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Heavy-flavour measurements in pp and Pb-Pb collisions with the ALICE experiment at the CERN LHC

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The ALICE experiment at the CERN LHC has conducted first systematic studies of heavy-flavour hadron production in pp collisions at $\sqrt{s} = 7$ TeV and in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. In pp collisions the differential production cross sections of D mesons at mid-rapidity, as well as the cross sections for electrons and muons from semileptonic heavy-flavour hadron decays at mid- and forward-rapidity, respectively, have been measured. These data provide a crucial testing ground for perturbative QCD calculations in the new LHC energy regime. In Pb-Pb collisions, the nuclear modification factor $R_{\rm AA}(p_{\rm t})$ has been measured for D mesons and for leptons from heavy-flavour decays, indicating energy loss of heavy quarks in the partonic medium produced in Pb-Pb collisions at the LHC. The strong interaction of charm quarks with this medium might also generate a non-zero elliptic flow of D mesons as first studies of the azimuthal anisotropy of $\rm D^0$-meson production suggest.

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1. Introduction

Particles carrying heavy flavour, *i.e.* charm or beauty quarks, are among the most interesting probes in contemporary particle and nuclear physics. Due to the large quark mass, heavy-flavour production proceeds dominantly through hard partonic scattering processes in the earliest stage of hadronic collisions. As such the measurement of heavy-flavour production in pp collisions at the LHC provides a crucial testing ground for perturbative Quantum Chromodynamics (pQCD), the theory of strong interactions, in a new high energy domain.

Furthermore, these measurements serve as a baseline for heavy-flavour studies in Pb-Pb collisions at the LHC, where the heavy quarks propagate through and interact with the hot and dense medium produced in the nuclear collisions. The investigation of medium modifications of heavy-flavour observables will shed light on the properties of the medium and the nature of the parton-medium interactions. In particular, in-medium energy loss of heavy quarks is sensitive to the energy density and will reflect itself in the suppression of heavy-flavour hadrons at high transverse momentum, $p_{\rm t}$. Such a suppression can be quantified using the nuclear modification factor $R_{\rm AA}(p_{\rm t})$, which is the ratio of the $p_{\rm t}$ distribution measured in nucleus-nucleus (in this case Pb-Pb) collisions at a given centrality and the corresponding distribution in pp collisions scaled by the average number of binary nucleon-nucleon collisions, $\langle N_{coll}\rangle$, in the selected centrality class of the nucleus-nucleus collisions:

$$R_{\rm AA}(p_{\rm t}) = \frac{1}{\langle N_{coll}\rangle}\frac{dN_{\rm AA}/dp_{\rm t}}{dN_{pp}/dp_{\rm t}} = \frac{1}{\langle T_{\rm AA}\rangle}\frac{dN_{\rm AA}/dp_{\rm t}}{d\sigma_{pp}/dp_{\rm t}} \tag{1.1}$$

In this expression, the average nuclear overlap integral $\langle T_{\rm AA}\rangle$, which is obtained from a Glauber model calculation of the collision geometry, provides a translation between cross sections as measured in pp collisions and particle multiplicities as measured in nucleus-nucleus collisions.

Energy loss of partons in a dense medium will lead to $R_{\rm AA}(p_{\rm t}) < 1$ for hadrons originating from the fragmentation of those partons. If energy loss proceeds mainly via induced gluon radiation in a coloured medium $R_{\rm AA}(p_{\rm t})$ should show a distinctive pattern. Gluons should lose more energy radiatively than quarks given the lower colour charge of quarks. For quarks, in addition, a mass hierarchy is expected. The 'dead-cone effect' should prohibit induced gluon radiation of a quark in a colour charged medium in a forward cone which increases in size with increasing quark mass [1]. Consequently, the nuclear modification factor of light hadrons, which predominantly originate from hard scattered gluons or light quarks, should be larger than that of D mesons originating from charm quarks, which in turn should be larger than that of B mesons from beauty fragmentation: $R^{\pi}_{\rm AA} < R^{D}_{\rm AA} < R^{B}_{\rm AA}$. This hierarchy expected for radiative energy loss was not observed for electrons from heavy-flavour decays at RHIC [2, 3], where, up to now, electrons from charm and beauty decays could statistically be separated from each other in pp collisions only [4, 5]. The direct measurement of $R^{D}_{\rm AA}$ in comparison with the nuclear modification factor of other probes is of prime importance to shed light on the mechanism of partonic energy loss.

