕ → $\mu^+\mu^-$



Dilepton Mass Spectra at PHENIX

PRD **102**, 072008 (2020)



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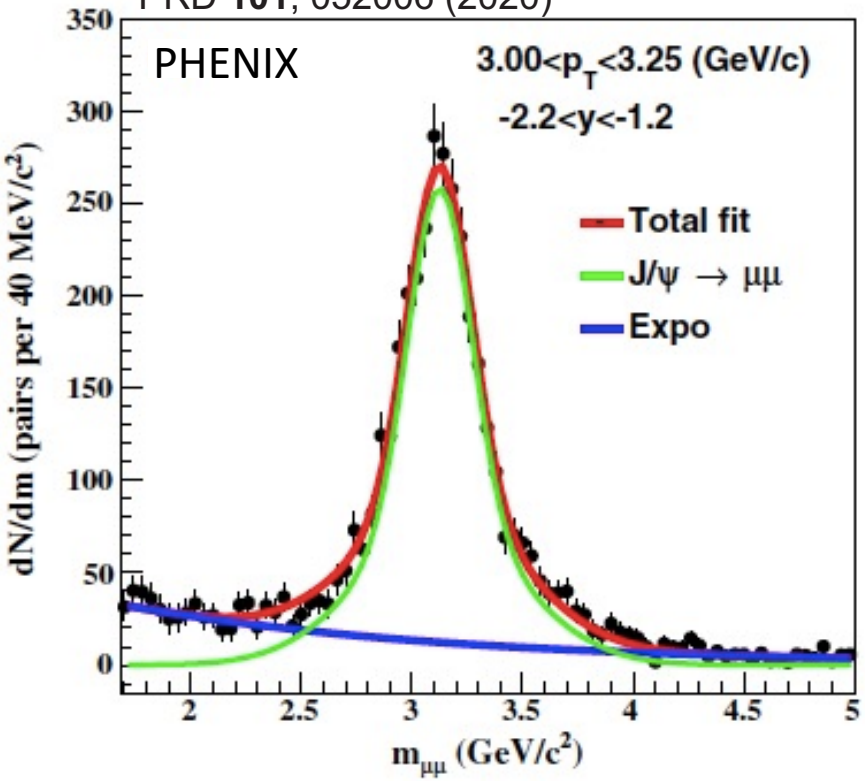
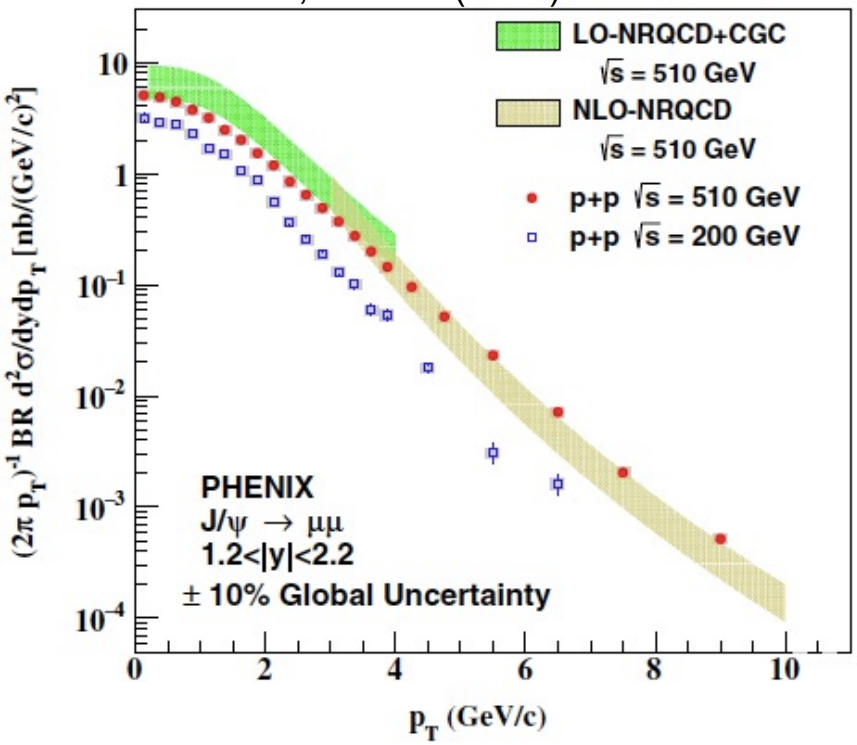
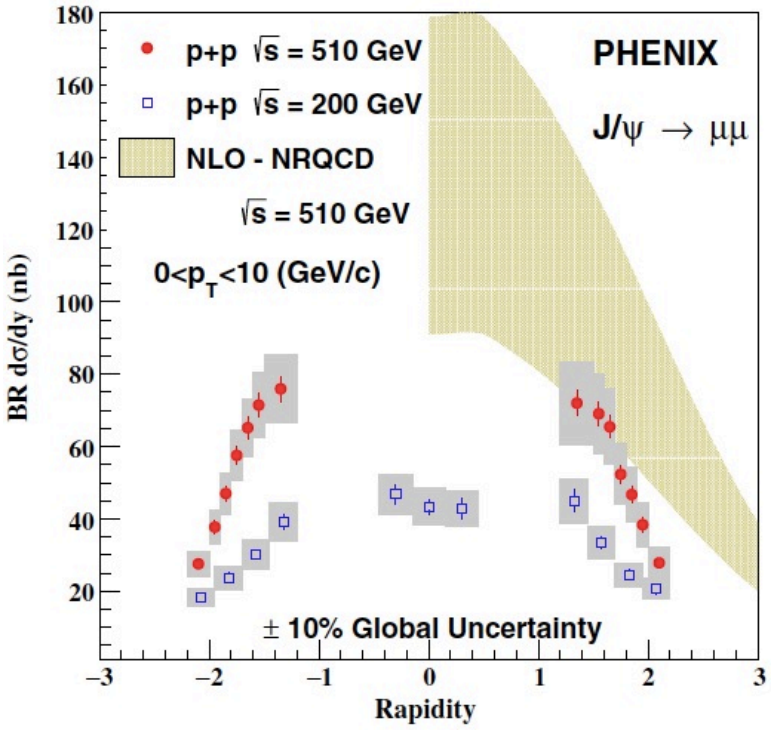


