Measurement of nuclear modification of lepton production from heavy flavour decays in Pb-Pb collisions with ALICE at the LHC

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Abstract. The heavy quark production cross-section and its nuclear modification factor can be measured by identifying single leptons from semi-leptonic heavy flavour hadron decays. In 2010, pp collisions at $\sqrt{s} = 7$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been recorded by ALICE at the LHC. We present the preliminary results of lepton $p_t$ spectra (electrons in $|\eta| < 0.8$ and muons in $2.5 < \eta < 4.0$) from heavy flavour hadron decays in pp collisions and their nuclear modification factor in Pb-Pb collisions with both the central barrel and forward muon detectors of ALICE.

1. Introduction
The ALICE experiment[1] is the dedicated heavy-ion experiment at the LHC, with the main goal of investigating the properties of the deconfined state of strongly interacting matter expected to be produced in Pb-Pb collisions. The properties of this matter can be studied by partons produced from initial hard scattering processes which are expected to suffer a significant medium induced energy loss prior to hadronization. According to perturbative QCD (pQCD), quarks should lose less energy than gluons and the energy loss of massive quarks with respect to light partons is expected to be reduced due to ‘dead-cone effect’[2, 3, 4]. At the LHC, heavy flavour particles are abundantly produced and this should allow investigation of the colour charge and quark mass dependence of energy loss mechanism in the medium produced in Pb-Pb collisions[5]. The precision measurement of heavy flavour production in pp collisions provides an important test of pQCD calculations and the necessary reference for the interpretation of the Pb-Pb collision results.

The medium produced in heavy-ion collisions can be characterized by comparing the observables measured in nucleus-nucleus collisions to the ones in pp collisions. We use the nuclear modification factor $R_{AA}$ and peripheral-to-central modification factor $R_{CP}$. The $R_{AA}$ is defined as $R_{AA}(p_t) = \frac{1}{<T_{AA}>} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$, where $<T_{AA}>$ is the average nuclear overlap function for a given centrality bin$^1$, $dN_{AA}/dp_t$ and $d\sigma_{pp}/dp_t$ correspond to the $p_t$-differential electron yield in nucleus-nucleus collisions and the $p_t$-differential cross-section in pp collisions respectively. The $R_{CP}$ is defined as the ratio of yields measured in central collisions to the yield measured

$^1$ The definition of centrality is shown in section 4.
in peripheral collisions, both scaled by the corresponding numbers of binary nucleon-nucleon collisions.

The ALICE detector[1] has lepton identification capability over a large kinematical range. In addition the central barrel of ALICE has very good spatial resolution to separate secondary vertices. Thus, to measure inclusive heavy flavour production, it is possible to use semi-leptonic heavy flavour hadron decays that has a relatively large branching ratio (∼10%). The analysis methods using this channel are shown in section 2. We present the preliminary results of lepton $p_t$ spectra (electrons in $|\eta| < 0.8$ and muons in $2.5 < \eta < 4.0$) from heavy flavour hadron decays in pp collisions measured with ALICE and compare with pQCD predictions in section 3. The lepton nuclear modification factors in Pb-Pb collisions are shown in section 4.

2. Heavy flavour measurement via single lepton decays

At mid-rapidity ($|\eta| < 0.8$) heavy flavour production is measured via electrons from decays of charm and beauty hadrons. The silicon Inner Tracking System (ITS) and the Time Projection Chamber (TPC) allow track reconstruction in the pseudo-rapidity range $|\eta| < 0.9$ with a momentum resolution better than 4% for $p_t < 20$ GeV/c and a transverse impact parameter resolution better than 75 μm for $p_t > 1$ GeV/c[6]. Electrons are identified using the signals provided by the Time Of Flight (TOF), the TPC and the Transition Radiation Detector (TRD). The measured time of flight is required to be within $3 \sigma$ from the time of flight for the electron hypothesis to reject kaons for $p < 1.5$ GeV/c and protons for $p < 3$ GeV/c. The electron likelihood of a track is calculated from the charge deposited in the TRD to separate electrons from pions. A cut on the likelihood value is applied to have 80% electron efficiency and achieve good pion rejection power in the momentum range 0.5-10 GeV/c. Further hadron rejection is done based on the TPC specific energy deposit expressed as a deviation from the expected electron line of the Bethe-Bloch parameterization. The remaining hadron contamination is calculated based on a fit of the TPC $dE/dx$ in momentum slices and subtracted from the electron spectra. This combined information allows us to keep the contamination level below 10% up to 10 GeV/c.

