Measurements of $J/\psi$ production in p+p and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR experiment

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Use quarkonium to probe QGP

• **Color-screening:** quark-antiquark potential is screened by surrounding partons, leading to dissociation

  ![Image]

  Illustration: A. Rothkopf

  T. Matsui and H. Satz, PLB 178 (1986) 416

  **J/ψ** suppression was proposed as a proof of QGP formation

  

  Ferreiro et al., PRC 81(2010) 064911
  Eskola et al., JHEP 0807 (2008) 102
  Eskola et al., JHEP 0904 (2009) 065
  De Florian et al., PRD69 (2004) 074028

**However**

• **Cold nuclear matter effects also play an important role**
  - Nuclear PDF (nPDF) effect
  - Nuclear absorption effect
  - Co-mover effect

• **Quarkonium production mechanism in elementary collisions is not fully understood**

**Shadowing** $R_{Pb}^{Pb}$

$R_P(x,Q^2=1.69\text{ GeV}^2)$
Quarkonium production mechanism

- **Various production mechanism**
  - Prompt J/ψ: direct production; decay of ψ(2S) and χ_c (~ 40%)  
    \[ J. \text{Phys. G} \ 35, \ 104134 \ (2008) \]
  - Non-prompt J/ψ: B-hadron decay (up to 10-15% at high \( p_T \))  

- **Different models on the market**
  - Color Singlet Model
  - Color Evaporation Model
  - NRQCD approach
  - CGC+NRQCD

- **Measurements of quarkonium polarization** provide further constraints on production models
  - Competing theoretical approaches predict similar production cross-sections, but different polarizations
J/ψ polarization measurement

- J/ψ polarization can be analyzed via the angular distribution of the decayed positively charged leptons, which can be expressed as:

\[
W(\cos\theta, \varphi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta + \lambda_\varphi \sin^2 \theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos \varphi)
\]

- **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 axis z**
  - **Helicity (HX) frame**: along the J/ψ momentum in the center-of-mass of the colliding beams
  - **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
The **Solenoidal Tracker At RHIC**

- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$

- **TPC**: measure momentum and energy loss
- **TOF**: measure particle’s time of flight. Extend PID to higher $p_T$.
- **BEMC**: trigger on and identify electrons
- **MTD (45% in $\varphi$, $|\eta| < 0.5$)**: trigger on and identify muons
  - precise timing measurement ($\sigma \sim 100\,\text{ps}$)
  - spatial resolution ($\sim 1\,\text{cm}$)
  - reduced Bremsstrahlung radiation compared to electrons
Inclusive J/ψ cross section in p+p collisions

- Inclusive J/ψ cross section is measured for 0 < p_T < 14 GeV/c

- CGC+NRQCD together with NLO NRQCD (prompt J/ψ) can qualitatively describe data in the full p_T range within uncertainties
  - There seems tension towards very low p_T

- Improved CEM model (direct J/ψ) describes data well at low p_T
  - Data are above ICEM calculation at 3.5 < p_T < 12 GeV/c

- B-hadron feed-down needs to be taken into account
• First inclusive $J/\psi$ polarization measurement via the dimuon decay channel in both HX and CS frames in 200 GeV p+p collisions at RHIC

• $\lambda_\theta$ and $\lambda_\phi$ parameters are consistent with 0 in HX and CS frames
Frame invariant quantity

\[ \lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi} \]

- Any arbitrary choice of the experimental observation frame will give the same value of this quantity
- Good cross-check on measurements performed in different frames

\[ \lambda_{inv} \] as a function of \( p_T \) are consistent between HX and CS frames
J/ψ polarization: dimuon vs. dielectron

- Consistent results from the two decay channels in overlapping region
  - The dimuon results have different acceptance, efficiency and systematics compared to dielectron results
- The $\lambda_\theta$ parameters are consistent with 0 at $0 < p_T < 8$ GeV/c.
J/ψ polarization in 200 GeV p+p collisions

- Newly measured $\lambda_\theta$ parameters using 2012 and 2015 data are consistent with previous publication with 2009 data
- But the overall trend seems a bit different:
  - Current data are compatible with 0 without strong $p_T$ dependence, while the published data seem to indicate a decreasing trend towards high $p_T$
First $J/\psi$ $R_{pAu}$ measurement at RHIC

