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Ph.D. THESIS

Maciej Paweł Szymański, M.Sc.

**Femtoscopic analysis of baryon correlations
in ultra-relativistic heavy-ion collisions registered by ALICE**

Supervisor
Prof. Adam Kisiel

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Abstract

Heavy-ion collisions at ultra-relativistic energies give a unique possibility to create and to analyse the Quark-Gluon Plasma predicted by the theory of Quantum Chromodynamics. The research on the properties of such state of matter is crucial for understanding the features of the strongly interacting system.

Experimental results reveal the collective behaviour of matter created in the heavy-ion collisions at ultra-relativistic energies. The existence of this effect can be verified by the measurement of the transverse mass dependence of the source size extracted using different particle species. Such characteristics can be determined using the analysis technique called femtoscopy. This method is based on the correlations of particles with small relative momenta which originate from the effects of Quantum Statistics as well as the strong and Coulomb Final State Interactions.

A recent analysis of the particle production at the highest available collision energies of heavy-ion collisions reveals the puzzling result of the proton yield to be significantly smaller comparing with the thermal model expectations. It is argued that the annihilation during the hadronic rescattering phase of the collision is the possible explanation of this effect. The caveat is the meagre knowledge of baryon-antibaryon cross-sections both from the theoretical and experimental point of view. Hence, commonly used rescattering models need to base these parameters on a number of assumptions. Femtoscopy, however, is also sensitive to the strong Final State Interaction of the analysed pairs. The amplitude of the strong interaction is directly related to the interaction cross section. Therefore, the cross-sections constrained by the femtoscopic analysis of collision data might help to correctly describe the rescattering phase of the heavy-ion collisions, which can be useful in solving the riddle of the unexpectedly small proton yield.

This thesis includes the femtoscopic analysis with pp , $\bar{p}\bar{p}$, $p\bar{p}$, $p\bar{\Lambda}$, and $\bar{p}\Lambda$ pairs measured in Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{NN}}=2.76$ TeV collected by A Large Ion Collider Experiment at the Large Hadron Collider. The outcome of the experimental part of this study covers the centrality and the pair transverse mass dependence of the source size and λ parameter describing the dilution of the correlation functions. In addition, the feasibility of the extraction of the strong interaction parameters using the low relative momentum correlations of baryon pairs is confirmed.

The femtoscopic radii derived from the one-dimensional correlation functions of pp and $\bar{p}\bar{p}$ pairs, combined with the analogous measurements with kaon pairs, follow the transverse mass scaling within the systematic uncertainties. Such behaviour is consistent with the predictions of the hydrodynamic model. The agreement of pp and $\bar{p}\bar{p}$ radii

supports the assumption of the equal values of the strong interaction parameters for these pair types. The λ parameters were found to be smaller than unity, which is understood to be the consequence of the number of factors, such as the non-Gaussian shape of the source, and the long-lived resonances.

In this thesis the femtoscopic analyses with pp , $\bar{p}\bar{p}$, $p\bar{p}$, $p\bar{\Lambda}$, and $\bar{p}\Lambda$ pairs were performed taking into account all the relevant contributions from the residual correlations. This phenomenon arises due to the femtoscopic correlations of the parent particles, produced directly in the collision which decay to the particles registered in the detector. The effect of residual correlations was found to be vital for the description of the baryon-antibaryon correlation functions, and in consequence the extraction of the system size and the strong interaction parameters. The formalism treats the residual correlations as a source of additional information. The method of dealing with the so-called residual correlations developed here is the innovative contribution of this thesis.

Furthermore, the novel input of this thesis is the indication that femtoscopy can indeed put constraints on the strong interaction parameters for baryon-antibaryon pairs. In particular, the estimations of the values of the imaginary part of the scattering length, which characterises the annihilation channel, are given in this thesis for $p\bar{\Lambda}$ and $\bar{p}\Lambda$ systems.

The introduced methodology of the residual correlations allows to estimate the parameters of the strong interaction for any baryon-antibaryon pair type for which the precise femtoscopic data would be available. Therefore, one will be able to put constraints on the values of the scattering length for such pairs as $p\Xi^0$, $\Lambda\Lambda$, or $\Lambda\Xi^0$, which are currently known with a low precision.

Streszczenie

Ultrarelatywistyczne zderzenia ciężkich jonów są unikalnym źródłem plazmy kwarkowo-gluonowej, której istnienie przewiduje teoria chromodynamiki kwantowej. Analiza właściwości tego stanu materii jest niezbędna do szczegółowego zrozumienia silnie oddziałującej materii.

Analiza femtoskopowa pozwala wyznaczać czasowo-przestrzenną charakterystykę źródła powstałego w zderzeniu ciężkich jonów. Jego rozmiary są rzędu femtometrów, a czas życia rzędu 10^{-23} sekundy. Femtoskopia opiera się na analizie korelacji cząstek o małym pędzie względnym. Źródłem korelacji są efekty statystyki kwantowej (w przypadku cząstek identycznych) oraz oddziaływania w stanie końcowym (silne i kulombowskie). Jednym z intrygujących wyników eksperymentów zderzeń ciężkich jonów jest dowód na istnienie kolektywności materii powstałej w takich reakcjach. Femtoskopia pozwala zweryfikować obecność tego efektu poprzez analizę zależności rozmiaru źródła w funkcji masy poprzecznej pary. Analiza femtoskopowa pozwala również na pomiar parametrów oddziaływania silnego. Jest to szczególnie istotne w przypadku par barion-antybarion, dla których znajomość parametrów oddziaływania jest znikoma zarówno od strony teoretycznej jak i doświadczalnej. Badanie produkcji cząstek w zderzeniach jąder ołowiu przy najwyższych obecnie dostępnych energiach przyniosło nieoczekiwany wynik, wskazujący na istotnie niższą produkcję protonów w porównaniu do przewidywań modelu termicznego. Uważa się, iż obecność zjawiska anihilacji cząstek w fazie rozpraszania jest wyjaśnieniem tej obserwacji. Jednak uboga wiedza o wartościach przekrojów czynnych na oddziaływanie par barion-antybarion uniemożliwia dokładne modelowanie fazy rozpraszania. Amplituda oddziaływania silnego w stanie końcowym, będącego jednym ze źródeł korelacji femtoskopowych jest bezpośrednio związana z przekrojem czynnym na oddziaływanie. Zatem wyznaczenie przekrojów czynnych metodą femtoskopii może pozwolić na poprawne opisanie anihilacji, mogące następnie przyczynić się do zrozumienia produkcji protonów w zderzeniach ciężkich jonów przy najwyższych obecnie dostępnych energiach.

Niniejsza rozprawa zawiera analizę femtoskopową par pp , $\bar{p}\bar{p}$, $p\bar{p}$, $p\bar{\Lambda}$ i $\bar{p}\Lambda$ zmierzonych w zderzeniach jąder ołowiu o energii w środku masy na parę nukleonów $\sqrt{s_{NN}}=2.76$ TeV zebranych przez eksperyment ALICE na akceleratorze LHC. Wynikiem części doświadczalnej pracy jest wyznaczenie rozmiaru źródła w funkcji centralności i masy poprzecznej dla par pp i $\bar{p}\bar{p}$. Ponadto praca wykazuje, iż analiza femtoskopowa par barion-antybarion umożliwia wyznaczenie parametrów oddziaływania silnego dla tych par.

Promienie femtoskopowe otrzymane z analizy funkcji korelacyjnych par pp i $\bar{p}\bar{p}$ są zgodne w ramach niepewności systematycznych z trendem skalowania z masą poprzeczną rozmiarów źródeł otrzymanych dla par kaonów. Jest to spójne z przewidywaniami modelu

hydrodynamicznego. Zgodność promieni dla par pp i $\bar{p}\bar{p}$ potwierdza hipotezę identycznych wartości parametrów oddziaływania silnego dla tych par.

Innowacyjnym wkładem pracy jest również stworzona metoda analizy korelacji rezydualnych, powstających wskutek femtoskopowej korelacji par cząstek pierwotnych, które ulegają rozpadowi do cząstek wtórnych, rejestrowanych ostatecznie w detektorze. Analiza femtoskopowa par barion-barion oraz barion-antybarion została przeprowadzona z uwzględnieniem wkładów korelacji rezydualnych, gdyż zjawisko to istotnie wpływa na funkcje korelacyjne, a w konsekwencji na zmierzone wartości rozmiarów źródła i parametrów oddziaływania silnego.

W rozprawie pokazano, iż femtoskopia może służyć do wyznaczenia parametrów oddziaływania silnego dla par barion-antybarion. W szczególności, praca zawiera oszacowania parametrów oddziaływania silnego dla par $p\bar{\Lambda}$ i $\bar{p}\Lambda$ wartości części urojonej długości rozpraszania opisującej zjawisko anihilacji.

Formalizm korelacji rezydualnych rozwinięty w niniejszej pracy pozwala wyznaczać parametry oddziaływania silnego dla dowolnych par barion-antybarion, dla których w przyszłości będą dostępne dokładne dane femtoskopowe. Pozwoli to np. na wyznaczenie eksperymentalnych ograniczeń na wartości długości rozpraszania dla takich par jak $p\Xi^0$, $\Lambda\Lambda$ czy $\Lambda\Xi^0$, które obecnie znane są jedynie z niewielką precyzją.

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Introduction

Physics, the fundamental science, aims to understand all the details of the Universe, beginning with the elementary particles and their interactions. The pursuit of the answers to the most vital questions of the “how does it work” kind are what makes the progress in science. Numerous ideas explaining the surrounding nature have been developed only after the unexpected experimental results. Hence, it is crucial to conduct the research in both theoretical and experimental fields of science in parallel.

In accordance with the current understanding, the matter is composed of fundamental particles: quarks and leptons, which are the constituents of more complex objects, e.g. nucleons, nuclei, or atoms. Their mutual interaction is governed by the fundamental forces: strong, weak, electromagnetic, and gravitational. Although the relative strength and the range of the interaction of those forces differ significantly, physicists conduct the research on the possible unification in order to create the concise description of the Universe. Currently it is well-known that electromagnetic and weak interaction can be considered as two facets of the unified electroweak force. This discovery was essential in developing the Standard Model, which describes a lot of experimental results with great precision. However, this theory is still incomplete since several observables, such as the asymmetry between matter and antimatter, are waiting for the commonly accepted explanation. Therefore, a number of experiments in the field of particle physics are being carried out.

The theory named Quantum Chromodynamics (QCD) characterises the features of the strong interaction. The features of the strongly interacting matter are not entirely understood. For instance, the existence of the state of matter called the quark-gluon plasma (QGP) is predicted. The research on QGP might shed some light on the evolution of the early Universe because such state of matter is presumed to have existed in the first microseconds after the Big Bang. Ultra-relativistic heavy-ion collisions provide the unique opportunity to produce the QGP and thus study its properties.

The size scale of the medium created in the collisions of the nuclei at ultra-relativistic energies is of the order of 10^{-15} m = 1 fm, and the time scale is of the order of 10^{-23} s. Sophisticated analysis methods are needed to access such a small and short-lived state of matter. Femtoscopy, the analysis of particle correlations at low relative momentum, enables to infer the spatiotemporal extent of the source produced in the collisions. Moreover,

it gives insight into the evolution of the system created in such collisions. Femtoscopy can also provide some knowledge of the parameters of strong interaction which are currently barely known for numerous pairs of particles. This is of great importance e.g. for constraining hyperon-hyperon potentials for the equation of state of dense matter of compact stars.

Experimental results from the heavy-ion collisions exhibit the signatures of hydrodynamic flow, resulting in e.g. a decrease of the source radii extracted from pion femtoscopic correlations with increasing transverse mass. The question arises whether this collectivity goes beyond mesons and includes baryons as well. This thesis attempts to verify if the femtoscopic radii extracted from proton correlations follow the global trend of the transverse mass dependence of the radii. Such behaviour is a necessary condition for the confirmation of collective behaviour of the medium created in the heavy-ion collisions since all the particle species should obey the hydrodynamic flow. STAR experiment observed the violation of the transverse mass scaling, i.e. the $p\Lambda$ source size appears to be two times larger than the one for $p\bar{\Lambda}$. This thesis aims to prove that $p\Lambda$ and $p\bar{\Lambda}$ source sizes are consistent if one takes the so-called residual correlations effect into account, and thus the transverse mass dependence of experimental femtoscopic radii is compatible with the expectations from the hydrodynamic models.

The understanding of baryon interactions is one of the major challenges in Quantum Chromodynamics. Despite numerous measurements for baryon-baryon pairs, the knowledge of interaction parameters for baryon-antibaryon pairs is meagre. As a matter of fact only few pair types including proton, neutron and deuteron were analysed in the dedicated experiments. Furthermore, the theory does not provide much information about interactions in baryon-antibaryon pairs. In femtoscopy one employs the strong Final State Interaction to describe the measured correlations. Therefore, such analysis can put experimental constraints on the values of strong interaction parameters. The attempt to estimate values of the scattering length for $p\bar{\Lambda}$ pair using femtoscopic correlations is made in this work.

This thesis includes the analysis of femtoscopic correlations of baryon pairs: pp , $\bar{p}\bar{p}$, $p\bar{p}$, $p\bar{\Lambda}$, $\bar{p}\Lambda$ measured by A Large Ion Collider Experiment in Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{NN}}=2.76$ TeV. The goal of this work is the measurement of the source size obtained using pp and $\bar{p}\bar{p}$ pairs. Such analysis is performed simultaneously as a function of the collision centrality and the pair transverse mass for the first time. Furthermore, the feasibility of extracting $p\bar{\Lambda}$ ($\bar{p}\Lambda$) strong interaction parameters from the femtoscopic correlations is investigated. Both of these topics required the development of the residual correlations formalism which is a novel input of this thesis to the field of physics of heavy-ion collisions.

The organisation of the thesis is as follows. In Chapter 1 the basic introduction to the physics of heavy-ion collisions is presented, in particular the present state of knowledge regarding the strongly interacting matter, the phenomenological models, subsequently used in this work, and the selected experimental results. Chapter 2 contains the description of the facility which provided the data essential for this thesis, namely A Large Ion Collider Experiment. The general presentation of the subdetectors, as well as the data processing are given. Chapter 3 introduces the analysis technique, called femtoscopy. This includes historical perspective, the general formalism, the discussion of the sources of the correlations in various pair types of bosons and fermions. In particular, the description of baryon correlations is emphasised. In Chapter 4 the issue of residual correlations is discussed in detail, especially the innovative formalism of dealing with such type of correlations. Chapter 5 presents the test of this method by the reanalysis of the femtoscopic measurement with $p\bar{\Lambda}$, and $\bar{p}\Lambda$ pairs performed by STAR experiment. Chapter 6 encloses the details of the experimental analysis performed with ALICE detector, including e.g. the specific data selection criteria. In Chapter 7 the results of the femtoscopic analysis with pp and $\bar{p}\bar{p}$ pairs in Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{NN}}=2.76$ TeV are presented, in particular the transverse mass dependence of the size of the source. Finally, Chapter 8 provides the preliminary outcome of the femtoscopic analysis with $p\bar{p}$, $p\bar{\Lambda}$, $\bar{p}\Lambda$ pairs measured by ALICE, including the estimation of the strong interaction parameters. Both Chapter 7 and Chapter 8 significantly rely on the formalism introduced in Chapter 4.

1. Physics of the ultra-relativistic heavy-ion collisions

This chapter introduces the foundations of the ultra-relativistic heavy-ion collisions including general concepts of the Quantum Chromodynamics theory, description of the Quark-Gluon Plasma state, and modelling of the collision. In the end, the overview of the experimental results is given.

1.1. Quantum Chromodynamics

According to the Standard Model, the state-of-the-art theory of fundamental constituents of matter and their mutual interactions, the Universe is formed of point-like particles with spin $\frac{1}{2}$, called fermions. They are categorised into six leptons and six quarks. The family of leptons, which have an integer electric charge, is composed of electron, muon and taon together with their associated neutrinos (i.e. electron neutrino, muon neutrino and taon neutrino). As far as quark flavours are concerned one can distinguish: up, charm, top (having electric charge equal to $+\frac{2}{3}|e|$) and down, strange, beauty (electric charge equal to $-\frac{1}{3}|e|$). Furthermore, for each particle a corresponding antiparticle exists with the same mass but opposite charges (i.a. electric charge, baryon number, and lepton number). The Standard Model includes also the force carriers which have an integer spin (bosons). Gluon octet is used to describe the strong interaction, the carriers of the weak force are $W^\pm$ and Z^0 bosons and finally, the electromagnetic interaction is mediated by the photon. The theory has predicted that the Higgs boson, the carrier of the Higgs mechanism, exists. This phenomenon is the source of breaking of the electroweak symmetry, explaining why the fundamental particles have masses. The particle has been recently observed by the ATLAS and CMS experiments [1, 2].

Although the Standard Model describes most of the data gathered by the high energy physics experiments with a good precision, there are few open issues. For instance, the gravitational interaction is not described. Next, massless neutrinos are assumed whereas experimental results suggest their finite masses. Furthermore, the model does not explain the prevalence of the matter over the antimatter as well as the existence of the dark matter [3].

Quantum Chromodynamics (QCD) is the gauge field theory describing the strong interaction. Partons (common name for quarks and gluons) are the fundamental particles of strong interaction, characterised by the colour charges (red, green and blue by analogy to the human vision). This property was proposed as a result of the observation of particles built of three quarks of the same flavour (such as Δ^{++} with the spin 3/2, consisting of three up quarks in the same spin state) which was inconsistent with the Pauli exclusion principle. With such postulation only "white" particles are observed in nature, i.e. mesons composed of quark and antiquark (colour and its anticolour), and baryons which are triplets made of red, green and blue quarks. For example, π^+ meson (pion) contains quarks up and antidown, whereas two antiup and one antidown are the valence quarks of the antiproton $\bar{p}$.

QCD predicts the running coupling constant to be dependent on momentum transferred in the interaction Q^2 :

$$\alpha_s(Q^2) \propto \frac{1}{\ln(Q^2/\Lambda^2)}, \quad (1.1)$$

where Λ is a constant defining the scale. For the large values of Q^2 (small α_s) methods used in Quantum Electrodynamics (QED) might be applied (this is a so-called perturbative region). In the regime of small values of Q^2 the numerical calculations on discrete space-time points (a so-called Lattice QCD) are performed.

The QCD potential, shown in Fig. 1.1, for quark and antiquark depends on the separation distance r :

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr, \quad (1.2)$$

where k is the factor of proportionality.

There are two peculiar features of strong interaction which are the consequence of Eq. (1.1). At short distances quarks behave as free particles. Such an effect is called the asymptotic freedom. On the other hand, the attractive force increases with increasing distance between quarks as the second term in Eq. (1.2), proportional to the separation distance, becomes more and more important. Therefore quarks cannot be easily separated in space which is known as the confinement phenomenon. The implication is that quarks are bound within hadrons. Once the energy of the interaction between quarks gets larger (due to the increasing separation) than the sum of its masses, a new quark-antiquark pair would be created [4, 5].

1.2. Quark-Gluon Plasma

The Quark-Gluon Plasma (QGP) is the matter composed of quarks and gluons which are no longer confined, but may propagate in the whole volume of the medium. It is expected that the phase transition from the hadronic matter to QGP occurs at sufficiently high temperature and (or) baryon density.

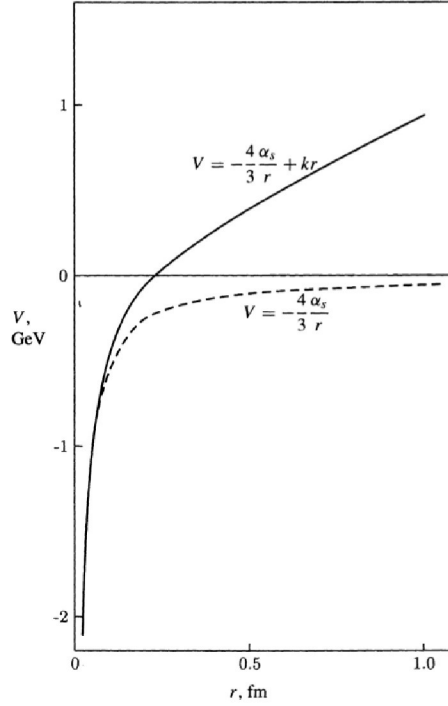


Figure 1.1: Quantum Chromodynamics potential for $k = 1$ GeV/fm and $\alpha_s = 0.2$ [4].

The phase diagram of Quantum Chromodynamics can be inferred from the lattice QCD calculations (Fig. 1.2). From these results one may estimate the critical values of the temperature and the baryon chemical potential μ_B (defined as the partial derivative of the internal energy with respect to the amount of baryons at constant entropy, volume of the system, and the constant number of all other particle types [3]; the measure of baryon density) for which the phase transition to QGP happens. It is shown that the state of deconfined partons exists at temperatures $T \gtrsim 162$ MeV at $\mu_B = 0$. One expects that the phase transition from hadronic matter to QGP is of the first order at non-zero baryon density, whereas for baryon density approaching zero, the experimental data suggest the smooth phase transition (a so-called cross-over). Hence, the research on the critical point separating different kinds of transition from hadronic matter to QGP is being carried out [3].

Another example of the lattice QCD calculations is presented in Fig. 1.3. The plot shows the rapid (but continuous) increase of the energy density ϵ divided by fourth power of the temperature T^4 , which corresponds to a number of degrees of freedom, for certain critical value of the temperature T_c . Such result might indicate the creation of QGP.

1.3. Ultra-relativistic heavy-ion collisions

One may distinguish two methods of forming the QGP state, namely a slow compression of the hadronic matter which leads to the creation of the cold matter at large baryon

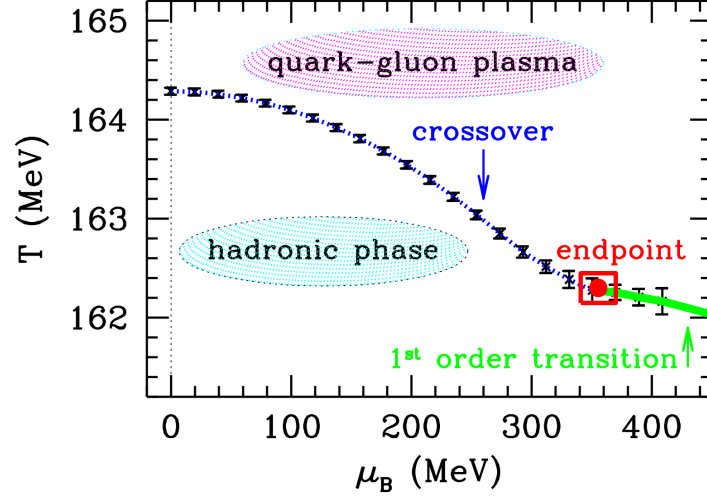


Figure 1.2: The phase diagram of the QCD matter obtained with the calculations on lattice [6].

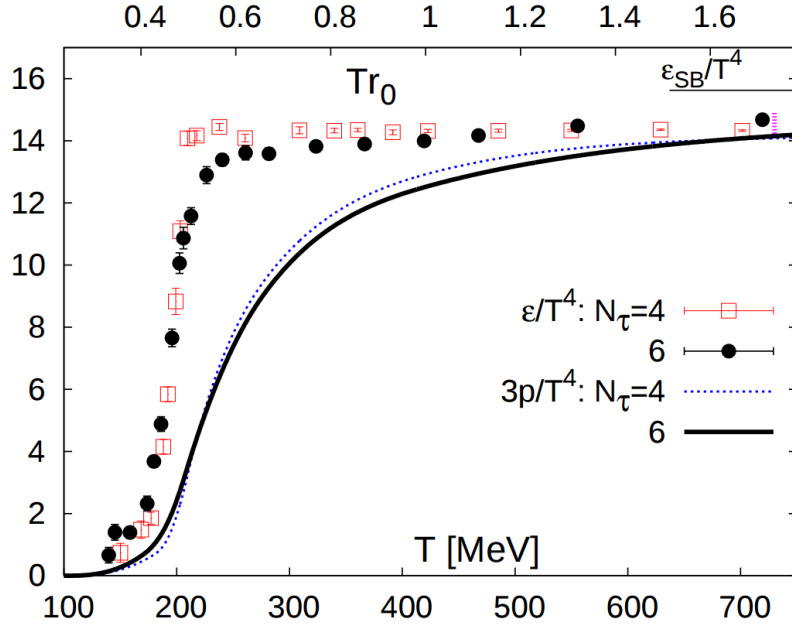


Figure 1.3: The energy density as a function temperature from QCD [7].

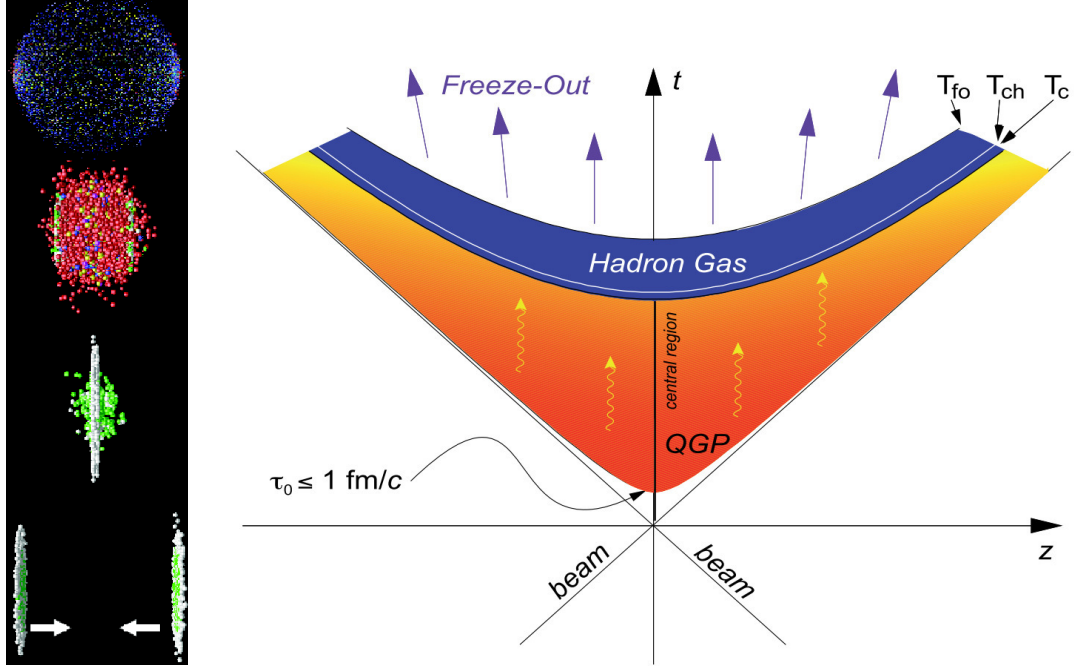


Figure 1.4: Space-time evolution of the heavy-ion collision [3, 8]. See text for details.

chemical potential, and fast compression resulting in the system at high temperature. Nonetheless, only the latter can be realised in the experiments. Indeed, the collisions of heavy ions at ultra-relativistic energies can be used to produce the matter with extremely high temperature and vanishing baryon chemical potential. The space-time evolution of such process is depicted in Fig. 1.4. The scheme shows that after the collision of nuclei (presented as thin discs due to the Lorentz contraction), a non-equilibrium state of matter is created. The thermalisation is reached after the time of the order of $\tau_0 \leq 1 \text{ fm}/c$ leading to the QGP phase. When the system cools down to the chemical freeze-out temperature (T_{ch}) the inelastic collisions cease. At that moment hadronisation occurs, i.e. quarks group into hadrons. In this stage the unstable particles may still decay into the final state hadrons. The elastic collisions may happen until the system reaches the kinetic freeze-out temperature (T_{fo}). It should be emphasised that the lifetime of the matter composed of quarks and gluons is of extremely short duration and scientists reverse-engineer its properties by measuring the particles in the final state. It is noticeable that the medium created in heavy-ion collisions expands in the longitudinal and transverse directions analogously to the Hubble expansion in cosmology, where one observes that the outward velocity of a galaxy increases with distance [5, 8].

Two general setups of the heavy-ion collision experiments can be distinguished, namely the fixed target and the collider. In the former the beam of accelerated particles hits the stationary target. High luminosity (i.e. the number of particles in the beam per unit area per unit time) is one of the most vital benefits of such experiments. Besides, higher collision rate and higher acceptance for particles with small momenta can be achieved in the fixed-target experiments comparing with the colliders. However, due to the higher energy

in the centre-of-mass that can be achieved (see the next paragraphs) and availability of the midrapidity region, the colliders, i.e. experiments with two accelerated beams hitting each other, are ideally designed for the analysis of the properties of the QGP.

Below a few useful variables used in the high-energy experiments are defined [4]. The square of four-momentum of the system where a particle (projectile) with a rest mass m_p , momentum $\vec{p}_p$ and energy E_p hits a particle (target) with mass m_t , momentum $\vec{p}_t$ and total energy E_t , can be expressed by:

$$p^2 = -s = (\vec{p}_p + \vec{p}_t)^2 - (E_p + E_t)^2 = -m_p^2 - m_t^2 + 2\vec{p}_p \cdot \vec{p}_t - 2E_p E_t. \quad (1.3)$$

In the fixed target experiments a target particle rests in the laboratory frame and thus:

$$s = m_p^2 + m_t^2 + 2m_t E_p. \quad (1.4)$$

In the collider experiments the projectile and the target move in the opposite directions:

$$s = -p^2 = 2(E_p E_t + |\vec{p}_p| |\vec{p}_t|) + (m_p^2 + m_t^2) \simeq 4E_p E_t. \quad (1.5)$$

The latter approximation is valid for $E_p, E_t \gg m_p, m_t$. From Eq. (1.4) and Eq. (1.5) one can notice the linear increase of the energy in the centre of mass with the energy of the beams ($\sqrt{s} \simeq 2E$) in case of colliders. On the other hand, in the fixed target experiments the $\sqrt{s}$ increases more slowly and depends on the square-root of the projectile's energy ($\sqrt{s} \simeq \sqrt{2m_t E_p}$) [4]. The energy in the centre-of-mass system per nucleon pair is defined as:

$$\sqrt{s_{\text{NN}}} = \frac{2}{A_p + A_t} \sqrt{(E_p + E_t)^2 - (\vec{p}_p + \vec{p}_t)^2}, \quad (1.6)$$

where A_p, A_t are the mass numbers of the projectile and target.

NA49 and NA61 experiment at the Super Proton Synchrotron (SPS) at CERN are the examples of the fixed target experiments which studied collisions of, for instance, Pb–Pb, C–C, Si–Si and pp systems at $\sqrt{s_{\text{NN}}} = 6.3 \div 17.3$ GeV. As far as the collider experiments are concerned one should mention the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory with the Beam Energy Scan program studying Au–Au collisions $\sqrt{s_{\text{NN}}} = 5.0 \div 39$ GeV as well as the collisions of gold ions at energies up to $\sqrt{s_{\text{NN}}} = 200$ GeV. Furthermore, there are ALICE, LHCb, CMS and ATLAS experiments at the Large Hadron Collider at CERN where the energy of Pb–Pb collisions reached $\sqrt{s_{\text{NN}}} = 5.02$ TeV so far.

For the ultra-relativistic heavy-ion collisions, a geometric description of the collision is often applied. In such model one introduces the participants i.e. nucleons which interact with each other, and the spectators, nucleons which do not collide with any other nucleon during the collision. Participants which took part in an inelastic collisions are called the

wounded nucleons [9]. The number of the spectators is determined in experiments by the measurement of the energy deposited in the calorimeters located at zero-degree angle with respect to beam trajectories.

During the data analysis in the heavy-ion experiments, collisions are usually divided into so-called centrality classes, which are calculated using the distributions of the multiplicity of particles registered in detectors. From the theoretical point of view, centrality is described by the impact parameter that is a magnitude of the impact vector defined as the vector which connects centres of the colliding nuclei in the transverse plane with respect to the nucleon trajectory. The impact parameter is directly related with the number of participants, and thus wounded nucleons.

In the ultra-relativistic energies regime it is advantageous to use the rapidity, which is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}, \quad (1.7)$$

where $E = \sqrt{m^2 + |\vec{p}|^2}$ is the particle energy and p_L denotes the longitudinal momentum. Another commonly used variable in the experiments is pseudorapidity which depends only on the polar angle θ (defined by the beam axis and the momentum vector) that can be easily measured:

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right). \quad (1.8)$$

Pseudorapidity is equivalent to the rapidity in the limit of the infinite momentum. The region with $y \approx \eta \approx 0$ in the centre-of-mass frame, called midrapidity, is particularly interesting since in such phase-space there are mainly particles which are created directly in the collision or particles from the colliding nuclei which suffered multiple rescattering processes [10].

1.4. Models of the heavy-ion collisions

As mentioned beforehand, one is not able to easily calculate the production of particles in processes where transverse momentum transfers are below ~ 2 GeV/ c (they are usually called soft) directly from the QCD. Therefore, the phenomenological models are commonly used. Two general methods can be distinguished. Microscopic models are focused on the dynamics of single objects such as hadrons or strings. The simulation in string models is composed of the formation of strings by exchanging momentum or colour, and later the string fragmentation. One should emphasise that such models need as the input the cross sections for known processes and the kinematic distributions. Regarding the collisions of heavy ions, they are usually treated as a superposition of nucleon-nucleon collisions. UrQMD [11, 12] and HIJING [13] are most common examples of that way of modelling the collisions. Such models do not assume the transition to quark-gluon plasma state,

though. The second method to model the heavy-ion collision uses macroscopic approach. The medium produced in the collision is analysed using statistical thermodynamics. The evolution is governed by the equation of state and the macroscopic parameters. Especially, the hydrodynamic models are applied to characterise the collective motion of the matter produced in the heavy-ion collisions [14, 15]. The created fireball is treated as a fluid described by the equations of fluid mechanics and parameters such as viscosity. Current state-of-art method of modelling the evolution of the heavy-ion collision consists typically of three steps: the initial conditions, the hydrodynamic evolution and the hadronic rescattering phase [3, 16].

1.4.1. THERMINATOR

THERMINATOR (THERMal heavy-IoN generATOR) [17] is a particle generator based on Monte Carlo methods. The model's objective is to analyse the production of particles in the ultra-relativistic collisions of heavy ions at the RHIC and the LHC collision energies. THERMINATOR applies the statistical method to calculate the particle production. The model assumes simultaneous chemical and kinetic freeze-outs (single freeze-out model). The simulation starts with the generation of the positions and velocities of all the particles including hadronic resonances on the given hypersurface. In the next step, the particles follow the classical trajectories with velocities calculated as a sum of thermal motion and collective velocity of the medium. Decays of the resonances occur until all the remaining particles are stable. In this model secondary rescatterings are not considered. In the updated version of THERMINATOR [18], the user is able to use the chosen expansion velocity field as well as the shape of the freeze-out hypersurface, in particular those generated with hydrodynamic calculations.

1.4.2. UrQMD

UrQMD (Ultra-relativistic Quantum Molecular Dynamics) [11, 12] is the model which is based on the theory of microscopic transport. Produced hadrons are propagated along the classical trajectories taking into account stochastic binary scatterings, formation of colour strings as well as decays of resonances. Hadron-hadron and nucleus-nucleus collisions at low energies are modelled using interaction cross-sections between hadrons and resonances on the particle level. At higher energies, the excitation of colour strings fragmenting into hadrons is applied. The caveat of such approach is that cross sections are measured only for few hadron pairs, and thus one needs to rely on theoretical models or extrapolations. The collisions in UrQMD may be realised for 55 baryons and 45 mesons along with corresponding antiparticles and isospin-related states. Furthermore, the model assumes the same number of baryons and antibaryons as well as the same interaction cross-sections for baryon-baryon and antibaryon-antibaryon pairs. Collisions of two hadrons happen once

the distance between them is less than $\sqrt{\sigma/\pi}$, where σ is the total cross section dependent on the energy and pair type. The most precise method for the determination of such cross-section is the fit to the data from dedicated experiments. However, it is available only for few pair systems (including e.g. protons, neutrons, pions and kaons), therefore simplifications have to be usually applied. As far as baryon-antibaryon interactions are concerned, it is commonly known that at low energies, annihilation is the important contribution to the total cross section. Experiments indicate differences between $p\bar{p}$ annihilation and non-annihilation channels possibly caused by available kinematic phase-space or dynamical differences between these channels [12]. However, it was observed that pp and non-annihilation $p\bar{p}$ interactions are the same. In UrQMD experimental data are used to describe $p\bar{p}$ cross-section avoiding complicated theoretical scenarios of the annihilation process. However, the sum of elastic and annihilation cross sections are not equal to the total cross section which is interpreted as a diffractive cross section describing the excitation of particles to resonances or strings. The cross section for baryon-antibaryon pairs heavier than $p\bar{p}$ at certain centre-of-mass energy of the pair $\sqrt{s}$ is assumed to be the same as $p\bar{p}$ calculated at the same $\sqrt{s}$ [12]. This means that annihilation cross section decreases with increasing mass because $\sigma \propto s^{-1/2}$. One needs to emphasise that this thesis includes the discussion on the possible extraction of the baryon-antibaryon strong interaction parameters using femtoscopy techniques (see Sec. 1.5.4, Sec. 3.3, Sec. 3.4, Chap. 5, and Chap. 8) which might complement the knowledge of baryon-antibaryon cross sections.

1.4.3. HIJING

HIJING (Heavy-Ion Jet INteraction Generator) [13] is a Monte Carlo model developed to study phenomenology of proton-proton, proton-nucleus and nucleus-nucleus collisions at high energies. A particular emphasis is put on the production of jets using perturbative QCD. HIJING takes also into account multiple minijet production including radiation in initial and final states. The number of inelastic processes is determined as a function of the impact parameter using exact diffuse nuclear geometry. Furthermore, the interactions of jets with dense matter are implemented. Nuclear shadowing of parton distribution function is also included in this model. HIJING successfully connects nonperturbative physics at intermediate collision energies (e.g. SPS) with perturbative QCD physics explored in ultra-relativistic collisions at RHIC and LHC. However, the model does not take into account final state interactions of particles at low transverse momentum, and thus it cannot be used to study the approach to local equilibrium.

1.4.4. AMPT

AMPT (A Multi-Phase Transport) [19, 20] is a model focusing on the description of dynamics of the heavy-ion collisions at highest available energies. It includes HIJING model for modelling the initial conditions. Further steps are the simulation of partonic scatterings, based on Zhang's Parton Cascade model [21], and hadronisation described by Lund string fragmentation [22] or quark coalescence models. Finally, A Relativistic Transport model [23] is used to model the stage of hadronic scatterings.

1.4.5. HKM

HKM (HydroKinetic Model) [24, 25, 26] was created to study the evolution of the medium produced in the ultra-relativistic heavy-ion collisions. The simulation involves the following steps: expansion of the dense medium using ideal hydrodynamic equations (assuming local chemical and thermal equilibrium), gradual decoupling of the system, and hadronic rescattering stage described by UrQMD.

1.5. Overview of the results from ultra-relativistic heavy-ion collisions

In this section the selected experimental results directly related to the subject of this thesis are discussed.

1.5.1. Global observables

The charged particle pseudorapidity density per participant pair is one of the fundamental results from the heavy-ion collisions obtained usually within the first days of gathering collision data. The comparison of the results from central nucleus-nucleus and proton-proton collisions, presented in Fig. 1.5, demonstrates that the heavy-ion collisions are not a superposition of independent collisions of two nucleons. Results of $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle$ obtained for Au–Au and Pb–Pb collisions increase as $s_{\text{NN}}^{0.155}$ reaching the value 10.2 ± 0.3 for $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Such dependence on the centre-of-mass collision energy is stronger compared with proton-proton collisions where $s_{\text{NN}}^{0.103}$ increase is observed.

Space-time characteristic of the medium created in heavy-ion collisions are inferred from the pion femtoscopy (for more information see Chap. 3). At the highest currently available collision energy at the Large Hadron Collider the freeze-out volume, i.e. the size of the system at the time when particles do not interact any more is about 5000 fm^3 , and the lifetime of the system exceeds $10 \text{ fm}/c$ which is, respectively, 50% and 40% larger than at top energy at the Relativistic Heavy Ion Collider (Fig. 1.6). These quantities increase linearly with the charged particle pseudorapidity density.

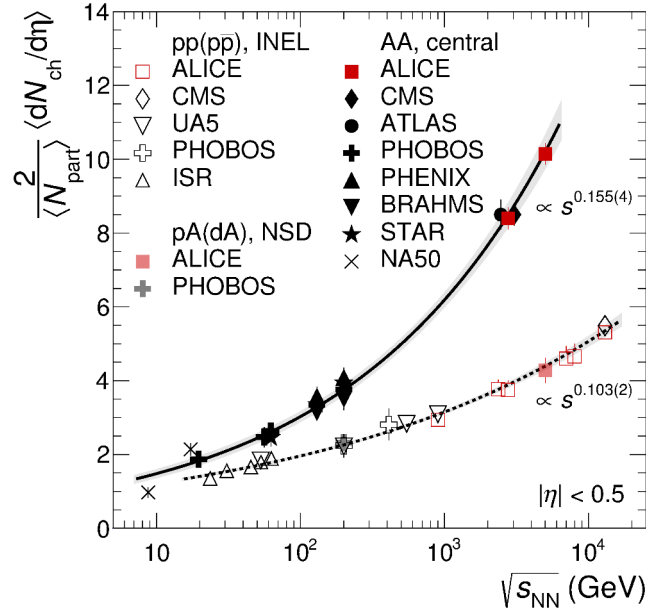


Figure 1.5: Charged particle pseudorapidity density per participant pair for central nucleus-nucleus and proton-proton collisions vs. the energy of the collision [27].

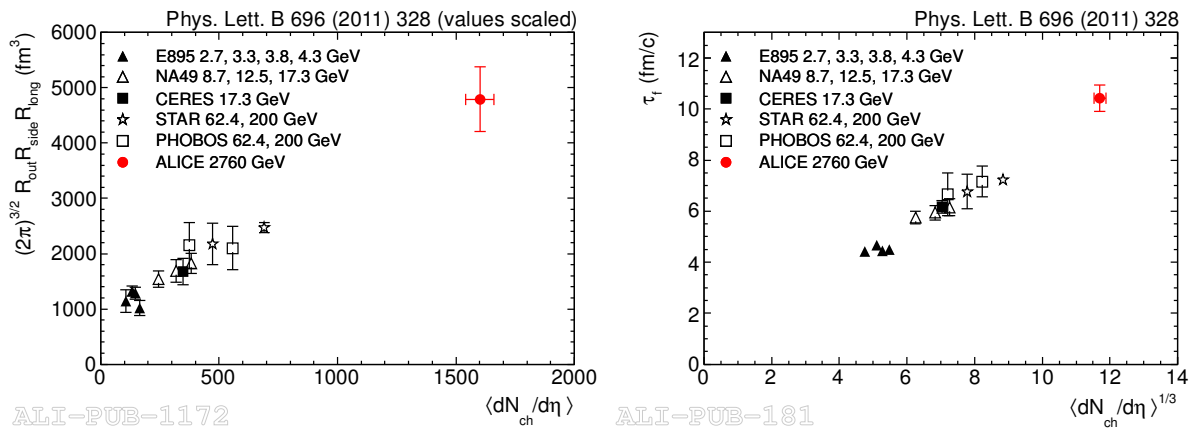


Figure 1.6: Left plot: freeze-out volume. Right plot: the system lifetime. Results obtained using identical particle interferometry [28].

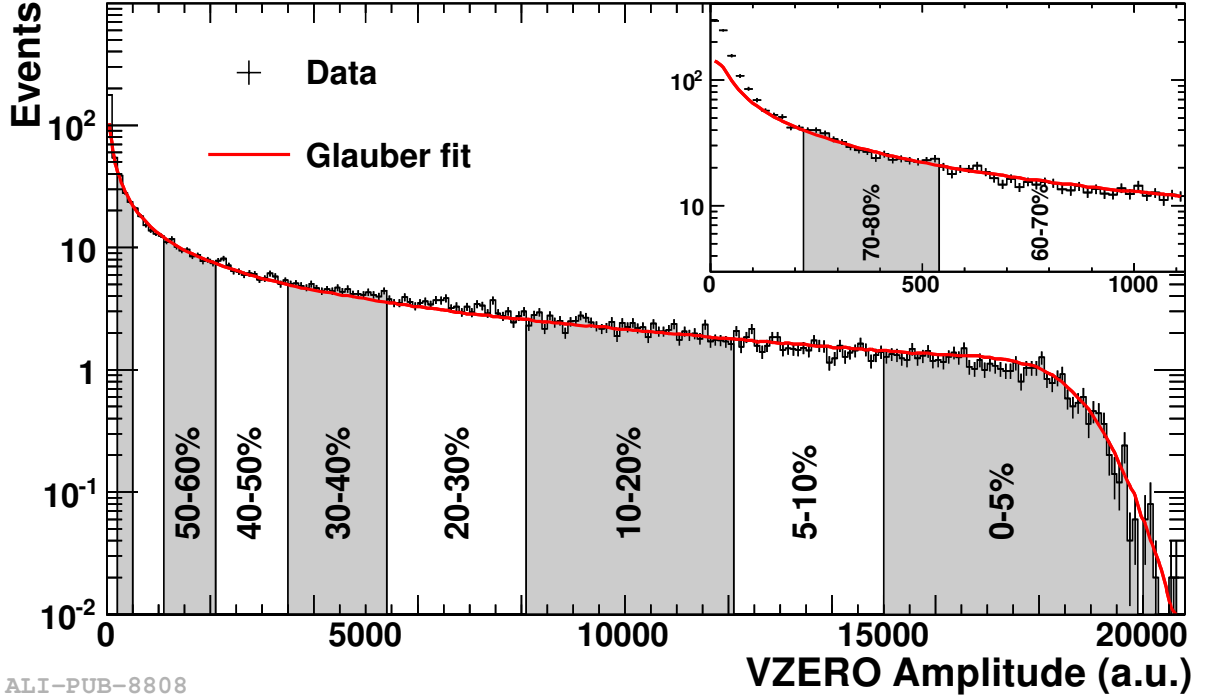


Figure 1.7: Distribution of the amplitude in V0 scintillator (correlated with the event multiplicity) registered by ALICE. The solid line is the fit based on the Glauber model [29].

The multiplicity of the charged particles created in the collision of heavy ions at midrapidity is another essential characteristics of the produced medium. It is directly connected with the collision centrality. In Fig. 1.7 one can see the distribution of the amplitude registered by the detector located at small angles relative to the beam axis which is correlated with the multiplicity registered in the collision, obtained by the ALICE collaboration. The distribution is fitted with the function calculated with the Glauber model [30]. The assumption of the model is that there are $f \times N_{part} + (1 - f) \times N_{coll}$ sources of particles. Here N_{coll} denotes a number of binary collisions, N_{part} is the number of participants, and f describes the relative contribution of hard and soft processes, proportional to N_{coll} and N_{part} , respectively. The number of particles generated by each source is determined using a negative binomial distribution [29]. The Glauber model treats the collision of two nuclei as the superposition of independent nucleon-nucleon collisions [3].

The high multiplicity of particles produced in the heavy-ion collisions allows to perform analysis of femtoscopic correlations which requires high statistics of pairs, especially with low relative momentum. Such study is the main subject of this thesis.

