Study of charged pion, kaon, and (anti)proton production at high transverse momenta in pp and p–Pb collisions with the ALICE experiment at the CERN LHC

Ph.D. Thesis Booklet

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1 Introduction

The fundamental theory of strong interactions, the Quantum Chromodynamics (QCD), is formulated in terms of quarks and gluons which, to our present knowledge, are the basic degrees of freedom that compose hadronic matter. The QCD succeeds in providing a qualitative description of a wide range of observations in hadronic collisions. One of the most important properties of QCD is the color confinement which is an experimentally well-established phenomenon. It states that no single free quarks, carrying fractional charge, can be observed, as they are bound into color singlet states with zero net-color charge. The other property is the asymptotic freedom which is a consequence of the decrease of the QCD running coupling $\alpha_S(Q^2)$ with increasing momentum transfer $Q^2$. At typical hadron collider energies, i.e. at large $Q^2$, its perturbative expansion permits a detailed quantitative comparison with experimental data. In contrast, at small $Q^2$ the coupling is in the order of unity where perturbative methods fail and only phenomenological models can be applied, which mostly cannot be derived from first principles. In this domain, the lattice QCD provides also a non-perturbative tool for calculating the hadron spectrum and the operator matrix elements within these hadronic states based on first principles. Lattice calculations predict that the ordinary nuclear matter under extreme conditions (high temperature and energy density) transforms into a deconfined state of quarks and gluons, which is called Quark-Gluon Plasma (QGP). This hot and dense strongly interacting phase of QCD matter is believed to existed in the early Universe just a few microseconds after the Big Bang. On Earth, ultra-relativistic heavy-ion collisions, performed at large particle accelerators like in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and in the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN), are well suited to reproduce and to study the generated QGP phase in a controlled laboratory environment.

The main characteristic features of the QGP are the bulk collectivity and opacity to jets. The collective behavior is observed as a mass-dependent hardening of transverse momentum ($p_T$) spectra by the radial flow which is more pronounced for heavier hadrons. Hard and strongly interacting partons, forming a collimated spray of particles referred to as a jet, produced at the early stage of heavy-ion collision traverse the plasma and lose their energy. This partonic energy loss is observed as a reduction of the amount of produced high-$p_T$ particles and fully reconstructed jets.

A Large Ion Collider Experiment (ALICE) is a dedicated heavy-ion experiment at the CERN LHC which is optimized to study the properties of the strongly interacting QGP created in ultra-relativistic heavy-ion collisions. The ALICE detector has a unique capability among the other main LHC experiments to identify a large variety of particles using different particle identification (PID) techniques and track reconstruction in a wide
$p_T$ range. The PID is necessary as the amount of suppression of high-$p_T$ particles was found to depend strongly on the hadrochemical composition of the produced particles.

Measurements of inclusive hadron production at mid-rapidity at the LHC probe longitudinal parton momentum fraction, Bjorken $x$, in the range $10^{-4} < x < 10^2$. This range extends the measurements to lower $x$ values by an order of magnitude with respect to that reached by other colliders at lower center-of-mass energy ($\sqrt{s}$).

With the increase of the center-of-mass energy $\sqrt{s}$ reached at the LHC opens up new domains in $x$, where the contribution of gluons to inclusive hadron production becomes dominant. Therefore, identified particle spectra at the top LHC energy in pp collisions can provide new constraints on the gluon fragmentation. More precisely, on the gluon-to-pion and gluon-to-kaon fragmentation functions which are poorly constrained and have larger uncertainties in theoretical calculations due to limited amount of data at LHC energies. In this kinematic regime, the nuclear modification to hadronic structure is expected to be sizable. By using a proton instead of a heavy nucleus as one of the projectiles, measurements of proton-lead ($p$–Pb) collisions have unique sensitivity to the initial-state nuclear wave function. High-$p_T$ identified particle spectra measured in $p$–Pb collisions provide new constraints on the nuclear-modified parton distribution functions (nPDFs) and the flavor dependence of sea-quark nPDFs. These are key inputs in interpreting a large amount of experimental data like deuterium-gold and deep inelastic scattering.

