



UNIVERSIDADE ESTADUAL DE CAMPINAS

Instituto de Física “Gleb Wataghin”

Danilo Silva de Albuquerque

**Hádrons multi-estranhos em colisões Pb–Pb no LHC
com o ALICE**

**Multi-strange hadrons in Pb–Pb collisions at the LHC
with ALICE**

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Tese apresentada ao Instituto de Física “Gleb Wataghin” da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Ciências.

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Supervisor: Prof. Dr. Jun Takahashi

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Resumo

Um estado da matéria altamente interagente, conhecido como o Plasma de Quarks e Glúons (QGP, do inglês Quark-Gluon Plasma), é produzido nas condições de alta temperatura e densidade de energia atingidas em colisões de íons pesados ultra-relativísticos, como as colisões de Pb–Pb medidas no Grande Colisor de Hádrons (LHC, do inglês Large Hadron Collider). Uma medida chave para a compreensão das propriedades do QGP produzido nestas colisões é taxa de produção de bárions estranhos e multi-estranhos. ALICE (do inglês, A Large Ion Collider Experiment) é um dos quatros principais experimentos em atividade no LHC e tem detectores especialmente projetados para estudar taxas de produção de partículas identificadas em colisões de íons pesados. A excelente capacidade para reconstrução de trajetórias e identificação de partículas permite a reconstrução de bárions multi-estranhos (Ξ^- , Ξ^+ , Ω^- e $\bar{\Omega}^+$), através de canais de decaimentos fracos, em uma larga faixa de momento transversal (p_T). Nesta tese, estudamos a produção de partículas multi-estranhas na região de rapidez central em colisões de Pb–Pb medidas pelo ALICE na nova energia de $\sqrt{s_{NN}} = 5.02$ TeV e em 2.76 TeV. As taxas de produção obtidas são normalizadas pelas medidas correspondentes para píons na mesma classe de centralidade para estudar o aumento relativo da produção de bárions multi-estranhos, que é um dos sinais propostos do QGP. Comparações da razão de híperons para píons entre diversos sistemas, como colisões de pp, p–Pb e Pb–Pb, mostram que a taxa produção de bárions multi-estranhos em relação a píons segue uma evolução contínua desde colisões pp de baixa multiplicidade até colisões centrais de Pb–Pb.

Palavras-chave: Grande Colisor de Hádrons, Produção de Estranheza, Experimento ALICE, Plasma de Quarks e Gluons

Abstract

A strongly interacting state of matter known as the Quark-Gluon Plasma (QGP) is formed in the high temperature and high energy density conditions reached in ultra-relativistic heavy-ion collisions, such as the Pb–Pb collisions measured at the Large Hadron Collider (LHC). One of the key measurements for the understanding of the properties of the QGP medium created in these collisions is the production of strange and multi-strange hadrons. ALICE is one of the four major experiments of the LHC and has a detector designed to study identified particle production rates from heavy-ion collisions. The excellent tracking and particle identification capabilities allow the reconstruction of multi-strange baryons (Ξ^- , Ξ^+ , Ω^- and $\bar{\Omega}^+$) via their weak decay channels over a large range in transverse momentum (p_T). In this thesis, we study the multi-strange particle production at central rapidity Pb–Pb collisions measured by ALICE at the unprecedented energy of $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV. The yields are normalized by the corresponding measurement of pion production in the same centrality class in order to study the strangeness enhancement, effect predicted as a probe of the QGP. Comparison of hyperon-to-pion ratio between different systems, such as pp, p–Pb and Pb–Pb collisions, shows that production of multi-strange baryons relative to pions follows a continuously increasing trend from low multiplicity pp to central Pb–Pb collisions.

Keywords: Large Hadron Collider, Strangeness Production, ALICE Experiment, Quark-Gluon Plasma

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Chapter 1

Introduction

One of the major goals of the relativistic heavy-ion (HI) program at the LHC is to study nuclear matter under extreme conditions, where a novel state of matter called Quark-Gluon Plasma (QGP) is expected to be produced. In this chapter, we discuss why HI collisions are used to study the QGP and the importance of measuring strange particles in this context.

1.1 Matter under extreme conditions

The hadrons that constitute the nuclei are composed of elementary particles, quarks and gluons, that are confined by the strong interaction in the context of the Quantum Chromodynamics theory (QCD).

Lattice QCD results [1–3] show a phase transition for the QCD matter, suggesting that the partonic degrees of freedoms are excited for extremely high temperature (about 10^5 times the temperature of the Sun’s core) and density. As an example, Fig. 1.1 shows the fast increase of the energy density of a system, used here as a proxy to the thermodynamics degrees of freedom, around a critical temperature, T_c . The value of this temperature depends on the assumptions of the model, ranging from 150 to 175 MeV. Therefore, the temperatures of the system for different models are normalized to T_c to improve the comparison. The study of this phase transition can shed further light on the phase diagram of QCD matter, sketched on Fig 1.2.

For small baryonic potential ($\mu_B \approx 0$), the order of this phase transition is dependent on

the quark masses and number of flavours. For three-flavour QCD (u,d,s) with massless quarks, the transition is of the first-order type. When considering physical masses for the quarks ($0 < m_u = m_d < m_s$), this transition is of the crossover type, with a smooth transition between the Hadron Gas (HG) at low temperatures and the QGP at higher temperatures [4–6].

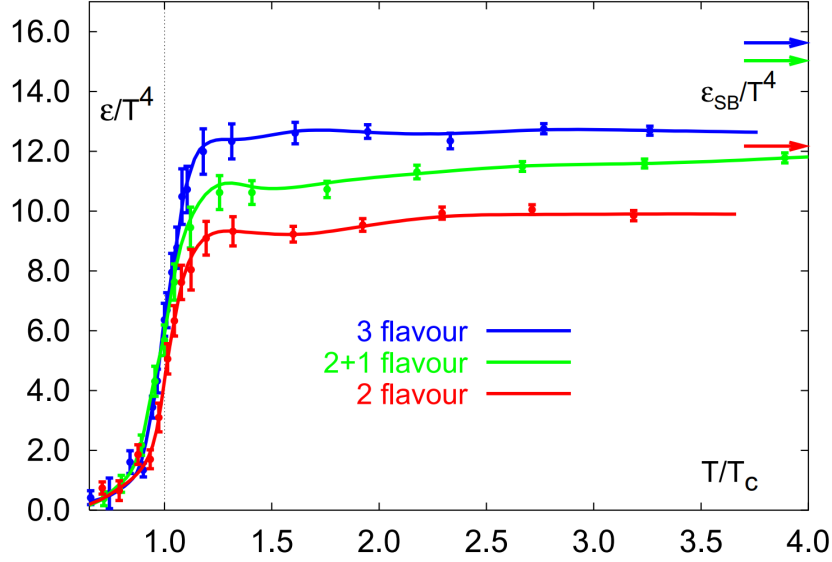


Figure 1.1: The energy density in lattice QCD calculations, used here as a proxy to the thermodynamics degrees of freedom of the system. A crossover transition phase is observed around $T = T_c$, when the partonic degrees of freedom are excited [1].

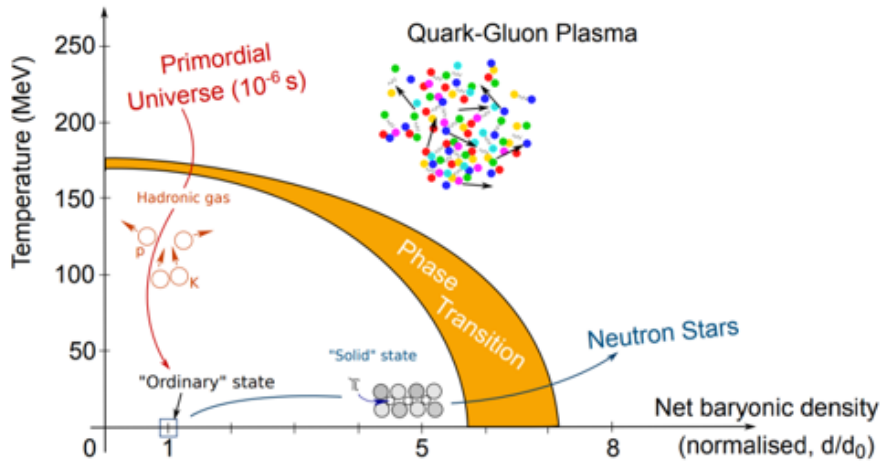


Figure 1.2: Sketch of the QCD phase diagram, from [7].

In order to achieve such extreme conditions, ultra-relativistic heavy-ion collisions are employed. The energy density achieved in this scenario is expected to be enough for the QGP

transition, with the high number of nucleons (208 for Lead ions) with collision energy of up to 5.02 TeV per nucleon pair in a region with radius in the atomic scale.

1.2 Strangeness as a QGP signature

The particles discussed in this thesis (Ξ and Ω) are known as hyperons for having at least one strange quark (s). Being of second generation, s quarks are only present in the original nuclei (before the collision) as sea quarks and in negligible numbers, in comparison to the number of s and $\bar{s}$ inside hadrons after in the collision. Therefore, most of the strangeness is produced in the collision. Furthermore, the small mass of these quarks – close to the temperature of the QGP transition – allows for thermal production of s and $\bar{s}$ pairs through the annihilation of gluon pairs, see sketch of Fig. 1.3. The abundant presence of gluonic excitations is also responsible for a fast rate of thermalization. Compared to a Hadron Gas scenario (HG), the QGP formation would lead to an enhancement of multi-strange hadrons with respect to non-strange particle production. Historically, the *strangeness enhancement* was the first proposed signature for the QGP, by Rafelski and Müller in the late 80's [8, 9].

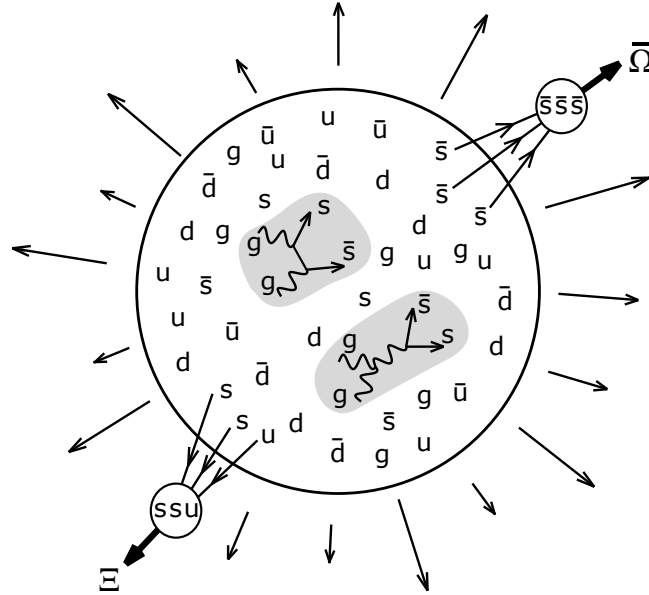


Figure 1.3: Multi-strange (anti-)baryons production in a deconfined medium. Figure adapted from [10].

This enhancement was observed in HI collisions from energy ranges of the CERN Super Proton Synchrotron (SPS), with $\sqrt{s_{NN}} = 17.3$ GeV, through the Relativistic Heavy Ion Collider (RHIC), with $\sqrt{s_{NN}} = 200$ GeV, and confirmed by ALICE at LHC with collisions of $\sqrt{s_{NN}} = 2.76$ TeV [11–18]. Figure 1.4 shows the total production rate (yield) of Ξ and Ω at mid-rapidity ($|y| < 0.5$) normalized by the average number of nucleons that interacted in the collision, $\langle N_{\text{part}} \rangle$, relative to pp/p-Be as a function of $\langle N_{\text{part}} \rangle$. The increase of the production rate of strange particles with respect to pp collisions (where no QGP was expected) is clear, with up to 20 more Ω per event for the most central event class of analysed by the NA57 experiment.

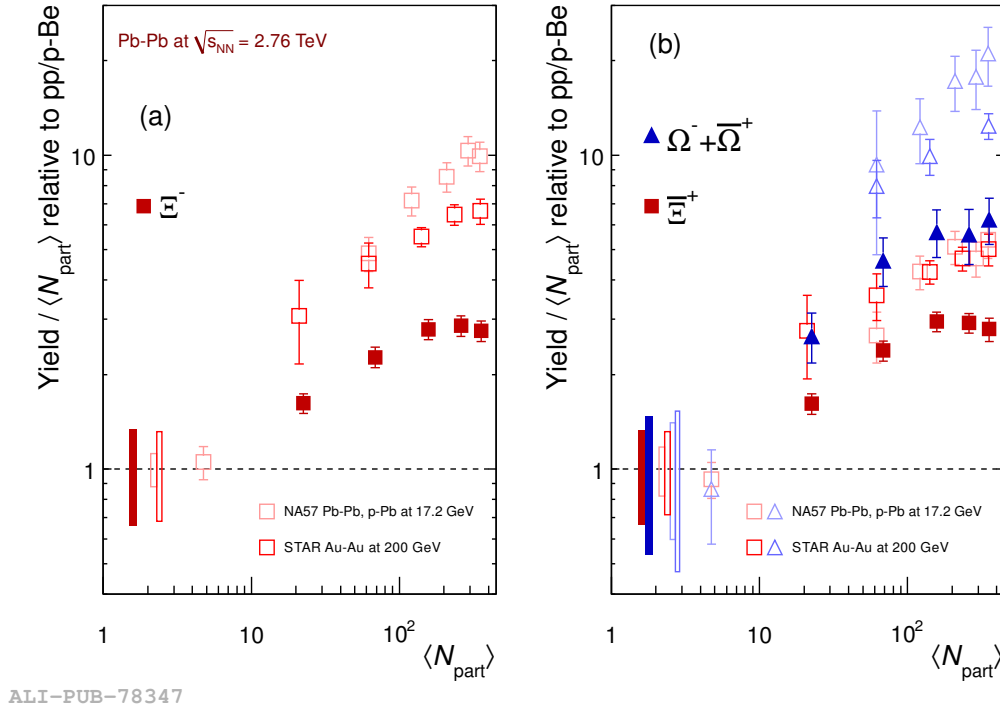


Figure 1.4: Enhancement of multi-strange particles in the mid-rapidity range ($|y| < 0.5$) as a function of the number of nucleons participants in the collisions, $\langle N_{\text{part}} \rangle$, observed at the LHC (ALICE with full markers), RHIC and SPS (light hollow markers). Boxes on the dashed lines represents the statistical and systematic uncertainties of the pp/p-Be reference. Figure published in [18].

The increase of the relative hyperon production with multiplicity can also be understood as the removal of the Canonical Suppression [19–21]. For small systems, exact quantum numbers

conservation is required, unlike AA where the larger volume allows for the treatment within the grand-canonical formalism. In this context, the exact conservation of the quantum number is enforced by working in the canonical ensemble for the statistical model. This conservation leads to a reduction of the phase space available for particle production, which reduces the relative strangeness production for smaller systems. The effect of the removal of this suppression as the system size increases can be seen in Fig. 1.5, where predictions of hyperon production in the canonical ensemble [22] are shown. Moreover, we observe the quark content hierarchy, with Ω being the most affected by this model. The predictions also show a saturation around $\langle A_{\text{part}} \rangle 100$, where the enhancement becomes almost constant. For comparison, data from WA97 is also shown [12].

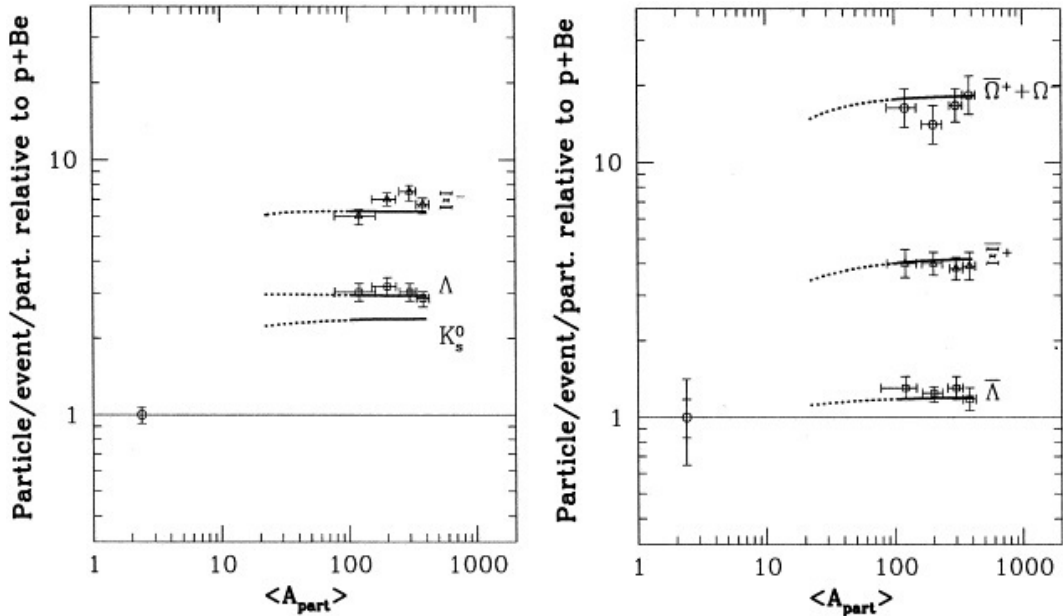


Figure 1.5: Strangeness enhancement calculated in the canonical ensemble, with the particle yields/participant for strange baryons and antibaryons as a function of the number of participant nucleons, $\langle A_{\text{part}} \rangle$, together with data of Pb–Pb relative to p–Be from WA97 [12]. Figure from [22].

One of the main differences between the predictions of these two models is related to the ϕ meson production. Being composed of strange quark and anti-quark pair, this particle has zero net strangeness and charge, therefore should not be subjected to the canonical suppression

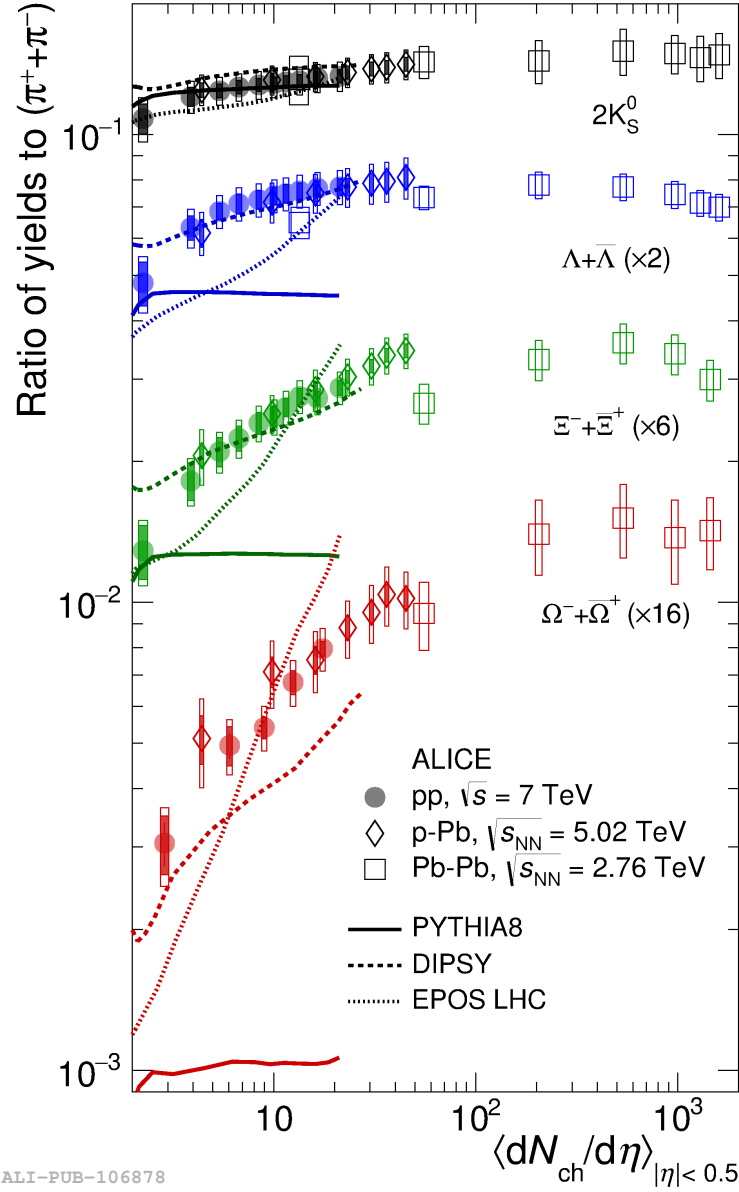
mechanism. On the other hand, the ϕ meson production should increase with multiplicity in the context of the classic strangeness enhancement mechanism – which is due to strange quark/antiquark production through gluon pairs annihilation. Not only that, being composed of two strange quarks, its enhancement should be similar to the one observed for Ξ .

Moreover, a similar enhancement can also be achieved in a scenario without QGP [23–25]. In this model, the particle production in hadron collisions is based on the Lund string fragmentation model [26]. Usually, strings – the confined colour field – are treated independently, with independent hadronization for each hard-scattering in a nucleon-nucleon collision. However, as number of nucleon-nucleon collisions per event increases, so does the string density in the event. By allowing strings that originates from different hard-scattering to fuse, in what is known as a colour rope, it is possible to obtain a higher yield of strange particles and baryons.

In the experimental side, recent ALICE results [27–29] show that the hyperon-to-pion ratio as a function of the charged particle at mid-rapidity in the final state has an universal behaviour across different collision systems and energies, showing a continuous increase from low multiplicity pp collisions, through the intermediate system of p–Pb and reaching a saturation value for central Pb–Pb collisions, as can be seen in Fig. 1.6. Furthermore, we see that the usual string fragmentation model (shown here as the PYTHIA8 curve) alone cannot describe the data well [30], only after the inclusion of the colour rope mechanism, present in the DIPSY model [31], we achieve a good agreement between data and model.

Therefore, it is vital to perform this measurement in the higher energy of $\sqrt{s_{NN}} = 5.02$ TeV and test if this universal behaviour is also present. Moreover, the comparison between Ξ and ϕ production rates is of great importance to understand which mechanism drives the observed strangeness enhancement. Finally, the production rates of multi-strange particles are compared to model predictions in two scenarios: one with an initial hydrodynamic evolution simulating the QGP phase and other where the nucleon-nucleon interactions are simulated with PYTHIA8, where the hadronization is performed via the Lund string model. This way, we can study the multi-strange particle production in collisions with/without the QGP phase.

During the analysis of the higher energy data, a re-analysis of the previous measurement



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Figure 1.6: Relative strangeness productions (measured as the to-pion-ratio of the total yield) as a function of $dN_{ch}/d\eta$ in the mid-rapidity region measured by ALICE in different colliding systems [27–29]. Here, the pseudorapidity, η , is used to define the mid-rapidity region. Therefore, the charged tracks used in the definition of $dN_{ch}/d\eta$ are required to have $|\eta| < 0.5$. More information about this geometric variable is found in Section 2.1. The empty and dark-shaded boxes show the total systematic uncertainty and the contribution uncorrelated across multiplicity intervals, respectively. The lines represent theoretical predictions from different models [30–32]. A continuous increase can be seen across the full multiplicity range, showing a universal behaviour in the to-pion-ratio in the strange sector. Figure from [29].

[28] was performed. This way, during this thesis, results from both $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ and $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ will be shown.

Chapter 2

A Large Ion Collider Experiment

The Large Hadron Collider (LHC) is currently the world's largest and most powerful particle accelerator. It consists of a two-ring superconductor accelerator and collider, installed in a 27-kilometer ring of superconducting magnets. It was designed to unravel fundamental open questions in physics such as the mass generation for the elementary particles by the Higgs mechanism and the properties of the quark-gluon plasma (QGP), a state of hadronic matter believed to have existed in the early universe.

Heavy-ion collisions are part of the LHC program since its conceptual design through the collisions of fully-stripped lead ions $^{208}\text{Pb}^{82+}$. In this context, ALICE (A Large Ion Collider Experiment) is a general-purpose heavy-ion experiment designed to study the physics properties of the strongly interacting matter produced in collisions of relativistic nuclei, including the QGP state of matter [33]. The detector is designed to cope with the extremely high-energy density produced in nucleus-nucleus collisions (with charged particles at mid rapidity of up to 8000), and provide good tracking, particle identification and vertexing capabilities making it especially suited to measure nucleus-nucleus collisions. Collisions of protons and lighter ions are also addressed by ALICE, with measurements for pp and p-Pb collisions and the unprecedented collision system of Xe-Xe, recorded during 2018. The collisions of lighter nuclei provide a way to vary the system size formed in these collisions and the pp collisions can be used as reference data for the heavy-ion collisions. On top of that, dedicated physics studies of the pp data are

also performed.

In this chapter, we introduce the relevant kinematic variables and the main subdetector used in this study. The particle identification technique and the centrality determination strategy used in this analysis are also discussed.

2.1 ALICE coordinate system and relevant variables

The ALICE detector has the typical collider geometry, with cylindrical symmetry around the beam pipe. However, the detector is asymmetrical along the beam direction with a dedicated detection system, known as the muon arm, installed in one of its extremities and responsible for the detection of charged particles produced with small angles with respect to the beam pipe. The global ALICE coordinate system [34], depicted in Fig. 2.1, is a right-handed orthogonal Cartesian system, with origin at the center of the main tracking detector system. The z -axis is defined to be along the direction of the incident beam, pointing away from the muon arm. The $\hat{x}$ is in the horizontal plane and points to the center of the LHC ring. The $\hat{y}$ direction is chosen to define a right-handed system, therefore pointing upwards.

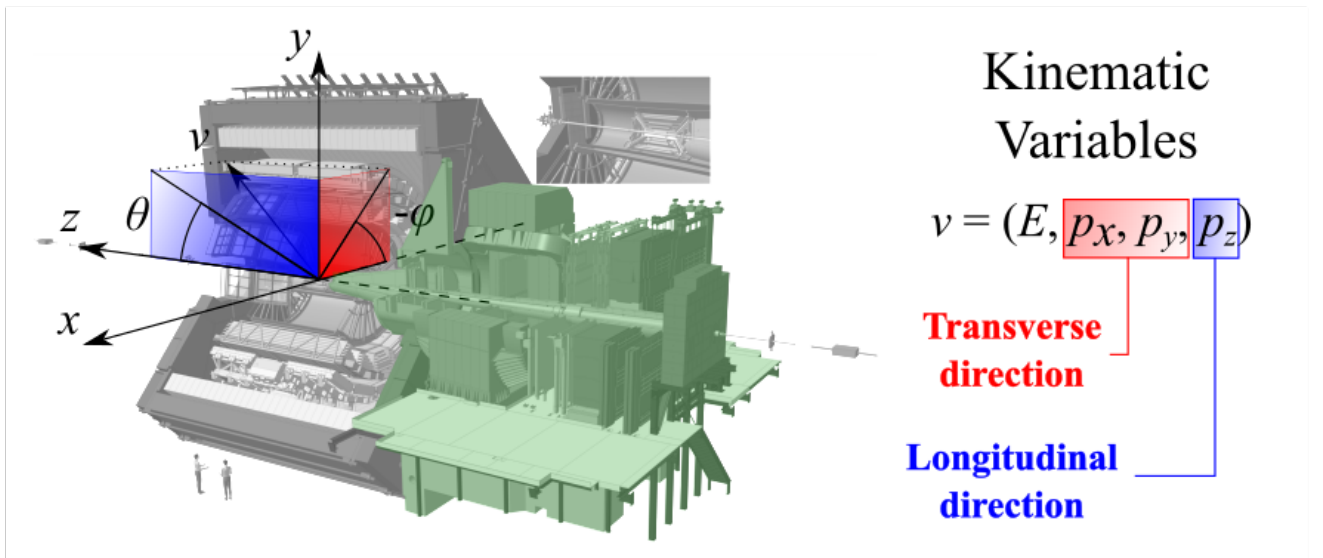


Figure 2.1: ALICE coordinates system and relevant variables. The muon arm system is highlighted here in light green. Adapted from [35].

It is possible to divide the relevant kinematic variables of a collision in two types: transverse and longitudinal variables [36]. We can define the transverse momentum of a particle as

$$p_T^2 = p_x^2 + p_y^2, \quad (2.1.1)$$

where p_x and p_y are the momentum components along the x and y axis. Before the collision, the p_T of the colliding particles is close to zero. Therefore, the transverse plane is associated to quantities created in the collision.

The most-used longitudinal variable in this study is the pseudorapidity, η , given by:

$$\eta = \frac{1}{2} \ln \left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right) = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (2.1.2)$$

where $\vec{p}$ is the momentum vector for a given particle, $p_z = \vec{p} \cdot \hat{z}$ is the particle momentum component along the z axis and θ is the angle between the particle momentum and the z axis, as shown in Fig. 2.1. The fact that the pseudorapidity is independent of the particle mass allows us to compute it for all charged tracks measured by the detector.

Another important longitudinal variable is the rapidity, y , given by:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.1.3)$$

where E is the total energy of the particle. Even though this dimensionless quantity depends on the reference system, the dependence is very simple: the rapidity of a particle in one reference system is related to the rapidity in another Lorentz frame of reference by an additive constant [36], making this variable especially useful for fixed target experiments or asymmetrical collisions (such as p-Pb) since, in these situations, the laboratory reference frame is not the center of mass reference frame. Since in order to compute E it is necessary to know the particle mass (and therefore its identity), this quantity can only be computed for identified particles.

The longitudinal variables can be used to define the forward and mid-rapidity region. Particles produced with small θ (pointing approximately in the direction of the beam) are associated

to the forward region, with usually $|\eta| \gtrsim 3$. Similarly, by requiring the particle to have $\theta \approx \pi/2$, it is possible to define the mid-rapidity region, with $|\eta| < 0.5$, being closely associated with the transverse direction.

As previously mentioned, the transverse direction is associated with particle production in the collision. Therefore, one of our interests is the computation of the transverse momentum spectrum of charged particles. This distribution is usually denoted in the literature as

$$\frac{d^2N}{dp_T dy} = f(p_T). \quad (2.1.4)$$

The formal way to define this distribution is the following:

$$f(p_T) = \frac{1}{\int_{y_{\text{inf}}}^{y_{\text{sup}}} dy} \int_{y_{\text{inf}}}^{y_{\text{sup}}} \frac{d^2N}{dp_T dy} dy \approx \frac{1}{\Delta y} \left(\frac{dN}{dp_T} \right)_{y=0}, \quad (2.1.5)$$

where y_{inf} and y_{sup} are the rapidity limits of the analyzed particles and $\Delta y = y_{\text{sup}} - y_{\text{inf}}$. Here, we assume that, by making Δy small enough, dN/dp_T is constant in this rapidity interval.

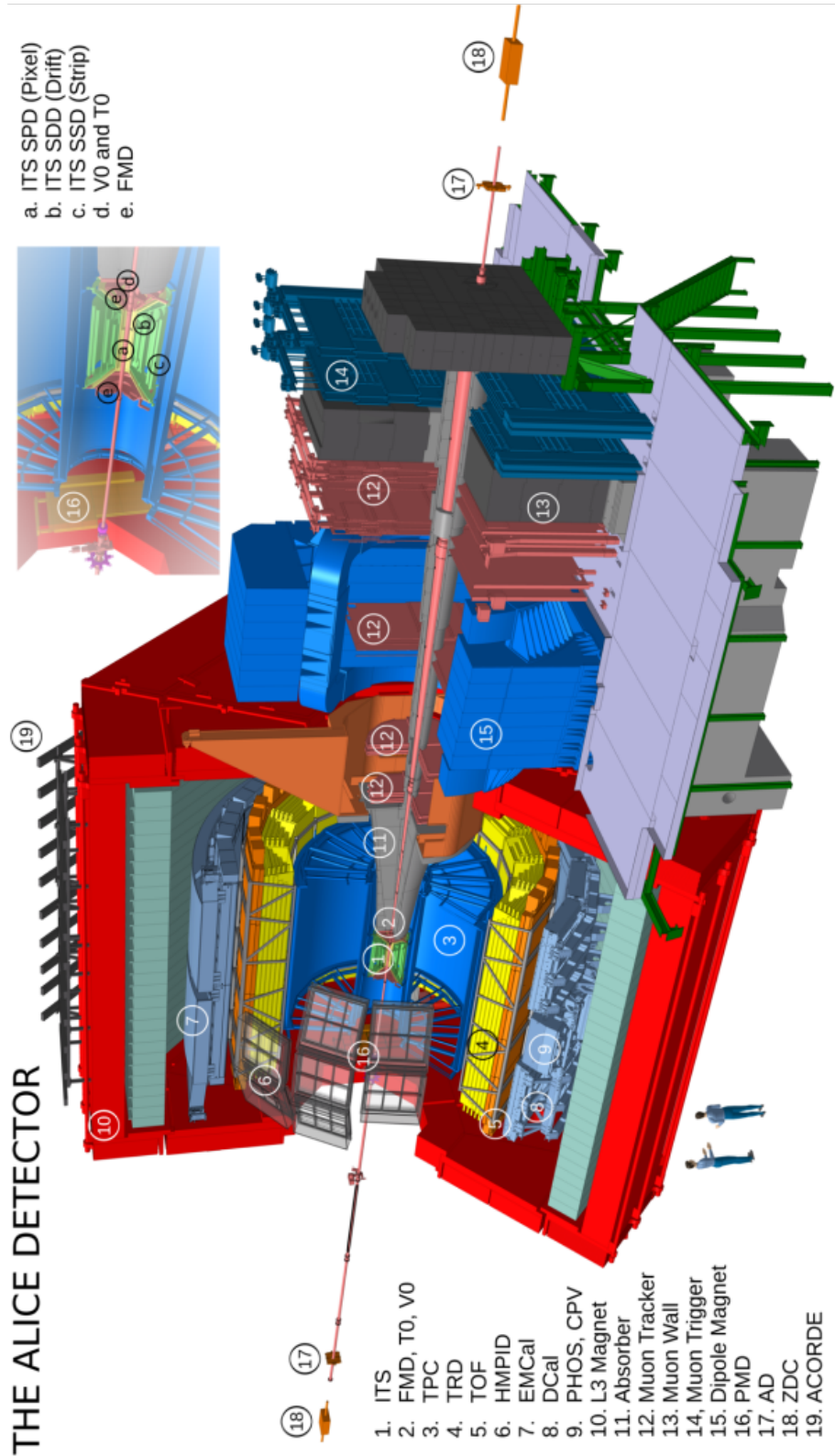


Figure 2.2: The ALICE detector setup with all the subdetector modules. Figure from [37].

