Measurement of the suppression and $v_2$ of heavy flavor muons in lead-lead collisions with the ATLAS detector

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Motivation

- \( c(m \sim 1.3 \text{ GeV}) \) and \( b(m \sim 4.7 \text{ GeV}) \). Unique probe to study QGP. Mass not affected by interaction with QCD medium.

- Produced at early stage and can be used to probe QGP medium properties and evolution.

- Suppression and elliptic flow of heavy flavor leptons, originating from semileptonic decays of \( D \) and \( B \) mesons, observed at RHIC energy.
ATLAS detector

Inner Detector (ID) $|\eta| < 2.5$
Calorimeter (CALO) $|\eta| < 4.9$
Muon Spectrometer (MS) $|\eta| < 2.7$

Forward Calorimeter (FCal) $3.1 < |\eta| < 4.9$

Event characteristics (centrality, event plane)
Muon detecting

$$\eta = 1.05$$

Barrel $$|\eta| < 1.05$$
End-cap $$1.05 < |\eta| < 2.4$$

High quality muons leave tracks in ID and MS, and lose energy in the Calorimeter.
Heavy flavor muon extraction

Momentum imbalance:

\[
\frac{\Delta p}{p_{\text{ID}}} = \frac{p_{\text{ID}} - (p_{\text{MS}} + \Delta p_{\text{calo}})}{p_{\text{ID}}}
\]

- Heavy flavor (HF) muons have quite different momentum imbalance distribution from the decay-in-flight
- Sufficient discrimination variable but sensitive to momentum resolution
- Very similar for pp and Pb+Pb, no centrality dependence
Signal extraction in data

- Templates are builded in simulation. Fits performed to extract heavy flavor muon fraction
- Good agreements between data and templates
Other background contamination

- Inclusive single muon $p_T$ spectrum after subtracting decay-in-flight using 2010 $pp$ data at 7 TeV
- For $p_T < 14$ GeV, other sources of background are negligible
- HF muon fiducial volume:
  
  $4 < p_T < 14$ GeV
  
  $|\eta| < 1.0$

Best momentum resolution

Signal purity ~100%

Small systematic uncertainty
HF muon production

- HF muon differential fiducial cross section in $pp$:
  \[
  \frac{d^2\sigma_{HF\mu}}{dp_Td\eta} = \frac{1}{\mathcal{L}} \frac{\Delta N_{\mu f_{sig}}}{\Delta p_T \Delta \eta} \cdot \frac{1}{\varepsilon_{trig}\varepsilon_{reco}}
  \]

- HF muon differential fiducial per-event yields in Pb+Pb:
  \[
  \left. \frac{1}{N_{evt}} \frac{d^2N_{HF\mu}}{dp_Td\eta} \right|_{cent} = \frac{1}{N_{evt}^{\text{cent}}} \frac{\Delta N_{\mu f_{sig}}^{\text{cent}}}{\Delta p_T \Delta \eta} \cdot \frac{1}{\varepsilon_{trig}\varepsilon_{reco}}
  \]

Corrected for muon trigger and reconstruction efficiency per muon
Nuclear modification factor

\[ R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{(1/N_{evt})d^2N/(dp_Td\eta)}{d^2\sigma^{pp}/(dp_Td\eta)} \]

- HF muon \( R_{AA} \) measured in 5 centrality slices covers 0-60%
- Significant suppression (0.4) in most central
- Strong centrality dependence. No strong dependence on \( p_T \)
Mid-rapidity vs. forward

- Good agreement between ATLAS and ALICE
- No obvious rapidity dependence
HF muon vs. D meson

- Very different behavior compared to the $D^0$ or inclusive hadron
- Significantly smaller suppression for inclusive HF muons
- Strong momentum dependence for hadrons and $D^0$
**HF muon vs. B meson**

- **Different energy and different centrality**
- **Similar behavior within uncertainties**

![Graphs showing comparison between ATLAS HF muon and CMS B+ meson data](image)

**ATLAS HF muon**

**CMS B+ meson**

**CMS-HIN-16-011**

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*ATLAS Preliminary*

*CMS Preliminary*

<table>
<thead>
<tr>
<th>Centrality</th>
<th>ATLAS 2011 Pb+Pb L_int = 0.14 nb^{-1}</th>
<th>CMS 2013 pp L_int = 4.0 pb^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>R_{AA} = 0.14 ± 0.02</td>
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</tr>
<tr>
<td>20-30%</td>
<td>R_{AA} = 0.14 ± 0.02</td>
<td>R_{AA} = 0.14 ± 0.02</td>
</tr>
<tr>
<td>40-60%</td>
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<td>R_{AA} = 0.14 ± 0.02</td>
</tr>
</tbody>
</table>