- Uncorrelated background is calculated using the mixed-event method and subtracted before fitting
- Exponential function is used to fit the correlated background

J/ψ Production at Forward Rapidity at $\sqrt{s} = 510$ GeV

PRD**101**, 052006 (2020)

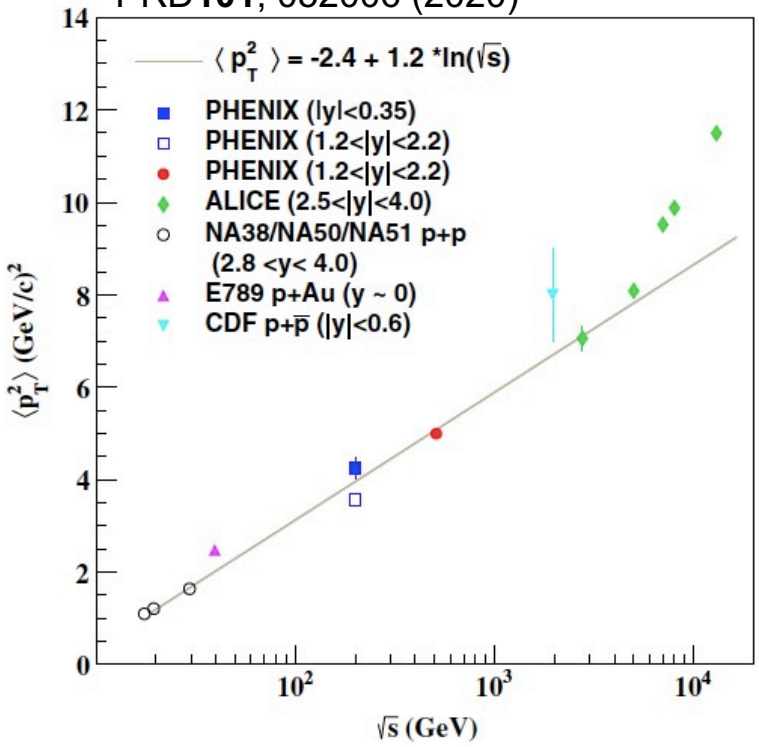


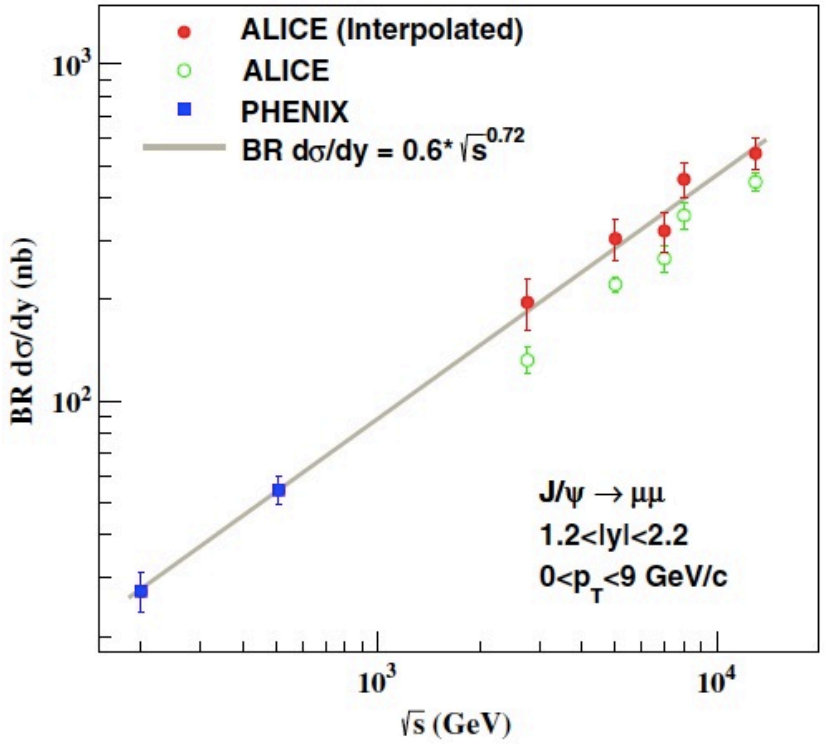


- LO-NRQCD+CGC calculations overestimate the data at low p_T
- NLO-NRQCD calculations underestimate the data at high p_T while to some extent, are consistent with the data at intermediate p_T, 3–5 GeV/c.
  - Nonprompt J/ψ contribution is not included in NLO-NRQCD calculations

J/ψ Production at Forward Rapidity at $\sqrt{s} = 510$ GeV

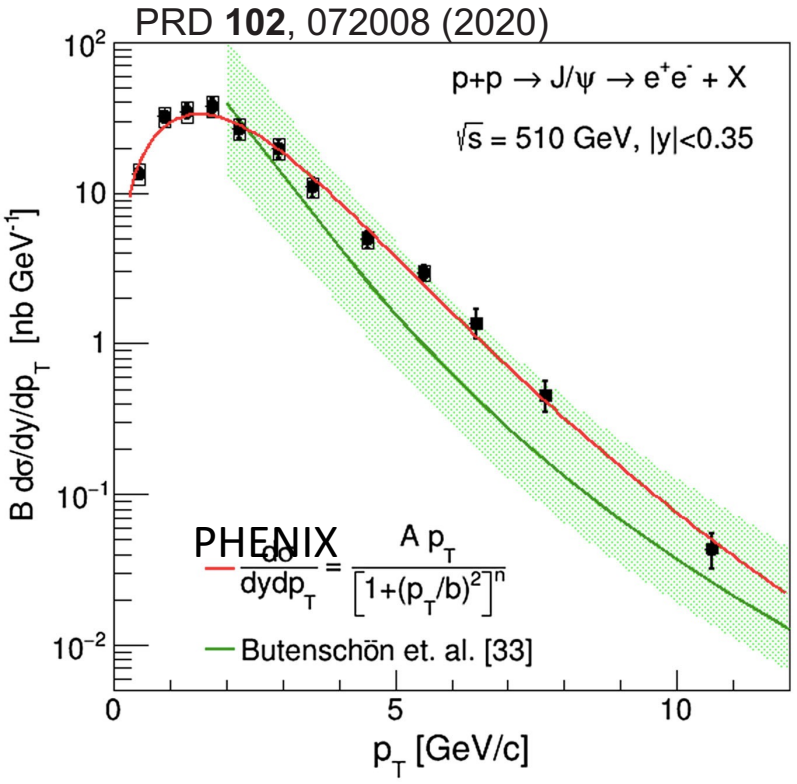
PRD**101**, 052006 (2020)