Further insight can be gained from the measurement of the azimuthal anisotropy of the charm hadron $p_{\rm t}$ spectra with respect to the orientation of the reaction plane. In particular, the second Fourier coefficient, v_2, of this azimuthal distribution is expected to be sensitive to the degree of thermalisation of charm quarks within the partonic medium. A non-zero v_2 would certainly be indicative of a strong interaction of charm quarks with the medium.

The ALICE experiment was optimised for heavy-flavour measurements in various decay channels (see Section 2). Measurements in pp collisions at $\sqrt{s} = 7$ TeV are presented in Section 3 and compared with pQCD calculations, which are in good agreement with the data. This justifies to use pQCD to scale the pp data from $\sqrt{s} = 7$ TeV to 2.76 TeV in order to obtain a reference for Pb-Pb collisions at that energy per nucleon-nucleon pair as described in Section 4. Results from heavy-flavour observables in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV are summarised in Section 5.

2. Heavy-flavour measurements with ALICE

The tracking and particle identification detectors of the ALICE experiment, which is described in detail elsewhere [6], allow for excellent measurements of heavy-flavour production through the full reconstruction of hadronic D-meson decays at central rapidity as well as via semileptonic decays of charm and beauty both at central and forward rapidities.

The tracking system consists of the silicon Inner Tracking System (ITS) [6, 7] and the Time Projection Chamber (TPC) [6, 8] located in a solenoidal magnetic field of 0.5 T. In the pseudorapidity range $|\eta| < 0.9$ tracks are reconstructed with a momentum resolution better than 4% for $p_{\rm t} < 20$ GeV/c. The distance of closest approach of tracks to the interaction vertex is measured with a resolution better than 75μm for $p_{\rm t} > 1$ GeV/c in the plane transverse to the beam direction [9].

Charged hadrons are identified via their specific energy loss dE/dx in the TPC and a time-of-flight (TOF) measurement in the ALICE TOF detector. The same techniques allow for a clean electron identification in the range $p_{\rm t} < 6$ GeV/c. At higher $p_{\rm t}$, the Transition Radiation Detector (TRD) and, alternatively, the Electromagnetic Calorimeter (EMCal) are necessary to identify electrons. Muons are identified and their momenta are measured in the forward muon spectrometer which covers the pseudorapidity range $-4 < \eta < -2.5$.

The measurement of D mesons at mid-rapidity ($|y| < 0.5$) is based on the selection of displaced-vertex topologies [9]. Tracks are selected which originate from a secondary vertex consistent with a large decay length as expected from the D-meson lifetimes. In addition, a good alignment of the reconstructed D-meson momentum with the flight line from the collision vertex to the secondary vertex is required. Since all D-meson decay channels studied (the most important are $\rm D^0 \rightarrow K^-\pi^+$, $\rm D^+ \rightarrow K^-\pi^+\pi^+$, and $\rm D^{*+} \rightarrow D^0\pi^+$) involve a kaon as decay product the identification of the charged kaon in the TPC and TOF detectors helps to reduce the background. In an invariant mass analysis the raw D-meson yields are determined which, then, are corrected for geometrical acceptance and for reconstruction and particle identification efficiency based on a detailed simulation of the apparatus. Feed down from B-meson decays is estimated from a fixed-order next-to-leading-log (FONLL) pQCD calculation [10] and it is subtracted.

Electrons from heavy-flavour decays are measured at mid-rapidity ($|y| < 0.8$) in a two step procedure. First, the inclusive electron spectrum is determined. Electron candidate tracks are identified with the TPC, TOF, and TRD detectors. The small remaining hadron background is estimated via fits of the TPC dE/dx distribution in momentum slices and it is subtracted from the electron candidate spectra. After corrections for geometrical acceptance and tracking and particle identification efficiencies derived from simulations the inclusive electron spectrum is obtained.

