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Heavy Flavour in ALICE

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Abstract

The production of heavy flavoured hadrons will allow to study the strongly interacting medium created in heavy ion collisions at LHC with probes of known mass and colour charge. The ALICE detector will be able to measure heavy flavour production down to low transverse momentum, combining leptonic and hadronic channels. The main physics motivations for the study of heavy flavour production at LHC energies and some examples of physics analyses developed so far by the ALICE heavy flavour working group are discussed.

1 Introduction

The LHC, designed to collide protons at a c.m.s. energy $\sqrt{s} = 14$ TeV, will also accelerate ions up to the same magnetic rigidity and allow the study of both symmetric systems (e.g. Pb–Pb) and asymmetric collisions, such as proton–nucleus (pA). In Table 1, we give examples of the c.m.s. energy and design

Table 1: *Examples of c.m.s. energies, design luminosities at the ALICE interaction region and geometrical cross sections for different collision systems in the LHC. Estimates of the production yields for charm and beauty* $\mathrm{Q\overline{Q}}$ *pairs are also given (for Pb-Pb collisions, in the centrality range corresponding to the most central 5% of the inelastic cross section).*

System	$\sqrt{s_{\mathrm{NN}}}$ (TeV)	L_0 ($\mathrm{cm^{-2}s^{-1}}$)	σ_{geom} (b)	$N^{\mathrm{c\overline{c}}}$	$N^{\mathrm{b\overline{b}}}$
pp	14.0	10^{31} [1]	0.07	0.16	0.0072
Pb–Pb	5.5	10^{27}	7.7	115	4.56
pPb	8.8	10^{29}	1.9	0.78	0.029

luminosity [1] at the ALICE interaction region for some collision systems. The typical yearly effective running times are of the order of 10^7 s for pp collisions and 10^6 s for the heavier systems. The expected yields for heavy-quark production, as obtained from a next-to-leading order perturbative QCD calculation [1)] including nuclear shadowing effects, are also reported in Table 1 [2)].

The study of quarkonia production in heavy ion collisions represents one of the most powerful methods to probe the nature of the medium the fireball is made of. In fact, quarkonia are sensitive to the collision dynamics at both short and long timescales, and are expected to be sensitive to plasma formation.

The measurement of open charm and open beauty production allows one to investigate the mechanisms of heavy-quark production, their propagation and, at low momenta, their hadronisation in the hot and dense medium formed in high-energy nucleus–nucleus collisions. The total open charm and open beauty cross sections are also needed as a reference to measure modifications in the quarkonia production rate. In fact, since at LHC energies heavy quarks are mainly produced through gluon–gluon fusion processes ($gg \rightarrow Q\bar{Q}$), the Drell-Yan process ($q\bar{q} \rightarrow l^+l^-$) does not provide an adequate reference, besides having a very small cross section at these energies, a direct measurement of the D and B mesons yields will provide a natural normalization for charmonia and bottomonia production. Finally, the measurement of B meson production is necessary in order to estimate the contribution of secondary J/Ψ (from B→J/Ψ + X) to the total J/Ψ yield. The measurement of charm and beauty production

[1] Due to the limited rate capability of the ALICE detector, in pp collisions we must reduce the luminosity at our interaction region with respect to the LHC design value of 10^{34} $\mathrm{cm^{-2}s^{-1}}$ to a maximum of 10^{31} $\mathrm{cm^{-2}s^{-1}}$.

in pp and pA collisions, besides providing the necessary baseline for the study of medium effects in nucleus–nucleus collisions, is of great interest *per se*, as a test of both perturbative and nonperturbative QCD in a new energy domain.

2 Heavy-flavour detection in ALICE at LHC

The design of the ALICE apparatus [3)] will allow the detection of open heavy-flavour hadrons and quarkonia in the high-multiplicity environment of central Pb–Pb collisions at LHC energy, where up to few thousand charged particles might be produced per unit of rapidity. The heavy-flavour capability of the ALICE detector is provided by:

- Tracking; the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Transition Radiation Detector (TRD), embedded in a magnetic field up to 0.5 T, will allow for track reconstruction in the pseudorapidity range $|\eta| < 0.9$ with an expected momentum resolution better than 2% for $p_t < 20$ GeV/c and a transverse impact parameter[2] resolution better than 60 μm for $p_t > 1$ GeV/c.