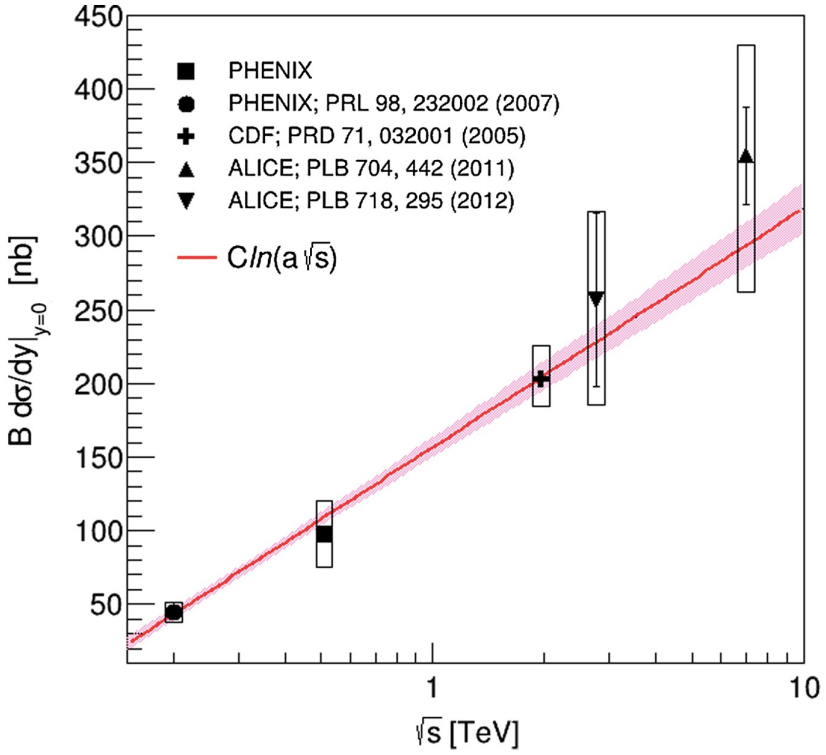




- $\langle p_T^2 \rangle$ follows the increasing pattern versus $\sqrt{s}$ established by several sets of data over a wide range of energies.
- PHENIX's $BR\, {d\sigma}/{dy}\ (1.2 < |y| < 2.2)$ is consistent with interpolated ALICE's data

