Quarkonium Production in $pp$ and $p+Pb$ Collisions with ATLAS at the LHC

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Quarkonium suppression in A-A collisions due to color screening provides signature of formation of deconfined QGP.

Quarkonium suppression is also observed in p-A collisions due to Cold Nuclear Matter (CNM) effects. The CNM effects must be understood before suppression in A-A collisions can be fully understood.

CNM effects:

- Shadowing + other gluon PDF modification
- Medium-induced gluon radiation
- Absorption of the QQ pair
The ATLAS Detector

Event trigger: di-muon trigger with 2 GeV $p_T$ threshold

Muon candidates:
Successful combinations of ID and MS tracks.

$p+$Pb @ 5.02 TeV, $\int \mathcal{L} dt = 28$ nb$^{-1}$ in 2013
$pp$ @ 2.76 TeV, $\int \mathcal{L} dt = 4.0$ pb$^{-1}$ in 2013

Recent ATLAS Heavy Ion $p+$Pb quarkonium results:
$p+$Pb $J/\psi$

$\psi$(nS)$\rightarrow\mu^+\mu^-$

$Y$(nS)$\rightarrow\mu^+\mu^-$

New $\psi$(nS)$\rightarrow\mu^+\mu^-$

Revised $\psi$(nS)$\rightarrow\mu^+\mu^-$

$Y$(nS)$\rightarrow\mu^+\mu^-$
Correct every event for acceptance and efficiencies.

**Prompt \(\psi(nS)\):**
- Direct production
- Feed-down contribution

**Non-prompt \(\psi(nS)\):**
- Decays from B hadrons

\[
\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}
\]

\(Y(2S)\) and \(Y(3S)\) are combined as \(Y(2S+3S)\).
Forward to Backward Ratio

**ATLAS**
2013 p+Pb, 28.1 nb⁻¹
$|S_{NN}| = 5.02$ TeV

Prompt $J/\psi$
$8 < p_T < 30$ GeV

Nonprompt $J/\psi$
$8 < p_T < 30$ GeV

- **(Left)** Prompt $J/\psi$ $R_{FB}$
- **(Right)** Non-prompt $J/\psi$ $R_{FB}$

Prompt $J/\psi$ $R_{FB}$ is compatible with both EPS09 models.

$R_{FB}(p_T, y^*) \equiv \frac{d^2\sigma(p_T, y^* > 0)/dp_Tdy^*}{d^2\sigma(p_T, y^* < 0)/dp_Tdy^*}$.

$y^*$: CM rapidity being positive in forward (proton beam direction)
Nuclear Modification Factor — $\psi(nS)$

$$R_{pPb} = \frac{1}{A_{pPb}} \frac{d^2\sigma_{\psi}^{p+Pb}}{dy^* dp_T} / \frac{d^2\sigma_{\psi}^{pp}}{dy dp_T},$$

$pp$ reference is constructed using interpolations

- **(Top)** Prompt $J/\psi$
- **(Middle)** Non-Prompt $J/\psi$
- **(Bottom)** Prompt $\psi(2S)$

No significant suppression or enhancement for the kinematics range of $|y^*| < 1.5$ and $10 < p_T < 30$ GeV
Nuclear Modification Factor — $\Upsilon(1S)$

**Left** $\Upsilon(1S) \ R_{pPb}$ vs. $p_T$.

Compatible with inclusive $J/\psi \ R_{pPb}$ at low $p_T$ (ALICE) and prompt $J/\psi \ R_{pPb}$ at higher $p_T$ (ATLAS)

**Right** $\Upsilon(1S) \ R_{pPb}$ vs. $y^*$

In comparison with ALICE and LHCb results. Provide constrains for models at central rapidity.
• (Left) Prompt charmonium double ratio  
• (Right) Bottomonium double ratio

No obvious $p_T$ and rapidity dependence

$$\frac{[\Upsilon(2S + 3S)/\Upsilon(1S)]_{pPb}}{[\Upsilon(2S + 3S)/\Upsilon(1S)]_{pp}}$$

$pp @ 2.76$ TeV
Centrality in $p+Pb$

**FCal sum $E_T$ in Pb beam direction**

$\Rightarrow$ Centrality $\Rightarrow \langle N_{part} \rangle$

Two models:
- Glauber Model
- Glauber-Gribov Color fluctuation (GGCF) Model

Only focus on the Glauber model in this talk.

