THE ORIGIN OF COLLECTIVITY IN SMALL SYSTEMS VIA HEAVY-FLAVOUR MEASUREMENTS AT THE ALICE LHC EXPERIMENT

PhD thesis booklet

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Introduction

In quantum chromodynamics (QCD), quarks and gluons are confined into hadrons at low energies and cannot be observed in a free state. However, modern-day particle accelerators, such as the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), have made it possible to reach the energy densities at which partons exist in a deconfined phase in a unique state of quark-gluon plasma (QGP). Originally, the QGP was assumed to behave like ideal gas, until experiments at RHIC found strong collective motion in the final state of heavy-ion collisions, with quark degrees of freedom. This was therefore interpreted as hydrodynamic behaviour of a strongly coupled, fluid-like QGP. Later, LHC measurements found collective behaviour not only in heavy-ion collisions but also in smaller systems of p–Pb and pp. The QGP is not expected to form in such smaller collision systems due to much lower energy densities. While the creation of QGP in small volumes cannot be entirely ruled out, several theoretical works explain the observed collective behaviour in small systems with vacuum-QCD processes like multiple-parton interaction (MPI) or rope hadronisation with string shoving.

In high-energy collisions, hadrons containing light or strange quarks mostly carry information about the final state. However, heavy-flavour charm (c) and beauty (b) quarks are predominantly produced in the initial stages of the collisions. Since heavy-flavour production can be perturbatively described down to low momenta, they serve as a test bench for QCD. On the other hand, they provide an excellent opportunity to explore the properties of the QGP not only as a reference, but as tomographic probes: due to their long lifetime and negligible annihilation cross section, heavy flavour experiences the whole evolution of the strongly interacting system.

The transverse momentum (p_{T}) spectra of identified hadrons incorporate information about the ongoing parton-level processes during hadronisation. The understanding of hadron formation is not possible based on first principles, because of the non-perturbative nature of the strong interaction at the corresponding energy scales. While the high-p_{T} part of the spectrum is determined by jet-like hard production of hadrons, the low-p_{T} part corresponds to soft production, which can be described in terms of thermodynamics and hydrodynamics. The development of a unified model capable of simultaneously explaining both hard and soft regions is in the focus of extensive research. Among various approaches, non-extensive statistics has proven effective in describing the spectra of identified particles.

Objective

In my thesis, I studied the production of heavy-flavour mesons in high-energy collisions. My primary objective was to understand the source of collectivity in small collision systems with high final-state multiplicity. I used heavy-flavour probes in order to study the processes taking place in hadron collisions. First, I studied the production of D and B mesons, as well as c and b quarks, as a function of the transverse activity in simulations. This allowed me to distinguish between the hard and soft production processes, thus providing an opportunity to connect the collectivity to vacuum-QCD processes like MPI. Another goal was to investigate the role of the MPI in small collision systems. For this, I performed the analysis of the production of D^0 mesons in the ALICE experiment and compared the models to the data. Lastly, I explored the non-extensive thermodynamical nature of various collision systems measured by STAR and ALICE experiments to estimate how early in the collisions the heavy-flavour quarks are produced, and to determine if heavy-flavour probes are a viable option for gaining information about the early stages of the collision.

Applied methods

The results from the ALICE experiment showed that particle production in the transverse region is disconnected from the hard processes of the collisions and is described by the soft underlying events. In my work, I applied the classification of D mesons based on the transverse activity in generated pp collisions. For event generation, I used the PYTHIA 8 Monte Carlo simulation apparatus. With the help of the transverse activity classifier, I investigated the influence of soft processes on D-meson and B-meson production.

The ALICE detector has excellent capabilities for studying heavy flavour down to low momenta. Its Inner Tracking System (ITS) has a resolution of a few microns, allowing for the reconstruction of the secondary vertex with high precision. I analysed the data collected in the ALICE experiment during the Run 2 data-taking period to apply the method of the transverse activity classifier and compare the results to my predictions.

The transverse-momentum distributions of identified particles comprise two fundamentally different regimes: a low-momentum region, where particle production is governed by soft processes, and a high-momentum region with jetty processes described by perturbative QCD. The low-p_{T} part of the spectrum can be described using Boltzmann – Gibbs statistics, while the high-p_{T} part has a power-law tail. The non-extensive Tsallis – Pareto statistical framework allows for a smooth connection between these two parts and therefore a universal description of the whole spectrum under one theory. In the thesis, I applied the Tsallis – Pareto distribution to the spectra of identified D mesons from the STAR and ALICE experiments to obtain the Tsallis parameters describing each spectrum. This allowed me to compare the heavy-flavour D mesons to light-flavour hadrons and better understand the processes connected to the production of different flavours.

