Recent heavy-flavour results from ATLAS

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Motivations

Colliding systems

- Suppression of production (colour screening)
- Statistical recombination leading to regeneration
- b-quark energy loss in the medium
- Anisotropy arise from hydrodynamic expansion of QGP
- Modifications of nPDFs
- Induced medium energy loss
- Nuclear absorption
- An azimuthal anisotropy due to the collective expansion of the medium or based on saturation of parton distributions (under debate)

Heavy flavor muon Quarkonia

- Hot matter effects

Cold nuclear matter (CNM) effects

Reference
The ATLAS detector

Calorimeters (CALO)
- Pb/LAr accordion structure for EM
- $e/\gamma$ trigger identification and measurement: $\sigma/E \sim 10\%/\sqrt{E}$
- HAD: trigger and measurement of jets and $E_T^{miss}$
- Forward calorimeters (FCAL): covers up to $|\eta| < 4.9$

Inner detector (ID)
- $|\eta| < 2.5$
- Si pixels, Si strips, TRT
- Precise tracking and vertexing (in 2014, add Insertable B-layer)
- $e/\pi$ separation

Muon Spectrometer (MS)
- Triggering $|\eta| < 2.4$
- Precision Tracking $|\eta| < 2.7$
- Magnetic filed produced by toroids
- Muon momentum resolution < 10% up to 1 TeV
Recent results

Data samples:

- **2010**
  - Pb+Pb 2.76TeV 7ub⁻¹

- **2011**
  - Pb+Pb 2.76TeV 0.14nb⁻¹

- **2013**
  - p+Pb 5.02TeV 28.1nb⁻¹
  - p+p 2.76TeV 4pb⁻¹

- **2015**
  - Pb+Pb 5.02TeV 0.42nb⁻¹
  - p+p 5.02TeV 25pb⁻¹

- **2016**
  - p+Pb 8.16TeV 171nb⁻¹

Heavy flavor muon quarkonia

- Muon production and $R_{CP}$ at 2.76 TeV
- $J/\psi$ production and $R_{FB}$ at 5.02TeV
- $J/\psi$ and $\psi(2S)$ production at 5.02TeV in pPb 2.76TeV in pp
- $\Upsilon(nS)$ production at 5.02TeV in pPb 2.76TeV in pp
- The suppression and elliptic anisotropy of heavy flavor muons at 2.76 TeV
- $J/\psi$ and $\psi(2S)$ production at 5.02 TeV
- Azimuthal anisotropy of charged particles and muons at 8.16 TeV

New results on the way
**J/ψ and ψ(2S) candidates**

- To distinguish prompt and non-prompt charmonium production:
  \[ \tau = \frac{L_{xy} m_{\mu\mu}}{p_{T}^{\mu\mu}} \]

- The corrected prompt and non-prompt Charmonium yields are extracted from 2D weighted unbinned maximum likelihood fits performed on \( m_{\mu\mu} \) and \( \tau \).

\( L_{xy} \): distance between the reconstructed secondary vertex and the primary vertex.
\( \Upsilon(nS) \) candidates

The corrected \( \Upsilon \) yields are extracted from binned least square fits performed on \( m_{\mu\mu} \).

G - single Gaussian function
CB - Crystal Ball function
erf - error function
E - exponential function
P - 2nd order polynomial function
\( \omega \) - fraction of the Gaussian function in the signal

| Signal            | \( f_T(1S)(m_{\mu\mu}) \)                                                                 | \( \omega G(m_{\mu\mu}; M_{1S}, \sigma_{1S}) + (1 - \omega) CB(m_{\mu\mu}; M_{1S}, 2\sigma_{1S}, \alpha, n) \) |
|-------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| \( f_T(2S)(m_{\mu\mu}) \)                        | \( \omega G(m_{\mu\mu}; M_{2S}, \sigma_{2S}) + (1 - \omega) CB(m_{\mu\mu}; M_{2S}, 2\sigma_{2S}, \alpha, n) \) |
| \( f_T(3S)(m_{\mu\mu}) \)                        | \( \omega G(m_{\mu\mu}; M_{3S}, \sigma_{3S}) + (1 - \omega) CB(m_{\mu\mu}; M_{3S}, 2\sigma_{3S}, \alpha, n) \) |

| Background        | \( \text{low } p_T f_{bkg}(m_{\mu\mu}) \)                                              | \( \text{erf}(m_{\mu\mu}) \times E(m_{\mu\mu}) \)                                                              |
|-------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
|                   | \( \text{high } p_T f_{bkg}(m_{\mu\mu}) \)                                              | \( P(m_{\mu\mu}) \)                                                                                              |

\( p + \text{Pb}, \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
\( \int \text{Ldt} = 28.1 \text{ nb}^{-1} \)

-2.25 < \( \gamma^{*} \) < 1.20
\( p_T < 40 \text{ GeV} \)
Heavy flavor muon candidates

Two-particle h–μ correlation functions in 8.16 TeV p+Pb collisions

Using **template fit** to estimate signal and background.

