



Open heavy flavour production via semi-leptonic decay muons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC

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Abstract

Measurements of heavy quark production and suppression in ultra-relativistic nuclear collisions probe the interactions of heavy quarks with the hot, dense medium created in the collisions. ATLAS has measured heavy quark production in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions via semi-leptonic decays of open heavy flavour hadrons to muons. Results are presented for the per-event muon yield as a function of muon transverse momentum, p_T , over the range of $4 < p_T < 14$ GeV. The centrality dependence of the muon yields is characterized by the “central to peripheral” ratio, R_{CP} . Using this measure, muon production from heavy quark decays is found to be suppressed by a centrality-dependent factor that increases smoothly from peripheral to central collisions. Muon production is suppressed by approximately a factor of two in central collisions relative to peripheral collisions. Within the experimental errors, the observed suppression is independent of muon p_T for all centralities.

Keywords: Heavy Ion, Heavy flavor suppression, Semi-leptonic decayed muons, R_{CP}

1. Introduction

Collisions between lead ions at the LHC are thought to produce strongly interacting matter at temperatures well above the QCD critical temperature. At such temperatures, strongly interacting matter is expected to take the form of “quark-gluon plasma.” High- p_T quarks and gluons generated in hard-scattering processes during the initial stages of the nuclear collisions are thought to lose energy in the quark-gluon plasma resulting in “jet quenching” [1]. Since the energy loss results from the interaction of a quark or gluon with the medium, jet quenching is thought to provide a valuable tool for probing the properties of the quark-gluon plasma [2, 3, 4]. The contributions from radiative [5] and collisional [6] energy loss in weakly coupled calculations are expected to depend on the heavy quark mass. In particular, the mass of heavy quarks is expected to reduce radiative energy loss for quark transverse momenta less than or comparable to the quark mass (m), $p_T \lesssim m$, through the dead-cone effect [7]. However, measurements of heavy quark production at RHIC via semi-leptonic decays to electrons showed a combined charm and bottom suppression in Au+Au collisions comparable to that observed for inclusive hadron production [8, 9, 10]. There is disagreement in the theoretical literature regarding the interpretation of the RHIC heavy quark suppression measurements [11, 12, 13] particularly regarding the role of non-perturbative effects [14]. It is clear that measurements of heavy quark quenching at the LHC are an essential complement to inclusive jet or single hadron measurements.

This paper presents results on heavy-quark production through muon semi-leptonic decay, using the ATLAS detector [15] and approximately $7 \mu\text{b}^{-1}$ of Pb+Pb data at $\sqrt{s_{NN}} = 2.76$ TeV collected in 2010. Further details of the analysis can be found in [16]. The measurements were performed for several intervals of collision centrality over the muon transverse momentum range $4 < p_T < 14$ GeV and the yields compared to those in a peripheral bin using

R_{CP} , $R_{CP} = \frac{\langle N_{\text{coll}}^{\text{periph}} \rangle dn^{\text{cent}}}{\langle N_{\text{coll}}^{\text{cent}} \rangle dn^{\text{periph}}}$, where dn^{cent} and dn^{periph} represent the per-event differential rate for the same observable in central and peripheral collisions, respectively. $\langle N_{\text{coll}}^{\text{cent}} \rangle$ and $\langle N_{\text{coll}}^{\text{periph}} \rangle$ represent $\langle N_{\text{coll}} \rangle$ values calculated for the corresponding centralities.

2. Experimental setup and muon reconstruction

Muons were detected by combining independent measurements of the muon trajectories from the inner detector (ID) and the muon spectrometer (MS), which cover $|\eta| < 2.5$ and $|\eta| < 2.7$ in pseudorapidity respectively. Two forward calorimeters placed symmetrically with respect to the collision point and covering $3.2 < |\eta| < 4.9$ are used to characterize Pb+Pb collision centrality. Minimum bias Pb+Pb collisions were identified using measurements from the zero degree calorimeters (ZDCs) and the minimum-bias trigger scintillator (MBTS) counters. Cuts are imposed both online and offline to reject background and ensure selection of heavy ion collision events. In total, 53 million minimum-bias Pb+Pb events are selected. Previous studies [17] indicate that the criteria used to select minimum-bias hadronic Pb+Pb collisions have an efficiency of $98 \pm 2\%$. The centrality of Pb+Pb collisions was characterized by $\Sigma E_{\text{T}}^{\text{FCal}}$, the total transverse energy measured in the forward calorimeters (FCal). A standard Glauber Monte-Carlo analysis was used to estimate the average number of participating nucleons, $\langle N_{\text{part}} \rangle$, and the average number of nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, for Pb+Pb collisions in each of the centrality bins. The R_{CP} measurements presented in the paper use the 60-80% centrality bin as a common peripheral reference.

