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ALICE results on heavy-flavour production at the LHC

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In ultra-relativistic heavy-ion collisions, heavy quarks, i.e. charm and beauty, are of particular interest, since they are produced in the early stage of the reaction and coexist with the surrounding medium. Therefore the measurement of open heavy-flavour production in Pb-Pb collisions at the LHC gives access to the mechanisms of heavy-quark transport and energy loss in hot and dense QCD matter. The ALICE apparatus allows us to measure heavy-flavour particles down to low transverse momentum p_{T}, using hadronic and semi-electronic final states at mid-rapidity and semi-muonic final states at forward rapidity. We first present results in pp collisions at center-of-mass energies $\sqrt{s}$ of 2.76 and 7 TeV. These measurements provide information on heavy-quark production at LHC energies and constitute the reference for heavy-ion studies. We focus then on the observation of the suppression and azimuthal anisotropy of heavy-flavour production in Pb-Pb collisions at 2.76 TeV.

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1. Introduction

Ultra-relativistic nuclear collisions allow to study nuclear matter under extreme conditions. A deconfined state of quarks and gluons, the Quark-Gluon Plasma (QGP), is expected to be formed in such collisions. The study of the heavy-quark production is of particular interest since charm and beauty quarks are produced via hard partonic scattering processes at the beginning of the collision and interact strongly with the surrounding medium. Therefore, the measurement of open heavy-flavour production and their elliptic flow allows one to test models of in-medium parton energy-loss and probe the level of thermalization of heavy quarks in the medium at low transverse momentum $p_{\rm T}$. At high $p_{\rm T}$, the elliptic flow measurement can address the path-length dependence of the heavy-quark energy loss. For this purpose the open heavy-flavour production in elementary pp collisions at the same center-of-mass energy has to be as well measured, since it provides the necessary baseline for heavy-ion studies. In addition it tests perturbative Quantum ChromoDynamics (pQCD) calculations in pp collisions.

ALICE (A Large Ion Collider Experiment) collected data during the pp and Pb-Pb collisions at center-of-mass energies $\sqrt{s}$=7 and 2.76 TeV, and $\sqrt{s_{NN}}$=2.76 TeV respectively, delivered by the LHC (Large Hadron Collider) at CERN. A detailed description of the experiment can be found in [1]. At mid-rapidity, open heavy-flavour production is measured in the central barrel via the hadronic decay of D mesons, as well as the semi-electronic decays of heavy-flavour D and B hadrons. At foward rapidity, muons from heavy-flavour hadron decays are reconstructed in the muon spectrometer. The data readout was triggered by a minimum-bias interaction trigger based on the trigger signals from two forward scintillator hodoscopes (VZERO-A and VZERO-C) and two layers of Silicon Pixel Detectors (SPD). The summed amplitudes in the VZERO scintillator tiles were used to determine the centrality of the Pb-Pb collisions, employing a model of particle production based on a Glauber description of the nuclear collision geometry. In addition to the minimum-bias trigger, the muon spectrometer provided a single muon trigger at foward rapidity for the heavy-flavour muon analysis. At mid-rapidity, the ElectroMagnetic Calorimeter (EMCal) allowed us to trigger on single electrons for the heavy-flavour elecron analysis.

2. Results in pp collisions at $\sqrt{s}$ = 7 TeV

In the central barrel of ALICE, the D^0 , D^+, D^{*+} and D_s^+ mesons, and their charge conjugates, are reconstructed from their decays into charged hadrons, $D^0 \rightarrow K^-\pi^+$ (with branching ratio, BR of 3.87±0.05 %), $D^+ \rightarrow K^-\pi^+\pi^+$ (BR of 9.13±0.19 %), $D^{*+} \rightarrow D^0\pi^+$ (BR of 67.7±0.5 %) and $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR of 2.32±0.14 %) within the rapidity range $|y| < 0.5$. Due to their large lifetime (cτ=123 μm, 312 μm for D^0 and $D^\pm$, respectively), the D mesons do not decay at the primary vertex. The tracking capabilities of the Inner Tracking System (ITS) and Time Projection Chamber (TPC) are used to reconstruct the displaced secondary vertices. The TPC and Time Of Flight (TOF) detectors provide moreover the possibility to identify $\pi^\pm$ and $K^\pm$. The $p_{\rm T}$-differential production yields of prompt D mesons are determined after efficiency correction and feed-down correction for B decays. In pp collisions at 7 TeV, the D^0, D^+ and D^{*+}, and D_s^+ are measured in the $p_{\rm T}$ range $1< p_{\rm T} <16$ GeV/c, $1< p_{\rm T} <24$ GeV/c and $2< p_{\rm T} <12$ GeV/c respectively [2] [3]. The left panel of Fig. 1 shows the measured $p_{\rm T}$-differential cross section of