In this thesis, I present measurements in collisions of protons, and of protons and lead nuclei at the CERN LHC recorded by the ALICE experiment. The interpretation of the QGP properties requires comparisons with control (or reference) measurements carried out in proton-proton (pp) and p–Pb collisions. However, recent results on particle production at the LHC obtained in high-multiplicity pp and p–Pb collisions revealed phenomena which are similar to those seen in lead-lead (Pb–Pb) collisions—where they are attributed to bulk collective effects. The origin of these phenomena is debated, and the analysis of pp and p–Pb collision data provides further inputs to this discussion.

2 Objectives

The prime objective of this thesis is to provide precise measurements of identified charged hadron spectra over wide transverse momentum ranges at different LHC energies at mid-rapidity. In order to achieve these goals, it is essential to study the production of charged pions, kaons, and (anti)protons in pp and p–Pb collisions with the best possible accuracy at high $p_T$ (up to 20 GeV/$c$). Such studies extend the existing measurements over new, yet unmeasured kinematic regimes at the LHC which are of particular importance for the quantitative description of particle production at the LHC.
On the one hand, high-precision measurements are achieved in the intermediate \( p_T \) region \((2 - 10 \text{ GeV}/c)\) where initial state (cold) nuclear matter effects, such as shadowing and Cronin enhancement, have been reported by previous experiments. In this \( p_T \) regime, particle ratios \((K/\pi\) and \(p/\pi\)) are affected also by large final state effects in central \( \text{Pb-Pb} \) collisions. The particle species dependency of the nuclear modification factor in pp collisions is important to better understand parton energy loss mechanisms in heavy-ion collisions. On the other hand, the measurements of charged pions, kaons and (anti)protons in minimum bias (MB) pp collisions also contribute as reference data to study nuclear effects in \( p-\text{Pb} \) and \( \text{Pb-Pb} \) collisions and provide input to tune the modeling of several observables in Monte Carlo event generators.

The performed measurements are summarized in the following points:

- Single-inclusive identified charged particle \( p_T \) spectra were measured in minimum bias inelastic pp collisions in the mid-rapidity region at \( \sqrt{s} = 7 \) and \( \sqrt{s} = 13 \text{ TeV} \) during Run 1 and Run 2 data taking periods of the LHC, respectively. These are important results in order to determine the collision energy dependence of various measured observables, such as \( p_T \)-differential as well as \( p_T \)-integrated particle yields, yield ratios, and average transverse momenta.

- Single-inclusive identified charged particle \( p_T \) spectra were measured in non-single diffractive \( p-\text{Pb} \) collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) near mid-rapidity in intervals of charged-particle multiplicity, generally called as “event activity” classes, determined in the forward rapidity region (Pb-going side). Basic observables, such as particle yields and ratios of yields were determined as a function of \( p_T \), based on selections made in event activity classes.

- Nuclear modification factors \((R_{p\text{Pb}})\) were determined in non-single diffractive \( p-\text{Pb} \) collisions at high \( p_T \). Their dependence on particle species is investigated. Due to lack of measurements in pp collisions at \( \sqrt{s} = 5.02 \text{ TeV} \) during LHC Run 1, the \( R_{p\text{Pb}} \) for all considered particle species was constructed using data-based pp reference spectra obtained by interpolation of data at different collision energies.

### 3 Applied methods

The ALICE detector recorded minimum bias pp collision data at \( \sqrt{s} = 7 \text{ TeV} \) in 2010, p–Pb data at a nucleon-nucleon center-of-mass energy of 5.02 TeV in 2013, and \( \sqrt{s} = 13 \text{ TeV} \) pp data in 2015. The large amount of data collected during each of these periods are essential to measure the production of identified charged particles at high \( p_T \) (up to 20 GeV/c).
Besides colliding heavy ions, ALICE provides important contributions to the LHC pp physics program, which is complementary to other LHC experiments due to its capability to measure particle production down to very low transverse momentum ($p_T \simeq 100\text{MeV}/c$) thanks to its moderate solenoidal magnetic field ($B = 0.5\text{T}$), and to its excellent PID capabilities at mid-pseudorapidity $|\eta| < 0.9$.