J/ψ Prodution at mid-rapidity at $\sqrt{s} = 510$ GeV

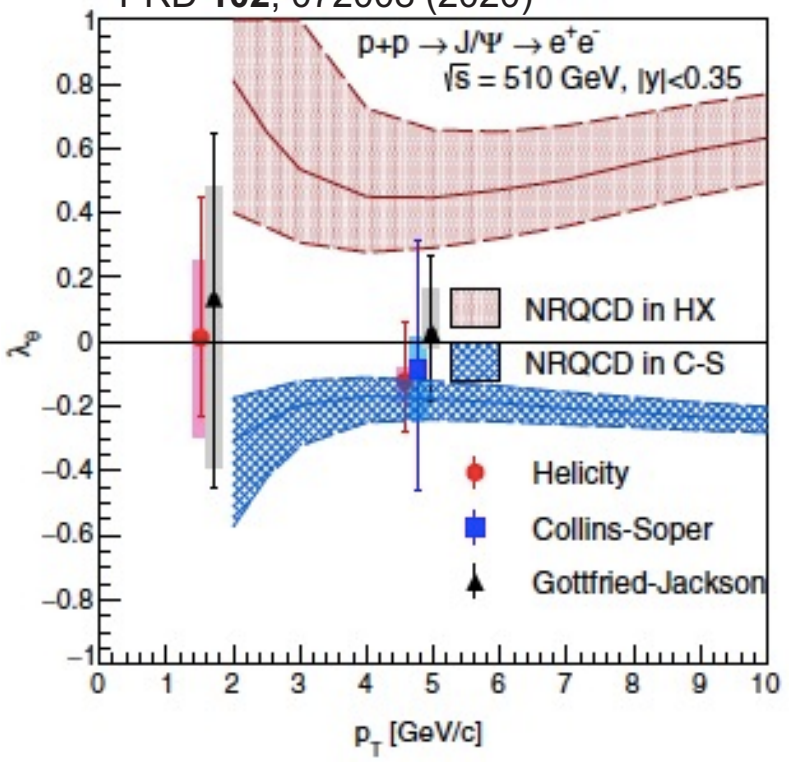


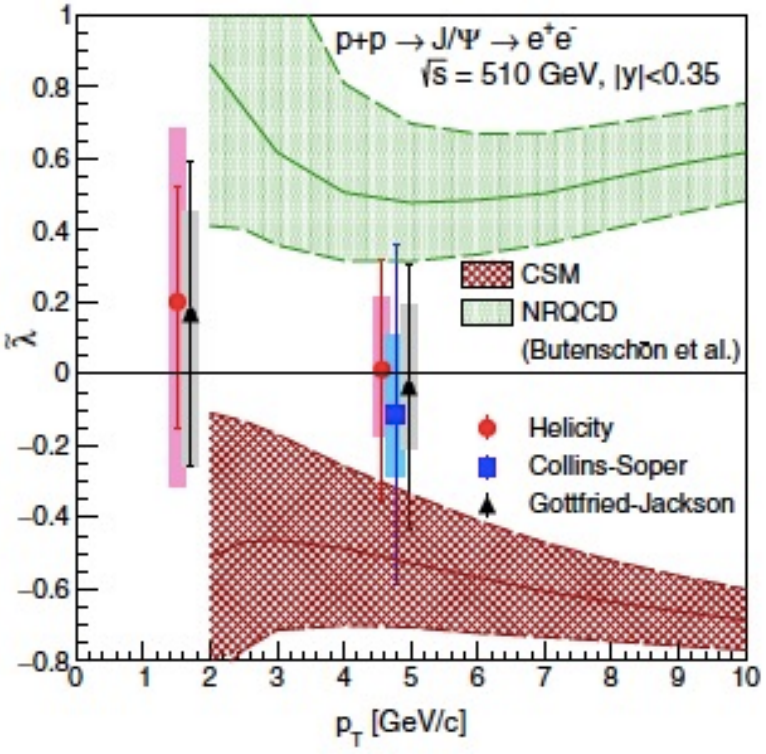


- NLO-NRQCD with leading relativistic corrections that includes CS and CO states (Mod.Phys.Lett.A **28**, 1350027 (2013)) agrees with data within uncertainties

J/ψ Polarization vs p_T at Mid-Rapidity

PRD **102**, 072008 (2020)