- Particle identification; charged hadrons (π, K, p) are identified via $\mathrm{d}E/\mathrm{d}x$ in the TPC and in the ITS and via time-of-flight measurements in the Time Of Flight (TOF) detector; electrons are separated from charged pions in the dedicated Transition Radiation Detector (TRD), and in the TPC; muons are identified in the muon spectrometer covering in acceptance the range $-4 < \eta < -2.5$.

Simulation studies [2)] have shown that ALICE has good potential for heavy-flavour physics. Among the main analyses in preparation there are:

- Quarkonia (section 3): ψ and Υ states in the e^+e^- ($|\eta| < 0.9$) and $\mu^+\mu^-$ ($-4 < \eta < -2.5$) channels.

- Open charm (section 4.1): fully reconstructed hadronic decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$ (under study), $\Lambda_c^+ \to pK^-\pi^+$ (under study), $D^0 \to K^-\pi^+\pi^+\pi^-$ (under study) in $|\eta| < 0.9$.

[2]The transverse impact parameter, d_0, is defined as the distance of closest approach of the track to the interaction vertex, in the plane transverse to the beam direction.

- Open beauty (sections 4.2–4.4): inclusive single leptons $\mathrm{B} \to \mathrm{e} + X$ in $|\eta| < 0.9$ and $\mathrm{B} \to \mu + X$ in $-4 < \eta < -2.5$; inclusive displaced charmonia $\mathrm{B} \to \mathrm{J}/\psi\,(\to \mathrm{e}^+\mathrm{e}^-) + X$ in $|\eta| < 0.9$.

For all simulation studies, conservative values of charged-particle mid-rapidity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 6000$–$8000$) were assumed for central Pb–Pb collisions. In the following, we report the results of performance studies corresponding to the expected statistics collected by ALICE per LHC year: 10^7 central (0–5% σ^{inel}) Pb–Pb events and 10^9 pp events in the barrel detectors; the forward muon arm will collect about 4×10^8 central (0–5% σ^{inel}) Pb–Pb and 10^{12} pp events [2].

3 Quarkonia capabilities

ALICE can detect quarkonia in the e^+e^- channel at central rapidity ($|\eta| < 1$) and in the $\mu^+\mu^-$ channel at forward rapidity ($-4 < \eta < -2.5$). For both channels the acceptance extends down to $p_{\mathrm{t}} = 0$, the minimum p_{t} for e and μ identification being about 1 GeV/c. The high p_{t} reach is expected to be 10 (20) GeV/c for the J/ψ in $\mathrm{e}^+\mathrm{e}^-$ ($\mu^+\mu^-$), for a one month Pb–Pb run at luminosity $L_0 = 5 \cdot 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. We emphasize the importance of separating the Υ, Υ' and Υ'', to probe the initial temperature of the medium; given that the mass difference between bottomonium states is about 400 MeV, a mass resolution of order 100 MeV at $M_{\ell^+\ell^-} \sim 10$ GeV, i.e. $\sigma_M/M \approx 1\%$, is required. This requirement is fulfilled for both dielectrons and dimuons, with a mass resolution of about 90 MeV. For illustration, in Figure 1 we show the simulated $\mathrm{l}^-\mathrm{l}^+$mass spectra in the Υ region after background subtraction [2].

4 Open charm and open beauty capabilities

4.1 Exclusive charm meson reconstruction

Among the most promising channels for open charm detection are the $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ ($c\tau \approx 120$ μm, branching ratio $\approx 3.8\%$) and $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ ($c\tau \approx 300$ μm, branching ratio $\approx 9.2\%$) decays. The detection strategy to cope with the large combinatorial background from the underlying event is based on the selection of displaced-vertex topologies, i.e. separation from the primary vertex of the tracks from the secondary vertex and good alignment between the reconstructed D meson momentum and flight-line [2, 4]. Invariant-mass analysis is used to extract the raw signal yield, to be then corrected for selection

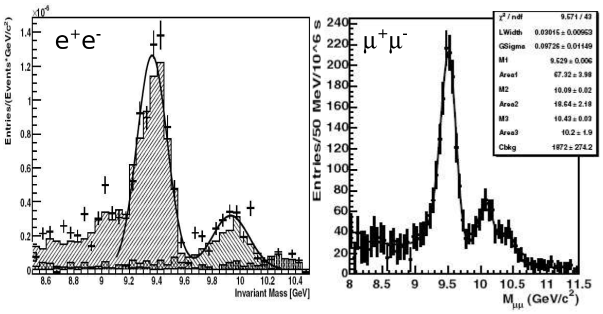

Figure 1: The signal of Υ states in central Pb–Pb collisions, as reconstructed by ALICE [2)], in the e^+e^- and in the $\mu^+\mu^-$ channel, in one month of data-taking.