2.2 The ALICE detector

The ALICE detector is composed of 18 subdetectors (shown in figure 2.2), divided in three categories: central detectors, forward detectors and the muon arm. The central tracking system is composed of the Inner Tracking System (ITS) and Time Projection Chamber (TPC) and is complemented by other subdetectors for specific analyses, such as the Time-Of-Flight (TOF) and the Electromagnetic Calorimeter (EMCal). The forward detectors, such as the VZERO, are used mainly for trigger and centrality estimation. The muon arm, located in the forward pseudorapidity region ($-4.0 < \eta < -2.5$), is a dimuon spectrometer that consists of a front absorber (which absorbs hadrons and photons from the interaction vertex), a dipole magnet and a dedicated system for tracking and triggering. The complete description of all detectors can be found in [34, 38].

In the following sections, we give a brief description of the detectors used in the analysis discussed in this thesis.

2.3 The Time Projection Chamber (TPC)

The TPC is the main detector used in this analysis. It consists of a cylindrical drift volume with 5 m of length, 0.85 cm of inner radius and 250 cm of outer radius and the read-out chambers which are located at the endplates, as shown in the scheme of Fig. 2.3. TPC was designed to have excellent tracking capability in the high-multiplicity environment of Pb–Pb collisions. For instance, in the data taking period of 2015, the interaction rate of Pb–Pb was of up to 300 Hz with 2.5% of the most central collisions with a charged-particle density at mid rapidity of up to $dN_{\text{ch}}/d\eta = 2000$.

The TPC 90 m³ drift volume is filled with a gas mixture (90% Ne and 10% CO₂) and is immersed in an electric field. The gas atoms inside the drift chamber are excited and ionized by charged particles travelling through the detector. The electrons created by this ionization processes are moved to the end of the detector by a constant electric field of 400 V/cm. This electric field is generated by applying a voltage difference between the TPC central electrode and

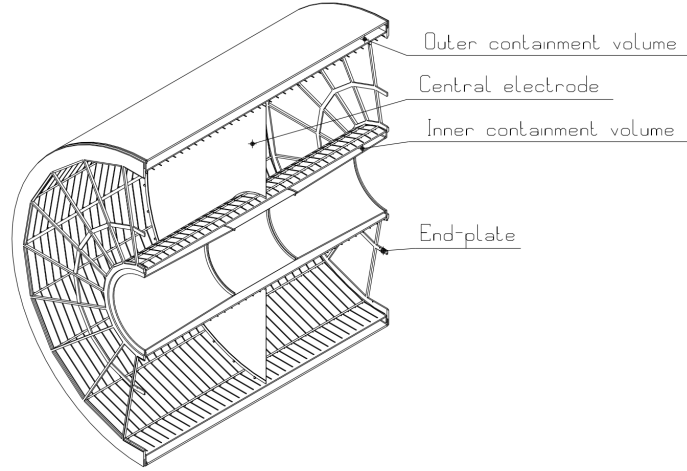


Figure 2.3: TPC assembled field cage scheme. Figure from [39].

the endplates of 100 kV. The read-out chambers at the endplates register the charge deposition and determine the path of the original charged particle inside the TPC, while the arrival time of the drifted electric charge provides the longitudinal coordinate of the track allowing for a 3D reconstruction of the track.

Furthermore, the energy deposition of charged particles while traversing the TPC is used to infer the particle identity, as described in the following section.

2.3.1 Particle identification with the TPC

The TPC provides particle identification (PID) of charged particles through the measurement of the energy loss inside the chamber. As a charged particle travels through the TPC chamber, interactions occur which lead to energy loss of the particle. For instance, the charged particle can undergo inelastic collisions with atomic electrons of the material or deflection due to elastic scattering off nuclei.

The first description of the energy loss of a charged particle in a material was from Bethe [40]. We adopt the ALEPH Bethe-Bloch parameterization [41], in which the mean energy loss of a charged particle with mass m and momentum $\vec{p}$ is given by

$$\left\langle dE/dx \right\rangle = \frac{\aleph_1}{\beta^{\aleph_4}} \left\{ \aleph_2 - \beta^{\aleph_4} - \ln \left[\left(\frac{1}{\beta\gamma} \right)^{\aleph_5} + \aleph_3 \right] \right\}, \quad (2.3.1)$$

where β is the velocity of the particle, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ is the Lorentz factor and $\aleph_i$ are five free parameters adjusted to data.

Figure 2.4 shows the average energy loss in the TPC as a function of the particle momentum divided by its charge (in multiples of the electron charge), p/z , for different particles from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with superimposed Bethe-Bloch parameterization curves. It is possible to observe good discrimination power for particles with low momentum, especially between protons, kaons and pions, particles used in this study. The Bethe-Bloch curves for nuclei (deuterium, tritium and Helium-3) are also present.

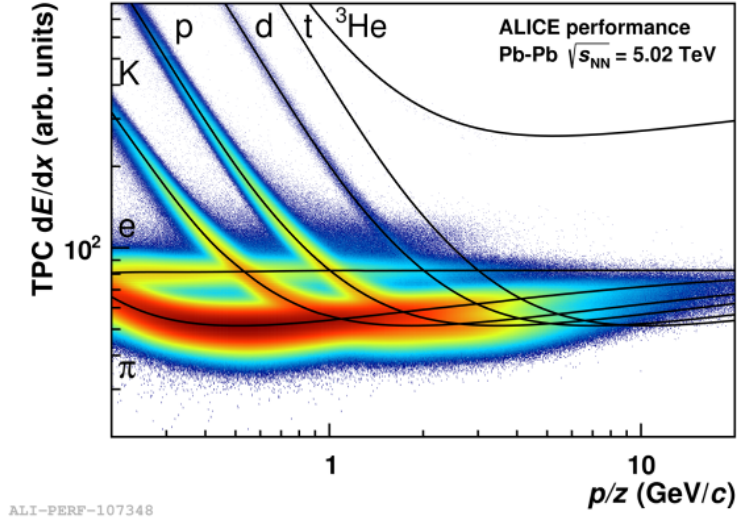


Figure 2.4: TPC energy loss (dE/dx) as a function of momentum with superimposed Bethe-Bloch lines for various particle species for Run 2 Pb–Pb data with low interaction rate, with approximately 2×10^6 events. Figure from [37].

For each track, we can compute the difference between the measured and the expected energy loss inside the TPC and normalize to the expected TPC resolution, σ_{TPC} , as

$$n_\sigma = \frac{(dE/dx)_{\text{measured}} - (dE/dx)_{\text{Bethe-Bloch}}}{\sigma_{\text{TPC}}}. \quad (2.3.2)$$

To avoid loss in efficiency, this selection is used as loose 4σ band around the expected energy loss for a given momentum, rejecting particles that are far from the expected energy loss of a given species. By changing the size of the band, it is possible to estimate the effect of this

selection on the final result. This study is part of the systematic uncertainty computation described in chapter 4. The good discrimination power at low p_T is of great interest, since this is the region where the combinatorial background is more pronounced.

2.4 The Inner Tracking System (ITS)

The Inner Tracking System (ITS) is composed of six layers of silicon detectors located close to the beam pipe, at radii = 4, 7, 15, 24, 39 and 44 cm. Its pseudorapidity coverage is of $|\eta| < 0.9$ for all vertices located within ± 10.6 cm along the beam axis (measured from the center of the detector). The major tasks of the Inner Tracking System are listed below:

- Localization of the primary vertex of the collision with resolution better than $100 \mu\text{m}$ in the xy plane.
- Reconstruction of secondary vertices from decays of hyperons, D and B mesons.
- Track reconstruction and PID for particles with momentum below $200 \text{ MeV}/c$.
- Improvement of momentum and angle resolutions for high p_T particles detected with the TPC.
- Reconstruction of particles that traversed dead zones of the TPC, although with limited momentum resolution.

Due to the high hit occupation density, of up to 80 particles per cm^2 , and to achieve the desired impact parameter resolution, the two innermost sections of the detector are composed of pixel detectors (silicon pixel detector, SPD), with silicon drift detectors for the following two layers (SDD). The two outermost layers, where the track density is below 1 particle per cm^2 , are composed of double-sided silicon micro-strip detectors (SSD). The scheme of the ITS can be seen in Fig. 2.5.

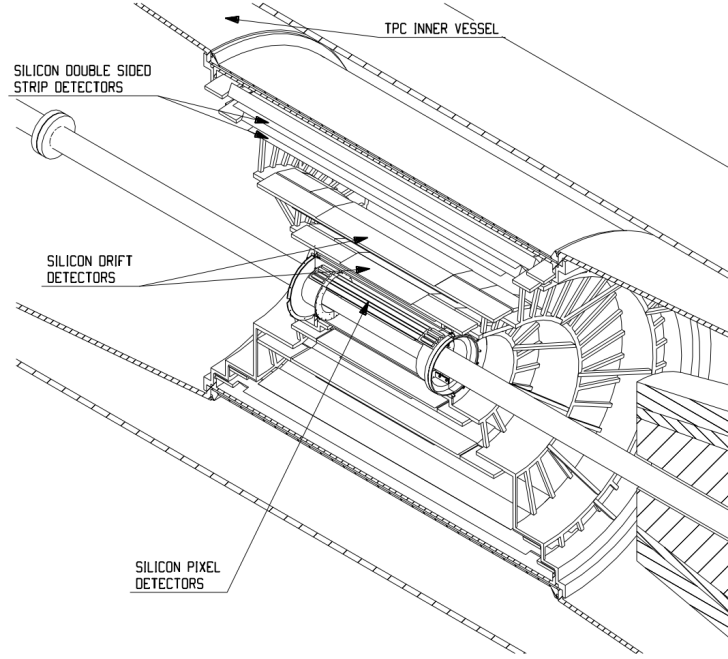


Figure 2.5: Layout of the ITS system. Figure from [42].

2.5 The V0 detectors

Located at the forward region, the V0 detector consists of two arrays of scintillator counters, called V0A and V0C, installed at the opposite sides of the ALICE detector. The V0A detector is located 340 cm from the collision vertex on the opposite side of the muon spectrometer, while the V0C detector is installed at the front face of the hadronic absorber, at 90 cm from the vertex. The pseudorapidity coverage is $2.8 < \eta < 5.1$ for the V0A and $-3.7 < \eta < -1.7$ for the V0C, being asymmetrical due to the different distances to the center of the detector.

The major objectives of the V0 system are to provide:

- a minimum-bias trigger for the central barrel detectors in pp and AA collisions;
- a centrality indicator for AA collisions;
- a control of the luminosity of the experiment;
- a validation signal for the muon trigger to filter the background in pp mode.

The V0 detectors are segmented into 32 elementary counters distributed in four rings, as

sketched in Fig 2.6. Each ring covers $0.4 - 0.6$ units of pseudorapidity. The rings are divided into eight sectors of 45° . The V0 setup is able to provide a temporal resolution better than 1 ns.

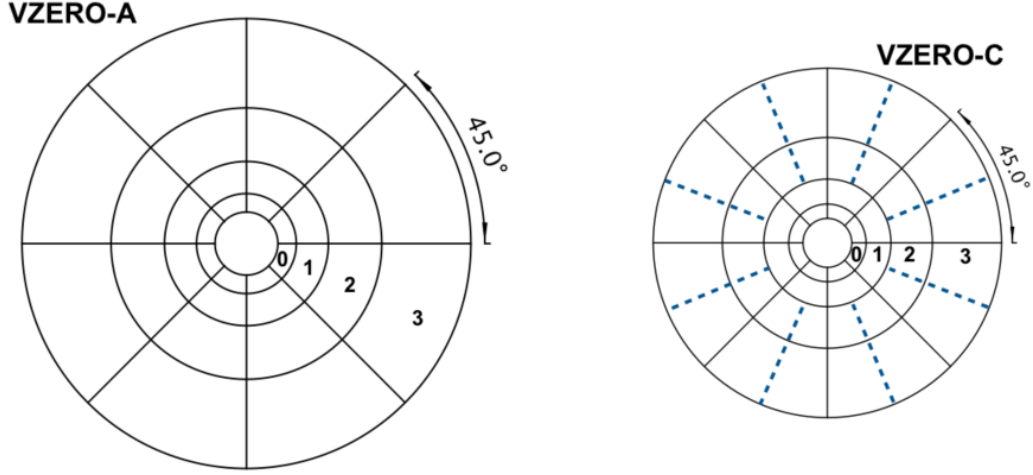


Figure 2.6: Layout of the V0A and V0C detectors showing their segmentation. Figure from [43].

During normal operation, events are triggered when there is a signal for both arrays of scintillators (V0 AND mode). This is defined as the minimum bias trigger and will be discussed further in detail in Section 3.1.

2.5.1 ALICE Trigger System

The ALICE Central Trigger Processor (CTP) is responsible for the selection of events that contains physics processes of interest, rejecting those that do not, while optimizing the detector efficiency during the data taking. Different detectors have different busy times – where no data is taken – following a valid trigger and the CTP is tasked with the optimization of the detectors usage. Moreover, due to the broad physics program of ALICE, the CTP is required to operate in different running conditions: ion (Pb–Pb and lighter species), p–Pb, and pp, with the production of charged particles in the central region varying by almost three orders of magnitude.

The experiment was designed to work in the high multiplicity central Pb–Pb collisions, that is also characterized by the relatively low rates (with interaction rates usually lower than 10 kHz at designed luminosity). This design requirement determines the choice of detectors used in the experiment, particularly the TPC as the main tracking detector.

2.5.2 Centrality estimation in ALICE

Usually, in the literature related to heavy-ion collisions, the centrality is expressed as a percentage of the total interaction cross section σ [44]. For AA collisions, the centrality percentile c , corresponding to an impact parameter smaller than b , is defined by integrating the impact parameter distribution $d\sigma/db$:

$$c = \frac{\int_0^b d\sigma/db' db'}{\int_0^\infty d\sigma/db' db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db'. \quad (2.5.1)$$

From the basic assumption that b decreases monotonically with the number of charged particles detected (both in mid and forward pseudorapidity), it is possible to write the percentile c corresponding to a particle multiplicity above a given threshold (N_{ch}^{THR}) as

$$c \approx \frac{1}{N_{evt}} \int_{N_{ch}^{THR}}^\infty \frac{dN_{evt}}{dN'_{ch}} dN'_{ch}, \quad (2.5.2)$$

where the total cross-section is also approximated by the total number of events corrected by the efficiency, N_{evt} .

For instance, the 5-10% most-central event class is defined by the boundary values N_{ch}^5 and N_{ch}^{10} , for which

$$\frac{1}{N_{evt}} \int_{N_{ch}^5}^\infty \frac{dN_{evt}}{dN'_{ch}} dN'_{ch} = 0.05 \quad \text{and} \quad \frac{1}{N_{evt}} \int_{N_{ch}^{10}}^\infty \frac{dN_{evt}}{dN'_{ch}} dN'_{ch} = 0.1. \quad (2.5.3)$$

The definition of centrality used in this thesis follows the prescription from [45, 46], where the centrality percentile is defined as in Eq. 2.5.2 and the sum of the amplitudes in the V0 (V0A and V0C) scintillators is used as a proxy for the number of charged particles in the forward

region. The distribution of the sum of the amplitudes in the V0 detectors is shown in Fig. 2.7 for Pb–Pb at both $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The threshold boundaries that define each centrality class are represented by the vertical lines. The Glauber Negative Binomial Distribution (NBD-Glauber) fit shown in red is used to estimate centrality-related observables, such as the impact parameter, the number of participant nucleons and the number of nucleon-nucleon collisions [44].

The measurement of the number of charged particles, $dN_{\text{ch}}/d\eta$, is performed using two points tracks, referred as tracklets, using the two innermost layers of the ITS, the SPD. In addition to the two hits on the SPD layers, information from the position of the PV is used in the selection of tracklets candidates. The charged particle density at mid-rapidity, $dN_{\text{ch}}/d\eta$ is obtained from the number of tracklets within $|\eta| < 0.5$, $dN_{\text{tracklets}}/d\eta$ after efficiency corrections as described in [47].

The average charged particle at mid-rapidity, $\langle dN_{\text{ch}}/d\eta \rangle$, is computed for each centrality interval, determined by the measurement in the V0 detectors. The results are shown in Tab. 2.1 for Pb–Pb at both $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The centrality intervals shown in these tables are the ones used for this analysis. The reason that the intervals are divided in thinner bins for $\sqrt{s_{\text{NN}}} = 5.02$ TeV dataset is due to the larger amount of data available. Other analysis may use thinner or wider centrality bins, depending on the statistical uncertainties of the signal of interest.

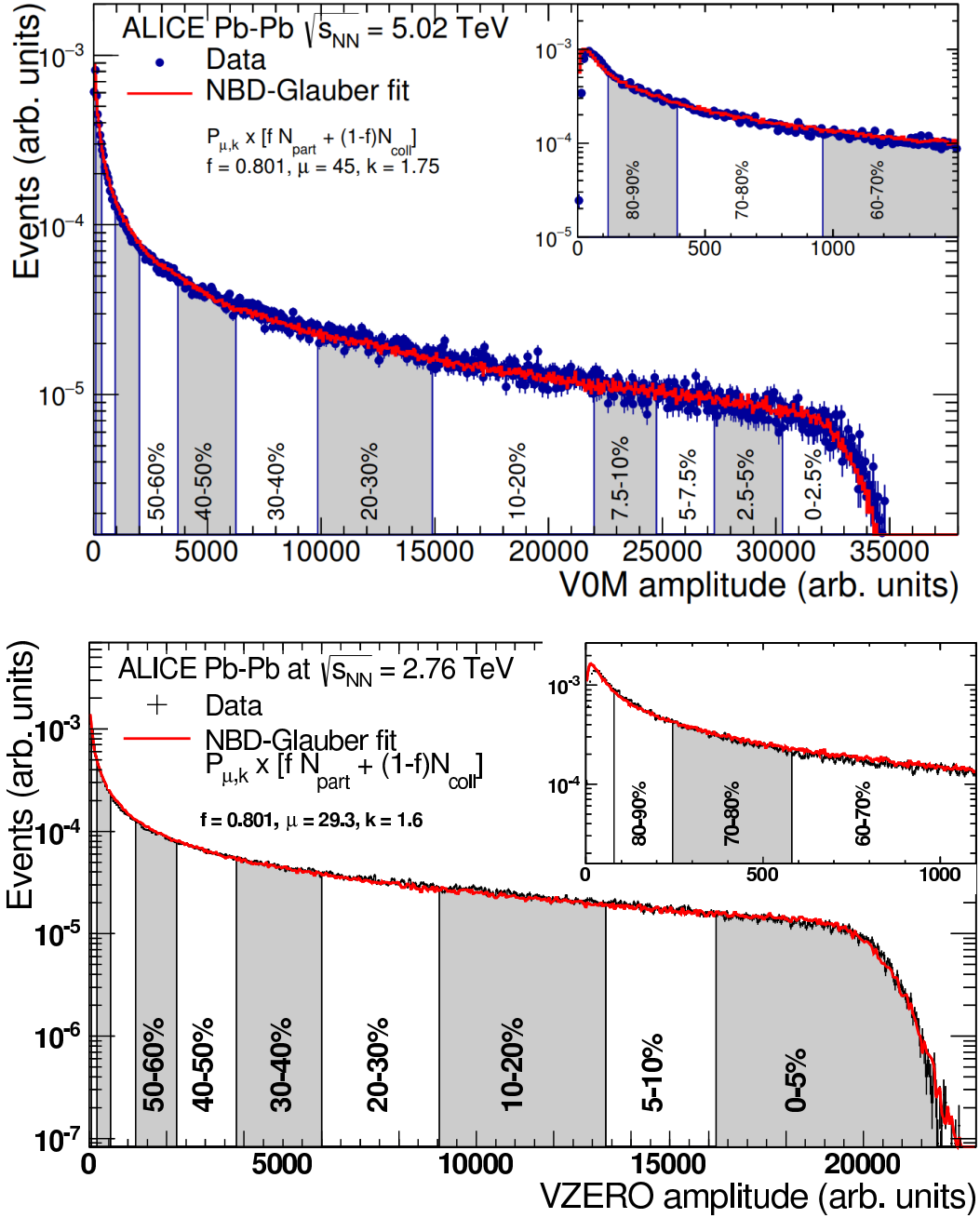


Figure 2.7: Distribution of the sum of the amplitudes in the V0 scintillators. The distributions are fitted with the NBD-Glauber function (explained in the text) shown as the red line. The centrality classes used in the analysis are indicated in the figure, with the boundaries indicated with the vertical lines. The inset shows a zoom of the most-peripheral region. Figures from [45, 46].

Table 2.1: The $\langle dN_{\text{ch}}/d\eta \rangle$ values measured in $|\eta| < 0.5$ for the centrality classes analyzed in this thesis. The values are obtained from [48–50].

Collision Energy ($\sqrt{s_{\text{NN}}}$)	Centrality	$\langle dN_{\text{ch}}/d\eta _{ \eta <0.5} \rangle$
2.76 TeV	0-10%	1447.5 ± 54.5
	10-20%	966 ± 37
	20-40%	537.5 ± 19
	40-60%	205 ± 7.5
	60-80%	55.5 ± 3
5.02 TeV	0-10%	1764 ± 49.75
	10-20%	1180 ± 31
	20-30%	786 ± 31
	30-40%	512 ± 15
	40-50%	318 ± 12
	50-60%	183 ± 8
	60-70%	96.3 ± 5.8
	70-80%	44.9 ± 3.4
	80-90%	17.52 ± 1.9

Chapter 3

Measuring multi-strange particles in Pb-Pb collisions

The multi-strange hadrons studied in this thesis, Ξ and Ω , are measured through the reconstruction of the trajectories of their weak decay mode. The details of these hadrons and the measured decay channels are listed in Tab. 3.1.

The decay chains studied here include two weak decays, the first being of the cascade particle (Ξ or Ω) and the second of a Λ particle. Due to the long lifetime ($c\tau > 1$ cm) of these particles, each of these decays happens a few centimeters away from where the particle was produced, resulting in a characteristic *cascading* topology, as shown in Fig. 3.1. The measured tracks are the final charged particles, π , K and p , which are combined as a cascade candidate. The cascade topology is used to filter candidates and is discussed in Section 3.3, where the main goal is to reject candidates that are not consistent with the desired decay topology.

Once the three charged tracks are combined and filtered, the invariant mass of the combination of the system is computed through the energy and momentum of the tracks. Being a Lorentz invariant quantity, this invariant mass has the same value in every reference frame. Therefore, if the three-track combination is indeed originated from a cascade decay, the invariant mass should be equal to the rest mass of the cascade particle, since it is computed from

Table 3.1: Valence quark content, mass and $c\tau$ of the multi-strange particles studied in this thesis. The decay channel reconstructed and its corresponding branching ratio (B.R.) is also shown. The Λ is included here, since the decay of a secondary Λ is part of the decay chain studied. Data from [51].

Hadron	Valence quark content	Mass (GeV/ c^2)	$c\tau$ (cm)	Decay channel	B.R.(%)
Ξ^-	dss	1.32171	4.911	$\Xi^- \rightarrow \Lambda + \pi^-$	99.89
$\bar{\Xi}^+$	$\bar{d}\bar{s}\bar{s}$	1.32171	4.911	$\bar{\Xi}^+ \rightarrow \bar{\Lambda} + \pi^+$	99.89
Ω^-	sss	1.67245	2.461	$\Omega^- \rightarrow \Lambda + K^-$	67.8
$\bar{\Omega}^+$	$\bar{s}\bar{s}\bar{s}$	1.67245	2.461	$\bar{\Omega}^+ \rightarrow \bar{\Lambda} + K^+$	67.8
Λ	uds	1.11568	7.89	$\Lambda \rightarrow p + \pi^-$	63.9
$\bar{\Lambda}$	$\bar{u}\bar{d}\bar{s}$	1.11568	7.89	$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$	63.9

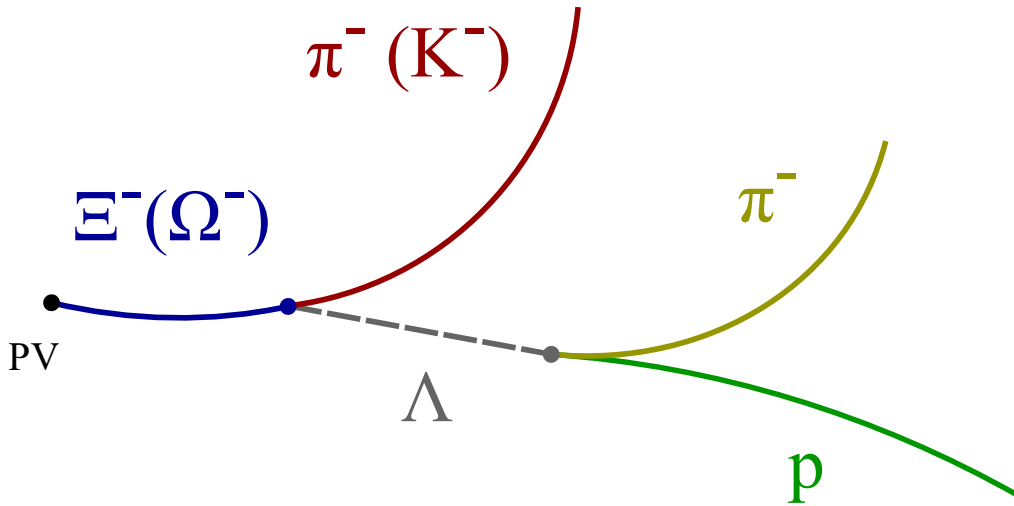


Figure 3.1: Cascade decay topology for Ξ^- and Ω^- .

quantities conserved in decays. The invariant mass is computed as:

$$M^2 = \left(\sum_i E_i \right)^2 - \left\| \sum_i \vec{p}_i \right\|^2. \quad (3.0.1)$$

The invariant mass is computed for all selected combination of tracks, and a spectrum of this quantity should show an excess around the cascade mass of 1.321 GeV/ c^2 for Ξ and 1.672 GeV/ c^2 for Ω [51].

In this chapter, we discuss all the selection criteria used in this analysis, starting with the data sample and event selections in Section 3.1. The tracking determination algorithm is covered in Section 3.2, where the quality selection criterion that is applied to all tracks is discussed. We present the cascade selections used in this thesis in Section 3.3, including the topological ones mentioned earlier. After this, the study of a structure in the invariant mass of cascades is presented in Section 3.4. At this point, we are ready to compute the invariant mass spectrum for each particle and a procedure for the extraction of the signal is performed to extract the total measured yield for a given p_T of the candidate. This signal extraction is covered in Section 3.5. Finally, in order to estimate the number of multi-strange baryons produced in the collision, the efficiency of the measurement is estimated via Monte Carlo (MC) simulations. This is discussed in Sections 3.6 and 3.7.

3.1 Data sample and event selections

This analysis covers the study of multi-strange particle production in Pb–Pb collisions at two different energies. The $\sqrt{s_{NN}} = 2.76$ TeV dataset consists of approximately 45×10^6 events, measured in November and December of 2010 and is internally referred as the period *LHC10h*. For the $\sqrt{s_{NN}} = 5.02$ TeV data, a higher number of events was collected, totalling approximately 420×10^6 events in the dataset, which was measured in November and December 2015 and is referred as *LHC15o*.

The basic event selection performed in this analysis follows the ALICE convention regarding Pb–Pb analyses performed in multiplicity bins. The following selections were performed:

- Minimum bias trigger selection: Selected events were required to have signals in both the V0A and V0C detectors. For this analysis, only events acquired with the minimum bias trigger mode was used. Other trigger modes exist for other types of analysis, and a more detailed list of such triggers can be found in [34].
- $N_{\text{contributors}} > 0$: Events selected for this analysis were required to have a primary vertex with at least one contributor. Here, the $N_{\text{contributors}}$ represents the number of tracks used in the primary vertex determination.
- Vertex z position: Only events whose primary vertex lies within $|z| < 10$ cm were accepted for this analysis.
- Pile-up rejection: Events with more than one vertex reconstructed by the ITS are rejected. For Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, a second pile-up rejection event selection was used. This extra selection was based on the correlation between the number of tracks in the TPC and the sum of amplitudes in the VZERO scintillators and is described in Appendix B.

The remaining sample after this event selection comprised of approximately 72×10^6 events for Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and 16×10^6 events at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

3.2 Track determination and quality selections

After the TPC raw data are recorded, it is necessary to filter and store them in an output that can be easily analyzed. This step is known as the event reconstruction and avoids the usage of too many CPU-intensive processes for each individual physics analysis.

The first step in the track reconstruction is the clusterization of the TPC raw signals from neighboring pads and time-bins, which are assumed to be originated from a single charged track. This clusterization is done for each pad row, as shown in Fig. 3.2.

Then, the cluster from different pad rows are connected in order to build tracks. This step is performed employing a Kalman filter [52] approach, which allows a continuous variation of the

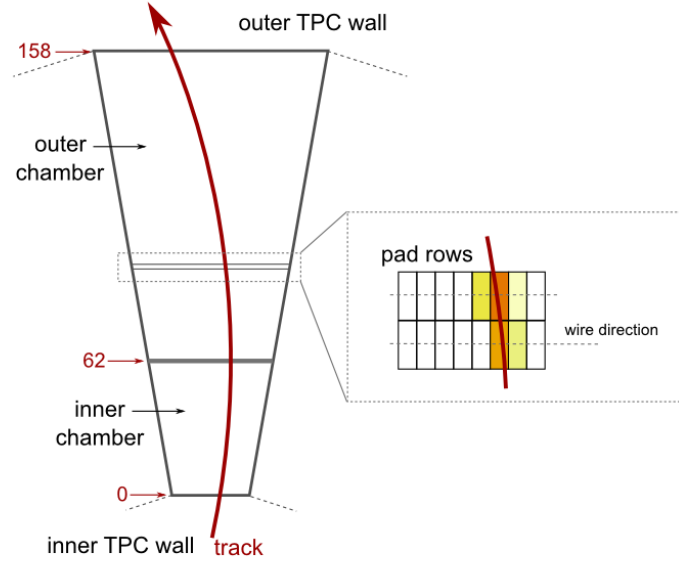


Figure 3.2: TPC sector readout segmentation into pad rows. Figure from [7].

track parameters along the trajectory. Starting from the outer pad-rows, the clusters are added to the track in an inward propagation, where the track parameters are continuously updated.

The uncertainty on the momentum for a given track reduces with the increase of the number of crossed rows, $N_{\text{crossed rows}}$, and with the increase of the total track length, L [39]. Therefore, these two quantities are used as a track quality criterion. A further selection on the ratio of these two values is used to reject track outliers with high track length and small $N_{\text{crossed rows}}$.

Lastly, a required quality flag, known as the TPC refit, is attributed to tracks that are successfully propagated until the inner TPC wall, which is 85 cm away from the beam pipe. The summary of the track selection criteria with the corresponding selection values is shown in Tab. 3.2.

3.3 Cascade selections

Multi-strange baryon candidates are obtained by combining three charged tracks in an event. Considering the extremely high number of charged tracks produced in Pb–Pb collisions (on average, 1600 charged tracks at mid rapidity per event in the most central event class of

Table 3.2: Summary of track selections applied in this analysis, containing both the basic η and p_T limits and the quality selection criteria discussed in section 3.2.

Summary of tracking selection	
<i>Pseudorapidity (η)</i>	< 0.8
<i>Transverse momentum (p_T)</i>	$> 0.15 \text{ GeV}/c$
<i>Tracking quality flag</i>	TPC refit
<i>Number of crossed rows ($N_{\text{crossed rows}}$)</i>	≥ 80
<i>Track Length (L)</i>	$\geq 90 \text{ cm}$
<i>Crossed rows over length ($N_{\text{crossed rows}}/L$)</i>	≥ 0.8

Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$), the application of particle identification only is not sufficient. Therefore, a list of topological selection criteria is employed to filter the tracks used in the hyperon reconstruction. These selections rely on the geometry of the cascade decay chain, as can be seen in Fig. 3.3, where a scheme for the cascade decay chain is presented. These several topological parameters, sketched in the figure, are listed and described below.

Maximum DCA V0 Daughters. Parameter 1 on Fig. 3.3. The distance between the two tracks associated to the V0 must be smaller than one standard deviation¹ of the resolution of the DCA between two tracks ($< 1\sigma$) to ensure that the tracks originated from the Λ decay.

Minimum DCA Negative/Positive to PV. Parameter 2 and 3 on Fig. 3.3. The distance of closest approach between tracks associated to the Λ decay (π or p) and the primary vertex should be at least 0.2 cm to reject tracks from primary particles to be used as daughter of the Λ decay.

Minimum/Maximum V0 decay radius. Parameter 4 on Fig. 3.3. A minimum cut on the Λ decay radius of 3 cm is necessary to reduce the combinatorial background associated to random pairing of primary tracks. A maximum cut of 100 cm is used to select only Λ decays that happen not far from the internal radius of the TPC (of 85 cm), assuring better detection

¹Unlike the other selections, the DCA of the V0 daughters is not expressed in absolute distance, but in σ , where σ is the resolution of the DCA between two tracks. This is necessary to take into account the quality disparity between tracks defined only from TPC cluster and those where additional hits on the ITS allows for better tracking quality.