1.5.2. Nuclear modification factor

Another fundamental observable in the high energy heavy-ion experiments is transverse momentum spectra of charged particles, usually presented in the form normalised to

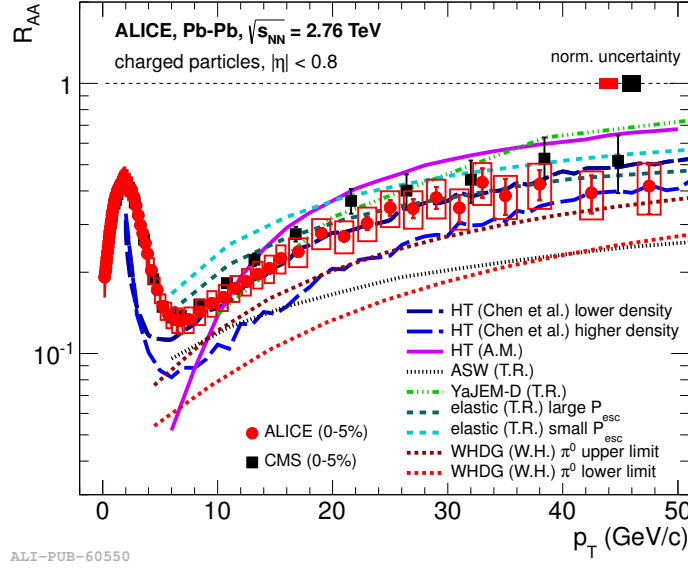


Figure 1.8: Nuclear modification factor of charged particles measured by ALICE and CMS experiments in the most central Pb–Pb collisions in comparison with the model calculations [32].

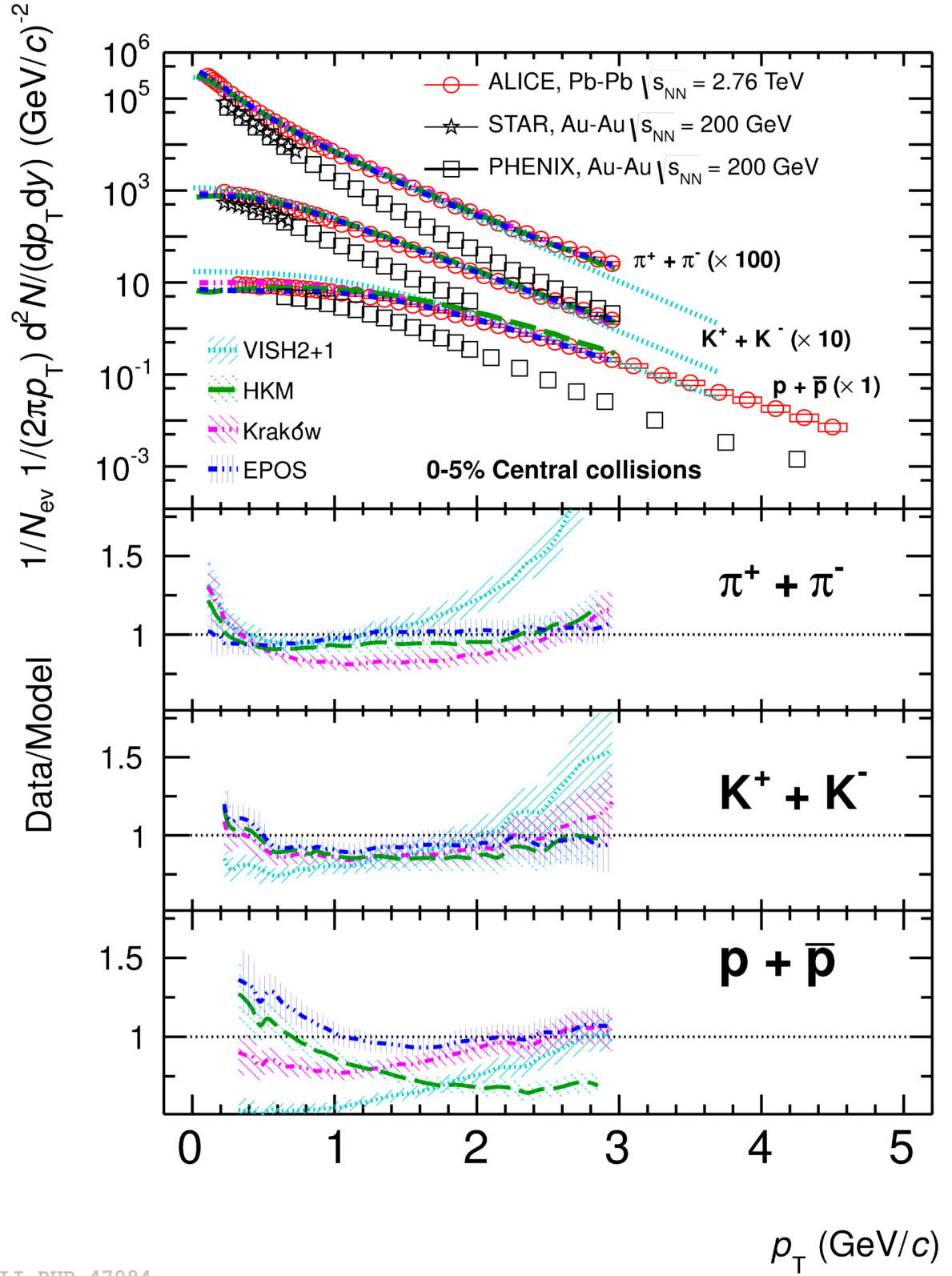
proton-proton collision at the same energy, called nuclear modification factor:

$$R_{AA}(p_T) = \frac{1}{N_{coll}^{AA}} \frac{d^2 N^{AA}/dy dp_T}{d^2 N^{pp}/dy dp_T}, \quad (1.9)$$

where N^{AA} , N^{pp} are the multiplicities of particles produced in nucleus–nucleus and proton–proton collisions, respectively. If one assumes that nucleus–nucleus collision is a superposition of N_{coll} nucleon–nucleon collisions, then the $R_{AA} = 1$. The scaling with N_{coll} is expected for hard processes (with large momentum transfer) whereas for soft processes the scaling with number of participants is predicted. Therefore, the R_{AA} should be less than unity. In fact the LHC experiments (as shown in Fig. 1.8) found the suppression of high- p_T particles which is attributed to strong parton energy loss and large medium density in ultra-relativistic heavy-ion collisions [31, 32, 33].

1.5.3. Transverse momentum spectra of identified hadrons

Transverse momentum dependence of the particle production, presented in Fig. 1.9, shows the mass hierarchy of particle abundances which is explained as an effect of common radial-velocity field coming from the expansion of the fireball created in the collision. Another consequence of such radial flow is the decrease of the femtoscopic radii with pair transverse mass [34] (see Sec. 3.2.5 and Chap. 7 for more details).



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Figure 1.9: ALICE results of the transverse momentum spectra of particles in the centrality bin 0-5%, compared with the hydrodynamical models and results from RHIC [35].

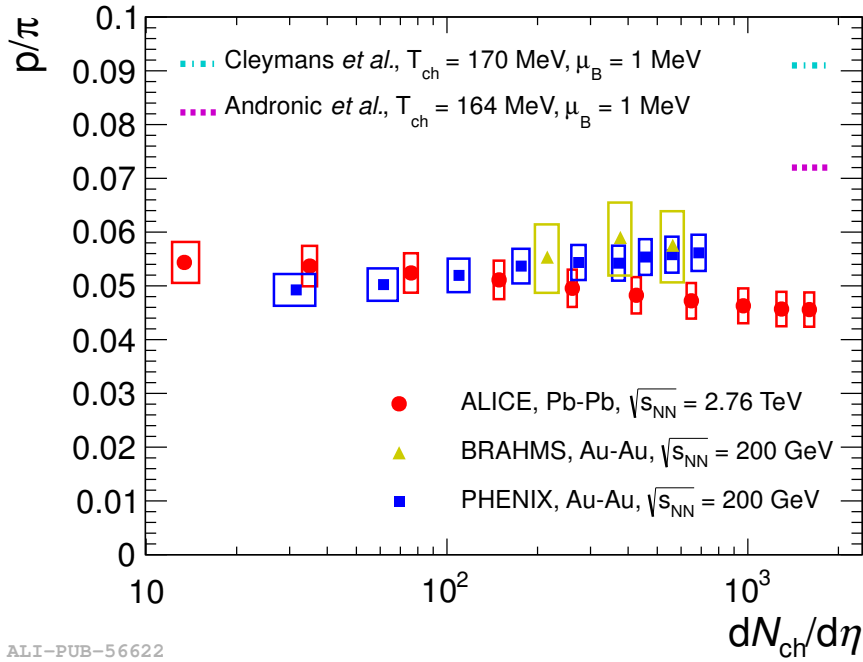


Figure 1.10: ALICE measurement of the p/π ratio as a function of $dN_{ch}/d\eta$, compared with the results from RHIC and the statistical model expectations [35].

Hydrodynamic model calculations describe the p_T spectra well for central collisions up to 2-3 GeV/ c , especially those which apply the hadronic rescattering phase after the hydrodynamic stage. However, for more peripheral collisions and higher values of p_T the description of data is much worse, indicating the limits of applicability of hydrodynamic modelling for the heavy-ion collision [33, 35].

1.5.4. Particle yields

Particle yields, obtained by integrating the transverse momentum spectra, are usually analysed in the frame of statistical hadronisation models [36]. Such models allow to extract the yields of particle species produced in high energy collisions assuming the grand-canonical ensemble which is parametrised by chemical freeze-out temperature T_{ch} , the baryon chemical potential μ_B and the volume in equilibrium. The good agreement between measured yields of most particles and model calculations was observed from the low energy heavy-ion collisions up to the top RHIC energies. However, at the LHC collision energy, the significant discrepancy was found. Namely, as one can see in Fig. 1.10, the proton yield in central Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV appeared to be 1.5 times lower than the one predicted by the statistical model with $T_{ch} = 164$ MeV (such value was observed at RHIC). Proton yield could be described by the lower temperature of $T_{ch} = 152$ MeV (T_{ch} is not expected to decrease with increasing collision energy, though) but then one underestimates the yields of multi-strange baryons. The fit of the available

LHC data gives $T_{ch} \approx 156$ MeV, but the description of the particle yields is worse than at lower energies. There are several possible explanations of this puzzle [33]. For instance, it is argued that final state rescattering, in particular the baryon-antibaryon annihilation, needs to be applied for the LHC data [35, 37]. Due to the larger density, protons are thought to be more affected with respect to the strange baryons. Also, such effect became more important only at the LHC because of the longer lifetime of the rescattering phase. Opponents claim that the reverse process: recreating the baryon-antibaryon pairs through rescattering of several mesons should compensate the annihilation, but the calculations showed that this is not likely to be the case [38].

If the baryon-antibaryon annihilation is indeed important for the understanding the particle yields, it should be reflected in the baryon-antibaryon femtoscopic correlations which are one of the topics of this thesis. In fact, the baryon-antibaryon strong interaction potentials are not known. UrQMD [11, 12], the rescattering model typically used in the mentioned calculations only assumes them to be the same as for the proton-antiproton, expressed as a function of the relative momentum or the centre-of-mass energy of the pair. Therefore, femtoscopic measurements may provide feedback for the hadron rescattering calculations by putting constraints on the parameters of baryon-antibaryon interactions. See Sec. 3.4 for the details.

Other explanations of the low proton yield include non-uniform chemical freeze-out temperature, non-equilibrium effects and influence of high-mass resonances [33, 35].

1.5.5. Production of strange particles

Enhancement of strangeness production in collisions of heavy ions with respect to the elementary reactions was one of the first proposed signatures of the transition to the quark-gluon plasma [39]. The reason is that the energy threshold for the production of strange quarks is smaller in the QGP comparing with the hadron gas. Moreover, strangeness content may be decreased only through weak decays for which time scale is much longer compared with the lifetime of the fireball. Hence, strange quarks may survive hadronisation to become constituents of the strange hadrons. In fact, experimental data reveal that strangeness enhancement in nucleus–nucleus collisions is observed compared with pp collisions. Furthermore, the more strange quarks the hadron is composed of, the stronger the observed enhancement is. Fig. 1.11 presents the enhancement factor as a function of number of participants for different energies at several heavy-ion collision experiments. The enhancement increases with the centrality but is less prominent at higher energies [40].

Abundant production of strange particles makes it possible to perform correlation analysis with Λ hyperons presented in this thesis (see Chap. 6 and Chap. 8).

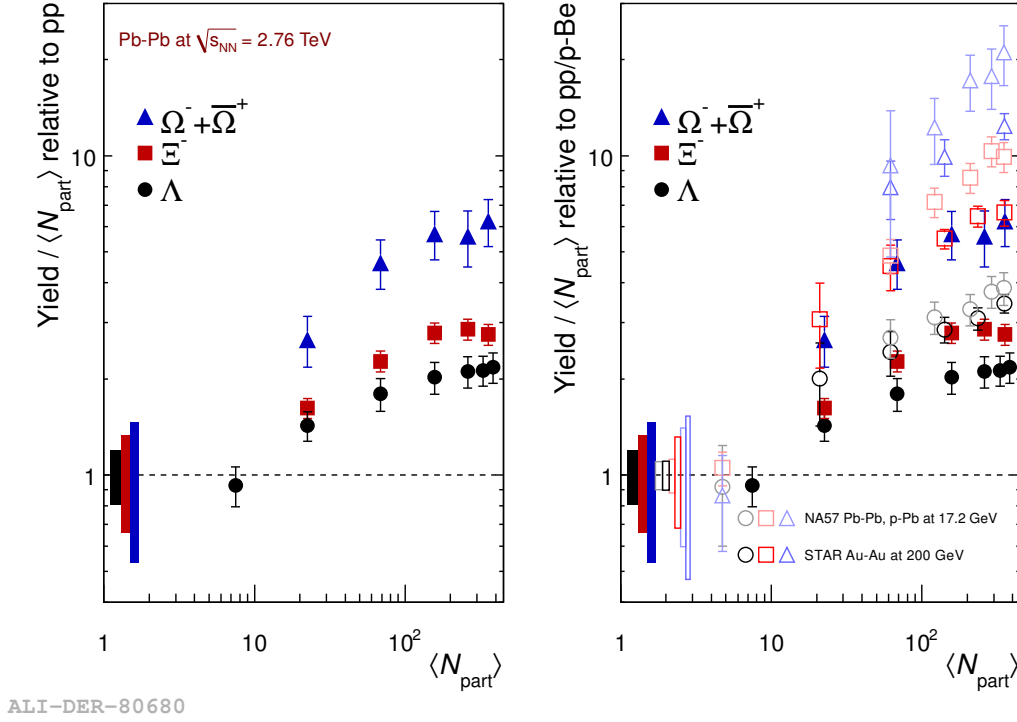


Figure 1.11: Strangeness enhancement factor in Pb–Pb and Au–Au collisions registered by NA57, STAR and ALICE experiments [40, 41].

1.5.6. Collective flow

As mentioned already in Sec. 1.5.3, the hydrodynamic model was found to be applicable for the description of the heavy-ion collisions at ultra-relativistic energies. Indeed, data from the RHIC and the LHC [42, 43] reveal that the matter created in the heavy-ion collision exhibits collectivity. The QGP can be well described as an almost perfect fluid [44], i.e. the value of the ratio of shear viscosity to entropy density is close to the limit calculated using AdS/CFT theory [33, 45]. Collective flow is a crucial observable for the discovery of strongly-coupled quark-gluon plasma [33].

Most of the heavy-ion collisions are non-central, meaning that the initial overlap region has the ellipsoidal shape in the transverse plane. The density gradient emerging in the collision transforms into the pressure gradient due to particle interactions. Pressure gradients are larger along the shorter axis of the ellipse, thus created acceleration is larger in this direction (in-plane). Such phenomenon of the spatial asymmetry which generates the azimuthal anisotropy of the momentum distributions is called an elliptic flow. Generally speaking, flow may be quantified using the equation:

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_R)] \right), \quad (1.10)$$

where $v_n = \langle \cos[n(\phi - \Phi_R)] \rangle$ are the Fourier coefficients, $\phi = \arctan \frac{p_x}{p_y}$ is the azimuthal angle, Φ_R is the orientation of the reaction plane (determined by the beam axis and the

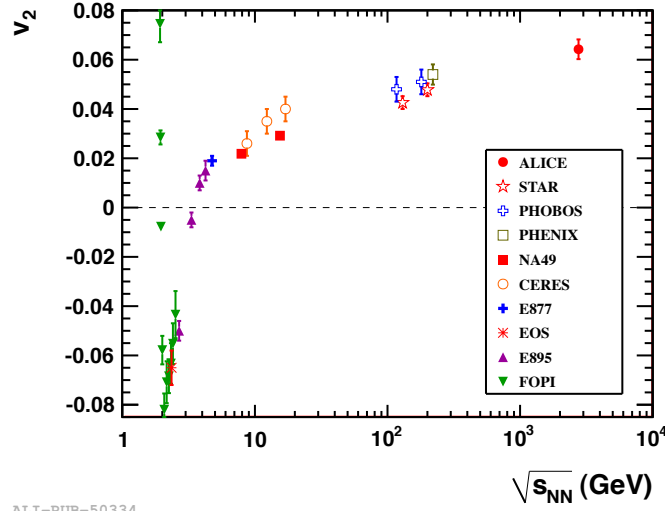
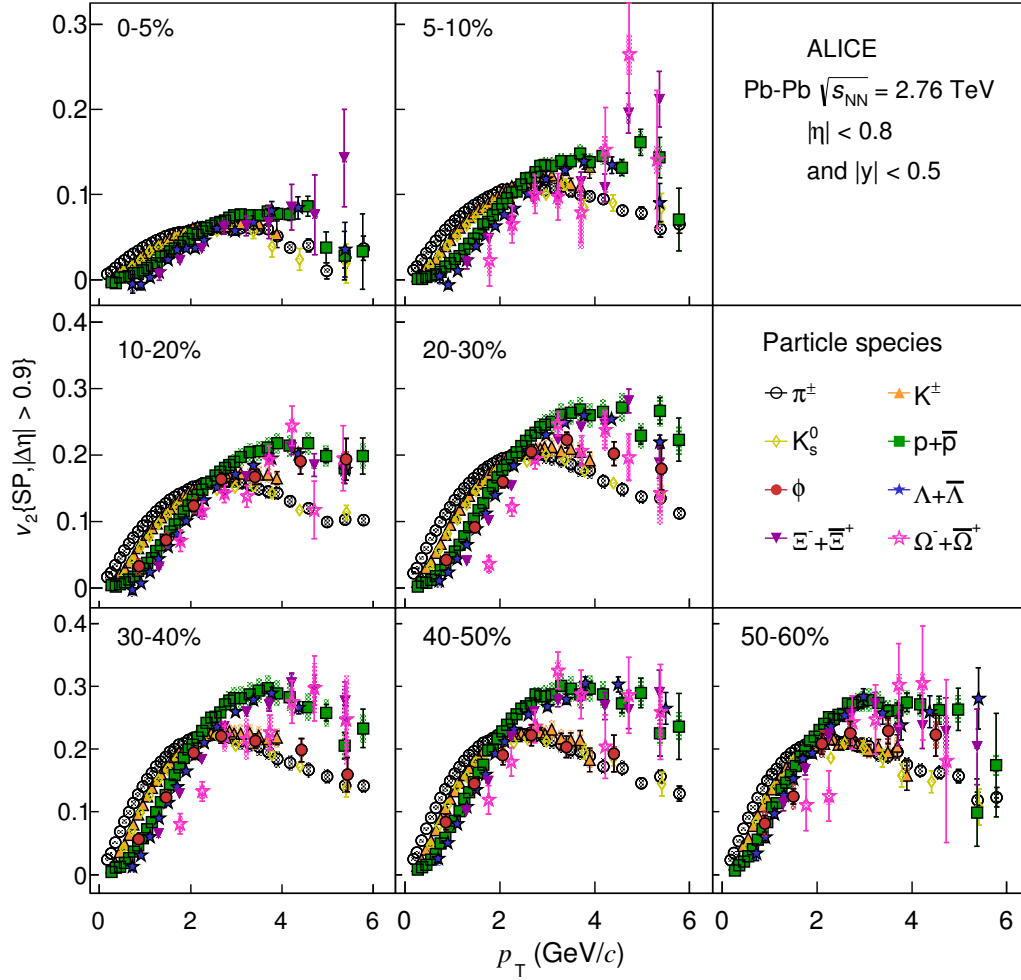


Figure 1.12: Elliptic flow of the charged particles vs. the collision energy [43].

impact vector). The unity inside a bracket of Eq. (1.10) refers to the radial flow, i.e. the flow in the transverse plane averaged over the azimuthal angle. The v_1 , called the directed flow measures the sideways motion of the produced particles in the reaction plane. At midrapidity the elliptic flow quantified by v_2 coefficient is dominating, though. The feature of v_2 is self-quenching due to the faster expansion of the system in-plane which leads to the decrease of the pressure gradient and thus generation of the momentum anisotropy. As a result, the momentum anisotropy emerges at the beginning of the evolution of the fireball, thus v_2 is sensitive to the early phase of the collision.

In Fig. 1.12 one can observe that elliptic flow of the charged particles increases for higher collision energy. The plot shows that for the lower energies, negative values of v_2 are measured which means that the presence of spectators decreases the particle emission in the reaction plane. In such case particles are produced mostly in the plane perpendicular to the reaction plane in order to reduce the pressure gradient. At higher collision energies spectators immediately escape from the region of interaction and do not influence the particle emission in the reaction plane.

Fig. 1.13 shows that the value of v_2 increases for more peripheral collisions as expected from the final state anisotropy induced by the geometry of the collision. Detailed measurements of the elliptic flow showed that v_2 increases with increasing transverse momentum up to $\sim 2 \div 3$ GeV/c and then saturates or decreases. Besides, a clear mass hierarchy of the values of v_2 is seen for low p_T which is thought to be the effect of the interplay of elliptic and radial flow. Also, one observes a crossing between v_2 values of mesons and baryons. For higher values of v_2 a tendency of grouping into mesons and baryons can be noticed. For the small p_T region as well as for the peripheral collisions, hydrodynamic models assuming a small value of the viscosity describe the data fairly well for pions and kaons [46].



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Figure 1.13: The transverse momentum dependence of the elliptic flow measured in Pb–Pb collisions for various particle species and collision centrality classes [46].

Recently the first measurements of the higher harmonic anisotropic flow coefficients v_n , sensitive to the geometrical fluctuations of the initial state, have been done [47, 48].

Another signature of the hydrodynamic flow in the heavy-ion collisions is the decrease of the source radii with an increasing transverse mass m_T [49] (see also the discussion in Sec. 3.2.5). Results presented in Chap. 7 of this thesis include such m_T -dependence of radii obtained using femtoscopic correlations of pion, kaon, and proton pairs.

1.5.7. Summary of the experimental results

Heavy-ion experiments delivered a thorough collection of data, characterising the medium created in the heavy-ion collisions at ultra-relativistic energies. The significant particle production (including not only the lightest mesons, but also e.g. protons and Λ baryons) enables the detailed studies of the system produced in the collisions. The main discovery is the existence of the Quark-Gluon Plasma which exhibits the collective behaviour. The common flow of particles manifests in e.g. the decrease of the source size with the increasing transverse mass, the shape of the transverse momentum spectra of various particle species, and the momentum anisotropy. Nonetheless, not all observables are fully understood. In particular, the description of particle yields in the frame of the thermal model still needs further investigations. Results from this thesis, putting constraints on the baryon-antibaryon strong interaction parameters, may contribute to the process of understanding the influence of the rescattering phase which possibly has the impact on the measured particle abundances.

2. A Large Ion Collider Experiment at the Large Hadron Collider

The physics measurements presented in this thesis have been obtained in A Large Ion Collider Experiment described in the following chapter. This experiment is designed for the study of the Quark-Gluon Plasma. Indeed, abundant production of particles in the heavy-ion collisions at ultra-relativistic energies and superior particle identification capabilities of the detector make this experiment ideally tailored for the femtoscopic measurements presented in the next chapters of this thesis.

2.1. Large Hadron Collider at CERN

The Large Hadron Collider (LHC) [50] is currently the biggest particle accelerator, built from 1998 to 2008 at the European Organisation for Nuclear Research (CERN). It is placed on the French-Swiss border in the vicinity of Geneva in a circular tunnel of 26.7 km in circumference, 45 to 170 meters underground. The LHC is a synchrotron which uses two separate beam pipes. At the beginning of the operation in March 2010, the energy of the proton beam was 3.5 TeV and increased to 4 TeV in 2012. Finally, the upgrade of the accelerator, finalised in April 2015, allowed to reach the proton-proton collisions at 13 TeV (6.5 TeV per beam). As far as lead ions are concerned, there were dedicated heavy-ion runs with collision energy $\sqrt{s_{\text{NN}}} = 2.76$ TeV at the end of 2010 and 2011. In addition, at the end of 2015 collisions of lead ions at the increased energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV have been delivered. At the turn of 2012 and 2013, p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV were performed. Although they were expected to be used mainly as a reference for pp and Pb-Pb collisions, they brought exciting results (including the possibility of the collective matter created in high multiplicity p-Pb collisions) arising much interest in the field [48, 51, 52].

Four major and several small experiments are operating at the LHC. The goal of ATLAS (A Toroidal LHC Apparatus) is to look for the Higgs Boson, supersymmetry and extra dimensions [53]. The physics programme of CMS (Compact Muon Solenoid) is similar to ATLAS but uses other detection techniques making both these experiments complementary [54]. ALICE (A Large Ion Collider Experiment) was designed to analyse the properties of strongly interacting matter [55]. LHCb (Large Hadron Collider beauty) is dedicated to carry out the research on the asymmetry between matter and antimatter, especially in interactions of particles which contain beauty quarks [56]. As far as smaller experiments are concerned, TOTEM (TOTAl Elastic and diffractive cross section Measurement) measures proton-proton interaction cross section, studies the structure of the proton and monitors the luminosity of the LHC [57]. The LHCf experiment (Large

Hadron Collider forward) analyses forward particles produced in the LHC to learn about the origin of high-energy cosmic rays [58]. MoEDAL (Monopole and Exotics Detector at the LHC) is dedicated to the investigation of the possible existence of the magnetic monopole and highly ionising stable massive particles [59].

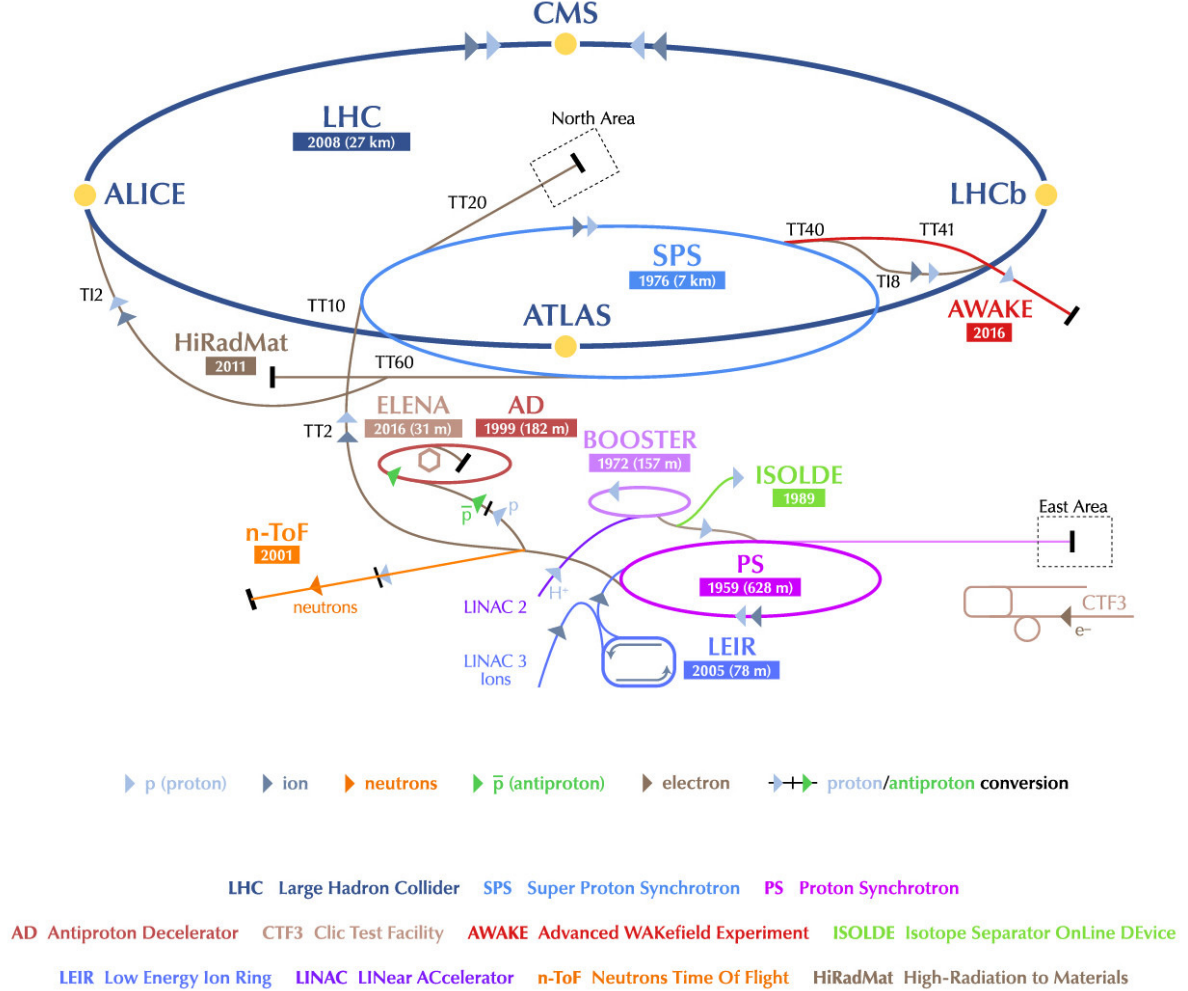


Figure 2.1: The complex of the CERN accelerators [60].

The complex of the CERN accelerators is presented in Fig. 2.1. The source of the ions is the electron cyclotron resonance providing ^{208}Pb isotope which is then stripped to the Pb^{29+} and initially accelerated to 4.2 MeV per nucleon. After passing through the carbon foil, the Pb^{54+} ions are delivered to the Low Energy Ion Ring which creates shorter bunches with higher intensity. Such bunches of lead ions are sent to the Proton Synchrotron where they are stripped to Pb^{82+} by passing through 0.8 mm aluminium foil and accelerated to 5.9 GeV per nucleon. Later on, they are sent to the Super Proton Synchrotron which accelerates them to 177 GeV per nucleon and finally they are injected into the Large Hadron Collider [33].

2.2. ALICE

A Large Ion Collider Experiment is designed to carry out research on a state of matter called the Quark-Gluon Plasma which is produced in collisions of lead ions at energies available at the LHC. It is commonly accepted that the Universe was in the QGP state at the time scale of $1 \mu\text{s}$ after the Big Bang [61]. Studying properties of the QGP is crucial for the deep understanding of the QCD. The physics programme of ALICE covers comprehensive analysis of particles registered in collisions of Pb ions with the emphasis on their identification. What is more, proton-proton and proton-lead runs complement the heavy-ion campaign and serve as the cross-check of the results from other experiments in the high-energy physics. ALICE involves the collaboration of more than 1000 scientists. The dimensions of the detector weighting 10^4 t are $16 \times 16 \times 26 \text{ m}^3$. ALICE is composed of the central barrel embedded in a solenoid magnet, and a forward muon spectrometer. It covers polar angles from 45° to 135° . In the barrel there is the Inner Tracking System (ITS), made of six planes of silicon detectors, the Time Projection Chamber (TPC), arrays of the Time-of-Flight (TOF), the Transition Radiation (TRD), Ring Imaging Cherenkov (HMPID) detectors, as well as the electromagnetic calorimeters (EMCAL and PHOS). Furthermore, there is the forward muon arm ($2^\circ - 9^\circ$) with a dipole magnet, absorbers, tracking and triggering chambers. Additionally, there is Zero Degree Calorimeter, Photon Multiplicity Detector, Forward Multiplicity Detector, T0, V0 and Alice Diffractive detector located at small polar angles. On the top of the solenoid magnet an ACORDE, array of scintillators, is installed to trigger on cosmic rays [55]. The layout of the ALICE is depicted in Fig. 2.2.

2.2.1. Inner Tracking System

The main tasks of the ITS are to localise the primary vertex of the collision (with the design resolution of $100 \mu\text{m}$), to find the secondary vertices, to perform tracking and identification of particles with the low momentum ($< 200 \text{ MeV}/c$) as well as to enhance the momentum resolution of the particles reconstructed with the TPC. The ITS is composed of six layers of silicon detectors as illustrated in Fig. 2.3. ITS covers the range of pseudorapidity $|\eta| < 0.9$. The Silicon Pixel Detector (SPD) is the innermost layer of the ITS. Its main function is to determine the location of the primary vertex. Due to proximity of the interaction point SPD works in the region with the high track density reaching $50 \text{ tracks}/\text{cm}^2$. The middle layers of the ITS are composed of the Silicon Drift Detector (SDD) which supports the particle identification by measuring the energy loss per unit of the distance covered by the charged particle. Particle density is estimated at $7 \text{ tracks}/\text{cm}^2$. The Silicon Strip Detector (SSD) is the outermost layer of the ITS. It enhances tracking and identification for particles with small momentum [55].

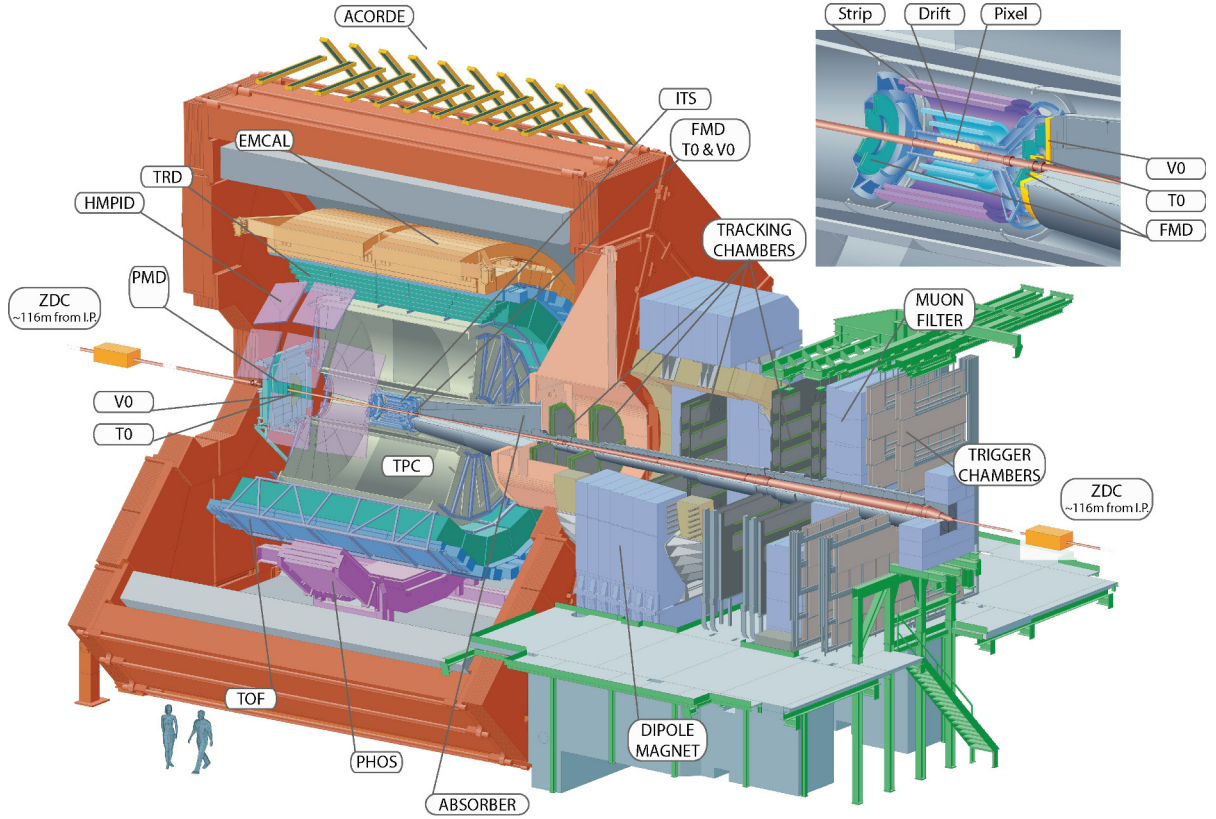


Figure 2.2: The setup of ALICE detectors [62].

2.2.2. Time Projection Chamber

The Time Projection Chamber (TPC) serves as a major tracking detector in ALICE. Besides, it is used to measure the momentum of charged particles, to identify the charged particles and to determine the vertex of the collision. The pseudorapidity range of the TPC is $|\eta| < 0.9$. The detector covers the transverse momentum from $\simeq 0.1 \text{ GeV}/c$ to $\simeq 100 \text{ GeV}/c$. The TPC has also the full coverage of the azimuthal angle (excluding the dead zones of the detector). The scheme of the TPC is shown in Fig. 2.4.

The skeleton of the TPC is built of a cylindrical field cage which is filled with 90 m^3 of the mixture $\text{Ne}/\text{CO}_2/\text{N}_2$. Both end plates are segmented into 18 trapezoidal sectors where multi-wire proportional chambers and cathode pad readout are installed. 557 568 readout pads are mounted. In the centre of the field cage, there is a high voltage electrode and two potential degraders creating a uniform electrostatic field along the beam axis. The drift gas was optimised subject to eligible drift speed, and to ensure low multiple scattering.

The working principle of the TPC is based on the ionisation effect induced by charged particles traversing the barrel. Freed electrons drift towards the end plates. Since they cannot induce sufficiently large signal in the readout pads, it needs to be amplified by the creation of an avalanche near the anode wires. Cathode planes are segmented in two dimensions, therefore one can measure many space points per track in the transverse

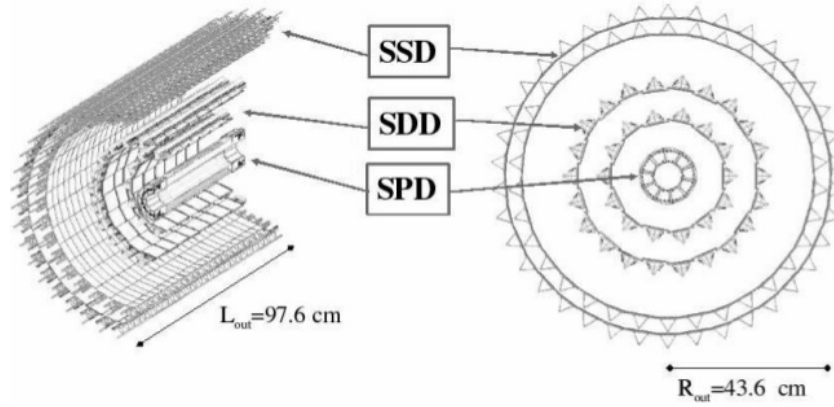


Figure 2.3: Layout of the Inner Tracking System [55].

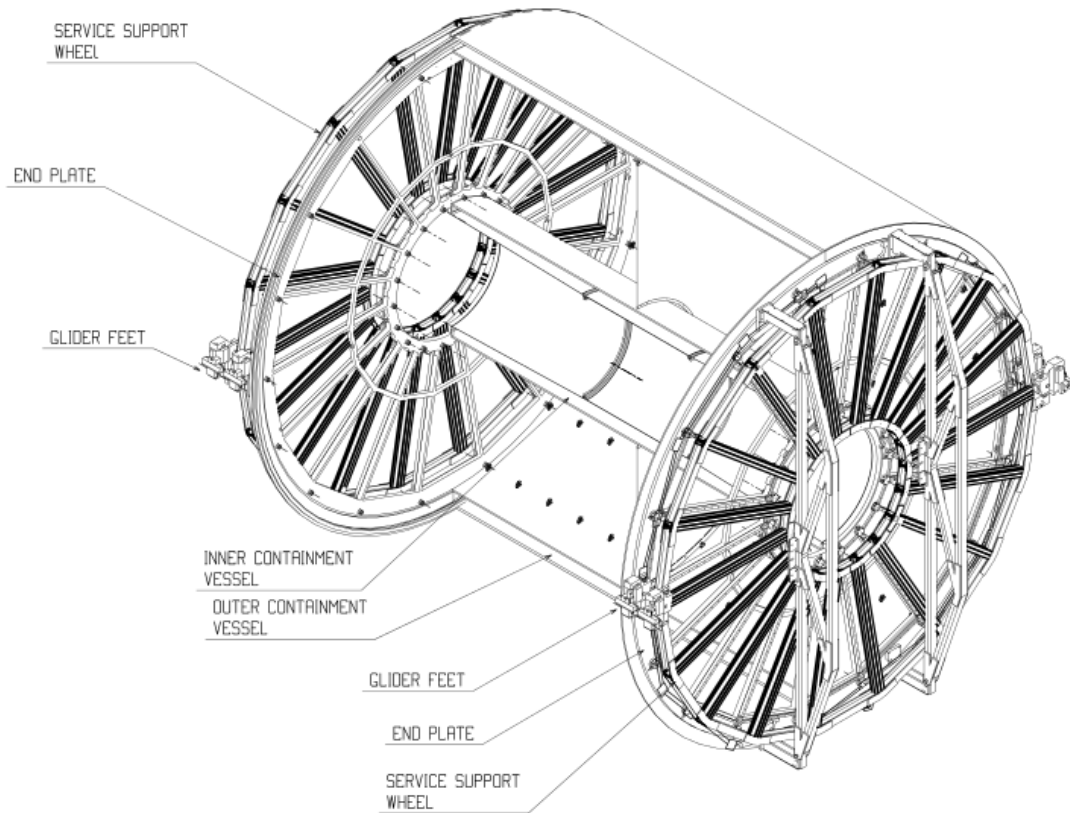


Figure 2.4: The schematic view of the TPC [55].

plane. In addition, the three-dimensional reconstruction of the track is possible by the measurement of the arrival time of the ionisation electrons to the pad with respect to the certain reference time, e.g. the collision time from the LHC.

Identification of charged particles traversing the TPC volume is based on the calculation of their momentum and charge in combination with the measurement of the specific ionisation energy loss per unit path length dE/dx . The former is done using the radius and the direction of curvature of the particle trajectory bent in ALICE magnetic field. The dE/dx value for a given track is extracted using the total or maximum charges de-

posited within each cluster¹ assigned to the track. Then, the TPC signal is calculated as the truncated mean of the energy loss $\langle dE/dx \rangle$, discarding 40% of clusters with the highest charge in order to reduce the Landau tail. The values of $\langle dE/dx \rangle$ follow the Gaussian distribution [55, 63, 64, 65]. More details can be found in Sec. 6.3.2.

2.2.3. Time-of-Flight Detector

The Time-of-Flight detector covers the pseudorapidity range $|\eta| < 0.9$. The detector is composed of 18 sectors in azimuthal angle and 5 segments in the direction of the beam axis. Multigap Resistive-Plate Chamber (MRPC) technology is used to built the TOF. The detector can measure the arrival time of a particle with a precision of the order of 80 ps. Particle identification in TOF is achieved by the measurement of this time along with the calculation of the momentum of the track using tracking detectors. The information on the values of these observables allows to calculate the mass, hence identity, of the registered particle. The TOF is mainly used for the track-by-track identification of pions and kaons up to about 2.5 GeV/ c as well as protons up to 4 GeV/ c [55].

2.2.4. V0 Detector

The V0 are the two arrays of scintillator counters [55, 66]. The detector is composed of two parts: V0-A and V0-C, covering pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. This corresponds to the V0-A located 329 cm from the nominal interaction point on the side opposite to the muon spectrometer, and V0-C installed on the front of the hadronic absorber, about 90 cm from the vertex. The schematic picture of the V0 arrays is presented in Fig. 2.5. Each of the V0 components is divided in 4 rings in the radial direction, whereas each ring has 8 sections in the azimuthal directions. The thickness of the V0-A and V0-C scintillators is 2.5 cm and 2 cm, respectively.

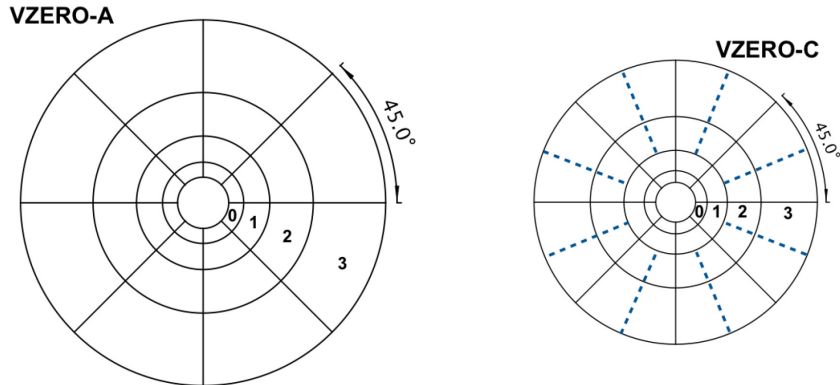


Figure 2.5: The schematic view of the V0 detector [66].

¹Cluster is the group of signals from various detectors, see Sec. 2.3 for details.

The main application of the detector is to provide the trigger signal for the detectors from the central barrel (see Sec. 6.1). The V0 is also used to measure the centrality by registering the amplitude correlated with the multiplicity of the event. In addition, V0 is applied for the luminosity measurements in pp collisions. As described in Sec. 6.5.1, V0 is used to measure the event plane angle as well.

2.2.5. Other detectors

The Transition Radiation Detector (TRD) is built to identify the high-momenta electrons. Transition radiation caused by electrons passing the radiator in combination with the data from the ITS and the TPC serve to reject pions from the sample. Main goals of the TRD are to analyse the production of vector mesons, the continuum in dilepton channels and to reconstruct open charm and beauty in semi-leptonic decays.

The High Momentum Particle Identification (HMPID) extends the range of momentum for which the separation power is high enough to discriminate between pions and kaons even to 3 GeV/ c , and kaons and protons to 5 GeV/ c . The detector uses the ring-imaging Cherenkov counters.

The ElectroMagnetic CALorimeter (EMCAL) is a Pb-scintillator sampling calorimeter with the cylindrical geometry covering the phase-space: $|\eta| < 0.7$, $\Delta\phi = 107^\circ$. The main application is the analysis of jet physics.

The PHOton Spectrometer (PHOS) is an electromagnetic calorimeter consisting of lead-tungstate crystals. It enables the study of the initial state of the system produced in the heavy-ion collision by the measurement of the direct photons. In addition it is used to analyse the jet quenching using π^0 with high p_T .

The ALICE COsmic Ray DEtector (ACORDE) is an array of plastic scintillator counters. The detector's purpose is to provide a trigger signal for the calibration and the alignment of the tracking detectors. ACORDE may also be used to study the atmospheric muons together with TPC, TRD and TOF.

The muon spectrometer is optimised to analyse the heavy quark resonances, such as J/ψ , using their decay pattern into $\mu^+\mu^-$ pair. The acceptance of the spectrometer is $-4 < \eta < -2.5$. The detector is built of the front absorber, the tracking and the trigger system.

The Zero Degree Calorimeter (ZDC) is composed of two neutron and two proton calorimeters located symmetrically on both sides of the interaction point. It is used for the measurement of the spectator nucleons and serves mainly for the triggering. In addition there is an electromagnetic calorimeter which helps to distinguish between most central and most peripheral events since in both cases the number of nucleons registered by the nucleon calorimeters is small: in former there are few spectator nucleons, in latter they are bound in nuclear fragments.

The Photon Multiplicity Detector (PMD) is used to obtain the multiplicity measurement as well as a spatial distribution of photons in the pseudorapidity range $2.3 < \eta < 3.7$ employing the so-called preshower method. The detector has the honeycomb structure.

The Forward Multiplicity Detector (FMD) is dedicated to measure the charged particles at small polar angle with respect to the beam line. FMD consists of five silicon detectors with 51200 silicon strips in total.

The T0 detector is composed of two arrays of Cherenkov counters providing the measurement of the time-stamp of the collision for the TOF detector. Moreover, the T0 can be used to determine the location of the vertex or to trigger [55].

