

**Nuclear Modification of
charged-particles production at
 $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ in ALICE**

Master thesis

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0 Abstract

1 Introduction

1.1 The Structure of Matter

Throughout the twentieth century, successive crucial advances in the field of particle physics led to a revolution of the world-view on the structure of matter and the fundamental forces that govern the universe. Following these developments, it became necessary to consolidate the acquired knowledge into a single theory: the Standard Model, which marked by the end of the 1970s the foundation of modern particle physics. This systematization provided from a theoretical point of view subsequently confirmed experimentally a comprehensive description of the nature of elementary particles and the fundamental interactions they mediate: the electromagnetic, the weak and the strong interaction.

All matter in the universe is composed of indivisible particles that lack spatial extension and substructure, the so-called elementary particles. The first particles to be proposed as elementary were the atoms. This picture changed in the early 20th century after it was proved that atoms are made up of a nucleus constituted by protons and neutrons, around which electrons orbit. In the subsequent decades, an extensive number of other subatomic particles were discovered, raising the question among physicists of whether all of them were in fact structureless. The Standard Model sorted out this confusion, historically known as particle zoo, describing the existence of a low number of elementary particles subdivided into two types named quarks and leptons that build all known particles, including protons and neutrons. In addition, the Standard Model clarified that the interactions between quarks and leptons occur by means of an exchange of force-carrier particles, also considered elementary.

In order to classify the elementary particles, it is required to consider the immutable and distinguishable physical properties each of them possess. In this regard, the most fundamental distinction between the building blocks of matter and the force-carrier particles lies in the intrinsic angular momentum, known generally as spin, all particles carry, whether or not they are elementary. Particles of half-integer spin in units of the Planck's constant \hbar are named fermions

and present an antisymmetric wave function, whereas those of integer spin are known as bosons and their wave function describes a symmetric behavior. In this context, quarks and leptons are considered elementary fermions since their spin is equal to $\pm 1/2$, while the force-carriers, which have a spin 1, are referred to as gauge bosons.

The Standard Model states the existence of six quarks and six leptons, summarized in Figure 1.1. Both groups of elementary fermions are arranged according to the mass in three doublets named generations. Each pair of quarks or leptons have a mass one or two orders of magnitude lower than the pair of the next generation. Furthermore, the electrical charge is another feature used to sort elementary fermions. The triplets composed of elementary fermions from different generations have the same electrical charge, namely $+2/3$ and $-1/3$ for the case of the quarks and 0 and -1 for the one of the leptons. The Standard Model predicts also the occurrence in Nature of antiquarks and antileptons, elementary fermions with identical mass as their counterparts but opposite electrical charge and spin.

The six species or flavours of quarks known at the present day are up u , down d , charm c , strange s , top t and bottom b . At this point, it should be emphasized that quarks could not yet be observed existing on their own, but only building bound states named hadrons. These composite particles, detected for the first time during the era of the particle zoo, come in two types: hadrons built from three different quarks are called baryons, while those constituted of a quark-antiquark pair mesons. For instance, the quark composition of protons and neutrons, respectively uud and udd , allows to identify them as baryons. All known hadrons, excluding the proton, decay after a given period of time. It should be also noted that since the spin is an additive property, baryons are considered fermionic particles and mesons, by contrast, bosonic particles.

The quark composition of a hadron determines intrinsic facets of the particle, which are associated with additive quantities named quark quantum numbers: the well-known electrical charge, a parametrization of the number of quarks called baryon number B and other parametrization of the second- and third-generation flavours. However, the valence quarks, i.e. the quarks that determine the identity of a hadron, aren't the only components. In fact, a hadron should be understood as a more complex and dynamic structure that contains, aside from the valence quarks, an amalgam of quark-antiquark pairs named sea quarks in a constant process of creation and annihilation as well as a large number of gluons, the force-carrier of the strong interaction, which will be discussed later. This picture is consistent with the fact that the sum of the masses of the valence quarks of a given hadron doesn't coincide with the observed mass of the hadron,

3 MeV $\frac{1}{2}$ $+\frac{2}{3}$ <i>u</i> up	1.24 MeV $\frac{1}{2}$ $+\frac{2}{3}$ <i>c</i> charm	172.5 GeV $\frac{1}{2}$ $+\frac{2}{3}$ <i>t</i> top	0 1 0 <i>g</i> gluon
6 MeV $\frac{1}{2}$ $-\frac{1}{3}$ <i>d</i> down	95 MeV $\frac{1}{2}$ $-\frac{1}{3}$ <i>s</i> strange	4.2 GeV $\frac{1}{2}$ $-\frac{1}{3}$ <i>b</i> bottom	0 1 0 γ photon
<2.2 eV $\frac{1}{2}$ 0 <i>ν_e</i> electron neutrino	<0.17 MeV $\frac{1}{2}$ 0 <i>ν_μ</i> muon neutrino	<15.5 eV $\frac{1}{2}$ 0 <i>ν_τ</i> tau neutrino	91.19 GeV 1 0 <i>Z</i> Z boson
0.511 MeV $\frac{1}{2}$ -1 <i>e</i> electron	105.7 MeV $\frac{1}{2}$ -1 <i>μ</i> muon	1.777 GeV $\frac{1}{2}$ -1 <i>τ</i> tau	80.39 GeV 1 ± 1 <i>W</i> W boson

Figure 1.1: (Das Bild ist nicht fertig!) Elementary particles of the Standard Model.

being this significantly larger.

As already mentioned, six flavours of leptons are known at this time: three electrically charged leptons, the electron e , the muon μ and the tau τ , and the corresponding electrically neutral leptons that complete each generation, the electron neutrino ν_e , the muon neutrino ν_μ and the tau neutrino ν_τ . In contrast to quarks, leptons don't arrange themselves to form composite particles, with the big exception of the electron shell of an atom, and can exist on their own.

According to our actual understanding, all observed phenomenon at subatomic level, such as the formation of composite particles or the particle decays, manifest themselves by means of the existence of three fundamental interactions: the electromagnetic, the weak and the strong interaction. In modern particle physics, each of these interactions is explained as an exchange of quanta of elementary bosons between the elementary particles that exert the force. In order to experience a given fundamental force, an elementary particle must carry the corresponding charge. Particles are charged in different magnitudes, which determines the intensity with they create or undergo the force.

The force-carrier particle of the electromagnetic interaction is named photon γ , a massless boson that mediates the attraction and repulsion forces between all electrically charged particles. In the case of the weak interaction, which all elementary fermions can experience, there are three massive mediators: one electrically neutral, namely the Z boson, and two electrically charged, the W^\pm bosons. Finally, the strong interaction is mediated by the already introduced gluon g .

The charge of the strong interaction is called color, but it should not be mistaken for the concept generally known and described by the optical physics. Quarks are the only elementary fermions that have color charge and therefore gluons can couple to them. In addition to quarks, gluons carry also color what allows them to couple to themselves, a particularity only present in the strong interaction. The basic processes of the strong interaction are described by a theory named quantum chromodynamics (QCD). Since some of these processes represent a key knowledge for the understanding of this thesis, this theory will be treated in the coming section more exhaustive.

1.2 Quantum Chromodynamics

1.3 Phase diagram and Quark-Gluon-Plasma

1.4 Physics of particle collisions (pp, A-A col.)

1.5 (charged particle) p_T spectra and nuclear modification factor

In order to understand R_{AA} explain pseudorapidity

1.6 Monte Carlo simulations

Comparison of spectra with HIJING models

2 The ALICE Experiment at CERN

2.1 The LHC

2.2 ALICE

2.2.1 ITS

2.2.2 TPC

explain clusters

2.2.3 Track reconstruction

Explain track variables

2.2.4 V0 detectors

Centrality determination

3 Analysis

Once defined the subject of analysis, the details of the used approach will be described in this chapter. The analysis studies pp and Pb-Pb collisions at a center-of-mass energy $\sqrt{s_{\text{NN}}} = 5.02$ TeV gathered with the ALICE experiment. Towards the transverse momentum spectra of charged particle required for the the nuclear modification factor distributions, various well-known detector effects that have an impact on the data collections must be handled properly. This implies to redress these effects in the first place on the basis of a data selection followed by the implementation of a series of corrections on the p_{T} spectra of both studied collision systems. Following the calculation of the R_{AA} distributions, a final discussion of the results based on the systematic uncertainties and a comparison with a previous ALICE publication on the same topic will be presented (cite paper here).

3.1 Data sample

System	statistics (M)	MC generator	MC statistics
pp	560 (FAST)	PYTHIA + GEANT3	25%
	318 (CENT)		
Pb-Pb	110	HIJING + GEANT3	2%

Table 3.1: Overview of the used data periods, the approximate number of events contained in them and the MC productions they are associated with including the percentage of simulated statistics.

This thesis will avail of the latest pp and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV recorded by the ALICE detector system. The particle collisions took place respectively in the years 2017 and 2018. In the ALICE collaboration, collisions

measured within the same time frame in equal physical conditions are grouped in so-called periods. In the pp periods, the interaction rate was hold at 50 kHz, whereas in the Pb-Pb ones, at 7.5 kHz, it was much lower. Furthermore, for each data period there is at least one MC production anchored to which simulates the exact same conditions and technical specifications of the detector response at the time of the data taking. The events of the MC productions were generated by PYTHIA and the correspondig detector response was simulated by GEANT3 in the case of pp collisions and by HIJING as regards the Pb-Pb collisions. It is also important to notice the limited computing time available for these simulations allows to cover only a percentage of the total statistics. All this information as well as an overview of the number of events contained in each data set are summarized in Table 3.1.

The examined pp data sets present a significantly increased number of collisions in comparison to all previous analogous data taking periods. This increment is caused by the higher interaction rate used for the analysed collisions. Moreover, as seen in Table 3.1, the pp data sets are grouped into two categories. In order to understand this fact, a particularity of the SDD layers of the ITS should be introduced. All particle detectors experience an elapse of time after the recording of a particle, the dead time, during which the apparatus is unable to detect another event due to technical characteristics. The SDD layers present a dead time markedly longer than the rest of the detectors involved. Therefore, a measurement of collisions dispensing with the SDD layers allow an increase in the data taking rate with the inconvenience of a loss of accuracy in the determination of the collision vertex.

In this context, the 2017 pp data periods contain two separated data subsets that differ according to the readout configuration: the first data subset corresponds to collisions measured excluding the information of the SDD layers, which in this thesis will be referred to as *FAST*. The information is excluded whenever the SDD is inoperable at the time of a collision due to the dead time. In contrast, the collisions in the second data subset were reconstructed including this information since the SDD was presumably ready. These collisions are labeled as *CENT*. In Figure ??, a conceptual diagram of this process is shown. Furthermore, the events of the *CENT* subset were reconstructed also without the SDD information allowing to study the impact of the absence of the SDD layers during the tracking. For this purpose, a comparison of the same observable extracted from *CENT* with SDD and from *CENT* without SDD can be undertaken.

