Recent Quarkonia Results from PHENIX Experiment

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Motivation

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

• Many $J/\psi$ 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:

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

$\lambda_\theta$, $\lambda_{\theta\phi}$ and $\lambda_\phi$ 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):** $J/\psi$ momentum in lab frame (traditionally used in collider experiments)
  
  • **Gottfried-Jackson (GJ):** direction of $h_1$ or $h_2$ in $J/\psi$ rest frame (typically used in fixed target experiments)
  
  • **Collins-Soper (CS):** bisector between $h_1$ and (-) $h_2$ directions in $J/\psi$ rest frame (widely used in Drell-Yan measurements)

  \[v\lambda\] 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:
• Y',J/ψ, ψ' → e⁺e⁻
• D → X+e
• ρ,ω,φ → e⁺e⁻, K⁺K⁻

Muon Arms:
• Y',J/ψ → µ⁺µ⁻
• D → X+µ
• ρ,ω,φ → µ⁺µ⁻

p, d, Cu, Au

µ⁺

µ⁻
e⁺
e⁻
Dilepton Mass Spectra at PHENIX

Uncorrelated background is calculated using the mixed-event method and subtracted before fitting.

Exponential function is used to fit the correlated background.
$J/\psi$ Production at Forward Rapidity at $\sqrt{s} = 510$ GeV

- 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 $J/\psi$ contribution is not included in NLO-NRQCD calculations

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\(J/\psi\) Production at Forward Rapidity at \(\sqrt{s} = 510\) GeV

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

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

- \( \lambda \) is consistent among all frames and show strong polarization across all \( p_T \)
- NRQCD calculations consistent with \( \lambda_\theta \) results at high \( p_T \) while show strong deviation at low \( p_T \)
\( \lambda \) shows strong \( J/\psi \) polarization at forward rapidity

\( \lambda \) is largely negative at forward rapidity indicating longitudinal polarization
Summary & Conclusions

- PHENIX measured $J/\psi$ 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 $J/\psi$ 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

$$W(\cos \theta, \varphi) \propto 1 + \left[ \begin{array}{c} \lambda_\theta \cos^2 \theta \\ \lambda_\theta \varphi \sin 2\theta \cos \varphi \\ \lambda_\varphi \sin^2 \theta \cos 2\varphi \end{array} \right]$$

“transverse”/ “longitudinal” polarization

azimuthal anisotropy

Additionally, $\lambda_{\theta \varphi} \neq 0$ 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 $90^\circ$

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 $p_t \gg M$, the fragmenting gluon is almost on-mass shell, and is therefore transversely polarized.
- The produced quarkonium inherits **transverse polarization at high $p_t$**

- Perturbative calculations only. The basic subprocess: $g(gg)_8 \rightarrow J/\psi$
- Cross sections are in agreement with CDF and RHIC experiments
- **Transverse polarization at small $p_t$, longitudinal polarization at high $p_t \gg M$.**
Previous $J/\psi$ Measurements at PHENIX

**Helicity Frame**

- PHENIX $p+p$ $\sqrt{s}=200$ GeV
- HERA-B $p+(C,W)$ $\sqrt{s}=41.6$ GeV

**Gottfried-Jackson Frame**

- PHENIX $p+p$ $\sqrt{s}=200$ GeV
- HERA-B $p+(C,W)$ $\sqrt{s}=41.6$ GeV
- E771 $p+Si$ $\sqrt{s}=38.8$ GeV
- E866/NuSea $p+Cu$ $\sqrt{s}=38.8$ GeV (CS)