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**Two-particle correlations as a function of relative azimuthal angle and
pseudorapidity in proton-proton collisions registered by the ALICE
experiment**

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Abstract

Two-particle angular correlations are a powerful tool developed to explore the mechanisms of particle production in collisions of hadrons and nuclei at relativistic energies. The angular correlations open up the possibility to study different physics mechanisms at the same time, i.e include minijet correlations, effects of Bose-Einstein quantum statistics, conservation laws, resonance decays and others. Each of these effects is a distinct correlation source and exhibits individual behavior in $\Delta\eta\Delta\varphi$ space (where $\Delta\eta$ is the pseudorapidity difference and $\Delta\varphi$ is the azimuthal angle difference of two particles).

Studies of particle production mechanisms in elementary collisions date back to R. Feynman and R. Field, who introduced in 1970's the basic concept of jet production. The proposed model describes the rules of particle creation and their correlations, i.e., the energy that needs to be distributed or restrictions originating from the conservation laws, etc. However, the details of its implementation have to be constrained by experimental data. In particular, how the conservation laws should be obeyed? At the level of the whole event, or for each individual fragmentation? How strong should be the correlation between outgoing hadrons? Until now, to address such questions, only the e^+e^- reactions were studied. This work extends these measurements to hadron-hadron collisions.

This thesis presents the angular correlations measured with the ALICE detector in proton-proton collisions at the LHC at collision energies of $\sqrt{s} = 0.9, 2.76, \text{ and } 7 \text{ TeV}$. A highly differential analysis was performed including the dependence on the charge and the transverse momenta of particles in the pair, as well as the event multiplicity, with the aim to disentangle and quantify the contributions from distinct correlation sources. Typically, correlations of charged hadrons are studied; however, the excellent particle identification capabilities of ALICE allow us also to perform these measurements using identified particles (pions, kaons, and protons) in order to analyze correlations induced by strangeness conservation or by specific baryon production mechanisms. To quantitatively describe the measured correlation functions, in particular the multiplicity and pair transverse momentum dependence, a generic fitting procedure was developed.

There are several conclusions that can be drawn from the analyzed collision data regarding the effects of specific physics mechanisms. Each one of the correlation sources manifests in a particular manner; therefore, we can disentangle them and address their properties separately.

Firstly, the dependence of the $\Delta\eta\Delta\varphi$ correlation function on the pair transverse momentum ($p_{T\text{-sum}}$) was studied. The results show that the contribution from minijets to the overall shape of the $\Delta\eta\Delta\varphi$

correlation function is rising with increasing values of the pair transverse momentum. In contrast, the Bose-Einstein correlations manifest the strongest at low transverse momenta. For the like-sign pairs (where both Bose-Einstein and minijet components exist) the correlation decreases with increasing p_T -sum at low transverse momenta because of the decreasing contribution from Bose-Einstein correlations. Then it rises for higher values of the p_T -sum due to the increasing minijet contribution. The analysis of unlike-sign pairs, where the Bose-Einstein component is not present, shows that the minijet contribution is almost negligible for the lowest and rises for higher values of p_T -sum.

Secondly, the dependence of the $\Delta\eta\Delta\varphi$ correlation function on the event charged particle multiplicity N_{ch} was studied. The results show that structures induced by minijets decrease with increasing multiplicity at a lower rate than a trivial $1/N_{\text{ch}}$, suggesting the presence of additional mechanisms that enhance the correlation. This trivial decrease is expected because the less particles are produced in a collision, the more pronounced the correlations are. A decrease compatible with $1/N_{\text{ch}}$ was observed for the structure emerging from the resonance contribution.

Thirdly, a comparative analysis was performed to study the same underlying physics, however, in two different representations; the femtoscopic correlation functions, used for the measurements of the system size, and the $\Delta\eta\Delta\varphi$ correlations. The results show that any correlation in $\Delta\eta\Delta\varphi$ creates a corresponding structure in the representation typically used in femtoscopy.

Finally, the analysis reveals substantial differences in the shapes of the correlation functions of identified particles performed separately for different charge combinations of particle pairs (for like-sign and unlike-sign pairs) and for three particle types (pions, kaons, protons). The results suggest that conservation laws (strangeness, baryon number) have a great impact on the observed two-particle correlations.

To complement the analysis of collision data, corresponding studies were performed using the general purpose Monte Carlo event generators, Pythia and Phojet. We observe that the Monte Carlo models reproduce only some aspects of the collision data, usually qualitatively but not quantitatively. In particular the correlation functions of protons, especially of like-sign pairs, are surprisingly different than the collision data. The presented analysis not only shows that the current MC models do not reproduce the data accurately, but also provides guidance in an effort to improve them, pointing to specific parameters that need to be tuned.

A dedicated model, called CALM (ConservAtion Laws Model), was developed in order to study in detail the influence of basic correlation sources and conservation laws on the shape of the $\Delta\eta\Delta\varphi$ correlation function. With the aim to reproduce the structures seen in the data the correlations were systematically added one by one in a transparent, straightforward manner. The model validated the proposed explanations of the behavior of the structures seen in the data.

Streszczenie

Dwucząstkowe korelacje w funkcji względnego kąta azymutalnego oraz pseudopospieszności w zderzeniach proton-proton zarejestrowanych przez eksperyment ALICE

Dwucząstkowe korelacje kątowe są bogatym źródłem informacji o produkcji cząstek w wysoko-energetycznych zderzeniach hadronów. Korelacje kątowe umożliwiają przekrojową analizę wielu zjawisk fizycznych, między innymi korelacji “minijetów,” korelacji wynikających ze statystyki kwantowej Bosego-Einsteina, zasad zachowania i rozpadów rezonansów. Każdy ze wspomnianych efektów odznacza się odmiennym zachowaniem w przestrzeni $\Delta\eta\Delta\varphi$ (gdzie $\Delta\eta$ jest różnicą w pseudopospieszności, a $\Delta\varphi$ różnicą w kącie azymutalnym).

Badania mechanizmów produkcji cząstek w zderzeniach elementarnych sięgają czasów R. Feynmana i R. Fielda, którzy w 1977 r. zaproponowali model opisujący zasady wytwarzania tzw. “jetów”, czyli skolimowanych pęków cząstek. Przedstawili oni zasady powstawania cząstek, sposób podziału energii oraz ograniczenia związane z prawami ich zachowania. Szczegóły implementacji zaproponowanego modelu muszą jednakże zostać powiązane z danymi eksperymentalnymi. Przykładowe problemy wymagające odpowiedzi to np. Czy zasady zachowania powinny być przestrzegane globalnie, dla całego zderzenia, czy też lokalnie, dla każdej poszczególnej fragmentacji? Jak silne powinny być korelacje między powstałymi hadronami? Odpowiedzi na te pytania poszukiwano dotychczas jedynie w zderzeniach e^+e^- . Celem tej pracy jest rozszerzenie wykonanych wcześniej pomiarów o zderzenia hadronów.

Niniejsza rozprawa doktorska prezentuje pomiary korelacji kątowych zmierzonych przy użyciu detektora ALICE w zderzeniach proton-proton o energiach $\sqrt{s} = 0.9, 2.76$, oraz 7 TeV uzyskiwanych za pomocą Wielkiego Zderzacza Hadronów. Przeprowadzono analizy dla różnych kombinacji ładunków elektrycznych w parze, zakresów pędu poprzecznego pary cząstek oraz zakresów krotności zderzenia. Szczegółowa obserwacja umożliwiła scharakteryzowanie wielu aspektów źródeł korelacji. Ponadto, by zmierzyć korelacje związane z zachowaniem dziwności oraz mechanizmem produkcji barionów została wykonana analiza dla poszczególnych typów cząstek zidentyfikowanych (pionów, kaonów oraz protonów).

Wyniki pokazują, że wpływ “minijetów” na kształt funkcji korelacyjnej rośnie wraz ze zwiększającym się pędem poprzecznym pary (p_T -sum). W przypadku korelacji Bosego-Einsteina zależność jest przeciwna, najsilniej uwidaczniając się dla niewielkich pędów poprzecznych. Analiza par cząstek o przeciw-

nych ładunkach, gdzie korelacje Bosego-Einsteina nie występują, pokazuje, że wpływ “minijetów” jest nieistotny przy niskich i szybko rośnie dla wysokich pędów poprzecznych. Dla par cząstek o tym samym ładunku zaobserwowano korelacje Bosego-Einsteina przy niskich pędach poprzecznych pary oraz korelacje wynikające z “minijetów” przy pędach wysokich.

Badano również zależność funkcji korelacyjnych $\Delta\eta\Delta\varphi$ od krotności zderzenia. Wyniki pokazują, że struktury tworzone przez “minijety” nie zmniejszają się wraz ze wzrostem krotności zgodnie z prostą zależnością $1/N_{\text{ch}}$. Maleją one wolniej, co sugeruje obecność dodatkowych mechanizmów zwiększających korelacje. W przypadku struktury wytwarzanej przez rozpad rezonansów zależność typu $1/N_{\text{ch}}$ została jednakże zaobserwowana.

Dokonano też porównania dwóch reprezentacji funkcji korelacyjnej, femtoskopowych funkcji korelacyjnej używanej w pomiarach wielkości źródła oraz rozkładu $\Delta\eta\Delta\varphi$. Wyniki pokazują, że każda korelacja widoczna w przestrzeni $\Delta\eta\Delta\varphi$ tworzy odpowiadającą jej strukturę w reprezentacji pędu względnego, naturalnego dla pomiarów femtoskopowych. Wpływ ten widać szczególnie w przypadku kolimacji cząstek wynikających z “minijetów.”

Analiza wykazała istotne różnice w kształcie funkcji korelacyjnej cząstek jednoimiennych i różnoimiennych dla trzech typów cząstek (pionów, kaonów i protonów). Wyniki sugerują, że zasady zachowania (dziwności, liczby barionowej) mają znaczący wpływ na obserwowane korelacje dwucząstkowe.

Podobną analizę wykonano również dla zderzeń wygenerowanych przez modele Monte Carlo, Pythia oraz Phojet. Badane symulacje wykazują jedynie pewne podobieństwo do zderzeń zarejestrowanych przez eksperyment, zwykle jakościowe, a nie ilościowe. Dla cząstek zidentyfikowanych wyniki symulacji wykazują zupełnie inne cechy niż te widoczne w danych. Zawarte w niniejszej rozprawie pomiary umożliwiły rozpoczęcie prac nad poprawą implementacji mechanizmów produkcji cząstek w modelu Pythia.

Opracowany został generator zderzeń CALM (ConservAtion Laws Model), dedykowany studiom nad podstawowymi efektami korelacyjnymi wpływającymi na kształt funkcji $\Delta\eta\Delta\varphi$. Szczegółowe badania przeprowadzone przy użyciu tego modelu pozwoliły na wgląd w korelacje dwucząstkowe wynikające z podstawowych mechanizmów produkcji cząstek.

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Chapter 1

Introduction

The goal of physics has always been to study and comprehend the world we live in. Through the work of many scientists this understanding was developed and the boundaries of knowledge have been pushed further and further. The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) collide particles with an energy that has never been achieved before by a particle accelerator and is a most complex experimental facility ever built. In many aspects, both connected to physics and technical, it symbolize a breakthrough for mankind's knowledge. It is devoted to answering basic questions that we tried to address for thousands of years, like questions about the structure of matter or the birth of the Universe.

The goals of the LHC are impressive, covering the verification of the Standard Model via the discovery of the Higgs boson¹, the study of properties of antimatter and extensions of the Standard Model, like supersymmetry or extra-dimensions, as well as recreation of the conditions similar to those of the very early universe, the Quark-Gluon Plasma state. To complete those studies we need to gain a thorough understanding of the registered collisions. This includes the detailed comprehension of measurements of pp collisions as well as the study of heavy-ion collisions that are also performed at the LHC by colliding lead beams. Only a through comparison of heavy-ion and proton collisions can expose many of the Quark-Gluon Plasma properties, which makes a deep understanding of pp collisions mandatory.

ALICE (A Large Ion Collider Experiment) at the LHC is optimized for the measurement of collisions of heavy ions. Its aim is to study the characteristics of the Quark-Gluon Plasma, which is expected to be produced in such collisions. The creation, observation and characteriza-

¹The Higgs boson was discovered at CERN on 14 March 2013, with the Nobel Prize for Francois Englert and Peter Higgs following shortly after. The prize was motivated as follows: “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, *by the ATLAS and CMS experiments at CERN's Large Hadron Collider.*”

tion of such a hot, dense and strongly interacting matter is the main focus of the experiment. In the context of the LHC, ALICE also takes important part in the analysis of pp collisions. Possibility of reliable tracking at low transverse momentum p_T and excellent particle identification and makes possible to perform measurements that are unique among the LHC experiments.

Several observables have been proposed over the years to probe the nature of the systems created in high-energy collisions and provide information on their composition and dynamic evolution. In this study we focus on two-particle correlations that arise in the collisions and contribute to a global correlations picture. The technique used in this thesis is measuring the angular correlations between particles in the $\Delta\eta\Delta\phi$ space. Physics mechanisms which induce contributions to $\Delta\eta\Delta\phi$ distributions include minijet correlations, Bose-Einstein correlations, elliptic flow, energy-momentum conservation, resonance decays and others. The excellent particle identification capabilities of ALICE also allow us to perform novel measurements of correlations induced by strangeness conservation or by specific baryon production mechanisms.

In this thesis, a novel analysis approach is presented that encompasses both the information about the correlations in the particle production as well as knowledge of charge, momentum and event multiplicity. The $\Delta\eta\Delta\phi$ correlations have been studied at LHC energies for the first time ever with such highly differential samples. Moreover, unique analysis of identified particles (pions, kaons, and protons) that has never been done before for hadron-hadron collisions, was performed. It is a powerful tool to explore the mechanisms of particle production in collisions of hadrons and nuclei at high energy, and to improve existing Monte Carlo models.

This thesis is structured as follows: in Chapter 2 we present a brief review of high energy physics aspects that are important for this thesis. In Chapter 3 we discuss the historical background and theoretical aspects of the two-particle angular correlations. We present ALICE experiment in Chapter 4. Chapters 5 and 6 are devoted to the data selection and formalism of the construction of the experimental correlation function respectively. Experimental results are presented in Chapter 7, together with the evaluation of systematic uncertainties in Chapter 8. In Chapter 9 the interpretation of experimental results is discussed and the comparison with Monte Carlo simulations are shown. Finally, we summarize in Chapter 10.

This thesis includes material that has been already published in Refs. [1–4]. In addition, the most recent results will be the subject of future publications.

Chapter 2

High-energy nuclear collisions

In this chapter, the theoretical background of high-energy proton-proton collisions is introduced. First, basic concepts of the Standard Model of particle physics and quantum chromodynamics are described in Sec. 2.1. Then, the physics of the heavy-ion collisions and the Quark-Gluon Plasma are detailed in Sec. 2.2. In Sec. 2.3 more information about hadron-hadron collisions, that are the topic studied in this thesis, is provided. Finally, Sec. 2.4 introduces the Monte Carlo generators that are used for the comparison to experimental collision data and describe the underlying physics.

2.1 Standard Model and quantum chromodynamics

Standard Model

The *Standard Model* (SM) is a theory which introduces the basic particles and the rules of their combinations and interactions. SM incorporates three of the four main forces that exist in nature: electromagnetic, weak and strong. These three forces together with the gravitation, which is not a part of the SM, describe all known fundamental interactions.

SM predicts that each force is mediated by force carriers, the *gauge bosons*¹. The carriers of the electromagnetic interaction between charged particles are photons (γ). The weak interaction has three force carriers, massive particles W^+ , W^- , and Z^0 . The strong interaction is mediated by eight gluons (g) carrying combinations of color charges. Similarly, it could be possible to mediate the gravitation by hypothetical gravitons; however, such particles still have not been observed. The interactions included in the SM are listed in Table 2.1.

¹Bosons are particles with integer spin and obey Bose-Einstein quantum statistics.

Force	Carriers	Affects
strong	8 gluons g	quarks
electromagnetic	photon γ	charged particles
weak	$W^\pm, Z^0$	quarks, leptons

Table 2.1: The fundamental forces and carriers of the Standard Model of particle physics [5].

Apart from the carriers of the interactions, the SM includes the quarks, the leptons, and the Higgs boson. All of these particles are elementary². The quarks and leptons³ are divided into three *generations*, two quarks or two leptons in each one.

	Quarks			Leptons		
Generation	Symbol	Charge	Mass	Symbol	Charge	Mass
1	u	$2/3 e$	$1.7 - 3.3 \text{ MeV}/c^2$	e	$-e$	$0.511 \text{ MeV}/c^2$
	d	$-1/3 e$	$4.1 - 5.8 \text{ MeV}/c^2$	ν_e	0	$2 \text{ eV}/c^2$
2	c	$2/3 e$	$1.18 - 1.34 \text{ GeV}/c^2$	μ^-	$-e$	$105 \text{ MeV}/c^2$
	s	$-1/3 e$	$80 - 130 \text{ MeV}/c^2$	ν_μ	0	$0.19 \text{ MeV}/c^2$
3	t	$2/3 e$	$169.8 - 174.2 \text{ GeV}/c^2$	τ^-	$-e$	$1.78 \text{ GeV}/c^2$
	b	$-1/3 e$	$4.1 - 4.4 \text{ GeV}/c^2$	ν_τ	0	$18.2 \text{ MeV}/c^2$

Table 2.2: Table of the elementary particles and their masses as described in the Standard Model of particle physics [5].

The names of the six known quark flavors are: u - up, d - down, s - strange, c - charm, t - top, b - bottom⁴. Similarly, there are six lepton flavors: e - electron, ν_e - electron neutrino, μ - muon, ν_μ - muon neutrino, τ - tau, ν_τ - tau neutrino. The particles of the first generation form nearly all of the known universe, as they are lightest and most stable, e.g. atoms are built

²According to the current knowledge.

³Quarks and leptons have spin $1/2$; hence, they are fermions. Fermions obey Fermi-Dirac statistics.

⁴Originally only three types of quarks – u , d , and s were proposed, independently, by Murray Gell-Mann and George Zweig in 1964 [6–8]. Shortly after, Sheldon Lee Glashow and James Bjorken introduced fourth flavor of quark, c [9]. The current number of quark flavors was established in 1973, when Makoto Kobayashi and Toshihide Maskawa explained experimentally observed CP violation with an additional pair of quarks [10].

of protons (uud), neutrons (udd), and electrons. The elementary particles that belong to higher generations are more massive and decay quickly into lighter particles e.g. quarks like s , c , t , and b decay weakly into u and d . Table 2.2 summarizes all known quarks and leptons together with their electric charge and mass.

Leptons have only been observed as free particles, whereas quarks always create composite particles called *hadrons*. Systems of two quarks are called *mesons* and systems of three quarks are called *baryons*. Recently also the existence of a four quark (tetraquark) state, named the $Z(4430)^-$, has been confirmed by the LHCb collaboration⁵ [12]. All particles in the Standard Model have corresponding antiparticles commonly denoted with a bar; so, i.e. for every quark q there is also an anti-quark labeled $\bar{q}$. Antiparticles have the same mass but opposite electric charge and baryon number⁶ (quarks) or lepton number⁷ (leptons).

Furthermore, the Standard Model includes the Higgs boson which explains why some of the elementary particles are massive [13–15]. The mass of the Higgs boson itself is not predicted by the SM; however, it was recently measured by ATLAS and CMS Collaborations to be $\sim 125 \text{ GeV}/c^2$ [16, 17]⁸.

Elementary particles and gauge bosons included in the SM are shown in Fig. 2.1.

Quantum chromodynamics

Quantum chromodynamics (QCD) is a quantum field theory which describes the strong interactions between quarks and gluons. It was formulated in the years 1972-73 by Murray Gell-Mann and Steven Weinberg, both Noble Prize winners [19]. The name of the theory, analogous to that of the quantum electrodynamics (QED), refers to the color charge characterizing the fundamental particles of strong interaction.

Like in quantum electrodynamics, where electric charge plays a key role, partons (quarks and gluons) have the QCD's equivalent, which is called *color*. There are three colors (*red*, *green*, *blue*) and, accordingly, three anticolors (*antired*, *antigreen*, *antiblue*). Historically, the

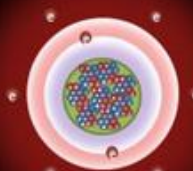
⁵Similarly, other types of exotic hadrons may exist, such as pentaquarks, but no current evidence conclusively proves their existence [11].

⁶Each baryon has a baryon number of $B = \pm 1$. Equivalently, we can assign for each quark a baryon number of $\pm 1/3$. Therefore, the mesons (quark – anti-quark pairs), have a baryon number $B = 0$. There is no known process in nature that changes the net baryon number.

⁷Each lepton has lepton number of $L = 1$, antilepton $L = -1$ and non-leptonic particles $L = 0$. Conservation law of lepton number states that total lepton number should be conserved in interactions.

⁸ $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.}) \text{ GeV}/c^2$ (CMS [16]), $126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.}) \text{ GeV}/c^2$ (ATLAS [17]).

Elementary Particles & Field Forces

Quarks Leptons	I			II			III			Bosons	Force Carriers	Higgs Boson 	
	u up 2/3	c charm	t top	d down 1/3	s strange	b bottom	e electron	μ muon	τ tau	Z z-boson			
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino							W w-boson			
Three Generations of Matter & Forces													

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Figure 2.1: Table of the elementary particles described by the Standard Model. From Ref. [18].

idea of color comes from the observations of particles like Δ^{++} , Δ^- and Ω^- which are build up from three quarks of the same flavor (uuu , ddd , and sss respectively). This seemed to be in conflict with Pauli's exclusion principle; therefore, a new quantum number (color) was introduced by Greenberg in 1964 and, independently, by Han and Nambu in 1965 [20, 21]. The theory says that free particles can only be color neutral (*white*); therefore, *mesons* are color-anticolor doublets and *baryons* are red, green, and blue triplets. Moreover, the gluons are color-charged (a gluon carries any combination of one color and one anticolor; on the other hand, the electromagnetic charge carrier in QED, the photon, is a neutral particle). By exchanging colored gluons (strong force carriers) quark change their color. Quark of given mass, charge and *any color* is treated as one particle, therefore we do not discriminate 18 quarks but 6.

The Lagrangian of quantum chromodynamics is given by:

$$L = -\frac{1}{4} \sum_{n=1}^8 F_{\mu\nu}^n F^{\mu\nu n} + \sum_q \bar{\psi}_q \left(i\gamma^\mu \partial_\mu - 2\sqrt{\alpha_s} \gamma^\mu \sum_{n=1}^8 A_\mu^n \frac{\lambda^n}{2} - m_q \right) \psi_q, \quad (2.1)$$

where $n = 1, 2, \dots, 8$ is the color index, q the flavor index ($q = u, d, s, c, b, t$), ψ_q describe the quark fields with quark masses m_q , $A_{\mu\nu}^n$ correspond to the gluon field. The quantity α_s is the

strong coupling constant⁹, γ^μ are Dirac matrices and λ^q are Gell-Mann matrices¹⁰.

The main difference between QED and QCD is the behavior of the *coupling constant*. In the case of QED the electromagnetic coupling constant is of small value $\alpha = e^2/\hbar c = 1/137$. In contrast, the QCD coupling constant α_s might be of the order of one. Moreover, the QCD constant is, in fact, not constant, since it depends on the momentum transferred in the interaction Q^2 [19, 22]:

$$\alpha_s(Q^2) \propto \frac{1}{\ln(Q^2/\Lambda^2)}, \quad (2.2)$$

where $\Lambda \approx 127 \text{ MeV}$ ¹¹ is a scale constant. The evolution of the QCD coupling constant as a function of Q can also be seen in Fig. 2.2, which represents a summary of different measurements.

Directly from Eq. (2.2) we can draw two notable features of colored objects – *confinement* [25–27] and *asymptotic freedom* [28–30]. Confinement is dominant at low energies and asymptotic freedom at high energies.

- *Confinement* – means that the quarks and gluons, at low energies, cannot exist as independent particles, since the amount of energy needed for the separation of quarks is infinite. When two quarks are pulled apart and the distance between them grows, the momentum transfer decreases and the coupling constant increases. If the accumulated energy of interaction becomes high enough, it becomes energetically favorable to produce new quarks and gluons. However, such newly produced particles couple immediately into hadrons. This is the reason that color charged particles cannot be isolated as separate objects; they are always confined in the hadrons, which are colorless.
- *Asymptotic freedom* – means that the interaction between particles vanishes at short distances (comparable to the nucleon radius). In such case the momentum transfer is high, which means that the coupling constant (strong interaction) is low – at short distances partons become asymptotically free. This is the main reason for the prediction of the existence of the so-called Quark-Gluon Plasma described in detail in Sec. 2.2.

⁹ $\alpha_s = g_s^2/4\pi$, where g_s is the strong (color) charge.

¹⁰For more information see Refs.[19, 22].

¹¹According to generally adopted convention one defines the value of α_s at the mass of the Z^0 boson to be $\alpha(m_Z) = 0.118 \pm 0.002$. This gives the scale of the constant $\Lambda = 217^{+25}_{-23} \text{ MeV}$ [23].

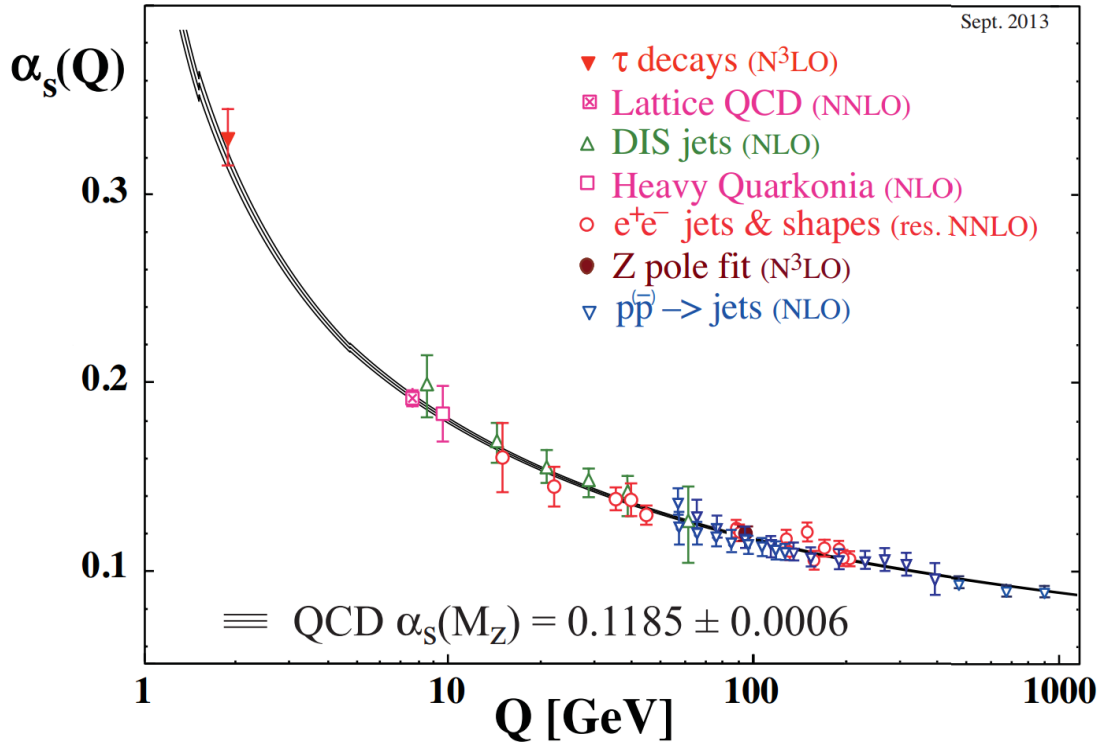


Figure 2.2: Summary of measurements of α_s as a function of the energy scale Q . The respective degree of QCD perturbation theory used in the extraction of α_s is indicated in brackets (NLO – next-to-leading order calculations, NNLO – next-to-next-to-leading order calculations, N³NLO – next-to-NNLO calculations). From Ref. [24].

There are several approaches to solve the QCD equations, but generally speaking there are two main ones: (1) for large values of Q^2 – distances much lower than the nucleon radius (*hard* collisions) we enter the region where perturbative theory (so-called *perturbative QCD*) can be applied (the same calculation methods that were developed for QED), while (2) for small Q^2 (*soft* collisions) other methods had to be developed (*non-perturbative QCD*). In the latter the common calculation techniques are based on the *lattice*. This means that we perform numerical calculations at discrete space-time points. Phenomenological models are also very convenient in clarifying some of the mechanisms observed in experiments. Figure 2.3 shows the QCD coupling constant as a function of the distance which is the variable “inverse” to Q^2 (large Q^2 probes small distances). The vertical band represents the intermediate region between “perturbative QCD” at small distances and “strong QCD”, usually also called “non-perturbative QCD”, at distances close to the nucleon radius.

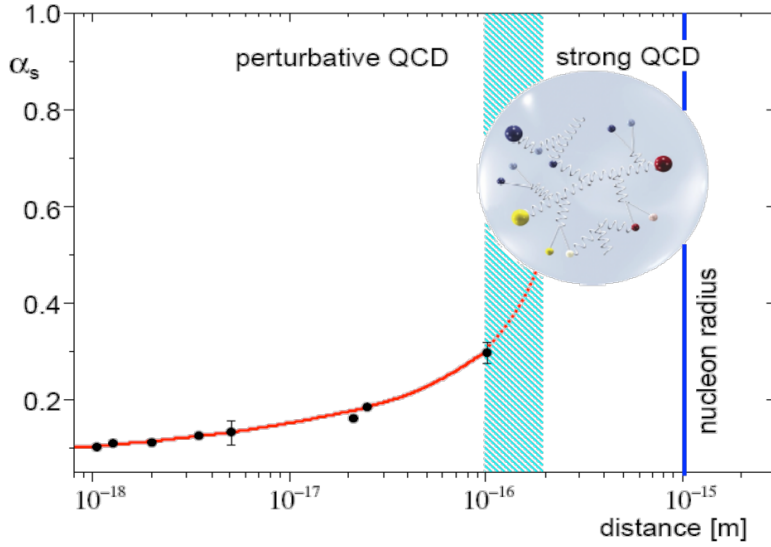


Figure 2.3: Coupling constant of the strong interaction as a function of distance. Experimental values are shown with points. From Ref. [31].

2.2 Relativistic heavy-ion collisions

As it has been mentioned before, the consequence of the asymptotic freedom is the prediction of the existence of a deconfined state of quarks and gluons, the *Quark-Gluon Plasma* (QGP).

At low temperatures, the matter can be described in terms of a dilute hadron gas. When a transition from this bulk hadronic state at low temperatures to the QGP at high temperatures occurs a sudden increase of the number of degrees of freedom is expected. It can be seen e.g. as a characteristic behavior (a step-like structure) of energy density with increasing temperature. This dependence can be calculated using lattice QCD and the results of such calculations are shown in Fig. 2.4.

This figure shows the relation between the energy density ϵ divided by T^4 which corresponds to the number of degrees of freedom of the system, versus temperature T normalized to the critical temperature T_C . The lines of different colors represent calculations for different numbers of quark flavors that were taken into account. When the temperature reaches the critical value T_C , the number of degrees of freedom rapidly and substantially increases. This is the signature of the Quark-Gluon Plasma – the number of degrees of freedom in normal hadronic matter, where the quarks and gluons are combined in hadrons, is smaller than in QGP.

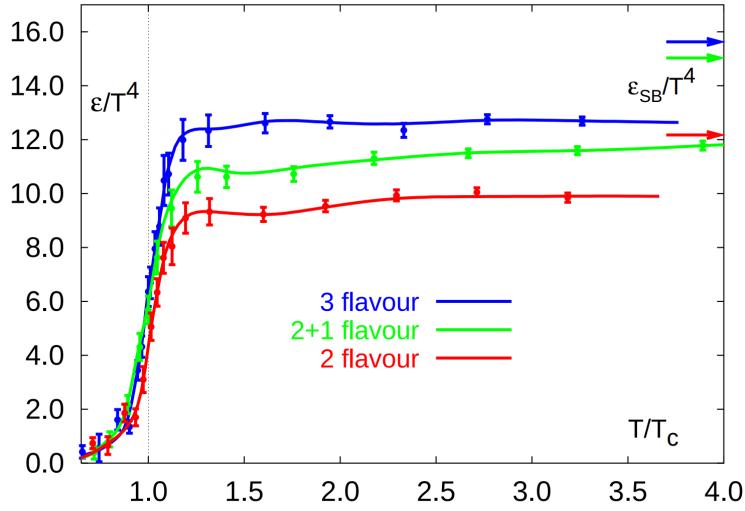


Figure 2.4: Energy density as a function of temperature calculated from lattice QCD. From Ref. [32].

Another essential information that we attempt to retrieve from the lattice calculations as well as from the experiments are the values of the critical temperature T_C and baryon chemical potential μ_B ¹² for which the phase transition from the hadronic matter to QGP occurs. The schematic picture showing such relation, the phase diagram, is shown in Fig. 2.5.

As we see from the diagram, the QGP state of matter is formed at high temperatures. The phase transition between the Quark-Gluon Plasma and the hadronic matter is expected to be 1st order at non-vanishing baryon chemical potential μ_B . However, as the baryon chemical potential goes towards zero, the phase transition becomes a smooth cross-over. The point where the phase transition changes from the 1st order to the cross-over is called the *critical point*. The transition is assumed to take place at a temperature around 160 MeV [35] at low to medium values of μ_B .

Experimentally collisions of heavy ions at very high energies are employed to reach the necessary conditions for the phase transition to the Quark-Gluon Plasma. Although it is believed that in nature QGP exists in the cores of neutron stars (see e.g. Ref. [36]), we do not have any means (so far) to study it there. Therefore, in the experiments we collide ions of different sizes to produce sufficiently high energy densities to directly probe the QGP and study its properties. Several facilities have been designed to map out different regions of temperature and baryon chemical potential in the QCD phase diagram. At the top RHIC (Brookhaven’s Relativistic

¹²Baryon chemical potential μ_B is the measure of the change of the energy in the system as the baryon number changes and all other thermodynamic variables are kept constant. Therefore μ_B is a measure of the “imbalance between matter and antimatter and zero indicates perfect balance” [33].

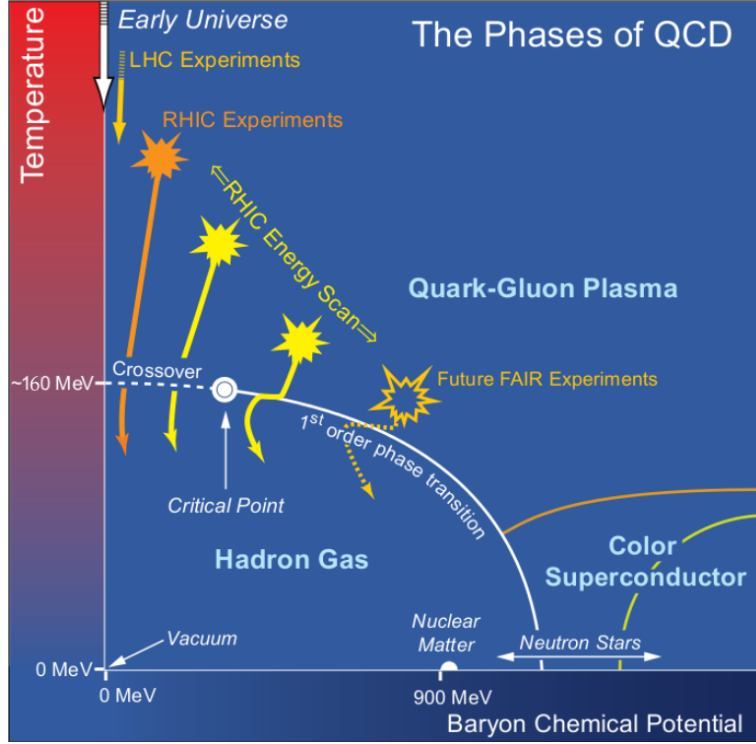


Figure 2.5: Sketch of the phase diagram of the strongly interacting matter. From Ref. [34].

Heavy-Ion Collider) and LHC collider energies, the system is produced with very small net baryon densities and high temperature. Planned low energy fixed-target facilities, such as FAIR (Facility for Antiproton and Ion Research) and NICA (Nuclotron-based Ion Collider fAcility) complement the search started at SPS and RHIC for the conjectured QCD critical point and probe the matter that will be produced at lower temperatures but relatively high baryon chemical potential.

Let us now consider a high-energy collision in terms of formation of the Quark-Gluon Plasma. Figure 2.6 presents a scheme of the space-time evolution of the system in a scenario where QGP is created.

The scenario of the collision in which the QGP is formed can be divided into certain stages: (a) prior to the collision two Lorentz-contracted nuclei move towards each other, (b) collision occurs, (c) a non-equilibrium initial state is created just after the collision (d) then, QGP is formed, (e) after the so-called *chemical freeze-out* the phase transition to the hadron gas takes place (the inelastic collision rate becomes smaller than the elastic collision rate – the chemical composition of the system is fixed from that moment), (f) the so-called *kinetic freeze-out* (sometimes called thermal freeze-out) follows; particles are no longer produced and a stream

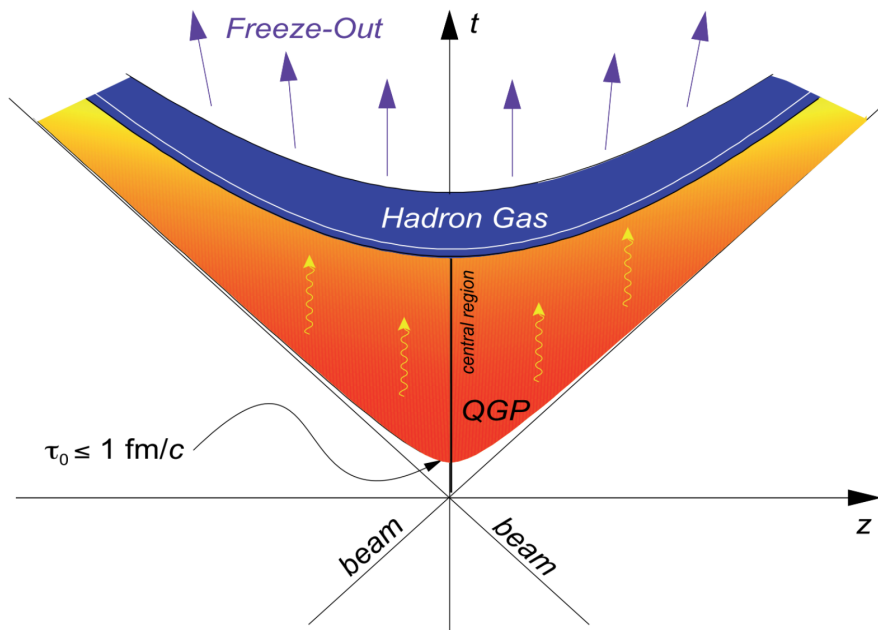


Figure 2.6: Evolution of the system created in a heavy-ion collision assuming formation of QGP in one space (z) dimension and time (t). From Ref. [37].

of particles, as they are at the moment, will reach the detectors (elastic collisions stop – the particle momenta are essentially fixed from that moment). This scenario results in three time scales: the first one is the time after the initial state when matter is thought to be thermalized τ_0 ; we assume that it is of the order of 1 fm/c. The chemical and kinetic freeze-outs are also associated with their own temperatures.

Only the particles after kinetic freeze-out are then measured in a high-energy physics experiment. It is not possible to directly detect the QGP, therefore a set of indications (so-called “signatures”) is investigated that can provide considerable evidence to confirm its existence. In Sec. 4.6 selected ALICE physics results related to the main signatures of the QGP are presented. Detailed discussion on this topic can also be found in Refs. [38, 39]. A comprehensive summary of results from the SPS is provided in Ref. [40]. The experimental evidence from RHIC is extensively discussed in Ref. [41].

The main goals of the ALICE physics program are the analysis of collisions of heavy-ions to study properties of the QGP as well as the phase transition between nuclear matter and the deconfined state of quarks and gluons. A common strategy in physics involves study of certain effects by comparing cases including those effects and without them. A new discovery can be claimed only with a very scrupulous study and detailed understanding of such a comparison.

The volume of the system created in proton-proton (pp) collisions is expected to be too small to form a QGP state. Therefore it is a perfect reference (baseline) for heavy-ion data¹³. An example of such comparison, the nuclear modification factor studies, is presented in Sec. 4.6.2. Hadron-hadron collisions are described in detail in the next section.

2.3 Elementary hadron-hadron collisions

For many years the comparison of the results from small systems to a larger system had been dubious and tricky due to two main reasons. Firstly, measurements were performed differently by various experiments, which makes direct comparisons challenging. Secondly, the detector acceptance, different analysis techniques, different kinematic ranges of the studied particles and even different definitions of basic observables that underlie the measurements, i.e. multiplicity, caused that any comparison was very difficult if not impossible.

Nowadays, dedicated heavy-ion experiments at SPS, RHIC and LHC can overcome these complications since both pp collisions and bigger systems are investigated at the same facility, employing the same detector and the same analysis methods. All these advantages severely reduce the systematic uncertainties of comparison between small and big systems.

Naturally, pp collisions are interesting in their own right as well. Just to name few of their features:

- **Simple system** While the most central heavy-ion collisions can involve even a thousand separate nucleon–nucleon collisions a pp collision cannot involve more than one. Some effects, i.e. certain properties of conservation laws considered in this thesis, can only be studied in smaller, simpler systems.
- **Jet studies** One of the observed QGP signatures is a suppression of high- p_T particles in heavy-ion collisions in respect to the pp case. This suppression is usually associated with the interactions of the jets emitted in the collision with the produced dense plasma. Since it is expected that the mechanism of jet production is similar (hard parton-parton interactions) in both systems, the analysis of pp collisions allows for detailed studies of jets in a more elementary setting, where they are not affected by the QGP.

¹³It should be noted, however, that there may be some effects, like for example the phase-space constraints, that affect small and big systems differently.

- **No collective effects** The minimum bias pp collisions have never exhibited collective motions (see Sec. 3.2.3) that are observed in heavy-ion collisions. This suggests that properly scaled-up pp collisions can serve as a model A–A system without collective effects¹⁴.

In this thesis collisions of protons at collision energies of $\sqrt{s} = 0.9, 2.76, \text{ and } 7 \text{ TeV}$ are studied¹⁵.

Even though the system may be simpler, the analysis of collisions of protons is not necessarily easier than studying the properties of collisions of heavy-ions. Firstly, the measurements of pp collisions are influenced more strongly by the detector effects, due to the lower particle production in such collisions; this results in smaller signal to noise ratio. Similarly, some phenomena are more pronounced for high multiplicities, and for low multiplicities they are harder to distinguish from other effects. An example of the analysis with such issues is discussed in Sec. 3.2.6.

2.4 Monte Carlo event generators

A *Monte Carlo (MC) event generator* [45–48] is a software designed to provide simulated high-energy collisions. MC event generators simulate collisions that are as similar as possible to real events which are provided by the accelerator, down to the level of final stable particles, which may be detected by the experiments. The similarity is naturally limited by the present understanding of the intrinsic physics. Generated collisions usually consist of a list of produced particles and their momenta. The probability to generate an event with a given particles' list is roughly proportional to the probability that the corresponding physical event is produced in the

¹⁴However, it has been predicted that some collective effects would begin to manifest in high multiplicity pp collisions at LHC [42–44]. If one considers the energy density to be the crucial parameter, then the final state energy- or particle density (particles per unit volume) in high multiplicity pp is comparable to or even larger than in central Pb–Pb. Such considerations, intensified after the “Ridge” LHC discovery, explained in detail in Sec. 3.2.4.

¹⁵In particle physics $\sqrt{s}$ is the Lorentz-invariant Mandelstam variable used to encode energy. If collision of two particles with four momenta p_1 and p_2 is considered, one can define Lorentz-invariant variable $s = (p_1 + p_2)^2$. In the center-of-mass frame, where there is no net momentum, the four momenta are defined $p_1 = (E_1, \mathbf{p})$, $p_2 = (E_2, \mathbf{p})$, from which we obtain $s = (p_1 + p_2)^2 = (E_1 + E_2)^2(\mathbf{p} - \mathbf{p})^2 = (E_1 + E_2)^2$. Hence, the Lorentz-invariant quantity $\sqrt{s}$ can be identified as the total energy available in the centre-of-mass frame. In heavy-ion physics, where heavy atomic nuclei are studied, the collision energy per nucleon pair is denoted as $\sqrt{s_{NN}}$.

real world. The name Monte Carlo comes from the fact that they make extensive use of random number generators and Monte Carlo methods. They incorporate perturbative solutions for large momentum transfers (hard interactions) and phenomenological models for other areas.

Generated events facilitate the understanding of the data by predicting signals that are to be expected, as well as help in preparation of analysis strategies and needed software. They enable the estimation of the corrections needed to eliminate (or reduce) the influence of the detector effects on the measurement. In addition, the results obtained from event generators complemented with the transport packages describing the passage of particles through matter are commonly used to plan and optimize the detector design. Finally, the comparison of results from event generators to actual events measured in the experiment allow us to further understand the underlying physics.

Following Ref. [45], there are several necessary stages of the simulation of hadron–hadron collisions: a primary hard subprocess, parton showers which originate from the colored subprocess participants (both incoming and outgoing), non-perturbative interactions converting these showers into outgoing hadrons, secondary interactions, and the decays of unstable particles. A complete sketch of a hadronic collision is shown in Fig. 2.7, where the distinct components are represented in individual colors. There are corresponding steps in the event generation for each of the mechanisms shown.

To perform the analysis presented in this thesis two general purpose event generators were used to simulate high-energy proton-proton collisions, Pythia 6.4 [47, 50] and Phojet 1.12 [51]. Since generators were used for aspects both technical (calculation of the corrections, estimation of the influence of the detector) as well as connected to physics (comparisons between collision data and simulated events) in the following sections physics models implemented in both of them are briefly described, and the underlying physics is introduced.

2.4.1 Hard process

Simulation of a collision commonly begins with an elementary subprocess resulting from a highly energetic collision of constituents of colliding particles [45–48]. There are many interesting mechanisms, especially important at LHC energies, that involve large momentum transfers (e.g. production of jets or heavy quarks). Thus, the simulation of such subprocesses is at the foundation of many of the Monte Carlo event generators.

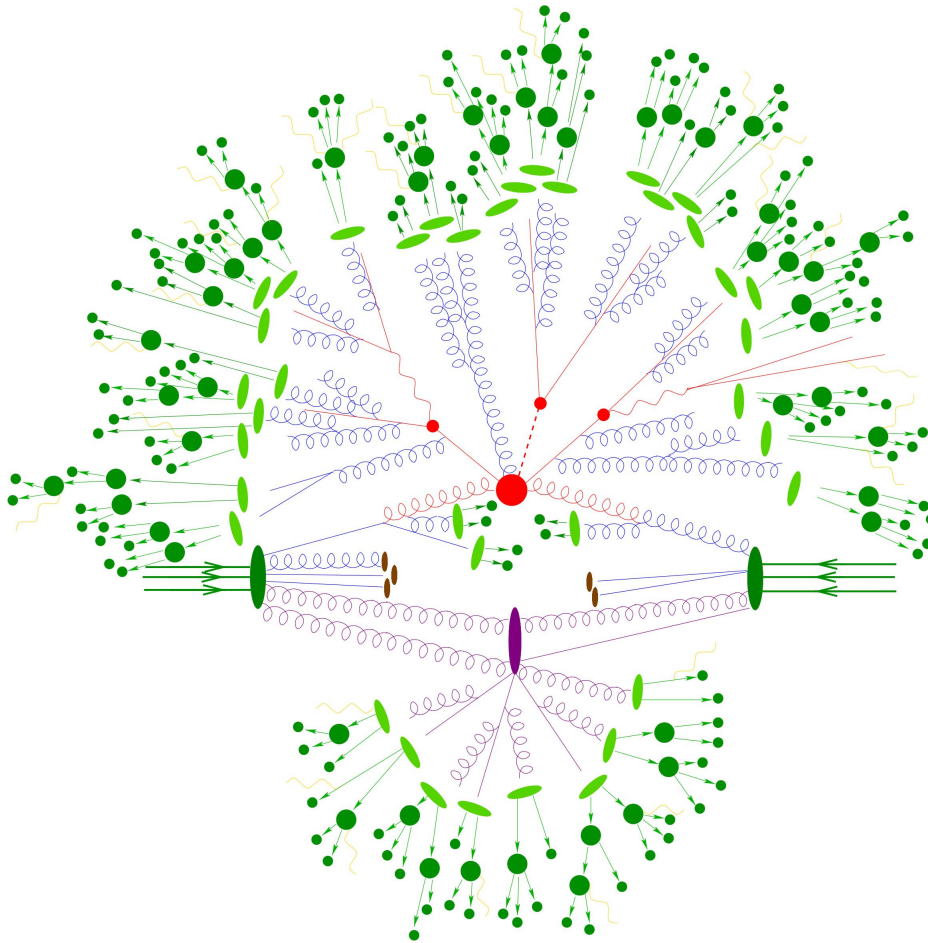


Figure 2.7: Sketch of a hadronic collision: hard scattering between two partons (high $|Q|^2$) is represented in red, the initial- and the final-state showers are pictured in blue, a multi-parton interaction in purple, beam remnants of the incoming protons (partons which do not take part in the hard scattering) are sketched in brown. At the far end of the lines, the particles produced in the hadronization process are shown in light and dark green. From Ref. [49].

Let us consider two particles from the opposite beams that move towards each other. Those incoming hadrons, traveling at velocities close to the speed of light, appear to be composed of a number of point-like strongly-interacting partons [52, 53]. Distributions of partons can be characterized by parton distribution functions (PDFs). PDFs have been measured at lower energies and in other processes and are calculated for higher scales using the QCD evolution equations for parton densities ¹⁶.

¹⁶Several parameterizations exist; therefore, the generated events additionally rely upon the choice of the PDFs, i.e. the default setup for PDFs in Pythia is CTEQ5L [54]. This parametrization results from a global fit to high-energy lepton-hadron and hadron-hadron collision measurements.

The momentum selection of the colliding partons is based on the sampling of those parton distribution functions. The production cross section is obtained from convolution of the PDFs with the differential cross section of the subprocess and integration over phase space. If the Monte Carlo methods are used for these operations we can simultaneously obtain the momentum distributions of the primary products, which are represented as a set of phase-space points.

In the next stage of the simulation the colored objects of the hard subprocess (both incoming and outgoing) can undergo a parton showering.

2.4.2 Parton showers

The hard subprocesses require large momentum transfers which result in intensive acceleration of the involved partons. Similarly as in QED, where the acceleration of the electric charges causes the emission of the radiation in the form of photons¹⁷, the acceleration of colored partons causes the emission of the radiation in the form of gluons. However, in contrast to the neutral photons, the gluons are colored and can thus emit further radiation, producing additional parton showers [45–48].

Final-state showers

A *final-state shower* (or *final state radiation*) is the radiation that develops from an outgoing parton of the hard subprocess. This process is especially important for higher energies and fundamentally influence the structure of jets. Partons experience a series of branchings, e.g. $q \rightarrow qg$, $q \rightarrow q\gamma$, and $g \rightarrow gg$. Produced particles (also called *daughters*) can undergo further branching. The splitting is initiated at energy of the hard interaction, loses it during the evolution, and aborts when the remaining energy (of parton and all its decedents) is below 1 GeV.

One of the simulation difficulties is the fact that the partons used for hard subprocess generation were on-mass-shell¹⁸, whereas the partons that initiated showers are off mass-shell. To restore momentum conservation some momentum reshuffling is applied. Proper energy-momentum conservation of all processes is an important part of modeling the global correlation picture which is a subject addressed in this thesis.

¹⁷For more information about QED radiation see for example Ref. [55], chapter 15.

¹⁸Particles are said to be “on the mass shell,” or simply “on-shell,” if their behavior satisfies the relationship between energy and momentum given by Einstein in his theory of special relativity $E^2 = (pc)^2 + (mc^2)^2$ (from Ref. [56]).

Initial-state showers

An *initial-state shower* (or *initial state radiation*) is the radiation that develops from incoming partons. At a hadron collider, high energy constituent partons from each one of the incoming hadrons lose their energy by emitting further partons. The showering finishes when they interact and induce the hard subprocess. However, simulating this process in the proper time order would make Monte Carlo efficiency very low. Therefore, in most of the event generators the *backward evolution* procedure is employed: the incoming partons are evolved backwards in time, acquiring energy in each emission.

2.4.3 Multi-parton interaction and beam remnants

It is possible that more than one pair of partons from the incoming hadrons may interact in a single high-energy hadron-hadron collision (so-called *Multi-parton Interaction*, MPI) [57]. These multiple interactions produce additional partons throughout the event. There are number of models employing MPI in proton-proton collisions, e.g. *pQCD inspired*¹⁹ or *Dual Parton Model* (DPM)²⁰.

In addition, only the fraction of the total beam energy is consumed by partons that took part in the hard interaction. The remaining energy is taken by the non-interacting partons, called *beam remnants*, e.g. in a pp collision: a u quark that was involved in an interaction results in remnant of a ud diquark, with an antitriplet color charge. The remnant is therefore color-connected to the hard interaction and forms part of the same fragmenting system.

2.4.4 Hadronization

As the series of processes are simulated, the energy of the event is decreasing, finally reaching the region in which QCD becomes strongly interacting and perturbation theory can not longer be applied. Thus the perturbative evolution must be replaced by a non-perturbative *hadronization (fragmentation) model* that describes the process of confining the colored partons into hadrons [45–48]. A distinctive feature of these models is the collective hadronization of many individual

¹⁹The pQCD inspired models assume that parton interactions can be described by the pQCD [57]. pQCD inspired model is used by Pythia.

²⁰The Dual Parton Model describes the soft physics with the pomeron exchange theory [58] and includes the pQCD only for the hard interactions [59]. The Dual Parton Model is used by Phojet.

partons: they do not hadronize independently, but in color-connected systems. This process does not depend on the manner in which the system was produced and thus, “*once tuned on one data set, the models are predictive for new collision types or energies*” [45].

The leading theories regarding hadronization include the string model [60], the independent fragmentation model [61], and the cluster model [62, 63]. Since both Pythia and Phojet use the Lund string hadronization model, we will describe it in detail in the next subsection.

String fragmentation

Since the first ideas dating back to 1974 [64] a number of string²¹ hadronization models have been proposed [45]. Nowadays, the so-called Lund model [60, 65] is the one most commonly used. In following sections we focus on this particular model, although most of the general concepts would be common for all string-inspired methods.

The underlying assumption of the string model is the linear confinement of quarks in the pair [47, 66]. Considering the simplest case, that is a $q\bar{q}$ pair, one can imagine a color flux tube (*string*) stretched between them, with the transverse size of typical hadronic length, 1 fm.

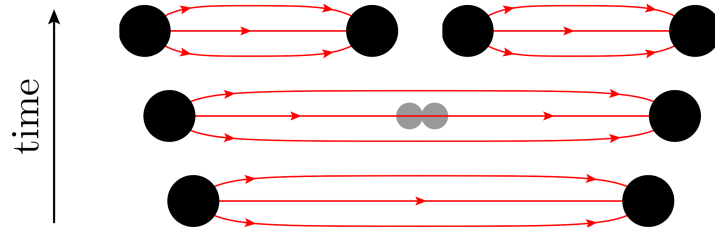


Figure 2.8: Illustration of string breaking by quark pair-creation in the string field. From Ref. [46].

When quarks move apart from the common vertex, the potential stored in the string increases linearly and it can break, producing a new pair $q\bar{q} \rightarrow q\bar{q}' + q'\bar{q}$ via non-perturbative process, as illustrated in Fig. 2.8. In this process a meson is created. The transverse momenta of the newly produced $q'\bar{q}'$ comes from the flavor independent Gaussian spectrum, with local compensation between quark-antiquark in the pair. The total p_T of the hadron is the result of the transverse momenta of the contributing (anti)quarks. The flavor of the quark pair produced in a string

²¹Strings mentioned in this section should not be linked to the string theory of quantum gravity.

breaking is given by the probabilistic rules, suppressing the production of heavy quarks (the ratio of the probabilities to produce quarks is $u : d : s : c \approx 1 : 1 : 0.3 : 10^{-11}$ [47]). An intrinsic property of meson creation in the string fragmentation picture is the fact that strangeness is always conserved: quarks are created as $q'\bar{q}'$ doublets. This property of the studied models is important for the comparisons with the collision data, which are presented in Sec. 9.2.

Baryon production is realized by two mechanisms: the *diquark production* model and the *popcorn* model [47]. Since the baryon conservation law is important for the analysis presented in this thesis, we will explain them in detail.

The main assumption of the diquark model is that the string can break producing a pair of diquarks, which are loosely bound states of two quarks (denoted as $D\bar{D}$), instead of pairs of single quarks. This process is very similar to producing a $q\bar{q}$ pair, since both states, the $D\bar{D}$ and $q\bar{q}$, are pairs of color triplets and color anti-triplets. With the neighboring quark and antiquark in the string, the $D\bar{D}$ pair will form a baryon-antibaryon ($B\bar{B}$) pair.

The popcorn model [67] is a more general framework of baryon production. This model produce quark-antiquark pairs with a different color than the initial pair employing fluctuations of the color field. Diquarks as such are never produced, instead baryons appear from the subsequent production of several $q'\bar{q}'$ pairs. Sometimes, the end outcome will be precisely the same $B\bar{B}$ system as in the diquark model, i.e. with an adjacent baryon B and antibaryon $\bar{B}$ sharing a diquark-antidiquark pair. However, there is also a chance that the systems of $BM\bar{B}$, $BMM\bar{B}$, etc., can occur, where in between the baryon and antibaryon a varying number of mesons M are produced.

Neighboring baryons in the string typically differ in rapidity²² by about 1 unit [68], with popcorn fragmentation leading to bigger rapidity differences than diquark fragmentation. Therefore, using the popcorn model results in a weaker correlation (in flavor and momentum space) between baryon-antibaryon pair in comparison to the diquark model. Analyses that can give us insight into the correlation strength between the baryons (i.e. angular correlation analysis of identified particles presented in this thesis) can help us distinguish between different baryon production mechanisms and tune the parameters of the models.

²²Rapidity is a measure of motion alternative to velocity. It is used in particle physics since it is additive under Lorentz transformation. More information can be found in Sec. 3.1.

In contrary to meson production mechanism, which allows to create single mesons in the fragmentation process, baryons must be always formed as baryon-antibaryon doublets. This essentially assures baryon number conservation in the Lund string fragmentation model. This information should be noted, since it is essential for further comparisons with collision data (see Sec. 9.2).

Decays

Finally, a number of the particles that are produced during hadronization stage are unstable resonances. There are dedicated models simulating decays of such hadrons to the lighter particles, which live long enough to be registered by the detectors. Therefore, event generators contain lists of decay properties (life times, decay products, branching ratios, etc., see e.g. Ref. [24]) of unstable particles. This part of the simulation chain is important for the analysis presented in this thesis, since we expect the resonances to create certain structures in the correlation distribution (see Sec. 3.3).

2.4.5 Jets

The high- p_T partons produced during the parton shower evolution are emitted in the same direction as the partons which initiated the shower. Therefore, intrinsically, in the final state of the shower, the most of the energy is carried by localized collinear spray of partons. Such spray is called a *jet* [69]. The jet structures are then preserved in hadronization process.

Jets are a prominent feature of hadronic events; they are not artifacts of the simulation chain, but can be observed in experiments. However, as stated in Ref. [45] “*they are not fundamental objects that are defined by the theory*”. In the literature also a term *minijet* is frequently used for jets originating from low momentum-transfer scatterings. However, we should not dwell too much on discriminating between those two concepts. As P.V. Landshoff pointed out in Ref. [70]: “*it is just an ordinary jet, usually a gluon. It is called mini because its p_T is not very large.*”

In Fig. 2.9-left two back-to-back jets produced in a e^+e^- collision are shown. Jets (minijets) influence strongly the global correlation picture. More information can be found in Sec. 3.3.

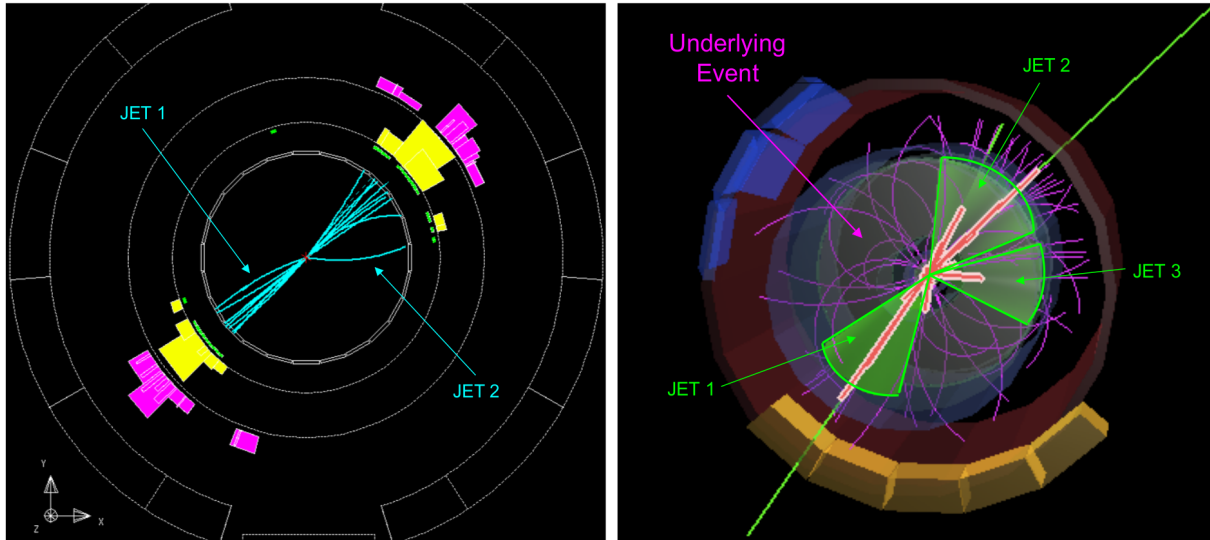


Figure 2.9: Left: a di-jet event in e^+e^- collisions at LEP, as seen by the OPAL experiment. Two back-to-back jets are produced from the decay of the exchanged vector boson. No Underlying Event is present. Right: hadronic pp collision seen by the ALICE detector. Three jets are reconstructed (green areas and red tracks). The Underlying Event, fragmentation of beam remnants and multi-parton interactions, also contribute to the multi-particle final state (magenta tracks). From Ref. [71].

2.4.6 Underlying event

Underlying Event (UE) is a component of a hadronic collision, which includes most of the occurring partonic interactions. It can be easily defined as “everything that happens in the collision excluding the hard scattering.” This general definition results from the fact that UE combine various phenomena which underlie (as the name implies) the primary hard interaction. In particular, many of the effects described in the previous section can be associated with the UE:

- initial- and final-state radiation (soft products),
- multiple parton interaction,
- beam remnants.

These components provide contribution to the collision events which influence mostly the production of hadrons with low transverse momenta. Since the measurement of low p_T particles play a major role in this thesis, we would like to emphasize the importance of those processes for the performed analysis. The e^+e^- collision with a clean jet signal from Fig. 2.9-left can be compared to Fig. 2.9-right, where a pp collision event is shown. The event is populated by the

bulk of soft particles – the underlying event (magenta tracks) and three reconstructed jets – hard interactions (green areas) are shown. In hadron–hadron collisions the interplay of “hard” and “soft” processes results in non-trivial correlations.

It should be also underlined, that the “soft” component is, so far, described only phenomenologically. In Ref. [47], it is stated that *“In fact, in the full event generation process, probably no other area is as poorly understood as this one”*. Therefore, providing diversity of high quality measurements is essential in constraining this part of QCD.

2.4.7 Pythia

Pythia [47] is one of the most commonly used event generators allowing to simulate collisions of different combinations of hadrons and leptons at high energies. It uses the string fragmentation Lund model for the simulation of the hadronization (see Sec. 2.4.4) and pQCD inspired model for multiple parton interaction (see Sec. 2.4.3). Pythia combines perturbative QCD for hard interaction and phenomenologically motivated models for the description of soft hadronic interactions. This approach results in many parameters (especially from phenomenological models) that need to be adjusted. The set of all these parameters that are optimized in order to describe particular result is referred to as a “tune”. In the following paragraphs two specific tunes are introduced, Pythia Perugia-0 [50] and Pythia D6T [72]. These tunes are used in Sec. 9.2 for the comparison to ALICE collision data.

Monte Carlo generators encompass immense number of parameters which can be independently adjusted. However, as stated in Ref. [50] *Most of these parameters only control relatively small (exclusive) details of the event generation. The majority of the (inclusive) physics is determined by only a few, very important ones*. Such important parameters are e.g. the strong coupling value (in perturbative region), and the fragmentation function form for massless partons (in the non-perturbative domain) [50].

Pythia Perugia-0

Pythia Perugia-0(320) tune is based on Pythia 6.4 S0(A) version [73, 74]. The parameters of S0(A) were tuned for the best description of minimum bias data obtained with hadron colliders (Tevatron at Fermilab, USA and SPS at CERN, Switzerland) up to center-of-mass energy $\sqrt{s} = 1.96$ TeV. Starting from this point, the parameters were re-tuned in Perugia-0 to describe more advanced data analysis, such as charged particle multiplicity distributions, transverse momentum distributions and the correlation between the two. Such studies were also performed in different regions, i.e. “toward region,” containing all particles in $\Delta\varphi < 60^\circ$ and $|\eta| < 1$ or “away region” containing particles with $\Delta\varphi > 120^\circ$ and $|\eta| < 1$) [50].

Pythia D6T

Pythia D6T(109) tune is based on Pythia 6 version. The parameters were tuned to describe Tevatron data. This tune uses the non-default CTEQ6L1 parton distribution [50]. More information can be found in Ref. [72, 75]. This tune will be used further only for comparisons to $\sqrt{s} = 0.9$ TeV collision data.

2.4.8 Phojet

Phojet (version 1.12) [51, 76] is a general purpose event generator for pp, γp , and $\gamma\gamma$ interactions. The simulation of hard processes is based on perturbative QCD, similarly as in Pythia. For the simulation of soft processes, Phojet uses the Dual Parton Model (DPM) (see Sec. 2.4.3).

In this model, due to the implementation combining both soft and hard processes with the unitarity considerations [58], many soft and hard scatterings in one collision can occur [77]. Phojet focuses mainly on the soft mechanisms, while the hard component of the collision is inserted at the later stage.

Similarly as in Pythia, Phojet incorporates initial- and final-state showers as well as the Lund string fragmentation. Unlike Pythia, Phojet simulation includes central diffractive events based on double pomeron exchange.

Phojet successfully described experimental results obtained at collision energies up to $\sqrt{s} = 1.8$ TeV.

2.4.9 Summary

The sequential steps of the evolution of the hadron collision are listed below, following Ref. [47]. Each of the steps follow our current understanding of different phases of the collision²³ and as such are implemented in common general-purpose MC generators:

1. *“Initially two beam particles are coming in towards each other. Normally each particle is characterized by a set of parton distributions (PDFs), which defines the partonic substructure in terms of flavor composition and energy sharing.*
2. *One parton initiating a shower from each beam starts off a sequence of branchings, such as $q \rightarrow qg$, which build up an initial-state shower.*
3. *One incoming parton from each of the two showers enters the hard process, where then a number of outgoing partons are produced. It is the nature of this process that determines the main characteristics of the event.*
4. *The hard process may produce a set of short-lived resonances.*
5. *The outgoing partons may branch, just like the incoming did, to build up final-state showers.*
6. *In addition to the hard process considered above, further semi-hard interactions may occur between the other partons of the two incoming hadrons.*
7. *When a shower initiator is taken out of a beam particle, a beam remnant is left behind.*
8. *The QCD confinement mechanism ensures that the outgoing quarks and gluons are not observable, but instead fragment to color neutral hadrons (hadronization process occurs).*
9. *Many of the produced hadrons are unstable and decay further.”*

All above processes are modeled in both Pythia and Phojet event generators that are used in the comparison to ALICE collision data in Sec. 9.2. Both mentioned models use the Lund string model for the fragmentation processes; therefore, both strangeness and baryon number are conserved for the studied simulated events.

²³For simplicity of this summary, not all known or even implemented scenarios or effects are listed. As an example of a known but not listed effect, we would like to mention quantum effects (e.g. influence of Bose-Einstein statistics) that are not implemented in Pythia nor Phojet, but relevant for this thesis.

Chapter 3

Two-particle angular correlations

This chapter focuses on the two-particle angular correlations. Firstly, observables studied in this work are introduced in Sec. 3.1. Afterwards, the selected topics connected to the analysis of this thesis are discussed in a historical introduction to the correlation measurements in Sec. 3.2. Finally, correlation sources contributing to the $\Delta\eta\Delta\varphi$ correlation function and the structures they are expected to create are thoroughly described in Sec. 3.3.

3.1 Choice of observables

This work concentrates on the $\Delta\eta\Delta\varphi$ correlations in proton-proton collision data recorded by the ALICE experiment¹. In this section pseudorapidity η and azimuthal angle φ observables are introduced, as well as the procedure of obtaining the $\Delta\eta\Delta\varphi$ correlation function.

Pseudorapidity

Pseudorapidity η is a commonly used quantity describing the production angle of a particle with respect to the beam axis. It is defined as:

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (3.1)$$

where θ is the angle between the particle momentum $\mathbf{p}$ and the beam axis. In terms of momentum, the pseudorapidity variable can be written as:

$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L} \right), \quad (3.2)$$

¹In ALICE a right-handed coordinate system is used. Its origin is associated with the primary vertex (interaction point) near the center of the detector. The coordinates are defined as follows: z -axis is parallel to the beam pipe, y points upwards, while x is perpendicular to the other two. In the transverse plane the cylindrical coordinates (r, φ) can be used (φ is the azimuthal angle around the beam pipe).

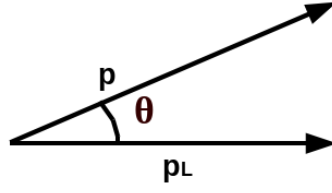


Figure 3.1: The polar angle θ definition.

where p_L is the component of the momentum along the beam axis. In the limit where a particle is relativistic (moves with speed comparable to the speed of light), it is also a good approximation of the *rapidity* y :

$$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right). \quad (3.3)$$

In many experiments, it is impossible to measure simultaneously two properties of a particle, such as its mass and its longitudinal momentum, which are necessary to characterize rapidity. In such a case, when it is only possible to measure the angle of a detected particle relative to the beam axis, it is convenient to utilize this information by using the pseudorapidity to characterize it. Rapidity and pseudorapidity differences are Lorentz-invariant under longitudinal boosts.

In the case of $\Delta\eta\Delta\varphi$ analysis we measure the difference of the pseudorapidity between two particles (see Fig. 3.2):

$$\Delta\eta = \eta_1 - \eta_2, \quad (3.4)$$

which also allows for direct comparisons between correlations of particles with different masses.

Azimuthal angle

The azimuthal angle φ is the angle between the positive x -axis and the projection of the momentum vector onto the xy -plane (see Fig. 3.3):

$$\varphi = \arctan \left(\frac{p_y}{p_x} \right). \quad (3.5)$$

In the case of $\Delta\eta\Delta\varphi$ analysis we measure the difference of the azimuthal angle between two particles (see Fig. 3.4):

$$\Delta\varphi = \varphi_1 - \varphi_2. \quad (3.6)$$

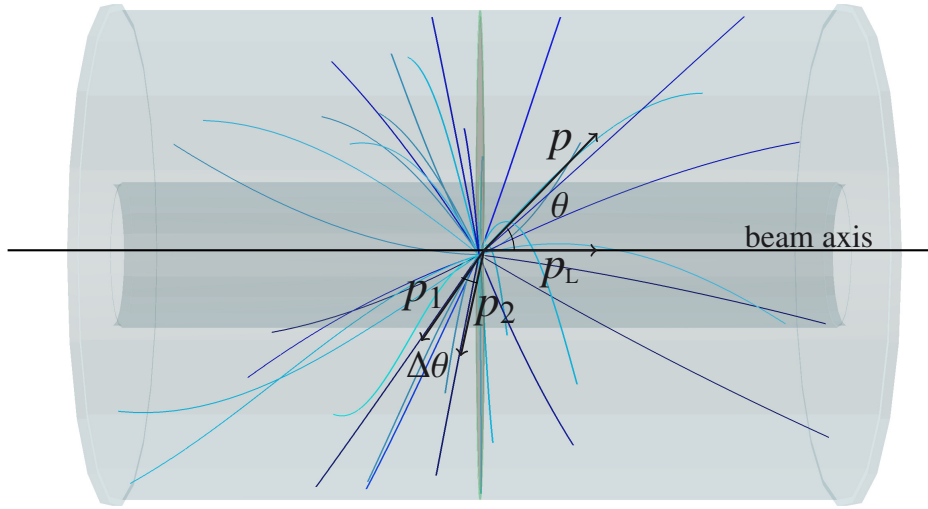


Figure 3.2: Definition of the difference of the polar angle $\Delta\theta$ with the ALICE detector geometry and a pp collision in the background (p is the total particle momentum, p_L is the longitudinal momentum). From Ref. [78].

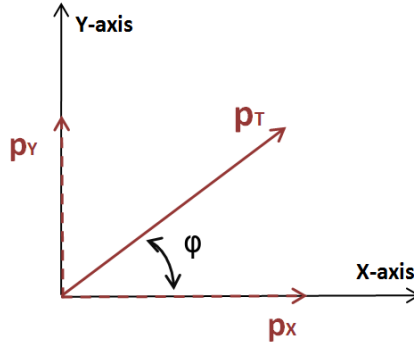


Figure 3.3: The azimuthal angle φ definition.

