D^0 - leptons azimuthal correlations in pp and lead-lead collisions in the ALICE experiment.

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under the supervision of Zaida Conesa Del Valle & Davide Cafarri

Abstract

Leader experiment in the heavy ions collisions field, ALICE (A Large Ion Collision Experiment) manages to bring matter into quarks and gluons plasma (QGP), one of its most extreme states. One of its objectif is to bring under scrutiny the caracteristics of this QGP by studying differences between proton proton and lead lead collisions. During the (too) short time of the 2011 Summer School, I tried to developpe a method to probe the ration of heavy flavour quarks c/b produced by a collision using azimuthal correlations between D^0 mesons and electrons.

This report presents the work I've done, with the essential help of Zaida Conesa Del Valle and Davide Cafarri. It first focuses on the underlying physics, then exposes the simulations work and eventually explains how the method could be used on real data.

1 A bit of physics

Thermodynamics provides a good description of the different states taken by baryonic matter. Let us consider a grand potential $\Omega = E - TS - \mu B$, where $B = n_B - n_{\bar{B}}$ is the net baryonic number of the system and μ is the baryon chemical potential which is to be interpreted as the increase of energy $dE = \mu dB$ of the system at equilibrium (ie $\Omega = cste$) when a baryon quantity dB is added. With those variables, we draw a qualitative phase diagram (Figure 1).

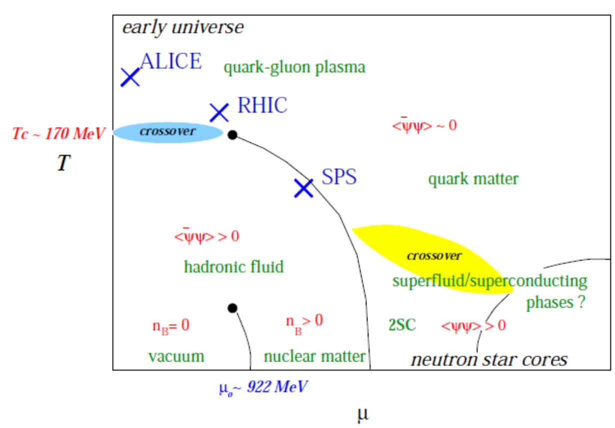

Figure 1 : Qualitative phase diagram for QCD [3].

Baryonic matter enters in a specific state called *quark-gluon plasma* at very high temperature ($T > T_c \simeq 170MeV \simeq 10^{12}K$) and high energy density ($\rho \simeq 1GeV.fm^{-3}$). This density can also be expressed as a low baryon chemical number ($\mu < 922MeV$) : the denser matter is, the closer particles are from one another and the weaker gets the strength of the strong interaction (asymptotic freedom), making the addition of a new baryon in the medium easier. This particular state, which is considered as a relevant description of the early universe, a few microseconds after the Big Bang, represents a challenging field since it enables one to study processes at the very limit of our usual models. The behaviour of the matter is indeed quite different at those scales, as epitomized by the celebrated J/ψ suppression.

It can be quite difficult to trap a part of the early universe in the lab in order to study its caracterisitcs ; however, thanks to the high energy ions colliders, it is now possible to recreate similar conditions within detectors. In the field, ALICE (A Large Ion Collision Experiment) is the state of the art, studying lead-lead collisions at 1.38 TeV per nucleon (and up to 2.76 TeV per nucleon in a few years). Those collisions (Figure 2.a) generate a QGP, in which quarks and gluons can be considered as free (Figure 2.b). This state can of course not be observed directely : as the plasma expands and the temperature quickly cools down, the QGP turns into an hadronic fluid (chemical freezeout, Figure 2.c), in which the quarks are already linked in hadronic bound states. This gas keeps cooling until hadrons get free to stream away (thermal freezeout, Figure 2.d). Only those particles can be detected, and the properties of the QGP have to be inferred from those measurement.

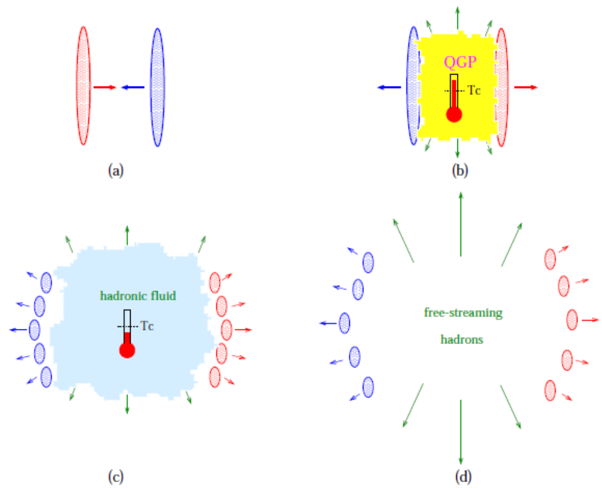

Figure 2 : Evolution of QGP created by an ion-ion collision [3].

