Measurements of heavy-flavour decay leptons in pp, p-Pb, and Pb-Pb collisions with ALICE

Sarah LaPointe on behalf of the ALICE Collaboration

Istituto Nazionale di Fisica Nucleare, Via P. Giuria 1, 10125 Torino
E-mail: s.lapointe@cern.ch

Abstract.
We present measurements of electrons and muons originating from the semi-leptonic decays of heavy-flavour hadrons at central and forward rapidities with ALICE in pp (√s = 2.76 and 7 TeV), p-Pb (√sNN = 5.02 TeV), and Pb-Pb (√sNN = 2.76 TeV) collisions. The measured pT-differential production cross sections in pp collisions, the nuclear modification factors in p-Pb and Pb-Pb, and the ν2 measurements in Pb-Pb collision are discussed. In addition, the angular correlation distribution between heavy-flavour decay electrons and charged particles, measured in p-Pb collisions, is shown. The results are compared to their corresponding theoretical predictions.

1. Introduction
The main objective of ALICE is to investigate the strongly interacting, partonic medium that forms from high energy collisions of heavy ions [1]. At the CERN LHC heavy quarks, i.e. charm and beauty, are abundantly produced [2, 3] and, because of their large masses, they predominately originate from hard parton scattering processes in the initial phase of the collision. Thus their production occurs early relative to the expected formation time of the Quark-Gluon Plasma (QGP). Additionally, in-QGP annihilation and production of heavy quark pairs is negligible, thus it is expected that they sample each stage of the QGP phase.

While propagating through the medium, heavy quarks are expected to lose energy via elastic scatterings and radiative processes. An experimental observable sensitive to the energy loss is the nuclear modification factor (RAA), which quantifies the modification of heavy-flavour transverse momentum (pT) distributions in Pb-Pb collisions, relative to pp collisions. RAA is expected to be equal to unity in the absence of initial and final state medium effects. Another experimental observable of interest is ν2, which is the second Fourier coefficient of the azimuthal distribution of particles in the transverse plane with respect to the orientation of the reaction plane. Studying the ν2 of heavy-flavour decay particles can provide knowledge of path-length dependent quark energy loss at high transverse momentum, while at low transverse momentum it offers information on the degree of thermalization of heavy quarks within the medium. An additional, relevant measurement is the azimuthal correlation of heavy-flavour decay electrons and charged hadrons, which can be utilized to estimate the relative contribution of charm and beauty hadrons to the measured heavy-flavour decay electron yield in pp collisions, while also providing a tool to examine the production and fragmentation of heavy quarks in other systems.
The measurement of heavy-flavour production in pp collisions provides the necessary reference for the measurements carried out in heavy-ion collisions, while it also provides essential tests of perturbative Quantum Chromodynamics (pQCD). However, any modification observed in Pb-Pb arises from either initial or final state effects and the pp reference alone cannot allow to decipher the origin. Therefore p-Pb collisions are necessary to disentangle initial state effects, such as the modification of parton distributions in nuclei or energy loss in cold nuclear matter, from final state effects in Pb-Pb collisions.

In the following, the ALICE measurements of electrons and muons originating from the semi-leptonic decays of heavy-flavour hadrons in pp and Pb-Pb, and electrons in p-Pb collisions are presented. The measured $p_T$-differential production cross sections, nuclear modification factors, $\nu_2$, and electron-charged particle angular correlation distributions are shown and compared to the respective theoretical predictions.

