Measurements of Quarkonium Polarization and Production versus Charged-Particle Multiplicity in p+p Collisions at $\sqrt{s} = 500$ GeV in the STAR experiment

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Quarkonia in p+p collisions

- **Quarkonium Production mechanism** in elementary collisions is not fully understood
  - Color singlet vs color octet intermediate state

- **Different models on the market:**
  - Color Singlet Model
  - Color Evaporation Model
  - NRQCD approach – applicable at high $p_T$
  - CGC+NRQCD – applicable at low $p_T$

- **Feed-down**
  - Inclusive $J/\psi$ production:
    - prompt $J/\psi$
    - direct $J/\psi$ ($\sim 60\%$), feed down from $\psi(2S)$ ($\sim 10\%$) and $\chi_c$ ($\sim 30\%$) decays

- Measurements of quarkonium production and polarization - tests of different production models, help to understand QCD
Quarkonia in the STAR Experiment

\[ J/\psi /\Upsilon \rightarrow e^+ e^-, \mu^+ \mu^- \]

\[ 0 < \phi < 2\pi \]

\[ e: |\eta| < 1, \mu: |\eta| < 0.5 \]

- VPD - minimum bias trigger
- TPC – tracking PID: dE/dx
- TOF – time resolution < 100 ps PID: 1/\beta
- BEMC – PID: E/p trigger on electron high-p_T J/\psi
- MTD - trigger on muon improve low-p_T J/\psi
**J/ψ production in p+p 500 GeV**

**High-p_T J/ψ**

\[ J/ψ → e^+ e^- \]

- NLO NRQCD for prompt J/ψ describes the data well for \( p_T > 4 \) GeV/c

**Low-p_T J/ψ**

\[ J/ψ → μ^+ μ^- \]

- Dimuon trigger – two hits in MTD
- More precise low-p_T J/ψ measurements

NLO NRQCD:

- Private communication

Kuang-Ta Chao, Hao Han, Hua-Sheng Shao

September 30, 2015

Barbara Trzeciak, QM 2015
J/Ψ $x_T$ scaling in p+p collisions

$x_T$ scaling observed in STAR at 200 and 500 GeV

$$x_T = 2p_T/\sqrt{s}$$

$$\frac{d^2\sigma}{2\pi p_T dp_T dy} = g(x_T)/(\sqrt{s})^n$$

✓ $p_T > 5$ GeV/c - J/ψ production follows the $x_T$ scaling of cross-section at mid-rapidity, with $n \sim 5.6$

→ $x_T$ scaling breaking - transition from hard to soft process

$n$ - number of constituents taking an active role in hadron production

In high energy proton-proton collisions Multi-Parton Interactions (MPI) may be important on a hard scale. At LHC correlation between quarkonium production and event activity has been observed.

MPI? String screening? or ?


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→ MPI? String screening? or ?
J/Ψ production vs. event activity

→ STAR observes correlation between relative J/Ψ yield and relative event multiplicity at 500 GeV

→ At higher multiplicities stronger than linear growth at $p_T > 4$ GeV/c
  • Hint of $p_T$ dependence

STAR p+p @ 500 GeV

- $J/Ψ → μ^+μ^-$, $p_{T,J/Ψ} > 0$ GeV/c
- $J/Ψ → e^+e^-$, 4 < $p_{T,J/Ψ}$ < 8 GeV/c
- $J/Ψ → e^+e^-$, $p_{T,J/Ψ} > 8$ GeV/c

TofMult - Multiplicity of TOF matched tracks, $|\eta| < 0.9$
STAR observes correlation between relative $J/\psi$ yield and relative event multiplicity at 500 GeV

- At higher multiplicities stronger than linear growth at $p_T > 4$ GeV/c
  - Hint of $p_T$ dependence
  - Similar trend at LHC for $J/\psi$ and open charm production

$J/\psi$ production vs. event activity

+15% one-sided error along both x- and y- direction

TofMult - Multiplicity of TOF matched tracks, $|\eta| < 0.9$
**J/Ψ production vs. event activity - models**

- Correlation between relative J/ψ yield and relative event multiplicity

**Possible explanations:**

- Multiple parton-parton interactions - *PYTHIA 8*
  - Default Pythia tune, $p_T$ dependence

- String screening - *percolation model* – quadratic dependence at high multiplicities
  - *PRC 86 (2012) 034903, and private communication*

- Hadronic activity associated with J/ψ production

- Percolation Model and PYTHIA8 (in two $p_T$ bins) can describe the observed correlation

- In order to distinguish between the models measurements need to be extended to higher event activity bins – *in progress*
Polarization provides further constraints on J/ψ production models

- Similar production cross-sections but different production mechanisms in competing theoretical approaches lead to different polarization

- CSM vs different NRQCD calculations

J/ψ polarization can be analyzed via the angular distribution of the decay lepton pair:

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

- \(\theta\) - polar angle between momentum of a positive lepton in the J/ψ rest frame and the polarization axis \(z\)
- \(\phi\) - corresponding azimuthal angle

**Polarization z axis:**

- **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
**Polarization parameters**

- The angular distribution, integrated over azimuthal angle:
  \[ W(\cos \theta) \propto 1 + \lambda_\theta \cos^2 \theta \]
- Polar angle:
  \[ W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta} \cos 2\varphi \]

**Frame invariant quantity:**

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

**Transverse polarization**

- \( \lambda_\theta = +1 \)
- \( \lambda_\varphi = 0 \)
- \( J_z = \pm 1 \)

**Longitudinal polarization**

- \( \lambda_\theta = -1 \)
- \( \lambda_\varphi = 0 \)
- \( J_z = 0 \)

Good cross-check on measurements performed in different frames.