**Centrality Bias**: hard scatterings are often correlated with a larger transverse energy of the underlying event.


How would the bias correction factor work for quarkonium production?
J/ψ $R_{pPb}$ VS. $\langle N_{\text{part}} \rangle$

J/ψ to Z boson yield ratio can serve as a baseline.

No obvious centrality dependence of J/ψ production.

$R_{pPb} = \frac{1}{\langle T_{pPb} \rangle_{\text{cent}}} \frac{1/N_{\text{evt}} d^2 N^{p+Pb}_{\psi} / dy d\eta} {d^2 \sigma^{pp}_{\psi} / dy d\eta},$

Biased corrected $R_{pPb}$ gives expected trend.

The bias correction works for quarkonium.
**$\psi(2S)$ and $\Upsilon(1S)$ $R_{pPb}$ vs. $\langle N_{\text{part}} \rangle$**

**Prompt $\psi(2S)$ to Z boson yield ratio**

- $10 < p_T^\psi < 30 \text{ GeV}$
- $-1.5 < y_\psi^* < 1.5$
- $-3.0 < y_Z^* < 2.0$

**ATLAS Preliminary**
$p+Pb \sqrt{s_{_{NN}}} = 5.02 \text{ TeV}$
Prompt $\psi(2S)$ to Z ratio

**Bias corrected $\Upsilon(1S)$ $R_{pPb}$ is consistent with being constant.**

- Evident decrease trend as $\langle N_{\text{part}} \rangle$ or $\Sigma E_T$ increases for prompt $\psi(2S)$ production.
- Suppressed in more central collisions wrt. more peripheral collisions.
Double Ratio vs. FCal $\Sigma E_T$

- (Left) Prompt charmonium double ratio
- (Right) Bottomonium double ratio

Both show sizable $\Sigma E_T$ dependence. Excited states ($\psi(2S)$ and $\Upsilon(2S+3S)$) are more suppressed wrt. ground states in more central collisions in a similar way.
Self-normalized Ratio (I)

Y yields are binned in centrality according to $E_T$ of $\Upsilon$ events.

$$\frac{\Upsilon}{\langle \Upsilon \rangle} = \frac{N_{cen}^{0-90\%}}{N_{evt}^{0-90\%}}$$

$$\frac{\sum E_T^{FCal, cen}}{\langle \sum E_T^{FCal} \rangle^{0-90\%}}$$

Obtained from MinBias events

Obtained from MinBias events

$\sum E_T / \langle \sum E_T \rangle < 2.3$

Self-normalized $\Upsilon$ yields are consistent with the unitarily sloped line. Compatible with $\text{CMS}$.

$\sum E_T / \langle \sum E_T \rangle = 3.1$

$2\sigma$ deviated from line at for both $\Upsilon(1S)$ and $\Upsilon(2S+3S)$. 

\[ p+Pb \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ \text{ATLAS } \langle \Upsilon(1S) \rangle, |y^*| < 1.20 \]

\[ \text{ATLAS } \langle \Upsilon(2S+3S) \rangle, |y^*| < 1.20 \]

\[ \text{CMS } \langle \Upsilon(1S) \rangle, |y^*| < 1.93 \]
Self-normalized Ratio (II)

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

Self-normalized ratio still suffers centrality bias by definition.

- **(Left)** Uncorrected self-normalized ratio for charmonium and Z.
  Consistent with line when \( \Sigma E_T / \langle \Sigma E_T \rangle < 2.3 \), more than \( 3\sigma \) deviated from line at \( \Sigma E_T / \langle \Sigma E_T \rangle = 3.1 \).

- **(Right)** Bias corrected ratios. More significant deviations.
Summary

• Charmonia and bottomonia production in $pp$ and $p+$Pb collisions are presented.