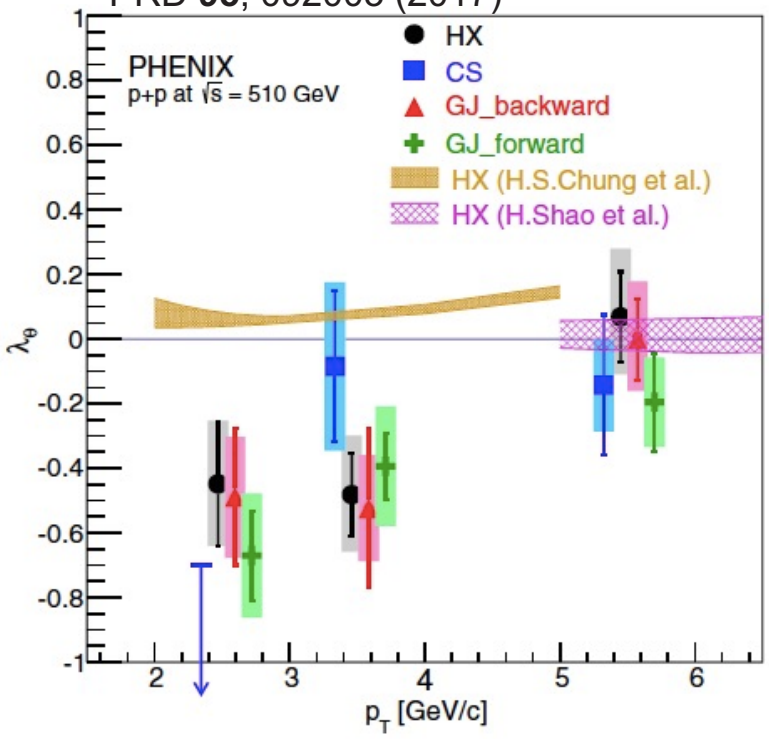


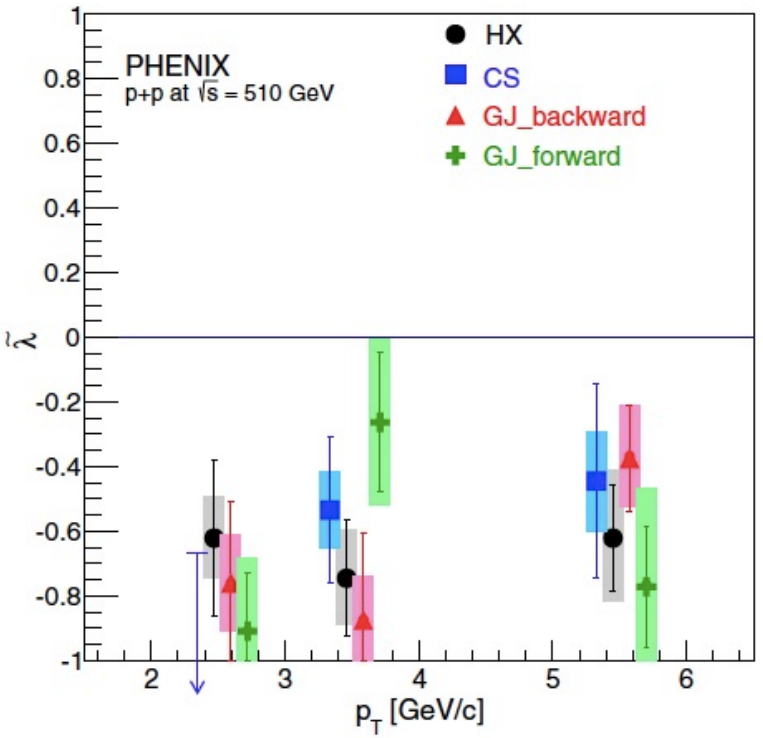


- Data consistent with no J/ψ polarization
- C-S frame measurement at low p_T not possible due poor acceptance
- NRQCD and CSM ($v \to 0$ limit of NRQCD) predict qualitatively different strong polarization

J/ψ Polarization vs p_T at Forward Rapidity

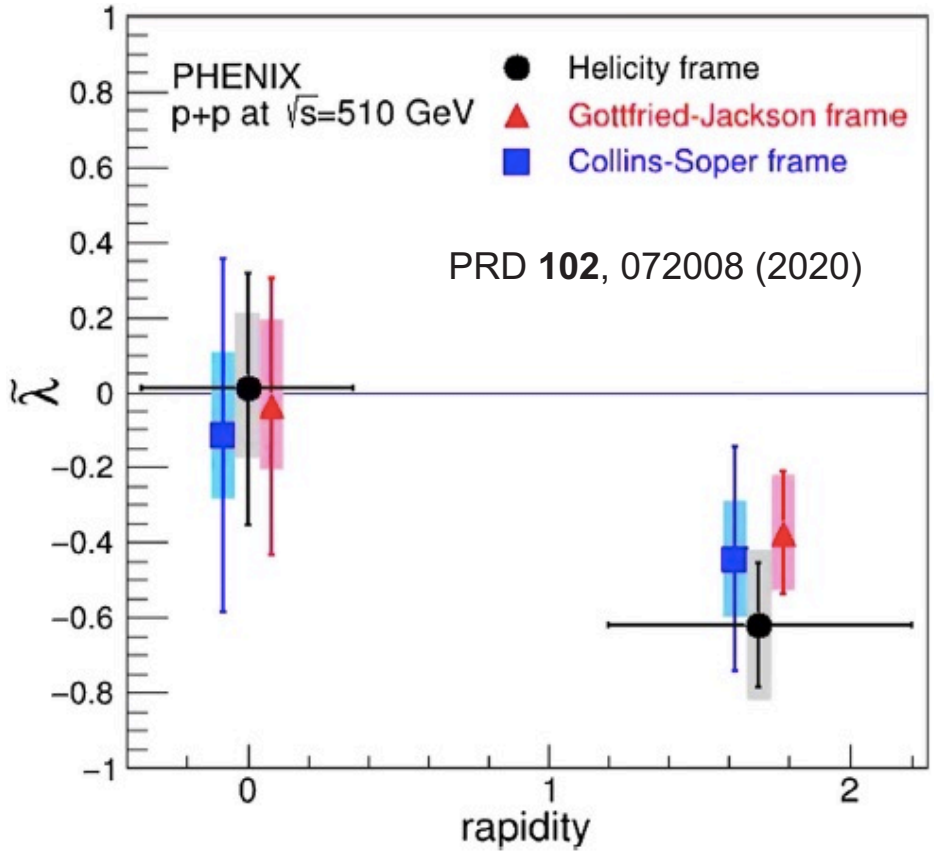
PRD **95**, 092003 (2017)





- $\tilde{\lambda}$ is consistent among all frames and show strong polarization across all p_T
- NRQCD calculations consistent with λ_θ results at high p_T while show strong deviation at low p_T

J/ψ Polarization vs Rapidity



- $\tilde{\lambda}$ shows strong J/ψ polarization at forward rapidity
- $\tilde{\lambda}$ is largely negative at forward rapidity indicating longitudinal polarization