2. Heavy-flavour measurements with electrons and muons in ALICE

The heavy-flavour particle detection performance of ALICE is detailed in [4]. Concerning the measurements presented here, the detectors utilized are located in the central rapidity ($|\eta| < 0.9$) and forward rapidity ($-4 < \eta < -2.5$) regions. Open heavy-flavour hadrons are measured via their semi-electronic decay channels in the central rapidity region and in the forward region through their semi-muonic decay channels. Track reconstruction in the central region is based on the Inner Tracking System and the Time Projection Chamber (TPC). Electrons are identified with TPC and Time-of-Flight (TOF) detectors and at higher momentum using the ElectroMagnetic Calorimeter (EMCal) and the Transition Radiation Detector. The electron sample includes electrons from the decay of heavy-flavour hadrons and from background sources, dominated by photon conversions in detector material and Dalitz decays. The background is estimated using either an $e^+e^-$ invariant mass method or a Monte Carlo (MC) calculation of the contributions based on measured $\pi^0$ and $\eta$ meson cross sections [5]. In addition, electrons from decays of beauty hadrons can be identified statistically using a track displacement based selection which exploits the relatively long lifetime of $B$ mesons ($c \tau \sim 500 \mu m$). In the forward region, muon tracking and identification is provided by the muon spectrometer. The dominant background sources for the muon measurement are from the decays of pions and kaons. They are estimated in pp collisions using a MC simulation, while in Pb-Pb collisions they are extrapolated from the measured pions and kaons at central rapidity.

3. Measurements in pp collisions

The $p_T$-differential production cross section of electrons from heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 7$ TeV at central rapidity ($|y| < 0.5$) and in the $p_T$ range 0.5–8 GeV/c [5] is shown in Fig. 1 (left). The measurement is compared to the complementary result of the ATLAS experiment [6], measured in the rapidity interval $|y| < 2$ (excluding $1.37 < |y| < 1.52$), which spans the $p_T$ range 7–26 GeV/c. Shown in Fig. 1 (right) is the $p_T$-differential production cross section of muons from heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 7$ TeV at forward rapidity ($2.5 < y < 4$) and in the $p_T$ range 2–12 GeV/c [7]. Also shown in both panels of Fig. 1 is a comparison of the corresponding pQCD FONLL predictions [8] in the respective rapidity intervals, along with the ratio between data and FONLL. Within the experimental and theoretical uncertainties, both the electron and muon data are well described by the predictions.

In pp collisions at $\sqrt{s} = 7$ TeV electrons from beauty-hadron decays have been measured with ALICE [9]. The relatively long lifetime of beauty hadrons was exploited by selecting on the track impact parameter ($d_0$), which is the projection, in the transverse plane, of the charged track distance of closest approach to the interaction vertex. This selection enhances the relative contribution of electrons from beauty-hadron decays in the total heavy-flavour decay electron sample.
Heavy-flavour decay leptons have been measured in pp collisions at $\sqrt{s} = 2.76$ TeV, the reference energy for Pb-Pb collisions. Relative to the $\sqrt{s} = 7$ TeV sample, the running time for this data sample was short, and the uncertainties of the electron $p_T$-differential cross section from the 7 TeV sample were significantly lower compared to those at 2.76 TeV. Hence the cross section at $\sqrt{s} = 7$ TeV was scaled down to 2.76 TeV using the FONLL prediction and used as the pp reference for Pb-Pb measurements. The resulting scaled $p_T$-differential cross section was compared to the one measured at $\sqrt{s} = 2.76$ TeV and it was found to be in agreement, validating the use of the scaling method [10]. The heavy-flavour decay muon $p_T$-differential production cross section in pp collisions at $\sqrt{s} = 2.76$ TeV in the $p_T$ range 2–10 GeV/c and $2.5 < y < 4$ has been measured [11]. With a statistical precision better than that of the scaled 7 TeV $p_T$-differential cross section it is thus used as the pp reference directly.

In pp collisions at $\sqrt{s} = 2.76$ TeV electrons from beauty-hadron decays have been measured [12]. The primary analysis technique used the track impact parameter as a selection criterion. A second method discriminates beauty from charm production using the distribution of the azimuthal angle between heavy-flavour decay electrons and charged hadrons, $\Delta \varphi$. Due to the different decay kinematics of charm and beauty hadrons, the width of the peak in the $\Delta \varphi$ distribution around zero is larger for beauty than for charm hadron decays and from this