As shown in Table 3.1, the *FAST* subset contains almost three times as many events as *CENT*. In order to be able to use all the available data, it will be demonstrated the equivalence of the *FAST* and the *CENT* without SDD subsets

and, therefore, the feasibility of combining them. In the big picture, this increase of the statistics should lead to an improvement of the precision of the charged-particle p_T spectra in pp collisions, specially in the high p_T region, which in turn could also enhance the precision of the R_{AA} distributions. In this thesis, to determine the viability of this merging, the final corrected p_T spectra obtained from the *CENT* with and without SDD subsets will be compared at the end of the chapter.

3.2 Trigger and event selection

3.2.1 Trigger overview

In order to ensure the quality of the analysed particle production, all studied events must meet certain conditions in a selection procedure. During the data taking, a complex electronic system named trigger makes a decision in real time based on physical requirements whether a collision candidate is worth to be stored or not. As already discussed, the ALICE experiment focuses its research activities on the investigation of strongly interacting matter and therefore inelastic collisions are of particular importance. The trigger decision is also motivated by the large detector readout time and a limited data storage capacity which represent obstacles that prevent the recording of all events that take place.

The ALICE trigger operates every 25 ns or one bunch crossing which corresponds to the time distance between two bunches of protons. The trigger configuration which imposes the smallest bias and thus accepts the majority of the overall inelastic cross section is called Minimum Bias (MB). Furthermore, various trigger configurations which differ in the detectors involved in the signal condition are used depending on the particularities of the studied collision system. For the periods used in this thesis, a MB trigger that requires signals in the V0A and V0C detectors in coincidence with the bunch crossing (MB_{and}) was chosen over other MB triggers as it offers more advantages for collision systems with large luminosities such as Pb-Pb collisions (cite here).

3.2.2 Selection of events

In an offline stage of the event selection, collision candidates that satisfy the trigger condition undergo a selection process in aim to reject contaminated and poor quality events. A part of this contamination corresponds to background events, a particle-flux caused by the interaction between the beams and the matter in the machine. The beam background is discriminated mainly by means of the signal

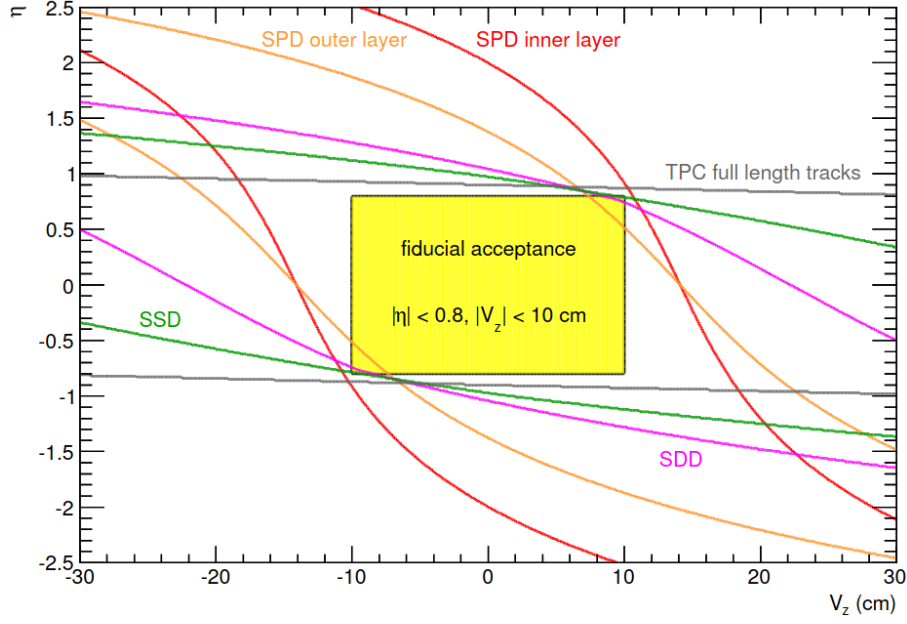


Figure 3.1: Pseudorapidity acceptance of the SPD, the SDD, the SSD and the TPC shown as function of the position of the primary vertex along the z -axis. The fiducial acceptance represents the region where most tracks can be reconstructed (cite mknichel).

arrival time of the events in the V0 modules. The arrival time of background events is shorter than the one of a collision produced in the nominal interaction point. This difference is exploited to exclude background events from the data sample. Another source of contamination are the so-called pile-up events, multiple collisions which occur within the same bunch crossing. In addition, events produced in a bunch crossing different from the one that triggered the data recording are also considered pile-up. An event is identified as pile-up and thereby removed from the data sample when multiple primary vertices are reconstructed using the information from the SPD in a single event. In the case of the Pb-Pb collisions, the pile-up rejection is not only performed for data, but also for the corresponding MC production, being this one of the novelties in respect with previous analogous analysis.

Considering the acceptance coverage for vertices located in close proximity to the nominal interaction point of the ITS and the TPC, the main tracking devices of ALICE, in this thesis it will be established a pseudorapidity range of $|\eta| < 0.8$ for the charged particle production. The pseudorapidity acceptance exhibits a dependency on the position of the primary vertex V_z along the beam axis z as illustrated in Figure 3.1 for the ITS subdetectors and the TPC. Here, it is observed that the influence of this correlation on the detectors increases with the radius of these, being the TPC the detector less affected. In the middle of the plane, marked in yellow, a region in which most of the tracks are covered arises.

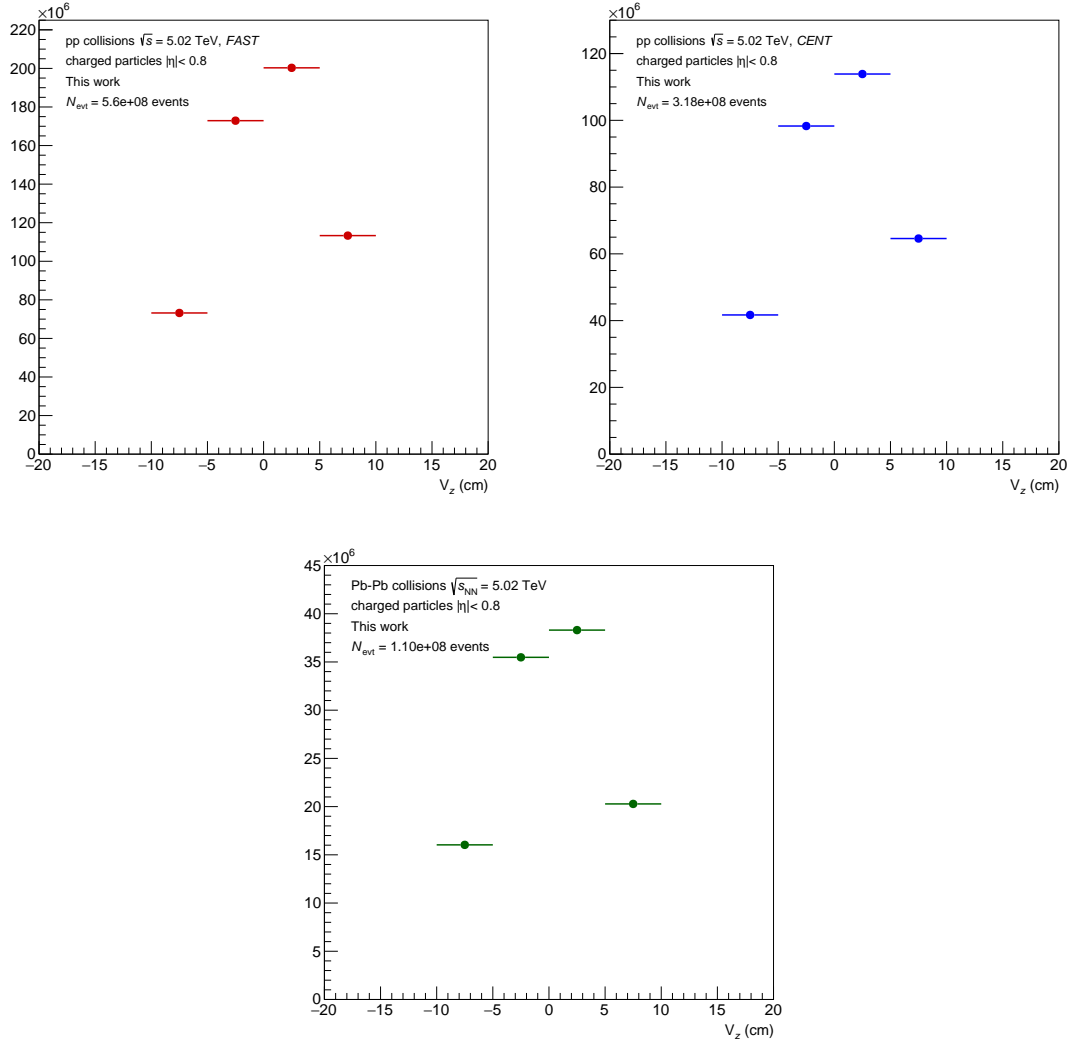


Figure 3.2: Distribution of events as function of the position of the primary vertex along the beam axis V_z in pp collisions from the subsets *FAST* and *CENT* as well as in Pb-Pb collisions.

Therefore, to ensure the pseudorapidity range, only events with a position of the primary vertices along the beam axis of $|V_z| < 10$ cm will be selected. Figure 3.2 illustrates the distribution of events that fulfill the above-mentioned event selection criteria as function of the position of the primary vertex $|V_z|$ for the pp data sets *FAST* and *CENT* with SDD as well as for the Pb-Pb data sets. In each figure, the total number of reconstructed events N_{evt} is also displayed.

3.3 Track selection

Primary charged particles traverse the TPC-ITS detector system and leave a track that can be reconstructed by means of the procedure described in (cite section). To guarantee the quality of the analysis, the resulting tracks must fulfill several

Track cut	Condition
Selection of primaries	
DCA_z	$\leq 2 \text{ cm}$
DCA_{xy}	$\leq 7\sigma$
ITS selection	
at least one hit in the SPD	required
ITS refit	required
χ^2 per ITS cluster	≤ 36
TPC selection	
TPC refit	required
χ^2 per TPC cluster (pp collisions)	≤ 4
χ^2 per TPC cluster (Pb-Pb collisions)	≤ 2.5
fraction of shared TPC clusters	≤ 0.4
ratio of crossed rows over findable clusters	≥ 0.8
geometric length in the active TPC area	130, 3, 1.5, 0.85, 0.7
TPC-ITS selection	
χ^2 TPC constrained track vs. global track	≤ 36

Table 3.2: Standard track selection criteria used for analysis on primary charged particles in ALICE.

requirements which aim for an optimization of the p_T resolution as good as a reduction of the contamination from secondary particles present in the data sample. In this analysis, this control of the track quality is carried out using predefined track selection criteria or track cuts which correspond to variations of track variables related to technical specifications of the detector response. Over the years, several analysis on the charged-particle production in ALICE, such as (cite theses), have refined this method and, as result, the standard track selection listed in Table 3.2 has been established. The track cuts are implemented in both collision systems pp and Pb-Pb for primary charged particles measured in the kinematic range $p_T > 0.15 \text{ GeV}/c$ and $|\eta| < 0.8$, not only in data but also in the corresponding MC productions.