**Background**: pion or kaon decays in flight, muons produced from the decays of particles produced in hadronic showers, and mis-associations of ID and MS tracks.
Cold nuclear matter (CNM) effects
p+Pb collisions
The prompt $J/\psi$ modification factor no obvious $p_T$ or $y^*$ dependence.
Nuclear modification factor - non-prompt $J/\psi$

Similar trends show in non-prompt $J/\psi$ nuclear modification factor.
Nuclear modification factor - $\Upsilon(1S)$

- $p_T$ dependence of $\Upsilon(1S)$ nuclear modification factor is similar between ATLAS and ALICE

- No obvious $y$ dependence of $\Upsilon(1S)$ nuclear modification factor
Y(2S + 3S) to Y(1S) double ratio

- Provides information on the difference of the CNM effects on states with different binding energy.
- No significant dependence of excited states production with respect to the ground state production.
Azimuthal Anisotropy

- Anisotropies are measured using the two-particle correlation method.
- $v_2$ at the two collision energies are quite similar and the difference between them is covered by the systematic uncertainties.
- The muon-$v_2$ values are largest at 4 GeV and decrease with increasing $p_T$. 

h: hadron  \[ v_2(p_T) \] 
\[ v_2(p_T) \] 
\[ v_2(p_T) \]
• The $v_2$ for charged particles increases with $N_{ch}^{rec}$ at low $N_{ch}^{rec}$ and eventually saturates for $N_{ch}^{rec}>150$. However even at the lowest measured multiplicity, a large $v_2$ is observed.
• The $v_2$ for the muons, over this $p_T$ range the measurements are consistent with no $N_{ch}^{rec}$ dependence.
• Here a significant dependence of $v_2$ on $|\Delta \eta|$ is observed. On the other hand the template $v_2$ vary by less than 10% over the whole $|\Delta \eta|$ range. (A strong bias in the $v_2$ values from dijets, which are accounted for and removed in the template fits.)
Hot matter effects
Pb+Pb collisions
Nuclear modification factor - $J/\psi$

$p_T, |y| < 2, 0-80\%$ centrality

$\frac{J}{\bar{\psi}}$ production:
- Prompt $J/\psi$: a small increase in $R_{AA}$ with increasing $p_T$.
- Non-prompt $J/\psi$: constant in $p_T$ within the uncertainties.

ATLAS-CONF-2016-109
Nuclear modification factor - $J/\psi$

$y, 9 \text{ GeV} < p_T < 40 \text{ GeV}, \, 0\text{-}80\%\text{ centrality}$

$R_{AA}$ is essentially constant as a function of rapidity within the systematic uncertainties.
Nuclear modification factor - $J/\psi$

$|y| < 2, \ 9 \ \text{GeV} < p_T < 40 \ \text{GeV}$

$J/\psi$ production is most strongly suppressed in central collisions, as expected.
The suppression of prompt $\psi(2S)$ relative to $J/\psi$ indicate the more tightly bound quarkonium system, the $J/\psi$, survives the temperature of the hot dense medium with a higher probability than the more loosely bound quarkonium, the $\psi(2S)$.

Non-prompt mesons (originating from b-quarks) were essentially always formed outside the medium. The unity double ratio was expected.
**Nuclear modification factor - HF muon**

- Independent of $p_T$
- Centrality-dependent
- Less than unity
  --indicates suppressed production of heavy flavor muons in Pb+Pb collisions
Azimuthal Anisotropy

HF $v_2$ decreases with $p_T$, but is still significant at 10 GeV.