$\Delta\eta\Delta\varphi$ correlation function

Untriggered $\Delta\eta\Delta\varphi$ correlation functions are calculated without specification of the first and the second particle (by associating every particle with every other particle in the event). The measured correlation function includes physical correlations as well as trivial effects from detector acceptance. In order to avoid concealing physical correlations with those trivial effects the correlation function is constructed as follows:

$$C(\Delta\eta, \Delta\varphi) = \frac{N_{pairs}^{mixed}}{N_{pairs}^{signal}} \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}, \quad (3.7)$$

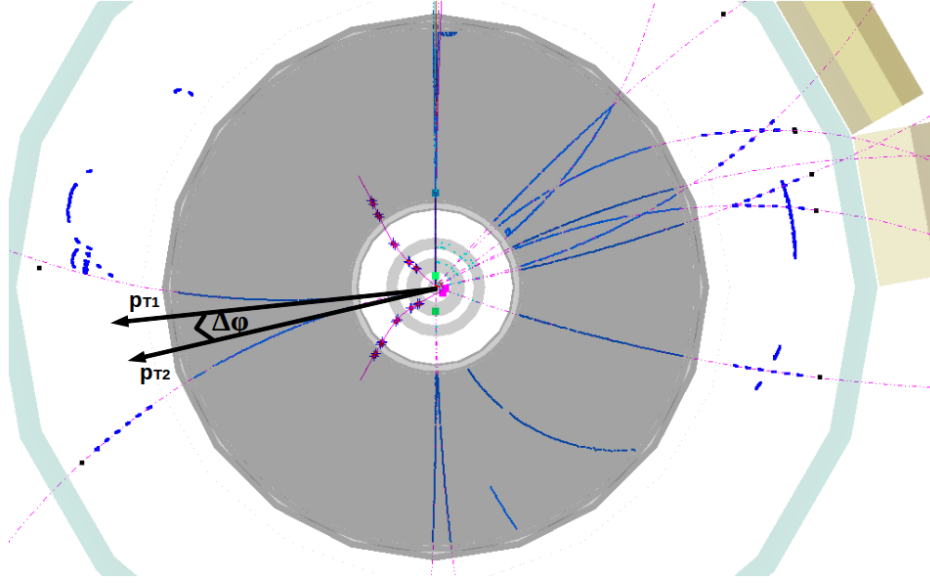


Figure 3.4: Definition of the difference of the azimuthal angle $\Delta\varphi$ with the ALICE detector geometry and a pp collision in the background.

where $S(\Delta\eta, \Delta\varphi)$ is called the signal distribution and $B(\Delta\eta, \Delta\varphi)$ is called the background distribution (containing only the detector effects). The signal distribution is constructed from particle pairs coming from the same event:

$$S(\Delta\eta, \Delta\varphi) = \frac{d^2 N_{pairs}^{signal}}{d\Delta\eta d\Delta\varphi}, \quad (3.8)$$

where N_{pairs}^{signal} is the number of pairs of particles. The background distribution is constructed using the procedure of event mixing, where each particle in the pair comes from a different event² and can be expressed as:

$$B(\Delta\eta, \Delta\varphi) = \frac{d^2 N_{pairs}^{mixed}}{d\Delta\eta d\Delta\varphi}, \quad (3.9)$$

where N_{pairs}^{mixed} is the number of pairs of particles in the background distribution B . Since the particles in the pair originate from two different events they cannot be physically correlated. In order to improve the background estimation, each event is mixed with ten different events similar in terms of multiplicity and primary vertex location.

An example of the signal $S(\Delta\eta, \Delta\varphi)$ and the background $B(\Delta\eta, \Delta\varphi)$ distributions as well as the correlation function $C(\Delta\eta, \Delta\varphi)$ is presented in Fig. 3.5. Background distribution consists

²Although event mixing is the most popular technique, other procedures of constructing the background also exist, i.e. for detectors with symmetrical acceptance, momentum conservation effects may be eliminated by mixing pairs from the same event, with the lab momentum of one particle rotated by 180° [79, 80].

of trivial effects from single-particle detector acceptance that we want to remove from the studied correlation functions. The triangular shape of the background distribution (in variable $\Delta\eta$) results from the convolution of two uniform distributions³ of the pseudorapidity (at the chosen pseudorapidity range $|\eta| < 0.8$). Since the distributions are not ideally uniform, sometimes additional unwanted effects may appear (see description of the “wing structure” in Sec. 6.3).

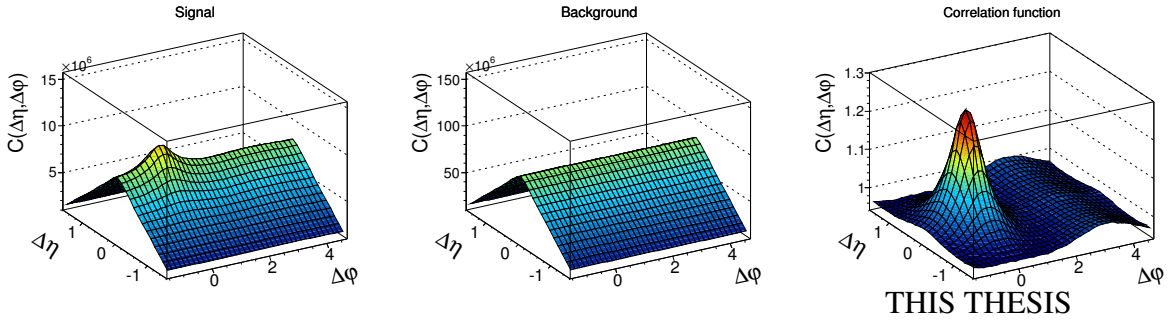


Figure 3.5: Construction of the $\Delta\eta\Delta\phi$ correlation function. Signal distribution (left), background distribution (middle) and correlation function (right).

3.2 Historical perspective

Particle correlation measurements [82, 83] are used in a broad range of studies. In this section we would like to focus on the ones that are particularly important for the topic of this thesis. In Sec. 3.2.1 the studies on the conservation laws are presented. Next, the resonance particles studies are described in Sec. 3.2.2. The measurements of collective effects and long-range correlations in $\Delta\eta$ are presented in Sec. 3.2.3 and Sec. 3.2.4 respectively. The investigations of the minijets are presented in Sec. 3.2.5. Finally, femtoscopy analyses are briefly described in Sec. 3.2.6.

³The ϕ and η of particles coming from two different events can be treated as independent random variables. The distribution resulting from the sum (difference) of independent random variables is the convolution of distributions of those variables. In the case of ϕ we obtain data with full 2π acceptance (ϕ is periodic), not creating any structures in $\Delta\phi$. However, in the case of η the acceptance is limited. η distribution can be approximated with a uniform distribution; therefore, taking particles from selected η ranges can be treated as obtaining random values from the uniform distribution. The convolution of two uniform distributions such as $\eta = \eta_1 - \eta_2$ create a characteristic triangular shape centered at $\eta = 0$ visible in the middle panel of Fig. 3.5 [81].

3.2.1 Conservation laws studies with two-particle rapidity correlations

In 1970's R.D. Field and R.P. Feynman, during studies of the properties of jet production mechanisms, described the basic principle of hadron production used till this day in many models [61]. It is the assumption of the recursive principle of hadron production. This “chain decay” ansatz⁴ assumes that, if the firstly produced primary meson carries away a momentum ξ_1 (from a quark jet of type a and momentum W_0) the remaining cascade starts with a quark of type b with momentum $W_1 = W_0 - \xi_1$ and the remaining hadrons are formed in exactly the same way as the hadrons which come from a jet originating by a quark of type b with momentum W_1 . A “hierarchy” of primary mesons is formed of which ab is first in the so-called “rank,” bc is second in rank, etc., as shown in Fig. 3.6.

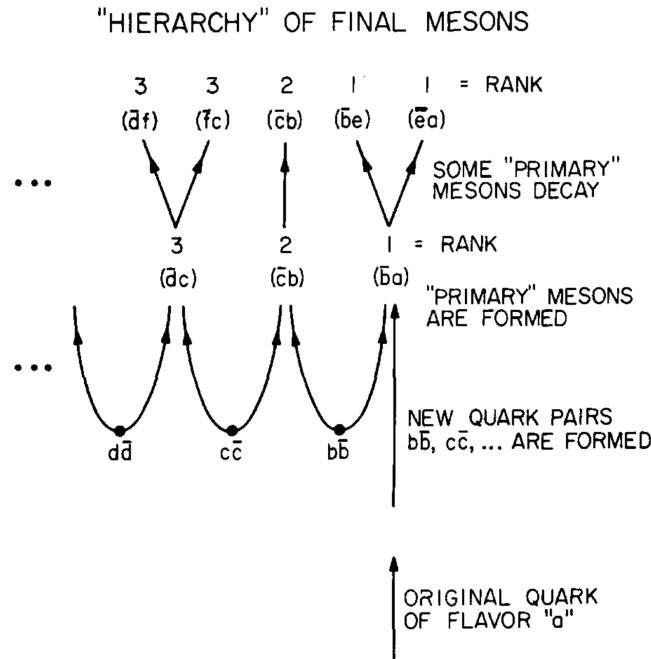


Figure 3.6: Illustration of the “hierarchy” structure of the final mesons produced when a quark of type a fragments into hadrons. New quark pairs $b\bar{b}$, $c\bar{c}$, etc., are produced and “primary” mesons are formed. The “primary” meson $\bar{b}a$ that contains the original quark is said to have “rank” one and primary meson $\bar{c}b$ rank two, etc. Finally, some of the primary mesons decay and we assign all the decay products to have the rank of the parent. The order in “hierarchy” is not the same as the order in momentum or rapidity. From Ref. [61].

⁴This recursive principle was first suggested by Krzywicki and Petersson [84] and by Finkelstein and Peccel [85] in an analysis of proton-proton collisions [61].

At the time, the proposed model did not yet include baryons; however, already some non-trivial questions arose: *are the conservation laws compensated globally, if the jets are produced? Are they also conserved locally, for each fragmentation separately? Does the “rank hierarchy” exist, and is it reflected in the rapidity of produced particles?*

To answer those questions, the two-particle rapidity correlations were employed. e^+e^- collisions of several energies: 14, 22, 29, 30-36.7, 92 GeV and different particles p , Λ , K , K^0 , Ξ , π were studied searching for evidence of global and local compensation of quantum numbers as well as chain-like production of hadrons [68, 86–93]. The studies confirmed the global conservation of quantum number [89, 91–93] and provided many indications for the local compensation [68, 86–92]. Similarly, results provide evidence for a chain-like production of baryon-antibaryon pairs and color-ordering effects [87, 89–92].

For illustration, results from 29 GeV [87] are presented, see Fig. 3.7. The TPC/Two-Gamma Collaboration analyzed protons and lambdas (all combinations) and found a strong positive correlation between baryons and antibaryons (Fig. 3.7 a, b) with evidence of local compensation of baryon number. Furthermore, local anticorrelation was observed between two particles with the same baryon number (Fig. 3.7 c, d). Similarly, in Fig. 3.7 e-h clear evidence for local conservation of baryon number is visible as well as an anticorrelation between particles with the same value of baryon number. Comparison of measured $\bar{p}p$ correlation functions with models (Fig. 3.8) has shown that the latter effect can be interpreted as evidence for close correspondence between order in which particles are created in rank and their rapidity order. The proposed model, called “symmetric Lund”, incorporates those mechanisms and agrees well with the data.

The rapidity measurements of identified particles have never been performed in pp collisions. This thesis presents the first results of similar studies in this collision system and, therefore, can bring new information on baryon or strangeness production mechanisms.

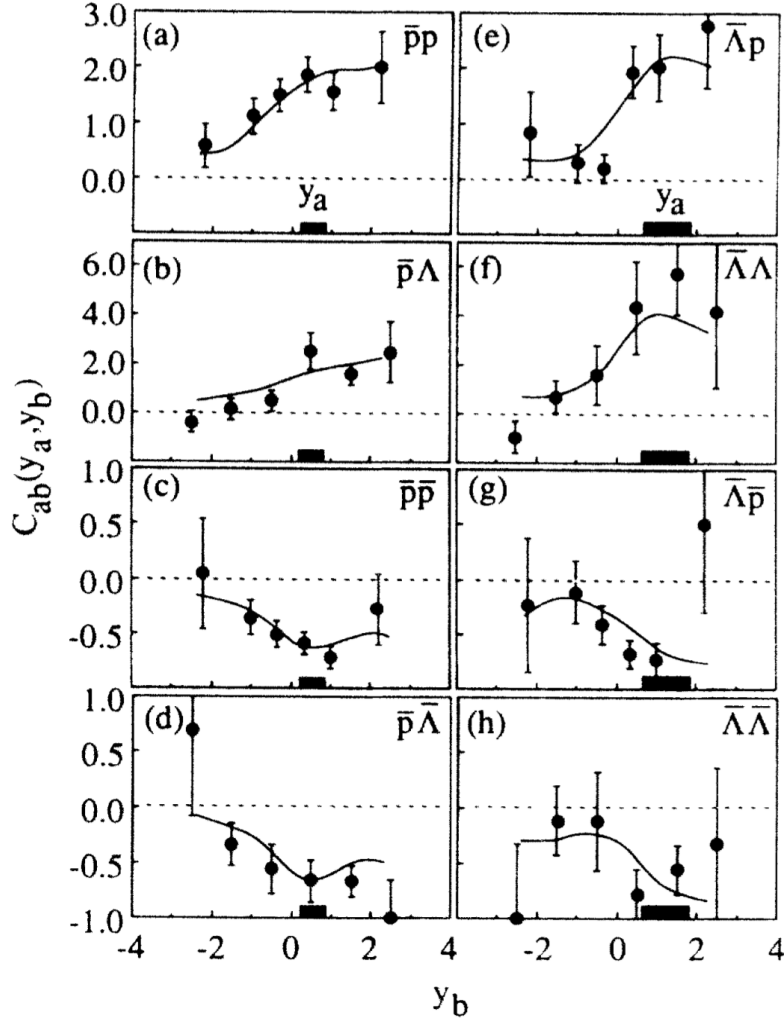


Figure 3.7: (a)–(d) Correlation function $C_{ab}(y_a, y_b)$ for a $\bar{p}$ in the rapidity interval $0 < y < 1.25$ and an additional baryon b at rapidity y_b , for (a) p , (b) Λ , (c) $\bar{p}$, (d) $\bar{\Lambda}$. The rms width of the rapidity distribution of the $\bar{p} a$ is indicated by the black bar. (e)–(h) The corresponding correlation functions for a $\bar{\Lambda}$ in the rapidity range $y_a > 0$ as particle a . Curves indicate predictions by the Lund hadronization model. From Ref. [87].

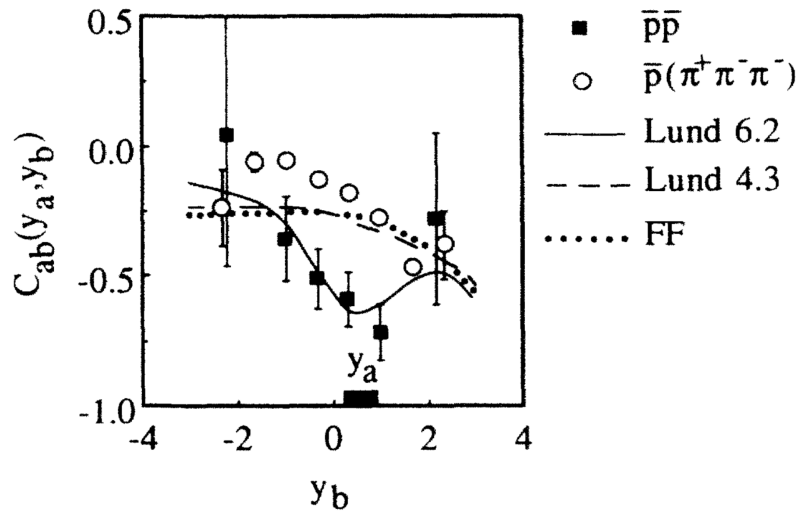


Figure 3.8: Comparison of the measured $\bar{p}\bar{p}$ correlation function (see Fig. 3.7 (c)) with the correlation observed between a $\bar{p}$ and a $\pi^+\pi^-\pi^-$ system in the 2–3 GeV mass range. Also shown are predictions of $C_{\bar{p}\bar{p}}$ from the “symmetric” Lund fragmentation model (solid line), the “standard” Lund model (dashed line), and the Lund model with Feynman-Field fragmentation functions (dotted line). The “symmetric” Lund model is the only one that incorporates rank-rapidity correspondence. From Ref. [87].

3.2.2 Resonance studies with two-particle angular correlations

Resonance particles, or resonances, are extremely short-lived particles (their lifetime is of the order of 10^{-23} seconds) formed via hard processes. Traveling at almost the speed of light, prior to the decay these particles can only move about 10^{-15} meters. Resonances are usually characterized by the energy released in the decay of the particle at rest Q .

Contributions from resonances to $\Delta\eta\Delta\phi$ correlation functions as well as the structures they produce were studied in detail by ISR and PHOBOS experiments:

- The ISR [94] states that a mesons' decay can produce structures near $\Delta\phi = \pi$ (two particles traveling at opposite directions). Any two-body decay with a Q value large in comparison with its transverse momentum will behave in the same way as the mesons. Three-body decays can produce different structures i.e. at near-side or contributing to the longitudinal ridge. Calculated correlation functions are presented in Fig. 3.9.

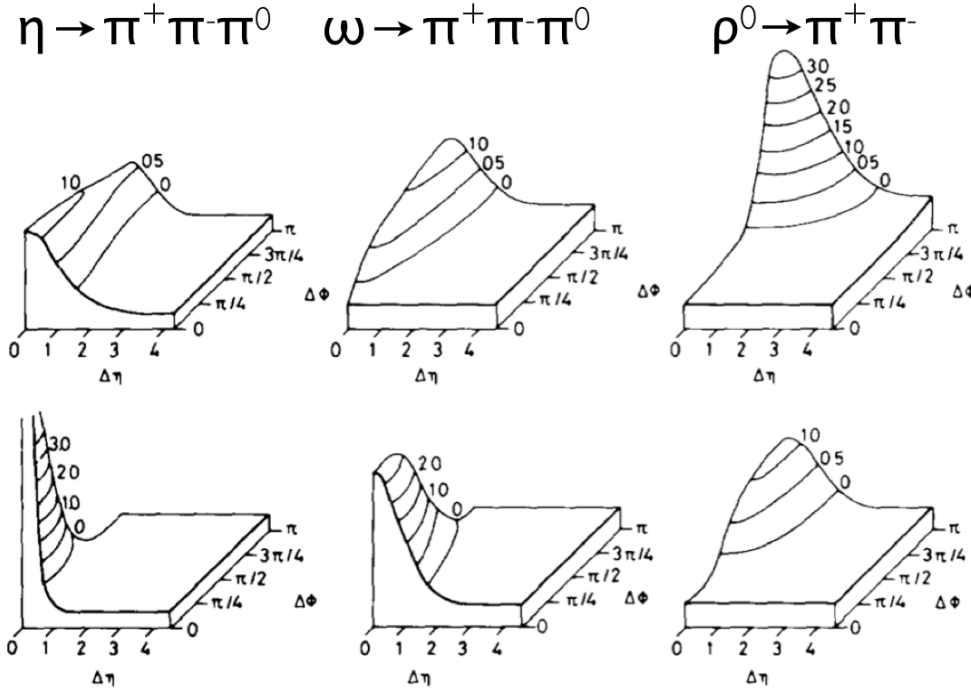


Figure 3.9: Calculated angular correlation functions, $C^{II}(\Delta\eta, \Delta\phi)$, for $\rho^0 \rightarrow \pi^+\pi^-$, η and $\omega \rightarrow \pi^+\pi^-\pi^0$ decays. Invariant cross sections for meson production have the form $\exp(-1/4y^2) \times \exp(-Bp_T)$, where y and p_T are the rapidity and transverse momentum of the decaying meson. B has the value 6 GeV^{-1} in the case of the top curves. For the bottom curves, B was adjusted to yield an invariant cross section of the form $\exp(-6p_T)$ for the decay pions. Density functions are normalized in the square $|\eta| < 2.5$. Lines of constant $C^{II}(\Delta\eta, \Delta\phi)$ are labeled in units of 10^{-3} . From Ref. [94].

- The PHOBOS experiment studied the longitudinal structure centered in $\Delta\eta \approx 0$ at collision energies of $\sqrt{s} = 200$ GeV and 410 GeV [95]. They reported that “*the qualitative features of the observed correlation structure are consistent with an independent cluster approach, and refer to a simulation study from the ISR experiment using a low-mass resonance (ρ, ω, η) gas model.*” Correlation functions from pp data measured by PHOBOS are shown in Fig. 3.10.

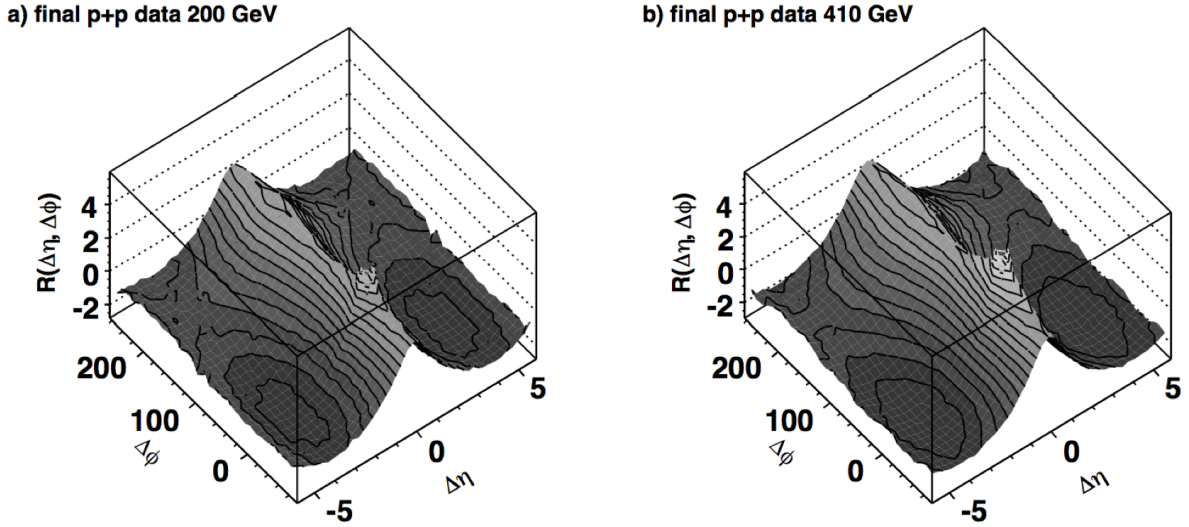


Figure 3.10: PHOBOS results consistent with the low-mass resonance gas model used earlier by ISR to explain the longitudinal structure. From Ref. [95].

- The CMS experiment refers to the analysis of ISR and PHOBOS. In the results published in Ref. [96] (also shown in Fig. 3.11) an approximately Gaussian ridge at $\Delta\eta \approx 0$ is visible. It extends over the whole range of $\Delta\phi$ and becomes broader toward larger $\Delta\phi$ values. The result was compared with Pythia; qualitatively, a similar structure also exists in this MC model, although it does not reproduce the strength of the correlations seen in the data. They report that it arises from the decay of clusters with lower transverse momenta (e.g., soft QCD string fragmentation). The qualitative features of the structures that were observed in the data agree with an independent cluster approach employed in the simulations performed by the ISR experiment with a low-mass resonance (ρ, ω, η) gas model as well as a isotropic cluster decays model used by the PHOBOS experiment. Moreover, in Ref. [97] it is stated that although the qualitative features are the same, the short-range correlation strength exceeds the expectation from the decays of resonance particles, suggesting the need for other short-range correlations.

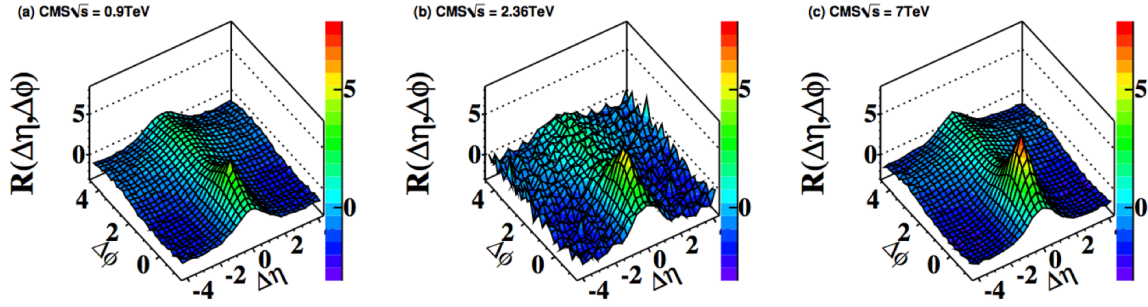


Figure 3.11: CMS results consistent with ISR and PHOBOS results. From Ref. [96].

3.2.3 Flow studies with two-particle azimuthal correlations

In the previous sections we have focused on angular structures mostly visible in small systems. If heavy-ion collisions are considered, while studying the two-particle correlations we have to take into account the additional contribution coming from collective effects, i.e. *flow*, creating distinct correlations extending to large $\Delta\eta$, as can be seen in Fig. 3.12-left.

Those azimuthally dependent collective motions are usually [98–100] analyzed in terms of a Fourier expansion of the azimuthal (angular) correlation function with respect to the reaction plane:

$$\frac{dN}{d\varphi} = \frac{N}{2\pi} \left[1 + \sum_n 2v_n \cos(n\Delta\varphi) \right], \quad (3.10)$$

with the first order component ($v_1 \propto \cos(\varphi)$) called *directed flow*⁵ and the second order component ($v_2 \propto \cos(2\varphi)$) being the experimental observable related to *elliptic flow*⁶. An example of the correlation function together with the distribution resulting in from the superposition of the first five harmonics of the Fourier decomposition can be seen in Fig. 3.12-right.

In addition to the contributions due to collective flow effects, the two-particle azimuthal correlations also receive significant contributions from other correlation sources, like resonances, minijets, femtoscopy. Such non-flow contributions are usually short-ranged. Therefore, to limit the influence of those additional effects, the measurements aiming to study collective flow phenomena focus on long-range correlations. To determine precisely the range in $\Delta\eta$ in which non-flow contributions are minimal, the $\Delta\eta\Delta\varphi$ correlation functions are studied.

⁵Directed flow is created by a non-zero density gradient between the innermost and outermost regions of the fireball.

⁶Elliptic flow is related to anisotropic hydrodynamic expansion of the medium from an anisotropic (almond-shaped) initial state.

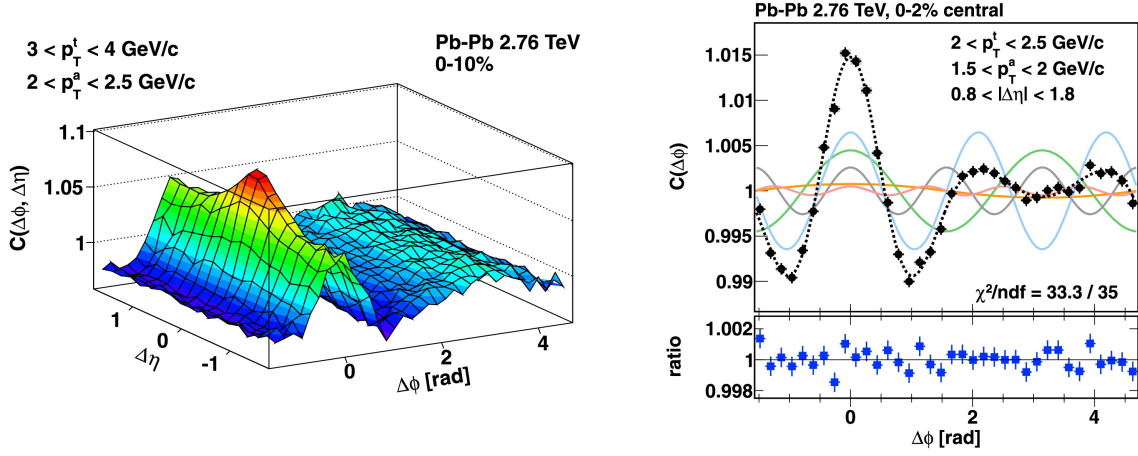


Figure 3.12: Left: example of two-particle correlation functions $C(\Delta\phi, \Delta\eta)$ for central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at low to intermediate transverse momentum. Right: $C(\Delta\phi)$ for particle pairs at $0.8 < |\Delta\eta| < 1.8$. The Fourier harmonics for v_1 to v_5 are superimposed in color. Their sum is shown as the dashed curve. The ratio of data to the $n \leq 5$ sum is shown in the lower panel. From Ref. [100].

Although the analysis of heavy-ion collisions is not the topic of this thesis, it should be mentioned that the observation of robust collective flow phenomena in heavy-ion reactions [101, 102] is probably the most direct evidence for the creation of a macroscopic, strongly interacting, dense matter in nuclear collisions. By comparison of the measurements with hydrodynamic model calculations we can extract properties like the equation of state, sound velocity or shear viscosity. The measurements [103] of the high order harmonic terms (measurable and significant up to at least 6th order) that made the observation and interpretation of complex correlations straightforward and unambiguous⁷ is argued to be one of the most important LHC results [104]. The pp results are an important baseline for those studies; the results presented in this thesis provide a contribution enabling comparisons between elementary systems and QGP created in heavy-ion collisions. Example of flow measurements from ALICE is presented in Sec. 4.6.1.3.

⁷As stated in Ref. [104], before 2011, “the observed structures were in general not recognized as hydrodynamic in origin but discussed in terms of fancy names (“near side ridge, away side cone”) and fancy explanations (“gluon Cerenkov radiation, Mach cone, ...”)” [105].

3.2.4 The Ridge

The *Ridge*⁸, a correlation at small $\Delta\phi$ and large $\Delta\eta$, also commonly referred to as *long-range correlation*, was first observed in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV at RHIC by the STAR experiment [111]. The initial measurement of two-particle correlations was performed relative to a high momentum trigger particle $p_{\text{T}} > 4$ GeV/c. Subsequently the correlations were measured at momenta in the (semi-)soft range for both trigger and associated particle⁹. Measurements were also performed using untriggered correlations [112, 113]. It has been observed that the ridge extends to several units in η by both PHOBOS [112] and STAR [114]. Figure 3.13 shows an untriggered two-particle angular correlation function for Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV with the ridge structure clearly visible.

As stated in the Sec.3.2.3, the standard explanation of the ridge in heavy-ion collisions is associated with collective flow phenomena, characteristic of bulk macroscopic systems [115, 116] (see also Sec. 4.6.1). In particular, angular collimation in azimuthal angle ϕ can be attributed to the radial flow that boosts particles along the radial direction [117, 118].

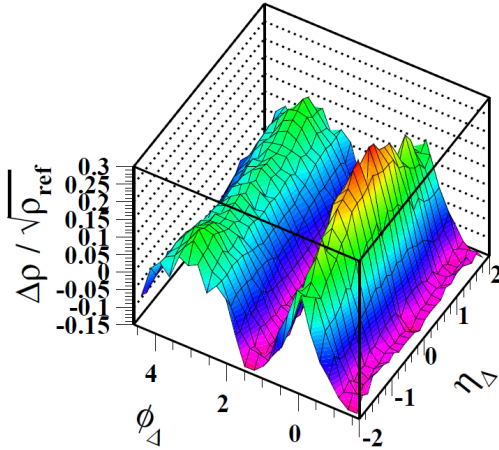


Figure 3.13: Untriggered (no p_{T} cut) two-particle correlations as a function of $\Delta\eta$ and $\Delta\phi$ in the top 5% central Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. From STAR [119].

However, to the great surprise of the community a mysterious “long range rapidity correlation” was found by the CMS Collaboration also in a tiny subset of extremely high multiplicity pp collisions at $\sqrt{s} = 7$ TeV [96]. This structure, often described as the first LHC discovery [104], is shown in the left panel of Fig. 3.14.

⁸Capital letter used deliberately. Due to the notoriety of this effect in the recent years, referring to “the ridge” without further explanation is usually a relation to this particular structure [106–110].

⁹When pairs of particles are formed we can specify different selections for each of the particles of the pair. In such case first particle in the pair is referred to as “trigger” and the second one as “associated.”

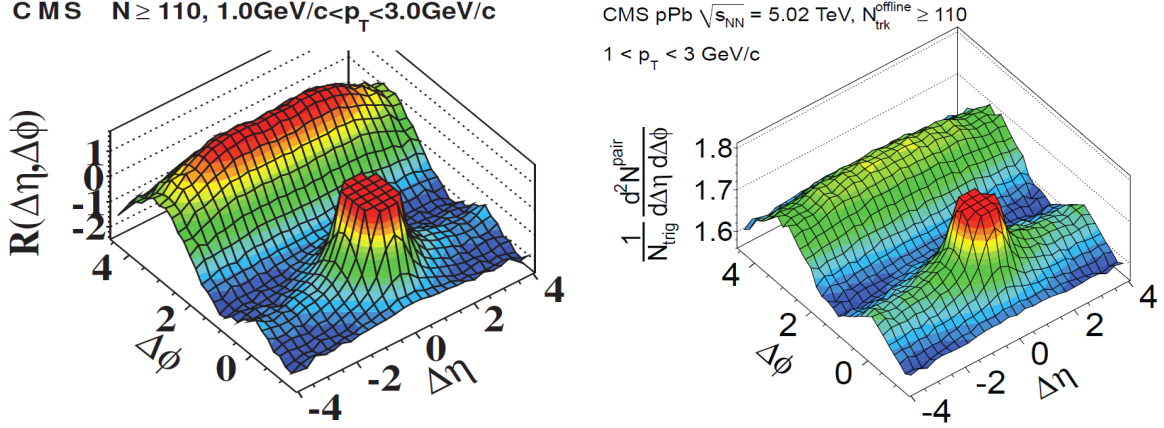


Figure 3.14: Two-particle correlation functions in $\sqrt{s} = 7$ TeV pp [96] (left panel) and $\sqrt{s_{NN}} = 5.02$ TeV p–Pb [120] (right panel) collisions for pairs of charged particles. High-multiplicity events with $N_{\text{trk}}^{\text{offline}} > 110$ (at $|\eta| < 2.4$ and $p_T > 0.4$ GeV) are used. From CMS [96, 120].

The CMS detector measured angular correlations between charged particles up to $|\Delta\eta| < 5$ and over the full range of $\Delta\phi$ in pp collisions at $\sqrt{s} = 7$ TeV. The ridge structure is clearly seen for large rapidity differences $|\Delta\eta| > 2$ in events with an observed charged particle multiplicity of $N_{\text{trk}}^{\text{offline}} > 90$. It is most pronounced in the intermediate transverse momentum range, $1 < p_T < 3$ GeV/c. The structure resembled similar features observed in heavy-ion experiments, however, the underlying physics of this observation in small systems is still to be investigated.

Further detailed studies were performed at the LHC p–Pb run at $\sqrt{s_{NN}} = 5.02$ TeV. A ridge correlation was observed by all three LHC experiments [120–122]¹⁰. The result from CMS [120] is shown in the right panel of Fig. 3.14. The ridge in p–Pb is significantly larger than in pp for data samples in the same multiplicity range and p_T range. However, the dependencies of the ridge magnitude on both the transverse momentum and event multiplicity are consistent between pp and p–Pb collisions.

The origin of the ridge structure in small systems is still under discussion. The results from pp and p/d–A “data spawned a large variety of different explanations, from mildly speculative to outright weird” (following Ref. [104]). The most serious candidates are saturation physics, as formulated in the Color Glass Condensate model (CGC)¹¹, and collective hydrodynamic flow [102, 104]. Recent reviews of the ridge effect can be found in Refs. [125–128].

¹⁰Moreover, the PHENIX experiment motivated by the p–Pb data from the LHC has analyzed the d–Au data at $\sqrt{s_{NN}} = 200$ GeV at RHIC [123].

¹¹The Color Glass Condensate is a state of high density gluonic matter proposed as an initial state preceding a QGP formation [37, 124].

3.2.5 Minijet studies with two-particle angular correlations

Jets (minijets), explained in detail in Sec. 2.4.5, create characteristic and very distinct structures in $\Delta\eta\Delta\phi$ correlation functions. This makes the angular correlations a perfect tool to study minijet production and their contribution to the correlation landscape.

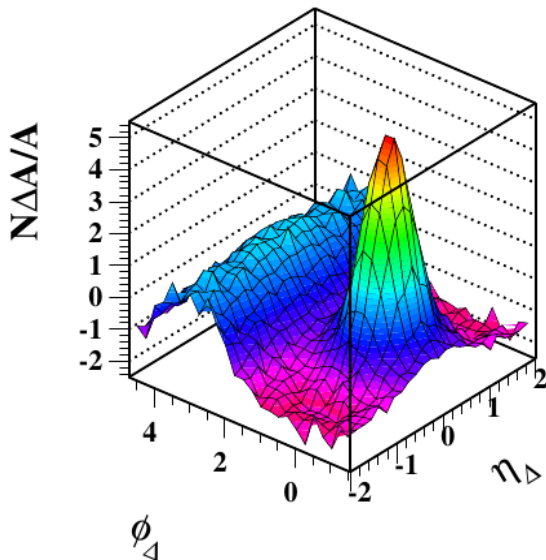


Figure 3.15: Hard component of the $\Delta\eta\Delta\phi$ correlation function. From STAR [129].

Two distinctive structures should be mentioned: a large peaked distribution at small opening angles $(\Delta\eta, \Delta\phi) \approx (0, 0)$ and a broad $\Delta\eta$ -independent structure at $\Delta\phi \approx \pi$, coming from back-to-back jet correlations [130]. Both structures are visible in Fig. 3.15. Minijet contributions are most pronounced for high- p_T particles. More information is provided in Sec. 3.3.

Minijets were studied in pp collisions [131–134], as well as in larger systems [100, 135–137]. It should be also mentioned here that angular correlations are extensively used for medium modification studies, i.e. measurement of the *jet quenching* effect [138, 139].

3.2.6 Non-femtoscopic correlation studies with femtoscopy and two-particle angular correlations

Femtoscropy is a measurement allowing to study the size and the space-time evolution of the particle emitting sources (for recent reviews see e.g. Refs. [80, 140, 141]). It is a technique based on nuclear interferometry developed by Hanbury-Brown and Twiss (HBT) in astronomy [142, 143] to measure the size of the stars; it is also applied to measure the size and lifetime of the systems created in high-energy collisions [144]. It allows to combine the momentum

characteristics of particles registered by the detectors with the space-time characteristics of the sources. Generally, the extracted source parameters, as measured by the femtoscopy, are driven by space-time correlations; therefore, the results are sensitive to expansion dynamics integrated throughout the collision.

Femtoscopic techniques are widely used to study heavy-ion collisions [145–148]. Due to Bose-Einstein statistics in case of identical bosons (e.g. pions) an excess of pairs at low relative momenta exists which is inversely proportional to the size of the system at freeze-out [149]. It is predicted that those source sizes will grow with rising multiplicity. Moreover, a decrease of the extracted radii with pair transverse momentum, $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$, is interpreted as a sign of hydrodynamic collectivity. An example of the correlation function for pion pairs, obtained from such measurement, is shown in Fig. 3.16.

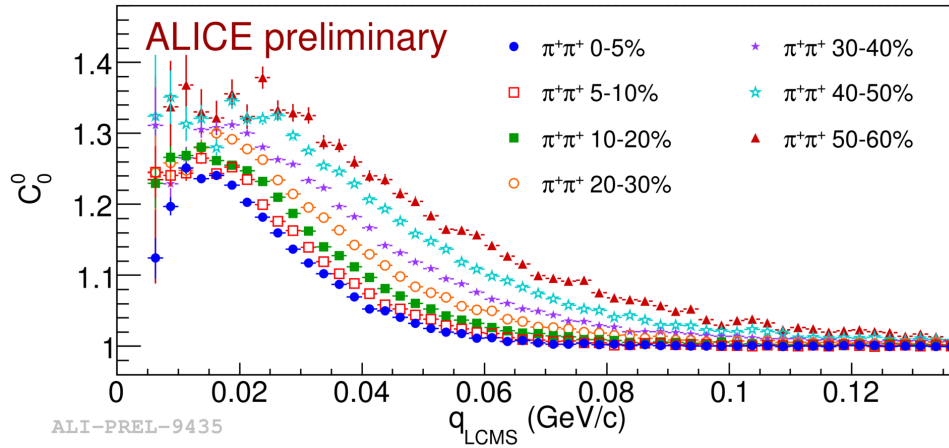


Figure 3.16: Comparison of the C_0^0 component of the femtosopic correlation functions in spherical harmonics representation for $\pi^+\pi^+$ for seven centrality classes for $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb collisions. Excess of pairs at low relative momenta due to Bose-Einstein statistics can be observed. It can be seen that source sizes (correlation width) decrease (increase) with decreasing multiplicity of the event. Functions are flat for high q values. From Ref. [150].

However, if smaller systems (e^+e^- [151, 152], pp [153–156], d–Au [157, 158], p–Pb [159]) are studied, an additional non-femtoscopic component (not directly related to the spatio-temporal scales of the emitter) arising from other type of correlations has to be taken into account [154, 160]. This component can be seen in Fig. 3.17 as a non-flat wide structure, which extends up to 1.0 GeV/c (note different scales on x -axis between Fig. 3.16 and Fig. 3.17). It is most visible for the highest k_T range. If these were femtosopic-like structures, they would correspond to the emission region of an unusual size of 0.2 fm. The problem of disentangling

non-femtoscopic structures from the femtoscopic peak must be addressed to obtain proper results.

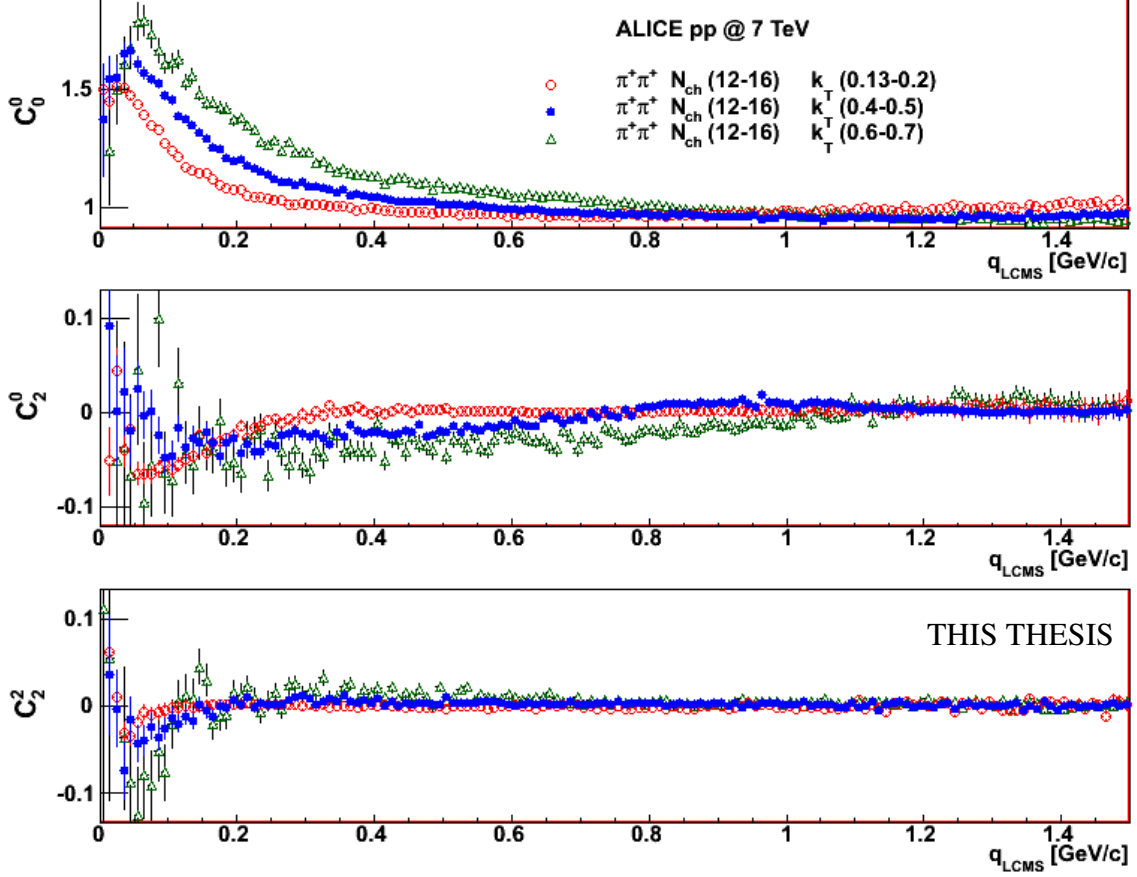


Figure 3.17: Components of the spherical harmonics decomposition of the $\pi^+\pi^+$ femtoscopic correlation functions for three k_T ranges for $\sqrt{s} = 7$ TeV pp collisions. Excess of pairs at low relative momenta due to Bose-Einstein statistics can be observed. Additionally, the slope, a manifestation of the non-femtoscopic contributions, extending till $q = 1$ GeV/ c is clearly visible.

The most common procedure is to use results from Monte Carlo calculations in models that do not include the wave function symmetrization for identical boson pairs. An example of such calculations are shown in Fig. 3.18. Characteristic slopes, rising with k_T , are clearly visible. As a next step, MC functions can be used to correct the data. Alternatively one can use MC information during the fitting procedure.

Although the existence of this non-femtoscopic structure is well established, its origin is not yet clear. There is a hypothesis, introduced in Ref. [153] that these correlations may originate from minijets. Minijets are well reproduced by common MC generators; they also are

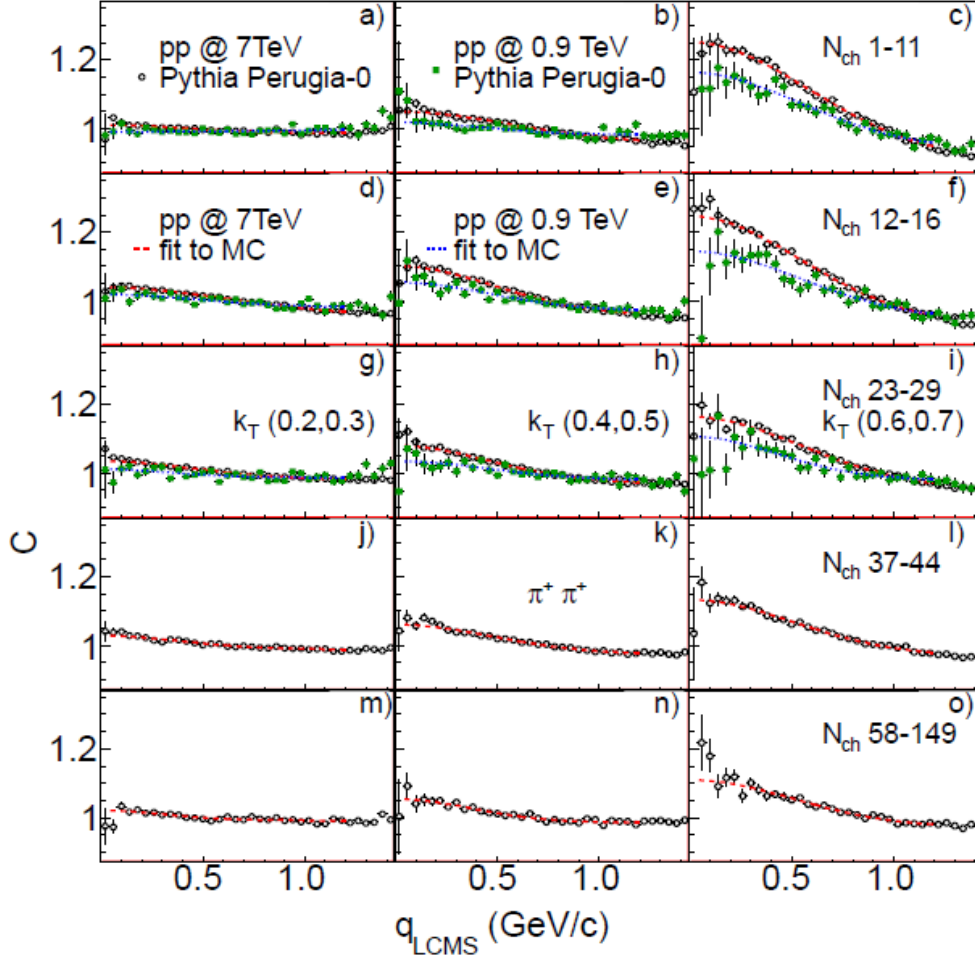


Figure 3.18: C_0^0 components of spherical harmonics decomposition for the pp Pythia Monte Carlo data at collision energies of $\sqrt{s} = 7$ TeV (open black dots) and $\sqrt{s} = 0.9$ TeV (closed green dots) for selected k_T ranges. Characteristic slopes rising with k_T from non-femtoscopic effects are clearly visible. From Ref. [154].

more pronounced for higher pair transverse momenta (k_T). Since a natural representation to study minijets is the $\Delta\eta\Delta\varphi$ correlation function, such a comparative analysis was employed for this thesis (see Appendix A.2). Moreover, there is a direct relation between $\Delta\eta$, $\Delta\varphi$ and the components of relative momentum of the pair q , which are used in femtoscopic studies (see Appendix A.1).

Results from the $\Delta\eta\Delta\varphi$ correlation studies on the non-femtoscopic background are discussed in detail in Sec. 7.1.4.

3.3 Expected correlation sources

In the previous section different studies of two-particle correlations have been presented. Here we focus on $\Delta\eta\Delta\phi$ angular correlation measurements that are the subject of this thesis. The $\Delta\eta\Delta\phi$ distribution gives us a visual impression of the whole landscape of correlations. In general it is sensitive to a number of correlations originating from different sources i.e. minijets, elliptic flow, Bose-Einstein correlations, resonance decays, photon conversions, conservation laws, etc. The final result is the combination of all those correlations. Each of the correlation sources has its own structure in $\Delta\eta\Delta\phi$ space. The goal of this study is to decompose them and gain information from each contribution separately.

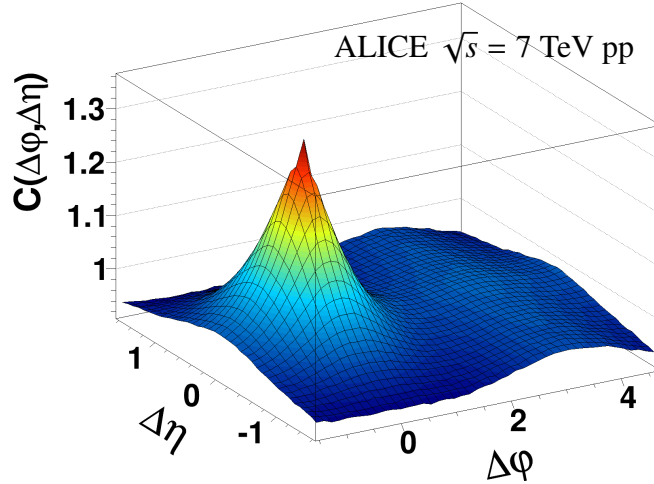


Figure 3.19: $\Delta\eta\Delta\phi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data.

Figure 3.19 shows the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 7$ TeV pp minimum bias collision data.

Contributing effects

Conservation laws

The production of particles in the collision is governed by the energy and momentum conservation laws on the global scale. Strangeness and baryon number are also compensated by producing the same number of strange quarks and antiquarks as well as baryons and antibaryons. Since every single collision is an independent system, it must conserve all of these quantities.

However, it was shown [68, 86–91] that for each parton fragmentation the conservation laws are also obeyed locally. A parton fragments isotropically in its rest frame which results in a boosted stream of particles due to the partons' initial momentum. That fragmentation should conserve the initial momentum, charge, strangeness, and baryon number of a parton (for gluon only momentum, for quark it could be also other mentioned variables) which is an additional constraint to the global-scale conservation laws.

The conservation laws influence the shape of the correlation function especially in small systems. Momentum conservation ensures that for all particles going in similar direction, there would be also a number of particles going in the opposite direction, creating a specific structure shown in Fig. 3.20. The momentum conservation law is especially important while considering back-to-back minijets (further explanation in the next subsection). Moreover, a valuable source of information on the conservation laws is the analysis of correlations of pairs of particles with different charge, strangeness or baryon number combinations. It is expected that antimatter and matter are governed by the same physics laws. Hence, the pairs of either particle-particle or antiparticle-antiparticle can be treated in the same manner and can be called commonly *like-sign pairs*. However, the interactions between particle and antiparticle differ and such pairs can be called *unlike-sign pairs*. Due to the charge, baryon number and strangeness conservation laws we would expect more unlike-sign pairs produced close together in phase space than like-sign pairs, creating appropriate differences in the near-side peak (peak at $\Delta\eta\Delta\varphi \approx 0, 0$) structures. As mentioned in Sec. 3.2.1 those differences can provide useful information e.g. on baryon or strange particles production mechanisms and are one of the topics studied in detail in this thesis.

Minijets

In the processes of parton scattering with high-momenta transfers in a short time, cascades of collimated quarks and gluons are created. They finally hadronize producing collimated streams of hadrons, called *jets* or (at low-momenta) *minijets* (see Sec. 2.4.5).

The $\Delta\eta\Delta\varphi$ analysis was developed mainly as a tool to study minijets. It is based on the two-particle correlation effects created by jets and while low-momentum jets cannot be reconstructed event-by-event, their event averaged effect generates an observable correlation. Moreover, from the momentum conservation law, if a collimated stream of particles is created, their momenta need to be compensated with particles going in the opposite direction. A schema of the two-minijet production (called also *back-to-back* minijets) is presented in Fig. 3.21.

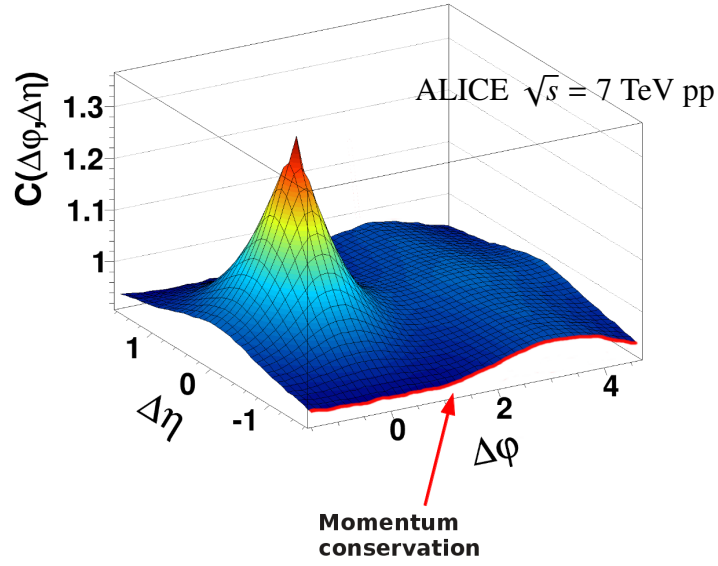


Figure 3.20: Contribution from momentum conservation to the $\Delta\eta\Delta\phi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data.

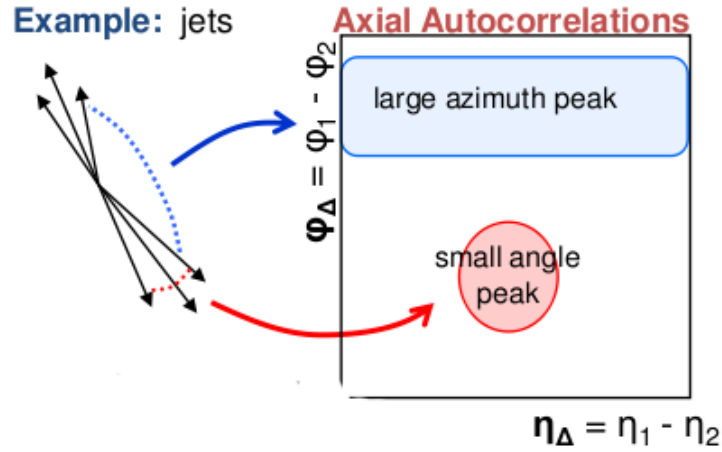


Figure 3.21: The contribution of the minijets to the $\Delta\eta\Delta\phi$ correlation function. Particles coming from the same minijet produce the near-side peak (red), and particles from two opposite back-to-back jets produce the away-side ridge (blue). From Ref. [161].

To understand the process of obtaining a certain shape in $(\Delta\eta, \Delta\phi)$ coordinates for minijets we look at jets as streams of particles. While looking at pairs of particles coming from jets, there are two scenarios:

1. Both particles come from the same jet. In this case both particles are going in almost the same direction; therefore, there is a small difference between their azimuthal angles, $\Delta\phi$,

and also a small difference of their polar angle $\Delta\theta$, and therefore (by $\eta = -\ln \tan(\theta/2)$) small $\Delta\eta$. Pairs of particles from the same jet form a minijet peak centered at (0,0) – latter referred to as the *near-side peak*.

2. Particles are from two opposite back-to-back jets. Then, $\Delta\varphi$ is close to 180° . However, there is no such dependence on $\Delta\theta$. θ depends on how jets are placed in space; so, for many events and many jets, $\Delta\eta$ is uniform, producing a wide ridge for $\Delta\varphi = \pi$ – later referred to as *away-side ridge*.

Figure 3.22 shows the $\Delta\eta\Delta\varphi$ correlation function for the $\sqrt{s} = 7$ TeV pp collision data with contributions coming from minijets marked with a dashed line.

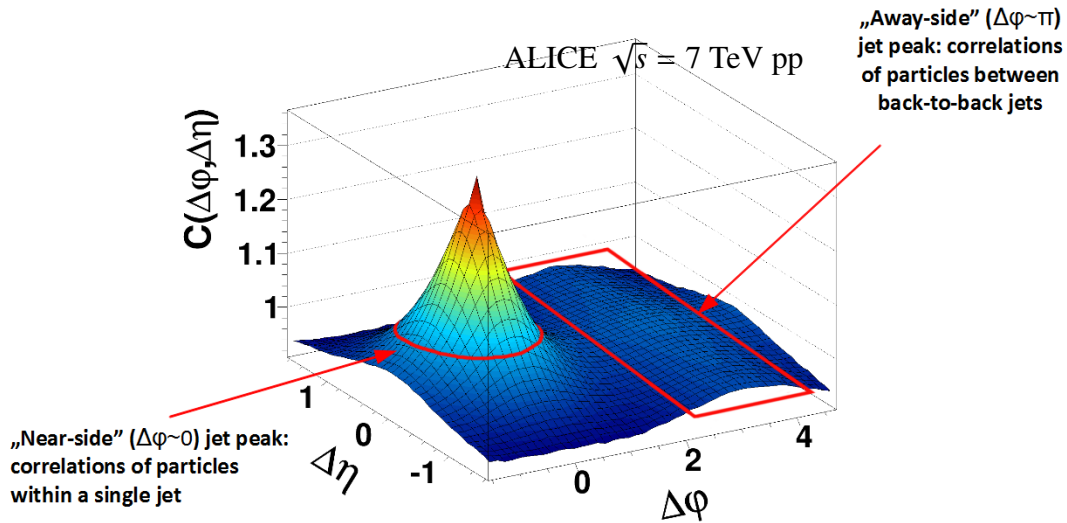


Figure 3.22: The contribution from minijets to the $\Delta\eta\Delta\varphi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data.

Bose-Einstein correlations

Bosons (e.g. pions) obey Bose-Einstein statistics, i.e. the wave-function describing two identical bosons is symmetric under particle exchange. This means that pairs of identical bosons are likely to be emitted in the same quantum state (see also Sec. 3.2.6); so, with similar η and φ . Therefore we have an additional contribution from this kind of correlations to the near-side peak. Figure 3.23 shows the contribution coming from Bose-Einstein correlations.

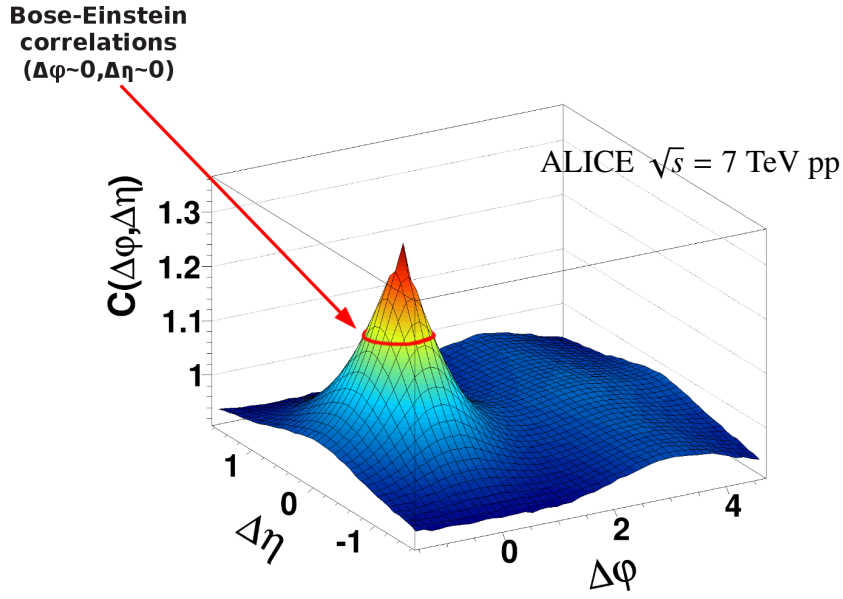


Figure 3.23: The contribution from the Bose-Einstein correlations to the $\Delta\eta\Delta\phi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data.

Resonances

Resonances, as was mentioned in Sec. 3.2.2, are short-lived particles, which decay isotropically in their rest frame. Decaying resonances produce correlated particles, which are emitted over a broad range of energy, but with a tendency to move in the direction that reflects the initial momentum of the resonance. It is associated with value Q , which is the kinetic energy released in the decay of the particle at rest. If Q is low enough in comparison with the transverse momentum particles will end up with small difference in $\Delta\eta$ and $\Delta\phi$. This way they give a contribution to the near-side peak of the $\Delta\eta\Delta\phi$ correlation function. However, if the Q value is large or we are dealing with a three-body decay this can give a correlation contributing to the *longitudinal ridge structure*.

Longitudinally fragmenting strings

The string fragmentation models treat gluons as field lines, which are attracted to each other due to the gluon self-interaction and therefore form a narrow tube (or string) of strong color field, see Sec 2.4.4. If enough energy is stored in the string, it may break up resulting in the production of new quarks. In high energy collisions, the energy is placed along the beam axis, that is why such strings will fragment in the longitudinal direction. Hadrons which are produced in this

process will have a small difference in $\Delta\eta$ and there will be no dependence in $\Delta\varphi$; therefore, they will contribute creating the “longitudinal ridge”. The STAR experiment explained [132] the longitudinal ridge structure as a product of longitudinally fragmenting strings.

Figure 3.24 shows contributions coming from resonances and longitudinally fragmenting strings.

Photon conversion

Gamma conversion, also referred to as *photon conversion*, is a process in which a photon is converted into an electron and a positron in the proximity of an additional object (usually a nucleus or subatomic particle), so that the energy and momentum are conserved. Production of electron-positron pair by photon conversion is an example of the pair production mechanism: direct conversion of a neutral boson to an elementary particle and its antiparticle. Such process of energy materialization is predicted by the theory of special relativity and is described by quantum electrodynamics. The pair production can occur if the photon energy $\hbar\nu$ (where $\hbar$ is the reduced Planck’s constant and ν is the photon frequency) exceeds at least twice the rest mass of the electron $2m_e c^2 = 1.022 \text{ MeV}/c^2$.

Electrons and positrons originating from photon conversion tend to go in almost the same direction, with small angle differences; therefore, they also contribute to the near-side peak. The effect is a very narrow (in comparison to experimental momentum resolution) spike at $\Delta\eta\Delta\varphi \approx (0, 0)$. Figure 3.24 shows contributions coming from photon conversion.

Coulomb interactions

Due to the Coulomb final state interactions, the particles carrying the same electric charge repel and those with opposite charge attract each other. This effect is visible for particles close enough in momentum space, therefore it influences the near-side peak. For like-sign pairs of particles it decreases that structure and for the unlike-sign pairs of particles it increases the magnitude of the near-side peak.

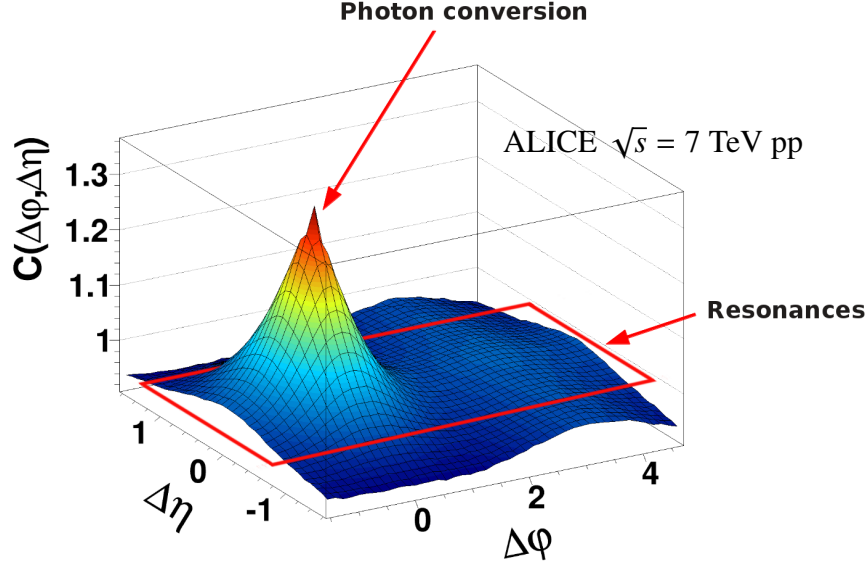


Figure 3.24: Contribution coming from resonances and photon conversion to the $\Delta\eta\Delta\phi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data.

Ridge structure

The ridge structure, explained in detail in Sec. 3.2.4, is a broad correlation for $\Delta\phi \approx 0$ extending to large $\Delta\eta$ values. However, it is not expected to be observed in minimum bias pp collisions. Moreover, in the η acceptance of the ALICE experiment even for high multiplicity collisions studies of this structure is difficult. The acceptance of the ALICE central barrel is $|\eta| < 0.9$, which results in $|\Delta\eta| < 1.8$. The ridge effect is usually studied for $|\Delta\eta| > 2.0$. Therefore, the expected effect is convoluted with widening of the pronounced minijet peak.

Elliptic flow

Collective effects introduce correlations among particles which manifest as a contribution from the anisotropy parameter ($v_2 = \langle \cos 2\phi \rangle$) – elliptic flow – that adds a $\cos(2\Delta\phi)$ type oscillation. Also, higher order harmonics v_n can contribute to the overall shape of the correlation function in a non-trivial manner; relevant studies were extensively performed for heavy-ion collisions. However, there is no experimental evidence of collective effects in minimum bias pp collisions registered at the LHC. More information on the correlations originating from elliptic flow is provided in Sec. 3.2.3.

Overall picture

Contributions coming from all the above mentioned correlation sources, combine to create one collective distribution of different physical phenomena that are related to the collisions of particles. Figure 3.25 shows the different contributions creating this global picture of the correlation function.

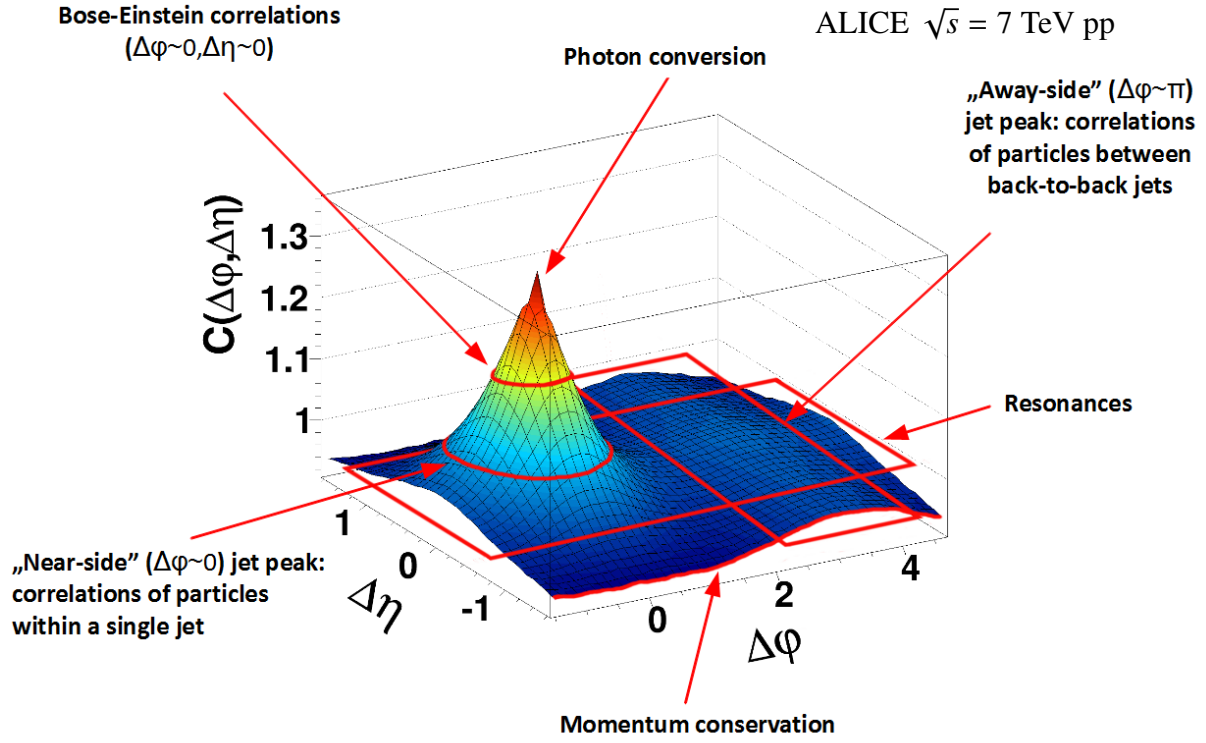


Figure 3.25: Contributions from different correlation sources to the $\Delta\eta\Delta\phi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data.

Chapter 4

ALICE experiment

A Large Ion Collider Experiment (ALICE) [162] is optimized to investigate the new deconfined state of matter, the Quark-Gluon Plasma (QGP), which is created in high-energy heavy-ion collisions. This chapter describes the experimental setup of the ALICE detector at the LHC, with special emphasis on the sub-detectors which are important for recording the data and performing the analysis for this thesis.

4.1 Large Hadron Collider

The Large Hadron Collider (LHC), built by the European Organization for Nuclear Research (CERN) on the borders of Switzerland and France, is the biggest particle accelerator in the world. It is a synchrotron which accelerates two beams of particles in opposite directions in separate beam pipes. LHC is designed to accelerate protons at energies up to 7 TeV and lead ions up to 2.76 TeV/nucleon which provides collisions at a center of mass energy of 14 TeV for protons and 5.52 TeV/nucleon for lead ions.

The accelerator started its operation in 2009¹ with proton-proton collisions at a center of mass energy $\sqrt{s} = 900$ GeV and later at 2.36 TeV, which was already the largest achievable so far in high-energy physics experiments. Subsequently, the energy was increased to $\sqrt{s} = 7$ TeV in March 2010 and to $\sqrt{s} = 8$ TeV in March 2012. The first run with lead beams took place in November 2010 at $\sqrt{s_{NN}} = 2.76$ TeV. The LHC is also able to accelerate proton and lead beams in two rings and perform asymmetric collisions. Such collisions were taken on September 2012 and at the beginning of 2013.

¹The first beam actually circulated on September 2008, but 9 days after the start-up a faulty electrical connection caused the accelerator to postpone the data-taking by another year.

Beams collide in four collision points where the main experiments are located: ALICE, ATLAS², CMS³ and LHCb⁴. Three of them are involved in heavy-ion programme, namely the two general-purpose detectors ATLAS [163] and CMS [164], and the dedicated heavy-ion detector ALICE. LHCb also participates, contributing with measurements of the p–Pb which is used as a reference system to compare to the results of the Pb–Pb collisions.

4.2 Physics programme

The main goal of the ALICE experiment is to perform comprehensive studies of the QGP signatures that may also lead to discoveries of new phenomena which can occur at the very high energies of the LHC [165]. ALICE measures a number of observables which characterize the different stages of the collision [166, 167] including detection of large variety of hadrons, as well as electrons, muons, and photons. The most distinctive features of the experiment are its excellent tracking and particle identification capabilities over a broad momentum range, from just a few MeV/*c* as far as 100 GeV/*c*. This opens up the possibility of studying physics from “soft” to “hard” interactions.

In addition to heavy systems, ALICE studies collisions of protons (both pp and p–A), which principally provide a reference for the nucleus-nucleus collisions. The pp data allows also for a number of genuine pp physics studies, as described in Sec. 2.3. Finally, other physics subjects within the capabilities of ALICE shall also be mentioned, e.g. cosmic-ray physics or ultra-peripheral collisions.

4.3 Experimental setup

In ALICE, detection and identification of hadrons, electrons, and photons is performed in the mid-rapidity region ($-0.9 < \eta < 0.9$) by a number of dedicated detectors immersed in a moderate (0.5 T) magnetic field. Tracking relies on a set of high-granularity detectors: an Inner Tracking System (ITS) consisting of six layers of silicon detectors, a large-volume Time-Projection Chamber (TPC) and a Transition-Radiation Detector (TRD). The identification of particles is

²A Toroidal LHC Apparatus

³Compact Muon Solenoid

⁴Large Hadron Collider beauty

4.3. EXPERIMENTAL SETUP

based on the number of different techniques, including the measurements of the energy loss in the tracking detectors, time-of-flight in TOF, transition radiation in the TRD as well as the Cherenkov radiation in the High-Momentum Particle Identification Detector (HMPID), and photons are detected with Photon Spectrometer (PHOS). The Electro-Magnetic Calorimeter (EMCAL) provides a trigger for high- p_T particles and improves measurements of jets. ALICE Cosmic Ray Detector (ACORDE), placed on top of the ALICE magnet, is designed to detect cosmic rays. Supplementary detectors placed at large rapidities provide complementary information to the central detection system. The measurement of charged particles and triggering is performed by Forward Multiplicity Detector (FMD), V0 and T0 detectors which cover a wide acceptance ($-3.4 < \eta < 5.1$). Photon multiplicity is measured by the Photon Multiplicity Detector (PMD) located at large rapidity ($2.3 < \eta < 3.5$). The beams' rapidity is covered by the Zero-Degree Calorimeters (ZDC) to measure nucleons not interacting in heavy-ion collisions (so-called “spectators”). The experimental setup is complemented by the forward muon spectrometer which covers large rapidities $-4.0 < \eta < -2.5$ devoted to measurements of muons. The ALICE layout is shown in Fig. 4.1.