Figure 1. Left: $p_T$-differential production cross section of electrons from heavy-flavour hadron decays measured in pp collisions at $\sqrt{s} = 7$ TeV with ALICE in $|y| < 0.5$ and ATLAS in $|y| < 2$, excluding $1.37 < |y| < 1.52$ [6]. The solid (dashed) curve shows the corresponding FONLL prediction (uncertainty). Right: $p_T$-differential production cross section of muons from heavy-flavour hadron decays measured in pp collisions at $\sqrt{s} = 7$ TeV in $2.5 < y < 4$. The solid curve (band) is the corresponding FONLL prediction (uncertainty). The dashed (dot–dashed) curve is the FONLL prediction of muons from charm (beauty) hadron decays. Both figures show the corresponding ratio between the data and the FONLL central prediction in the lower panels.
the relative beauty contribution to the measured heavy-flavour decay electron \( p_T \)-differential production cross section is extracted. Fig. 2 shows the \( p_T \)-differential production cross section of electrons from beauty-hadron decays measured in pp collisions at \( \sqrt{s} = 2.76 \) TeV. The result in the \( p_T \) range 1–8 GeV/c and \(|y| < 0.8\) was supplied by the impact-parameter based analysis, while the \( p_T \) interval 8–10 GeV/c was taken from the electron-hadron azimuthal correlation based analysis, measured in \(|y| < 0.7\). The \( p_T \)-differential cross section is compared to three pQCD calculations [8, 13, 14] and the data and theory are consistent within the experimental and theoretical uncertainties.

4. Measurements in Pb-Pb and p-Pb collisions

In the following, the nuclear modification factors (\( R_{AA} \) and \( R_{pPb} \)), the \( \nu_2 \) coefficient of electrons and muons from heavy-flavour hadron decays measured in Pb-Pb collisions, and the electron-hadron angular correlations measured in p-Pb collisions are presented and compared to the most current theoretical predictions.

The nuclear modification factor is defined as:

\[
R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}}{dp_T} ; \quad R_{pPb}(p_T) = \frac{1}{A} \frac{d\sigma_{pPb}}{dp_T} \frac{d\sigma_{pp}}{dp_T}
\]

where \( dN_{AA}/dp_T \) is the yield in Pb-Pb collisions, \( d\sigma_{pp}/dp_T \) is the differential cross section in pp collisions, and \( \langle T_{AA} \rangle \) is the average nuclear overlap function, calculated using the Glauber model [15]. For the calculation in p-Pb collisions the \( p_T \)-differential cross section is taken as the numerator and \( \langle T_{AA} \rangle \) is replaced by \( A \), the mass number of the Pb nucleus.

In Pb-Pb collisions the \( p_T \)-differential yield of heavy-flavour decay electrons in the range 3 < \( p_T \) < 18 GeV/c is measured at central rapidity. The measurement extends above the upper
Figure 3. Left: Nuclear modification factor ($R_{AA}$) of electrons (circle and star symbols, depending on the pp reference) and muons [7] (triangles) from heavy-flavour hadron decays as a function of $p_T$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for the centrality class 0–10 %. Center: $R_{AA}$ of electrons measured in the 40–80 % and muons in the 40–50 % centrality classes. Right: $R_{p_{T}p_{T}}$ of electrons from the decay of heavy-flavour hadrons as a function of $p_T$. The circle symbols represent the electrons identified using TPC-TOF, while those identified using TPC-EMCal are shown as square symbols. For all panels, the muons are measured in the forward rapidity region ($2.5 < y < 4$), while the electrons are observed at central rapidity ($|y| < 0.6$).

limit (8 GeV/c) of the measurement in pp at $\sqrt{s} = 7$ TeV, hence the FONLL calculation was used as the reference in the range $p_T > 8$ GeV/c. The heavy-flavour decay muons are measured in the forward region in the range $4 < p_T < 10$ GeV/c. Fig. 3 (left) shows the measured $R_{AA}$ of the heavy-flavour decay electrons and muons for the centrality class 0–10 %. Both the muons and electrons reach a suppression factor 3–4 for $p_T > 5$ GeV/c, which is where pQCD calculations predict that leptons from beauty-hadron decays start to dominate the $p_T$-differential cross section in pp collisions. This suggests that not only charm, but also beauty quarks are experiencing significant in-medium energy loss. Also shown in Fig. 3 (center) is the resulting $R_{AA}$ measured in less central collisions, muons in the 40–80 % and electrons in the 40–50 % centrality class. The observation of less modification of the $p_T$ spectrum is expected, as the medium formed in peripheral collisions should be less dense that that formed in a central collision.