During the collision, pairs of heavy quarks can be produced and represent a way of probing the QGP : more precisely, it can be interesseting to determine the ratio of heavy flavour c/b and to compare it with the value obtained for instance in pp collisions, where the QGP is supposed to be more or less inexistent. The hadronic reconstruction of D^0 $(c\bar{u})$ and $\bar{D^0}$ $(\bar{c}u)$ mesons provide a nice way to determine this ratio [5], in both pp and lead-lead collisions. Those mesons can be created from a c quark $(c \rightarrow D^0)$ as well as from a b quark $(b \rightarrow B \rightarrow D^0 + X)$; in both cases their antiparticle is emmited and both of them propagate mostly back-to-back because of the Lorentz boost. However, the azimuthal corellations between D^0s and leptons from the medium depend of the origin of the D^0 (Figure 3) : D^0 coming from b quarks can be generated with leptons $(B \rightarrow D^0 + l + \bar{\nu}_l)$ and therefore the propagation direction of both this meson and the antimeson in the opposite jet are correlated with the direction of the lepton ; on the other hand, D^0 coming from c quarks are not emmited with leptons. One should also take into account the decay products of D^0, which may include some leptons as well $(D^0 \rightarrow K^- + \nu_l + l^+)$. However, those leptons can be distinguished from the ones previously mentionned : in the first case, the lepton is positively charged whereas in the second case it is negatively charged. One shall therefore make the difference between meson - lepton (or anti meson - anti lepton) and meson - anti lepton (or anti meson - lepton) correlations.

Since we reconstruct D^0 from its hadronic $K\pi$ decay products, it is possible to determine whereas the meson was a particle $\left(D^0 \rightarrow K^-\pi^+\right)$ or an antiparticle $\left(\bar{D^0} \rightarrow K^+\pi^-\right)$ using, for instance, the sign of the K. Therefore, we can distinguish in the data D^0 from $\bar{D^0}$.

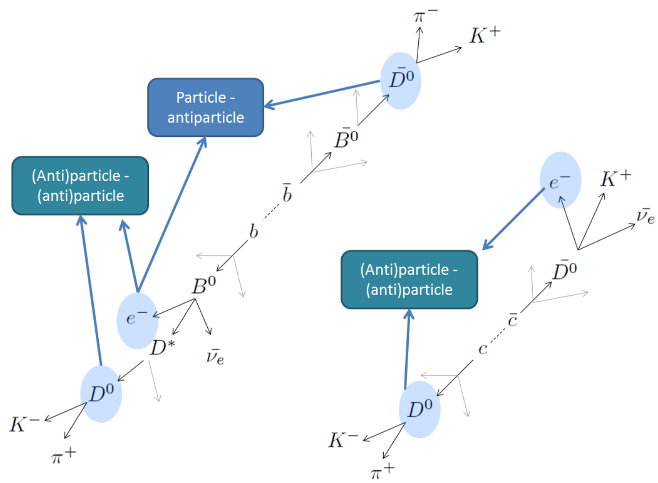

Figure 3 : $\Delta\varphi$ correlations between leptons and D^0 coming from $b\bar{b}$ and $c\bar{c}$ [4].

We have decided to use those correlations to try to caracterise the c/b ratio in both pp and lead-lead collisions. However, it appears to be extremly difficult to calculate the theoretical profile of D^0-leptons correlations beacause many parallel processes have to be taken into account ($B \leftrightarrow \bar{B}$ and $D \leftrightarrow \bar{D}$ oscillations for instance). Therefore, we ran simulations to identify the shapes of $D-$lepton correlations with Ds comming from $b\bar{b}$ pairs and $c\bar{c}$ pairs, the idea being to fit the data with those two shapes.

2 Simulations : azimuthal correlations in pure charm and pure beauty cases

We used Pythia v6.4.21 to generate 500 000 events with D^0 or $\bar{D^0}$ coming from a c quark (pure charm case) and 200 000 events including a D^0 or $\bar{D^0}$ coming from a b quark (pure beauty case). For both of those simulations, we ploted the histograms of the azimuthal differences $\Delta\varphi$ between D and electrons, separating same type particles from anti-type particles and considering three ranges of p_t for the D^0 $(1 < p_t < 2,\ 2 < p_t < 3,\ 3 < p_t)$. We also took into account cuts on the rapidity of the D $(y_{D^0} < 0.5)$ and on the pseudorapidity of the electron $(\eta_e < 0.5)$. Those plots are presented in Figures 4, 5, 6 & 7. The background is ploted on figures 8 & 9.