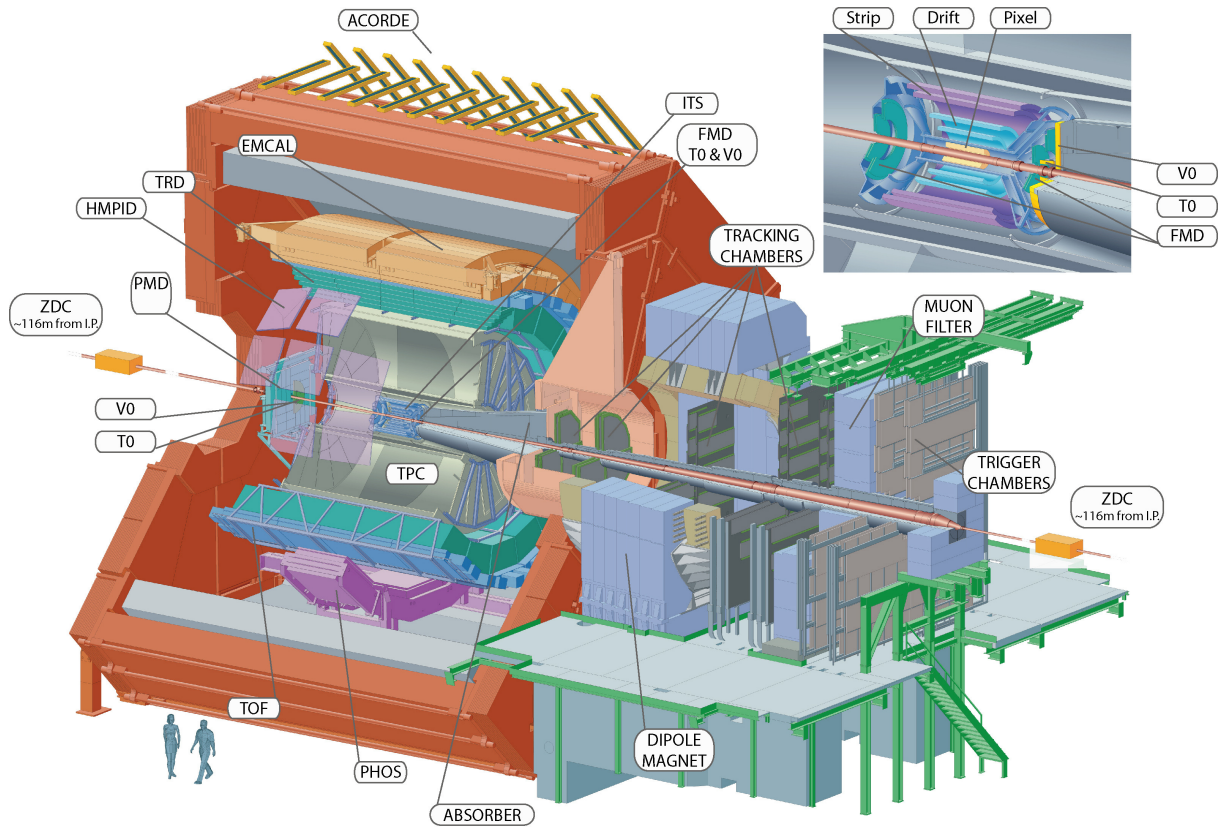


Figure 4.1: The ALICE experiment at LHC. From Ref. [168].

The ALICE sub-detectors are listed below. The detectors involved in the current analysis are described in more details in Sec. 4.3.1 (ITS), Sec. 4.3.2 (TPC), and Sec. 4.3.3 (TOF).

- **Inner Tracking System (ITS)** The *Inner Tracking System* [169] is a high granularity tracking and vertexing device. The system consists of six cylindrical layers of coordinate-sensitive detectors, all of them covering the pseudorapidity range of at least $|\eta| < 0.9$. Also particle identification is available via energy loss. More about the ITS detector can be found in Sec. 4.3.1.
- **Time Projection Chamber (TPC)** The *Time Projection Chamber* [170], the main tracking detector of ALICE, is central to the design of the experiment. Its task is track finding, momentum measurement and particle identification by dE/dx . More about the TPC detector can be found in Sec. 4.3.2.
- **Transition Radiation Detector (TRD)** The main task of the *Transition Radiation Detector* [171] is to differentiate electrons from charged hadrons, but it is also capable of contributing to the track reconstruction and is involved in triggering. Its detection technique utilizes the transition radiation (TR) emitted when charged particles cross the boundary between media with different dielectric constants. The detector is located at radii from 2.9 m to 3.7 m. It is split into 18 sectors, each one consisting of six layers.
- **Time-Of-Flight Detector (TOF)** The *Time-Of-Flight Detector* [172], located at 3.7 m from the beam line, covers a cylindrical surface of polar acceptance from 45 to 135 degrees and has a full azimuthal coverage in φ angle. It utilizes MRPC (Multigap Resistive Plate Chamber) strips. The primary function of TOF is to improve particle identification. It contributes to identification of charged particles in the intermediate momentum range ($p_T < 5$ GeV/c) by measuring the time between the collision and the arrival of the particles in the TOF.
- **High-Momentum Particle Identification Detector (HMPID)** The *High-Momentum Particle Identification Detector* [173] is based on the proximity focusing Ring Imaging Cherenkov (RICH) counters with CsI photocatode. It is designed to identify the high-momentum hadrons (p_T range from 1 to 5 GeV/c, mainly pions, kaons, and protons).

- **Photon Spectrometer (PHOS)** The *Photon Spectrometer* [174] is a high-granularity electromagnetic calorimeter designed to perform photon measurements. It is capable of detecting photons in a momentum range from 0.5 to 10 GeV/c. Located on the bottom of the ALICE setup, PHOS consists of 17820 fast scintillating PbWO₄ crystals. In front of the detector a set of multi-wire proportional chambers is placed in order to reject charged particles.
- **Electromagnetic Calorimeter (EMCal)** The *Electromagnetic Calorimeter* [179] is a lead scintillator sampling calorimeter. It covers pseudorapidity range of $-0.7 < \eta < 0.7$ and azimuthal angle φ of 110 degrees. EMCal enables triggering and full reconstruction of high energy jets in ALICE and improves existing capabilities to measure high momentum photons and electrons.
- **Photon Multiplicity Detector (PMD)** The *Photon Multiplicity Detector (PMD)* [177, 178] performs measurements of event-by-event photon multiplicity and spatial distribution of photons. It is located at $2.3 < \eta < 3.7$ and consists of two gas proportional chambers.
- **Forward Multiplicity Detector (FMD)** The *Forward Multiplicity Detector* [177] is a system designed to provide precise charged particle multiplicity information. Located at $-3.4 < \eta < 1.7$ and $1.7 < \eta < 5.03$, it consists of 51200 silicon strip channels distributed over 5 ring counters of two types which have 20 and 40 sectors each in azimuthal angle.
- **T0 Detector** The *T0* [177] detector comprise 2 arrays of photomultiplier tubes (PMTs) equipped with Cherenkov radiators. The arrays are installed on the opposite sides of the interaction point, located at $-3.27 < \eta < 2.97$ and $4.6 < \eta < 4.9$. The main functionality of T0 is to provide fast timing signals which are used in the *Level 0* trigger for ALICE to dispatch a wake-up call for the TRD and to contribute with collision time reference for the TOF.
- **V0 Detector** The *V0* (also referred to as *VZERO*) [177] is a small-angle detector consisting of two arrays of 32 scintillator counters, each installed on both sides of the ALICE interaction point: VZERO-A at $z = 3.4$ m, covering the pseudorapidity range $2.8 < \eta < 5.1$, and VZERO-C at $z = -0.9$ m, covering the pseudorapidity range $-3.7 < \eta < -1.7$.

The main functionality of the VZERO system is to provide the online *Level 0* centrality trigger for ALICE by setting a threshold on deposited energy as well as to contribute to the background rejection (i.e. rejection of asymmetric beam-gas events). The time resolution of this detector is better than 1 ns. Its response is recorded in a time window of ± 25 ns around the nominal beam crossing time. The negative arrival times are also possible. They can occur when the particles hit one of the detectors before the beam crossing; such behavior is usually an indication that the collision took place outside the central region of ALICE.

- **MUON Spectrometer** The *MUON spectrometer* (sometimes referred to as the *MUON arm*) [175] is a system which provides measurements of the particles containing heavy quarks (including J/ψ , ψ' , Y , Y' , Y'') via the muonic channel. The muon spectrometer is located downstream of the ALICE detector covering the angular range from 171 to 178 degrees, consisting of 3 absorbers, a muon dipole magnet, a trigger system and a tracking system.
- **Zero-Degree Calorimeter (ZDC)** The *Zero Degree Calorimeter* [176] is designed to measure the centrality of heavy-ion collisions. It allows to count the number of spectator nucleons in the collision. The ZDC is located on both sides of the ALICE detector at a distance of 116 m from the interaction point. The measurement is performed by three calorimeters: the neutron calorimeter called ZN, proton calorimeter called ZP and electromagnetic calorimeter, ZEP.
- **ALICE Cosmic Ray Detector (ACORDE)** The *ALICE Cosmic Ray Detector* [180] is an array of plastic scintillator modules, placed on the top 3 sides of the central ALICE magnet. ACORDE was designed to provide *Level 0* cosmic ray trigger and, together with other ALICE subsystems, to provide precise information on cosmic rays with primary energies around $10^{15} \div 10^{17}$ eV.

4.3.1 Inner Tracking System (ITS)

The *Inner Tracking System* [169] is the innermost subdetector. The basic roles of ITS are the determination of the primary vertex (point where the collisions occur) and of the secondary vertices, important for the reconstruction of short-lived charm and hyperon particles. Additionally,

it is used for PID of low-momentum particles and improves the momentum and angle measurements of the main tracking detector – the Time Projection Chamber (TPC) which is described in Sec. 4.3.2.

The ITS consist of six layers of high-precision silicon detectors, with double-sided silicon strips (*SSD* – Silicon Strip Detector) in the outer two layers, silicon drift detectors (*SDD*) in the two middle layers and silicon pixels (*SPD*) in the two inner layers. The layers encircle the collision point pin-pointing positions of the produced particles to a fraction of a millimeter. The ITS can contribute to recognition of particles containing heavy quarks by identifications of the points at which they decay. The detector layout is shown in Fig. 4.2.

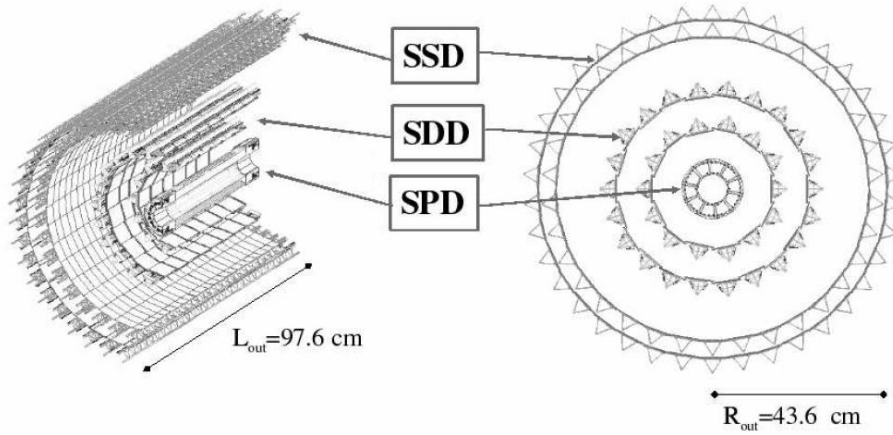


Figure 4.2: A schematic overview of the Inner Tracking System. It consists of six cylindrical layers using three different silicon detector technologies. From Ref. [181].

4.3.1.1 Silicon Pixel Detector (SPD)

The two innermost layers, called *Silicon Pixel Detector (SPD)* [169], are based on hybrid silicon pixels consisting of silicon detector $200\ \mu\text{m}$ wide diodes. The SPD plays crucial role in determination of the position of the primary vertex in ALICE. It was designed to function in a zone where the charged particle density was expected to exceed $50\ \text{particles}/\text{cm}^2$. Therefore it was crucial to use a detector of high precision and granularity. Moreover, the detector was required to operate in a relatively high-radiation environment. Its two layers cover pseudorapidity ranges $|\eta| < 2$ and $|\eta| < 1.4$ and is located at radii of 3.9 cm and 7.6 cm for the SPD inner and outer layers respectively, for particles originating from the center of the detector.

4.3.1.2 Silicon Drift Detector (SDD)

The third and fourth layer are called *Silicon Drift Detector (SDD)* [169]. The SDD consists of a 300 μm thick layer of homogeneous high-resistivity silicon and covers the region $|\eta| < 0.9$. Since analog readout is employed, the energy-loss information used for the particle identification can be retrieved, unlike in the first two inner layers. It is located between radii of 15 cm to 23.9 cm.

4.3.1.3 Silicon Strip Detector (SSD)

The two outermost layers are called *Silicon Strip Detector (SSD)* [169]. These are double sided detectors with silicon micro-strips located at radii of 38 and 43 cm respectively, covering $|\eta| < 0.97$. SSD, arranged under a stereo angle of 35 mrad, allows to perform two-dimensional track position measurements as well as contributes to the particle identification with the energy-loss measurement.

4.3.2 Time Projection Chamber (TPC)

The main tracking detector in the ALICE experiment is the *Time Projection Chamber (TPC)* [170]. Its sensitive volume is located between radii of 0.85 m and 2.5 m and has a length of 5 m. It provides information on charged particles, like their momenta, positions of vertices and particle identification. Figure 4.3 shows a schematic picture of the TPC. Generally speaking, it is a gas detector with an effective volume of 90 m^3 , filled with Ne-CO₂-N₂ gas. The drift field of 100 kV is stretched between the central electrode (which is located at the middle of the detector, at $z = 0$) and the two readout planes are located at $z = 2.5$ m and $z = -2.5$ m. It is the largest TPC ever built.

The readout of the signal is performed by the 570132 pads of 3 different sizes which form the cathode of multi-wire proportional chambers located at the TPC end caps. The end caps are segmented into 18 trapezoidal sectors. To optimize for the radial dependence of track density, these sectors are divided radially in two chambers with varying pad sizes. Pads are arranged radially in 159 rows.

The TPC is capable of tracking particles in the pseudorapidity range of $|\eta| < 0.9$ for full radial track length and up to $|\eta| < 1.5$ for 1/3 radial track length. In the nominal magnetic field of 0.5 T) it allows to measure particles with a transverse momenta p_T from about 200 MeV/c up

to 100 GeV/c. For tracks with momenta below 4 GeV/c the momentum resolution is better than 2.5%. In addition to the track reconstruction TPC provides particle identification, explained in detail in Sec. 4.4. The TPC was designed to reconstruct and identify up to 20000 tracks in one collision event.

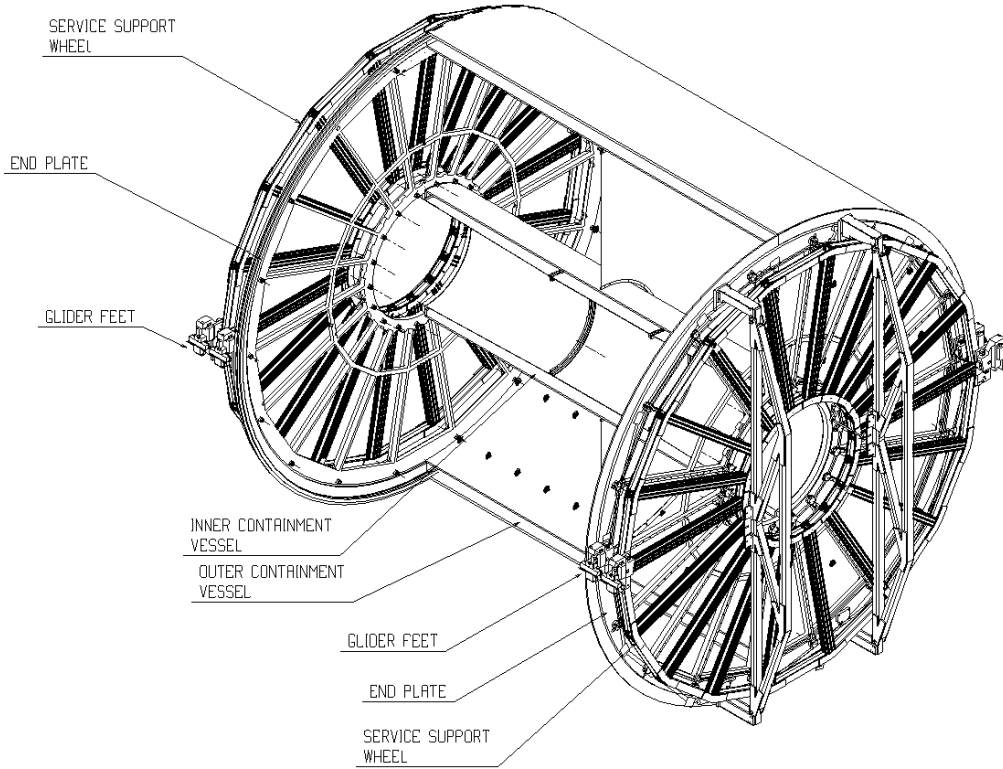


Figure 4.3: A schematic overview of the Time Projection Chamber. From Ref. [170].

4.3.3 Time-of-Flight detector (TOF)

The principle of the *Time-of-Flight (TOF)* detector is the measurement of the time in which the particles reach the detector and hence provide information about their velocity. At that moment the momentum of the particle is already provided by the other detectors and, therefore, the mass can be calculated allowing identification of different particle species (i.e. pions, kaons, and protons). In the initial design phase the Initially, several designs for TOF were considered, however the one finally selected was, due to its excellent efficiency of 99.9% and a time resolution better than 50 ps, the Multigap Resistive Plate Chamber (MRPC) [182]. The TOF detector is composed of 2 cathodes separated by 5 layers of glass, an anode and 5 more layers of glass, all of this filled with a pressurized gas. Across the anode and cathodes the differential high voltage

is applied[172]. When particles traverse the detector a cascade of electrons is formed and then read by the detector.

The TOF has an acceptance of $|\eta| < 0.9$ and has a full azimuthal coverage. It is located at 3.7 m from the beam line. Multi-gap resistive plate chambers (1638 of them) provide an intrinsic resolution of approximately 80 ps. The overall time resolution for particle identification depends additionally on the t_0 uncertainty, resulting in a resolution of $\sigma_{\text{TOF}} = \sqrt{\sigma_{\text{intr}}^2 + \sigma_{t_0}^2} \approx 86$ ps for Pb–Pb collisions and $\sigma_{\text{TOF}} \approx 120$ ps for pp collisions. Hence a 2σ -separation between protons and kaons up to 5 GeV/c can be reached even at high particle multiplicities [183].

4.4 Particle identification

TPC

The TPC, in addition to tracking information, provides important measurement of the energy loss of the traversing particle per unit path length dE/dx , allowing for particle identification. For a given particle $\langle dE/dx \rangle$ is described by the Bethe-Bloch formula, Eq. (4.1), where C_1 , C_2 and C_3 are the detector parameters, $\beta = v/c$ is the particle velocity and γ is the Lorentz factor. The Bethe-Bloch curves for the TPC, together with dE/dx measurements of $\sqrt{s} = 7$ TeV pp collision data are presented in Fig. 4.4.

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{C_1}{\beta^2} \left(\ln(C_2 \beta^2 \gamma^2) - \beta^2 + C_3 \right) \quad (4.1)$$

The particle identification method used in this thesis is the so-called *N σ method*. After obtaining the Bethe-Bloch curves and the dE/dx measurement, the next step of the procedure is the projection of the plot of Fig. 4.4 in the small momentum ranges. The resulting distributions are later fitted by the sum of Gaussians, one for each particle type, as presented on the top of Fig. 4.5. A particle is marked during the procedure for example as a possible pion, if its average energy loss per unit path length lays within a given number (N) of standard deviations (σ) of the Gaussian distribution around the expected signal for pions (hence the name “N σ method”). The expected signal is the value of the Bethe-Bloch curve calculated for the specified particle momentum (bottom of the Fig. 4.5). For more information see also Sec. 5.4 and 8.2.

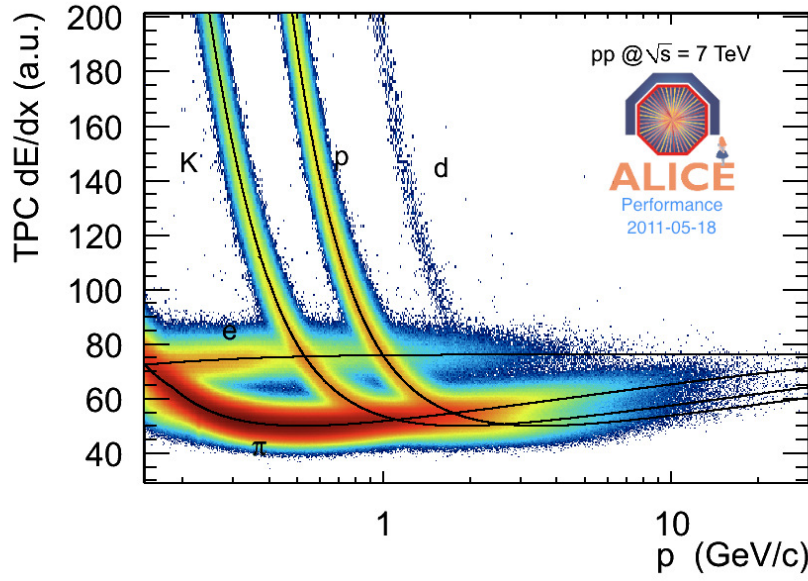


Figure 4.4: The dE/dx spectrum versus momentum in the TPC for $\sqrt{s} = 7$ TeV pp collisions. The lines are Bethe-Bloch curves for a specific particle species [184].

TOF

The TOF detector provides the information about the time t that it takes for a particle to reach the TOF pad (the start time t_0 is given by the triggering detector). Together with the information about the reconstructed trajectory L it enables the calculation of the particle velocity β , as shown in Eq.(4.2)

$$\beta = \frac{L}{tc} = \frac{1}{\sqrt{\left(\frac{mc}{p}\right)^2 + 1}}. \quad (4.2)$$

The combination of the information on the particle momentum and the velocity provides the particle mass and therefore determines its identity.

In Fig. 4.6 the velocity β measurement by the TOF detector is presented. Clear separation between different particle species can be observed.

Similarly as for the TPC, the TOF uses the $N\sigma$ method for the PID procedure. To classify the particles as certain species, we use the difference between the measured TOF arrival time and the expected arrival time for a given particle. In such a procedure we obtain the Gaussian distributions centered around the expected reference signal, and σ values can be extracted. The studies are always done in slices of momentum.

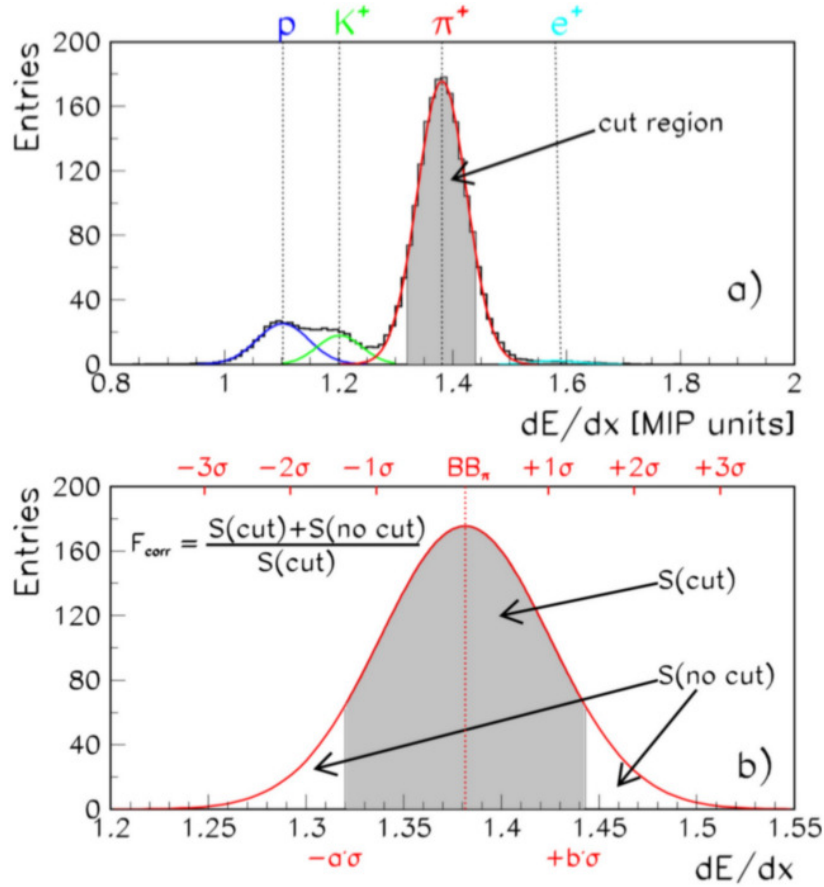


Figure 4.5: Example of the Gaussians fitted to the projection of the dE/dx spectrum in a small momentum range (top). Zoom to one Gaussian explaining the $N\sigma$ method (bottom). From Ref. [78].

Combined particle identification

The combination of the information of the average energy loss for ionization from the TPC and the time-of-flight from the TOF provides a reliable particle identification, presented in Fig. 4.7, crucial for this analysis. For the details about the experimental analysis procedure and used values of N see Sec. 5.4.

4.5 Software environment

The ROOT system [187], developed at CERN since 1995, provides a set of Object-Oriented C++ frameworks with all the functionality needed to handle and analyze large amounts of data in an extremely efficient manner. It includes advanced statistical analysis tools (classes for multi-dimensional histogramming, fitting and minimization), visualization tools (classes for 2D and 3D graphics including an OpenGL interface), a rich set of container classes, remote database

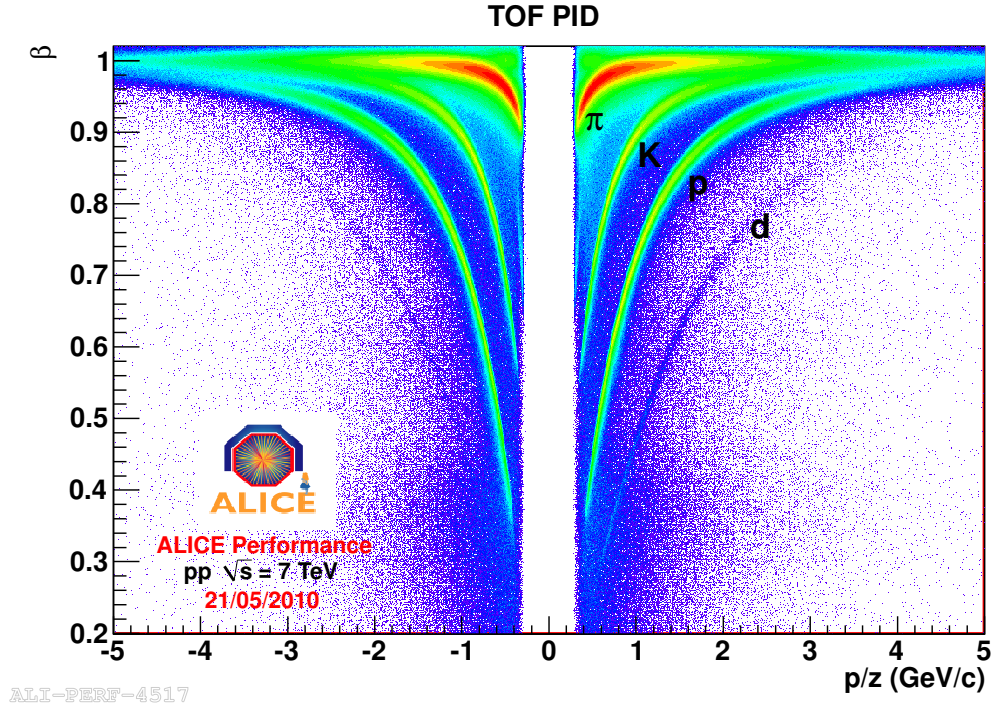


Figure 4.6: TOF measured particle β as a function of momentum divided by the sign of the particle in pp collisions at $\sqrt{s} = 7$ TeV [185].

access, and a C++ interpreter (CINT).

Data analysis in ALICE is performed using the AliRoot framework which emerged from extending the ROOT framework to ALICE purposes (integrates the simulation, reconstruction and analysis software of the ALICE experiment). Except for large existing libraries, such as GEANT 3 [188], GEANT 4 [189], FLUKA [190], JETSET [191], and some remaining legacy code, this framework is based on the Object-Oriented programming paradigm and it is written in C++. In order to analyze huge amounts of data coming from collisions, the ALICE Collaboration developed AliEn (*ALICE Environment*) [192, 193] tool that enabled managing GRID connections, as well as efficient and relatively easy data handling.

GRID is a distributed computing system, the combination of computer resources from multiple institutions. CERN maintains the *LHC Computing Grid* (LCG) to handle the huge amounts of data which are delivered by the LHC with storage rates exceeding several gigabytes per second and allows to perform complex analyses of them. One of the reports from the ALICE GRID online monitoring tool, called MonALISA [194] is shown in Fig. 4.8. The locations of computing centers connected to the ALICE GRID network around the world are marked as colorful points on the map.

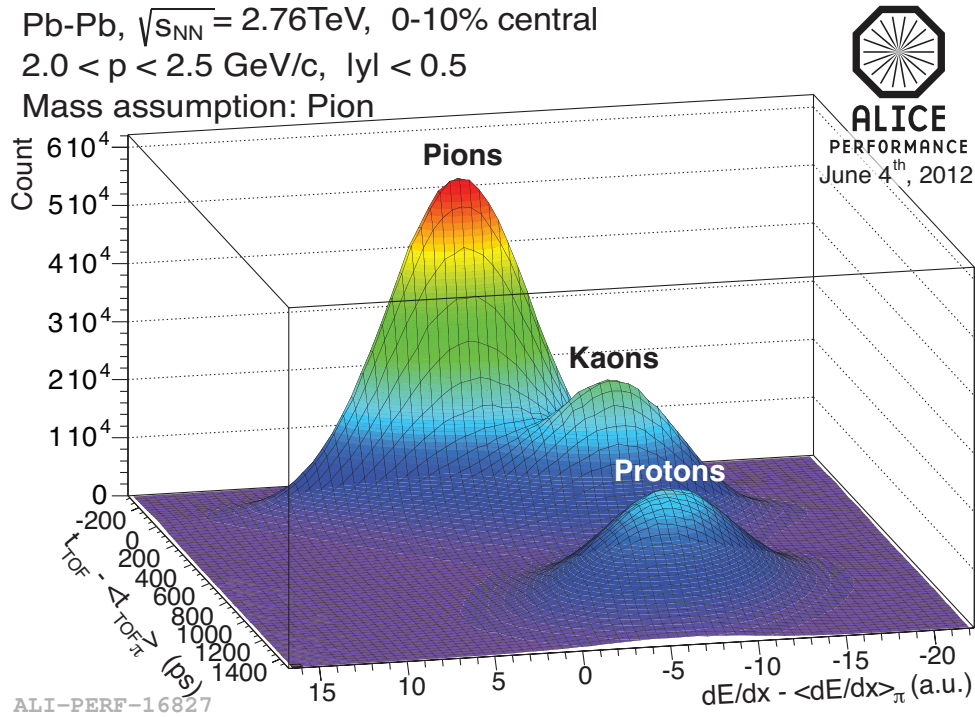


Figure 4.7: ALICE combined particle identification measurements: the Time-Of-Flight information from the TOF and ionization measurements (dE/dx) in the TPC [186].

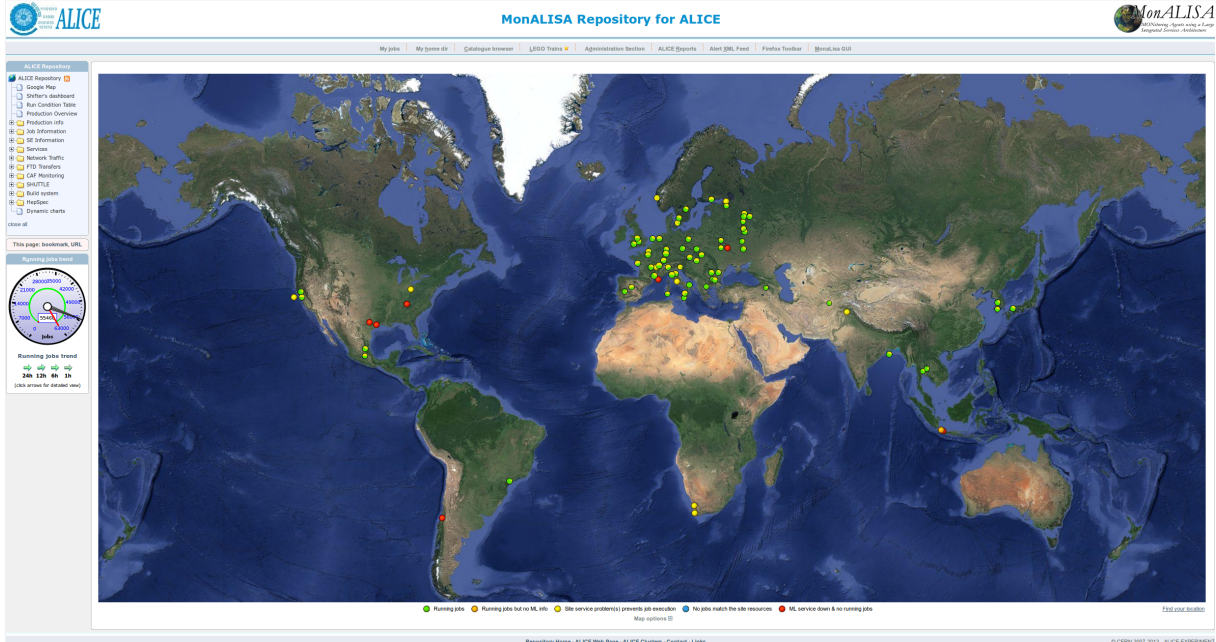


Figure 4.8: MonALISA – ALICE GRID monitoring webpage [194]. Points on the map show locations of computing centers around the World which are connected to ALICE GRID and are used to store and analyze ALICE data. Different colors correspond to the actual operational status.

The AliRoot software used by the ALICE collaboration both during the data taking as well as for the simulation and is publicly available at Ref. [195].

The analysis of this thesis was performed using the AliFemto package [196, 197] which is a part of the AliRoot framework. This package was especially designed for the analysis of two particle correlations. It was developed for the STAR experiment and later ported to ALICE. Appropriate modifications for the analysis of this thesis were applied. The code can be found in the AliRoot directory: \$ALICE_ROOT/PWGCF/FEMTOSCOPY.

4.6 Overview of results

Selected highlights of ALICE experimental results, mainly from the analysis of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, are presented below and detailed in Refs. [198–200]. We note that the content presented in this section is also published in the conference proceedings in Ref. [4].

4.6.1 Collectivity and bulk properties

The cumulative analysis of the bulk of particles produced in the collision allow us to extract information about the created dense matter, such as the temperature of the system, its initial energy density and the space-time evolution of the source.

4.6.1.1 Initial temperature

The initial temperature of Quark-Gluon Plasma can be inferred from the spectrum of the so-called *direct photons*. By definition, direct photons are produced from initial scattering processes, not from the hadron decays. They are produced in the initial stage of the collision and leave the reaction zone unaffected. There are two domains of direct photon production: thermal (at low and medium p_T) and prompt (at high p_T). The former carry information about early thermal state, the QGP. The latter come from hard scatterings of quarks and gluons and are calculable using perturbative QCD.

Figure 4.9–left shows the measured direct photon spectrum. The spectrum for $p_T > 4$ GeV/ c is indeed in agreement with that for prompt photons obtained in a next-to-leading-order pQCD calculation. However, for lower p_T the spectrum has an exponential shape and lies significantly above the predictions for hard scatterings, indicating additional contribution from thermal production mechanisms. This excess is a signature of the created QGP state and can be used to

calculate the mentioned initial temperature. This is performed by fitting an exponential function to thermal spectrum. The inverse slope parameter of this fit represents the temperature. It was measured by ALICE in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and found to be $T_{\text{LHC}} = 304 \pm 51$ (stat.+syst.) MeV which is about 40% larger than the value obtained in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 0.2$ TeV at RHIC, $T_{\text{RHIC}} = 221 \pm 19$ (stat.) ± 19 (syst.) MeV. This yields initial temperature well above the predicted critical temperature of the phase transition of 150–160 MeV ($\approx 1.8 \times 10^{12}$ K). Moreover, it suggests that the QGP produced at the LHC is the hottest matter created in a laboratory.

Based on the measurement of the charged particle pseudorapidity density, $dN_{\text{ch}}/d\eta$, and on a model of the collision geometry proposed by Bjorken [201] an initial energy density $\epsilon = 15$ GeV/fm³ is estimated for central Pb–Pb collisions which corresponds to an initial temperature of $T \approx 300$ MeV, in agreement with the temperature derived from the thermal photons measurement.

The energy dependence of $dN_{\text{ch}}/d\eta$ is presented in Fig. 4.9–right. For the measurements at lower energies the particle production exhibited logarithmic dependence with $\sqrt{s_{\text{NN}}}$. The Pb–Pb data from LHC do not follow previous scaling, but a power law with an exponent of 0.15. Small systems (pp, p $\bar{p}$) show less steep dependence of 0.11. Detailed comparisons with models are expected to contribute to the understanding of the underlying physics mechanisms of particle production in the different collision systems and energies.

4.6.1.2 Source size and lifetime

Femtoscopy measurements, allowing to measure size and lifetime of the system created in heavy-ion collisions, were introduced in Sec. 3.2.6. In short, the Bose-Einstein quantum statistics causes more bosons (i.e. pions) being produced close together in phase space, creating an excess of pairs with low relative momentum. This excess is inversely proportional to the system size at freeze-out. This size can be measured in three dimensions: *long*, parallel to the beam axis; *out*, parallel to the transverse momentum of the pair; and *side* in a direction perpendicular to the other two. The freeze-out volume of the system can be assessed from the product of the three sizes. Figure 4.10 presents the freeze-out volume and lifetime of the source as a function of charged particle multiplicity. The measurements from different experiments and different collision energies show a linear monotonic increase of both observables. We can observe that the volume created at LHC is two times larger than at RHIC and exists for about 10–11 fm/c,

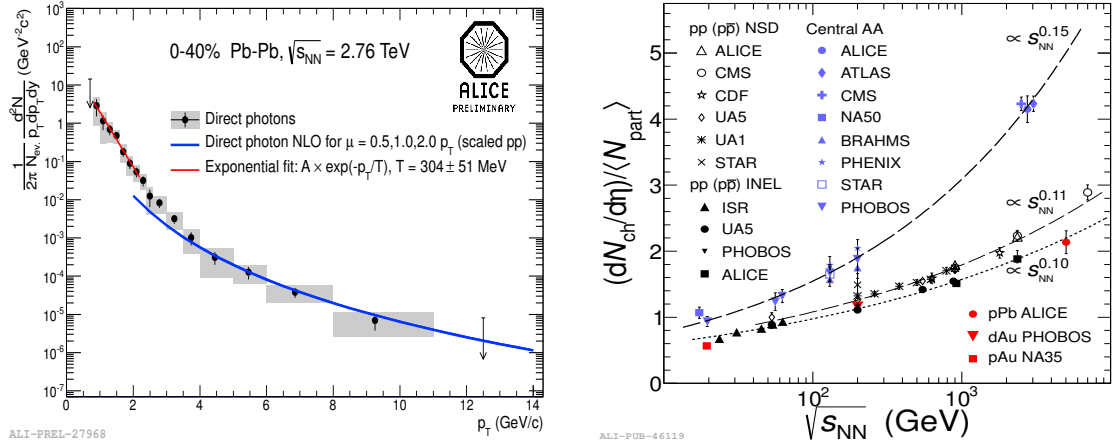


Figure 4.9: Direct-photon p_T -spectrum for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with next-to-leading order (NLO) prediction at the high- p_T and exponential fit at the low- p_T region (left). Charged particle pseudorapidity density, $dN_{ch}/d\eta$, per participant, as a function of $\sqrt{s_{NN}}$ for nucleus-nucleus, proton-nucleus and proton-proton collisions (right).

significantly longer than at RHIC. If the results are extrapolated to $dN_{ch}/d\eta = 0$ the source size agrees with the volume of a lead nucleus ($\approx 800 \text{ fm}^3$) and the source lifetime decreases to zero.

4.6.1.3 Azimuthal anisotropies

The important property of any fluid, including QGP, is the η/s ratio, where η is the shear viscosity and s the entropy. For example, water has small η/s values in comparison to honey. In heavy-ion collisions η/s is connected to elliptic flow, the second Fourier coefficient of the azimuthal angle distribution, which is introduced in Sec. 3.2.3. The RHIC flow measurements in heavy-ion collision showed that the produced dense matter behaves like an almost ideal fluid, with low friction coefficient, leading to η/s ratio close to its lower bound equal to $1/4\pi$ (with $\hbar = k_B = 1$), as estimated by AdS/CFT (Anti de Sitter/Conformal Field Theory) [206].

ALICE measurements [202] agree with the prediction of hydrodynamic models and suggest that the QGP produced at the LHC still resembles nearly perfect fluid with minimal η/s , comparable to the one produced at RHIC [41, 203–205]. Measurements of the elliptic flow as a function of p_T and centrality have been performed for different particles to obtain extra constraints on η/s . The comparison of the newly obtained experimental data with models gives

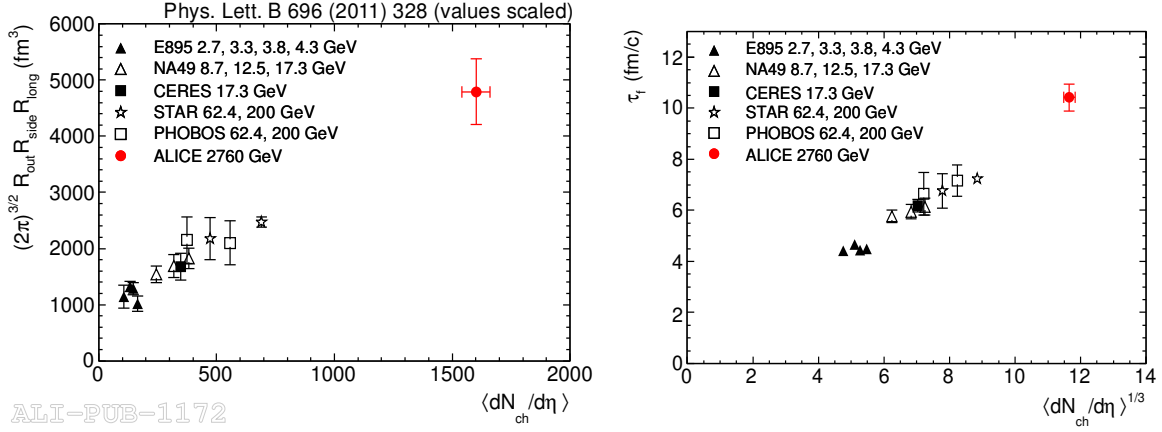


Figure 4.10: Freeze-out volume of the source (left) and decoupling time (right) from identical pion interferometry measurements. The ALICE result (filled red dot) is compared to measurements at lower energies. From Ref. [145].

value of η/s in the range $1-2.5 \times 1/4\pi$, very close to the limit for ideal liquid, and the uncertainty comes primarily from the definition of the initial conditions.

Extensive studies of fluctuations and non-flow effects can be performed by various experimental techniques. They focus on the measurements of numerous v_n coefficients via two- and multi-particle correlations. Each one of them is sensitive to different contributions.

v_n measurements in extended pseudorapidity

ALICE measured first five harmonics of azimuthal anisotropy as a function of pseudorapidity and transverse momentum. The v_2 and v_3 coefficients were measured up to $\eta = 5$, while the remaining three at mid-rapidity. The dependence on centrality of v_2 as a function pseudorapidity is shown in Fig. 4.11–left. One can see that there is practically no dependence of anisotropic flow on pseudorapidity for $|\eta| < 2$ and the v_2 decreases at larger rapidities. In comparison to RHIC the integrated v_2 is increased by 20–30% in the mid-rapidity region and about 30% at forward rapidities. It is consistent with higher limits of hydrodynamic model predictions for LHC. The v_3 exhibits similar behavior to v_2 for the most central (0–5%) collisions, as shown in Fig. 4.11–right. In addition, it reveals a weak centrality dependence, similar in magnitude for both central (0–5%) and peripheral (50–60%) collisions. These results suggest that v_2 depends mainly on geometry, while v_3 originates from initial state fluctuations. However, those fluctuations also produce a non-zero v_2 in the central collisions.

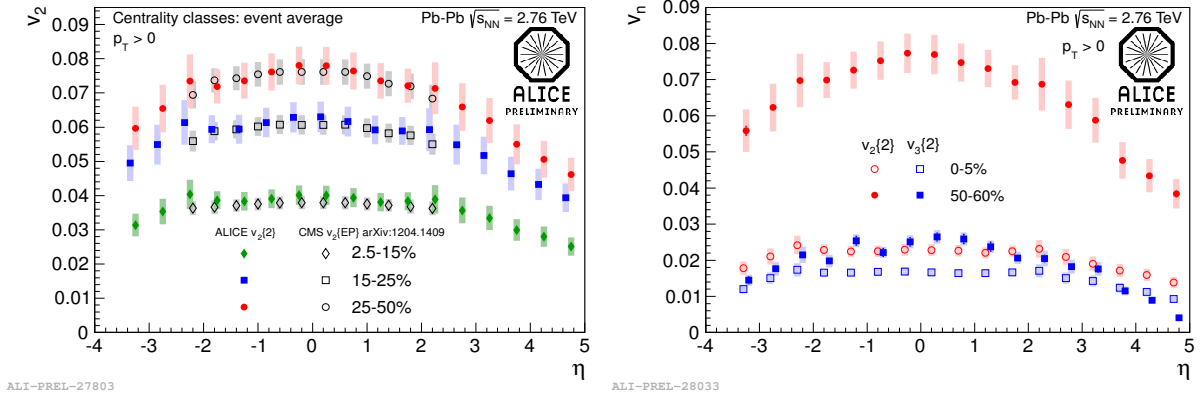


Figure 4.11: Left: v_2 pseudorapidity dependence compared to CMS data for different centralities. Right: v_2 and v_3 pseudorapidity dependence for very central (0–5%) and peripheral (60–80%) Pb–Pb collisions (right).

4.6.2 Jet modification and medium induced effects

Fast partons created in heavy-ion collisions traverse the dense medium and lose their energy via gluon radiation or elastic scattering. The energy loss increases with the medium density and the distance traveled by the parton. In addition it also depends on parton flavor. At the high energies at the LHC, the hard probes, i.e. the ones associated with high-momenta, are abundantly produced. These probes arise from hard scatterings of partons with large momentum transfer at the initial phase of the collision, and can be obtained by applying perturbative QCD calculations. Since these probes are expected to interact with the produced plasma prior to hadronization, they can be used to examine its properties. The QCD predicts that the amount of the lost energy is greater for gluons than quarks, due to its dependence on the color coupling factor [207]. The so-called “dead-cone effect” [208] (reduced small angle gluon radiation), causes further decrease of the in-medium effects related to heavy quarks. Moreover, pions, which mostly emerge from gluons, are expected to be more suppressed than particles containing a c quark. Particles comprising a b quark should be even more suppressed. All the mentioned effects lead to a hierarchy of suppressions.

The suppression can be studied by employing several experimental techniques, including the measurement of the production of particles in nuclear collisions (e.g. Pb–Pb, p–Pb) compared to expectations from superposition of independent elementary collisions, where the QGP is not produced. It is commonly quantified by the nuclear modification factor, R_{AA} , which is the ratio

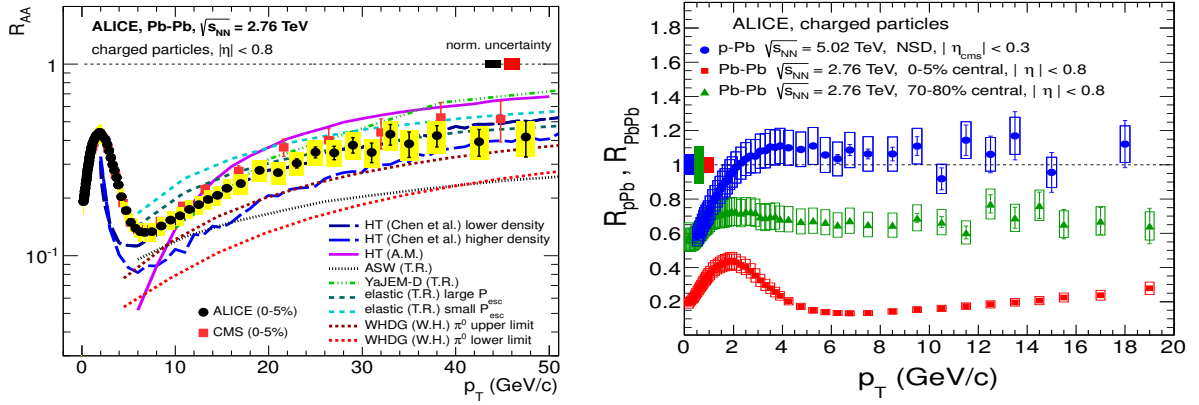


Figure 4.12: The nuclear modification factor R_{AA} for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to CMS data and model calculations (left). The nuclear modification factor R_{pPb} for p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to R_{PbPb} for the 5% most central and 70–80% peripheral Pb–Pb collisions (right).

of yields in A–A collisions to the proton-proton cross section scaled by the number of binary collisions. By construction R_{AA} is equal to 1 if no nuclear effects are present.

Charged particles R_{AA} in Pb–Pb collisions

A strong suppression of high- p_T particles in central nuclear collisions in relation to pp was first observed at RHIC [41, 203–205]. The suppression on the order of 5 at $p_T = 5$ –6 GeV/c and independent of p_T up to 20 GeV/c was measured in the Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Simultaneously photons, particles which do not interact strongly, were not modified.

The results from LHC, with significantly expanded p_T range, and including the measurements of Z and W bosons, confirm the suppression. In addition, no modification is observed for isolated photons [209, 210]. The R_{AA} of charged particles measured by ALICE and CMS at mid-rapidity for the 5% most central Pb–Pb collisions is shown in Fig. 4.12–left [211, 212]. The results of both experiments agree within the uncertainties. The distinct maximum seen around $p_T \approx 2$ GeV/c is possibly caused by the collective radial flow [165]. With increasing p_T , around $p_T = 5$ –7 GeV/c the minimum of ≈ 0.13 is observed. This value is slightly lower than the one measured at RHIC, where R_{AA} was ≈ 0.2 . The nuclear modification factor starts to increase above 7 GeV/c, and rises to ≈ 0.4 at $p_T > 30$ GeV/c and remains constant up to at least 100 GeV/c, as measured by CMS, see Ref. [212]. Comparisons of the measurements to model calculations that implement different energy-loss mechanisms are reported in Ref. [165].

Charged particles R_{AA} in p–Pb collisions

To determine the influence of the effects from initial state on the measured R_{AA} the p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from the pilot run were studied as reference [213]. Figure 4.12–right shows nuclear modification factor for p–Pb, R_{pPb} , which is compared to Pb–Pb measurement. The p_T spectrum of charged particles is measured in the interval $0.5 < p_T < 20$ GeV/ c at mid-rapidity. A suppression of production of charged particles in p–Pb collisions for $p_T < 2$ GeV/ c is observed. It might be related to parton shadowing or saturation mechanisms. For $p_T \approx 4$ GeV/ c it rises to $R_{pPb} \approx 1.1$. This can be explained with multiple scatterings in the initial state, referred to as Cronin effect. For $p_T > 6$ GeV/ c the nuclear modification factor in p–Pb is consistent with 1.

The R_{pPb} is compared to R_{PbPb} from the central (0–5%) and peripheral (70–80%) collisions. The results for $p_T > 5$ GeV/ c reveal the scaling with N_{part} ($R_{PbPb}^{0-5\%} < R_{PbPb}^{70-80\%} < R_{pPb}$). These measurements indicate that the strong suppression of particle production at high transverse momenta observed in central Pb–Pb collisions is not an initial state effect and therefore a signature of the dense quark-gluon plasma created in collisions of heavy ions.

The R_{pPb} at the LHC can also be compared to the RHIC data [214]. Its dependence on transverse momentum is less enhanced than the R_{dAu} ; however the relation of R_{pPb} to R_{PbPb} exhibit similar trend as R_{dAu} to R_{AuAu} .

Identified particles R_{AA}

Nuclear modification factor for identified particles can be employed to determine the energy loss mechanism and constrain the models describing this process. It was measured at RHIC and different suppression factors were observed for mesons and baryons [215].

The R_{AA} measured by ALICE for identified pions, kaons, and protons, for the 5% most central Pb–Pb collisions is presented in Fig. 4.13–left. The results exhibit, up to p_T of 6–7 GeV/ c , a suppression hierarchy between less suppressed baryons (protons) and more strongly suppressed mesons (pions and kaons). The nuclear modification factor becomes similar for $p_T \gtrsim 8$ –10 GeV/ c for all studied particles which is an indication that the medium influence light hadrons in the same manner. The R_{AA} of D-mesons which was averaged from D^0 , D^+ and D^{*+} [216] is shown Figure 4.13–right. It was compared to the R_{AA} measured for charged particles as well as non-prompt J/ψ (products of B decays) measured by CMS [217]. Measurements exhibit

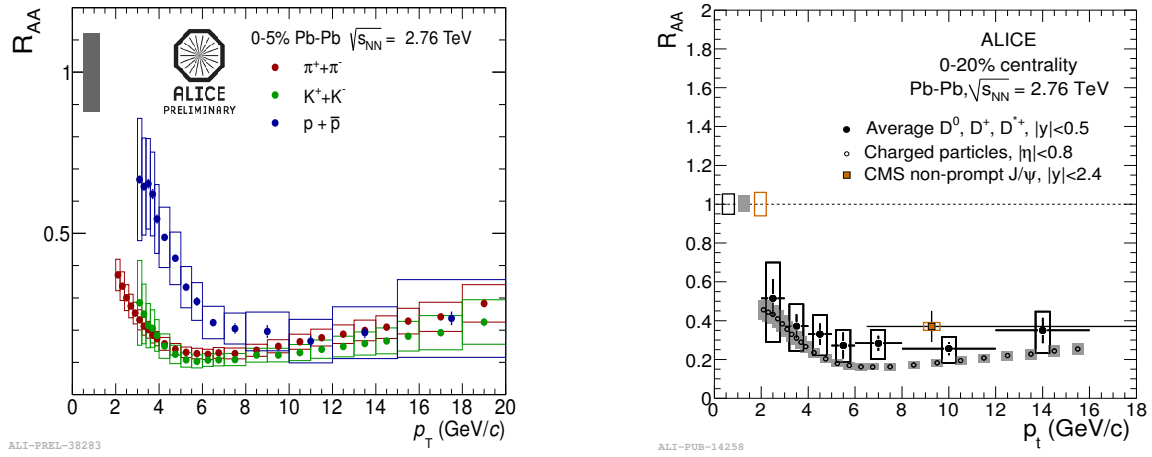


Figure 4.13: The nuclear modification factor R_{AA} for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, for identified particles: pions, kaons, and protons separately (left). The R_{AA} for the average D-meson compared to non-prompt J/ψ from CMS and charged particles (right).

the indications of the expected suppression hierarchy in the shown transverse momentum range, however the large systematic errors does not allow to draw definite conclusions.

Outlook

As shown, ALICE, optimized for the study of heavy-ion physics, delivered a comprehensive set of results characterizing the different stages of Pb–Pb collisions. The produced matter shows the expected effects extrapolating from RHIC. The studies of the p–Pb data offer evidence that the features seen in the Pb–Pb collisions are not a cold matter effect but the signature of the created hot Quark-Gluon Plasma. However, while p–Pb analysis advance, unexpected features emerge [127, 218]. With these new results from p–Pb measurements we need to look even more closely into the elementary pp systems. Precise studies providing extensive description of different aspects of simple hadronic collisions are particularly important for establishing a firm baseline.

Chapter 5

Data, event and track selection

In this chapter, the data, event, and track selections used in the data analysis are described. Section 5.1 specifies the proton-proton collision data sets, with the event selection further specified in Sec. 5.2. In Sec. 5.3 the track selection is presented, and the particle identification procedure for pions, kaons, and protons is described in Sec. 5.4. Finally, two-track selection is specified in Sec. 5.5.

5.1 Data samples

The analysis is performed on proton-proton collision data recorded at the center-of-mass energies of $\sqrt{s} = 0.9, 2.76, \text{ and } 7.0 \text{ TeV}$ in 2010 during LHC run I. The selection of the datasets is based on the quality assessment performed in the ALICE-wide framework. The central quality assurance is based on several conditions as detailed below.

First, the sets of events that can not be described as physics datasets are rejected. This includes e.g. the events registered during luminosity scans of the LHC. Moreover, the quality of the calibration and reconstruction is taken into account. It is assessed basing on indications of mis-calibration or defects of the reconstruction that are discovered in the properties of the events and tracks. The calibration and the reconstruction of the data sets is iteratively repeated until all of the problems are removed. Finally, the datasets for which any of the detectors that take part in this analysis (ITS, TPC, TOF, see Chapter 4 for details) was marked with reported problems during data-taking was rejected.

Moreover, the analysis was performed with several independent data samples recorded under different data-taking conditions (so-called *productions*). They have been checked for statistical consistency at the level of the correlation function and the results shown in Chapter 7 are statistical averages of them; the uncertainty related to the observed differences are assessed in Chapter 8.

5.2 Event selection

Once the physics datasets have been selected we further constrain the data sample using the minimum bias trigger. It requires a signal in either of the two VZERO counters or one of the two inner layers of the Silicon Pixel Detector (SPD). Moreover, the background events (beam-halo, beam-gas), as well as pile-up events are rejected.

Finally, due to the size and acceptance of the ALICE central barrel, especially the TPC detector, we use only events that come from collisions that occurred close to the center of the detector. Thus, we require the z -component (along the beam axis) of the primary vertex to be within 10 cm from the center of the detector, $|z_{\text{vtx}}| < 10$ cm, see Fig. 5.1 (d).

After selection, about 250 million minimum bias events from pp collisions at $\sqrt{s} = 7$ TeV, 10 million minimum bias events from pp collisions at $\sqrt{s} = 900$ GeV and 15 million minimum bias events from pp collisions at $\sqrt{s} = 2.76$ TeV were used for this analysis.

5.3 Track selection

The primary tracks were chosen within the pseudorapidity range $|\eta| < 0.8$. Due to the limited detector efficiency we selected pions with transverse momentum $p_T > 0.2$ GeV/ c , kaons with $p_T > 0.3$ GeV/ c , and protons with $p_T > 0.5$ GeV/ c . For the data sample without particle identification a particles with $p_T > 0.12$ GeV/ c were selected.

The resulting distributions of p_T , η and φ for positive tracks, after all applied selections (also called *cuts*), can be seen in Fig. 5.1 (a), (b), and (c) respectively.

Two subsystems were used for particle trajectory reconstruction: the ITS and the TPC. Additionally the TOF was used in the procedure of particle identification. Furthermore, in order to reduce the contamination from background and secondary particles, we require a track to project back to the primary interaction vertex with a p_T -dependent distance (so-called cut on the *Distance of Closest Approach* or *DCA*). Particles located within $(0.018 + 0.035p_T^{-1.01})$ cm in the transverse plane and 2.0 cm in the beam direction with respect to the primary vertex were accepted; see Fig. 5.1 (e) and (f). A track was required to have at least 70 TPC clusters (the maximum number is 159, which corresponds to the number of the TPC padrows). The maximum value of χ^2 per TPC cluster was 4.0 (2 degrees of freedom per cluster).

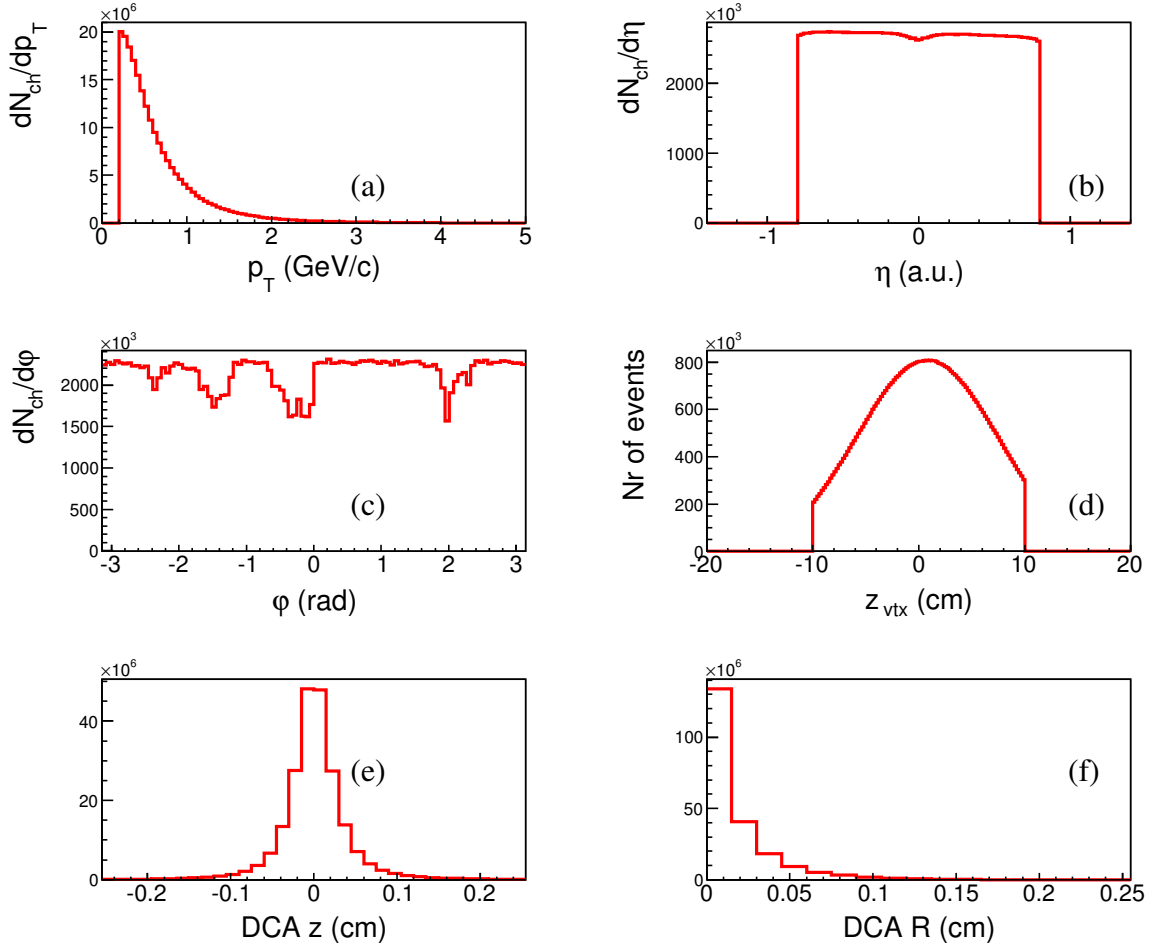


Figure 5.1: Single particle distributions of accepted positive tracks after all the cuts were applied: (a) p_T , (b) η , (c) ϕ . In the bottom panels the Distance of Closest Approach are shown, in z direction (e) and in xy plane (f). In panel (d) position of the vertex along the beam axis with respect to the TPC center is shown.

5.4 Particle identification

The particle identification (PID) of pions, kaons, and protons is performed track-by-track using information from the TPC and TOF detectors. It is based on the $N\sigma$ method, where σ is the standard deviation from the Bethe-Bloch parameterization of the energy loss signal, dE/dx , of the analyzed particle in the TPC or the time-of-flight deviation from the analyzed particle expected arrival time in the TOF, as explained in Sec. 4.4.

The dE/dx distributions for the $\sqrt{s} = 7$ TeV pp collision data are reported in the left panels of Fig. 5.2, without particle identification cut and for pion hypothesis¹. The electron rejection

¹For the $N\sigma$ calculations and the computation of time from the TOF detector, reference values are needed (see

cut can be seen as a white band near dE/dx of ~ 75 a.u. Similarly, the difference of the measured TOF time and the expected TOF time for given particle species is shown in the right plot.

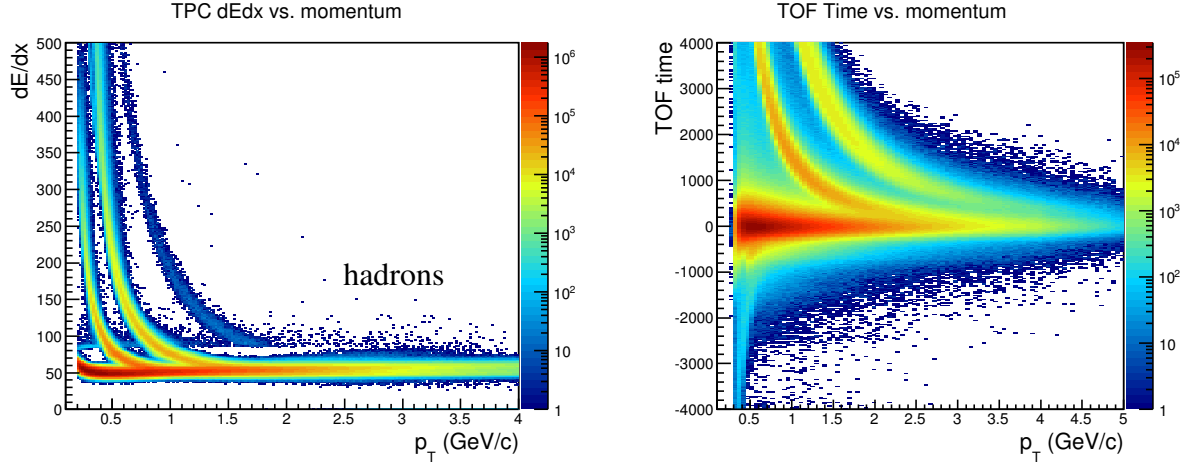


Figure 5.2: Distributions for all particles, without PID selection, with pion mass hypothesis. Left: dE/dx distribution as function of transverse momentum. The electron rejection cut can be seen as a white band near dE/dx of ~ 75 . Right: TOF time distribution (zero indicates that the time from TOF is equal to the expected time for pions).

The selection criteria, specific for this analysis, constructed using the combined $N\sigma$ approach and information from the TPC and TOF, are as follows:

- below $p_T = 0.5$ GeV/c only the TPC information is used and $N_{\sigma, \text{PID}} = N_{\sigma, \text{TPC}}$,
- above $p_T = 0.5$ GeV/c a combined $N\sigma$ is used: $N_{\sigma, \text{PID}}^2 = N_{\sigma, \text{TPC}}^2 + N_{\sigma, \text{TOF}}^2$.

The default cut on $N_{\sigma, \text{PID}}$ is 3, which means a linear cut on the TPC distribution below $p_T = 0.5$ GeV/c and a circular cut (with radius equal to 3) in the $(N_{\sigma, \text{TPC}}, N_{\sigma, \text{TOF}})$ plane above $p_T = 0.5$ GeV/c. No double counting is allowed: if the track passes the $N_{\sigma, \text{PID}}$ cut, before accepting such a track an additional check is made – if a track is recognized by the cuts as two different particles (e.g. as pion and as kaon), a comparison is made and only the track with the smaller value of $N_{\sigma, \text{PID}}$ is accepted. Therefore, tracks are never counted twice.

In Fig.5.3 the distributions of $N_{\sigma, \text{TPC}}$ versus $N_{\sigma, \text{TOF}}$ are shown. The band of $N_{\sigma, \text{TPC}} < 3$ is present for particles below $p_T = 0.5$ GeV/c (for such particles only the TPC information is used). It is not visible for protons, since the lower cut-off for protons is 0.5 GeV/c. Similarly, (Sec. 4.4). Such values are obtained for given particle species and their particle mass, and are usually referenced to as “mass hypothesis”.

the outline of the circular cut (with radius equal to 3) for particles with $p_T > 0.5 \text{ GeV}/c$ is clearly visible.

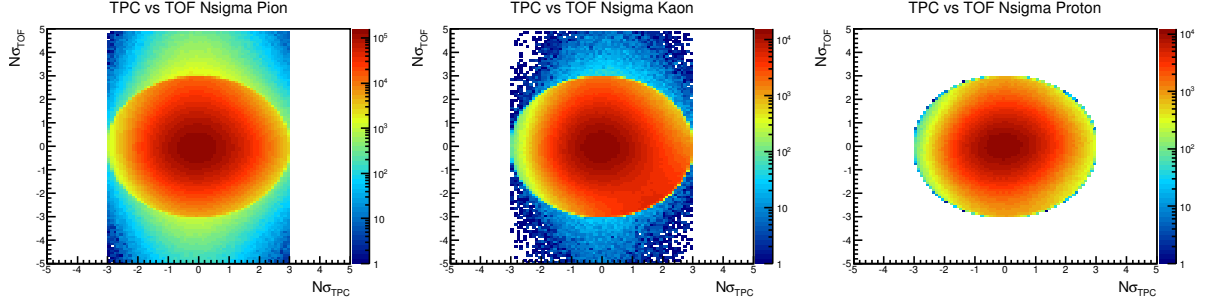


Figure 5.3: $N_{\sigma,TPC}$ versus $N_{\sigma,TOF}$ distributions for pions (left), kaons (middle), protons (right). The outline of the linear cut on $N_{\sigma,TPC}$ for $p_T < 0.5 \text{ GeV}/c$ and the circular cut with radius $\sqrt{N_{\sigma,TPC}^2 + N_{\sigma,TOF}^2} < 3$ for particles with $p_T > 0.5 \text{ GeV}/c$ are clearly visible.

In Fig. 5.4 $N_{\sigma,TPC}$ and $N_{\sigma,TOF}$ distributions as a function of transverse momenta for the pion mass hypothesis are shown, together with the corresponding projections in the $0.5\text{--}1.0 \text{ GeV}/c$ p_T bin. The $N_{\sigma,TPC}$ and $N_{\sigma,TOF}$ distributions are expected to be Gaussian distributions centered at $\mu = 0$ with $\sigma = 1$. The projections are fitted with a Gaussian and the corresponding σ is indeed close to unity.

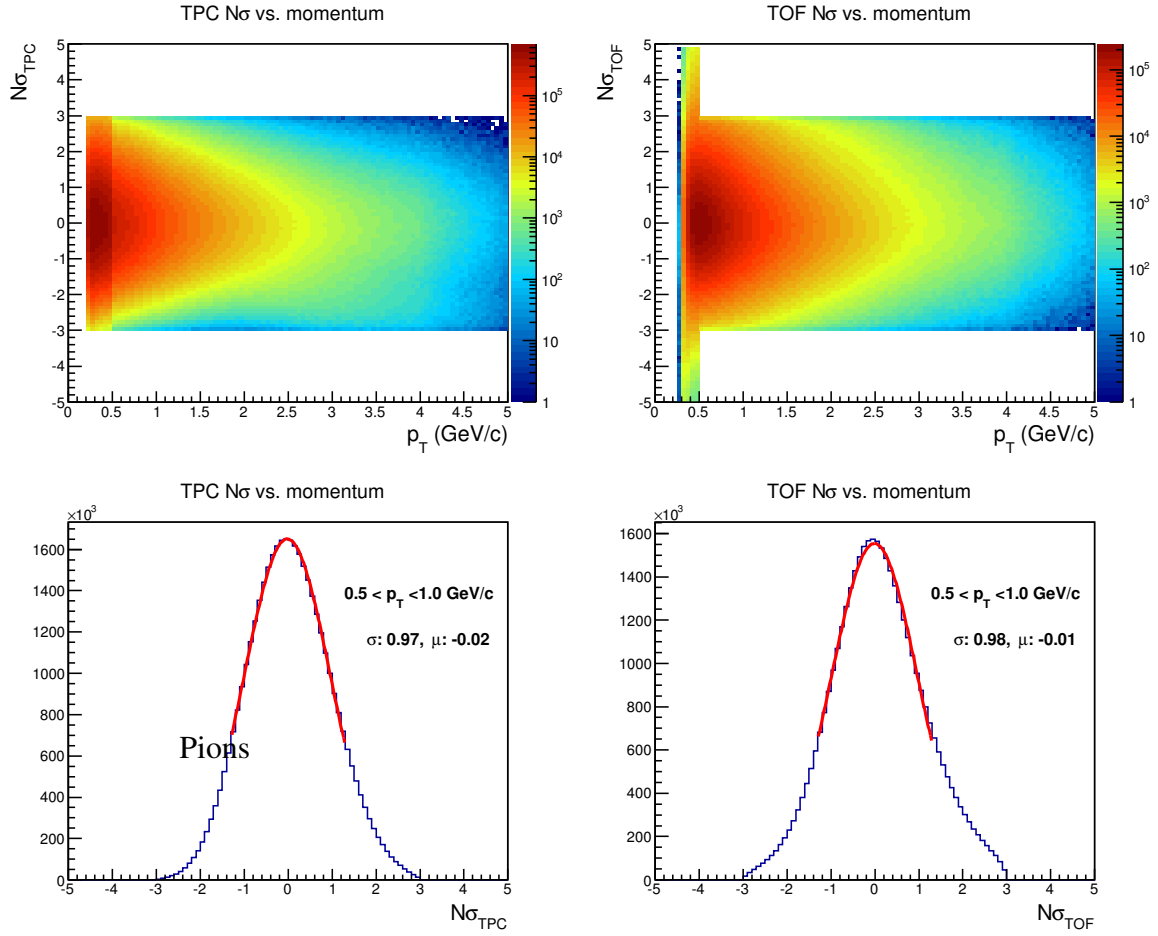


Figure 5.4: Top row: $N_{\sigma, \text{TPC}}$ (left) and $N_{\sigma, \text{TOF}}$ (right) distributions for the pion sample. Bottom row: the corresponding projections in $0.5\text{--}1.0$ GeV/c p_T bin are reported. The N_{σ} distributions are expected to be Gaussian distributions centered at $\mu = 0$ with $\sigma = 1$.