$R_{pAu}$ is consistent with unity at high $p_T$ and is less than unity at low $p_T$
$J/\psi$ $R_{pAu}$ vs. $R_{dAu}$ at 200 GeV $p+Au$ collisions

- $R_{pAu}$ is consistent with $R_{dAu}$ within uncertainties
  - There seems to be tension at 3.5-5 GeV/c with a significance of $1.4\sigma$
- Suggest similar CNM effects in these collision systems

PHENIX, PRC 87 (2012) 034903

Global Uncertainty
Inclusive $J/\psi$ $R_{pAu}$: data vs. models

- Model calculations with only nPDF effect can touch the upper limit of data within uncertainties

Comp. Phys. Comm. 198 (2016) 238-259

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- **Data favor a model calculation including an additional nuclear absorption effect on top of the nPDF effect**
Summary and outlook

- **p+p collisions at** $\sqrt{s_{NN}} = 200$ GeV
  - Inclusive J/$\psi$ cross section is measured for $0 < p_T < 14$ GeV/c
    - Can be described by CGC+NRQCD and NLO NRQCD (prompt J/$\psi$) in the full $p_T$ range within uncertainties
    - ICEM (direct J/$\psi$) describes data at low $p_T$ while underestimates data at $3.5 < p_T < 12$ GeV/c
  - First measurements of J/$\psi$ polarization in the HX and CS frames from the dimuon channel for $0 < p_T < 5$ GeV/c
    - Both $\lambda_\theta$ and $\lambda_\varphi$ parameters are consistent with 0 in the both frames
    - The $\lambda_\theta$ parameter in the HX frame is consistent with the dielectron result ($2 < p_T < 8$ GeV/c) in the overlapping region

- **p+Au collisions at** $\sqrt{s_{NN}} = 200$ GeV
  - J/$\psi$ $R_{pAu} \sim R_{dAu}$: suggests similar CNM effects between p+Au and d+Au collisions
  - J/$\psi$ $R_{pAu}$ favors additional nuclear absorption effect on top of nPDF effect

- **Outlook:** the measurement of J/$\psi$ polarization parameters in p+Au collisions is underway
Back Up
• First inclusive J/ψ invariant yield measured in p+Au collisions at RHIC

• $N_{\text{coll}}$ scaling works reasonably well at high $p_T$ for p/d+Au

$\sqrt{s_{\text{NN}}} = 200$ GeV

STAR p+Au $|y|<0.5$ (dimuon)

STAR d+Au $(x \frac{N_{p+Au}}{N_{d+Au}}) |y|<1$

PHENIX d+Au $(x \frac{N_{p+Au}}{N_{d+Au}}) |y|<0.35$

\textit{STAR Preliminary}

PHENIX, PRC 87 (2012) 034903

STAR d+Au, PRC 93 (2016) 064904
• Measured $\psi(2S)/J/\psi$ ratio in 200 GeV p+p collisions is consistent with world-wide data

• The ICEM model describes the increasing trend
$\psi(2S)/\psi(1S)$ double ratio between $p+p$ and $p+Au$

- First $[\sigma_{\psi(2S)}/\sigma_{\psi(1S)}]_{pAu}/[\sigma_{\psi(2S)}/\sigma_{\psi(1S)}]_{pp}$ measurement at midrapidity at RHIC

$$1.37 \pm 0.42{\text{(stat)}} \pm 0.19{\text{(sys)}}$$

PHENIX $p+Au$, arXiv:1609.06550 (Accepted by PRC)
PHENIX $d+Au$, PRL111 (2013) 202301
Co-mover calculation, Ferreiro (2016) private communication
Calculation based on PLB749 (2015) 98-103
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- \( \theta \) - polar angle between momentum of a positive lepton in the J/ψ rest frame and the polarization axis z
- \( \varphi \) - corresponding azimuthal angle
- The angular distribution, integrated over azimuthal angle:

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

\[ W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3 + \lambda_\theta} \cos 2\varphi \]
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