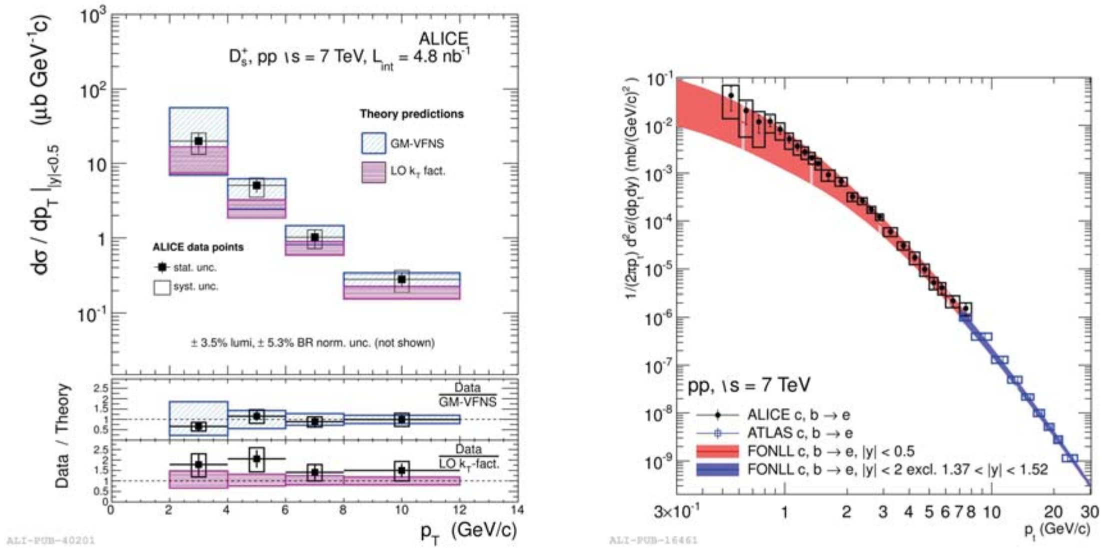

Figure 1: Left: p_T-differential cross section of D_s^+ mesons in pp collisions at 7 TeV compared to pQCD calculations [3] [17] [16]; Right: p_T-differential cross section of electrons from heavy-flavour hadron decays at mid-rapidity ($|y|<0.8$) in pp collisions at 7 TeV, compared to FONLL calculations and ATLAS results at high p_T [4] [5] [15]

D_s^+ mesons compared to different perturbative QCD calculations [17] [16]. The theory describes the data within uncertainties. The pQCD calculations are in reasonable agreement also with the differential cross sections measured for the other D-meson species.

Open heavy-flavour hadrons are measured indirectely via their semi-eletronic decays at mid-rapidity ($|y|<0.8$) in the central barrel. Electrons are tracked with the ITS and TPC, and they are identified using different approaches based on the energy loss in the TPC gas, the measured time of flight in TOF, the signal in the Transition Radiation Detector TRD and the measured energy in the EMCal. At low p_T, the main contributions to the background due to non heavy-flavour decay electrons come from Dalitz decays of π^0 and from gamma conversions in the detector material. Towards high p_T, the signal to background ratio increases. The π^0 spectra measured in ALICE are used as input for the background cocktail, which is subtracted from the measured inclusive electron spectrum to obtain the cross section of electrons from heavy-flavour hadron decays. The right panel of Fig. 1 shows the comparison of the p_T-differential cross section of electrons from heavy-flavour hadron decays with FONLL calculations [4]. The theory reproduces well the data. In addition, the ATLAS result extends the ALICE measurement to higher p_T [5].