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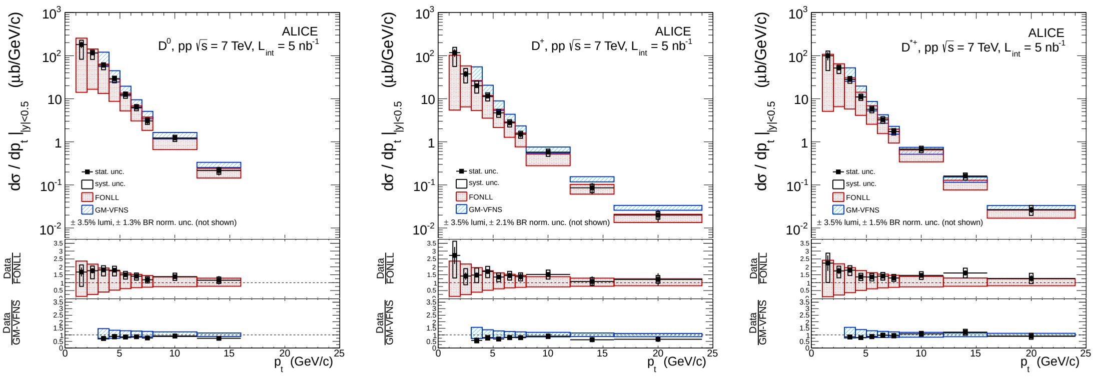

Figure 1: D^0, D^+, and D^{*+} p_t-differential production cross sections in pp collisions at $\sqrt{s} = 7$ TeV [9] in comparison with pQCD calculations [10, 21].

From this inclusive spectrum a cocktail of electrons from sources other than heavy-flavour decays is subtracted. The most important components of this background cocktail are Dalitz decays of the π^0 and η meson and photon conversions in the beam pipe and in the first pixel layer of the ITS. In addition, decays of light vector mesons (ρ, ω, ϕ), heavy quarkonia ($J/\psi, \Upsilon$), and direct radiation from hard scattering processes are included. The cocktail input is based on the π^0 and η spectra measured by ALICE [11], the known material budget of the ALICE apparatus [12] (conversions), m_t-scaling (light vector mesons), heavy quarkonia measurements from ALICE [13] and CMS [14, 15], and next-to-leading-order pQCD calculations [16, 17] (direct radiation).

In a similar approach muons from heavy-flavour decays are measured at forward rapidity [18]. From the inclusive muon spectrum three main background sources are subtracted: muons from the decay of primary light hadrons, muons from the decay of hadrons produced in secondary interactions in the front absorber, and hadrons that punch through the front absorber. Punch through hadrons can be rejected requiring that muon candidate tracks match a track in the muon trigger system. The decay muon background dominates in the low-p_t region and it can be subtracted using information from detailed simulations.

The results presented here were obtained from data recorded in pp and Pb-Pb collisions using minimum bias trigger selections. The minimum bias trigger in pp collisions required the presence of signals in either of two scintillator hodoscopes (VZERO detectors), located in the forward and backward regions of the experiment, or in the silicon pixel detector (SPD) of the ITS. In Pb-Pb collisions signals in both VZERO detectors and the SPD were required. For the results presented here, 100-300 million (depending on the analysis) pp collisions and 17 million Pb-Pb collisions were analysed. For pp collisions production cross sections were normalised relative to the minimum bias trigger cross section which was determined using a van der Meer scan [19]. Yields in Pb-Pb collisions were measured in classes of collision centrality which were defined based on a Glauber-model analysis of the sum of the amplitudes measured in the VZERO detectors [20].

3. Heavy flavour in pp collisions at $\sqrt{s} = 7$ TeV

The D^0, D^+, and D^{*+} p_t-differential production cross sections measured at mid-rapidity ($|y| < 0.5$) [9] are shown in Fig. 1. Theoretical calculations based on next-to-leading-order pQCD