Any arbitrary choice of the experimental observation frame will give the same value of this quantity.

P. Faccioli, CERN, April 23th 2013

J/Ψ polarization in p+p 200 and 500 GeV

Similar trend observed in 500 and 200 GeV p+p collisions

RHIC data indicate trend towards longitudinal polarization with increasing \( p_T \)

Measurement extended to higher \( p_T \) range, 5 < \( p_T \) < 16 GeV/c, with new 500 GeV data

**J/Ψ polarization vs model predictions**

### λ_θ parameter in HX frame

#### 200 GeV
- Consistency with NLO^+ CSM prediction

#### 500 GeV
- Lower value of λ_θ not constrained within the NLO NRQCD calculations for prompt J/ψ
- STAR data can help to constrain color-octet Long-Distance Matrix Elements for the NLO NRQCD
  
  > Predictions that can describe cross-sections well have little prediction power for the polarization – *input from data needed*
$x_T$ dependence of $\lambda_\theta$

$\lambda_\theta$ parameter in HX frame

$\rightarrow$ Common trend towards strong negative values with increasing $x_T$

$\rightarrow$ $x_T$ scaling of cross-section at $p_T > 5$ GeV/c

$x_T = 2p_T/\sqrt{s}$
\( \lambda_\phi \) and \( \lambda_{\text{inv}} \) parameters in HX frame

- No strong azimuthal anisotropy observed in the HX frame
- Negative values of the frame invariant \( \lambda_{\text{inv}} \) parameter
Different values of the $\lambda_\theta$ and $\lambda_\phi$ polarization parameters in the CS frame

- Frame invariant parameters, $\lambda_{inv}$, consistent in both frames
- Trend towards longitudinal polarization with increasing $p_T$
Summary

✔ J/ψ $p_T$ spectra at $\sqrt{s} = 200$ and 500 GeV measured, can be described well by NRQCD predictions

✔ Increase of relative J/ψ yield with relative charged-particle multiplicity in p+p at $\sqrt{s} = 500$ GeV

→ Stronger than linear rise at higher multiplicities at $p_T > 4$ GeV/c
→ PYTHIA8 and Percolation Model can describe the observed increase
→ Similar trend as observed at LHC

✔ Longitudinal J/ψ polarization in HX frame at $\sqrt{s} = 200$ and 500 GeV

→ No strong azimuthal anisotropy observed
→ $x_T$ dependence of $\lambda_\theta$ observed

✔ Frame invariant parameters agree in HX and CS frames at $\sqrt{s} = 500$ GeV

✔ Data will help to constrain J/ψ production models

✔ $\Upsilon$ analysis of cross-section at 500 GeV and relative yield vs event activity in progress – see Leszek Kosarzewski poster 0613
Thank you !
**J/ψ p_T spectrum in p+p 200 GeV**

- Test of different production models


\[ \sigma^{\text{inclusive}}_{J/\psi} = \int \frac{d^2\sigma}{d^2p_T} (2\pi p_T dp_T \, dy) \left[ \text{nb/(GeV/c)}^2 \right] \]

\[ p+p \rightarrow J/\psi + X, \ \sqrt{s} = 200 \text{ GeV} \]

- STAR 2009 EMC
- STAR 2009 MB
- STAR 2005 & 2006
- PHENIX 2006

- MB STAR Preliminary

- **NNLO* CS**, direct production, misses high-\( p_T \) part

- **CEM**, prompt production, can reasonably well describe the \( p_T \) spectra

- **NLO NRQCD**, prompt production, describes the data for \( p_T > 4 \) GeV/c

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• Test of different production models

- **NNLO* CS**, direct production, misses high-p\(_T\) part

- **CEM**, prompt production, can reasonably well describe the p\(_T\) spectra

- **NLO NRQCD**, prompt production, describes the data for p\(_T\) > 4 GeV/c

- **CGC + NRQCD**, describes the data in the full p\(_T\) range

\( J/\Psi \) \( p_T \) spectrum in p+p 200 GeV

\[ \sqrt{s} = 0.2 \text{ TeV for RHIC} \]
\[ \sqrt{s} = 7 \text{ TeV for LHC} \]

\[ d^2\sigma/dp_T dy (\text{nb/GeV}) \]

\[ p_T (\text{GeV/c}) \]

Comparison of CSM to RHIC data


(a) central
First measurement of $\frac{\psi(2S)}{J/\psi}$ ratio in p+p at 500 GeV

- Consistent with other experiments
- No collision energy dependence observed

Constrain $\psi(2S)$ feed-down contribution to inclusive $J/\psi$ production
B $\rightarrow$ J/$\Psi$ fraction in p+p 200 GeV

✓ Measurement based on azimuthal angular correlations between high-\(p_T\) J/$\Psi$ and charged hadrons

→ B-hadron feed-down contribution: 10-25%, in the range 4 < \(p_T\) < 12 GeV/c

→ Agreement with FONLL + CEM prediction
**B -> J/Ψ fraction in p+p 200 GeV**

- Measurement based on azimuthal angular correlation between high-\(p_T\) \(J/ψ\) and charged hadrons

- B-hadron feed-down contribution: 10-25%, in the range 4 < \(p_T\) < 12 GeV/c

- Agreement with FONLL + CEM prediction and with measurements from other experiments

![Graphs and data showing the measurement of B -> J/Ψ fraction in p+p 200 GeV.](image)