At fixed $p_T$, the $v_2$ values show a systematic variation with centrality that is characteristic of elliptic flow measurements.

$$\frac{dN}{d\phi} = \left(\frac{dN}{d\phi}\right) \left(1 + \sum_{n \geq 1} 2v_n \cos \left(n \left[ \phi - \Phi_n \right]\right)\right)$$

ATLAS-CONF-2015-053
Summary

Quarkonia

- Measured in p+Pb and Pb+Pb systems.
- The Pb+Pb results in high $p_T$ range show strong suppression with increasing centrality.
- Proton-lead interactions show little modification of the ground charmonium state.
- Upsilonls have been studied in p+Pb and found to show only a modest suppression.
- New quarkonia results based on p+Pb at 5TeV and pp at 5TeV will come soon.

Heavy flavor muons

- Measured in Pb+Pb and p+Pb collisions.
- Fourier coefficients associated with the azimuthal modulation ($v2$) has been measured.
- $\mu$–$h$ correlations have been studied in the 2016 8 TeV data.
- These results provide improved insight on the propagation of heavy quarks in QGP.
backup
Collision centrality

Correlation between activity in central pseudorapidity region, and activity in FCal

Bins in fraction of Pb-Pb total cross section

ATLAS
$J/\psi$ and $\psi(2S)$ candidates

ATLAS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$p+p$  

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

Entries / (20 MeV)

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

$\sqrt{s} = 2.76$ TeV

$p+p$  

Entries / (20 MeV)

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

Entries / (0.1 ps)

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

Entries / (0.1 ps)
Charmonium fits

\[
\psi(2S) \text{ and } J/\psi \text{ fit model:}
\]

| i | Type   | Source | \( f_i(m) \)                                | \( h_i(\tau) \) |
|---|--------|--------|---------------------------------------------|-----------------|
| 1 | \( J/\psi \)   | P       | \( \omega_i \text{CB}_1(m) + (1 - \omega_i) \text{G}_1(m) \) | \( \delta(\tau) \) |
| 2 | \( J/\psi \)   | NP      | \( \omega_i \text{CB}_1(m) + (1 - \omega_i) \text{G}_1(m) \) | \( E_1(\tau) \) |
| 3 | \( \psi(2S) \) | P       | \( \omega_i \text{CB}_2(m) + (1 - \omega_i) \text{G}_2(m) \) | \( \delta(\tau) \) |
| 4 | \( \psi(2S) \) | NP      | \( \omega_i \text{CB}_2(m) + (1 - \omega_i) \text{G}_2(m) \) | \( E_2(\tau) \) |
| 5 | Bkg    | P       | flat                                        | \( \delta(\tau) \) |
| 6 | Bkg    | NP      | \( E_3(m) \)                                | \( E_4(\tau) \) |
| 7 | Bkg    | NP      | \( E_5(m) \)                                | \( E_6(|\tau|) \) |

CB: Crystal Ball function  
G: Gaussian  
E: exponential  
\( \delta(\tau) \): Dirac delta function
Non-prompt fraction

- $f_{NP}^{\psi}$ of $J/\psi$ production is found to depend strongly on $p_T$. No significant rapidity dependence is observed.
- In pp and pPb collisions, this trend consistent with each other.
- $f_{NP}^{\psi}$ measured in Pb+Pb collisions as a function of $p_T$ does not depend on the collision centrality class.
Double differential cross section

The measured prompt $J/\psi$ and $\psi(2S)$ cross sections show good agreement with NRQCD predictions.

The measured non-prompt $J/\psi$ and $\psi(2S)$ cross sections show good agreement with FONLL predictions.
The prompt $\psi(2S)$ to $J/\psi$ double ratio show no obvious rapidity dependence, but a decreasing trend as the event activity increases.
Elliptic flow of HF muons
HF muon candidates

\[ \frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - p_{calo}}{p_{ID}} \]

**Background**: pion decays in flight, kaon decays in flight, muons produced by secondary interactions of prompt particles, and misassociations.

Using **template fit** to estimate signal and background.
Double differential cross sections (or per-event yields) are also measured in p+Pb and Pb+Pb collisions.
\( \Upsilon(nS) \) cross section

- \( \Upsilon(2S) \) and \( \Upsilon(3S) \) are combined as \( \Upsilon(2S + 3S) \)
- The differential cross sections are compared to the results measured by LHCb and ALICE
Two-particle correlations

ATLAS

ATLAS-CONF-2012-050
Heavy flavor muon $R_{AA}$

$R_{AA}$ shows a centrality-dependent suppression that is $p_T$-independent within uncertainties.