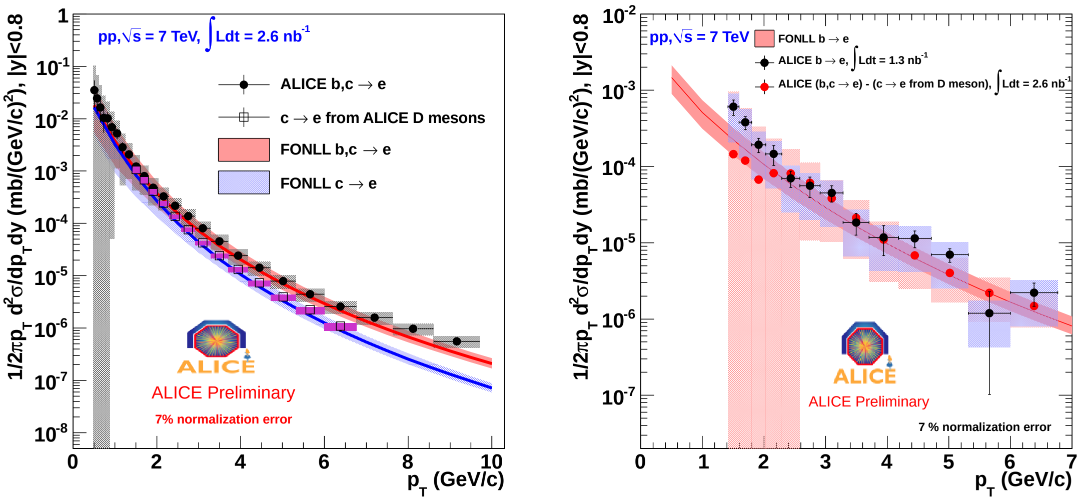

Figure 2: Differential production cross sections of electrons from heavy-flavour and D-meson decays [23] (left panel) and of electrons from beauty decays (right panel) in pp collisions at $\sqrt{s} = 7$ TeV in comparison with FONLL pQCD calculations [10].

calculations (FONLL [10] and GM-VFNS [21]) are in agreement with the data within substantial experimental and theoretical systematic uncertainties.

The p_t-differential production cross section of electrons from heavy-flavour decays is shown in the left panel of Fig. 2, which also depicts the contribution from charm decays. The latter was obtained from the measured D-meson spectra shown in Fig. 1 applying PYTHIA decay kinematics [22] to electrons [23]. FONLL calculations are compared to both measured electron cross sections. The agreement between the calculation and the data is reasonable within systematic uncertainties. Towards low p_t, the electron signal from heavy-flavour decays relative to the background from other sources becomes comparable to the combined systematic uncertainties of the inclusive electron measurement and the calculated background. After background subtraction, this gives rise to a $\geq 100\%$ systematic uncertainty of the electron signal from heavy-flavour decays at low p_t.

The production cross section of electrons from beauty decays can be measured using the ITS. Due to the rather long life time of beauty hadrons ($c\tau(B^0) = 457\mu$m, $c\tau(B^+) = 491\mu$m), electron tracks originating from the decay of beauty hadrons do not point back to the primary collision vertex. Therefore, requiring a minimum displacement of electron tracks from the collision vertex significantly enhances the beauty decay contribution to the electron sample. The remaining contribution from charm decays can be estimated from the D-meson cross section and it is subtracted [23]. The resulting measured production cross section of electrons from beauty decays is shown in the right panel of Fig. 2. A cross check is provided by the difference between the cross sections of electrons from heavy-flavour decays and the charm contribution (left panel of Fig. 2). These two measurements of electrons from beauty decays agree with each other within systematic uncertainties as demonstrated in the right panel of Fig. 2. Again a FONLL pQCD calculation is in reasonable agreement with the measurement.

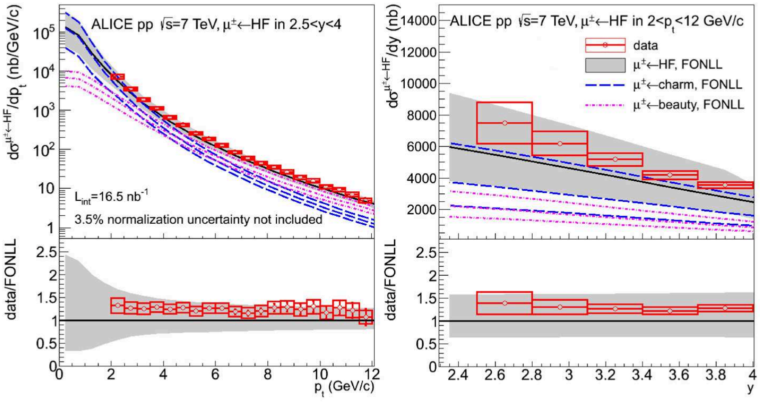

Figure 3: Production cross section of muons from heavy-flavour decays in the range $-4 < y < -2.5$ as function of p_t and η in pp collisions at $\sqrt{s} = 7$ TeV [18] in comparison with FONLL pQCD calculations [10].

