Results on J/$\psi$ and $\psi(2S)$ in p-Pb Collisions at 5.02 TeV with ATLAS

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Overview

Motivation

Analysis and Fit Method

$J/\psi$ Analysis and Results

$J/\psi$ and $\psi(2S)$ Analysis and Results

Conclusions

Backup
Motivation

Study fundamental QCD processes in nuclear medium at TeV scale.

Cold Nuclear medium effects as Heavy Ion baseline

- Final state effects due to hot matter not expected in p-A collisions but suppression observed.

Numerous insights

- J/ψ Production Mechanisms
- Saturation scale in QCD
- Medium-induced gluon radiation
- Shadowing and other modifications of the gluon PDFs
- Absorption of qqbar pairs
- Ion-direction observables vs. proton directions observables
Analysis Method

Reconstruct di-muon invariant mass $2.5 \ (2.6) \ GeV < m(\mu\mu) < 3.5 \ (4.1)$

Trigger
- L1 Trigger: Single MU0
- High-Level Trigger (no L1 seed): Full-scan Muon spectrometer 2 muons $> 2 \ GeV$

Two (almost) independent analyses
- June 2015 J/$\psi$ and $\psi$(2S) - ATLAS-CONF-2015-023

Measurement of prompt and non-prompt (b-quarks) fraction of J/$\psi$ and $\psi$(2S)
Kinematic range: $8.5 \ GeV < p_T < 30 \ GeV$, $|y^*| < 1.94 \ (1.5)$

Perform weighted simultaneous 2D unbinned maximum likelihood fit
- Invariant di-muon mass and lifetime
- Event weights: Trigger and reconstruction efficiency; acceptance
- Parameterise signal and background, non-prompt fraction
Comparison of J/ψ Analyses

Common elements
- Same pPb data sample, same triggers, same secondary di-muon vertex fitting
- Same muon selection criteria and reconstruction efficiency corrections
- Same version of J/ψ acceptance map

Elements that are different
- Included ψ(2S) in fit model; fit model was kept as similar as possible to 7 TeV and 8 TeV pp analyses to reduce interpolation uncertainties.
- Included 2.76 TeV pp data for calculation of $R_{pPb}$
- Finer binned high-level trigger efficiency
- Centrality dependence was studied using several centrality estimators
Fit Method

Simultaneous 2D unbinned ML fit to dimuon invariant mass and pseudo proper time

\[ \tau = \frac{L_{xx} m_{\mu\mu}}{p_{T}^\mu\mu} \]

$L_{xx}$ = projection of decay length on the transverse plane

PDF\((m, \tau) = \sum_{i=1}^{7} \kappa_{i} f_{i}(m) \cdot h_{i}(\tau) \otimes g(\tau)\)

- CB: Crystal ball function
- G: Gaussian
- E: Exponential
- g: Double Gaussian
- \(\delta\): Delta Function

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>(f_{i}(m))</th>
<th>(h_{i}(\tau))</th>
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<tbody>
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<td>(J/\psi) S</td>
<td>P</td>
<td>(\omega_{i} CB_{1}(m) + (1 - \omega_{i}) G_{1}(m))</td>
<td>(\delta(\tau))</td>
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<tr>
<td>(J/\psi) S</td>
<td>NP</td>
<td>(\omega_{i} CB_{1}(m) + (1 - \omega_{i}) G_{1}(m))</td>
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<td>(E_{2}(\tau))</td>
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<td>NP</td>
<td>(E_{5}(m))</td>
<td>(E_{6}(\tau))</td>
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Event Weights (Efficiency and Acceptance)

**L1 Trigger**: Measured with respect to Minimum Bias events

**EF Trigger**: Measured from pPb events using J/ψ Tag & Probe method (unbiased trigger efficiency measurement)

**Muon Reconstruction**: Same as proton-proton efficiency correction for 8 TeV

**Acceptance**: MC simulation for geometric acceptance ($p_T > 4$ GeV and $|η_μ| < 2.4$)
J/ψ Analysis pPb 5.02 teV


$R_{FB}$ — Asymmetry of J/psi production between the proton beam direction and lead beam direction

$R_{FB}$ vs. $y^*$ and $p_T$, prompt and non-prompt

$d^2\sigma/dy^*dp_T$, prompt and non-prompt

Non-prompt fraction vs $y^*$ and $p_T$

Non-Prompt Fraction for $J/\psi$ in $p+Pb$ vs. $p_T$ and $y^*$

Strong kinematic dependence on $p_T$
No significant $y^*$ dependence (possible hint of larger $b$-quark reduction, ion beam direction)
Similar trends observed in $pp$ collisions

\[
\text{nonprompt fraction}(p_T, y^*) = \frac{N_{\text{nonprompt } J/\psi}(p_T, y^*)}{N_{\text{total } J/\psi}(p_T, y^*)}
\]
J/ψ Differential Production Cross Section vs. $p_T$ in p+Pb