The analysis of the data taken by the ALICE detector is demanded to use the official analysis software framework of the experiment. The collection of program tools are generally inherited from the ROOT software, developed further and incorporated into the ALICE ROOT (AliRoot) framework. AliRoot is developed on a daily basis in the direction to fit the needs of the reconstruction, the data acquisition environment and the measurement of the produced particles during each collision in ALICE. The general way one has to follow in order to analyze the data sample is to write and develop an analysis class based on this framework which is specific to the physics analysis in question. These program codes are object-oriented that can have interface to other program elements, such as Monte Carlo (MC) event generators and transport codes where the geometry of the detector and its response as well as the data taking conditions are reproduced.

I developed a program code to analyze the pp and p–Pb collision data. For data analysis, minimum bias triggers were used which have high efficiency to select inelastic (INEL) pp and non-single diffractive (NSD) p–Pb collisions with negligible background arising from single diffractive and electromagnetic events. Additionally, events in p–Pb collisions were classified into multiplicity classes based on the total charge deposited in the forward (Pb-going direction) scintillator hodoscopes. Hence, the classification is made in event activity classes in different rapidity window than the actual $p_T$ spectra are measured. This requirement is mandatory in order to reduce effects which significantly alter the hadrochemical composition of particle production.

Global tracks from primary charged particles are reconstructed in the Time Projection Chamber (TPC) and the Inner Tracking System. Particle identification at high $p_T$ was performed using specific energy loss $dE/dx$ information provided by the TPC. Since the $dE/dx$ theoretically depends only on the particle’s velocity, the particle mass and thus the particle type can be determined knowing the momentum of the particle from track reconstruction. The energy loss measurement requires the reconstruction of the $dE/dx$ signal which depends not only on $\beta\gamma = p/m$ of the particles but on the track inclination length over the pad plane. Since at high momentum the $dE/dx$ resolution is only a few number of standard deviation between pions, kaons, and (anti)protons, the mean $dE/dx$, $\langle dE/dx \rangle$, has to be measured precisely. This suggests recalibrating the $\langle dE/dx \rangle$. I have performed various calibration checks on all analyzed data sample to achieve the best experimentally possible $dE/dx$ performance.
I determined the invariant production yields of charged pions, kaons, and (anti)protons at high $p_T$ (up to 20 GeV/c). I used the TPC relativistic rise technique to extract the raw particle abundances from multi-Gaussian fits to the $dE/dx$ distributions. The raw particle abundances were normalized to all charged particles, which are called particle fractions, and were obtained in narrow, equidistant pseudorapidity $|\eta|$ bins in order to reduce residual miscalibration effects. In p–Pb collisions, the procedure was completed as a function of charged-particle multiplicity.

I calculated the corrections to the raw particle fractions related to the PID procedure. Simulated MC events were used that included the propagation of particles through the ALICE detector material which was simulated using transport code and the resulting data are passed through track reconstruction algorithms. The relative (tracking $\times$ acceptance) efficiency correction is the largest component amongst the corrections, and it is calculated for all particle species. For p–Pb analysis, no unidentified spectrum was measured in the considered rapidity window therefore I recalculated the corresponding spectrum and corrected for tracking efficiency. The measured unidentified and identified charged hadron efficiencies were found to be independent of charged-particle multiplicity and pseudorapidity, which justified to extract them from the MB sample with high statistics and apply them to all multiplicity bins. The pion and proton fractions were corrected for feed-down from weak decays using simulated MC data then they were further scaled to the correction computed using data-driven methods. To obtain particle yields, the particle fractions were averaged over narrow $|\eta|$ bins and eventually multiplied by the measured inclusive (unidentified) charged hadron spectrum. The minimum bias yields were normalized to the total number of INEL/NSD events using a trigger and vertex reconstruction efficiency correction, whereas those obtained in multiplicity bins have been normalized to the visible (triggered) cross section correcting for the vertex reconstruction efficiency. This latter correction is in the order of 4% for the lowest multiplicity class and negligible for other event classes ($< 0.1\%$).