The production cross section of muons from heavy-flavour decays at forward rapidity ($-4 < y < -2.5$) in pp collisions at $\sqrt{s} = 7$ TeV is shown as function of p_t and η in Fig. 3 in comparison with results from FONLL pQCD calculations [18]. As observed in the other heavy-flavour channels, FONLL is in reasonable agreement with the data.

In both semileptonic decay channels, i.e. electrons and muons, the data and FONLL pQCD calculations indicate that for $p_\mathrm{t} > 5-6$ GeV/c the dominant contribution is from beauty decays while at lower p_t charm is the relevant lepton source.

4. Heavy-flavour pp reference at $\sqrt{s} = 2.76$ TeV

The heavy-flavour production cross sections measured in pp collisions at $\sqrt{s} = 7$ TeV have to be scaled to $\sqrt{s} = 2.76$ TeV in order to provide a reference for the Pb-Pb data at the same energy per nucleon-nucleon pair. Since FONLL pQCD calculations are in reasonable agreement with all heavy-flavour observables measured in pp collisions at $\sqrt{s} = 7$ TeV, FONLL was used for the necessary $\sqrt{s}$ scaling [24]. The scaling factors for D mesons, electrons, and muons were defined as the ratios of the corresponding cross sections from FONLL calculations at 2.76 and 7 TeV, where it was assumed that neither the factorisation and renormalisation scales nor the heavy quark masses used in the FONLL calculation vary with $\sqrt{s}$. To evaluate the uncertainties of the scaling factors the scales and heavy quark masses were varied and the envelopes of the resulting scaling factors were determined. For all heavy-flavour observables the uncertainties of the scaling functions are similar. They range from $\sim 25\%$ at $p_\mathrm{t} = 2$ GeV/c to less than 10% for $p_\mathrm{t} > 10$ GeV/c. D^0 and D^+ differential production cross sections were measured, with limited statistics, in pp collisions at $\sqrt{s} = 2.76$ TeV. These data are in agreement within uncertainties with the reference obtained via $\sqrt{s}$ scaling from the 7 TeV pp measurements.

5. Heavy flavour in Pb-Pb collisions at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV

The excellent vertexing precision and particle identification capabilities of the ALICE detector

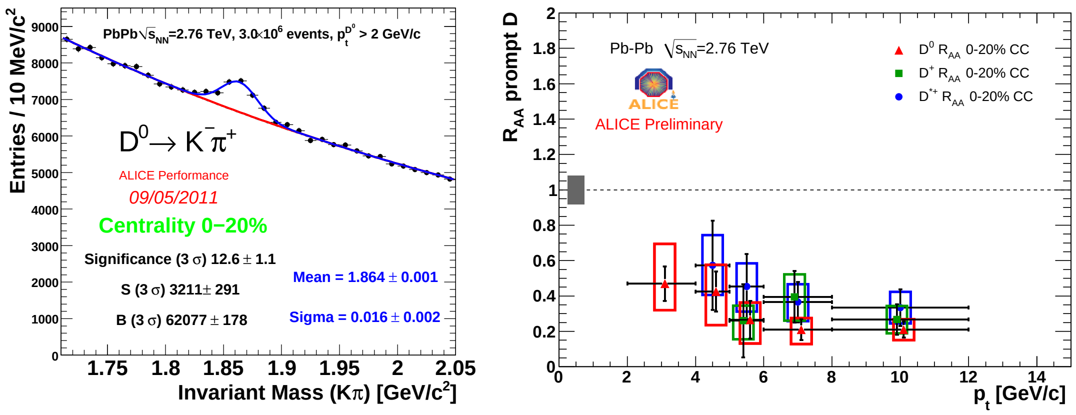

Figure 4: Kπ invariant mass distribution in the 20% most central Pb-Pb collisions showing the $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$ signal (left panel). Nuclear modification factor R_{AA} for D^0, D^+, and D^{*+} mesons in central Pb-Pb collisions (right panel). Error bars show the statistical errors. Empty and full boxes depict the systematic and normalisation uncertainties, respectively.