At forward rapidity ($2.5<y<4.0$), muons are reconstructed and identified in the muon spectrometer. From the inclusive muon spectrum the muon background component, mainly muons from primary $\pi^{\pm}$ and $K^{\pm}$ decays, must be subtracted. In pp collisions Monte Carlo simulations, using the Phojet and Pythia event generators, are used as input to estimate the muon background at foward rapidity. The right panel of Fig. 2 shows the measured p_T- and y-differential cross sections of muons from heavy-flavour hadron decays in pp collisions at $\sqrt{s}$=2.76 TeV, together with FONLL calculations [8] [15]. The ratio between data and FONLL calculations is shown in the

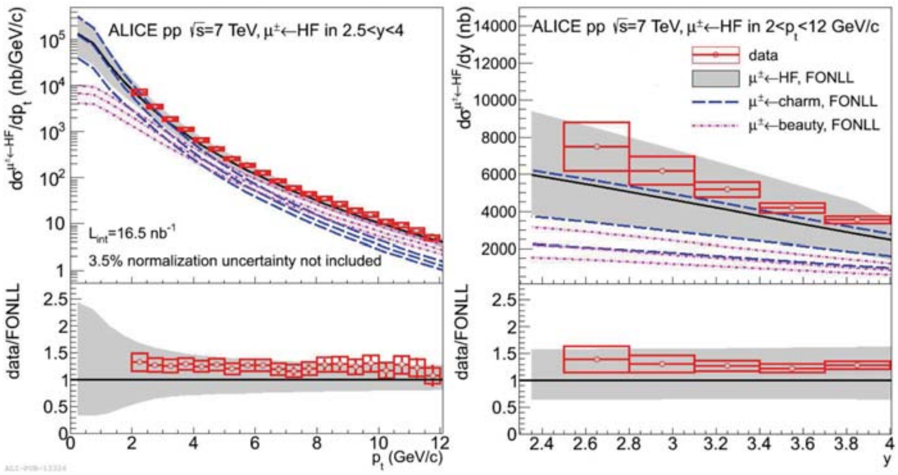

Figure 2: p_{T}-differential cross section of muons from heavy-flavour hadron decays at foward rapidity (2.5<y<4) in pp collisions at $\sqrt{s}$=7 TeV, compared to FONLL calculations [8].

bottom panel. The measurements are well reproduced by the model, although at the upper limit of the calculations.

Thanks to the large mass and large lifetime of B hadrons (cτ=500 μm), electrons from B-hadron decays can be separated from electrons from D-hadron decays. Therefore, a significant fraction of the trajectories of electrons from beauty-hadron decays does not point back to the primary collision vertex. Moreover, the electron-hadron correlation in azimuthal angle has a different shape in the near-side for beauty and charm electrons due to decay kinematics. The different approaches to measure electrons from B hadron decays are therefore: an impact parameter analysis with the requirement of a minimum distance of closest approach to the primary vertex for the electron candidate, a B-tagging analysis with the reconstruction of a secondary vertex and an electron-hadron correlation analysis based on the shape of the angular electron-hadron correlation. In pp collisions at 7 TeV, electrons from B hadron decays were measured in the range $1 < p_{\mathrm{T}} <$ 13 GeV/c at mid-rapidity and compared to FONLL calculations [6]. A good agreement with the theory was found.

3. Results in pp collisions at $\sqrt{s}$ = 2.76 TeV

The same analyses as in pp collisions at 7 TeV were performed in pp collisions at 2.76 TeV. At mid-rapidity, the D^0, D^+ and D^{*+}, and their charge conjugates are measured in pp collisions at $\sqrt{s}$=2.76 TeV in the transverse momentum range $1<p_{\mathrm{T}}<12$ GeV/c [7], whereas electrons from heavy-flavour hadron decays are measured from p_{T}= 2 to 12 GeV/c. At foward-rapidity, the p_{T}-differential cross section of muons from heavy-flavour hadron decays is measured in the p_{T} range $2 < p_{\mathrm{T}} < 10$ GeV/c [9]. All results are well described within uncertainties by FONLL and GM-VFNS calculations [15] [16]. The statistics are nevertheless limited for the D meson and electron analyses and do not allow a comparison with the Pb-Pb measurements for every p_{T} interval. Therefore the reference used for Pb-Pb studies is obtained from a pQCD-based (FONLL [15]) energy