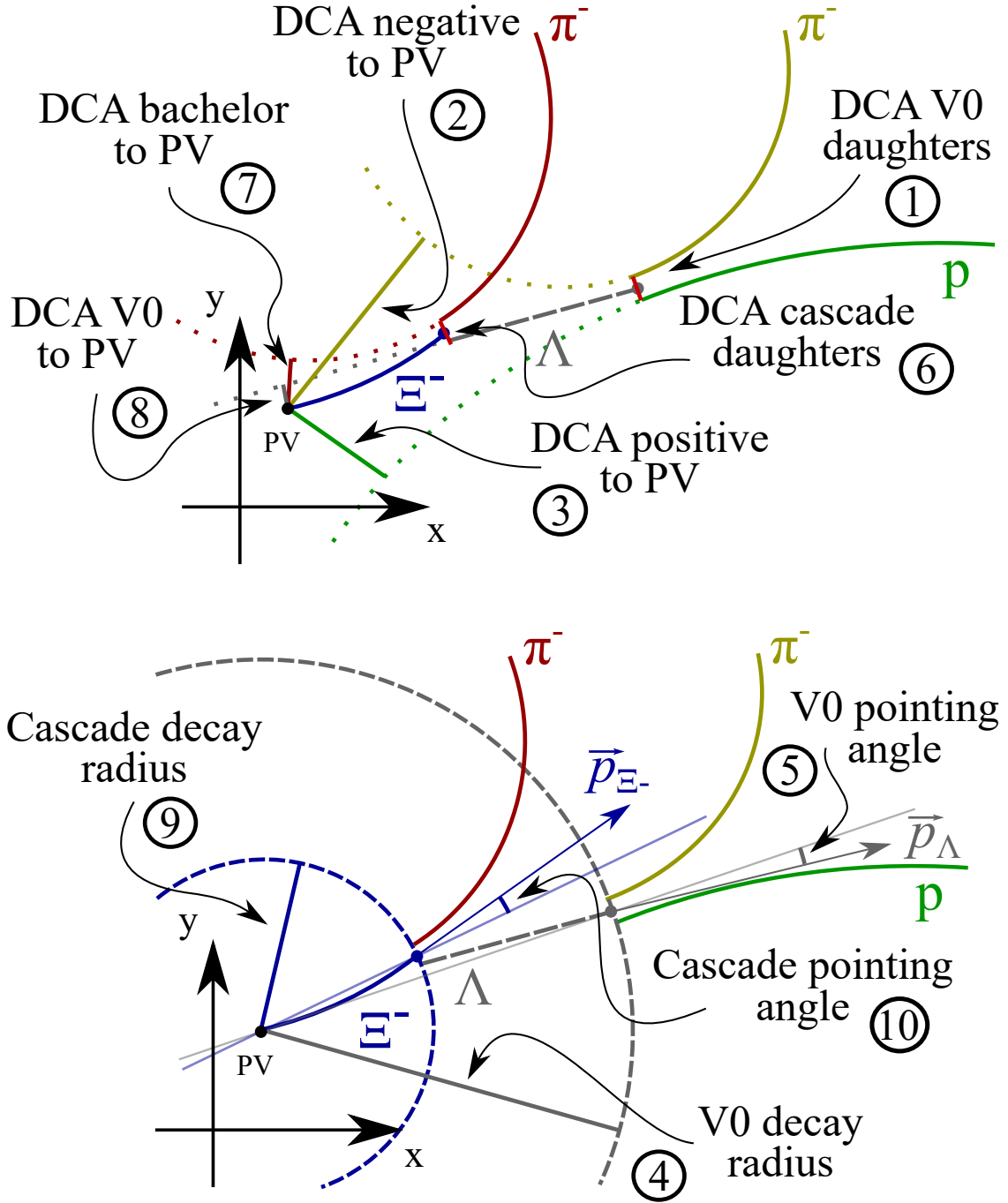


Figure 3.3: Sketch of the cascade decay topology and topological selection used in this analysis, exemplified here by the Ξ^- decay chain. The primary vertex (PV) is shown as the full black circle, where the Ξ is produced. Quantities related to the cascade are shown in blue, while for the V0 they are in grey. The measured tracks are shown in red (bachelor track), yellow (V0 negative daughter) and green (V0 positive daughter).

performance.

Maximum V0 pointing angle. Parameter 5 on Fig. 3.3. The V0 pointing angle is defined as the angle between the momentum of the reconstructed Λ and the straight line that connects the primary vertex and the Λ decay point. A maximum value of this angle is used as a selection to ensure that the Λ is originated from the direction of the primary vertex. This is a p_T -dependent selection and is described in section 3.3.2.

Maximum DCA cascade daughters. Parameter 6 on Fig. 3.3. A maximum value of the distance of closest approach between the bachelor track and the estimated V0 decay vertex is used to ensure that the tracks have a convergence point, the cascade decay vertex. This is a p_T -dependent selection and is described in section 3.3.2.

Minimum DCA bachelor to PV. Parameter 7 on Fig. 3.3. The distance of closest approach between the bachelor track and the point vertex should be at least 0.1 cm, to reject primary tracks.

Minimum DCA V0 to PV. Parameter 8 on Fig. 3.3. The distance of closest approach between the reconstructed Λ trajectory and the primary vertex should be greater than 0.1 cm to reduce the contribution from primary particles to the background.

Minimum/Maximum cascade radius. Parameter 9 on Fig. 3.3. A minimum cut on the cascade decay radius of 1.2 cm for $\Xi^\pm$ and 1.0 cm for $\Omega^\pm$ is necessary to reduce the combinatorial background made from primary tracks. A maximum cut of 100 cm is used to select only decays that happen not far from the internal radius of the TPC.

Maximum cascade pointing angle. Parameter 10 on Fig. 3.3. The cascade pointing angle is defined as the angle between the momentum of the reconstructed cascade and the straight line that connects the primary vertex and the cascade decay point. A maximum value of this

angle is used as a selection to ensure that the cascade is originated from the direction of the primary vertex. This is a p_T -dependent selection and is described in section 3.3.2.

V0 mass window. For the V0 used in the cascade reconstruction, the difference between its invariant mass and that of the PDG [51] Λ mass, $1.1157 \text{ GeV}/c^2$, must be smaller than $5 \text{ MeV}/c^2$. Figure 3.4 shows how this rejection removes the combinatorial background of the Λ invariant mass distribution.

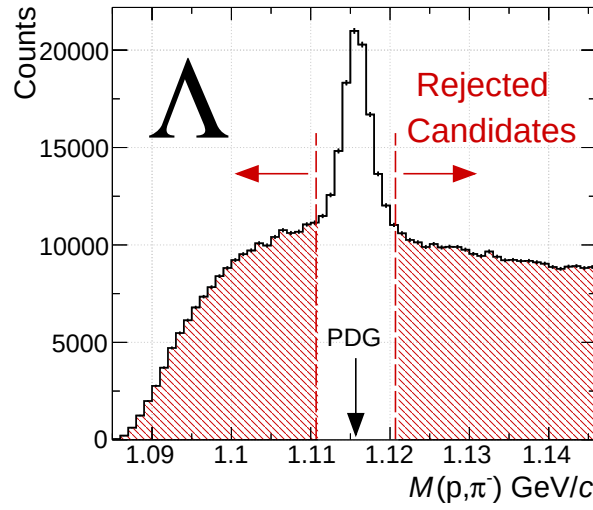


Figure 3.4: The V0 used in the cascade reconstruction must have an invariant mass close to the PDG Λ mass. Here we show the effect of this selection on the Λ invariant mass distribution, where the red region of the distribution represents the rejected candidates. This plot was made using the Pb–Pb at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ dataset.

Competing decay for Ω . Both Ξ and Ω share the same decay topology. Therefore, it is possible to have true a Ξ being reconstructed as an Ω candidate, being accepted by all the other topological selection criteria. Considering the fact that the production rate of Ξ is approximately 10 times higher than that for Ω , the contribution to the invariant mass of Ω is not negligible. By computing the invariant mass of the Ω candidate in the Ξ hypothesis (attributing the π mass for the bachelor) and applying a rejection window of $8 \text{ MeV}/c^2$ around the PDG [51] Ξ mass, it is possible to reject this contribution.

Proper Lifetime. A selection on the proper lifetime was applied to reject low-momentum candidates that originated unusually far from the primary vertex if compared to the lifetime of the desired weak decay. The requirement was that $mL/p < 15$ cm for Ξ and $mL/p < 12$ cm for Ω , where m is the desired cascade mass, L is the linear (3D) distance between the cascade decay point and the primary vertex, and p is the total momentum. On top of that, a lifetime selection was also applied on the V0 daughter, constraining its lifetime to $mL_{V0}/p < 30$ cm. It is worth noting that the cascades are charged particles and as such their trajectory in a magnetic field is not a straight line. Therefore, taking L to be a linear distance in three-dimensional space is an approximation, but this should be of no consequence given that this (loose) selection criterion is applied consistently in data and MC and thus efficiency corrections will already include, at least to first order, any deviations caused by this approximation.

Bachelor-Baryon pointing angle The Bachelor-Baryon (BB) system is composed of the bachelor and the baryon track (the positive/negative V0 daughter when reconstructing particle/antiparticle). The BB pointing angle is defined as the angle between the momentum of the BB system² and the straight line that connects the primary vertex and the point of DCA for the BB tracks. This new selection was devised during this work and its necessity is discussed in detail in section 3.4.

A summary of the selection criteria used in this analysis is shown in Tab. 3.3.

3.3.1 Optimization of topological selection criteria

While loosening the selection criteria clearly has a positive impact on reconstruction efficiencies, it also allows for a very significantly increased background, and therefore, topological variables require careful optimization.

The optimization strategy employed in this work consisted of the following: for each of the topological variables, we defined two limit values (loosest and tightest) and studied 100 different configurations for which the topological selection value was changed in an incremental

²The momentum of the BB system is computed using the momentum of the baryon track at the point of DCA for the BB system.

Table 3.3: Selections applied to charged Ξ and Ω candidates in this thesis. Values listed here were used for both the analyses at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

Cascade Selection	Ξ (Ω) Cut Value
Cascade transverse decay radius R_{2D}	> 1.2 (1.0) cm
V0 transverse decay radius	> 3.0 cm
DCA (bachelor - PV)	> 0.10 cm
DCA (V0 - PV)	> 0.10 cm
DCA (meson V0 track - PV)	> 0.20 cm
DCA (baryon V0 track - PV)	> 0.20 cm
DCA (V0 tracks)	$< 1.0 \sigma$
DCA (bachelor - V0)	< 1.0 (0.6) [‡] cm
Cascade $\cos(\text{PA})$	$> 0.95^{\dagger}$
V0 $\cos(\text{PA})$	$> 0.95^{\dagger}$
V0 invariant mass window	$\pm 0.005 \text{ GeV}/c^2$
Rapidity interval	$ y < 0.5$
Daughter rapidity interval	$ y < 0.8$
TPC dE/dx selection (Data only)	$< 4\sigma$
Proper lifetime (mL/p)	< 15 (12) cm
V0 lifetime (mL/p)	< 30 cm
Competing cascade rejection (only Ω)	$ \text{M}(\Xi) - 1.321 > 8 \text{ MeV}/c^2$
Tracking flags for daughters	TPCrefit
Daughter track ($N_{\text{crossed rows}}$)	≥ 80
Daughter track length (L)	≥ 90 cm
Daughter track ($N_{\text{crossed rows}}/L$)	≥ 0.8

[‡] - This represents the loosest value for the DCA cascade daughter selection. A parameterization was used to tighten this selection as a function of p_{T} and is discussed in section 3.3.2.

[†] - This represents the loosest value for the pointing angle selections. A parameterization was used to tighten this selection as a function of p_{T} and is discussed in section 3.3.2.

way. While tightening a given selection, all the other selections were fixed on the central (or default) value. For angle-type topological variables, the configurations are equally spaced in pointing angle space³.

These configurations were studied using full-analysis outputs with invariant mass information and, for each of these 100 configurations, the signal extraction was performed p_T -differentially in data and in MC following the prescription described in 3.5.

Remaining signal fractions for different p_T intervals were studied and used to define values of topological cuts that result in a fixed signal loss fraction. The method is exemplified in figure 3.5. For each distribution of raw signal, we first find the selection value that results in a signal loss closest to the desired percentage and then fit a 2nd-degree polynomial around this cut value in order to smoothen out any fluctuations. This fit was then used to determine the analysis-level selection criterion for each topological variable.

Since the percentage of signal loss due to a given selection can be p_T dependent, this study had to be performed for each p_T bin. Values of topological cuts that result in a constant fraction of signal loss are shown, for all the topological variables, in Figs. 3.6 through 3.11 for Ξ^- and Ω^- . Antiparticles have similar behaviour, and the plots are omitted. These plots were used to define the central values of the cuts and also to determine if a parameterization was needed. Note that the tightening of cuts is only useful if it is followed by a significant decrease in the statistical uncertainty. This is due to the fact that some topological selections reduce both signal and background in similar ways, and further tightening will only decrease the efficiency. It is also noted that due to the loose selections used in this study, instabilities in the signal extraction are reflected in the fluctuations observed in the plots. This is especially important when considering the black points, where an even looser selection, in which an addition of 1% of the reconstructed signal is attempted.

³It is often more convenient to use the actual pointing angle, as opposed to the cosine thereof, because of numerical reasons: the pointing angle will still vary visibly even when its cosine is quite close to unity.

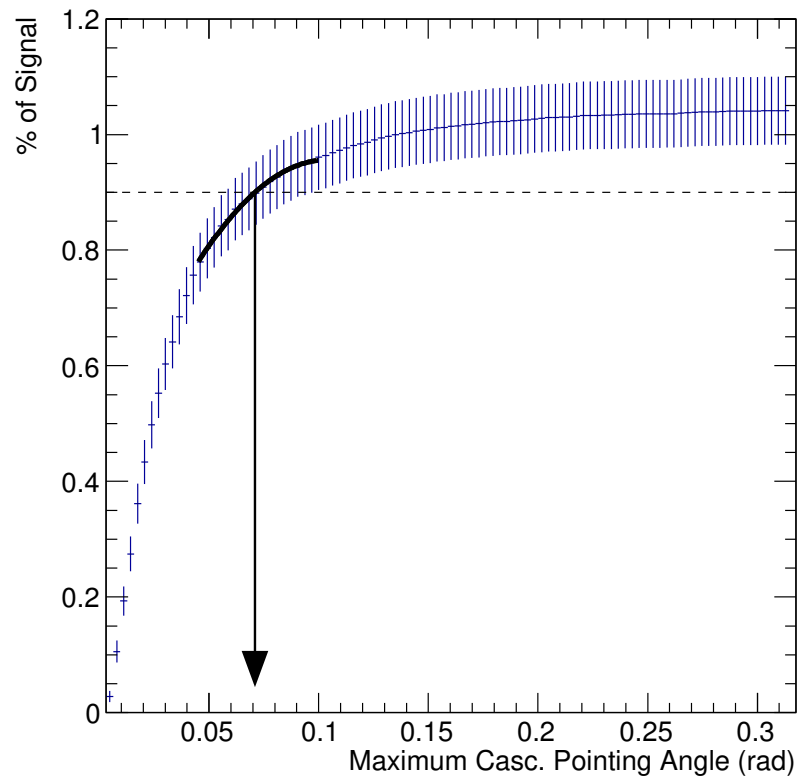


Figure 3.5: In this example, the desired percentage of signal loss is 10%. The fit is used to compute the value of the maximum cascade pointing angle that gives 10% of signal loss in this p_T interval. Performed on MC simulation.

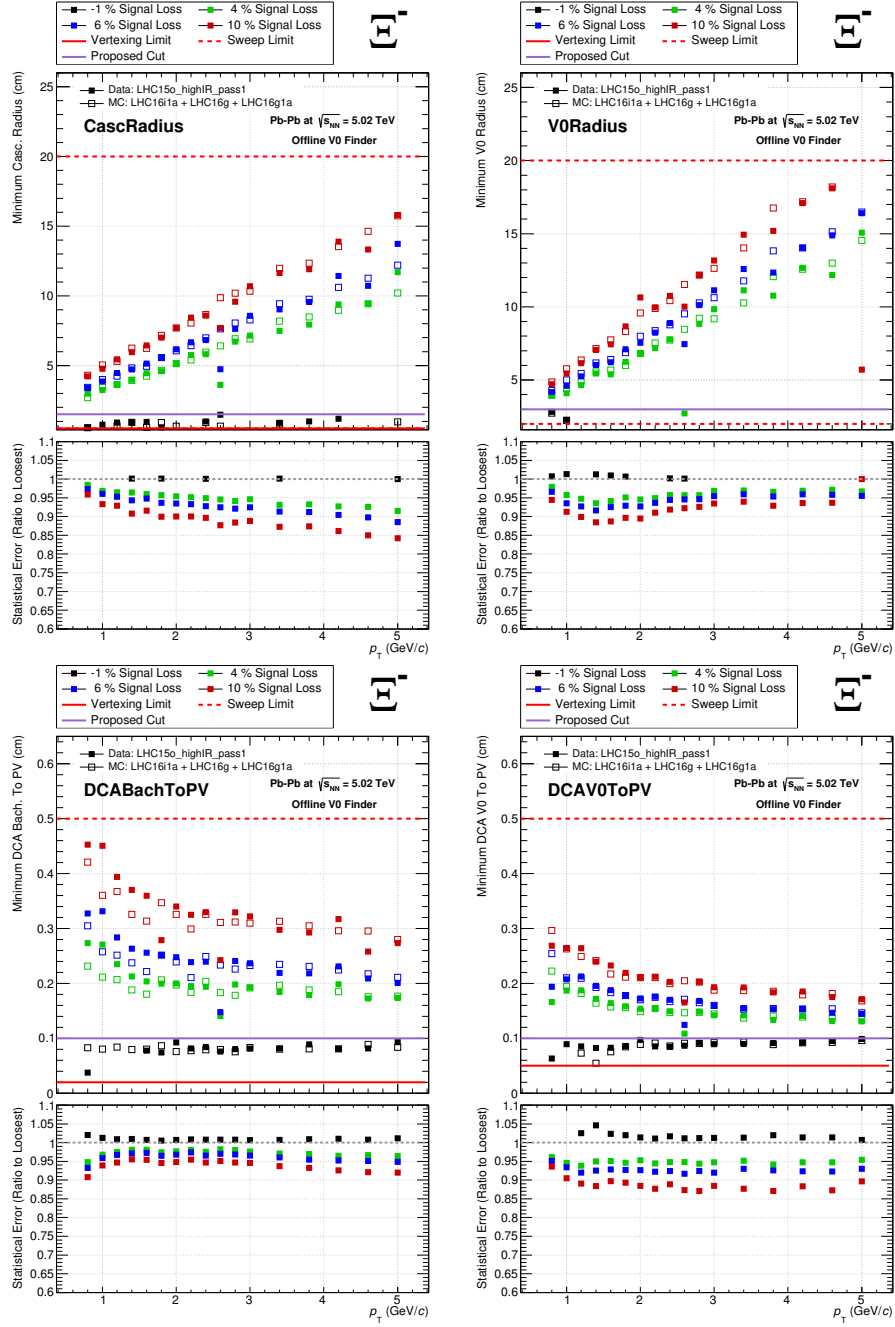


Figure 3.6: (top panel) Correlation between the cut values and the cascade signal loss as a function of the p_T of the reconstructed Ξ candidate for the following selections: cascade and V0 radius, DCA of the bachelor to the PV and DCA of the V0 to the PV. Curves represent values of topological cuts that result in a fixed % of signal loss (with respect to the central configuration) for all the p_T bins. The solid/dashed red line represents the loosest/tightest cut attempted in this study and the violet line is the proposed cut for the topological variable. (bottom panel) Statistical uncertainties of the raw counts normalized to the value of the proposed selection.

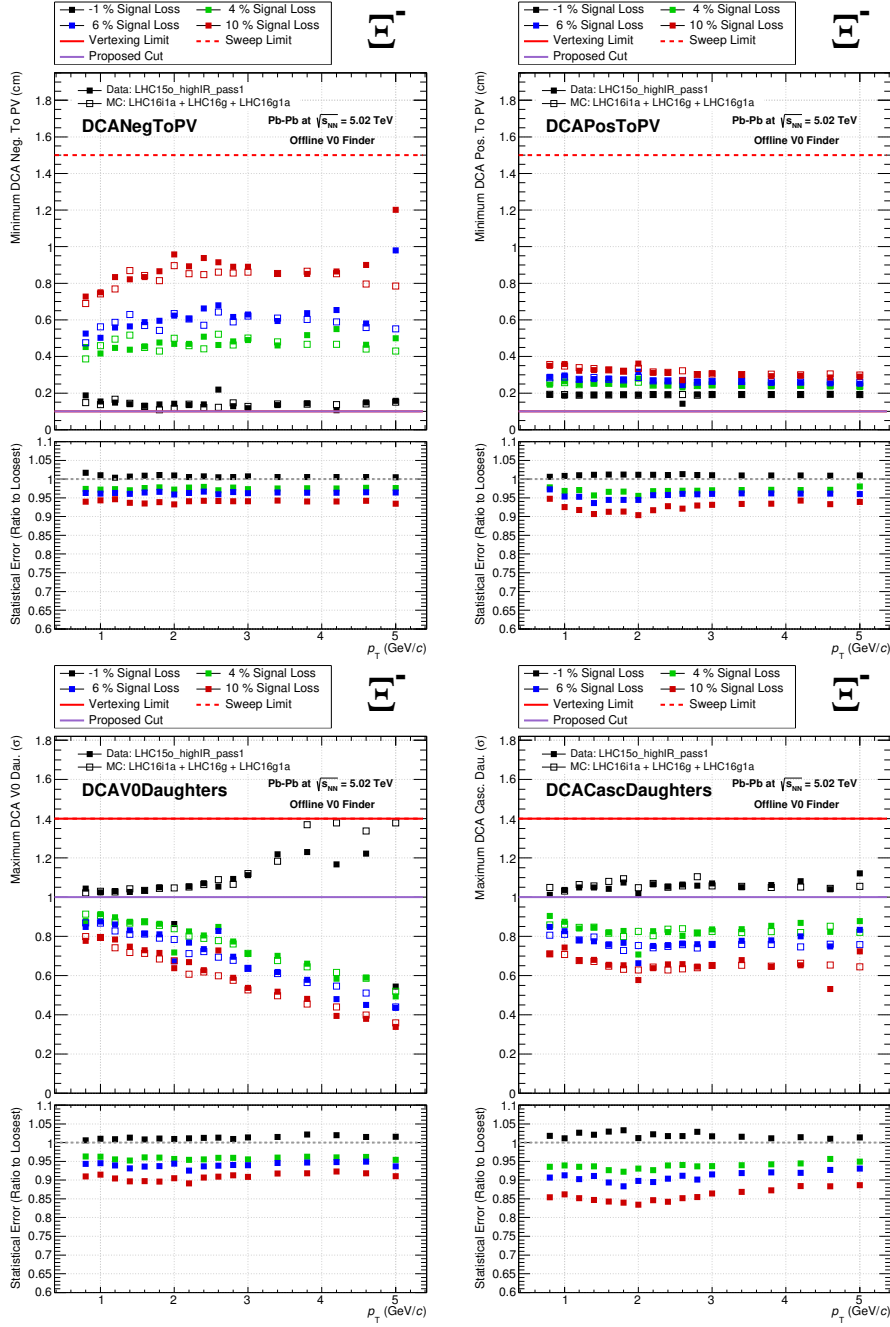


Figure 3.7: (top panel) Correlation between the cut values and the cascade signal loss as a function of the p_T of the reconstructed Ξ candidate for the following selections: DCA of single tracks to PV and DCA between V0/cascade daughters. Curves represent values of topological cuts that result in a fixed % of signal loss (with respect to the central configuration) for all the p_T bins. The solid/dashed red line represents the loosest/tightest cut attempted in this study and the violet line is the proposed cut for the topological variable. (bottom panel) Statistical uncertainties of the raw counts normalized to the value of the proposed selection.

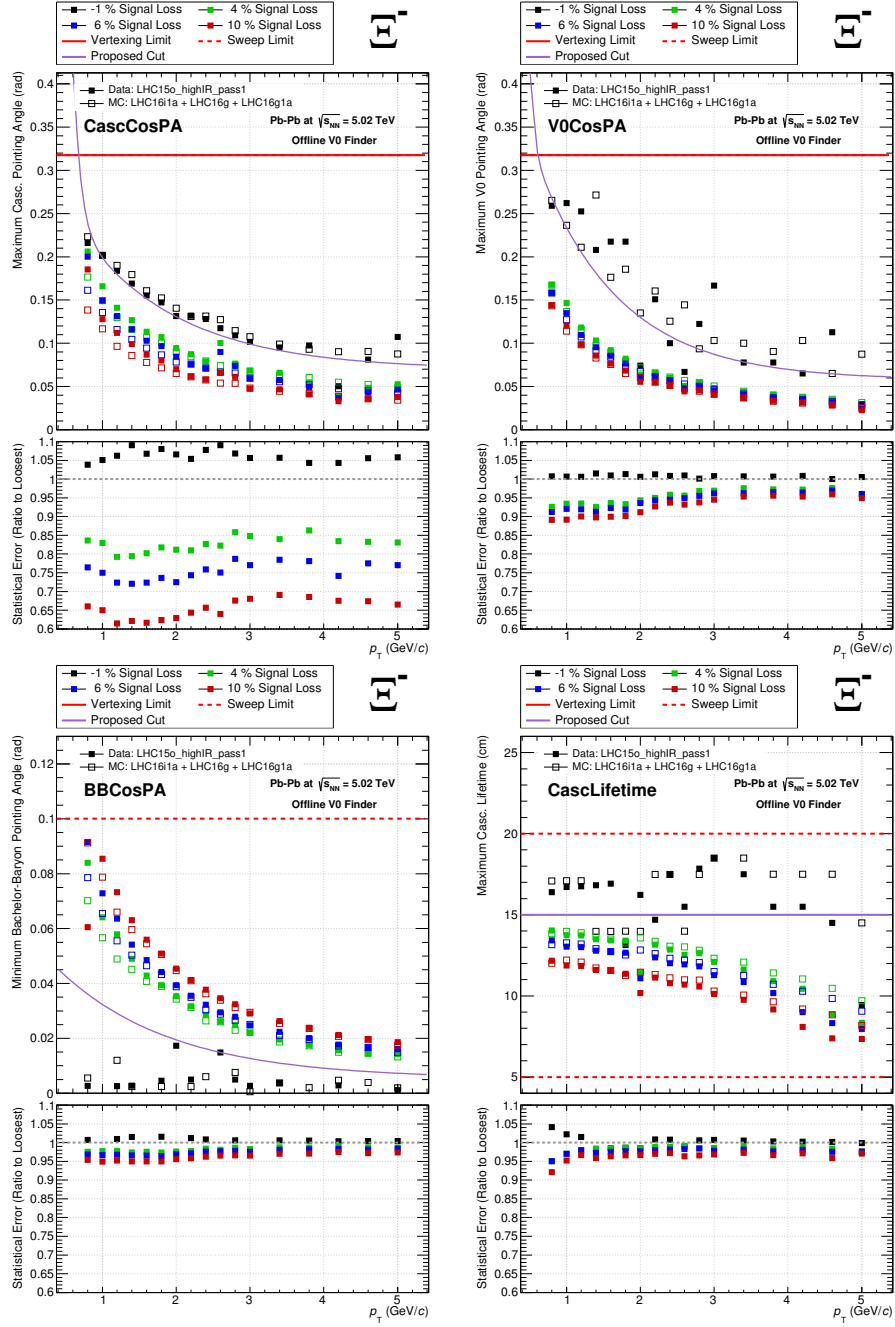


Figure 3.8: (top panel) Correlation between the cut values and the cascade signal loss as a function of the p_T of the reconstructed Ξ candidate for the following selections: cascade and V0 pointing angle, BB pointing angle and cascade lifetime. Curves represent values of topological cuts that result in a fixed % of signal loss (with respect to the central configuration) for all the p_T bins. The solid/dashed red line represents the loosest/tightest cut attempted in this study and the violet line is the proposed cut for the topological variable. (bottom panel) Statistical uncertainties of the raw counts normalized to the value of the proposed selection.

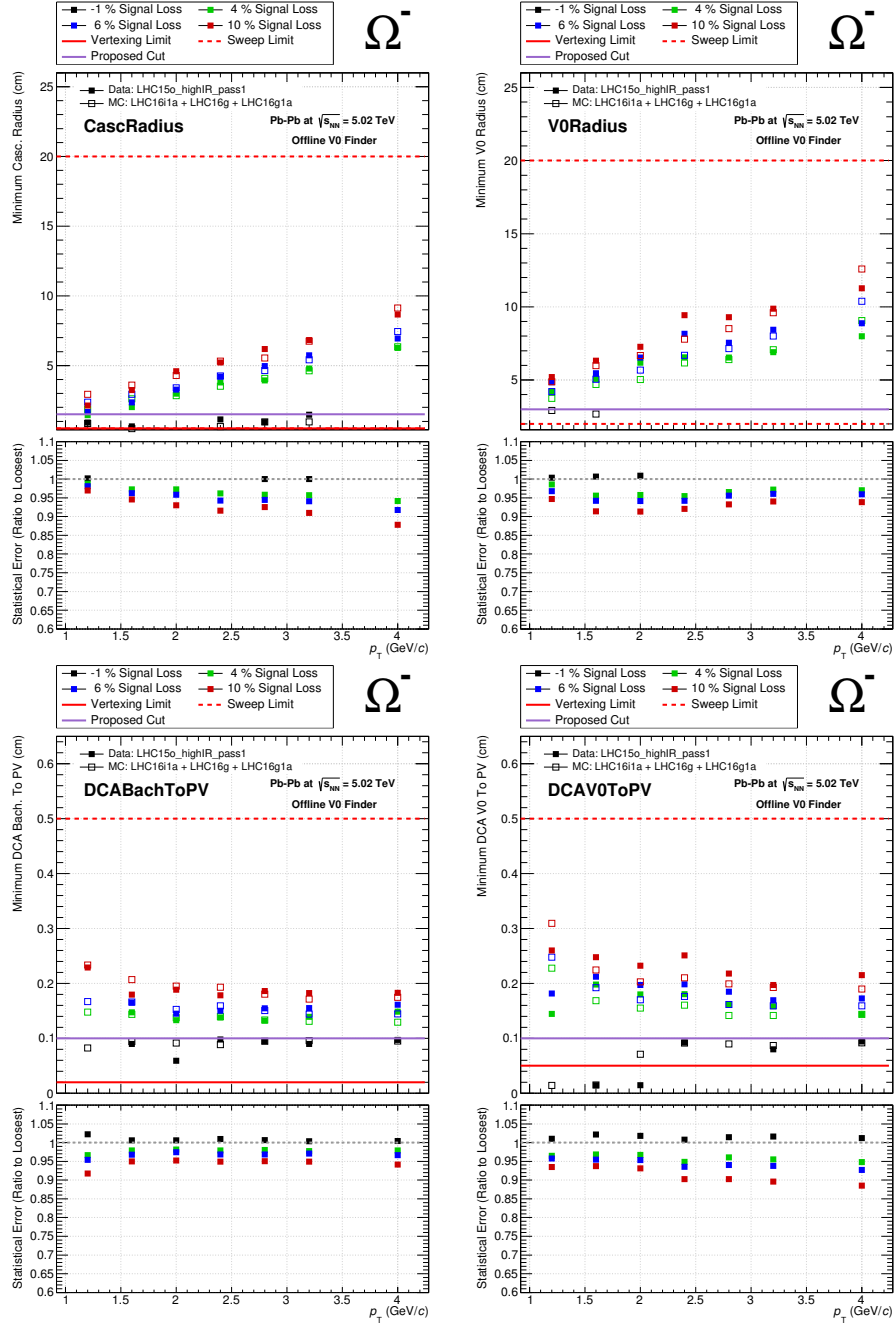


Figure 3.9: (top panel) Correlation between the cut values and the cascade signal loss as a function of the p_T of the reconstructed Ω^- candidate for the following selections: cascade and V0 radius, DCA of the bachelor to the PV and DCA of the V0 to the PV. Curves represent values of topological cuts that result in a fixed % of signal loss (with respect to the central configuration) for all the p_T bins. The solid/dashed red line represents the loosest/tightest cut attempted in this study and the violet line is the proposed cut for the topological variable. (bottom panel) Statistical uncertainties of the raw counts normalized to the value of the proposed selection.

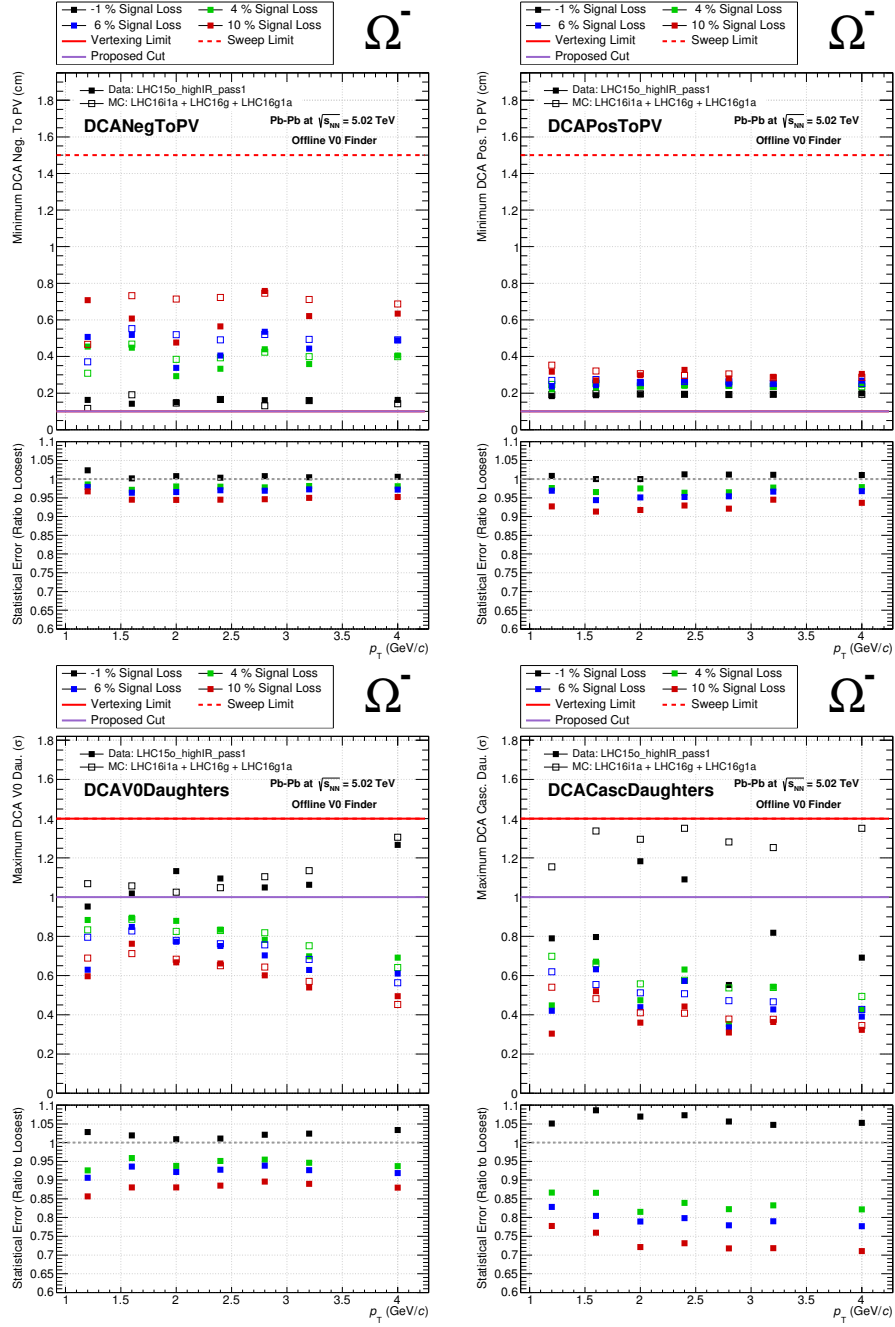


Figure 3.10: (top panel) Correlation between the cut values and the cascade signal loss as a function of the p_T of the reconstructed Ω candidate for the following selections: DCA of single tracks to PV and DCA between V0/cascade daughters. Curves represent values of topological cuts that result in a fixed % of signal loss (with respect to the central configuration) for all the p_T bins. The solid/dashed red line represents the loosest/tightest cut attempted in this study and the violet line is the proposed cut for the topological variable. (bottom panel) Statistical uncertainties of the raw counts normalized to the value of the proposed selection.