5.5 Pair-wise effects

The quality cuts remove undesired effects from *splitting* (one track is mistakenly reconstructed as two) and *merging* (two tracks are reconstructed as one).

The cuts that were applied to remove split tracks are composed of two parts. The first one is the *share quality*. It calculates the difference of the number of clusters on the same TPC padrow shared by two tracks, and the number of all clusters of those tracks. If this difference is positive, then the two tracks have more shared clusters than different clusters. If the difference is negative, more than half of the clusters are not shared by the two tracks. In our analysis the maximum of the share quality is set to 0. The second part is the *share fraction*. It is defined as the fraction of shared clusters to all clusters of two tracks. Since split tracks tend to produce pairs which share most of their clusters, we remove all pairs that share more than 5% of them.

Both these cuts are commonly used in ALICE femtoscopic analyses [153, 154, 219].

5.6 Data sample division

The selected data samples were further divided into smaller sets. Firstly, in Sec. 5.6.1 we describe the criteria of the data sample division in the event multiplicity (determination of multiplicity ranges). Secondly, in Sec. 5.6.2 the division of particle pairs in the events dependent on transverse momentum of the particles is presented (determination of pair transverse momenta p_T -sum ranges).

5.6.1 Multiplicity ranges

In order to perform our analysis we introduced ranges of the total measured charged-particle multiplicity of the event, N_{ch} , in the ITS detector acceptance² range $|\eta| < 1.2$ (later called shortly *multiplicity*). All the events from the proton-proton collisions at the energy of $\sqrt{s} = 7$ TeV were divided into eight multiplicity ranges and events from $\sqrt{s} = 0.9$ TeV pp collisions were divided into four multiplicity ranges. The division was made in such a way that in each multiplicity range in the $\sqrt{s} = 7$ TeV sample the number of like-sign pion pairs is comparable. To make the

²Multiplicity measurements are done in the expanded range of the ITS detector of $|\eta| < 1.2$. The analysis measurements are done in a range limited to the TPC and TOF acceptance.

comparisons straightforward, the same division was kept for the $\sqrt{s} = 0.9$ TeV data; however, the last 5 ranges had to be combined to obtain comparable statistics. Table 5.1 lists the average number of the charged particles per unit of rapidity obtained for different data samples. The ranges for the energy of $\sqrt{s} = 7$ TeV are also shown in the raw multiplicity distribution plot in Fig. 5.5.

Bin	N_{ch}	$\langle dN_{ch}/d\eta \rangle _{N_{ch} \geq 1}$	No. pairs $\times 10^6$
$\sqrt{s} = 0.9$ TeV			
1	1–11	2.5	8.8
2	12–16	6.4	8.6
3	17–22	9.0	9.5
4	23–80	13.0	12.9
$\sqrt{s} = 7$ TeV			
1	1–11	2.8	48.7
2	12–16	6.6	65.0
3	17–22	9.2	105.7
4	23–29	12.0	120.5
5	30–36	14.9	116.3
6	37–44	17.9	115.6
7	45–57	21.4	114.5
8	58–149	27.6	108.8

Table 5.1: Multiplicity selection for the analyzed sample. Uncorrected N_{ch} in $|\eta| < 1.2$, $\langle dN_{ch}/d\eta \rangle |_{N_{ch} \geq 1}$, number of events and number of identical pion pairs in each range are given. Note that for the multiplicity determination we counted the tracks reconstructed simultaneously in the ITS and the TPC, plus the tracks reconstructed only in the ITS in the case the track was outside of the TPC η acceptance.

For identified particles statistics allow to perform the analysis for 3 multiplicity ranges: $0 < N_{ch} < 20$, $20 < N_{ch} < 50$ and $N_{ch} > 50$.

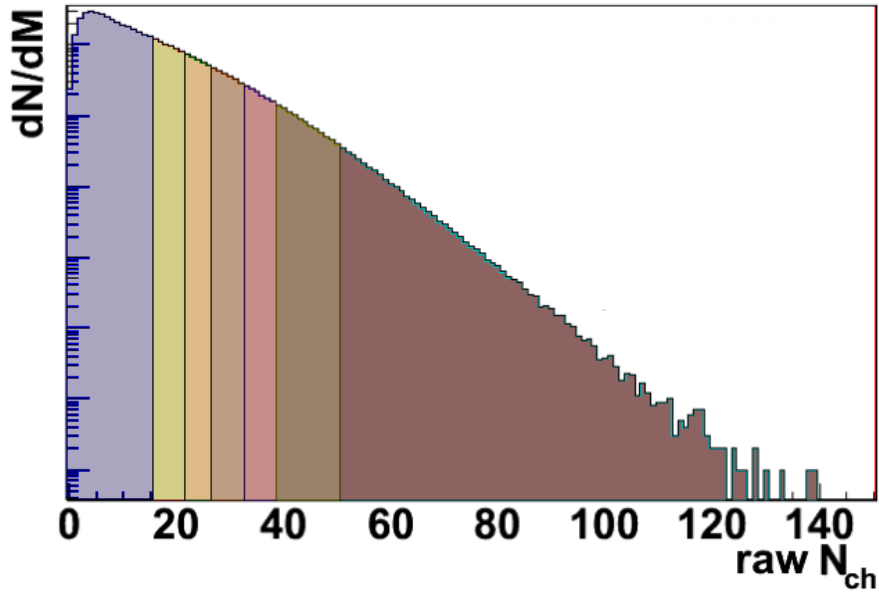


Figure 5.5: Multiplicity distribution for the $\sqrt{s} = 7$ TeV pp collision data with multiplicity ranges in colors.

5.6.2 Transverse momentum ranges

Since we would like to study untriggered correlations, without specifying the first and second particle, as well as cut in $(p_{T,1}, p_{T,2})$ space, we introduced a new quantity which we called p_T -sum. It is defined by the equation:

$$p_T\text{-sum} = p_{T,1} + p_{T,2} . \quad (5.1)$$

As already introduced in Sec. 3.2.6, the femtoscopic analysis is additionally complicated due to the influence of non-femtoscopic contributions to the measurement. Since the difference between the femtoscopic correlation functions in relative momentum q and $\Delta\eta\Delta\varphi$ correlation functions is only in the representation (the underlying physical contributions are the same) we can study exactly the same effects using different representations. The formula in the Eq. (5.1) includes the sum of the absolute values of the transverse momenta of the particles in the pair. This definition makes the p_T -sum quantity related to $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$ variable, commonly used in femtoscopic analyses. Hence, it facilitates comparisons between the two.

We introduced several p_T -sum ranges (depending on the particle species) which are presented in Table 5.2. The bins were created in such a way that the statistics between the samples would be sufficient for the fitting.

Particle	Range	p_T -sum (GeV/c)
π	0	0.4–0.7
	1	0.7–0.9
	2	0.9–1.1
	3	1.1–1.4
	4	1.4–2.5
	5	2.5–8.0
K	0	0.6–2.5
	1	2.5–3.5
	2	3.5–8.0
p	0	1.0–2.75
	1	2.75–8.0
no PID	0	0.0–0.7
	1	0.7–1.2
	2	1.2–2.0
	3	2.0–3.0
	4	3.0–4.0
	5	4.0–8.0

Table 5.2: Pair transverse momentum p_T -sum ranges for the $\sqrt{s} = 7$ TeV pp collision data.

The distributions of the p_T -sum together with the introduced binning, presented by different colors, are shown in Fig. 5.6 for pions, Fig. 5.7 for kaons, Fig. 5.8 for protons, and Fig. 5.9 for all the hadrons without particle identification.

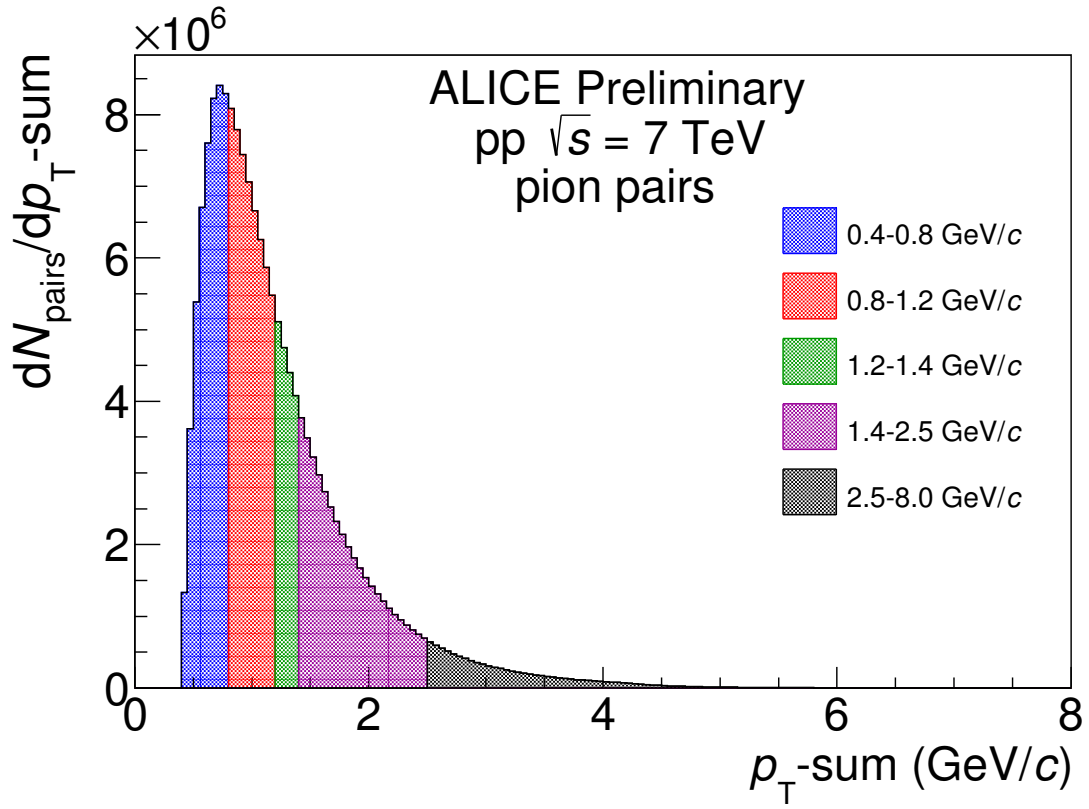


Figure 5.6: Pair transverse momentum $p_{\text{T-sum}}$ distribution for like-sign pairs of pions.

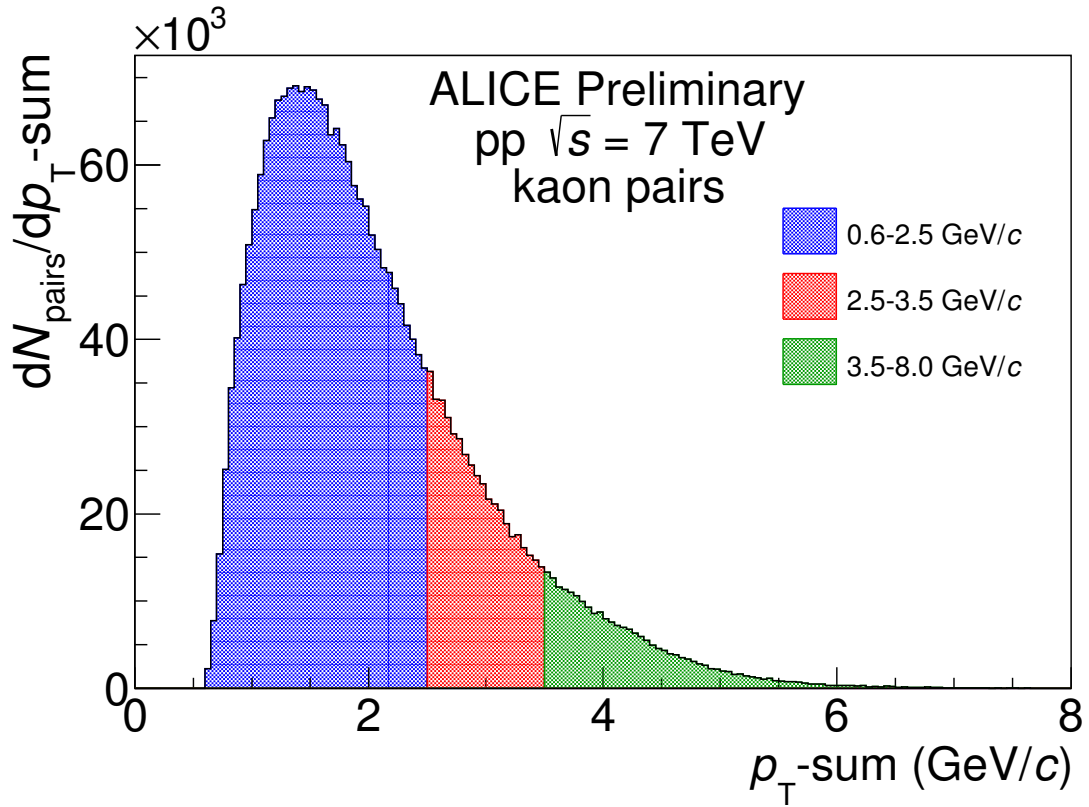


Figure 5.7: Pair transverse momentum $p_{\text{T-sum}}$ distribution for like-sign pairs of kaons.

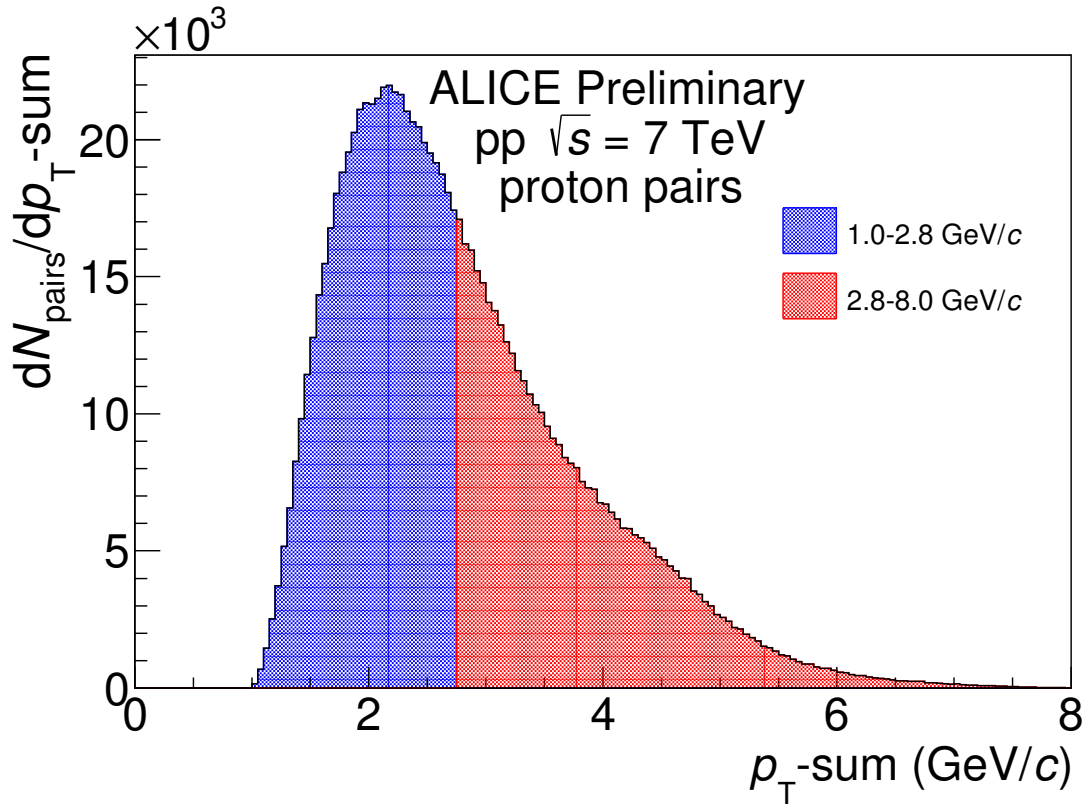


Figure 5.8: Pair transverse momentum $p_{\text{T-sum}}$ distribution for like-sign pairs of protons.

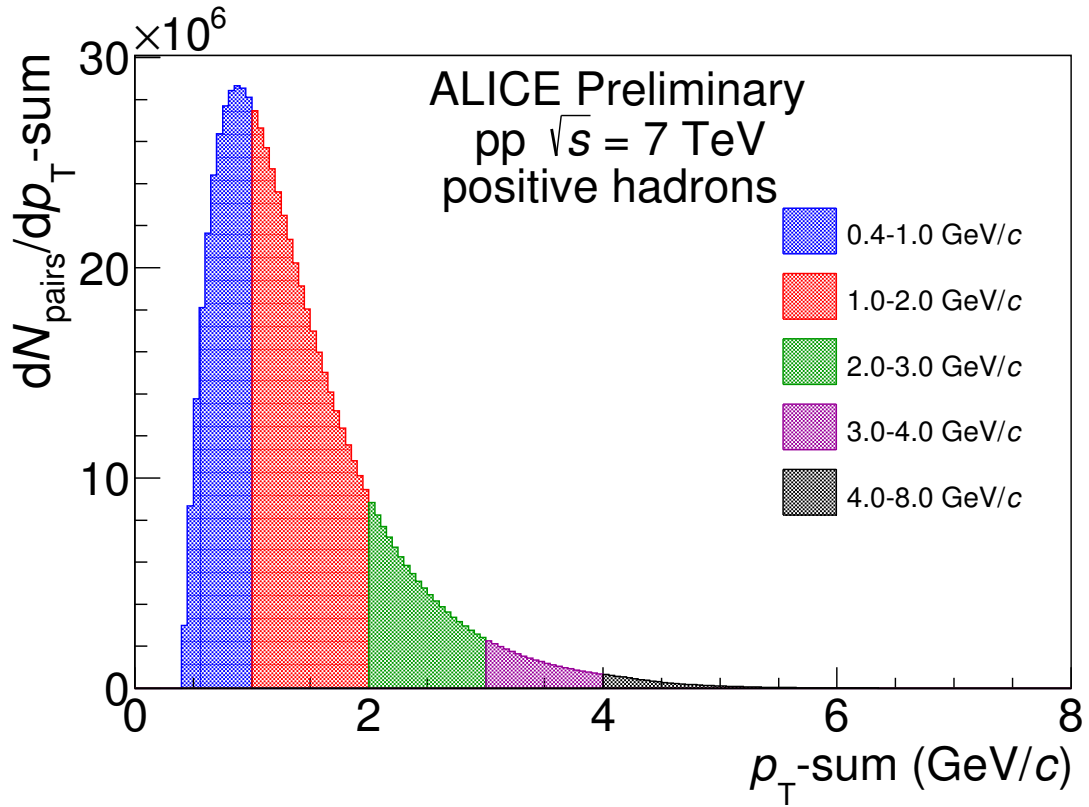


Figure 5.9: Pair transverse momentum $p_{\text{T-sum}}$ distribution for like-sign pairs of charged hadrons.

Chapter 6

Analysis method

The $\Delta\eta\Delta\varphi$ angular correlations were described in Chapter 3. In Sec. 6.1 the construction of the experimental correlation function is presented. The correction procedure applied to remove undesired effects of non-uniform acceptance and secondary particles is described in Sec. 6.2. The description of the procedure that was applied to quantify the structures observed in the shape of the correlation function is presented in Sec. 6.3.

6.1 Construction of experimental correlation function

The construction of the measured $\Delta\eta\Delta\varphi$ correlation function is described in Sec. 3.1. It includes physical correlations as well as undesired effects caused i.e. from non-uniform detector acceptance and other inefficiencies. Therefore, a correction procedure was introduced and applied for the signal and background distributions separately. The signal, as given by the Eq. (3.8), was corrected for efficiency losses applying the correction factor f as follows:

$$S'(\Delta\eta, \Delta\varphi) = \sum_{p_{T,1}, p_{T,2}} f(p_{T,1}, p_{T,2}) \cdot S(\Delta\eta, \Delta\varphi, p_{T,1}, p_{T,2}), \quad (6.1)$$

where S is the uncorrected signal distribution. The methodology of calculating the correction factor f is explained in detail in Sec. 6.2.

The background from Eq. (3.9) is corrected for efficiency with the same correction factor f in exactly the same way as the signal:

$$B'(\Delta\eta, \Delta\varphi) = \sum_{p_{T,1}, p_{T,2}} f(p_{T,1}, p_{T,2}) \cdot B(\Delta\eta, \Delta\varphi, p_{T,1}, p_{T,2}), \quad (6.2)$$

where B is the uncorrected background distribution. Moreover, in order to improve the background estimation, each event is mixed with ten different events similar in terms of multiplicity (only events from the same $5 N_{\text{ch}}$ wide multiplicity bin are mixed) and primary vertex location (2 cm wide z -vertex bins).

Then, similarly as in Eq. (3.7) we create the corrected correlation function as:

$$C(\Delta\eta, \Delta\varphi) = \frac{N_{pairs}^{mixed}}{N_{pairs}^{signal}} \frac{S'(\Delta\eta, \Delta\varphi)}{B'(\Delta\eta, \Delta\varphi)}. \quad (6.3)$$

6.2 Correction procedure

In this section, we describe the correction procedure developed for the two-particle angular correlation analysis of proton-proton collision data presented in this thesis. The process is designed to correct all relevant experimental biases influencing the results of the analysis.

To calculate the proper correction values Monte Carlo event generators and transport packages are employed. We compare two samples of simulated data:

1. **MC truth** Particles directly from the MC simulation, at the event generator level. This sample is usually referred to as *true MC data* or simply *MC truth* and consists of particles as they come from the initial interaction generated by the MC generator, not affected by detector effects.
2. **MC reconstructed** Tracks after simulation of particle transport through the medium and detector response, the so-called *reconstructed MC*. Particles in this sample are the same ones as in the MC truth, but after the initial generation of particles the transport through the detector volume and material is simulated with transport package, GEANT3 [188] for this work¹. As the last step the transport package simulates the detector response. Afterwards the whole reconstruction chain is performed on the simulated detector signal, and the track selection is applied as explained in Chapter 5 for the ALICE collision data. The final sample consist of tracks corresponding to the ones we observe in the experiment after the collision, affected by detector geometry, its properties, the reconstruction procedure, etc.

Then the analysis can be performed with the same methods on the particles at the event generator level and the reconstructed MC data and the results can be compared directly. From such comparisons one can calculate how many particles have been reconstructed, how many have been identified properly, and how many reconstructed particles are coming directly from

¹In high-energy physics also GEANT4 [189] or FLUKA [190] transportation packages are frequently used.

the collision. This information can be used to calculate the appropriate correction factor f (accounting for tracking inefficiencies and contamination from secondary particles) to correct the data.

The procedure for the inefficiency estimation is presented in Sec. 6.2.1 and estimation of the contamination from secondaries in Sec. 6.2.2. The calculation of the final correction factor f , combining the two, is described in Sec. 6.2.3. The correlation functions are corrected with a correction factor f as described in Sec. 6.1.

6.2.1 Reconstruction efficiency

The track reconstruction efficiency ϵ is defined as the ratio of the number of particles actually measured to the number of particles that would have been measured in an ideal detector. This quantity can be estimated using Monte Carlo data by comparing the number of reconstructed particles to the number of generated particles, as written in Eq. (6.4):

$$\epsilon = \frac{N_{\text{primaries}}^{\text{survived}}}{N_{\text{primaries}}^{\text{generated}}} . \quad (6.4)$$

The track reconstruction efficiency of the detector depends on various aspects:

- The detector geometry plays a significant role, since the reconstruction is possible only if the particle reaches the detector and if the length of the trajectory is not too short (in this analysis we cut on the minimal number of clusters of the TPC; the track has to have at least 70 clusters out of the maximum of 159).
- Particles with very low momentum cannot be detected, due to the bending of the tracks in the magnetic field; the low-momentum particles can spiral inside the TPC volume, making reconstruction not possible.
- As particle momentum increases tracks become more and more straight and thus, for some of them, most of their length may happen to be in the blind zones of the TPC, and therefore they cannot be registered by the detector².

²For details see TPC schema presented in Fig. 4.3. In the figure the edges of the readout sectors arranged radially on the end-plates of the detector are clearly visible. Between each sector, an angle of $\varphi = 2^\circ$ is not covered by sensitive detector material, creating blind zones for straight tracks.

Dependence on transverse momenta

The dependence of the tracking efficiency for the non-identified sample (charged hadrons) on the transverse momentum is presented in Fig. 6.1 as black points.

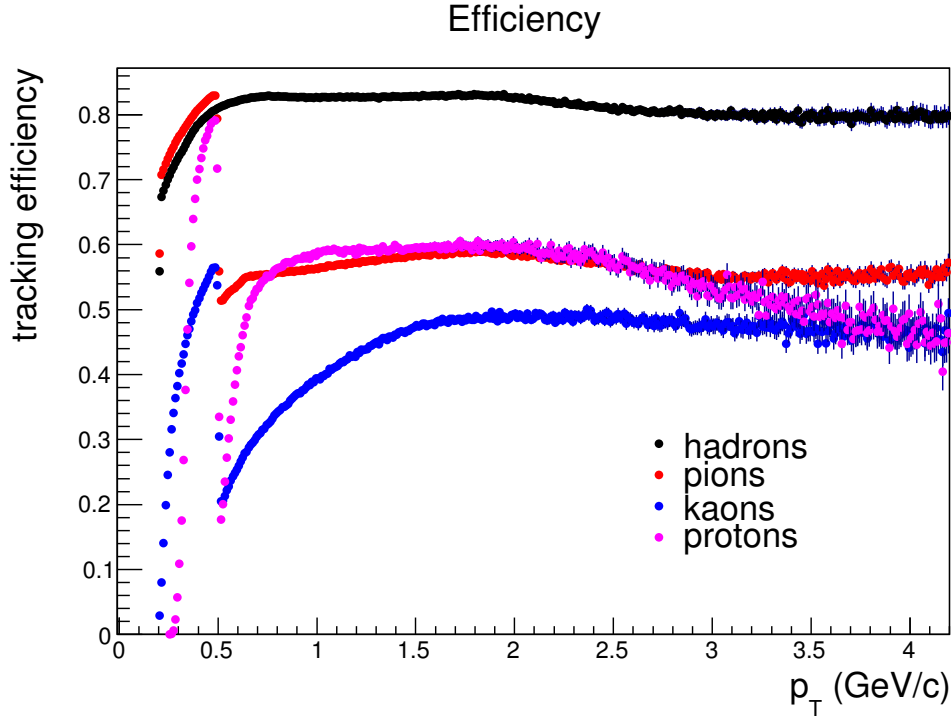


Figure 6.1: Efficiency as a function of p_T for different particle species. The values are estimated employing the full detector simulation of Pythia Perugia-0 events at $\sqrt{s} = 7$ TeV.

It can be seen that at low p_T the efficiency rises steeply with increasing transverse momentum; tracks with low momentum cannot be properly reconstructed due to the strong bending in the magnetic field. The efficiency rises, reaching at 2 GeV/ c a value of $\approx 80\%$ for hadrons. Beyond this value the tracks start to become more straight and thus being affected by the blind zones of the TPC; hence, the slight decrease of 2–3%.

The calculations also have been performed separately for each one of the analyzed particle types: pions, kaons, and protons, see points in colors in Fig. 6.1. In the case of identified particles not only the tracking efficiency is taken into account, but also the particle identification efficiency. Additional constraints on the track selection (i.e. the $N\sigma$ cut) reduce the total efficiency. The steep fall of the distribution for $p_T \approx 0.5$ GeV/ c for identified particles is expected due to the fact that for $p_T > 0.5$ GeV/ c the TOF detector starts contributing to the particle identification procedure, requiring appropriate track matching with the TOF signal. The TOF allows

us to obtain clean samples of specific particles, although it reduces efficiency severely. More information on the particle identification efficiency and PID procedure can be found in Sec. 8.2.

For this analysis, an alternative correction procedure was developed and tested; namely, a 4D correction ($p_T, \varphi, \eta, z_{\text{vtx}}$), dependent not only on transverse momenta, but also on azimuthal angle, pseudorapidity and position of the primary vertex along the beam axis (see for details Appendix B.2). The results of both approaches are consistent; it indicates that final correlation does not depend strongly on $\varphi, \eta, z_{\text{vtx}}$. However, the dependence of the corrections on p_T is crucial, as shown in Appendix B.1. For the final plots presented in this thesis only the results from the procedure described in this section will be shown.

6.2.2 Contamination from secondaries

For this analysis we are interested mostly in primary particles; hence, secondary particles are treated as contamination to the signal. Therefore, we correct for their contribution.

We can define the fraction of non-primary particles as a contamination from secondaries C_{sec} , see Eq. (6.5):

$$C_{\text{sec}} = \frac{N_{\text{secondaries}}^{\text{survived}}}{N_{\text{primaries}}^{\text{survived}} + N_{\text{secondaries}}^{\text{survived}}} . \quad (6.5)$$

The level of the contamination of the sample due to secondary particles can be obtained by checking if each particle was primary (or not) based on the MC generator information. The dependence of the contamination from secondaries on the transverse momentum is presented in Fig. 6.2.

The non-monotonic shape of the contamination for hadrons can be understood on the basis of the used electron rejection cut; see Fig. 6.3. The observed structures are expected due to the fact that the TPC dE/dx spectrum for electrons crosses the kaon and proton spectra at certain p_T ranges. For comparison see the Bethe-Bloch curves as a function of momentum for $\sqrt{s} = 7$ TeV pp collisions that was shown in Sec. 4.4 in Fig. 4.4.

The presented method is MC dependent: it is sensitive to the ratio of primary to secondary particles in the models. Comparison studies performed on collision and Monte Carlo data indicate that the Monte Carlo simulation using Pythia underestimates the particle yield of secondaries by 0–50%, depending on p_T , as was argued in Ref. [220]. This fact can be especially important in the case of the proton sample, since the yields of protons coming from the detector

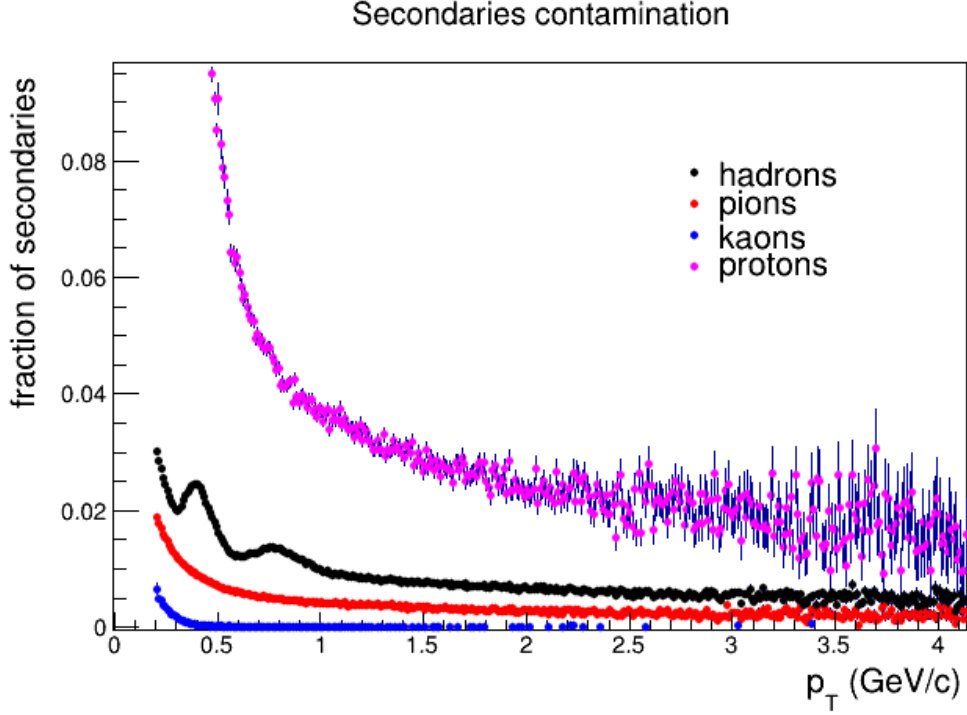


Figure 6.2: Contamination from secondaries as a function of p_T for different particle species. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

material are significantly underestimated. Therefore, for this analysis, a model-independent, data-driven, correction method was studied, the so-called *DCA-based contamination correction* method. It allows us to estimate the ratios between three sets of particles, (1) primary particles, (2) particles coming from weak decays as well as (3) particles coming from material, using collision data only. For this analysis the difference on the final correlation functions between the procedure using the MC-only method and the data-driven method for the estimation of the number of secondary particles turned out to be negligible. For more information see Appendix B.3.

6.2.3 Final correction factor

To combine the information about the efficiency and the contamination from secondaries, we can use the following equations:

$$N_{\text{primaries}}^{\text{generated}} = f \cdot N_{\text{particles}}^{\text{survived}}, \quad (6.6)$$

$$N_{\text{particles}}^{\text{survived}} = N_{\text{primaries}}^{\text{survived}} + N_{\text{secondaries}}^{\text{survived}}. \quad (6.7)$$

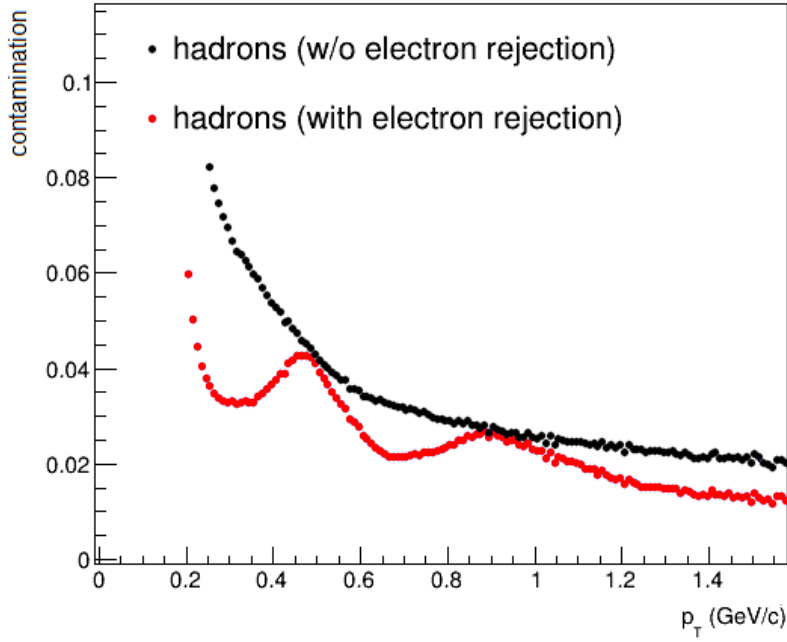


Figure 6.3: Contamination from secondaries for hadrons after the electron-rejection cut was applied (red), and without it (black). The observed structures in the sample where the electron rejection cut was applied are expected due to the electron Bethe-Bloch curve crossing the kaon and proton curves, see Fig. 4.4. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

Combined with Equations (6.4) and (6.5), we obtain:

$$f = \frac{1 - C}{\epsilon}, \quad (6.8)$$

where f is the correction factor that should be applied for each pair of particles to both signal and background distributions as explained in Sec. 6.1. In Fig. 6.4 the dependence of the correction factor on p_T for different particle species can be seen.

Misidentification

For this work no correction procedure for misidentification is applied. The error from neglecting these corrections is assessed in details in Sec. 8.2.

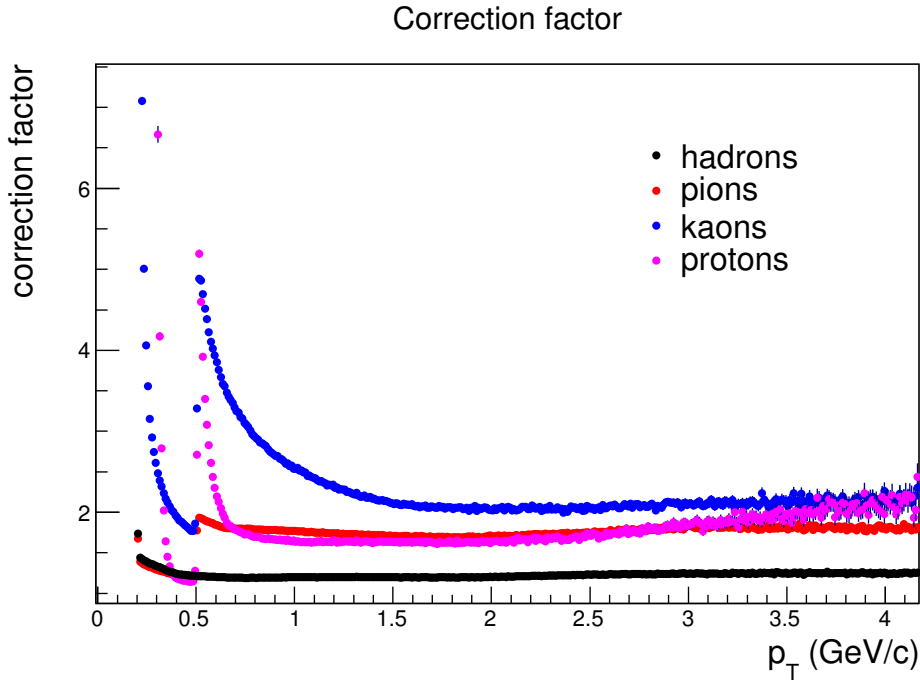


Figure 6.4: Correction factor as a function of p_T for different particle species. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

6.3 Quantitative analysis

After the correlation functions are constructed and suitably corrected, the next step of the analysis is to quantify the structures that emerge in the final shape. For this purpose a fitting was performed. The procedure is the same for identical and non-identical particles; however, the developed mathematical formula is different.

Each one of the proposed formulas describing the correlation function contain free parameters which are determined during the minimization procedure. `TMinuit`, a built-in minimization package of the `ROOT` framework, is used. The χ^2 value describes the quality of the fit (the difference between the analyzed data and the formula for a given set of parameters). The aim of the minimization task is to find a set of parameters that results in the lowest possible χ^2 value.

Fitting formula: non-identified particles

The $\Delta\eta\Delta\varphi$ correlation function reflects contributions from several different sources; therefore, the mathematical formula (presented in Fig. 6.5) is composed of several components:

- A two-dimensional modified Gaussian function (with an additional exponent term e_M), also known as Lévy stable distribution³ to fit the near-side peak, located at $\Delta\eta \approx 0$ and $\Delta\varphi \approx 0$. The magnitude of this Gaussian is described by M_M , the width in $\Delta\eta$ is given by the σ_{M_η} and the width in $\Delta\varphi$ is σ_{M_φ} . To reproduce the periodic nature of the correlation in $\Delta\varphi$, a second Gaussian is added, centered at $\Delta\eta = 0$, $\Delta\varphi = 2\pi$.
- An one-dimensional Gaussian in $\Delta\varphi$ for the away-side ridge, shifted to $\Delta\varphi = \pi$. The magnitude of this structure is described by M_A and the standard deviation is σ_{A_φ} . This Gaussian is periodic as well, which was obtained by adding or subtracting π in both components of this part of the formula.
- An one-dimensional Gaussian in $\Delta\eta$ for the longitudinal ridge, with maximum at $\Delta\eta = 0$. M_L is the magnitude and σ_{L_η} is the standard deviation.
- An one-dimensional parabola for the wing structure with minimum at $\Delta\eta = 0$ arising from the analysis procedure. It is expected not to carry any physical information. More information on the origin of this structure can be found in Sec. 8.5.2. The P parameter is the coefficient of the parabola.
- An offset value N – a constant vertical shift of the fit function.

Fitting formula: identified particles

In the case of the correlation functions of identified particles lower statistics makes the fitting of many components very unstable. Therefore, we focus on two structures, namely the near-side peak and away-side ridge, as well as on changes in their behavior with transverse momenta for different particle species. The formula is presented in Eq. (6.9).

³There are many studies on the peak-shapes ongoing [221], and it is well-known that the shape of the near-side peak is not a Gaussian. In Ref. [222] a Lévy distribution is suggested, with an exponential term responsible for giving this peak a stretched, exponential shape. For more information see also Ref. [223, 224].

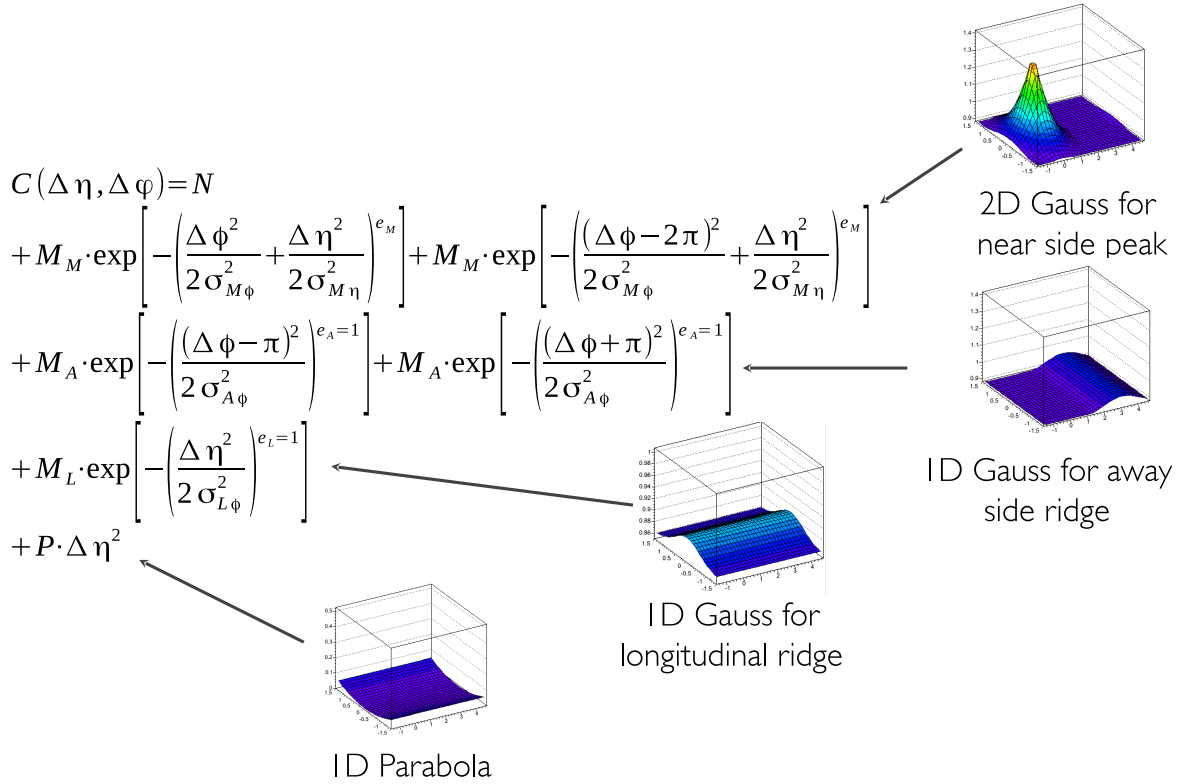


Figure 6.5: Mathematical formula to fit the correlation function with the corresponding structures. N is a normalization, P is the parabola coefficient, M_M , M_A and M_L are the magnitudes of the near-side peak, away-side ridge and longitudinal ridge respectively. Standard deviations are described by $\sigma_{M\eta}$, $\sigma_{M\phi}$, $\sigma_{A\phi}$ and $\sigma_{L\eta}$. The near-side peak exponent is e_M .

$$C(\Delta\eta, \Delta\varphi) = N \quad (6.9a)$$

$$\begin{aligned}
 & + M_M \left\{ \exp \left[- \left(\frac{\Delta\phi^2}{2\sigma_{M\phi}^2} + \frac{\Delta\eta^2}{2\sigma_{M\eta}^2} \right)^{e_M} \right] \right. \\
 & \quad \left. + \exp \left[- \left(\frac{(\Delta\phi - 2\pi)^2}{2\sigma_{M\phi}^2} + \frac{\Delta\eta^2}{2\sigma_{M\eta}^2} \right)^{e_M} \right] \right\} \quad (6.9b)
 \end{aligned}$$

$$\begin{aligned}
 & + M_A \left\{ \exp \left[- \left(\frac{(\Delta\phi - \pi)^2}{2\sigma_{A\phi}^2} \right)^{e_A=1} \right] \right. \\
 & \quad \left. + \exp \left[- \left(\frac{(\Delta\phi + \pi)^2}{2\sigma_{A\phi}^2} \right)^{e_A=1} \right] \right\} \quad (6.9c)
 \end{aligned}$$

Each component of Eq. 6.9 represents one structure observed in the correlation function:

- A two-dimensional modified Gaussian (Lévy distribution) to describe the near-side peak at $\Delta\eta \approx 0$ and $\Delta\varphi \approx 0$. Similarly, as for non-identified particles, it is defined with four parameters: magnitude M_M , widths σ_{M_η} and σ_{M_φ} and exponent term e_M . To reproduce the periodic nature of the correlation, a second Gaussian, centered at $\Delta\eta = 0$, $\Delta\varphi = 2\pi$, was added; Eq. (6.9b).
- An one-dimensional Gaussian function in the $\Delta\varphi$ plane, centered at $\Delta\varphi = \pi$, for the away-side ridge. It is described by M_A and the standard deviation is σ_{A_φ} . This Gaussian is periodic as well; hence, the two components of the function of Eq. (6.9c).
- An offset – normalization factor N , corresponding to the vertical shift of the fit function; see Eq. (6.9a).

These components can describe correlations of pions and kaons regardless of the charge combination in a pair as well as for pairs of proton-antiproton. However, for the like-sign pairs of protons a large dip centered at $(\Delta\eta, \Delta\varphi) = (0, 0)$ is observed. For this case the near-side peak is negative and an inverse Gaussian (one of negative magnitude) is used.

It should be stated here that the simple description used (near-side 2D Gaussian + away-side 1D Gaussian) is not perfect. However, with this simple procedure we aim to estimate the relative differences of the structures between different particle species and transverse momenta, and for this goal the used formula is satisfactory. The quality of the fit was checked with residuals, as described in Sec. 7.2.

Chapter 7

Experimental results

In this chapter, the results of the two-particle angular correlation analysis are presented. In Sec. 7.1 results for the non-identified data sample are reported. The analysis is performed for the collision energies of $\sqrt{s} = 0.9, 2.76$, and 7.0 TeV. The dependence on energy, pair-charge, multiplicity and transverse momentum was studied. The results on multiplicity and pair transverse momentum dependence were quantified using the fitting procedure developed for this work. In Sec. 7.2 results for the identified data sample are reported. The analysis is performed for the $\sqrt{s} = 7$ TeV collision energy, for samples of pions, kaons, and protons separately. The studies of pair-charge, multiplicity and transverse momentum dependence are presented. The results on pair transverse momentum dependence were quantified using the fitting procedure.

Details on the selection of the collision data samples, recorded by the ALICE experiment, are given in Chapter 5; the data is divided into different multiplicity and pair transverse momentum classes as detailed in Sec. 5.6. The applied analysis methodology and correction procedure is described in Chapter 6. Details on the uncertainties of the data points are reported in Chapter 8, in Sec. 8.4 and Sec. 8.5.

All plots in this chapter labeled as “ALICE Preliminary” have undergone internal approval procedure of the collaboration and were presented at international conferences and workshops. In general, Preliminary figures show the results of profoundly advanced analysis and must include estimates of all statistical and systematic uncertainties that are relevant for the interpretation of the measurement and the understanding of the underlying physics.

7.1 Non-identified particles

In this section the results of the $\Delta\eta\Delta\varphi$ correlation analysis for non-identified particles are presented. The analysis was performed for three energies, $\sqrt{s} = 0.9, 2.76$, and 7.0 TeV. The minimum bias data sample, without any additional selection, is presented in Sec. 7.1.1. The

dependence of the angular correlations on the charge combinations of particles in the pair is presented in Sec. 7.1.2. In Sec. 7.1.3 the multiplicity dependence is studied, and quantified using the fitting procedure. Finally, in Sec. 7.1.4 studies of the dependence on the pair transverse momentum are reported.

7.1.1 Energy dependence

The data analysis is performed based on three proton-proton collision data samples recorded at collision energies of $\sqrt{s} = 0.9, 2.76$ and 7 TeV. The $\Delta\eta\Delta\phi$ correlation functions for those three different energies are shown in Fig. 7.1.

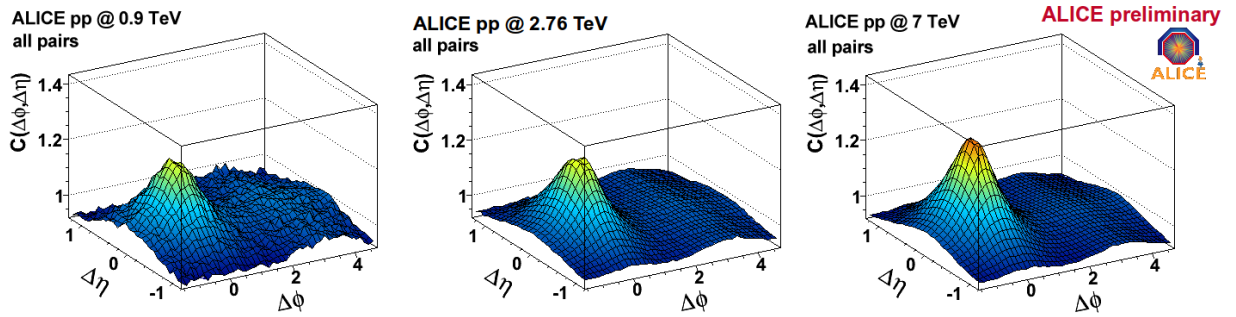


Figure 7.1: Dependence of the $\Delta\eta\Delta\phi$ correlation functions on the collision energy for pp collision data.

Similar shape of the correlation function is observed for all studied collision energies. As introduced in Sec. 3.3 there are number of different correlation sources that influence the observed $\Delta\eta\Delta\phi$ distributions and create distinct structures. The most pronounced one is the peak observed on the near-side around $(0,0)$, associated mainly with the high- p_T process (jets) and Bose-Einstein correlations. The second distinct structure is the away-side ridge observed as an extended correlation approximately at $\Delta\phi \approx \pi$, spanned over full $\Delta\eta$ range. It originates from the conservation of momentum, especially from back-to-back jets. The last prominent correlation structure located at $\Delta\eta = 0$ and elongated in $\Delta\phi$ can be described by the wide one-dimensional Gaussian function with large $\Delta\eta$ width. It can be attributed to mechanisms such as resonance decays or fragmentation of strings. Similar results were presented by CMS [97] and ATLAS [134] experiments.

The near-side peak increases as a function of the collision energy. This can be interpreted as a rise in the charged particle multiplicity per jet with increasing collision energy.

7.1.2 Charge dependence

Four different charge combinations of particles in a pair were analyzed: positive like-sign ($++$), negative like-sign ($--$), unlike-sign ($+-$), and all possible (a pair can be combined of any particle, independently of charge). The results of the charge dependent analysis performed for pp collision data at $\sqrt{s} = 7$ TeV are shown in Fig. 7.2. The near-side peak at $(0, 0)$, corresponding to the minijet and Bose-Einstein correlations, and the away-side ridge at $\Delta\varphi = \pi$, corresponding to back-to-back minijets, are both present for all shown plots. The correlation functions for like-sign pairs composed of negative ($--$) and positive ($++$) particles for the practically zero-net-baryon-density system produced at the LHC are expected to give consistent values. Indeed, they are identical within the statistical uncertainties. Therefore, in further sections we show only one of the two, or, to increase statistics, we calculate the statistical average of them. There is a significant difference between like-sign ($++$ and $--$) and unlike-sign distributions ($+-$). It is in agreement with the assumption that there is an additional source of correlation of identical particle pairs due to the Bose-Einstein statistics, which is not influencing unlike-sign pairs ($+-$). Similarly, we expect the correlation function of unlike-sign pairs to be influenced more by the resonance contributions than the correlation function of like-sign pairs. This expectation is consistent with the observed longitudinal ridge structure, more pronounced for the correlation function of unlike-sign pairs.

Similarly, Fig. 7.3 shows the equivalent plots for $\sqrt{s} = 2.76$ TeV pp collision data. Since the energy of the collision is lower, we expect that there would be a smaller production of particles within minijets which would result in a smaller correlation at the near- and away-side. This is indeed what can be seen in the plots (especially for the unlike-sign pairs ($+-$) where we do not have contribution from Bose-Einstein statistics). On the other hand, femtoscopic correlations are very slightly influenced by the increasing energy of the collisions [154]. This is why we would expect more similar correlation functions for both energies for like-sign pairs ($++$ and $--$) and this is what we observe comparing plots (b-c) in Fig. 7.2 and Fig. 7.3.

The results of the charge dependence analysis performed for the $\sqrt{s} = 0.9$ TeV pp collision data are shown in Fig. 7.4. The available statistics for the $\sqrt{s} = 0.9$ TeV pp collision data was much lower than for the $\sqrt{s} = 7$ TeV pp collision data; therefore, the statistical uncertainties of the correlation function are higher, which can be seen as statistical fluctuations of the correlation

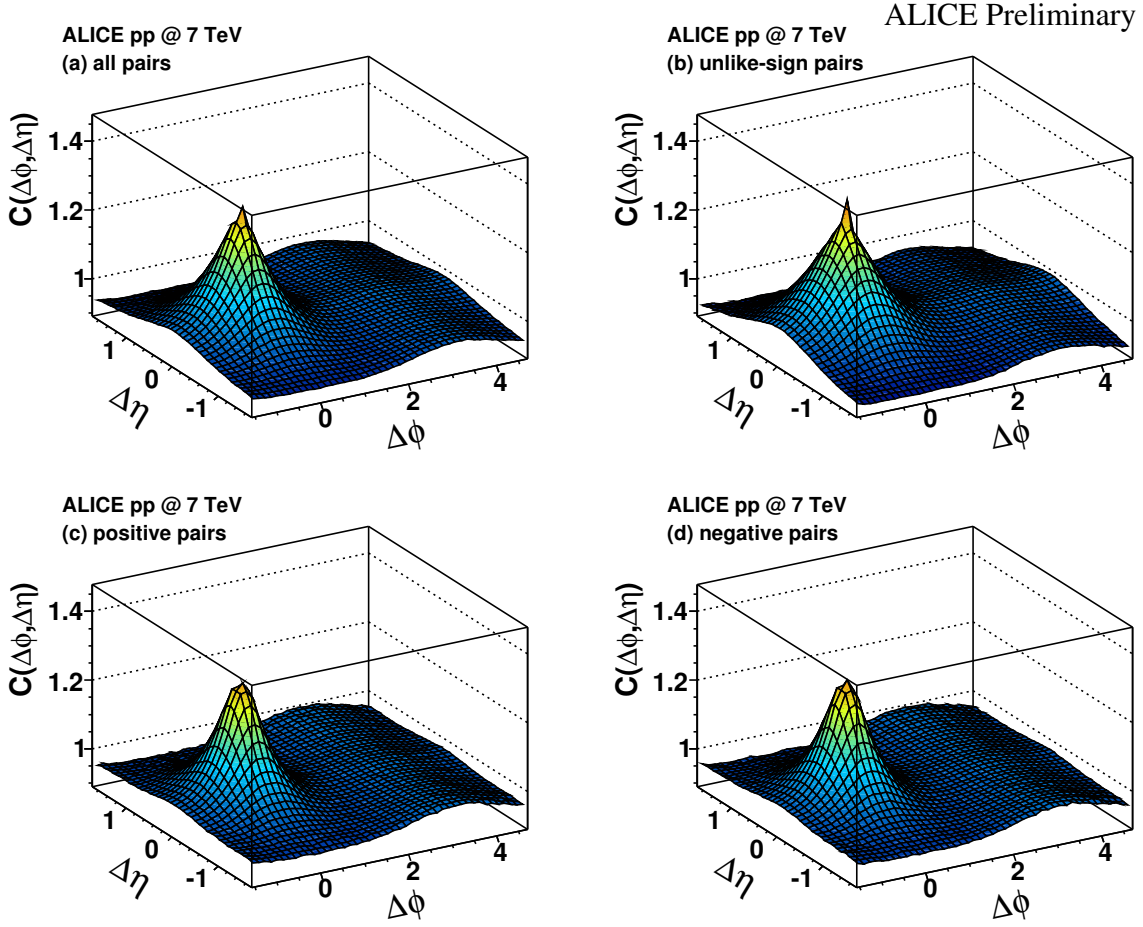


Figure 7.2: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for $\sqrt{s} = 7$ TeV pp collision data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

functions. The conclusions from the energy dependence studies remain valid: we observe a decrease of the near-side peak with decreasing energy.

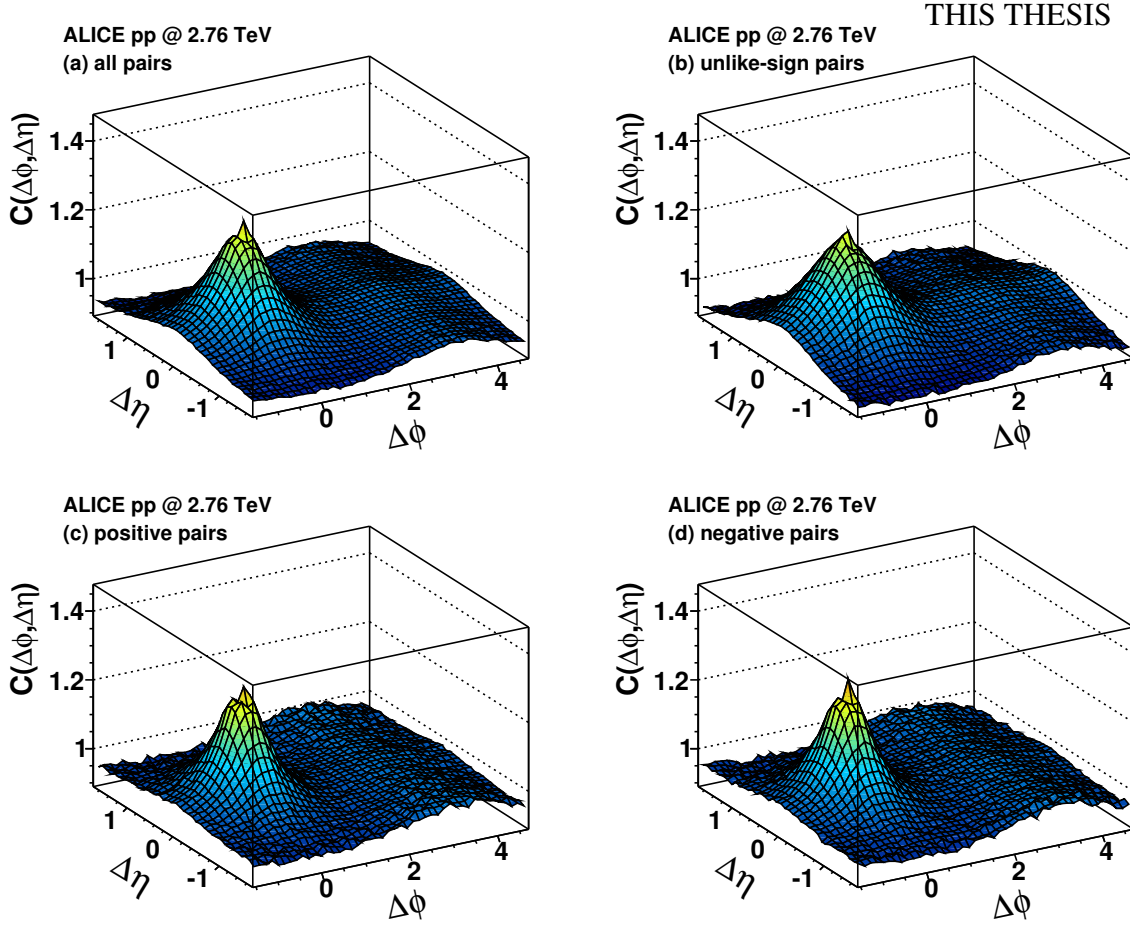


Figure 7.3: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 2.76$ TeV pp collision data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

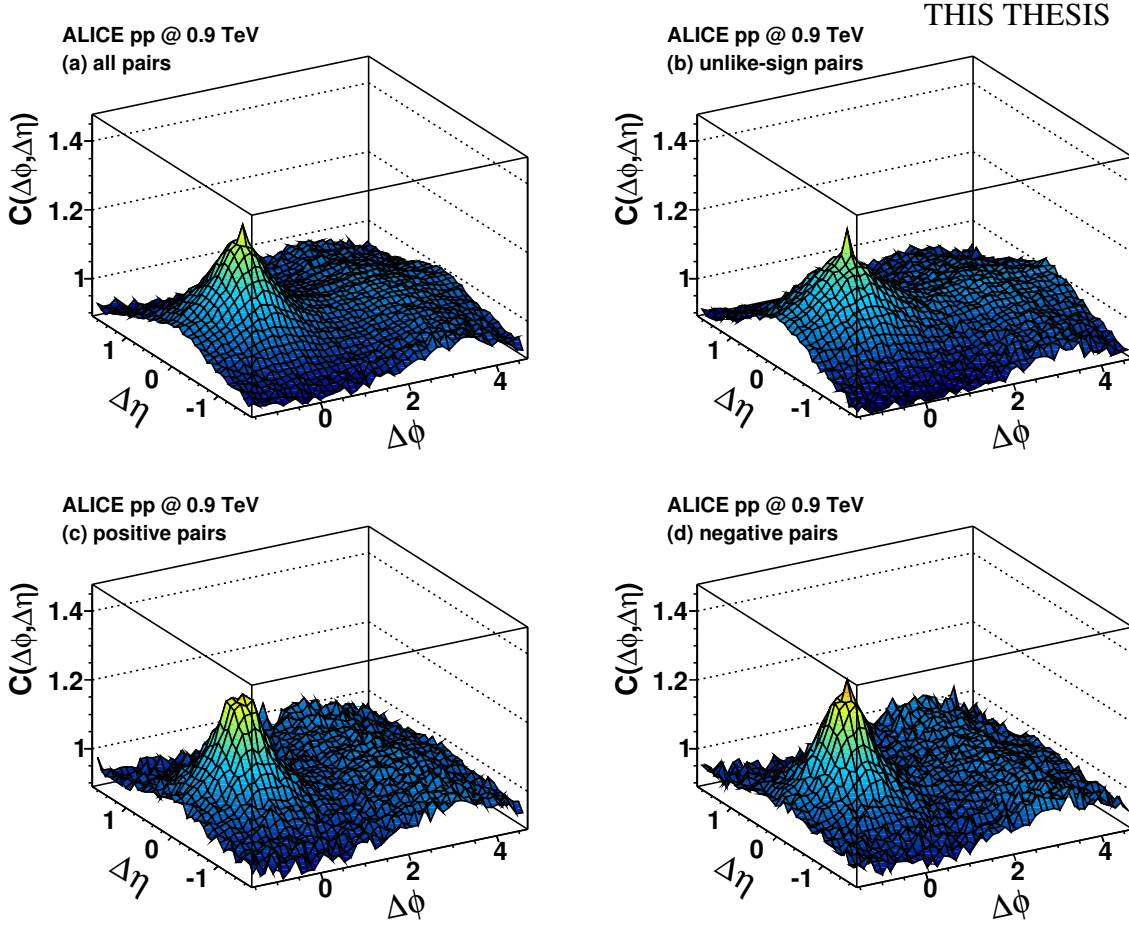


Figure 7.4: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 0.9$ TeV pp collision data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

7.1.3 Multiplicity dependence

The change of the correlation functions can be observed also for increasing multiplicities of collisions.

The events of the $\sqrt{s} = 7$ TeV data sample were divided into eight multiplicity ranges while the ones of the $\sqrt{s} = 0.9$ GeV were divided into four multiplicity ranges, as described in Sec. 5.6.1. The analysis was performed separately in each range, for different charge combinations of particles in the pair (all possible, like-sign, and unlike-sign).

Figure 7.5 and Fig. 7.6 show a decrease of the correlations with increasing multiplicity for positive and unlike-sign pairs respectively. We expect this decrease of the correlation structures with increasing multiplicity N_{ch} due to the construction of the correlation function (normalization to the number of pairs). If the mentioned decrease was only of this trivial origin, it would be approximately $\sim 1/N_{\text{ch}}$.

Studies of the femtoscopic correlations show that there is a decrease of the correlation with increasing multiplicity [154]. Similar conclusions can be obtained from $\Delta\eta\Delta\varphi$ studies by comparing the plots in Fig. 7.5 and Fig. 7.6. We can see that for unlike-sign (+ -) analysis this decrease is much less pronounced; on the other hand, it is significant when like-sign pairs (++) and (- -) are analyzed. This suggests that the minijet correlation changes less as a function of multiplicity than i.e. correlation from Bose-Einstein statistics.

Furthermore, the longitudinal ridge clearly seen in the first two bins, disappears for higher multiplicities.

All conclusions remain the same for the $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 2.76$ TeV pp collision data; an example for $\sqrt{s} = 0.9$ TeV is shown in Fig. 7.7.

This study can lead to crucial verification of MC models, since the observed behavior of the decrease of the correlation with increasing multiplicity is reproduced only by some MC event generators, as will be shown in Sec 9.2.2.

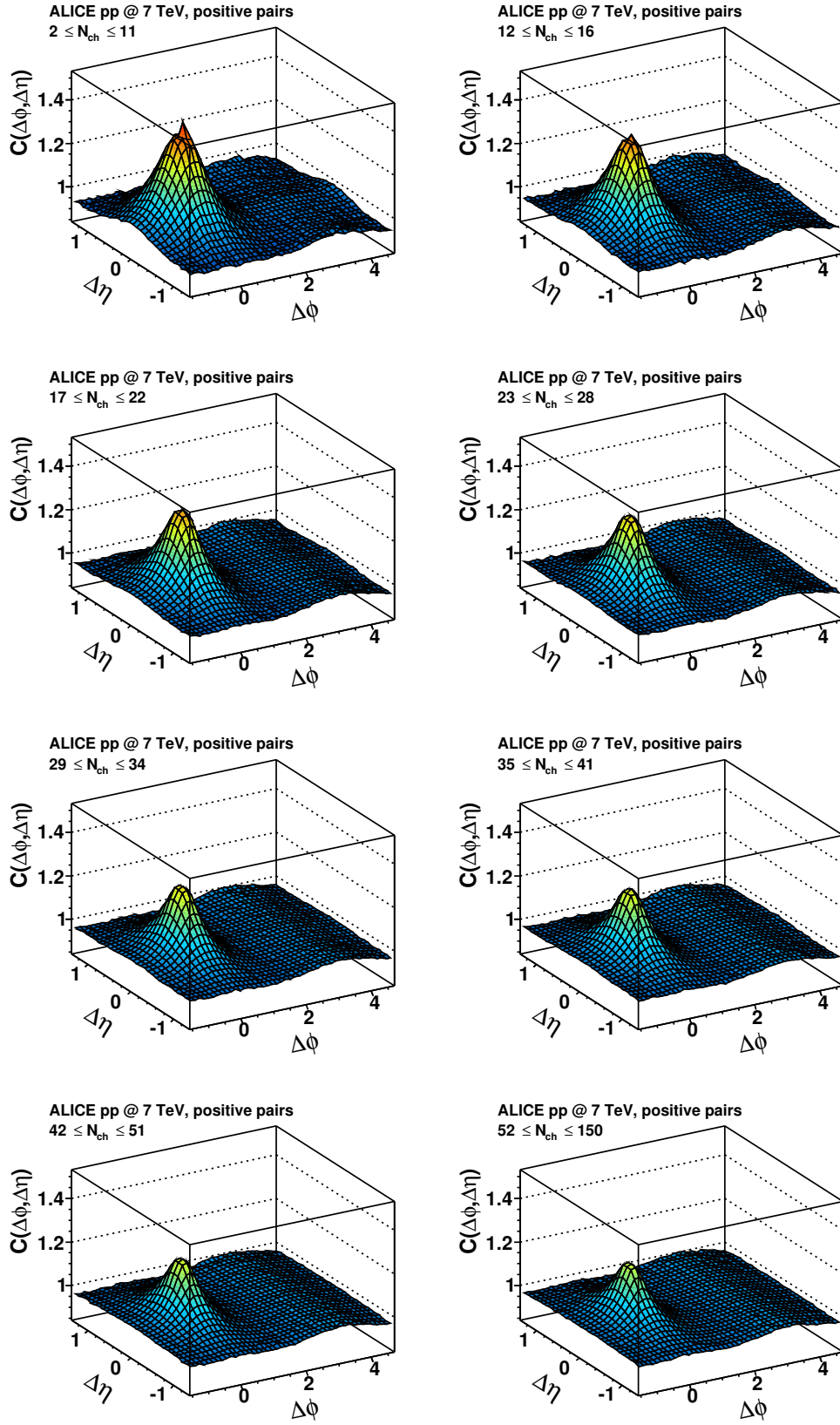


Figure 7.5: The multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for like-sign (positive) particle pairs (++), for the $\sqrt{s} = 7$ TeV pp collision data.

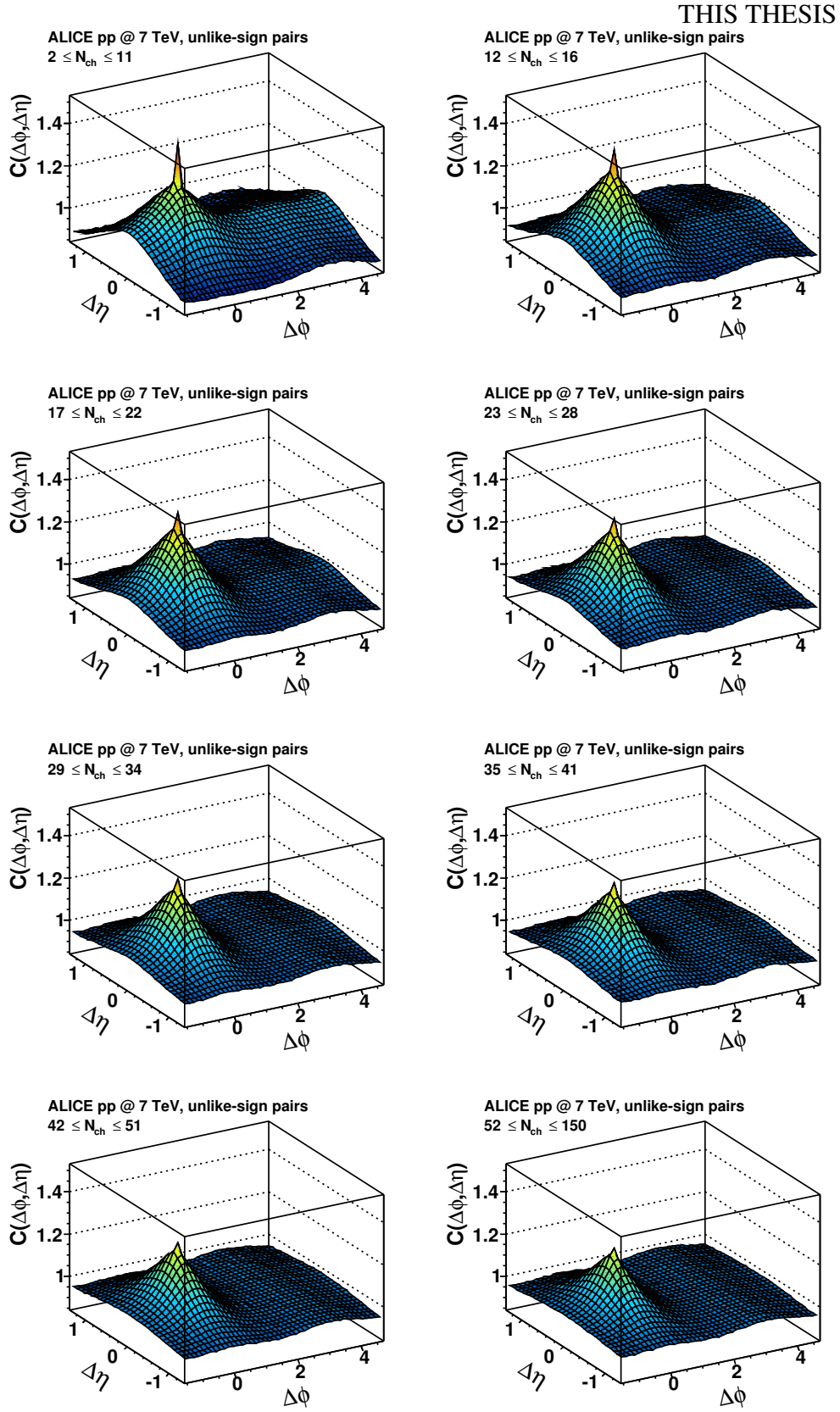


Figure 7.6: The multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for unlike-sign particle pairs (+ -), for the $\sqrt{s} = 7$ TeV pp collision data.