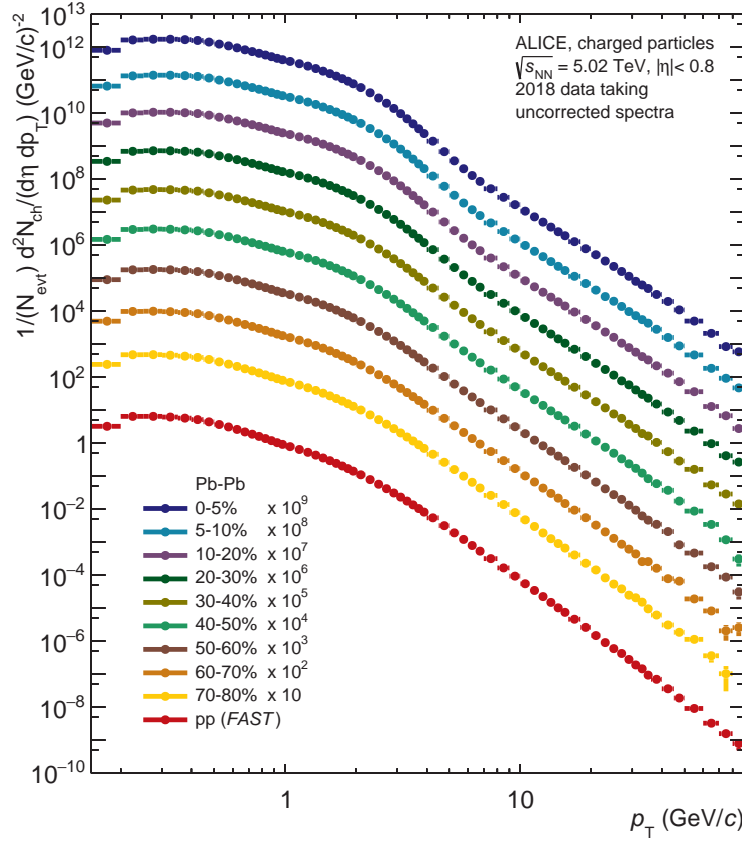


Figure 3.3: Uncorrected transverse momentum distributions of primary charged particles produced in pp and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The latest are divided into nine centrality classes. The p_T spectra of Pb-Pb collisions are shown scaled for a better visibility.

3.4 Corrections

After the implementation of the described event and track selection procedures, a representation of the p_T dependent distribution of the produced primary charged particles is performed taking into consideration the definitions and normalizations described in (cite section). As result, a so-called uncorrected p_T spectrum is obtained. In Figure 3.3, the uncorrected p_T spectra in pp and Pb-Pb are shown. In the case of heavy-ion collisions, the invariant yields are divided into nine centrality classes. The vertical bars present in each data point represent the statistical uncertainties, which increase with the transverse momentum since the high p_T regions of the spectra are less populated by tracks.

An analysis of nuclear modification factors demands a high accuracy of the observables used for their calculation. However, several effects related to the detector response as well as limitations of the above-described selections have an impact on the p_T spectra, which lead to a distorted picture of the physics

attempting to describe. The correction of these phenomena becomes thus unavoidable. To this end, a reproduction of the results provided by MC simulations, clear from such deviations, are exploited. For some of the corrections, data-driven approaches are also applied.

Two groups of corrections emerge according to the level at which they operate:

- corrections which affect the tracks and, therefore, possess a p_T dependent behavior. This group consequently conditions the shape of the spectrum.
- corrections which intervene at event-level and, as a result, influence the shift of the spectrum.

In the following sections, the corrections applied on the p_T spectra and the analysis strategies used for their implementation will be discussed.

3.4.1 Overall normalization

Trigger ϵ_{Trig}	Vertex reconstruction ϵ_{V_z}
75.25%	98.48%

Table 3.3: Trigger and event vertex reconstruction efficiencies for pp collisions at $\sqrt{s} = 5.02$ TeV recorded in ALICE in 2017.

The normalization of the p_T spectra is carried out by means of the total number of inelastic events N_{INEL} , as in Equation (cite formula). This value is approximated by using the number of events $N_{\text{ev}}^{\text{rec}}$ that were reconstructed according to the selection criteria. Nevertheless, this value is altered by two phenomena, namely the efficiencies inherent to the trigger system ϵ_{Trig} and the vertex reconstruction process ϵ_{V_z} :

$$N_{\text{ev}}^{\text{rec}} = N_{\text{INEL}} \cdot \epsilon_{\text{Trig}} \cdot \epsilon_{V_z} \quad (3.1)$$

The resulting bias is particularly notable in pp collisions. In heavy-ion collisions, both trigger and vertex reconstruction efficiency have been observed to be unity in the studied centrality interval 0-80% by previous works through MC simulations (cite mknichel/Pb-Pb papers). The determination of the respective efficiencies in pp collisions, described below, turns out to be necessary for the proper description of the transverse momentum distributions for this collision system.

Trigger efficiency

The ALICE trigger system, constrained by the MB_{and} condition, is able to measure a significant percentage of the total inelastic cross section, yet this measurement is limited due to the existence of a certain machine efficiency, the trigger efficiency ϵ_{Trig} . The value of this efficiency connects the visible and the total inelastic cross section as follows:

$$\sigma_{\text{vis}} = \epsilon_{\text{Trig}} \cdot \sigma_{\text{INEL}} \quad (3.2)$$

The measurement of these cross sections leads, therefore, to the determination of the trigger efficiency.

The ALICE collaboration provides the visible cross section for each data period first by determining the luminosity of the experiment, a quantity that evaluates the number of collisions produced in the detector and which is measured in events per time per area. For this purpose, a technique called van der Meer scan is used, in which the two beams are displaced with respect to each other in the transverse directions and the rate of interactions is monitored. The ratio of the head-on rate to the luminosity corresponds then to the desired visible cross section (cite S. vdM). In the studied pp collisions collected in 2017 at $\sqrt{s} = 5.02$ TeV, the visible cross section amounts to $\sigma_{\text{vis}} = 50.87 \pm 1.07$ mb (cite value).

ALICE quantifies the total inelastic cross section σ_{INEL} in the accelerator solving Equation 3.2 for it and using the visible cross section determined by means of van der Meer scans as well as trigger efficiencies approximated by MC simulations. However, this calculation is not available for $\sqrt{s} = 5.02$ TeV. This is resolved by a data-driven parametrization that predicts the value of σ_{INEL} as function of the center-of-mass energy as in (cite MC Glauber). Here, experimental values from several collaborations are utilized as input. According to the prediction, the total inelastic cross section at $\sqrt{s} = 5.02$ TeV is $\sigma_{\text{INEL}} = 67.6 \pm 0.6$ mb. The resulting trigger efficiency is shown in Table 3.3.

Vertex reconstruction efficiency

The reconstruction of the event vertex is also affected with a certain efficiency ϵ_{Vz} , which is defined as follows:

$$\epsilon_{\text{Vz}} = \frac{N_{\text{Vtx}}}{N_{\text{Trig}}} \quad (3.3)$$

where N_{Vtx} is the number of events with vertex and N_{Trig} is the total number of triggered events. Both values were measured disregarding the event selection.

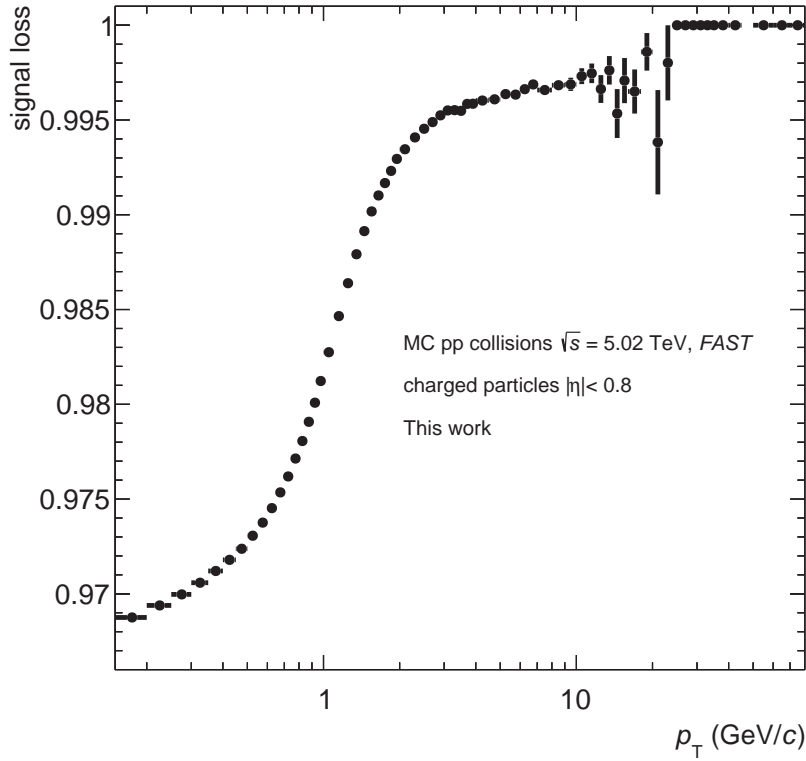


Figure 3.4: Signal loss correction for pp collisions.

The resulting efficiency can be found once again in Table 3.3.

Signal loss correction

As already seen, a fraction of the inelastic events is missing due to the vertex reconstruction efficiency and it must be thus restored. However, this correction has to be combined with a complementary correction at track-level in order to reestablish the tracks from events wrongly rejected by the event selection. This is achieved using the MC production to compare the distribution of primary tracks generated from inelastic events within the vertex cut $|V_z| < 10$ cm before and after they undergo the event selection:

$$\text{V. B.} = \frac{(dN/dp_T)_{\text{Gen}}^{\text{After event selection}}}{(dN/dp_T)_{\text{Gen}}^{\text{True INEL} > 0, |V_z| < 10 \text{ cm}}} \quad (3.4)$$

As result, a p_T dependent correction factor for the signal loss is obtained, whose distribution is shown in Figure 3.4. Here, it can be appreciated that the signal loss has overall a minor impact on the p_T distribution. The effect is more pronounced at low p_T , where it amounts to about 3% , and it then decreases until becoming meager above 10 GeV/c.

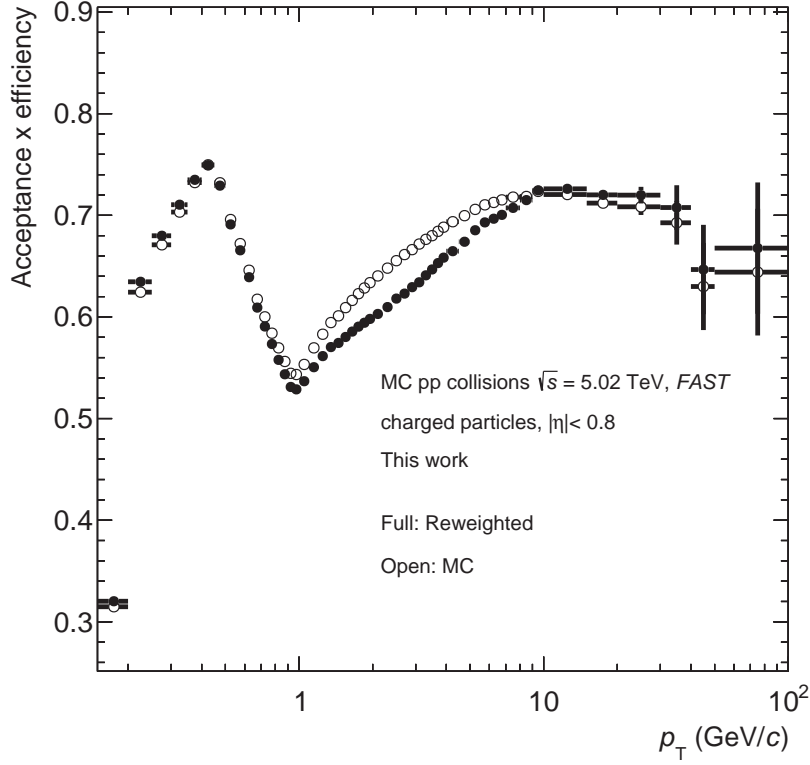


Figure 3.5: Acceptance and tracking efficiency as function of the transverse momentum for pp collisions obtained from MC simulations.