allow for D-meson reconstruction even in central Pb-Pb collisions. As an example the reconstruction of D^0 mesons in the Kπ decay channel in the 20% most central Pb-Pb collisions is shown in the left panel of Fig. 4. The reconstruction efficiency is centrality independent and rises from 1 to 10% at high p_{t} as was determined from detailed detector simulations. Feed down from B decays (10-15% after selection cuts) was subtracted and, since this was determined relying on FONLL calculations both for pp and Pb-Pb collisions, the associated systematic uncertainty cancels at least partially in the nuclear modification factor R_{AA}. However, the unknown R_{AA} of B mesons introduces an additional systematic uncertainty on the prompt D-meson R_{AA}. The resulting uncertainty of less than 15% was estimated based on the conservative assumption that the nuclear modification factor of B mesons relative to the prompt D-meson R_{AA} fulfils the condition $0.3 < R^B_{\mathrm{AA}}/R^D_{\mathrm{AA}} < 3$. The nuclear modification factors of prompt D^0, D^+, and D^{*+} mesons in the 20% most central Pb-Pb collisions is shown in the right panel of Fig. 4. A strong suppression is observed for all species reaching a factor 3-5 for $p_{\mathrm{t}} > 8$ GeV/c.

It is an interesting question whether the observed suppression of D mesons at high p_{t} might be related to shadowing of the parton distribution functions at the LHC. The comparison of an NLO pQCD calculation including the state of the art EPS09 parametrisation of parton shadowing [25] with the measured D-meson R_{AA} shown in the left panel of Fig. 5 demonstrates that this is not the case. Parton shadowing is not relevant for the interpretation of the D-meson R_{AA}, i.e. the observed suppression clearly is a final state effect related to the hot and dense medium produced in Pb-Pb collisions.

Furthermore, it is important to compare the measured D-meson R_{AA} to the nuclear modification factor of charged pions [26]. This comparison is depicted in the right panel of Fig. 5. While with the current statistical and systematic uncertainties a definite conclusion can not be drawn the data hint towards a stronger suppression of pions relative to D mesons, as one would expect from a scenario in which induced gluon radiation is the dominant energy loss mechanism for partons propagating through a dense and colour-charged medium.

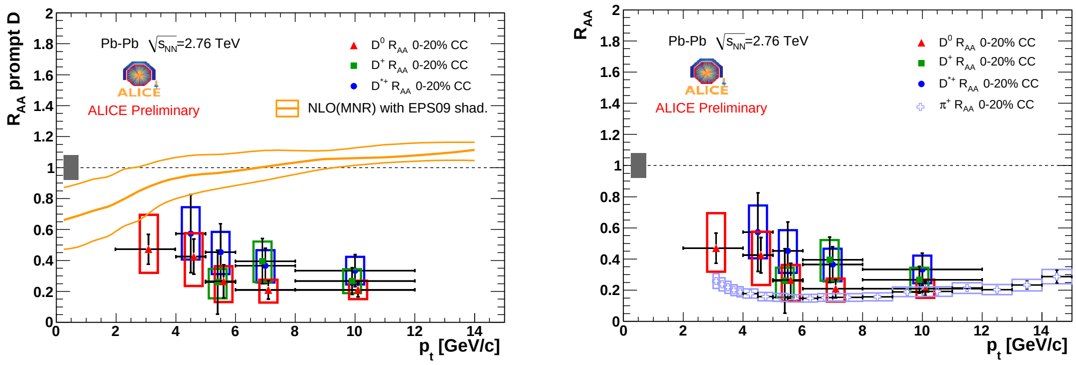

Figure 5: Comparison of the measured D-meson R_{AA} in central Pb-Pb collisions with results from an NLO pQCD calculation including EPS09 shadowing [25] (left panel) and in comparison with the nuclear modification factor measured for charged pions (right panel).