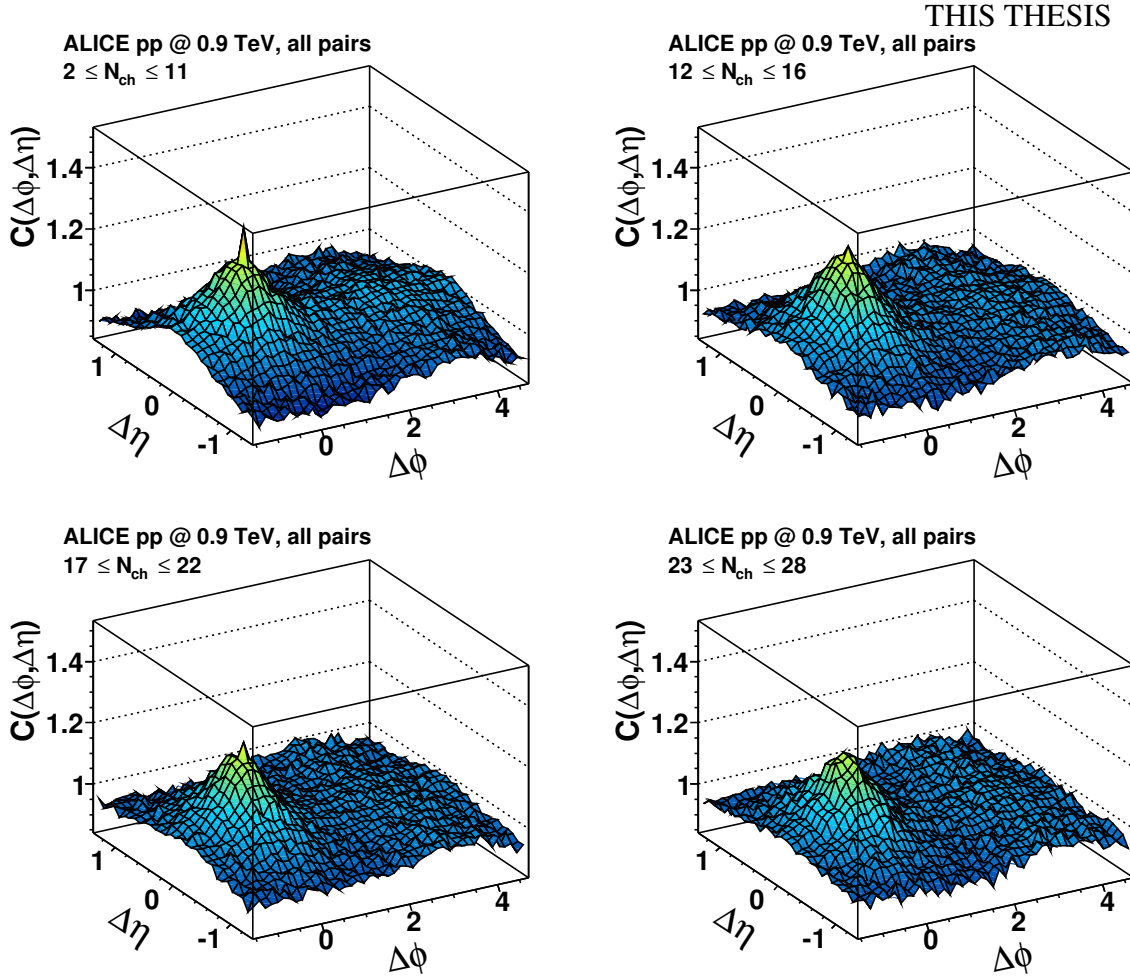


Figure 7.7: The multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for all pairs, for the $\sqrt{s} = 0.9$ TeV pp collision data.

Quantitative analysis

To observe global trends across multiplicity ranges and quantify the structures that emerge in the final shape, a fitting was performed, as explained in detail in Sec. 6.3. Results of the fitting of the 7 TeV pp collision data in multiplicity ranges are presented in Fig. 7.8. The decrease of all correlations with increasing multiplicity can be seen. The magnitude of the longitudinal ridge is clearly higher for unlike-sign pairs than for like-sign pairs; it is in agreement with the expectation that the structures emerge from the contribution coming from resonance decays, influencing the unlike-sign pairs more strongly. Also, the width of all structures decreases with multiplicity; smaller width corresponds to stronger collimation of particles, and higher event multiplicities dilute the collimation as well as the magnitude. The uncertainties for the higher multiplicity ranges for the longitudinal ridge are very big, but the magnitude is close to zero; so, the value of σ_L has no meaning in such case. For all other cases the systematic uncertainties are small, as well as the statistical ones, which are invisible due to their very small value.

As mentioned, the observed decrease of correlation strength with increasing multiplicity is at least partially coming from the trivial effect of $1/N_{\text{ch}}$ dilution of the correlation. To test if it originates only from this baseline effect the integrals under the three structures, i.e. near-side peak, away-side ridge and longitudinal ridge, were calculated. The results of this integration are shown in Fig. 7.9. The $\sim 1/N_{\text{ch}}$ lines are also superimposed on the plots. It can be observed that the longitudinal ridge structure I_L indeed follows the $1/N_{\text{ch}}$ scaling. However, both, near- and away-side structures do not follow such trivial dilution and decrease at a much slower rate (such consistent behavior of the two structures is expected, since both of them arise mostly from the same physical mechanism – minijet production).

The observations from the results of the fit that are presented in Fig. 7.8 correspond to the observations from the correlation functions presented in Fig. 7.5 and Fig. 7.6. However, the fit results allow us to quantify the differences comparing directly different data samples and also provide additional information i.e. about the decrease rate of the visible structures.

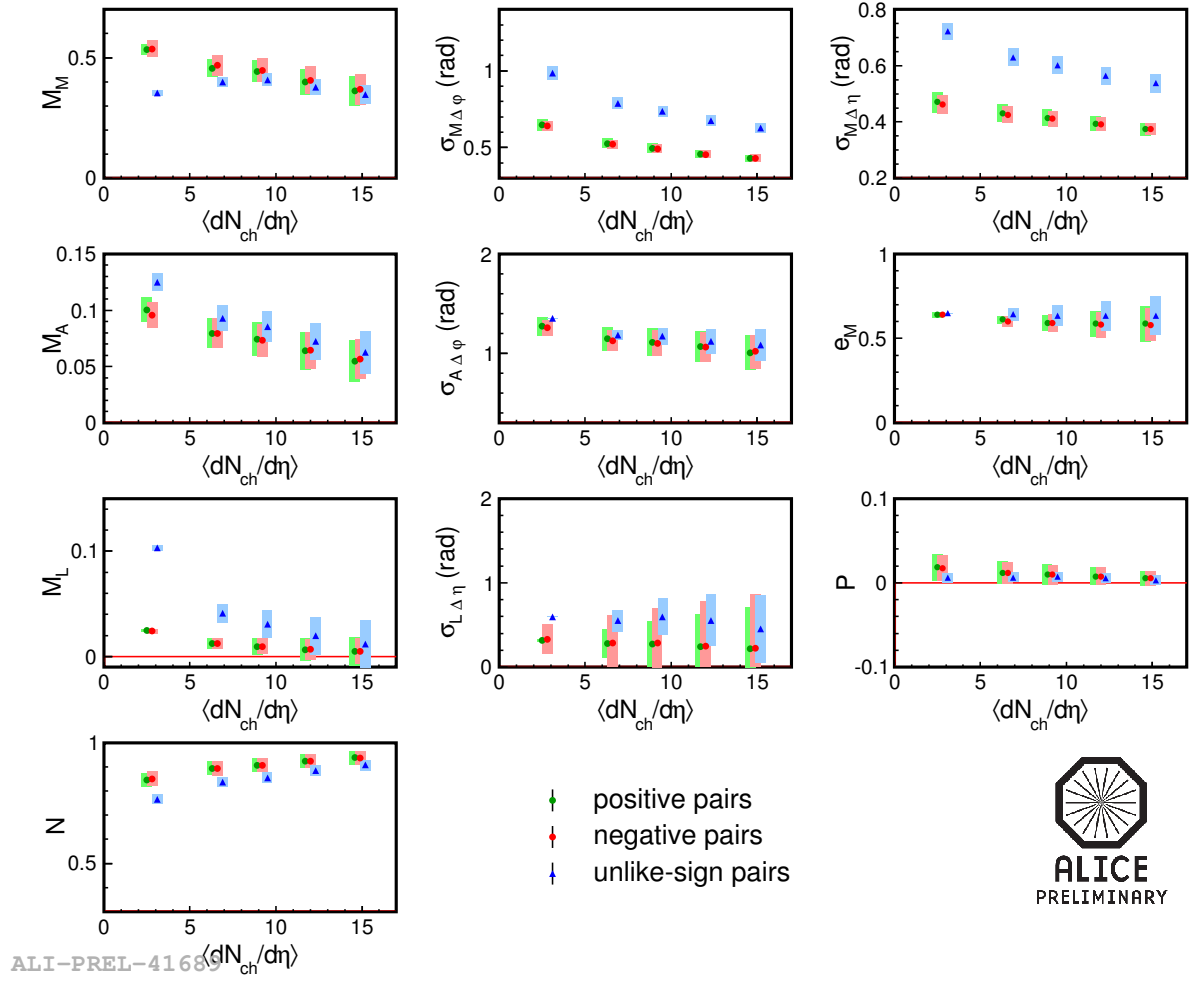


Figure 7.8: Results of the quantifying procedure applied for the $\sqrt{s} = 7$ TeV pp collision data: dependence of the parameters of the fit function on the event multiplicity for different charge combinations. M is the magnitude of the structure, σ is a parameter of the Gaussian function associated with the width of the structure, N is the normalization, ϵ_M is an exponent of the modified Gaussian function for the near-side peak and P is a coefficient of the parabola used to fit the wing structure.

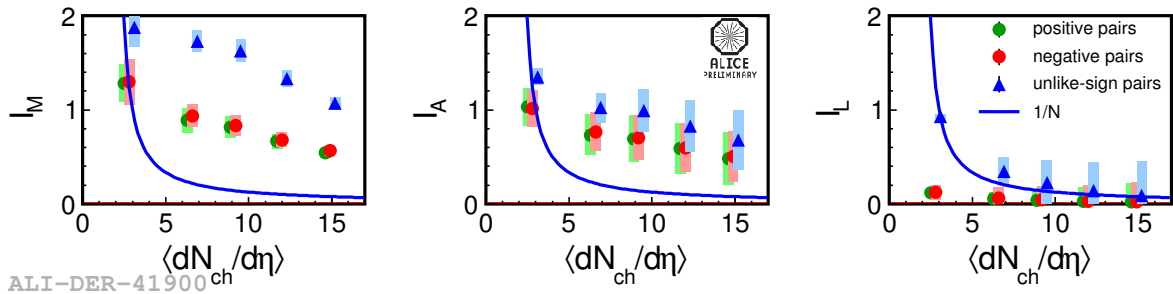


Figure 7.9: Left: integral of the near-side peak. Middle: integral of the away-side ridge. Right: integral of the longitudinal ridge.

7.1.4 Transverse momentum dependence

The analysis was performed in different ranges of pair transverse momenta. For each p_T -sum interval the dependence of the $\Delta\eta\Delta\varphi$ distribution on multiplicity and charge was also studied. This kind of analysis was introduced to more precisely distinguish femtoscopic correlations from minijets. Since femtoscopic correlations are stronger for lower values of transverse momenta of particles [154] and minijets are stronger for higher, we should be able to disentangle them by studying correlation functions in different p_T -sum ranges.

The results of the analysis are shown in the left column of Fig. 7.10 for unlike-sign pairs (+ -) and on the right for like-sign pairs (++) . The minijet correlations are rising with increasing values of the sum of transverse momenta of particles, both, at near-side peak and away-side ridge. This peak at high momenta is also higher for unlike-sign pairs (+ -), which is expected because during the minijet fragmentation process it is easier to produce an opposite-charge pair, due to local charge conservation.

At low momenta, minijets do not play a significant role; on the other hand, femtoscopic effects are expected to be prominent. The Bose-Einstein correlations exist only for identical particles. Indeed, appropriate structures confirming those expectations are observed in the data: in the right panel of Fig. 7.10 a pronounced correlation is seen at the near-side for the like-sign pairs in the lowest p_T -sum range. In contrast, for unlike-sign pairs the correlation function in this interval is almost flat¹. Our interpretation is the following: for like-sign pairs the correlation at low p_T is influenced almost only by the femtoscopic effect. As we go to higher values of p_T -sum, the correlation first drops in the second p_T -sum range and then rapidly grows in the last. This is in agreement with what we expect; namely, Bose-Einstein correlations are diluted and minijets rise for larger values of p_T -sum. Hence, the observed behavior is an interplay of those two processes. Those observations give us an interesting insight into the problem of non-femtoscopic correlations in the femtoscopic correlation functions (see Sec. 3.2.6). For those analyses long-range wide structures appear at high values of pair transverse momenta k_T , that cannot be attributed to femtoscopic effects alone. As explained in Appendix A, femtoscopic observables are in direct relation with $\Delta\eta$, $\Delta\varphi$ and the structures visible in $\Delta\eta\Delta\varphi$ distributions create some structures in femtoscopic correlation functions. Therefore, the significant near-side peak and away-side ridge emerging for high pair transverse momenta p_T -sum ranges,

¹The small spike visible at $(\Delta\eta\Delta\varphi) = (0, 0)$ comes from photon conversions to e^+e^- pairs.

arising from minijet contributions, create also some non-femtoscopic structures in the representation used in femtoscopic analyses. The conclusions from the analysis of the data from $\sqrt{s} = 2.76$ TeV collisions are the same.

Moreover, the analysis was also performed in p_T -sum and multiplicity ranges simultaneously. Such summary plots are shown in Fig. 7.11 for unlike-sign pairs (+ -) and Fig. 7.12 for like-sign pairs (++). The multiplicity rises from top to bottom, the p_T -sum rises from left to right. The interplay from both multiplicity and transverse momentum analyses is summarized below; it can be seen that certain correlation structures (i.e. near-side peak and away-side ridge) increase from left to right with increasing p_T -sum. It can also be seen that the correlation decreases with increasing multiplicity from top to bottom. It is interesting to see that mostly prominent longitudinal ridge is visible for low p_T and low multiplicity, for unlike-sign pairs, while the baseline structure under the near-side peak for like-sign pairs is almost flat.

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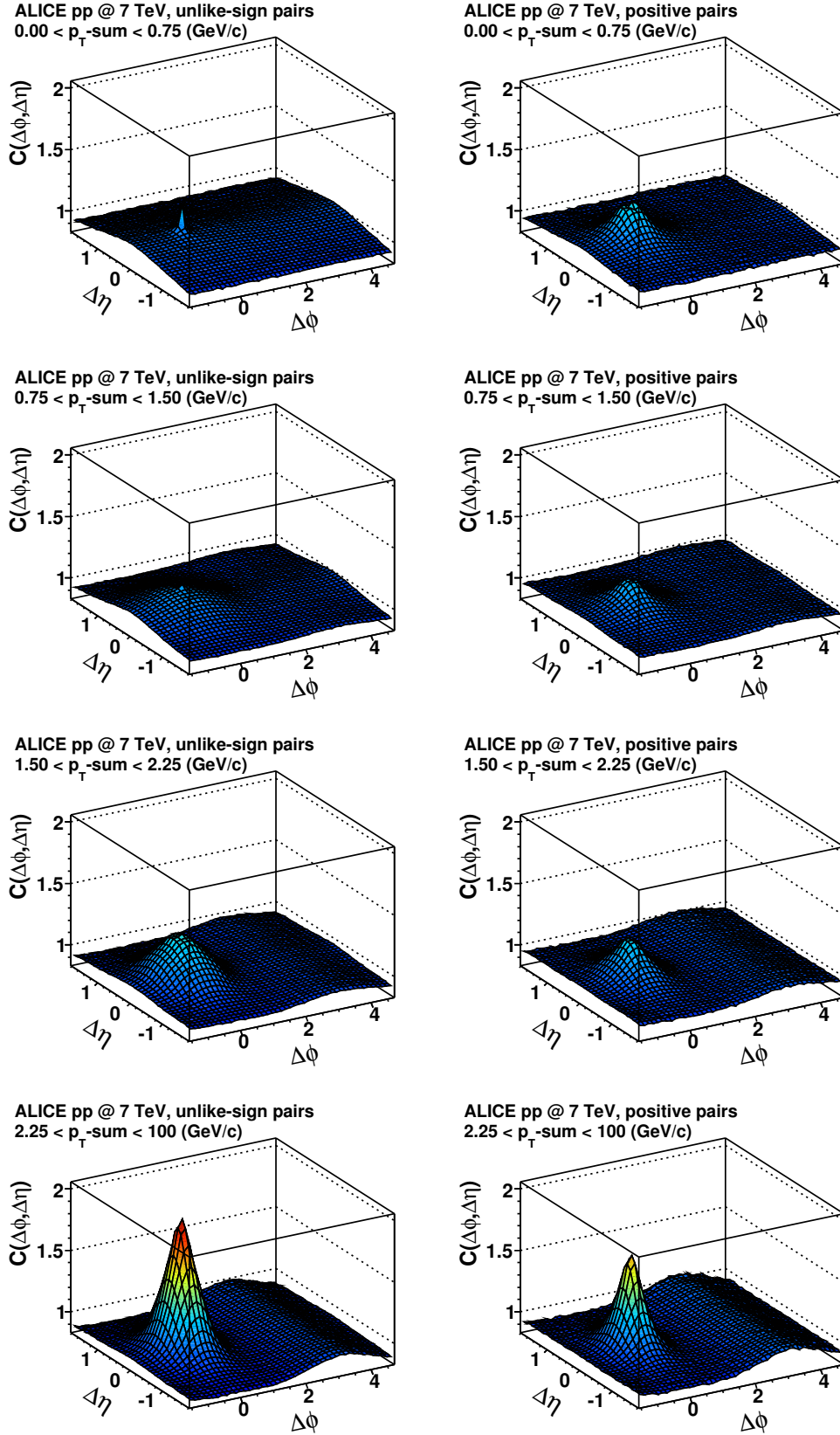


Figure 7.10: The dependence of the $\Delta\eta\Delta\phi$ correlation functions on the $p_{\text{T-sum}}$ for unlike-sign (left panel) and like-sign (right panel) particle pairs for the $\sqrt{s} = 7$ TeV pp collision data.

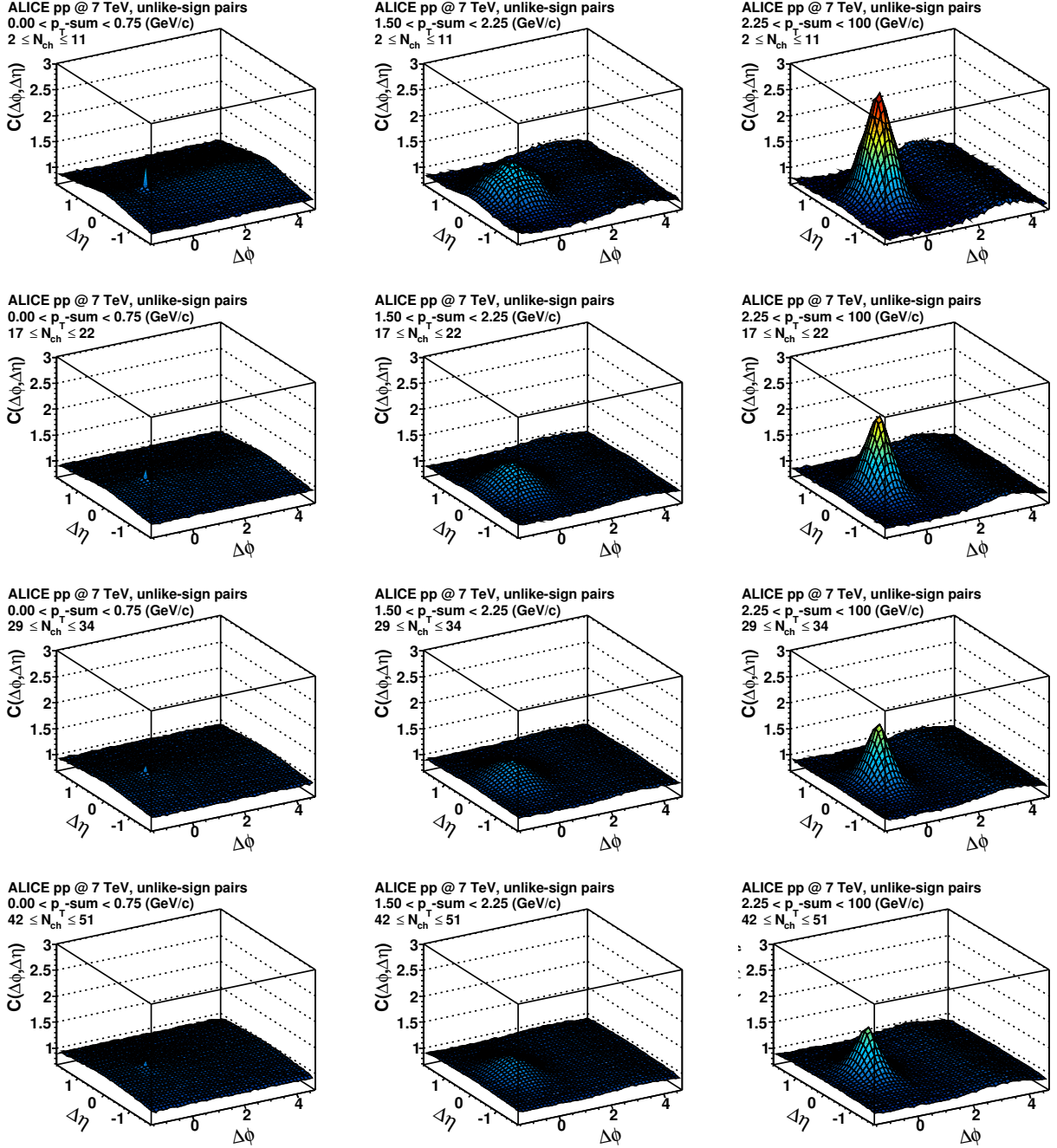


Figure 7.11: The dependence of the $\Delta\eta\Delta\phi$ correlation functions on the p_T -sum and multiplicity for unlike-sign particle pairs (+ -) for the $\sqrt{s} = 7$ TeV pp collision data.

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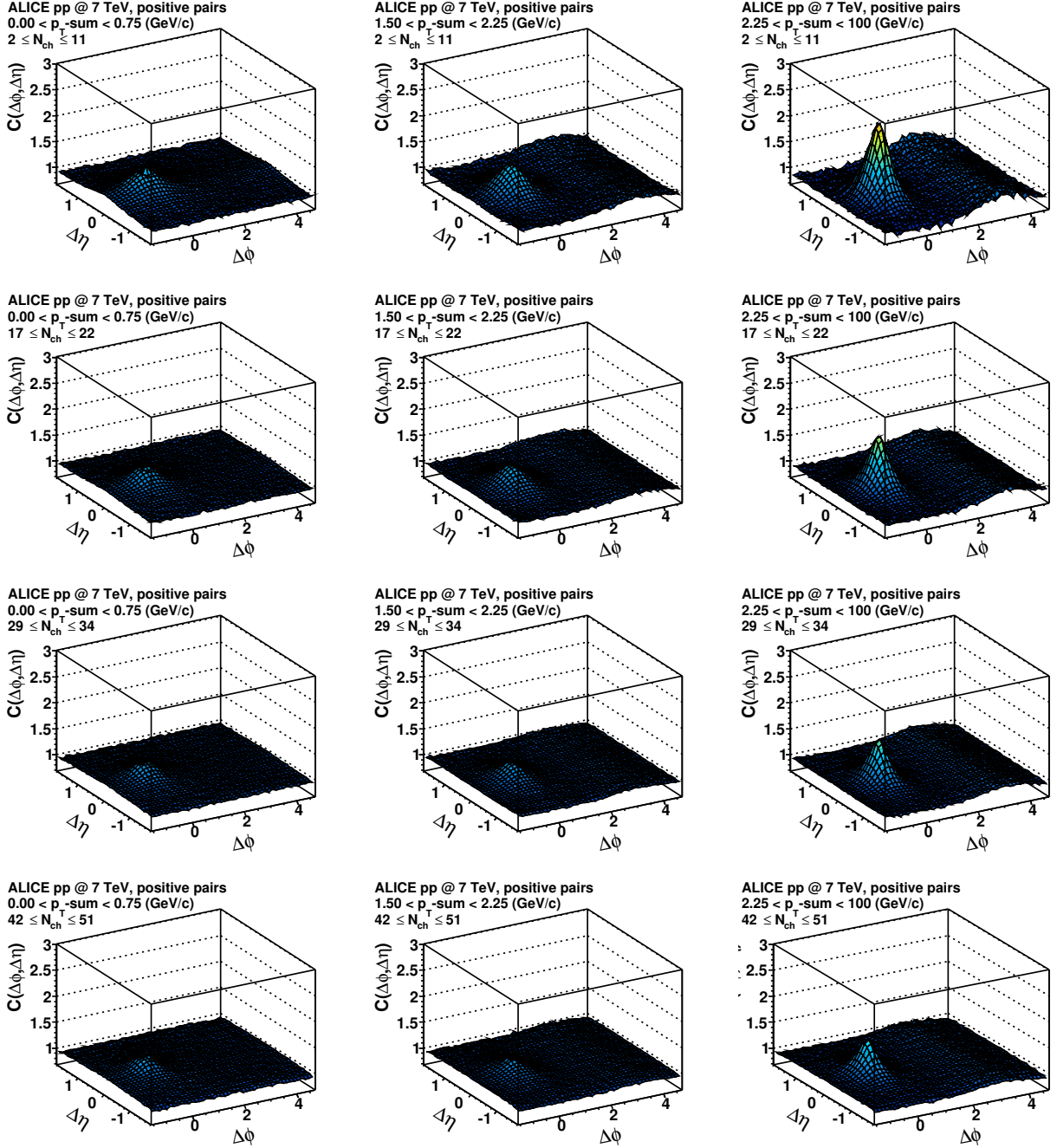


Figure 7.12: The dependence of the $\Delta\eta\Delta\phi$ correlation functions on the p_T -sum and multiplicity for like-sign (positive) particle pairs ($++$) for the $\sqrt{s} = 7$ TeV pp collision data.

Quantitative analysis

Results of the fitting of the data in p_T -sum ranges are presented in Fig. 7.13. Because of very big systematic uncertainty the first p_T -sum range for unlike-sign pairs was removed from the plots.

The magnitude of the near-side peak as well as of the away-side ridge is increasing with increasing p_T -sum. Since both those structures are strongly correlated with minijets, this observation is consistent with the expectation that the particles within jets (hard scattering processes) have relatively higher momenta than the bulk of particles produced in the collision. On the other hand, the magnitude of the longitudinal ridge structure decreases with increasing p_T -sum. Those conclusions can also be drawn from the correlation functions; however, quantification allows us to compare differences directly. The decrease of the width of all structures with p_T -sum is consistent with expectations, as particles from minijets with higher p_T will be more collimated.

Another effect that can be observed is that for the highest pair transverse momentum range the magnitude of the near-side peak is higher for unlike-sign pairs and the magnitude of the away-side ridge is higher for like-sign pairs, while the widths are comparable. This observation can be explained by the fact that for highest p_T -sum range (with strongest minijet contribution) we expect the charge conservation to induce trivial effects coming from local charge conservation, enhancing the near-side peak for unlike-sign pairs and the away-side ridge for like-sign pairs. More information and the test of this hypothesis is presented in Sec. 9.1.2.2.

The systematic uncertainties are very small, except for the parameters describing the longitudinal ridge. In the case of the longitudinal ridge, the uncertainties of M_L and $\sigma_{L\Delta\eta}$ for like-sign pairs were set to the value of the parameters, because of the small impact of this structure on the overall fit (see Sec. 8.5.2, paragraph “Longitudinal ridge fixed to zero”). Statistical uncertainties are not visible, similarly as for the analysis in multiplicity ranges.

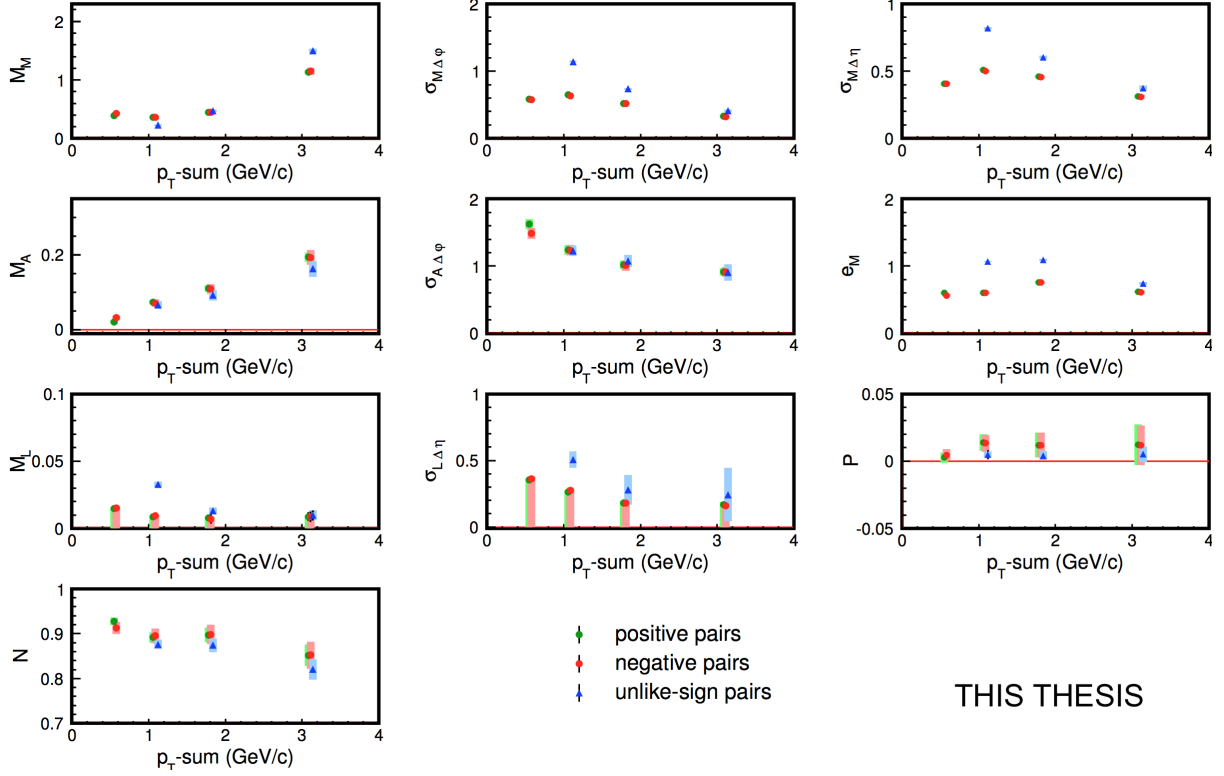


Figure 7.13: Results of the quantifying procedure applied for the $\sqrt{s} = 7$ TeV pp collision data: dependence of the parameters of the fit function on the p_T -sum. M is the magnitude of the structure, σ is a parameter of the Gaussian function associated with the width of the structure, N is a normalization, e_M is an exponent of the modified Gaussian function for the near-side peak and P is a coefficient of the parabola used to fit the wing structure.

7.2 Identified particles (π , K , p)

In this section the results of the $\Delta\eta\Delta\phi$ correlation analysis for identified particles are presented. The analysis was performed for $\sqrt{s} = 7.0$ TeV pp collision data for pions, kaons, and protons. The dependence on the charge combinations of particles in the pair is presented in Sec. 7.2.1. In Sec. 7.2.2 the multiplicity dependence is studied. Finally, in Sec. 7.2.3 studies of the dependence on the pair transverse momentum are presented and quantified using the fitting procedure.

7.2.1 Charge dependence

The measured correlation functions for all three analyzed particle types (pions, kaons, protons) are shown in Fig. 7.14 for unlike-sign pairs and in Fig. 7.15 for like-sign pairs. The magnitude of the near-side peak with a center at $(\Delta\eta, \Delta\phi) = (0, 0)$ is different for different particle species.

In the case of both, unlike-sign and like-sign pairs, the correlation is the strongest (the near-side peak is most distinct) for kaon pairs and significantly lower for proton and pion pairs. Moreover, a strikingly different behavior is present in the case of protons – for like-sign pairs instead of a near-side peak we observe a wide dip with a minimum at $(\Delta\eta, \Delta\phi) = (0, 0)$, even though for $p\bar{p}$ the pronounced near-side peak is visible. The magnitude of the away-side correlation is small in comparison to the near-side peak in the case of unlike-sign pairs for all particle types. However, it is more prominent for the like-sign pairs (stronger for protons and kaons, the weakest for pions).

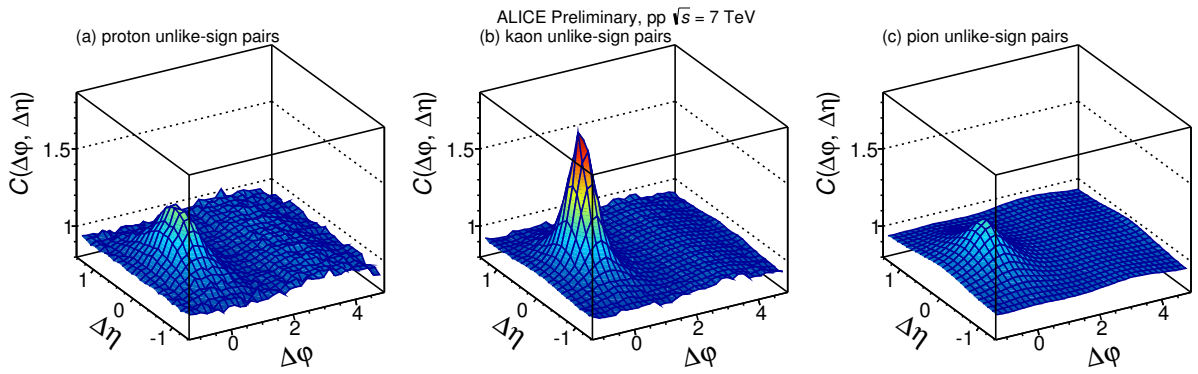


Figure 7.14: Correlation functions for unlike-sign pairs of protons, kaons, and pions.

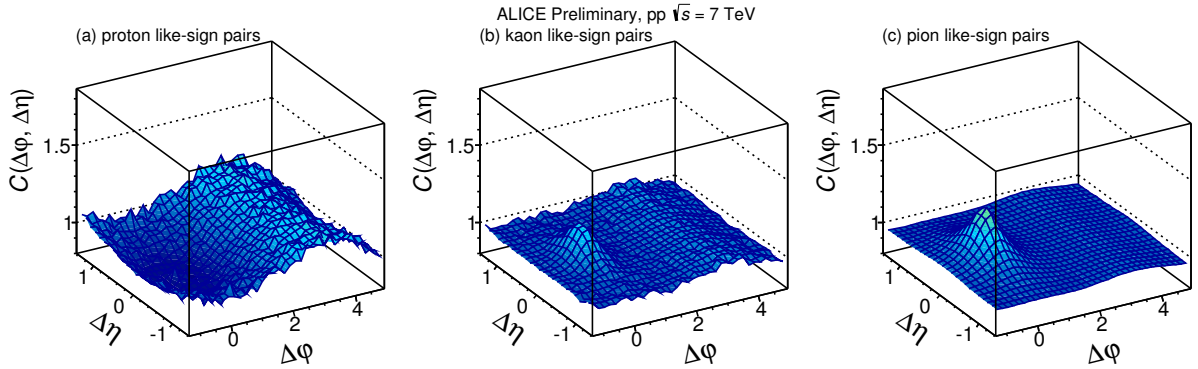


Figure 7.15: Correlation functions for like-sign pairs of protons, kaons, and pions.

Our hypothesis is that the following reasoning explains these results. The production of different types of particles is governed by various conservation laws, summarized in Table 7.1. In the case of pions (the lightest hadrons with a rest mass $0.140 \text{ GeV}/c$) only the momentum and electric charge must be conserved. In the case of charged kaons (with a rest mass $0.494 \text{ GeV}/c$), which contain a strange quark, strangeness must be conserved. In the case of protons (the heaviest of analyzed particles with a rest mass $0.938 \text{ GeV}/c$), the baryon number must be conserved.

Since every single collision is an independent system, it must conserve all of these quantities. We denote this set of rules as global conservation laws. Moreover, all the quantum numbers must be conserved in each parton fragmentation [68, 86, 87, 89–91]. We test how strongly such conservation laws may influence the particle correlations. The study of different particle species, where different conservation laws are present, should help to put constraints on the particle production models.

particles	momentum	charge	strangeness	baryon number
pions	✓	✓		
kaons	✓	✓	✓	
protons	✓	✓		✓

Table 7.1: The conservation laws and quantum numbers that are present for different particle species.

We first focus on the unlike-sign particle pairs which, in this analysis, were constructed in all cases from a particle and its antiparticle. It is always energetically most favorable to compensate all quantum numbers of the particles with their antiparticles. The strength of the correlation for such a pair depends then on the energetic price of an alternative solution (if the alternative solution is “cheap” then the correlation will be weaker than for the “expensive” alternative solutions, where the correlation will be stronger). By the term “alternative solution” we mean an example answer for the hypothetical question “*If particle 'a' would be produced, what other particle can compensate for its creation, apart from ' $\bar{a}$ ', so that all conservation laws are still obeyed?*”. Let us consider pions, kaons, and protons:

1. for pions the alternative solution is any opposite-charge particle. Since in a collision at the LHC energies, a great number of particles can be produced in the event, the cost of such solution is not very high and therefore the magnitude of the near-side peak is the lowest, see Fig. 7.14 (c);
2. for protons an additional constraint is the production of another baryon (charged, or neutral plus an additional charged particle); so, instead of an antiproton it could be e.g. an antineutron plus some charged particle. Producing two particles instead of one is more expensive energetically; hence, the correlation of unlike-sign pairs of protons should be stronger (the creation of $a\bar{a}$ pair should be more probable with respect to other possibilities) than of pions, see Fig. 7.14 (a);

3. for kaons, which carry a strange quark, strangeness must be conserved; so, the production of another strange particle is required. The next one which does not decay into a kaon, in terms of the mass hierarchy, is a lambda hyperon. However, it is a baryon; so, the alternative production to another kaon would be a lambda, an antibaryon, and possibly another charged particle. Therefore, the correlation of kaon pairs should be most pronounced (since in this case producing a pair other than $a\bar{a}$ is very expensive), see Fig. 7.14 (b).

On the other hand, for identical particle pairs the effect is different. In that case the masses of particles play a significant role. In addition, the femtoscopic effects (Bose-Einstein for identical bosons or Fermi-Dirac quantum statistics for identical fermions) which increases or decreases the near-side correlation have to be also taken into account. We will consider the pp case where a dip is observed (Fig. 7.15). If the conservation laws were obeyed only globally, then the momentum and baryon number could be compensated, for example, by two antiprotons going in the opposite direction. Such a solution has moderate energetic price which produces a relatively low correlation. If, in addition, these quantities should be conserved locally in the minijet, then, while producing two protons, two very heavy particles, we would have to produce another two antibaryons to compensate the baryon number; all in the same minijet. Moreover, in order to compensate the momentum, additional particles would have to be produced going in the opposite direction. Such a solution is an extremely expensive scenario, potentially producing an anticorrelation.

For further discussion and validation of this hypothesis see Sec. 9.1 for results of a model incorporating those mechanisms, and Sec. 9.2 in which the correlation functions of identified particles are compared to general purpose Monte Carlo generators.

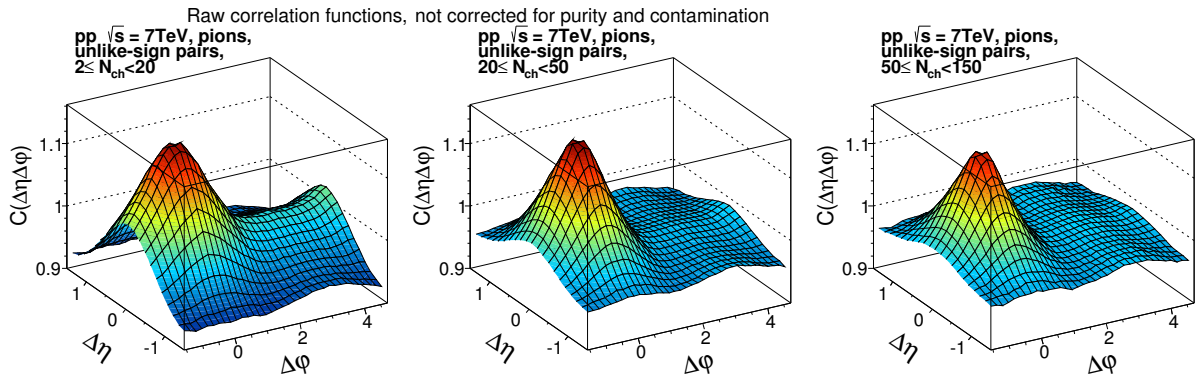
7.2.2 Multiplicity dependence

The analysis of identified particles was performed in three multiplicity ranges. Results presented in this section are not corrected for efficiency and contamination; therefore, should be treated qualitatively, not quantitatively². For pions the results are presented in Fig. 7.16 for unlike-sign pairs of $\pi^+\pi^-$ and in Fig. 7.17 for like-sign pairs (combined $\pi^+\pi^+$ and $\pi^-\pi^-$). In case of kaons, the results are presented in Fig. 7.18 and 7.19 for unlike-sign pairs and combined

²We note that, the particle identification procedure “with double counting” has been used in this case; therefore, the purity of the samples is lower than those presented in other sections.

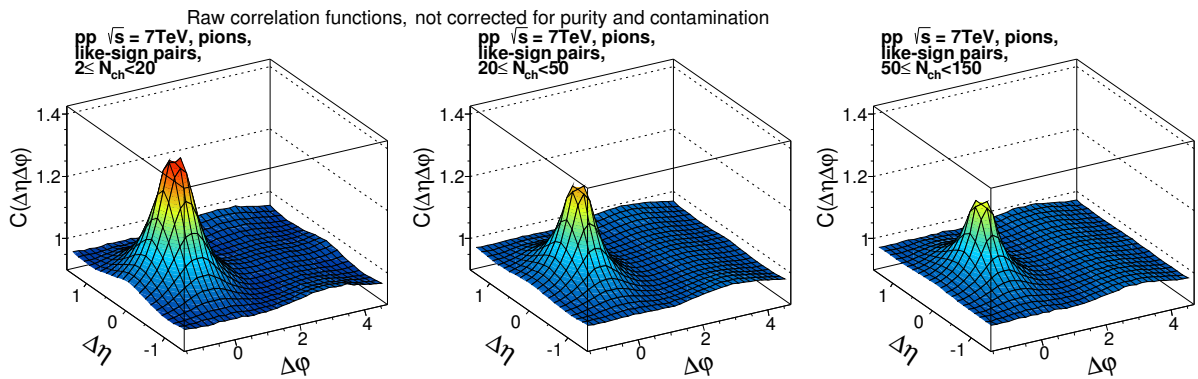
like-sign pairs respectively. For protons the correlation functions are shown in Fig. 7.20 for pairs of $p\bar{p}$ and in Fig. 7.20 for pp and $\bar{p}\bar{p}$ pairs. Worth noticing is the scale on the vertical axes which is different for each set of plots.

Comparing correlation functions obtained for different multiplicity ranges, one may observe that the higher the multiplicity of the collision, the weaker the correlation strength. Such dependence is visible for both the near-side peak structure, regardless of the particle type or charge combination, as well as for the anticorrelation dip in the correlation of like-sign pairs of protons³. That behavior is expected, similarly as for the non-identified case described in Sec. 7.1.3.



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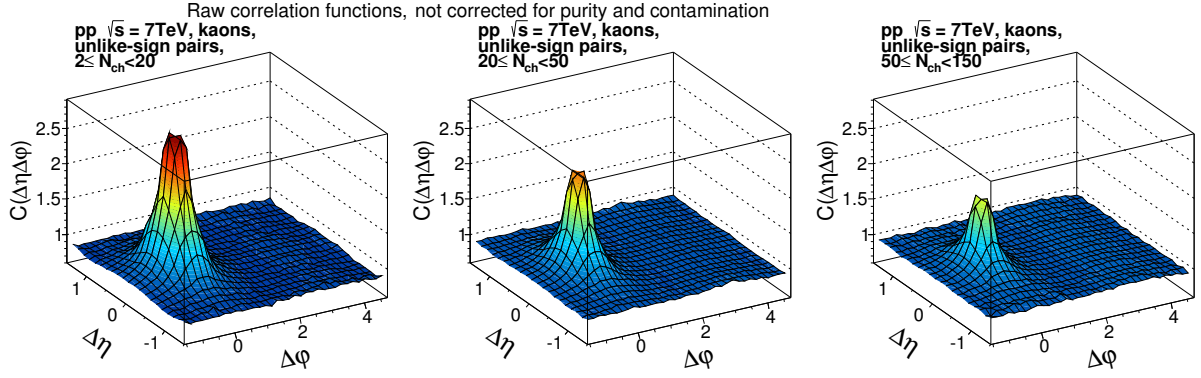
Figure 7.16: Correlation functions in ranges of the uncorrected multiplicity (2–19, 20–49, 50–150) for unlike-sign pairs of pions for $\sqrt{s} = 7$ TeV pp collision data.



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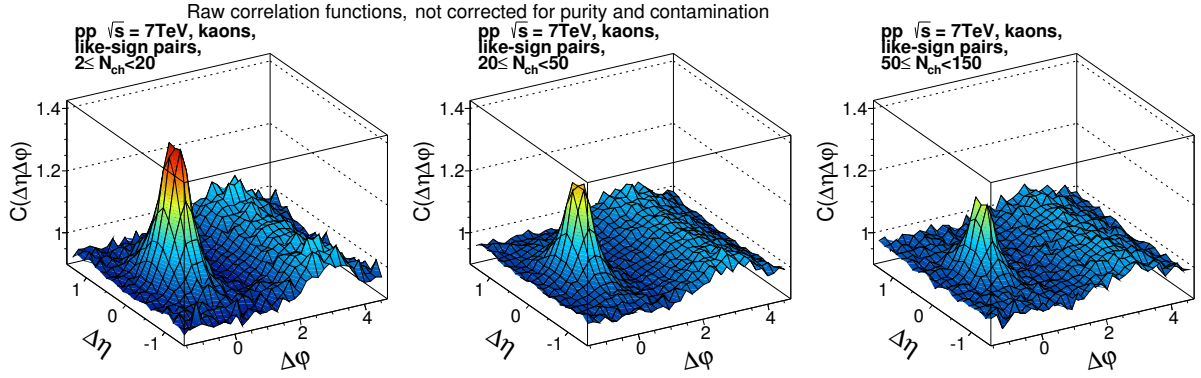
Figure 7.17: Correlation functions in ranges of the uncorrected multiplicity (2–19, 20–49, 50–150) for like-sign pairs of pions for $\sqrt{s} = 7$ TeV pp collision data.

³The peak at $\Delta\eta \approx 0$, $\Delta\phi \approx 0$ for like-sign proton correlation functions comes from uncorrected contamination from pions in the proton sample.



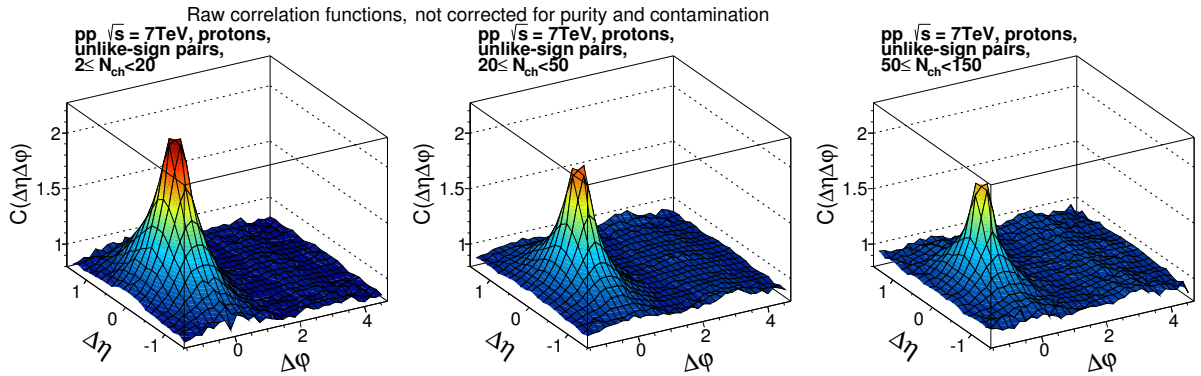
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Figure 7.18: Correlation functions in ranges of the uncorrected multiplicity (2–19, 20–49, 50–150) for unlike-sign pairs of kaons for $\sqrt{s} = 7\text{ TeV}$ pp collision data.



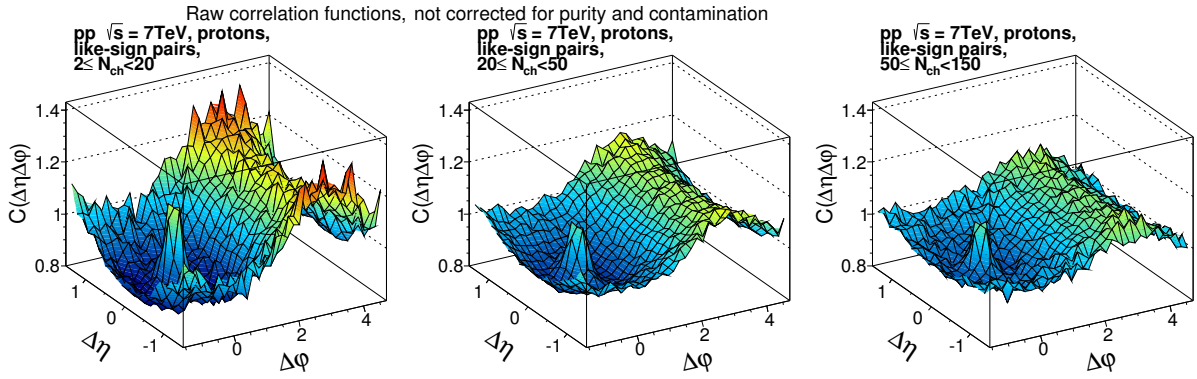
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Figure 7.19: Correlation functions in ranges of the uncorrected multiplicity (2–19, 20–49, 50–150) for like-sign pairs of kaons for $\sqrt{s} = 7\text{ TeV}$ pp collision data.



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Figure 7.20: Correlation functions in ranges of the uncorrected multiplicity (2–19, 20–49, 50–150) for unlike-sign pairs of protons for $\sqrt{s} = 7\text{ TeV}$ pp collision data.



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Figure 7.21: Correlation functions in the ranges of the uncorrected multiplicity (2–19, 20–49, 50–150) for like-sign pairs of protons for $\sqrt{s} = 7$ TeV pp collision data.

7.2.3 Transverse momentum dependence

In this section the dependence of the correlation functions on the pair transverse momentum are shown for different particle species. The pion sample is divided into five p_T -sum ranges, the kaon sample into four ranges, and the protons into two ranges. Details on the division are described in Sec. 5.6.2.

In Fig. 7.22 (like-sign) and Fig. 7.23 (unlike-sign) results for the pion sample are presented for three p_T -sum ranges for like and unlike-sign pairs respectively. We observe a growth of the correlation strength with increasing transverse momenta of particles in the near- and away-side regions.

For like-sign pairs (Fig. 7.22) we observe a behavior that was also seen for non-identified particles in Sec. 7.1.4: at first the correlation decreases, and then increases for higher p_T . This effect is consistent with a behavior coming from the interplay of Bose-Einstein and minijet correlation sources. For small transverse momenta Bose-Einstein effects play a significant role (also, the minijet structures are not visible at low p_T similarly to the unlike-sign pairs), and with rising transverse momentum of particles in the pair this correlation decreases, to be replaced by correlations coming from minijets. As already mentioned in Sec. 7.1.4 for non-identified particles case, this effect has a strong influence on femtoscopic correlation functions, creating significant structures at high pair transverse momentum k_T .

In Fig. 7.24 and Fig. 7.25 results for the kaon sample are presented. Similarly as for pions, we can see an increase of the correlation strength with increasing transverse momentum. More-

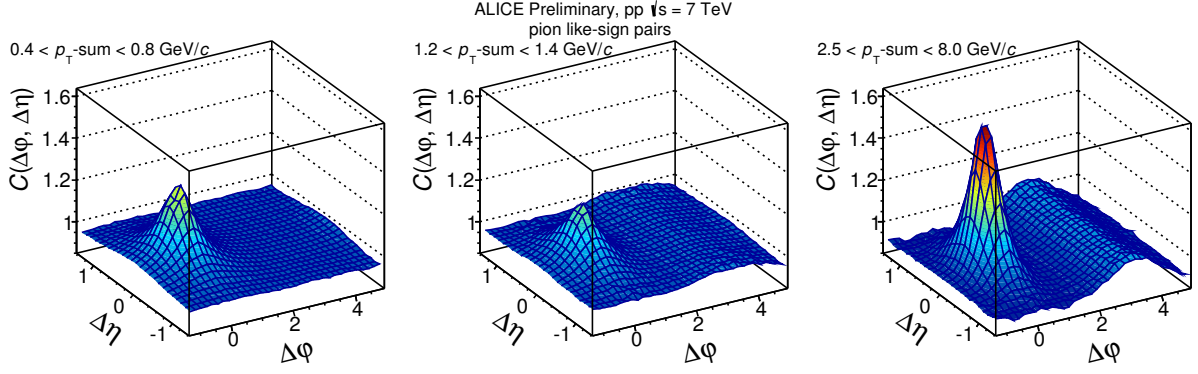


Figure 7.22: Correlation functions for like-sign pairs of the pion sample ($\pi^+\pi^+$) for three p_T -sum bins for $\sqrt{s} = 7$ TeV pp collision data.

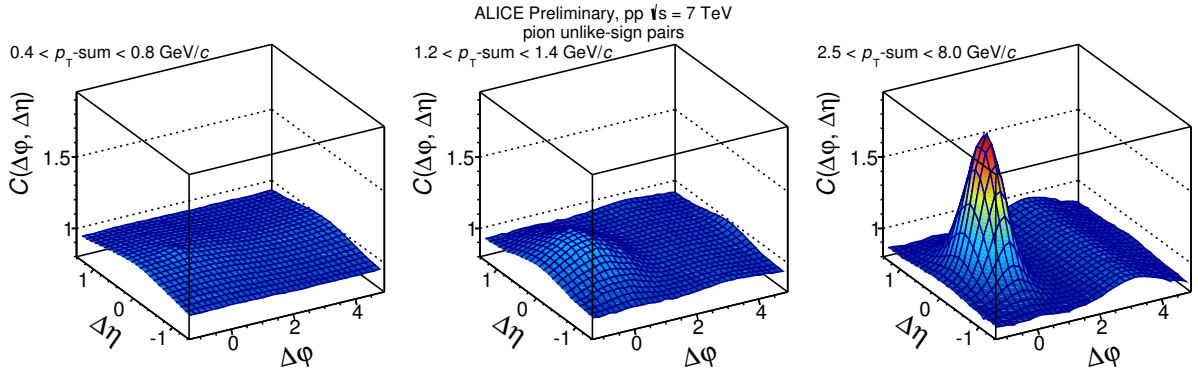


Figure 7.23: Correlation functions for unlike-sign pairs of the pion sample ($\pi^+\pi^-$) for three p_T -sum bins.

over, we should note here the difference between like- and unlike-sign correlation function: the correlations at all transverse momenta are much stronger for unlike- than for like-sign pairs.

Results for unlike-sign protons are shown in Fig. 7.27. Similarly as for pions and kaons, we can see a rise of the near-side peak and the appearance of the away-side ridge for higher transverse momenta. In the case of like-sign protons, presented in Fig. 7.26, it is the anti-correlation that is getting stronger with rising p_T -sum. In addition to the wide dip, for the lowest p_T -sum range, a narrow correlation peak is located at $(\Delta\eta, \Delta\phi) = (0, 0)$. It may arise due to the two-proton strong interaction (observed also in pp femtoscopic correlations [225, 226]).

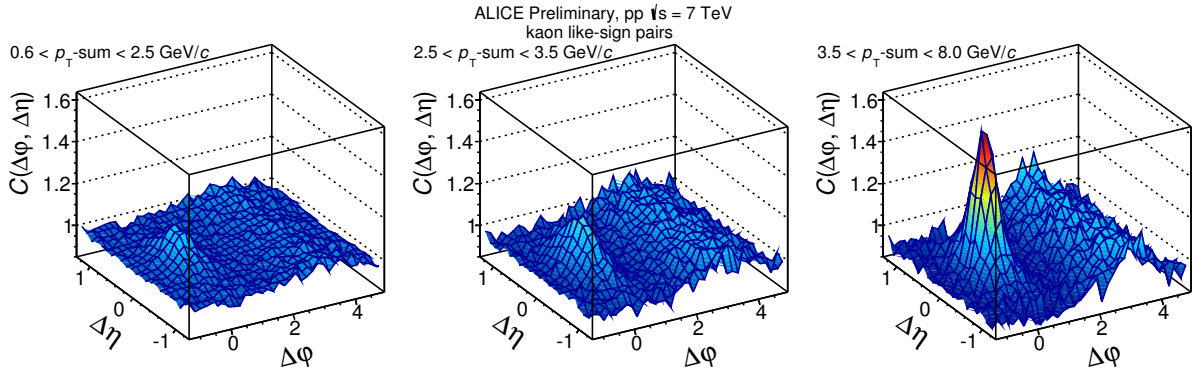


Figure 7.24: Correlation functions for like-sign pairs of the kaon sample (K^+K^+) for three p_T -sum bins for $\sqrt{s} = 7$ TeV pp collision data.

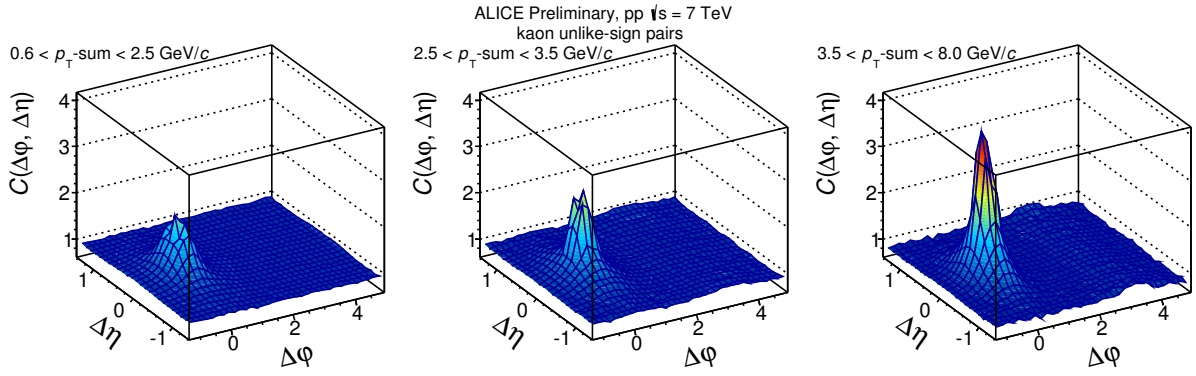


Figure 7.25: Correlation functions for unlike-sign pairs of the kaon sample (K^+K^-) for three p_T -sum bins for $\sqrt{s} = 7$ TeV pp collision data.

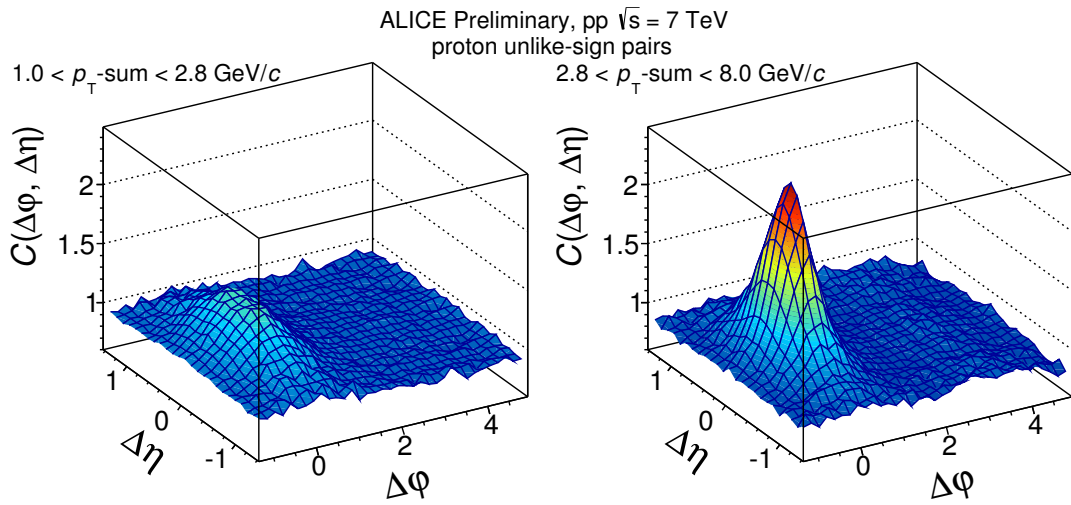


Figure 7.26: Correlation functions for unlike-sign pairs of the proton sample ($p\bar{p}$) for two p_T -sum bins for $\sqrt{s} = 7$ TeV pp collision data.

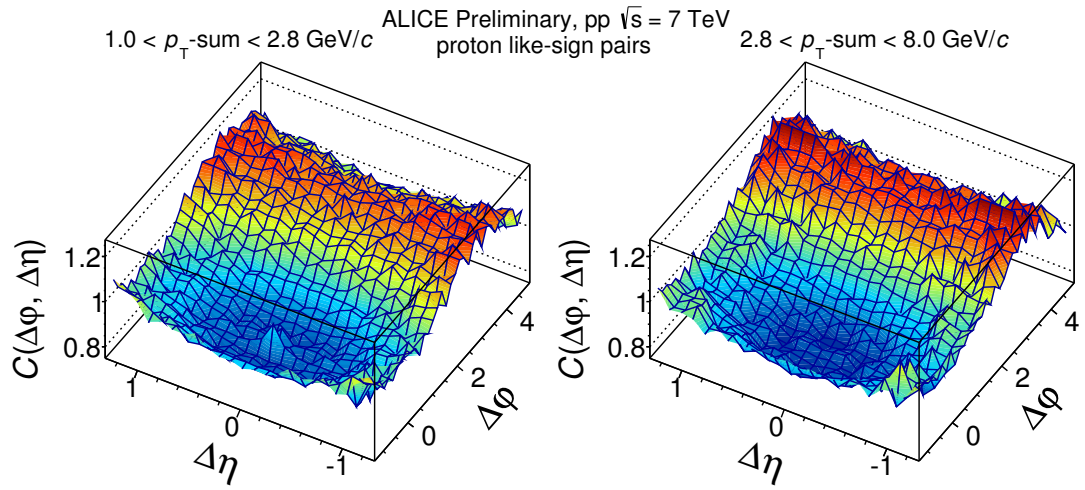


Figure 7.27: Correlation functions for like-sign pairs of the proton sample (pp) for two $p_{\text{T-sum}}$ bins. The plots are viewed from a different perspective in comparison to others presented in this section to facilitate the study of the anti-correlation dip for $\sqrt{s} = 7$ TeV pp collision data.

Quantitative analysis

The quantifying procedure was performed for the correlation functions resulting from pair transverse momentum analysis. As described in Sec. 6.3, the fitting formula consists of two components: a Lévy distribution for the near-side peak and an one-dimensional Gaussian for the away-side ridge. All the data samples were fitted, and an example of the fit for pions is shown in Fig. 7.28. In the top row of the plot we can see the (a) correlation function, (b) final fitted function, (c) residual: the difference between (a) and (b). In the bottom row the two fitted structures are presented separately: (d) the near-side peak and (e) the away-side ridge.

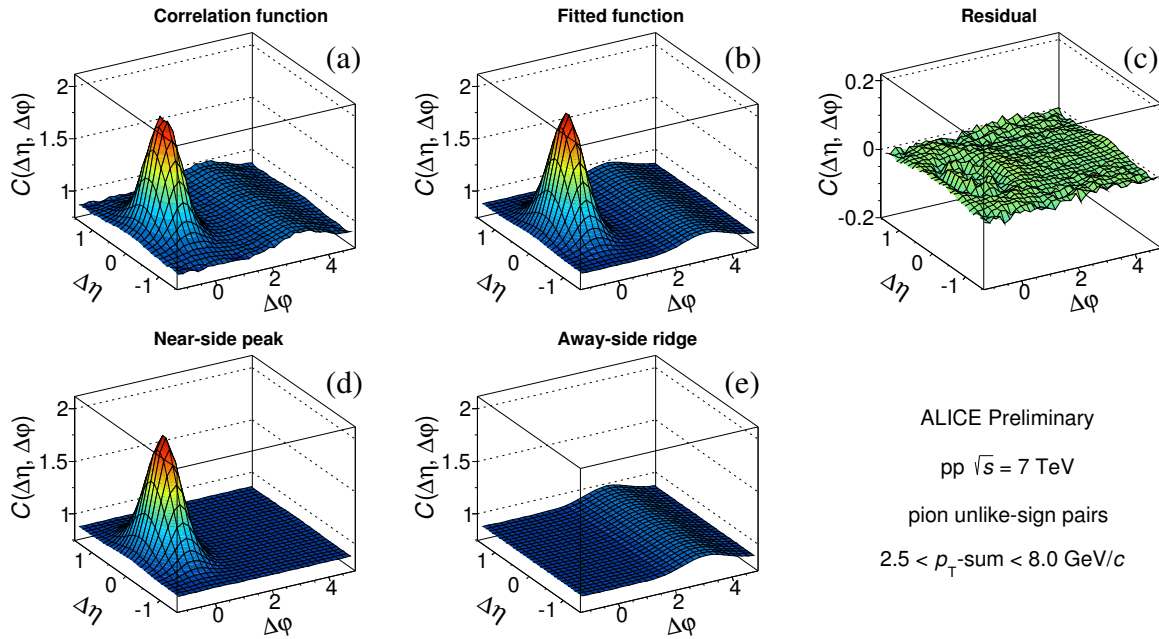


Figure 7.28: Components of the fitting: example for unlike-sign pion pairs, highest p_T -sum bin. (a) Correlation function, (b) result of the fit, (c) residual (difference between the correlation function and the fitted function), (d) fit result: near-side peak structure, (e) fit result: away-side ridge structure.

Similarly, in Fig. 7.29 we can see a fitting example for like-sign protons. Instead of the pronounced near-side peak the anti-correlation dip is visible, and it is fitted with an inverse Gaussian (Gaussian with negative magnitude).

The results of the fitting are presented in Fig. 7.30. Several features can be observed. If we focus on the near-side structure of the correlation (magnitude, widths in $\Delta\eta$ and $\Delta\phi$, and exponent term), it can be seen that the magnitude of the near-side peak is higher for like-sign than for unlike-sign pairs at the lowest p_T -sum range for pion pairs (red symbols). This effect is due to the Bose-Einstein statistics, that play a role only for like-sign pion pairs. If we look

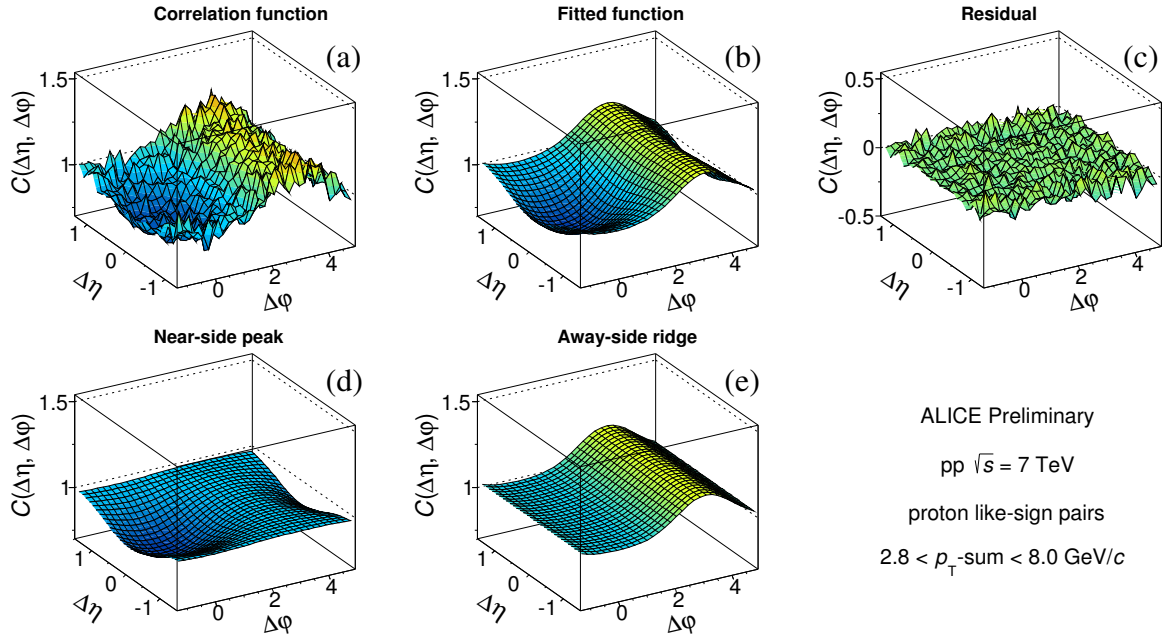


Figure 7.29: Components of the fitting: example for like-sign proton pairs. (a) Correlation function, (b) result of the fit, (c) residual (difference between the correlation function and the fitted function), (d) fit result: near-side peak structure, (e) fit result: away-side ridge structure.

at the kaon sample we clearly see a stronger near-side correlation for unlike-sign pairs than for like-sign pairs. This difference in correlation strength between like- and unlike-sign pairs is rising with pair transverse momentum, and is expected due to the influence of the conservation laws. For like-sign protons we see the anti-correlation (the magnitude of the near-side peak is below zero). If we move to the away-side structure (away-side ridge magnitude and $\Delta\varphi$ width) we can observe a stronger correlation for like-sign pairs at high p_T . For low transverse momentum the away-side correlation is not present for unlike-sign pairs. This can be expected due to combinatorial effects, also mentioned in the description of the non-identified sample; for more information and test of this hypothesis see Sec. 9.1.2.2).

The observations from results of the fitting presented in Fig. 7.30 correspond to the observations from the correlation functions of identified particles. Similarly, the results for charged hadrons (for non-identified sample) correspond to those presented in Sec. 7.1.4. However, this plot allows us to compare directly results from all particle species, and quantify the influence of different conservation laws. In particular, pions, as most abundantly produced particles at LHC energies, are expected to dominate results of charged hadrons, and indeed this is what we observe from comparison of red and black points.

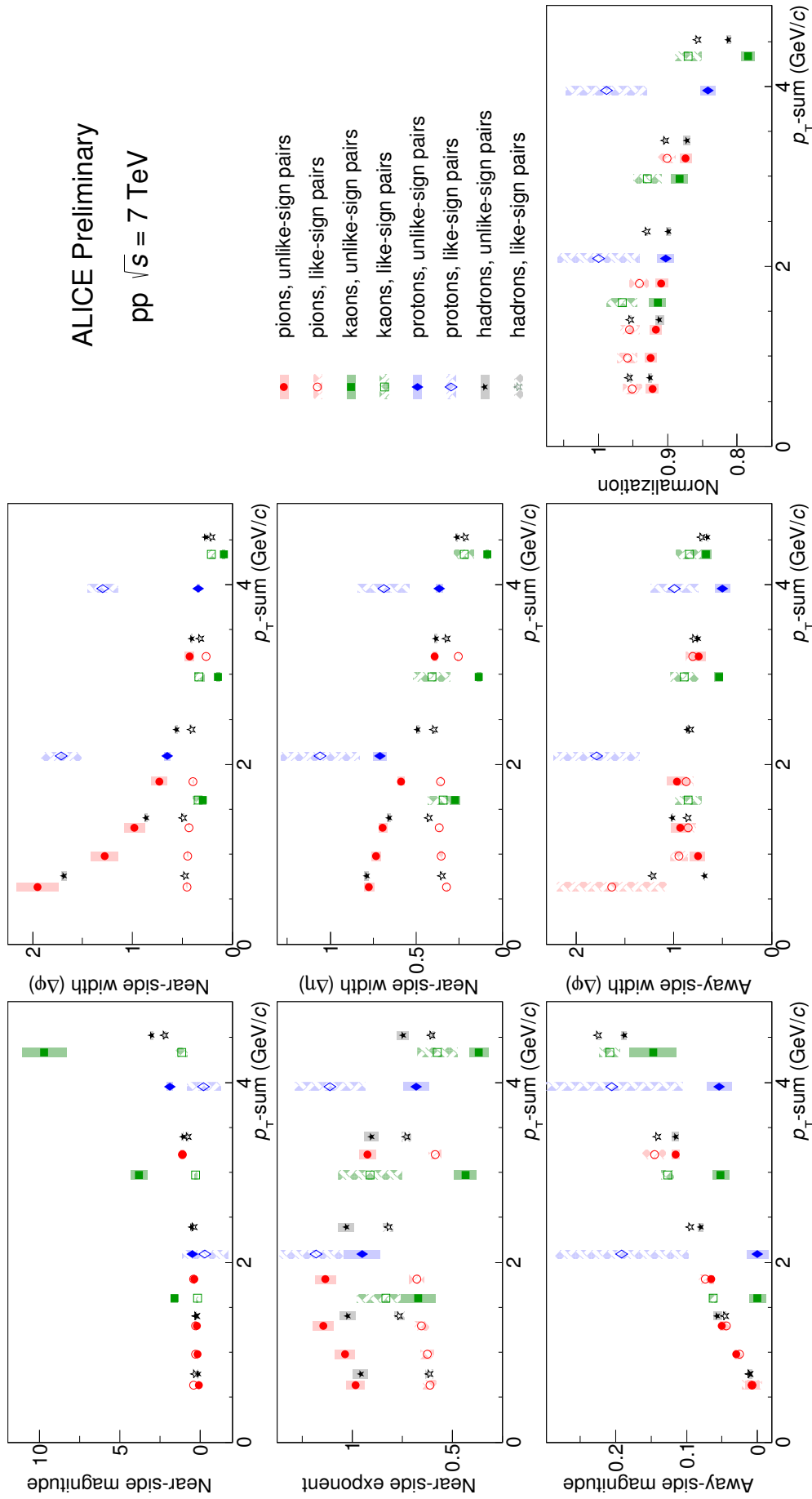


Figure 7.30: Results of the quantifying procedure applied for the $\sqrt{s} = 7$ TeV pp collision data for identified particles (pions, kaons, and protons): dependence of the parameters of the fit function on the $p_{T\text{-sum}}$. Also, results for charged hadrons are shown for comparison.

