Fragmentation through Heavy and Light-flavor Measurements with the LHC ALICE Experiment

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Ph.D. Thesis booklet

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Introduction

A few microseconds after the Big Bang, the universe was filled with an extremely hot and dense mixture of particles moving at near light speed. This matter was dominated by quarks and gluons that are subject to the strong force. Under usual circumstances, quarks are confined into hadrons. However, at extreme temperatures and densities, quarks and gluons can enter a deconfined state, forming the so-called quark-gluon plasma (QGP).

To recreate the extreme conditions of matter which existed in the very early universe, we use powerful accelerators to make collisions between protons or heavy-ions, such as gold or lead nuclei. In the heavy-ion collisions hundreds of protons and neutrons in two such nuclei collide into each other to form a minuscule fireball in which everything melts into the quark-gluon plasma. The fireball then starts cooling and the individual quarks and gluons (collectively called partons) recombine into ordinary matter that flies away in all directions until they end up in our detectors. The final state of the collision contains many species of particles such as pions and kaons, which are mesons consisting of a quark-antiquark pair; or protons and neutrons, which are baryons containing three quarks; and even antiprotons and antineutrons, which may combine to form the nuclei of antiatoms as heavy as helium.

Even though heavy-ion collisions are only on the femtoscale, in high-energy physics they are often referred to as large systems, because the volume of the system created in the collision is large enough for the quark-gluon plasma to form. In contrast, we call the system of colliding protons (or antiprotons) small system. In proton-proton collisions, no nuclear effects are present, therefore they serve as a baseline for heavy-ion collisions, while proton-heavy ion collisions are investigated to learn about cold nuclear matter effects. Recently, however, collisions of small systems with high final-state multiplicity became a focus of intensive investigation. With the advent of the Large Hadron Collider (LHC), features have been observed that had been associated with the presence of quark-gluon plasma, even though QGP is not expected to be formed in small systems in a significant volume. These observations include collectivity effects such as long-range near-side correlations and the asymmetry in the azimuthal distribution of final state particles, also called anisotropic flow. A possible explanation is that quark-gluon plasma can be created in a small volume in a fraction of collisions of small systems. There are, however, alternative explanations of these observed phenomena that do not assume the quark-gluon plasma. Semi-soft vacuum QCD effects such as multiple-parton interactions are shown to produce signatures of collectivity.

Objectives

The aim of this thesis is to study heavy and light-flavor jet fragmentation and hadronization properties in high-energy proton-proton collisions to shed light on the particle production mechanisms that lead to collective-like behavior in small systems.

One of the main research areas for this purpose is the study of jets. I characterized differential and integral jet shapes to look for modifications caused by non-trivial quantum chromodynamics (QCD) effects. I also investigated the multiplicity distributions (number of charged final state particles) as a function of the jet transverse momentum. Recent results show that the multiplicity distributions follow a scaling similar to the Koba-Nielsen-Olesen (KNO) scaling, which provides important lessons on jet fragmentation. In my studies, I searched for the KNO-like scaling in simulations for heavy-flavor jets, and I also carried out the first measurement of jet-momentum-dependent jet multiplicity distributions with the ALICE experiment.

Another major topic in my thesis, connected to jet fragmentation, concerns the understanding of heavy-flavor hadroproduction in proton-proton collisions at LHC energies. The production cross section of hadrons can be calculated using the factorization theorem, which usually assumes that the fragmentation functions are universal across different collision systems. Experimental results such as the enhanced production of charmed baryons question this assumption. I used a model with color reconnection beyond leading color approximation (CR-BLC) to seek explanation for the charm-baryon enhancement, and proposed new observables for future measurements. I characterized the collision events using different event-activity classifiers, that allow for investigating the connections between the leading QCD processes and the underlying event. The primary motivation driving my research is to explore the boundary between hard and soft processes occurring in proton-proton collisions, which is a significant yet relatively unexplored area.

Methods

The analysis of jet shapes, KNO-like scaling on heavy-flavor jets, and charm-baryon enhancement are based on data I created with the PYTHIA 8 Monte Carlo event generator. The PYTHIA 8 event generator is widely used in particle physics, as it provides an accurate description of high-energy proton–proton collisions. It is capable of generating both hard and soft interactions, initial and final-state parton showers, jet fragmentation, and multi-parton interactions (MPI). Its MPI framework relies on the so-called color reconnection mechanisms, that rearrange color connections between quarks and gluons during hadronization. Finally, we also know that PYTHIA 8 is capable of modelling the multiplicity distributions properly.