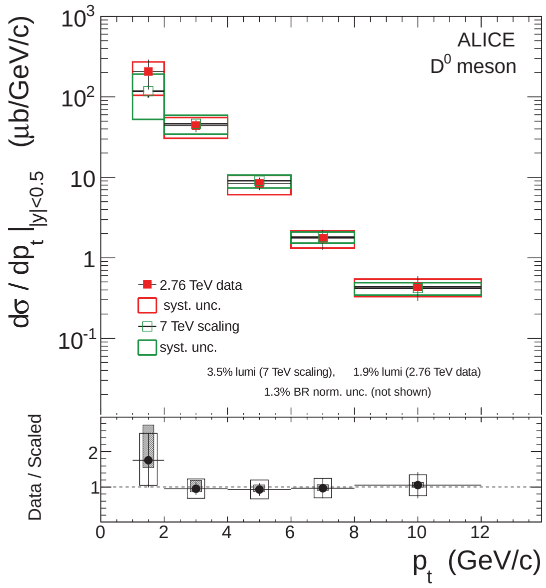

Figure 3: $p_{\rm T}$-differential cross section for prompt D^0 mesons in pp collisions at $\sqrt{s}$=2.76 TeV compared to the ALICE measurement at $\sqrt{s}$=7 TeV scaled to 2.76 TeV using FONLL (top), together with their ratio (bottom). The filled boxes represent the scaling uncertainties, whereas the empty boxes indicate the measurement systematics [7].

scaling of the 7 TeV $p_{\rm T}$-differential cross sections to 2.76 TeV. Figure. 3 shows the 2.76 TeV measured $p_{\rm T}$-differential cross section of D^0 mesons, together with the 7 TeV results scaled down to 2.76 TeV. The agreement is very good. Above 24 GeV/c for D mesons and 8 GeV/c for electrons, no measurement in pp collisions at 7 TeV are available. For the Pb-Pb studies, FONLL calculations are then used as reference for heavy-flavour decay electrons, whereas $p_{\rm T}$ extrapolations using theoretical calculations as baseline for the $p_{\rm T}$ shape was performed for the different D meson species. For heavy-flavour decay muons, the $p_{\rm T}$-differential cross section in pp collisions at 2.76 TeV is directly used as reference for heavy-ion studies.

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

The D meson and heavy-flavour decay lepton production in Pb-Pb collisions can be compared to pp collisions at the same energy with the nuclear modification factor R_{AA}:

$$R_{AA}(p_{\rm T}) = \frac{1}{\langle T_{AA}\rangle}\frac{dN_{AA}/dp_{\rm T}}{d\sigma_{pp}/dp_{\rm T}} \tag{4.1}$$

where $\langle T_{AA}\rangle$ is the average nuclear overlap function for the given centrality class which is proportional to the number of binary collisions, $dN_{AA}/dp_{\rm T}$ is the measured yield for Pb-Pb collisions in this centrality class, and $d\sigma_{pp}/dp_{\rm T}$ is the corresponding cross section in pp collisions. In the absence of any cold and hot matter effects, the nuclear modification factor is 1.0.

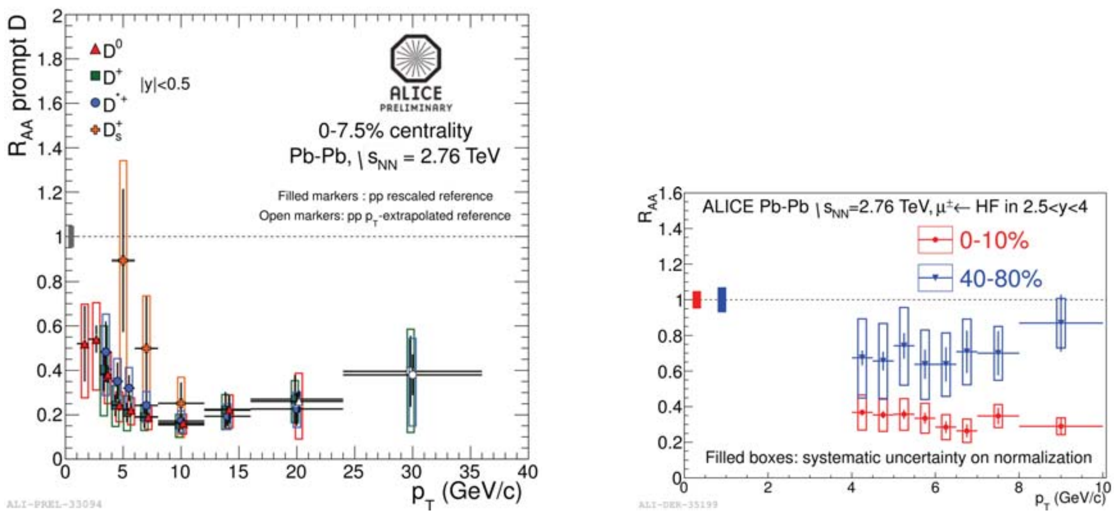

Figure 4: Left: Nuclear modification factor of D^0, D^+, D^{+*} and D_s^+ meson in 0-7.5 % central Pb-Pb collisions at 2.76 TeV. Right: Nuclear modification factor of muons from heavy-flavour hadron decays in 0-10 % and 40-80 % central Pb-Pb collisions at 2.76 TeV [11]