Chapter 8

Systematic uncertainties

In this chapter, the systematic uncertainties of the analysis results are discussed. All results of the measurements were presented in Chapter 7. As a first step for the estimation of the systematic uncertainty, the influence of the data sample selection is studied in Sec. 8.1. Then, we estimate the uncertainty of the particle identification procedure in Sec. 8.2. In Sec. 8.3, the deviations between the results obtained analyzing simulated data at the event generator level (MC truth) and after reconstruction and correction have been studied. A summary of the systematic uncertainties of the correlation functions is presented in Sec. 8.4. Finally, in Sec. 8.5 the calculation of the systematic uncertainties on the fitting results is described.

8.1 Uncertainty of data sample selection

In this section we present the variations of the data selection criteria that were performed in order to estimate the systematic uncertainty induced on the correlation functions. The analyzed data sets, as well as single- and two-track selections are introduced in Chapter 5. Here, we present the modifications of the default selections applied to estimate their influence on the final result.

Differences between productions

The analysis was performed with several independent data samples recorded under different data-taking conditions (see Sec. 5.1) and small differences in the reconstruction procedure. Each one of those data samples was always studied separately, as a single dataset, to check for any inconsistencies. Only for the final plots the statistical averages of them have been calculated. The differences observed in the correlation functions were of the order of $\sim 1\%$, no more than 2% .

Comparison of positive and negative pairs

For the practically zero-net-baryon-density system produced at LHC energies, we expect the differences between like-sign negative and positive pairs to be negligible. However, the particles of opposite charges can be differently influenced by the detector, i.e. due to the reversed bending in the magnetic field. Similarly, the particles from secondary interactions with the material would influence positive pairs more strongly. The comparison of the analyzed results was performed between the correlation functions of positive and negative pairs; no differences apart from the statistical ones were observed.

Differences between track cuts

The correlation functions were calculated separately for four different sets of track selection criteria:

1. **Default cuts** Tracks reconstructed with both ITS and TPC detectors are used. We would recall relevant information from Sec. 5.3: each track is required to have a signal coming either from an SDD or SPD ITS layer (see Sec. 4.3.1 for the ITS description). To select primary particles a strict, p_T -dependent DCA cut was used.
2. **Cuts variation: hybrid** This set of cuts ensures a flat φ distribution. For the pp data taken in 2010 the ITS detector created non-uniform acceptance holes in φ (as shown in Fig. 8.1). Therefore the “missing” tracks are taken from the TPC-only reconstruction. Since during this procedure the TPC+ITS tracks are mixed with the TPC-only ones in the same data sample, the name “hybrid” has been assigned. Moreover, in this case the loose DCA cut is used: $DCA_{xy} < 2.4$ cm, $DCA_{xy} < 3.2$ cm; so, more secondary particles contaminate the sample.
3. **Cuts variation: loose cuts** In this variation tracks obtained exclusively with TPC data are used. Since no ITS signal is required, this set of cuts also ensures flat φ distribution. A loose DCA cut is used, the same as for hybrid tracks: $DCA_{xy} < 2.4$ cm, $DCA_{xy} < 3.2$ cm. Moreover, a track is required to have a smaller number of clusters: 50 (instead of the default 70).
4. **Cuts variation: strict cuts** The same as the default cuts, but a hit in the SPD layer is always required. Such strict requirement creates very big acceptance holes in the φ distribution (see also Fig. 8.1).

Figure 8.1 shows φ , η , p_T , and z -vertex distributions for the mentioned four sets of cuts. The φ acceptance holes are clearly visible in the bottom left plot. Also, the acceptance holes in φ create distortions in η , seen as a slope of the distribution in the top right plot.

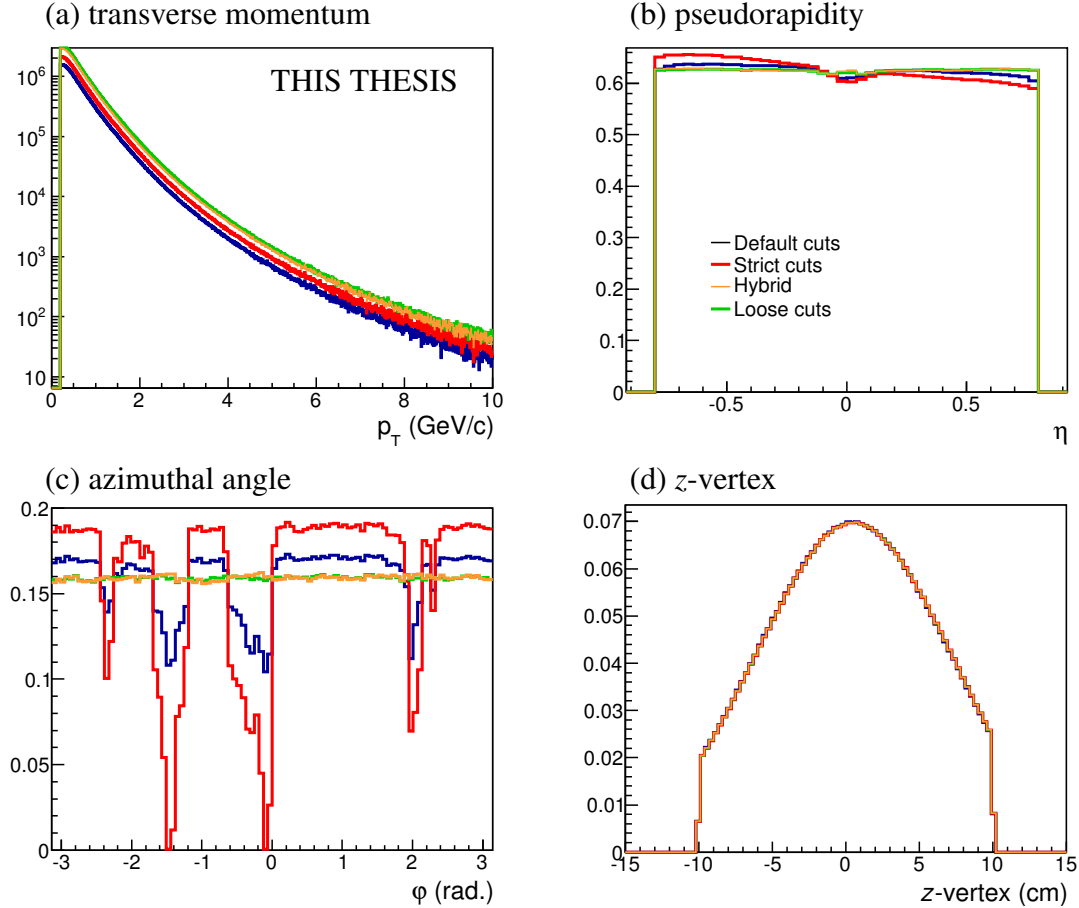


Figure 8.1: Single particle distributions for four track selection sets are presented: (a) transverse momentum p_T , (b) pseudorapidity η , (c) azimuthal angle φ , and (d) position along the beam direction, z -vertex. The p_T distribution is shifted vertically to facilitate comparisons.

It should be noted that the corrections described in Sec. 6.2 were calculated for each set of cuts separately and applied accordingly. For the difference in the correction factor for different sets of cuts see Fig. 8.2.

The differences in the resulting correlation functions coming from the analysis of data samples with different applied track cuts are less than 1% for the “no PID” case, less than 0.5% for pions (apart from the (0,0) bin, where the difference is of 1.5%), and smaller than the statistical fluctuations for kaons and protons.

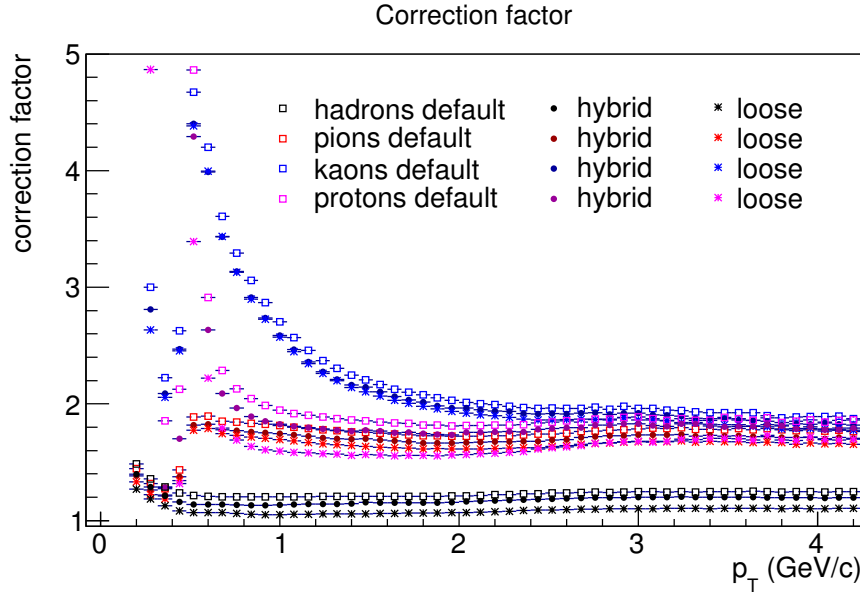


Figure 8.2: Correction factor as a function of p_T for different particle species for three cut sets. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

Dependence on pseudorapidity

A study on the dependence of the correlation functions on the kinematic range of the chosen particles was performed. Three kinematic ranges were studied: (a) $|\eta| < 0.6$, (b) the default value: $|\eta| < 0.8$, (c) $|\eta| < 1.0$.

It was observed that using a certain $|\eta|$ range affects the correlation function by creating a “wing” structure (the parabolic shape of the correlation functions, making the functions rise up for high $\Delta\eta$ values, see Fig. 8.14). A similar effect is created due to the finite width of the multiplicity range during the event mixing procedure (see below). Since those effects artificially change the shape of the correlation function they were taken into account in the fitting procedure as an additional “parabola” parameter (see Sec. 6.3). This effect is about 2% for kaons and protons and less than $< 1\%$ for pions and unidentified particles.

Electron rejection

The influence of the electron rejection cut on the correlation function was studied. This cut should have an impact only on the non-identified sample. No differences were seen for the correlation function of like-sign pairs. However, for the correlation functions of unlike-sign pairs, the difference is almost 15% and influences one bin only, the (0,0) bin. This difference is

expected because electrons coming from photon conversions ($\gamma \rightarrow e^+e^-$) contribute strongly to the correlation function in a very narrow spike with width of < 0.074 in $\Delta\eta$ and ~ 0.11 in $\Delta\varphi$ ¹.

Changes in the two-track cuts

The differences between applying the two-track cuts described in Sec. 5.5 and without any applied two-track cuts is $< 0.2\%$. Such small differences are expected for low multiplicity events of minimum bias pp data, since splitting and merging effects are mostly pronounced for high multiplicity events.

Impact of the pile-up rejection procedure

The pile-up rejection does not have any measurable impact on this analysis. The differences arising due to the application of this procedure were studied and found to be negligible.

Number of N_{ch} ranges in event mixing

It is well established that in the case of event mixing, the events should be mixed with others that have similar multiplicity and z -vertex position. To study the impact of neglecting this procedure we proposed a variation that does not follow that scheme. In this study we compared the default N_{ch} binning (bins are 5 tracks wide, in terms of N_{ch}) with the extreme “no-binning” case. It was observed that neglecting the narrow binning in multiplicity is resulting in “wing” structures. The magnitude of the effect is of the order of $\sim 1.5\%$ for the “no PID” and pions sample, and below statistical fluctuations for kaons and protons.

Number of z -vertex ranges in event mixing

For the same reason as above we employ a similar approach with the z -vertex position. We compare the default 2 cm wide ranges to the extreme no-binning case. It was observed that neglecting the narrow binning in multiplicity is resulting in a narrow band near $\Delta\varphi \approx 0$. However, the magnitude of the effect was minor: $\sim 0.2\%$ for the “no PID” and pions sample, and below statistical fluctuations for kaons and protons.

¹The correlation function was studied in 55 bins in each direction, where the range in $\Delta\eta$ was $(-2,2)$ and in $\Delta\varphi$ $(0,\pi)$. In $\Delta\eta$ the width of the observed peak was always one bin; in case of $\Delta\varphi$ it has one-bin width or one-and-a-half bin width depending on the track cuts used.

8.2 Particle identification systematics

As mentioned in Sec. 6.2 no correction procedure is applied for misidentification of particles. Therefore, the corresponding systematic uncertainty has to be estimated. Below, in Sec. 8.2.1, we present the tools for the quality assessment of the particle identification procedure. Four different PID methods are tested and results are presented in Sec. 8.2.2. The final systematic uncertainty is estimated in Sec. 8.2.3.

8.2.1 Quality assessment tools

We can estimate the performance of the particle identification procedure based on two quantities: purity (or contamination) and PID efficiency. Usually attempting to improve the one, we are decreasing the other. The goal is to choose the best possible purity to PID efficiency ratio.

The *contamination* C_{PID} of the sample that contains particle of species A can be defined as the fraction of non- A particles in the whole sample. A complementary quantity, *purity* P , can be defined as

$$P = 1 - C_{\text{PID}}. \quad (8.1)$$

An ideal PID procedure would be characterized by $C_{\text{PID}} = 0$ ($P = 1$). In the analysis we always try to minimize (maximize) contamination (purity).

The total efficiency, used in the correction procedure (see Sec. 6.2.3), can be separated into two components, as in Eq. (8.2):

$$\epsilon_{\text{Total}} = \epsilon_{\text{TR}} \times \epsilon_{\text{PID}}. \quad (8.2)$$

The *tracking efficiency* ϵ_{TR} depends on the used track cuts (for details on the track cuts see Sec. 5.3) and the *PID efficiency* ϵ_{PID} depends only on the PID procedure. While trying to tune the PID method we would always try to maximize the PID efficiency.

To estimate the efficiency we compared the number of reconstructed particles to the number of generated particles in the Monte Carlo generated events. The efficiency fractions mentioned in this section can be defined as follows:

$$\epsilon_{\text{Total}} = \frac{N_{\text{primaries}}^{\text{survived-all-cuts-including-PID}}}{N_{\text{primaries}}^{\text{generated}}}, \quad (8.3)$$

$$\epsilon_{TR} = \frac{N_{primaries}^{survived-reconstruction(no-PID-cuts-applied)}}{N_{primaries}^{generated}}, \quad (8.4)$$

$$\epsilon_{PID} = \frac{N_{primaries}^{survived-all-cuts-including-PID}}{N_{primaries}^{survived-reconstruction(no-PID-cuts-applied)}}. \quad (8.5)$$

8.2.2 Evaluation of methods

The particle identification procedure is explained in detail in Sec. 5.4. For this analysis four different sets of PID cut variations were studied:

1. **Without double counting** $N_{\sigma, \text{PID}} < 3$: *The default set of cuts.* If the track passes the PID $N\sigma$ cuts, before accepting such a track an additional check is made – if a track is recognized by cuts as two different particles (i.e. as pion and as kaon), a comparison is made and only the track with the smaller value of $N_{\sigma, \text{PID}}$ is accepted. Tracks are never counted twice.
2. **With double counting** $N_{\sigma, \text{PID}} < 3$: if the track passes the PID $N\sigma$ cuts, it is accepted as identified particle. No additional check is made, as each sample is treated separately. Therefore, it is possible that if one track passes the $N\sigma$ cuts for two samples, i.e. for kaons and pions, it is then used twice in the analysis (in separate samples).
3. **With double counting** $N_{\sigma, \text{PID}} < 2$: with this set we study a variation of set (2), “with double counting”. By default $N_{\sigma, \text{PID}}$ value is set to 3. In this case it is set to $N_{\sigma, \text{PID}} < 2$.
4. **Exclusive PID** $N_{\sigma, \text{PID}} < 3$: if the track passes the PID $N\sigma$ cuts for more than one particle species, it is rejected from the analysis.

All the estimates presented in this section were done employing the full detector simulation of Pythia Perugia-0 events.

In Figs. 8.3, 8.4, 8.5, 8.6 the contamination of the samples for different sets of PID cuts are presented. It can be seen that using “with double counting” case (Fig. 8.3) for high p_T particles we obtain purities of the sample of 90% for pions, 40% for kaons and 50% for protons (note that on the plots the contamination C_{PID} , not the purity, is presented). It is the sample with the lowest purity. For the default “without double counting” (Fig. 8.4) much higher purities

are obtained, for high p_T particles: 97% for pions, 80% for kaons, and 85% for protons. By restricting the cuts further with the “exclusive PID” procedure (Fig. 8.5) we can obtain even higher purities for high p_T particles of 99% for pions, 95% for kaons (but 80% near the electron band, $0.4 < p_T < 0.5$ GeV/c) and 97% for protons. By restricting $N_{\sigma, \text{PID}}$ with value 2 (Fig. 8.6) we would obtain better purities than for $N_{\sigma, \text{PID}} < 3$ case (as expected): 96% for pions, 70% for kaons, and 70% for protons, but significantly lower than “without double counting” case.

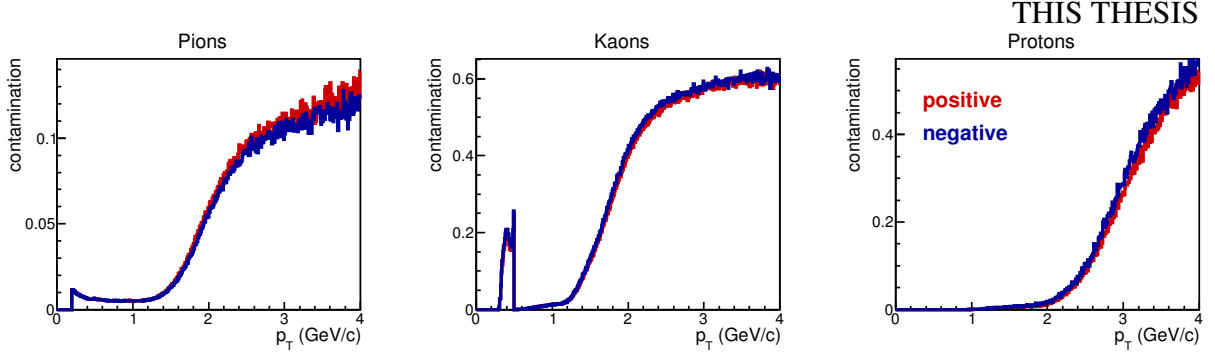


Figure 8.3: Contamination of the samples for pions, kaons, and protons as a function of p_T , for positive (red line) and negative (blue line) particles separately. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for “with double counting” case.

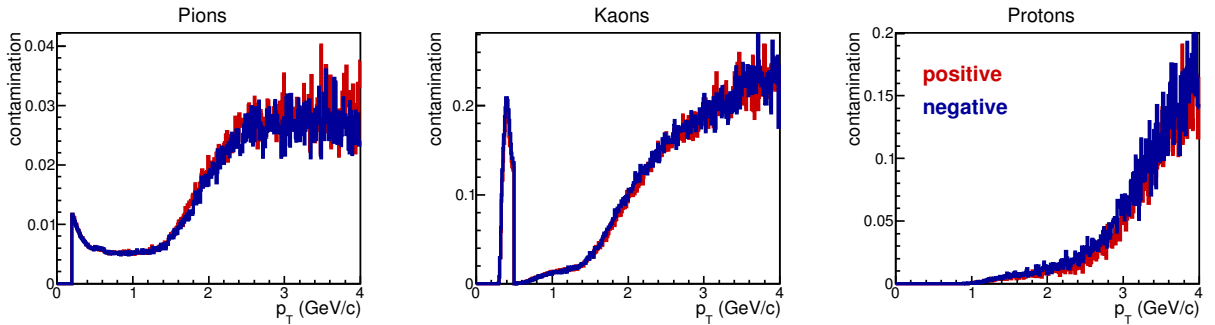


Figure 8.4: Contamination of the samples for pions, kaons, and protons as a function of p_T , for positive (red line) and negative (blue line) particles separately. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for “without double counting” case.

As discussed previously, the quality of the method is affected not only by the sample purity, but also by the PID efficiency. In Figs. 8.7, 8.8, 8.9 and 8.10 the efficiency of the procedure for different PID cut sets are reported.

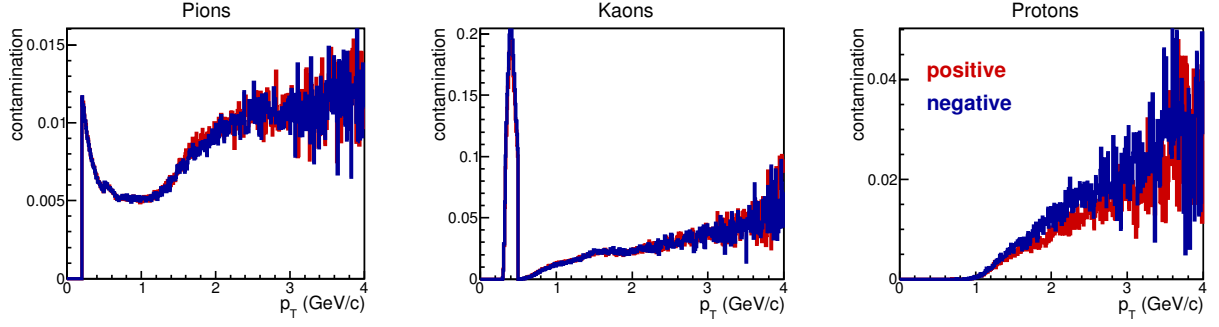


Figure 8.5: Contamination of the samples for pions, kaons, and protons as a function of p_T , for positive (red line) and negative (blue line) particles separately. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for “exclusive PID” case.

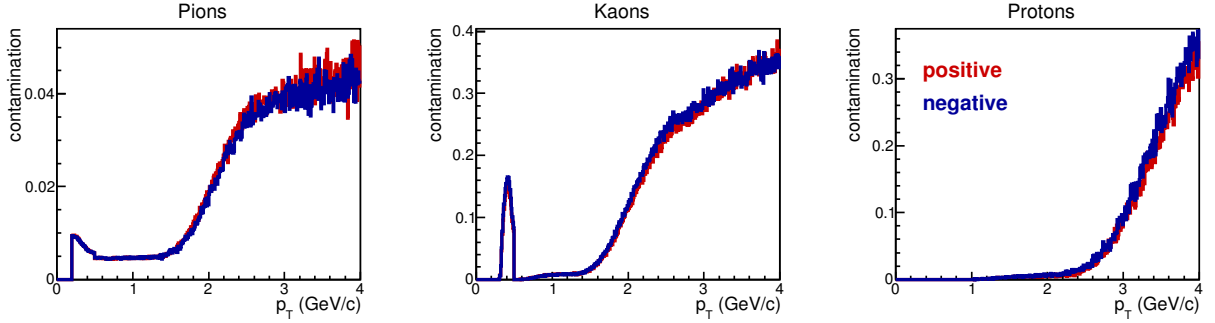


Figure 8.6: Contamination of the samples for pions, kaons, and protons as a function of p_T , for positive (red line) and negative (blue line) particles separately. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for “with double counting & $N_{\sigma, \text{PID}} < 2$ ” case.

As mentioned, the tracking efficiency for all samples remains the same regardless of the procedure. However, the PID efficiency varies significantly, influencing also the total efficiency. As expected, the efficiency is the highest for the least strict cuts of “with double counting” case (see Fig. 8.7). For the “without double counting”, Fig. 8.8, the efficiency decreases for higher values of transverse momenta. Using “without double counting & $N_{\sigma, \text{PID}} < 2$ ” case decreases the efficiency over the whole range of p_T significantly. The most drastic changes can be observed for the “exclusive PID” case. For this set of cuts the total efficiency for high- p_T particles (~ 4 GeV/c) drops to 10% (20%) for kaons (protons).

Taking into account both, contamination and PID efficiency of the studied samples, we conclude that the best sample for this analysis would be the one obtained applying the set of

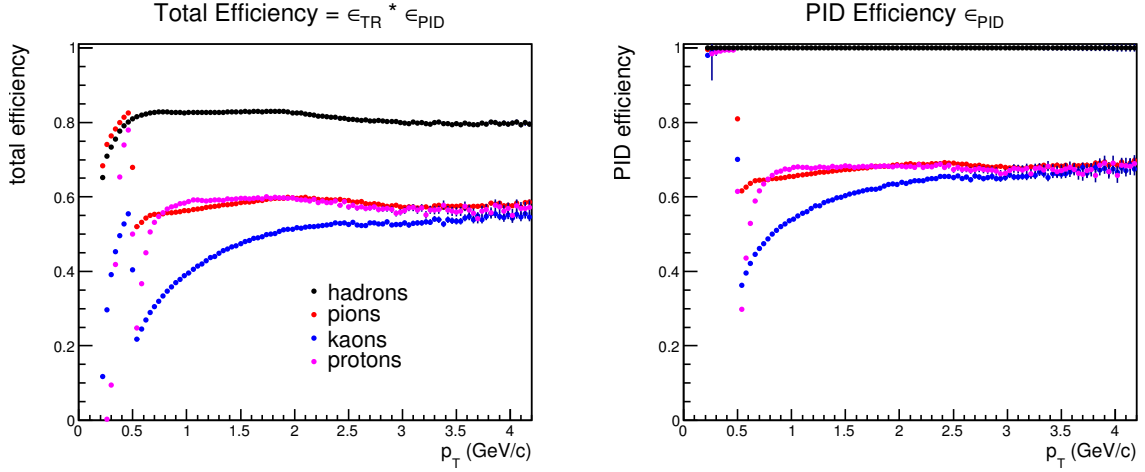


Figure 8.7: Efficiency estimation for primary particles, for the samples of pions, kaons, and protons as a function of p_T . Left panel: total efficiency (as used for correction). Right panel: PID efficiency. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for the “with double counting” case.

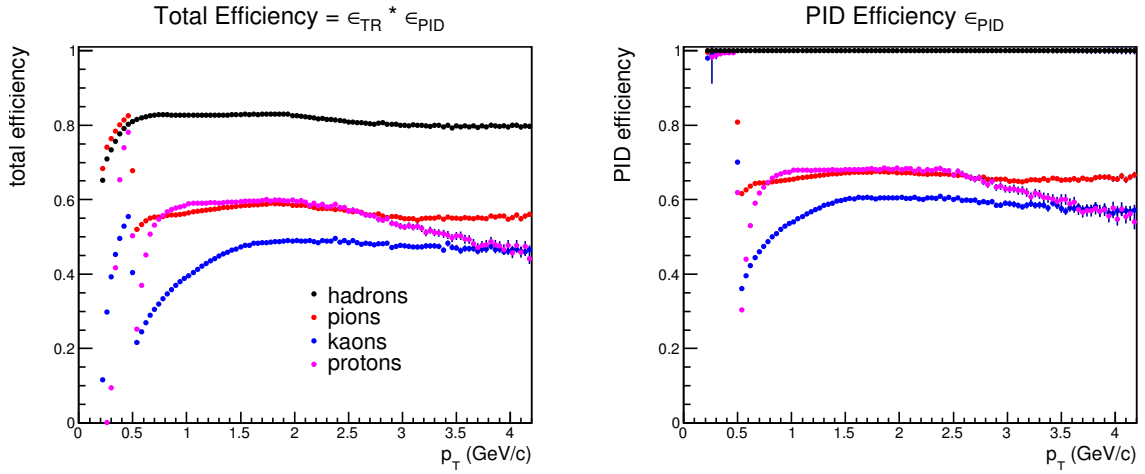


Figure 8.8: Efficiency estimation for primary particles, for the samples of pions, kaons, and protons as a function of p_T . Left panel: total efficiency (as used for correction). Right panel: PID efficiency. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for the “without double counting” case.

cuts under the name “without double counting”. In terms of purity it is significantly better than “with double counting” and “with double counting & $N_{\sigma, PID} < 2$ ” cases. Using the “exclusive PID” set of cuts results in far too severe reduction in statistical precision. However, all the PID sets of cuts are used to estimate the systematic uncertainties, as described in Sec 8.2.3.

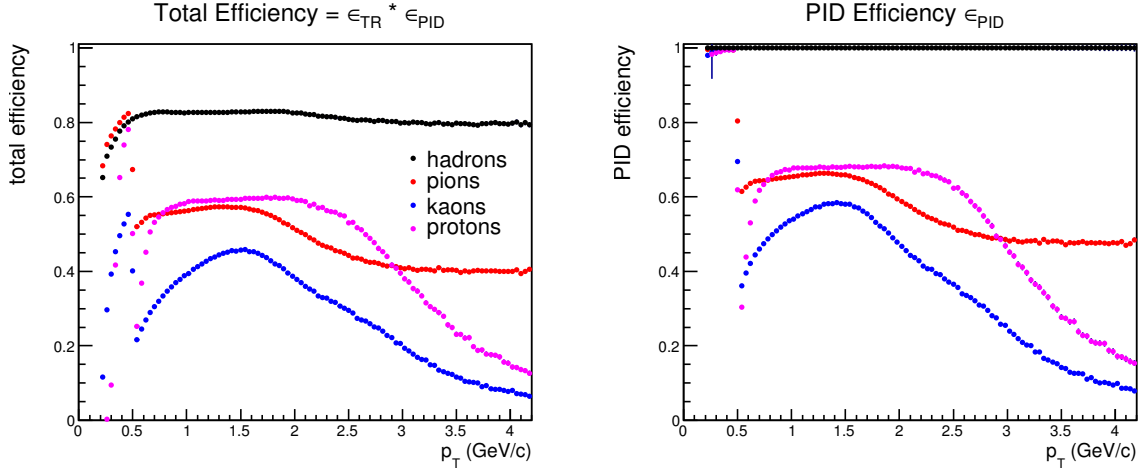


Figure 8.9: Efficiency estimation for primary particles, for the samples of pions, kaons, and protons as a function of p_T . Left panel: total efficiency (as used for correction). Right panel: PID efficiency. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for the “exclusive PID” case.

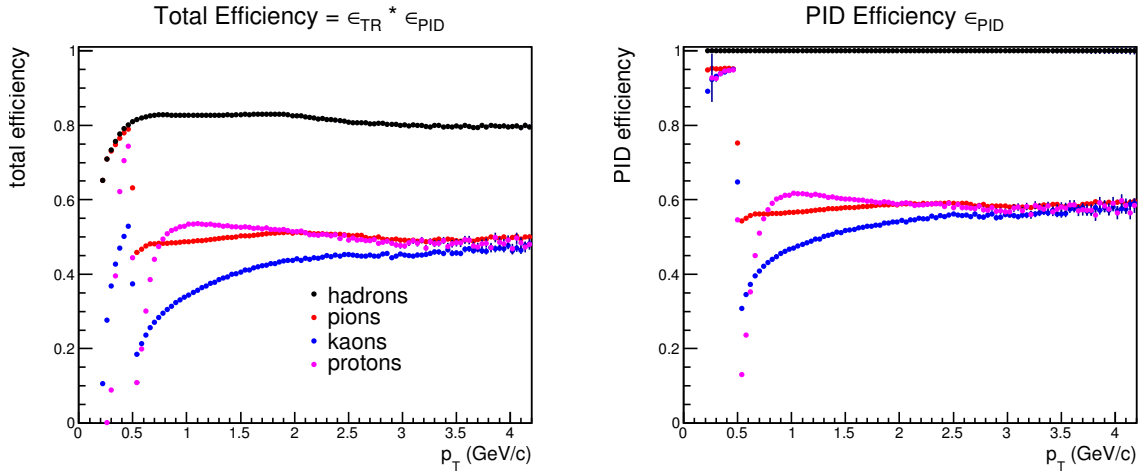


Figure 8.10: Efficiency estimation for primary particles, for the samples of pions, kaons, and protons as a function of p_T . Left panel: total efficiency (as used for correction). Right panel: PID efficiency. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV. Presented results are for the “with double counting & $N_{\sigma, PID} < 2$ ” case.

To complement the information about the contamination of the default sample, we also report the exact percentage of contaminations for different particle species in Fig. 8.11. A set of plots with information about the contamination and purities of the samples is presented. The total percentage in each of the rows adds up to 1. The contaminations are calculated in the appropriate kinematic range (p_T) for given particle species (0.2–4.0 GeV/c for pions, 0.3–4.0

GeV/ c for kaons, and 0.5–4.0 GeV/ c for protons).

The first column is devoted to the proton sample. It can be seen that over 99% of particles in this sample are protons (so, the purity is more than 99%) and contaminations from other types of particles are negligible. In the second column are the kaons; the purity in this sample is 92% and most of the contaminations come from electrons (4–5%) and pions (2.5%). In the third column the contents of the pion sample is presented; the pion purity is also very high, 99%.

8.2.3 Uncertainty estimation

The uncertainty coming from the applied PID procedure and contamination from wrongly identified tracks was estimated using the differences between the PID cut sets presented in the previous section (Sec. 8.2.2). The differences between the default set of cuts and (a) strict cuts (with very high purity) of “exclusive PID”, (b) loose cuts (low purity) of “with double counting case” give a reasonable reference for such an estimation. The results are summarized in Table 8.1, for the full sample as well as in different transverse momentum ranges (for details see Sec. 5.6.2).

Further assessment of the PID quality using MC simulations is presented in Sec. 8.3.

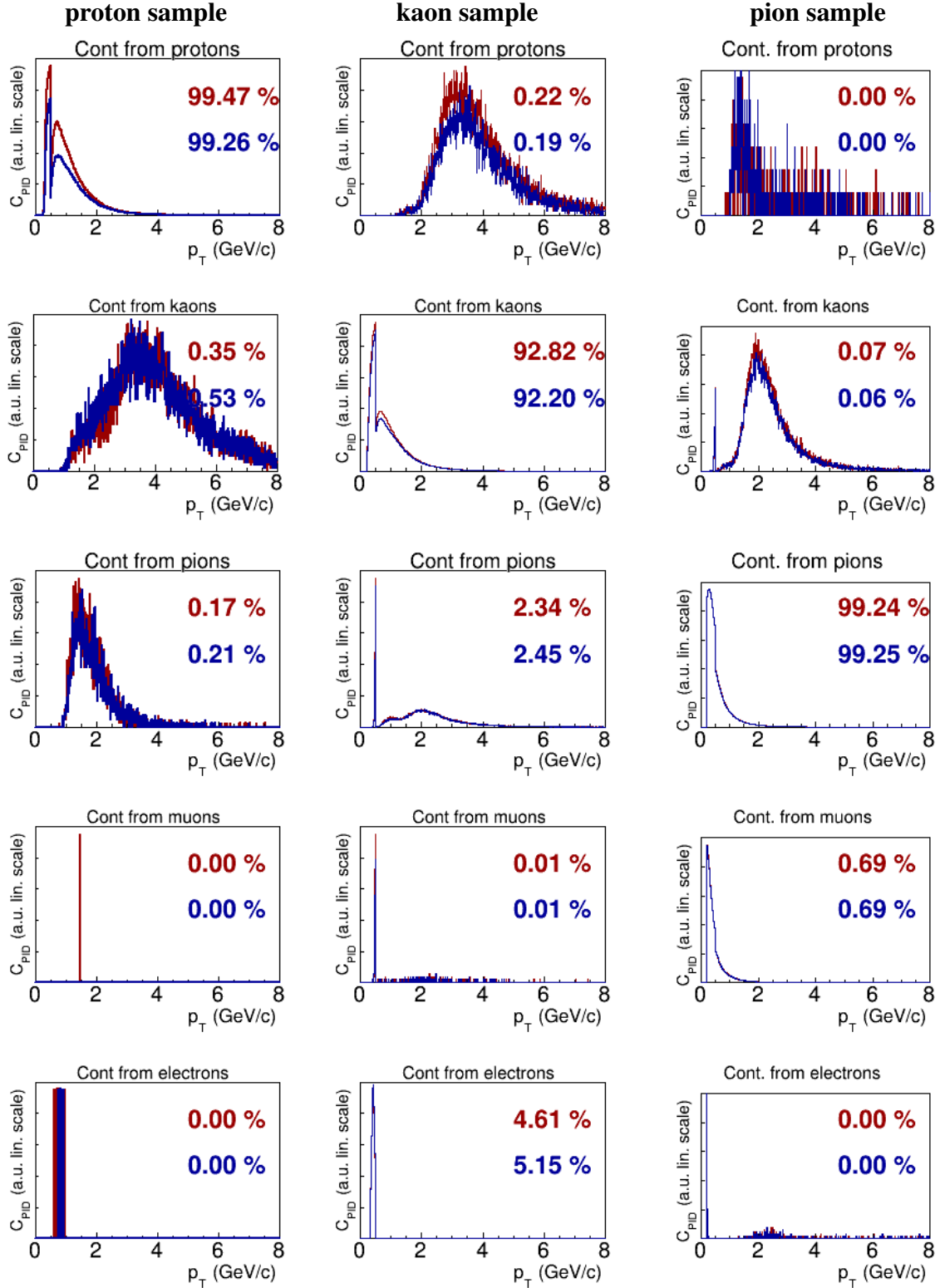


Figure 8.11: Information about contamination of the samples, as a function of p_T . The first column presents contributions of different particle species into the proton sample, the second one into the kaon sample, and the third into the pion sample. The numbers on the plots represent the contributions in the appropriate range for given particle species (as taken into the analysis), red for positive, blue for negative particles. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV, “without double counting” case.

Pair type		Relative uncertainty		
		No double vs double counting	No double vs exclusive	No double vs double $N_{\sigma, \text{PID}} < 2$
		Err.	Err.	Err.
$\pi^+\pi^+/\pi^-\pi^-$		<0.1%	<0.1%	<0.1%
$\pi^+\pi^-$		<0.2%	<0.2%	<0.1%
K^+K^+/K^-K^-		<6%	<1-2%	<1%
K^+K^-		<2%	<1 % (stat.)	<1%
$p\bar{p}/\bar{p}\bar{p}$		<3%	<1%	<3% (stat.)
$p\bar{p}$		<2%	<2%	<5%
$\pi^+\pi^+$	low $p_{T, \text{sum}}$	<1%	<1%	<1%
	med. $p_{T, \text{sum}}$	<1%	<1%	<1%
	high $p_{T, \text{sum}}$	<1%	<1%	<1%
$\pi^+\pi^-$	low $p_{T, \text{sum}}$	<1%	<1%	<1%
	med. $p_{T, \text{sum}}$	<1%	<1%	<1%
	high $p_{T, \text{sum}}$	<1%	<1%	<1%
K^+K^+	low $p_{T, \text{sum}}$	(stat.)	(stat.)	(stat.)
	med ₁ . $p_{T, \text{sum}}$	<1%	<1%(stat.)	<1%
	med ₂ . $p_{T, \text{sum}}$	<3%	<2%	<2%
	high $p_{T, \text{sum}}$	<20%	<6%	<3%
K^+K^-	$p_{T, \text{sum}}$	(stat.)	(stat.)	(stat.)
	med ₁ . $p_{T, \text{sum}}$	<1%	<1%(stat.)	<1%
	med ₂ . $p_{T, \text{sum}}$	<7%	(stat.)	<1%
	high $p_{T, \text{sum}}$	<7%	<5%	<1%
pp	low $p_{T, \text{sum}}$	(stat.)	(stat.)	(stat.)
	high $p_{T, \text{sum}}$	<5%	(stat.)	(stat.)
$p\bar{p}$	low $p_{T, \text{sum}}$	1%	(stat.)	3%
	high $p_{T, \text{sum}}$	<1%	2%	3%

Table 8.1: Summary on PID systematics: report on the relative difference between default “no double counting” and other PID cases. The text in the brackets “stat.” indicates that the uncertainty was only statistical, no systematic structure was observed. In the first three rows the results for the full sample are reported, in the next five rows the results in the different transverse momentum ranges are given (see Sec. 5.6.2 for details on the binning).

8.3 Monte Carlo closure tests

Detector effects and their impact on the final results can be estimated by applying a complete simulation of detector response of Monte Carlo events. The correction procedure used in this work for efficiency and contamination from secondary particles is described in Sec. 6.2. After applying the estimated correction factors for the detector effects to the reconstructed Monte Carlo data, the result should reproduce the Monte Carlo events as produced by the event generator (MC truth). For the correction procedure to be adequate, the difference between the initial sample and the corrected results after full simulation should be minor. If any discrepancies remain, they are referred to as Monte Carlo “*non-closure*”.

To validate the effectiveness of the applied corrections the *Monte Carlo closure test* can be employed. The correlation functions from reconstructed not-corrected data should differ from the Monte Carlo truth due to the efficiency and contamination effects. If we apply corrections, then in the ideal case both correlation functions should be the same. However, in reality, applying the correction procedure always results in a finite systematic uncertainty, i.e. in the case of this analysis we expect to see differences coming from the track misidentification. Therefore, as a result of this test we expect not the exact reproduction of the MC truth data, but a clear improvement after the correction relative to the not-corrected sample.

Figure 8.12 shows the difference between the not-corrected correlation function, and the one after applying 1D p_T -dependent efficiency correction (described in Sec. 6.2) for non-identified unlike-sign particles. The plot on the left is the MC truth plot (MC information as generated in Pythia Perugia-0 pp $\sqrt{s} = 7$ TeV simulated events without reconstruction). The middle plots present the correlation functions we are comparing; the raw correlation function (after the reconstruction but before the correction) is presented in the top panel, and the correlation function after the correction in the bottom. The right plots show the ratios between pure MC information (left plot) and the correlation function (middle plot). The scale is kept the same for both ratios. The MC truth plot is not repeated twice, since for both cases it is the same figure.

If we apply the correction procedure we observe a clear improvement: it can be seen in Fig. 8.12 for the pion sample that the correlation functions after applying the corrections are more similar to the MC truth ones than the correlation functions without any corrections². The

²For constant corrections see Sec. B.1.

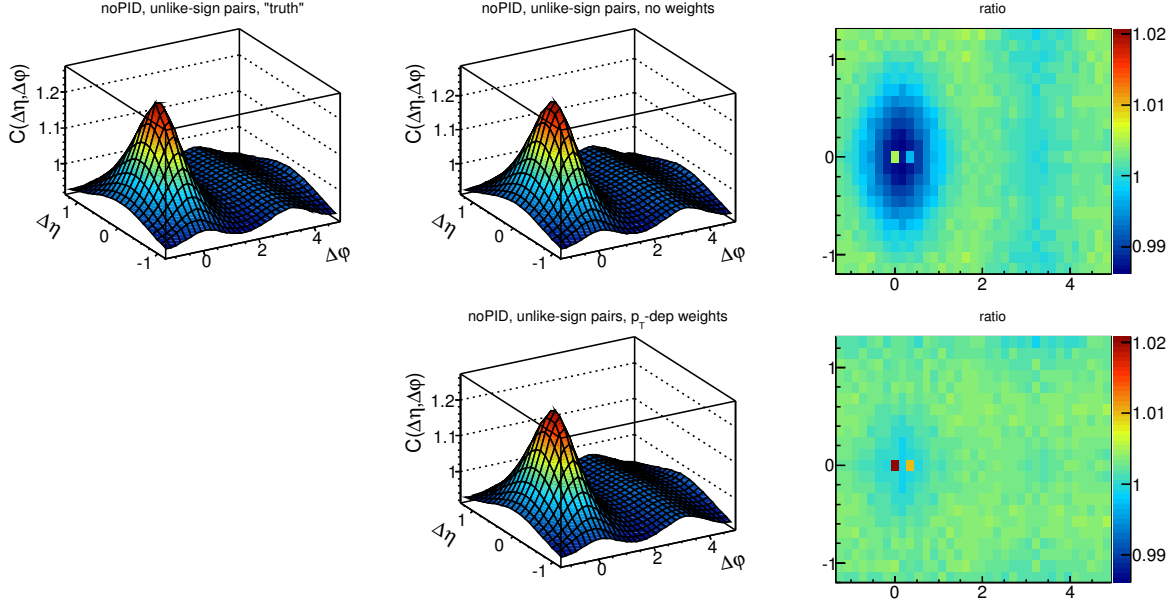


Figure 8.12: MC closure test for the correlation function of unlike-sign non-identified particle pairs. Left: MC truth (reference sample). Middle top: not corrected reconstructed sample. Middle bottom: corrected reconstructed sample. The ratios of the left to the middle plots are shown in the right panel. The scale is the same for both ratios. The “double counting” PID method is used. The calculations were performed employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

observed differences for most of the phase space is of the order of 0.5%. Figure 8.13 shows similar plots, for the kaon sample. The observed differences of the order of 10% in the near-side peak are expected due to the misidentifications (lower purity of the kaon sample). Note that for the Fig. 8.12 and Fig. 8.13 the PID method “with double counting” is used.

In Table 8.2 the report from the MC closure test for all the samples is presented. The table lists results for the:

- not corrected correlation functions,
- after corrections, for the highly contaminated sample obtained using “with double counting” PID procedure,
- after corrections, for the default “without double counting” PID procedure.

The relative uncertainties reported in the Table 8.2 are the maximum uncertainties in the two-dimensional $\Delta\eta\Delta\phi$ plots, usually coming from the near-side peak region. As mentioned, after the correction procedure still some differences are seen, due to the PID contamination of the samples. It can be observed that the PID procedure “without double counting” results in better

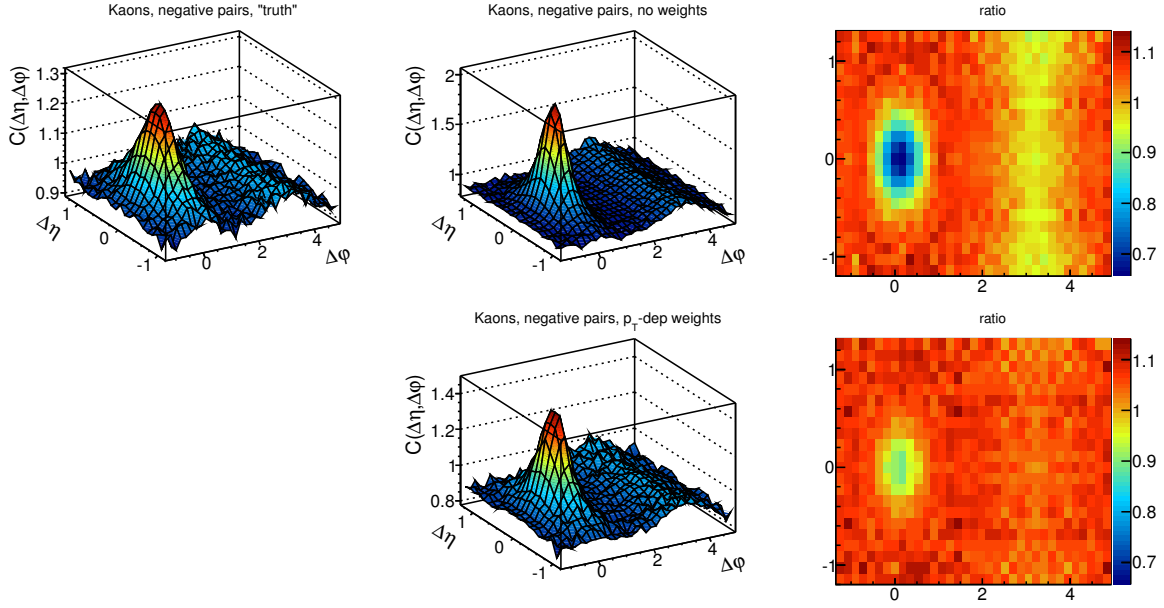


Figure 8.13: MC closure test for the correlation function of kaon like-sign (- -) pairs. Left: MC truth (reference sample). Middle top: not corrected reconstructed sample. Middle bottom: corrected reconstructed sample. The ratios of the left to the middle plots are shown in the right panel. The scale is the same for both ratios. The “double counting” PID method is used. The calculations were performed employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

similarity to the “true” sample than “with double counting”, as expected (the sample obtained with “without double counting” has higher purity, and lower contamination).

For the “without double counting” procedure, used as the default one for this analysis, we obtain MC non-closure not higher than:

- 1% for pions,
- 5% for protons,
- 5% for kaons.

More details on the MC closure tests can be found in the Appendices:

1. for using constant weights (constant corrections) see Appendix B.1,
2. for using 4D maps see Appendix B.2.

Pair type	Relative error		
	No corrections	Double counting	W/o double counting
	Err.	Err.	Err.
no PID (+,+)	<1.5%	<0.5%	<0.5%
no PID (+,-)	<1.5%	<0.5%	<0.5%
$\pi^+\pi^+/\pi^-\pi^-$	<2%	<1%	<1%
$\pi^+\pi^-$	<3%	<1%	<0.5%
K^+K^+/K^-K^-	<45%	<10%	<5%
K^+K^-	<20%	<5%	<3%
$p\bar{p}/\bar{p}p$	<8%	<5%	<5%
$p\bar{p}$	<5%	<5%	<3%

Table 8.2: MC closure summary: report on the relative uncertainty between MC truth and reconstructed MC samples.

8.4 Summary on uncertainty of correlation functions

Below we summarize all the systematic uncertainties for the correlation functions:

- the differences between the samples consisting of positive and negative pairs are only statistical,
- track cuts variation gives $< 1\%$ differences,
- η variation gives $< 2\%$ differences,
- results from different productions differ by no more than 2% ,
- PID systematics obtained from “exclusive PID” (strict cuts, high purity) and “double counting with $N_{\sigma, \text{PID}} < 2$ ” (loose cuts, low purity) gives a contribution of $< 1\%$ for pions, $< 6\%$ for kaons, $< 5\%$ for protons,
- electron rejection contributes only to the “no PID” sample and reduces the entries in one bin $(\Delta\eta\Delta\varphi) = (0,0)$,
- the extreme case of the N_{ch} bin width (no binning) in event mixing gives $< 1.5\%$ wing structure effect. It is not part of the final systematic uncertainty; however, it is taken into account in the quantifying procedure,
- the extreme case z_{vtx} bins width (20 cm) in event mixing gives an influence of $< 0.2\%$ effect (not part of the final systematics uncertainty),
- for the pile-up rejection procedure no effect is visible.

A summary of the contributions is presented in Table 8.3. Also the MC closure differences are added in the table, as they should be compared with the results of the PID systematic study procedure (both, the MC non-closure and the differences due to the variations of the PID procedure result from the contamination of the sample, for which we do not correct).

Moreover, it should be noted that the results of the $(0,0)$ bin should be treated with great care: systematic effects contribute the most to this bin. Also electron pairs from gamma conversion ($\gamma \rightarrow e^+e^-$) have the greatest influence to this bin. It is particularly important for the comparisons of the data of different experiments; i.e., to reject residual secondary effects CMS experiment applies a cut on $|\Delta\eta| < 0.06$ and $|\Delta\varphi| < 0.06$ (all such pairs are rejected). In the case of this analysis, due to the very fine binning, the contributions to this one bin have negligible effects on the quantifying procedure.

Pair type	Relative uncertainty					
	Trk. cuts	Prod.	vs db. count.	vs Exclusive	vs db. $N_{\sigma, \text{PID}} < 2$	MC clos.
	Err.	Err.	Err.	Err.	Err.	Err.
no PID (+,+)	<1%	<1%				<0.5%
no PID (+,-)	<1%	<1%				<0.5%
$\pi^+\pi^+/\pi^-\pi^-$	<1%	<1%	<1%	<0.1%	<0.1%	<0.5%
$\pi^+\pi^-$	<1%	<1%	<0.2%	<0.2%	<0.1%	<0.5%
K^+K^+/K^-K^-	<1%	<1%	<6%	<1-2%	<1%	<5%
K^+K^-	<1%	<1%	<2% (1)	<1 % (stat.)	<1%	<3%
$p\bar{p}/\bar{p}p$	<1%	<1%	<3%	<1%	<3% (stat.)	<5%
$p\bar{p}$	<1%	<1%	<2%	<2%	<5%	<3%

Table 8.3: Summary of the systematic uncertainties.

8.5 Uncertainty of quantitative results

In this section we report on the systematic uncertainty of the quantitative results. Since the fitting formula was different for identified and non-identified samples, the procedure for the estimation of the uncertainty was performed separately for each one of them.

8.5.1 Identified sample

The systematic uncertainty of the fitting procedure includes:

- Changing the range of the fitting** The uncertainty includes the difference between the default fitting and the parameters obtained from fitting the correlation functions with increased limits of the parameters by 50%–100%. It was observed that the results of the fit are not dependent on the parameters limits, apart from the σ_A parameter of the away-side which fluctuates considerably. Those fluctuations appear due to the low value (close to 0) of the magnitude of the away-side ridge. In such a case the σ of the Gaussian has no longer any physical meaning (since the integral of the Gaussian structure with magnitude ~ 0 as a whole is ~ 0) and therefore σ should be treated only as random artifact of the fitting procedure. For the final results the σ_A points which have a corresponding magnitude M_A of the away-side ridge equal to 0 are removed from the plots, i.e. the first p_T -sum bin for unlike-sign pairs of pions, kaons, and protons.

- **Influence of the PID procedure** This uncertainty is divided into two parts: (1) difference between default fitting and highly contaminated sample obtained with “ $N_{\sigma, \text{PID}} < 2$ and with double counting” PID procedure, (2) difference between default fitting and very pure sample obtained with “exclusive PID” procedure. This part of the uncertainty is propagated from the correlation function to the results of the fit. It can be seen that changes in the PID procedure influence mostly kaons and protons, and are the highest for the most contaminated high- p_T kaon sample, as observed for the correlation functions.
- **$\Delta\eta$ fitting range** The difference between the default fitting in the $|\Delta\eta| < 1.5$ range and the parameters obtained from fitting the correlation functions in a narrower range $|\Delta\eta| < 1.4$ was studied. Similarly, we investigated the difference between the default fitting in the $|\Delta\eta| < 1.5$ range and the parameters obtained from fitting the correlation functions in a wider range $|\Delta\eta| < 1.6$. Varying ranges in $\Delta\eta$ influences mostly the like-sign proton pairs.
- **Data sample** The uncertainty includes differences between the data taking periods and some aspects of the reconstruction procedure. This part of the uncertainty is propagated from the correlation functions. Subsets of the final dataset are used and the differences are evaluated.
- **Charge** Differences between positive and negative like-sign pairs are taken into account.

The summary of the uncertainty contributions is presented in Table 8.4. Unless stated differently the relative uncertainty is smaller than 1%.

Contribution	Relative uncertainty	Comment
Starting parameters		(1)
Parameter limits		(1)
Exclusive PID	10% for K^+K^- 5% for K^+K^+ 3% for pp	(1,2)
$N\sigma < 2$	5% for kaons 5% for pp	(2)
η range -0.1	10% for pp	(1,3)
η range +0.1	2% for pp	(1,3)
Productions separately	3% for kaons 5% for protons	(1,4) (1,4)

Table 8.4: Summary of contributions to the final uncertainty. Unless stated differently the difference is smaller than 1%. The numbers of the column “comment” correspond to list of the comments presented in the text.

Below we list the comments for the Table 8.4:

1. for the away-side ridge, for some points, the magnitude is ~ 0 ; for such cases the σ of this Gaussian does not carry any physical meaning and the obtained values vary,
2. the different PID methods have most influence on the most contaminated samples: kaons and protons,
3. protons are very sensitive to the $\Delta\eta$ range due to the limited statistics,
4. the limited statistics (only part of the dataset) mostly influence low-statistic samples of kaons and protons.

For the final systematic uncertainty all the relative uncertainties are added in quadrature.

8.5.2 Non-identified sample

The sources of uncertainties of the fit parameters for the non-identified sample are presented in Table 8.5. Every single uncertainty was calculated as the difference between the value of the

parameter from the standard fit (without any modifications) and the value of the same parameter from the modified fit, for example from the fit performed within a wider $\Delta\eta$ range. Below we describe in detail two cases that were not mentioned in the description of the fitting of the identified sample.

Systematic uncertainty	like-sign	unlike-sign
+10% parameters' limits	✓	✓
-10% parameters' limits	✓	✓
+0.1 range in $\Delta\eta$	✓	✓
-0.1 range in $\Delta\eta$	✓	✓
+5% starting parameters	-	✓
-5% starting parameters	-	✓
Wings correction	✓	✓
Long. ridge fixed to 0	✓	-
Differences between productions	✓	✓

Table 8.5: Systematic uncertainty components.

- Wings correction** One of the sources contributing to the systematic uncertainty was the “wings correction” procedure. The goal was to eliminate the wing structure and the longitudinal ridge and then fit a new function without those two components. To achieve that, the correlation function was probed on the away-side ridge at $\Delta\varphi = \pi$, where it should be flat in the $\Delta\eta$ coordinate (excluding the wing structure and longitudinal ridge, which we want to eliminate). Then, the whole irregularity observed in the away-side ridge was removed from the correlation function. The result of the procedure is presented in Fig. 8.14.
- Longitudinal ridge fixed to zero** The longitudinal structure is prominent for unlike-sign pairs, while for like sign-pairs it is almost not visible. Therefore, a fit with the longitudinal ridge magnitude fixed to zero was performed for like-sign pairs, decreasing the number of free parameters. The obtained fit was consistent with the previous results; hence, the difference between the fit parameters' values with and without this procedure was taken into account during the systematic uncertainty calculation.

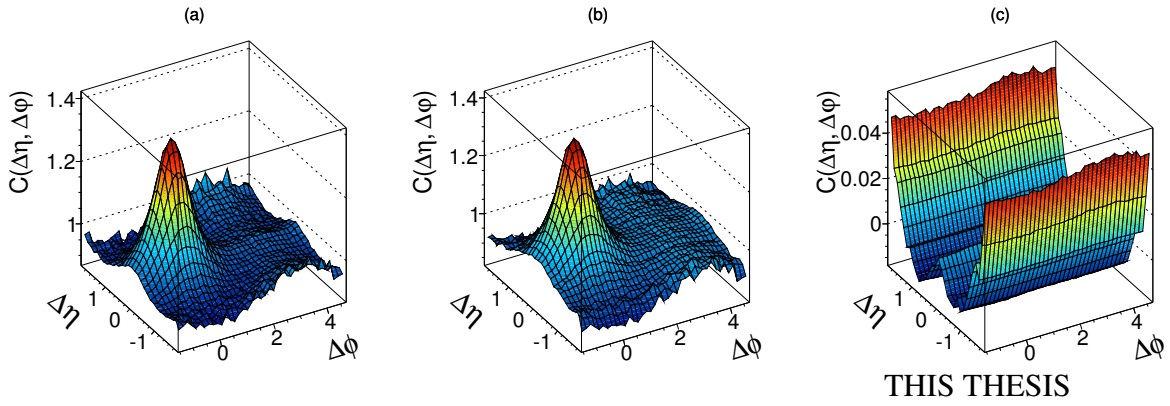


Figure 8.14: Effect of the wing correction procedure: (a) original correlation function shape, (b) correlation function shape after the correction of the wing structure and (c) subtraction of those two functions.

Chapter 9

Interpretation of results

The analysis of the collision data was complemented with Monte Carlo (MC) models studies. In particular, a simple MC model was developed to study the conservation laws for the purpose of this work. This model and the obtained results are presented below, in Sec. 9.1. Moreover, two general purpose MC event generators were used – Pythia tunes Perugia-0 and D6T [47, 50] and Phojet version 1.12 [51]. The mentioned generators are described in detail in Sec. 2.4 and the results of the performed studies are presented in Sec. 9.2.

9.1 CALM – ConservAtion Laws Model

As a basic step towards understanding the role of conservation laws and their influence on various observables, we study events in which energy and momentum are conserved and there is no other physics involved. For such a case a model was developed in order to explore the impact of the conservation laws on the correlation functions – CALM (ConservAtion Laws Model). In Sec. 9.1.1 the basic principles of the CALM model are described. In Sec. 9.1.2 results are presented.

9.1.1 Basic principles

The developed Monte Carlo event generator, CALM, is based on the ROOT framework and is written in C++ programming language. The model gives the possibility to generate events with all conservation laws obeyed. It uses constraints from the data obtained from proton-proton collisions in ALICE. Moreover, it allows us to study correlations generated by minijets and femtoscopic effects. For a given set of possible particle species the model returns a simulated event.

The codes used to develop the CALM event generator are described in Sec. 9.1.1.1. The particle generation process is described in Sec. 9.1.1.2 and the procedure to assure proper probability occurrence of the events is described in Sec. 9.1.1.4. Apart from the conservation laws, additional correlation sources that have also been incorporated in the model are described in Sec. 9.1.1.3 (minijets) and Sec. 9.1.1.5 (femtoscopic effects).

9.1.1.1 Base codes

In the development of the CALM model some publicly available codes were used:

- **GENBOD** In the process of creating the model we adapted the `TGenPhaseSpace` class from the ROOT framework. It is essentially based on the `GENBOD` [227] function from the CERN program library [228].

GENBOD is a N -body Monte Carlo event generator which computes the phase space distribution of particles produced in the collision. The only constraint for the event is the energy and momentum conservation [229], making it a perfect tool for the study of the correlations induced by the conservation laws. In addition, for each event it returns a weight proportional to the probability of the occurrence of such an event in the experiment.

As an input to GENBOD the user must specify the total event multiplicity N , the list of masses of produced particles and the total energy to distribute. The output is a list of particles' four-momenta that obey the energy-momentum conservation law.

- **THERMINATOR** The procedure of saving the events and the event structure was adapted from THERMINATOR 2 Monte Carlo event generator [230].
- **tpi** The calculation of the femtoscopic weights is based on the `tpi` software written in C++ by Prof. Adam Kisiel, advisor of this thesis. It was developed with the aim to calculate the two-particle correlation functions.

9.1.1.2 Generation process

The generation process can be described with the following scheme: (1) define the particles (their masses), (2) define the total energy to be distributed among the particles, (3) generate particles with GENBOD and (4) save the produced event.

Defining the particles

In order to utilize the GENBOD, one needs to supply it with a full list of particles (their masses and multiplicity of individual particles) to be generated in the event. To create such a list, with all conservation laws obeyed, the MC procedure described below is applied.

To ensure conservation of charge, strangeness, and baryon number, the particles that can be generated by this model have been divided into four groups: pions, kaons, nucleons, and lambda baryons. For each particle appropriate quantum numbers have been assigned. The yields of particles are taken from ALICE measurements¹ [220, 232] and are summarized in Table 9.1.

group	particles	integrated yield dN/dy
pions	π^+, π^0, π^-	8.94
kaons	$K^+, K^0, \bar{K}^0, K^-$	1.46
nucleons	$p, \bar{p}, n, \bar{n}$	0.648
lambda baryons	$\Lambda, \bar{\Lambda}$	0.19

Table 9.1: Integrated particle yields for the given particle groups [220, 232].

Then, for each event, the number of particles in each group is generated according to a Poisson distribution with the mean given by the particle yields presented in Table 9.1. Next, within each group, the particles are generated with equal probability. If we consider that N pions are generated in the event, then for each of those N particles we choose randomly from π^+, π^- and π^0 . Afterwards, the sum of quantum numbers for the whole list is calculated. The list of particles is accepted if the electric charge, strangeness, and baryon number are compensated in the whole event. Otherwise, the procedure starts from the beginning. The flow diagram of this algorithm is presented in Fig. 9.1.

Defining the energy

The GENBOD code needs as an input not only the full list of particles, but also the total energy to be distributed among them. Even though the energy in the center of mass of the colliding

¹One can expect the production yields of neutral particles (not measured by the experiment) to be the same as the one of their isospin partner [231].

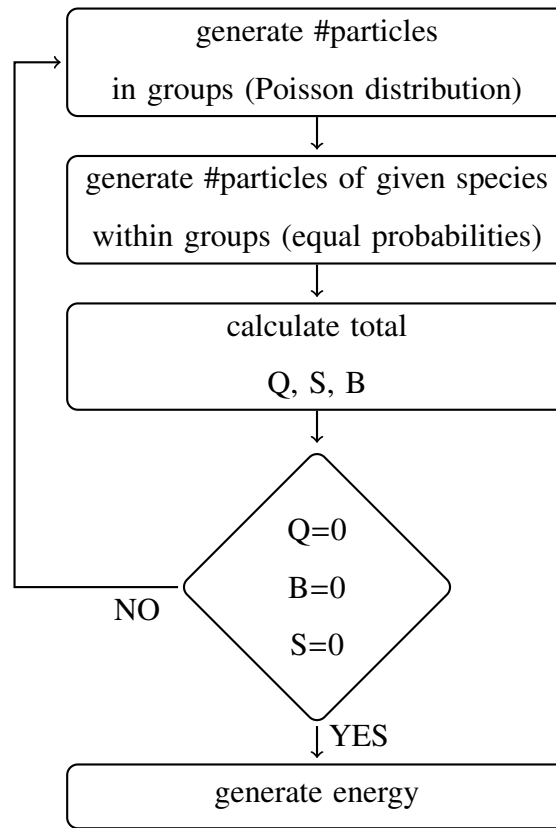


Figure 9.1: Flow diagram of the algorithm generating the particles in the event. The number of particles in the groups (pions, kaons, nucleons, lambdas) is generated according to a Poisson distribution, with a mean value taken from the ALICE measurements [220, 232]. The particles within the groups are generated with equal probabilities. If the electric charge Q , strangeness S and baryon number B are compensated in the whole event then the list of particles is accepted, and the algorithm proceeds to the energy-determination step. Otherwise, the procedure starts from the beginning.

protons is known, the estimation of the fraction that results in the hadron production is not straightforward. Firstly, the energy of the protons is distributed between the quarks and gluons and mostly the interacting partons' energy is observed in the collider experiments, while beam remnants remain undetected. Secondly, except for the hadrons there are also other particles produced in a real collision that are not simulated by the CALM model; for instance photons, carrying a fraction of the collision energy. Therefore, for this model, the total momentum spectrum of charged hadrons was used, as measured² in pp collisions in ALICE at the collision energy $\sqrt{s} = 7$ TeV.

²The total event particle momentum distribution (sum of momenta of all charged hadrons in the event) was calculated on the analyzed $\sqrt{s} = 7$ TeV pp ALICE data sample specifically for this purpose.

Generating particles with GENBOD

The generated list of particles and the total energy are used as input parameters to GENBOD. As an output, a list with particle momenta (four-momentum vectors, with momentum conserved) is produced. Additionally, a value proportional to the probability of occurrence of the event in the experiment is returned. For a schematic diagram see Fig. 9.2.

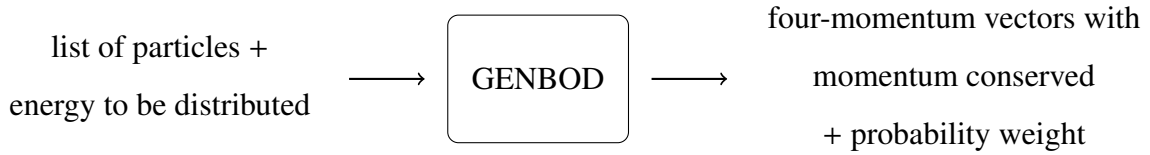


Figure 9.2: Use of GENBOD module.

Saving the produced event

Particles (their identities and momenta) need to be stored in a structure convenient for further analysis. The procedure of saving the events and the event structure was adapted from THERMINATOR 2 [230]. The events are saved in TTree structures in root files.

9.1.1.3 Minijets

The algorithm presented in the previous section generates the particles in the whole phase space with the only constraint of the conservation laws obeyed globally for the whole event. An additional option has been implemented, namely the generation of minijets.

A minijet is simulated as a collection of particles boosted together in a certain direction, creating a collimated spray. The minijets in CALM are always created in pairs, reflecting the scheme of back-to-back jet production, see Fig. 9.3. In each minijet there needs to be at least two particles. GENBOD is called twice, for each minijet separately. Regarding the total energy of the event, half of the energy is the boosting energy (creating the collimation) and the GENBOD input energy is one fourth of the generated value for each of the jets. The momentum of the boosting is calculated from Eq. (9.1), where N is the number of particles in the minijet and φ is the azimuthal angle generated from a uniform distribution from 0 to 2π . The polar angle θ is calculated as $\theta = 2 \tan e^{-\eta}$ where η is generated from a uniform distribution from -2 to 2 . Particles' momenta are increased by $p = (p_x, p_y, p_z)$ for one minijet and by $-p = (-p_x, -p_y, -p_z)$

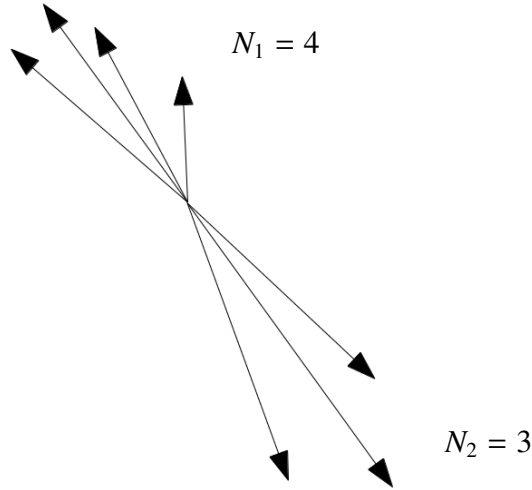


Figure 9.3: Back-to-back minijet production schema.

for the other, where p_x , p_y , p_z are defined as:

$$p_x = \frac{E_{\text{tot}}}{4N} \sin \theta \sin \varphi,$$

$$p_y = \frac{E_{\text{tot}}}{4N} \sin \theta \cos \varphi, \quad (9.1)$$

$$p_z = \frac{E_{\text{tot}}}{4N} \cos \theta.$$

The aim of the CALM model is to check the influence of conservation laws on the angular correlations. Therefore, two scenarios have been implemented: the minijets with laws conserved only globally (for the whole event) and minijets with local conservation laws (all quantum numbers conserved for each fragmentation – minijet separately).

For the generation of the minijets obeying the global conservation laws the list of particles resulting from the procedure described in Sec. 9.1.1.2 is divided into two groups, each one representing one minijet. For the generation of minijets with local conservation instead of one list, two sets of particles are created and for each one of them the checks on electric charge, strangeness, and baryon number compensation are performed separately.

9.1.1.4 Probability weights

In the case of the general purpose event generators like Pythia or Phojet each event has the same probability of occurrence. It is not the case for the events generated by GENBOD. In fact the probabilities differ a lot, even by a few orders of magnitude. However, additional information is provided, the so-called *probability weights*, and therefore, it should be utilized to create a realistic event sample.

The probability weight is based on the phase-space integral [233], see (Eq. 9.2):

$$R_N = \int^{4N} \delta^4 \left(P - \sum_{j=1}^N p_j \right) \prod_{i=1}^N \delta(p_i^2 - m_i^2) d^4 p_i, \quad (9.2)$$

where $P = (E_{tot}, 0)$ is the total momentum four-vector of the event. According to Fermi's statistical theory [234] the probability of having N particles in the final state is given by Eq. (9.3)

$$P_N \sim \bar{S}_N \cdot R_N, \quad (9.3)$$

where $\bar{S}_N$ is the phase-space-averaged S -function (or matrix element) associated with the process of generating the final state and R_N is expressed by Eq. (9.2).

Two extreme scenarios are presented in Fig. 9.4. The first, more “spherical” event (Fig. 9.4-left) is much more probable to occur, while the second one (Fig. 9.4-right) is a hundred million times less likely.

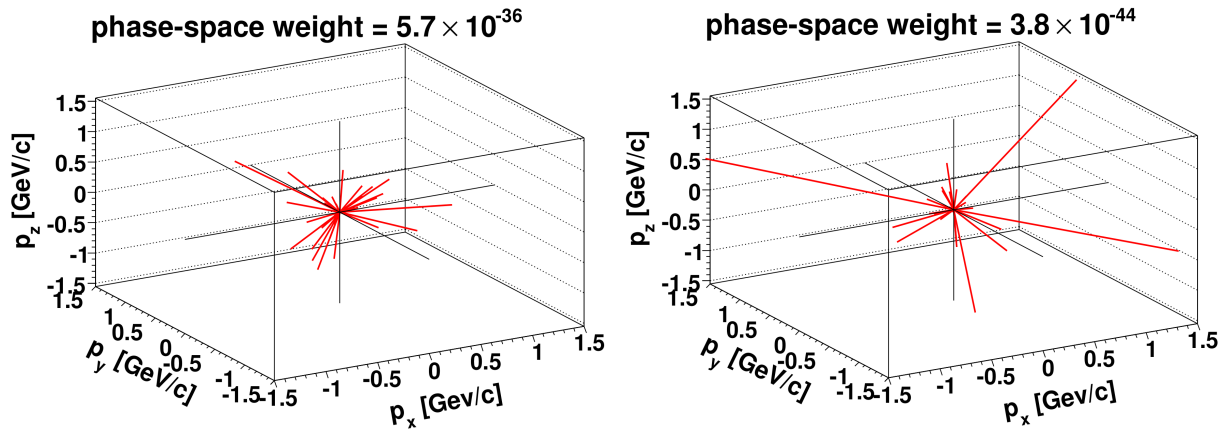


Figure 9.4: Events calculated by GENBOD. Left: high-probability event. Right: low-probability event. Lines correspond to particle momenta p_x , p_y , p_z . From Ref. [235].

An additional code, based on the concept of event sampling with the weights coming from the GENBOD generator, was introduced. All events are read in order to get information about

the appropriate weights and the occurrence probabilities for each event are calculated; for an example see Fig. 9.5-left. Afterwards, the set of events selected for the analysis is created, by choosing them randomly according to this distribution. The resulting incidence of generated events is presented in Fig 9.5-right.

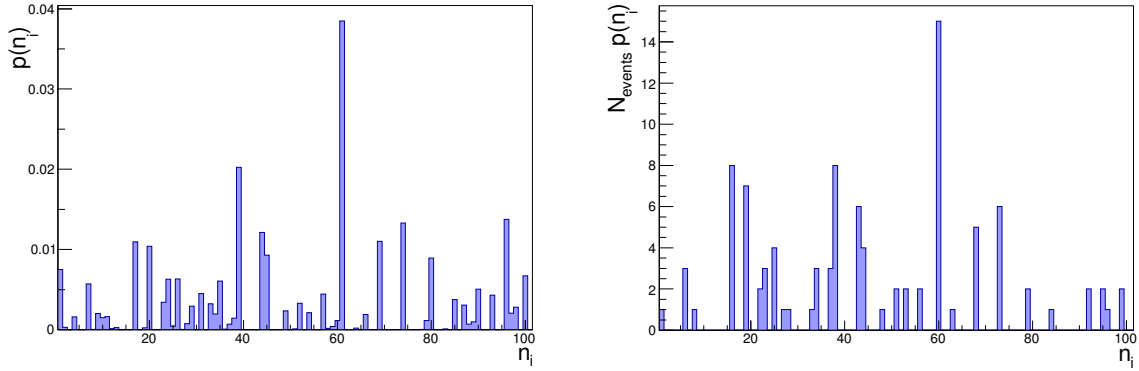


Figure 9.5: Occurrence probability for 100 events generated with the CALM model. Left: event probability from GENBOD. Right: actual event incidence for further analysis. n_i is the event sequential number.