The ALICE detector is a complex system of many subdetectors built for the study of heavy-ion collisions. The main subsystems relevant for the thesis are the following. The main tracking device in ALICE is the Time Projection Chamber (TPC), a gas-filled detector that identifies particles based on specific energy loss and determines their momentum. The Inner Tracking System (ITS) consists of silicon detectors. It aids particle tracking, and plays a crucial role in the identification of heavy-flavor hadrons by locating the secondary decay vertex. The Time of Flight (TOF) detector provides timing information. The Electromagnetic Calorimeter (EMCal) measures the energy of electromagnetic particles (electrons and photons). Trigger information is provided by the V0A and V0C scintillators placed in the forward and backward areas.

The ALICE Collaboration measured the angular correlations of heavy-flavor decay electrons with charged hadrons in pp and p–A collisions. I used the FONLL perturbative QCD model to determine the contribution of charm and beauty to the correlation peaks, and produced extensive simulations with PYTHIA 8 to compare the near- and away-side peaks of the azimuthal-correlation distribution in pp and p–Pb collisions to the model predictions. The correlation structures are fitted with a constant and two von Mises functions to obtain the baseline and the near- and away-side peaks, respectively. Since PYTHIA 8 does not natively support collisions involving heavy nuclei, I used the Angantyr model implemented for PYTHIA 8, which combines several nucleon–nucleon collisions to build a proton–nucleus (p–A) or nucleus–nucleus (A–A) collisions.

I analyzed ALICE data collected in the 2016-2018 period to measure the jet multiplicity distributions as a function of the jet transverse momentum, and investigated the KNO-like scaling within the measured jets. I did the calculation of these observables using the ALICE code framework by implementing my own analysis code. I corrected the extracted multiplicity distributions for detector effects utilizing Bayesian unfolding with the RooUnfold package.

Original Results

In my thesis I present my research on the fragmentation properties of light and heavy-flavor hadrons, covering jet shapes, multiplicity distribution scaling, azimuthal correlations of heavy-flavor decay electrons and hadrons, and charmed baryon production as a function of the event activity. In the following thesis statements I summarize my novel contributions to each of these subjects.

1. Multiplicity-dependent Jet Structure and Fragmentation

I analyzed the differential and integral jet shapes and performed an event multiplicity-differential study in proton-proton collisions created with the PYTHIA event generator. By utilizing a double ratio of observables to minimize the bias in the multiplicity measurement, I showed that the jet shapes depend on the event multiplicity, which can be used for model differentiation in experimental data. By looking at the multiplicity dependence of the jet shape distributions, I observed a characteristic jet size, which is robust against different parton density functions, jet reconstruction algorithms and multiplicity selections. It qualitatively follows a Lorentz-boost curve, which suggests it being an inherent property of the jets and is characteristic to the space-time evolution of the parton shower at a given momentum [1, 2, 3].

2. Scaling Properties of Jet Structure in Theory and the ALICE Experiment

The Koba-Nielsen-Olesen (KNO) scaling hypothesis is an influential contribution to the analysis of event multiplicities in high-energy particle collisions, according to which the event-multiplicity distributions can be all collapsed onto a universal scaling curve. Recent phenomenological studies suggest that a similar scaling may hold within single jets, if we consider the jet multiplicity as a function of the jet transverse momentum. I conducted an analysis on the KNO-like scaling for heavy-flavor jets in pp collisions at $\sqrt{s} = 13$ TeV using Monte Carlo event generators. I found that the KNO-like scaling stems from the partonic level of the interaction. Motivated by the results, I conducted the first measurement of the jet multiplicity distributions as a function of jet transverse momentum in pp collisions in the ALICE experiment at $\sqrt{s} = 13$ TeV, which allowed to quantify the KNO-like jet scaling properties and thus help further our understanding of jet fragmentation properties [4, 5].