The inclusive electron yield consists of electrons from various background sources in addition to electrons from heavy flavour hadron decays. The main background sources are electrons from Dalitz/di-electron decays of light flavour mesons ($\pi^0, \eta, \eta', \rho, \omega, \phi$) and $\gamma$ conversions in the beam pipe and the layer of innermost pixel. Those are calculated based on ALICE measured $\pi^0$ spectrum[7] and $m_{\pi}$ scaled spectra for other light flavour mesons using PYTHIA[8] decay kinematics. The contributions from quarkonia are estimated based on the parametrization of LHC measurements[9] and real and virtual QCD photons based on Next-to-Leading Order (NLO) predictions[10]. We obtain the $p_t$ spectrum of electrons from heavy flavour hadron decays by subtracting the sum of all background electron components from the inclusive $p_t$ distribution.

The electrons from beauty hadron decays are measured by applying an additional cut on the track impact parameter\(^2\) of identified electrons. This cut provides a high purity signal since hadrons containing beauty quarks have an mean proper decay length $c\tau \approx 500 \mu m$ and a hard momentum spectrum, which lead to larger impact parameter of decay electrons than those of background electrons. The remaining background electrons are subtracted based on yields calculated using ALICE measured $\pi^0$ $p_t$ spectra (as explained above) and D mesons $p_t$ spectra[11].

At forward-rapidity (-4 < $\eta$ < -2.5) heavy flavour production is measured via semi-muonic decays. The muon spectrometer consists of a front absorber followed by a 3 T-m dipole magnet, coupled to tracking and triggering devices providing the intrinsic spatial resolution of 70 μm in the bending direction and the time resolution of the order of 2 ns respectively. The inclusive muon $p_t$- and $\eta$-differential distributions are measured using the muon spectrometer and the

\(^2\) Distance of the closest approach to the primary vertex in the transverse plane
Figure 1. Production cross-section of single-electrons from heavy flavour hadron decays in pp collisions at $\sqrt{s} = 7$ TeV compared to pQCD calculations[15]. The lines are corresponding FONLL calculations with their uncertainties.

Figure 2. Production cross-section of single-muons from heavy flavour hadron decays in pp collisions at $\sqrt{s} = 7$ TeV compared to pQCD calculations[15].

following background muon sources are subtracted: i) muons from the decay-in-flight of light hadrons, ii) muons from the decays of light hadrons produced from interactions with the absorber and iii) hadrons that punch through the front absorber. The first component is subtracted based on Monte Carlo simulation$^3$, which is normalized to match the data at low $p_t$ where decay muons from light hadrons dominate. The last two contributions are rejected by requiring a matching between tracks reconstructed in the tracking and the trigger systems$^{14}$.

3. Results in pp collisions at $\sqrt{s} = 7$ TeV
The results we present were obtained from a sample of minimum bias pp collisions (2.6 nb$^{-1}$ for electrons and 16.5 nb$^{-1}$ for muons) recorded in 2010 at $\sqrt{s} = 7$ TeV. The minimum bias were defined by the presence of signals in the Silicon Pixel Detector (SPD) at mid-rapidity or in either of two scintillator hodoscopes (V0) at the forward- and backward-rapidity, in coincidence with the signal of two beam pick-up counters on both side of interaction region. For muon analyses, a muon trigger signal ($p_t > 0.5$ GeV/c) was required in addition to the minimum-bias condition.