I estimated the systematic uncertainties for the applied corrections. For p–Pb analysis, I also estimated the uncorrelated component of uncertainties across different multiplicity classes. The most relevant source of uncertainties are related to the incomplete knowledge in the determination of the $\langle dE/dx \rangle$ and $dE/dx$ resolution curves; except for pions where the uncertainty linked to event and track selection dominates.

I determined the pp reference cross section based on a data-driven approach. I implemented an interpolation method $p_T$-bin-by-$p_T$-bin, assuming a power-law behavior of the differential cross section as a function of $\sqrt{s}$ for a fixed $p_T$. Having determined the pp reference spectrum at $\sqrt{s} = 5.02$ TeV for the particle species under study, I extracted the related nuclear modification factors ($R_{pPb}$) in NSD p–Pb collisions and calculated...
the corresponding systematic uncertainties. For this, I constructed the minimum bias NSD sample out of the multiplicity-dependent measurement and applied the appropriate corrections.

In pp collisions, I studied the scaling properties of identified charged hadron production as a function of $x_T (= 2p_T/\sqrt{s})$ where I calculated the variation of the invariant cross section ratios at two distinct center-of-mass energies. Besides, I studied the transverse mass ($m_T$) scaling properties of the particle spectra on the $K/\pi$ particle ratio. I completed the combination of $p_T$ spectra obtained in my analysis with those determined in the low-to-intermediate $p_T$ region in the same rapidity window, to cover the largest possible $p_T$ range in the measurements, which is crucial for the accurate determination of the $p_T$-integrated particle yields and their ratios.

For pp and p–Pb collisions, I compared the results with predictions from general-purpose Monte Carlo event generators and recent next-to-leading order (NLO) perturbative QCD calculations.

As a part of my Ph.D. work, I did a phenomenological study to get better insight into the origin of the collective-like phenomena observed in low-multiplicity pp events by several experiments at the LHC. I applied the widely-used blast wave (BW) method by performing global simultaneous fits to identified particle $p_T$ spectra simulated by Pythia 8 and Epos 3 Monte Carlo event generators which are intensively used in high-energy collider and cosmic-ray physics. I extracted the kinetic temperature and the radial expansion velocity parameters of the BW fit and studied their dependence on charged-particle multiplicity and the $p_T$ of the leading (highest transverse momentum) jet.

Related to hardware developments for charged hadron measurements at high energies, I worked in the MTA Lendület Innovative Detector Development Research (REGARD) group at the Wigner RCP in Budapest. I determined the position resolution of a prototype asymmetric multi-wire proportional chamber. The resolution of the chamber is calculated from the difference between the reconstructed centroids of clusters and the track intersection calculated from track residuals. This quantity was evaluated by using both analog and digital readout and the obtained results were compared to each other. The significant improvement in resolution could be achieved for the case of field shaping wires. Here, one cannot use the center-of-gravity method since the induced signals among adjacent field shaping wires share to first approximation equal charges. Since the two signals are not exactly the same, I applied the charge sharing method — which was successfully used in the past — and calculated the position resolution with 2 mm-wide wire segmentation.
4 Results

My scientific results are summarized in the following thesis points:

1. I performed a double-differential study in pp collisions at LHC energies using two general-purpose Monte Carlo event generators, such as Pythia 8 and Epos 3, which are extensively applied, respectively, in high-energy collider and cosmic-ray physics. I explored an observable which is aimed at ruling out or validating the underlying physics mechanism (hydrodynamics or color reconnection) generating radial flow patterns in pp collisions. To this end, I studied the $p_T$ spectra of charged pions, kaons and (anti)protons as a function of the charged-particle multiplicity and the $p_T^{\text{jet}}$ of the leading jet. I found that in extremely-low multiplicity events, it is possible to find an event class where radial flow patterns arise, regardless of the weakness of collective flow effects caused by either hydrodynamics or color reconnection mechanism. I showed that the agreement between the blast wave model and the simulation improves with the increase of leading jet $p_T^{\text{jet}}$, suggesting that the presence of the collective-like behavior is caused by jets. The results indicate that the average transverse expansion velocity $\langle \beta_T \rangle$ is more affected by jets in Pythia 8 than in Epos 3. I found that in high-multiplicity events, generated by Epos 3, the magnitude of the $p/\pi$ ratio at intermediate $p_T$ increases with decreasing $p_T^{\text{jet}}$. No such evolution is present in Pythia 8, since hadrochemical composition is very different between Pythia 8 and Epos 3 in this event class. These results were published in Ref. [1], and motivate the high-energy physics community to perform a similar analysis using experimental data from BNL RHIC and CERN LHC.

2. I measured the invariant yields of charged pion, kaon, and (anti)proton as a function of charged-particle multiplicity up to $p_T = 20\text{ GeV}/c$ in non-single diffractive p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02\text{ TeV}$ at mid-rapidity. I found that at intermediate $p_T$ ($2-10\text{ GeV}/c$) the $p/\pi$ ratio shows a monotonic, precipitous increase with multiplicity towards higher values. However, a similar effect is not present for the $K/\pi$ ratio. I showed that the $p_T$-dependent structure of such an increase is qualitatively similar to those observed in pp and Pb–Pb collisions, albeit the underlying particle production mechanism might be different. I found that at high $p_T$ (above $10\text{ GeV}/c$) the $p_T$-integrated particle ratios are system-size independent for pp, p–Pb and Pb–Pb collisions [3, 12].

3. I measured the invariant yields of charged pion, kaon, and (anti)proton up to $p_T = 20\text{ GeV}/c$ in minimum bias inelastic pp collisions at $\sqrt{s} = 7\text{ TeV}$ at mid-rapidity. I determined the $\sqrt{s} = 5.02\text{ TeV}$ pp reference cross section based on previously published data at $\sqrt{s} = 2.76\text{ TeV}$ and those measured in this work at $\sqrt{s} = 7\text{ TeV}$. I constructed the nuclear modification factor $R_{p\text{Pb}}$ for the studied particle species. I showed that at
intermediate $p_T$ the (anti)proton $R_{pPb}$ indicates a characteristic enhancement, while pions and kaons show little or no nuclear modification, which is compatible with NLO pQCD predictions obtained with the EPS09 nuclear parton distribution functions. This observation confirms that the modest enhancement reported earlier for unidentified charged particles can be attributed to the modification of the proton spectral shape going from pp to p–Pb collisions. I found that the $R_{pPb}$ for charged pions, kaons, and (anti)protons at high $p_T$ is consistent with unity within statistical and systematic uncertainties, indicating binary nucleon scaling [3, 9, 12].

4. I measured the invariant yields of charged pion, kaon, and (anti)proton up to $p_T = 20 \text{ GeV}/c$ in minimum bias inelastic pp collisions at $\sqrt{s} = 13 \text{ TeV}$ at mid-rapidity. I found that the identified particle spectra are consistent with the empirical $x_T$ scaling over the accessible $x_T$ range in the hard scattering regime. I showed that a relation between the charged pion and kaon invariant yields is given by the transverse mass scaling for $p_T \gtrsim 6 \text{ GeV}/c$, however a significant deviation from the empirical scaling law is observed below $p_T \lesssim 6 \text{ GeV}/c$ in the $K/\pi$ ratio. I found that the $p_T$-dependent $p/\pi$ ratio in the intermediate $p_T$ region shows a modest departure towards higher $p_T$ going from $\sqrt{s} = 7$ to $\sqrt{s} = 13 \text{ TeV}$, while the $K/\pi$ ratio does not feature any dependence on collision energy. The results for the $p_T$-integrated particle ratios indicate saturation in the LHC-energy regime. The results for the average transverse momentum $\langle p_T \rangle$ show a monotonic increase with center-of-mass energy in minimum bias pp collisions, with the $\langle p_T \rangle$ being larger for heavier hadrons [10, 13]. The comparison of data to NLO pQCD calculations shows that the theoretical calculations overpredict the measured identified particle yields, suggesting that the fragmentation functions are not well tuned at the accessible kinematic regime at the LHC.