and reconstruction efficiency and for detector acceptance. As shown in Figure 2 (left), the accessible $p_{\rm t}$ range for the $\rm D^0$ is 1–20 GeV/c in Pb–Pb and 0.5–20 GeV/c in pp, with statistical errors better than 15–20% at high $p_{\rm t}$. Similar capability is expected for the $\rm D^+$ (right-hand panel), though at present the statistical errors are estimated only in the range $1 < p_{\rm t} < 8$ GeV/c. In both cases the systematic errors (acceptance and efficiency corrections, centrality selection for Pb–Pb) are expected to be smaller than 20%.

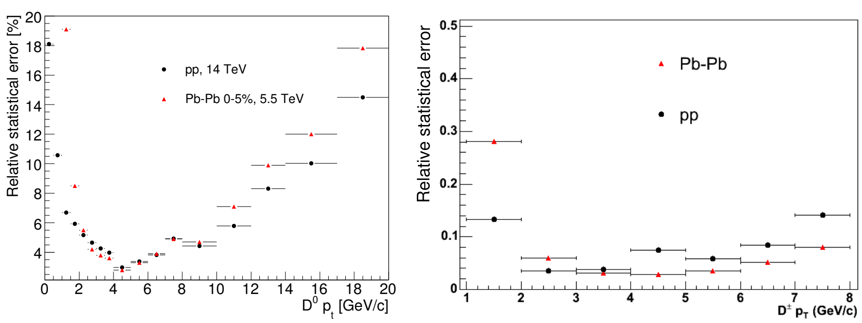

Figure 2: Expected relative statistical errors for the measurement in ALICE of the production cross sections of $\rm D^0$ in the $\rm K^-\pi^+$ channel (left) and $\rm D^+$ in the $\rm K^-\pi^+\pi^+$ channel (right), in 0–5% central Pb–Pb collisions and in pp collisions.

4.2 Beauty via single electrons.

The main sources of background electrons are: decays of D mesons; π^0 Dalitz decays and decays of light vector mesons (e.g., ρ and ω); conversions of photons in the beam pipe or in the inner detector layer and pions misidentified as electrons. Given that electrons from beauty have average impact parameter $d_0 \simeq 500$ μm and a hard $p_{\rm t}$ spectrum, it is possible to obtain a high-purity sample with a strategy that relies on: electron identification with a combined $\mathrm{d}E/\mathrm{d}x$ (TPC) and transition radiation (TRD) selection; impact parameter cuts to reduce the charm-decay component and reject misidentified $\pi^\pm$ and $\mathrm{e}^\pm$ from Dalitz decays and γ conversions. As an example, with $200 < d_0 < 600$ μm and $p_{\rm t} > 2$ GeV/c the expected signal purity of electrons from B decays is 80% and the statistics is 8×10^4 for 10^7 central Pb–Pb events, allowing the measurement of electron-level $p_{\rm t}$-differential cross section in the range $2 < p_{\rm t} < 20$ GeV/c with statistical errors smaller than 15% at high $p_{\rm t}$. Similar performance figures are expected for pp collisions [2].

4.3 Beauty via muons

B production in Pb–Pb collisions can be measured also in the ALICE muon spectrometer ($-4 < \eta < -2.5$) analyzing the single-muon $p_{\rm t}$ distribution [2]. The main backgrounds to the 'beauty muon' signal are $\pi^\pm$, $\mathrm{K}^\pm$ and charm decays. A cut $p_{\rm t} > 1.5$ GeV/c is applied to all reconstructed muons in order to increase the signal-to-background ratio. Then, a fit technique allows to extract a $p_{\rm t}$ distribution of muons from B decays. Since only minimal cuts are applied, the statistical errors are expected to be smaller than 5% up to muon $p_{\rm t} \approx 30$ GeV/c [2].