• Charmonia ($J/\psi$ and $\psi(2S)$):
  • Charmonia $R_{pPb}$ shows no obvious $p_T$ and rapidity dependence.
  • $J/\psi$ $R_{pPb}$ shows no centrality dependence.
  • Prompt $\psi(2S)$ is more suppressed in more central collisions wrt. more peripheral collisions.

• Bottomonia ($\Upsilon(1S)$ and $\Upsilon(2S+3S)$):
  • $\Upsilon(1S)$ $R_{pPb}$ is compatible with prompt $J/\psi$ $R_{pPb}$.
  • $\Upsilon(1S)$ $R_{pPb}$ shows no centrality dependence.
  • $\Upsilon(2S+3S)$ states are more suppressed in more central collisions.

Thank you!
ありがとう
Backup
The proton-nucleon center of mass (CM) frame has a shift of 0.465 in rapidity in the proton beam direction.

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

\[ y^* = y_{lab} - 0.465 \quad \text{p+Pb run period B} \]
Table 2: Probability density functions for individual components in the fit model used to extract the prompt (P) and non-prompt (NP) contributions for the $J/\psi$ and the $\psi(2S)$ signal (S) and background (Bkg). The index, $i$, runs from 1 to 7 for 7 different components. The composite pdf terms are defined as follows: $CB$ - Crystal Ball; $G$ - Gaussian; $E(\tau)$ - single sided exponential; $E(|\tau|)$ - double sided exponential; $\delta$ - delta function. The parameter $\omega$ is the fraction of CB function in the signal.
Table 1: Functional forms of individual components in the central fit model. The composite pdf terms are defined as follows: $G$ - single Gaussian function, $CB$ - Crystal Ball function, $erf$ - error function, $E$ - exponential function, $P$ - 2nd order polynomial function. The parameter $\omega$ is the fraction of the Gaussian function in the signal.
Selected $\psi(2S)$ fits

ATLAS Preliminary

- $8.5 < p_T < 30$ GeV
- $-1.5 < y < 1.5$

Data
Fit Model
Prompt Signal
Non-Prompt Signal
Prompt Bkg
Non-Prompt Bkg

ATLAS Preliminary

- $p+Pb \sqrt{s_{NN}} = 5.02$ TeV

- $8.5 < p_T < 30$ GeV
- $-1.5 < y^* < 1.5$

Entries / (20 MeV)

$ATLAS$ Preliminary

$spp \sqrt{s} = 2.76$ TeV

$spp \sqrt{s} = 2.76$ TeV

$m_{\mu\mu}$ [GeV]
Three interpolation functions used to calculate pp reference at 5.02 TeV, central values obtained from power law function.

\[
\sigma(\sqrt{s}) = \begin{cases} 
p_0 + \sqrt{s}p_1 & \text{linear} \\
(\sqrt{s}/p_0)^{p_1} & \text{power law} \\
p_0(1 - \exp(-\sqrt{s}/p_1)) & \text{exponential}
\end{cases}
\]

Three points for charmoina interpolation
Two points for bottomoina interpolation
Non-prompt fraction

ATLAS Preliminary

ATLAS 13 TeV, 6.4 pb⁻¹, |y| < 0.75
ATLAS 7 TeV, 2.1 fb⁻¹, 0.25 < |y| < 0.50
ATLAS 2.76 TeV, 4 pb⁻¹, |y| < 0.75
CDF (p+p) 1.96 TeV, 39.7 pb⁻¹, |y| < 0.60

ATLAS 2013 p+Pb, 28.1 nb⁻¹
√s_{NN} = 5.02 TeV

Non-prompt fraction

Non-prompt fraction

y*
Update 7 and 8 TeV results used in the interpolation
$E_T / \langle E_T \rangle$ Scale Factor

ATLAS definition:

$$\frac{\Sigma E_T^{FCal,cen}}{\langle \Sigma E_T^{FCal} \rangle_{0-90\%}}$$

- Obtained from MinBias events
- Obtained from MinBias events

CMS proposed definition:

$$\frac{\Sigma E_T^{FCal,cen}}{\langle \Sigma E_T^{FCal} \rangle_{0-90\%}}$$

- Obtained from Dimuon events
- Obtained from MinBias events