5. I participated in the developments of the ALICE Very High Momentum Particle Identification Detector (VHMPID) [5] and gave valuable contributions to the detector performance studies. I constructed and successfully tested a prototype asymmetric multi-wire proportional chamber with a reduced size, based on techniques developed by the Hungarian REGARD Group [2]. For this purpose, I took part in several test beam campaigns at the CERN PS accelerator, and I measured the position resolution of the prototype chambers [5]. Using their analog data, I found significant improvement, by more than a factor of 6 with respect to the digital readout, of the position resolution of the prototype chamber measured on their segmented cathode planes [2]. I contributed with a physics performance study to the Letter of Intent (LoI) document of the ALICE VHMPID where the results obtained from the detector and physics performance studies are summarized. I wrote a dedicated section (Sec.4.4.2) in the LoI, summarizing
my Monte Carlo simulation studies performed using identified two-particle angular correlations to help to verify the applicability of the ALICE VMHPID for physical analysis [4, 8].

My results have been published in 5 refereed journals: 2 articles with less than 5 authors [1, 2], and 3 collaboration articles with more than 50 authors [3–5]. I have presented my results in 10 talks on international conferences and workshops, from which I prepared 4 refereed conference proceedings [8–11]. I have received 34 independent citations until 01/03/2019. Additionally, I gave 7 seminars at different universities and I made 3 posters.

During my 7 years as an active member of the ALICE collaboration, I became a co-author of 216 collaboration papers until 01/03/2019. I gave ALICE-related services, including shift services, and I participated continuously in weekly analysis meetings. In 2016, I was elected as chair of the paper committee of an ALICE publication [7] to coordinate the paper writing; this publication is currently under preparation.

References

Refereed publications


(In this publication, my results of a Monte Carlo study performed using EPOS 3 are used. The article is written by me, and I am the contact author.)


(In this publication, my results of the measurement of the position resolution of a prototype asymmetric MWPC are used. I wrote section 3.)
Publications within collaboration

(In this publication, my results of $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$ measured at high $p_T$ in pp and p–Pb collisions are used. I was paper committee member; moreover, I prepared all the figures and tables, and the HEPData tables of the measured data points.)

(In this publication, my results of identified two-particle azimuthal correlations preformed in Monte Carlo simulations are used. I wrote section 4.4.2.)

(In this publication, my results of the measurement of the position resolution of a prototype asymmetric MWPC are used.)


Publication under preparation

(In this publication, my results of $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$ measured at high $p_T$ in pp collisions at $\sqrt{s} = 13$ TeV are used. I am the chair and a member of the paper committee.)

Refereed conference proceedings


ALICE internal analysis notes

[12] ALICE Collaboration, G. Bencedi et al., Analysis Note (2016), “Identification of \( \pi^\pm, K^\pm \) and p(\( \bar{p} \)) at high \( p_T \) in pp collisions at \( \sqrt{s} = 7 \) TeV and in p-Pb collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV”, https://aliceinfo.cern.ch/Notes/node/428, ALICE-AN 428, 2016.

(The note contains the analysis methods for measuring the high-\( p_T \) \( \pi^\pm, K^\pm \), and p(\( \bar{p} \)) yields in pp and p–Pb collisions and the obtained results. The entire document is written by me.)


(The note contains the analysis methods for measuring the high-\( p_T \) \( \pi^\pm, K^\pm \), and p(\( \bar{p} \)) yields in \( \sqrt{s} = 13 \) TeV pp collisions and the obtained results. The entire document, except those parts which include the analysis methods of ITS-sa, TPC-TOF, HMPID, topological identification of charged kaons in the TPC (Kinks), and the TPC Multi-Template Fit, is written by me.)