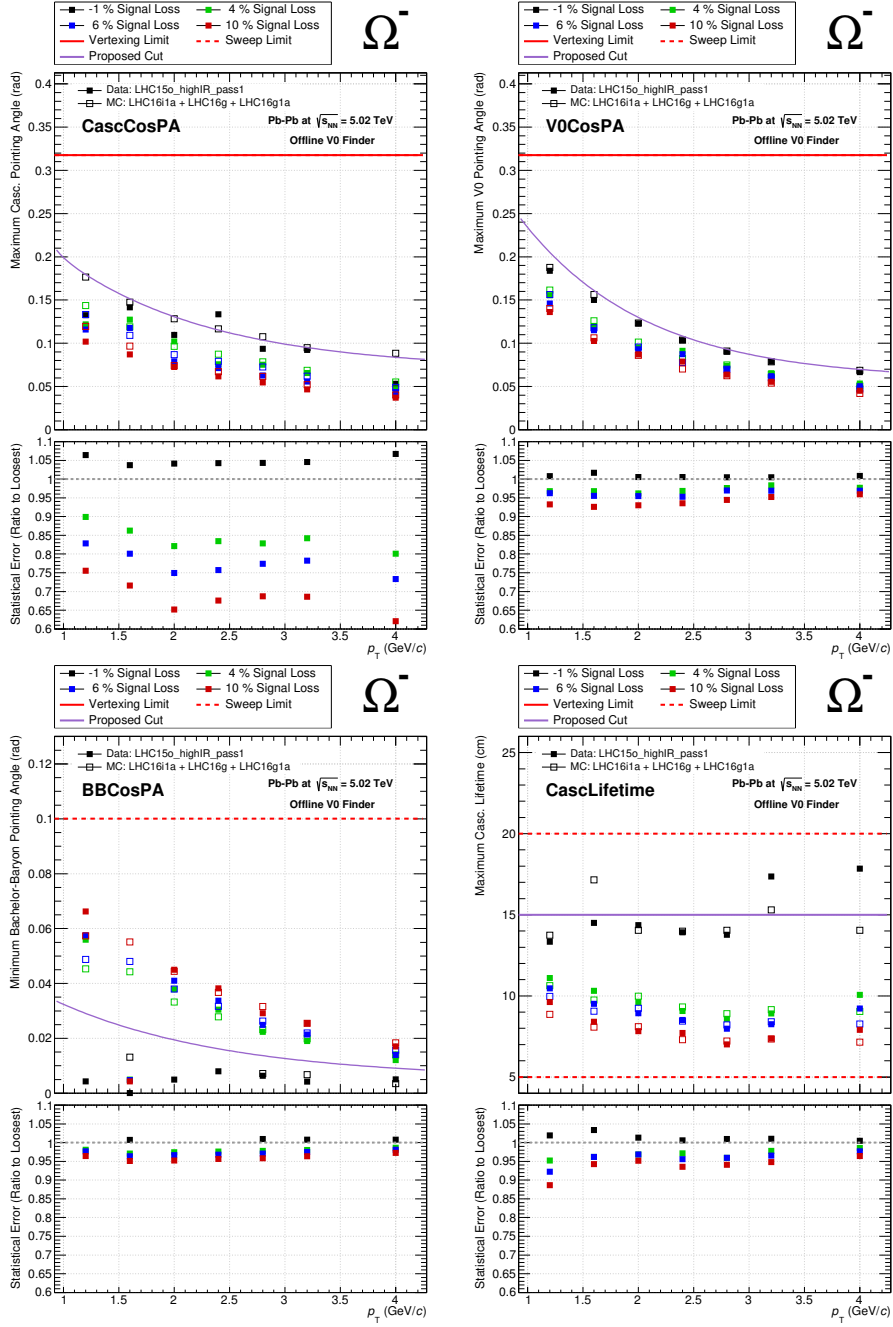


Figure 3.11: (top panel) Correlation between the cut values and the cascade signal loss as a function of the p_T of the reconstructed Ω candidate for the following selections: cascade and V0 pointing angle, BB pointing angle and cascade lifetime. Curves represent values of topological cuts that result in a fixed % of signal loss (with respect to the central configuration) for all the p_T bins. The solid/dashed red line represents the loosest/tightest cut attempted in this study and the violet line is the proposed cut for the topological variable. (bottom panel) Statistical uncertainties of the raw counts normalized to the value of the proposed selection.

3.3.2 Topological selections dependent on p_T

From the plots of the previous section, it is clear that the values that yield fixed signal loss are strongly p_T -dependent. The strong correlation between the pointing angle resolution and the p_T of the cascade candidate becomes clear when observing the plots shown in Figs. 3.8 and 3.11. For instance, for Ξ^- , a maximum pointing angle of 0.1 represents $\sim 10\%$ of signal loss at $p_T \cong 1$ GeV/ c and no signal loss at all for $p_T \cong 5$ GeV/ c (signal loss with respect to the loosest selection attempted). Therefore, to profit from the improvement of the pointing angle resolution with momentum, a parameterization with p_T was used.

Moreover, we see that the Bachelor-Baryon (BB) pointing angle selection has poor agreement between data and MC and is also strongly p_T -dependent. Therefore, a parameterization was used to ensure a loose selection throughout all p_T .

Finally, the DCA Cascade Daughter selection was also tightened as a function of p_T . Coupled with the tightening of the pointing angles, this ensures better signal extraction in the mid and high p_T region, reducing the overall systematic uncertainty. In this section, we report the parameterization used for the central values and systematic variations for the mentioned selections.

Figure 3.12 shows the p_T dependence of these selections for the central value and the systematic variations. For both the cascade and V0 pointing angle, the loosest value possible corresponds to the cosine of pointing angle of 0.95.

The BB pointing angle selection has poor agreement between data and MC and, to keep the rejection of true candidate to a minimum, the tightest value was fixed to an angle of 0.03 (corresponding to a cosine of the pointing angle of 0.99955). More details on these selections will be discussed in Sec. 3.4.

The tightening of the DCA cascade daughters was done in such a way that in the low p_T region it recovers the default value used in the analysis (of 1.0 cm for the Ξ), while at high p_T it tends to a value of 0.5 cm. The loose variation was obtained by scaling the default by 1.2, while the tight, by 0.8. In this way, even in the tight variation, the selection was always looser than the one used in the published $\sqrt{s_{NN}} = 2.76$ TeV.

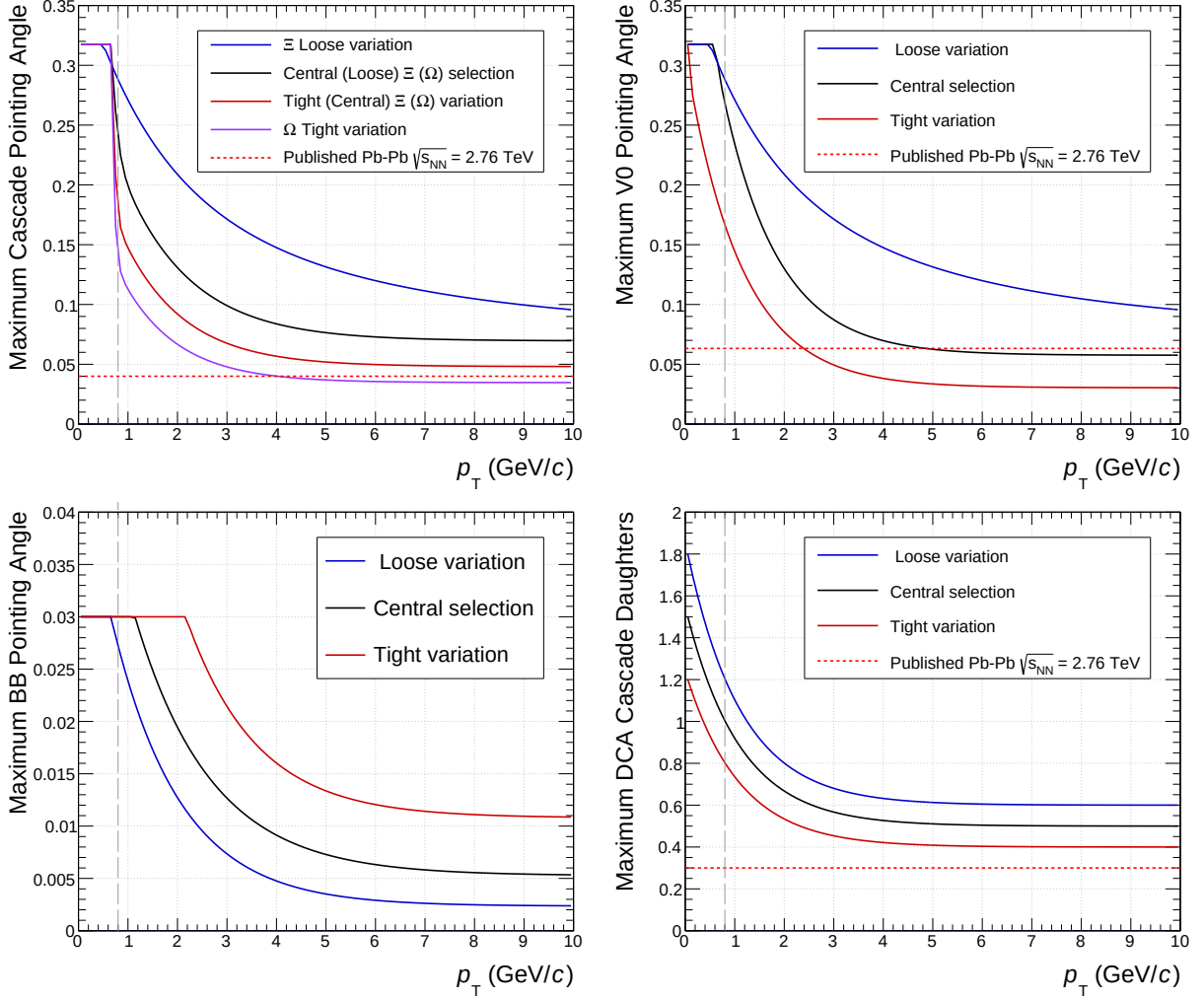


Figure 3.12: Value of topological selection (central and systematic variation) as a function of p_T for cascade pointing angle, V0 pointing angle, Bachelor-Baryon pointing angle and DCA cascade daughters. The (constant) value used for the published Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV is shown in a red dashed line. The vertical grey dashed line represents the lowest p_T bin used in this analysis, 0.8 GeV/c.

3.3.3 Stability of topological selections

After defining the central value for each topological selection as described in the previous section, a study of the stability of the yield with respect to changes in the selection was performed to confirm that the corrected results are indeed stable.

Figure 3.13 shows the evolution of the raw data signal (black squares), raw MC signal (red circles) and corrected yield (green crosses) for Ξ^- as a function of the Cascade Pointing Angle cut value for three p_T intervals of the 0 – 10% event class at both $\sqrt{s_{NN}} = 5.02$ TeV (full marker) and $\sqrt{s_{NN}} = 2.76$ TeV (open marker). The vertical lines represent the values used for the published paper of $\sqrt{s_{NN}} = 2.76$ TeV (red), the value used today in this analysis (black). The distributions were normalized in a way that the value of the distribution for the default cut value is unity. This way, we can easily see that as we tighten the pointing angle cut at the lowest p_T bin, the corrected yield gets up to 20% smaller. We observe a strong dependence of the corrected yield with the pointing angle value used, especially for very tight cuts. Therefore, the selection threshold used needs to be as loose as possible. It can also be noted that the cut value used (which is p_T dependent) is not in a problematic region.

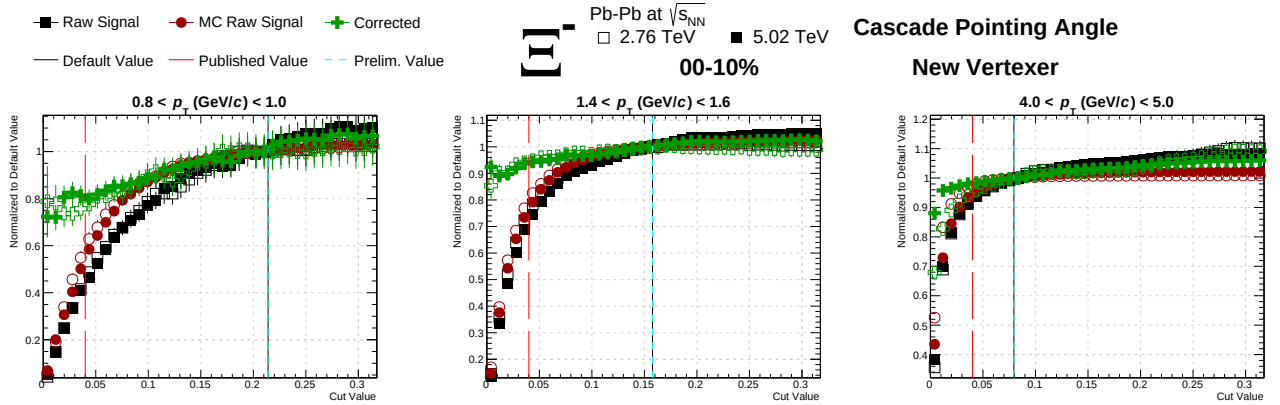


Figure 3.13: Raw-signal (black squares), MC-signal (red circles) and corrected-yield (green crosses) dependence with the Cascade Pointing Angle selection for three p_T bins at 0 – 10%. The distributions were normalized to unity at the default selection, represented by the black vertical line. The selection value used for the published Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV is shown as the red dashed line.

3.4 Invariant mass structure studies

The loosening of the topological selections coupled with the improvements in the vertexing algorithm introduced a structure in both Ξ and Ω invariant mass spectra, as shown in red in Fig. 3.14. In order to determine the origin of this invariant mass structure, a systematic study of both data and MC was conducted. This study was performed in Ξ due to the higher statistics available. It was found that the structure was present in both data as well as MC, for p_T bins from about 1 GeV/ c up to about 4 GeV/ c and located approximately in the same invariant mass range: from 1.28 to 1.31 GeV/ c^2 for Ξ . This suggested that the structure was due to a kinematic restriction of some sort.

Because the structure was also present in MC, a study of parenthood information of all tracks comprising cascade candidates was performed. It was then found that the invariant mass structure is exclusively due to the following association during cascade vertexing:

- A bachelor track which was actually the π^- (π^+) daughter of a Λ ($\bar{\Lambda}$);
- A positive (negative) track which was actually the p ($\bar{p}$) daughter of the same Λ ($\bar{\Lambda}$);
- A negative (positive) track which was any other random track in the event.

The diagram of Fig. 3.15 illustrates this association.

Once the cause of this invariant mass structure was discovered, a number of strategies was devised in order to specifically remove this contamination. The two most effective strategies are to

1. Use a minimum value for the DCA of bachelor and baryon track or
2. Use a maximum cosine of pointing angle cut for the V0 comprised of the bachelor and baryon tracks,

where the baryon was the positive track of the V0 for Ξ^- and Ω^+ decays and the negative track for Ξ^+ and $\bar{\Omega}^+$ decays.

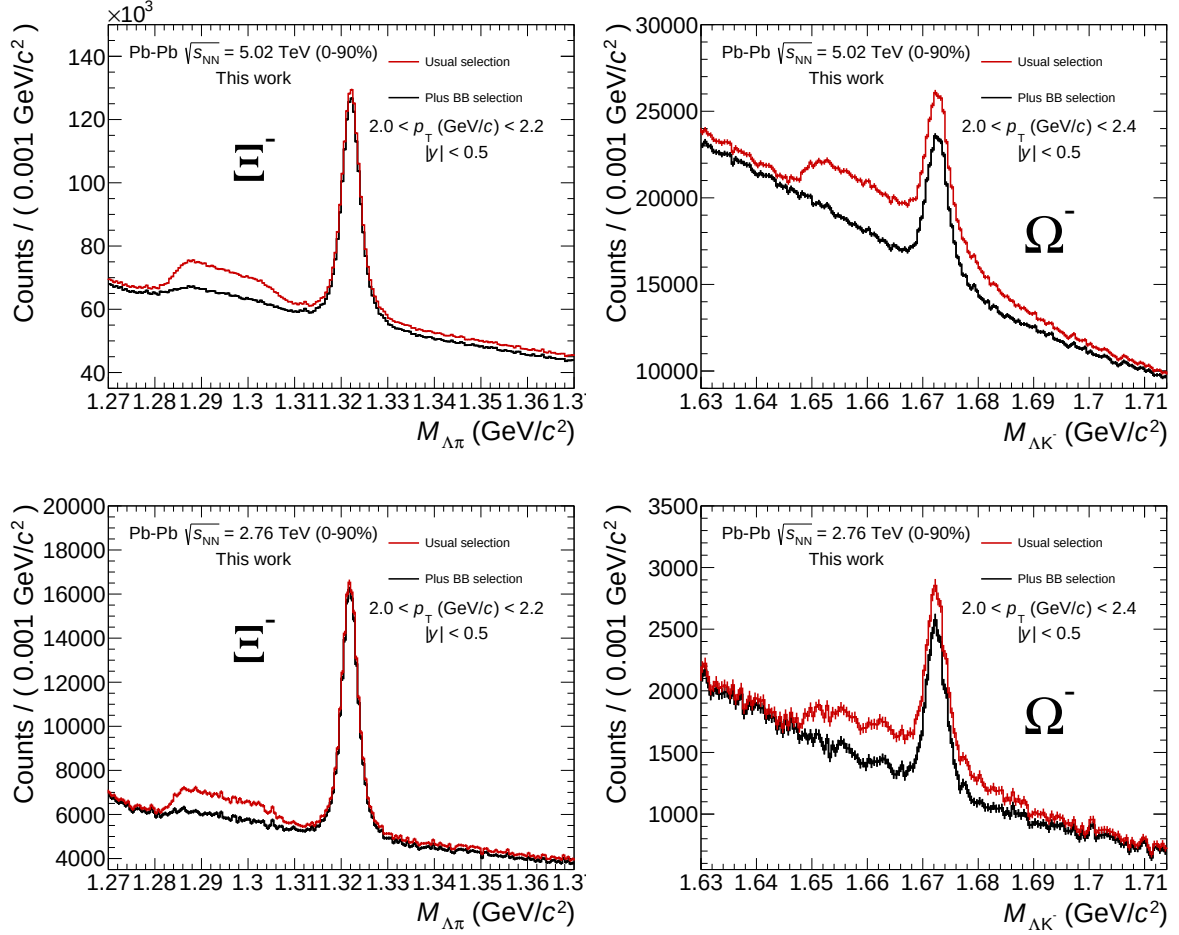


Figure 3.14: Invariant mass for Ξ and Ω at 0-90% centrality classes for Pb-Pb at both $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV after the loosening of the topological selections and inclusion of the latest vertexing techniques, in red. A structure in the invariant mass distribution can be observed and, in order to remove it, a new selection was added to the analysis. The new Bachelor-Baryon pointing angle selection removes the undesired structure without significant loss of true cascade candidates, as can be seen in the black distribution.

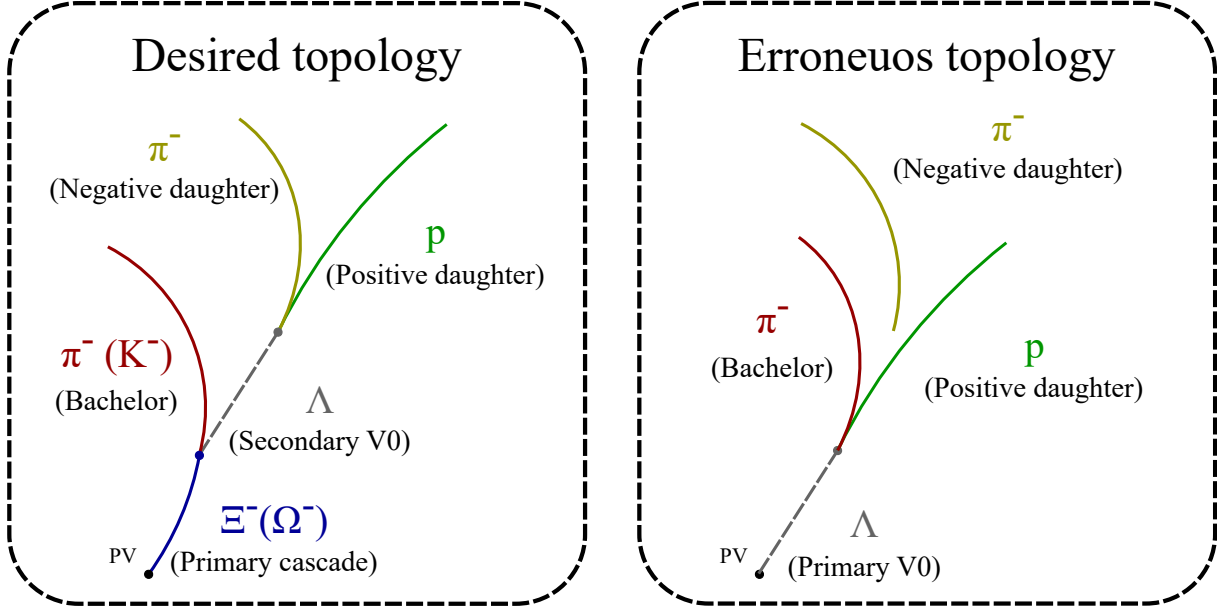


Figure 3.15: Illustration of the desired cascade decay (left diagram) and the incorrect combination (right diagram) which leads to the invariant mass structure shown in Fig. 3.14.

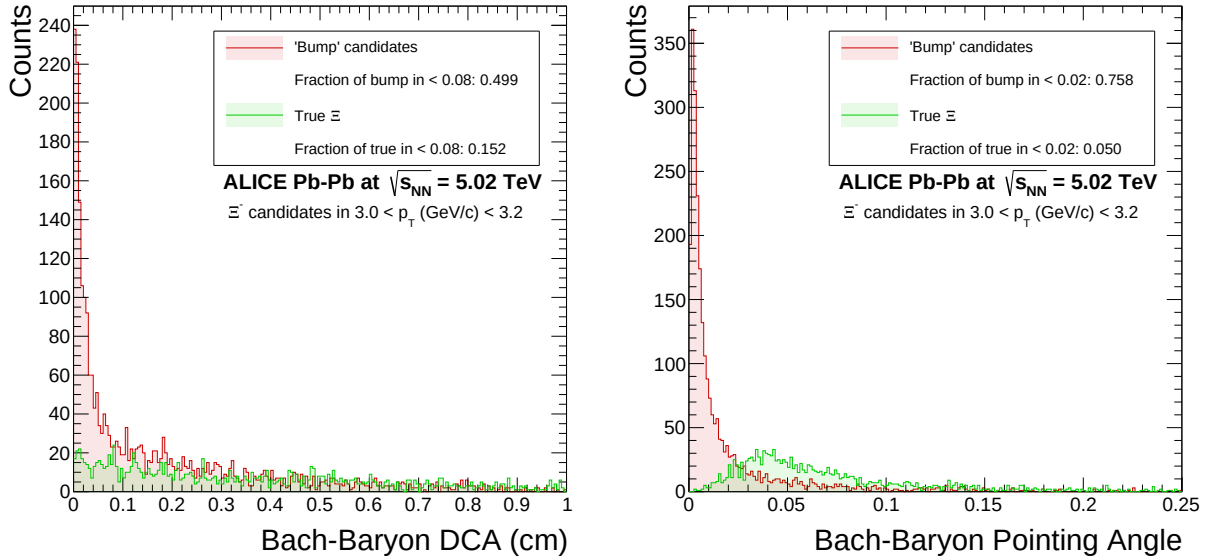


Figure 3.16: Distribution of DCA between bachelor and baryon (left plot) and pointing angle of the bachelor baryon combination (right plot) for true associated Ξ and for candidates comprising the erroneous invariant mass structure ('bump').

Both options seem to remove a sizeable amount of the structure, with the latter option being the preferred selection because of the smaller true signal losses due to very high pointing angle resolution, as can be seen in Fig. 3.16. The effect of the addition of this selection is shown in the black distributions of Fig. 3.14. A rejection based on the difference between the invariant mass of the two tracks (bachelor and baryon daughters) and the Λ PDG mass was also attempted, but this introduced unnatural structures in the invariant mass spectra of the cascades. The analysis reported in this document utilizes a p_T dependent cosine of pointing angle rejection, in a way that this selection was loosened as a function of p_T to avoid mismatch between data and MC.

3.5 Signal extraction

In order to stabilize the signal extraction, the evolution as a function of p_T of the peak mean, $\mu(p_T)$, and its width, $\sigma(p_T)$, was parameterized. These values were obtained through a Gaussian plus linear polynomial fit of the invariant mass for each p_T bin. To avoid instabilities in the low p_T region, the parameterizations were done only for antiparticles, since they have smaller background (smaller contribution from secondaries), and for the centrality class of 30-90%. The functions used to parameterize the evolution are given in equations 3.5.1 and 3.5.2.

$$\mu(p_T) = [0] + [1] \times e^{-[2] \times x} + [3] \times e^{-[4] \times x}, \quad (3.5.1)$$

and

$$\sigma(p_T) = [0] + [1] \times x + [2] \times e^{-[3] \times x}. \quad (3.5.2)$$

The results of such parameterizations are shown in Figs. 3.17 and 3.18.

The parameterizations described above were used to determine the μ and σ for each p_T bin, in order to define the peak and background regions in the invariant mass spectra:

- Peak region: ($\mu - 3\sigma$, $\mu + 3\sigma$).
- Background region: ($\mu - 6\sigma$, $\mu - 3\sigma$) + ($\mu + 3\sigma$, $\mu + 6\sigma$).

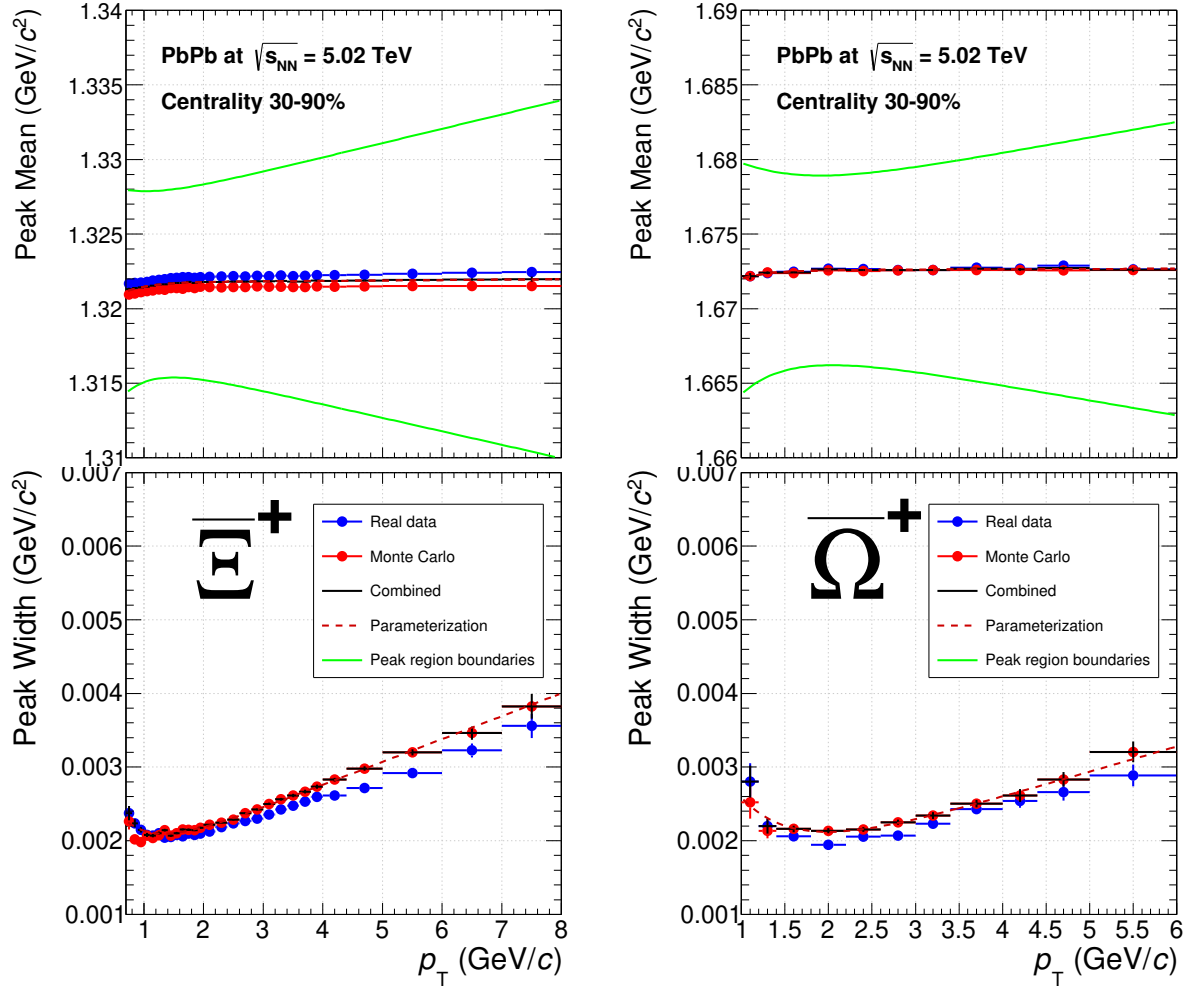


Figure 3.17: Evolution of the mean and width of the peak in the invariant mass spectrum for Ξ^+ and Ω^+ as a function of p_T for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The fits were used to stabilize the results of the signal extraction. The green curves in the upper panel represent the evolution of the peak region ($\mu \pm 3\sigma$) with p_T .

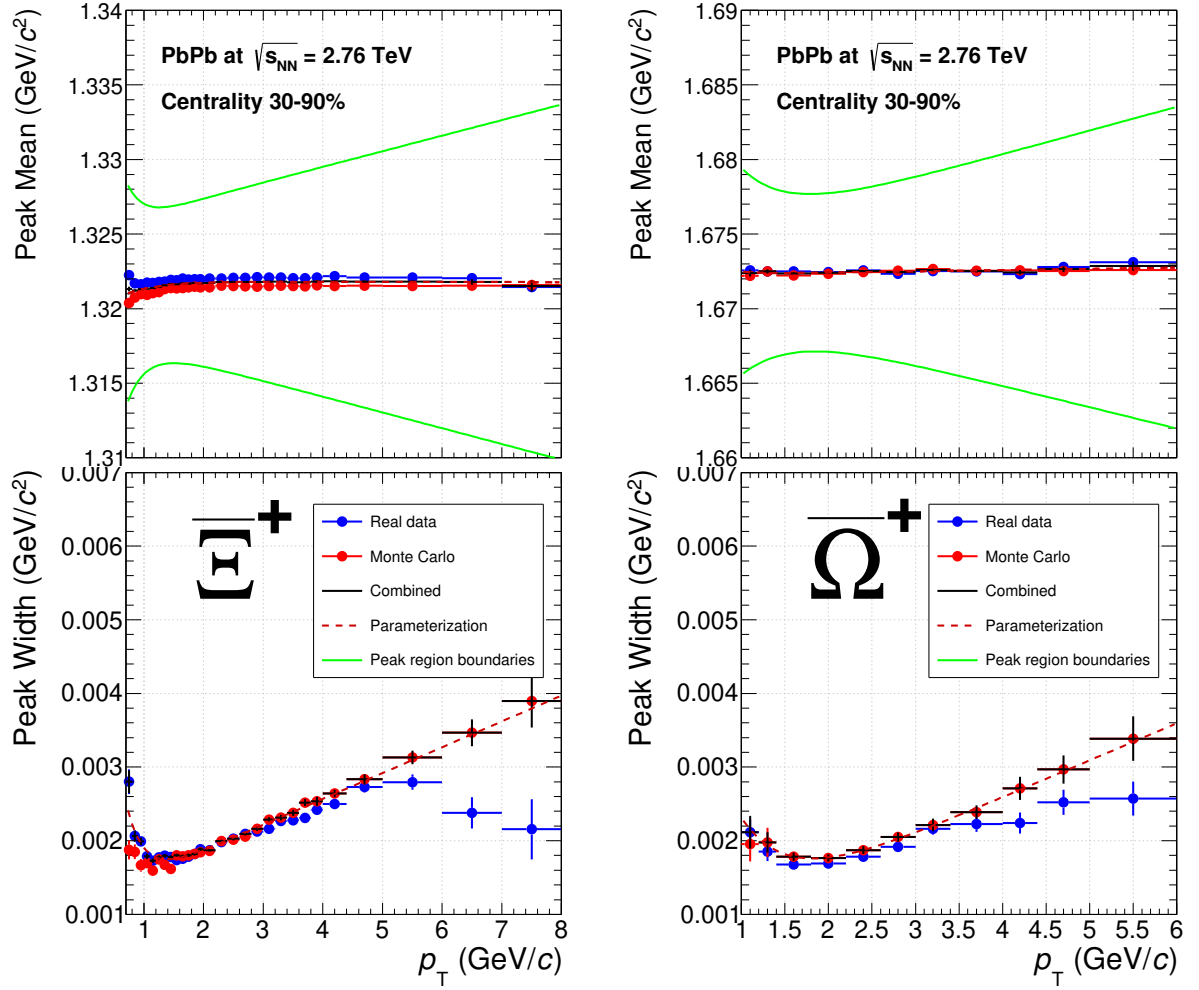


Figure 3.18: Evolution of the mean and width of the peak in the invariant mass spectrum for Ξ^+ and Ω^+ as a function of p_T for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. The fits were used to stabilize the results of the signal extraction. The green curves in the upper panel represent the evolution of the peak region ($\mu \pm 3\sigma$) with p_T .

The peak counts were computed as the sum of the bin counts inside the peak region. To compute the background counts, a polynomial fit was done to the background region, and the integral of the polynomial function in the peak region was computed. The difference between these two counts is defined as the raw signal in the given p_T bin. The degree of the polynomial function used to fit the background was:

- 2^{nd} degree : $4 \text{ GeV}/c > p_T$.
- 1^{st} degree : $p_T > 4 \text{ GeV}/c$.

Figs. 3.19 and 3.20 show samples of invariant mass distributions for Ξ and Ω with the background region highlighted in blue for three p_T regions for the most central event classes at both Pb–Pb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ and $\sqrt{s_{NN}} = 2.76 \text{ TeV}$.