The performance of the ATLAS detector and offline analysis in measuring muons in Pb+Pb collisions was evaluated using a Monte Carlo (MC) data set [18]. The MC data set was obtained by overlaying GEANT4-simulated [19] $\sqrt{s} = 2.76$ TeV $p+p$ dijet events on to 1 million GEANT4-simulated minimum-bias Pb+Pb events obtained from version 1.38b of the HIJING event generator [20]. HIJING was run with default parameters, except for the disabling of jet quenching. To simulate the effects of elliptic flow in Pb+Pb collisions, a parameterized $\cos 2\phi$ modulation that varies with centrality, η and p_{T} was imposed on the particles after generation. The efficiency for reconstructing muons associated with heavy flavour decays was evaluated using the MC sample described above for different bins in collision centrality.

3. Muon signal extraction and results

The measured muons consist of both ‘‘signal’’ muons and background muons. The signal muons are those that originate directly from the Pb+Pb collision, from vector meson decays, and from heavy quark decays. The background muons arise from pion and kaon decays, muons produced in hadronic showers in the calorimeters, and mis-associations of MS and ID tracks. For this analysis a weighted combination of two discriminant quantities has been used to form a ‘‘composite’’ discriminant, C . These two quantities are: a) the fractional momentum imbalance, $\Delta p_{\text{loss}}/p_{\text{ID}}$, which quantifies the difference between the ID and MS measurements of the muon momentum after accounting for the energy loss of the muon in the calorimeters, and b) the ‘‘scattering significance’’, S , which characterizes deflections in the trajectory resulting from (e.g.) decays in flight. Further details are given in [16].

The signal and background distribution of C were obtained separately from the MC and used to perform template fits to the C distribution of the data. Specifically, a probability density distribution for C , dP/dC , is formed assuming that a fraction, f_{S} , of the measured muons is signal, $\frac{dP}{dC} = f_{\text{S}} \frac{dP}{dC} \Big|_{\text{S}} + (1 - f_{\text{S}}) \frac{dP}{dC} \Big|_{\text{B}}$, where $dP/dC|_{\text{S}}$ and $dP/dC|_{\text{B}}$ represent the Monte Carlo C distributions from signal and background sources, respectively. To account for possible differences in the C distribution between data and MC due to (e.g.) inaccuracies in the MC description of multiple scattering, the fits allow for limited adaptation of the MC templates to the data. In particular, the fit allows a shift and re-scaling of the C distribution, $C' = a + \langle C \rangle + b(C - \langle C \rangle)$, where $\langle C \rangle$ is the mean of the C distribution. In addition, a Gaussian smearing of the MC C distribution was included such that the data C distribution was fit to $\frac{dP'}{dC'} \equiv \left(f_{\text{S}} \frac{dP}{dC} \Big|_{\text{S}} + (1 - f_{\text{S}}) \frac{dP}{dC} \Big|_{\text{B}} \right) \otimes \frac{e^{-C'^2/2\sigma^2}}{\sqrt{2\pi}\sigma}$. A kernel estimation method [21] was used to produce the unbinned probability density distribution, dP'/dC' from the MC signal and background samples. The signal fraction, f_{S} , was then evaluated for each centrality and muon p_{T} bin using unbinned maximum likelihood fits with four free parameters, f_{S} , a , b , and σ . Examples of the resulting template fits are shown in the left panel of Fig. 1 for the 0-10% and 60-80%