3. Azimuthal Correlations of Heavy-flavor Decay Electrons with the ALICE Experiment

In high-energy hadron collisions, heavy quarks (charm and beauty) are mainly produced in hard parton scattering processes. Two-particle angular correlations originating from heavy-flavor particles allow for the characterization of parton shower and fragmentation. The ALICE collaboration measured the heavy-flavor electron-hadron azimuthal correlation distributions between heavy-flavor decay electrons and associated charged particles in pp and p–Pb collisions at $\sqrt{s} = 5.02$ TeV. My main contribution to the analysis was to create detailed simulations to compare the near- and away-side peaks of the azimuthal-correlation distribution in pp and p–Pb collisions to the model predictions. This allowed verifying the model implementation of the processes of charm- and beauty-quark production, fragmentation, and hadronization, which have an impact on the observables studied in this analysis. I also determined the correlation peak shape using FONLL pQCD calculations for the modelling of charm and beauty contributions. The correlation structures are fitted with a constant and two von Mises functions to obtain the baseline and the near- and away-side peaks, respectively. The evolution of the near- and away-side peaks of the correlation functions in pp and p–Pb collisions was found to be similar in all the considered kinematic ranges. This suggests that the modification of the fragmentation and hadronization of heavy quarks due to cold-nuclear-matter effects is indistinguishable within the current precision of the measurements [6].

4. Charm-baryon Enhancement and the Role of the Underlying Event

Perturbative quantum chromodynamics (pQCD) calculations have been successful in describing the production of heavy-flavor mesons for several collision energies at the LHC. The usual description relies on the factorization approach, in which the production cross section of heavy-flavor hadrons in the hadronic collisions is calculated as a convolution of the parton density functions (PDFs) of the colliding hadrons, the cross section of the hard-scattering process and the heavy-quark fragmentation function. However, recent experimental results from the CERN LHC show a relative enhancement of charmed baryons compared to the factorization approach expectations based on electron-positron collisions. I utilized the PYTHIA 8 Monte Carlo event generator with color reconnection beyond leading-color approximation and proposed experimental methods based on event-activity classifiers to probe the source of the charmed-baryon enhancement. I concluded, that in the considered model class the Λ_c^+ enhancement is connected to the underlying event and does not depend significantly on the processes inside the jet region [7, 8].

5. Production of Excited Charm and Charm-strange Baryon States

I extended the studies of the Λ_c^+ baryon enhancement to several different charmed baryons and I also investigated the production of charmed baryons with different isospin and strangeness content, then compared it to both charmed D^0 mesons and to Λ_c^+ baryons in pp collisions at LHC energies. I showed that the isospin of the charmed-baryon state has a strong impact on the enhancement pattern. Using the observables I propose, upcoming high-precision experimental data will be able to differentiate between mechanisms of strangeness and charm enhancement [9, 10].

Publications

[1] Varga, Z.; Vértesi, R.; Gábor Barnaföldi, G. Modification of jet structure in high-multiplicity pp collisions due to multiple-parton interactions and observing a multiplicity-independent characteristic jet size. Adv. High Energy Phys. **2019**, 2019, 6731362.

[2] Varga, Z.; Vértesi, R.; Barnaföldi, G. G. Jet Structure Studies in Small Systems. Universe **2019**, 5, 132.

[3] Varga, Z.; Vértesi, R.; Barnaföldi, G. G. Multiplicity Dependence of the Jet Structures in pp Collisions at LHC Energies. MDPI Proc. **2019**, 10, 3.

[4] Varga, Z.; Vértesi, R. The Partonic Origin of Multiplicity Scaling in Heavy and Light Flavor Jets. Symmetry **2022**, 14, 1379.

[5] Varga, Z. Jet momentum dependence of jet multiplicity in pp collisions at 13 TeV. ALICE Analysis Note **2024**,

[6] Acharya, S.; others (ALICE Collaboration), Azimuthal correlations of heavy-flavor hadron decay electrons with charged particles in pp and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Eur. Phys. J. C **2023**, 83, 741.

[7] Varga, Z.; Vértesi, R. The role of the underlying event in the Λ_c^+ enhancement in high-energy pp collisions. J. Phys. G **2022**, 49, 075005.

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[9] Varga, Z.; Misák, A.; Vértesi, R. Event-activity-dependent production of strange and non-strange charmed baryons in the enhanced color-reconnection scheme. J. Phys. G **2023**, 50, 075002.

[10] Vértesi, R.; Varga, Z. Connection of event shapes to the heavy-flavor baryon enhancement. arXiv:2402.01234 [hep-ph]. 2024.

Further publications not related to the thesis points:

[P1] D. Nógrádi, L. Szikszai, Z. Varga, ”SU(2) Lattice gauge theory with a topological action”, JHEP 1808 (2018) 032.