9.1.1.5 Femtosopic afterburner

In addition to the conservation laws and minijets, we implemented a code giving the possibility to study the impact of the femtosopic effects on the $\Delta\eta\Delta\varphi$ correlation functions. It is based on the `tpi` software, developed with the aim to calculate the two-particle correlation functions. In addition to the basic possibility to calculate typical femtosopic functions (see Sec. 3.2.6), it was further expanded for this thesis to compute also the angular correlations in $\Delta\eta\Delta\varphi$ space. As an input, `tpi` takes generated events in the form of a list of particles stored in a specific format (`root` files) which includes information about particle ID and their space-momentum coordinates. This information, at the level of constructing the correlation functions, allows us to assign femtosopic weights for each pair, corresponding to the quantum statistics as well as Coulomb and strong final state interactions. The procedure results in the creation of the $\Delta\eta\Delta\varphi$ correlation functions which include those effects.

9.1.2 Results

In the following sections we will present correlation functions for samples of events generated by CALM model. For all samples the correlation due to the energy-momentum conservation is present, and with each section an additional correlation source is introduced. The correlation functions are shown for two scenarios: (1) particles are distributed in the whole space, as well as (2) with collimation that simulates minijet contributions (for a description see Sec. 9.1.1.3).

In Sec. 9.1.2.1 the π^0 sample with only momentum conservation and minijet contribution are studied. The impact of the addition of the charge conservation constraint is presented in Sec. 9.1.2.2. The influence of conservation of quantum numbers, strangeness and baryon number, are present in the event samples described in Sec. 9.1.2.3. Finally, in Sec. 9.1.2.4 femto-scopic effects are studied.

9.1.2.1 Momentum conservation

To study the effect of the momentum conservation, unaltered by other correlation sources, events were generated with π^0 particles only. For such a case we generated 8 million events free from any correlations due to charge, strangeness or baryon number conservation. In Fig. 9.6-left the correlation function presenting neutral pions distributed isotropically in the whole phase-space, with momentum conservation as the only constraint, is shown. The characteristic shape created by momentum conservation can be seen (compare with the description of the conservation laws in Sec. 3.3). The wing structure visible for the away-side ridge is expected due to the non-uniform η distribution of the CALM model.

Also, 12 million events with the particles collimated into back-to-back sprays (simulating the minijet behavior) were generated with the CALM model. The effect of such a simulation can be seen in Fig. 9.6-right. Characteristic structures, the near-side peak at the $\Delta\eta\Delta\varphi \approx (0, 0)$ and away-side ridge at $\Delta\varphi \approx \pi$ can be observed (similarly as for the previous case; see minijet description in Sec. 3.3).

9.1.2.2 Charge conservation

To study the influence of the charge conservation on the global event shape data samples composed of π^+ , π^- and π^0 's were generated. For each event the charge has to be globally conserved. Moreover, for the minijet samples two options were studied: (1) the charge has to be conserved

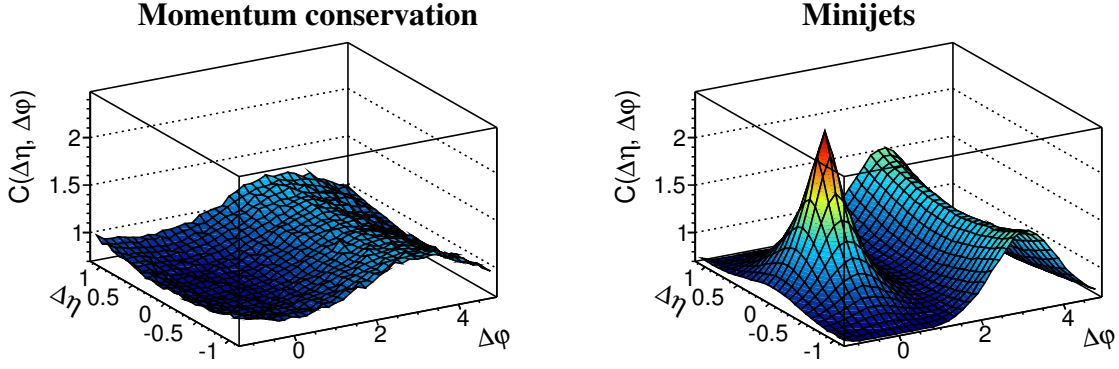


Figure 9.6: Events generated by the CALM model, composed of neutral pions only. Left: pions distributed in the whole phase-space, with the momentum conservation law obeyed. Right: events generated with the “minijet” option. Collimated sprays of particles in back-to-back directions create the characteristic near-side and away-side structures.

only globally, for the whole event, and (2) the charge has to be conserved for each fragmentation (single particle spray) separately. The correlation functions resulting from those studies are presented in Fig. 9.7.

In the first row the events without any minijet collimation are shown. The differences between like- and unlike-sign samples for the case where particles can be distributed in the whole phase-space are negligible. However, if we move to the studies of the correlation created by minijet-like collimation, the differences start to emerge. For minijets, with charge conserved globally for the whole event (second row of Fig. 9.7) we can see that the near-side peak is more pronounced for like- than for unlike-sign pairs. This is a trivial statistical effect. As an example let us consider possible events with four charged particles generated with minijet collimation, two particles per minijet. For a visual representation see Fig. 9.8, where the possible production scenarios are shown. In Fig. 9.8-left the charge is conserved globally, but not locally. In this case, for the like-sign correlation, there is a pair contributing to the near-side (NS) but not to the away-side (AS). On the other hand, for the unlike-sign correlation function all four pairs contribute to the AS. The second scenario can be studied in Fig. 9.8-right. In this case for the like-sign pairs the only pair contributes to the AS, not NS. However, for the unlike-sign the number of pairs contributing to the AS and NS is the same. The final result comes from the superposition of all possible cases. For the selected example we would obtain a ratio of NS : AS = 1 : 1 for like-sign pairs and NS : AS = 2 : 6 for unlike-sign pairs. On average, especially if

the charge is conserved globally, the ratio of pairs in the near-side to the pairs in the away-side will be higher for like-sign pairs, than for unlike-sign pairs.

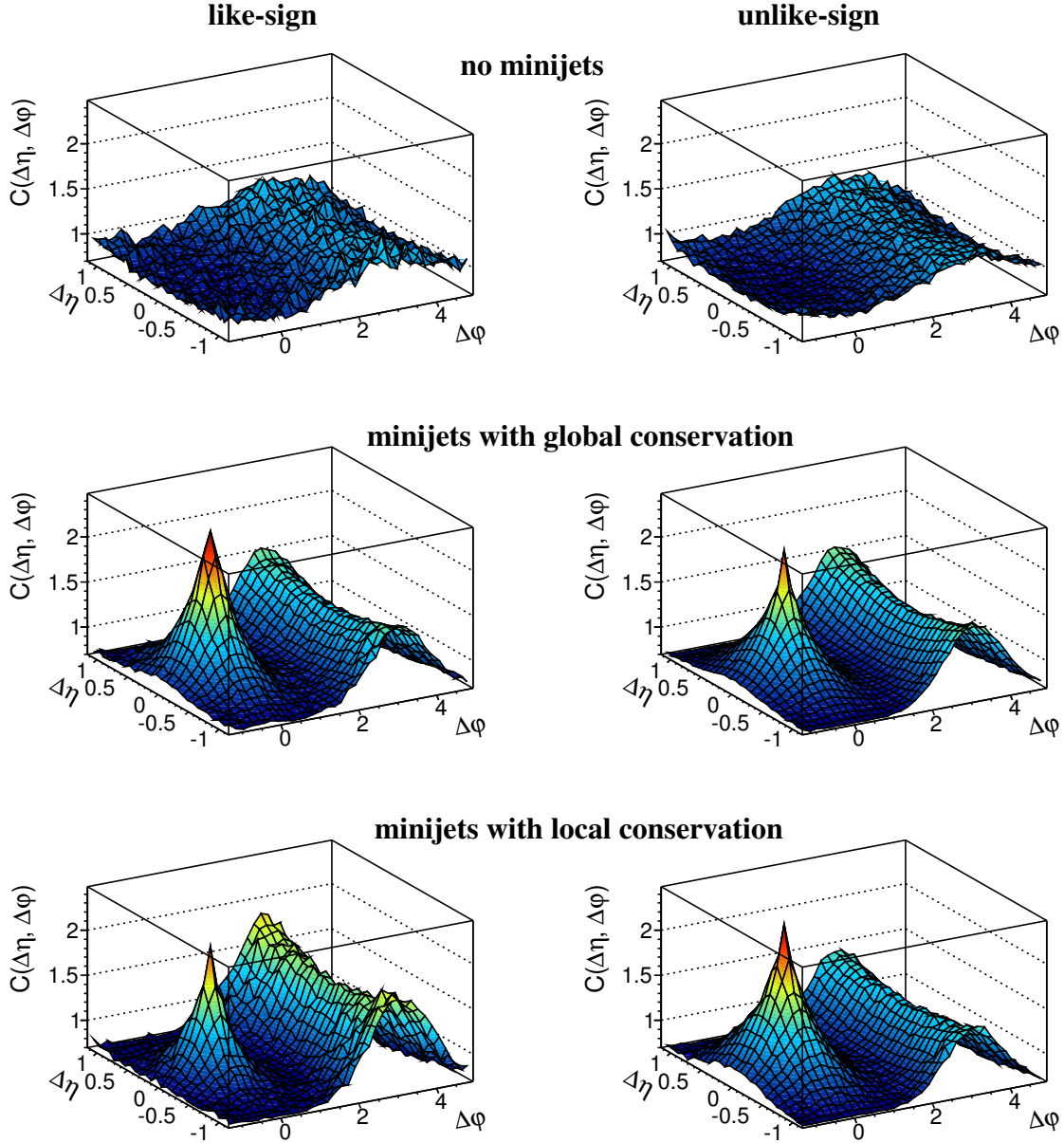


Figure 9.7: Correlation functions for events generated by the CALM model, composed of pions (π^+ , π^- and π^0) only. Left column: correlation functions of like-sign $\pi^+\pi^+/\pi^-\pi^-$ pairs. Right column: correlation functions of unlike-sign $\pi^+\pi^-$ pairs. The top row shows correlation functions for pions distributed isotropically in the whole phase-space, with momentum and charge conservation laws obeyed. Middle row: particles in the events were collimated to create minijet effects. The charge is conserved only globally, for the whole event. Bottom row: particles collimated into minijet, with charge conserved for each of the minijets separately.

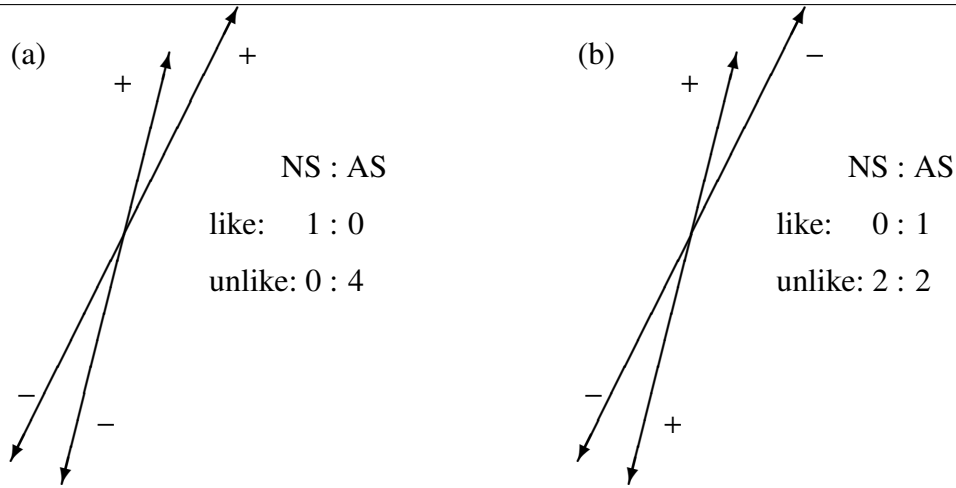


Figure 9.8: Example of trivial statistical effects for four charged particles in the collimated event. (a) Charged conserved globally for the whole event, but not for each fragmentation. Such a case contributes to the near-side (NS) for like-sign pairs, and strongly to the away-side (AS) for unlike-sign pairs. (b) Charge conserved both, globally and locally, for each fragmentation. Such a case contributes to the AS for like-sign pairs, and uniformly to NS and AS for unlike-sign pairs.

However, it will be different, if the charge is conserved also locally (third row of Fig. 9.7). The ratios of NS : AS will trivially reshuffle. For example, for this scenario the case of Fig. 9.8-left cannot occur, but the one of Fig. 9.8-right is still possible and contributes more. This time, the ratio of NS : AS is higher for unlike-sign pairs, than for like-sign pairs. This is visible in the results of the CALM model, making the near-side peak more pronounced for unlike-sign pairs than for like-sign pairs.

It should be stressed that the mentioned effects, regardless of their triviality, strongly influence the shape of the correlation function. It is visible e.g. in the results of the fitting presented in Sec. 7.2.3, where the like-sign pairs create, on average, higher away-side contribution than the unlike-sign pairs. Similarly, for high transverse momenta, where femtoscopic effects do not play a significant role and minijet contribution dominates, the near-side is higher for unlike-sign pairs than for like-sign pairs.

The $\pi^0\pi^0$ correlation functions (not shown) are the same as the $\pi^+\pi^+$ correlation functions without local charge conservation, as expected. The addition of the constraint on the charge, which forces it to be conserved for each fragmentation, does not influence neutral particles, therefore also does not change the $\pi^0\pi^0$ correlation functions.

9.1.2.3 Strangeness and baryon number conservation

To study the influence of other quantum numbers, i.e. strangeness or baryon number conservation another event sample was produced, with all types of particles mentioned in Sec. 9.1.1.2 present. This way we ensure that strangeness can be conserved not only inside the group of kaons, but also with other particles (i.e. lambda baryons). Similarly, the baryon number is carried by protons, neutrons, and lambda baryons.

An example result for kaons can be seen in Fig. 9.9. It should be stressed that for the shown sample each event had at least one K^+ and one K^- particle.

In the first row the events with minijet-like collimation and with quantum numbers conserved globally for the whole event are shown. We can see that the near-side peak is more pronounced for like- than for unlike-sign pairs. Again, this is a trivial statistical effect that creates the differences between like- and unlike-sign pairs. However, one can observe that those differences are much bigger than for the case of pions. If we consider the second row, which shows the correlation functions with quantum numbers conserved also locally, we can see that the relation also changes.

Moreover, the magnitude of the away-side ridge structure is relatively lower for the kaon sample than for pions (see second row of Fig. 9.9: the away-side is almost non-existent for unlike-sign pairs). This behavior of the correlation functions can be explained by the fact that for kaons we consider frequently cases, when two kaons are produced in a single jet, and the momentum of the second jet is compensated with different particles' e.g. pions; so, no away-side correlation is present. The same effect can be observed in collision data, e.g. as seen in the results of the fitting presented in Sec. 7.2.3. It can be seen that the magnitude of the away-side ridge in a given transverse momentum range is higher for pions than for kaons.

9.1.2.4 Femtoscopic effects

To study the influence of the femtoscopic effects on the correlation functions the procedure described in Sec. 9.1.1.5 was employed. The femtoscopic component (in case of pions: quantum statistics effects related to Bose-Einstein correlations) can be treated separately (see Fig. 9.10-left) or as part of the global correlation picture (see Fig. 9.10-right). It should be noted that the contribution from the femtoscopic effects in the near-side is comparable in width to the structure created by minijet collimation. These observations are consistent with ALICE results at

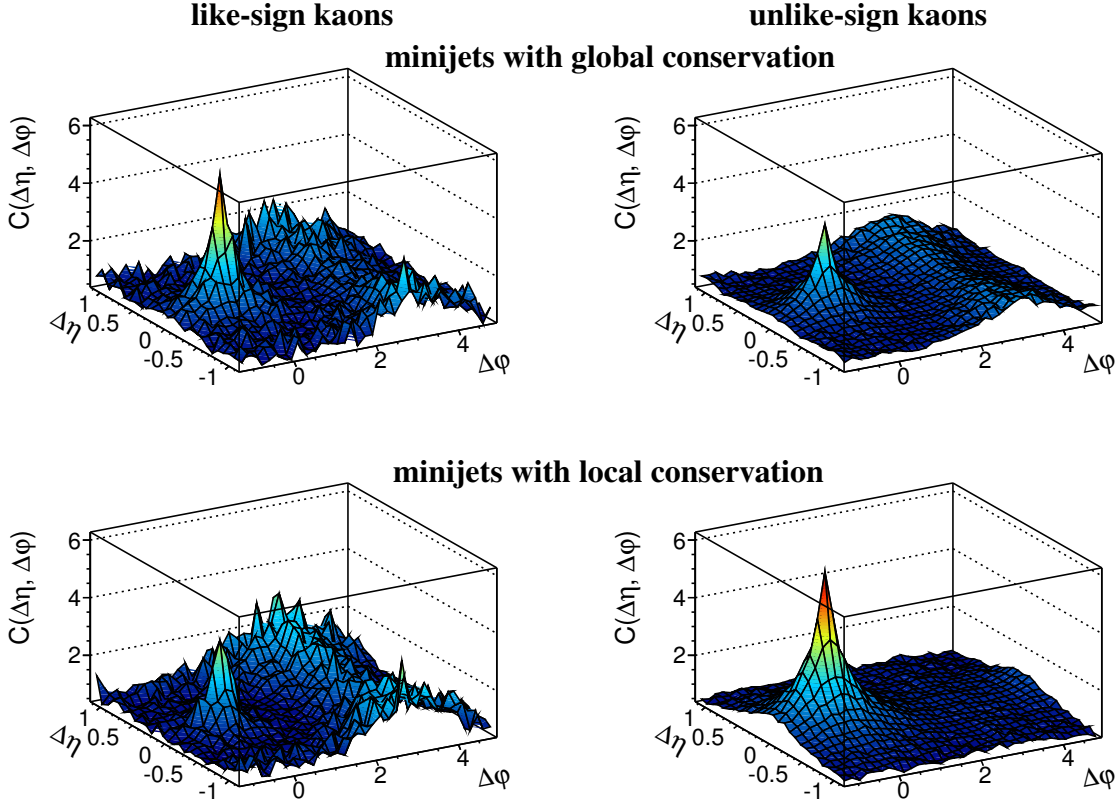


Figure 9.9: Correlation functions for events generated by the CALM model. Left column: correlation functions of like-sign K^+K^+/K^-K^- pairs. Right column: correlation functions of unlike-sign K^+K^- pairs. The top row shows particles in the events that were collimated to create minijet effects. The charge is conserved only globally, for the whole event. Bottom row: particles collimated into minijets, with charge conserved for each of the minijets separately.

low pair transverse momentum presented in Sec. 7.1.4.

9.1.3 Conclusions from CALM model

A number of correlation sources contribute to the $\Delta\eta\Delta\phi$ distribution, influencing the final shape of the correlation function. In Sec. 3.3 we described the theoretical physical mechanisms that are expected to occur in pp collisions, as well as associated structures that are predicted to emerge. In Chapter 7, we have studied the behavior of the observed effects.

To validate our hypotheses, instead of using general purpose MC generators (which, due to their complexity, can be treated as “black boxes”), we have developed a dedicated model called CALM. With the aim to reproduce the structures seen in the data we systematically added the effects one by one in a transparent, straightforward manner. We observed that the momentum

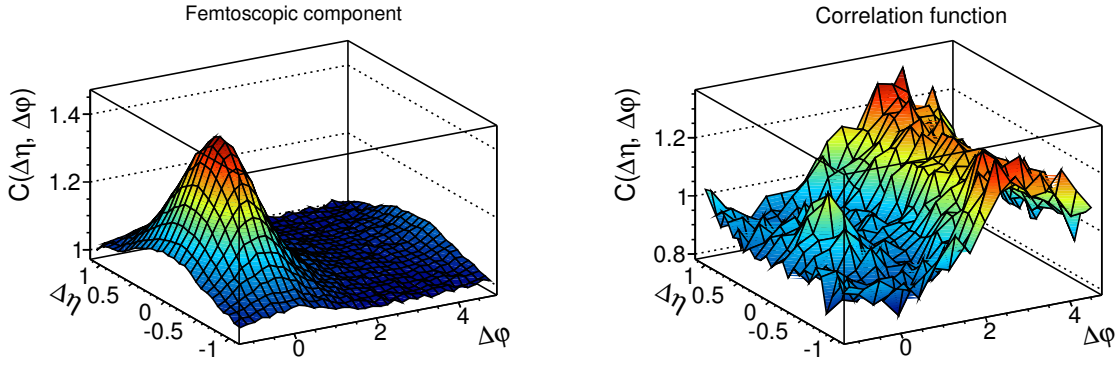


Figure 9.10: Left: pure femtoscopic (quantum statistics) component of the correlation function of like-sign pions. Right: the femtoscopic component added to the global correlation created by momentum conservation.

conservation law, without any additional correlation sources, generates the characteristic inverse $\sin(\Delta\varphi)$ -like shape in $\Delta\eta\Delta\varphi$. When the minijet back-to-back correlation was added, distinctive near-side peak and away-side ridge structures developed, similar to ones seen in the data. However, the near-side peak for like-sign pairs was of higher magnitude than for unlike-sign pairs, opposite to the trends seen in the results obtained from the collision data. To account for this effect the local charge conservation was added; with this constraint the correlation strength between like- and unlike-sign reversed due to trivial combinatorics. Further resemblance was achieved when additional conservation laws were included, like strangeness and baryon number conservation. It resulted in the noticeable differences in the shapes of the near- and away-side structures between the kaon and pion samples. Moreover, studies of the Bose-Einstein correlations were performed, confirming the assumption that the quantum statistics effect creates the near-side structure for like-sign (identical) pairs, which is comparable in width with the correlation arising from minijets.

The inclusion of the listed elements of the initial hypothesis allowed us to qualitatively reproduce all features observed in the collision data. This not only gives a strong confidence that we interpret correctly the structures observed in the experimental data, but also shows that the effects generated by each one of the correlation sources are properly understood. Additionally, those results strongly validate the proposed explanations of the behavior of the structures seen in the data. These conclusions are summarized in Table 9.2.

	Correlation source	Effect	CALM	Theory	ALICE results
1	momentum conservation	characteristic inverse $\sin(\Delta\varphi)$ -like shape in $\Delta\eta\Delta\varphi$	Sec. 9.1.2.1	Sec. 3.3	Sec. 7.1.2
2	back-to-back minijets	near-side peak and away-side ridge	Sec. 9.1.2.1	Sec. 3.3 Sec. 3.2.5	Sec. 7.1.4 high- p_T
3	charge conservation	enhancement for unlike-sign pairs due to trivial combinatorics	Sec. 9.1.2.2	Sec. 9.1.2.2	Sec. 7.1.4 high- p_T
4	mass difference and strangeness	differences in shapes of near- and away-side between kaons and pions	Sec. 9.1.2.3	Sec. 3.3 Sec. 9.1.2.3	Sec. 7.2.3
5	quantum statistics	near-side correlation in width comparable to minijets	Sec. 9.1.2.4	Sec. 3.3 Sec. 3.2.6	Sec. 7.1.4 low- p_T

Table 9.2: Compilation of insights from the CALM model, together with corresponding theory reference and ALICE collision data reference.

9.2 Results of the angular correlations for general purpose event generators

General purpose event generators simulate a wide range of processes for a MC collision. By direct comparison of collision data and MC simulation we can get useful information about which processes are still not well understood. To make this comparison possible MC data was analyzed by applying the same set of particle and pair selection criteria as for the collision data. Moreover, to ensure apples-to-apples comparison, studies on the influence of the detector were performed: for generated events the simulation of the detector response was conducted and then the MC generated events were processed through the reconstruction chain of the ALICE framework. The results of the comparison were presented in Sec. 8.3.

The charge dependence studies are presented in Sec. 9.2.1. The multiplicity dependence in Sec. 9.2.2. The dependence on transverse momenta is shown in Sec. 9.2.3 and the results for identified particles (pions, kaons, and protons) in Sec. 9.2.4.

9.2.1 Charge dependence

The analysis was performed on pp Monte Carlo reconstructed data generated by three different models: (a) Pythia Perugia-0 at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV, (b) Pythia D6T at $\sqrt{s} = 0.9$ TeV and (c) Phojet at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV. To facilitate comparisons the same scale on the z -axis (value of the correlation function) is used for all plots from pp Monte Carlo reconstructed data as well as ALICE collision data presented in Sec. 7.1.

Figures 9.11 and 9.12 should be compared with $\sqrt{s} = 7$ TeV pp collision data, shown in Fig. 7.2. It can be seen in the correlation functions for unlike-sign pairs, both for Pythia and Phojet, that at the near-side peak region ($\Delta\eta\Delta\varphi \approx 0, 0$) the correlation is stronger for the MC data. Since the near-side correlations come mostly from the minijets this can be an indication of the fact that in the MC models too many jets are produced in comparison to the data.

If we compare the correlation functions for like-sign pairs, the near-side peaks for the MC data are smaller than the ones for the collision data. This is expected since there are no Bose-Einstein correlations implemented in the studied models; therefore, without an additional source of the correlations, the like-sign correlation functions are lacking the additional near-side contribution.

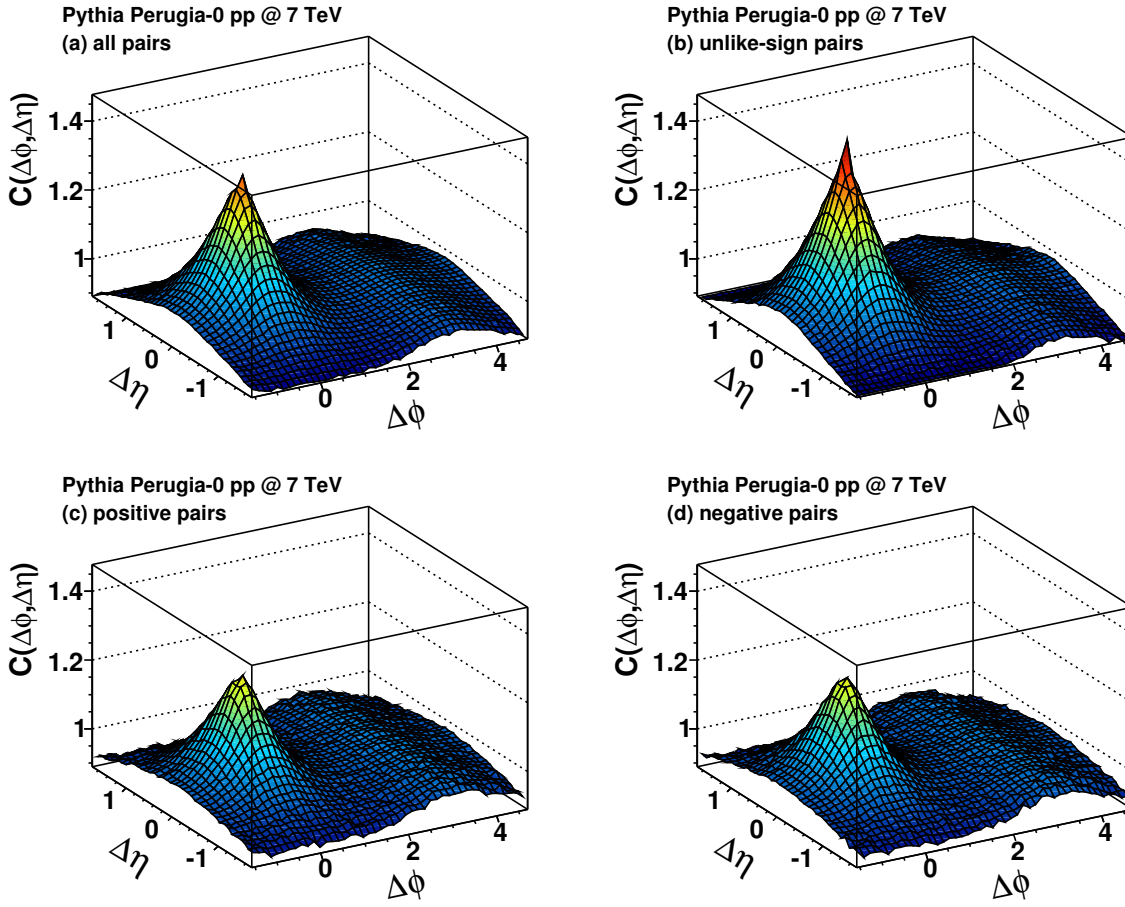


Figure 9.11: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 7$ TeV Pythia Perugia-0 pp data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (--).

Figures 9.13, 9.14 and 9.15 should be compared with the $\sqrt{s} = 0.9$ TeV pp collision data (see Fig. 7.4). We can see that for Pythia D6T tune (Fig. 9.13) the correlation structure at the near-side is too high (indicating that the production of minijets is too large). On the other hand, the correlation functions obtained from the Phojet pp data at $\sqrt{s} = 0.9$ TeV (Fig. 9.15) are almost flat in comparison to the collision data. The best agreement with the collision data is obtained using the Pythia Perugia-0 tune.

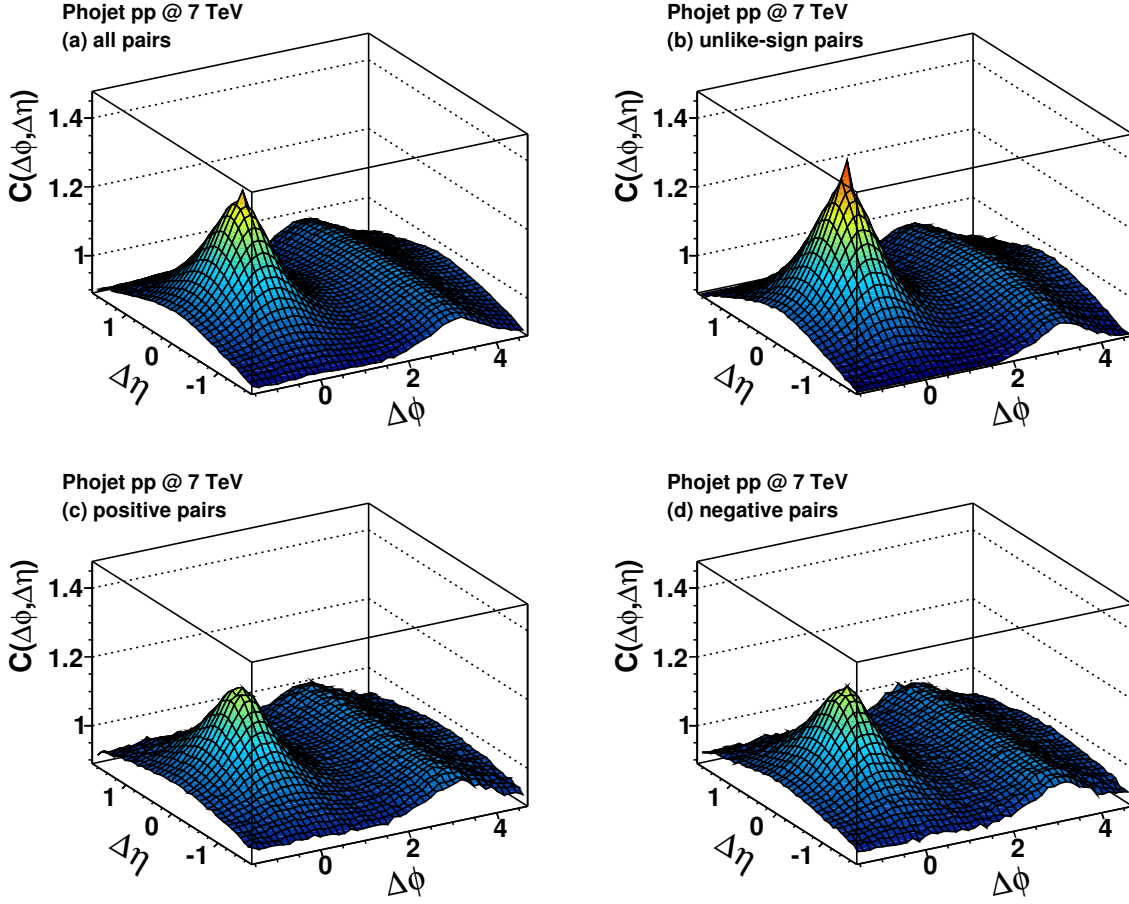


Figure 9.12: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 7$ TeV Phojet pp data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

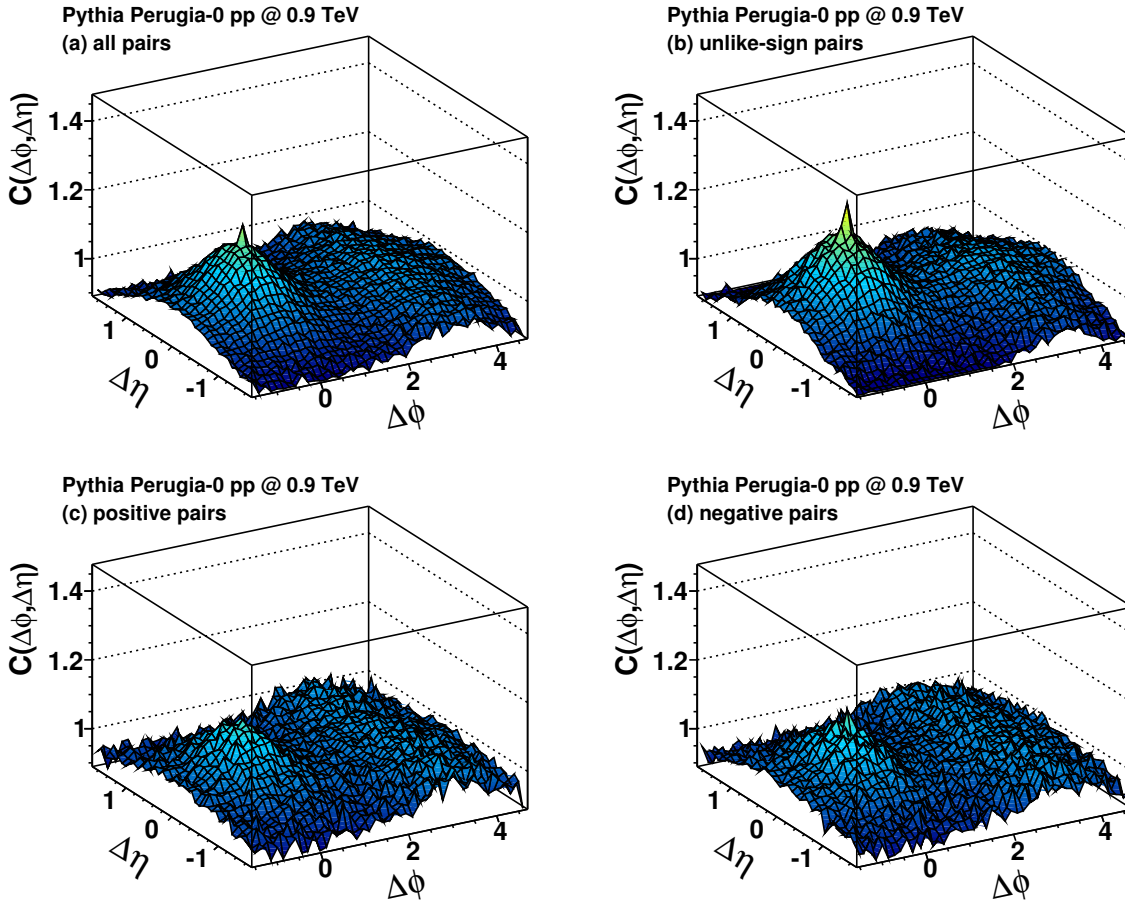


Figure 9.13: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 0.9$ TeV Pythia Perugia-0 pp data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

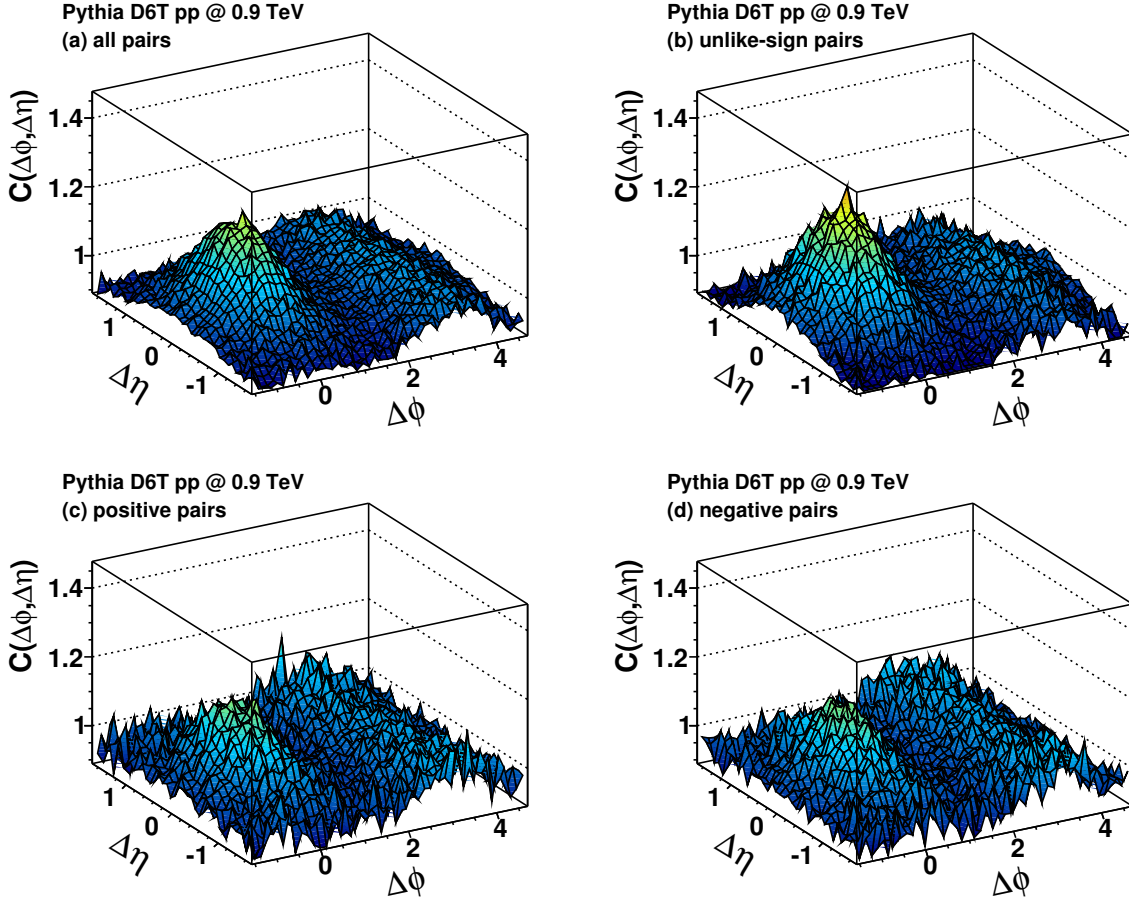


Figure 9.14: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 0.9$ TeV Pythia D6T pp data. Correlation functions (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

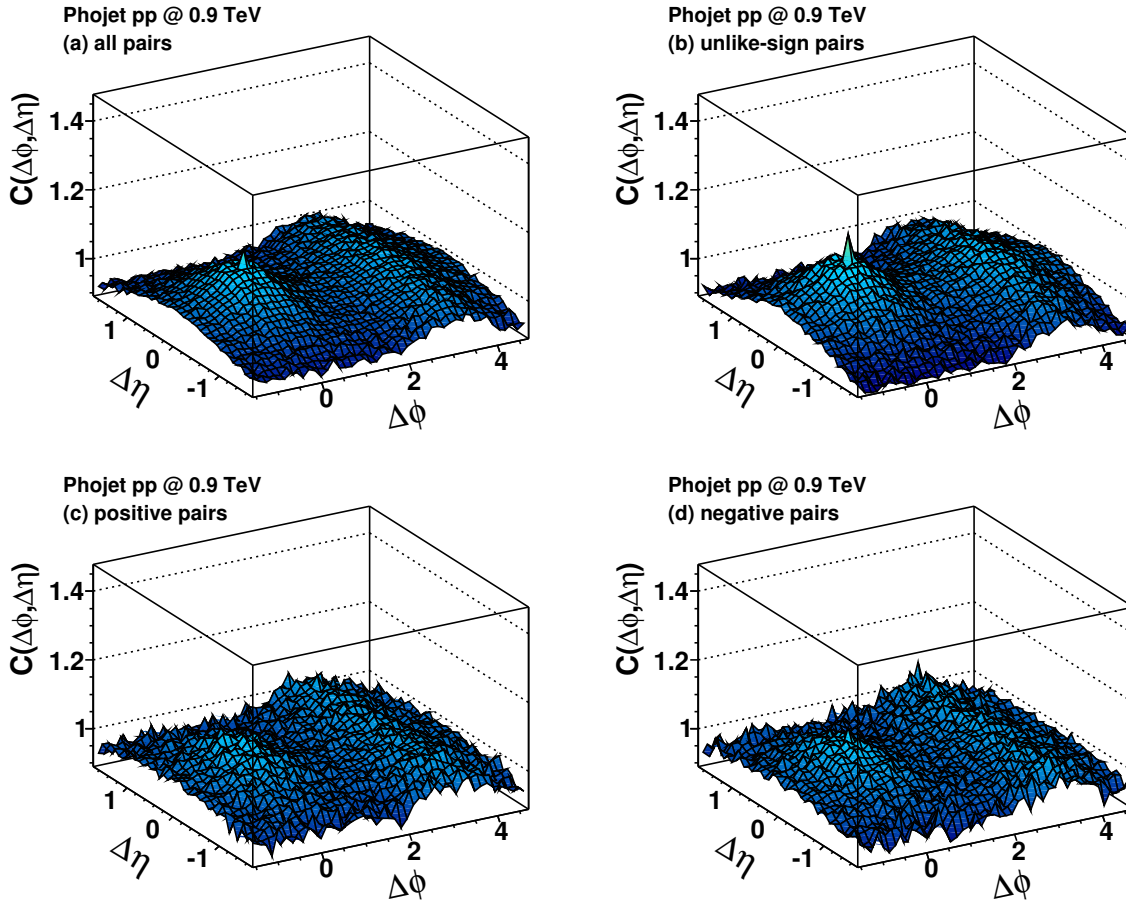


Figure 9.15: The charge dependence of the $\Delta\eta\Delta\phi$ correlation function for the $\sqrt{s} = 0.9$ TeV Phojet pp data. Correlation functions: (a) for all charge combinations, (b) unlike-sign particle pairs (+ -), (c) pairs composed of two positive particles (++), (d) pairs of two negative particles (- -).

9.2.2 Multiplicity dependence

The multiplicity ranges were introduced in Sec. 5.6.1. The correlation functions from the Pythia and Phojet reconstructed data at the energy of $\sqrt{s} = 7$ TeV are very similar; so, only one set of plots (for Pythia), are presented here (see Fig. 9.16). Like in the collision data, shown in Fig. 7.5 for like-sign and in Fig. 7.6 for unlike-sign pairs, we can see a similar decrease of the correlation with increasing multiplicity.

For the $\sqrt{s} = 0.9$ TeV collision energy, Pythia Perugia-0 tune describes the collision data fairly well (see Fig. 9.17).

Very surprising results were obtained for Pythia D6T tune for the $\sqrt{s} = 0.9$ TeV collision energy. As we can see in the Fig. 9.18, the correlations are rising with multiplicity in contrast to any other results. This fact makes this tune of Pythia unusable for further studies, because we want to find a Monte Carlo model, which reproduces the experimental data best.

Similarly, as seen in the previous section, the near-side correlation is higher in MC than in collision data, indicating the possibility of too large minijet production.

Quantitative analysis

Fitting the formula introduced in Sec. 6.3 to Pythia and Phojet simulated data gave results which are shown in Fig. 9.19 and Fig. 9.20. The trends observed for MC data are, in general, in agreement with the collision data (the magnitude of all structures decrease with increasing multiplicity). However, there are differences in details. For unlike-sign pairs we do not observe a growing correlation in the first two multiplicity ranges. This can be seen in the top-left panel of Fig. 9.19 and Fig. 9.20. Moreover, the magnitude of the near-side peak, shown in the top-left panels of Fig. 9.19 and Fig. 9.20, is higher for unlike-sign pairs in all multiplicity ranges. This is different than in the collision data. We speculate that the reason is that the Bose-Einstein correlations are not implemented in those models. The width of the structures is almost constant, which is also different for the collision data. The systematic uncertainties are bigger than for collision data analyses. Also the statistical uncertainties are more prominent for some parameters.

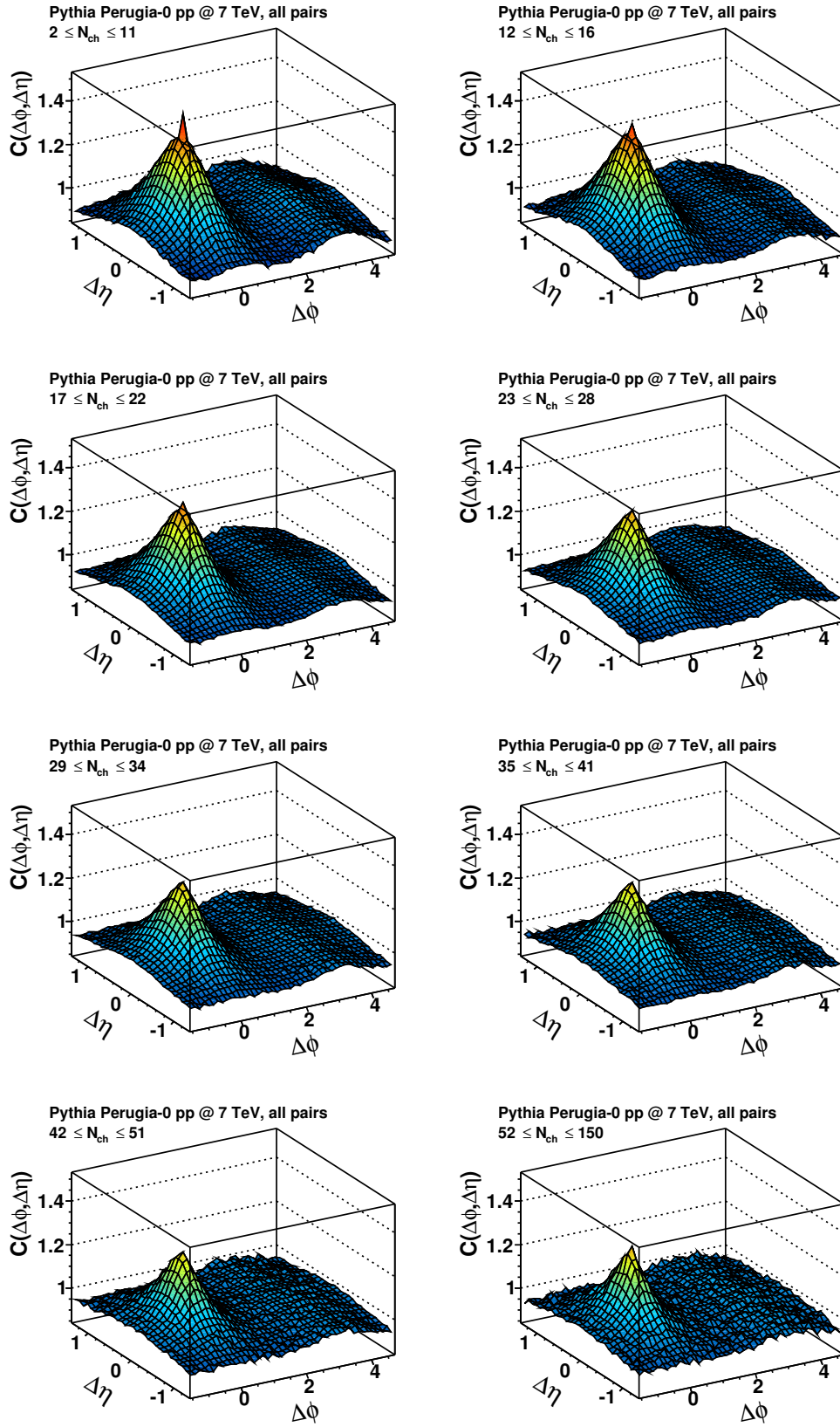


Figure 9.16: The multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for all charge combinations of particles in the pair for the $\sqrt{s} = 7$ TeV Pythia Perugia-0 pp data.

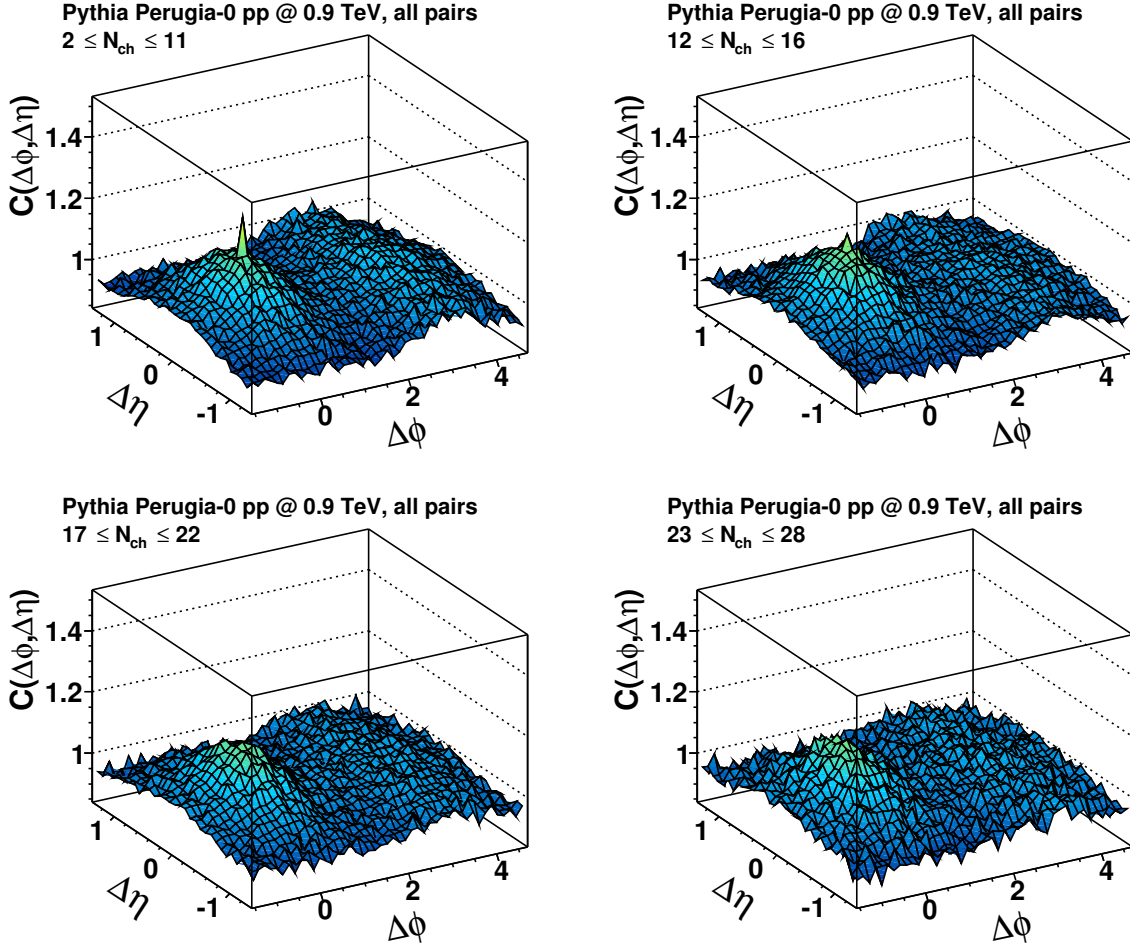


Figure 9.17: The multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for all charge combinations of particles in the pair for the $\sqrt{s} = 0.9$ TeV Pythia Perugia-0 pp data.

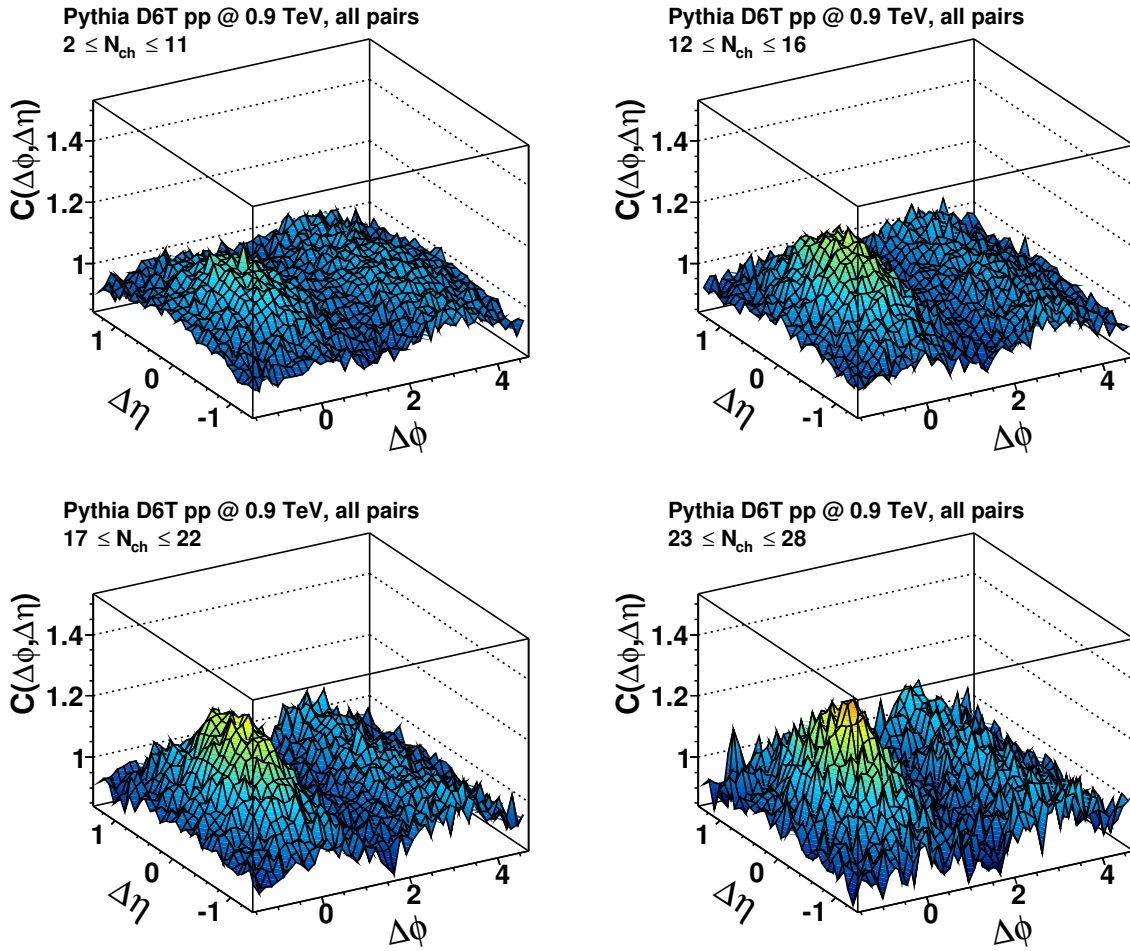


Figure 9.18: The multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for all charge combinations of particles in the pair for the $\sqrt{s} = 0.9$ TeV Pythia D6T pp data.

9.2. RESULTS OF THE ANGULAR CORRELATIONS FOR GENERAL PURPOSE EVENT GENERATORS

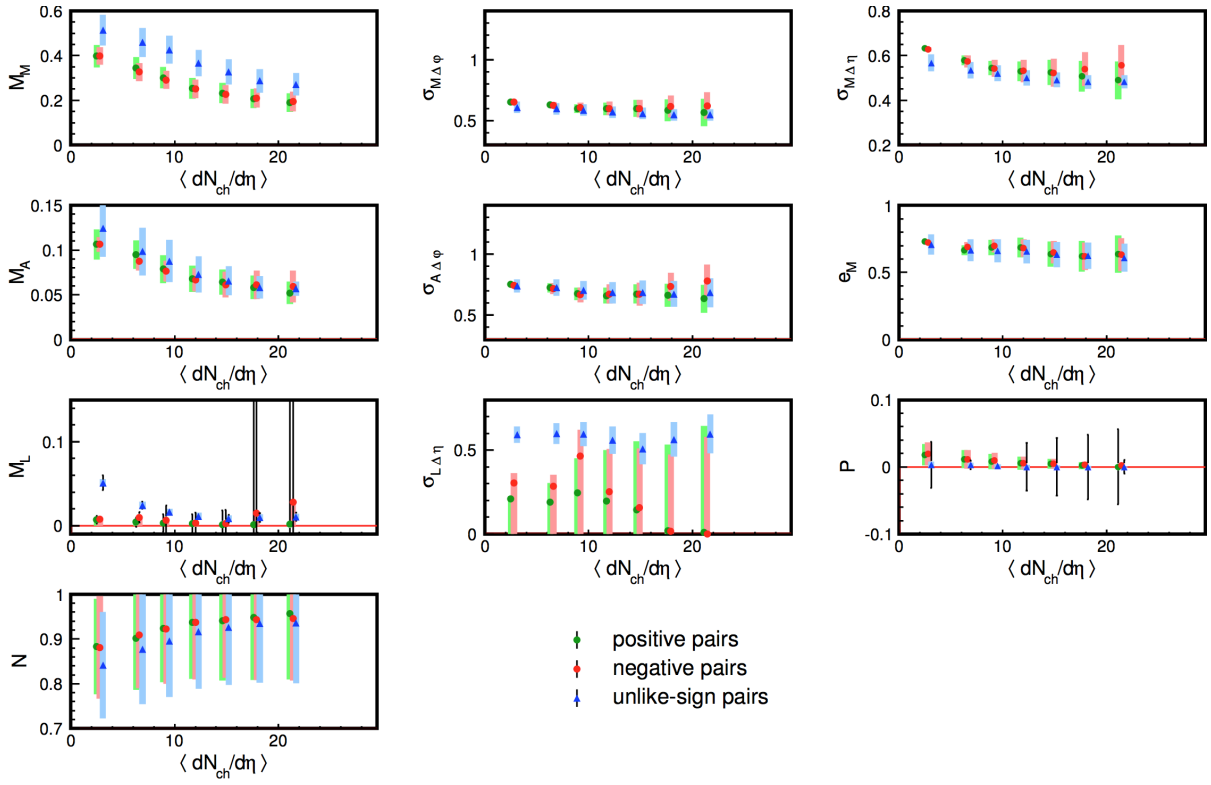


Figure 9.19: Results of fitting function in multiplicity ranges for $\sqrt{s} = 7$ TeV Phojet pp simulated events. Detailed explanation in Fig. 7.8.

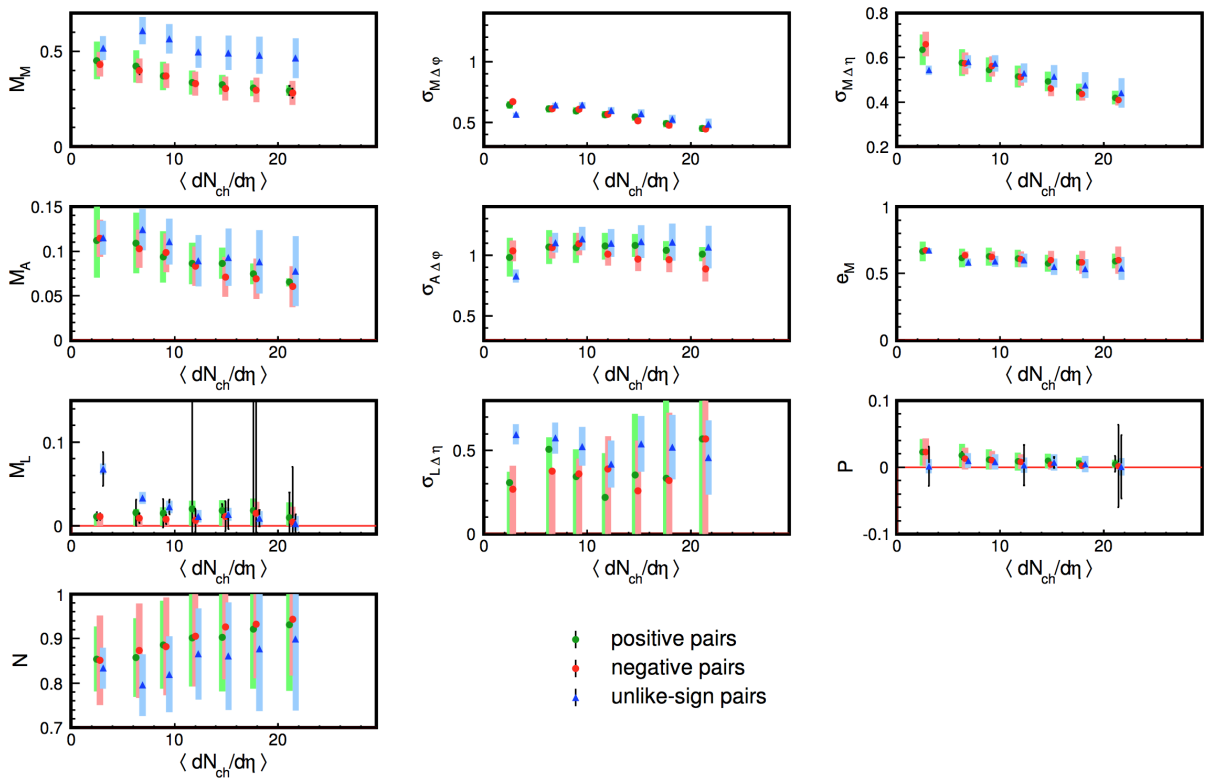


Figure 9.20: Results of fitting function in multiplicity ranges for $\sqrt{s} = 7$ TeV Pythia Perugia-0 pp simulated events. Detailed explanation in Fig. 7.8.

9.2.3 Transverse momentum dependence

The transverse momentum ranges were introduced in Sec. 5.6.2. Since the p_T -dependence analysis has shown that all MC models behave in a similar way and the conclusions remain the same, in this section only the Pythia Perugia-0 pp simulated data at $\sqrt{s} = 7$ TeV are shown (see Fig. 9.21).

For small p_T -sum there are almost no correlations, for both like- and unlike-sign pairs. As it was already mentioned, the studied Monte Carlo event generators did not include Bose-Einstein correlations. Since Bose-Einstein correlations are most pronounced for low transverse momenta, we can see the biggest differences between MC and collision data at those lowest p_T -sum ranges. Also, this is a strong indication that indeed the near-side structure seen at the low p_T MC data comes from the quantum statistics effects.

With increasing transverse momenta of particles the correlation originating from minijets appears, similarly as for the collision data. As mentioned in Sec. 3.2.6, for the femtoscopy analyses it is important to show that other (non-femtoscopic) two-particle correlations are modeled correctly. Since for both, Pythia Perugia-0 and Phojet, the multiplicity and transverse momentum binning are reproducing fairly well the non-femtoscopic correlations, it leads to the conclusion that generators, that include minijet phenomena, can be used to get an estimate of the underlying correlation in the studies of the femtoscopic correlation functions.

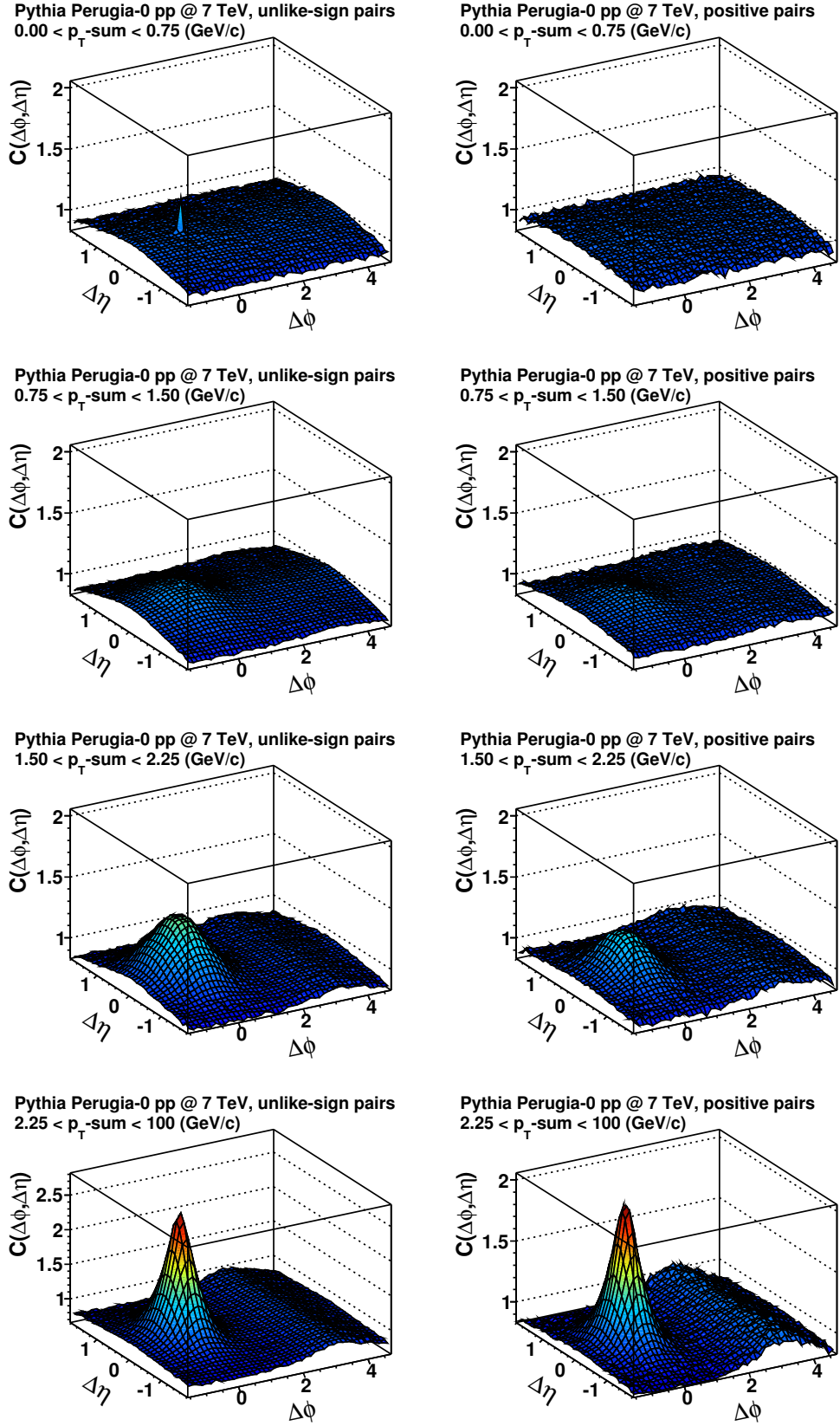


Figure 9.21: The dependence of the $\Delta\eta\Delta\phi$ correlation function on the $p_{\text{T-sum}}$ for the simulated $\sqrt{s} = 7$ TeV Pythia pp data. The correlation functions are for: (a-d) unlike-sign particle pairs (+ -) and (e-h) like-sign particle pairs (++).

9.2.4 Dependence on particle species

The analysis was also performed on Monte Carlo data from Pythia Perugia-0 and Phojet for different particle species: pions, kaons, and protons. Figures 9.22 and 9.23 present correlation functions for Pythia data and Fig. 9.24 and Fig. 9.25 present the correlation functions for Phojet data. For comparison, the ALICE collision data was presented in Fig. 7.14 and Fig. 7.15.

It can be seen that both models give a similar picture of the correlations and neither of them is reproducing the data well. Especially the anti-correlation dip seen in collision data for like-sign protons is not reproduced; instead the MC data from both studied event generators show a pronounced near-side peak. This is an indication that the baryon production parameters may not be tuned correctly, or that the baryon production mechanism is wrongly modelled.

From Ref. [236] it is known that the presented studies are very useful for improving the MC models. This is also a topic for future studies, see Sec. 9.3. Similarly, the difference between like- and unlike-sign correlation functions for kaons can help to improve the implementation of the strange particle production mechanisms.

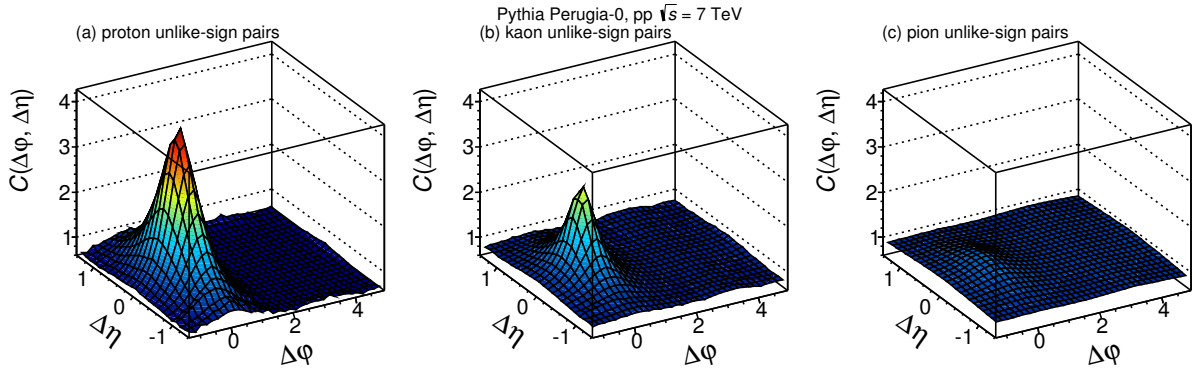


Figure 9.22: Correlation functions for unlike-sign pairs of protons, kaons, and pions obtained from Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

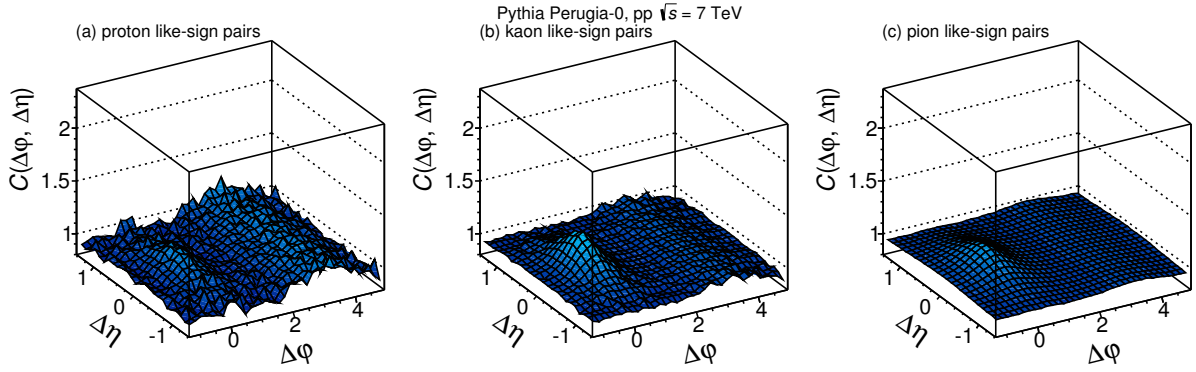


Figure 9.23: Correlation functions for like-sign pairs of protons, kaons, and pions obtained from Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

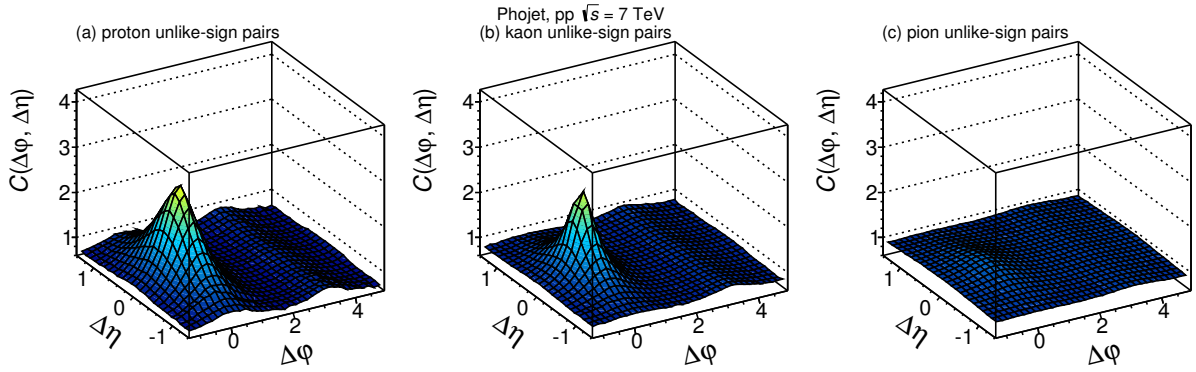


Figure 9.24: Correlation functions for unlike-sign pairs of protons, kaons, and pions obtained from Phojet pp events at $\sqrt{s} = 7$ TeV.

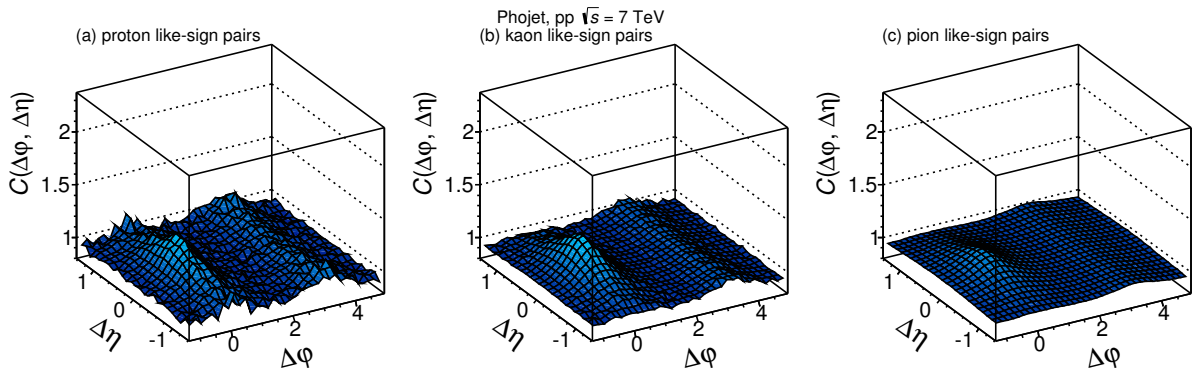


Figure 9.25: Correlation functions for like-sign pairs of protons, kaons, and pions obtained from Phojet pp events at $\sqrt{s} = 7$ TeV.