Heavy-flavour decay electrons were measured in minimum bias p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the rapidity interval $|y| < 0.6$. Using the TPC and the TOF for electron identification the measurement spans the $p_T$ range 0.5–6 GeV/c, while electrons identified utilizing the TPC and the EMCal were measured in the $p_T$ range 2–12 GeV/c. In the overlap region these results are in agreement, with the TPC–TOF based measurement featuring smaller uncertainties. The nuclear modification factor $R_{p_{T}p_{T}}$ is shown in Fig. 3 (right). For $p_T < 8$ GeV/c the p-Pb $p_T$-differential cross section is compared to the pp reference measured at $\sqrt{s} = 7$ TeV and scaled to 5.02 TeV, while above 8 GeV/c the FONLL calculation was used as the reference. Although the experimental uncertainties are large, this result suggests small cold nuclear matter effects and indicates that the observed suppression observed in Pb-Pb collisions is a dense medium effect.

For non-central heavy-ion collisions, an azimuthal anisotropy in momentum space can be observed in the measured final state particle distributions. The particle distribution can be expanded in a Fourier series [16]

$$L \frac{d^3N}{dp_T} = \frac{1}{2\pi} \frac{d^2N}{dp_Tdy} \left(1 + 2 \sum_{n=1}^{\infty} \nu_n \cos[n(\varphi - \Psi_{R_P})]\right)$$

(2)

Here $\nu_2$ is the second Fourier coefficient, often referred to as "elliptic flow", $\varphi$ is the particle
azimuthal angle, $\Psi_{RP}$ is the reaction plane azimuthal angle. The reaction plane is defined by the beam direction and the collision impact parameter.

Fig. 4 (left) shows the $p_T$-integrated ($3 < p_T < 10 \text{ GeV}/c$) heavy-flavour decay muon $\nu_2$ as a function of centrality. From central (0–10 %) to semi-central (20–40 %) collisions $\nu_2$ increases. The near-zero $\nu_2$ for the most central collisions is consistent with the expectation that the initial geometrical anisotropy vanishes. The comparison of the heavy-flavour decay electron $\nu_2$ as a function of $p_T$ measured in $|y| < 0.7$ for the centrality class 20–40%, to the heavy-flavour decay muons measured in the same centrality class but in the range $2.5 < y < 4$ is shown in Fig. 4 (right). The values of heavy-flavour decay lepton $\nu_2$ measured in the two rapidity regions are similar.

In Fig. 5 the measured electron $R_{AA}$ (left) and $\nu_2$ (right) are compared to five parton transport models: BAMPS, which includes collisional in-medium energy loss and mimics the radiative processes by increasing the elastic cross section [17], BAMPS + rad., where this version includes radiative processes [18], TAMU, which includes collisional energy loss, with resonance formation and dissociation in an evolving hydrodynamic medium [19], POWLANG, which is based on the Langevin equation with collisional energy loss in an expanding, deconfined medium [20], and MC@shG+EPOS, which includes radiative and collisional energy loss in an expanding medium based on the EPOS model. The comparison to the models suggests that re-scatterings transfer to heavy quarks information on the azimuthal anisotropy of the medium.

