$R_{AA}$ and $v_2$ of muons from heavy quark decays in 2.76 TeV data with ATLAS

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For the ATLAS Collaboration
# Data sample summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Species</th>
<th>$\sqrt{s_{NN}}$ [TeV]</th>
<th>$L_{int}$ [nb$^{-1}$]</th>
<th>Triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pb+Pb</td>
<td>2.76</td>
<td>0.01</td>
<td>Minimum Bias</td>
</tr>
<tr>
<td>2011</td>
<td>p+p</td>
<td>2.76</td>
<td>300</td>
<td>$\gamma$, $\mu$, jets, MB</td>
</tr>
<tr>
<td>2011</td>
<td>Pb+Pb</td>
<td>2.76</td>
<td>0.15</td>
<td>$\gamma$, $\mu$, jets, MB, UPC</td>
</tr>
<tr>
<td>2012</td>
<td>p+Pb</td>
<td>5.02</td>
<td>0.001</td>
<td>Minimum Bias</td>
</tr>
<tr>
<td>2013</td>
<td>p+Pb</td>
<td>5.02</td>
<td>30</td>
<td>$\gamma$, $\mu$, jets, MB, HM, UPC</td>
</tr>
<tr>
<td>2013</td>
<td>p+p</td>
<td>2.76</td>
<td>5000</td>
<td>$\gamma$, $\mu$, jets, HM, MB</td>
</tr>
</tbody>
</table>

7, 8 & 13 TeV pp runs, small sample at 2.36 TeV

Previous analysis:  
ATLAS-CONF-2012-050

This analysis:  
ATLAS-CONF-2015-053
The ATLAS detector

- Muon Detectors: $|\eta|<2.7$
- Tile Calorimeter: $|\eta|<4.9$
- Liquid Argon Calorimeter: $3.1<|\eta|<4.9$
- Forward Calorimeter

- Toroid Magnets
- Solenoid Magnet
- SCT Tracker
- Pixel Detector
- TRT Tracker

$|\eta|<4.9$
Consistency criterion:

\[
\frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - \Delta p_{calo}(p, \eta, \phi)}{p_{ID}}
\]
Muon identification

\[
\frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - \Delta p_{calo}(p, \eta, \phi)}{p_{ID}}
\]
Background removal

\[ \frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - \Delta p_{calo}(p, \eta, \phi)}{p_{ID}} \]
Background removal

\[
\frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - \Delta p_{calo}(p, \eta, \phi)}{p_{ID}}
\]
Background removal

Templates approximates data in pp and in PbPb at all centralities.
Fraction of muons coming from HF quark decays

ATLAS Preliminary

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

2011 Pb+Pb \( L_{\text{int}} = 0.14 \text{ nb}^{-1} \)

| \( |\eta| < 1 \)

\[ \sqrt{s} = 2.76 \text{ TeV} \]

2013 pp \( L_{\text{int}} = 4.0 \text{ pb}^{-1} \)

| \( |\eta| < 1 \)
Fully corrected spectra

\[
\frac{d^2\sigma^{\text{HF}}_{\mu}}{dp_T d\eta} = \frac{1}{\mathcal{L}} \frac{\Delta N_{\mu} f^{\text{sig}}}{\Delta p_T \Delta \eta} \frac{1}{\varepsilon_{\text{trig}} \varepsilon_{\text{rec}}}
\]

\[
\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{HF}, \mu}}{dp_T d\eta}_{\text{cent}} = \frac{1}{N_{\text{cent}}} \frac{\Delta N_{\mu}^{\text{cent}} f^{\text{sig}}}{\Delta p_T \Delta \eta} \frac{1}{\varepsilon_{\text{trig}} \varepsilon_{\text{rec}}}
\]

\[
\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{HF}, \mu}}{dp_T d\eta}
\]

\[
\frac{d^2\sigma^{\text{HF}}_{\mu}}{dp_T d\eta}
\]

\[
\text{Covered range } 4<p_T<14 \text{ GeV}
\]

\[
\text{Results are in } |\eta|<1
\]

\[
\times 20 \text{ statistics of 2010}
\]
Nuclear modification factor

Significant suppression in central
Weak (if any) dependence on \( p_T \)
Good consistency with 2010 data
μ-R\textsubscript{AA} vs. inclusive h-R\textsubscript{AA}

Very different behavior compared to the inclusive hadrons:

Significantly smaller suppression for muons
Strong momentum dependence for hadrons
μ-R_{AA} vs. inclusive jet-R_{AA}

Similar behavior compared to the inclusive jets.
(not the same centrality bins!)