3.4.2 Tracking efficiency and acceptance

The primary charged-particle production is analysed in terms of the track information reconstructed by the TPC-ITS detector system. Nevertheless, the tracking process is subject to the technical limitations of this system, which prevent the reconstruction algorithm from detecting all produced particles. In fact, the detection of a particle is dictated by a probabilistic process that depends on the kinematic properties of the track. Moreover, the acceptance coverage of the detector, defined by the kinematic range of $0 \leq \phi^1 \leq 2\pi$, $|\eta| < 0.8$ and $p_T > 0.15$ GeV/c, affects also the measurement of charged particles.

Both of these two phenomena, the tracking efficiency and the acceptance, imply the existence of an overall efficiency ϵ for the reconstruction of tracks which depends on the kinematic variables: the transverse momentum p_T , the pseudorapidity η , the position of primary vertex along the beam axis V_z and the multiplicity class N_{ch} . The implementation of the corresponding correction will thus affect the shape of the p_T distributions. The p_T dependent efficiency is calculated using the information gathered by the MC production as the ratio of

¹azimuthal angle ϕ

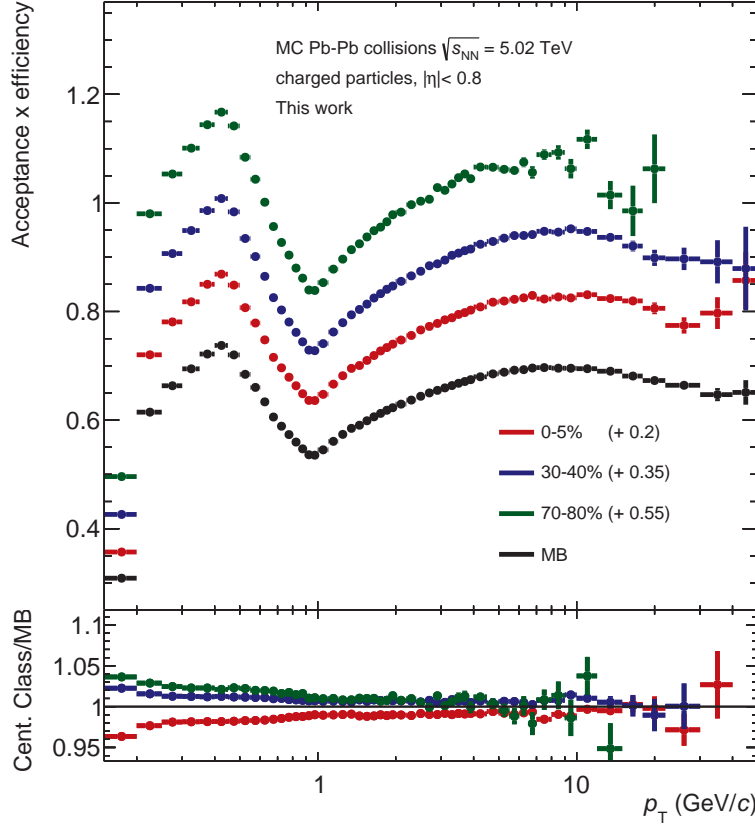


Figure 3.6: Tracking efficiency as function of the transverse momentum for MB, central, semi-central and peripheral Pb-Pb collisions obtained from MC simulations. The efficiencies are scaled with an additive factor for a better overview. In the bottom panel, the ratio of the individual efficiencies to the MB efficiency is shown. Data points with very large statistical deviations are excluded.

reconstructed primary tracks that survive the track selection $N_{\text{rec}}^{\text{MC}}$ to generated primary charged-particles $N_{\text{gen}}^{\text{MC}}$:

$$\epsilon(p_T) = \frac{N_{\text{prim,rec}}^{\text{MC}}(p_T)}{N_{\text{prim,gen}}^{\text{MC}}(p_T)} \quad (3.5)$$

Additionally, the overall efficiency is contingent on the type of particle measured. This prompts for a complementary correction, later on explained, that scales the overall efficiency by means of the relative abundance of each particle type (cite Patricks thesis).

In Figure 3.5, the distribution of the overall efficiency as function of p_T is shown for pp collisions. Here, it can be seen the characteristic p_T -shape also observed in all previous studies of the charged-particle production regardless of the energy or the collision system. In this case, the efficiency amounts to a value constrained

Centrality class	Scaling factor
0-5%	0.982
5-10%	0.990
10-20%	0.999
20-30%	1.006
30-40%	1.012
40-50%	1.016
50-60%	1.019
60-70%	1.020
70-80%	1.021

Table 3.4: Scaling factors obtained from the parametrization of the ratios in Figure 3.6.

between 54% and 75% for the entire p_T range. At low p_T , below 4 GeV/ c , there is a rapid growth of the efficiency which can be explained by the large curvature that the tracks in this p_T -range experience due to the influence of the magnetic field. Such a curvature reduces the uncertainty of the track reconstruction increasing, as result, the overall efficiency. After reaching the maximum, the curve drops quickly and hits its minimum around 1 GeV/ c . This slump is caused mainly by the track length cut listed in Table 3.2. The influence of this requirement on the selection process rises within this particular p_T -range given that the corresponding tracks tend to cross the TPC boundaries reducing hence their probability to be selected. Once this effect fades, the efficiency increases asymptotically due to the acceptance restrictions of the detector.

This same behavior is also observed in Pb-Pb collisions analysed in this thesis as illustrated in Figure 3.6, which shows the overall efficiency in dependency of p_T for MB, central (0 – 5%), semi-central (30 – 40%) and peripheral (70 – 80%) collisions. It can be seen that the tracking efficiency exhibits a certain dependency on the centrality class as it decreases with this quantity. As also observed in this figure, the mid and high p_T ranges of the centrality-dependent efficiencies are dominated by very large statistical fluctuations which would contribute to increase the statistical uncertainties of the later calculated p_T spectra. To avoid that, the ratios of the individual efficiencies to the MB efficiency, illustrated in the bottom panel, are parametrized from a p_T of 2 GeV/ c with a constant function. The obtained factors, summarized in Table 3.4, are used to scale the MB tracking efficiency. As result, The distributions obtained using this approach are

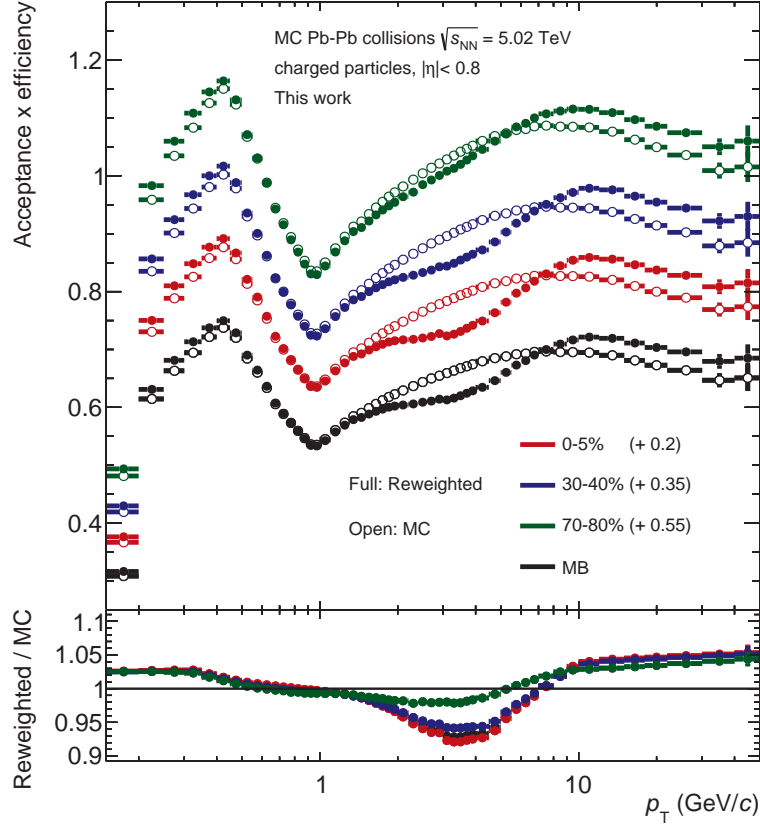


Figure 3.7: Tracking efficiency as function of the transverse momentum for MB, central, semi-central and peripheral Pb-Pb collisions obtained from the scaling of the distributions in Figure 3.6 using the values listed in Table 3.4. The distributions are scaled with an additive factor for a better overview.

represented in 3.7 with open marks.

Dependency on the particle type

Among the primary charged particles that compound the studied sample, a sharp disparity in terms of the lifetime τ is noticeable. For instance, the pions (π^\pm), the most frequent particle type produced in particle collisions, can travel in average 7.8 m within their lifetime, whereas the sigma baryons (Σ^\pm) have a decay length of only 2.4 cm (cite pdg booklet). As consequence, some particles are more likely to be rejected by the track length requirement than others, which creates a dependency of the tracking efficiency on the particle type. The probability P for the measurement of a certain particle of mass m and transverse momentum p_T after crossing a distance d in the detector volume is well-defined by:

$$P = \exp\left(-\frac{d \cdot m}{p_T \cdot \tau}\right) \quad (3.6)$$

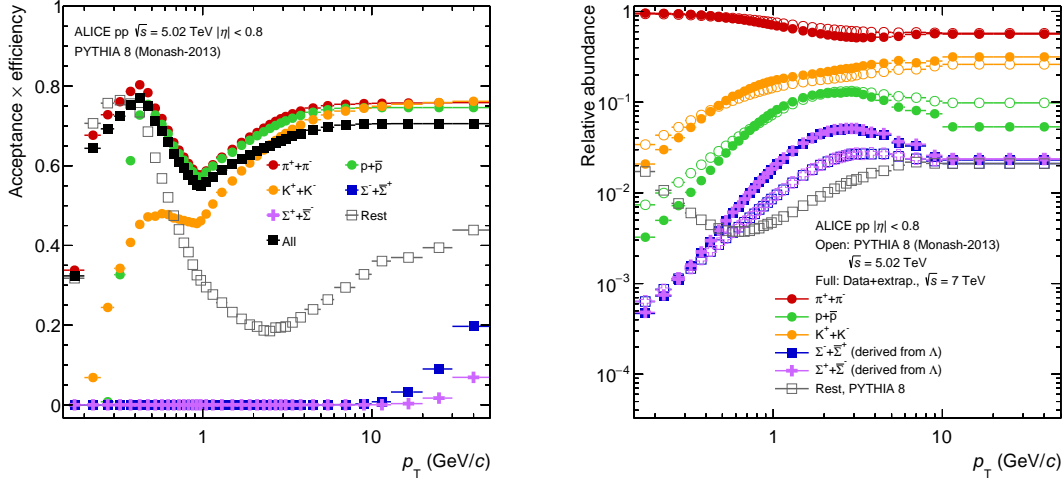


Figure 3.8: **Left:** Tracking efficiencies as function of the transverse momentum for different particle species obtained with a PYTHIA (Monash 13) simulation of pp collisions at $\sqrt{s} = 5.02$ TeV. **Right:** Relative particle abundances in dependency of the transverse momentum in data (full symbols, $\sqrt{s} = 7$ TeV) and in MC (open symbols, $\sqrt{s} = 5.02$ TeV) (cite paper)