The Alice Diffractive detector (AD) is a recently installed forward detector built for the triggering of diffractive events and to extend the pseudorapidity coverage [67].

2.3. Online and offline computing

The ALICE trigger system includes the hardware-level Central Trigger Processor (CTP) as well as the software trigger called the High Level Trigger (HLT). The main task of the trigger is to use all detectors as efficiently as possible. This is a serious challenge as the detectors have different busy periods. Furthermore, the triggers decide which events are interesting from the physics point of view. The HLT uses multiprocessor system to provide the trigger signal for the rare events (such as jets or muon pairs) and to reduce the event size by compressing the data selecting information crucial for physics. Other online system: data acquisition framework (DAQ) was designed to handle data taking at sufficiently high rate and to register all the essential information from the detectors to define the physical event. The objective of the DAQ is to work at a bandwidth reaching 1.25 GB/s. Remaining online systems are: Detector Control System (DCS) ensuring safe operation of the detectors and Experiment Control System (ECS) which synchronises and oversees the rest of online systems.

The major aim of the offline framework in ALICE is to provide the system to process the data collected in collisions and simulated using models. That means handling the processes of simulation, reconstruction, visualisation and, as a main objective, the physics analysis being the most important aspect of the collaboration after all. Size of the data taken in the experiment is estimated at 1.1 MB and 13.75 MB per average pp and Pb–Pb event, respectively. Such large amount of information accumulates to approximately $10 \div 15$ PB data each year for 10^9 pp and 10^8 Pb–Pb events. Since handling the enormous data-flow is a challenge for the standard computer technologies, the computing model called Grid [68] was developed. Its main task is to ensure the homogeneous access for the whole collaboration to the experiment resources (computing units and data) distributed in the multiple computer centres grouped in the so called tiers.

The reconstruction of the collisions occurring in the detector begins with processing the raw data coming straight from the detectors by the Local Data Collectors (LDCs). Sub-events, i.e. the result of this stage, are combined in the events by the Global Data Collectors (GDCs). As the next step, the events are saved on a disk buffer at the CERN (Tier-0) and copied on tapes using CASTOR system in case of proton-proton running mode. At the Tier-0 the first pass of the reconstruction and the calibration is done. After that, the data is exported to Tier-1 computing centres where additional reconstruction processes are performed. As far as Pb–Pb runs are concerned, the raw events are collected in CASTOR and exported to Tier-1 nodes to be examined by users. Then those events are partially reconstructed at the Tier-0. Calibration, alignment, reconstruction processes can be run using the CERN Analysis Facility (CAF). During the data taking period, it is vital to register the so-called conditions data (such as calibration and alignment) which is provided by Shuttle software.

AliRoot, the ALICE offline framework, was developed for the simulation, alignment, calibration, reconstruction, visualisation and physics analysis. Its technology is based on C++ and ROOT framework [69]. As far as the simulation process is concerned, AliRoot provides the interface to the Monte-Carlo generators such as Pythia [70], Phojet [71], HIJING, and THERMINATOR. As a result one can obtain the structure with generated particles. Next, the propagation of particles through the detector material and simulation of the interactions and decays is modelled by frameworks, such as GEANT [72] or Fluka [73] to take into account the conditions of the experiment. In this phase so-called *summable digits* are simulated. These are the hits of the generated particles in the sensitive regions of the given detectors. After that, a detector noise is added in order to model the *digits*. Further steps of the processing are the same for simulated and collision events. At first, the groups of signals from various detectors located in close proximity, *clusters*, are found. Then the track reconstruction is started by looking for the track seeds in the TPC in the outward pad rows where their density is smallest. At this point, one assumes that the track originates from the primary vertex. As the next step, tracks are propagated towards the interaction point using the algorithm based on the Kalman filter [74]. The parameters of the track are updated during each iteration when the subsequent clusters may be added to the track. The procedure is then performed again, starting with seeds selected closer to the vertex. In the output various types of tracks are stored, for instance *TPC-only tracks* or *global tracks* which include the data not only from the TPC but also from other detectors (e.g. ITS or TOF). The result of the reconstruction (e.g. the position of the primary vertex, parameters of the tracks, particle identification signals, condition of the detector) is saved in the Event Summary Data (ESD) file. However, for the purposes of the physics analysis these data are compressed to the Analysis Object Data (AOD) files keeping only crucial information [55, 75]. The diagram illustrating the flow of control in AliRoot is pictured in Fig. 2.6.

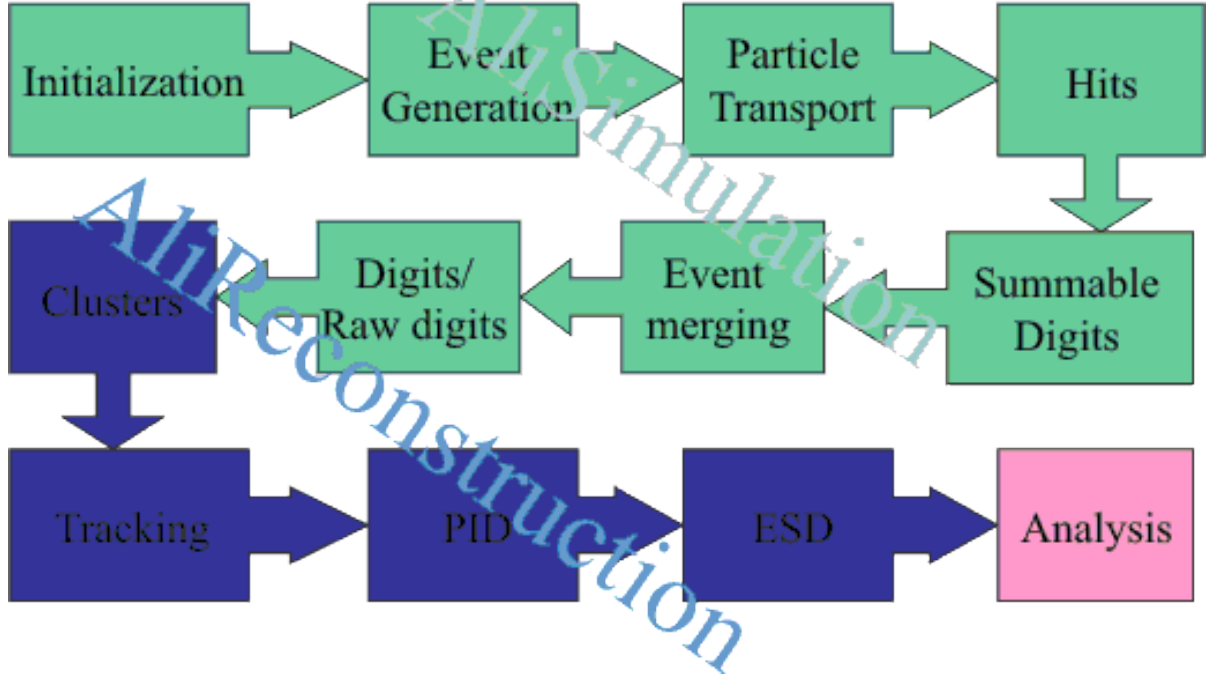


Figure 2.6: The AliRoot control flow [76].

2.4. Event Display

In order to visualise collisions in the ALICE detector AliEVE, ALICE Event Visualisation Environment was developed. The software is based on ROOT, in particular its GUI classes [77]. It allows for displaying the detector geometry, online visualisation of currently recorded events (using the simplified offline reconstruction algorithm), events from High Level Trigger and offline events (stored in the local files in the native format of ROOT). The design of the system is shown in Fig. 2.7. The main features of the AliEVE include displaying 3D view and 2D projections, visualisation of tracks, V^0 's, kinks, cascades, calorimeters, clusters, easy navigation between events, intuitive interface for manipulating the appearance, ready-to-use screen-shots with ALICE logo and details of the event. The example of the visualisation of a Pb–Pb collision is shown in Fig. 2.8.

AliEVE was found to be extremely useful tool, especially for outreach activities to attractively present the high energy collisions as well as for scientists to deepen the understanding of the phenomena occurring in such collisions. Although ROOT-based AliEVE is stable and useful system, currently the software based on the Total Event Display framework is being developed. It will provide the support for the web browsers and mobile platforms [78].

The author of this thesis was taking part in the development of the current Event Display framework in ALICE as a so-called service task for the ALICE community. In particular this work included the improvement of the stability of the system and the implementation of new features.

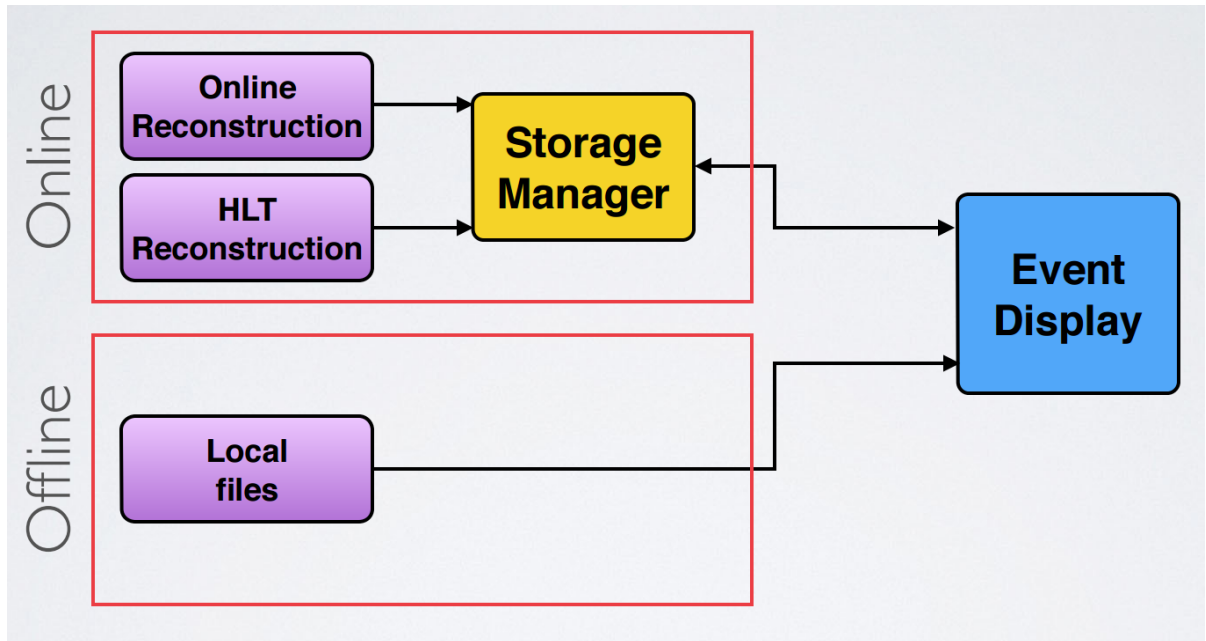


Figure 2.7: Design of the ALICE event display [78].

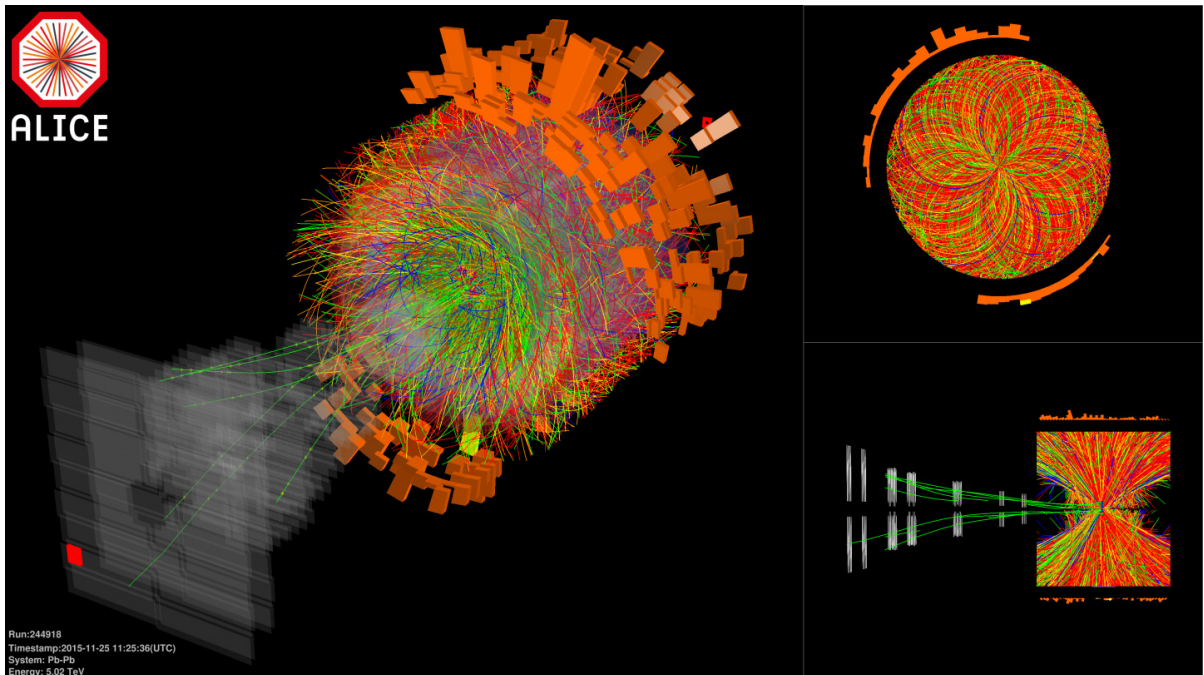


Figure 2.8: Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV in ALICE visualised with AliEVE [79].

2.5. ALICE upgrade

Since the first runs of the LHC appeared to be extremely successful, ALICE extends the physics program for the deeper understanding of the hot, dense and strongly interacting matter created in the heavy-ion collisions. The LHC will be increasing luminosity of the lead ions in 2018, hence the ALICE collaboration plans to upgrade the detector to fully utilise the potential of the collider [80]. The main objectives of the upgrade are the enhancement of the vertexing and the tracking at low-momentum as well as the ability to collect data at significantly higher rates. It will require the improvement of the Inner Tracking System which will have 3 times better resolution of the distance of closest approach between the primary vertex and the track. Moreover, the new Time Projection Chamber will use the Gas Electron Multiplier detectors instead of the multi-wire proportional chambers to be able to operate with 50 kHz collision rate. The upgrade will also cover, amongst others, the readout electronics of TRD, TOF and PHOS as well as DAQ system and offline data processing framework to handle the increased rate and number of events coming from the detector.

3. Femtoscopy

Femtoscopy, the analysis of the particle correlations at low relative momentum, is a robust tool extensively used in proton-proton, proton-nucleus and heavy-ion collisions. Femtoscopic correlations are induced by Quantum Statistics (QS) as well as by the strong and Coulomb Final State Interactions (FSI). The primary application of this method is to measure the spatial extents of the fireball created in the collisions of heavy ions. That means extracting the size of the order of 10^{-15} m, but femtoscopy also includes studies of the freeze-out eccentricity, the quantum coherence of particles, coalescence, and the parameters of strong interactions [81, 82, 83, 84, 85]. This chapter introduces basic concepts of the femtoscopy with a particular emphasis on the correlations of baryon pairs.

3.1. Historical perspective

Correlations of bosons with small relative velocity were initially observed by Goldhaber et al. in 1959 [86]. Study of the reaction $\bar{p} + p \rightarrow n\pi^+ + n\pi^- + m\pi^0$ showed that pairs of π mesons with the same electric charge, i.e. $\pi^+\pi^+$ and $\pi^-\pi^-$, are emitted with smaller opening angles (closer to each other) comparing with opposite charged pairs ($\pi^+\pi^-$). Such phenomenon was explained as the effect of Bose-Einstein statistics. Indeed, the probability that bosons are in the same quantum state is increased [81]. Interestingly, the observation was made that such correlations exhibit sensitivity to the size of the source emitting particles. The foundations of modern femtoscopy were established by Kopylov and Podgoretsky [82, 83]. In particular, they introduced the correlation function tool, and defined the assumptions essential for the extracting the space-time information from the low relative momentum correlations. Femtoscopic methods were also settled by, amongst others, Koonin [87] who studied the FSI effects on proton-proton correlation function in nonrelativistic approximation in the source rest frame, Pratt [88, 89], Gyulassy et al. [90] as well as Lednicky and Lyuboshitz [91] .

The analogous phenomenon has been observed in astronomy by R. Hanbury–Brown and R.Q. Twiss who have shown how to derive the angular size of stars through the measurement of the intensities of electromagnetic waves [92]. Indeed, the momentum characteristic of the source and thus the angular size of the star can be determined by the analysis of the intensity signals in two distant telescopes as a function of their separation. The technique used in particle physics is complementary, namely the measurement of the low-relative momentum correlations of particles can be used to infer the average separation between sources [93, 94].

3.2. Femtoscopic formalism

3.2.1. Theoretical technique

In general, the correlation function can be defined as the ratio of the two-particle momentum distribution $\frac{dN}{d\vec{p}_1 d\vec{p}_2}$ and the product of the single-particle momentum distributions $\frac{dN}{d\vec{p}}$:

$$C(\vec{p}_1, \vec{p}_2) = \left(\frac{dN}{d\vec{p}_1 d\vec{p}_2} \right) \left(\frac{dN}{d\vec{p}_1} \frac{dN}{d\vec{p}_2} \right)^{-1}. \quad (3.1)$$

Here $\vec{p}_1, \vec{p}_2$ are the three-momenta of the particles.

Extracting the space-time information from the low relative momentum correlations is based on the several assumptions [93,95]. Firstly, the freeze-out phase space density needs to be small enough to ensure that the two-particle correlation function at small relative momentum could be determined using QS and FSI phenomena only. Next, since the correlations induced by energy and momentum conservation scale inversely proportional to the number of particles [96], the multiplicity of particles produced in the collision should be sufficiently large in order to neglect such effects. Furthermore, the mean space-time distance between particle emitters is assumed to be significantly larger with respect to the space-time dimensions of the emitters (this is known as the smoothness approximation). Those assumptions are well justified in the heavy-ion collisions [93].

3.2.2. Nonrelativistic approach

The nonrelativistic approach to the femtoscopy is motivated by the fact that the correlation effect is limited to small relative momenta which means that the relative motion of particles is nonrelativistic. Then, one can use the nonrelativistic wave function in the pair centre of mass frame and express the correlation function in the source rest frame as [87,97]:

$$C(\vec{p}_1, \vec{p}_2) = \int S(t_1, \vec{r}_1 - \vec{v}_1 t_1) S(t_2, \vec{r}_2 - \vec{v}_2 t_2) |\Psi(\vec{r}_1, \vec{r}_2)|^2 d^3 \vec{r}_1 dt_1 d^3 \vec{r}_2 dt_2. \quad (3.2)$$

Here Ψ is the pair wave function, and S is the emission function corresponding to the probability of emitting the particle from the given space-time point. Using the centre of mass variables, i.e.: $\vec{r} = \vec{r}_1 - \vec{r}_2$, $\vec{q} = \frac{1}{M}(m_2 \vec{p}_1 - m_1 \vec{p}_2)$, $M = m_1 + m_2$, $\vec{P} = \vec{p}_1 + \vec{p}_2$ the correlation function can be written as:

$$C(\vec{q}) = \int S_r(\vec{r}) |\varphi_{\vec{q}}(\vec{r})|^2 d^3 \vec{r}, \quad (3.3)$$

with the effective, relative emission function:

$$S_r(\vec{r}) = \int S_r(t, \vec{r} - \vec{v}t) dt, \quad (3.4)$$

expressed by the single-particle emission functions:

$$S_r(t, \vec{r}) = \int S(T - \frac{m_2}{M}t, \vec{R} - \frac{m_2}{M}\vec{r}) S(T + \frac{m_1}{M}t, \vec{R} + \frac{m_1}{M}\vec{r}) d^3R dT, \quad (3.5)$$

using the centre of mass variables $\vec{R} = \frac{1}{M}(m_1\vec{r}_1 + m_2\vec{r}_2)$, $T = \frac{1}{M}(m_1t_1 + m_2t_2)$, $t = t_1 - t_2$. In Eq. (3.3) $\varphi_{\vec{q}}(\vec{r})$ is the wave function of the relative motion in the pair centre of mass frame applying the factorisation of the pair wave function:

$$\Psi(\vec{r}_1, \vec{r}_2) = \varphi_{\vec{q}}(\vec{r}) e^{i\vec{P}\vec{R}}. \quad (3.6)$$

Let us consider two identical noninteracting bosons emitted from the space points $\vec{r}_1$ and $\vec{r}_2$ with momenta $\vec{p}_1$ and $\vec{p}_2$. Since the particles are indistinguishable, one needs to take into account all the trajectories connecting the initial and the final state. Hence the pair wave function is of the form:

$$\Psi(\vec{r}_1, \vec{r}_2) = \frac{1}{\sqrt{2}}(e^{i\vec{p}_1\vec{r}_1 + i\vec{p}_2\vec{r}_2} + e^{i\vec{p}_1\vec{r}_2 + i\vec{p}_2\vec{r}_1}) = \frac{1}{\sqrt{2}}(e^{i\vec{q}\vec{r}} + e^{-i\vec{q}\vec{r}}) e^{i\vec{P}\vec{R}}, \quad (3.7)$$

which leads to the modulus square of the wave function of relative motion in the form:

$$|\varphi_{\vec{q}}(\vec{r})|^2 = 1 + \cos(2\vec{q}\vec{r}). \quad (3.8)$$

Assuming Gaussian shape of the single-particle emission function, one obtains the correlation function:

$$C(\vec{q}) = 1 + \exp(-4(\tau^2(\vec{q}\vec{v})^2 + R_x^2q_x^2 + R_y^2q_y^2 + R_z^2q_z^2)), \quad (3.9)$$

where τ , R_x , R_y , R_z are the space-time characteristics of the source.

The assumption of noninteracting particles can be justified for example for pions since the influence of strong FSI is relatively small while the contribution from Coulomb FSI can be corrected for in the simplified approach [95].

3.2.3. Relativistic approach for noninteracting particles

Relativistic formulation of the correlation function defined in the previous chapter for noninteracting particles requires its Lorentz covariance. For two identical noninteracting bosons with four-positions x_1 and x_2 and four-momenta p_1 and p_2 , the pair wave function

is the Lorentz scalar:

$$\Psi(x_1, x_2) = \frac{1}{\sqrt{2}}(e^{ip_1x_1+ip_2x_2} + e^{ip_1x_2+ip_2x_1}). \quad (3.10)$$

Furthermore, the Lorentz covariant emission function has to be introduced to provide the covariant form of the correlation function [97]:

$$C(p_1, p_2) = \int S(x_1)S(x_2)|\Psi(x_1, x_2)|^2 d^4x_1 d^4x_2. \quad (3.11)$$

Applying the covariant form of the Gaussian parametrisation of the emission function [97], and relative four-coordinates for pairs of identical particles $x = \{t, \vec{r}\} = x_1 - x_2$, $q = \{q_0, \vec{q}\} = \frac{1}{2}(p_1 - p_2)$, one gets the correlation function in the following form:

$$C(q) = 1 + \exp(-4(q_0^2\tau^2 + R_x^2q_x^2 + R_y^2q_y^2 + R_z^2q_z^2)). \quad (3.12)$$

Correlation function defined by Eq. (3.12) is equivalent to the nonrelativistic formulation of the correlation function given by Eq. (3.9) since $q_0 = \vec{q}\vec{v}$ [97]. Assuming that the velocity of the centre of mass frame in the source rest frame is along x axis, the correlation function may be written as:

$$C(\vec{q}) = 1 + \exp(-4((v^2\tau^2 + R_x^2)q_x^2 + R_y^2q_y^2 + R_z^2q_z^2)). \quad (3.13)$$

In such a formulation, one can notice that the effective source radius in the x direction ($\sqrt{R_x^2 + v^2\tau^2}$) includes the lifetime of the source τ .

The transition to the pair centre of mass frame is a boost along the velocity direction, and thus assuming the velocity of the centre of mass frame in the source rest frame along the x axis:

$$C(q^*) = 1 + \exp(-4(\gamma^2(v^2\tau^2 + R_x^2)q_x^{*2} + R_y^2q_y^{*2} + R_z^2q_z^{*2})), \quad (3.14)$$

where $\gamma = \frac{1}{\sqrt{1-v^2}}$, and the variables marked with the asterisk correspond to the centre of mass frame.

Bertsch-Pratt parametrisation of the momentum difference vector $\vec{q}$ is often used [89]. Decomposition is done into longitudinal component q_{long} parallel to the beam line, q_{out} parallel to the pair transverse momentum, and the component q_{side} which is perpendicular to the others. The directions are defined separately for each pair. Using such parametrisation, the correlation function takes the form:

$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda \exp(-4(q_{out}^2 R_{out}^2 + q_{side}^2 R_{side}^2 + q_{long}^2 R_{long}^2)), \quad (3.15)$$

where λ , commonly referred to as the chaoticity parameter, characterises the strength of the correlation and corresponds to the fraction of pairs contributing to the correlation

function. R_{out} , R_{side} , R_{long} represent the source sizes in “out”, “side” and “long” directions. They are often called also “HBT radii”, “femtoscopic radii”, or “radii”.

In a situation of limited pair statistics which is often the case in experiments, the correlation function is analysed as a function of the magnitude of the relative momentum $q = |\vec{q}|$ providing only one-dimensional effective source size r_0 [94]:

$$C(q, \lambda) = 1 + \lambda e^{-4r_0^2 q^2}. \quad (3.16)$$

3.2.4. Relativistic approach for interacting particles

The problem of two relativistic interacting particles can be reduced by treating the relative motion of two particles nonrelativistically, while the centre of mass motion being considered in the relativistic approach. This can be justified since the correlation effect is present mostly for pairs with small relative momentum. Here, the motion of particles with respect to the source is treated relativistically, while the relative motion of particles is considered in a nonrelativistic approach.

The correlation function can be expressed as a square of the Bethe-Salpeter amplitude averaged over the four-coordinates $x_i = \{t_i, \vec{r}_i\}$ of the emitters and over the total spin of the system [98]. This amplitude is studied in the pair centre of mass frame and, after separating the phase factor related with the motion of the centre of mass, depends on the relative four-coordinate $x = x_1 - x_2 = \{t^*, \vec{r}^*\}$ and relative four-momentum $\tilde{q} = \{0, 2\vec{k}^*\}$. In the equal time approximation, i.e. $t^* = 0$, the amplitude corresponds to a stationary solution of the scattering problem $\psi_{-\vec{k}^*}^{S(+)}(\vec{r}^*)$ with reverse time direction corresponding to the emission process. The solution of the problem has the asymptotic form of a superposition of the plane and outgoing spherical waves at large $r^* = |\vec{r}^*|$. In case of noninteracting particles Quantum Statistics is the only source of the correlation. Then, the Bethe-Salpeter amplitude reduces to the plane wave: $e^{i\tilde{q}x/2} = e^{-i\vec{k}^* \cdot \vec{r}^*}$ which does not depend on the relative time in the pair centre of mass frame. For interacting particles, the equal time approximation can be justified assuming $|t^*| \ll mr^{*2}$, which is valid for kaons and protons whereas for pions leads to an overestimation of the strong FSI effect not exceeding 5% [99]. Therefore, the correlation function takes the form:

$$C(p_1, p_2) = \sum_S \rho_S \left\langle |\psi_{-\vec{k}^*}^{S(+)}(\vec{r}^*)|^2 \right\rangle_S. \quad (3.17)$$

For identical particles the amplitude needs to be additionally symmetrised, i.e.:

$$\Psi_{-\vec{k}^*}^{S(+)}(\vec{r}^*, \vec{k}^*) \rightarrow \left[\Psi_{-\vec{k}^*}^{S(+)}(\vec{r}^*, \vec{k}^*) + (-1)^S \Psi_{\vec{k}^*}^{S(+)}(\vec{r}^*, \vec{k}^*) \right] / \sqrt{2} \quad (3.18)$$

To take into account the spin state of the particles, the Eq. (3.17) is averaged over the four-coordinates of the particles at given total spin S with weights equal to the population

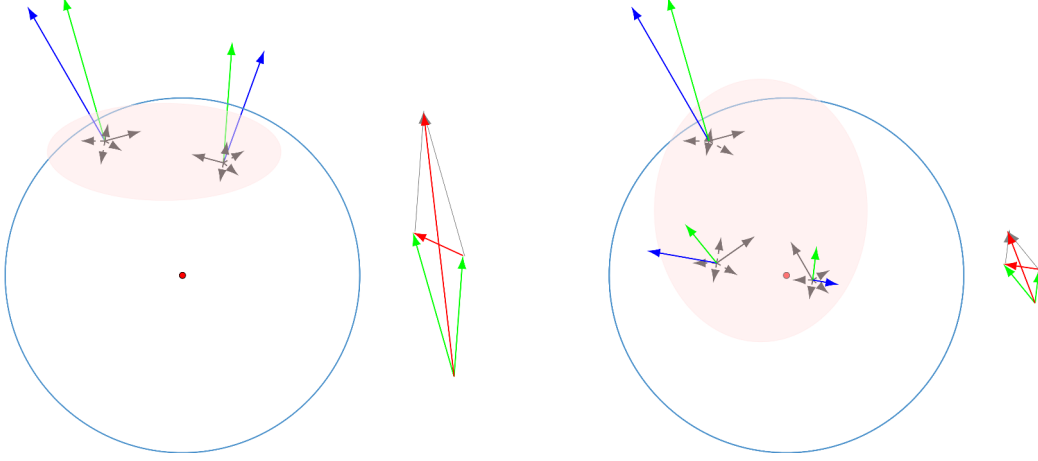


Figure 3.1: Velocities of particles (green arrows) are composed of thermal (black) and collective (blue) components. Pairs with small relative momentum and large pair momentum can be emitted from a small region of the fireball (left panel), whereas pairs with small relative momentum and small pair momentum can originate from relatively larger part of the source (right panel).

probability of this state: $\rho_S = (2S + 1)/[(2s_1 + 1)(2s_2 + 1)]$, for unpolarised particles with spin s_1 and s_2 .

3.2.5. Length of homogeneity

The term *length of homogeneity* was proposed [49] to address the dynamics of the source resulting from the flow. In fact, the femtoscopic radii characterise the averaged homogeneity lengths rather than the size of the whole fireball. The motivation for such reasoning comes from the hydrodynamics. A particle velocity is composed of two elements: a random (thermal) velocity and a common one resulting from the collective flow. The femtoscopic signal is limited to the region of small relative momentum of pairs. If such pairs have also the small pair transverse momentum k_T , the velocities of their constituents are mostly influenced by the thermal component. This means that such particles can be emitted from the distant points of the fireball. Therefore, the measured radius will be large. On the other hand, the large k_T and the small relative momentum can be obtained only for particles with a similar direction of the flow and the thermal velocity vectors. This can be achieved for particles created in neighbouring points of the source since only then the flow velocity vectors (which have the radial direction pointing outwards from the centre of the fireball) of two particles are aligned. Hence, the resulting size of the source is smaller compared with the radius at smaller k_T . This idea is depicted in Fig. 3.1.

3.2.6. Experimental technique

Using the information available from the experiments, the femtoscopic correlation function is expressed by:

$$C(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}, \quad (3.19)$$

where $\vec{q} = \vec{p}_1 - \vec{p}_2$ is the relative momentum, $A(\vec{q})$, commonly called *signal*, is the relative momentum distribution of pairs of particles produced in the same event (correlated pairs), and $B(\vec{q})$, *background*, is the distribution of pairs which are not correlated. In general, there is no universal method of the background construction. The perfect $B(\vec{q})$ should be equal to the $A(\vec{q})$ distribution apart from the presence of the femtoscopic correlations. The most common way of creating the background distribution is a so-called event-mixing technique in which pairs are built of particles coming from different events similar to each other in terms of e.g. the centrality and the primary vertex position. Other methods of the background construction include, for instance, the relative momentum distribution of unlike-charge pairs, and distributions generated in Monte Carlo models. This thesis considers the heavy-ion collisions for which the event-mixing technique is best suited. Indeed, the possible violation of the total energy-momentum conservation resulting from this method is negligible in case of the high multiplicity of particles produced in such collisions [85]. In addition this thesis introduces the novel modification to the event-mixing technique. It is shown that pairing particles from the events with similar event plane angle (apart from the centrality and the primary vertex position) to construct the background distribution can reduce nonfemtoscopic correlations coming presumably from the elliptic flow. See Sec. 6.5.1 for details.

3.2.7. Example of the measurements of the pion correlations

Femtосcopy of identical pion pairs has been analysed over a few orders of magnitude of collision energies available in the heavy-ion experiments. For instance, Fig 3.2 presents the femtoscopic results measured in ALICE at the LHC. The Bose-Einstein enhancement at small relative momentum is prominent. Moreover the width of the correlation effect clearly increases for the peripheral collisions which means the decrease of the source size for such collisions. As a matter of fact, the radii depend linearly on the charged particle multiplicity density. The salient feature present in the experimental data is a decrease of the radius with increasing transverse momentum of the pair k_T . Such effect is understood as the decrease of the lengths of homogeneity due to the collectivity produced in the heavy-ion collision [49].

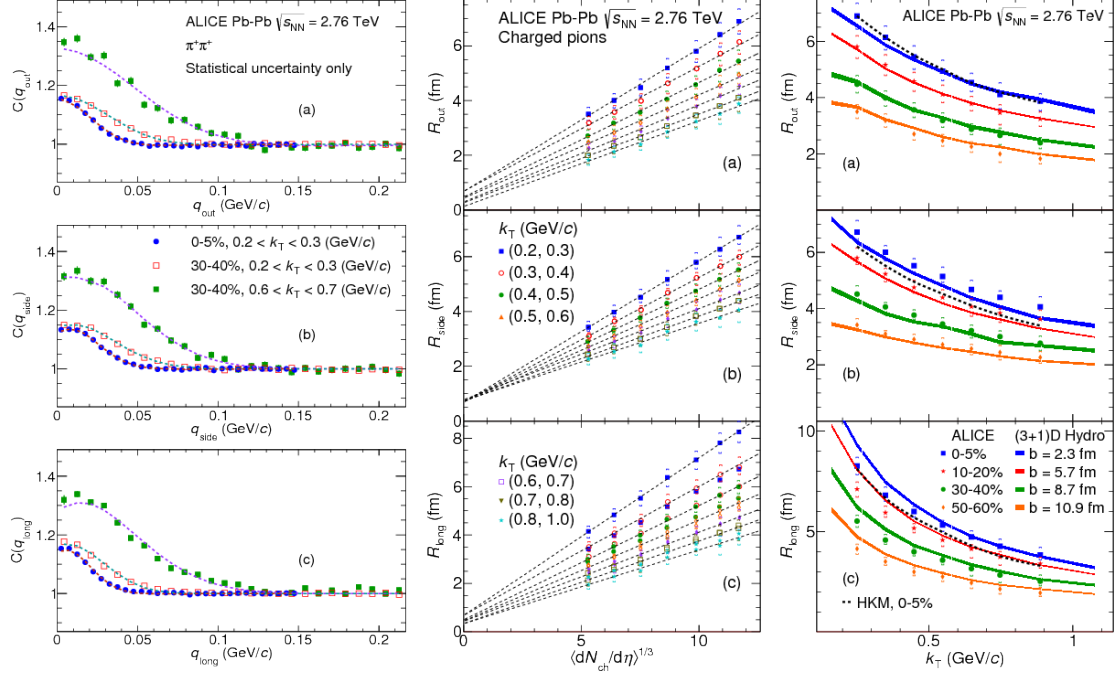


Figure 3.2: Left panel: the correlation functions of identical pion pairs in out-side-long coordination system. Middle panel: extracted radii as a function of measured pseudorapidity charged particle density, in cube root. Right panel: radii as a function of pair transverse momentum compared with hydrodynamic models [100].

3.3. Final State Interactions

Apart from the Bose-Einstein and the Fermi-Dirac statistics, correlations of particles registered in heavy-ion collisions may be also induced by strong and Coulomb Final State Interactions (FSI). Below we show how FSI are taken into account following [91].

3.3.1. Strong interaction

Let us consider a pair of particles with the four-momenta p_1 , p_2 and spin j in space-time points x_1 and x_2 . The pair weight due to strong FSI may be written as [91]:

$$b(p_1, p_2) = \frac{j+1}{2(2j+1)} \left| \Psi_{p_1 p_2}^*(x_1, x_2) + (-1)^{2j} \Psi_{p_2 p_1}^*(x_1, x_2) \right|^2 + \frac{j}{2(2j+1)} \left| \Psi_{p_1 p_2}^*(x_1, x_2) - (-1)^{2j} \Psi_{p_2 p_1}^*(x_1, x_2) \right|^2 - 1, \quad (3.20)$$

where $\Psi_{p_1 p_2}(x_1, x_2)$ is the nonsymmetrised Bethe-Salpeter amplitude, $\frac{j+1}{2(2j+1)}$ and $\frac{j}{2(2j+1)}$ are the fractions of even and odd two-particle spin state, respectively. The Bethe-Salpeter amplitude for interacting particles with mass m is given by:

$$\Psi_{p_1 p_2}(x_1, x_2) = e^{ip(x_1+x_2)} (e^{iqx/2} + \phi_{p_1 p_2}(x)), \quad (3.21)$$

where

$$\phi_{p_1 p_2}(x) = \frac{8\pi\sqrt{p^2}}{(2\pi)^4 i} e^{ipx} \int \frac{e^{-i\kappa x} f(p_1, p_2, \kappa, 2p - \kappa)}{(\kappa^2 - m^2 + i0)((2p - \kappa)^2 + m^2 + i0)} d^4\kappa. \quad (3.22)$$

Here: $q = p_1 - p_2$, $p = \frac{p_1 + p_2}{2}$, $x = x_1 - x_2$ are the four-momenta, and $f(p_1, p_2, \kappa, 2p - \kappa)$ is the nonsymmetrised scattering amplitude. For the following considerations two assumptions are made: only contribution from the s-wave interaction is taken into account (which is dominant at small relative momenta) and the intrinsic range of the interaction potential is smaller than the distance between the emission points. Then, after performing the integration in the approximation of small relative momenta in the centre of mass of the pair, one obtains the contribution due to strong FSI to the correlation function:

$$b_i(p_1, p_2) = 2 \sum_{S=\text{even}} \rho_S \{ |f^S(k^*) \Phi_{p_1 p_2}(x)|^2 + 2\Re\{f^S(k^*) \Phi_{p_1 p_2}(x)\} \cos(qx/2) \}, \quad (3.23)$$

$$\Phi_{p_1 p_2}(x) = i \frac{\sin(k^* r^*)}{r^*} + \frac{1-i}{2r^*} \{ e^{ik^* r^*} (C_1(z_-) + iS_1(z_-)) + e^{-ik^* r^*} (C_1(z_+) + iS_1(z_+)) \},$$

$$z_{\pm} = \sqrt{\frac{m}{2|t^*|}} \left(r^* \pm \frac{k^* |t^*|}{m} \right),$$

$$C_1(z) + iS_1(z) = \sqrt{\frac{2}{\pi}} \int_0^z e^{iy^2} dy.$$

The s-wave amplitude f^S depends only on the magnitude of the $\vec{k}^*$. ρ_S is the emission probability of the identical particles with small relative momentum in a state with total spin S . In general, the s-wave scattering amplitude $f^S(k^*)$ might be different in states with different total spin if the final-state interaction depends on spin. The cross section for the elastic scattering of two unpolarised identical particles with the nonzero mass is given by the simple relation: $\sigma = 4\pi(1 + g_0)|f(k^*)|^2$, $g_0 = (-1)^{2j}/(2j+1)$. In the effective range approximation the scattering amplitude may be written as:

$$f^S(k^*) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^* \right)^{-1}. \quad (3.24)$$

Crucial parameters of the strong interaction: f_0 and d_0 (complex numbers) are the scattering length and the effective range of the strong interaction, respectively. To obtain the final correlation function one needs to average the source of the correlation over the space-time distribution of the particle emitters. A spherically symmetric source in the

pair centre of mass frame with the one-dimensional size r_0 is often assumed:

$$S(\vec{r}^*) \sim \exp\left(-\frac{|\vec{r}^*|^2}{4r_0^2}\right). \quad (3.25)$$

This formulation neglects the time dependence based on equal time approximation in the pair centre of mass frame [34]. Parametrisation of the emission function from Eq. (3.25) is often applied in case of analysis of pairs for which statistics in experiments is limited, e.g. for pairs of baryons.

The correlation function which depends only on the strong FSI takes the form [91]:

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi}r_0} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}r_0} F_1(2k^*r_0) - \frac{\Im f^S(k^*)}{r_0} F_2(2k^*r_0) \right] \quad (3.26)$$

$$F_1(z) = \int_0^z dx e^{x^2 - z^2} / z, \\ F_2(z) = (1 - e^{-z^2}) / z.$$

The vital feature resulting from Eq. (3.26) is that the correlation function depends only on relative momentum of the pair and is parametrised by the source size r_0 and the strong interaction parameters f_0 and d_0 . Therefore, providing femtoscopic data and fitting Eq. (3.26) to the correlation function, one may extract these parameters. For most baryon-antibaryon (e.g. $p\bar{\Lambda}$, $\bar{p}\Lambda$) pairs which are one of the topic of this thesis, the strong FSI is the only source of femtoscopic correlation and thus Eq. (3.26) will be repeatedly used (see Chaps. 4, 5, and 8).

3.3.2. Coulomb interaction

The contribution of Coulomb FSI is usually approximated by the Gamow factor:

$$A_c^\pm(k^*) = \pm \frac{2\pi}{k^* a_c} (e^{\pm \frac{2\pi}{k^* a_c}} - 1)^{-1}, \quad (3.27)$$

where $a_c = (\mu z_1 z_2 e^2)^{-1}$ is the two-particle Bohr radius (e.g. $a_c = 57.6$ fm for pp pair). The signs $+$ and $-$ refer to repulsion and attraction, respectively. As one can see from Eq. (3.27) the width of the contribution from Coulomb FSI increases with the pair mass. The Gamow factor is the squared modulus of the nonrelativistic Coulomb wave function taken at the distance between particles equal to zero [101]. In general, one should consider the wave function dependent on the pair relative distance, as shown in Sec. 3.3.3. The

pair types for which correlations arise mainly due to the Coulomb FSI are various charge combinations of πK pairs [94].

3.3.3. Combination of strong and Coulomb FSI with QS correlations

The contributions of QS and strong FSI are additive [91]. Combining strong and Coulomb FSI requires the modification of the pair wave function [99]:

$$\Psi_{-\vec{k}^*}(\vec{r}^*) = e^{i\delta_c} \sqrt{A_c(\eta)} \left[e^{-i\vec{k}^* \cdot \vec{r}^*} F(-i\eta, 1, i\xi) + f_c(k^*) \frac{\tilde{G}(\rho, \eta)}{|\vec{r}^*|} \right], \quad (3.28)$$

where $\vec{r}^*$ is the spatial separation of particle emitters at generally different emission moments in the pair centre of mass frame, $\delta_c = \arg \Gamma(1 + i\eta)$ is the Coulomb s-wave phase shift, $\eta = (a_c k^*)^{-1}$, F is the confluent hypergeometric function, $\xi = k^* r^* (1 + \cos \theta^*)$, θ^* is the angle between $\vec{k}^*$ and $\vec{r}^*$, $\tilde{G}$ is the combination of the regular and singular s-wave Coulomb functions, and $\rho = k^* r^*$. The amplitude of the low-energy s-wave elastic scattering due to the short range interaction $f_c(k^*)$ may be expressed as

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{d_0 k^{*2}}{2} - i k^* A_c(\eta) - \frac{2}{a_c} h(\eta) \right]^{-1}, \quad (3.29)$$

where f_0 is the scattering length, d_0 is the effective radius of the interaction, $h(\eta) = [\Psi(i\eta) + \Psi(-i\eta) - \ln(\eta^2)]/2$, and Ψ is the digamma function. For the pp system in the singlet (triplet) state, f_0 and d_0 are 7.77 fm (-5.4 fm) and 2.77 fm (1.7 fm). The pair of protons is the system where all of the following effects: Fermi-Dirac statistics, Coulomb and strong FSI need to be taken into account. As far as the contribution of the QS correlations is concerned, protons (which are fermions) obey the Pauli exclusion principle. Hence the probability to observe them close in the momentum space is decreased, and quantum statistics correlation function should have the minimum at small relative momentum. However, one needs to take also into account the total spin of the pair composed of two identical fermions with spin 1/2. Such an object might be in a singlet ($S = 0$) or a triplet ($S = 1$) state with the relative weights 1/4 and 3/4. The spin part of the wave functions in the triplet states is symmetric as opposed to the singlet state. Therefore, the spatial part of the wave function for the triplet state should be antisymmetric to create the antisymmetric total wave function. The latter means that the triplet state leads to the decrease of the correlation function while the singlet state causes an increase of the correlation. Since the probability of the triplet state is three times larger than the singlet, the final correlation function will have a minimum at small relative momentum. The interplay of Coulomb and strong interactions in proton-proton system leads to a peak lo-

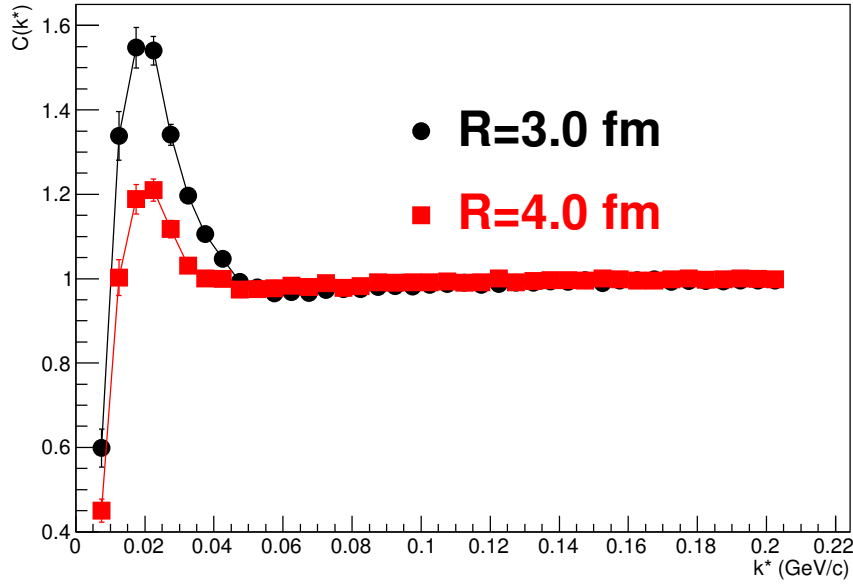


Figure 3.3: Theoretical correlation functions of pp pairs for the source sizes of 3 fm and 4 fm.

cated at $k^* \simeq 2\pi/a_c = 21.6 \text{ MeV}/c$. The height of the peak depends on the spatial extent of the proton source [91]. The theoretical predictions for the pp correlation function are presented in Fig. 3.3. For the pair composed of proton and antiproton, the correlation is due strong and Coulomb FSI. However, in this case one has to take into account both elastic and inelastic transitions which lead to the two-channel scattering problem. The $p\bar{p}$ correlation function calculated using considerations presented in [99] is shown in Fig. 3.4. One can observe that annihilation process present in this channel leads to a wide dip of the correlation function. At lowest relative momentum there is a positive correlation due to the attractive Coulomb forces.

