Vector boson and quarkonia production in $p+Pb$ and $Pb+Pb$ collisions with ATLAS at the LHC

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University of Birmingham
Why measure the Quarkonia and Vector bosons in A+A collisions

Vector bosons
• don’t interact with quark gluon plasma
• provide information on nuclear collision geometry and cold nuclear matter effects

Quarkonia
• bound states of c or b quarks and antiquarks
• interacts strongly with environment
• two types of interactions – cold and hot matter effects

Nuclear modification factor

\[
R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}
\]

\[T_{AA} = \text{nuclear thickness function}\]

courtesy of A. Mocsy
ATLAS detector

- 2013 p+Pb @ 5.02 TeV
  - 28 nb$^{-1}$
- 2013 p+p @ 2.76 TeV
  - 4.0 pb$^{-1}$
- 2015 Pb+Pb @ 5.02 TeV
  - 0.49 nb$^{-1}$
- 2015 p+p @ 5.02 TeV
  - 25.0 pb$^{-1}$
Z boson measurements

Presented new measurements

• February 2017 Z boson production - ATLAS-CONF-2017-010
  • 2015 Pb+Pb $\sqrt{s_{NN}} = 5.02 \, TeV$

• September 2016 Z boson production - ATLAS-CONF-2016-107
  • 2015 p+p $\sqrt{s} = 5.02 \, TeV$ and 2013 p+Pb $\sqrt{s_{NN}} = 5.02 \, TeV$
Method

\textbf{p+p}

\textbf{Trigger p+p}
- one muon MU14 at HLT

\textbf{Analysis range}
- 2 muons, $p_T > 20$ GeV, $|y| < 2.4$
- $m_{\mu\mu} \in (66;116)$ GeV

\textbf{Pb+Pb}

\textbf{Event selection}
- $|z_0| < 150$ mm
- no pile-up

\textbf{Trigger}
- one muon MU8 at HLT

\textbf{Analysis range}
- 2 muons, $|y| < 2.5(2.4)$, $p_T > 20$ GeV
- $m_{\mu\mu} \in (66;116)$ GeV
- centrality 0–80%

\textbf{Yields are calculated by}
- subtracting the background
- applying the corrections
Data compared to prediction

Detector performance of the measurement is well described by simulations
Yields per event scaled by $T_{AA}$ and $R_{AA}$

**ATLAS** Preliminary

$pp$, $\sqrt{s} = 5.02$ TeV, 24.7 pb$^{-1}$

**pp**

- data (statistical uncertainty)
- systematic uncertainty
- Powheg+Pythia CT14

rapidity $y$ is the closest observable to $x$

**pp** data agree with by pQCD

$R_{AA} = 1$ mean same cross section as in $pp$

Pb+Pb measurements are compatible with $pp$ measurement after scaling.

**ATLAS-CONF-2016-107**

**ATLAS-CONF-2017-010**

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Yields in centrality scaled by $T_{AA}$

Yield scales well with $T_{AA}$ in all centrality bins, in some bins yield has smaller uncertainty than $T_{AA}$.

ATLAS-CONF-2017-010
Nuclear modification function $R_{pPb}$

We observe suppression in forward rapidity in events corresponding to low $x$ on nucleus, measurement is sensitive to nuclear shadowing which is not simulated in our MC.

ATLAS-CONF-2016-107
**$J/\psi$ and $\psi(2S)$ measurements**

  - 2013 p+Pb $\sqrt{s_{NN}} = 5.02$ TeV
- June 2015 $J/\psi$ and $\psi(2S)$ - ATLAS-CONF-2015-023
  - 2013 p+Pb $\sqrt{s_{NN}} = 5.02$ TeV and p+p $\sqrt{s} = 2.76$ TeV
- September 2016 $J/\psi$ and $\psi(2S)$ - ATLAS-CONF-2016-109
  - 2015 Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV and p+p $\sqrt{s} = 5.02$ TeV
Method

Trigger: different for p+Pb and Pb+Pb
- p+Pb: at least one muon at L1 (MU0), 2 muons with $p_T > 2 \text{ GeV}$ at HLT
- Pb+Pb: at least one muon at L1 (MU4), 2 muons with $p_T > 4 \text{ GeV}$ at HLT

Analysis range
- p+Pb: $p_T \in \langle 8.5; 30 \rangle \text{ GeV}, |y^*| < 1.94 (1.5)$
- Pb+Pb: $p_T \in \langle 9; 40 \rangle \text{ GeV}, |y| < 2$, centrality 0–80%

Perform weighted 2D unbinned maximum likelihood fit
- dimuon invariant mass and lifetime
- extract fraction of prompt and non-prompt
  - Prompt – direct production, feed-down contribution
  - Non-prompt – decay from B hadrons
- per-Dimuon weight: trigger, reconstruction, acceptance
Non-Prompt fraction of $J/\psi$ as a function of $p_T$

No visible $|y|$ dependence, but significant $p_T$ dependence, both distributions are comparable.