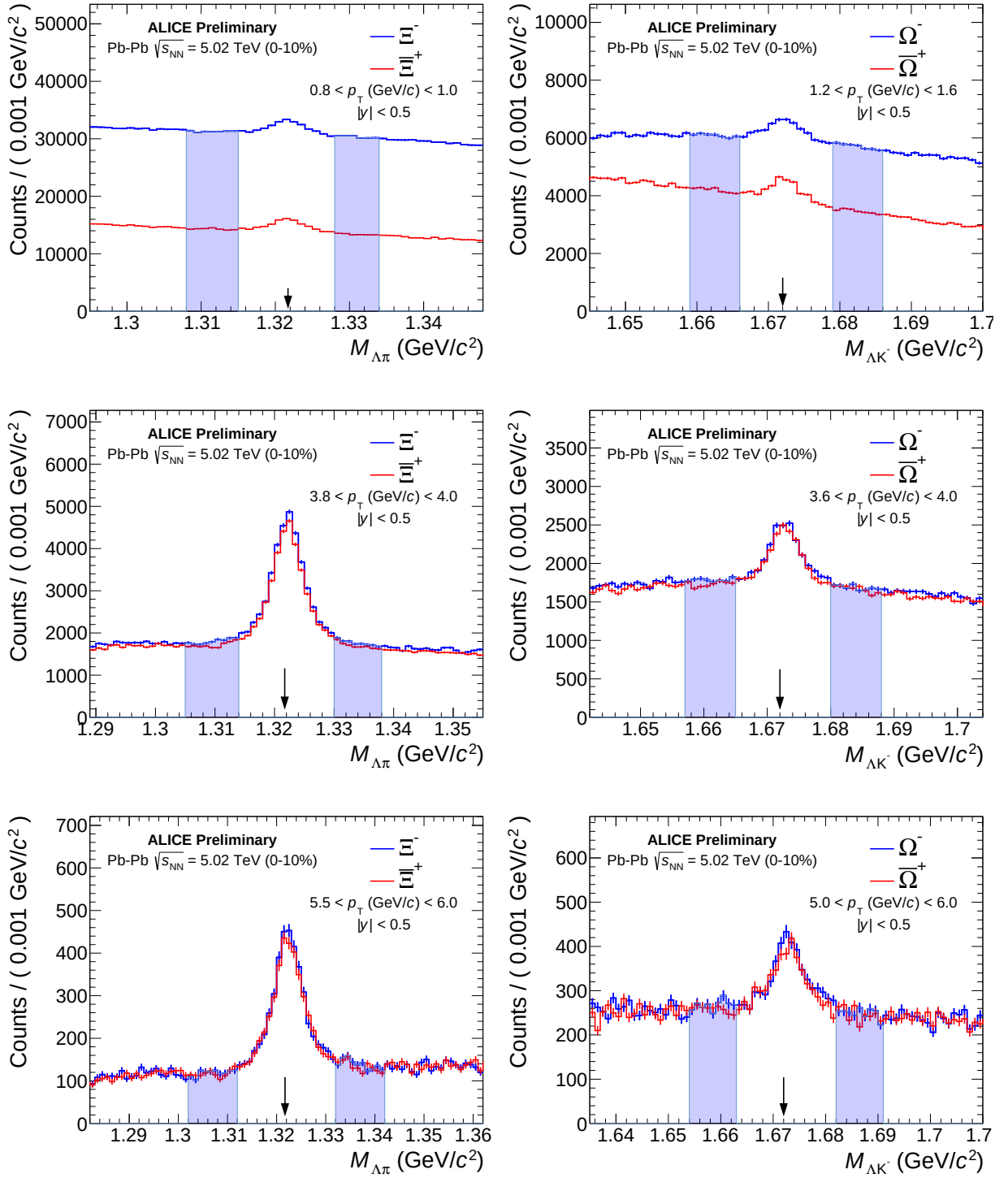


Figure 3.19: Peak and background regions for Ξ (left plots) and Ω (right plots) in low-, mid- and high- p_T for 0-10% central Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV collisions.

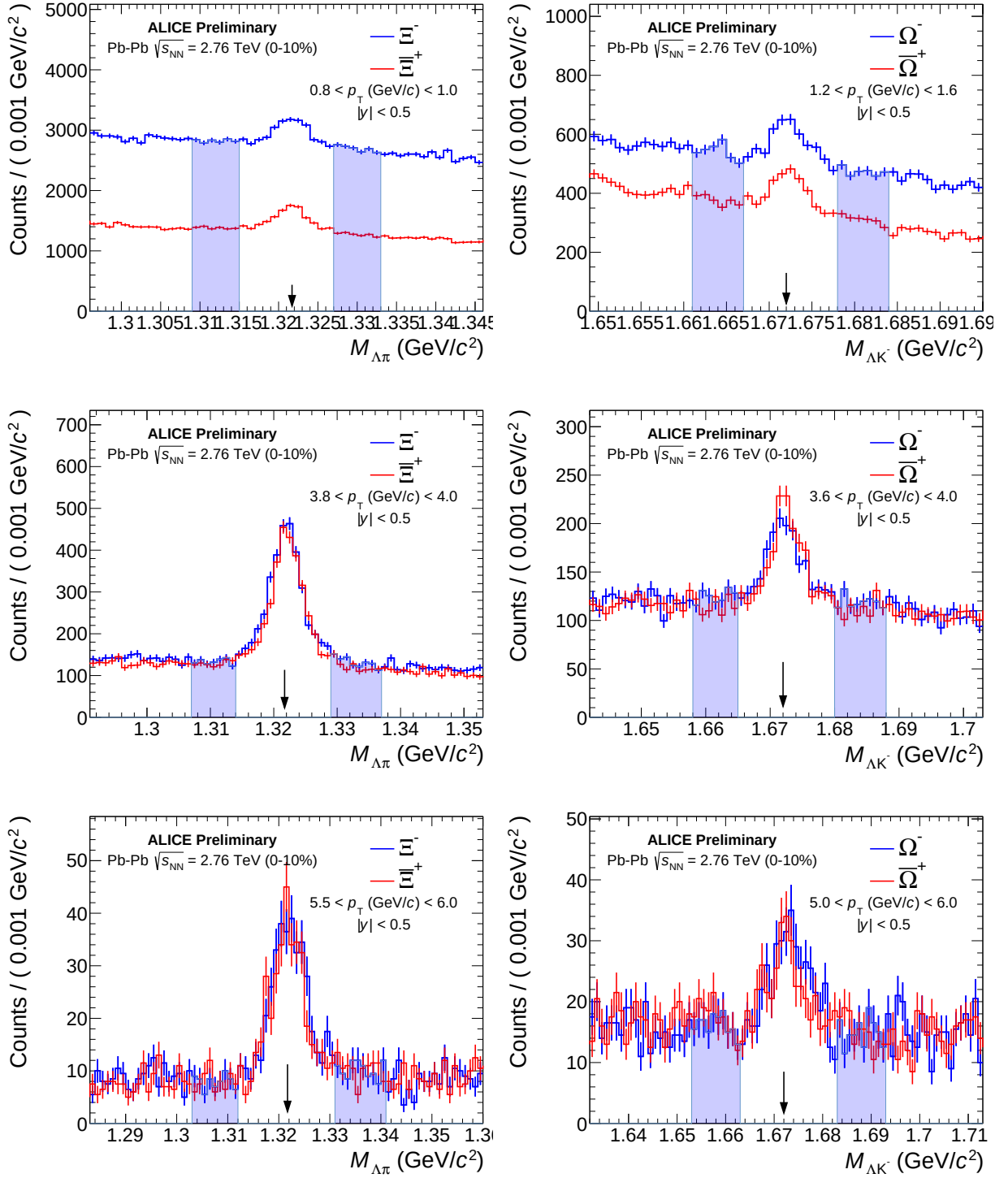


Figure 3.20: Peak and background regions for Ξ (left plots) and Ω (right plots) in low-, mid- and high- p_T for 0-10% central Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV collisions.

3.6 Efficiency computation

By simulating heavy-ion collisions, it is possible to estimate how many particles are detected in a given p_T bin for a given number of particles produced in the event. Simulated data was generated using the realist MC Pb–Pb event generator, HIJING [53], and propagated through GEANT4 [54, 55] for particle decay and a full detector response simulation.

Simulated data is analyzed with exactly the same prescription as real data, and cascade signals were extracted in invariant mass space with the same procedures. The only notable difference is that, since this is MC, the cascade candidate was further checked to match a true primary particle of the exact desired species (Ξ^- , $\bar{\Xi}^+$, Ω^- or $\bar{\Omega}^+$) in the event record.

The event record was then inspected to determine the generated primary cascades and the efficiency correction in each momentum interval was calculated as:

$$\epsilon(p_T) = \frac{N(\Xi)_{reconstructed+associated}(p_T)}{N(\Xi)_{generated\ primaries}(p_T)}. \quad (3.6.1)$$

From the MC simulation, the generated distribution is constructed, showing how many primary cascades were generated as a function of p_T for a given centrality. Since cascades have small production rates, and the generation and propagation of MC events are computationally expensive, an injection strategy is employed. By injecting cascade signals (usually up to 5 cascades per event) in a generated event before the transport simulation, we can manually increase the statistical significance of the peak. This is especially important in high p_T regions. The injected MC sample was compared to the non-injected, showing that this procedure has negligible effects in the efficiency.

Because the particle reconstruction efficiencies change as a function of centrality in Pb–Pb collisions, these must be computed in centrality intervals. The resulting efficiency distributions can be seen in Fig. 3.21 for Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV and Fig. 3.22 for $\sqrt{s_{NN}} = 2.76$ TeV. The efficiencies that would have been obtained with the selection criteria used in the published $\sqrt{s_{NN}} = 2.76$ TeV analysis are also shown for comparison and are lower by at more than a

factor 2 at low p_T because of the tighter selections used.

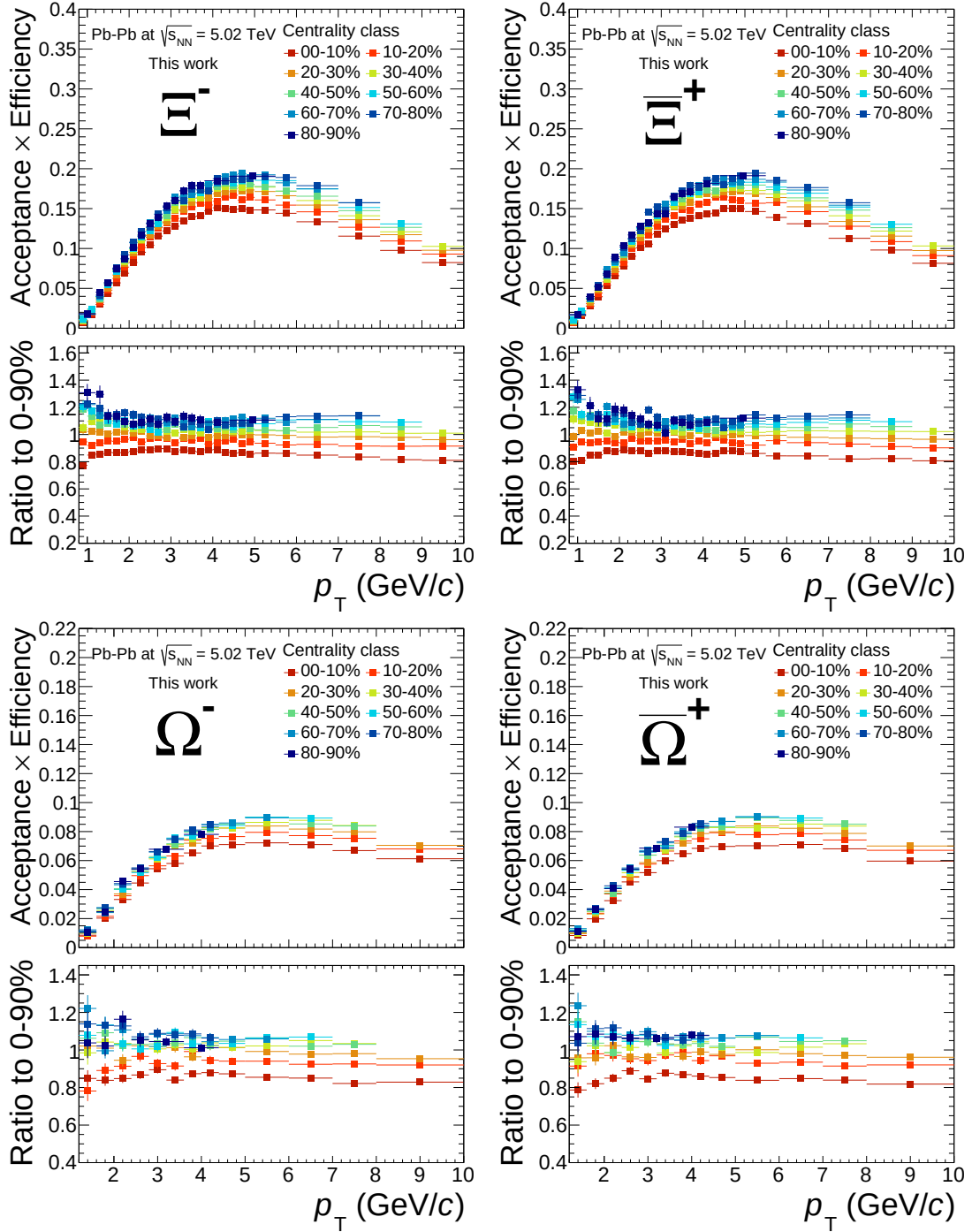


Figure 3.21: Efficiency as a function of p_T for Ξ^- (top left), Ξ^+ (top right), Ω^- (bottom left) and Ω^+ (bottom right) for different centrality classes for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The bottom pad shows the ratio between these and the integrated 0-90% efficiency.

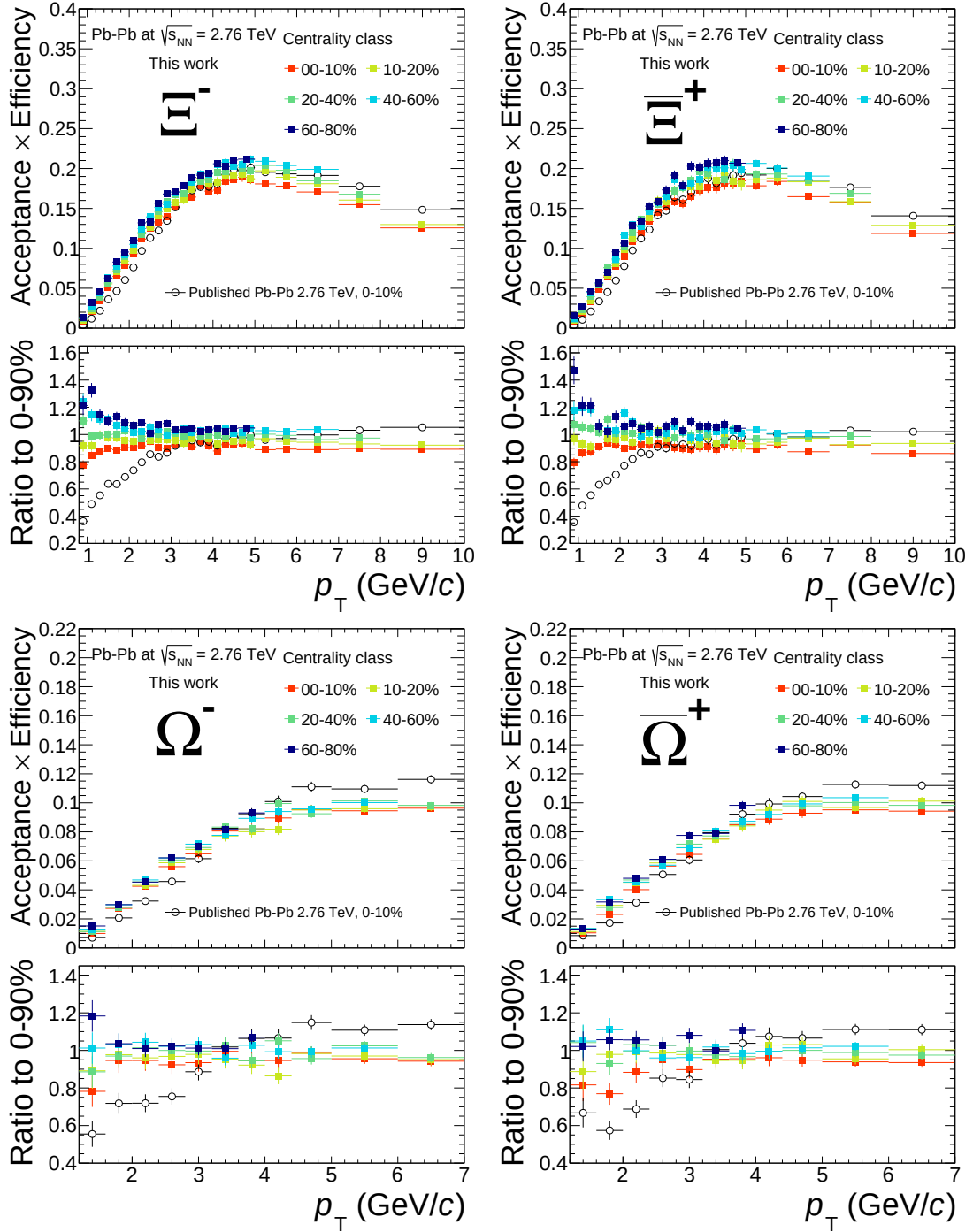


Figure 3.22: Efficiency as a function of p_T for Ξ^- (top left), Ξ^+ (top right), Ω^- (bottom left) and Ω^+ (bottom right) for different centrality classes for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. The bottom pad shows the ratio between these and the integrated 0-90% efficiency. A comparison to the 0-10% efficiency for the tighter selection used in the published Pb-Pb analysis is also shown as open black circles.

3.7 Corrections for Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Due to peculiarities of the MC productions used for the analysis of Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, the addition of two corrections was necessary. In this section, we describe the effect of these corrections on the p_{T} spectra of cascades.

GEANT3/FLUKA correction

The MC used in the Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV was generated with HIJING, and the particle transport was handled using the GEANT3 transport code. In GEANT3, the values of the proton and antiproton absorption cross-sections are overestimated, being better described in FLUKA. The discrepancy is asymmetrical, being larger for antiprotons.

In order to correct the efficiency for this effect, the efficiency ratio curve was computed using GEANT3 and FLUKA for protons and antiprotons:

$$\frac{\varepsilon_{\text{GEANT3}}}{\varepsilon_{\text{FLUKA}}}, \quad (3.7.1)$$

which is shown in the left plot of Fig. 3.23.

This correction is dependent on the (anti)proton p_{T} , and therefore, the correlation between the cascade p_{T} and its (anti)proton daughter p_{T} must be computed. This correlation is shown on the right plot of Fig. 3.23. This way, for a given cascade p_{T} , the average transverse momentum of the (anti)proton daughter was used, and the correspondent correction was determined, as exemplified by the red line (for a Ξ of $p_{\text{T}} \sim 1$ GeV/ c). The effect on the corrected p_{T} spectra is shown in Fig. 3.24. The basic assumption is that the correction, that was calculated for primary (anti)protons, can also be used for secondary (anti)protons.

As previously mentioned, the effect of this correction is asymmetrical, being of up to 10% at low- p_{T} for antiparticles, while for particles it is less than 1%.

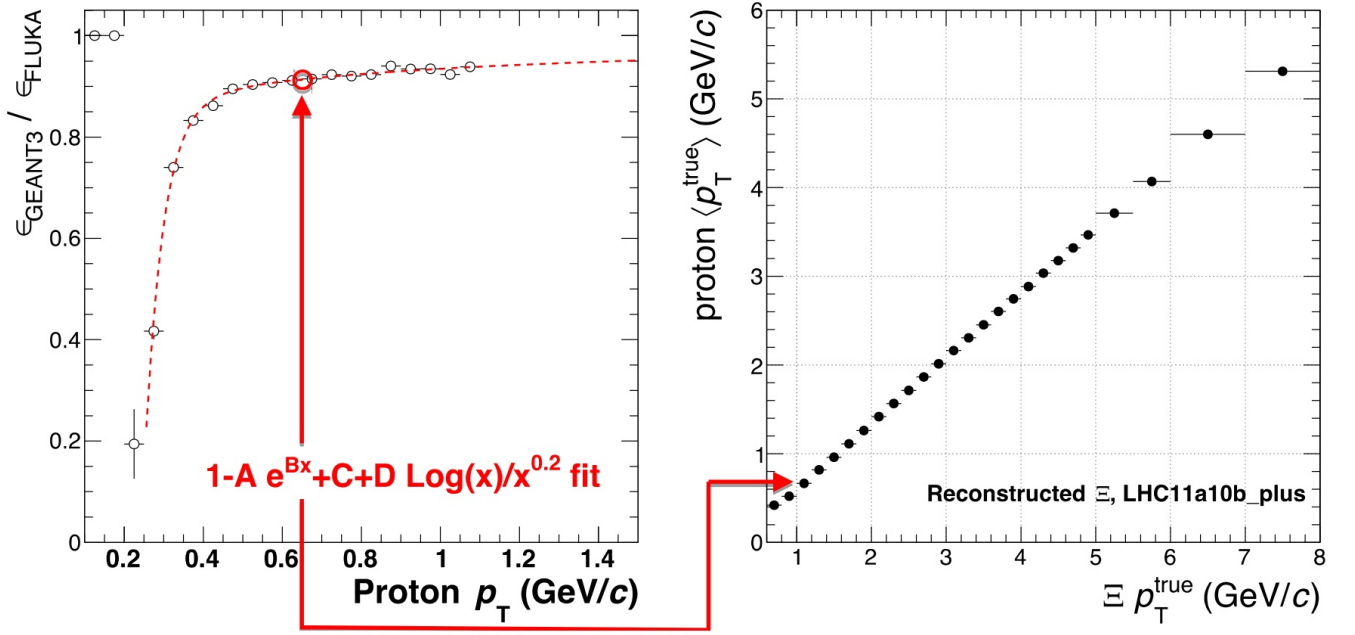


Figure 3.23: (left plot) Effect of the GEANT3/FLUKA correction on primary protons. (right plot) Correlation between Ξp_T and the average p_T of its proton daughter.

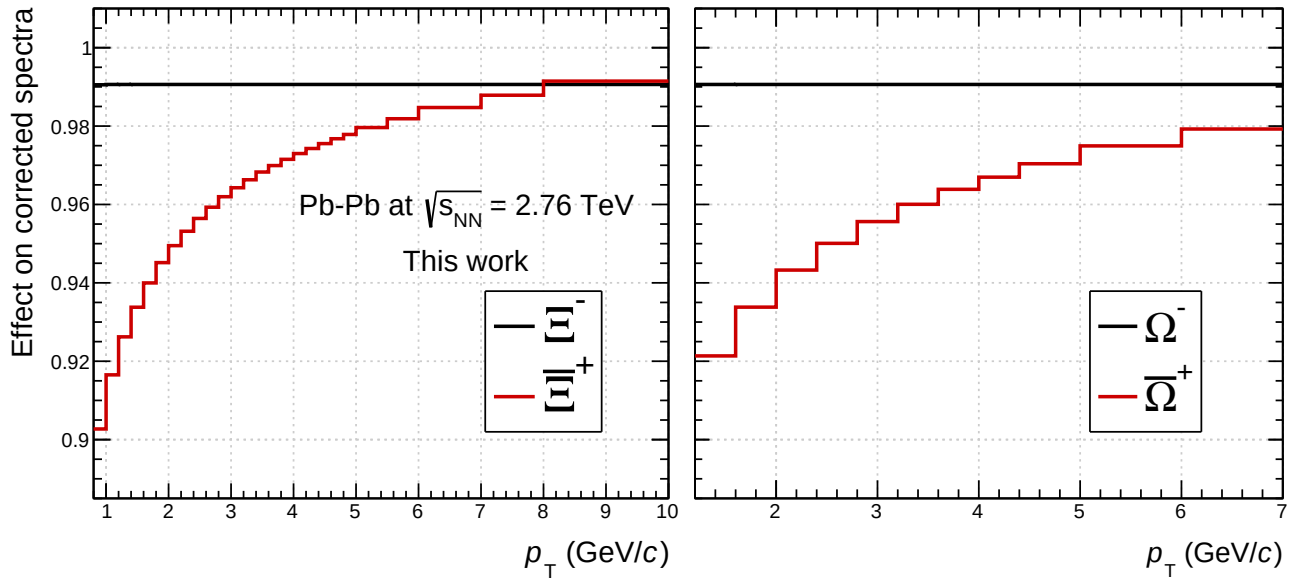


Figure 3.24: Effect of the GEANT3/FLUKA correction on the corrected spectra of cascades. The effect on antiparticles can be up to 10% on the low- p_T region, while an effect of $\lesssim 1\%$ is observed for particles.

$dy/d\theta$ correction

Since the cascade injection strategy used in the MC production of Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV adopted a flat distribution in θ , instead of in y , a correction of the efficiency is necessary.

The differential (in p_{T} and y) number of reconstructed candidates can be expressed as

$$N_{\text{reco}}(p_{\text{T}}, y_i) = N_{\text{gen}}(p_{\text{T}}, y_i) \epsilon(p_{\text{T}}, y_i). \quad (3.7.2)$$

Using the efficiency definition from equation 3.6.1, the efficiency can be written as

$$\epsilon(p_{\text{T}}) = \frac{\sum_y N_{\text{gen}}(p_{\text{T}}, y_i) \epsilon(p_{\text{T}}, y_i)}{\sum_y N_{\text{gen}}(p_{\text{T}}, y_i)}. \quad (3.7.3)$$

The correct way to combine the local $\epsilon(p_{\text{T}}, y_i)$ can be assumed to be such that we have a flat-in- y N_{gen} distribution:

$$N_{\text{gen}}(p_{\text{T}}, y_i) \equiv N_{\text{gen}}^{\text{per-}y\text{-bin}}(p_{\text{T}}). \quad (3.7.4)$$

This way, we can rewrite equation 3.7.3 as:

$$\epsilon(p_{\text{T}}) = \frac{N_{\text{gen}}^{\text{per-}y\text{-bin}}(p_{\text{T}}) \sum_y \epsilon(p_{\text{T}}, y_i)}{N_{\text{gen}}^{\text{per-}y\text{-bin}}(p_{\text{T}}) \times N_{\text{bins}}} = \frac{1}{N_{\text{bins}}} \sum_y \epsilon(p_{\text{T}}, y_i). \quad (3.7.5)$$

Therefore, the re-weighted efficiency was computed, for each p_{T} bin, by taking a simple average of the efficiency in the y slice. Fig. 3.25 shows $\epsilon(p_{\text{T}}, y)$ used in this computation for Ξ^- at 0-10%, where the y -dependency of the efficiency can be observed.

The effect of this procedure can be estimated by dividing the efficiency obtained as described above and the usual one. Fig. 3.26 shows the ratio between these two efficiencies for both Ξ and Ω for all centralities analyzed in this work.

Since this correction was necessary due to the non-flatness in y of the injected cascades, it was expected to be stronger the higher the ratio between injected to non-injected true cascades. This effect can be observed in Fig. 3.26, where a stronger effect for peripheral centrality classes and Ω is observed. A difference between the corrections for Ξ^- and Ξ^+ is explained by the

difference in the injection strategy for the two particles.

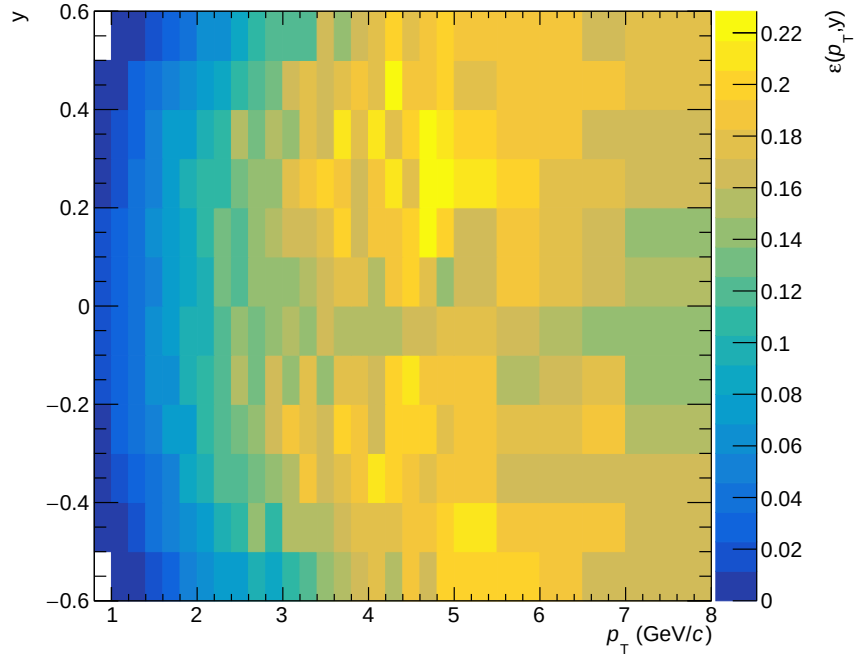


Figure 3.25: Efficiency as a function of p_T and rapidity, $\epsilon(p_T, y_i)$, for Ξ^- in Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

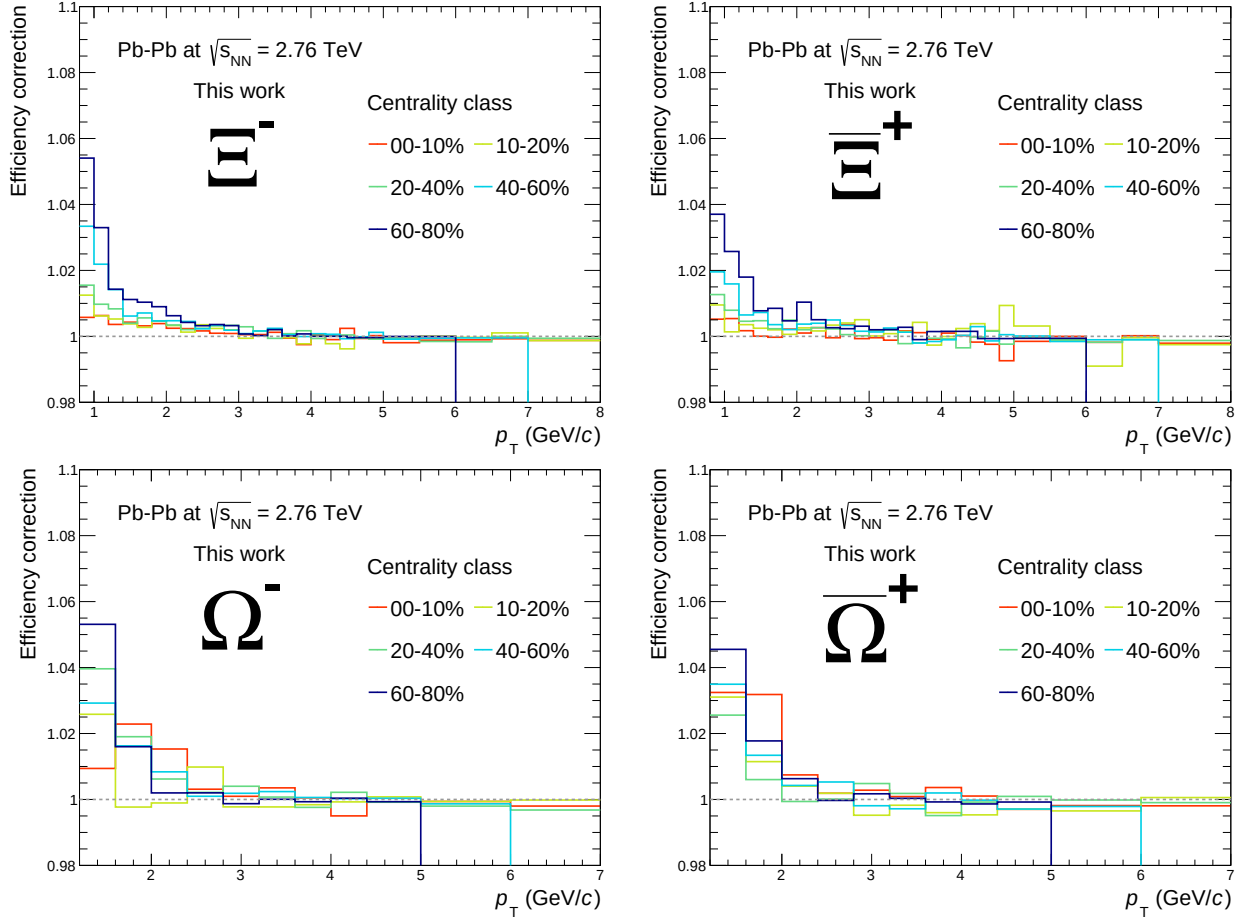


Figure 3.26: Efficiency correction due to the flat-in- θ injection as a function of p_T for Ξ and Ω in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Chapter 4

Evaluation of systematic uncertainties

As it became clear in chapter 3, the measurement of multi-strange baryons relies on several parameters, such as the length of the track inside the TPC detector, the distance of closest approach between the detected tracks, etc. The physical quantity of interest, the total production rate of hyperons, should not depend on any of these parameters. When small variations in the selections change the final corrected spectra, systematic uncertainties are assigned.

In this chapter, the strategy for the computation of the systematic uncertainty for the corrected spectra and extrapolation to low p_T is described.

4.1 Uncertainty computation

Topological selections: To determine any systematic effects due to topological selections, these were individually varied in ways that produced up to 10% variation of the uncorrected raw yield in data. The deviations on the corrected yields after this change were treated as systematic uncertainty and summed quadratically for each selection. Overall, the topological variations accounted for approximately a 5% (10%) systematic uncertainty for the Ξ (Ω). The higher systematic uncertainty for the Ω is due to the lower peak significance and the concave behaviour of the background around the peak.

Track quality: In this analysis, three selections were used to ensure good tracking conditions. In order to study if these selections produce any systematic effects on the analysis, they were varied in the following manner:

- **Minimum Track Length:** changed from default (90 cm) to a looser variation of 100 cm and a tighter of 80 cm.
- **Minimum Number of Crossed Rows:** changed from default (80) to a looser variation of 90 and a tighter of 70.
- **Crossed Rows over Findable:** changed from default (0.8) to a looser variation of 0.9 and a tighter of 0.7.

The corresponding deviations in the corrected results were treated as systematic uncertainties due to this selection and result in a systematic uncertainty that is less than 2% for all particles.

TPC dE/dx selections: In order to investigate any effects due to the 4σ TPC dE/dx selection used in the cascade analysis, we varied this selection to 3σ and 5σ . The deviations from unity in the ratio of the corrected spectra were used as systematic uncertainties and represent $\sim 2.5\%$ of systematic uncertainty of both Ξ and Ω .