The electron identification in Pb-Pb collisions does not yet include information from the TRD. Therefore, the measured inclusive electron spectra are limited to the p_t range below 6 GeV/c. In this range the hadron contamination is less than 15% and it is subtracted. The comparison of the inclusive electron spectra measured in six centrality classes with corresponding electron background cocktails shows a hint for an excess at low p_t (up to $\sim$ 3 GeV/c) which increases towards central collisions [27] and might be related to thermal photon emission from the hot medium as was observed in central Au-Au collisions at RHIC [28]. No indication for such an excess is observed in pp and peripheral Pb-Pb collisions. For p_t above 3-4 GeV/c the background-subtracted inclusive electron spectra should be dominated by heavy-flavour decays. The corresponding R_{AA} as function of p_t is shown in the left panel of Fig. 6 for central and peripheral Pb-Pb collisions. Above 4 GeV/c a strong suppression is observed in central collisions although the systematic uncertainties are large.

The inclusive muon R_{CP} is shown for various centrality bins as function of p_t in the right panel of Fig. 6. R_{CP} is the ratio of yield divided by the average number of binary collisions in central and

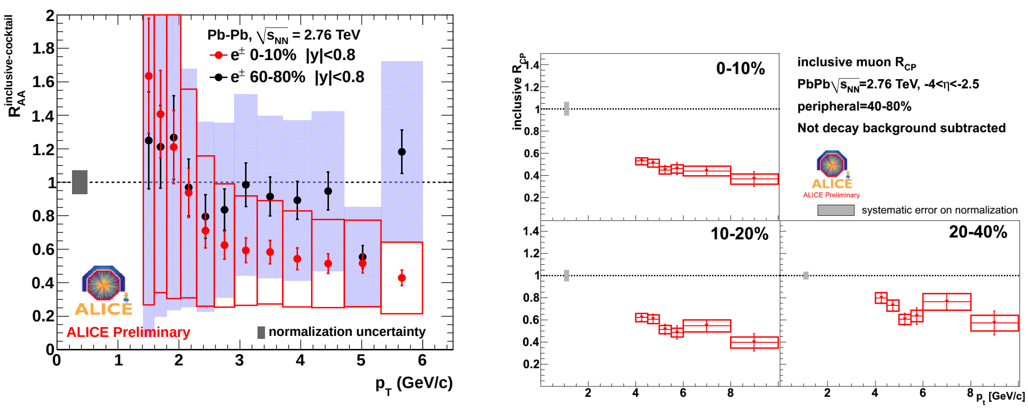

Figure 6: R_{AA} of cocktail subtracted electrons in central and peripheral Pb-Pb collisions as function of p_t (left panel). R_{CP} of inclusive muons as function of p_t in various Pb-Pb centrality classes (right panel).

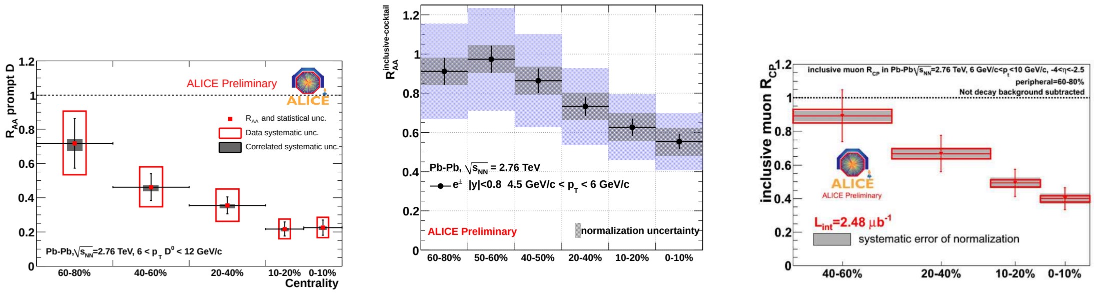

Figure 7: Centrality dependence of R_{AA} for prompt D mesons (left panel) and cocktail-subtracted inclusive electrons (middle panel) as well as of R_{CP} for inclusive muons in Pb-Pb collisions in different high p_{t} intervals, which are indicated in the figures.

peripheral Pb-Pb collisions. In the inclusive muon R_{CP} the background from light flavour decay muons was not subtracted. However, simulations indicate that this background is less than 10-15% for $p_{\mathrm{t}} > 6$ GeV/c. A strong suppression of inclusive muons is observed in central relative to peripheral Pb-Pb collisions at high p_{t}.