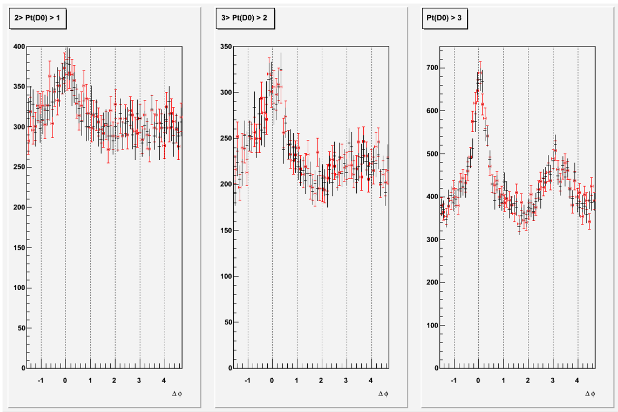

Figure 4 : $\Delta\varphi\left(D^0, e\right)$ with D^0 and e coming from c quark, with no cut on $\eta(e)$ or $y(D^0)$.

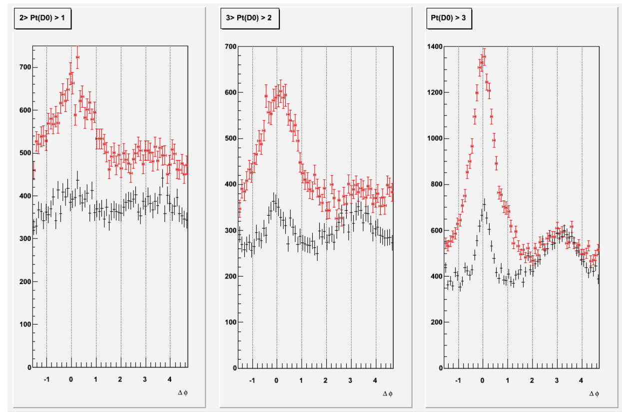

Figure 5 : $\Delta\varphi\left(D^0, e\right)$ with D^0 and e coming from b quark, with no cut on $\eta(e)$ or $y(D^0)$.

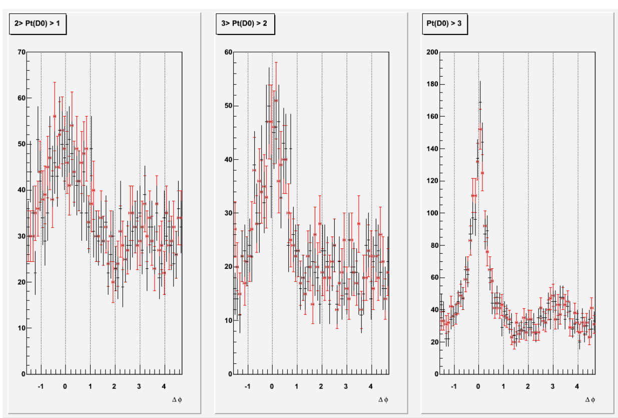

Figure 6 : $\Delta\varphi\left(D^0, e\right)$ with D^0 and e coming from c quark, with $\eta(e) < 0.5$ and $y(D^0) < 0.5$.

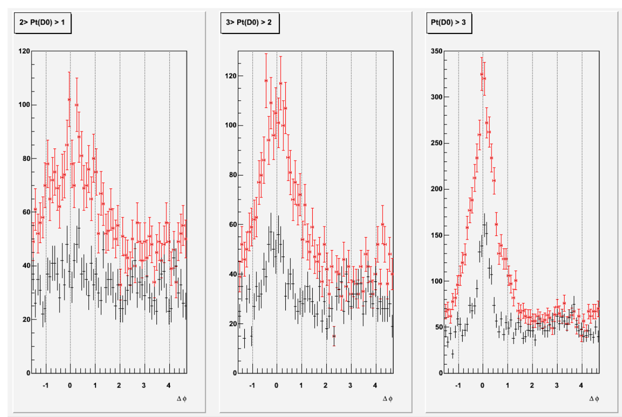

Figure 7 : $\Delta\varphi\left(D^0, e\right)$ with D^0 and e coming from b quark, $\eta(e) < 0.5$ and $y(D^0) < 0.5$.