Comparable degree of suppression
Different momenta ranges – hard to interpret
μ-R_{AA} vs. b-jet-R_{AA}

ATLAS-CONF-2015-053

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

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

PRL 113 (2014) 132301
PbPb, 150 \( \mu \text{b}^{-1} \)
\( \text{pp, 5.3 pb}^{-1} \)

Compatible suppression between HF-muon and b-jets

Centralalities (averaged over measured ranges) are similar
Weak (or none) \( p_{T} \) dependence in both measurements
Similar results for mid-rapidity and forward regions.

Close (well within errors) results for $R_{AA}$ magnitudes
Weak or none $p_T$ dependence in both measurements
Signal fraction

ATLAS Preliminary

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

2011 Pb+Pb $L_{\text{int}} = 0.14$ nb$^{-1}$

$|\eta| < 1$

$\sqrt{s} = 2.76$ TeV

2013 pp $L_{\text{int}} = 4.0$ pb$^{-1}$

$|\eta| < 1$

Fraction of muons coming from HF quark decays
Fraction of muons coming from HF quark decays
Differentially in angle w.r.t. Event Plane

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

\( \sqrt{s} = 2.76 \text{ TeV} \)
2013 pp \( L_{\text{int}} = 4.0 \text{ pb}^{-1} \)
\( |\eta| < 1 \)
Strong azimuthal anisotropy “visible by eye”.

ATLAS-CONF-2015-053

ATLAS Preliminary
\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
2011 Pb+Pb \( L_{\text{int}} = 0.14 \text{ nb}^{-1} \)

signal counts [K]

10-20%
|\eta|<1
4 < \( p_T \) < 4.5 GeV

2|\phi - \Psi^2|

14

40-60%
|\eta|<1
4 < \( p_T \) < 4.5 GeV

2|\phi - \Psi^2|

12

ATLAS Preliminary
\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
2011 Pb+Pb \( L_{\text{int}} = 0.14 \text{ nb}^{-1} \)

signal counts [K]

10-20%
|\eta|<1
8 < \( p_T \) < 10 GeV

2|\phi - \Psi^2|

5

40-60%
|\eta|<1
8 < \( p_T \) < 10 GeV

2|\phi - \Psi^2|

2.5
$V_2$ vs. $p_T$

Largest $v_2$ at the lowest measured $p_T$

Significant flow even at very high $p_T$

Highest amplitudes in 10-40% central
$\mu$-$v_2$ vs. inclusive $h$-$v_2$: momentum

ATLAS-CONF-2015-053

ATLAS Preliminary
\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
2011 Pb+Pb $L_{\text{int}} = 0.14 \text{ nb}^{-1}$
$|\eta|<1$

0-10%

10-20%

20-30%

30-40%

40-60%

5-10%

10-20%

20-30%

30-40%

40-50%

50-60%

60-70%

\[ p_T \text{ [GeV]} \]

Pb-Pb $\sqrt{s_{NN}}=2.76 \text{ TeV}$
$L_{\text{int}}=8 \mu\text{b}^{-1}$ $|\eta|<2.5$
full FCal EP

PRC86 (2012) 014907
Muon amplitudes are smaller

Is the shape similar?
$\mu - v_2$ vs. inclusive $h - v_2$: centrality

**ATLAS** Preliminary

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

2011 Pb+Pb $L_{int} = 0.14$ nb$^{-1}$

1$< p_T < 2$ GeV

$ATLAS$

$n=2$

$n=3$

$n=4$

$n=5$

$n=6$

Pb-Pb $\mid s_{NN}=2.76$ TeV

$L_{int}=8$ $\mu b^{-1}$ $|n|<2.5$

full FCal EP

3$< p_T < 4$ GeV

4$< p_T < 8$ GeV

8$< p_T < 12$ GeV

12$< p_T < 20$ GeV

PRC86 (2012) 014907
**μ-v_2 vs. inclusive h-v_2: centrality**

Muon amplitudes are smaller

Is the shape similar?