As demonstrated in Fig. 7 the nuclear modification factors of prompt D mesons and cocktail-subtracted inclusive electrons as well as R_{CP} of inclusive muons at high p_{t} show a pronounced centrality dependence. While in peripheral Pb-Pb collisions the observed suppression is small, it increases strongly towards central collisions.

The measurements of nuclear modification factors of heavy-flavour probes indicate a strong interaction of heavy quarks produced in the earliest phase of Pb-Pb collisions at the LHC with the hot and dense partonic medium that is formed afterwards. It is an important question whether heavy quarks thermalise in this medium. This question can be addressed via the measurement of the elliptic flow strength v_2 of particles carrying heavy quarks. v_2 is the second coefficient of the Fourier expansion of the azimuthal distribution of particles relative to the reaction plane of the collision, which is defined by the azimuth of the impact parameter and the beam direction. The fireball produced in the initial state of a nucleus-nucleus collision exhibits a spatial anisotropy with respect to this reaction plane. The resulting asymmetric pressure gradients lead to an asymmetric momentum distribution of particles in the final state, quantified by a non-zero value of v_2. The elliptic flow strength v_2 was measured for neutral D mesons [29] as shown in Fig. 8. A correction for feed down from B mesons was not applied yet. While statistical and systematic uncertainties are still large, an indication for a non-zero v_2 of D mesons is observed.

6. Summary

The production of heavy flavour has been investigated with the ALICE experiment at the CERN LHC in pp collisions at $\sqrt{s} = 7$ TeV and in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. In pp collisions the differential production cross sections of D mesons at mid-rapidity, as well as the cross sections for electron and muon production from semileptonic heavy-flavour hadron decays at mid- and forward-rapidity, respectively, have been measured. State of the art FONLL pQCD calculation are in agreement with all of these measurements within statistical and systematic uncertainties. In

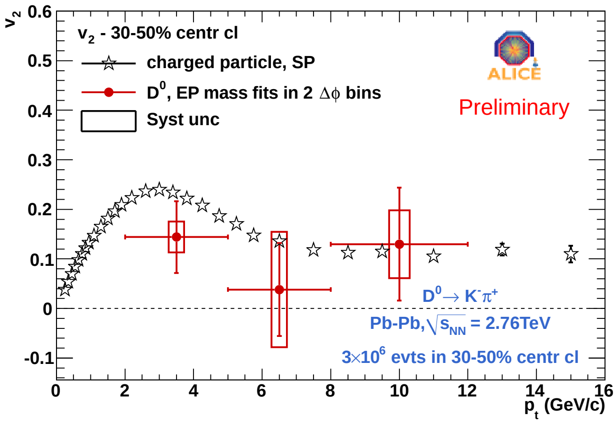

Figure 8: Elliptic-flow strength v_2 of D^0 mesons as function of p_t in mid central Pb-Pb collisions in comparison with the corresponding unidentified charged particle v_2.

Pb-Pb collisions nuclear modification factors have been measured for D mesons as well as electrons and muons from heavy-flavour decays. A suppression indicating the energy loss suffered by heavy quarks while they propagate through the medium produced in central Pb-Pb collisions is observed. In addition, a hint for non-zero elliptic flow of neutral D mesons might indicate that charm quarks participate in the collective dynamics of this strongly coupled partonic medium.

Additional data from both the pp and, in particular, the Pb-Pb running periods with ALICE in the year 2011 at the LHC, going hand in hand with an even improved understanding of the detector response and better calibration and reconstruction procedures, will significantly enhance the heavy-flavour physics reach of ALICE. Not only will the p_t reach of the observables presented in this writeup be increased considerably, both to lower and to higher values of p_t, but also new observables will become accessible, e.g. baryons carrying charm (Λ_c), heavy-flavour correlations, and beauty jets.

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