The usage of MC event generators, such as PYTHIA or HIJING, allows to obtain the tracking efficiencies for different particle species as shown in the left panel of Figure 3.8. Here, results from an analysis on the particle dependent efficiency for pp collisions at $\sqrt{s} = 5.02$ TeV are presented. As seen in the plot, the dependency of the efficiency on the particle type is strong, specially below 1 GeV/c: while pions (π^\pm) are measured with an above-average efficiency, the probability to detect sigma baryons (Σ^\pm) is significantly smaller or even marginal at low p_T . The efficiency of protons (p) and kaons (K) also improves significantly from the intermediate p_T region. The efficiency for protons even reaches an efficiency higher than the one for inclusive particles for high p_T . In the figure, the efficiency for an amalgam of unidentified charged particles, mainly electrons, muons as well as Ξ and Ω baryons, is also illustrated.

In Pb-Pb collisions, similar effects are observed as can be acknowledged in Appendix A.1. Because of these similarities, the correction procedure is only shown for pp collisions, although an analogous procedure is also implemented for Pb-Pb collisions.

Note that the individual efficiencies were parametrized above 1 GeV/c in order to eliminate statistical fluctuations (cite Patrick). For the parametrization, a combination between Equation 3.6 and the function $f(p_T)$, which describes the exponential behavior of the TPC tracking efficiency, was applied, being $f(p_T)$ given by:

$$f(p_T) = a \cdot (1 - b \cdot e^{-c \cdot p_T}) \quad (3.7)$$

where a , b and c represent free parameters.

Considering the particle dependency of the efficiency, the abundance of each particle type plays an important role and must therefore be reflected in the correction. However, MC event generators present limitations in the description of the particle production, specially in the one regarding strange particles. In fact, the production of the baryons Σ^+ and Σ^- are marked by a significant underestimation as seen in (cite 38,39 paper). As consequence, the efficiency is considerably affected by this underestimation and a correction by means of a reweighting with the relative abundance of each particle type becomes unavoidable.

The relative abundances are determined through a measurement of the production of the above-listed particles. To correct the underestimation of the yield of Σ^+ and Σ^- , the yield of Λ hyperons is used as an approximation. The right plot of Figure 3.8 shows the relative abundances measured in pp collisions recorded by ALICE at $\sqrt{s} = 7$ TeV. For this particular end, this center-of-mass energy will be used since no significant energy dependency has been observed experimentally and because of the lack of experimental data at the energy studied in this work. The relative abundances that result from MC simulations at $\sqrt{s} = 5.02$ TeV using the event generator PYTHIA 8 (Monarch 13) are also shown for comparison purposes. These distributions were calculated using a data-driven procedure detailed in (cite Patrick).

In summary, the overall efficiency for inclusive particles should be understood as a weighted superposition of the individual efficiencies for each particle type with the relative particle abundances. This is expressed by:

$$\epsilon^{\text{corr}}(p_T) = \epsilon_{\text{Rest}}^{\text{MC}}(p_T) \cdot f_{\text{Rest}}^{\text{MC}}(p_T) + \sum_{i=\pi,K,p,\Sigma} \epsilon_i^{\text{MC}}(p_T) \cdot F_i^{\text{MC}}(p_T) \cdot (1 - f_{\text{Rest}}^{\text{MC}}(p_T)) \quad (3.8)$$

where ϵ_i^{MC} is the efficiency for each particle type, $f_{\text{Rest}}^{\text{MC}}$ the p_T dependent relative abundance of unidentified particles and F_i the fraction for each particle type in relation to the total sample. The resulting reweighting factors can be consulted in Appendix A.1.

After applying this reweighting on the distributions represented in Figures 3.5 and 3.7 with open symbols, the corrected tracking efficiencies for inclusive particle are obtained and shown in these same figures with full markers. These distributions are utilized ultimately to correct the p_T distributions.

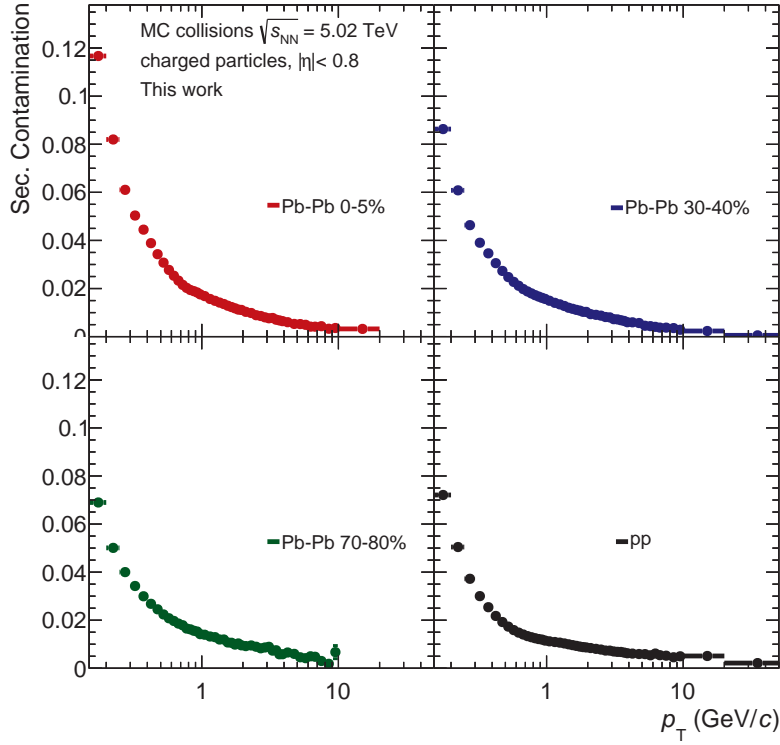


Figure 3.9: Contamination with secondary particles as function of the transverse momentum obtained from MC simulations for pp collisions as well as central, semi-central and peripheral Pb-Pb collisions.

3.4.3 Contamination by secondary particles

Despite the selection procedure described in Section ??, which aims for the elimination of secondary particles from the data sample, a small amount of these particles persists in it. This remnant can be explained by weak decays of kaons, Λ baryons and muons as well as by interactions in the detector material. In any event, the remaining fraction of secondary particles has to be subtracted from the p_T distributions to ensure their purity.

The estimation of contamination by secondaries is carried out using the MC productions anchored to the analysed data periods. In Figure 3.9, the result of these estimations can be seen for pp collisions as well as for MB, central (0 – 5%), semi-central (30 – 40%) and peripheral (70 – 80%) Pb-Pb collisions. In general, a contamination of around 10% at low p_T can be observed. The distributions then decline monotonously with increasing p_T up to reaching a minimum below 1% at the high p_T region. These observations are consistent with the steeply falling form of the p_T distributions and with the assumption that secondaries are inclined to carry small momenta since they correspond essentially to fractions of

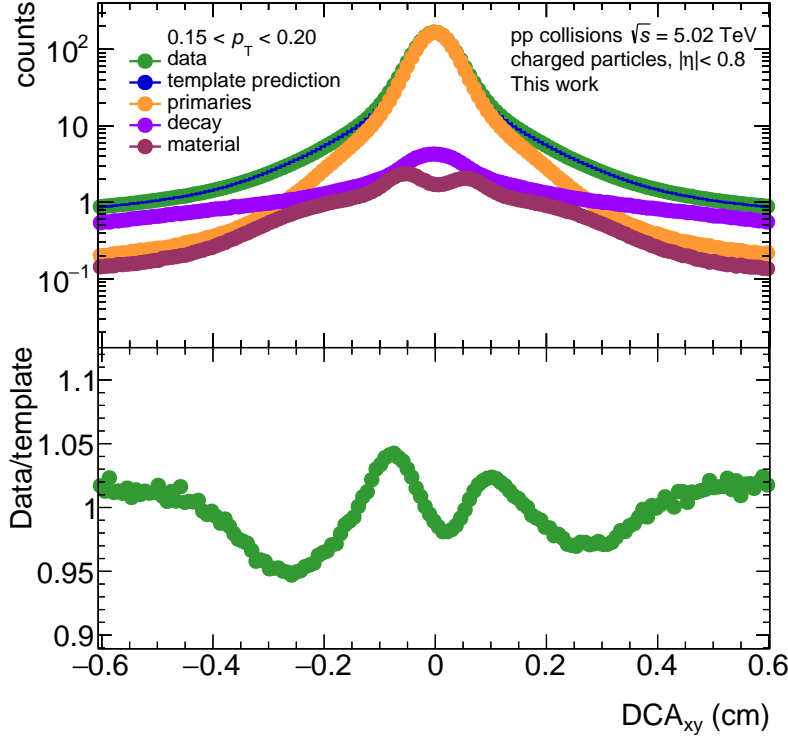


Figure 3.10: DCA_{xy} distributions for data and MC simulations for pp collisions at $\sqrt{s} = 5.02$ TeV for the p_T range $0.15 < p_T < 0.2$ GeV/c. The MC predictions correspond to primaries, secondaries from decay and secondaries from interactions in the detector material. In the bottom panel, the ratio of distribution for data to the fit resulting from the MC templates is shown.

the momenta of the mother particles. A certain dependency of the contamination on the centrality is observed in Pb-Pb collisions. At low p_T , the contamination in central collisions (0 – 5%) amounts to almost twice as much as the contamination in the most peripheral (70 – 80%) collisions. This is result of a suppression of the yield of strange particles observed in systems with low energy densities. The dependence on the centrality dissipates in the high p_T range.

Secondary scaling

As stated in the previous section, MC productions are affected by an underestimation of the yield of strange particles. This limitation distorts the true contamination by secondaries which is not entirely reflected in Figure 3.9. For this reason, an additional correction that scales the contamination according to the relative abundances of primary and secondary charged particles is required. The corresponding scaling must therefore focus on a property which distinguishes between primaries and secondaries. In this regard, the distance of closest

approach (DCA) offers the possibility for a clear discrimination between these two groups given that secondaries present larger values than primaries since they origin, by definition, in a later stage. This implies that the respective DCA_{xy} distributions should describe distinct shapes. The differences should be particular noticeable in the region of the tails, where the largest DCA_{xy} values are located.