3.4. Overview of the results from baryon femtoscopy

3.4.1. Motivation

The main focus of the baryon femtoscopy concerns the extraction of the strong interaction parameters. The understanding of baryon interactions is one of major challenges in QCD [102, 103]. Although there are many experiments designed for measuring such parameters for baryon-baryon pairs [104, 105, 106], the knowledge of interactions in the baryon-antibaryon sector is meagre. Indeed, the only pair types analysed experimentally are $p\bar{p}$, $p\bar{n}$, $\bar{p}d$ [107, 108, 109, 110, 111]. What is more, the theory does not provide much knowledge regarding the interactions in such pairs. The idea to use femtoscopy for such measurements is based on Eq. (3.17). In the standard femtoscopic analysis performed e.g. for pairs of identical pions, one measures the correlations, knows the interactions and

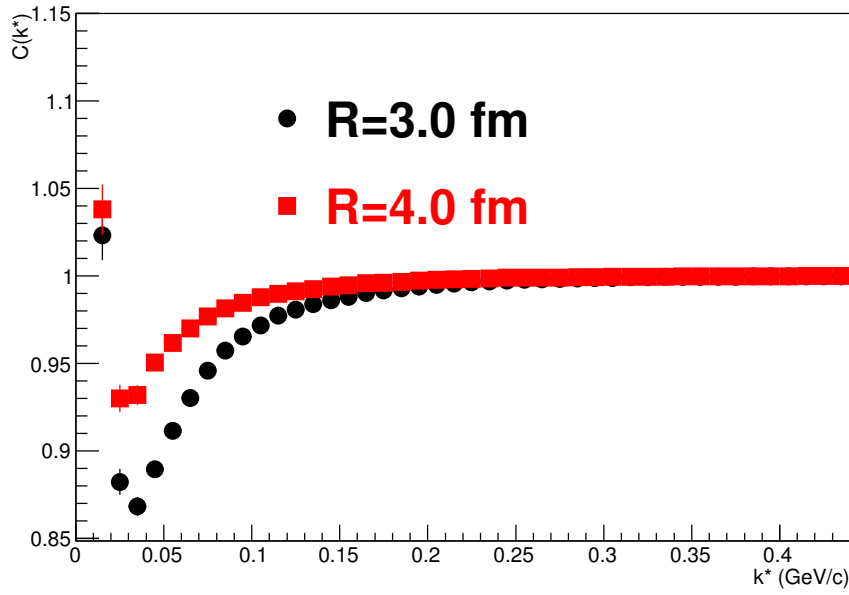


Figure 3.4: Theoretical correlation functions of $p\bar{p}$ pairs for a source sizes of 3 fm and 4 fm.

thus extracts parameters of the source distribution. If the interaction is not known one may assume certain source size for given pair (e.g. following m_T -scaling obtained with lighter particles) and extract parameters of the wave function. In particular, for systems where strong FSI is the only source of correlation one may fit Eq. (3.26) to the measured correlations and thus extract the source size as well as the scattering length and the effective range of the interaction. One should emphasise that ALICE with its excellent particle identification and abundant production of baryon-antibaryon pairs is perfectly suited for such measurements. As it was already mentioned in Sec. 1.5.4, knowledge of interaction parameters may be crucial for the description of the rescattering phase of the heavy-ion collision and thus understanding of the low proton yield at the LHC. Furthermore, baryon interactions are essential in astrophysics to comprehend the properties of neutron stars [112].

Another purpose of studying femtoscopy with baryon pairs is to extend the range of the pair transverse mass (m_T) dependence of the source sizes derived from the correlations of mesons π and K . The scaling of the radius with m_T is usually interpreted as an evidence of the collective behaviour of matter produced in the heavy-ion collisions [85, 113].

3.4.2. Correlations of baryon-baryon pairs

The field of proton femtoscopy was initiated by the theoretical paper of Koonin who showed that correlations of proton with small relative momenta are sensitive to the space-time characteristics of the heavy-ion collision [87]. From the experimental point of view, the proton correlations at small relative momenta were observed in $\pi^- + Xe$ interactions

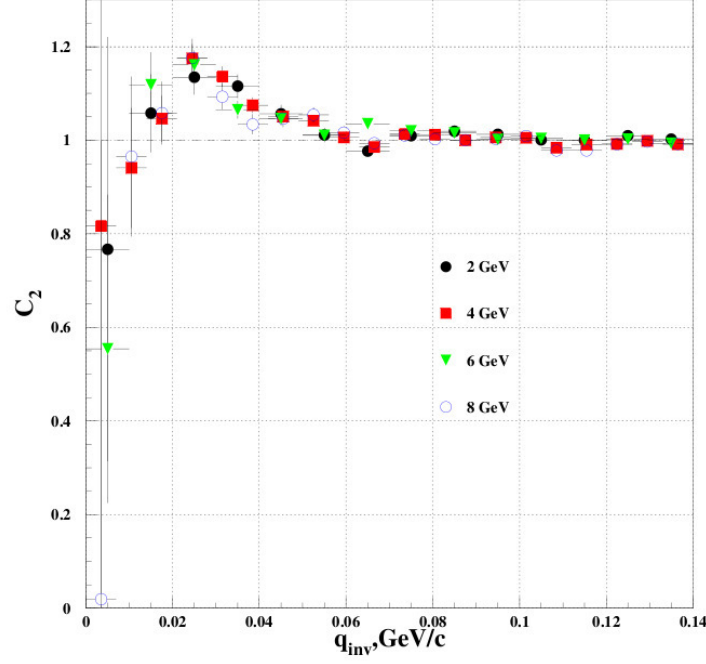


Figure 3.5: Proton-proton correlation functions as a function of beam energy for Au–Au central collisions measured by E895 experiment [117].

at 9 GeV/c for the first time [114]. As far as the heavy-ion collisions are concerned, proton-proton correlations were measured for the very wide range of collision energies, from 4.2 GeV/c per nucleon [115, 116], $2 \div 8$ GeV/c (see Fig. 3.5, [117]), 11.5 GeV/c, 14.6 GeV/c [118] to SPS [119, 120], RHIC [121, 122] and LHC energies [123]. Nevertheless, it should be pointed out that for lower energies registered protons mainly come from the colliding nuclei, whereas starting from RHIC energies, protons produced directly in the collision become dominant.

In Fig. 3.5 pp correlation functions from central Au+Au collisions at the beam energies $2 \div 8$ GeV per nucleon are presented. Extracted radii are of the order of 6 fm and do not depend significantly on the collision energy. Two-proton correlation function obtained from $\sqrt{s_{NN}} = 17.3$ GeV Pb–Pb central collisions is shown in Fig. 3.6. Correction for the contamination coming from protons from the weak decays was applied in these results. The data are well described by the Gaussian source with the size $\simeq 3.8$ fm.

Data from Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented in Fig. 3.7. Correlation functions were analysed as a function of centrality which indicated that the strength of the correlation is bigger for more peripheral events. Indeed, derived source sizes scale with the charged particle multiplicity density $(dN_{ch}/d\eta)^{1/3}$. Radii extracted from the fits to two-proton correlations in the central collisions follow m_T dependence observed also in meson correlations. This analysis carefully studied the effect of nonprimary protons, accounting for the residual correlations effect [121, 124]. In that method, the correlation function is corrected for the expected contribution from the residual correlations. This is

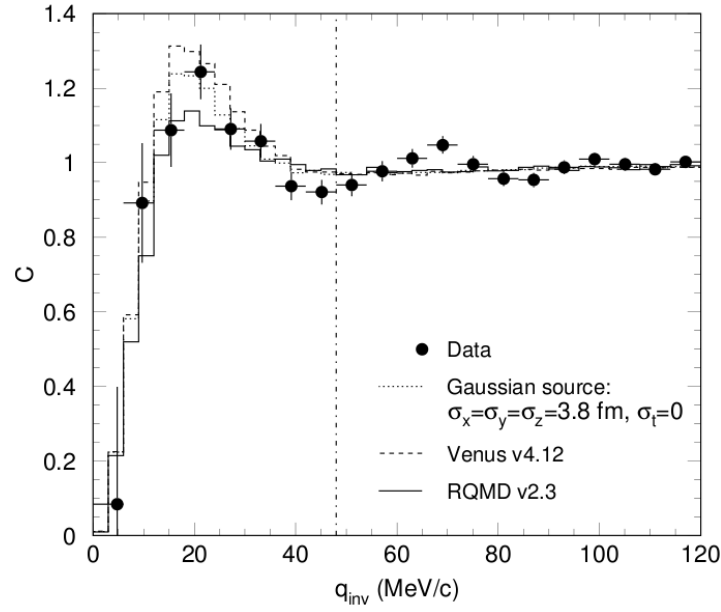


Figure 3.6: Proton-proton correlation function from $\sqrt{s_{NN}} = 17.3$ GeV Pb-Pb central collisions measured in NA49 experiment [120].

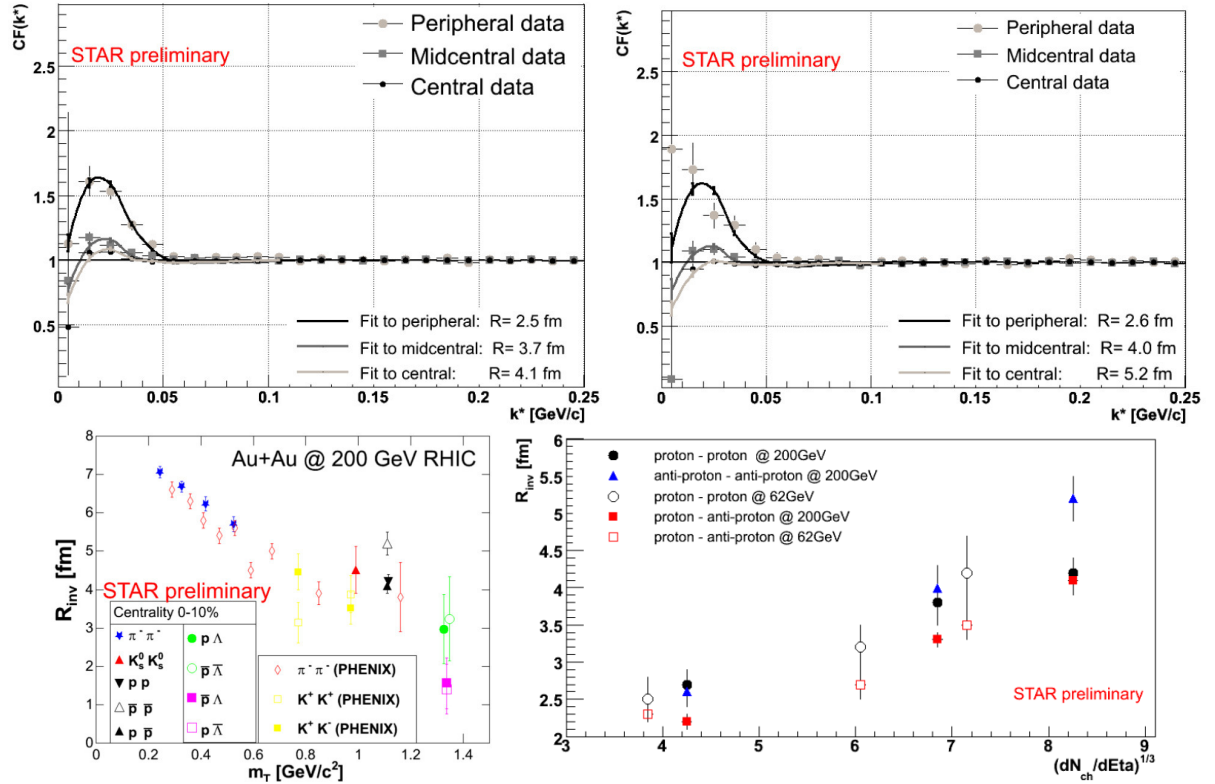


Figure 3.7: Proton femtoscopy from Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Top left panel: two-proton correlation functions for three centrality classes. Top right panel: two-antiproton correlation functions for three centrality classes. Bottom left panel: radii as a function of the pair transverse mass. Bottom right panel: $(dN_{ch}/d\eta)^{1/3}$ dependence of source sizes from proton femtoscopy [121].

in contrast to the technique developed in this thesis where no correction is applied, but instead the experimental correlation function is fitted by the function taking into account the residual correlations. See Chap. 4 for details.

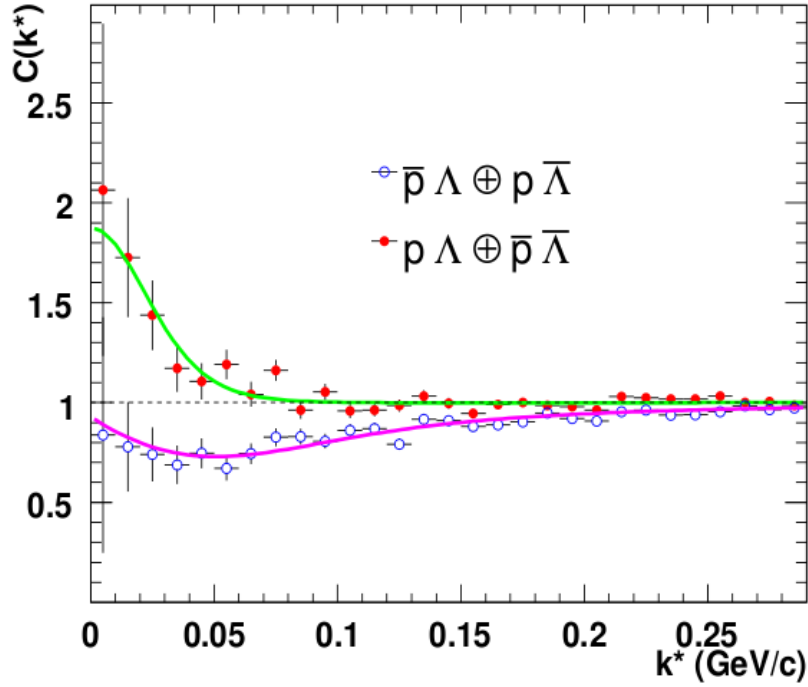


Figure 3.8: $(p\Lambda) \oplus (p\bar{\Lambda})$ and $(\bar{p}\Lambda) \oplus (\bar{p}\bar{\Lambda})$ correlation functions measured by STAR experiment [128].

STAR collaboration has recently published the results of the measurement of $\bar{p}\bar{p}$ strong interaction parameters extracted from the femtoscopic correlations [122]. This article applies the residual correlations technique introduced in this thesis (see Chap. 4). Results of extracted parameters appear to coincide with the values for the pp pair obtained using other methods [125] which is an important outcome validating the femtoscopic formalism [126].

Furthermore, femtoscopic correlations of $p\Lambda$ pairs have been studied from the theoretical [127] and experimental [128] point of view. The peak in the $p\Lambda$ correlation function coming from strong FSI allows to extract the source size. It was shown that $p\Lambda$ correlation function is much more sensitive to the source size comparing with the pp correlation function, especially for sizes above 6 fm. Additionally the feasibility of the space-time asymmetry analysis of $p\Lambda$ emission was suggested [127]. Experimental results of $p\Lambda$ femtосcopy have been also used to study the strong interaction potential which is difficult to achieve by other means [128]. Results from the $p\Lambda$ correlations from Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented in Fig. 3.8.

Two-particle correlations of $\Lambda\Lambda$ pairs were analysed in multihadronic Z decays (see Fig. 3.9). The depletion of the correlation functions observed for momentum difference $Q < 2$ GeV was interpreted as the result of Fermi-Dirac statistics [129]. Femtосcopy with $\Lambda\Lambda$ pairs has also been analysed by the STAR collaboration [130]. This measurement emphasises the importance of residual correlations in extracting physical parameters: source size and the parameters of strong interaction. The extracted radius is in good agreement

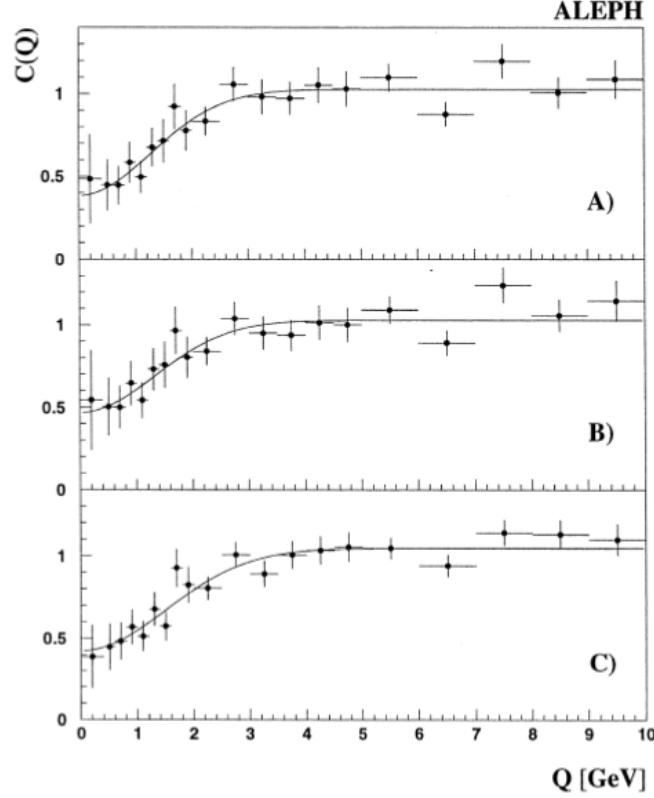


Figure 3.9: $\Lambda\Lambda$ correlation function. Panel A shows Monte Carlo data, panels B and C show different samples of real events. The measurements were performed using multihadronic Z decays with the ALEPH detector at LEP [129].

with the trend obtained with lighter pairs in STAR. Fits to the data which are based on the Eq. (3.26) suggest rather weak interaction of $\Lambda\Lambda$ pair. In addition, the results put some constraints on the existence of the H-dibaryon (the hypothetical particle composed of two up, two down and two strange quarks) [131].

3.4.3. Correlations of baryon-antibaryon pairs

As far as baryon-antibaryon pairs are concerned, proton-antiproton system has been analysed at RHIC and LHC [124, 132, 133]. For this pair type correlations arise due to the strong annihilation process which results in a wide depletion of the correlation function as well as Coulomb attraction leading to the maximum at $k^* \rightarrow 0$. STAR data suggest that radii extracted from the fits to $p\bar{p}$ correlations are substantially smaller than pp and $\bar{p}\bar{p}$ radii. The possible solution of this puzzle was to take into account the residual correlations. The influence of the residual correlations on the $p\bar{p}$ correlation function is presented in Fig. 3.10. After such correction, the strength of $p\bar{p}$ correlation becomes significantly smaller compared with the function without the residual correlation correction, indicating larger size of the source.

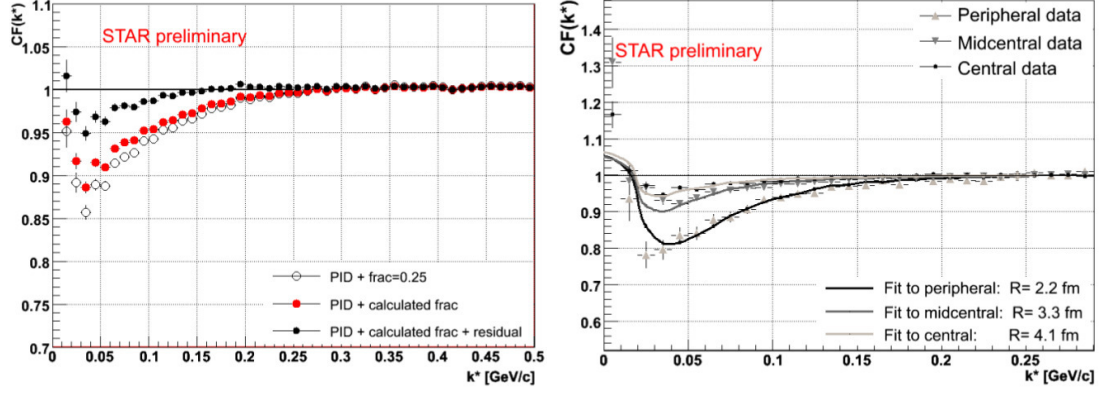


Figure 3.10: Left panel: the influence of residual correlations on proton-antiproton correlation function. Right panel: proton-antiproton correlation functions from Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [132].

As one can notice in Fig. 3.11, STAR experiment observed approximate scaling of the invariant radius except for the value extracted for the $p\bar{\Lambda}$ pair type. In particular the $p\bar{\Lambda}$ source size appeared unexpectedly to be two times bigger than in case of $p\bar{\Lambda}$. In this thesis, the explanation of this inconsistency using the residual correlations is proposed in Chap. 5. Furthermore, this thesis contains the updated version of the Fig. 3.11 obtained in A Large Ion Collider Experiment which encloses the femtoscopic measurements with identical pion, charged kaon, neutral kaon and (anti)proton pairs (see Chap. 7 for details).

ALICE collaboration has also shown preliminary results on $\Lambda\bar{\Lambda}$ femtосcopy. These correlation functions (Fig. 3.12), similarly as $p\bar{p}$, reveal an anticorrelation wide in k^* . This may be attributed to the annihilation channel in strong FSI which is manifested by a nonzero imaginary part of the scattering length. Indeed, Fig. 3.13 obtained using Eq. (3.26), presents that finite $\Im f_0$ produces the wide negative correlation effect, as observed in the experiment. The real part of the scattering length can cause the positive or negative correlation effect depending on its value, but it always affects only region of small k^* .

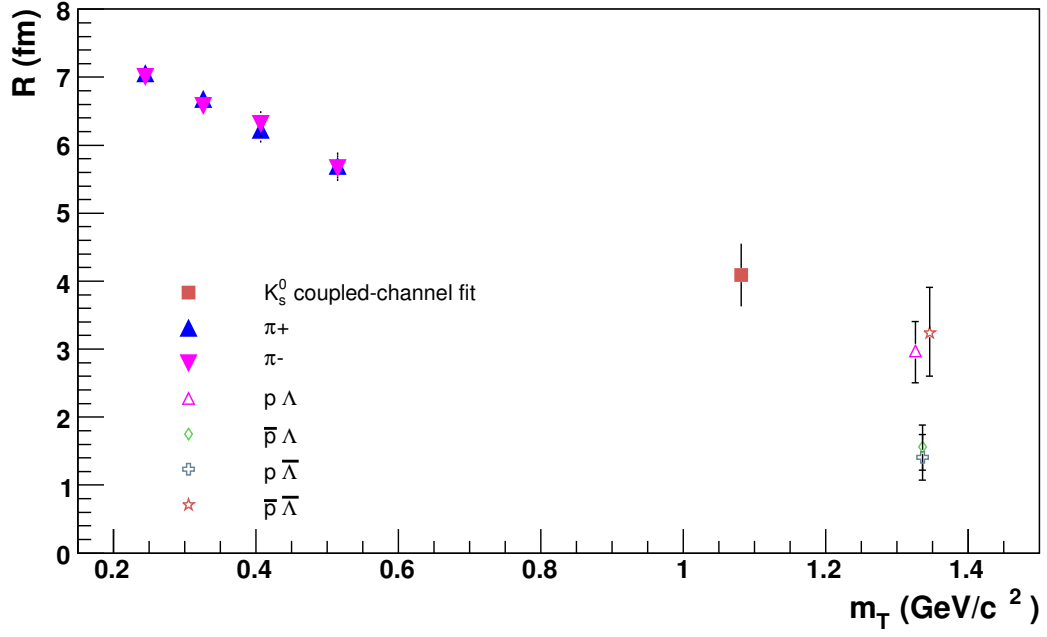


Figure 3.11: Source size R as a function of pair transverse mass m_T obtained in STAR experiment [134].

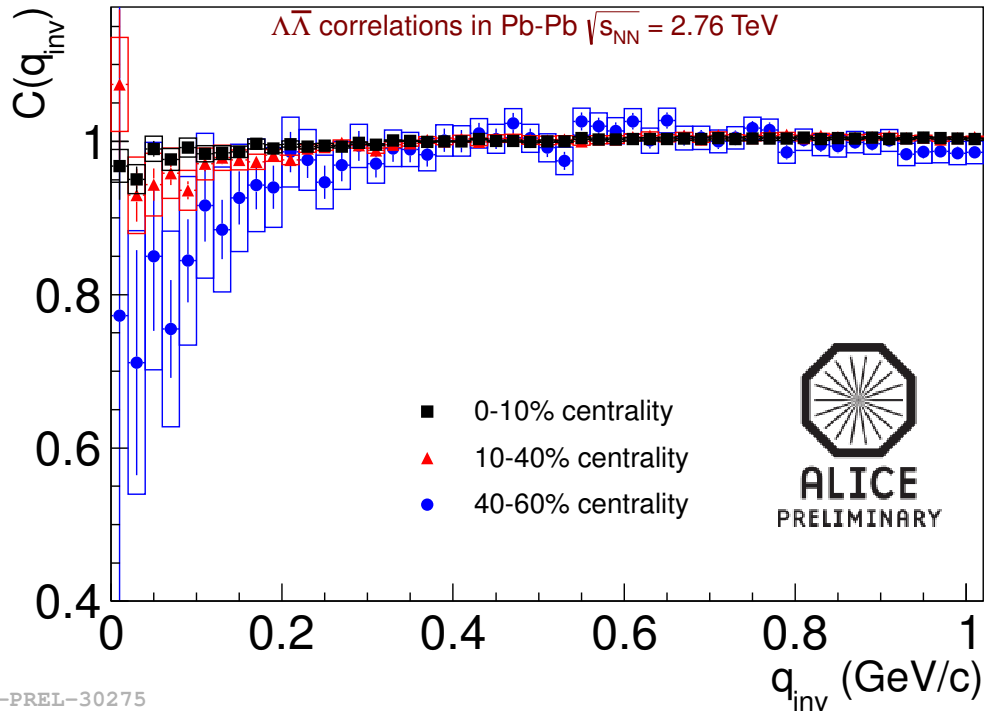


Figure 3.12: $\Lambda\bar{\Lambda}$ femtoscopic correlation function measured by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [133].

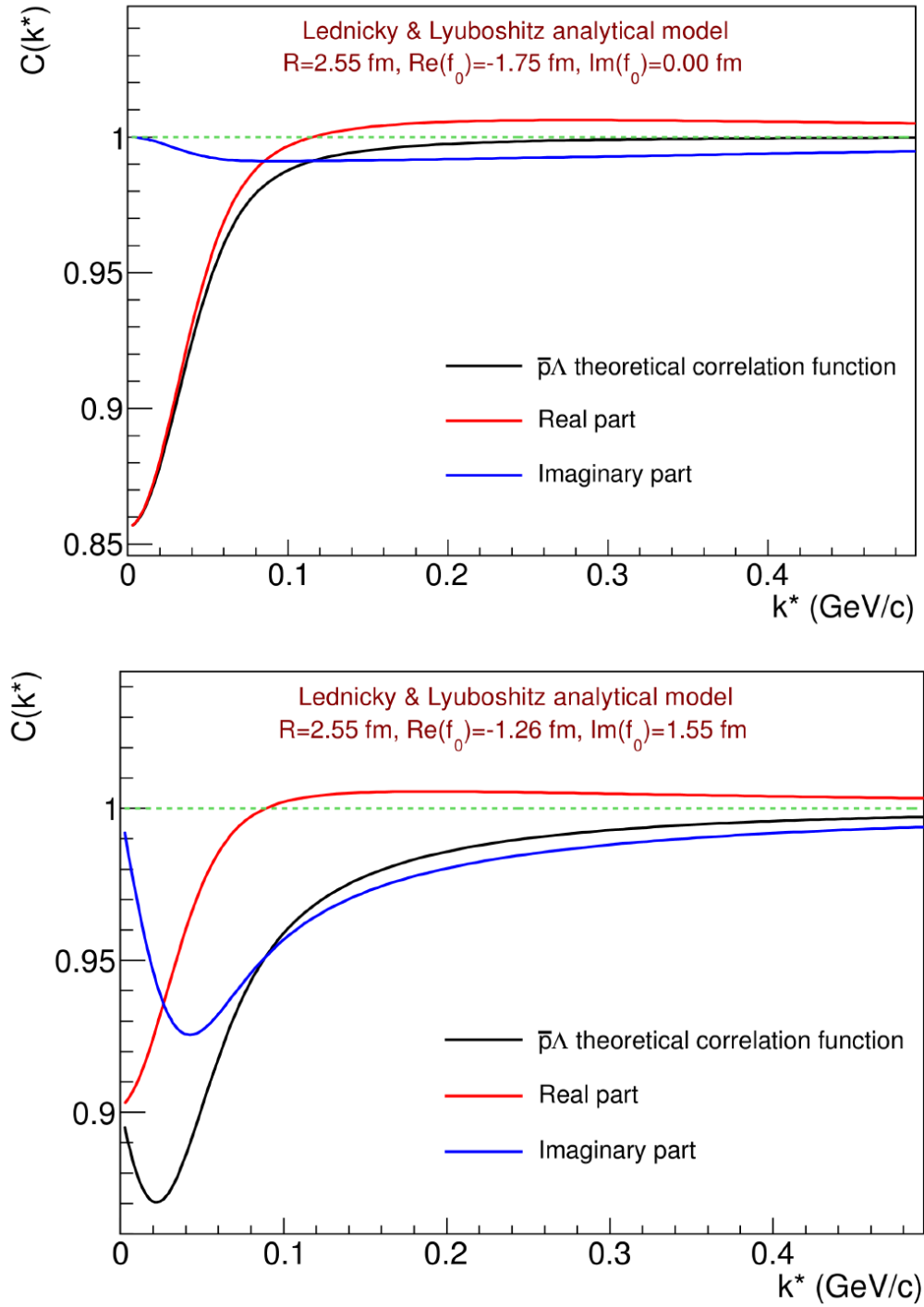


Figure 3.13: Theoretical calculations of strong FSI correlation functions obtained using Eq. (3.26). Top panel: the correlation function with imaginary part of the scattering length set to zero (the real part only cannot reproduce wide anticorrelation effect). Bottom panel: the correlation function with nonzero imaginary part of the scattering length (anticorrelation reproduced as observed in data).

4. Residual correlations

As it was indicated in the previous chapter, the femtoscopic correlations with baryon-(anti)baryon pairs appear to be extremely sensitive to the contribution from particles originating from weak decays. In this chapter the topic of the residual correlations is presented. In particular, the formalism for dealing with this phenomenon is introduced, which will be applied in the following chapters containing experimental results of baryon femtoscopy. This methodology is also the subject of the work [135] prepared by the author of this thesis in collaboration with the supervisor and the co-author.

4.1. General description

In the collider-type heavy-ion experiments, it is difficult to distinguish fully the primary baryons from the secondary ones. Therefore, a number of measured pairs is composed of at least one particle which is a decay product of another primary baryon. The timescale of the strong FSI which is the main source of the femtoscopic correlations for baryon pairs is of the order of fm/c (10^{-24} s): particles interact directly after they are created. On the other hand, the typical lifetime of particles decaying due to weak forces is of the order of 10^{-10} s. Hence, the correlations measured for such pairs arise because of the interactions between primary particles, not those registered in the detector. In fact the modified version of the Eq. (3.17) should be applied for such pair, namely the pair wave function ought to be calculated for k^* , r^* , and interaction parameters of parent particles. When one or both particles decay, one measures in the experiment the k^* of the daughter pair. The phenomenon described above is called residual correlation. Such effect becomes important once three conditions are fulfilled simultaneously:

- the momentum of the decay products in the rest frame of the parent particle (usually called the decay momentum) is comparable or smaller than the expected width of the femtoscopic correlation in k^* ,
- the genuine correlation of parent particles is large,
- the fraction of pairs which contain at least one secondary particle is substantial.

For instance, pp femtoscopic correlations are affected by the correlations coming from the p Λ pair. The peak from the strong interactions in p Λ system is only smeared by the Λ decay (decay momentum of 101 MeV/ c), but still may be observed in the pp correlation function. The diagram explaining the origin of residual correlations is given in Fig. 4.1.

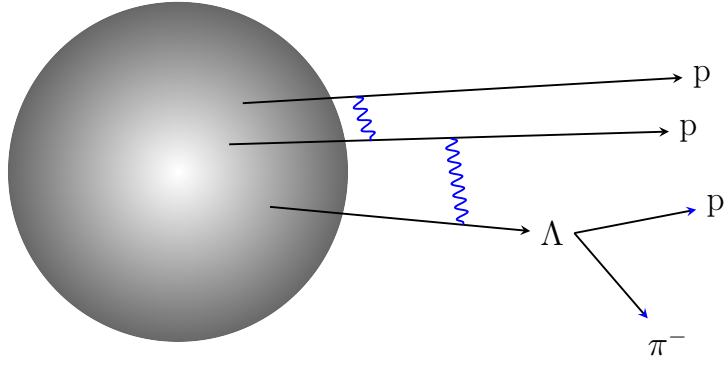


Figure 4.1: The origin of the residual correlations: correlations of measured particles may arise due to interactions of parent particles.

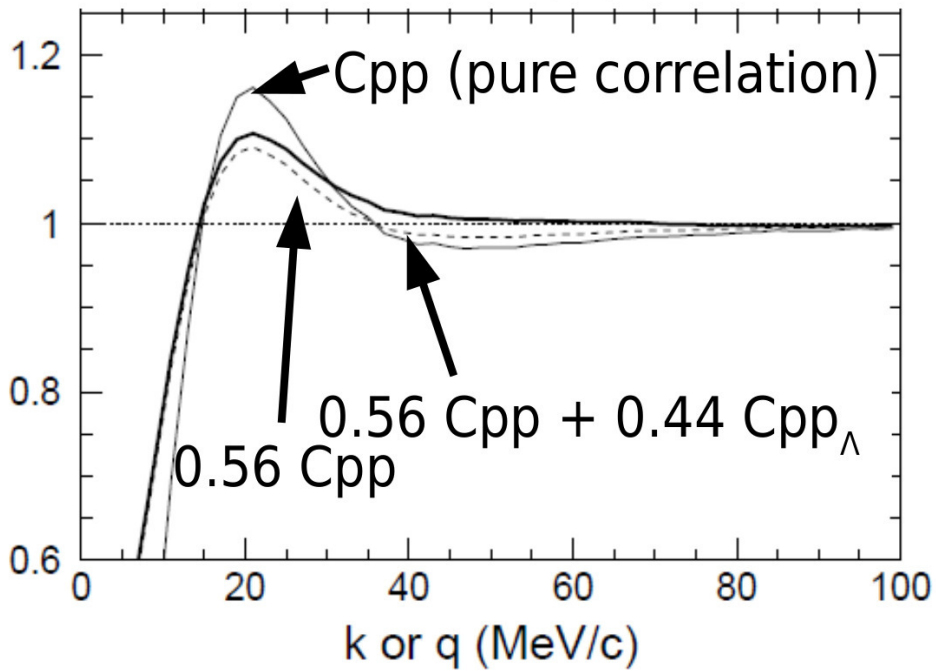


Figure 4.2: Contribution of $p\Lambda$ residual correlation to pp correlation [136]. Arrows and description of the plot were added by the author of this thesis.

There is one important caveat in these considerations. For baryon pairs, which are most affected by residual correlations, the knowledge of the strong FSI parameters is meagre as it was mentioned in Sec. 3.4. Therefore, a number of assumptions need to be made in order to reliably study this phenomenon.

4.2. Previous studies

The issue of the importance of residual correlation was raised in [136]. It was found that the residual $p\Lambda$ correlation has about ten percent strength of the original correlation and its broad distribution distorts the proton-proton correlation function as depicted in Fig. 4.2.

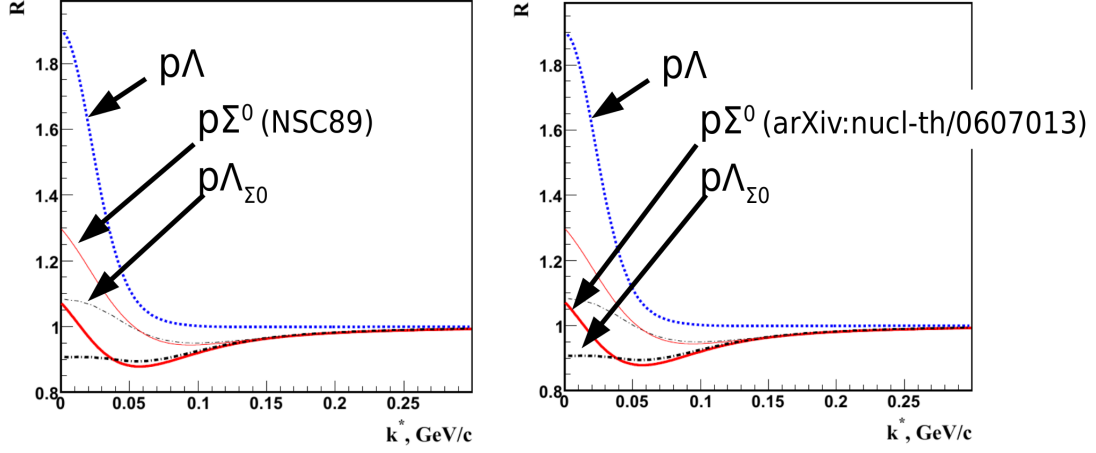


Figure 4.3: Importance of the knowledge of strong FSI in residual correlations studies [137]. Arrows and description of the plots were added by the author of this thesis.

Furthermore, it was noticed that such effect may be crucial in femtoscopy with heavier baryons including Σ^0 , $\Sigma^\pm$, Ξ as well as in neutral pion femtoscopy where $\gamma\gamma$ residual correlations may serve as a source of information about the fraction of direct photons [137, 138]. In particular, the shape and the intensity of $p\Sigma^0$ correlation were observed to be sensitive to the strong FSI parameters as it is presented in Fig. 4.3. Indeed, the two types of calculations with the different values of the strong FSI parameters may lead to the totally different shapes of the residual contribution to the $p\Lambda$ correlation function (denoted as $p\Lambda_{\Sigma^0}$). The $p\Lambda_{\Sigma^0}$ function calculated using $p\Sigma^0$ parameters from NSC89 model [139] exhibit the positive correlation which has about 12% strength of the $p\Lambda$ correlation function. Using the $p\Sigma^0$ strong FSI parameters from [140] the $p\Lambda_{\Sigma^0}$ residual correlation function reveals the anticorrelation wide in k^* . Therefore, one can see that the residual correlations are crucial for the correct description of the femtosopic correlation function.

From the experimental point of view, it was found as well that measured parameters may change dramatically when taking into account the residual correlations [119, 121]. For instance, Fig. 3.10 presents the residual correlations correction applied to $p\bar{p}$ correlation function that leads to the decrease of the anticorrelation effect and thus larger extracted radii. Furthermore, STAR femtosopic measurement with $p\bar{\Lambda}$ and $\bar{p}\Lambda$ pairs indicated that the radius extracted from the fits to the correlation functions is about twice smaller than the radius obtained for the $p\Lambda$ pairs [128]. Such observation is not compatible with the hydrodynamics models [113, 141] as well as the measurements of momentum correlations of lighter pairs. STAR paper clearly states that residual correlations might be the crucial piece for the understanding of this puzzle, but no method accounting for such effect was applied in that analysis. The possible solution for the disagreement of the $p\Lambda$ and $\bar{p}\Lambda$ radii may be found in [135], which is one of the bases of this thesis (see Chap. 5), as well as in [142].

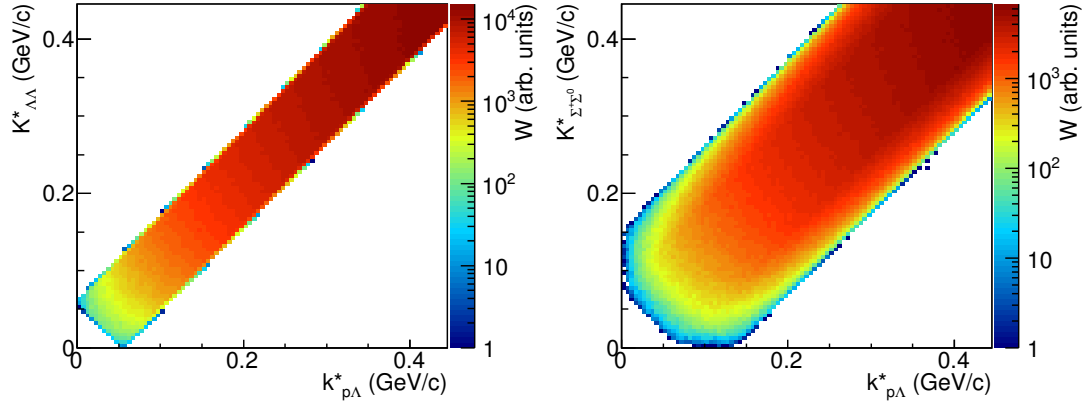


Figure 4.4: The transformation matrix for $\Lambda\bar{\Lambda}$ (left plot) and $\Sigma^+\bar{\Sigma}^0$ (right plot) pairs which decay into $p\bar{\Lambda}$ pairs, as a function of relative momentum [135].

4.3. Formalism

In general, the formalism of the residual correlations presented below can be applied to any parent and daughter pairs. For the sake of definiteness in the following lines, any parent pair which feeds down to the $p\bar{\Lambda}$ correlation function is considered. The residual correlation function may be then expressed as:

$$C^{X\bar{Y} \rightarrow p\bar{\Lambda}}(k_{p\bar{\Lambda}}^*) = \frac{\int C^{X\bar{Y}}(k_{X\bar{Y}}^*) W(k_{X\bar{Y}}^*, k_{p\bar{\Lambda}}^*) dk_{X\bar{Y}}^*}{\int W(k_{X\bar{Y}}^*, k_{p\bar{\Lambda}}^*) dk_{X\bar{Y}}^*}, \quad (4.1)$$

where $W(k_{X\bar{Y}}^*, k_{p\bar{\Lambda}}^*)$ is the probability that parent pair composed of baryon X (proton or other baryon which decays into proton) and antibaryon $\bar{Y}$ ($\bar{\Lambda}$ or other antibaryon which decays into $\bar{\Lambda}$) with the relative momentum $k_{X\bar{Y}}^*$ decays into $p\bar{\Lambda}$ pair with $k_{p\bar{\Lambda}}^*$. The magnitude of the daughter momentum $k_{p\bar{\Lambda}}^*$ differs from $k_{X\bar{Y}}^*$ by decay momentum, but the direction is changed randomly for each pair. The distribution $W(k_{X\bar{Y}}^*, k_{p\bar{\Lambda}}^*)$ may be obtained from the model of heavy-ion collision which provides final-state space-time coordinates of the particles and their history of decays, e.g. THERMINATOR (see Sec. 1.4.1). Examples of such distributions for $\Lambda\bar{\Lambda}$ and $\Sigma^+\bar{\Sigma}^0$ pairs are shown in Fig. 4.4. In the former, only one particle decays and the function has a typical rectangular shape for low relative momenta [136]. The vertical width of the $W(k_{\Lambda\bar{\Lambda}}^*, k_{p\bar{\Lambda}}^*)$ distribution is similar to the value of the decay momentum for $\Lambda \rightarrow p + \pi^-$. In the latter case both particles decay, the distribution's width is of the order of the sum of decay momenta, and the shape at low relative momentum is less sharp comparing with the first case. Contributions from $\Lambda\bar{\Lambda}$ and $\Sigma^+\bar{\Sigma}^0$ residual correlations to $p\bar{\Lambda}$ system compared with the standard $p\bar{\Lambda}$ correlation function are presented in Fig. 4.5. They are determined using Eq. (3.26). The same radius and the strong FSI parameters for all considered pairs are assumed. It is worth noticing that at high k^* the shape and the strength of the residual correlations are comparable

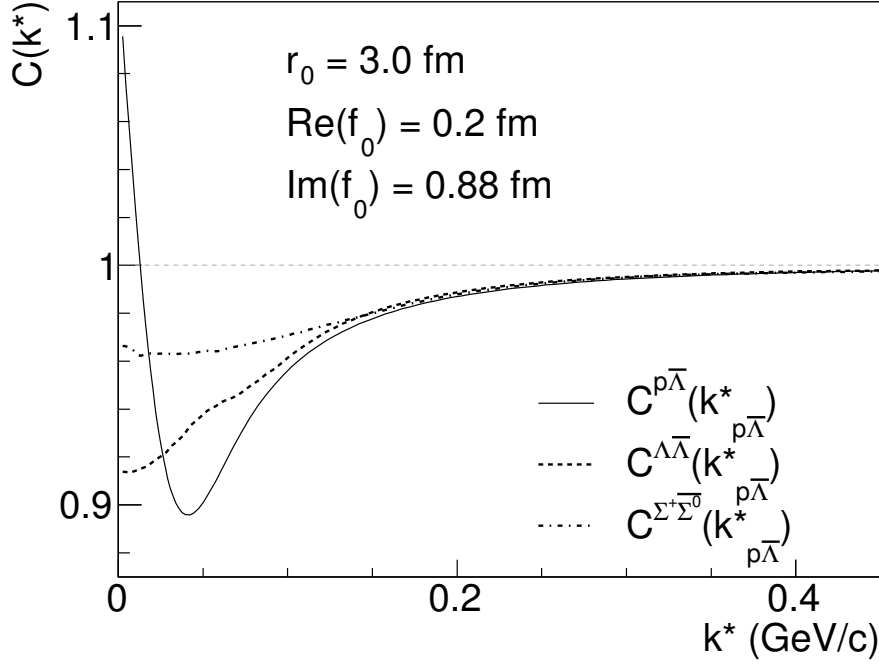


Figure 4.5: The correlation function for $p\bar{\Lambda}$ calculated using Eq. (3.26) with the examples of residual correlation contributions from $\Lambda\bar{\Lambda}$ and $\Sigma^+\bar{\Sigma}^0$ pair types. Arbitrary source size and parameters of the strong FSI parameters are applied [135].

with the parent one. The dilution being the consequence of the randomness of the decays depends on whether one or two particles from the studied pair decayed, and it has the influence mainly on the region of small k^* .

The final form of the $p\bar{\Lambda}$ correlation function taking into account all the residual components might be expressed in the following way:

$$C(k_{p\bar{\Lambda}}^*) = 1 + \lambda_{p\bar{\Lambda}} \left(C^{p\bar{\Lambda}}(k_{p\bar{\Lambda}}^*) - 1 \right) + \sum_{X\bar{Y}} \lambda_{X\bar{Y}} \left(C^{X\bar{Y}}(k_{p\bar{\Lambda}}^*) - 1 \right). \quad (4.2)$$

In Eq. (4.2), $\lambda_{X\bar{Y}}$ symbol describes the fraction of $X\bar{Y}$ pair which may affect the $p\bar{\Lambda}$ correlation function. In general, each $C^{X\bar{Y}}$ depends on the source size, the scattering length and the effective range. Hence certain assumptions should be made to reduce the number of the free parameters of the fit. For instance, one may argue that source sizes of all baryon pairs are comparable basing on the hydrodynamics prediction suggesting that homogeneity length is approximately proportional to $1/\sqrt{\langle m_T \rangle}$. As baryons have relatively large $\langle m_T \rangle$, the radii in fact should be similar. Another assumptions might be introduced concerning the values of the scattering length and the effective range which are not precisely known for most baryon-antibaryon pairs.

It should be also emphasised that the residual correlations are expected to have bigger impact on the baryon-antibaryon pairs comparing with baryon-baryon pairs. The reason for that is the following. The correlation effects for baryon-baryon pairs are typically

much narrower in terms of relative momentum comparing with the corresponding baryon-antibaryon pairs. This is because of the lack of contribution from the imaginary part of the scattering length which is present for baryon-antibaryon pairs producing the wide anticorrelation effect. For baryon-baryon pairs the width of the correlation effect from the real part of the scattering length is limited to approximately $50 \text{ MeV}/c$ (see Fig. 3.13) which is small with respect to the decay momenta (see Tab. 5.1). Therefore, the residual effect is diluted more strongly due to the decay kinematics in case of the pair of two baryons.

5. Results of the residual correlations analysis

This chapter encloses the results of the reanalysis of $p\bar{\Lambda}$, and $\bar{p}\Lambda$ correlation functions measured in the STAR experiment taking into account the formalism of the residual correlations presented in the previous chapter. The results presented below were published in [135]. This paper was prepared by the author of this thesis in collaboration with the supervisor and the co-author.