**ATLAS**
2013 p+Pb, 28.1 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV

-1.94 < $y^*$ < 0

**Ion beam direction**

1. $d^2\sigma / dp_T dy^* \times BR(J/\psi \rightarrow \mu \mu)$ vs. $p_T$ (GeV)

2. $d^2\sigma / dp_T dy^* \times BR(\psi(2S) \rightarrow \mu \mu)$ vs. $p_T$ (GeV)

**Proton beam direction**

0 < $y^*$ < 1.94

**Data, FONLL**
Differential Production Cross-section for J/ψ in pPb vs. y*

Larger variation for J/ψ from b
R_{FB} for Prompt and Non-prompt J/ψ vs p_{T}

No significant p_{T} dependence observed.
In agreement with theoretical predictions which include shadowing effects.

ALICE: R_{FB} ~ 0.6, y* ~ 3-3.5, p_{T} < 15 GeV, inclusive J/ψ Indicates strong kinematic dependence
LHCb results: ~ 0.9, non-prompt J/ψ, p_{T} < 15 GeV
$R_{FB}$ for Prompt and Non-prompt J/ψ vs $y^*$

No significant $y^*$ dependence observed in the kinematic range $8 < p_T < 30$ GeV. Complementary results to LHCb and ALICE which do observe $R_{FB}$ below unity and strong kinematic dependence at low $p_T$ suggest a strong kinematic dependence of the cold medium effects on both charmonium and b-quark production.

LHCb results: ~0.75 for $y=2.8$ for prompt J/ψ, $p_T<15$ GeV
LHCb results: ~0.9 for $|y|=2.8$ for non-prompt J/ψ, $p_T<15$ GeV
J/ψ and ψ(2S) Analysis pPb 5.02 TeV and pp 2.76 TeV

d²σ/dy*dp_T, prompt and non-prompt J/ψ and ψ(2S)

Non-prompt fraction vs y* and p_T J/ψ and ψ(2S)

R_pPb vs. y* and p_T, prompt and non-prompt, J/ψ and ψ(2S)

Single and double-ratio, prompt J/ψ and ψ(2S)
Fit Results

Simultaneous fit in invariant mass and pseudo proper time

Fit model similar to $J/\psi$ fit but includes both $J/\psi$ and $\psi(2S)$
Non-prompt fraction of $\psi(2S)$ and $J/\psi$ in 2.76 TeV $pp$ vs. $p_T$
Differential Production cross-section Prompt $\psi(2S)$ and $J/\psi$ in 2.76 TeV pp
Differential Production cross-section Non-Prompt $\psi(2S)$ and $J/\psi$ in 2.76 TeV $pp$
Interpolation of pp Cross-Section to 5.02 TeV ($R_{pPb}$)

Interpolation between 2.76 TeV and at 7 TeV and 8 TeV to determine pp cross-section at 5.02 TeV
Interpolation used three functional forms to evaluate systematic uncertainty
$R_{pPb} \text{ vs. } p_T \text{ and } y^*$

$$R_{pPb} = \frac{1}{A} \cdot \frac{\frac{d^2\sigma_{p+Pb}}{dy^* dp_T}}{\frac{d^2\sigma_{p+p}}{dy^* dp_T}}$$

- **Prompt J/ψ**
- **Non-Prompt J/ψ**
- **Prompt ψ(2S)**
$R_{pPb}$ vs. centrality

**Prompt $J/\psi$**

$R_{pPb} > 1$

$J/\psi$ independent of centrality

Decreasing trend for the $\psi$

**Non-Prompt $J/\psi$**

$R_{pPb} > 1$

mid-centrality

**Prompt $\psi(2S)$**

$R_{pPb} > 1$

low-centrality
Number of Z bosons scale with number of nucleon-nucleon interactions.

Ratio of yields provide a test of production scaling independent of geometric models.

Check of the centrality dependence by normalising to the number of Z bosons.

\[ \frac{N_\psi}{N_Z} \text{ vs. FCal } E_T \]

Prompt J/\(\psi\)

Non-Prompt J/\(\psi\)

J/\(\psi\) appears to be flat

J/\(\psi\) to Z ratio independent of event activity, nuclear modification also independent of centrality.