In the upper panel of Figure 3.10, MC predictions for pp collisions of the DCA_{xy} for primaries, secondaries from decays and secondaries originated from interactions in the detector material are represented for the lowest p_T interval considered. In fact, it can be observed that significant differences between the distributions arise. Primaries present a shape with a prominent peak at 0 cm that far exceeds the small peak that characterize both distributions for secondaries. The differences become even more marked in the tails, where secondaries, as expected, show much broader curves. In this same plot, the DCA_{xy} distribution for pp collisions recorded by ALICE is also illustrated. This distribution clearly resembles the shape for primary particles since these dominate the particle production. These observations can be extended for the rest of p_T intervals.

The correction used to redress the underestimation of strangeness involves a data-driven approach that fits the data distribution with a linear combination of the MC templates. The most notable feature of the method is that both data and MC statistical uncertainties are taken into consideration in the calculation (cite TFractionFitter). The goal of this template fit is to determine the fraction of primaries and secondaries in the data sample for each p_T range. This is achieved by performing a likelihood fit using Poisson statistics which describes accurately the occurrence of secondaries. The lower panel of Figure 3.10 shows the ratio of the distribution for data to the result of the template fit.

One can predict the fraction of secondaries in data ρ_{Data} by means of the fit and then use this fraction to calculate the factor c_{sec} that scales the contamination in the given p_T with:

$$c_{sec} = \frac{\rho_{Data}}{\rho_{MC}} \quad (3.9)$$

where ρ_{MC} represents the fraction of secondaries in the MC sample.

It is worth pointing out that the track selection must be modified in order to obtain a statistically significant result. In particular, this specific procedure dispenses with the cuts on the DCA_{xy} and on the $\chi^2_{TPC-ITS}$, both of which suppress the yield of secondaries. This modification of the track selection leads to an amount of secondaries sufficiently large to extract scaling factors for a few intervals at low p_T . To adapt this result to the binning of the p_T distributions, the data points within these intervals are constructed by a linear interpolation. For

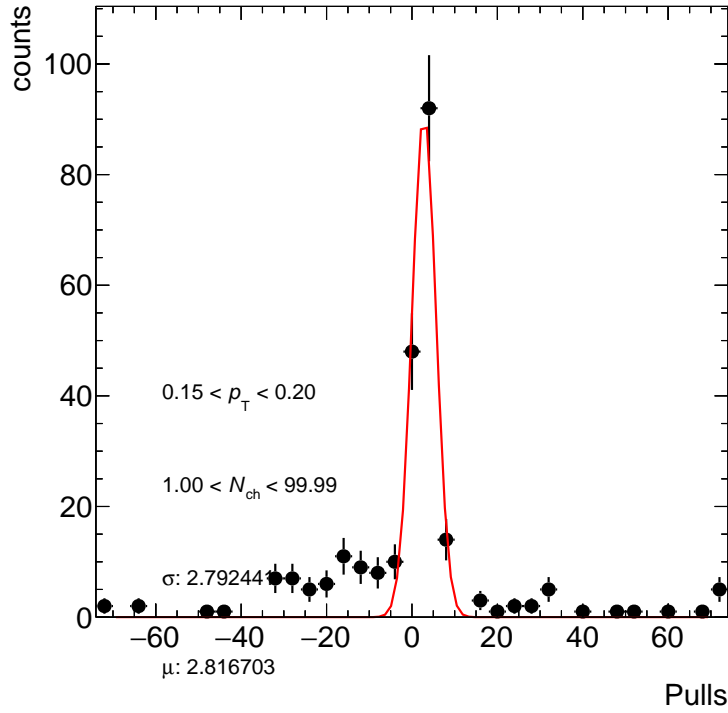


Figure 3.11: Pull distribution obtained from the comparison between the data points and the fit shown in Figure 3.10 for the p_T interval $0.15 < p_T < 0.2$ GeV/c.

the high p_T range, namely from $p_T = 10$ GeV/c, the value of the scaling factor corresponding to the last considered p_T interval is taken as reference since the amount of secondaries varies scarcely beyond this limit (see Figure 3.9).

To ensure the goodness of the fit, two statistical hypothesis tests were implemented: a test regarding a concept of the statistics called pulls and a Pearson's chi-squared test. On the one hand, the binning of the DCA_{xy} distributions as well as the p_T intervals for which the fit is performed are optimized using the so-called pulls (cite paper). Pulls g_i are utilized to test the consistency of a given fit with the fitted data and are defined as follows:

$$g_i = \frac{y_{\text{data},i} - y_{\text{fit},i}}{\sqrt{\sigma_{\text{data},i}^2 + \sigma_{\text{fit},i}^2}} \quad (3.10)$$

where $y_{\text{data},i}$ represents a data point, $y_{\text{fit},i}$ the corresponding prediction of the fit and $\sigma_{\text{data},i}^2$ and $\sigma_{\text{fit},i}^2$ the respective statistical uncertainties. As explained in the referred documentation, it can be proofed that the distribution of pulls in the case of a fit in perfect agreement with the data follows a Gaussian distribution of mean $\mu = 0$ and standard deviation $\sigma = 1$. The limited amount of secondaries as well as the approximations made prevent a perfect pull distribution

in the presented case. Nevertheless, this approach offers the possibility to optimize effectively the DCA_{xy} binning as well as the p_T intervals since these can be easily tuned taken in account the evolution of the pull distribution. In Figure 3.11, the pull distribution for the fit in Figure 3.10 is shown. The mentioned intervals were thus varied until obtaining the pull distribution which shows the best agreement with the standard normal distribution.

The goodness of fit test and the subsequent possible rejection are carried out by means of a Pearson's chi-squared test with a significance level of 0.05 (cite documentation). In this approach, the likelihood ratio χ^2 for the fit as well as the number of degrees of freedom in the fit are computed. The documentation in (cite TFractionFitter) is referred for a complete explanation of the obtainment of these parameters. The significance value and the number of degrees of freedom allow to calculate the critical χ^2 value by means of the quantiles of the chi-squared probability distribution function. According to the chi-squared test, the evaluated fit is rejected whenever the test statistic χ^2 exceeds the critical χ^2 value. All fits used for the calculation of the scaling factors are statistically significant according to this test. The results of the reweighting of the p_T dependent contamination by secondaries with these scaling factors are shown in Figure 3.9 with full markers.

3.4.4 Transverse momentum resolution

The transverse momentum p_T serves in this thesis as the main variable for the study of the charged-particle production. As already seen, the trajectory of a charged particle is characterized by a helical form caused by the prevailing magnetic field. This phenomenon is conditioned by the occurrence of the Lorentz force which connects the radius r of the track curvature with the transverse momentum of the particle p_T :

$$r = \frac{p_T}{e \cdot B} \quad (3.11)$$

where B is the magnetic flux density perpendicular to the particle of charge e . In practice, the measurement of this radius is demanding since even particles with low transverse momenta present radii that far exceed the outer radius of the TPC. For this reason, the radius is substituted by another quantity which parametrizes the track curvature and which can be measured within the detector volume. This is the so-called sagitta, an arc parameter which turns inverse proportional to the radius of the track for the extreme case of a chord $L \ll r$ spanning the base of the arc (cite here):

$$s = \frac{L^2}{8r} \quad (3.12)$$

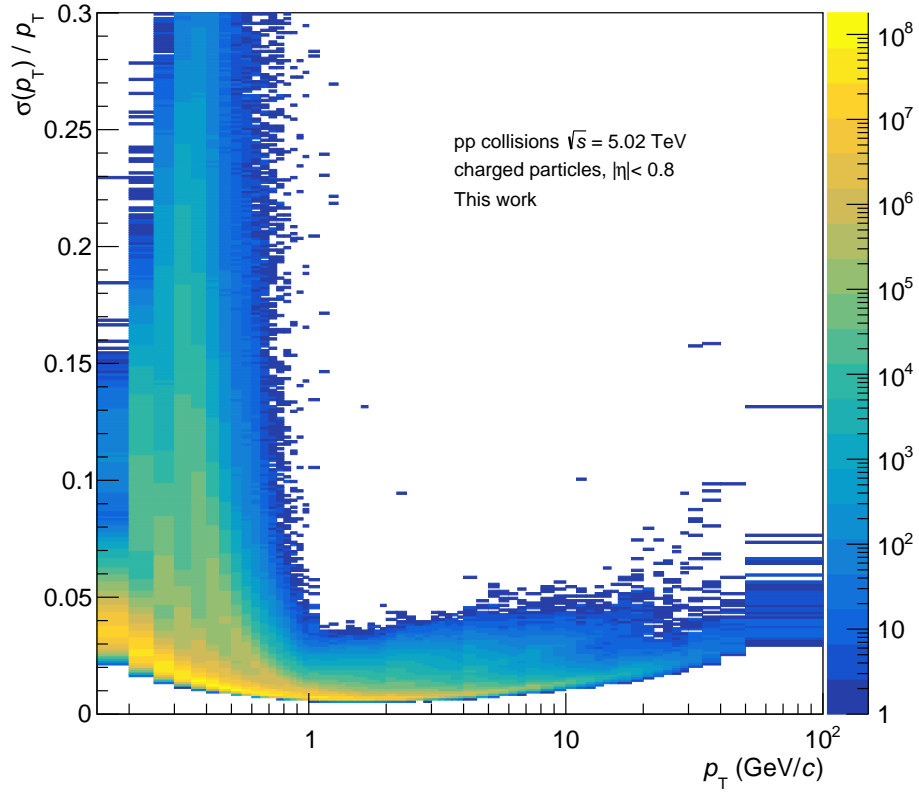


Figure 3.12: Transverse momentum resolution as function of the transverse momentum for pp collisions at $\sqrt{s} = 5.02$ TeV recorded in ALICE in 2017.

Therefore, we obtain for B given in T, L in m and p_T in GeV/c

$$s = \frac{0.3e \cdot B \cdot L^2}{8p_T} \quad (3.13)$$

The inverse of the transverse momentum $1/p_T$ is therefore one of the track parameters provided by the covariance matrix.