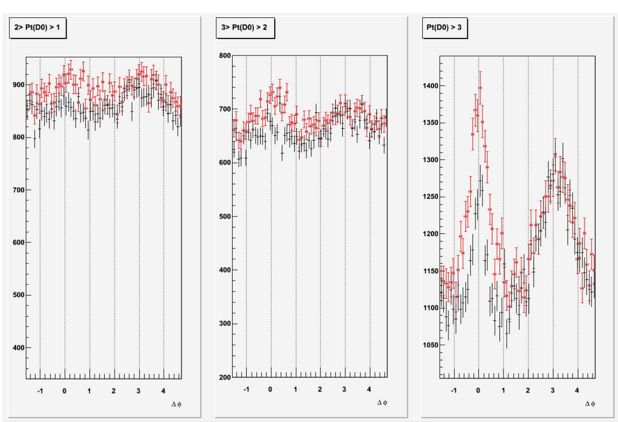

Figure 8 : $\Delta\varphi\left(D^0, e\right)$ background, with no cut on $\eta(e)$ or $y(D^0)$.

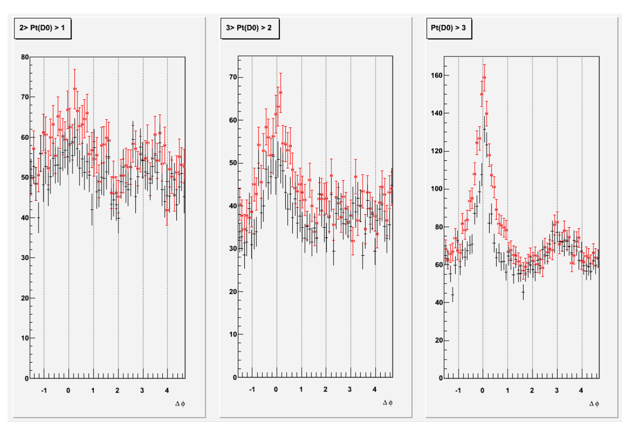

Figure 9 : $\Delta\varphi\left(D^0, e\right)$ background, $\eta(e) < 0.5$ and $y(D^0) < 0.5$.

On all plots above, the red markers show correlations between particles of the same type (particle - particle or antiparticle - antiparticle) whereas the black ones show correlations between particles of different sort (antiparticle - particle).

The difference between Ds coming from c quarks and Ds coming from b quarks appears clearly at high p_t : in the first case, the distribution is very much alike for $D^0 - e^-$ $(\bar{D^0} - e^+)$ and $D^0 - e^+$ $(\bar{D^0} - e^-)$, whereas in the second case, the peak at $\Delta\varphi = 0$ is almost twice as high for $D^0 - e$ than for $D^0 - \bar{e}$. It is to be emphasized that this difference only exists in the near-side peak and disapears in the back to back peak. The background seems to be mostly responsible for the back to back peak and can be measured thanks to it. The results are essentially independent of the cuts on y_{D^0} and η_e ; those cuts only reduce the statistics.

Those observations confirm the relevance of the method proposed before : one can evaluate the distribution of azimuthal correlations between $D^0 - e^-$ and between $D^0 - e^+$; the more different those distributions are, the smallest the ratio c/b is. Quantitativly speaking, it is possible to fit an unknown distribution f of same type particle aziumthal correlation by a linear combination of the background (f_{BG}) and the distributions obtained is the pure charm case (f_c) and in the pure beauty case (f_b) :

$$f = \alpha f_b + \beta f_c + \gamma f_{BG}.$$

We simulated a distribution with 80% charm and 20% beauty, for particles with $p_t\left(D^0\right) > 3\,GeV$ and cuts taken into account, and tried to analyse it with this fitting method (Figure 10). We find $(\pm 5\%)$ $\alpha = 0.21$, $\beta = 0.79$, $\gamma = 0.02$, which is quite accurate.

We can compute a qualitative evaluation of the integrated luminosity $\mathcal{L}$ required to reach a 5% uncertainty on the fit, ie 500000 events (200000 events with $p_t > 3\,GeV$). Considering

$$\mathcal{L} = \frac{1}{\epsilon_{rec}}\frac{1}{A}\frac{N}{\sigma} \simeq 40\,mb^{-1},$$

where $\epsilon_{rec} = 0.07$ is the reconstruction efficiency for electrons and D^0 in K, π with $p_t > 3\,GeV$, $A = 0.1$ is the acceptance with $\eta(e) < 0.5$ and $y(D^0) < 0.5$, $N = 200000$ is the number of $D^0 - e$ candidates and $\sigma = 0.465\,mb$ is the production cross section of D^0 in $K\,\pi$ (see [2]).