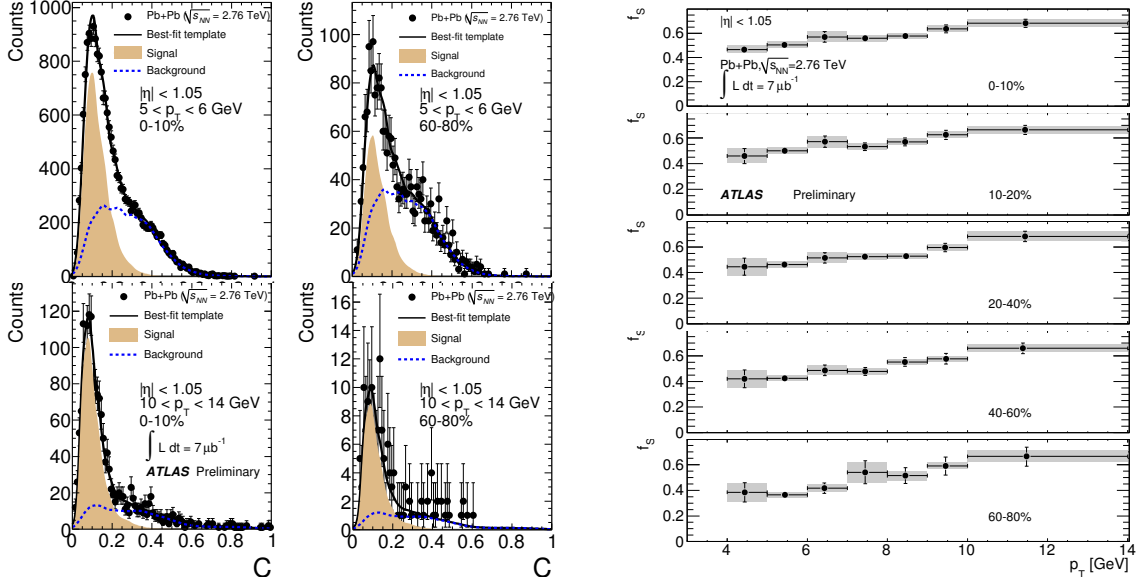


Figure 1: **Left:** Examples of the template fits to measured C distributions (see text) in 0-10% (left) and 60-80% (right) centrality bins for two p_T intervals: $5 < p_T < 6$ GeV (top) and $10 < p_T < 14$ GeV (bottom). The curves show the contributions of signal and background sources based on the corresponding C distributions obtained from MC including the shift, re-scaling, and smearing modifications (see text). **Right:** Fractions of signal muons, f_S , in the measured muon yields as a function of muon p_T in different bins of collision centrality. The points are shown at the mean transverse momentum of the muons in the given p_T bin. The shaded boxes indicate systematic errors, which can vary from point-to-point. The error bars show combined statistical and systematic uncertainties. Please refer to [16] for details.

centrality bins and for two muon p_T intervals. Typical fitted values for the a , b , and σ parameters are, $a \sim 0.02$, $b \sim 0.95 - 1.05$, and $\sigma \sim 0.002$. The combination of the MC signal and background C distributions are found to describe well the measured C distributions. The description remains good even if the adaptation of the template is not implemented, and the resultant variation in the fit contributes to the systematic error, as discussed below.

The signal muon fractions extracted from the template fits for all p_T and centrality bins are shown in the right panel of Fig. 1. The statistical uncertainties on f_S from the fits represent 1σ confidence intervals that account for the limited statistics in the data C distributions and correlations between the fit parameters. The uncertainties in the fit results due to the finite MC statistics were evaluated using a pseudo-experiment technique in which new pseudo-MC C distributions with the same number of counts as the original MC C distributions were obtained by statistically sampling the MC distributions. The resulting pseudo-MC distributions were then used to perform template fits. The procedure was repeated eight times for each p_T and centrality bin and the standard deviation of the resulting f_S values in each bin was combined in quadrature with the statistical uncertainty from the original fit to produce a combined statistical uncertainty on f_S . The fractional uncertainties on f_S due to MC statistics are found to be below 2% and are typically much smaller than the uncertainties from the template fits.