Prompt D mesons are measured from a p_T of 1 GeV/c up to a p_T of 36 GeV/c, depending on the D-meson species [10]. A strong suppression compared to pp collisions is observed in the 0-7.5 % and 0-20 % central Pb-Pb collisions. The left panel of Fig.4 shows the nuclear modification factors of the different D-meson species in 0-7.5 % central Pb-Pb collisions. A similar suppression is observed for all the D mesons in particular D_s^+. Some models predicted an enhancement of strange with respect to non-strange D mesons at intermediate p_T due to recombination of quarks in the medium [12] [13]. [14]. The measurements need better precision for a conclusive statement. A strong suppression compared to pp collisions is also found for the electrons and muons from heavy-flavour hadron decays in central Pb-Pb collisions at mid-rapidity and foward rapidity, respectively. The right panel of Fig.4 shows the nuclear modification factor of heavy-flavour muons in 0-10 % and 40-80 % Pb-Pb collisions. A smaller suppression is observed in peripheral Pb-Pb collisions. The suppression at mid-rapidity of D mesons and heavy-flavour decay electrons and, at foward rapidity, of heavy-flavour decay muons are similar and compatible taking into account the decay kinematics.

In Fig. 5, the nuclear modification of prompt D mesons as a function of p_T is compared to the one of charged hadrons [22] and $\pi^\pm$ [21] in central Pb-Pb collisions (left panel) and to the one of non-prompt J/ψ from B decays [18] as a function of the mean number of participant in the Pb-Pb collisions (right panel). There is an indication for $R_{AA}^D > R_{AA}^{charged,\pi^\pm}$ at low p_T, whereas the suppression of non-prompt J/ψ, although the p_T range is different, is clearly smaller than that of D mesons in central Pb-Pb collisions, taking the decay kinematics into account.

In Fig. 6, the nuclear modification of prompt D mesons in 0-7.5 % central Pb-Pb collisions is compared to the expectation from NLO pQCD [20] with nuclear shadowing [19] and three different models taking into account energy loss at partonic level. The effect of shadowing on the R_{AA} is of the order of 15 % for p_T>6 GeV/c. This suggests that the strong suppression observed in the data is dominated by final-state effects. The analysis of the p-Pb collisions delivered by the LHC in

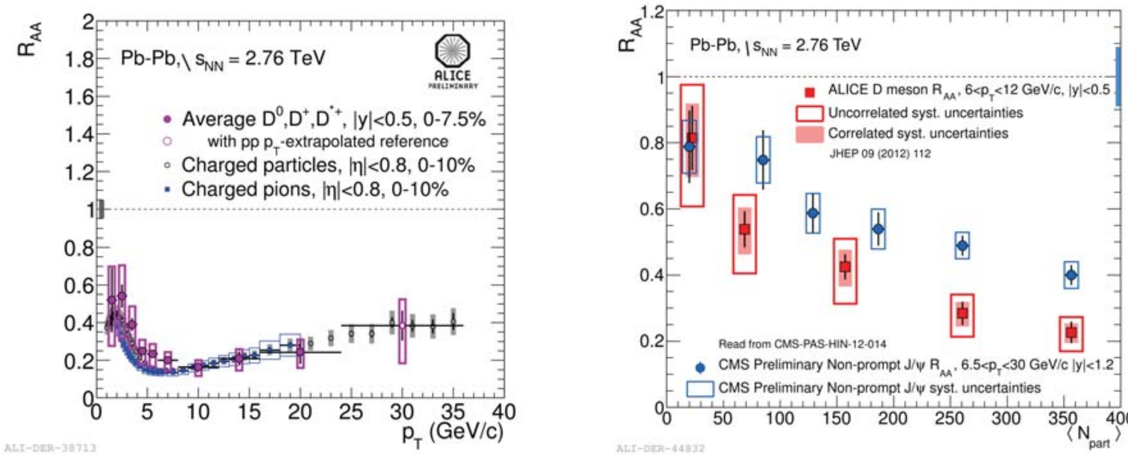

Figure 5: Left: average R_{AA} of D mesons in 0-7.5 % central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV compared to charged particles and $\pi^{\pm}$ [22] [21] in 0-10 % central collisions; Right: nuclear modification factors of D mesons and non-prompt J/ψ from B decays [18] as function of the average number of participants in Pb-Pb collisions at 2.76 TeV