4.4 Beauty in the J/Ψ channel

Simulation studies are in progress to study the capability to separate J/Ψ of the B decay products from that of prompt origin. Such measurement can be performed by studying the separation from the main interaction vertex of the dilepton pairs in the J/ψ invariant mass region and it will also provide a measurement of the beauty $p_{\rm t}$-differential cross section down to $p_{\rm t} \approx 0$. The signed projection of the flight distance of J/Ψ on its transverse momentum, $L_{xy} = \vec{L} \cdot \vec{p}_{\rm T}(J/\Psi)/|p_{\rm T}|$, is a good measurement of the separation from the main vertex. To reduce the dependence on the J/Ψ transverse momentum bin size and placement, the variable x is used instead of L_{xy}, $x = L_{xy} \cdot M(J/\Psi)/p_{\mathrm{T}}$, where the $M(J/\Psi)$ is taken as the known J/Ψ mass [5]. Expected distributions of x for 10^9 pp collisions are shown in Figure 3.

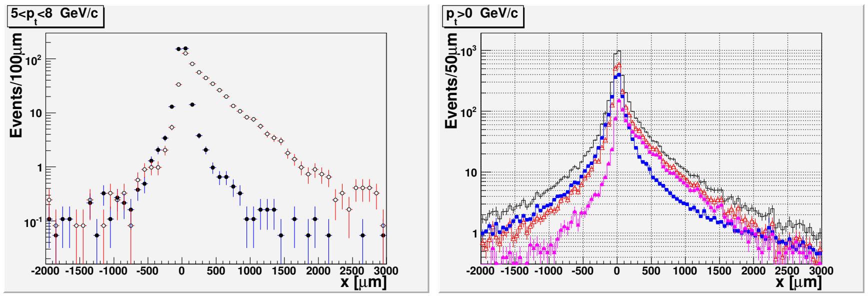

Figure 3: Distributions of the x variable, defined in the text, for $5 < p_{\mathrm{t}} < 8$ GeV/c (left) showed for secondary (open circles) and prompt (closed circles) J/Ψ, and for $p_{\mathrm{t}} > 0$ (right) showed for total J/Ψ (open triangles), secondary J/Ψ (closed triangles), total background (closed squares) and their sum (lines).

4.5 Nuclear modification factors

We investigated the possibility of using the charm and beauty measurements to study the high-p_{t} suppression induced by parton energy loss, by evaluating their nuclear modification factors $R_{\mathrm{AA}}(p_{\mathrm{t}}, \eta) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \cdot \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{t}}\mathrm{d}\eta}{\mathrm{d}^2 N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{t}}\mathrm{d}\eta}$. The sensitivity to $R_{\mathrm{AA}}^{\mathrm{D}}$ and $R_{\mathrm{AA}}^{\mathrm{e\ from\ B}}$ is presented in Figure 4. Predictions [6] with and without the effect of the heavy-quark mass, for a medium transport coefficient $\hat{q}$ (a measurement of the medium density) in the range 25–100 GeV^2/fm, are also shown.

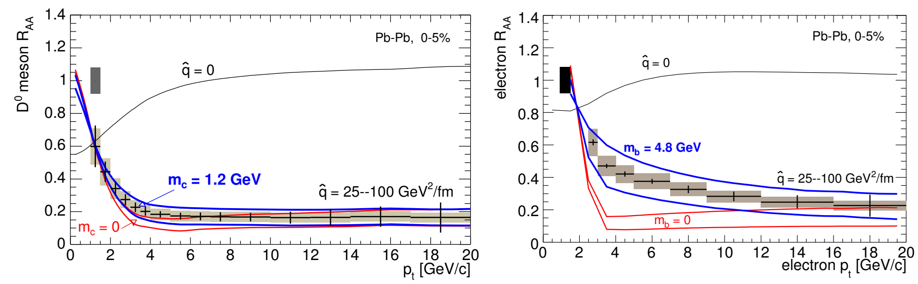

Figure 4: Nuclear modification factors for D^0 mesons (left) and for B-decay electrons (right). Errors corresponding to the centre of the prediction bands for massive quarks are shown: bars = statistical, shaded area = systematic.

5 Conclusions

We have discussed how heavy quarks, abundantly produced at LHC energies, will allow to address several issues at the heart of heavy-ion physics. They provide tools to probe the density (via parton energy loss and its predicted mass dependence) and the temperature (via successive dissociation patterns of quarkonia) of the high-density QCD medium formed in Pb–Pb collisions. The excellent tracking, vertexing and particle identification performance of ALICE will allow to explore deeply this rich phenomenology.

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