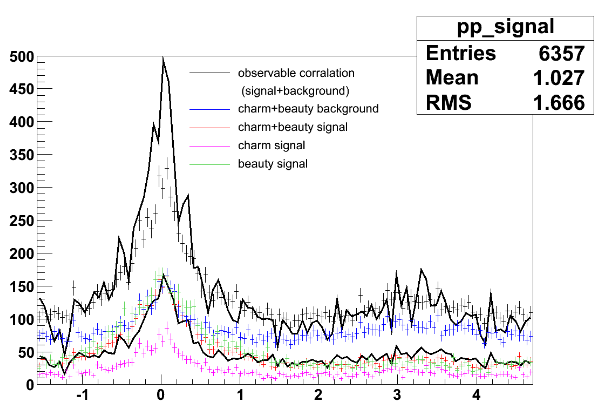

Figure 10 : Azimuthal correlations distribution, same type particles, $p_t(D^0) > 3\,GeV$, with cuts. Simulations and fits.

3 Applying the method on real data.

The first step of the data analysis is identify D^0s and to determine their caracteristics. To do so, we chose to reconstruct them from their hadronic decay [1] $D^0 \to K^-\pi^+$ & $\bar{D^0} \to K^+\pi^-$, which enables one to know the type of the D (particle or antiparticle) by measuring the sign of the K's charge. The invariant mass for six ranges of p_t is ploted on Figure 10.

The idea was to select Ds within the peak of mass at one σ, to determine their type (D^0 or $\bar{D^0}$) and then to evaluate their correlations with electrons. It appeared complicated to identify electrons with a satisfying accuracy.

I didn't have enough time to run the complete analysis on data. I still had time to evaluate the background of D^0 - particle angular correlation, as shown in Figure 12.

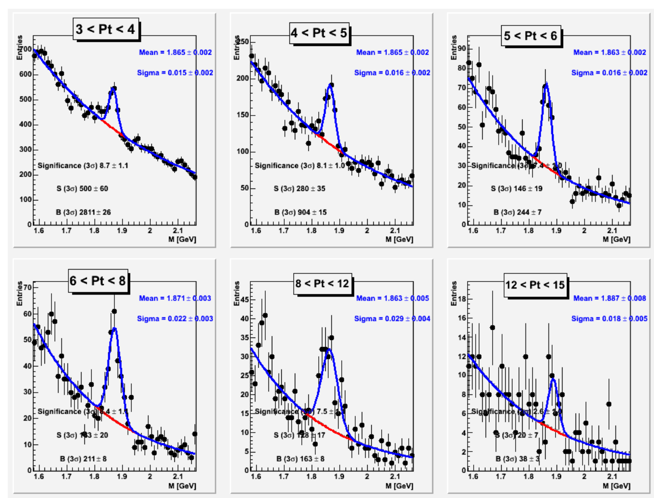

Figure 11 : Invariant mass of (K, π) from pp collisions with LHC10d data.

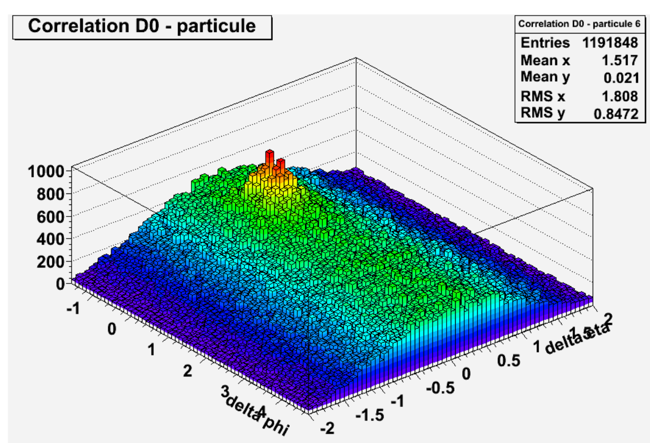

Figure 12 : D^0 - particle $(\Delta\varphi, \Delta\eta)$ distribution with LHC10d data.

Conclusion

This short analysis shows that it is possible to evaluate the ration of heavy flavour quarks charm over beauty by fitting the distribution of $D^0 - e^-$ and $\bar{D}^0 - e^+$ azimuthal correlations. A pessimistic evaluation of the integrated luminosity required to reach 5% uncertainty is the composition of the medium gives $\mathcal{L} \simeq 40\, nb^{-1}$; there should therefore be enough statistics at LHC for this method to be applied.

I would like to finish this report by warmly thanking all the Summer Students Team for organizing this amazing summer we will all remember for the rest of our lives and Zaida Conesa del Valle & Davide Cafarri for their expertise, their patience and their friendship.

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