\(\psi(2S)\) has a decreasing trend
Self-normalising ratios

Correlation of charmonium production with size of underlying event activity. Deviation from linear scaling enhanced when centrality bias corrections applied.

\[ \frac{\psi}{\langle \psi \rangle} = \frac{\frac{N_{\psi}}{N_{\text{evt}}}}{\frac{N_{\psi}^{0-90\%}}{N_{\text{evt}}^{0-90\%}}} \]

\[ \frac{E_T^{FCal}}{\langle E_T^{FCal} \rangle} = \frac{\left\langle E_T^{FCal} \right\rangle_{\text{cent}}}{\left\langle E_T^{FCal} \right\rangle_{0-90\%}} \]

Centrality bias corrections with standard Glauber model and GGCF.
Suppression of $\psi(2S)$ to $J/\psi$ vs FCal $E_T$

Evidence for centrality dependence
Decreasing trend with centrality; magnitude > ALICE
Prompt double ratio \( \equiv \frac{N_{\psi(2S)}^{pPb}}{N_{J/\psi}^{pPb}} \frac{N_{\psi(2S)}^{pp}}{N_{J/\psi}^{pp}} \)

Clear enhancement at low FCal \( E_T \), consistent with \( R_{pPb} \)
Conclusions

First precision measurement of quarkonia production with ion beams in ATLAS

- Differential production cross sections
- \( R_{FB} \) for \( J/\psi \)
- \( R_{pPb} \) for \( J/\psi \) and \( \psi(2S) \) via pp interpolation
- Non-prompt fraction
- Single and double ratios for \( J/\psi \) and \( \psi(2S) \)

Separation: prompt and non-prompt (b) components

Nuclear medium effects seen in a number of observables and hints in others - most prominently:

- \( R_{FB} \) significantly larger than ALICE’s (at forward \( y^* \))
- \( R_{pPb} > 1 \) for \( J/\psi \) and \( \psi(2S) \), ~all measured kinematics
- Double ratio of \( \psi(2S)/J/\psi \) enhanced at low centrality
Backup
Acceptance
ALICE J/ψ results
arXiv:1308.6726 [nucl-ex]
JHEP 02 (2014) 073
ALICE Results on J/ψ in pPb at 5.02 TeV

J/ψ in pA collisions

$R_{pPb}$ close to unity at backward (Pb-going) rapidity
CNM effects at mid- and forward (p-going) rapidity

ALICE (JHEP 02 (2014) 073): inclusive $J/\psi \rightarrow \mu^+\mu^-$, $0<p_T<15$ GeV/c
$L_{\text{int}} (-4.46<y_{\text{cms}}<-2.96) = 5.8$ nb$^{-1}$, $L_{\text{int}} (2.03<y_{\text{cms}}<3.53) = 5.0$ nb$^{-1}$
$L_{\text{int}} (-1.37<y_{\text{cms}}<0.43) = 51$ µb$^{-1}$

global uncertainty = 3.4%

ALICE 2015 Results on $J/\psi$ and $\psi(2S)$ Production in p-Pb Collisions at 5.02 TeV with Atlas
ALICE $\psi(2S)$ results (I)


JHEP 1412 (2014) 073
ALICE $\psi(2S)$ results (II)


JHEP 1412 (2014) 073

ALICE, p-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV, inclusive $J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$

- $2.03 < y_{\text{ cms}} < 3.53$
- $-4.46 < y_{\text{ cms}} < -2.96$

$|\alpha_{\text{pp}}| / |\alpha_{\text{p-Pb}}|$

$p_T$ (GeV/c)

$R_{\text{p-Pb}}$

ALICE, p-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV, $2.03 < y_{\text{ cms}} < 3.53$

- EPS09 NLO + ELoss with $q_g = 0.055$ GeV/fm (Arleo et al.)
- ELoss with $q_g = 0.075$ GeV/fm (Arleo et al.)
- EPS09 NLO (Vogt)

$J/\psi$

$\psi(2S)$

$p_T$ (GeV/c)
J/ψ and Y in pPb with LHCb
J/\psi Production in pPb with LHCb

![Graphs showing J/\psi production in pPb with LHCb](image-url)
J/ψ $R_{pPb}$ with LHCb
Definition of $y^*$

\[ y^* = -(y_{\text{lab}} + 0.465) \quad \text{p+Pb run period A} \]
\[ y^* = y_{\text{lab}} - 0.465 \quad \text{p+Pb run period B} \]

$y^*$ is defined as positive in the proton beam direction.