Proper lifetime selections: A selection of $mL/p < 15$ cm and $mL/p < 8$ cm is applied to the Ξ and Ω analyses, respectively. In order to investigate if such selections introduce systematic biases, they were varied to 17.5 cm and 12.5 cm for Ξ and 12.5 cm and 6 cm for the Ω . The selection of $mL_{V0}/p < 30$ cm was changed to 20 cm and 40 cm. Deviations in the corrected yield were treated as systematic uncertainties and summed in quadrature, resulting in a systematic uncertainty of $\lesssim 2\%$ for all particles.

Competing decay rejection (for the Ω analysis only): The effect of the competing rejection on the yield of the Ω was tested by removing the rejection and increasing the rejection

to 10 MeV/ c^2 around the Ξ PDG mass. The systematic uncertainty due to this selection is $\lesssim 2.5\%$.

Signal extraction: The systematic uncertainty due to the signal extraction was divided in two sources and added in quadrature.

- **Peak region ($n\sigma$):** changed the definition of the peak region from the default ($\mu - 3\sigma$, $\mu + 3\sigma$) to
 - Peak : ($\mu - 2.75\sigma$, $\mu + 2.75\sigma$).
 - Peak : ($\mu - 3.25\sigma$, $\mu + 3.25\sigma$).
- **Background estimation function:** changed the polynomial function to a 1st degree and 3rd degree. For the 3rd degree function, the background region was re-defined to $(\mu - 7\sigma, \mu - 3\sigma) + (\mu + 3\sigma, \mu + 12\sigma)$ in order to obtain good quality fits of the background. The background left band is chosen to be smaller than the right band to avoid instabilities in the fitting procedure due to residue of the structure described in Section 3.4 and due to the concave behavior of the background for low invariant mass values.

For each of these sources, the maximum deviation in each p_T bin with respect to the default signal extraction strategy was used as the systematic uncertainty. The systematic uncertainty due to signal extraction depends strongly with the cascade momentum and can be up to 15% in the low- p_T region.

Material budget: To investigate the effect of the material budget on the efficiency of detection, five sets of dedicated MC productions were generated, LHC17d7a, LHC17d7b, LHC17h5a, LHC17h5b and LHC17h5c. These productions have a configuration equal to the LHC16i1c, apart from the material budget and the injection strategy for strange particles. By artificially increasing/decreasing the density of the material budget inside the detector in the MC simulation, it is possible to study the uncertainty in the measurement due to the uncertainty on the determination of the ALICE material budget. The corresponding difference in the material budget for each simulation is the following:

- LHC17d7a : +4.5% of material.
- LHC17d7b : -4.5% of material.
- LHC17h5a : -10% of material.
- LHC17h5b : no change in material.
- LHC17h5c : -10% of material.

The value of $\pm 4.5\%$ used for the variation of LHC17d7(a,b) corresponds to the uncertainty on the material budget inside the ALICE detector, as estimated in previous analyses of photon conversions [38, 56]. This variation was raised for LHC17h5(a,b,c) to increase the effect of the material budget and better estimate its contribution. Therefore, when comparing the two variations, the results for LHC17h5(a,b,c) are normalized by 0.45 to obtain the variation in the efficiency due to the expected $\pm 4.5\%$ material uncertainty.

Since the material budget variations are particularly important at low- p_T , the injection was changed in order to increase statistics in the region of interest. For Ξ , the injection goes up to 6 GeV/ c and up to 5 GeV/ c for Ω for the LHC17d7(a,b) productions. For the LHC17h5(a,b,c), the injection strategy is further concentrated in the low p_T region, with injection of 5 Ξ and 5 Ω per event up to 3 GeV/ c .

The effects of the material budget on the efficiency for Ξ and Ω can be seen in Fig. 4.1. For the low p_T region, the ratio of the efficiencies from LHC17h5a and LHC17h5c to the one of LHC17h5b was used to compute the uncertainty. For p_T greater than 3 GeV/ c , the ratio between the efficiency obtained from LHC17d7b and LHC17d7a was used to compute the uncertainty. The uncertainty was estimated to be half of the deviation from unity of this ratio.

The information of the two regions was combined in a way that we have an uncertainty associated to the increase of material (blue) and to the decrease of material (red). The efficiency related to an increase of the material, in blue, has been reflected around 1 to improve visibility in the comparison to the one related to a decrease of the material budget. A combined fit was performed (dashed black line) and the fitted function was used as the material budget uncertainty as a function of p_T .

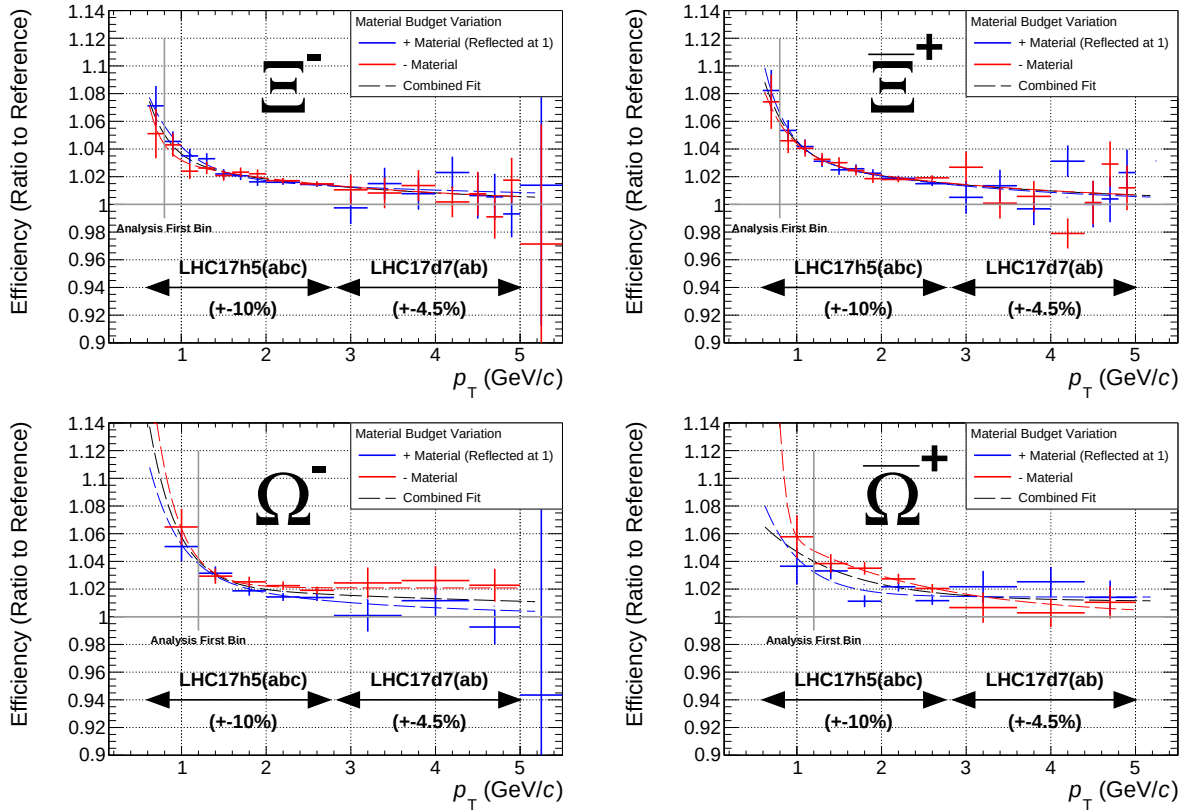


Figure 4.1: Ratio of the efficiency obtained with MC productions with different amount of material. For the low p_T region, the deviations obtained with the LHC17h5(abc) datasets are scaled by 0.45 to obtain the expected change due to a $\pm 4.5\%$ change in material.

Centrality dependence of efficiency: As already mentioned in section 3.6, the efficiency in Pb–Pb collisions presents a strong dependence with N_{ch} . As discussed in Sec. 2.5.2, the N_{ch} computation relies on the measurement of the number of tracklets inside the ITS, $N_{\text{tracklets}}$. Therefore, to ensure that the simulation used in the efficiency computation reflects the running conditions observed in data, the MC centrality-multiplicity classes are defined in such a way that the number of tracklets in the *SPD*, $N_{\text{tracklets}}$, in data and MC match for a given centrality.

However, deviations between the $N_{\text{tracklets}}^{\text{Data}}$ and $N_{\text{tracklets}}^{\text{MC}}$, coupled to the N_{ch} dependence of the efficiency, can affect the corrected result. This effect was treated as a systematic uncertainty in this analysis.

To estimate this uncertainty, the dependence of the efficiency with N_{ch} , $\partial\epsilon/\partial N_{\text{ch}}$, was assumed to be linear and was computed as a function of p_{T} . For this uncertainty estimation, we treat $N_{\text{tracklets}} \approx N_{\text{ch}}$. Thus, the systematic uncertainty of the efficiency was computed in the following way:

$$\frac{\delta\epsilon}{\epsilon} = \frac{1}{\epsilon} \left(\frac{\partial\epsilon}{\partial N_{\text{ch}}} \right) \Delta N_{\text{Tracklets}} = \frac{1}{\epsilon} \left(\frac{\partial\epsilon}{\partial N_{\text{ch}}} \right) |\langle N_{\text{Tracklets}}^{\text{Data}} \rangle - \langle N_{\text{Tracklets}}^{\text{MC}} \rangle|. \quad (4.1.1)$$

Although dependent with centrality, this uncertainty is consistently lower than 1% for all centralities, as can be seen in Fig. 4.2. The dependence of this uncertainty with centrality can be seen to be period dependent. The improvements in the agreement between data and MC in the centrality estimation algorithm is responsible for the smaller uncertainties of the peripheral events of Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

Systematic uncertainty computation: The deviations in raw yield, efficiencies and corrected result across the measured p_{T} range were then systematically studied, as can be seen in Figs. 4.3 through 4.6 for the Ξ^- and 4.7 through 4.10 for the Ω^- . Results for antiparticles show similar behavior and are omitted. Since we use the same dataset to compute the uncertainty, the errors on the ratio were defined taking into consideration the Roger-Barlow [57]

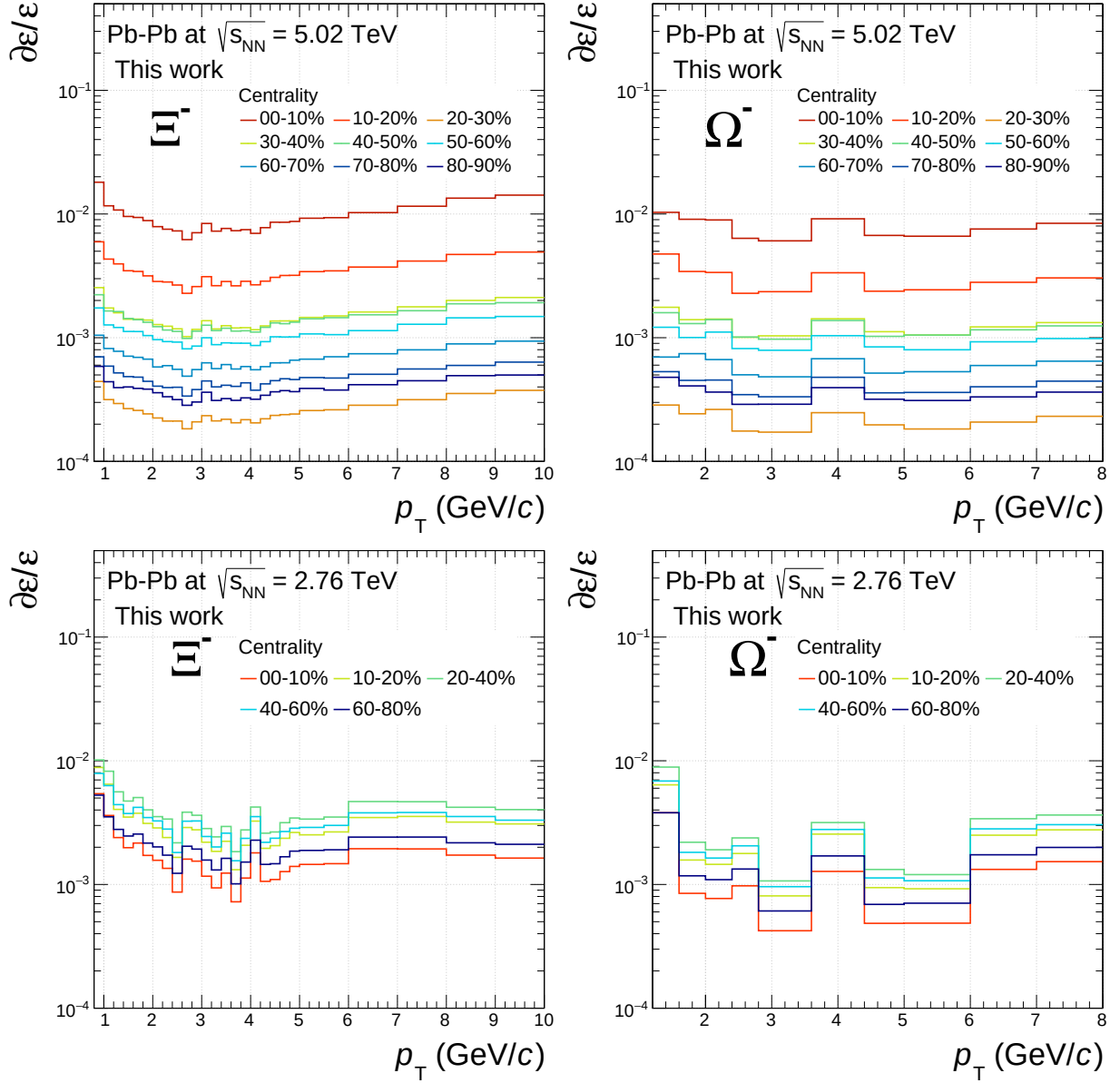


Figure 4.2: Systematic uncertainty due to the centrality dependence of the efficiency for Ξ^- and Ω^- for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV (top plots) and $\sqrt{s_{NN}} = 2.76$ TeV (bottom plots). The effect on the efficiency of the antiparticle is similar to this and is omitted.

prescription:

$$\sigma_B^2 = \sigma_{\text{central}}^2 - \sigma_{\text{loose/tight}}^2. \quad (4.1.2)$$

If the deviation was less than σ_B , it was not taken into consideration for the systematic uncertainty computation.

The result of summing in quadrature all the sources of systematic uncertainties for the most central class of events is shown for all particles and both energies in Figs. 4.11 through 4.19.

4.2 Multiplicity dependent systematic uncertainty

In order to determine the fraction of the systematic uncertainty that is dependent on multiplicity, we follow the same procedure adopted in the p-Pb analysis [27]. This way, for each systematic uncertainty source, k , and centrality, we compute the double ratio:

$$R_k = \frac{Y_{\text{cent. class}}^{\text{cent. class}}}{Y_{\text{default}}^{\text{cent. class}}} \bigg/ \frac{Y_{k\text{-variation}}^{00-90\%}}{Y_{\text{default}}^{00-90\%}}, \quad (4.2.1)$$

where $Y_{\text{default}}^{\text{cent. class}}$ is the corrected yield obtained with the default cascade selections in a given centrality class and $Y_{k\text{-variation}}^{\text{cent. class}}$ is the one obtained when changing a given k selection (cascade pointing angle, TPC dE/dx , and so on) to its systematic variation value.

In order to obtain the N_{ch} -dependent fraction, we perform:

$$\left(\frac{\delta S^i}{S^i} \right)^2 = \sum_k (|R_k - 1|^2). \quad (4.2.2)$$

Statistical fluctuations and instabilities on the signal extraction can affect the estimation of this multiplicity dependent uncertainty. Therefore, to minimize these problems, this uncertainty was only estimated for Ξ and only in three centrality classes: 0-20%, 20-40% and 40-90%. On top of that, the p_{T} binning used for the estimation was coarser than the one used in the analysis.

After obtaining the fraction of the systematic uncertainty that is multiplicity dependent, the p_{T} spectra with N_{ch} dependent systematic uncertainty was generated for each centrality in

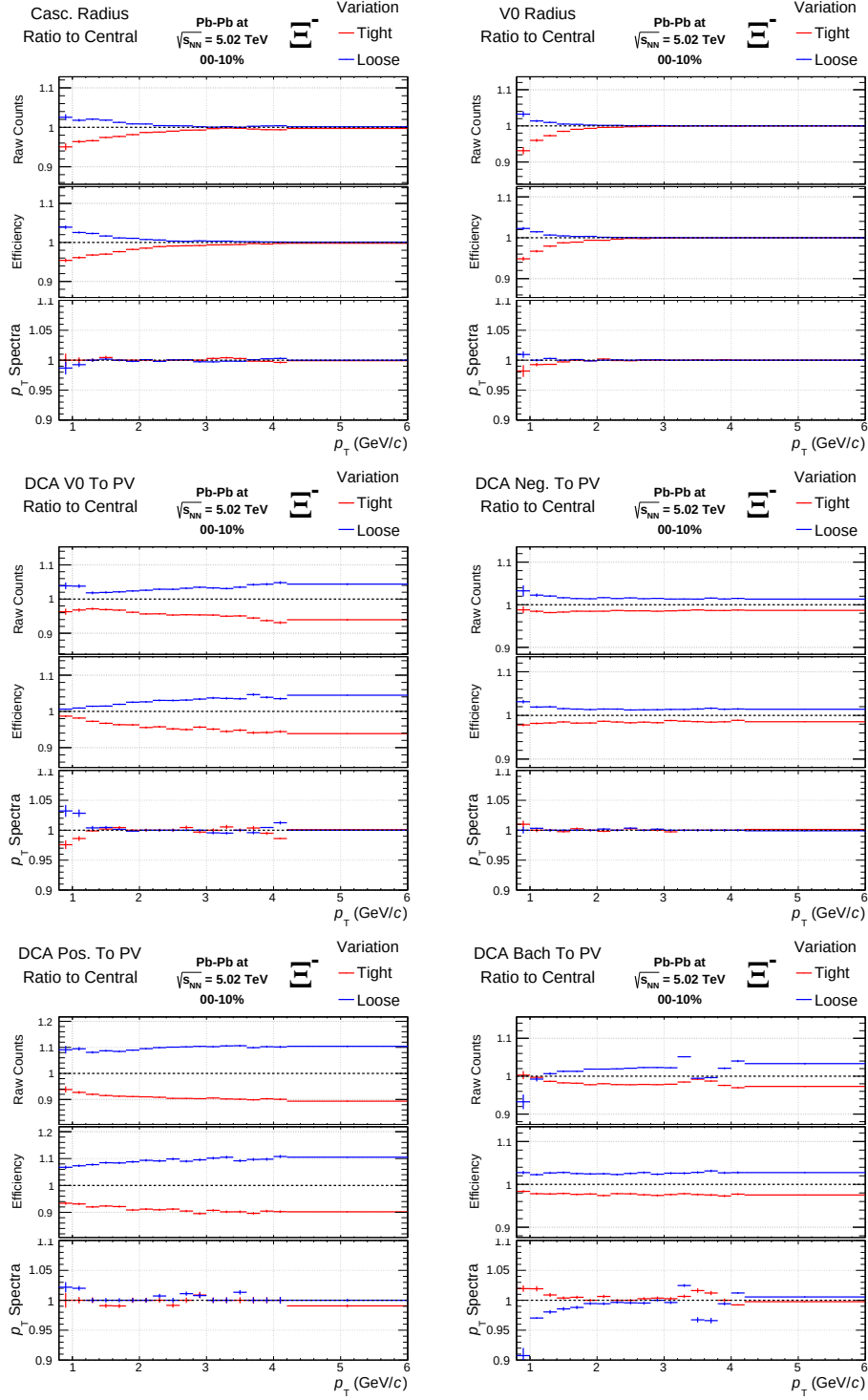


Figure 4.3: Systematic uncertainty computation for Ξ^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to selections on the cascade and V0 radius, on the DCA between the V0 to the PV and on the single-track DCAs to the PV.

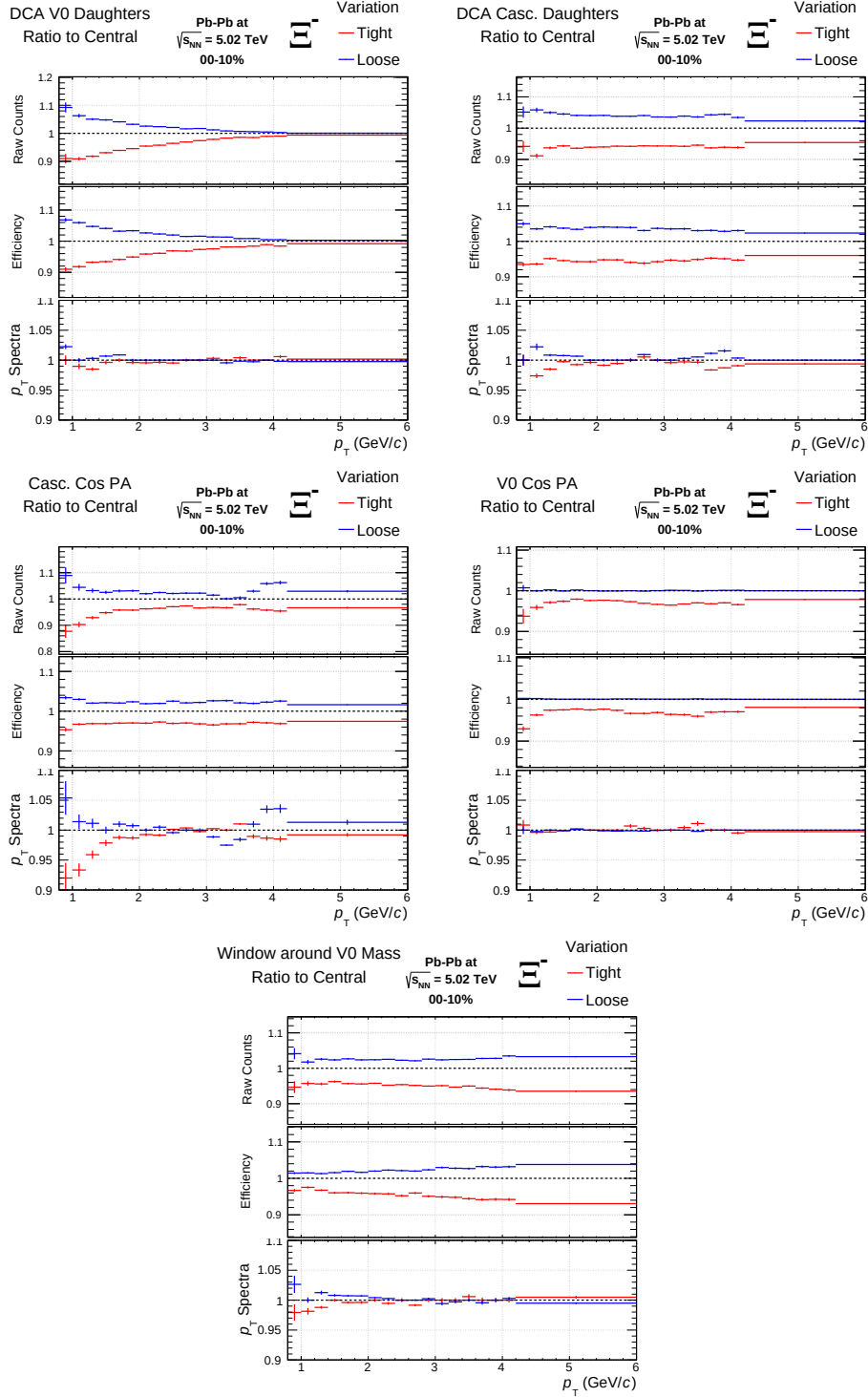


Figure 4.4: Systematic uncertainty computation for Ξ^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to selections on the DCA between V0 and cascade daughters, on cascade and V0 pointing angle and on the mass window of the V0 candidate.

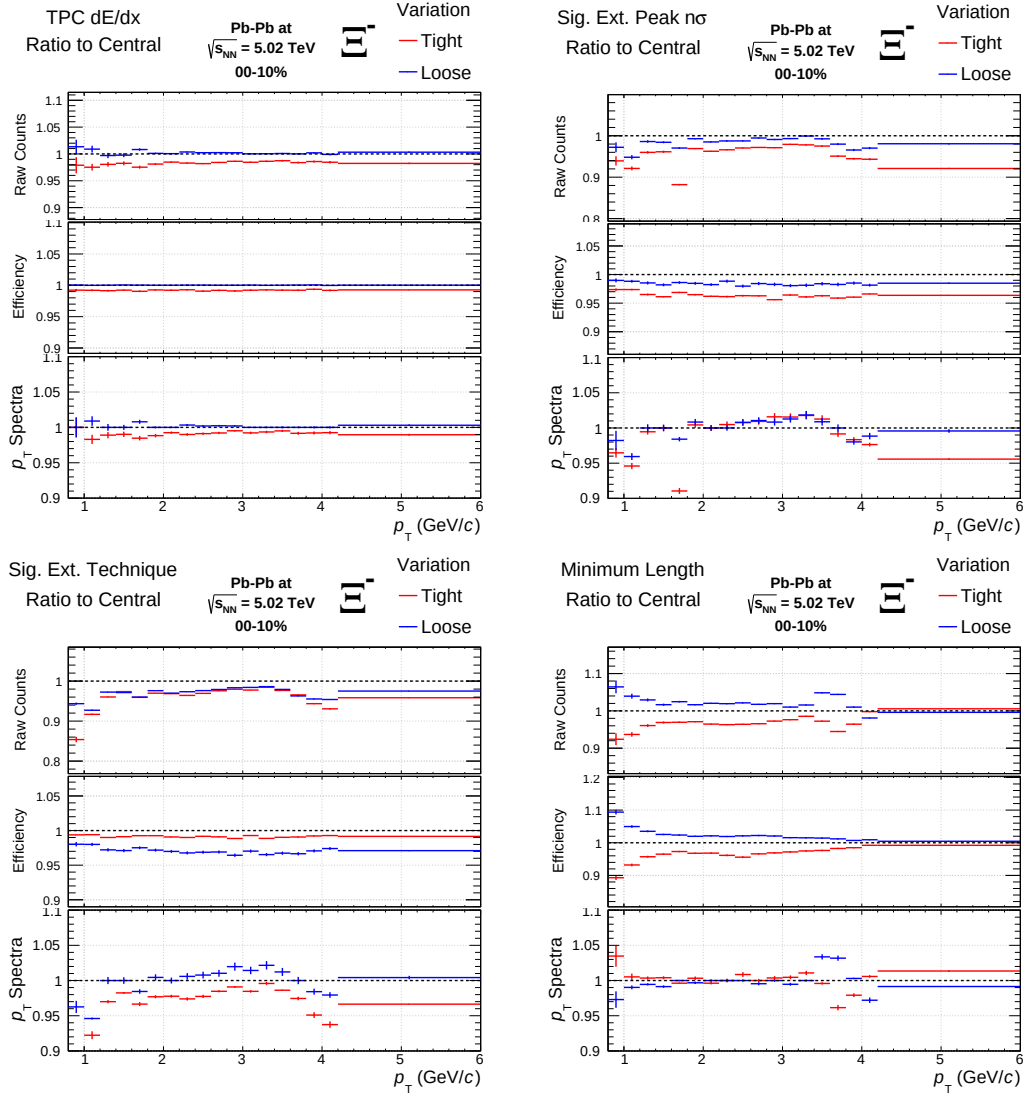


Figure 4.5: Systematic uncertainty computation for Ξ^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to TPC dE/dx selection, signal extraction and minimum track length.

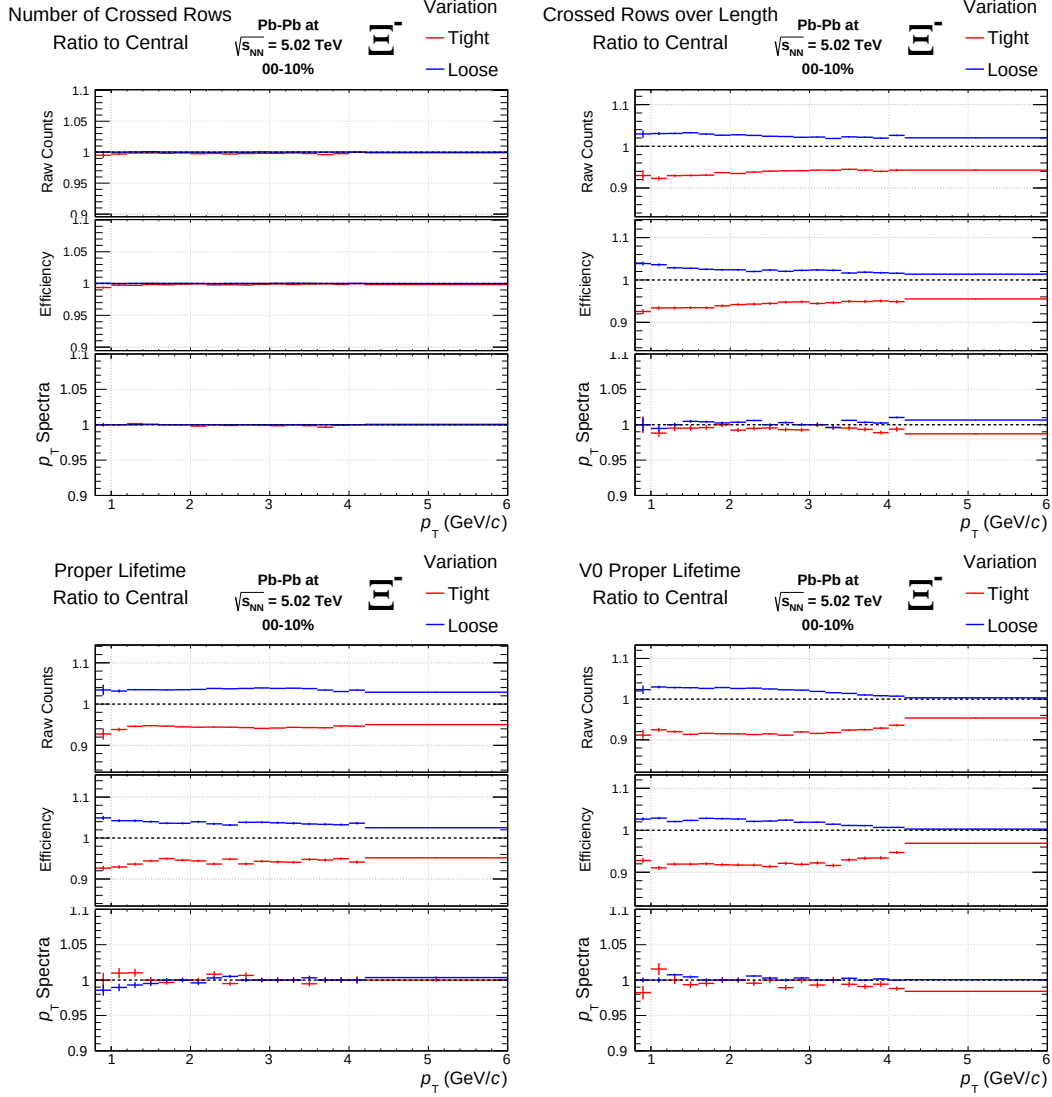


Figure 4.6: Systematic uncertainty computation for Ξ^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to selection on the smallest number of crossed rows, on the minimum ratio of crossed rows over length and lifetime selections.

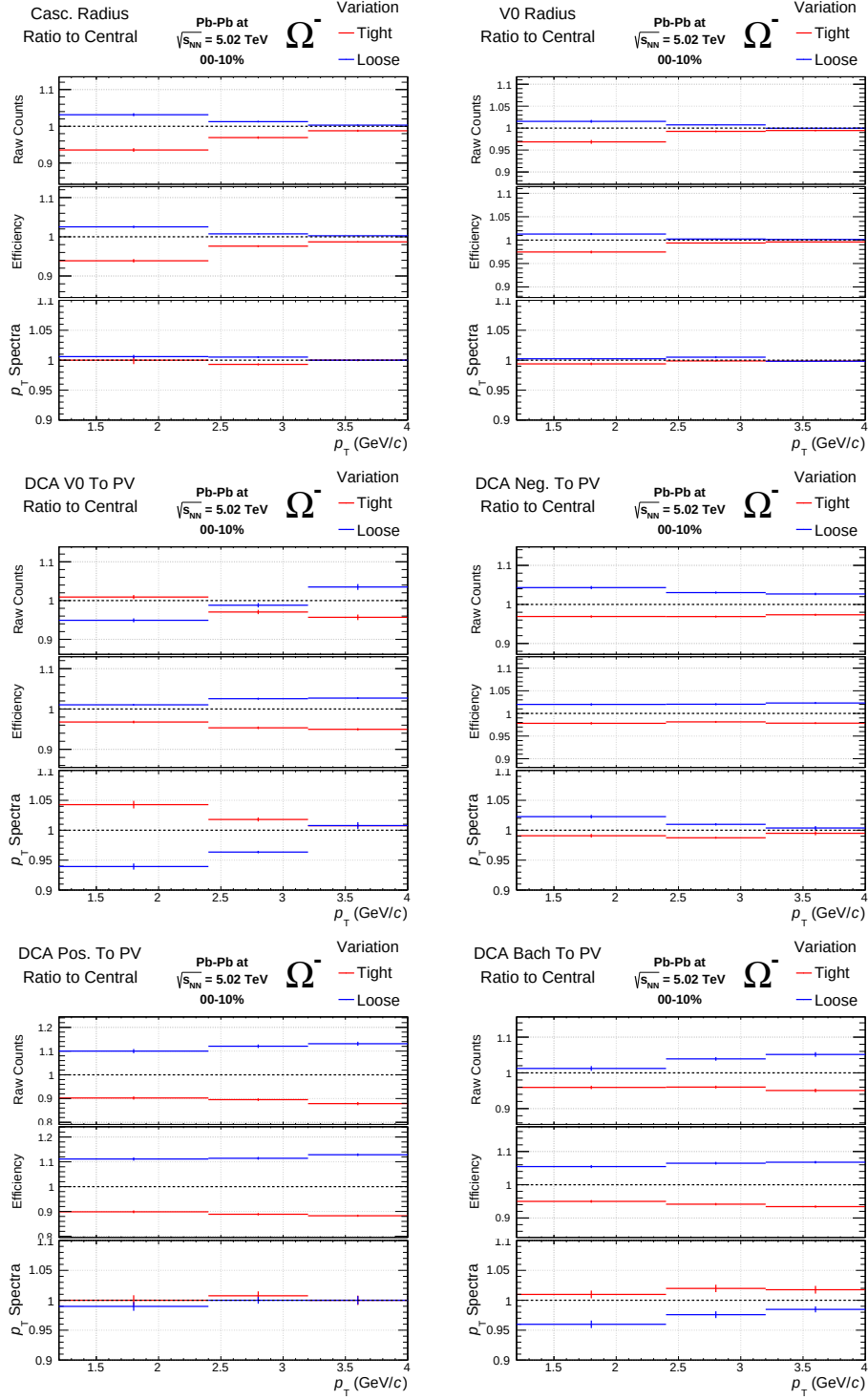


Figure 4.7: Systematic uncertainty computation for Ω^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to selections on the cascade and V0 radius, on the DCA between the V0 to the PV and on the single-track DCAs to the PV.