The measurement of the sagitta is produced with a certain uncertainty due to the spatial resolution of the detectors which in turn implies that the resulting inverse of the transverse momentum is affected by an uncertainty $\sigma(1/p_T)$. It can be then shown that the relative transverse momentum resolution $\sigma(p_T)/p_T$ is defined by (cite knichel):

$$\frac{\sigma(p_T)}{p_T} \approx p_T \cdot \sigma(1/p_T) \quad (3.14)$$

In Figure 3.13, the relative p_T resolution as function of p_T for the analysed pp collisions is shown. For a more clear representation, this distribution and its analogous in MB Pb-Pb collisions are projected into the x -axis obtaining as re-

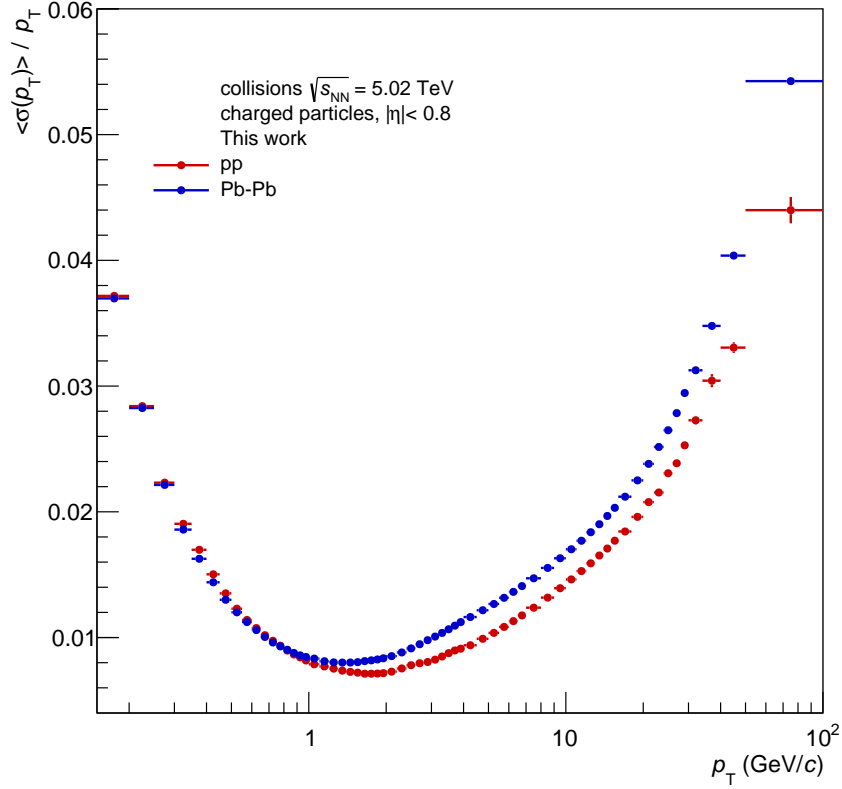


Figure 3.13: After a projection of Figure 3.13 into the x-axis, the mean relative transverse momentum resolution as function of the transverse momentum is obtained for pp and, analogously, for MB Pb-Pb collisions.

sult the mean relative p_T resolution $\langle \sigma(p_T) \rangle$ as function of p_T as shown in Figure 3.12. At low p_T , the relative p_T resolution distributions are influenced mainly by the multiple scattering of the charged particles in the detector material. In this region, the results in pp and Pb-Pb as well as among the different centrality classes resemble each other. At $p_T = 0.15$ GeV/c, the resolution is around 3.7%. The effect of the multiple scattering dissipates gradually until the distribution hits the minimum around 1.5 GeV/c with a p_T resolution of approximately 0.7% in pp and 0.8% in Pb-Pb. At high p_T , charged particles experience a less pronounced curvature according to Equation 3.11, which causes a deterioration of the spatial resolution. As consequence, the uncertainty grows linearly reaching values of 4.4% in pp and 5.4% in Pb-Pb.

The existence of the p_T resolution results in a smearing of the transverse momentum distributions which must be corrected. This effect becomes more notable in the high p_T region of the p_T spectra, where the resolution is most deteriorated. The corresponding correction is thus implemented in the range $7 \leq p_T \leq 100$ GeV/c. The true p_T spectrum results from a convolution between the measured

p_T spectrum and the momentum resolution response function $R(p_T)$ which determines the influence of the detector and tracking procedure on the p_T resolution (cite knichel):

$$\left(\frac{d^2 N_{ch}}{dp_T d\eta} \right)_{\text{measured}}(p_T) = \left(\left(\frac{d^2 N_{ch}}{dp_T d\eta} \right)_{\text{true}} * R \right)(p_T) \quad (3.15)$$

To adjust the smearing in each p_T distribution, a correction by means of a p_T -dependent factor is applied. The approach is based on the notion that this factor corresponds to the quotient of the true p_T distribution and the measured one. Since the true p_T distribution is unknown and assuming that the effect of the above mentioned convolution has a minor impact on it, this quotient can be modified as follows (cite mknichel):

$$C_{\text{res}}(p_T) = \frac{\left(\frac{d^2 N_{ch}}{dp_T d\eta} \right)_{\text{true}}(p_T)}{\left(\frac{d^2 N_{ch}}{dp_T d\eta} \right)_{\text{measured}}(p_T)} \approx \frac{\left(\frac{d^2 N_{ch}}{dp_T d\eta} \right)_{\text{measured}}(p_T)}{\left(\left(\frac{d^2 N_{ch}}{dp_T d\eta} \right)_{\text{measured}} * R \right)(p_T)} \quad (3.16)$$

Due to the impossibility to determine analytically the function $R(p_T)$, the measured p_T distribution is smeared in such a way as to emulate the effect of this function. The same approach is employed in pp and Pb-Pb collisions and its details are outlined in the following.

Calculation of the correction factor

The simulation required for this procedure uses as input a sample of filtered high p_T tracks that underwent the same track requirements summarized in Table 3.2. The corresponding covariance matrix provides the track parameter $\sigma(1/p_T)$ which is considered as function of $1/p_T$ as shown in the top-left panel of Figure 3.14 for the case of pp collisions. This two-dimensional representation is projected into the x-axis producing as result a distribution of the mean uncertainty $\langle \sigma(1/p_T) \rangle$ as function of $1/p_T$. In addition, the projection is parametrized with a quadratic polynomial $n(1/p_T)$ which is then subtracted from the original uncertainty $\sigma(1/p_T)$ in order to reduce statistical fluctuations as seen in the top-right panel of Figure 3.14. The scaled $\sigma(1/p_T)$ distribution (see bottom left panel of Figure 3.14) is subsequently projected into the y -axis obtaining thereby a distribution that reveals the probability function of $\sigma(1/p_T)$ as shown in the bottom-right panel of Figure 3.14.

After determining the shape of $\sigma(1/p_T)$, the smearing of simulated p_T spectra

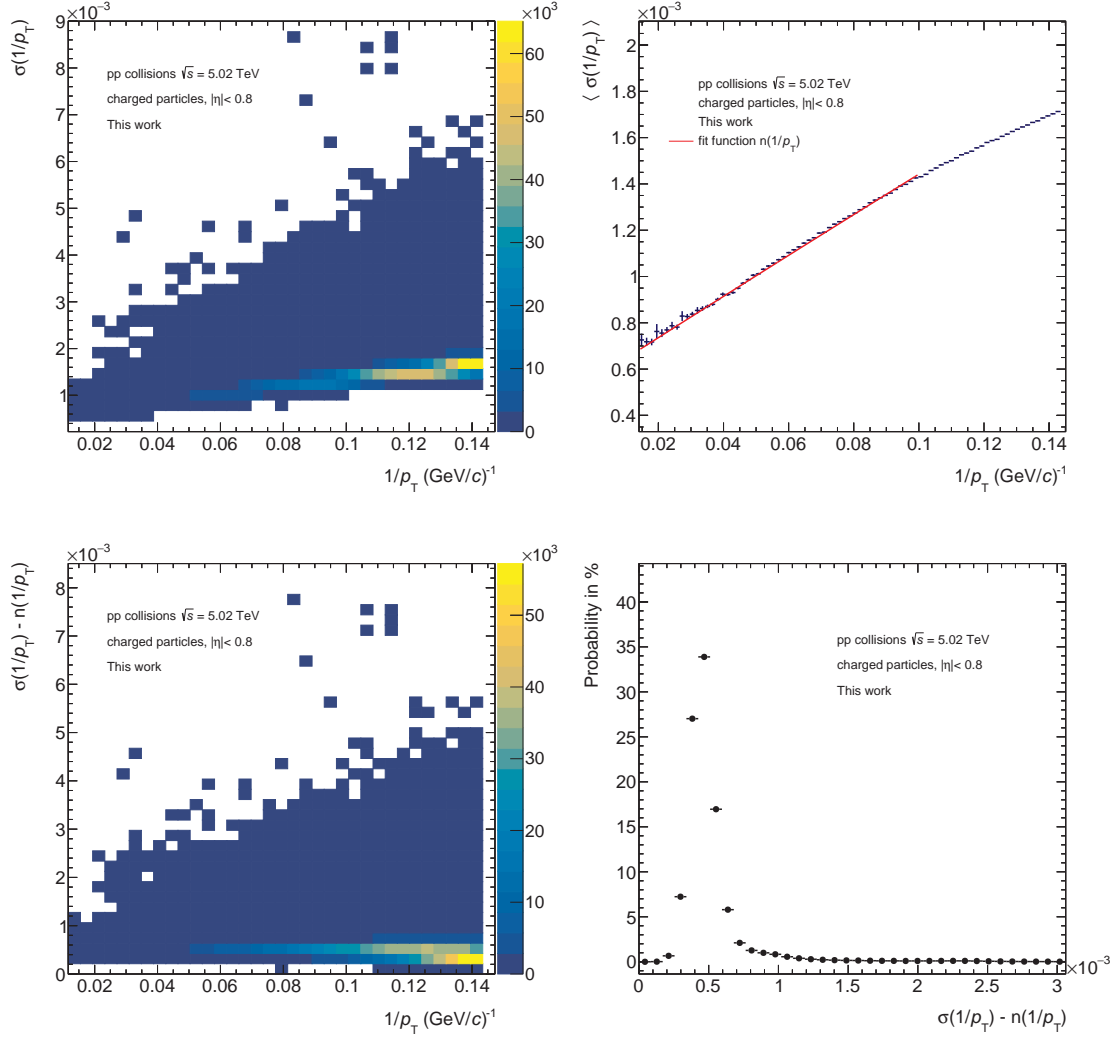


Figure 3.14: **Top.** Left: Two-dimensional distribution of the uncertainty on the inverse of the transverse momentum $\sigma(1/p_T)$ as function of $1/p_T$. Right: Quadratic polynomial parametrization $n(1/p_T)$ of the mean uncertainty $\langle \sigma(1/p_T) \rangle$ as function of $1/p_T$. **Bottom.** Left: Two-dimensional distribution of the scaled uncertainty $\sigma(1/p_T)$ as function of $1/p_T$. Right: Probability function of $\sigma(1/p_T)$ obtained after projecting the scaled uncertainty into the y -axis.

is carried out. In this process, a billion tracks are simulated and distributed according to a power-law fit of a p_T distribution in the range $7 \leq p_T \leq 100$ GeV/ c . As input for that purpose, the p_T spectra from the previous ALICE publication, depicted in Section (cite theo. section), are used given that they offer a better approximation of the true p_T distributions. As consequence, correction factors are calculated for pp collisions and for each centrality class in Pb-Pb.