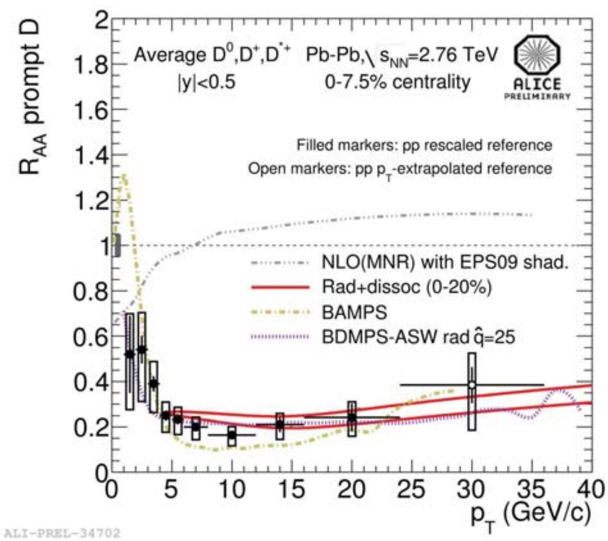

Figure 6: Average R_{AA} of D mesons in 0-7.5 % central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV compared to model calculations.

January 2013, will allow to measure directly the initial state effects. The models with various parton energy loss mechanisms can describe relatively well the D meson, heavy-flavour leptons, and charged particle nuclear modification factor.

In heavy-ion collisions the initial state spatial anisotropy in non-central collisions is converted into a momentum anisotropy if the in-medium mean free path allows for sufficient rescattering. The resulting azimuthal distribution of the final state particles reflects the initial geometrical anisotropy and the transport properties of the medium. The azimuthal dependence of the particle yield can be written in the form of a Fourier series:

$$Ed^3N/d^3p = \frac{1}{2\pi}\frac{d^2N}{p_{\rm T}dp_{\rm T}dy}(1+\sum_{n=1}^{\infty}2v_n cos[n(\phi-\Phi_R)])$$

where E is the energy of the particle, p the momentum, ϕ the azimuthal angle, and Φ_R the reaction plane angle. The reaction plane is the plane defined by the beam axis and the impact parameter direction. The second coefficient is the so called elliptic flow v_2.

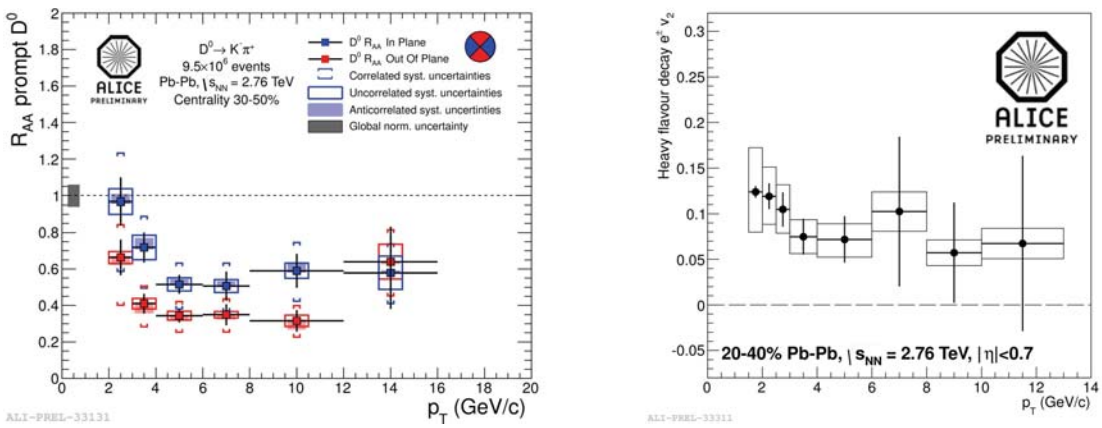

Figure 7: Left: Nuclear modification factor of D^0 mesons in- and out-of-plane in 30-50 % central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV; Right: Elliptic flow of electrons from heavy-flavour hadron decays in 20-40 % central Pb-Pb collisions at 2.76 TeV.