5.1. Motivation

STAR analysis of $p\bar{\Lambda}$ and $\bar{p}\Lambda$ femtoscopic correlations in Au–Au collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{NN}} = 200$ GeV indicated that the size of the source for these systems is approximately twice smaller than the one for the $p\Lambda$ [128]. Such observation does not agree with the hydrodynamics models which suggest approximate scaling of the radius as $1/\sqrt{m_T}$ [113, 141], hence the radius should be the same for both $p\Lambda$ ($\bar{p}\bar{\Lambda}$) and $p\bar{\Lambda}$ ($\bar{p}\Lambda$). Femtoscopic radii obtained for $p\Lambda$ ($\bar{p}\bar{\Lambda}$) follow the m_T -dependence with lighter pairs. The probable solution of this puzzle might be the proper treatment of the residual correlations effect which was not considered in the STAR analysis. In addition, in that work a novel method for the extraction of the $p\bar{\Lambda}$ ($\bar{p}\Lambda$) strong interaction parameters was introduced indicating the substantial imaginary part of the scattering length which characterises the annihilation channel in baryon-antibaryon interaction. Therefore, the sensitivity of the femtoscopic correlations to the residual correlations is of great importance. In this thesis, the reanalysis of the STAR $p\bar{\Lambda}$ ($\bar{p}\Lambda$) correlation functions taking into account the residual correlations is performed to check its influence on the extracted radius and the strong interaction parameters.

5.2. Assumptions for the strong interaction parameters

The results presented in this chapter are based on the theoretical considerations introduced in Chap. 4. As it was mentioned, the formula describing the full correlation function including the residual correlation components (Eq. (4.2)) which may be fitted to the experimental correlation function, in general depends on a number of parameters. STAR analysis indicates 10 possible parent pairs of the measured $p\bar{\Lambda}$ ($\bar{p}\Lambda$) pairs, listed in Tab. 5.1. Femtoscopic correlations of these pairs depend on four parameters (each source size, real and imaginary part of the scattering length and the effective range). If one assumes that parameters of the strong interaction are known for $p\bar{p}$ system, there are 37 independent parameters (nine pairs times four parameters plus the source size for the $p\bar{p}$). Undoubtedly, one needs to introduce some assumptions for the robust fitting.

Pair	Fraction	Decay momentum (MeV/c)
p Λ	15%	0
$\Lambda\Lambda$	10%	101
$\Sigma^+\Lambda$	3%	189
p Σ^0	11%	74
$\Lambda\Sigma^0$	7%	101, 74
$\Sigma^+\Sigma^0$	2%	189, 74
p Ξ^0	9%	135
$\Lambda\Xi^0$	5%	101, 135
$\Sigma^+\Xi^0$	2%	189, 135
pp	7%	101

Table 5.1: Parent pairs of the p Λ (and p $\bar{\Lambda}$), along with their values of decay momentum and relative contribution in the STAR analysis [128].

Firstly, the effective range was taken as $d_0 = 0$ fm following the procedure adopted in [128]. Furthermore, since the transverse mass dependence of the source size expected from the hydrodynamics ($\simeq 1/\sqrt{\langle m_T \rangle}$) is rather flat for the mass range of the baryon pairs (see e.g. Fig. 7.7), the radii for all the considered pairs are assumed to be equal to each other.

As far as the values of the scattering length for baryon-antibaryon pairs are concerned, they are poorly known from both experimental and theoretical side. In the procedure applied in the UrQMD model, the imaginary part of the scattering length for all the considered baryon-antibaryon pairs is assumed to be equal to p $\bar{p}$ value $\Im f_0 = 0.88 \pm 0.09$ fm [108]. As a default case (later referred to as the case №1) both real and imaginary part of the scattering length are equalised for all pairs, but they are not fixed to p $\bar{p}$ value, but treated as the free fit parameters. As an alternative approach one may consider the annihilation cross section for any baryon-antibaryon pair to be the value for p $\bar{p}$ taken at the equal centre-of-mass energy instead of relative momentum. In case of femtoscopy, the difference between two approaches is significant. The small value of k^* for heavy baryon pairs, where the signal is present, will be transformed into a relatively high value of k^* for p $\bar{p}$ pairs for the same value of $\sqrt{s}$. Another approach is based on the Additive Quark Model (AQM) used in the UrQMD for the calculation of the unknown baryon-baryon interactions. In this model values of the scattering length decrease with increasing strangeness content in the pair. Hence, both proposed alternatives suggest the monotonic decrease of the cross section with the increasing pair mass thus they are treated together (case №2). Furthermore, one can consider the case in which the annihilation is present only for pairs of particles with opposite quark content (e.g. p $\bar{p}$, $\Lambda\bar{\Lambda}$), i.e. for all other baryon-antibaryon pairs $\Im f_0$ is fixed to 0 (case №3). Finally, as a consistency check, the STAR method, not taking the residual correlations into account, is repeated (case №4).

5.3. Analysis of $p\bar{\Lambda}$, and $\bar{p}\Lambda$ femtoscopic correlations measured by STAR

For fitting the STAR $p\bar{\Lambda}$ correlation function, Eq. (4.2) is applied. Residual correlation functions $C^{X\bar{Y}}$ are calculated according to Eq. (3.26). The only exception is the $p\bar{p}$ correlation function. In fact $p\bar{p}$ contribution is not the residual correlation from the physics point of view, but it arises from the false assignment of the primary p to Λ . In experiments Λ baryons are selected by the identification of their daughters: protons and pions. Then, the invariant mass (m_{inv}) spectrum is calculated. Such distribution, apart from the peak around m_{inv} of Λ baryon, contains a combinatorial background of the random π - p pairs. Therefore, the sample of Λ baryons selected to the analysis can include “fake” Λ ’s composed of the random π - p pair. Nevertheless, the formalism for the $p\bar{p}$ contribution is equivalent to the one described for the residual correlations. However, since the $p\bar{p}$ femtoscopic correlations arise from Coulomb FSI in addition to strong FSI, Eq. (3.26) is not applicable. Therefore, the correlation function is calculated using Eq. (3.17). The $p\bar{p}$ femtoscopic weight is determined using Lednicky method [99]. Essential distributions of the relative momentum and pair separation are derived from the simulation in the THERMINATOR model [17, 18]. The size of the $p\bar{p}$ source is assumed to be equal to the one used for other baryon-antibaryon pairs.

The STAR $p\bar{\Lambda}$ femtoscopic correlation functions published in [128] were corrected for purity, i.e. they were scaled by the fraction of primary pairs (equal to 15% according to Tab. 5.1). Nonetheless, such procedure is correct only if all other measured $p\bar{\Lambda}$ pairs are uncorrelated, which is not the case because of the effect of the residual correlations. Thus, the correction procedure was reverted before fitting Eq. (4.2) to the experimental data. Standard χ^2 minimisation was applied. The fitting range was set to 0.45 GeV/ c which is the total range of the correlation function published by STAR.

In Fig. 5.1 the fit taking into account the residual correlation (case №1) to the STAR $p\bar{\Lambda}$ correlation function is shown. The extracted source size equals 2.83 ± 0.12 fm which is substantially larger than the value obtained in [128]. In addition, it is in agreement with the radius for $p\Lambda$ pair type obtained therein. As far as the scattering length is concerned, the obtained result is:

$f_0 = ((0.49 \pm 0.21) + i(1.00 \pm 0.21))$ fm. Such value is consistent with the one measured for $p\bar{p}$ system in the dedicated experiments. Hence, the scenario of the annihilation, reflected by the non-zero $\Im f_0$, to be present in interactions for all baryon-antibaryon pairs is supported by the STAR femtoscopic measurement. Therefore, it is evident that taking the contribution of residual correlations into account appears to be vital in the baryon-antibaryon femtoscopy.

As an alternative approach values of the scattering length were scaled according to the centre-of-mass energy of the pair $\sqrt{s}$ instead of the relative momentum (case №2).

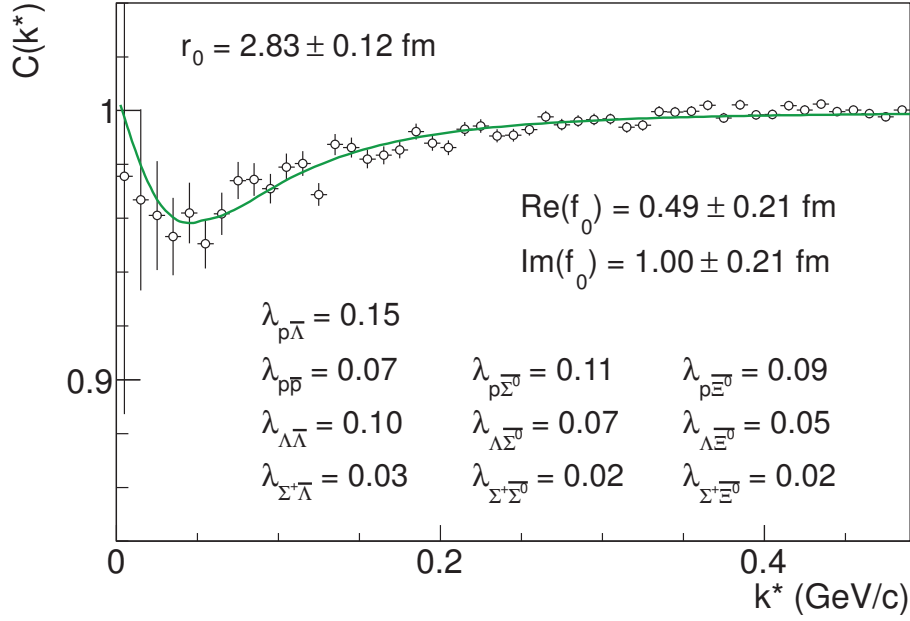


Figure 5.1: $p\bar{\Lambda}$ correlation function measured by STAR along with the fit using Eq. (4.2) (case №1, see text for details) [135].

These values are different for each pair. As a result of scaling, the scattering length values decrease with the pair mass. The results of the fit give the radius similar to the case №1, but the $\Im f_0$ is significantly larger. Moreover, the extracted $\Im f_0$ is even larger than the $p\bar{p}$ value. Therefore, case №2 is rather unlikely due to the resulting nonmonotonic dependence of the cross section as a function of the pair mass.

Next, the case of the annihilation occurring only for the particles with the opposite quark content is considered (case №3). In such situation the residual correlations contributions originate only from the $p\bar{p}$, $\Lambda\bar{\Lambda}$ and $\Lambda\bar{\Sigma}_0$ systems. The result leads to the relatively small value of the radius parameter equal to 1.5 ± 0.1 fm, which is similar to the one measured by STAR. Since such value is not realistic (see Sec. 5.1), the conclusion is that annihilation is present in all baryon-antibaryon channels.

Finally, the introduced formalism of the residual correlations in $p\bar{\Lambda}$ femtoscopy is checked by repeating the STAR procedure, i.e. the residual correlations were not considered in the fitting (№4). In Fig. 5.2 the STAR result is reproduced. The interesting observation comparing with the case №1 is that the real part of the scattering length changes its sign in contrast to the imaginary part which stays similar.

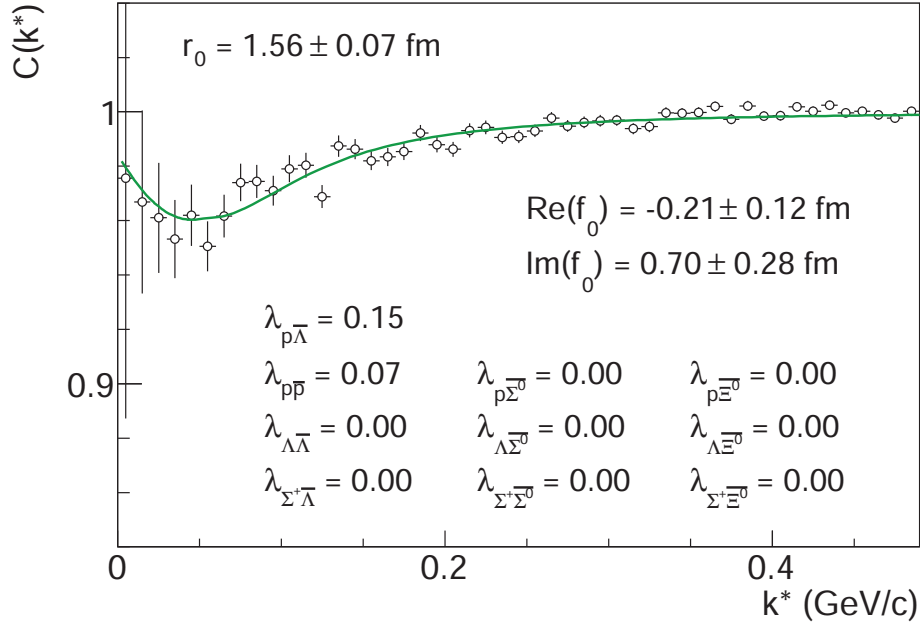


Figure 5.2: $p\bar{\Lambda}$ correlation function measured in STAR fitted without taking the residual correlations into account (case №4, see text for details)) [135].

5.4. Systematic uncertainties

The systematic uncertainties of the extracted values of the source size and the scattering length were estimated by varying assumptions described above in plausible range. By limiting the fitting range from 0.45 GeV/c to 0.35 GeV/c, the extracted radius parameter changes by 5% with respect to the case №1, the imaginary part of the scattering length decreases by about 40%, and the real part of the scattering length becomes consistent with zero. Furthermore, the fit was done separately for $p\bar{\Lambda}$ and $\bar{p}\Lambda$. The source size is then consistent with the default case, whereas $\Im f_0$ and $\Re f_0$ change by 20% and 50% respectively. Such difference is understandable since, as it was mentioned in Sec. 3.4, $\Re f_0$ influences mostly the region of the small relative momentum where statistical uncertainties are the largest while $\Im f_0$ describes anticorrelation wide in k^* where the data is more precise. Regarding the effective range parameter d_0 , the precision of the STAR data on $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation functions does not allow to check its influence on the results. Finally, one can conclude that the $p\bar{\Lambda}$ source size appears to be well constrained and its value is similar to the one measured by STAR for $p\Lambda$ system. As far as the imaginary part of the scattering length is concerned, its value is non-zero and positive as well as compatible with the value measured for $p\bar{p}$ system, with the systematic uncertainty estimated to be not less than 20%. The real part of the scattering length is less constrained as the systematic uncertainty was estimated to be at least 50%. Nevertheless, its value is compatible with being positive. However one should consider this value as the effective $\Re f_0$ as

the theory does not predict this value to be the same for all considered baryon-antibaryon pairs.

All in all, the results presented in this chapter reveal that the femtoscopic analysis of $p\bar{\Lambda}$ and $\bar{p}\Lambda$ pairs can be indeed used to put constraints on the baryon-antibaryon strong interaction parameters. In particular, the data favour the scenario in which all baryon-antibaryon pairs have similar values of the imaginary part of the scattering length which accounts for the annihilation channel in such interactions. Furthermore, using the developed methodology of accounting for the residual correlations applied for the STAR measurements of $p\bar{\Lambda}$ ($\bar{p}\Lambda$) correlation functions, the source size derived for these systems is consistent with the results for $p\Lambda$ ($\bar{p}\bar{\Lambda}$) and the expectations from models.

6. Experimental analysis

This chapter covers all the experimental details relevant to the analysis of the one-dimensional femtoscopy with pp and $\bar{p}\bar{p}$ pairs as well as baryon-antibaryon studies with $p\bar{p}$, $p\bar{\Lambda}$ and $\bar{p}\Lambda$ systems presented in the following parts of the thesis. This work was performed entirely by the author of the thesis on behalf of the ALICE collaboration.

6.1. Data selection and software environment

The collision data used in this thesis originate from Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV registered in 2011 by the ALICE detector. In this work, about 35 million events have been analysed. Selected *runs*, i.e. periods of data taking with constant conditions, were required to be recorded and reconstructed with good quality. Data collected in 2010 during the first Pb ion run at the LHC were used to cross-check the results. ALICE was recording data at the luminosity of the order of $10^{25} \text{ s}^{-1}\text{cm}^{-2}$ and $10^{26} \text{ s}^{-1}\text{cm}^{-2}$ as well as with the average number of interactions per bunch crossing of approximately $10^{-5} \div 10^{-4}$ and $10^{-4} \div 10^{-3}$ in 2010 and 2011 respectively. During 2011 Pb–Pb run, ALICE used mostly central (0-10%) and semicentral (10-50%) triggers which were defined by the summed signals from V0-A and V0-C detectors. The simultaneous excess above the threshold in both sides of the detector was required. In 2010 events were registered using the minimum-bias trigger which is based on the signals from the V0 and SPD detectors in coexistence with the LHC bunch-crossing signal. The trigger required at least two out of the following conditions: two hits in the SPD, the signal in V0-A, and the signal in V0-C. More details about the run conditions might be found in [64]. Furthermore, this thesis involves the collisions generated with Monte Carlo models AMPT [19,20] and HIJING [13] corresponding to the LHC collision energies, taking into account the detector effects (geometry and interactions) simulated using GEANT3 package [72].

The experimental analysis was performed using the common framework, well tested AliFemto package [143] which is a part of AliRoot. This software was used to handle tasks such as reading the data files (Analysis Object Data, see Sec. 2.3), selecting events and tracks fulfilling specific criteria, creating pairs of particles from the same and different events to construct the correlation functions (see Eq. (3.19)). The package also allowed to create the quality assurance histograms. The work presented in this thesis required development of the AliFemto code which has been committed to the AliFemto repository [144] by the author. Calculations presented in the following sections were mostly performed using the distributed computing environment GRID.

6.2. Event selection

In this analysis the events with the collision vertex position within ± 8 cm from the centre of the TPC, measured along the beam axis, were selected. The position of the vertex is firstly estimated using pairs of hits registered in SPD detector and later calculated more precisely during the offline track reconstruction. Such selection minimises the contribution of undesirable events, such as beam-gas collisions, and allows to employ full range of ALICE acceptance. The centrality selection classes are determined using the amplitudes measured in V0 detector. To account for the non-flat centrality distribution observed in 5-10% centrality class, due to the combination of different triggers, a dedicated procedure which randomly rejects events was implemented. The effect of the procedure and its impact on the correlation function is presented in Fig. 6.1. It is shown that centrality flattening does not influence the correlation function significantly.

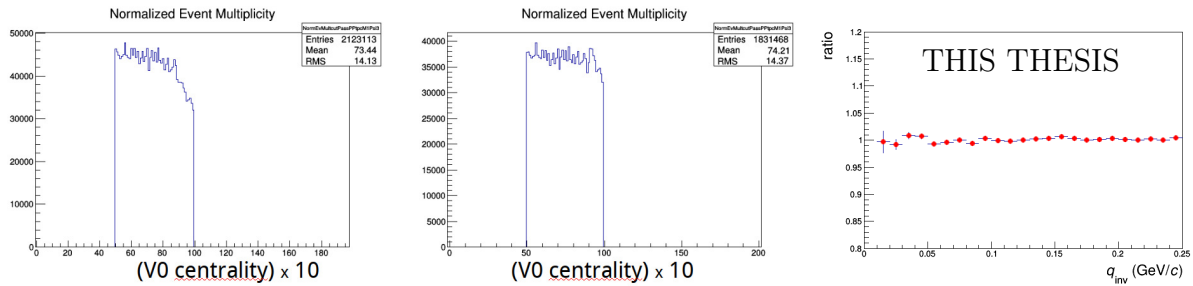


Figure 6.1: Left plot: V0 centrality distribution before the centrality flattening procedure. Middle plot: V0 centrality distribution after the centrality flattening procedure. Right plot: the ratio of pp correlation functions without and with centrality flattening procedure applied.

6.3. Particle identification

6.3.1. General approaches

Robust particle identification (PID) is vital in numerous analyses performed in the heavy-ion collisions. In particular, femtoscopic correlation studies with particles which are not as abundantly produced in collisions as pions (e.g. protons) are extremely sensitive to the track selection. On one hand high-purity sample is essential to obtain reliable result. On the other hand, there is a need to collect as big statistics of particles of interest as possible since the signal measured in femtoscopy is typically limited to the small values of pair relative momentum where pair statistics scales as $1/q^2$.

Generally speaking, one can distinguish two methods of track-by-track identification. The first one is a so-called Bayesian PID [145]. The probability that the track is the

particle i if the signal s is measured is defined as [146]:

$$w(i|s) = \frac{r(s|i) \cdot C_i}{\sum_{k=e,\mu,\pi,\dots} r(s|k) \cdot C_k}, \quad (6.1)$$

where C_i are *a priori* probabilities to be the i -type particle, and $r(s|i)$ is a conditional probability density function of measuring the signal s if the particle i is detected.

Another approach to particle identification is a *number of σ method* (commonly referred to as *$n\sigma$ method*). It might be applied for the detectors with a Gaussian response function. The $n\sigma$ observable is defined as:

$$n\sigma = \frac{S - \hat{S}(H_i)}{\sigma}, \quad (6.2)$$

where S is the measured signal, $\hat{S}(H_i)$ is the expected signal for a hypothesis of the i -type particle, and σ is the resolution of the detector. The variable defined by Eq. (6.2) follows the standard normal distribution. A particle is identified to be of an i -type once the $n\sigma$ value computed using Eq. (6.2) is smaller than the assumed n value which defines how rigorous the PID selection is. For instance, the notation "3 σ cut" denotes that $n\sigma < 3\sigma$ for a given detector and an analysed particle. The specific value of n depends on desired precision and statistics required for a given analysis. The larger the n value is, the more particles are selected, but simultaneously the probability of false identification increases. In this thesis, PID $n\sigma$ method is applied using the Time Projection Chamber ($n\sigma_{TPC}$) and the Time-of-Flight detector ($n\sigma_{TOF}$). In such cases the measured signals are: the ionisation energy loss per unit distance dE/dx for TPC, and the time difference between the beginning of the event and the arrival of the particle to the detector for TOF. The signal $\hat{S}(H_i)$ expected for a given mass in TPC can be calculated using the Bethe-Bloch formula [147]. Concerning TOF, the time required for the i -type particle to reach the detector is used as $\hat{S}(H_i)$ [65, 148]. See Sec. 6.3.2 for more details.

6.3.2. PID methods used in ALICE

The hallmark of the ALICE detector system is its excellent particle identification capability. It makes use of numerous techniques including amongst others: the ionisation of the medium caused by charged particles, the bremsstrahlung radiation, the Cherenkov radiation, time measurements, and the weak decay topology. In this thesis PID of charged particles using TPC and TOF detectors as well as a topological reconstruction of Λ hyperons are utilised and therefore discussed in the next paragraphs.

Each particle which traverses the TPC gas is identified by the simultaneous measurement of the charge, momentum (from the direction and the radius of the curvature of the trajectory), and the specific energy loss described by the Bethe-Bloch formula and

parametrised by a function [64]:

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln\left(P_3 + \frac{1}{(\beta\gamma)^{P_5}}\right) \right). \quad (6.3)$$

$P_1 \div P_5$ are the fit parameters, β denotes the velocity of the particle and γ is the Lorentz factor. The dE/dx distribution as a function particle momentum in the TPC measured in Pb–Pb collisions is presented in Fig. 6.2, along with the parametrisation from the Eq. (6.3) represented by lines. It evidently shows the separation between various particle types. Although for momenta $p \gtrsim 1$ GeV/ c the track-by-track identification exclusively with the TPC is not doable, one can still identify particles on a statistical basis using multi-Gaussian fits.

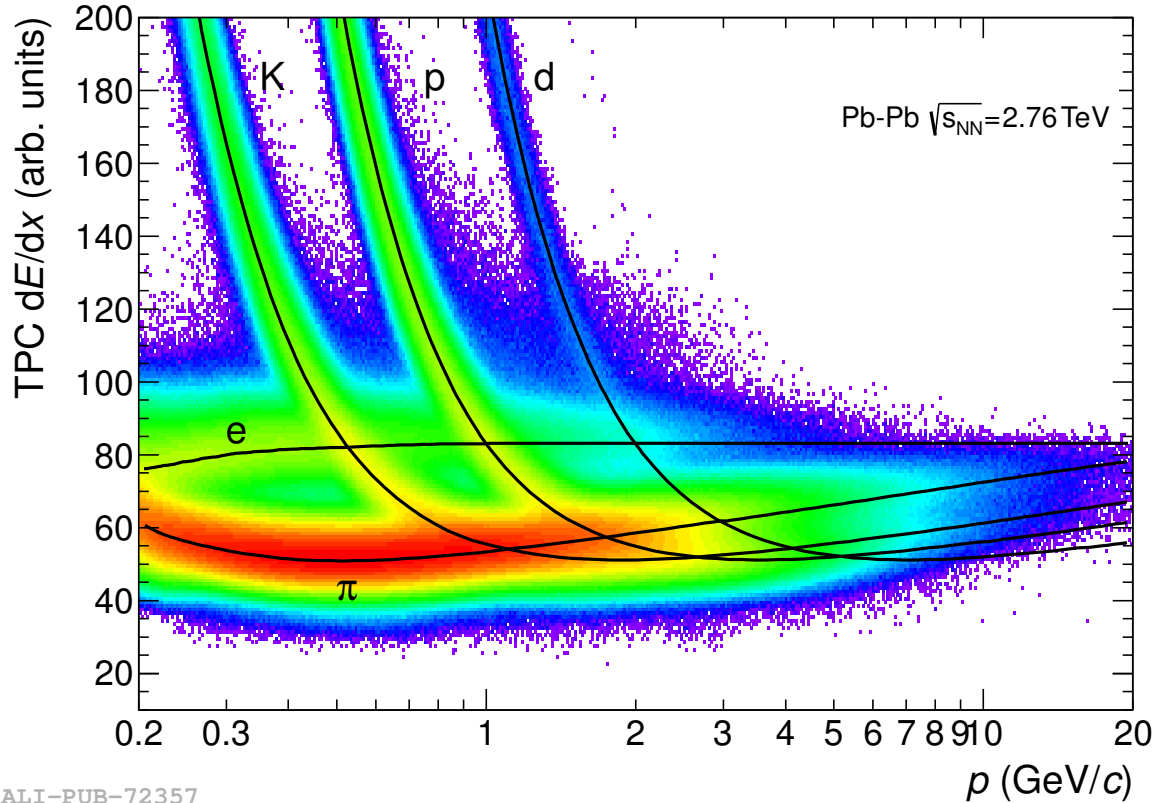


Figure 6.2: Specific energy loss in the TPC as a function of the particle momentum in Pb–Pb collisions. Lines represent the parametrisation from the Eq. (6.3) [64].

Particle identification in the TOF detector is done by measuring the time t which elapsed from the start of the event (given by the trigger detector) to the arrival of the given particle at TOF. Then, one can determine the velocity:

$$\beta = \frac{d}{tc} = \frac{1}{\sqrt{\left(\frac{mc}{p}\right)^2 + 1}}, \quad (6.4)$$

where d is the length of the trajectory. It can be noticed that plotting β vs. momentum

p one can obtain separate curves for particles with different masses. The performance of the TOF detector is illustrated in Fig. 6.3.

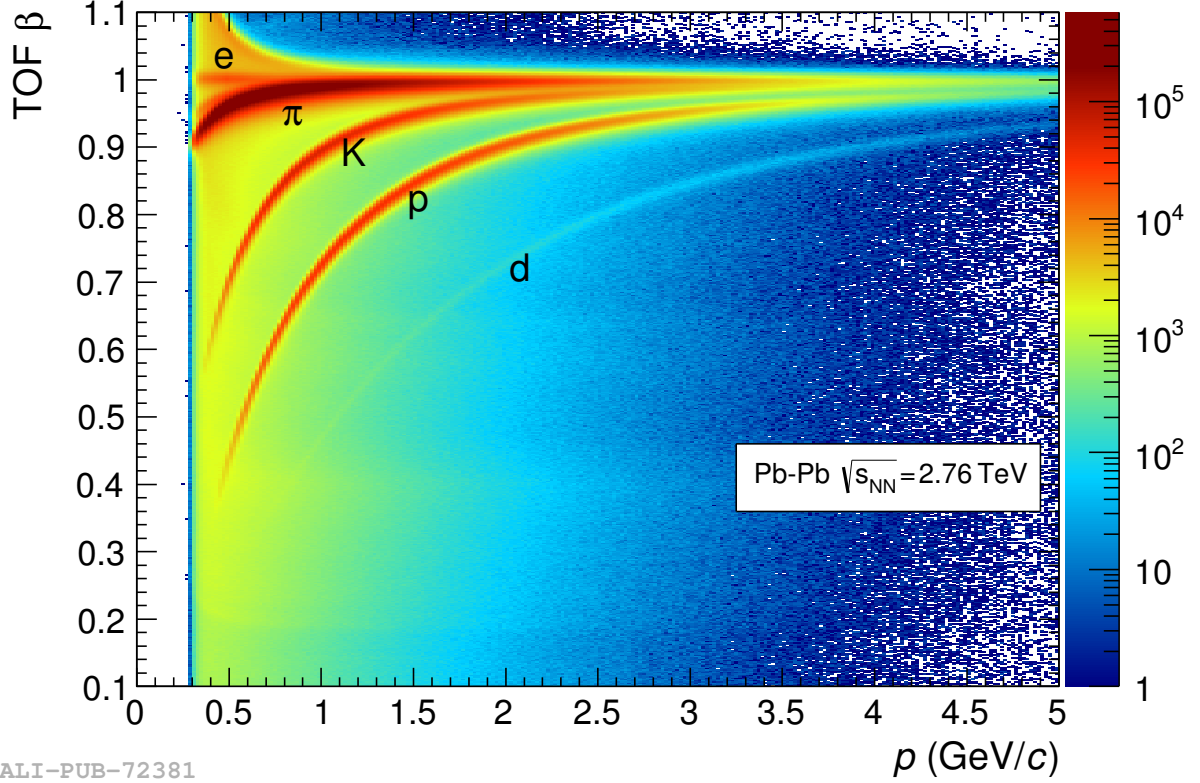
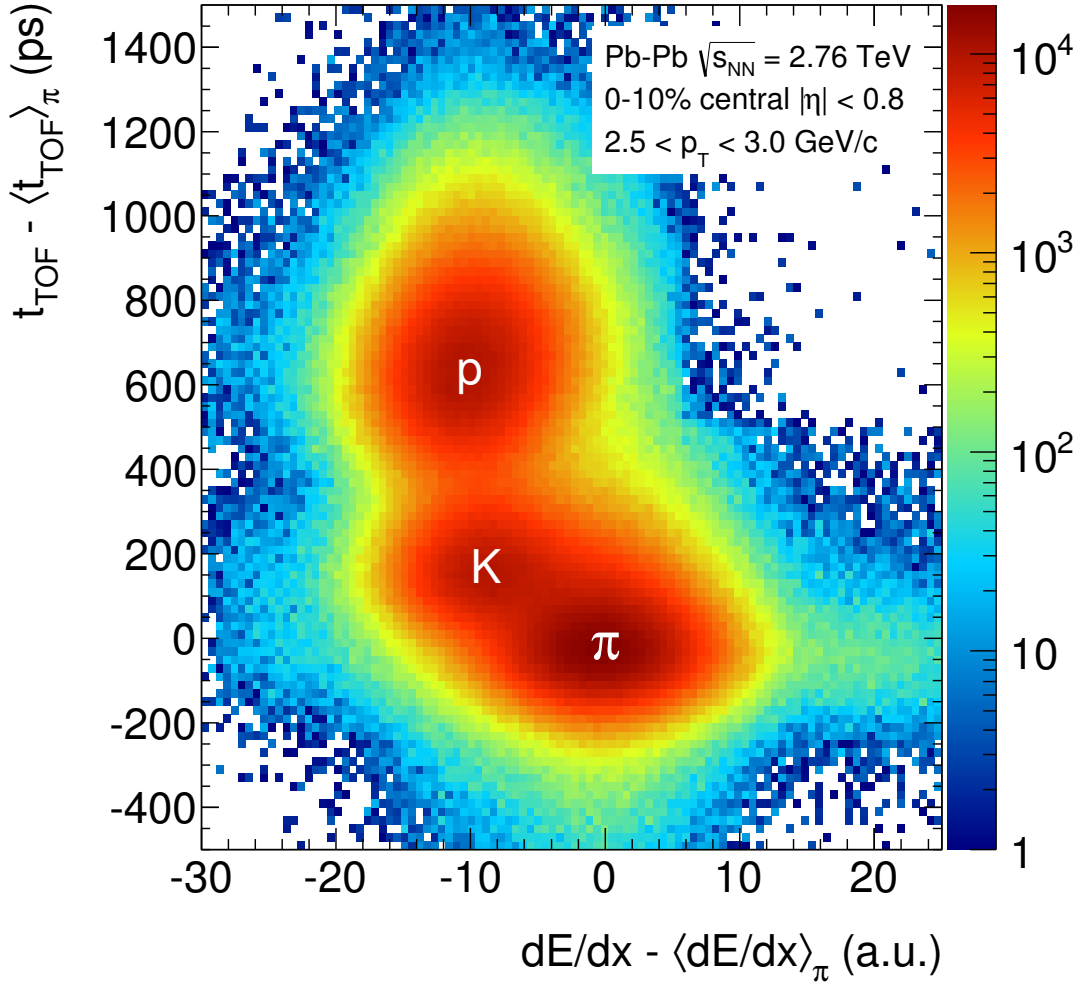


Figure 6.3: Velocity of particles measured by the TOF detector as a function of momentum in Pb-Pb collisions [64]. Symbols on the plot mark the separate curves corresponding to electrons, pions, kaons, protons, and deuterons.

The purity of particle identification might be further enhanced by combining the information from multiple detectors. For instance, one can improve the separation between various particle species by using simultaneously the information from TPC and TOF detectors. Such approach is used in this analysis as shown in Sec. 6.3.3. An example of the performance of such method is shown in Fig. 6.4.

Furthermore ALICE detector enables identification of hadrons via their weak decay topology, including i.a. meson K_S^0 , baryons Ξ , Ω and finally Λ used in this analysis (see Sec. 6.3.4). Such approach is based on the search for the secondary vertices from particle decays by selecting tracks with the distance of closest approach to the primary vertex larger than 1 mm (in case of Pb-Pb collisions). Then, each pair of such tracks with opposite electric charge is marked as a V^0 candidate. The name V^0 refers to the typical V-shaped topology of tracks originating from the decay of a neutral particle. For the initial selection of V^0 particle, the points of closest approach (PCA) of two tracks are determined and the distance between them is requested to be less than 1.5 cm. These points are also required to be closer to the primary vertex than any of the hits generated by these tracks. Finally, V^0 candidates with cosine of the pointing angle (defined by the



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Figure 6.4: Performance of the combined PID using TPC and TOF detectors [64].

pair momentum vector and the line connecting primary and secondary vertices) smaller than 0.9 are rejected from further analysis. More details concerning the selection criteria of Λ baryons are given in Sec. 6.3.4.

6.3.3. Proton identification

Tracks within the pseudorapidity range $|\eta| < 0.8$ and transverse momentum $0.7 < p_T < 4.0$ GeV/c have been selected. To assure good reconstruction of tracks and to reduce the number of tracks not coming from the primary vertex, the number of the TPC clusters corresponding to the given track was required to exceed 80 (out of maximum possible 159 clusters), and the maximum value of χ^2 per TPC cluster was set to 4.0 (2 degrees of freedom per cluster). Fig. 6.5 presents the phase-space of the accepted tracks. Furthermore, the cut on the Distance of Closest Approach to the primary vertex (DCA) was applied: in the transverse plane $\text{DCA}_{xy} < 2.4$ cm, in the longitudinal plane $\text{DCA}_z < 3.2$ cm. Distributions of DCA values for protons accepted in the analysis are shown in Fig. 6.6.

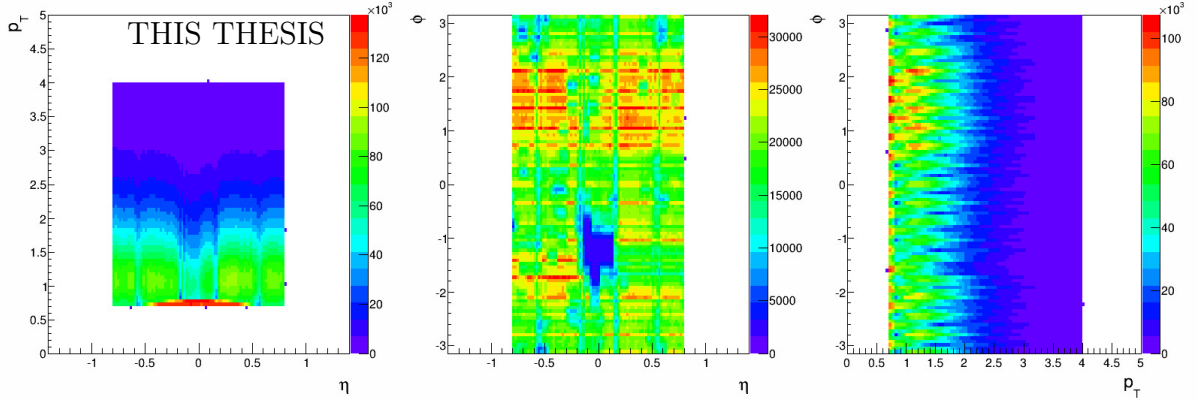


Figure 6.5: Left plot: Pseudorapidity vs. transverse momentum of accepted protons. Middle plot: pseudorapidity vs. azimuthal angle of accepted protons. Right plot: transverse momentum vs. azimuthal angle of accepted protons. Irregularities visible on these plots reflect the structure of the detector (e.g. the dead zones in the TPC) and the specific selection criteria.

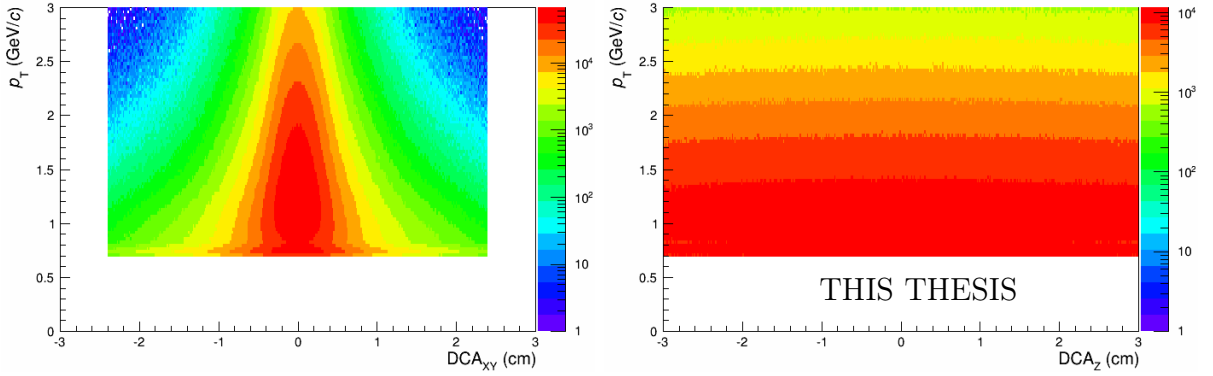


Figure 6.6: DCA distribution of accepted tracks in the transverse plane (left panel) and in z direction (right panel).

Such selection is done in order to decrease the contribution of the secondary tracks, i.e. originating from weak decays or from the interaction with the detector material.

As the next stage of the analysis, the combined TPC and TOF method of PID was used to select p and $\bar{p}$. The details of the selection are the following:

- tracks with the momenta smaller than 0.8 GeV/ c are selected if $n\sigma_{TPC} < 3\sigma$,
- tracks with the momenta larger than 0.8 GeV/ c are selected if $\sqrt{n\sigma_{TPC}^2 + n\sigma_{TOF}^2} < 3\sigma$.

The goal of the particle selection in this analysis is to obtain as many primary (anti)protons as possible. Therefore, the estimation of the so-called purity is needed. This variable can be defined as the ratio of the primary (anti)protons in the obtained sample to all the particles which passed all the selection criteria. One can distinguish two components of the purity. The first one concerns only the particle identification (PID pu-

rity), and quantifies how many (anti)protons are in the sample, regardless of their origin. The second one is related to the contamination from secondary particles, i.e. tells how many (anti)protons were produced directly in the collision or come from the resonance decays (primary particles) and what is the fraction of (anti)protons from weak decays or from interactions with the detector material (secondary particles). The total purity is equal to the product of the PID purity and the primary proton contribution under the assumption that both variables are independent. The PID purity was estimated with Monte Carlo simulation in HIJING model. Results are summarised in Tab. 6.1.

<i>identified as</i>	PID purity	
	selected protons	selected antiprotons
$p/\bar{p}$	95.45%	95.23%
$K^\pm$	0.79%	0.80%
$\pi^\pm$	0.75%	0.99%
$\mu^\pm$	0.15%	0.15%
$e^\pm$	2.86%	2.83%

Table 6.1: Proton and antiproton PID purities estimated from MC simulations.

PID signals of protons selected for this analysis are presented in Fig. 6.7. The PID

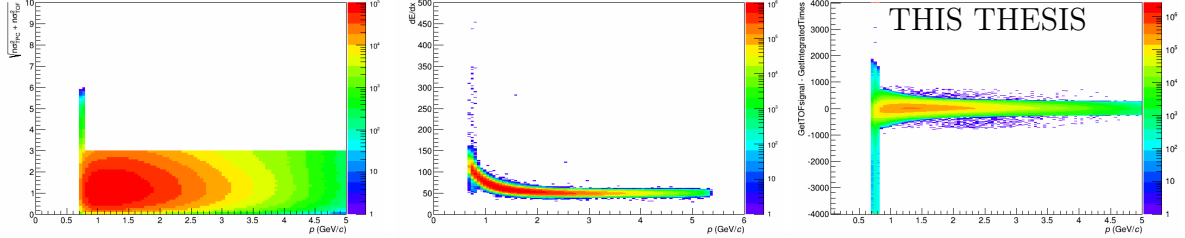


Figure 6.7: Left plot: combined TPC and TOF $n\sigma$ separation vs. momentum for proton mass hypothesis of accepted tracks. Middle plot: dE/dx signal from TPC as a function of momentum. Right plot: time signal from TOF for proton mass hypothesis.

purity of the proton sample was also estimated using data distributions. The worst case scenario was chosen, namely the momentum range where only TPC is used ($p < 0.8$ GeV/c). In Fig. 6.8 dE/dx distributions in momenta range $0.66 < p < 0.72$ GeV/c and $0.72 < p < 0.78$ GeV/c are presented. The sum of four Gaussian functions (corresponding to signals from pions, kaons, electrons and protons) was fitted to those distributions. The purity of protons was calculated as $(N_p - N_e)/N_p$ where N_p is the integral of the Gaussian function fitted to the proton peak in 3σ range, N_e is the integral of the Gaussian function fitted to electron peak in 3σ range corresponding to the proton peak. The purity calculated in this way is 98% and 70% in momenta range $0.66 < p < 0.72$ GeV/c and $0.72 < p < 0.78$ GeV/c, respectively. Particles with momenta $0.72 < p < 0.78$ GeV/c constitute 1.7% of all particles from the sample. For higher momenta signal from TOF

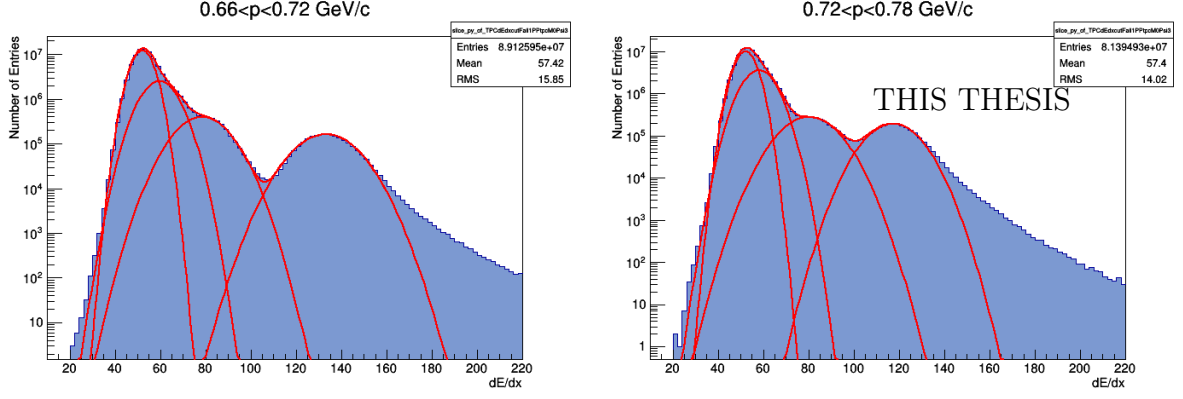


Figure 6.8: Projections of dE/dx distributions for momenta ranges $0.66 < p < 0.72$ GeV/c (left plot) and $0.72 < p < 0.78$ GeV/c (right plot). The red line is a fit in the form of the sum of the four Gaussian functions corresponding to pions, kaons, electrons and protons.

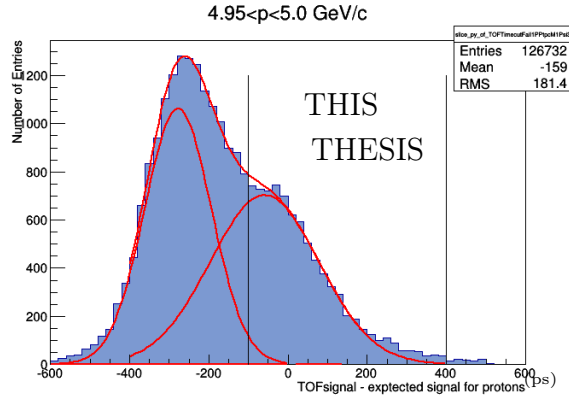


Figure 6.9: Projections of the time distribution from TOF for the momentum range $4.95 < p < 5.0$ GeV/c with two Gaussian functions fitted (corresponding to a common signal for pions, kaons, and electrons as well as signal for protons). Vertical lines correspond to the $\sqrt{n\sigma_{TPC}^2 + n\sigma_{TOF}^2} < 3\sigma$ cut.

is required. For the momentum range $4.95 < p < 5.0$ GeV/c the purity was estimated to be 97% (see Fig. 6.9). This demonstrates that particle identification using ALICE TPC and TOF detectors allows for obtaining the high-purity sample of (anti)protons.

The contamination from secondary particles ((anti)protons from weak decays and those produced by interactions of particles with the detector material) was estimated using template distributions of DCA_{xy} for protons and antiprotons from Monte Carlo simulations in HIJING, shown in Fig. 6.10. Such templates describe the shape of the distribution separately for the primary particles and all types of contributions from weak decays. In addition, protons from the interactions with the material were taken into account (such contamination is negligible for antiprotons). Estimation of the relative contribution of each source of contamination was performed using the method described in [149] and implemented in TFractionFitter class in ROOT. Data distribution is fitted with the combination of templates, separately for several p_T intervals (10 for protons,

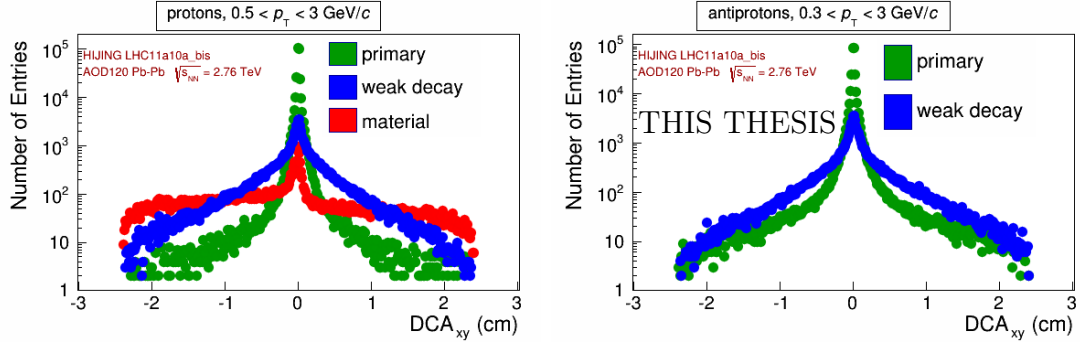


Figure 6.10: The DCA_{xy} template distributions of protons (left plot) and antiprotons (right plot) with respect to their origin.