The sensitivity of the measured f_S values to the adaptation of the MC C distributions to the data was evaluated by performing the fits without implementing the adaption, i.e. by fixing the a and σ parameters to zero and b to one. To test the sensitivity to the primary hadron composition in the MC, and in particular to the relative proportion of kaons and pions (K/π), which may differ from that in the data, new MC background C distributions were obtained by separately doubling the π and K contributions. Potential systematic uncertainties resulting from the template fitting procedure were evaluated using a simple cut-based procedure applied to the C distributions. The total uncertainties from the above considerations are around 7% and 5% for 7 – 8 GeV and 10 – 14 GeV bins in the 0 – 10% centrality interval, and are around 19% and 6% for 7 – 8 GeV and 10 – 14 GeV bins in the 60 – 80% centrality interval.

The resulting central-to-peripheral values, R_{CP} , are shown in the left panel of Fig. 2. The R_{CP} values vary weakly with p_T , and the points for each centrality interval are consistent with a p_T -independent R_{CP} within the uncertainties on the points. The R_{CP} varies strongly with centrality, increasing from about 0.4 in the 0-10% centrality bin to about 0.85 in the 40-60% bin. The variation of R_{CP} with centrality as characterized by the average number of participants,

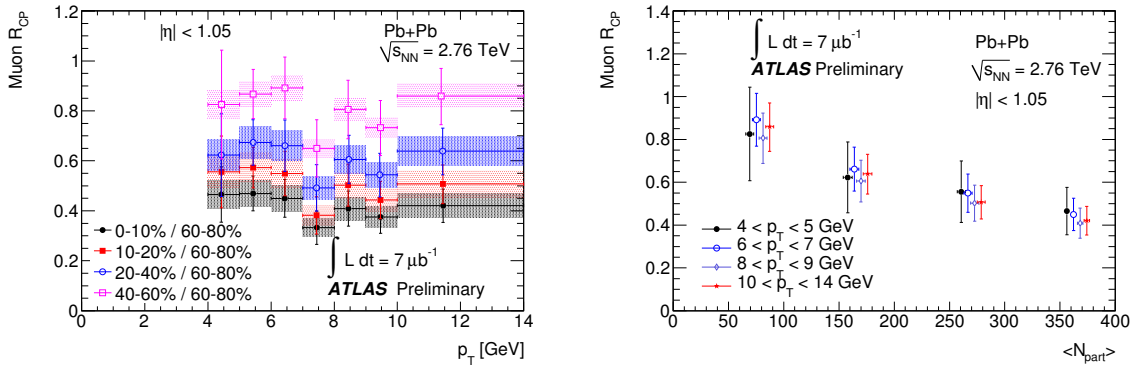


Figure 2: **Left:** Muon R_{CP} as a function of p_T for different centrality bins. The points are shown at the mean transverse momentum of the muons in the given p_T bin. The error bars include both statistical and systematic uncertainties. The contribution of the systematic uncertainties from R_{coll} and ϵ , which are fully correlated between p_T bins, are indicated by the shaded boxes. **Right:** Muon R_{CP} as a function of $\langle N_{part} \rangle$ for different bins in muon p_T . The sets of points for the different p_T bins are successively displaced by $\Delta N_{part} = 6$ for clarity of presentation. Please refer to [16] for details.

$\langle N_{part} \rangle$, is shown in the right panel of Fig. 2 for the different p_T bins included in the analysis. The R_{CP} decreases smoothly from peripheral to central collisions. The centrality dependence is observed to be the same for all p_T bins within the experimental uncertainties.

4. Conclusions

This paper has presented ATLAS measurements of muon production and suppression in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions in a transverse momentum range dominated by heavy flavour decays, $4 < p_T < 14$ GeV, and over the pseudo-rapidity range $|\eta| < 1.05$. The fraction of prompt muons was estimated using template fits to the distribution of a quantity capable of distinguishing statistically between signal and background. The centrality dependence of muon production was characterized using the central-to-peripheral ratio, R_{CP} , calculated using the 60-80% centrality bin as a peripheral reference. The results for R_{CP} indicate a factor of about 2.5 suppression in the yield of muons in the most central (0-10%) collisions compared to the most peripheral collisions included in the analysis. No significant variation of R_{CP} with muon p_T is observed. The R_{CP} decreases smoothly from peripheral to central collisions.

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