The event plane is reconstructed in each event using the TPC or the VZERO detector with a limited resolution. The yield of D mesons or heavy-flavour electrons is then measured with respect to the event plane. The left panel of Fig. 7 shows the D^0 nuclear modification factor in- and out-of-plane in 30-50 % central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. For $p_{\rm T}$ < 12 GeV/c, the observed suppression is larger out-of-plane than in-plane, consistent with the non-zero v_2 measured for all D-meson species in such collisions. The right panel of Fig. 7 shows the v_2 of heavy-flavour electrons in 20-40 % central Pb-Pb collisions. At low $p_{\rm T}$, there is an indication for a non-zero v_2 of electrons from heavy-flavour hadron decays. Fig. 8 shows the nuclear modification factor in 0-7.5 % central Pb-Pb collisions (left panel) and the elliptic flow in 30-50 % central Pb-Pb collisions (right panel) compared to different theoretical models. The simultaneous description of R_{AA} and v_2 is challenging for the models.

5. Summary and outlook

We presented the measured $p_{\rm T}$-differential cross section of D mesons ($|y|$<0.5), electrons ($|y|$<0.8) and muons (2.5<y<4) from heavy-flavour hadron decays in pp collisions at 7 TeV and 2.76 TeV with ALICE. The results are reasonably well reproduced by pQCD calculations. In Pb-Pb collisions at 2.76 TeV, we showed the measurements of the D^0 , D^+, D^{*+} and D_s^+ mesons

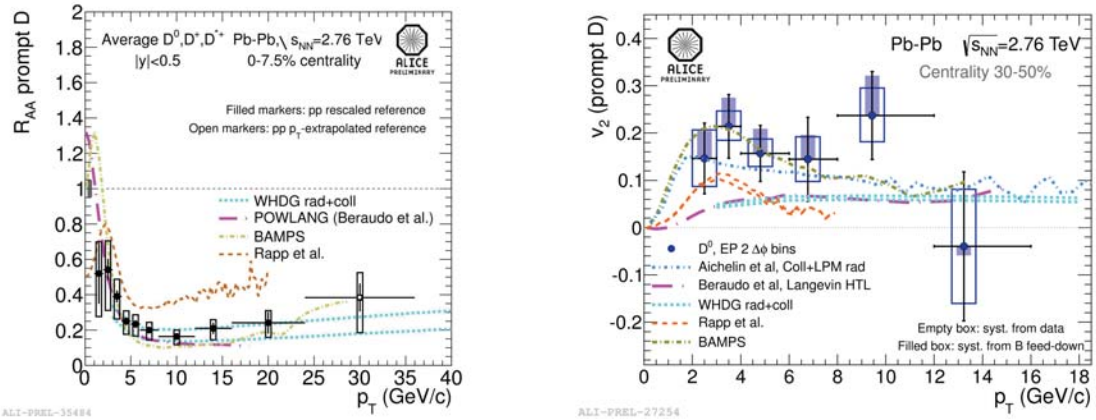

Figure 8: Average R_{AA} of D mesons in 0-7.5 % central Pb-Pb collisions (left) and elliptic flow of D mesons in 30-50 % central Pb-Pb collisions (right) at $\sqrt{s_{NN}}$=2.76 TeV compared to different models

and heavy-favour electrons in central collisions at mid-rapidity, as well as heavy-flavour muons in central and mid-peripheral collisions at foward rapidity. A large suppression of open heavy-flavour production is observed at high momentum, along with an azimuthal anisotropy with respect to the event plane at low and intermediate p_{T}. Compared to charged hadrons, there is a hint for $R_{AA}^{D} > R_{AA}^{charged,\pi^{\pm}}$ at low p_{T}. Effects due to shadowing can not explain such a large suppression. At foward rapidity, the suppression of muons from heavy-flavour hadron decays is similar to the one of heavy-flavour electrons at mid-rapidity. Theoretical models with radiative energy loss describe reasonably well at the same time the charm, the heavy-flavour leptons and the charged-hadron suppression. A positive elliptic flow is observed for D mesons and heavy-flavour electrons in semi-central Pb-Pb collisions at low p_{T}.

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