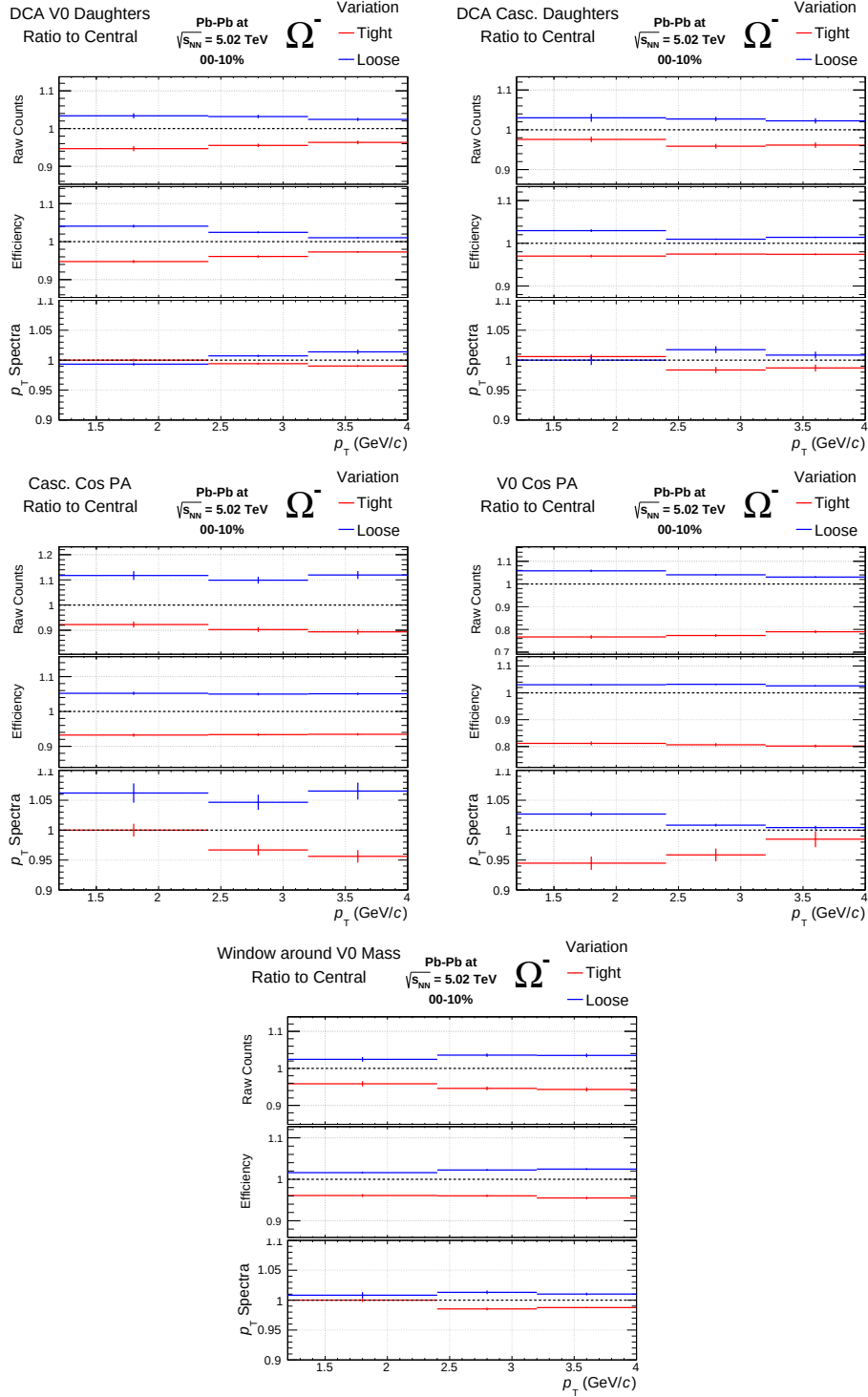


Figure 4.8: Systematic uncertainty computation for Ω^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to selections on the DCA between V0 and cascade daughters, on the cascade and V0 pointing angle and on the mass window of the V0 candidate.

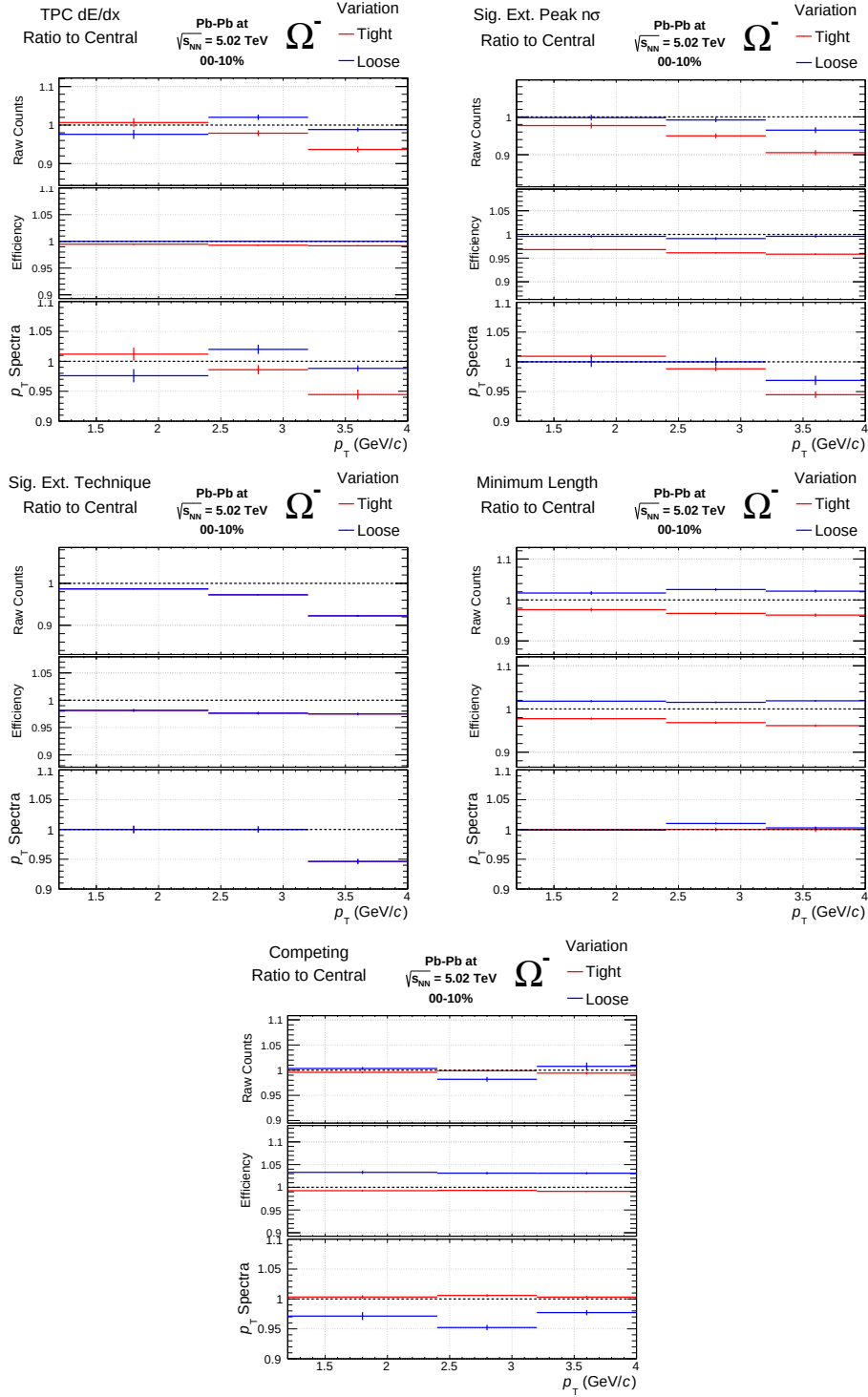


Figure 4.9: Systematic uncertainty computation for Ω^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to TPC dE/dx selection, signal extraction, competing decay rejection selection and minimum track length.

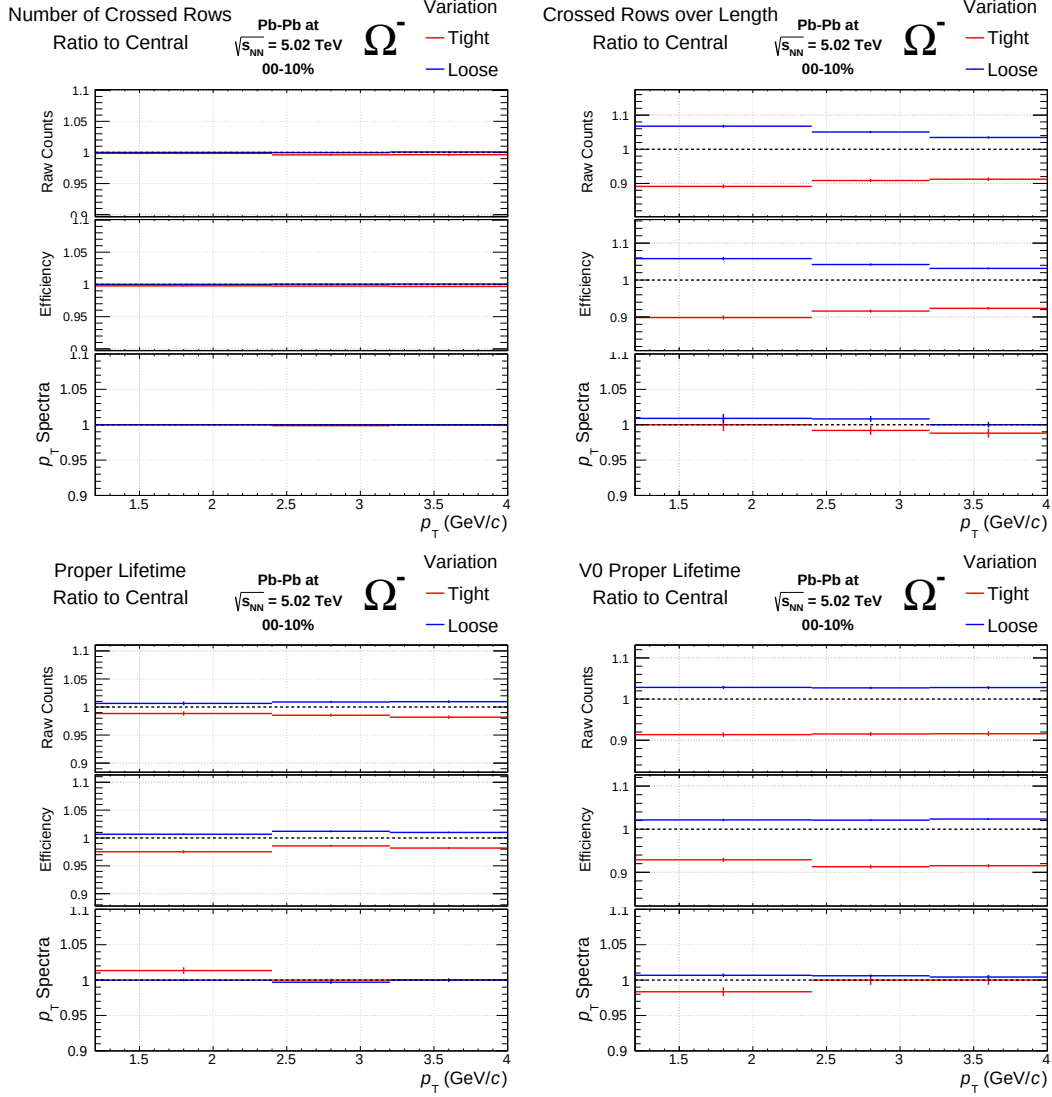


Figure 4.10: Systematic uncertainty computation for Ω^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV due to selection on the smallest number of crossed rows, on the minimum ratio of crossed rows over length and lifetime selections.

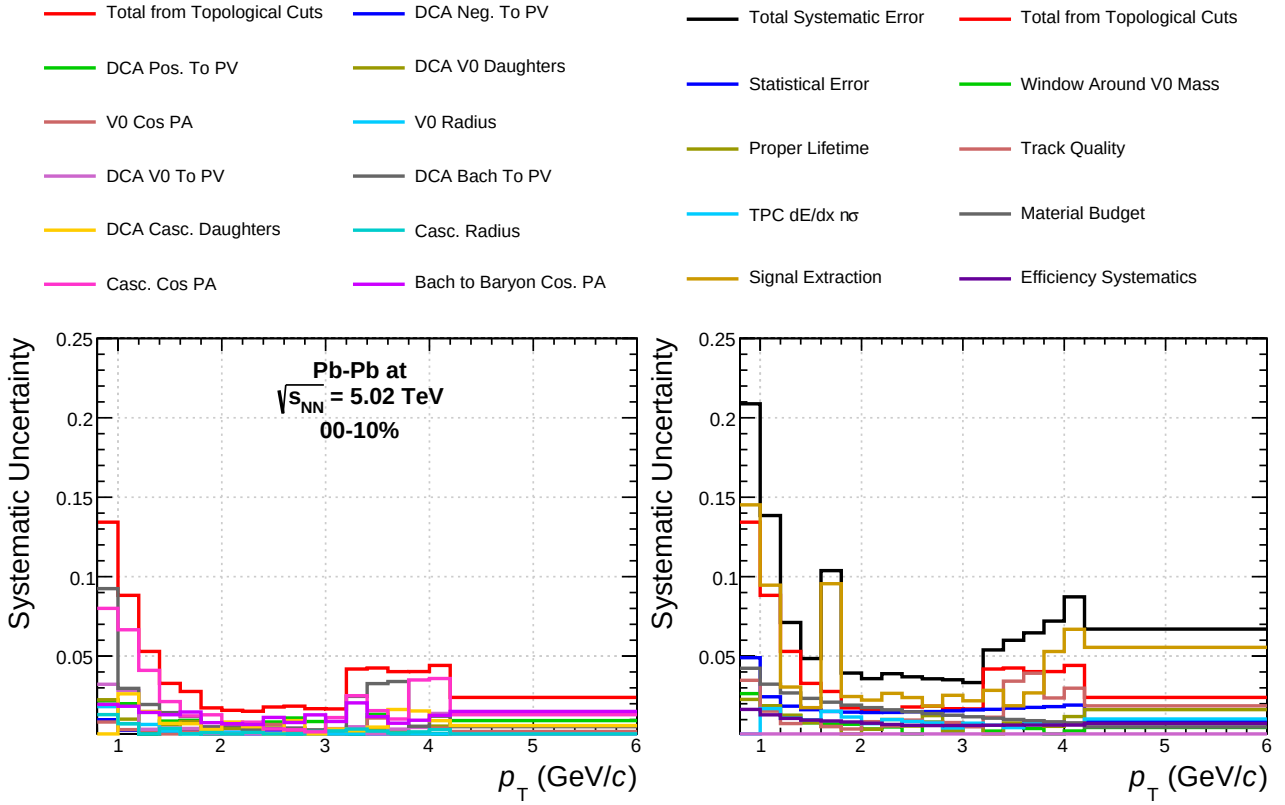


Figure 4.11: Computation of the total systematic uncertainty for Ξ^- in 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

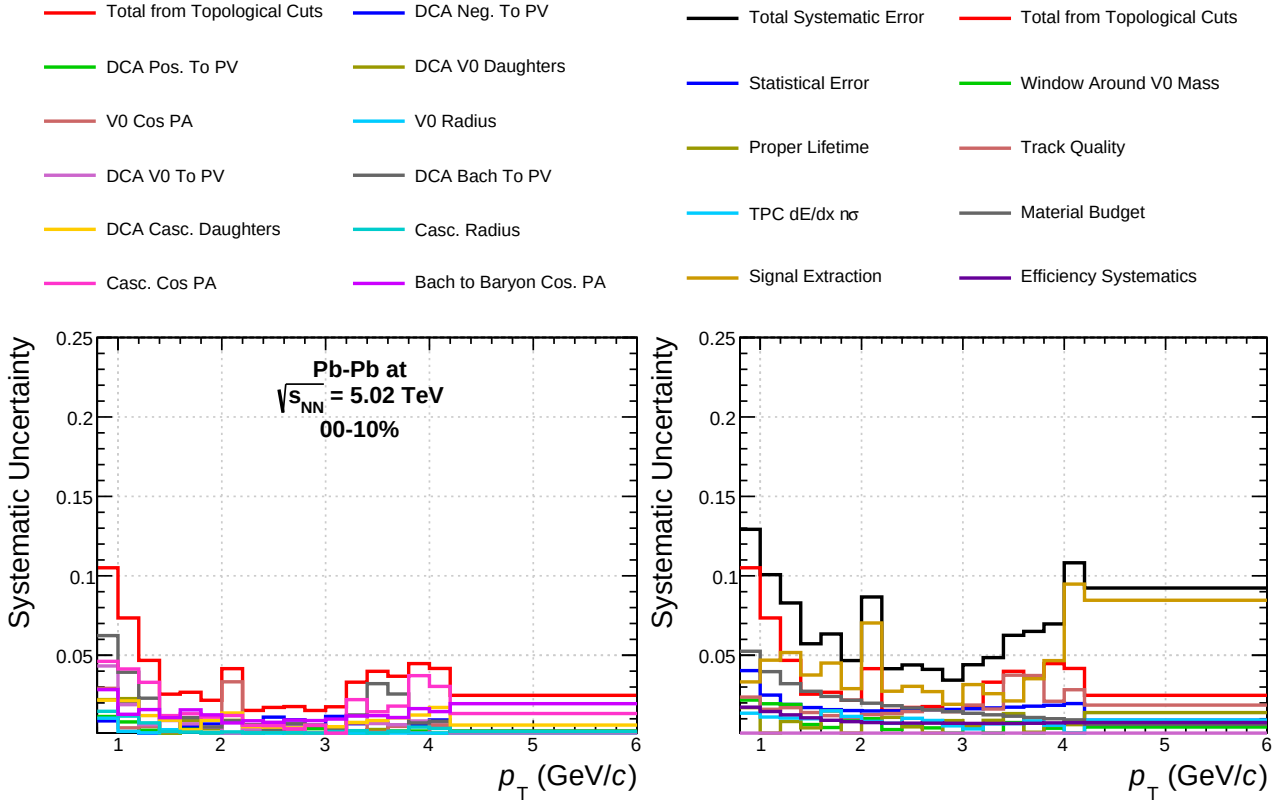


Figure 4.12: Computation of the total systematic uncertainty for $\Xi^+_{\bar{}}$ in 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

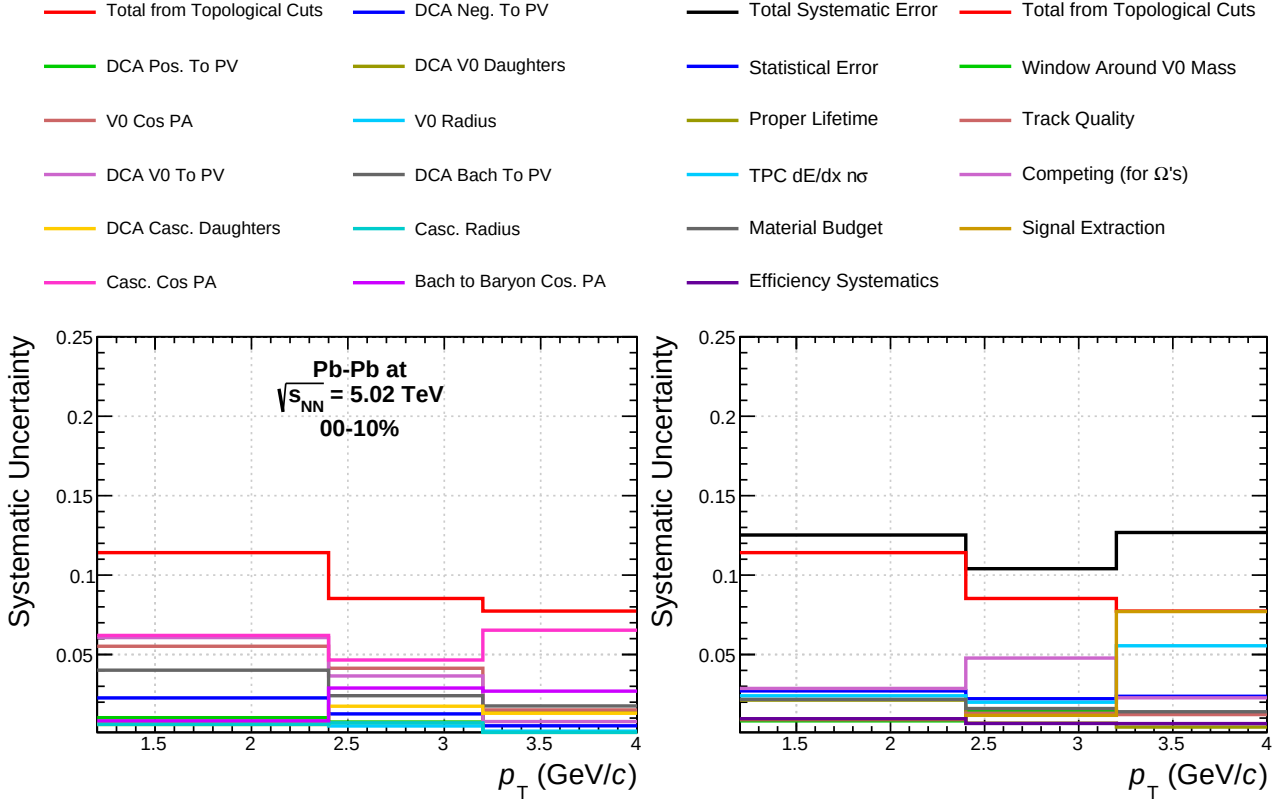


Figure 4.13: Total Systematics for Ω^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 4.14: Computation of the total systematic uncertainty for Ω^- in 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

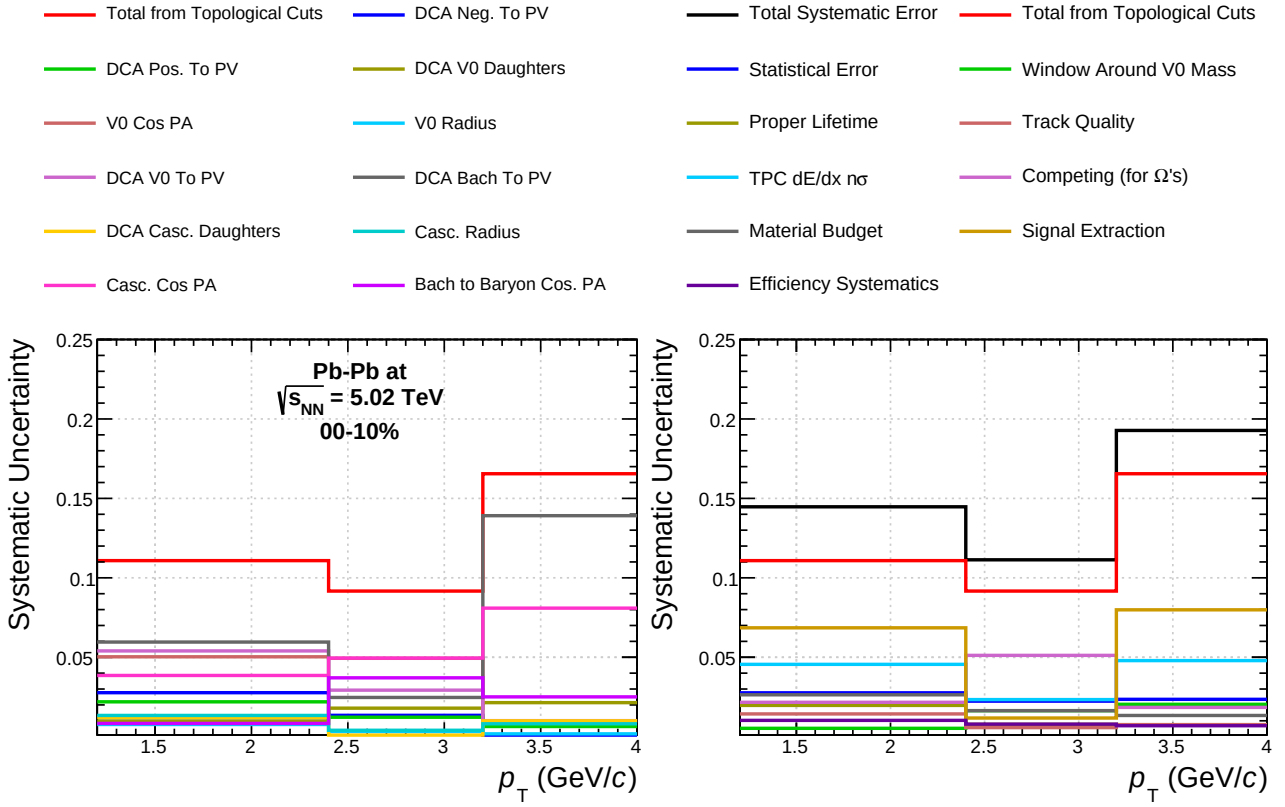


Figure 4.15: Computation of the total systematic uncertainty for $\bar{\Omega}^+$ in 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

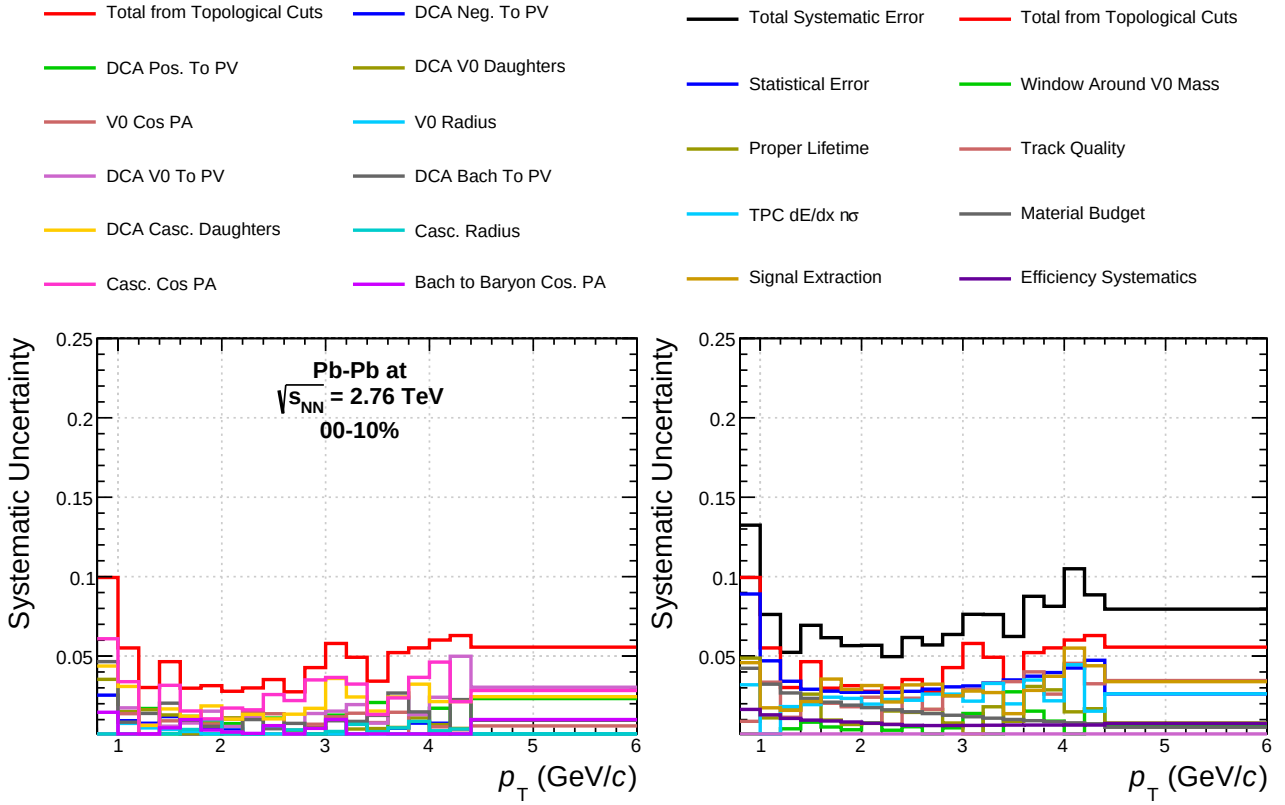


Figure 4.16: Computation of the total systematic uncertainty for Ξ^- in 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

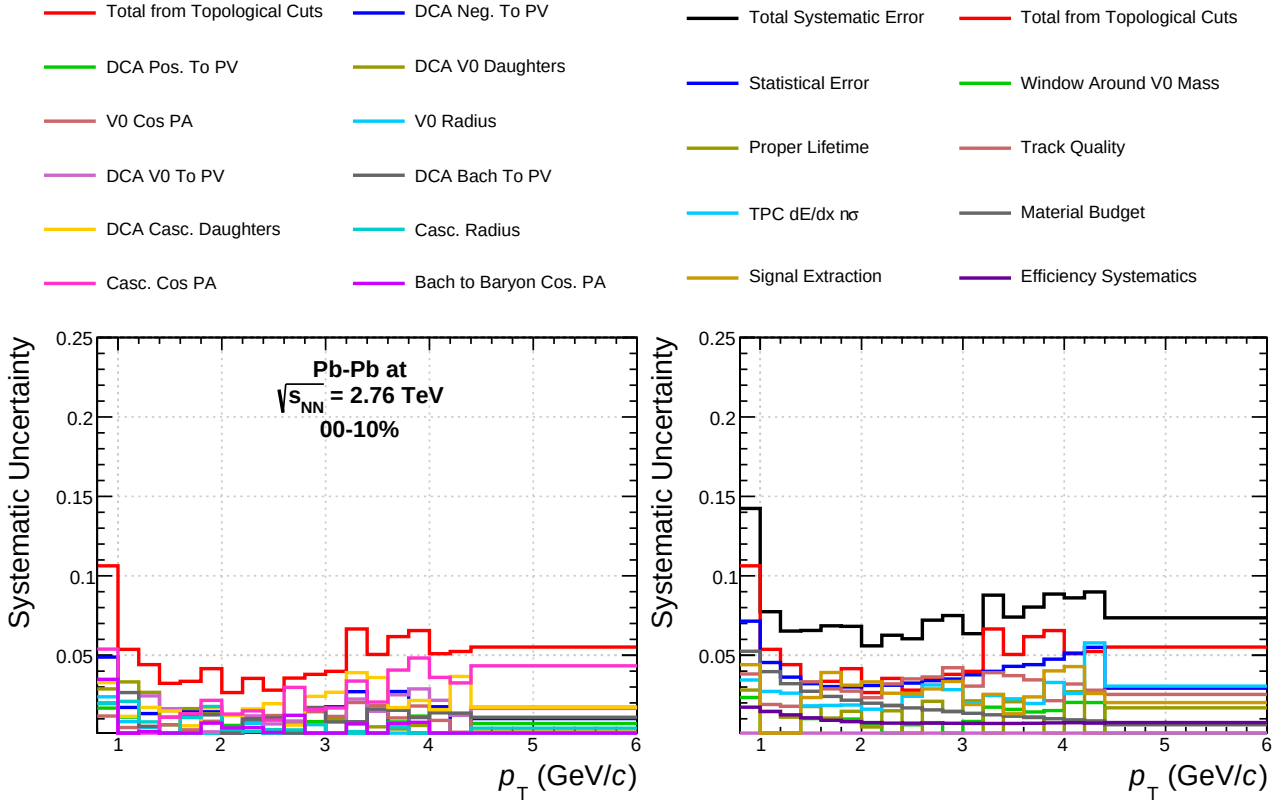


Figure 4.17: Computation of the total systematic uncertainty for $\Xi^+_{\bar{}}$ in 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

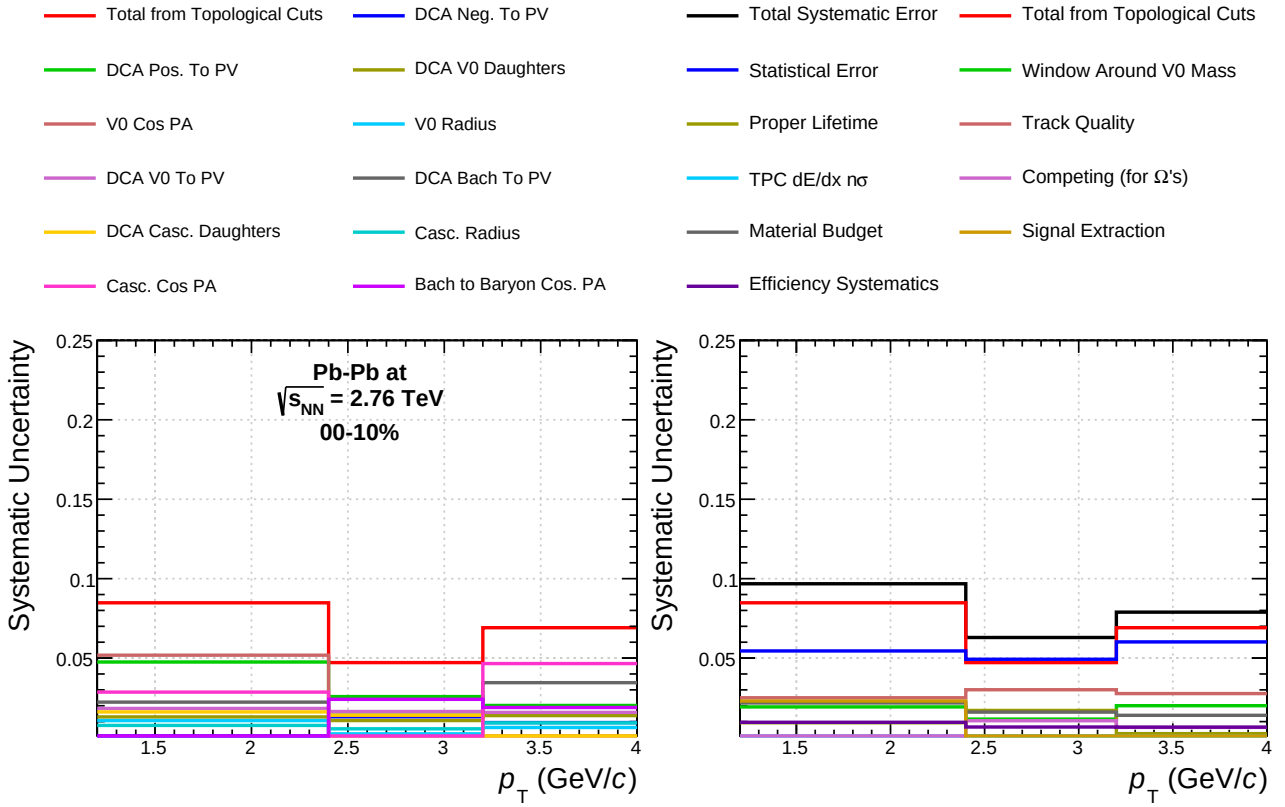


Figure 4.18: Computation of the total systematic uncertainty for Ω^- at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

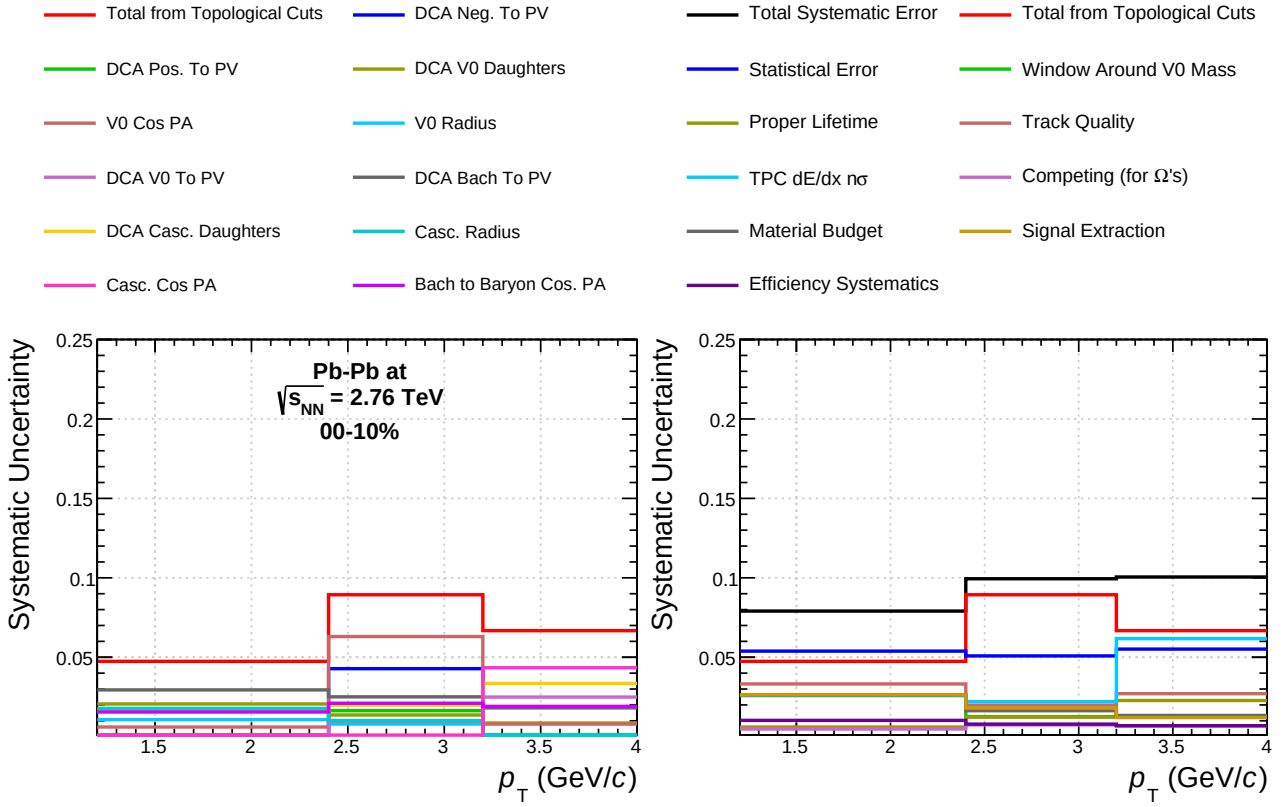


Figure 4.19: Computation of the total systematic uncertainty for $\bar{\Omega}^+$ at 0-10% for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV. (left plot) Systematic uncertainty for each topological selection and its quadratic sum (in red). (right plot) Uncertainties due to other sources and the total systematic uncertainty (in black), obtained through the quadratic sum of all sources.

the analysis using the fraction estimated with the coarser centrality binning.