The starting point towards the calculation of the correction factor is the conversion of each p_T spectrum in a $1/p_T$ distribution. Moreover, a random value $\sigma(1/p_T)_{\text{rand}}$ is generated for each $1/p_T$ interval according to the probability function. This value is re-adjusted with an additive factor extracted from an

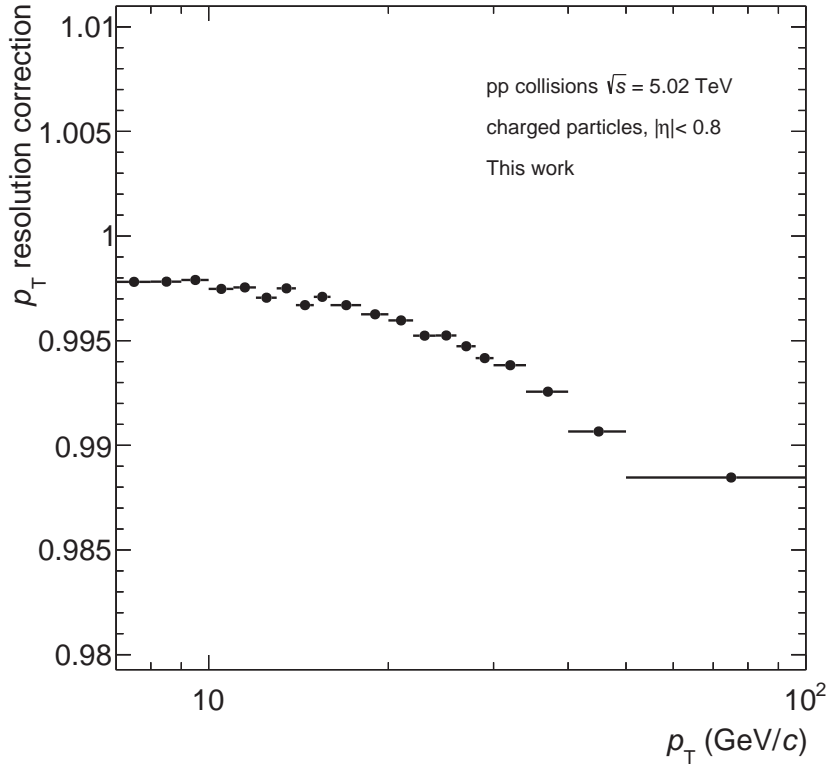


Figure 3.15: p_T resolution correction factor as function of p_T in pp collisions at $\sqrt{s} = 5.02$ TeV recorded in ALICE in 2017.

evaluation of the polynomial $n(1/p_T)$ as re-correction for the above mentioned suppression of statistical fluctuations (see bottom-left panel of Figure 3.14). Each value of the $1/p_T$ distribution is then smeared with a Gaussian of mean p_T and standard deviation $\sigma(1/p_T)_{\text{rand}}$. Finally, the smeared $1/p_T$ distribution is re-converted in a p_T spectrum.

The p_T resolution correction factors are calculated by means of the quotient of the original simulated p_T spectrum and the smeared one. In Figures 3.15 and 3.16, the resulting correction factors for the analyzed pp and Pb-Pb collisions are respectively illustrated. In pp collisions, the correction factor falls monotonically and the effect finds its maximum at the largest p_T interval with a percentage value of around 1.2%. On the other hand, the Pb-Pb results behave similarly as in the pp data collection. Nevertheless, a centrality dependence of the correction factors is observed which reflects that the impact of the correction on the p_T distributions increases with this quantity.

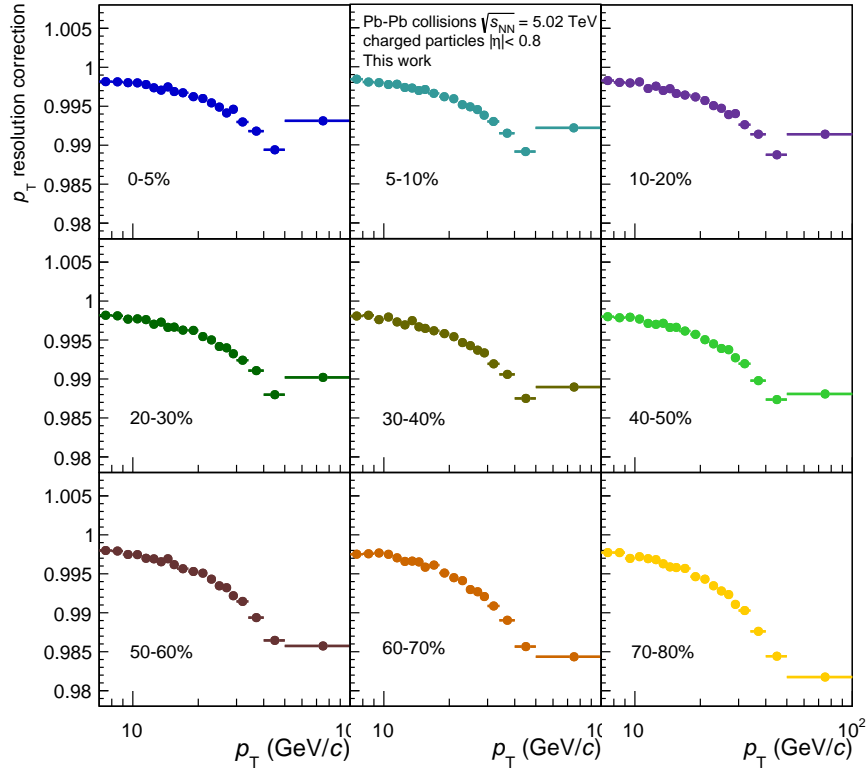


Figure 3.16: p_T resolution correction factor as function of p_T in nine centrality classes collisions of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV recorded in ALICE in 2018.

3.5 Implementation of the corrections

The analysis strategies presented in the previous sections aim to neutralize the effects derived from the detector response and from the limitation of the event and track selection. Both phenomena distort the true picture of the p_T distributions shown in Figure 3.3, a fact that motivates the implementation of the above-described correction methods. As already mentioned, the track-level corrections affect the spectral shape of the primary track distribution $N(p_T)$. The corrected primary track distribution $N_{\text{corr}}(p_T)$ can be defined follows (cite mknichel):

$$\begin{aligned}
 N_{\text{corr}}(p_T) = & N(p_T) \times c_\epsilon(p_T) \cdot c_{\text{par comp}}(p_T) \\
 & \times (1 - c_{\text{cont}}(p_T) \cdot c_{\text{sec sca}}(p_T)) \\
 & \times c_{\text{reso}}(p_T) \times c_{\text{sig loss}}(p_T)
 \end{aligned} \tag{3.17}$$

where c_i represent the contributions of each correction: $c_\epsilon(p_T)$ is the tracking efficiency, $c_{\text{par comp}}(p_T)$ the particle composition, $c_{\text{cont}}(p_T)$ the secondary contamination, $c_{\text{sec sca}}(p_T)$ the secondary scaling, $c_{\text{reso}}(p_T)$ the p_T resolution and

$c_{\text{sig loss}}(p_T)$, which is only applied in pp collisions. Once the corrections are implemented, the p_T distributions can be declared following the definitions explained in Section (cite theory section). According to the definition of the nuclear modification factor, the results in pp collisions are expressed in form of a differential cross section:

$$\frac{d^2\sigma_{\text{ch}}^{\text{pp}}}{d\eta dp_T} = \sigma_{\text{vis}} \cdot \frac{1}{N_{\text{INEL}}} \cdot \frac{d^2N_{\text{corr}}^{\text{pp}}}{d\eta dp_T} \quad (3.18)$$

where N_{INEL} corresponds to the total number of inelastic events and σ_{vis} the visible inelastic cross section as already explained in Section 3.4.1. In the case of Pb-Pb collisions, the physical quantity used for the determination of nuclear modification factors is the invariant yield and it is calculated as follows

$$\frac{d^2N_{\text{ch}}^{\text{Pb-Pb}}}{d\eta dp_T} = \frac{1}{N_{\text{INEL}}} \cdot \frac{d^2N_{\text{corr}}^{\text{Pb-Pb}}}{d\eta dp_T} \quad (3.19)$$

3.6 Systematic uncertainties

The p_T distributions as well as the nuclear modification factors are affected by uncertainties product of inaccuracies in the measurement instruments or assumptions made during the development of the analysis approaches. These are the so-called systematic uncertainties. In this thesis, the source of systematics considered arises from the track selection criteria and from the secondary scaling correction. However, other sources of systematic uncertainties have been identified in a previous analysis of nuclear modification factors (cite paper). In this chapter, these sources will be described and the correspondent contributions will be assumed for the presented results.

Each source of systematic uncertainty σ_i^{sys} contributes to the total systematic uncertainties $\sigma_{\text{tot}}^{\text{sys}}$ independently of the rest. For this reason, the total value of $\sigma_{\text{tot}}^{\text{sys}}$ is calculated via the root sum squared method:

$$\sigma_{\text{tot}}^{\text{sys}} = \sqrt{\sum_i \sigma_i^{\text{sys}}} \quad (3.20)$$

In the following sections, the approaches applied for the calculation of the individual contributions σ_i^{sys} are explained in detail.

3.6.1 Track selection

As in Section 3.3 explained, the track selection has been develop in the course of the years and validated through cross-checks. Nevertheless, the choice of the selection criteria, yet justified via these studies, is intrinsically subjected to a

Track cut	Condition	Variations	
Selection of primaries			
DCA _z	≤ 2 cm	1 cm	5 cm
DCA _{xy}	≤ 7σ	4σ	10σ
ITS selection			
at least one hit in the SPD	required	not required	
χ ² per ITS cluster	≤ 36	≤ 25	≤ 49
TPC selection			
χ ² per TPC cluster (pp collisions)	≤ 4.0	≤ 3.0	≤ 5.0
χ ² per TPC cluster (Pb-Pb collisions)	≤ 2.5	≤ 1.7	≤ 3.4
fraction of shared TPC clusters	≤ 0.4	≤ 0.2	≤ 1.0
ratio of crossed rows over findable clusters	≥ 0.8	≥ 0.7	≥ 0.9
geometric length (dead TPC area)	3 cm	2 cm	4 cm
geometric length (track length)	130	120	140
TPC-ITS selection			
χ ² TPC constrained track vs. global track	≤ 36	≤ 25	≤ 49

Table 3.5: Variations for the standard track selection criteria used for the calculation of the systematic uncertainties.

systematic uncertainty. Each criterion contributes independently of the rest to the systematic uncertainties of the p_T spectra, and as a consequence, of the nuclear modification factors. Due to this combination of the individual systematic uncertainties σ_i^{sys} , the total value $\sigma_{\text{tot}}^{\text{sys}}$ results from the root sum squared method: To determine the individual contributions, each nominal track requirement listed in Table 3.2 is varied twice within a range in which it is believed to be physically meaningful. The variations correspond to the maximum and the minimum of this range. The mentioned variations are listed in Table 3.5. Next, the analysis approach is repeated by performing one variation at a time and calculating the corresponding fully corrected p_T distribution. These p_T distributions are compared to the nominal one by means of a ratio, obtaining as result two ratios for each track cut, with the exception of the required hit in the SPD. Finally, the two ratios are evaluated in each p_T interval and the largest deviation from the

nominal p_T spectrum between the both of them is assumed as systematic uncertainty in the corresponding p_T interval. Thereby, the systematic uncertainty corresponding to each track cut is presented as function of p_T as shown in Figure ???. The combined systematic uncertainty is calculated subsequently applying a root sum squared in each p_T interval.

In the previous analysis of nuclear modification (cite paper), the systematic uncertainties of the nuclear modification factors were calculated propagating the uncertainties of the p_T distributions used for their calculation. In thThis same approach is also used to determine the systematic uncertainties that affect the nuclear modification factors as seen in Figure ??.

4 Results

Appendices

A Appendix

A.1 Tracking efficiency