Results

I conclude my results in the following thesis statements:

1. I determined the event-activity-dependent production of heavy quarks (c and b) and heavy-flavour mesons (D and B), produced by the fragmentation of heavy quarks, in pp collisions at $\sqrt{s} = 13$ TeV collision energy in simulations using the PYTHIA 8 Monte Carlo event generator. To evaluate the transverse activity of the events R_{T}, I applied an event selection based on the transverse momentum of leading (highest-transverse-momentum) trigger hadrons, as well as jets. I studied the production of heavy-flavour hadrons in the toward region (azimuthally close to the leading trigger) and in the transverse region (perpendicular to the trigger in the azimuth plane). I found that the production of D and B mesons in the toward region depends on the transverse event activity at low transverse momentum p_{T} values for both trigger types. In the case of hadron triggers, this dependence vanishes at high momenta, while for the c- and b-jet triggers (leading jets containing a c or a b quark, respectively), a dependence on R_{T} is preserved due to autocorrelation effects attributed to wide-angle gluon splitting. This allowed me to conclude that low-transverse-momentum D and B mesons are produced in connection with the underlying event, while high-p_{T} heavy-flavour mesons are mostly formed as part of the leading hard process. I also studied the production of heavy quarks in events triggered by a leading hadron. As expected, I found a shift in the transverse momentum scale between c quarks and D mesons, connected to the hadronisation of c quarks into D mesons, while this effect is minimal when comparing b quarks and B mesons, due to much harder fragmentation. Lastly, my studies showed that the production of heavy flavour in the transverse region depends on R_{T} over the full transverse momentum range, meaning that D and B mesons in this region are produced mainly in connection with the underlying event. Interestingly, I observed similar behaviour in the toward region in the case of light-jet triggers, where the leading jet does not contain heavy-flavour quarks, suggesting that heavy-flavour production is fully independent of the hard processes in these events [1]. These results paved the way for the data analysis described below.

2. I measured the production of heavy-flavour D^0 mesons in dependence on the transverse activity R_{T} in pp collisions at $\sqrt{s} = 13$ TeV collision energy in the LHC ALICE experiment. I based the event selection on hadron triggers, and studied the production only in the toward region due to the limitations of the available data collected during the LHC Run 2 data-taking period. I obtained the raw yields of D^0 mesons by fitting the invariant mass peak of the D^0 candidates. To acquire the actual p_{T}-distribution of the D^0 mesons, I applied corrections for the charged-particle tracking and D-meson reconstruction efficiencies

of the ALICE detector system, as well as for its geometrical acceptance. I determined the fraction of non-prompt D^0 mesons, stemming from feed-down from weak b-hadron decays, and subtracted it from the D^0 meson yield to obtain a sample of prompt D^0 mesons. I also investigated and evaluated the magnitude of different sources of systematic uncertainties, such as topological selection of D^0 mesons, fitting of the invariant mass peak, bin migration and feed-down evaluation. I compared my results with PYTHIA 8 simulations with two different tunes, and the results agree with simulations within uncertainty [2, 5, 6]. This proves the applicability of the studied method, however, the higher luminosity of the Run 3 data-taking period is needed to test different models. A journal publication corresponding to these results is under preparation within the Collaboration.

3. I studied the production of D mesons within a non-extensive statistical framework. I used the transverse momentum distributions of the identified D meson species measured in the ALICE and STAR experiments across multiple collision systems, ranging from pp to A–A, and at collision energies varying from $\sqrt{s_{\rm NN}} = 200$ GeV to $\sqrt{s_{\rm NN}} = 7$ TeV. I showed that the Tsallis – Pareto distribution accurately describes the transverse momentum spectrum of D mesons, similarly to light-flavour hadrons. I confirmed the validity of the applied model by verifying that the thermodynamical consistency is fulfilled. I demonstrated that the Tsallis parameters extracted from the transverse momentum spectra of D mesons exhibit scaling behaviour with the charged-particle multiplicity and collision energies. However, this scaling is quantitatively different from the light-flavour and strange-hadron case. I determined the common grouping point, corresponding to a dilute (low-multiplicity) system limit, for D mesons and found that it corresponds to higher values of both the Tsallis temperature T and the non-extensivity parameter q. The shift of the common grouping point supports the fact that heavy flavour is produced at earlier stages of the reaction than light-flavour hadrons, which are formed at the freeze-out stage. I assumed Bjorken expansion to connect the temperature difference between heavy and light flavours to their production timescale. I concluded that the D mesons are formed at proper times 0.18 ± 0.06 times smaller compared to the light-flavour hadrons [3].

4. I determined the spectrum formation timescales of various hadron species (charged pions and kaons, K^0, (anti-)protons, ϕ mesons, Λ^0 hyperons, and D mesons) in pp, p–Pb and Pb–Pb collisions recorded by the ALICE experiment at energies from $\sqrt{s_{\rm NN}} = 2.76$ TeV up to $\sqrt{s_{\rm NN}} = 13$ TeV. I found that the Tsallis temperature of the common grouping points, $T_{\rm eq}$, for mesons scales with the meson mass. On the other hand, the $T_{\rm eq}$ values for baryons are significantly smaller than those of mesons with similar masses. I observed that the non-

extensivity parameter of the common grouping points, q_{eq}, does not depend significantly on the hadron mass. Assuming the Bjorken expansion, I observed that the meson formation times are ordered by meson mass. Pion spectra are formed substantially later than those of other hadrons: the formation timescale corresponding to pions is three times as large as that of kaons, and about thirty times larger than that of D mesons. I also estimated the specific heat of the system based on the values of q_{eq} and the relative multiplicity fluctuations δ^2. The results across the different particle species are consistent with each other, yielding a lower boundary for the specific heat $C > 5$. The large C values corresponding to light-flavour hadrons imply a largely thermalised system [4].

References

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