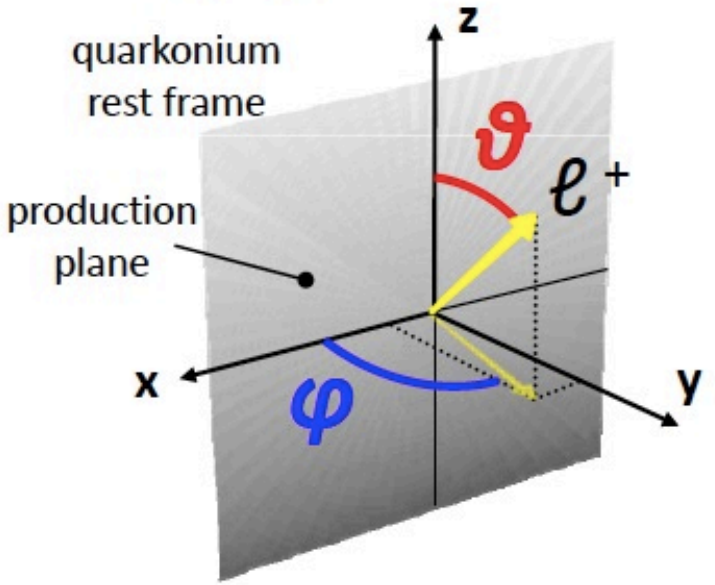
Summary & Conclusions

- PHENIX measured J/ψ production vs p_T, rapidity and p_T-integrated cross-section in p+p collisions at 200 and 510 GeV both at mid- and forward rapidities.
  - Cross-section's $\sqrt{s}$ dependence follows simple logarithmic trend from different measurements.
  - NRQCD calculations do not describe the data very well especially at forward-rapidity

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

Backup

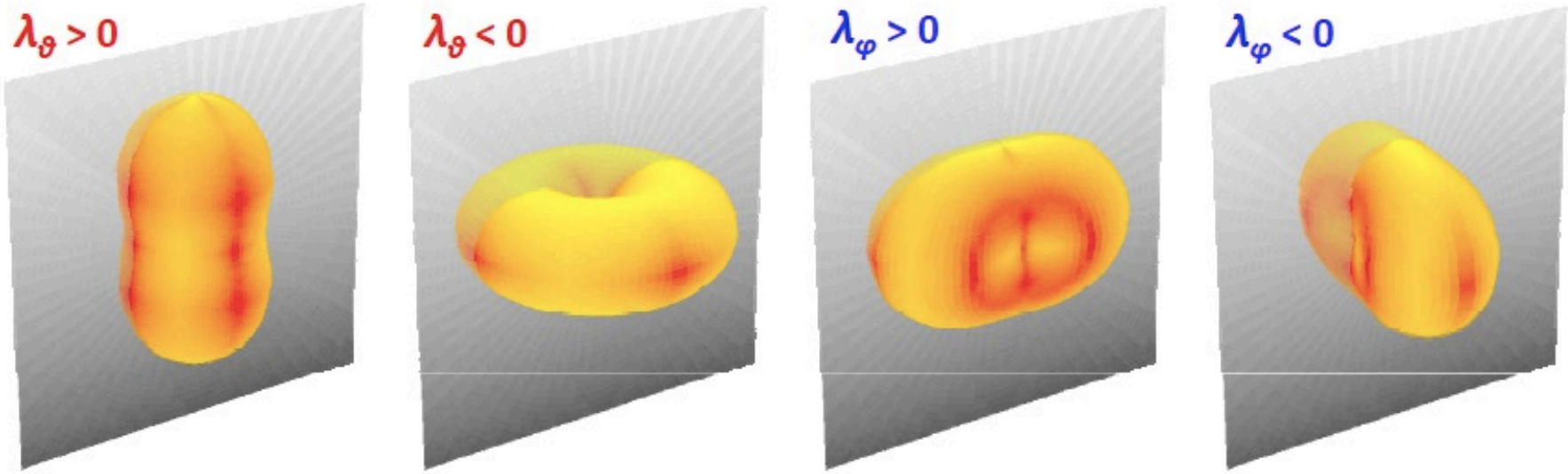
Pedagogical illustration of the decay angular distribution