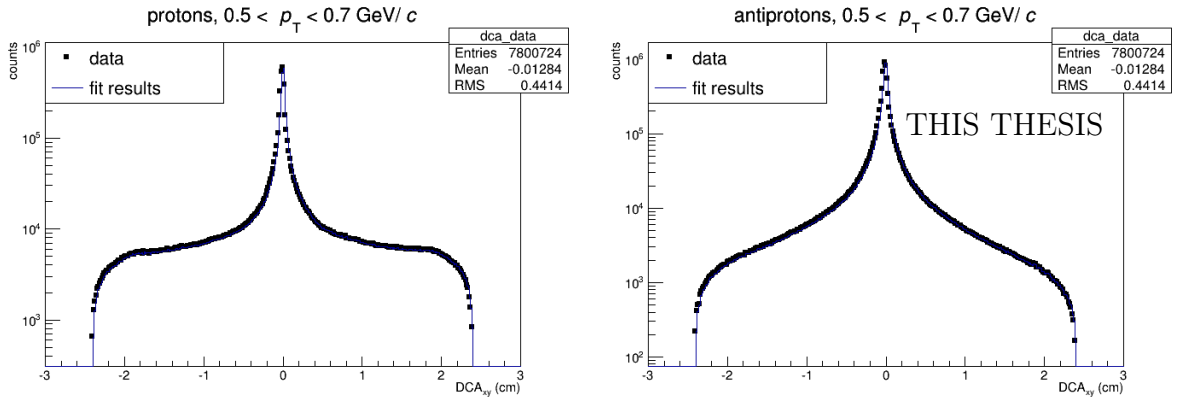


Figure 6.11: Examples of fitted DCA_{xy} distributions with MC templates.

11 for antiprotons). As one can observe in Fig. 6.11, such combined fit reproduces the data well. The transverse momentum dependence of the fractions of (anti)protons with respect to their origin is presented in Fig. 6.12. As one can notice therein, the primary particles become dominant starting only from 0.7 GeV/c. Therefore, the minimal p_T required for (anti)protons in this analysis was set to such value in order to suppress secondary (anti)protons.

ALICE detector enables to obtain immensely pure sample of (anti)protons. Indeed, combining the information from Time Projection Chamber and Time-of-Flight detector, one is able to exclude most of the other particles (electrons, kaons, pions etc.). According to the Monte Carlo studies, the PID purity of protons exceeds 95%. On the other hand, there is a significant contribution from the secondary (anti)protons originating from the weak decays or the interactions in the detector material, reaching even about 40% at $p_T \approx 0.8$ GeV/c. Due to the uncertainty of this estimation, the λ parameter (taking into account i.a. the misidentification) in pp and $\bar{p}p$ femtoscopic analysis were not fixed to the values obtained herein, but were left to be the free fit parameter by default (see Sec. 7.1 for details).

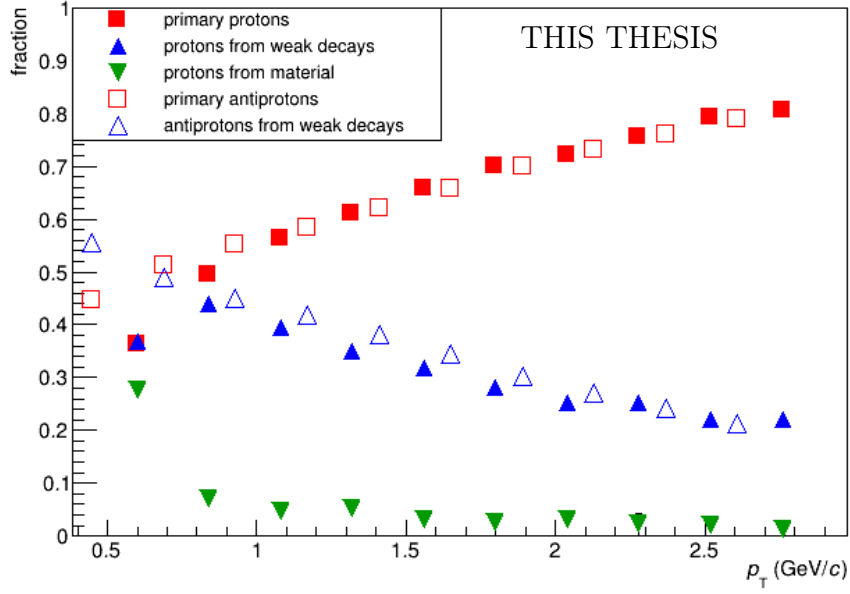


Figure 6.12: Fractions of (anti)protons with respect to their origin obtained from MC template fits.

6.3.4. Λ identification

The identification of Λ ($\bar{\Lambda}$) baryons starts with the selection of V^0 candidates as described in Sec. 6.3.2. Then, daughter tracks are requested to be identified as p ($\bar{p}$) and π^- (π^+) using TPC and TOF detectors. Pion daughters are identified solely with the TPC, under the condition that $|n\sigma_{TPC}| < 3$. Proton daughters are required to have $|n\sigma_{TPC}| < 3$ if their momentum is below 0.8 GeV/c or there is no TOF signal available. Otherwise, these tracks must additionally be identified by TOF and fulfil the condition of $|n\sigma_{TOF}| < 3$. Then, for each pair the invariant mass is calculated using conservation of total four-momentum, assumed masses and measured momenta of daughter particles:

$$m_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2} = \sqrt{m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)}. \quad (6.5)$$

The expected mass of Λ is $m_\Lambda = 1115.683 \pm 0.006$ MeV/ c^2 [150]. Λ ($\bar{\Lambda}$) candidates were required to have the invariant mass within range $[m_\Lambda - 3.8, m_\Lambda + 4.3]$ MeV/ c^2 ($[m_\Lambda - 3.6, m_\Lambda + 4.1]$ MeV/ c^2). Such range was chosen to obtain a sufficiently abundant sample of Λ baryons essential for the correlation analysis while maintaining the PID purity above 90%. This selection helps to minimise the contribution from the other V^0 particles (mainly K_S^0 which are much more copiously produced). The plot illustrating the characteristic peak of Λ baryons is shown in Fig. 6.13. The PID purity of selected Λ ($\bar{\Lambda}$) was estimated by the simultaneous fit of the Gaussian function to the peak region and exponential function to the background and found to be not less than 94% (92%).

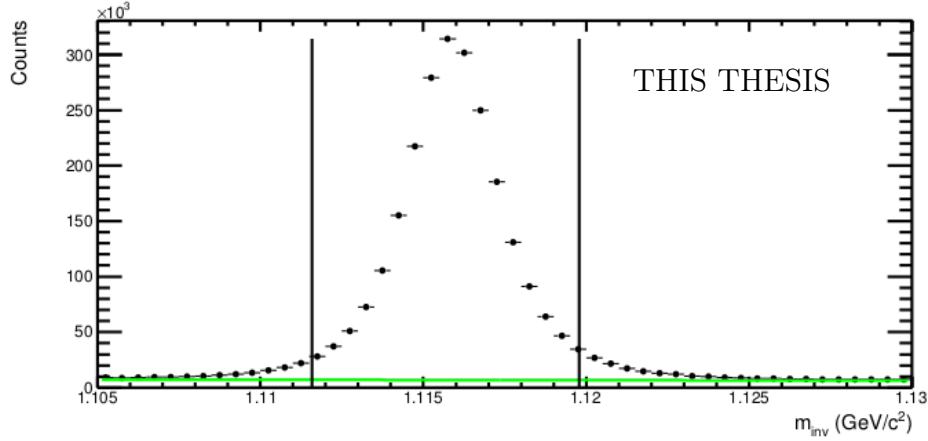


Figure 6.13: Invariant mass distribution of Λ candidates in most central Pb–Pb collisions at 2.76 ATeV in ALICE [151].

Furthermore, the potential Λ ($\bar{\Lambda}$) baryons were requested to have exactly two daughter tracks with different charges assigned. V^0 candidates with the pseudorapidity $|\eta| < 0.8$ were selected in order to prevent the undesired effects of the limited TPC acceptance. To reduce the contribution from falsely identified V^0 candidates, i.e. those coming from the random combination of tracks, only the potential Λ ($\bar{\Lambda}$) baryons with the cosine of the pointing angle $\cos\theta > 0.9993$, and decay length < 60 cm were accepted in this analysis. What is more, V^0 candidates were requested to have the transverse momentum $0.7 < p_T < 5.0$ GeV/ c , and distance of the closest approach to the interaction vertex $\text{DCA}_{xy} < 1.0$ cm to maximise the contribution of primary Λ ($\bar{\Lambda}$) hyperons. In addition, it was noticed that two separate Λ ($\bar{\Lambda}$) baryons may have been reconstructed with the same daughter track. Therefore, once such situation was spotted, the V^0 with smaller value of the DCA to primary vertex was chosen, and the other was removed from the further analysis. As far as the selection of daughter tracks is concerned, they were requested to have the pseudorapidity $|\eta| < 0.8$ and at least 80 TPC clusters. Moreover, protons and antiprotons must have the transverse momentum $0.5 < p_T < 4.0$ GeV/ c and the distance of the closest approach to the primary vertex within the range: $0.1 < \text{DCA}_{xy} < 0.4$ cm, whereas pions were obliged to have the transverse momentum $0.16 < p_T < 4.0$ GeV/ c and $0.3 < \text{DCA}_{xy} < 0.4$ cm.

6.3.5. Feed-down estimation

As it was mentioned in Sec. 4.3, the knowledge of the specific types of feed-down contribution (i.e. to determine what was the parent particle of its decay product measured in the detector) amongst selected (anti)baryons is crucial in the analysis of the residual correlations. Such information is obviously not available experimentally, therefore one needs to estimate it using model simulations. In this thesis fractions of p , $\bar{p}$, Λ and $\bar{\Lambda}$ which are

decay products of specific particles were calculated using HIJING and THERMINATOR models. In the former the effect of the reconstruction process simulated in GEANT was additionally studied. However the difference between fractions calculated before and after the reconstruction was found to be negligible. The kinematics cuts used for the selection of the particles of interest were analogous to those applied in the collision data, described in Sec. 6.3.3 and Sec. 6.3.4. Fractions of $p\bar{p}$, $p\bar{\Lambda}$ and $\bar{p}\Lambda$ pairs are presented in Figs. 6.14, 6.15, 6.16, 6.17, 6.18, 6.19. For instance, in Fig 6.14 labels in x-axis refer to the origin of proton (e.g. 'p' means primary, ' Λ ' denotes protons from weak decays), and labels in y-axis refer to the origin of antiproton. The values in the histogram describe the relative contribution of the given source (e.g. the value in the cell defined by Λ and $\bar{\Sigma}^+$ is the fraction of such $p\bar{p}$ pairs that proton is the product of Λ decay and antiproton comes from $\bar{\Sigma}^+$ decay). The fractions were obtained by multiplying the single-particle fraction of particles from the given source. In addition, they are multiplied by the corresponding PID purities of selected particles, as described in Sec. 6.3.3 and Sec. 6.3.4. One can notice that, according to HIJING, amongst $p\bar{p}$ pairs there are 54% pairs composed of primary particles. The most prominent residual contribution (24%) comes from primary p ($\bar{p}$) and $\bar{p}$ (p) being the product of $\bar{\Lambda}$ (Λ) decay. As far as $p\bar{\Lambda}$ ($\bar{p}\Lambda$) origin is concerned, pairs of primary particles constitute about 40%, whereas there are about 10% pairs which consist of primary p ($\bar{p}$) and $\bar{\Sigma}^0$ (Σ^0) as well as primary $\bar{\Lambda}$ (Λ) and p ($\bar{p}$) from Λ ($\bar{\Lambda}$) decay. It is worth emphasising that fractions predicted by THERMINATOR differ from those obtained in HIJING, in particular the contribution of pairs of primary particles is $\approx 40 \div 50\%$ smaller. Such deviation was taken into account during the systematic study in baryon-antibaryon femtosopic analysis presented in Chap. 8.

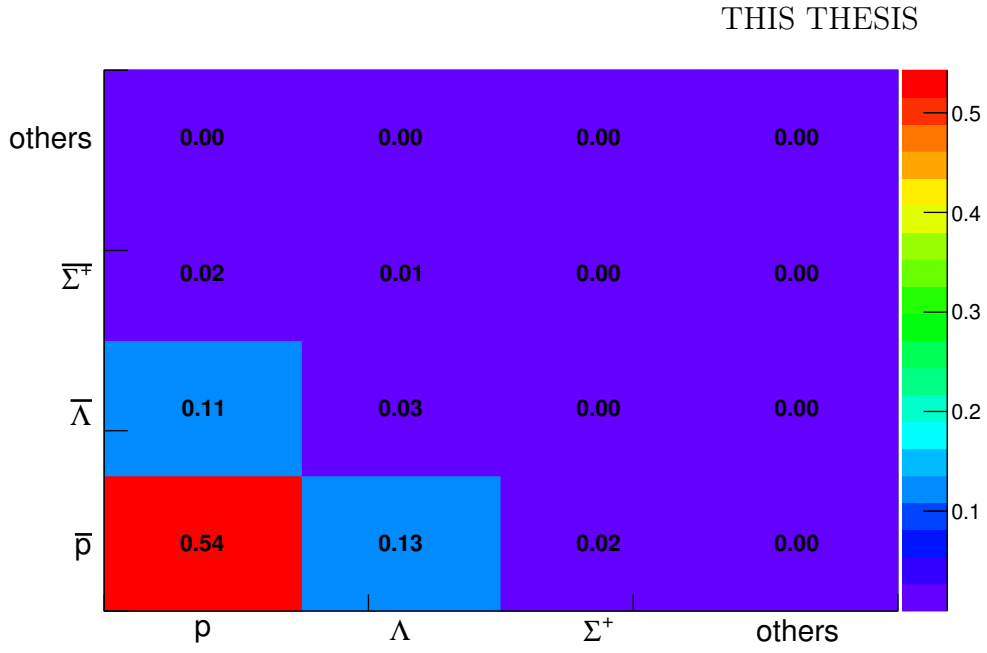


Figure 6.14: Fractions of $p\bar{p}$ pairs obtained using simulation in HIJING and taking into account detector response modelled in GEANT. See text for details.

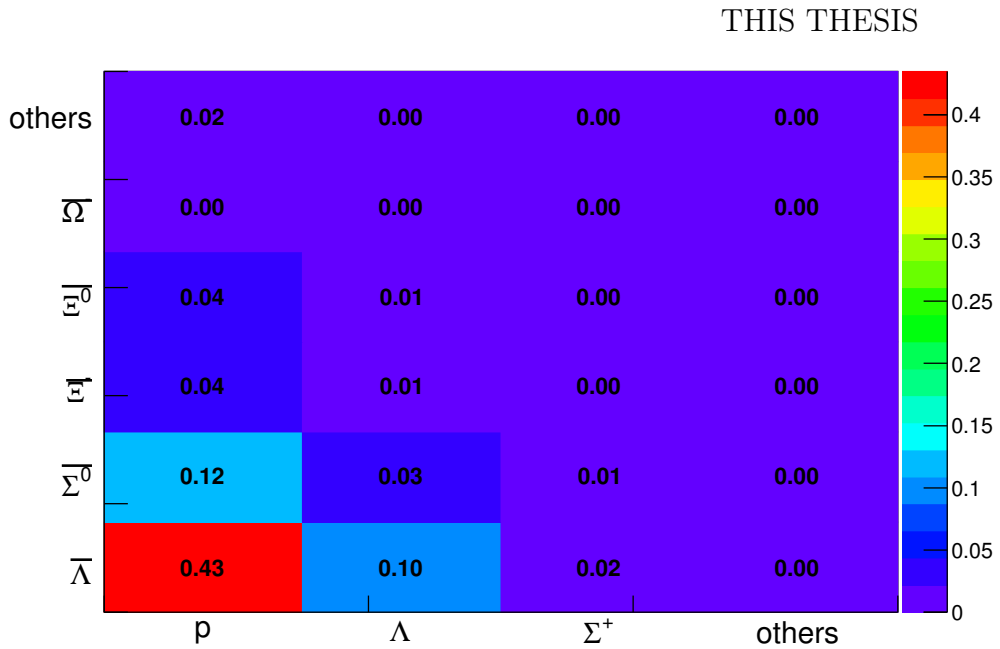


Figure 6.15: Fractions of $p\bar{\Lambda}$ pairs obtained using simulation in HIJING and taking into account detector response modelled in GEANT. See text for details.

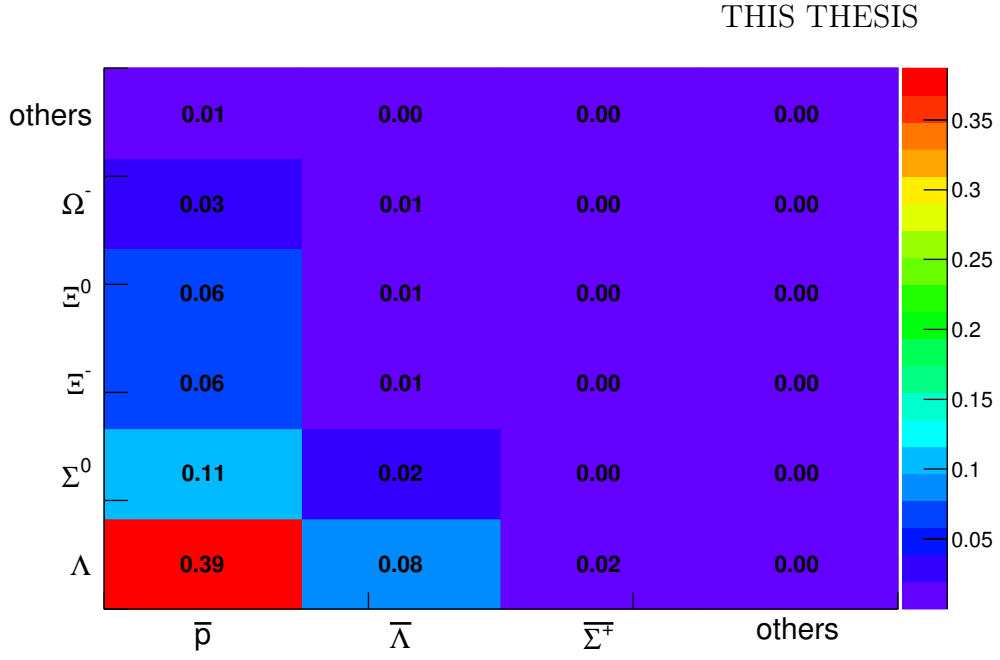


Figure 6.16: Fractions of $\bar{p}\Lambda$ pairs obtained using simulation in HIJING and taking into account detector response modelled in GEANT. See text for details.

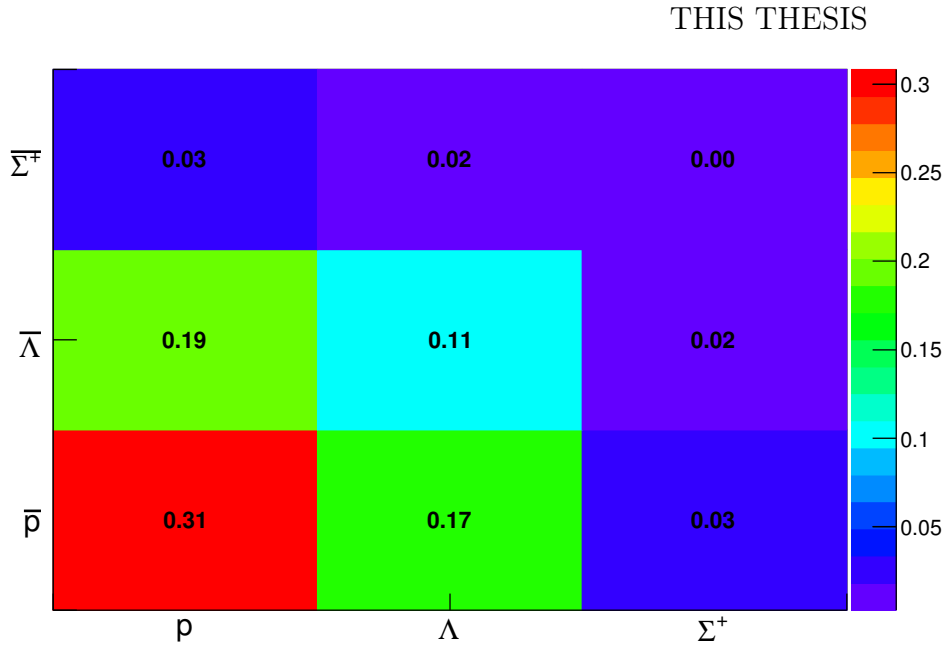


Figure 6.17: Fractions of $p\bar{p}$ pairs obtained using simulation in THERMINATOR. See text for details.

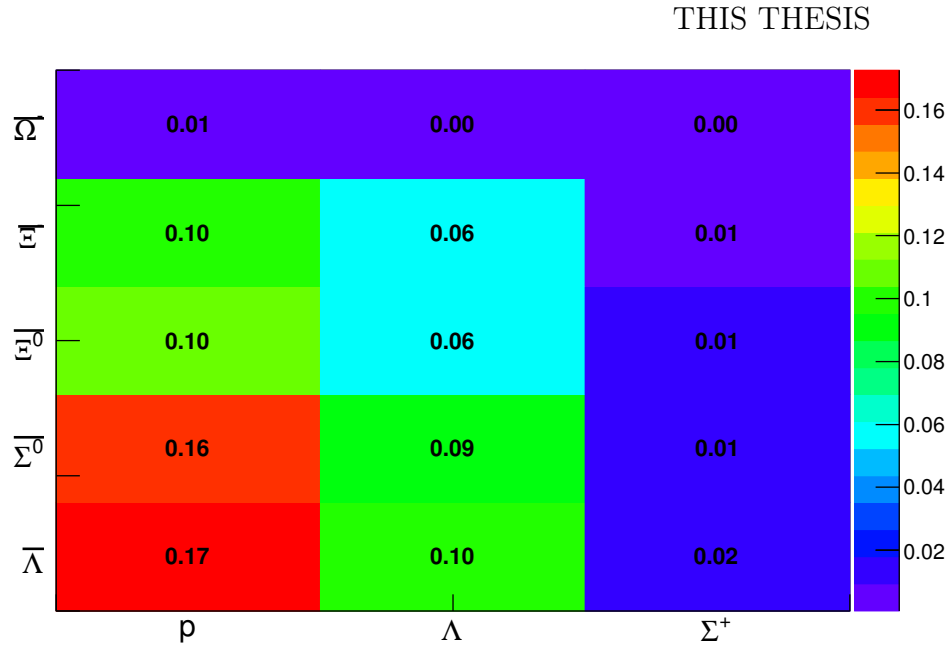


Figure 6.18: Fractions of $p\bar{\Lambda}$ pairs obtained using simulation in THERMINATOR. See text for details.

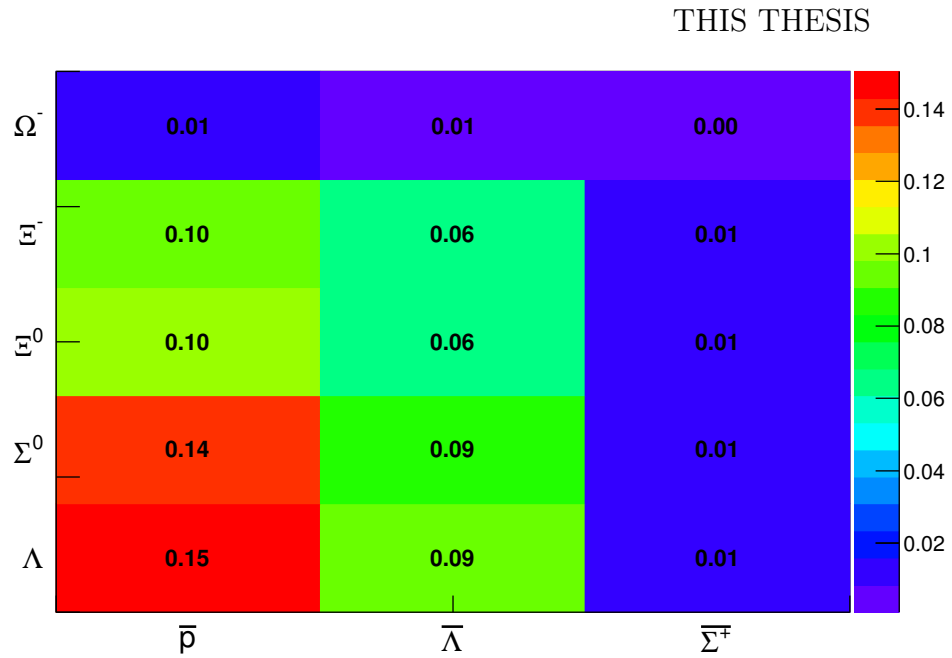


Figure 6.19: Fractions of $\bar{p}\Lambda$ pairs obtained using simulation in THERMINATOR. See text for details.

6.4. Pair selection

6.4.1. Tracks from the primary vertex

Concerning the two-track selection criteria, the cuts preventing the effects of merging (two tracks reconstructed as one) and splitting (one track reconstructed as two) were applied. This is of great importance as any inefficiencies at small relative momentum region may affect the extraction of femtoscopic results. As the first step, all pairs which share more than 5% TPC clusters (see Sec. 2.3) are rejected from the analysis to minimise the contribution of split tracks. Furthermore, the cut on the angular distance between two tracks was applied to handle the issue of track merging. This cut is determined according to the formula [152]: $|\Delta\varphi^*| = \varphi_1 - \varphi_2 + \arcsin(\frac{eBR}{2p_{T1}}) - \arcsin(\frac{eBR}{2p_{T2}})$, where φ is the azimuthal angle of the track, e denotes elementary charge (equals to -0.3 in Heaviside-Lorentz units), B is the magnetic field of the ALICE magnet, and R is the radius in the TPC at which the separation is calculated. Pairs of (anti)protons were required to have the separation of $|\Delta\eta| > 0.01$ and $|\Delta\varphi^*| > 0.045$ measured at the radial distance 1.2 m. Such values were chosen following the previous ALICE studies on this topic [152, 153]. Regarding this analysis, as one can observe in Fig. 6.20, the stricter the selection is, the higher the pp femtoscopic peak becomes. This clearly suggests the sensitivity of the correlation function to the pair selection criteria. The required minimal $|\Delta\eta|$ and $|\Delta\varphi^*|$ values were set to the 0.01 and 0.045, respectively, since larger values did not lead to significant change of the correlation function, but resulted in the noticeable decrease of the pair statistics. In addition, Fig. 6.21 presents proton-proton correlation functions from the simulation in HIJING combined with the reconstruction in GEANT. HIJING model does not incorporate the femtoscopic effects, thus one expects the correlation function to be flat. Any correlations at low relative momentum can be assigned to the finite resolution of the detector. As one can notice, the MC correlation function becomes flat only after applying the described selection criteria.

6.4.2. Tracks from the different vertices

For pairs composed of particles coming from the secondary vertices, the angular distance introduced in Sec. 6.4.1 is not well defined. The reason is that the angular distance in the polar direction for tracks originating from different vertices is not equal to the difference in pseudorapidity which is the case for particles coming from the primary vertex. The possible solution is to use the cut on the average separation between the two tracks in the TPC. The algorithm is the following: one propagates the tracks through the TPC volume and calculates the separation between the tracks at several radii in the chamber. Then one determines the average separation for each pair and stores it in the histogram. The ratio of such histograms obtained for pairs of particles coming from the same event

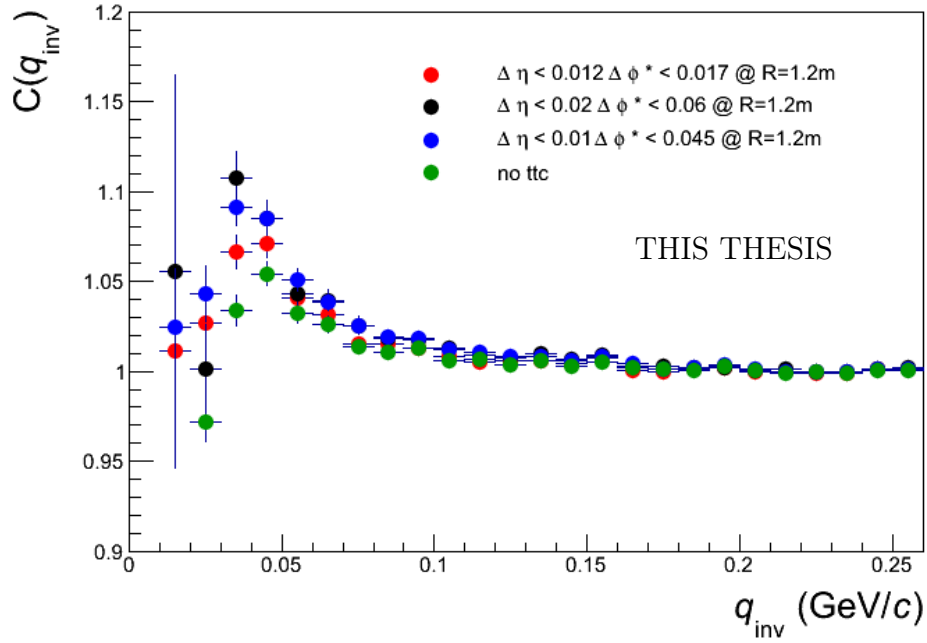


Figure 6.20: The comparison of pp correlation functions with the various two-track selection criteria. The results were obtained for the centrality class 0-10 % and the pair transverse momentum interval $0.01 < k_T < 5$ GeV/c.

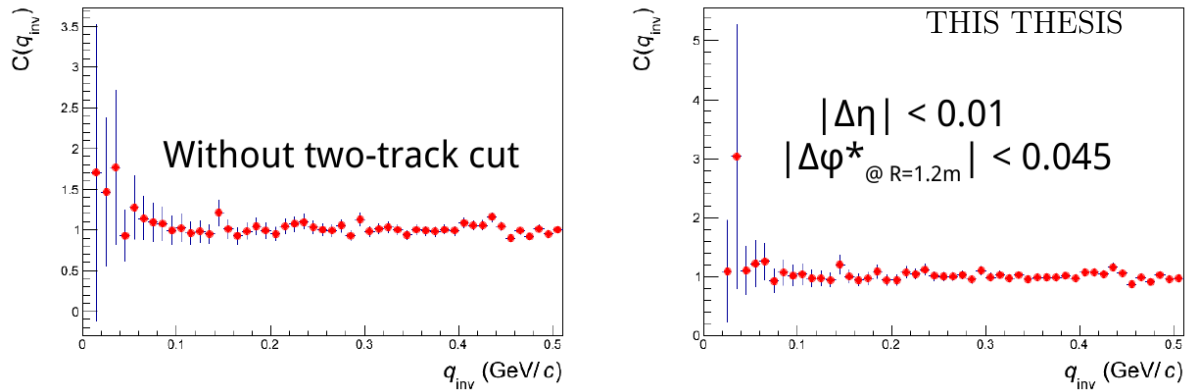


Figure 6.21: pp correlation function from HIJING simulations without the cut on the angular distance (left panel) and with the cut selecting only the pairs with $|\Delta\varphi^*| > 0.045$, and $|\Delta\eta| > 0.01$ measured at the radial distance 1.2 m (right panel).

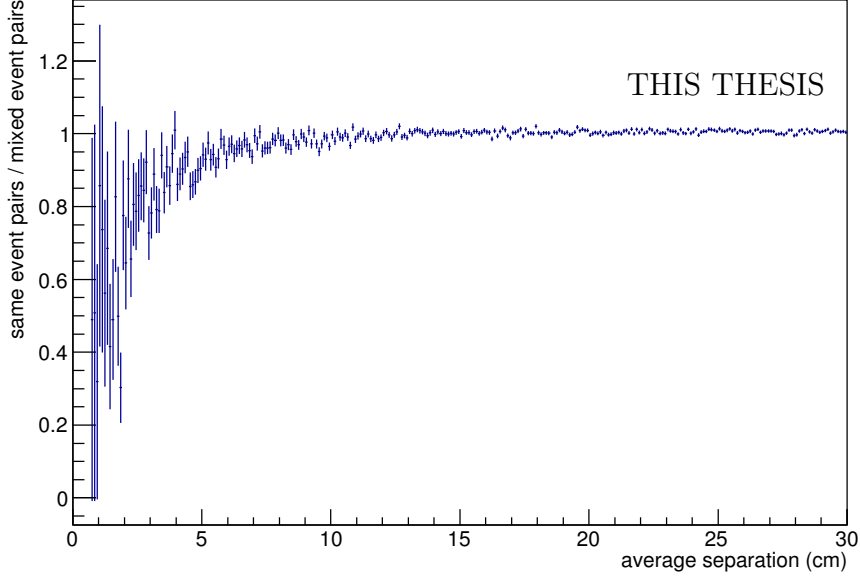


Figure 6.22: Average separation in the TPC between primary proton and π^+ from $\bar{\Lambda}$ decay presented in the form of ratio of distribution of same- and mixed-event pairs.

and those from mixed events (where two-track inefficiencies are not present) is shown in exemplary Fig. 6.22. The dip visible at small values of the average separation between primary proton and π^+ from $\bar{\Lambda}$ decay is caused by track merging. To correct for this effect one needs to reject all pairs with the average separation less than 11 cm.

Another approach to handle the two-track selection is the generalised angular distance cut [153]. The idea is to propagate the tracks considering that they may come from the secondary vertices in calculation of the azimuthal and polar position. The generalised angular distance is calculated using only the space coordinates of the tracks (x, y, z) propagated to the given radius R :

$$\Delta\eta^* = \eta_1^* - \eta_2^*, \quad (6.6)$$

$$\Delta\varphi^* = 2 \arctan \left(\frac{\sqrt{(\Delta x')^2 + (\Delta y')^2}}{2R} \right), \quad (6.7)$$

where $\eta^* = -\ln(\tan(\theta^*/2))$, $\theta^* = \pi/2 - \arctan(z'/R)$ and prime symbols refer to the positions of the tracks shifted by the space coordinates of the primary vertex. The example of the two-dimensional correlation function in $\Delta\eta^*\Delta\varphi^*$ space of the primary antiproton and π^- from Λ decay is shown in Fig. 6.23. One can notice the $\simeq 3\%$ depletion around $(0,0)$ due to merging of the tracks, thus one should cut out the pairs from this region. However, as one can see in Fig. 6.24, the details of the two-track selection have little influence on the baryon-antibaryon correlation functions themselves in contrast to the same-charge pairs. This can be understood to be the result of the opposite direction of

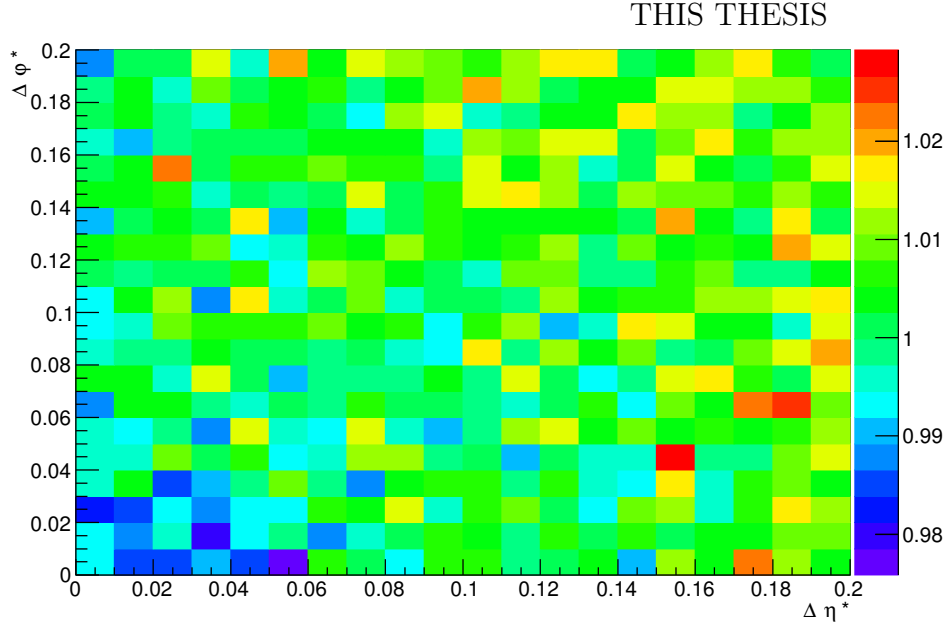


Figure 6.23: The two-dimensional correlation function in $\Delta\eta^*\Delta\varphi^*$ space of the primary antiproton and π^- from Λ decay.

the curvatures for particles with different charges. Such topology of the tracks is less vulnerable to two-track inefficiencies comparing with same-charge tracks which are bent in the same direction.

6.5. Construction of the correlation functions

Two-particle correlations were studied in one dimensional representation with respect to the relative momentum $q_{\text{inv}} = 2 \cdot k^*$ in the the pair centre of mass frame. The correlation

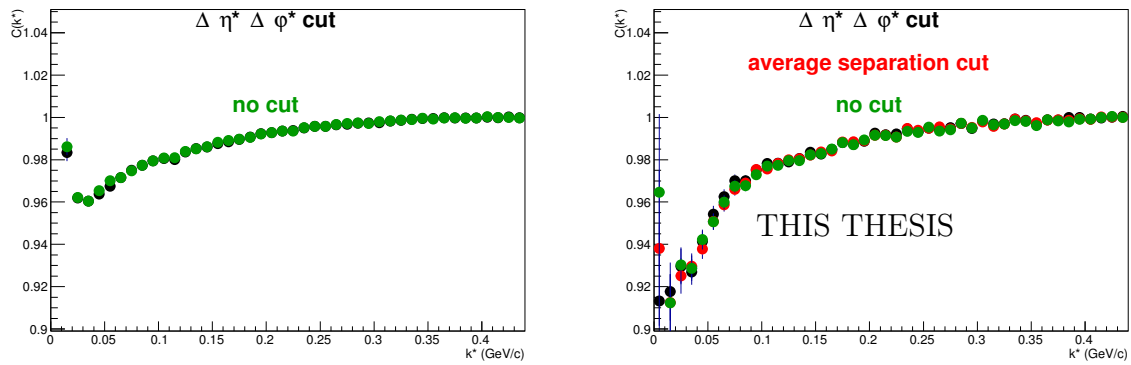


Figure 6.24: The influence of the two-track selection on $p\bar{p}$ (left plot) and $\bar{p}\Lambda$ (right plot) correlation functions.

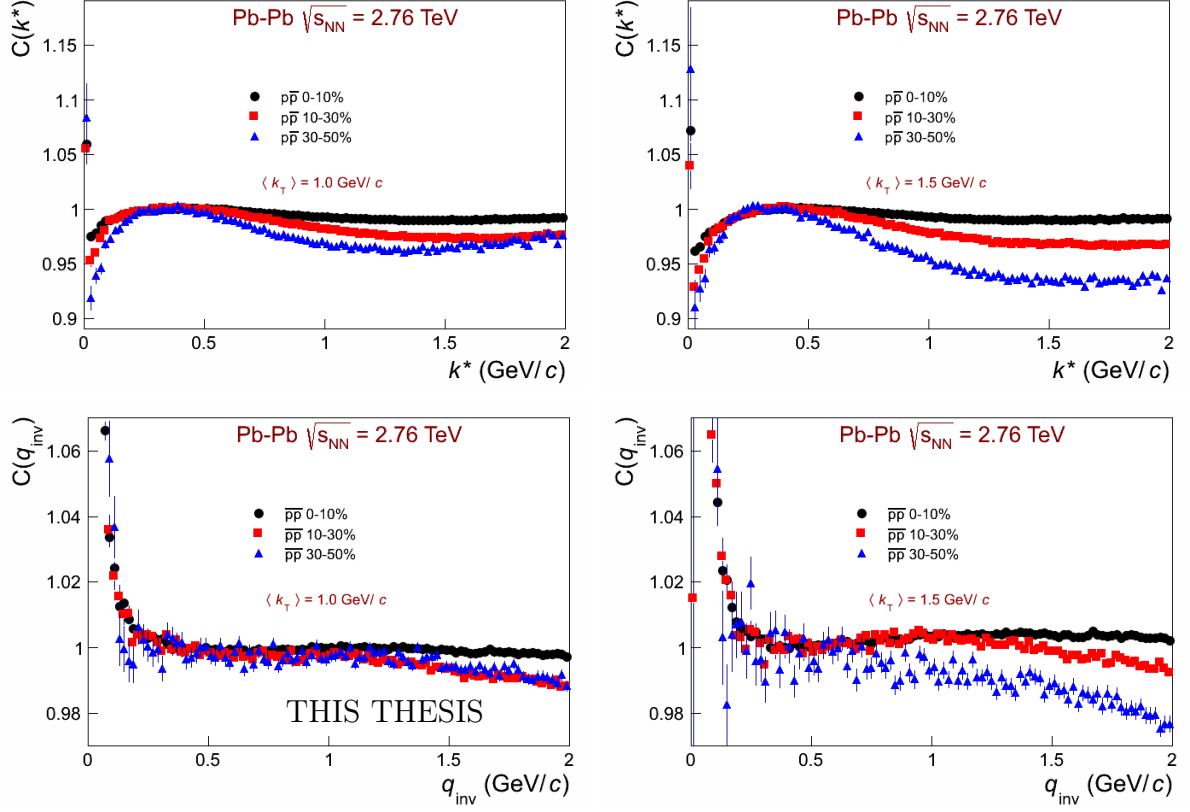


Figure 6.25: Proton-antiproton (top plots) and antiproton-antiproton (bottom plots) correlation functions for $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb in the wide range of the relative momentum. Left plots show results for $\langle k_T \rangle = 1.0$ GeV/c and right plots were obtained for $\langle k_T \rangle = 1.5$ GeV/c.

effect was measured using the function defined as:

$$C(q_{inv}) = \frac{A(q_{inv})}{B(q_{inv})}, \quad (6.8)$$

where $A(q_{inv})$ is a distribution of the same-event pair momentum difference and $B(q_{inv})$ is the reference distribution (where QS and FSI correlations are absent). The latter is built by selecting a particle from a certain event and then pairing it with a particle from another event to remove the combinatorial background of random baryon-(anti)baryon pairs. To assure that the phase space of the reference distribution has the same structure as the distribution of same-event pairs, only events from the same centrality and 2 cm vertex position bins were used to create $B(q_{inv})$. The analysis was performed using six centrality bins ($0 \div 5\%$, $5 \div 10\%$, $10 \div 20\%$, $20 \div 30\%$, $30 \div 40\%$, $40 \div 50\%$), later merged into three classes: $0 \div 10\%$, $10 \div 30\%$ and $30 \div 50\%$ due to the statistics limitations. Also, pp and $\bar{p}\bar{p}$ correlation functions have been calculated for two bins of the pair transverse momentum $k_T = |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$: $0.01 < k_T < 1.00$ GeV/c and $1.00 < k_T < 5.00$ GeV/c.

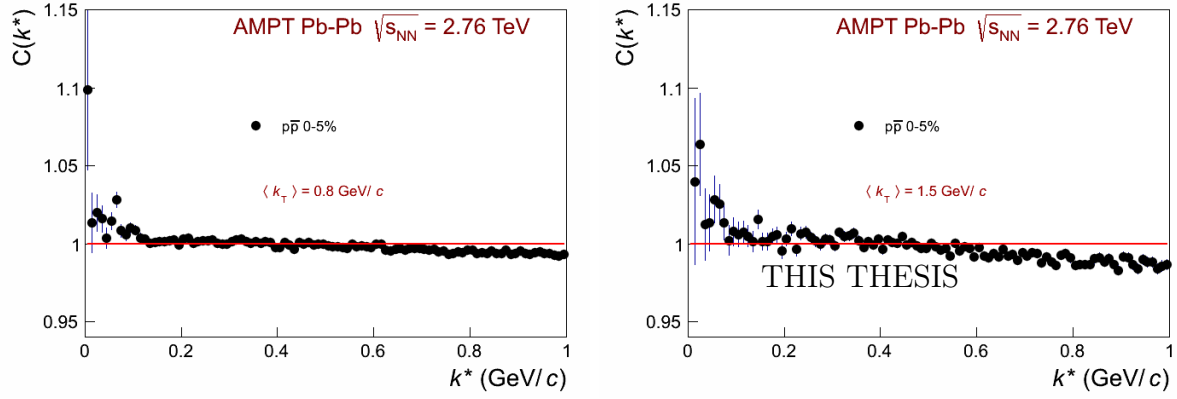


Figure 6.26: Proton-antiproton correlation functions from the AMPT simulations of $\sqrt{s_{\text{NN}}} = 2.76$ TeV Pb–Pb collisions in the wide range of the relative momentum.

6.5.1. Dealing with the non-flat background

The formalism of the femtoscopic correlation functions assumes that $C(q) \rightarrow 1$ for sufficiently large values of the momentum difference (specific values depend on the given pair type). Nonetheless, the non-flat background at high values of the relative momentum was found to be an important issue in femtoscopic analyses in pp and p–Pb collisions [154,155]. In Pb–Pb collisions such effect is not so prominent. However, as one can see in Figs. 6.25 and 6.26, there is a non-flat behaviour of the correlation function which in principle may affect extracted femtoscopic results. The origin of this phenomenon in pp collisions is thought to be due to the minijets, i.e. spray of collimated particles created in multi-parton scatterings at low momentum transfer [154] and the global conservation laws [156]. In heavy-ion collisions at ultra-relativistic energies, strong elliptic flow is present (see Sec. 1.5.6). In general, its influence on the same-event pair momentum difference $A(q_{\text{inv}})$ may be different than on the reference distribution $B(q_{\text{inv}})$. Hence, correlation due to the elliptic flow is not fully cancelled out in the femtoscopic correlation function $C(q_{\text{inv}})$. This is consistent with the observation that the effect of non-flat background becomes more evident in more peripheral collisions and for larger values of k_T similarly as the elliptic flow. Qualitatively similar behaviour of the correlation function is present in AMPT simulations. In addition, as one can see in Fig. 6.27, the shape and strength of the non-femtoscopic correlations at high- k^* region are similar for all studied baryon-antibaryon pairs. Hypothesis of the non-flat background of the correlation function caused by the elliptic flow was tested by creating the reference distribution $B(q_{\text{inv}})$ using events with similar value of the event plane angle (apart from the same centrality class and the vertex position bin). Comparable influence of the elliptic flow on both numerator and denominator of the correlation function should lead to the decrease of the non-flat behaviour of the correlation function at large values of q_{inv} . Therefore, the numerator and denominator were obtained separately in six bins of the second order event

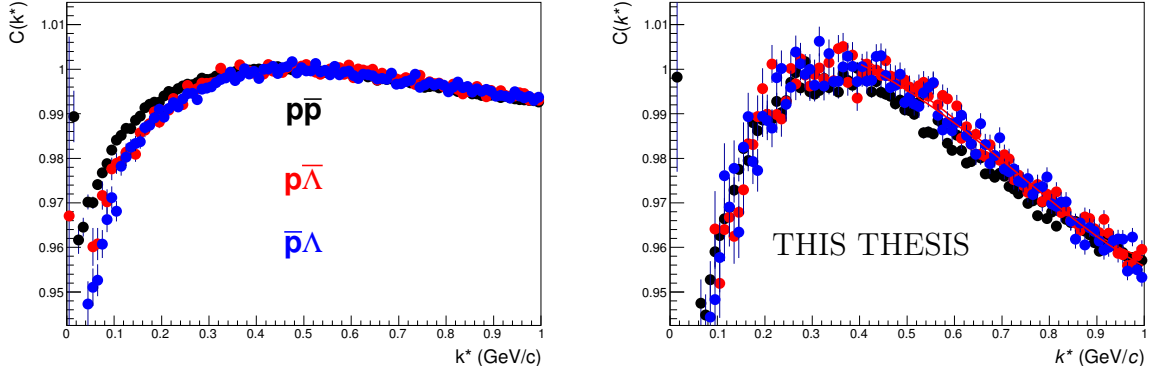


Figure 6.27: Comparison of the non-flat background in $p\bar{p}$, $p\bar{\Lambda}$, and $p\Lambda$ correlation functions for 0-10% (left plot) and 30-50% (right plot) centrality bin.

plane angle Ψ_2 calculated using V0 detector:

$$\Psi_2 = \text{atan2}(Q_{2,y}, Q_{2,x})/2, \quad (6.9)$$

where $Q_{2,x} = \sum_i w_i \cos(2\varphi_i)$, $Q_{2,y} = \sum_i w_i \sin(2\varphi_i)$, w_i is the multiplicity in the given V0 cell, $\varphi_i = \pi/8 + \pi/4 \cdot (ch_i \bmod 8)$, and ch_i is the number of the sector. The example of the event plane angle distribution is shown in Fig. 6.28. Next, the correlation function was constructed for each event plane angle bin separately, and later such functions were averaged using the number of entries in the numerator as the weight. The comparison of this method of construction the $p\bar{p}$ correlation function with the standard method in which numerator and denominator are calculated without the event plane angle binning is presented in Fig. 6.29. One can observe that the effect of the non-flat background can be partially reduced. Therefore, the hypothesis that the elliptic flow might lead to the non-flat behaviour of the femtoscopic correlation function cannot be ruled out. However, such approach has a drawback, namely the computational cost is slightly bigger. Nevertheless, this procedure with event plane angle binning was applied to calculate the baryon-antibaryon correlation functions (this was not done for baryon-baryon pairs since the influence on the final results was negligible).