Larger difference at lower p_T

At higher p_T the v_2 are not the same, but closer to each other in amplitude and in shape.

Overplayed and combined plots are not the official ATLAS figures.
Muon $v_2$ is very similar between mid-rapidity and forward region.

Overplayed and combined plots are not the official ATLAS figures.
Conclusion

ATLAS measured muons coming from HF quark decays in PbPb & pp @ 2.76TeV in $|\eta|<1$ in the range $4<p_T<14$ GeV

Residual background is removed on a statistical basis.

Measured results are for the Nuclear Modification Factor $R_{AA}$:
- centrality-dependent suppression reaching 0.4 in 0-10%
- weak or no $p_T$-dependence
  - not consistent with suppression of inclusive hadrons
  - consistent with jets (ATLAS) and b-jets (CMS)
  - consistent with forward rapidity (compared ALICE)

and second order azimuthal anisotropy $v_2$:
- values up to about 0.08 at $p_T$ of 4 GeV
- in mid-central the $v_2$ decreases with $p_T$
- still significant at $p_T$ of 10 GeV
  - shape differs from inclusive hadrons (ATLAS)
  - amplitudes better agree at higher $p_T$ (ATLAS)
  - consistent with forward rapidity (ALICE)

No comparisons to RHIC data are shown – wait for Ralf’s talk
Thank you for your attention

@ Kobe, Japan
BKPs
This slide needs thinking: what else to show?

Possibly other experiments too: LHC and RHIC
Nuclear modification factor

**ATLAS** Preliminary
\(\sqrt{s_{NN}} = 2.76\) TeV

**ATLAS**
anti-\(k_t\), \(R = 0.4\) jets
2011 Pb+Pb data, 0.14 nb\(^{-1}\)
2013 pp data, 4.0 pb\(^{-1}\)

\(|y| < 2.1\)

**CMS**
\(\sqrt{s_{NN}} = 2.76\) TeV

PbPb, 150 \(\mu\text{b}^{-1}\)
pp, 5.3 pb\(^{-1}\)

**pQCD:** PLB 726 (2013) 251-256
- \(g_{\text{med}} = 1.8\)
- \(g_{\text{med}} = 2.0\)
- \(g_{\text{med}} = 2.2\)

\(b\)-jet \(R_{AA}\)

0-100%
\(|\eta| < 2\)

\(\text{PbPb, 150 \(\mu\text{b}^{-1}\)}\)
\(\text{pp, 5.3 pb}^{-1}\)

**CMS**
\(\sqrt{s_{NN}} = 2.76\) TeV

\(|\eta| < 2\)

\(b\)-Jet \(R_{AA}\)

\(80 < p_T < 90\) GeV/c
\(90 < p_T < 110\) GeV/c

Sasha Milov  QM 2015. Kobe Island  Sept. 29, 2015 29
### Centrality

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Average $N_{\text{part}}$</th>
<th>Average $N_{\text{coll}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5%</td>
<td>382±0.7%</td>
<td>1683±8%</td>
</tr>
<tr>
<td>5-10%</td>
<td>330±1%</td>
<td>1318±8%</td>
</tr>
<tr>
<td>10-20%</td>
<td>261±1.5%</td>
<td>923±7%</td>
</tr>
<tr>
<td>20-40%</td>
<td>158±2.5%</td>
<td>441±7%</td>
</tr>
<tr>
<td>40-80%</td>
<td>46±6%</td>
<td>78±9%</td>
</tr>
</tbody>
</table>

**Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV, data 2011**

**MB fraction $98 \pm 2\%$**