*CMS | B^+ | | y < 2.4 | M. Djordjevic et al. | M. He et al. | CUJET3.0 0-20% |
Centralities (averaged over measured ranges) are similar

- Weak (or none) $p_T$ dependence in both measurements

ATLAS Preliminary

$\sqrt{s_{NN}} = 2.76$ TeV

ATLAS HF muon

CMS b-jet

PRL 113(2014)132301
Elliptic flow of HF muons

- Event plane method is used to extract HF muon elliptic flow
- Reaction plane angle $\Psi_2$ is determined based on FCal energy deposition
- Decay-in-flight subtracted
- EP resolution correction applied

$$\frac{dN}{d\phi} = N_0 \left[ 1 + 2v_2^{\text{obs}} \cos(2(\phi - \Psi_2)) \right]$$

$$v_2 = \frac{v_2^{\text{obs}}}{\text{Res}\{2\Psi_2\}}$$
Significant $v_2$ (~8%) at lower $p_T$. Still significant up to $p_T \sim 10$ GeV

Good agreement between ATLAS and ALICE
HF muon flow vs. $D^0$ flow

- Similar decrease trend for $p_T > 4$ GeV
- $v_2$ (HF muon) < $v_2$ ($D^0$)
Summary

- HF muons found to be suppressed in Pb+Pb collisions with a strong centrality dependence
- HF muon $R_{AA}$ similar with $b$-jet, but different from $D^0$ and charge hadron
- Significant non-zero $v_2$ of HF muons up to 10 GeV. Good agreement between ATLAS and ALICE.
- $v_2$ (HF muon) < $v_2$ ($D^0$)

Thanks!
HF muon extraction for 2010 data

\[ \frac{\Delta p}{p_{ID}} = \frac{p_{ID} - (p_{MS} + \Delta p_{\text{calo}})}{p_{ID}} \]

momentum imbalance

scattering angle significance

decay-in-flight would cause large deflection, useful for very low \( p_T \) (\( \lesssim 4 \) GeV)

\[ C = \left| \frac{\Delta p_{\text{loss}}}{p_{ID}} \right| + 0.07 \cdot S \]

Composite

\( L \cdot dt = 7 \text{ub}^{-1} \)

ATLAS PRELIMINARY
Signal fraction and spectra

\begin{itemize}
\item \textbf{ATLAS Preliminary}
\item \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)
\item 2011 Pb+Pb \( L_{\text{int}} = 0.14 \text{ nb}^{-1} \)
\item \(|\eta| < 1\)
\end{itemize}

\begin{itemize}
\item \( \sqrt{s} = 2.76 \text{ TeV} \)
\item 2013 pp \( L_{\text{int}} = 4.0 \text{ pb}^{-1} \)
\item \(|\eta| < 1\)
\end{itemize}

2010 Data

2011 Data
HF fraction and spectra in 2010 data

\[ \frac{1}{N_{\text{evt}}} \frac{d^2N}{dp_T d\eta} \]

\( \int L \, dt = 7 \, \mu b^{-1} \)

\( \sqrt{s_{NN}} = 2.76 \, \text{TeV} \)

\( |\eta| < 1.05 \)
Mass ordering of $R_{AA}$

$m_b \sim 5 \text{ GeV}$

$m_c \sim 1.5 \text{ GeV}$

Bugatti, Gyulassy 2011
Event plane determination

- Reaction plane ($\Psi_{RP}$) is approximated by event plane ($\Psi_{n \, EP}$) measured in FCal:

$$\Psi_{n \, EP} = \frac{1}{n} \tan^{-1} \left( \frac{\sum_i E_{T,i}^{tower} w_i \sin(n\phi_i)}{\sum_i E_{T,i}^{tower} w_i \cos(n\phi_i)} \right)$$

- The event plane resolution correction factor $R$ is obtained using two-sub event and various tree-subevent method
- Significant resolution for harmonics $n=2$–$6$
- Resolution corrected harmonics:

$$\nu_n = \langle \cos(n(\Phi - \Psi_n)) \rangle / R$$