Figure 1 shows the $p_t$-differential cross-section of electrons from heavy flavour hadron decays (solid circles) and charmed hadron decays (open squares) obtained by applying PYTHIA decay kinematics to the ALICE measured D meson $p_t$ spectra$^{11}$ in the rapidity range $|y| < 0.8$. The present estimate of the systematic uncertainty is $\sim 20\%$ on the measured electron spectrum and $\sim 10\%$ on the sum of background electrons$^{16}$. Figure 2 shows $p_t$-differential cross-section of muons from heavy flavour hadron decays in $-4 < \eta < -2.5$. The data are compared to the corresponding Fixed-Order plus Next-to-Leading Log (FONLL) prediction$^{15}$, and shows a good agreement within uncertainties.

The first beauty production cross-section was measured in ALICE with the method described in the previous section. Figure 3 shows the $p_t$-differential cross-section of electrons from beauty

$^3$ Monte Carlo simulations are done with PYTHIA tune Perugia-0$^{12}$ and PHOJET$^{13}$
hadron decays and it is compared with FONLL prediction. FONLL prediction describes the data within uncertainty although the present uncertainty on the measurement is too large to draw final conclusions.

4. Results in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The same analysis approach was used for the first Pb-Pb collisions recorded in November and December 2010 at $\sqrt{s_{NN}} = 2.76$ TeV. The SPD and the V0 detector provide the minimum bias trigger (corresponding to 97% of the hadronic Pb-Pb cross-section). Events are classified according to their centrality in terms of percentiles of the distribution of the sum of the amplitudes in the V0 detector[17]. Electrons are identified with the TOF and TPC detectors. The subtracted hadron contamination is below 10% in the momentum range 1.5-6 GeV/c. The inclusive electron spectra are obtained in 6 centrality bins and background electron contributions are calculated based on the charged pion spectra measured by ALICE. In this analysis, the systematic uncertainties are $\sim 35\%$ on the inclusive spectra, which is dominated by particle identification, and $\sim 25\%$ on electron background calculation[18]. The uncertainty on the inclusive spectra will be improved by using the TRD and the Electromagnetic Calorimeter (EMCAL) in the future. The systematic uncertainty on estimating background electrons will be also reduced by improved $\pi^0$ measurements and direct measurements of other background sources. For semi-central and most central Pb-Pb collisions, the ratio of the inclusive electron spectrum to the sum of background electrons shows a hint for an excess of electrons in the low $p_t$ region ($1.5 < p_t < 3.5$ GeV/c)[18]. Thermal radiation from the hot and high-density medium could be a possible explanation. This is being further investigated.

The reference cross-section in pp collisions at $\sqrt{s} = 2.76$ TeV is obtained by applying a $p_t$ dependent scaling factor to the cross-section measured at $\sqrt{s} = 7$ TeV. The scaling factors are defined as the ratios of the cross-section from the FONLL calculations[15] at 2.76 and 7 TeV with fixed pQCD scale values and heavy quark masses. The theoretical uncertainty on the scaling factor was evaluated by considering different values of the pQCD scales and heavy quark masses[19].

Figure 4 shows the resulting $R_{AA}$ of background-subtracted electrons for the centrality
ranges 0-10% and 60-80%. We observe factor 1.5-4 suppression in the transverse momentum region 3.5-6 GeV/c, which is dominated by electrons from heavy flavour hadron decays. This implies a strong energy loss of heavy quarks in the medium produced in central Pb-Pb collisions. Figure 5 shows the inclusive muon $R_{CP}$ in four centrality bins, 0-10%, 10-20%, 20-40% and 40-60% (the peripheral bin is 60-80%). The background muons are not subtracted in Pb-Pb collisions. The muon $R_{CP}$ shows a suppression of factor about 3 for the centrality bin 0-10%. This suppression decreases in non-central collisions.

5. Conclusions
The transverse momentum spectra of single leptons from heavy flavour hadron decays have been measured by ALICE in pp collisions at $\sqrt{s} = 7$ TeV. FONLL predictions are in good agreement with the data. The first measurement of electrons from beauty hadron decays has been performed in pp collisions. The electron spectra corrected for the known background electrons have been measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The nuclear modification factor of electrons and peripheral-to-central modification factor of muons show an indication of strong energy loss of heavy quarks with the medium produced in Pb-Pb collisions. The measurement of electrons from beauty hadron decays in Pb-Pb collisions is under way, which will provide strong constraints to understand the colour charge and quark mass dependences of parton energy loss.

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