In p-Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ the angular correlation between heavy-flavour decay electrons and charged particles has been measured in three multiplicity classes. The multiplicity was measured with the V0A detector ($2.8 < \eta < 5.1$) in the Pb hemisphere. A typical two-particle angular correlation distribution is the difference in azimuth ($\Delta \phi$) and in pseudorapidity ($\Delta \eta$) between a trigger particle and associated particle, normalized to the number of trigger particles. Here the trigger particle is the electron and the associated are the charge particles produced in the event. The electron sample contains a background contribution which is subtracted via the $e^+e^-$ invariant mass method, so as to obtain the correlation between heavy-flavour decay electrons and charged particles. In Fig 6 (left) the measured angular correlation,
**Figure 5.** Left: Heavy-flavour decay electron $R_{AA}$ as a function of $p_T$ measured in the 0–10% centrality class in $|y| < 0.6$. The circles (stars) indicate where the pp reference is taken as the cross section scaled from $\sqrt{s} = 7$ TeV (FONLL calculation at $\sqrt{s} = 2.76$ TeV). The results are compared to four parton transport models: BAMPS [17], BAMPS+rad. [18], TAMU [19], POWLANG [20], and MC@aHQ+EPOS, Coll+Rad(LPM) [21]. Right: Heavy-flavour decay electron $v_2$ as a function of $p_T$ measured in the 20–40% centrality class in $|y| < 0.6$. The results are compared to the aforementioned models.

after the projection on the $\Delta \varphi$ axis, for three multiplicity classes in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and for pp collisions at $\sqrt{s} = 7$ TeV is shown, where the heavy-flavour decay electron is in the $p_T$ range of 1-2 GeV/c. The distribution observed in the low multiplicity events has a similar shape on the near ($-\frac{\pi}{2} < \Delta \varphi < \frac{\pi}{2}$) and away ($\frac{\pi}{2} < \Delta \varphi < \frac{3\pi}{2}$) side to that obtained from pp collisions. However, a clear modification of the correlation function on both the near and away side is visible in high multiplicity p-Pb collisions compared to pp and low multiplicity p-Pb collisions. $I_{CP}$, the ratio between the per-trigger yield in high and low multiplicity collisions, can be used to quantify the observed modification. In Fig 6 (center) the near side $I_{CP}$ is shown as a function of the electron $p_T$ and demonstrates that for low $p_T$ electrons there is an unexpected enhancement of associated particles.

To further characterize the modification, the correlation distribution in $\Delta \varphi \Delta \eta$ measured in the low multiplicity event class was subtracted from that in the high multiplicity event class to reduce the contribution from jets. The result is shown in Fig 6 (right) and suggests a long range correlation in $\Delta \eta$, also observed for various hadron-hadron angular correlations measured in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [22, 23]. The ‘double ridge’ structure can be described by either initial state effects, e.g. parton saturation in the nucleus [24], or by final state effects, e.g. hydrodynamic expansion in small systems [25, 26]. Regardless of which process(es) is(are) responsible for the ‘double ridge’, it seems that heavy-flavour hadrons are also affected by it.

**5. Summary**

Electrons and muons, which originate from the semi-leptonic decays of heavy-flavour hadrons, have been measured at mid-rapidity and forward rapidity in pp, Pb-Pb, and p-Pb collisions. The $p_T$-differential production cross sections in pp collisions are well described by pQCD calculations. In Pb-Pb collisions, the nuclear modification factor indicates a strong suppression of the heavy-
flavour yield at high $p_T$ in the central collisions, which points to significant energy loss of heavy quarks in the produced medium. $\nu_2$ measurements of heavy-flavour decay leptons in Pb-Pb collisions indicate a positive $\nu_2$ in semi-central collisions, suggesting re-scatterings transfer information on the azimuthal anisotropy of the medium to heavy quarks. In p-Pb collisions, $R_{pPb}$ is consistent with small cold nuclear matter effects, demonstrating that the observed suppression in central Pb-Pb collisions is mainly a final state effect, due to in-medium energy loss. In high multiplicity p-Pb collisions the measurement of angular correlation between heavy-flavour decay electrons and charged particles reveals a double ridge structure, hinting that the mechanism responsible for the long range correlation observed for light-flavour hadrons may also affect heavy-quark dynamics.

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