**ATLAS-CONF-2016-109**

arXiv: 1505.08141 [hep-ex]
Non-Prompt fraction of $J/\psi$ as a function of $p_T$

No significant centrality dependence, different slope than pp due to different suppression of fractions.

ATLAS Preliminary

PbPb $\sqrt{s_{NN}} = 5.02$ TeV, 0.49 nb$^{-1}$

$J/\psi$, $|y| < 2.0$

ATLAS-CONF-2016-109
For prompt $J/\psi$ $R_{PbPb}$ is a function of $p_T$, for non-prompt $J/\psi$ no significant dependence of $R_{PbPb}$ on $p_T$. 

$R_{AA} < 1$ mean suppression.
Nuclear modification factor of $J/\psi$ ($R_{\text{PbPb}}$)

Suppression is strongly centrality dependent, regardless of on production mechanism.

ATLAS-CONF-2016-109
Comparison of Z boson and $J/\psi$ yields in $p+Pb$ collisions

**ATLAS** Preliminary

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

Prompt $J/\psi$ to Z ratio

**Prompt $J/\psi$**

Ratio of the yields is independent on event activity, number of Z and $J/\psi$ particles scale with the number of interactions

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

**ATLAS-CONF-2015-023**

30/03/2017   Petr Gallus - Vector boson and quarkonia production in $p+Pb$ and Pb+Pb collisions with ATLAS at the LHC
Summary

• Charmonia and Z boson production in p+Pb and Pb+Pb collisions are presented.

• Z boson
  • After scaling by $T_{AA}$, yields are described by pQCD
  • Nuclear modification factor $R_{PbPb}$ is consistent with unity in centrality and rapidity

• Charmonia ($J/\psi$ and $\psi(2S)$):
  • Charmonium $R_{pPb}$ shows no obvious $p_T$ and rapidity dependence.
  • Charmonium $R_{PbPb}$ shows different behavior for prompt and non-prompt $J/\psi$ in $p_T$ dependence.
  • Charmonium $R_{PbPb}$ shows strong centrality dependence.

• Ratio $N_{\psi}/N_{Z}$ in p+Pb is independent on event activity and could be used as a benchmark for $T_{AA}$ and $N_{coll}$.

• ATLAS HI Public Results
Additional slides
Pseudo-proper decay time

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

\( L_{xy} = \) projection of decay length on the transverse plane
Definition of $y^*$

\begin{align*}
  y^* &= y_{lab} - 0.465 \\
  y^* &= -(y_{lab} + 0.465)
\end{align*}

due to shift of center of mass

$y^*$ is defined as positive in proton beam direction
Nuclear modification factor $R_{AA}$ and $R_{pA}$

\[ R_{AA} = \frac{N^{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}} \]

- $N^{AA}$ - per-event yield of quarkonia states in A+A collisions
- $\langle T_{AA} \rangle$ - mean nuclear function $\psi$
- $\sigma_{pp}$ - cross section in pp collisions

\[ R_{pA} = \frac{1}{A^{Pb}} \frac{d^2 \sigma_{\psi}^{Pb}/dy \ast dp_T}{d^2 \sigma_{\psi}^{pp}/dy \ast dp_T} \]

\[ R_{pA}^{cent} = \frac{\langle 1/N_{evt}^{cent} \rangle \ d^2 N^{Pb}/dy dp_T |_{cent}}{\langle T_{pp} \rangle_{cent} d^2 \sigma_{pp}/dy dp_T} \]
Simultaneous Fit Method

\[ \text{PDF}(m, \tau) = \sum_{i=1}^{7} k_i f_i(m) \cdot h_i(\tau) \cdot g(\tau) \]

**CB:** Crystal ball function  
**G:** Gaussian  
**E:** Exponential  
**g:** Double Gaussian
Pb+Pb per-event yields

Yields are centrality and $p_T$ dependent

ATLAS-CONF-2016-109

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Nuclear modification factor of $J/\psi$ ($R_{pPb}$)

No significant $p_T$ dependence, $R_{pPb}$ is above unity, but within systematics uncertainties.

pp reference is interpolated from 2.76 TeV, 7 TeV and 8 TeV.

pp reference @5.02 TeV is in preparation.

ATLAS-CONF-2015-023