6.5.2. Momentum resolution correction

The influence of the momentum resolution on baryon-baryon correlation functions was studied using the HIJING model and the reconstruction process simulated in GEANT. The correlation functions $C(q_{\text{inv}}^{\text{generated}})$ and $C(q_{\text{inv}}^{\text{reconstructed}})$ (here $q_{\text{inv}}^{\text{generated}}$ is the value of the relative momentum obtained directly from the HIJING simulation, and $q_{\text{inv}}^{\text{reconstructed}}$ is the value of the relative momentum calculated after the GEANT simulation) were generated using Eq. (3.17). Only primary protons were selected to generate the $C(q_{\text{inv}}^{\text{generated}})$ and $C(q_{\text{inv}}^{\text{reconstructed}})$. The effect of smearing of the correlation function due to momentum

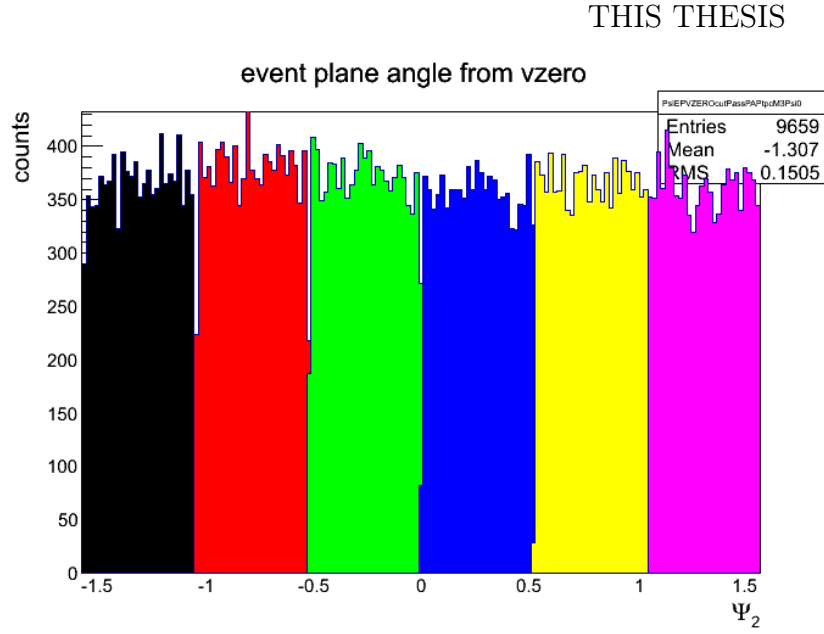


Figure 6.28: Distribution of the event plane angle calculated using V0 detector for selected run in the centrality class 20-30%.

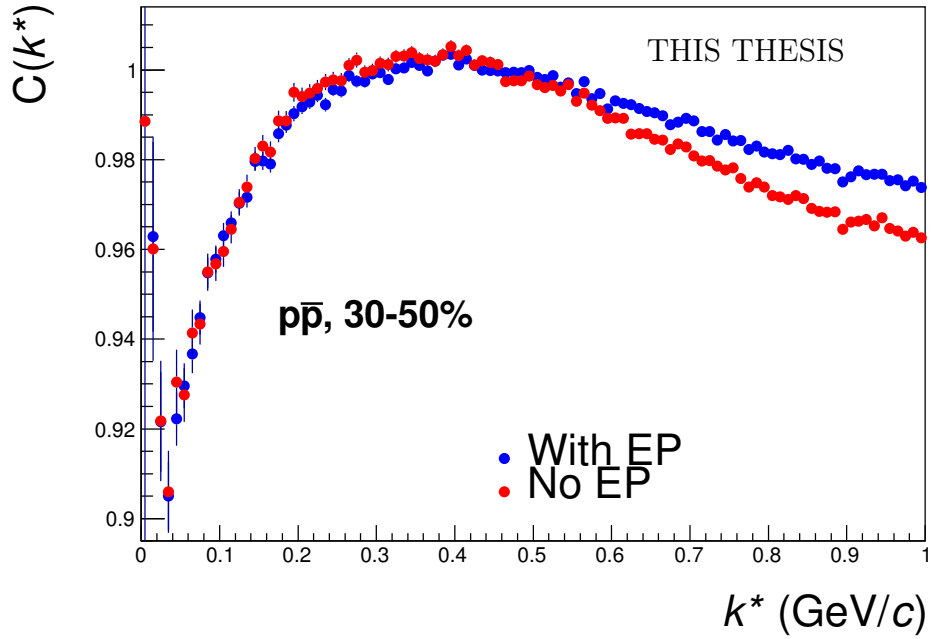


Figure 6.29: Comparison of $p\bar{p}$ correlation functions obtained using binning numerator and denominator in the event plane angle (“With EP”) and the standard method (“No EP”).

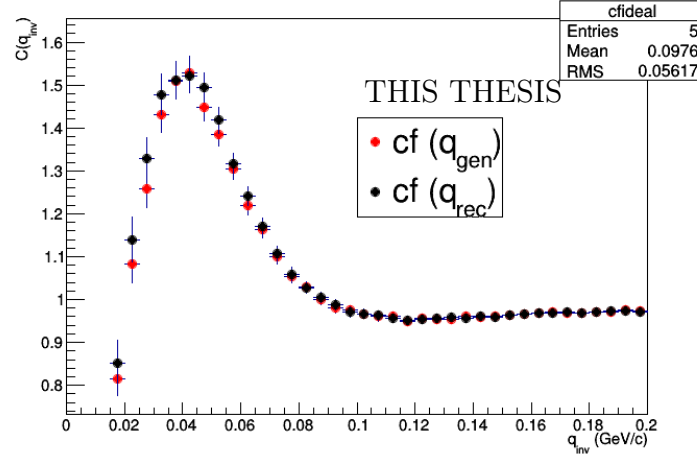


Figure 6.30: pp correlation function for $R_{\text{inv}} = 4$ fm calculated using the reconstructed (black) and generated (red) momentum difference q_{inv} .

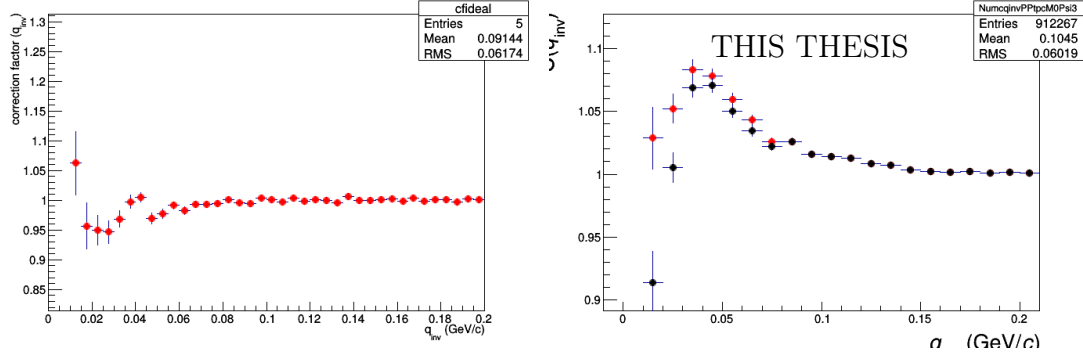


Figure 6.31: Left plot: correction function: $C(q_{\text{inv}}^{\text{generated}})/C(q_{\text{inv}}^{\text{reconstructed}})$. Right plot: experimental pp correlation function before (red) and after (black) momentum resolution correction.

resolution is presented in Fig. 6.30. The correction factor is calculated as a function of q_{inv} : $f(q_{\text{inv}}) = C(q_{\text{inv}}^{\text{generated}})/C(q_{\text{inv}}^{\text{reconstructed}})$ and is fitted by 8th order polynomial. Then, the experimental correlation function is scaled by $f(q_{\text{inv}})$. The results are shown in Fig. 6.31.

As for baryon-antibaryon case, the correction for the momentum resolution is taken into account directly in the fitting procedure. The fit function is smeared with the Gaussian with the width corresponding the momentum resolution for the pairs of interest. Following formula is used:

$$C_c(q_c) = \int_{-3\sigma}^{+3\sigma} C_{th}(q_c - q) \exp \frac{(q - q_t)^2}{2\sigma^2} |q_c - q|^2 dq, \quad (6.10)$$

where C_c is the corrected function, C_{th} is the ideal function, σ is the momentum resolution.

7. Results of one-dimensional femtoscopy with pp and $\bar{p}\bar{p}$ pairs in ALICE

In this chapter, the outcome of the femtoscopic analysis with pp and $\bar{p}\bar{p}$ pairs in Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{\text{NN}}}=2.76$ TeV registered by ALICE detector are given. They are based on the residual correlation formalism introduced in previous chapters. These results are the original work of this thesis and were the subject of the article published in [123]. The author of this thesis was a member of the group primarily responsible for the results, figures and the text of the publication.

7.1. Extracting femtoscopic parameters from the correlation functions

Extraction of the radius parameter from the pp and $\bar{p}\bar{p}$ correlation functions can be performed using the method described in Sec. 3.3.3. However, as it can be observed in Fig. 7.1, attempts to fit the obtained correlation functions directly using this approach failed, being unable to reproduce the shape of the measured correlation. Indeed, the correlation of pp pairs can be described by three components. The contribution from the Coulomb FSI and QS correlations have to be negative (i.e. the correlation function goes below unity). The effect coming from the strong FSI is positive but has limited width. Therefore, the excess in the range $30 \div 80$ MeV/ c of k^* cannot originate from the correlations arising due to the wave function of the pair of protons. A significant influence of residual correlations may be a possible explanation (see Chap. 4). In addition, to check this hypothesis a dedicated simulation was performed. Protons were generated using the simulation in the THERMINATOR model with the parameters corresponding to the central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. Then, for all the pp pairs from a certain event their relative momentum q_{pp} was calculated. After that, protons were checked if they are primary or come from the Λ decay. For pairs which contain the secondary proton, one calculates the relative momentum of the parent particles $q_{\text{p}\Lambda}$, i.e. the relative momentum of the primary proton and the primary Λ which decays to the proton. Primary pairs are stored in the histogram according to their q_{pp} with the pp femtoscopic weight obtained using the method described in Sec. 3.3.3. Residual p Λ pairs are also binned with q_{pp} , but with the p Λ femtoscopic weight calculated according to the parent relative momentum $q_{\text{p}\Lambda}$. The q_{pp} distributions obtained using pp or p Λ weights refers to the numerator of the correlation function in Eq. (6.8). The denominator of this function is constructed simply by storing q_{pp} values without any weights. This simulation allows to obtain the

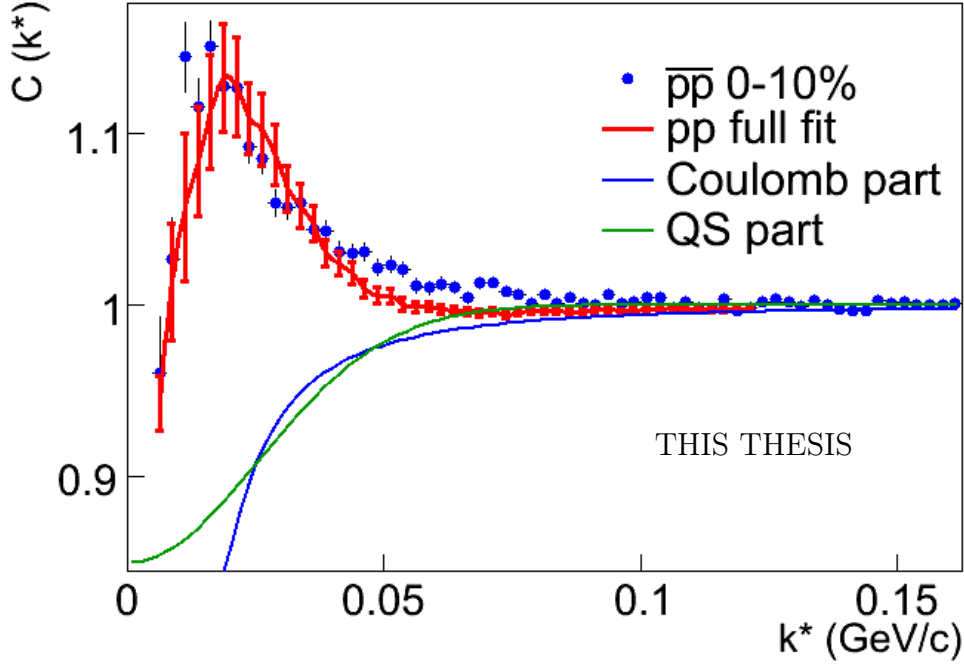


Figure 7.1: Comparison of experimental $\bar{p}\bar{p}$ correlation function and the theoretical fit. In addition contribution of Coulomb repulsion and QS correlations are shown.

three correlation functions: the one for all the pp pairs regardless of their origin, the other for the pairs composed only of the primary protons, and finally for the pairs with one primary proton and the other being the product of Λ decay. Results presented in Fig. 7.2 support the hypothesis that the broad excess correlation around $q_{\text{inv}} \approx 0.1$ GeV/c can be explained by the contribution from residual correlation from p Λ system.

Hence, the method of fitting the pp ($\bar{p}\bar{p}$) correlations taking into account residual effects from p Λ ($\bar{p}\bar{\Lambda}$) pairs was implemented. Such procedure was mentioned in [124], later it was developed for the need of this thesis and was firstly presented in [133] and then published in [123]. It is worth emphasising that the same method was thereafter applied by STAR experiment [122]. In this work the contributions from the residual correlations arising from the femtoscopic correlations of heavier than p Λ baryon-baryon pairs are not considered. The primary reason is that such correlations are more diluted comparing with p Λ due to the larger decay momentum. Moreover, the number of baryons with the mass larger than Λ decaying to proton is smaller compared with Λ hyperons. Another issue is that the knowledge of the strong FSI parameters for heavy baryon pairs (e.g. $\Lambda\Lambda$) is limited. Regarding the comparison with the baryon-antibaryon pairs (see Chap. 5 and 8), the width of the correlation for baryon-baryon pairs is expected to be much smaller. Thus, due to the decay kinematics, the effect is less prominent.

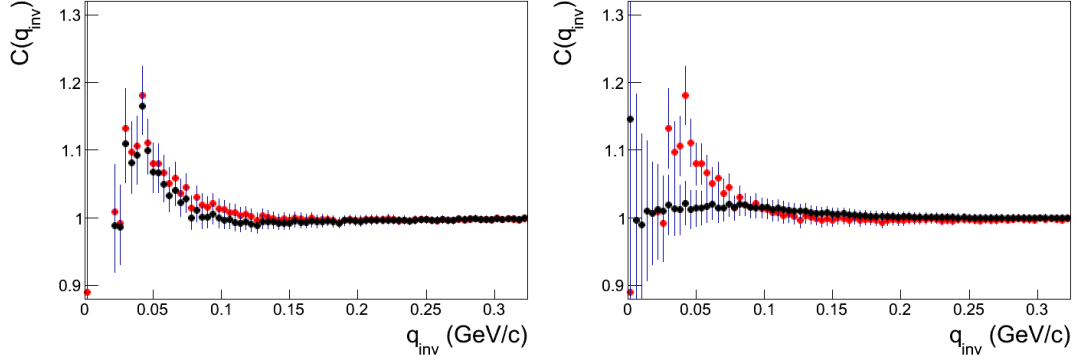


Figure 7.2: Left plot: the comparison of the pp correlation function obtained using all pp pairs regardless of their origin (red points) with the one obtained using only primary pairs of protons (black points). Right plot: the comparison of the pp correlation function obtained using all pp pairs regardless of their origin (red points) with the one obtained using pairs composed of the primary proton and the proton from the Λ decay. See text for details.

All things considered, the experimental correlation function of pp and $\bar{p}\bar{p}$ systems were fitted with the formula:

$$C_{\text{meas}}(q_{pp}) = 1 + \lambda_{pp}(C_{pp}(q_{pp}; R) - 1) + \lambda_{p\Lambda}(C_{p\Lambda}(q_{pp}; R) - 1), \quad (7.1)$$

where λ_{pp} is the fraction of such correlated pp pairs that both particles are primary, and $\lambda_{p\Lambda}$ describe the contribution of pp pairs composed of the primary proton and proton from the Λ decay. One needs to stress that in general λ parameter characterises the total decrease of the femtoscopic correlations due to e.g. long-lived resonances, non-Gaussian shape of the source distribution¹, and coherence of the sources [157, 158, 159]. The theoretical pp and $\bar{p}\bar{p}$ contribution $C_{pp}(q_{pp}; R)$ were calculated using the method described in Sec. 3.3.3. The same values of the strong FSI parameters were assumed for pp and $\bar{p}\bar{p}$ pair types. The term describing the theoretical p Λ correlation function $C_{p\Lambda}(q_{pp}; R)$ is determined using Eq. (3.26) and the transformation into the pp momentum space:

$$C_{p\Lambda}(q_{pp}; R_{p\Lambda}) = \frac{\sum_{q_{p\Lambda}} C_{p\Lambda}(q_{p\Lambda}; R_{p\Lambda}) W(q_{pp}, q_{p\Lambda})}{\sum_{q_{p\Lambda}} W(q_{pp}, q_{p\Lambda})}, \quad (7.2)$$

where $W(q_{pp}, q_{p\Lambda})$ are the transformation factors resulting from the Λ decay kinematics calculated using THERMINATOR model as described in Sec. 4.3 and shown in Fig. 7.3. Fig. 7.4 presents the example of the transformation of $C_{p\Lambda}$ into pp momentum space. In the fitting process the radii of pp and p Λ radii are assumed to be equal. Hence, the three fit parameters (λ_{pp} , $\lambda_{p\Lambda}$, and R) are free. The procedure of extracting the femtoscopic parameters is performed using the MINUIT minimisation package in ROOT framework:

¹By the ‘non-Gaussian shape’ all the deviations from the Gaussian distribution are meant, in particular the long range tails [34, 142].

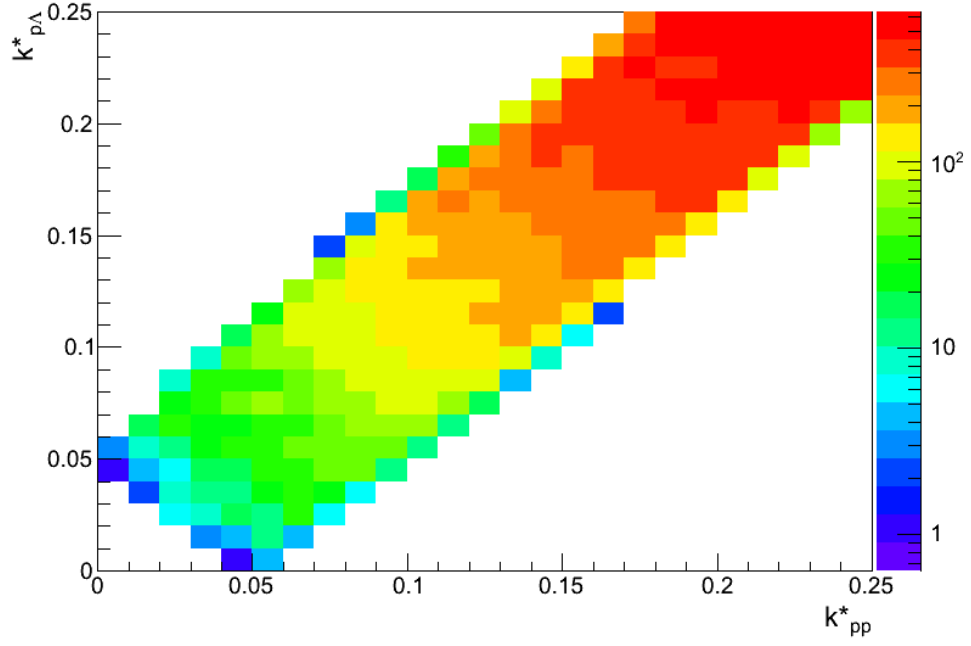


Figure 7.3: The transformation matrix of the relative momentum for $p\Lambda$ pairs which decays into pp , calculated with *THERMINATOR*.

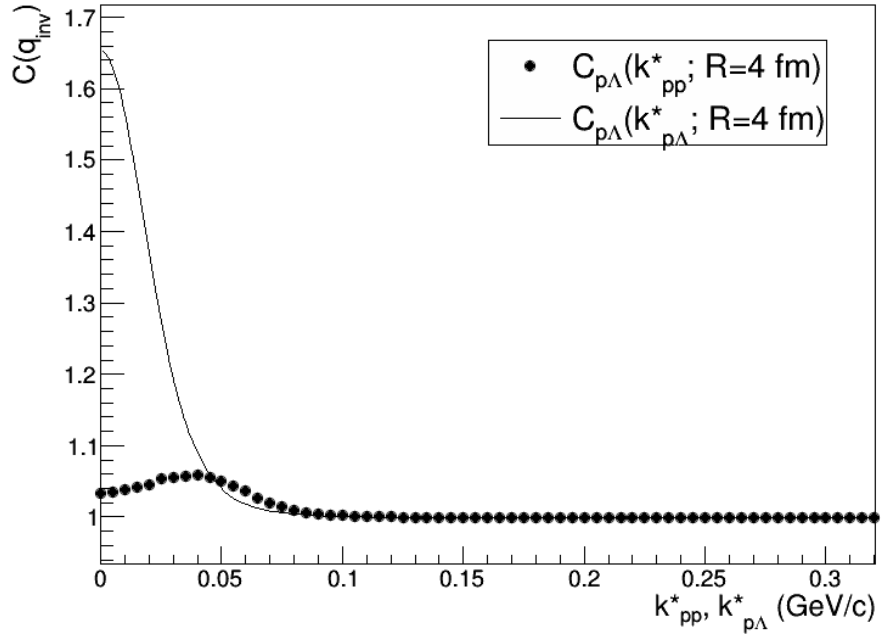


Figure 7.4: The transformation of $C_{p\Lambda}(k_{p\Lambda}^*) \rightarrow C_{p\Lambda}(k_{pp}^*)$.

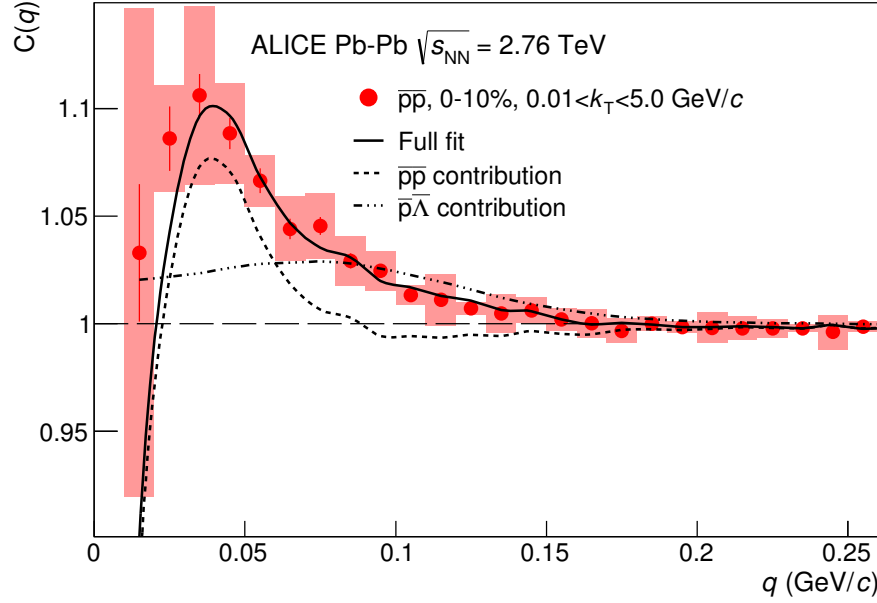


Figure 7.5: The $\bar{p}p$ correlation function with the fit for the centrality class $0 \div 10\%$ and $\langle k_T \rangle = 1.0$ GeV/c. Thin lines and boxes correspond to statistical and systematic uncertainties, respectively. The main source of the systematic uncertainty assigned to the correlation function is due to the variations of two-track cuts [123].

the gradient minimisation algorithm MIGRAD is applied to find a minimum χ^2 value of the fit of Eq. (7.1) to the experimental correlation function. The fitting function is calculated using the interpolation method. Firstly, a grid of C_{pp} and $C_{p\Lambda}$ theoretical correlation functions for $R = 1.0, 1.1, \dots, 6.0$ fm was obtained. Then, the fitting function is calculated using Eq. (7.1) for the specific radius by interpolating between the grid nodes of the simulated C_{pp} and $C_{p\Lambda}$ using the quadratic interpolation at each iteration of the fit. The example of the $\bar{p}p$ correlation function along with the fitted function is presented in Fig. 7.5. One can notice the clear maximum at $q \approx 40$ MeV/c due to the interplay of strong and Coulomb FSI as well as Fermi-Dirac statistics [91]. In addition, the positive correlation at $q \approx 100$ MeV/c which cannot be explained in frame of correlations coming from the pp wave function, is reproduced by the residual correlation component. The fit quality based on the χ^2/NDF value is in the range of $0.8 \div 3.2$ depending on centrality and pair transverse momentum bin.

7.2. Systematic uncertainties

Systematic uncertainties assigned to the correlation function were determined using the variation of single- and two-particle selection criteria. For each q -bin, the uncertainty was calculated as the square root of the squares of differences between the value of the correlation function obtained with the default set of cuts ($N^{\circ} 1$ from Tab. 7.1) and values of

set	p_T (GeV/ c)	DCA _{xy} (cm)	PID	$\Delta\eta$	$\Delta\varphi^*$
N ^o 1	0.7-4.0	2.4	3σ	$ \Delta\eta < 0.01$	$ \Delta\varphi^* < 0.045$
N ^o 2	0.7-4.0	1.0	3σ	$ \Delta\eta < 0.01$	$ \Delta\varphi^* < 0.045$
N ^o 3	0.7-4.0	2.4	2σ	$ \Delta\eta < 0.01$	$ \Delta\varphi^* < 0.045$
N ^o 4	0.7-4.0	2.4	3σ	$ \Delta\eta < 0.02$	$ \Delta\varphi^* < 0.06$
N ^o 5	0.7-4.0	2.4	3σ	$ \Delta\eta < 0.012$	$ \Delta\varphi^* < 0.017$

Table 7.1: The summary of the cuts used in the analysis.

the correlation functions obtained with other selection criteria (N^o 2 ÷ N^o 5 from Tab. 7.1).

Regarding the procedure of determination the systematic uncertainty of the extracted radius, λ_{pp} , and $\lambda_{p\Lambda}$ parameters, firstly the correlation function with certain default assumptions and selection criteria was identified (N^o 1 from Tab. 7.1) and fitted using Eq. 7.1 to obtain the default values of the femtoscopic parameters. Then, the systematic uncertainty assigned to R_{inv} , λ_{pp} , and $\lambda_{p\Lambda}$ parameters from each source is calculated as the square root of the squares of differences between those values and parameters extracted from the fits to the correlation functions obtained by varying certain assumptions described below. Such procedure is performed separately for each centrality and k_T bin.

- *Variation of selection criteria.* First group of the sources of the systematic uncertainty comes from different selection criteria. This is performed by fitting Eq. 7.1 to the correlation functions obtained using cuts N^o 2 ÷ N^o 5 from Tab. 7.1.
- *Momentum resolution correction.* Next, the contributions to the systematic uncertainty from the momentum resolution correction (see Sec. 6.5.2) is investigated. This is done by obtaining R_{inv} , λ_{pp} , and $\lambda_{p\Lambda}$ parameters from the fits to uncorrected correlation functions.
- *Non-flat background.* The treatment of the non-flat background of the correlation function (see Sec. 6.5.1) is the next analysed source of the systematic uncertainty. It is estimated by extracting the femtoscopic parameters from the correlation function divided by the second order polynomial fitted to the high- q region (to make the function flat as femtoscopic formalism assumes).
- *Fitting procedure.* Furthermore, the other sources of the systematic uncertainty related to the fitting procedure were investigated. The most important one is the treatment of λ parameters. By default they were treated as the free fit parameters. The variation was to fix them to the values shown in Tab. 7.2 estimated from MC template fits described in Sec. 6.3.3. In addition, the extracted parameters were found to be sensitive to the range of the fit and initial values of the fitted parameters. Finally, the assumption regarding pp and p Λ radii used in the fitting formula was studied by varying from the default case: $R_{pp} = R_{p\Lambda}$ to $R_{pp} = 1.1 \cdot R_{p\Lambda}$ following the hypothesis of approximate $1/\sqrt{m_T}$ scaling of the radii in hydrodynamic models.

$\langle k_T \rangle$ (GeV/ c)	λ_{pp}	$\lambda_{\bar{p}\bar{p}}$
0.75	0.22	0.28
1.23	0.28	0.34
1.5	0.38	0.38

Table 7.2: Fractions of primary pp ($\bar{p}\bar{p}$) pairs estimated using single-particle fractions of primary p and $\bar{p}$ presented in Fig. 6.12.

source of the systematic uncertainty	R_{inv}	λ
Event/particle/pair selection	2-27	12-58
Non-flat background	2-3	1-9
Fit range	3-26	3-57
PID and purity	4-18	13-41
Momentum resolution	3	1-8
Fixing λ_{pp}	1-29	—
$R_{pp}/R_{p\Lambda}$ ratio	1-13	20-52
Total (quad. sum)	10-40	30-80

Table 7.3: Minimal and maximal systematic uncertainty values for various sources in percent. The λ denotes the sum of λ_{pp} and $\lambda_{p\Lambda}$ parameters.

The minimal and maximal uncertainties assigned to derived radius and λ parameters are shown in Tab. 7.3.

7.3. Transverse mass dependence of the extracted femtoscopic parameters

Fitting parameters obtained using the method described above are summarised in Tab. 7.4–7.9. They were compared with the femtoscopic results obtained using pions as well as neutral and charged kaons correlations measured in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV registered by ALICE. Femtoscopic parameters derived from the fits to $\pi^\pm\pi^\pm$, $K^\pm K^\pm$, $K_S^0 K_S^0$, pp, and $\bar{p}\bar{p}$ correlations as a function of the collision centrality and pair transverse mass are presented in Figs. 7.6 and 7.7. The former presents the λ parameter as a function of the pair transverse mass m_T for three centrality bins. The proton’s λ parameter was obtained as the sum of λ_{pp} and $\lambda_{p\Lambda}$ parameters from Eq. 7.1. The extracted values

centrality	$R_{pp}(\text{fm})$		
	$\langle k_T \rangle = 0.6 \text{ GeV}/c$	$\langle k_T \rangle = 1.0 \text{ GeV}/c$	$\langle k_T \rangle = 1.4 \text{ GeV}/c$
0-10%	$4.06 \pm 0.09^{+0.84}_{-0.80}$	$3.53 \pm 0.06^{+0.60}_{-0.34}$	$3.24 \pm 0.06^{+0.55}_{-1.11}$
10-30%	$3.28 \pm 0.13^{+0.29}_{-0.75}$	$3.32 \pm 0.01^{+0.18}_{-0.79}$	$3.10 \pm 0.02^{+0.71}_{-0.41}$
30-50%	$2.65 \pm 0.28^{+1.06}_{-0.71}$	$2.72 \pm 0.19^{+1.07}_{-0.88}$	$2.40 \pm 0.18^{+0.60}_{-0.51}$

Table 7.4: Radii extracted from pp femtoscopy. Statistical and systematic uncertainties are shown.

centrality	$R_{\bar{p}p}$ (fm)		
	$\langle k_T \rangle = 0.6$ GeV/c	$\langle k_T \rangle = 1.0$ GeV/c	$\langle k_T \rangle = 1.4$ GeV/c
0-10%	$4.39 \pm 0.07^{+0.36}_{-0.77}$	$3.60 \pm 0.01^{+0.44}_{-0.65}$	$3.11 \pm 0.08^{+0.87}_{-0.94}$
10-30%	$3.44 \pm 0.03^{+0.96}_{-0.83}$	$3.24 \pm 0.02^{+0.29}_{-0.56}$	$3.12 \pm 0.14^{+0.69}_{-0.45}$
30-50%	$2.93 \pm 0.28^{+0.74}_{-0.47}$	$2.50 \pm 0.02^{+0.90}_{-0.26}$	$2.47 \pm 0.20^{+0.47}_{-0.69}$

Table 7.5: Radii extracted from $\bar{p}p$ femtoscopy. Statistical and systematic uncertainties are shown.

centrality	λ_{pp}		
	$\langle k_T \rangle = 0.6$ GeV/c	$\langle k_T \rangle = 1.0$ GeV/c	$\langle k_T \rangle = 1.4$ GeV/c
0-10%	$0.14 \pm 0.03^{+0.10}_{-0.13}$	$0.18 \pm 0.02^{+0.11}_{-0.09}$	$0.22 \pm 0.02^{+0.04}_{-0.19}$
10-30%	$0.14 \pm 0.04^{+0.02}_{-0.14}$	$0.21 \pm 0.01^{+0.09}_{-0.17}$	$0.26 \pm 0.05^{+0.12}_{-0.15}$
30-50%	$0.13 \pm 0.05^{+0.26}_{-0.07}$	$0.21 \pm 0.05^{+0.17}_{-0.17}$	$0.19 \pm 0.05^{+0.29}_{-0.07}$

Table 7.6: λ_{pp} parameters extracted from pp femtoscopy. Statistical and systematic uncertainties are shown.

centrality	$\lambda_{\bar{p}p}$		
	$\langle k_T \rangle = 0.6$ GeV/c	$\langle k_T \rangle = 1.0$ GeV/c	$\langle k_T \rangle = 1.4$ GeV/c
0-10%	$0.26 \pm 0.04^{+0.10}_{-0.18}$	$0.23 \pm 0.02^{+0.11}_{-0.14}$	$0.21 \pm 0.03^{+0.17}_{-0.15}$
10-30%	$0.20 \pm 0.07^{+0.16}_{-0.20}$	$0.23 \pm 0.04^{+0.04}_{-0.10}$	$0.26 \pm 0.05^{+0.11}_{-0.10}$
30-50%	$0.28 \pm 0.10^{+0.37}_{-0.11}$	$0.22 \pm 0.03^{+0.21}_{-0.05}$	$0.25 \pm 0.07^{+0.05}_{-0.14}$

Table 7.7: $\lambda_{\bar{p}p}$ parameters extracted from $\bar{p}p$ femtoscopy. Statistical and systematic uncertainties are shown.

centrality	$\lambda_{p\Lambda}$		
	$\langle k_T \rangle = 0.6$ GeV/c	$\langle k_T \rangle = 1.0$ GeV/c	$\langle k_T \rangle = 1.4$ GeV/c
0-10%	$0.17 \pm 0.04^{+0.22}_{-0.11}$	$0.31 \pm 0.02^{+0.24}_{-0.19}$	$0.37 \pm 0.03^{+0.08}_{-0.34}$
10-30%	$0.11 \pm 0.05^{+0.21}_{-0.07}$	$0.34 \pm 0.03^{+0.08}_{-0.28}$	$0.47 \pm 0.08^{+0.26}_{-0.37}$
30-50%	$0.19 \pm 0.09^{+0.20}_{-0.23}$	$0.34 \pm 0.09^{+0.20}_{-0.27}$	$0.36 \pm 0.09^{+0.20}_{-0.16}$

Table 7.8: $\lambda_{p\Lambda}$ parameters extracted from pp femtoscopy. Statistical and systematic uncertainties are shown.

centrality	$\lambda_{\bar{p}\bar{\Lambda}}$		
	$\langle k_T \rangle = 0.6$ GeV/c	$\langle k_T \rangle = 1.0$ GeV/c	$\langle k_T \rangle = 1.4$ GeV/c
0-10%	$0.21 \pm 0.06^{+0.12}_{-0.08}$	$0.38 \pm 0.02^{+0.16}_{-0.33}$	$0.38 \pm 0.04^{+0.04}_{-0.41}$
10-30%	$0.14 \pm 0.08^{+0.41}_{-0.22}$	$0.33 \pm 0.06^{+0.21}_{-0.37}$	$0.46 \pm 0.07^{+0.22}_{-0.22}$
30-50%	$0.21 \pm 0.17^{+0.28}_{-0.29}$	$0.22 \pm 0.05^{+0.28}_{-0.08}$	$0.32 \pm 0.10^{+0.09}_{-0.33}$

Table 7.9: $\lambda_{\bar{p}\bar{\Lambda}}$ parameters extracted from $\bar{p}p$ femtoscopy. Statistical and systematic uncertainties are shown.

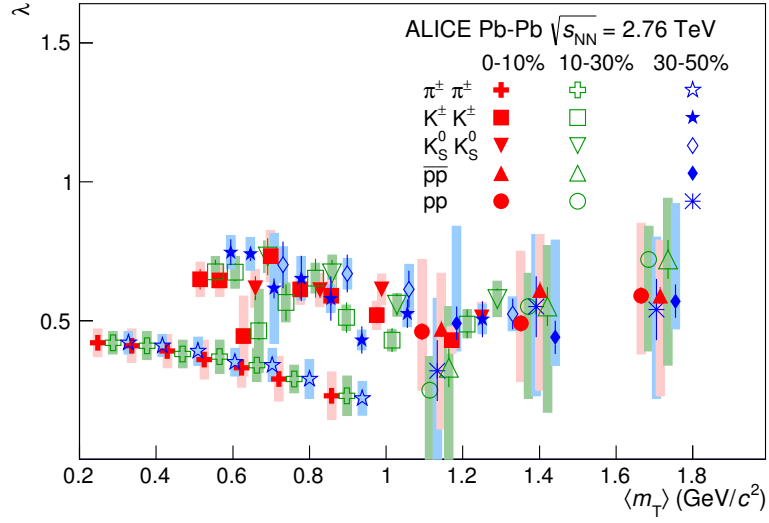


Figure 7.6: λ parameters ($\lambda_{pp} + \lambda_{p\Lambda}$ for (anti)proton pairs) as a function of m_T for the three centrality classes obtained using $\pi^\pm\pi^\pm$, $K^\pm K^\pm$, $K_S^0 K_S^0$, pp , and $\bar{p}p$ femtoscopy. Statistical and systematic uncertainties are marked as thin lines and boxes, respectively. The values of m_T for selected centrality bins are offset for better visibility [123].

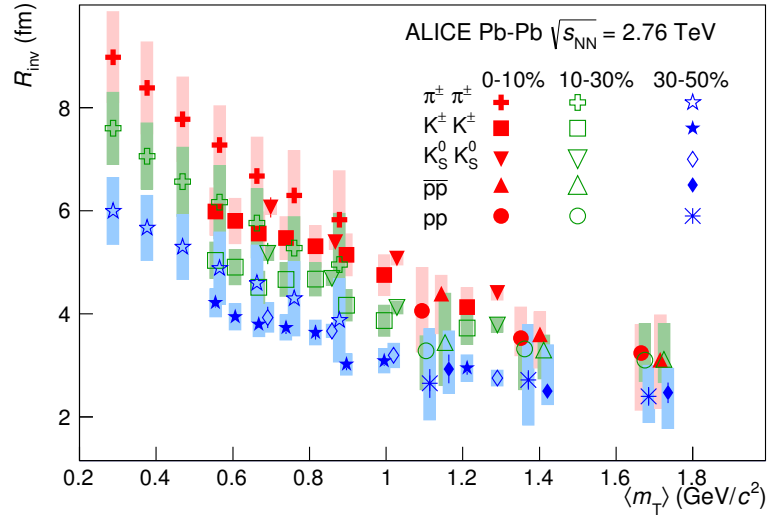


Figure 7.7: R_{inv} parameters as a function of m_T for the three centrality classes obtained using $\pi^\pm\pi^\pm$, $K^\pm K^\pm$, $K_S^0 K_S^0$, pp , and $\bar{p}p$ femtoscopy. Statistical and systematic uncertainties are marked as thin lines and boxes, respectively [123].

of the λ parameter for all pair types are about 0.3-0.7 and do not depend significantly on centrality. They are below unity mainly because of the long-lived resonances which lead to the dilution of the correlation functions as well as to non-Gaussian shape of the source distribution, in particular in case of the one-dimensional analysis [160]. Values of λ parameter for kaon and proton pairs are in agreement with each other at comparable values of the pair transverse mass. Results of λ values for pions are smaller comparing with kaons. Possible explanation is stronger influence of the particles from resonance decays, which cause the non-Gaussian features of the source distribution, in the pion sample comparing with the kaon one. In addition, the coherence of pions was also investigated as a possible source of the decrease of λ parameter [158].

As far as the pair transverse mass dependence of the radius parameter is concerned, results for different pair types are compatible with each other within systematics at the overlapping pair transverse mass. In particular, values obtained for pp and $\bar{p}\bar{p}$ coincide with each other which supports the assumption of the same strong interaction parameters for these pair types. The radii extracted from the K_S^0 femtoscopy are slightly larger than $K^\pm$ radii for most central collisions, however the difference is within the systematic uncertainties. The radius parameter increases for the more central collisions as one expects considering a geometric description of the collision proposed in the Glauber model. Furthermore, the radii decrease with increasing pair transverse mass which is explained as the consequence of the collective radial flow [49]. Such dependences of the radius parameters have already been observed in the previous femtoscopic studies with $\pi^\pm\pi^\pm$ pairs [28, 85]. Measurements from this thesis support the hypothesis of the collective medium created in the heavy-ion collisions for pions, kaons, and protons. Nevertheless, some deviations from the precise m_T -scaling of R_{inv} are observed in data. Hydrodynamic simulations [113] have shown that m_T -scaling is present if one analyses the three-dimensional radii in the LCMS. However, the one-dimensional radii obtained in this chapter were calculated in the pair centre of mass frame (PCOM). According to [113], in such case the scaling is broken. The explanation why the radii in the PCOM do not obey the m_T -scaling is the following. The transformation from the LCMS to the PCOM is a boost along the outward direction with the velocity $\beta_T = p_T/m_T$. Hence, only the radius in “out” direction changes: $R_{out}^{PCOM} = \gamma_T R_{out}^{LCMS}$, where $\gamma_T = 1/\sqrt{1 - \beta_T^2}$ is the Lorentz factor of the boost. There is no universal connection between R_{inv} , i.e. the source size averaged over all directions in the PCOM and three-dimensional radii except for the one special case in which R_{out} , R_{side} , and R_{long} describe the variances of three-dimensional Gaussian probability density, and fulfil the relation $R_{out} = R_{side} = R_{long}$. In such scenario R_{inv} is the variance of Gaussian source function. In reality, the assumptions mentioned beforehand are not fulfilled. The source distribution is only approximately Gaussian, and R_{inv} can be considered as the effective one-dimensional source size. The consequence of these considerations is the fact that at given m_T , the Lorentz factor will be larger for lighter particle species. The

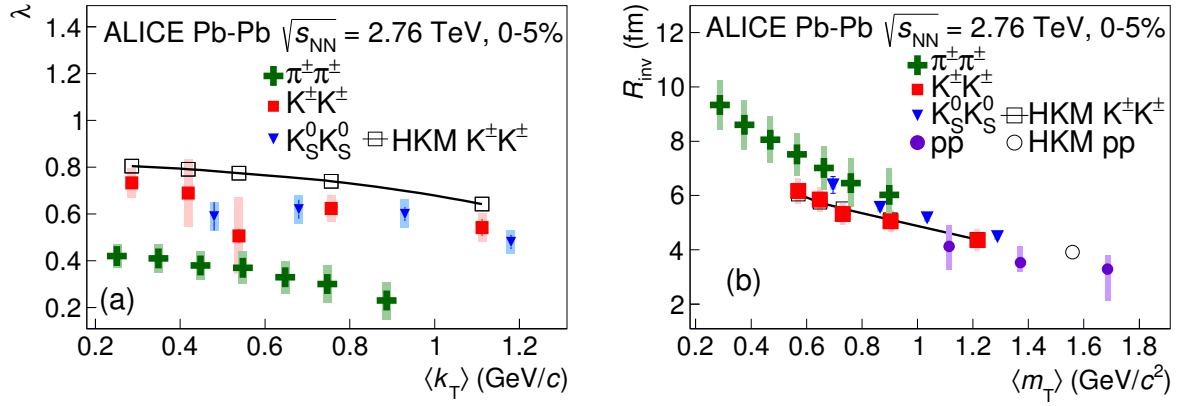


Figure 7.8: Comparison of the λ (left plot) and R_{inv} (right plot) parameters from the HKM model with the ALICE Pb-Pb collisions at $\sqrt{s_{NN}}$ for 0-5% centrality bin. Statistical and systematic uncertainties are marked as thin lines and boxes, respectively [123].

latter means that R_{out}^{PCOM} and thus R_{inv} will be larger at the same m_T for particles with the smaller mass. Such trend is indeed seen in experimental data, where the radii for pions are larger than those for kaons at the similar values of the transverse mass. The violation of the scaling between kaons and protons is expected to be less prominent.

7.4. Comparison with the model

Furthermore, the R_{inv} and λ parameters obtained in ALICE are compared with the results from the HKM model [161] for 0-5% centrality class in Fig. 7.8. HKM model includes the hydrodynamic evolution of the medium created in a heavy-ion collision and the rescattering phase. For protons, the HKM prediction is compatible with the data. Source size R_{inv} for the charged kaon results is compatible with the model predictions. In case of λ parameters, slightly decreasing trend is reproduced by the HKM, however the model overpredicts the collision data. Such disagreement might be caused by the non-Gaussian shape of the source distribution for kaons. HKM predictions of one-dimensional radii obtained using pion correlations are currently unavailable, however three-dimensional radii have been well reproduced [162].