$$W(\cos\theta,\varphi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$

"transverse"/ "longitudinal" polarization

azimuthal anisotropy

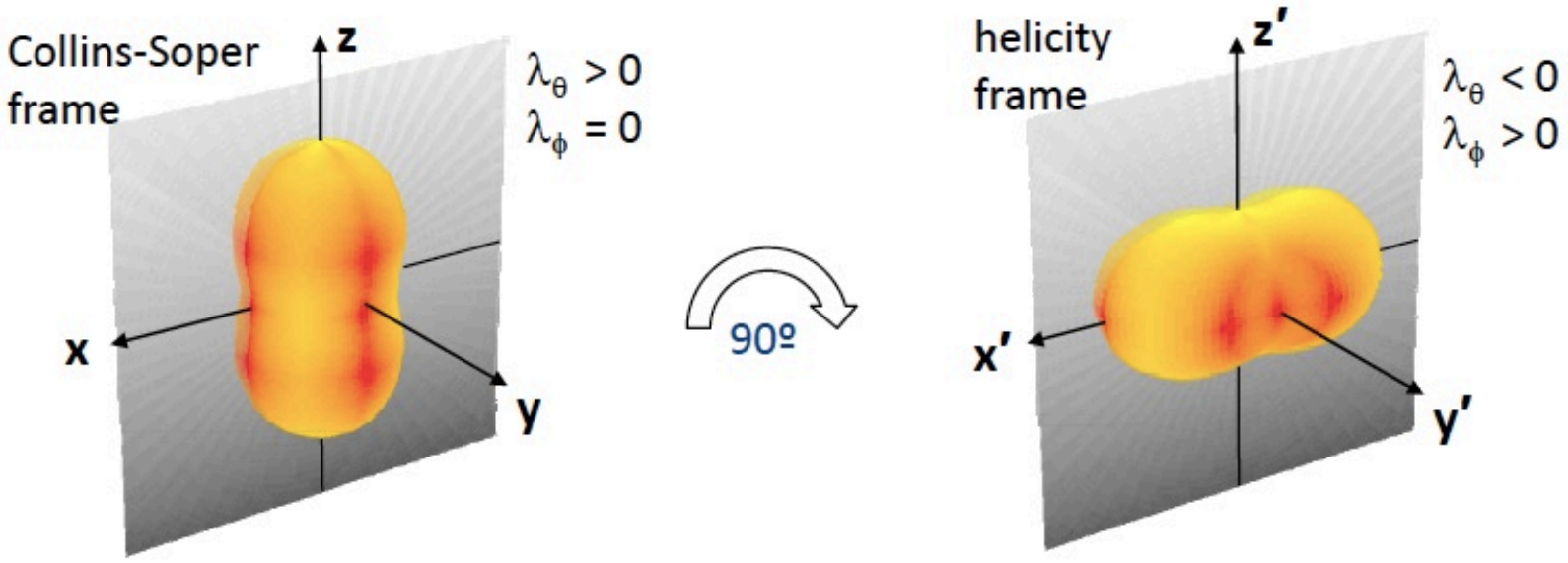


Additionally, $\lambda_{\vartheta\varphi} \neq 0$ means that the distribution is "tilted" wrt the chosen axes

The polarization depends on the frame

For $x_F = 0$ (or $y_{CM} = 0$) the CS and HX frames differ by a rotation of 90º

If the angular distribution shows a pure *transverse* polarization in the CS frame, e.g., then in the helicity frame we observe a smaller *longitudinal* polarization, together with some azimuthal anisotropy



Theoretical overview

Polarization in pp collisions - test of quarkonium production mechanisms:

CSM – Color Singlet Model:

- Perturbative QCD, underestimates quarkonium production cross-sections
- **Transverse polarization**

CEM - Color Evaporation Model:

- Soft gluon emission from the cc-pair during hadronization randomizes spin and color
- **No polarization**

NrQCD – Non-relativistic Quantum Chromodynamics:

- Takes into account non-perturbative effects in quarkonium production
- Dominance of the gluon fragmentation mechanism for $p_t >> M$, the fragmenting gluon is almost on-mass shell, and is therefore transversely polarized.
- The produced quarkonium inherits **transverse polarization at high p_t**

Khoze, Martin, Ryskin, Stirling, Eur. Phys. J., C39, 163 (2005):

- Perturbative calculations only. The basic subprocess: $g(gg)_{8s} \rightarrow J/\psi$
- Cross sections are in agreement with CDF and RHIC experiments
- **Transverse polarization at small p_t, longitudinal polarization at high $p_t >> M$.**

Previous J/ψ Measurements at PHENIX

PRD 82, 012001 (2010)