9.3 Outlook

The developed model, CALM, allowed us to qualitatively reproduce some of the effects observed in collision data presented in Chapter 7 with a set of clear and transparent tools. On the other hand, by using general purpose MC generators (Pythia, Phojet) we recreated correlations of a more complex origin. We have identified and disentangled many of the correlation sources contributing to the global picture and we have also shown that using $\Delta\eta\Delta\varphi$ correlations we can gain insight into the contribution of individual specific effects separately. The presented analysis has shown that the current MC models do not reproduce the data accurately. The obtained results also provide useful information for tuning specific parameters of the Pythia MC model. Even though the performed studies already measure properties of many different aspects of the high energy collisions, there is still a number of particularly interesting topics to be studied. As indicated in Sec. 3.2.4, the analysis of high multiplicity pp collisions can bring us some new insights about the differences between pp, p–Pb and Pb–Pb. Moreover, one of the most unexploited area of studies in the $\Delta\eta\Delta\varphi$ angular space is the study of short-lived resonances.

Model tuning

The presented analysis is a first step in the process of improving existing models. Detailed studies will be performed to check if proper parameter tuning can improve the resemblance of MC model data with collision data. From Ref. [236] it is known that, in Pythia 6, the main popcorn parameters (see Sec. 2.4.4) are PARJ(5) – PARJ(7), see Ref. [47] for details:

- **PARJ(5)**: determines the relative occurrence of baryon production by $B\bar{M}\bar{B}$ and by $B\bar{B}$ configurations in the simple popcorn baryon production model,
- **PARJ(6)**: introduces extra suppression for having a $s\bar{s}$ pair shared by the B and $\bar{B}$ of a $B\bar{M}\bar{B}$ situation,
- **PARJ(7)**: introduces extra suppression for having a strange meson M in a $B\bar{M}\bar{B}$ configuration.

Moreover PARJ(8) – PARJ(10) are also used in the advanced popcorn scenario. The studies will concentrate on modification of the mentioned parameters to study how they influence the correlation functions.

It should be noted that the already implemented scenarios may not be enough. In nature further baryon production mechanisms may exist. We have learned from Ref. [236] that the authors of Pythia are right now creating a new color-reconnection model (in the context of Pythia 8) which would have more global baryon number conserving mechanisms, in addition to the ones implemented in Pythia 6. This study comes exactly on time to contribute to the new developments in Pythia 8, giving valuable input to bring constraints on these new models as well [236].

Multiplicity dependence

The presented results show the decrease of correlation functions with increasing multiplicity. However, it would be most useful if direct comparison between pp, p–Pb and Pb–Pb collisions at comparable multiplicities was studied. As described in Sec. 3.2.4 there are many processes, still not well understood, that need further measurements. The study of long-range correlation (the Ridge) by the ALICE experiment is not straightforward, due to the limited η acceptance. The widening of the near-side peak convolutes with any expected ridge structure and the restriction on the acceptance makes it hard to disentangle the two effects. Nonetheless, as shown in Ref. [121] such studies can be performed, i.e. by subtracting high- and low-multiplicity events, if extra care is given.

Resonances

As was described in Sec. 3.2.2, $\Delta\eta\Delta\phi$ distributions had been already used since many years to study correlations induced by resonances. Recent papers still use the early results from low-energy collisions recorded in 1975 as a base. This gives a wide area of measurements not-covered experimentally; i.e. interesting structures hidden below other effects that still should be properly understood and, also, taken into account in studies of other phenomena. As an example in Fig. 9.26 correlation functions for low p_T unlike-sign kaon samples are shown for Pythia Perugia-0 events. The characteristic “ring” structures are pronounced especially for the lowest p_T -sum range (left plot); the diameter of the ring decreases with increasing transverse momentum. If pairs with invariant mass of ϕ resonance are cut out, the structures are no longer visible, see Fig. 9.27. Similar shapes are also seen in the ALICE collision data and require further studies.

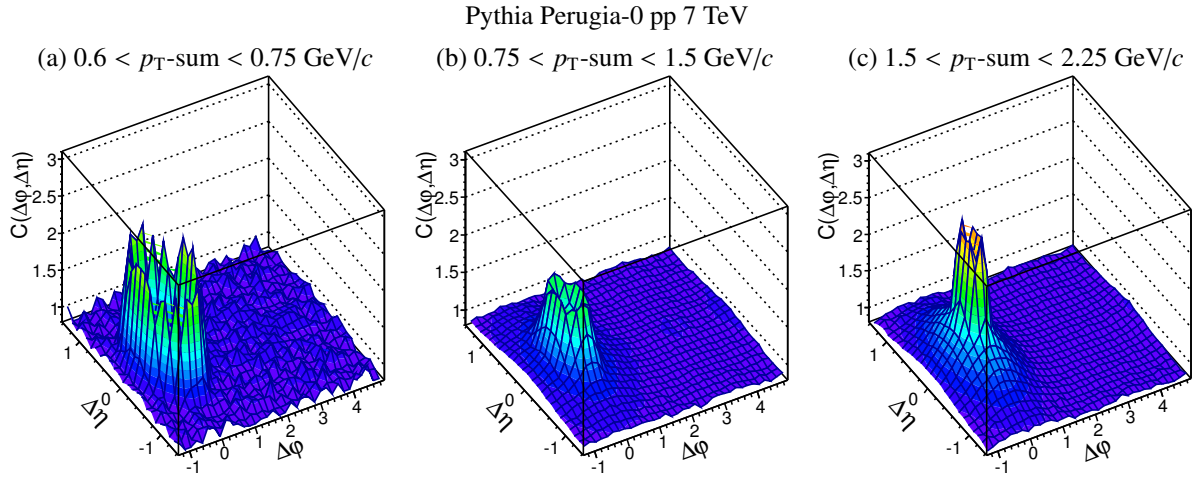


Figure 9.26: Correlation functions for unlike-sign pairs of kaons for three $p_{T\text{-sum}}$ ranges obtained from Pythia Perugia-0 pp events at $\sqrt{s} = 7 \text{ TeV}$. The characteristic ring structure coming from the ϕ resonance is visible. From Ref. [237].

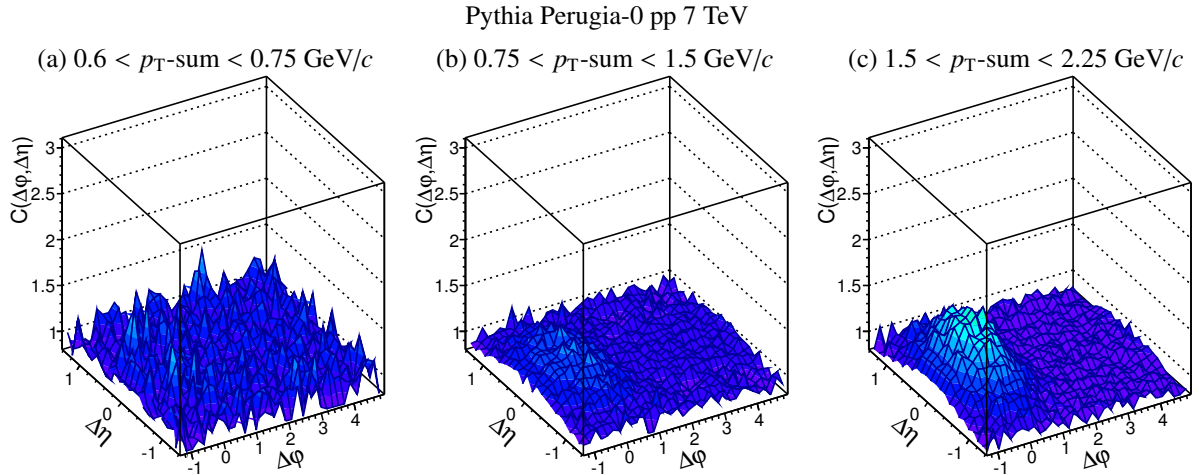


Figure 9.27: Correlation functions for unlike-sign pairs of kaons for three $p_{T\text{-sum}}$ ranges obtained from Pythia Perugia-0 pp events at $\sqrt{s} = 7 \text{ TeV}$ after subtraction of the contributions from ϕ the resonance. From Ref. [237].

Non-identical particle pairs

More information can still be obtained from non-identical particle pairs like i.e. π - K , π - p , p - K . An introduction to such studies is presented in Appendix D.

The performed analyses provide significant impact on the research of elementary particle collisions and yield a meaningful baseline for further studies; i.e. they provide unique information on the baryon and strange meson production mechanisms that can be used to improve the popular Pythia Monte Carlo event generator by tuning specific parameters. The appropriate studies are already ongoing.

Chapter 10

Summary and conclusions

Proton-proton collisions at center-of-mass energies of $\sqrt{s} = 0.9, 2.76$ and 7 TeV have been recorded by A Large Ion Collider Experiment (ALICE) at the Large Hadron Collider (LHC). They provide a unique opportunity to study quantum chromodynamics (QCD) at new energy scales. The two-particle angular correlations have proven to be a robust tool which allows us to explore the underlying physics phenomena of particle production in collisions of both protons and heavy ions. The excellent tracking and particle identification capabilities of ALICE allow us to make unique contributions to the studies of the particle production mechanisms in proton-proton collisions at the LHC covering a wide p_T range. In particular, this allows us to study the interplay of soft and hard processes.

In this work the analysis of untriggered $\Delta\eta\Delta\varphi$ angular correlations in pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV recorded by the ALICE experiment was presented.

The $\Delta\eta\Delta\varphi$ correlations have been studied at the LHC energies for the first time ever in a multidimensional space: for three collision energies, as a function of event multiplicity N_{ch} and transverse momenta p_T -sum of particles as well as for different charge combinations of the pair. Moreover, a unique analysis of identified particles (pions, kaons, and protons), that has never been done before for hadron-hadron collisions, was performed.

In order to quantitatively describe the correlation functions, in particular the multiplicity and pair transverse momentum dependence, a generic fitting procedure was developed for this work.

In addition, these studies were repeated employing the same analysis procedure and selection criteria on Monte Carlo data generated by the general purpose event generators Pythia and Phojet. We observe that the results of the angular correlations analysis performed using data from those Monte Carlo models reproduce only some aspects of the collision data, usually qualitatively but not quantitatively.

Furthermore, a dedicated model, CALM, was developed in order to study in detail the influence of the basic correlation sources on the shape of the $\Delta\eta\Delta\varphi$ correlation function and deepen our knowledge of the effects we observe.

The following conclusions can be drawn from this work:

- Each one of the correlation sources manifests in a particular manner; therefore, we can disentangle them and study their properties separately. We show that the minijet contribution to the overall shape of the $\Delta\eta\Delta\varphi$ correlation function is rising with increasing values of the pair transverse momentum $p_{T\text{-sum}}$. We also show that for like-sign pairs (where both femtoscopic and minijet components exist) the correlation decreases for the lowest values of $p_{T\text{-sum}}$ because of the decreasing contribution from Bose-Einstein correlations and then rises for higher values of the $p_{T\text{-sum}}$ due to the increasing minijet contribution. The analysis of unlike-sign pairs, where the femtoscopic component is not present, leads to the conclusion that the minijet contribution is almost zero for the lowest and rises for higher values of $p_{T\text{-sum}}$. The analysis of MC data confirms those observations. This represents the first quantitative separation of femtoscopic and minijet correlations in pp collisions.
- The structures induced by minijets (near-side peak and away-side ridge) decrease at a slower rate than a trivial $1/N_{\text{ch}}$, suggesting additional mechanisms that enhance the correlation. The trivial decrease is expected because the less particles are produced in a collision, the more pronounced the correlations are due to the specific correlation source. Any additional particles dilute those correlations; hence, they decrease the observed effects. Indeed the trivial $1/N_{\text{ch}}$ decrease was observed for another correlation structure, the longitudinal ridge emerging from the resonance contribution.
- The results of this thesis strongly support the hypothesis that the long-range correlations influencing the femtoscopic measurements of small systems originate from minijets. A comparative analysis has been employed and it was shown that any near-side peak structure in $\Delta\eta\Delta\varphi$ creates a corresponding structure in the q representation typically used in femtoscopy. Therefore, the minijet collimation visible in $\Delta\eta\Delta\varphi$ influences also the femtoscopic correlation functions. Correlations due to minijets are well reproduced by typical MC generators; they are more pronounced at higher pair transverse momenta (k_T). Since

it can be seen in ALICE data that the strongest near-side structures arise from minijets at high transverse momenta and low event multiplicity, we should observe the non-femtoscopic background to be most pronounced for high k_T and low N_{ch} . In addition, the MC generators should describe the non-femtoscopic background fairly well. Indeed, both those expectations were confirmed by femtoscopic measurements.

- The analysis reveals substantial differences in the shapes of the correlation functions of identified particles performed separately for different charge combinations of particle pairs (for like-sign and unlike-sign pairs) and for three particle types (pions, kaons, protons). The results suggest that conservation laws (strangeness, baryon number) have a great impact on the observed two-particle correlations. Moreover, the results from Monte Carlo model studies (Pythia, Phojet) show features in the correlation functions of protons, especially of like-sign pairs, surprisingly different than in the data. Also, for the unlike-sign pairs of kaons and protons both models show an opposite trend in the correlation strength than observed in the data. Those comparisons suggest that while the minijets are modeled correctly in both generators for pion pairs, their description of kaon and proton pairs' production is not sufficient.
- The presented analysis allows us not only to show that the current MC models do not reproduce the data accurately, but also to improve them, providing information that will be used to tune specific parameters. This work has initiated a combined effort of experimentalists and theorists to improve the basic QCD mechanisms implemented in MC event generators.
- The CALM model, developed specifically for this thesis, reproduces qualitatively all modeled structures i.e., the momentum conservation on the global scale creates a $\sin(\Delta\varphi)$ -like structure. Minijet-like correlations create the near-side peak and the away-side ridge. Bose-Einstein correlation creates a pronounced near-side correlation for identical particles, the local charge conservation influence the magnitude of the near- and away-side structures, and similarly other conservation laws influence the shape of the correlation function. This is a strong validation of our hypotheses and gives confidence into our understanding of the experimental results.

Appendices

Appendix A

$\Delta\eta\Delta\varphi$ and femtoscopy correlations

Femtoscopy is an intensity interferometry technique used to determine spatial sizes of the particle emitting sources which are created during collisions. Measuring correlations in momentum space between identical bosons (i.e. pions) which occur due to the Bose-Einstein statistics that determines their behavior, one can extract information about the size of their emitting region (more in Sec. 4.6.1). Since the difference between the femtoscopic correlation functions in relative momentum q and $\Delta\eta\Delta\varphi$ correlation functions is only in the representation (the underlying physical contributions are the same) we can study exactly the same effects using different representations.

As introduced in Sec. 3.2.6 the femtoscopic analyses of small systems (i.e. pp collisions) are strongly influenced by non-femtoscopic correlations. Their existence is well established, and their origin is connected to conservation laws or minijet correlations, however still not clear. Since the $\Delta\eta\Delta\varphi$ correlation functions are natural representation to study many of the effects producing two-particle correlations (see Sec. 3.3 for possible correlation sources) and there is a direct relation between $\Delta\eta$, $\Delta\varphi$ and the components of relative momentum of the pair q , which are used in femtoscopic studies, a comparative analysis was employed.

A.1 $\Delta\eta$, $\Delta\varphi$ and femtoscopy observables

There is a direct relation between $\Delta\eta$, $\Delta\varphi$, $p_{T,1}$, $p_{T,2}$ and the components of the relative pair momentum $\mathbf{q}$, where $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$:

$$q_{out} \sim p_{T,1} - p_{T,2}, \quad (\text{A.1})$$

$$q_{side} \sim (p_{T,1} + p_{T,2})\Delta\varphi, \quad (\text{A.2})$$

$$q_{long} \sim (p_{T,1} + p_{T,2})\Delta\eta. \quad (\text{A.3})$$

This means that the studies of angular correlations in $\Delta\eta\Delta\varphi$ space can, e.g., help to describe and give insight about non-femtoscopic correlation sources that influence the femtoscopic correlation functions.

A.2 Transformation from $\Delta\eta\Delta\varphi$ to q_{inv}

To study how structures in $\Delta\eta\Delta\varphi$ influence the q_{inv} representation we employed a Monte Carlo procedure which transforms $\Delta\eta\Delta\varphi$ representation into q_{inv} . We used the following scheme:

1. generate two random numbers $(\Delta\eta, \Delta\varphi)$ with the probability given by the $\Delta\eta\Delta\varphi$ distribution (separately for numerator and denominator),
2. generate random φ_1, η_1 from single particle distributions,
3. calculate φ_2, η_2 of the second particle using $\Delta\eta$ and $\Delta\varphi$,
4. generate random p_T for those two particles from single particle p_T distribution,
5. calculate p_x, p_y and p_z for each particle using p_T, φ and η ,
6. calculate q_{inv} from two sets of p_x, p_y, p_z .

We do not expect that the results obtained from the above procedure and the correlation functions in femtoscopic representation directly calculated from the collision data to be exactly the same. Some of the information about particle momentum encoded in the construction of the femtoscopic correlation functions is not stored in the $\Delta\eta\Delta\varphi$ distributions, hence achieving identical results is impossible. However, due to the relations listed in Sec. A.1 we predict that some structures should emerge.

For these studies the EPOS 3.076 event generator [238, 239] was used, with the addition of a femtoscopy afterburner, as explained in the description of the `tpi` software in Sec. 9.1.1.5. In Fig. A.1-left the $\Delta\eta\Delta\varphi$ correlation function for identical pions with the femtoscopic signal only (without underlying non-femtoscopic correlations) is shown. Bose-Einstein correlations are manifesting as a pronounced near-side peak. In Fig. A.1-right the same correlation function in q_{inv} representation is presented. The red hollow points represent true q_{inv} correlation function obtained directly from simulated events. The blue full points are result of the MC procedure transforming the $\Delta\eta\Delta\varphi$ distribution in the left plot into the q_{inv} representation.

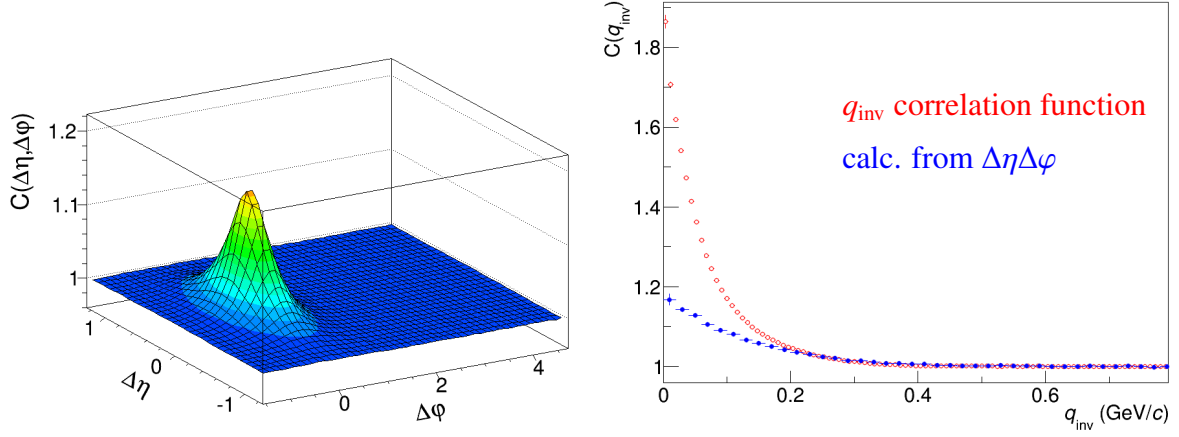


Figure A.1: Representation of the Bose-Einstein correlations in (left) $\Delta\eta\Delta\varphi$ space and (right) q_{inv} . The red hollow points represent true q_{inv} correlation function obtained directly from simulated events. The blue full points are result of the MC procedure transforming the $\Delta\eta\Delta\varphi$ distribution in the left plot into the q_{inv} representation. Calculation performed with p-Pb Monte Carlo events generated by EPOS event generator.

It can be observed that any near-side peak structure in $\Delta\eta\Delta\varphi$ creates a corresponding structure in the q_{inv} representation as well. Therefore, the minijet correlation visible in the $\Delta\eta\Delta\varphi$ representation influences also the femtoscopic correlation functions. Clearly, the magnitude and shape of the effect is not dependent on the information stored in the $\Delta\eta\Delta\varphi$ distributions alone; q_{inv} carries additional important information on correlations in p_T that are not represented in the angular space.

Similar studies were performed for the $\Delta\eta\Delta\varphi$ correlation function from EPOS events build only from non-femtoscopic correlations. The results are visible in Fig. A.2. It can be observed that smaller structures in the $\Delta\eta\Delta\varphi$ create smaller correlations in q_{inv} (compare the magnitude of the structures in Fig. A.1 and Fig. A.2). It can also be seen that non-trivial structures in the $\Delta\eta\Delta\varphi$ create long-range effects in the q_{inv} representation.

Those results strongly support a hypothesis that a long-range structure influencing the femtoscopic measurements of small systems originates from minijets. It was shown that any near-side peak structure in $\Delta\eta\Delta\varphi$ creates an corresponding structure in the q representation used in femtoscopy. Therefore, the minijet collimation visible in $\Delta\eta\Delta\varphi$ influences also the femtoscopic correlation functions. Since it can be seen in ALICE data that the strongest near-side structures arise from minijets at high transverse momenta and low event multiplicity, we should observe the non-femtoscopic background to be most pronounced for high k_T and low N_{ch} . This is con-

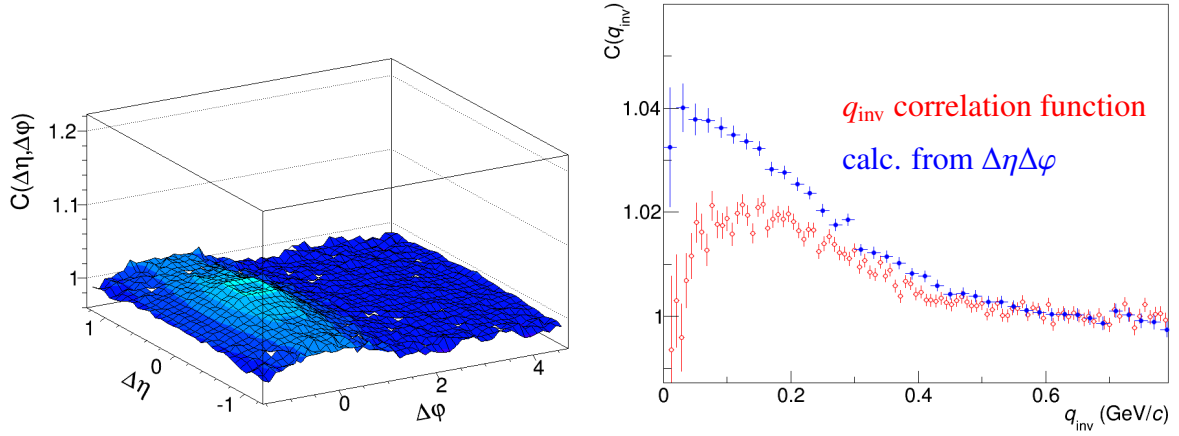


Figure A.2: Representation of the non-femtoscopic correlations in (left) $\Delta\eta\Delta\varphi$ space and (right) q_{inv} . The red hollow points represent true q_{inv} correlation function obtained directly from simulated events. The blue full points are result of the MC procedure transforming the $\Delta\eta\Delta\varphi$ distribution in the left plot into the q_{inv} representation. Calculation performed with p–Pb Monte Carlo events generated by the EPOS event generator.

firmed in femtoscopic measurements, see Ref. [154].

Appendix B

Corrections variations

In this appendix the variations and detailed studies of the correction procedure are presented. In the Sec. B.1 the effect of constant corrections on the correlation function is described, as well as the importance of the p_T -dependent correction is emphasized. In Sec. B.2 the four-dimensional correction map is introduced, with additional φ , η , and z_{vtx} dependent corrections. In Sec. B.3 the studies on the contamination from secondary particles are detailed.

B.1 Effect of constant corrections on the correlation function

Due to the way in which the correlation function is constructed, as in Eq. (6.3):

$$C(\Delta\eta, \Delta\varphi) = \frac{N_{\text{pairs}}^{\text{mixed}}}{N_{\text{pairs}}^{\text{signal}}} \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}, \quad (\text{B.1})$$

if we apply a constant correction $f = \text{const}$ to both signal and background distributions we would not observe any effect on the correlation function itself. Since we are dealing with the correlation functions, and not the yields, also the overall offset would be exactly the same. We performed a simple test of applying a constant weight to show this effect. The constant weights were set in such manner, so they would reflect the average value of the correction factor obtained from the p_T -dependent studies.

In Fig. B.1 and Fig. B.2 the effects of the exercise are shown:

1. the example result for the correlation function of like-sign pions is shown in Fig. B.1, with a constant weight of 1.7,
2. the example result for the correlation function of like-sign kaons is shown in Fig. B.2, with a constant weight of 1.9.

It can be observed that there are no differences between correlation functions with and without corrections applied, as expected. Only the p_T -dependent correction changes the shape of

the correlation function, as was shown in Fig. 8.12. Such effects are due to the fact that particles of different transverse momenta are not distributed uniformly in the $\Delta\eta\Delta\varphi$ space. It can be explained as follows: we expect more high momentum particles in the near-side region of the correlation function (i.e. particles coming from jets), and we know from the efficiency studies that particles with higher momentum will be more frequently reconstructed properly, this way artificially enhancing the near-side peak of the correlation function.

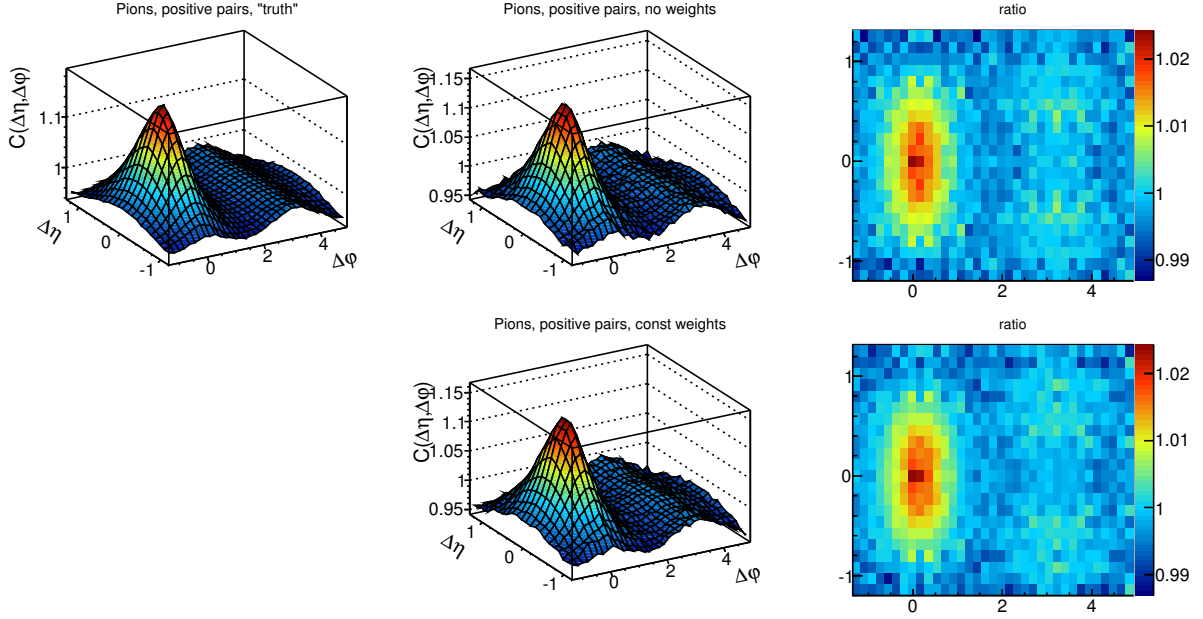


Figure B.1: Comparison of correlation functions of pion like-sign (+ +) pairs. Left: MC truth (reference sample). Middle top: not corrected reconstructed sample. Middle bottom: reconstructed sample corrected with constant weights of 1.7 (see text for details). The ratios of the left to the middle plots are shown in the right panel. The scale is the same for both ratios. Calculations done employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

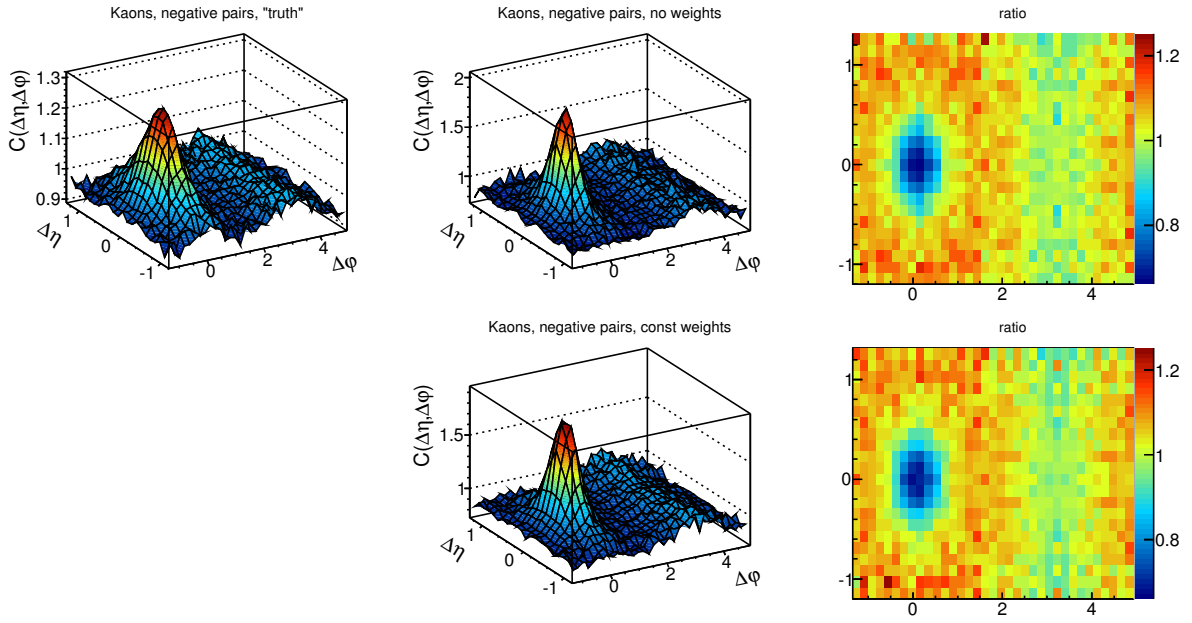


Figure B.2: Comparison of correlation functions of kaon like-sign (- -) pairs. Left: MC truth (reference sample). Middle top: not corrected reconstructed sample. Middle bottom: reconstructed sample corrected with constant weights of 1.9 (see text for details). The ratios of the left to the middle plots are shown in the right panel. The scale is the same for both ratios. Calculations done employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

B.2 Efficiency correction map

The efficiency can depend not only on the transverse momenta of particles p_T , but also on pseudorapidity η , azimuthal angle φ or position of the event along the beam axis z_{vtx} . To account for all possible correction factors, a four-dimensional correction map should be calculated $f(p_T, \eta, \varphi, z_{\text{vtx}})$. The procedure is explained on the flow diagram shown in Fig. B.3.

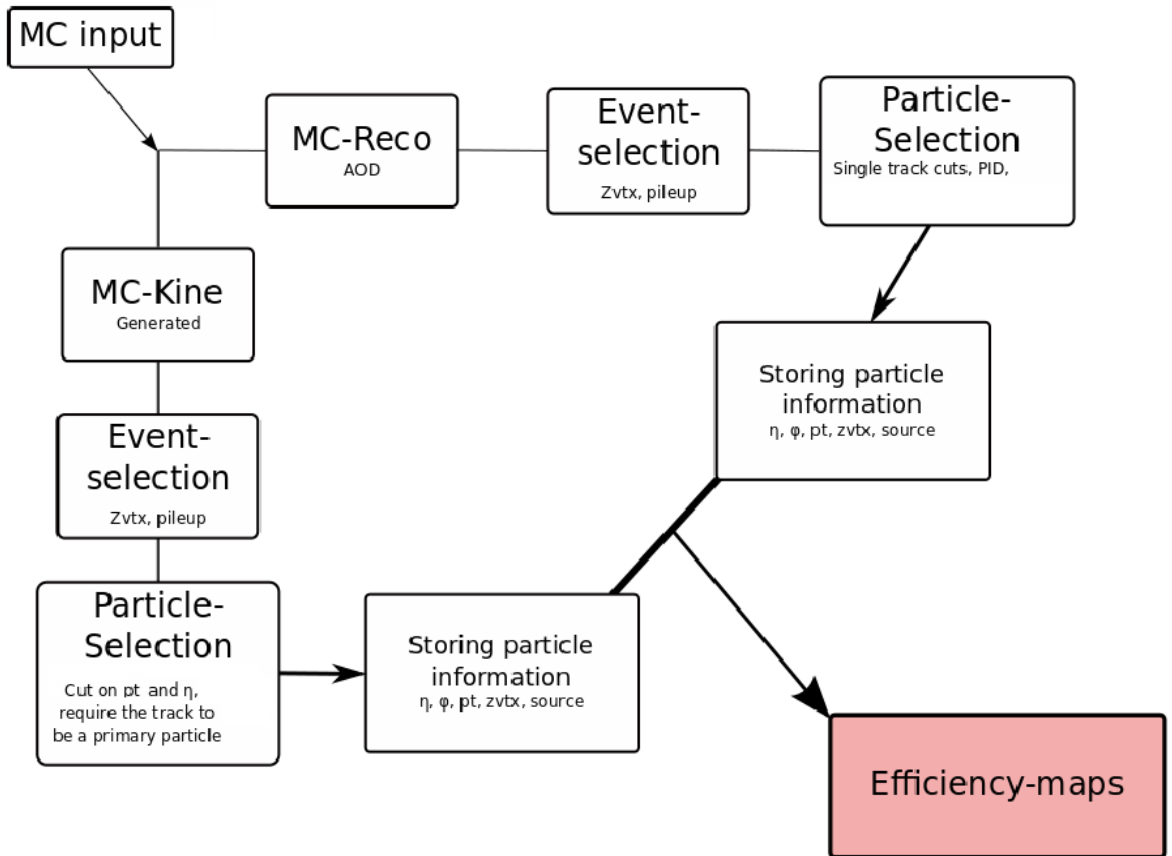


Figure B.3: Overview of the efficiency calculation. The generated and corresponding reconstructed particles are treated separately, and the outputs are used to compute the efficiency. Schema from [240].

Projections of all four dimensions can be seen in Fig. B.4. It can be observed that the z_{vtx} dependence is almost flat for the whole selected range. We can also observe distortions in φ and η distributions, but if the binning of the $\Delta\eta\Delta\varphi$ correlation functions is fine enough, we do not expect the effect to influence the correlation functions.

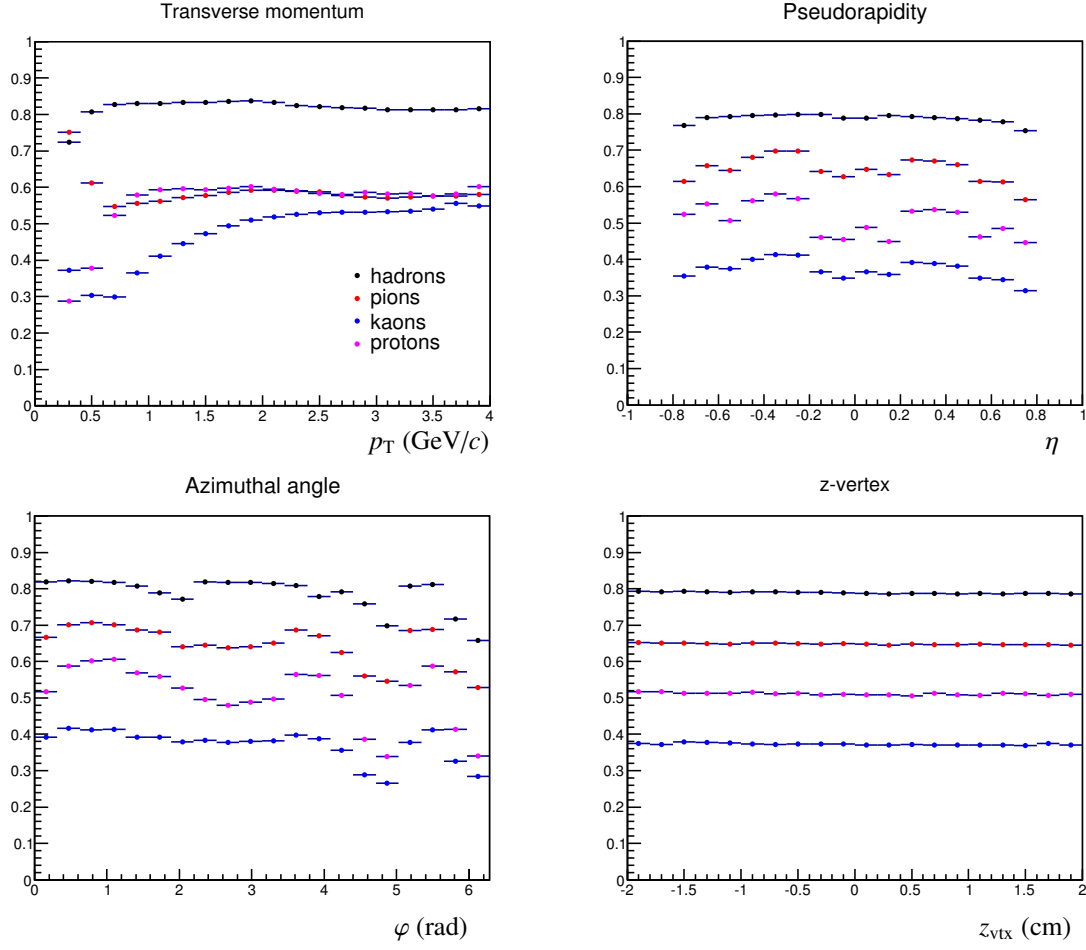


Figure B.4: Projection of 4D efficiency correction map on 4 axes: p_T (top left), η (top right), φ (bottom left) and z_{vtx} (bottom right). The colors correspond to different particle species (black – hadrons, red – pions, blue – kaons and pink – protons). The calculations were performed employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

4D and 1D correction maps (p_T , φ , η , z_{vtx})

The differences between the one-dimensional p_T -dependent correction and the one using the 4D maps and correcting simultaneously in p_T , φ , η , and z -vertex are shown in Fig. B.5, and Fig. B.6.

It can be seen that the differences are $< 0.2\%$, and moreover the difference between “truth” and “reconstructed and corrected” is in favor of 1D corrections. It should be noted that one-dimensional corrections have finer binning in p_T (100 bins), in comparison to 20 bins only in the same p_T range for a 4D map case. We included the 0.2 % differences into the systematic uncertainty.

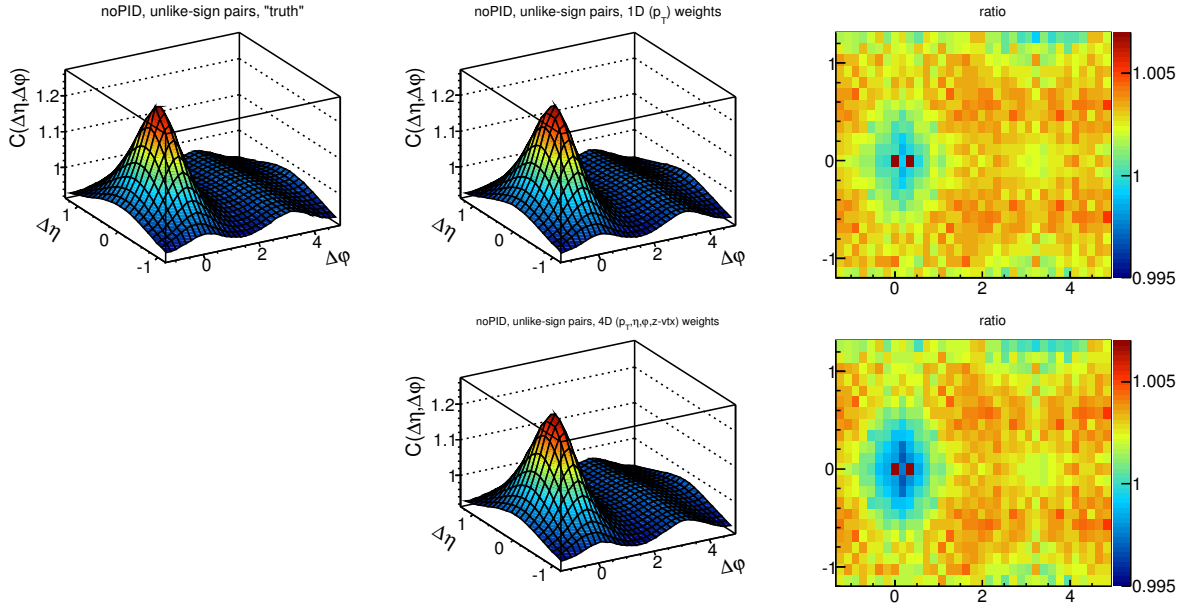


Figure B.5: Comparison of MC correlation functions of unlike-sign pairs. Left: MC truth. Correlation function after applying one-dimensional p_T dependent weight (middle top) and four-dimensional weight (middle bottom), no PID. The ratio of left and middle correlation functions is shown in the right panel. The calculations were performed employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

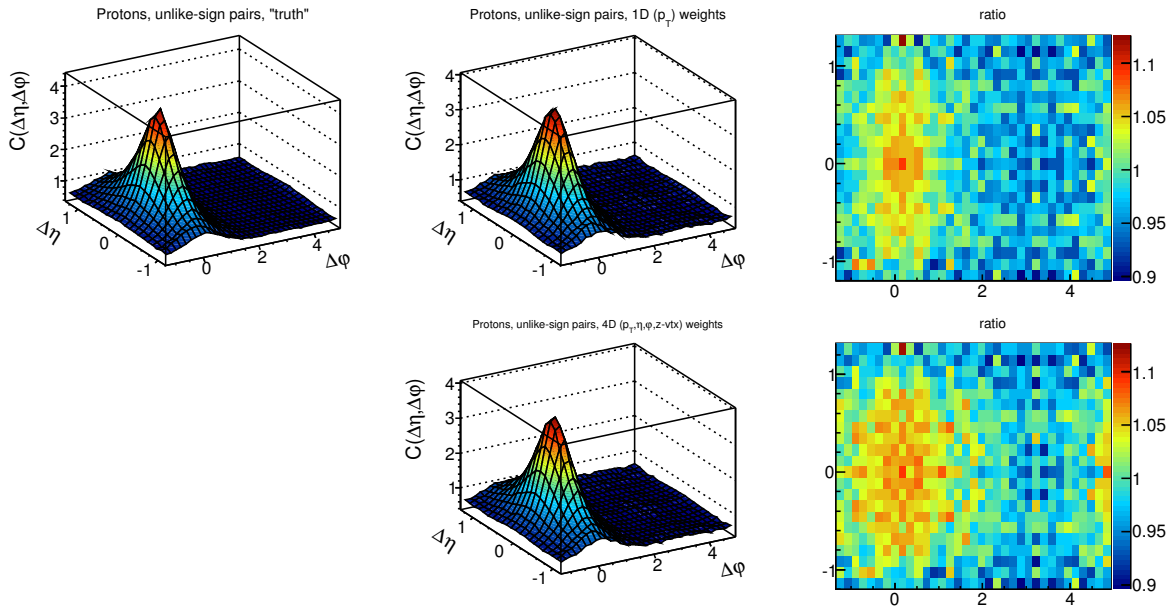


Figure B.6: Comparison of MC correlation functions of proton unlike-sign pairs. Left: MC truth. Correlation function after applying one-dimensional p_T dependent weight (middle top) and four-dimensional weight (middle bottom), no PID. The ratio of left and middle correlation functions is shown in the right panel. The calculations were performed employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

B.3 Data-driven DCA based contamination correction method

The secondary particles contaminating the correlation measurements are not of one kind; they come from weak-decays feed down and interactions with detector material or the beam pipe. The exact contributions from different kinds of secondary particles, as well as the ratio of primary to secondary particles may not be modeled correctly by the MC models and available transport packages. To account for this, a data-driven procedure was developed.

Firstly, the experimental DCA distributions in the transverse plane were obtained for Monte Carlo data corresponding to: (a) primary particles (primordial and resonance decays), (b) particles originating from interactions with the material, (c) particles coming from weak decays. Then, the corresponding DCA distribution from collision data was fitted with a combination of the DCA distributions obtained from Monte Carlo, in order to get the three corresponding scaling factors which are the free fit parameters. In this analysis the Pythia Perugia-0 event generator and GEANT3 transport package were used. The whole procedure was performed in p_T bins.

An example of how this procedure works and performs can be followed in Fig. B.7-left for protons and Fig. B.7-right for pions. The experimental DCA distributions (black) in slices of transverse momentum have been fitted with the sum of the scaled DCA distributions from MC of primary particles (blue), particles from material (green) and particles from weak decays (red) in order to find the corresponding scaling factors of the three components, the free parameters of the fit, see Fig. B.8. Once the scaling factors are obtained, they are used in the analysis of collision data where a DCA cut has been applied in order to find the percentage of the contributions of the secondary particles coming from interactions with the material and from weak decays when a specific cut is used.

In Fig. B.8-left, where fractions of secondary particles are detailed for protons, we can see the need of lower limit p_T cut of 0.5 GeV/ c for the proton sample; for lower values the sample is contaminated greatly by particles coming from material.

Since the contamination of the secondary particles to the kaon sample is minimal we do not correct the sample for this effect.

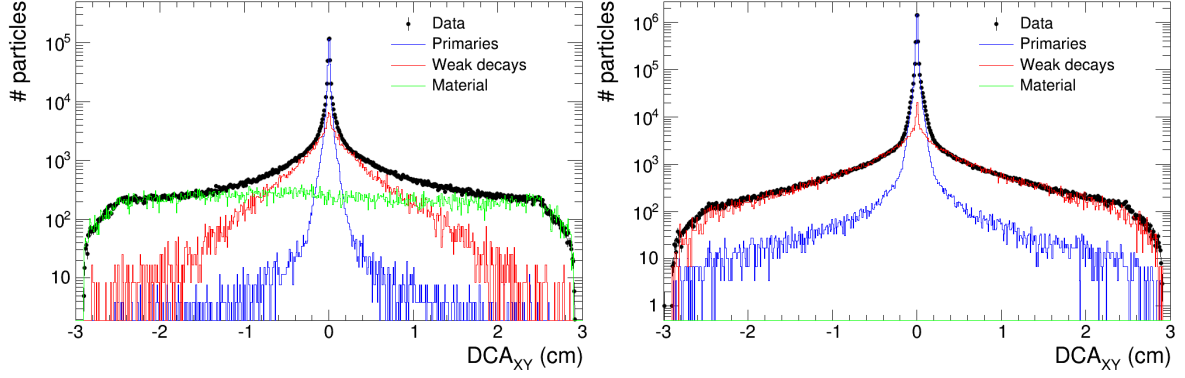


Figure B.7: Estimation of contamination due to the feed-down in one p_T range ($0.8 < p_T < 0.9$ GeV/c) for protons (left) and pions (right) in the $\sqrt{s} = 7$ TeV pp collision data. The collision data is represented as black points. In colors the simulated distributions fitted to the collision data are superimposed; primary particles in blue, secondary particles originating from weak decays in red and from interactions with material in green. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

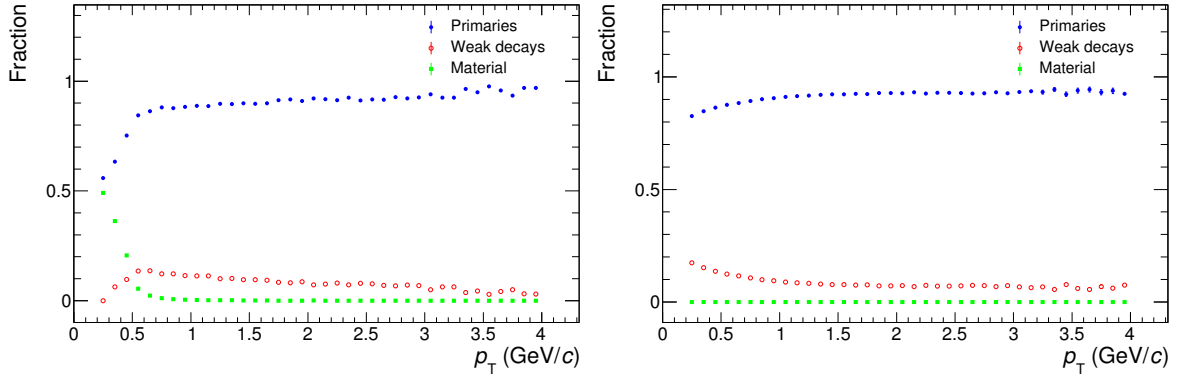


Figure B.8: Fractions of certain particle types for protons (left) and pions (right) in the $\sqrt{s} = 7$ TeV pp collision data. The fraction of primary particles is represented in blue. The contributions from the weak decays and interactions with material are represented in red and green, respectively. The values are estimated employing the full detector simulation of Pythia Perugia-0 pp events at $\sqrt{s} = 7$ TeV.

p_T dependent secondaries contamination: MC truth versus DCA based methods

The MC models do not reproduce properly the contamination from secondary particles. To get proper values a data-driven method can be derived. Such a procedure is usually important for protons, but also frequently used for pions (for kaons the contamination from secondaries is small, therefore no correction is applied). We calculated the contamination using those methods, and compared the correlation functions after such corrections to the ones corrected with MC-

only information (as in Sec. 6.2.2). It was observed that correlation functions do not depend in a statistically significant way on the extraction of the secondaries contamination procedure.

Appendix C

Angular correlations in p–Pb and Pb–Pb collisions

Pb–Pb results

The studies of the heavy-ion collisions at the LHC is the main area of study of the ALICE experiment. $\Delta\eta\Delta\phi$ correlation functions in such systems include a double ridge structure originating from collective effects, i.e. flow (introduced and described in detail in Sec. 3.2.3 and Sec. 3.2.4), not present in minimum bias pp data. The comparison between the two systems can give us insight about this correlation source in particular, as well as properties of the dense, strongly-interacting matter.

In Fig. C.1 we present the experimental results from $\sqrt{s_{\text{NN}}} = 2.76$ TeV Pb–Pb collision data in eight centrality ranges¹. A double ridge structure can be observed for the most central collisions, decreasing with decreasing centrality. A near-side peak can be observed for all centrality ranges; however, it is the most distinct for the least central collisions. The longitudinal ridge is clearly visible only for the lowest multiplicity (the least central collisions).

¹Centrality is a measure of the overlap of colliding nuclei, which determines the number of nucleons participating in the collision; it is strongly correlated with the multiplicity of the collisions (for details see Ref. [19]).

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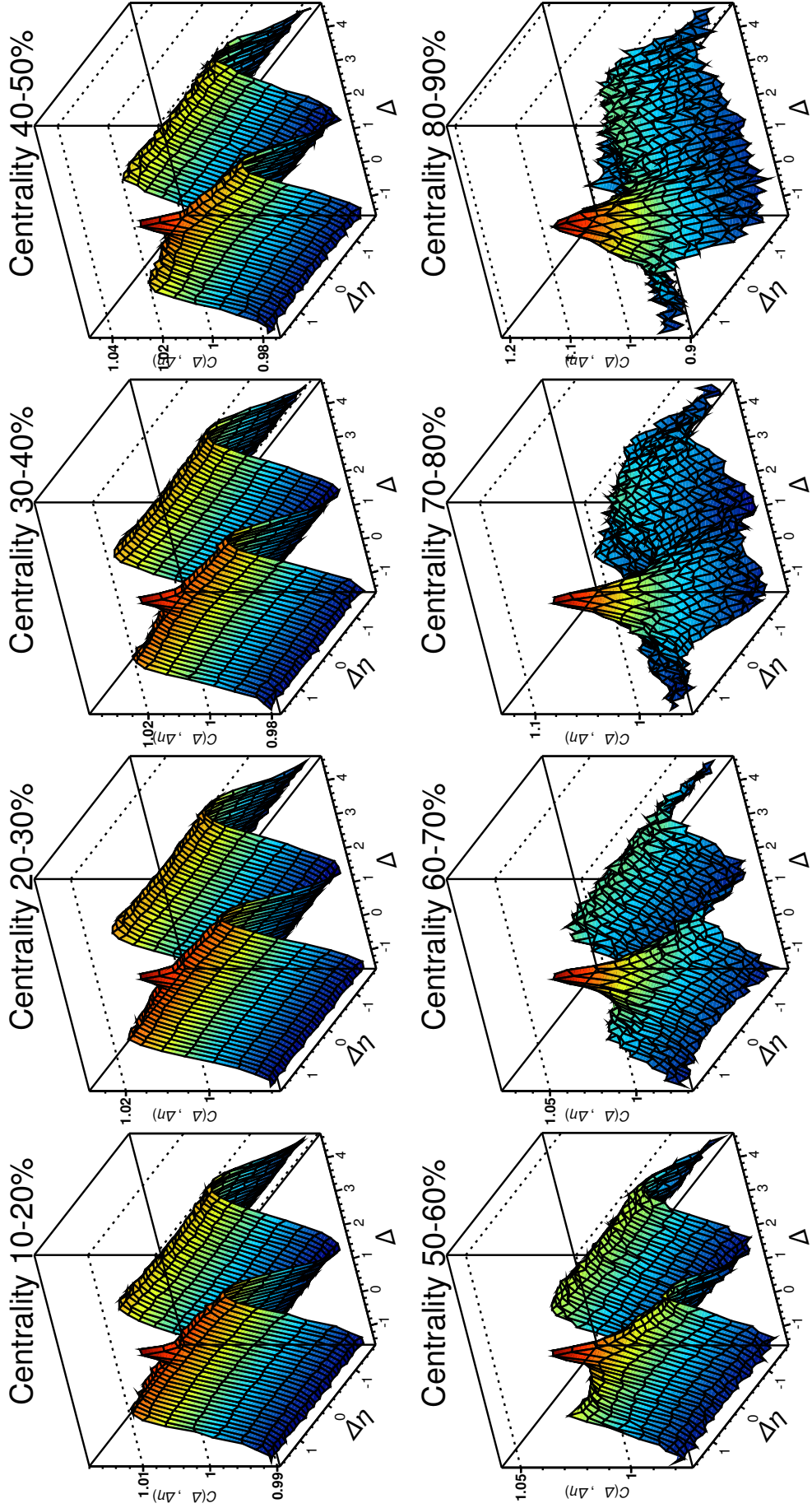


Figure C.1: $\Delta\eta\Delta\phi$ correlation functions for Pb-Pb collision data at $\sqrt{s_{NN}} = 2.76$ TeV for eight centrality ranges for $\pi^+\pi^+$ pairs.

p–Pb results

The p–Pb data delivered at the LHC are of great interest especially as a reference for heavy-ion data. The QGP probes need to be very precisely defined and tested. This validation requires the studies of the benchmark processes with small systems, where the QGP is not formed and therefore the final-state phenomena (such as collective behavior of QCD matter) are absent. To some extent such benchmarking can be performed using proton-proton collisions analyzed in this thesis, where both initial and final-state medium effects are absent. However, proton-nucleus collisions are crucial for completeness because of the presence of the initial-state effects and the absence of the final-state ones [241].

In Fig. C.2 and Fig. C.3 $\Delta\eta\Delta\varphi$ correlation functions are presented for p–Pb data registered by the ALICE experiment in four multiplicity classes. In the correlation functions effects similar to the ones seen in pp data are visible; i.e., pronounced near-side structures. A longitudinal ridge structure at $\Delta\eta = 0$ can be observed for unlike-sign pairs. Similarly, the multiplicity dependence (correlations decreasing with increasing multiplicity) can be observed as well. On the other hand, the away-side correlation is much less distinct in comparison to the pp data.

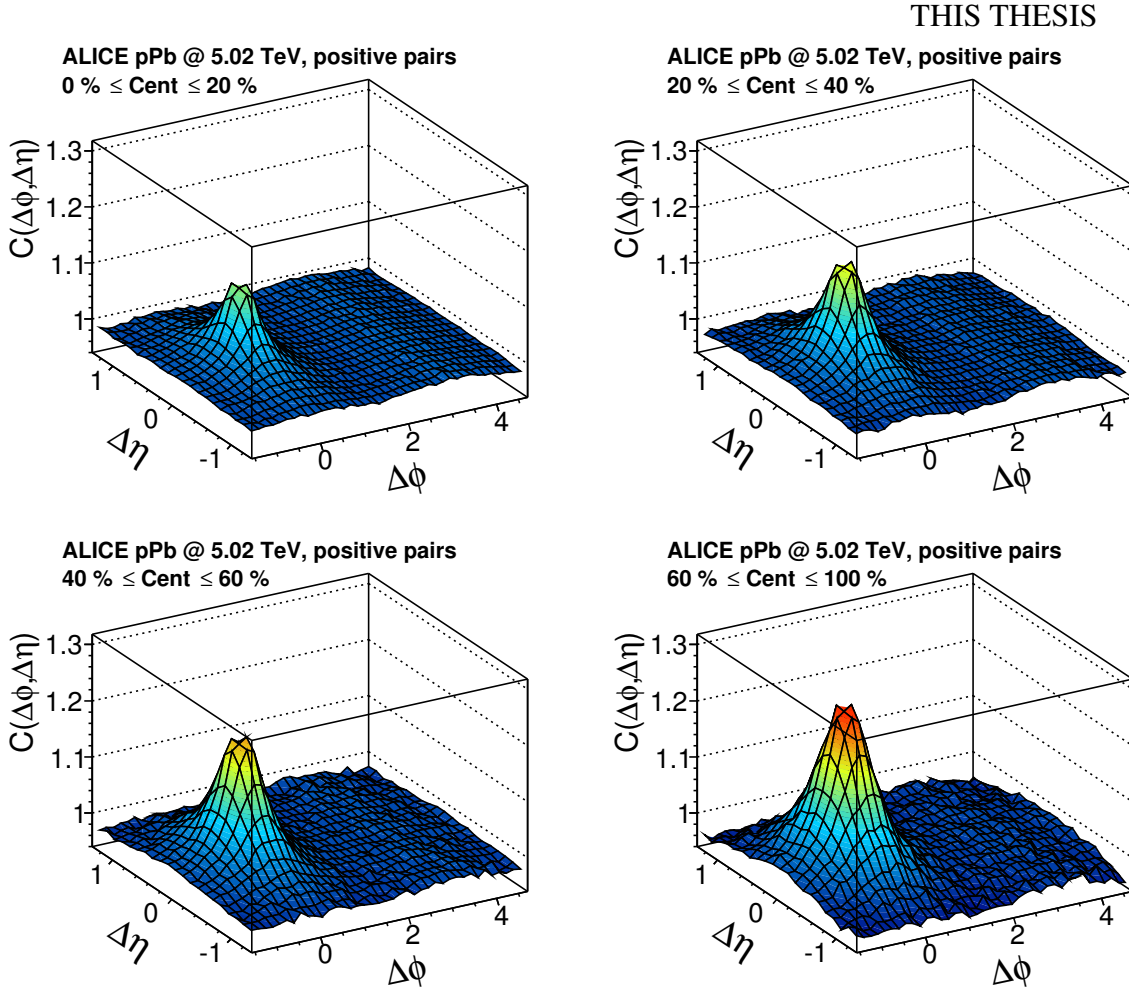


Figure C.2: $\Delta\eta\Delta\phi$ correlation functions for p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for four multiplicity ranges for $\pi^+\pi^+$ pairs.

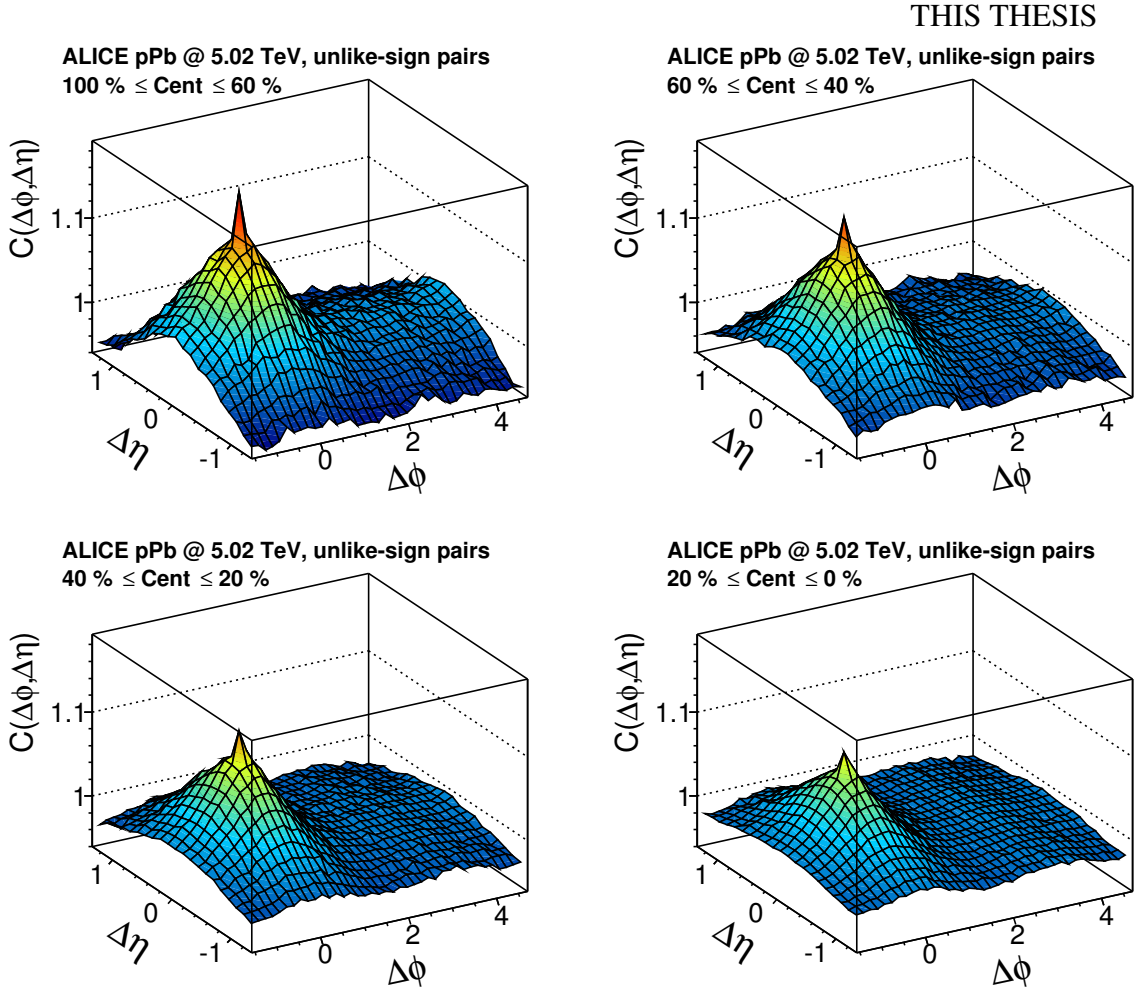


Figure C.3: $\Delta\eta\Delta\phi$ correlation functions for p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for four multiplicity ranges for $\pi^+\pi^-$ pairs.

Appendix D

Correlation functions for non-identical pairs

$(\pi K, \pi p, pK)$

$\Delta\eta\Delta\phi$ correlation functions for non-identical particle pairs (π -K, π -p, p-K) are shown in Fig. D.1 for unlike-sign pairs, and in Fig. D.2 for like-sign pairs. In Fig. D.1 it can be seen that there are no differences between corresponding pairs, i.e. between π^+K^- and π^-K^+ . In Fig. D.3 and Fig. D.4 the same plots are shown for Pythia Perugia-0 MC data.

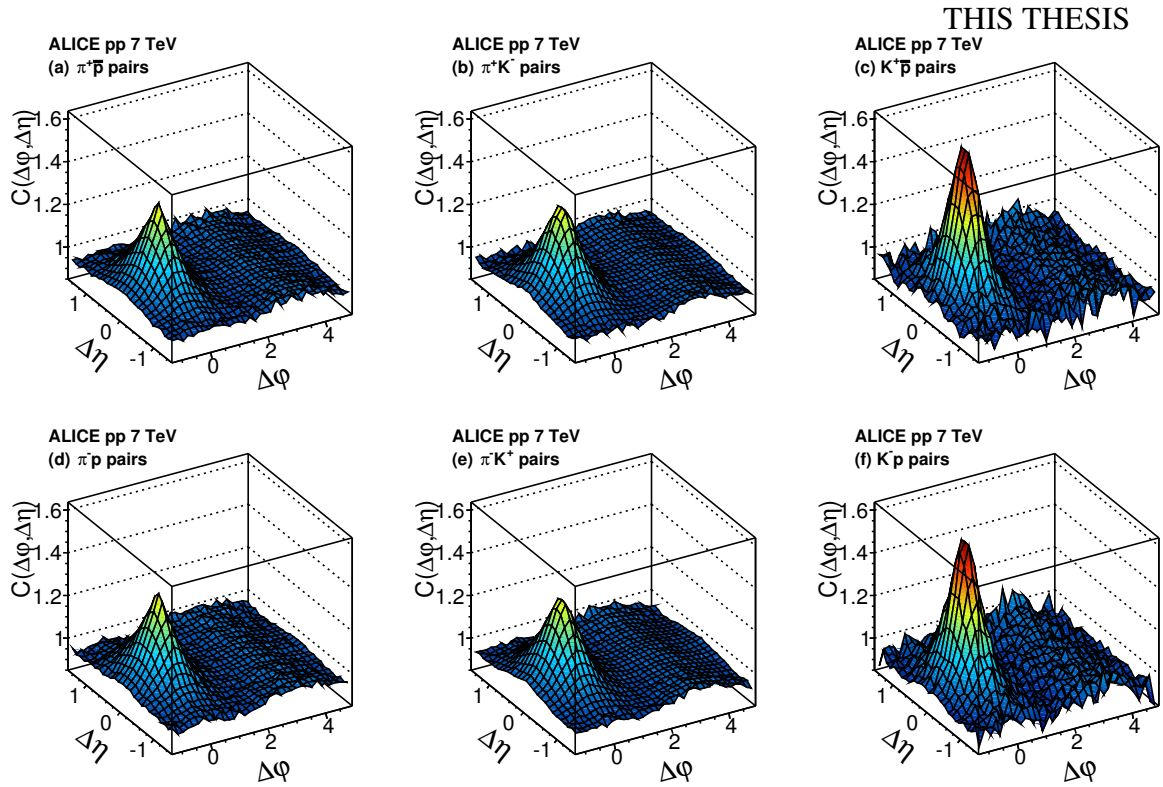


Figure D.1: Correlation functions for non-identical unlike-sign pairs: (a) $\pi^+\bar{p}$, (b) π^+K^- , (c) $K^+\bar{p}$, (d) π^-p , (e) π^-K^+ , (f) K^-p , pp collision data at $\sqrt{s} = 7$ TeV.

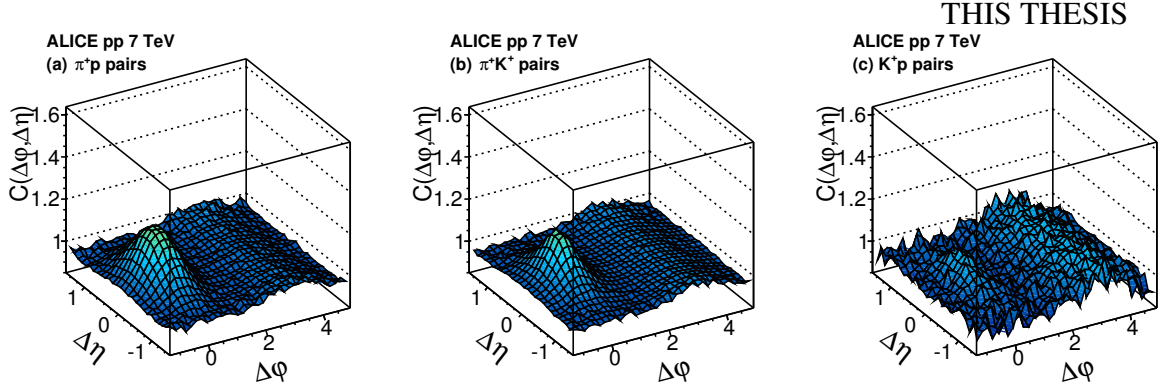


Figure D.2: $\Delta\eta\Delta\phi$ correlation functions for non-identical like-sign pairs: (a) π^+p , (b) π^+K^+ , (c) K^+p , pp collision data at $\sqrt{s} = 7$ TeV.

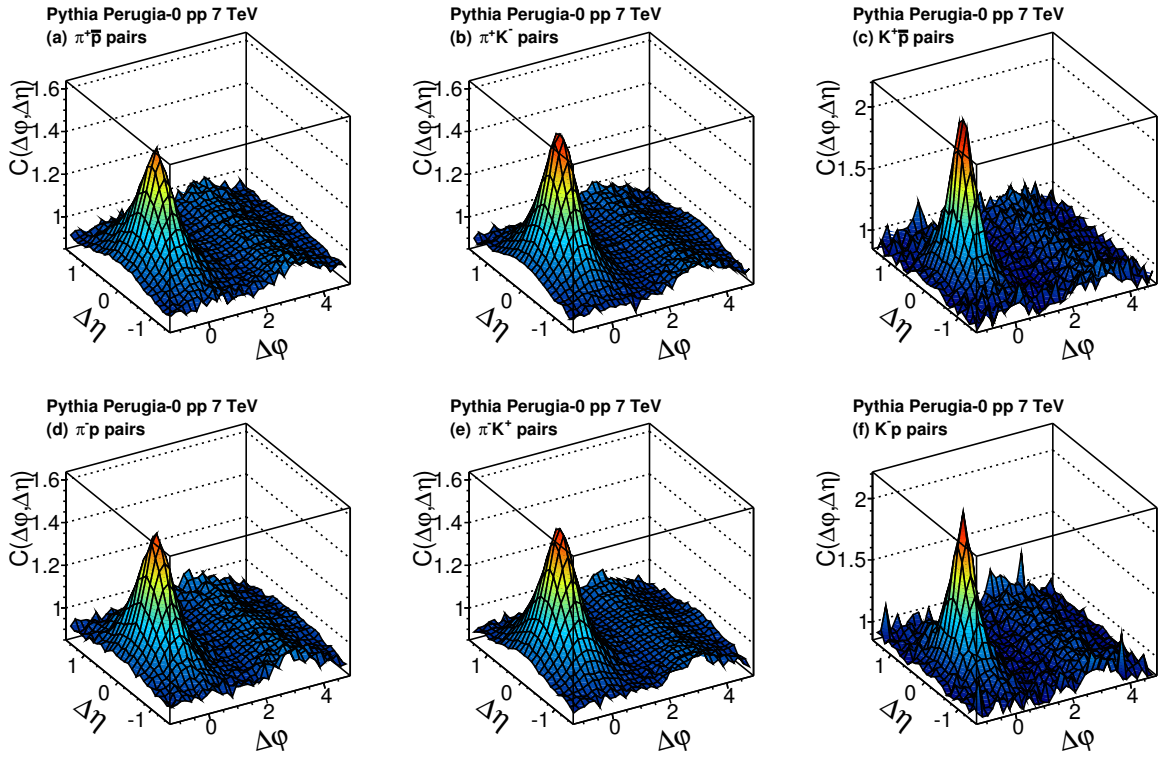


Figure D.3: Correlation functions for non-identical unlike-sign pairs: (a) $\pi^+\bar{p}$, (b) π^+K^- , (c) $K^+\bar{p}$, (d) π^-p , (e) π^-K^+ , (f) K^-p , Pythia Perugia-0 pp at $\sqrt{s} = 7$ TeV.

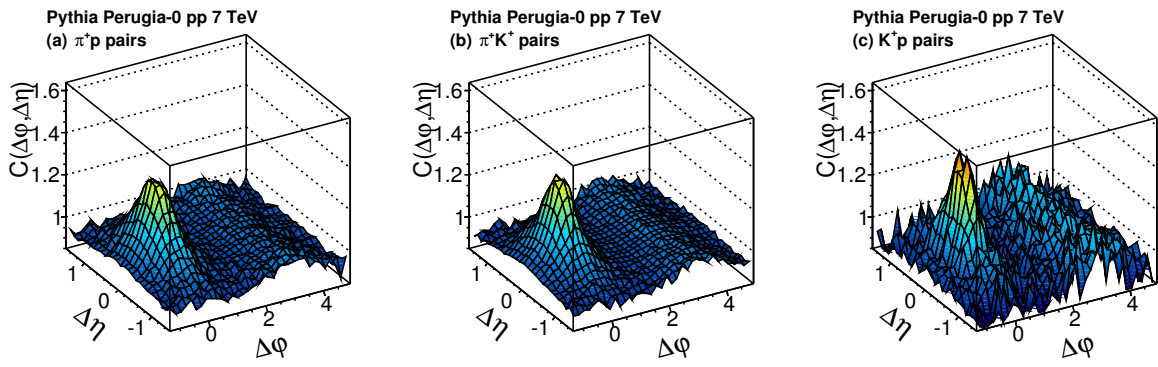


Figure D.4: Correlation functions for non-identical like-sign pairs: (a) π^+p , (b) π^+K^+ , (c) K^+p , Pythia Perugia-0 pp at $\sqrt{s} = 7$ TeV.

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