7.5. Discussion of the results

To summarise, the first simultaneous centrality- and m_T -differential measurement of pp and $\bar{p}\bar{p}$ femtoscopic correlations in heavy-ion collisions (including LHC experiments) has been presented. The radii extracted from the one-dimensional pp and $\bar{p}\bar{p}$ correlation functions in combination with the radii obtained from kaon femtoscopy were found to exhibit the transverse mass scaling within systematic uncertainties. Such dependence is consistent with the predictions of the hydrodynamic models with the collective flow.

Nonetheless, one can observe that the pion radii deviate from the exact m_T -scaling. The absence of the precise R_{inv} scaling with m_T can be interpreted as a simple consequence of the transformation from the LCMS to the PCOM which is the reference frame suitable for the one-dimensional femtoscopic analysis. The fact that R_{out} , R_{side} , and R_{long} in the LCMS preserve the scaling means unambiguously that R_{inv} in the PCOM cannot follow such behaviour exactly. The three-dimensional femtoscopic analysis with proton pairs was not feasible with the data available during the time of preparing this thesis due to statistics limitations. The strong influence of the hadronic rescattering phase of the heavy-ion collisions at the LHC energies could be another reason for the lack of the exact pair transverse mass scaling of the radii [113, 161]. The experimental results presented in this thesis triggered the discussion and allowed for the interpretation of the observed transverse mass dependence of the radii, presented in this section.

8. Results of baryon-antibaryon femtoscopy with $p\bar{p}$, $p\bar{\Lambda}$, $\bar{p}\Lambda$ pairs in ALICE

This chapter covers the preliminary data from the femtoscopic analysis with $p\bar{p}$, $p\bar{\Lambda}$, and $\bar{p}\Lambda$ pairs in Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{\text{NN}}}=2.76$ TeV registered by ALICE detector. These results complement the studies with the identical baryon pairs presented in the previous chapter. Moreover, they attempt to measure more precisely the strong interaction parameters in $p\bar{\Lambda}$, and $\bar{p}\Lambda$ systems with respect to the outcome of the analysis with the STAR data. Baryon-antibaryon correlation functions presented in the following chapter have been approved by the ALICE collaboration and were presented at the international conferences by the author of this thesis [133, 163, 164].

8.1. Correlation functions

The femtoscopic correlation functions of $p\bar{p}$ pairs obtained using Pb–Pb collisions at $\sqrt{s_{\text{NN}}}=2.76$ TeV collected by ALICE are presented in Fig. 8.1. Results are shown for three centrality bins: 0-10%, 10-30%, and 30-50%. The correlation functions exhibit an expected behaviour, namely there is a peak due to the Coulomb attraction at the lowest values of the relative momentum, and an anticorrelation wide in k^* being the consequence of the annihilation channel in the strong FSI. Furthermore, one can clearly observe the centrality dependence of the correlation effect: the strength of the correlation increases for more peripheral events indicating that the source size becomes smaller for such events.

The $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation functions are presented in Fig. 8.2. Femtoscopic correlations for these pair types arise only due to the strong FSI. A wide negative correlation is observed for both systems and all centrality intervals, qualitatively consistent with the effect seen in $p\bar{p}$ correlations. Moreover, the difference between $\bar{p}\Lambda$ and $p\bar{\Lambda}$ correlation functions is within the statistical uncertainties. Similarly to $p\bar{p}$ case the strength of the correlation effect decreases for more central collisions. That is consistent with the enlarging emitting source size for those events.

8.2. Fitting

The baryon-antibaryon correlation functions were fitted using the formalism presented in Chap. 4 as well as tested and successfully applied in Chap. 5 and Chap. 7. As mentioned thereby, one should introduce several assumptions to robustly fit the baryon-antibaryon correlation functions, taking into account contribution from the residual correlations. In this section the default scenario is presented. Other options will be discussed in Sec. 8.3.

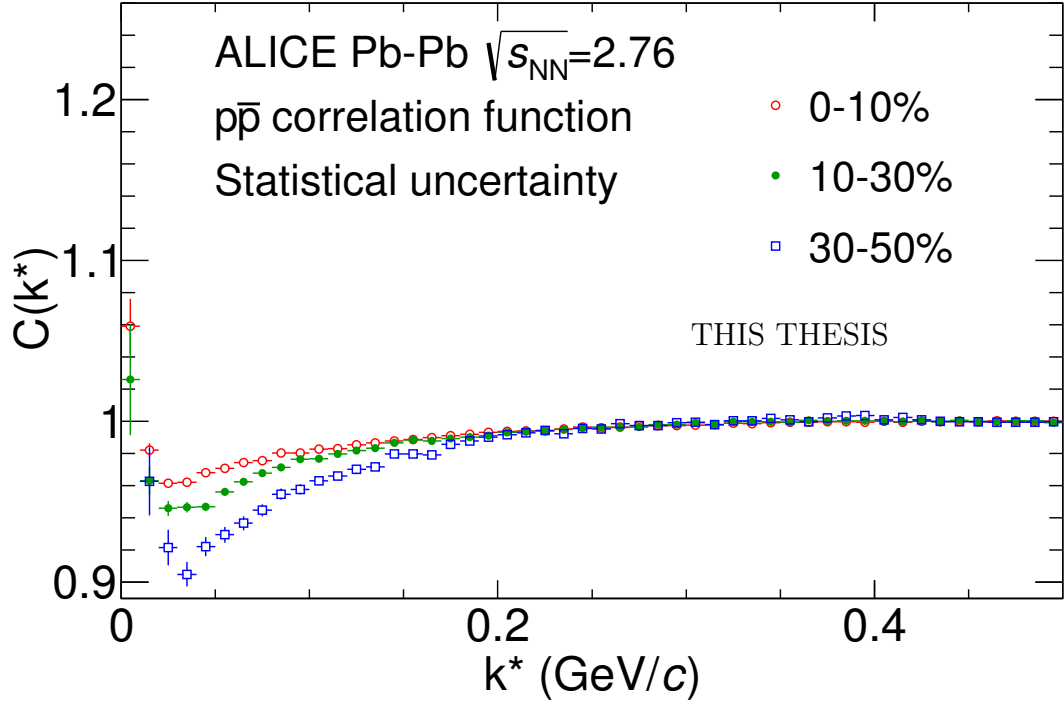


Figure 8.1: $p\bar{p}$ correlation function, centrality 0-10%, 10-30%, 30-50%.

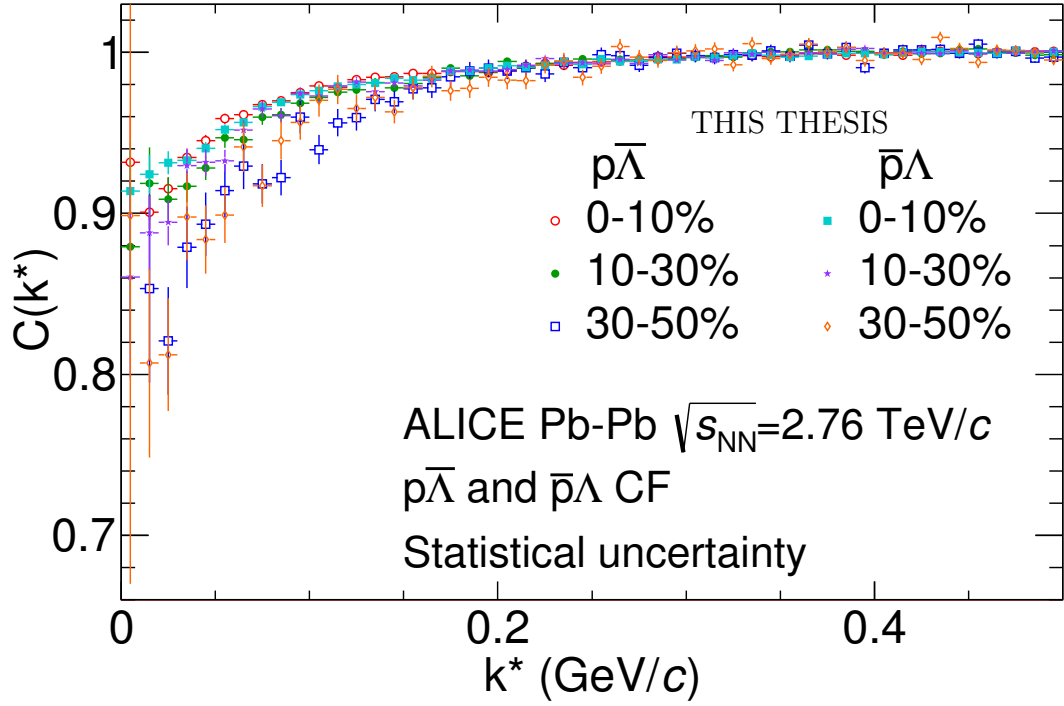


Figure 8.2: $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation function, centrality 0-10%, 10-30%, 30-50%.

The parameters $\lambda_{X\bar{Y}}$ describing the fractions of pairs which may affect the correlation function of interest were fixed to the values obtained from HIJING+GEANT simulations, as presented in Sec. 6.3.5. For the $p\bar{p}$ correlations only the residual contribution from $p\bar{\Lambda}$ ($\bar{p}\Lambda$) is considered, using the strong interaction parameters obtained from the fits to the STAR data shown in Chap. 5:

$f_0 = ((0.49 \pm 0.21) + i(1.00 \pm 0.21))$ fm. For the $p\bar{\Lambda}$ system, the residual correlations from the following parent pairs are taken into account: $\Lambda\bar{\Lambda}$, $p\bar{\Sigma}^0$, $p\bar{\Xi}^0$, $\Lambda\bar{\Sigma}^0$, $\Lambda\bar{\Xi}^0$, $\Sigma^+\bar{\Lambda}$, $\Sigma^+\bar{\Sigma}^0$, $\Sigma^+\bar{\Xi}^0$ (the analogous pairs were considered for $\bar{p}\Lambda$ pair type). For all those pairs the value of the scattering length as well as the radius parameters are assumed to be the same but treated as the free fit parameters. Since the interaction parameters do not depend on collision centrality, the same parameter is applied for all centrality intervals. The effective range d_0 was set to zero. As it was shown in Sec. 6.5.1, there is the remaining non-flat behaviour of the correlation functions at high values of k^* which in principle can affect the femtoscopic parameters extracted from the fits to those functions. Therefore, to correct for this effect the analogous correlation function was obtained from HIJING+GEANT simulations in which the femtoscopic correlations are absent. As one can observe in Fig. 8.3, such function is also non-flat, and the shape is well reproduced by the fourth order polynomial. Therefore, the non-flat background is fitted simultaneously with the femtoscopic functions by multiplying the fitting function (Eq. (4.2)) by fourth order polynomial in full k^* range. The fitting formula is also smeared with the Gaussian with the width corresponding to the momentum resolution for the studied pairs (see Sec. 6.5.2 for details).

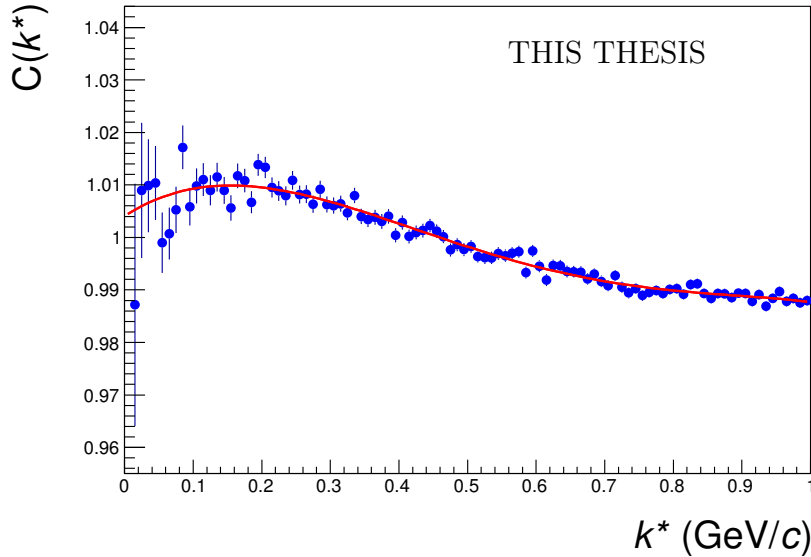


Figure 8.3: $p\bar{p}$ correlation function from HIJING+GEANT simulations fitted with the fourth order polynomial.

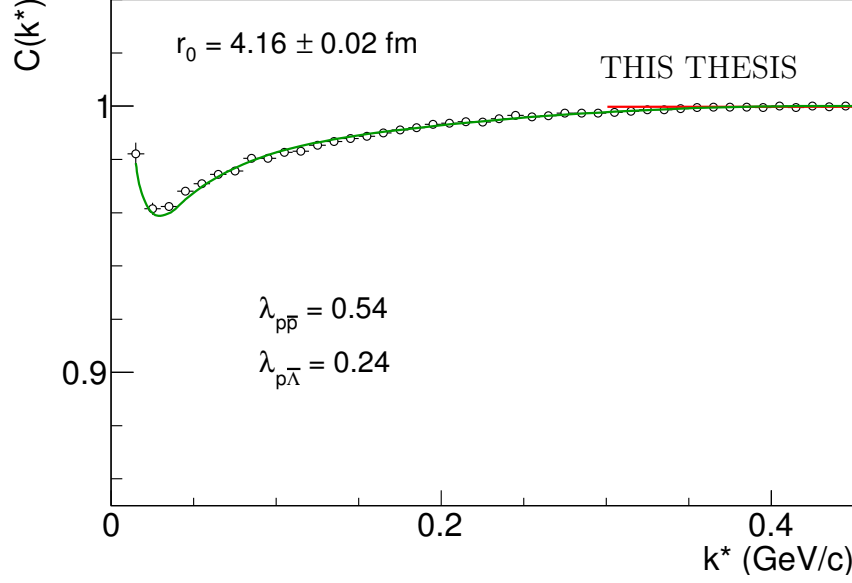


Figure 8.4: $p\bar{p}$ correlation function for 0-10% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV along with the fit taking into account the residual correlations from $p\bar{\Lambda}$ ($\bar{p}\Lambda$) pairs.

The results of fitting the $p\bar{p}$ correlation functions are presented in Figs. 8.4, 8.5, 8.6. In this case the radius is the only free fit parameter. Extracted values (4.16 ± 0.02 fm, 3.49 ± 0.04 fm, 2.73 ± 0.04 fm for 0-10%, 10-30%, 30-50% centrality bins, respectively) exhibit the centrality dependence: the radii increases with the increasing collision centrality, as expected. In addition, the values of $p\bar{p}$ source size are consistent with the ones obtained for pp and $p\bar{p}$ pairs within the systematic uncertainties.

The fits to $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation functions are presented in Figs. 8.7–8.12. Fitting functions taking into account residual correlations describe the data precisely. Radii extracted from $p\bar{\Lambda}$ are 4.75 ± 0.07 fm, 3.77 ± 0.08 fm, 2.87 ± 0.10 fm for 0-10%, 10-30%, and 30-50% centrality bins. Fits to $\bar{p}\Lambda$ give 4.30 ± 0.07 fm, 3.96 ± 0.09 fm, 2.76 ± 0.10 fm, respectively. Therefore, the source size for both systems exhibit the expected centrality dependence. The agreement between the $p\bar{\Lambda}$ and $\bar{p}\Lambda$ radii in corresponding centrality bins is within 10%. Those values also appear to be in a reasonable coincidence with $p\bar{p}$ values, being consistent within 14%. As far as the extracted values of the scattering length are concerned, the real part of f_0 is consistent with 0 for both $p\bar{\Lambda}$ and $\bar{p}\Lambda$ systems, whereas the imaginary part of f_0 is $\Im f_0 = 1.54 \pm 0.15$ fm for $p\bar{\Lambda}$ and $\Im f_0 = 1.45 \pm 0.12$ fm for $\bar{p}\Lambda$. This quantity accounts for the annihilation channel in the strong FSI. Therefore, its non-zero value suggests the existence of such phenomenon for the analysed baryon-antibaryon pairs.

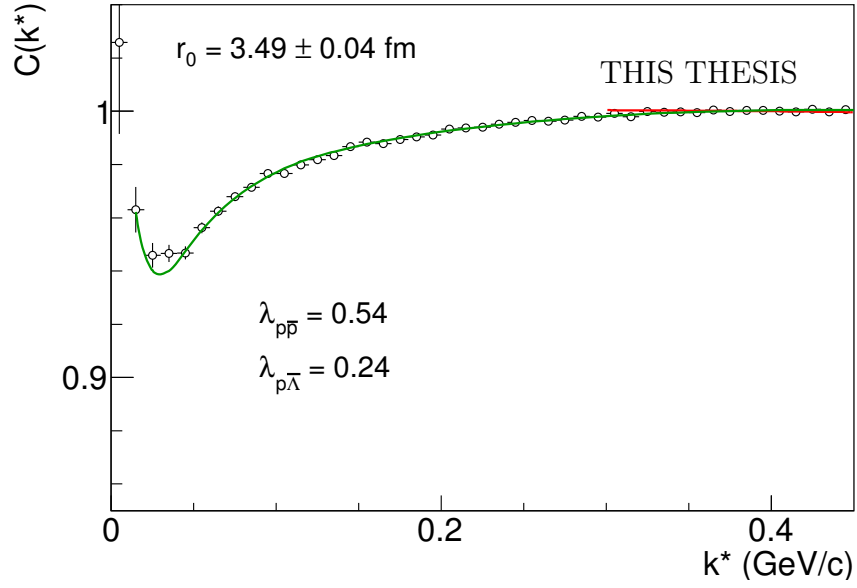


Figure 8.5: $p\bar{p}$ correlation function for 10-30% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations from $p\bar{\Lambda}$ ($\bar{p}\Lambda$) pairs.

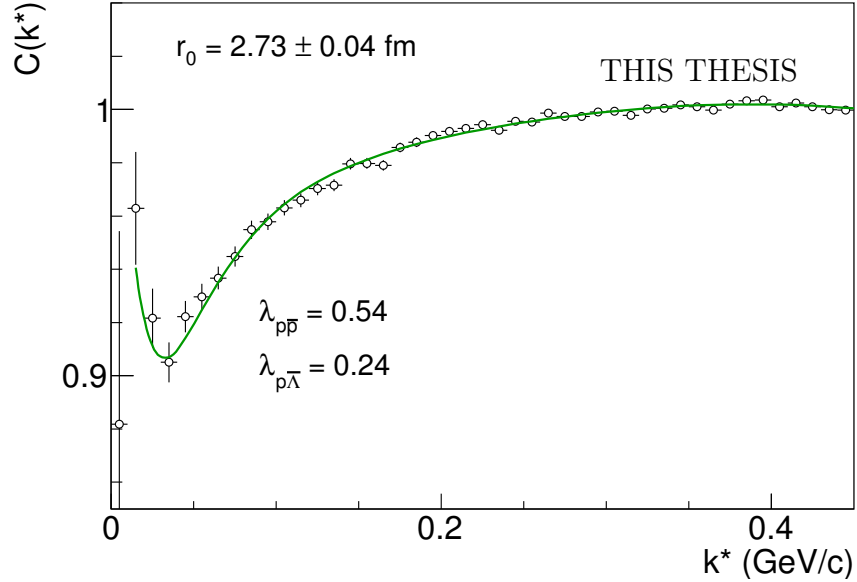


Figure 8.6: $p\bar{p}$ correlation function for 30-50% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations from $p\bar{\Lambda}$ ($\bar{p}\Lambda$) pairs.

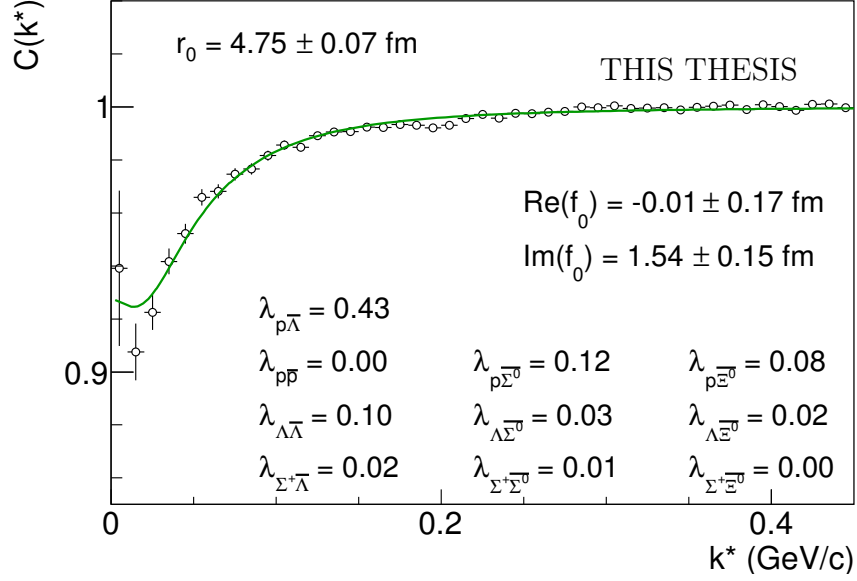


Figure 8.7: $p\bar{\Lambda}$ correlation function for 0-10% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations.

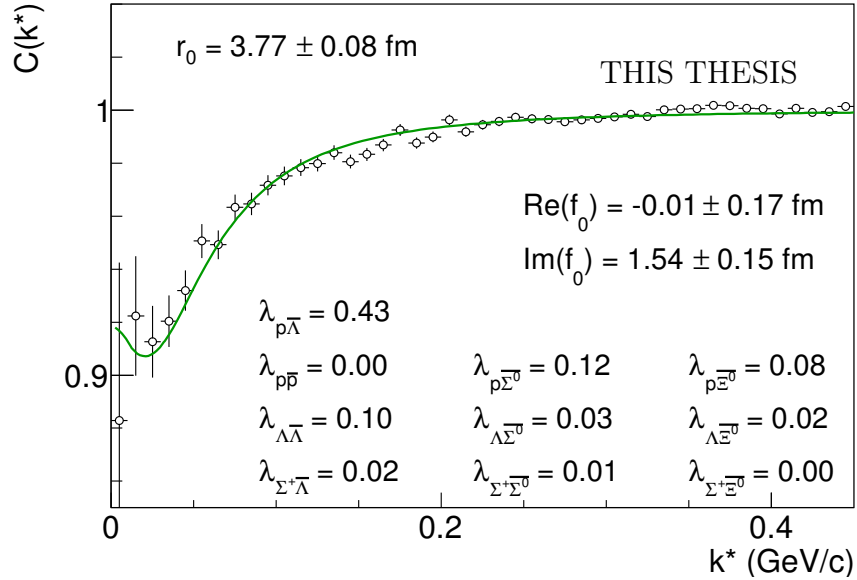


Figure 8.8: $p\bar{\Lambda}$ correlation function for 10-30% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations.

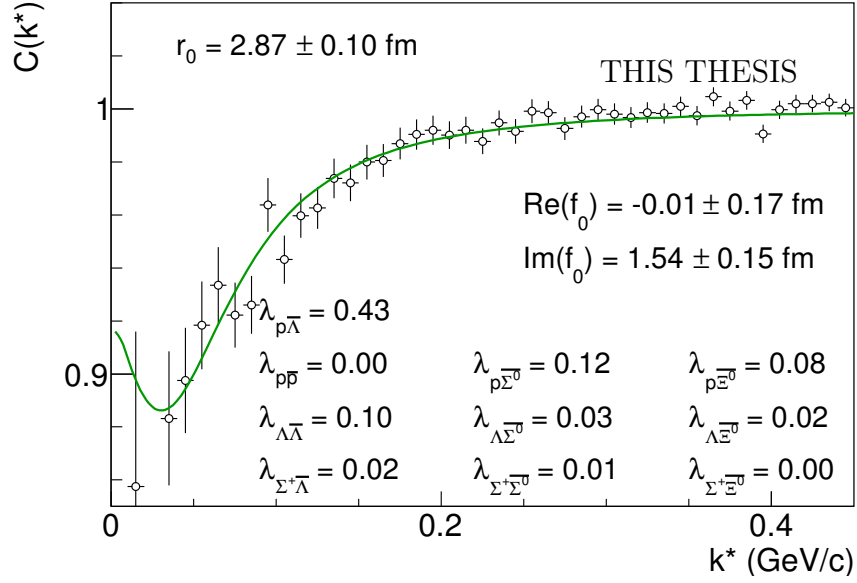


Figure 8.9: $p\bar{\Lambda}$ correlation function for 30-50% centrality class measured in ALICE Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations.

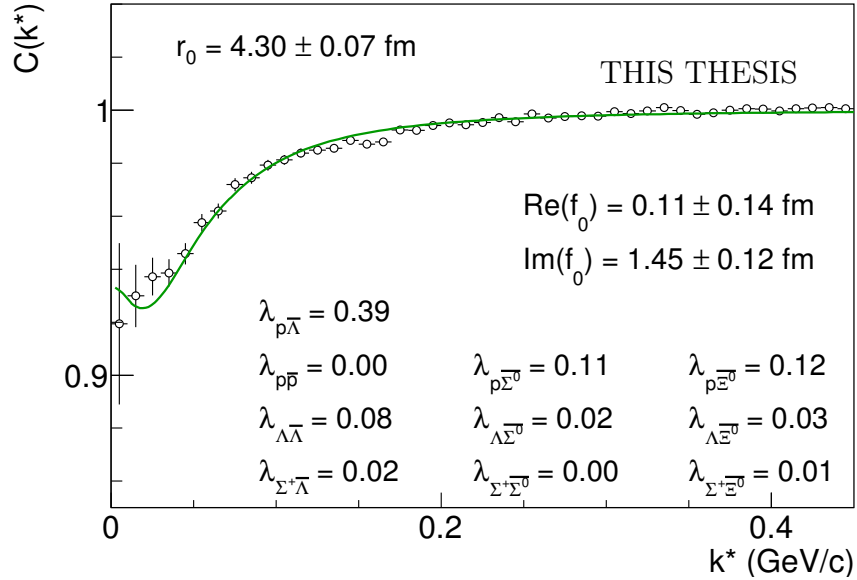


Figure 8.10: $p\bar{\Lambda}$ correlation function for 0-10% centrality class measured in ALICE Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations.

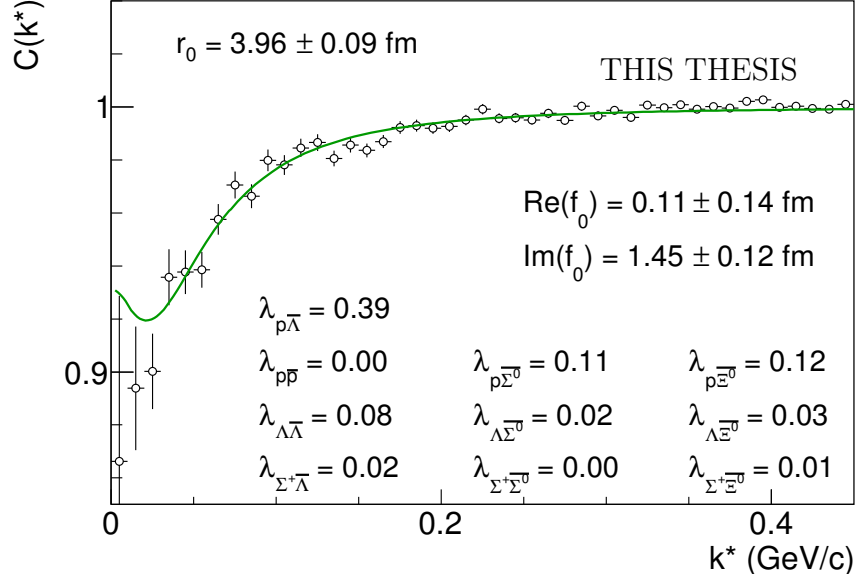


Figure 8.11: $\bar{p}\Lambda$ correlation function for 10-30% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ along with the fit taking into account residual correlations.

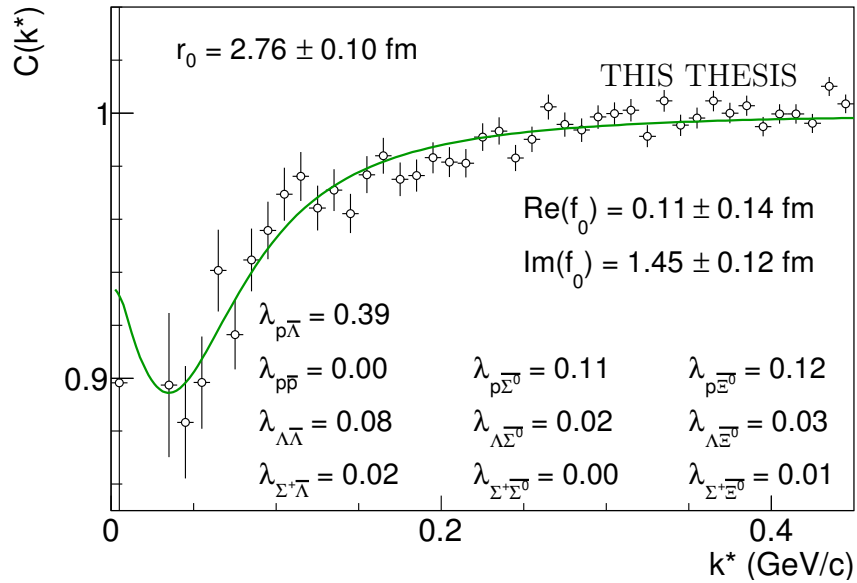


Figure 8.12: $\bar{p}\Lambda$ correlation function for 30-50% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ along with the fit taking into account residual correlations.

8.3. Systematic uncertainties

In this section the results of the fitting process, performed under different assumptions with respect to the default case, are presented. For clarity, the $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation functions from 0-10% centrality are shown.

Firstly, the alternative scenario of the parameters of baryon-antibaryon interaction included in the fit are considered. Following the case №2 from Chap. 5 in which the values of the scattering length monotonically decrease with increasing pair mass, one obtains $R = 4.75 \pm 0.07$ fm and $f_0 = ((0.00 \pm 0.07) + i(1.58 \pm 0.15))$ fm for $p\bar{\Lambda}$ and $R = 4.30 \pm 0.07$ fm and $f_0 = ((0.12 \pm 0.15) + i(1.48 \pm 0.12))$ fm for $p\bar{\Lambda}$, as seen in Fig. 8.13.

Another check for the extracted values of the f_0 parameter is the fitting scenario with the value of radius parameter fixed to the result obtained for $p\bar{p}$ system (Fig. 8.14). In such case, the scattering length is $f_0 = ((0.59 \pm 0.09) + i(1.64 \pm 0.14))$ fm, and $f_0 = ((0.42 \pm 0.06) + i(1.54 \pm 0.07))$ fm for $p\bar{\Lambda}$ and $p\bar{\Lambda}$, respectively.

Considering that THERMINATOR model predicts different values of the relative contribution of parent pairs comparing with HIJING (see Sec. 6.3.5), in the next scenario $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation functions are fitted with the residual correlations mechanism employing λ_{XY} values estimated using THERMINATOR. The results of the fit shown in Fig. 8.15 are the following: $R = 4.92 \pm 0.07$ fm and $f_0 = ((-0.48 \pm 0.64) + i(1.83 \pm 0.58))$ fm for $p\bar{\Lambda}$ and $R = 4.47 \pm 0.10$ fm and $f_0 = ((-0.13 \pm 0.39) + i(1.86 \pm 0.29))$ fm for $p\bar{\Lambda}$.

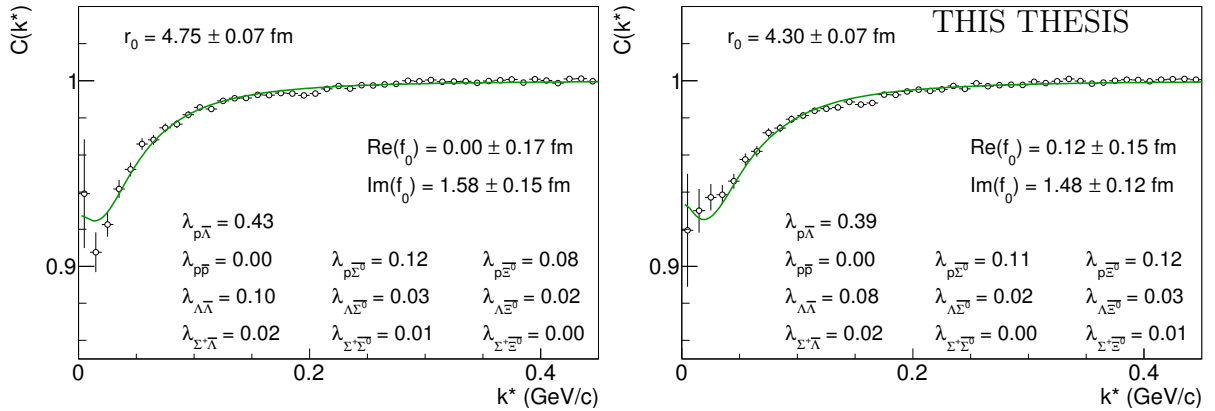


Figure 8.13: $p\bar{\Lambda}$ (left) and $\bar{p}\Lambda$ (right) correlation function for 0-10% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV along with the fit taking into account residual correlations. In this scenario the strong interaction parameters for baryon-antibaryon pairs are scaled according to their mass using weights from the AQM model.

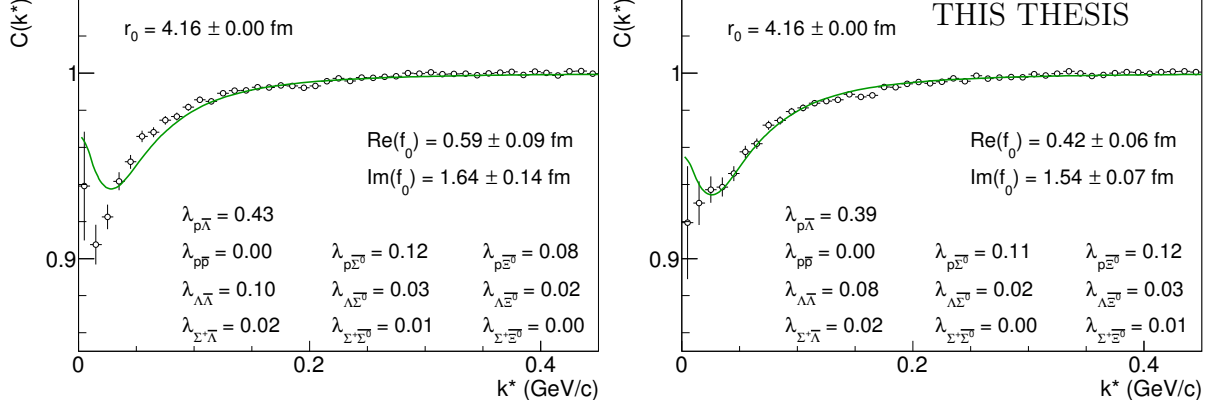


Figure 8.14: $p\bar{\Lambda}$ (left) and $\bar{p}\Lambda$ (right) correlation function for 0-10% centrality class measured in ALICE Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations. In this scenario the radii are fixed to the values obtained from $p\bar{p}$ correlations.

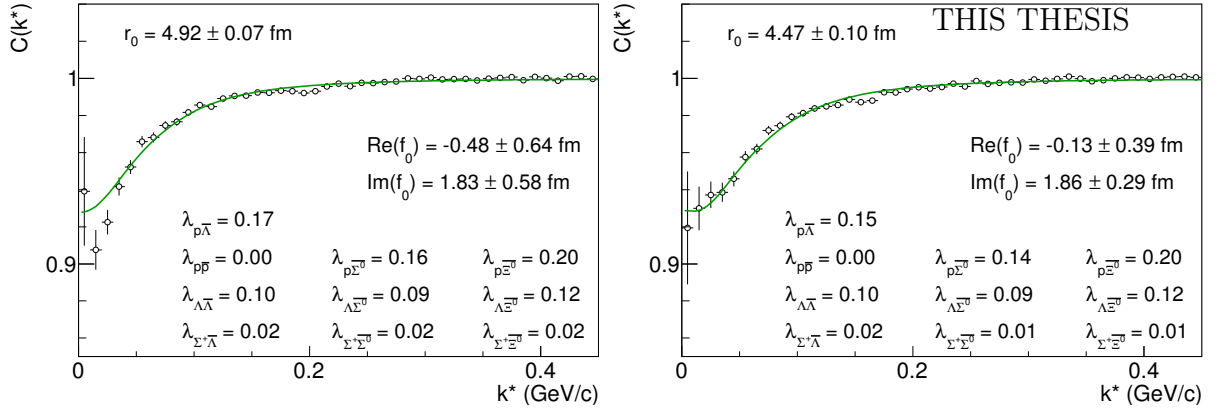


Figure 8.15: $p\bar{\Lambda}$ (left) and $\bar{p}\Lambda$ (right) correlation function for 0-10% centrality class measured in ALICE Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations. In this scenario the fractions of residual pairs are calculated using simulations in THERMINATOR model.

Performing the analysis without accounting for the non-flat behaviour of the correlation function (i.e. without dividing the experimental correlation function by the fourth order polynomial), one gets the following results: $R = 3.65 \pm 0.04$ fm and $f_0 = ((-0.10 \pm 0.08) + i(0.89 \pm 0.07))$ fm for $p\bar{\Lambda}$ and $R = 3.50 \pm 0.05$ fm and $f_0 = ((0.04 \pm 0.08) + i(0.95 \pm 0.07))$ fm for $\bar{p}\Lambda$. These correlation functions along with the fit are presented in Fig. 8.16. Furthermore, the results of the fit of the correlation functions calculated without binning the correlation function in the event plane angle (see Sec. 6.5.1) are $R = 4.78 \pm 0.14$ fm and $f_0 = ((-0.52 \pm 0.44) + i(1.30 \pm 0.45))$ fm for $p\bar{\Lambda}$ and $R = 4.57 \pm 0.10$ fm and $f_0 = ((-0.37 \pm 0.25) + i(1.19 \pm 0.24))$ fm for $\bar{p}\Lambda$, as presented in Fig. 8.17.

Finally, one can ask how the experimental selection criteria influence the extracted parameters. In order to answer this, $p\bar{\Lambda}$ and $\bar{p}\Lambda$ correlation functions are calculated using the single- and the two-track cuts varied in the reasonable range. Fitting such correlation

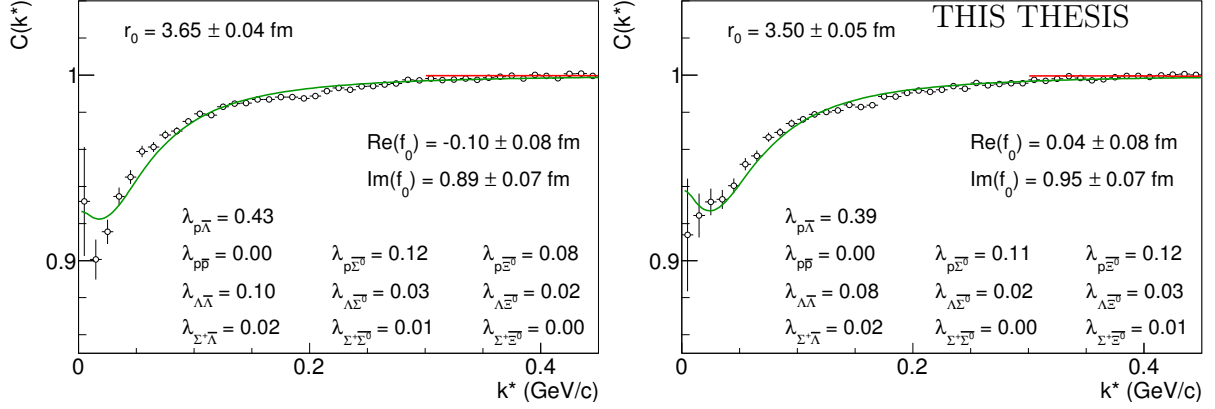


Figure 8.16: $p\bar{\Lambda}$ (left) and $\bar{p}\Lambda$ (right) correlation function for 0-10% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations. In this scenario the non-flat background is not accounted for by dividing the correlation function by the fourth order polynomial.

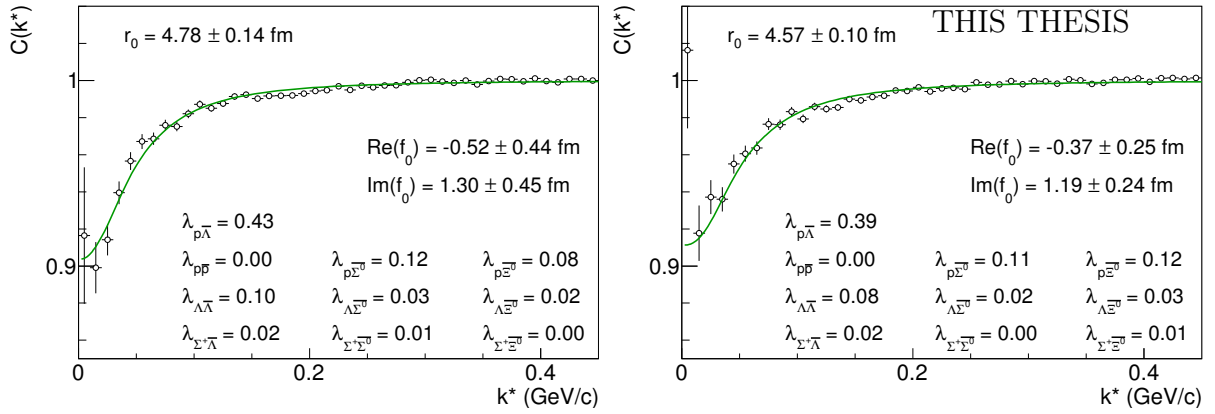


Figure 8.17: $p\bar{\Lambda}$ (left) and $\bar{p}\Lambda$ (right) correlation function for 0-10% centrality class measured in ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV along with the fit taking into account residual correlations. In this scenario the correlation function were not obtained in the event plane angle bins (see text for details).

functions leads to the maximal variation of the $\Im f_0$ to be 18%, while the change of the radius parameters is up to 3%.

All things considered, the systematic uncertainty of the extraction of the imaginary part of the scattering length is not less than 49%. Nevertheless, the conclusion that $\Im f_0$ is non-zero and positive is valid. The systematic uncertainty of the $p\bar{\Lambda}$ and $\bar{p}\Lambda$ radii is estimated at 26%. The results presented above indicate that the femtoscopic correlation functions of baryon-antibaryon are sensitive only to the imaginary part of the scattering length, being unable to reliably constrain the real part. It should be emphasised that the value of f_0 extracted here should be considered as the "effective" one taking into account the interaction for all heavier baryon-antibaryon systems analysed here, not only $p\bar{\Lambda}$ ($\bar{p}\Lambda$). This value is consistent within the systematic uncertainty with the one extracted from STAR data in Chap. 5 as well as the value measured for $p\bar{p}$ in the dedicated experiments.

Summary

This thesis presents the femtoscopic analysis with the following baryon pairs: pp , $\bar{p}\bar{p}$, $p\bar{p}$, $p\bar{\Lambda}$, $\bar{p}\Lambda$ measured in Pb–Pb collisions at the centre-of-mass collision energy per nucleon pair $\sqrt{s_{NN}}=2.76$ TeV. In addition, this work comprises the developed formalism for dealing with the so-called residual correlations effect. This thesis elaborates on all the steps performed in order to obtain the physics results. In particular, it includes the theoretical background, the process of collecting data, the specific experimental facets of baryon femtoscopy, the description of the innovative method of the analysis of residual correlations, and finally the physics results concerning the size of the source as well as strong interaction parameters extracted from correlations of baryons.

Experimental measurements presented in this thesis were performed at the Large Hadron Collider, located at CERN laboratory. The apparatus of A Large Ion Collider Experiment was used. The work was done on behalf of the ALICE collaboration.

Regarding the novel input of this thesis, the method of dealing with residual correlations proposed in this thesis is qualitatively new in the field of femtoscopy. Residual correlations have been so far treated as an undesired effect and a disturbance in the experimental correlation functions. Previous methods were focused on correcting for this effect, whereas the methodology introduced in this thesis uses the residual correlations as a source of additional information. Such signal is less accurate and depends on several assumptions, but still allows to infer the physical parameters. This thesis includes also the first measurements of pp and $\bar{p}\bar{p}$ femtoscopic radii obtained differentially in collision centrality and pair transverse momentum intervals. Furthermore, for the first time, $p\bar{p}$, $p\bar{\Lambda}$, and $\bar{p}\Lambda$ femtoscopic correlations were measured taking into account all the relevant contributions from the residual correlations. The innovative part of this thesis is also the estimation of the scattering length values for $p\bar{\Lambda}$ and $\bar{p}\Lambda$ pair systems.

The technical part of this work includes several aspects. First of them is the development of the software tools essential for the experimental analysis of baryon femtoscopy as well as the implementation of the formalism of residual correlations. Furthermore, the work required the optimisation of the experimental selection criteria. In addition, the development of the ALICE Event Display was performed as the service task for the ALICE collaboration.

As far as the physics part of the thesis is concerned, the analysis of baryon correlations includes two major components: experimental and methodological. The former includes the extraction of the source radii, λ parameters as well as the strong interaction parameters from low relative momentum correlations of pp , $\bar{p}\bar{p}$, $p\bar{p}$, $p\bar{\Lambda}$, and $\bar{p}\Lambda$ pairs. During the course of this work the need for the formulation of the robust formalism handling the residual correlations arose. This methodology was initially tested during the reanalysis of the STAR data which explained the unexpectedly small $p\bar{\Lambda}$ ($\bar{p}\Lambda$) radius obtained by STAR collaboration and led to new, more reliable estimates of the value of the scattering length for these pairs. Afterwards, the developed framework of dealing with the residual correlations phenomenon was applied to the ALICE femtoscopic data.

One can draw the following conclusions from the results presented in this thesis. The femtoscopic radii obtained from the one-dimensional correlation functions of pp and $\bar{p}\bar{p}$ pairs seen along with the measurements of meson pairs were found to exhibit the transverse mass scaling within the systematic uncertainties, compatible with the predictions of the hydrodynamic model with the collective flow. The good consistency of pp , and $\bar{p}\bar{p}$ radii reinforces the assumption of the same strong interaction parameters for these pair types. The λ parameters were observed to lay below unity, in agreement with the hypothesis of the long-lived resonances and non-Gaussian features of the source. These results are well described by the hydrokinetic model (HKM). Furthermore, it was shown that residual correlations are essential for the understanding of the baryon-(anti)baryon correlation functions, and thus extracting the physics parameters: the system size as well as the scattering length. Careful treatment of the residual correlations was vital to solve the riddle of the different source sizes for $p\bar{\Lambda}$ ($\bar{p}\Lambda$) and $p\Lambda$ ($\bar{p}\bar{\Lambda}$) measured by STAR experiment. This thesis also indicates that femtoscopy may provide some input regarding the strong interaction parameters for baryon-antibaryon systems, in particular the imaginary part of the scattering length which characterises the annihilation channel. The latter is of great importance since the knowledge of such parameters is meagre for most of baryon-antibaryon pairs. In addition, they may be applied in the phenomenological models of the heavy-ion collision for more accurate description of the rescattering phase which in turn may help to understand the deviation of low proton yield measured in ALICE with respect to the thermal models.

As far as the future analyses are concerned, the formalism of the residual correlations introduced in this thesis enables to measure the strong interaction parameters for numerous baryon-antibaryon pair types, including e.g. Λ and Ξ baryons. Precise femtoscopic data obtained for such pairs as e.g. $p\Xi^0$, $\Lambda\Lambda$, or $\Lambda\Xi^0$ would allow to constrain currently little-known values of the scattering length for such pairs. Particularly, Pb–Pb collisions at the $\sqrt{s_{NN}} = 5.02$ TeV recently recorded at the LHC should provide good quality and high statistics data facilitating the precise measurements of these values of interest.

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