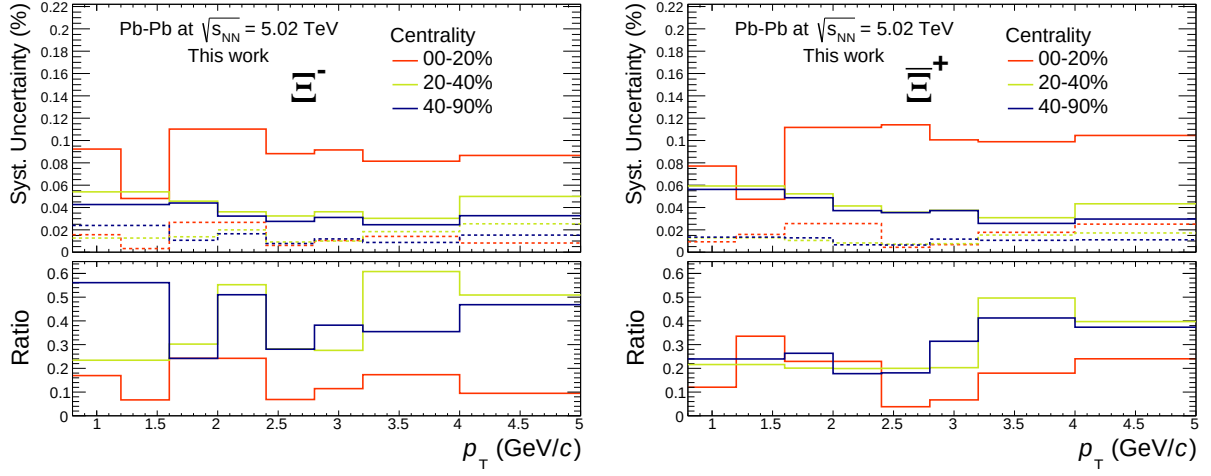


Figure 4.20: Total (full line) and N_{ch} dependent (dashed line) systematic uncertainty in each centrality for Ξ^- (left plot) and Ξ^+ (right plot) for Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. In the lower pad we can extract the N_{ch} dependent fraction of the uncertainty.

The contribution to the systematic uncertainty from each source for all particles studied in this thesis is shown for the most central event class in Tab. 4.1 for Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and in Tab. 4.2 at $\sqrt{s_{\text{NN}}} = 2.76$ TeV for three p_{T} regions.

Table 4.1: Main sources and values of the relative systematic uncertainties (expressed in %) of the p_T -differential yields of $\Xi^- (\Xi^+)$ and $\Omega^- (\Omega^+)$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The values are reported for low, intermediate and high p_T . The contributions common to all event classes are removed from the Total (quadratic sum of all contributions), defining the N_{ch} -independent ones, which are correlated across different multiplicity intervals.

Hadron p_T (GeV/ c)	$\Xi^- (\Xi^+)$			$\Omega^- (\Omega^+)$		
	0.9	2.5	5.1	1.8	2.8	3.6
Material budget	4.2 (5.3)	1.5 (1.7)	0.0 (0.0)	2.2 (2.6)	1.6 (1.6)	0.0 (0.0)
Transport code	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)
Track selection	3.5 (2.4)	1.0 (1.5)	1.9 (1.9)	0.9 (1.4)	1.3 (0.6)	1.2 (0.8)
Topological selection	13.4 (10.5)	1.8 (1.7)	2.4 (2.5)	11.4 (11.1)	8.5 (9.2)	7.7 (16.6)
Particle Identification	0.0 (1.4)	0.9 (1.0)	1.0 (0.9)	2.4 (4.6)	2.0 (2.3)	5.6 (4.8)
Signal Extraction	14.5 (3.3)	2.4 (3.0)	5.5 (8.5)	0.9 (6.9)	1.2 (1.2)	7.7 (8.0)
Proper Lifetime	2.3 (1.7)	0.6 (0.5)	1.6 (1.4)	2.1 (2.0)	0.7 (0.8)	0.4 (0.7)
Competing decay rejection		n/a		2.9 (2.2)	4.8 (5.1)	2.3 (1.8)
Event centrality selection	1.6 (1.7)	0.6 (0.7)	0.8 (0.8)	1.0 (1.0)	0.7 (0.8)	0.7 (0.7)
Total	20.9 (12.9)	3.7 (4.4)	6.7 (9.2)	12.5 (14.5)	10.4 (11.1)	12.7 (19.3)
Common (N_{ch} -independent)	3.5 (1.6)	0.3 (0.2)	0.6 (2.2)	3.0 (3.3)	1.2 (0.7)	2.2 (3.5)

Table 4.2: Main sources and values of the relative systematic uncertainties (expressed in %) of the p_T -differential yields of $\Xi^- (\Xi^+)$ and $\Omega^- (\Omega^+)$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The values are reported for low, intermediate and high p_T .

Hadron p_T (GeV/ c)	$\Xi^- (\Xi^+)$			$\Omega^- (\Omega^+)$		
	0.9	2.5	5.1	1.8	2.8	3.6
Material budget	4.2 (5.3)	1.5 (1.7)	0.0 (0.0)	2.2 (2.6)	1.6 (1.6)	0.0 (0.0)
Transport code	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)
Track selection	0.9 (3.8)	2.3 (3.5)	3.5 (2.5)	2.5 (3.3)	3.0 (2.0)	2.8 (2.7)
Topological selection	9.9 (10.6)	3.5 (2.8)	5.6 (5.5)	8.5 (4.7)	4.7 (8.9)	6.9 (6.7)
Particle Identification	3.2 (3.4)	2.2 (2.4)	2.6 (3.1)	0.0 (2.6)	0.0 (2.2)	0.0 (6.2)
Signal Extraction	4.6 (4.4)	3.2 (2.6)	3.4 (2.0)	2.3 (2.6)	0.0 (1.8)	0.0 (1.2)
Proper Lifetime	4.9 (2.8)	1.5 (0.0)	0.8 (1.7)	0.9 (0.6)	1.7 (1.2)	0.2 (2.3)
Competing decay rejection		n/a		0.0 (0.5)	1.1 (0.7)	0.6 (0.7)
Event centrality selection	1.6 (1.7)	0.6 (0.7)	0.8 (0.8)	1.0 (1.0)	0.7 (0.8)	0.7 (0.7)
Total	13.2 (14.2)	6.2 (6.0)	8.0 (7.4)	9.7 (7.9)	6.3 (9.9)	7.9 (10.1)

4.3 Extrapolation to low p_T

In order to determine the total yield of cascades, it was necessary to estimate the number of particles produced below the measured p_T range of 0.8 (1.2) GeV/ c for Ξ (Ω). This estimation was done by fitting the measured spectra with a Blast-Wave (BW) model parameterization [58]. This hydrodynamically inspired model assumes a transversely expanding emission source in a local thermal equilibrium at a given temperature and with statistical distribution approximated by the Boltzmann distribution.

The parameters of the model are the kinetic freeze-out temperature of the system, T_{kin} , the transverse flow velocity, β_T , and the parameter n , which describes the dependence of the flow velocity with r , the distance to the center of the fireball. In this model, the shape of the particle p_T spectra is described by

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{\text{kin}}} \right), \quad (4.3.1)$$

with

$$\rho = \tanh^{-1} \beta_T = \tanh^{-1} \left[\left(\frac{r}{R} \right)^n \beta_S \right], \quad (4.3.2)$$

where ρ stands for the velocity profile, m_T is the transverse mass, I_0 and K_1 are modified Bessel functions, R is the radius of the fireball and β_S is the transverse velocity at the surface of the fireball.

This way, the extrapolated fraction, i.e., the fraction of the p_T spectra in the non-measured region, is computed by fitting the BW model to the measured region and extrapolating this distribution to the non-measured region. The total yield is then obtained by integrating the fitted function in the non-measured region and adding the integral of the measured p_T distribution.

The statistical uncertainty of the spectra was estimated by generating 1000 copies of the original spectra and, for each data point, sorting a new value by sampling a Gaussian distribution. The mean of the Gaussian function was the original yield of the p_T bin and the width was the original statistical uncertainty. The total yield was then computed for each of these variations, as exemplified in Fig 4.21 for $\Xi^- + \bar{\Xi}^+$ in the most central multiplicity class of Pb–Pb

at $\sqrt{s_{NN}} = 5.02$ TeV. A Gaussian function is fitted to the distribution of the yields obtained in this manner and its standard deviation is treated as the statistical uncertainty of the total yield.

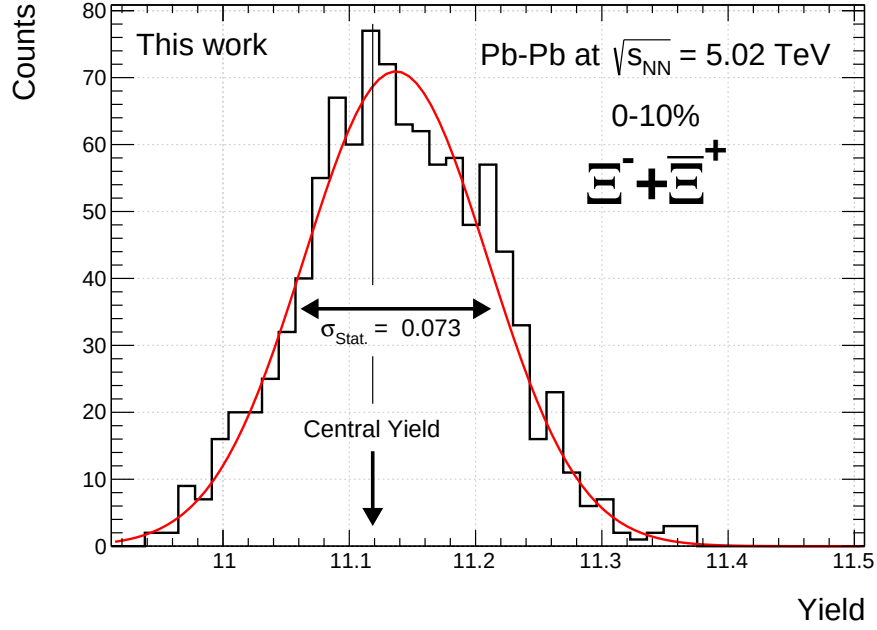


Figure 4.21: Estimation of the statistical uncertainty of the total yield. For each particle and multiplicity interval, one thousand copies of the p_T spectra were created by resampling the data points with a Gaussian. The distribution of total yield obtained for each of these variations was fitted with a Gaussian distribution (in red) and the standard deviation obtained from the fit was used to estimate the statistical uncertainty of the total yield. Exemplified here with the $\Xi^- + \Xi^+$ statistical uncertainty estimation for the most central multiplicity class of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV.

For the systematic uncertainty of the yield, two variations of the spectra were created. Each measured point of the p_T spectra was increased/decreased by its systematic uncertainty, creating the “extreme high” and “extreme low” p_T spectra variations. The yield was then computed for both variations by fitting a BW function. These yields variations were compared to the central yield and the maximum deviation was treated as the systematic uncertainty.

A second contribution for the systematic uncertainty of the yield was estimated by choosing different models to perform the yield evaluation. The different functions used in this estimation are listed below:

1. m_T **exponential**, where the invariant p_T spectrum is assumed to decrease exponentially

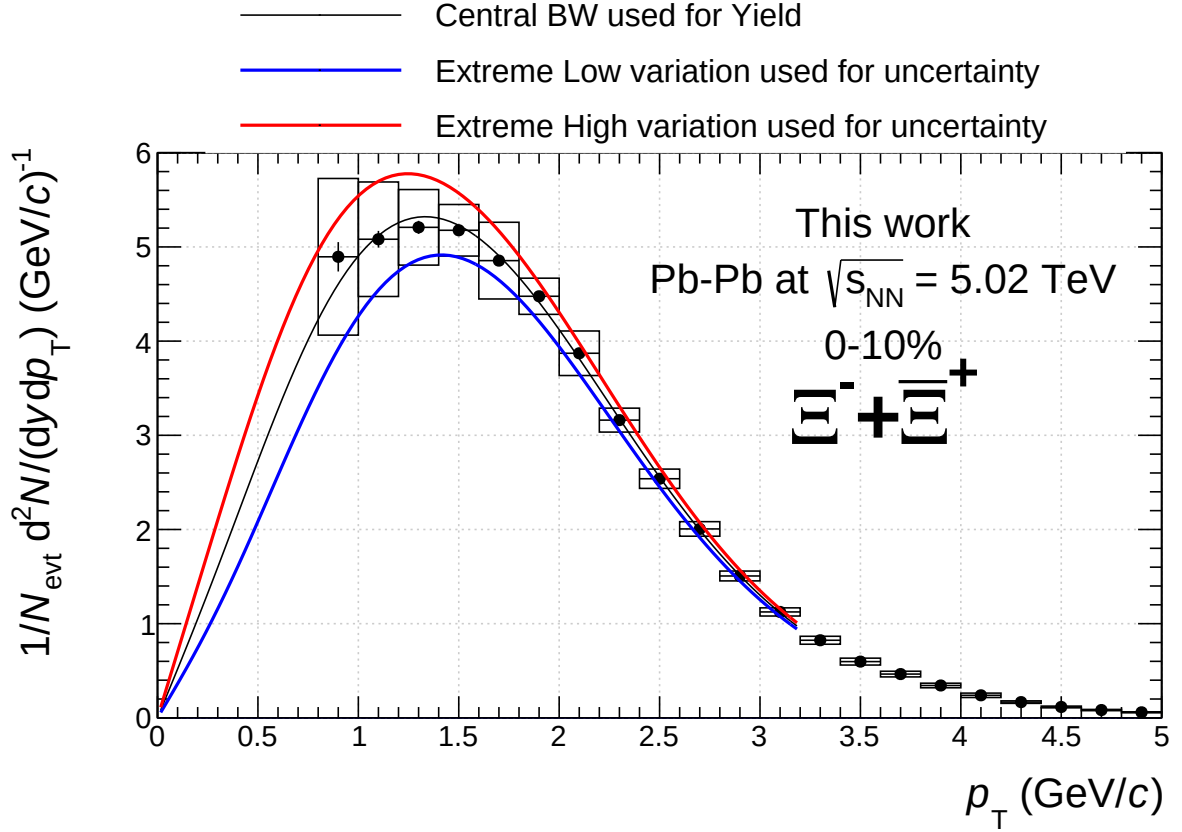


Figure 4.22: Estimation of the systematic uncertainty of the total yield due to the uncertainty of the spectra. For each particle and multiplicity interval, two copies of the p_T spectra were created by increasing/decreasing the data points values by their systematic uncertainty. The total yield was computed for these new histograms, named extreme high and low variations and the maximum deviation to the original yield was assigned as a systematic uncertainty of the total yield. The Blast-Wave function used in the extrapolation to low p_T is shown here for the extreme high (in red) and extreme low variation (in blue). Exemplified here with the $\Xi^- + \Xi^+$ statistical uncertainty estimation for the most central multiplicity class of Pb-Pb at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

with m_T :

$$\frac{1}{p_T} \frac{d^2 N}{dp_T dy} = A \times \exp\left(-\frac{m_T}{T}\right). \quad (4.3.3)$$

2. **Boltzmann**, assuming the standard Boltzmann distribution, the invariant p_T spectrum can be written as [59]:

$$\frac{1}{p_T} \frac{d^2 N}{dp_T dy} = A \times m_T \times \exp\left(-\frac{m_T}{T}\right). \quad (4.3.4)$$

3. **PHENIX modified Hagedorn**, a functional form that approaches an exponential at low p_T and a power law in the high p_T region [60, 61], describing the p_T spectrum very well across the full measured range:

$$\frac{1}{p_T} \frac{d^2 N}{dp_T dy} = A \times \left[\exp\left(-Bp_T - Cp_T^2\right) + \frac{p_T}{p_0} \right]^{-n} \quad (4.3.5)$$

In the expressions above, A , B , C , T , n and p_0 are free parameters.

The different fits used in the extrapolation can be seen in Figs. 4.23 and 4.24 for Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV, respectively. By computing the extrapolated fraction of the yield with different functions, it was possible to estimate the uncertainty on the yield due to the fitting model assumed. The uncertainty was estimated to be 20% (25%) of the extrapolated fraction for Ξ (Ω) from centrality classes of 0-80% and 25% (30%) for centrality classes of 80-90%. The extrapolated fraction used here was the one obtained with the Blast-Wave model. The two systematic uncertainties described were summed quadratically to obtain the total systematic uncertainty of the yield.

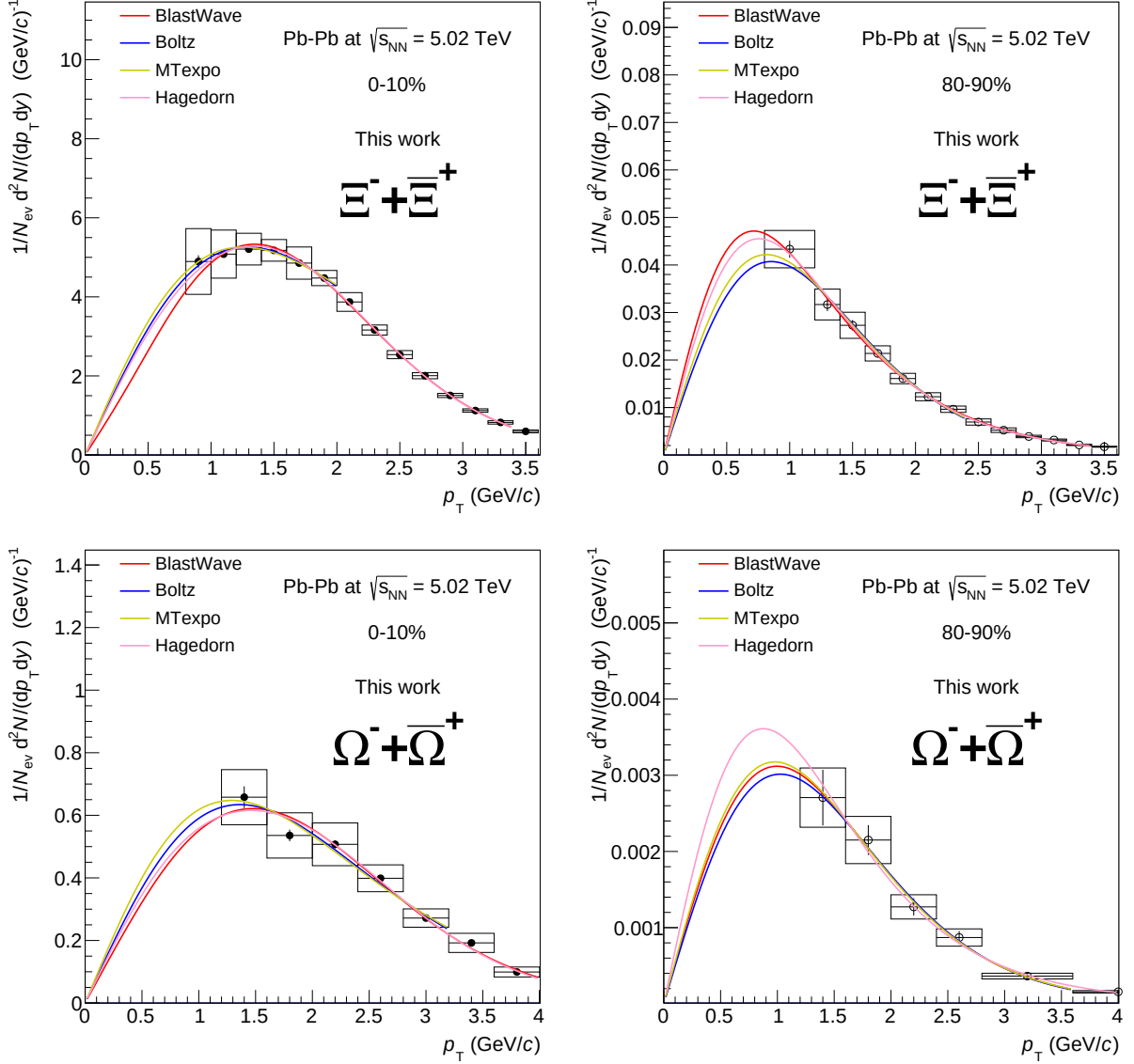


Figure 4.23: Systematic uncertainty of the yield due to the choice of model used in the extrapolation to low p_T for Ξ and Ω in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The different functions used here were the Blast-Wave model, the Boltzmann distribution, a m_T exponential distribution and the Hagedorn model. Although all the functions describe the measured data well, differences in the extrapolated fraction are reflected on the total yield.

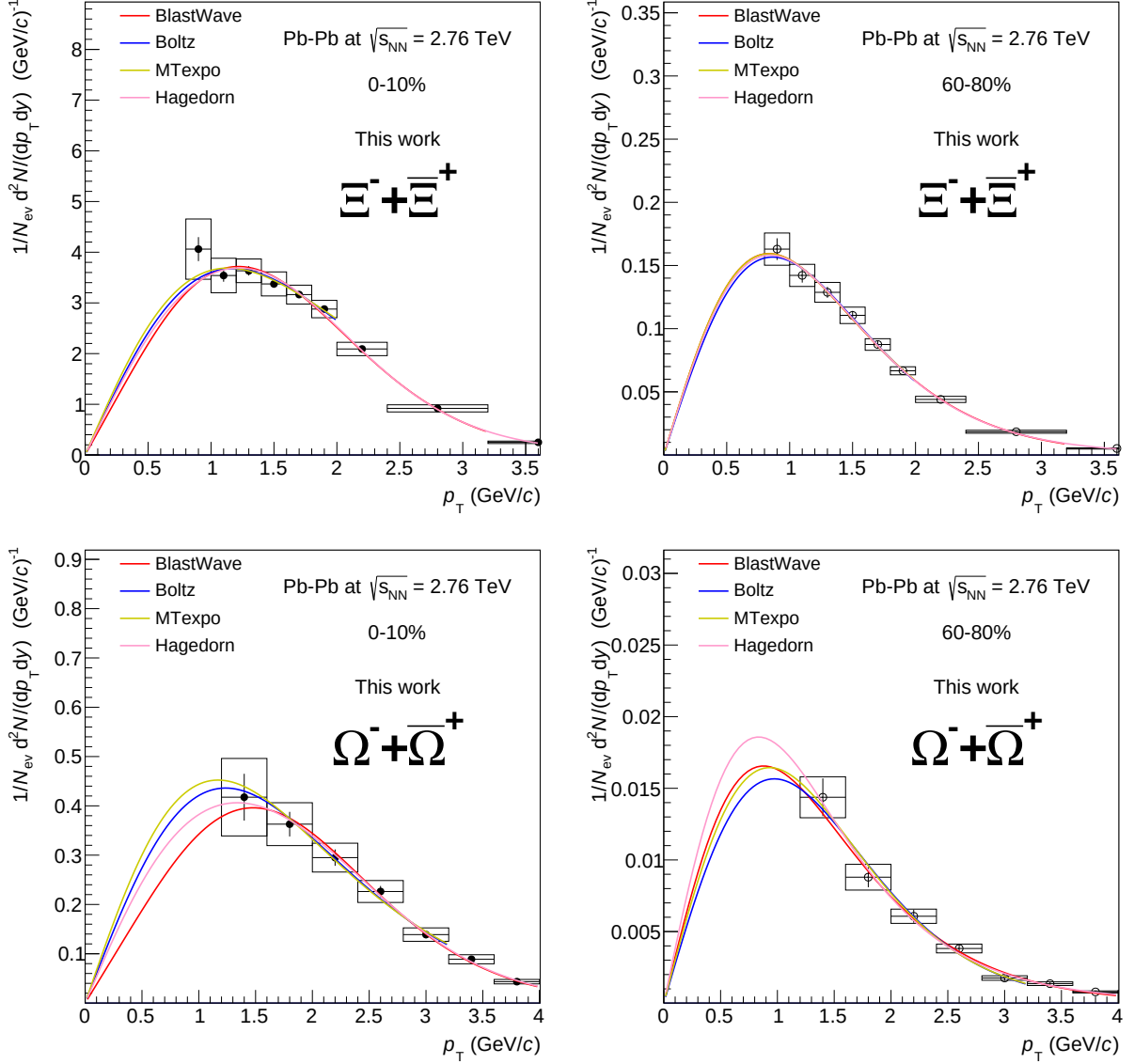


Figure 4.24: Systematic uncertainty of the yield due to the choice of model used in the extrapolation to low p_T for Ξ and Ω in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The different functions used here were the Blast-Wave model, the Boltzmann distribution, a m_T exponential distribution and the Hagedorn model. Although all the functions describe the measured data well, differences in the extrapolated fraction are reflected on the total yield.

Chapter 5

Results and discussion

Up to this point, we have discussed how to obtain the corrected p_T spectra and its statistical and systematic uncertainties (including the multiplicity-dependent fraction) for Ξ and Ω . The strategy to obtain the total yield for these particles in Pb–Pb was also discussed in the previous chapter, in section 4.3. In this chapter, we present two theoretical models to be compared with the measured data. Moreover, we present the corrected p_T spectra, the average transverse momentum, $\langle p_T \rangle$, and the total yield for the studied particles in Pb–Pb collisions at both energies. Finally, the strangeness enhancement is also studied, by comparing the ratio of strange to non-strange particles (pions) in Pb–Pb collisions to smaller systems, such as pp and p–Pb. The origin of the enhancement is also studied by investigating the Ξ/ϕ ratio as a function of multiplicity.

5.1 Comparison to theoretical models

Once we have our measurements done, it is important to check if the latest model predictions agrees with our data. Two models were compared to the data reported in this thesis: the PYTHIA Angantyr model and a Hybrid model. Both models use the UrQMD model [62, 63] for post-hadronization scattering simulation. Further studies are needed to perform good predictions for Ω . Therefore, we only report model comparisons to Ξ data.

5.1.1 The hybrid model

Many of the observables obtained in heavy ion collisions are well reproduced by viscous hydrodynamics simulations [64]. This scenario can be further enhanced with simulation of the late-stage scatterings expected to happen before the kinetic freeze-out of the system with cascading models. This combination of hydrodynamics simulation and hadronic cascading model is referred as a hybrid model [65].

The hybrid model used in this work [66] is comprised of the following ingredients:

- T_RENTo [67], for the generation of the initial conditions (IC) for the hydrodynamics via a parametric wounded nucleons model;
- KØMPØST [68], for a description of the space-time evolution of the energy-momentum tensor during the pre-equilibrium stage of the collision;
- MUSIC [69, 70], for event-by-event hydrodynamics evolution simulation;
- UrQMD [62, 63], for the simulation of late-stage post-hadronization scatterings.

Therefore, this model attempts to simulate the full chain of events expected to happen in a Pb–Pb collision.

Hereafter, this hybrid model will be referred as Hydro model, for simplicity.

5.1.2 The PYTHIA Angantyr model

The PYTHIA Angantyr [71] is a recently developed model for simulation of nucleus-nucleus collisions. It provides a direct extrapolation of the high energy pp collisions of PYTHIA8 [72]. Therefore, the model can serve as a baseline for understanding non-collective phenomena in the Pb–Pb collisions system. After the hadronization via the Lund string fragmentation model [26], the late-stage of the evolution is performed via UrQMD, in the same manner as the Hydro model.

In this context, the evolution of the system after the Pb–Pb collision can be imagined to happen without viscous hydrodynamics phase – the QGP phase. By replacing this phase with

the PYTHIA Angantyr simulation, we are able to study the effects of the presence of the QGP phase in the final observables. Figure 5.1 illustrates this scenario. Hereafter, this model will be referred as Angantyr model.

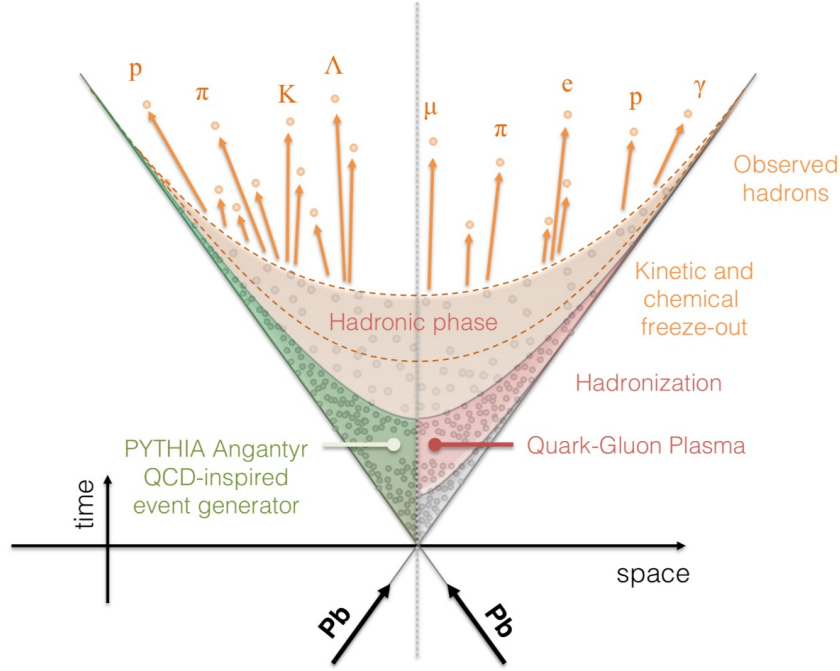


Figure 5.1: Sketch of the system evolution after a Pb–Pb collision. The right side represents the usual evolution, with the presence of the QGP phase. The left side of the figure replaces the QGP phase with the PYTHIA Angantyr simulation, a QCD-inspired model where collective effects are not expected to be observed. Figure from [73].

5.2 Hyperon transverse momentum distributions

The transverse momentum spectra for Ξ^- , Ξ^+ , Ω^- and $\bar{\Omega}^+$, corrected for acceptance and detection efficiency, are reported in Fig. 5.2 to 5.5 for the different V0M-selected centrality classes. In order to improve visibility, a scaling factor is applied. A significant hardening of the spectra with centrality is visible in the figure. This hardening can be quantified measuring the $\langle p_T \rangle$ as a function of the multiplicity, as reported in Fig. 5.6.

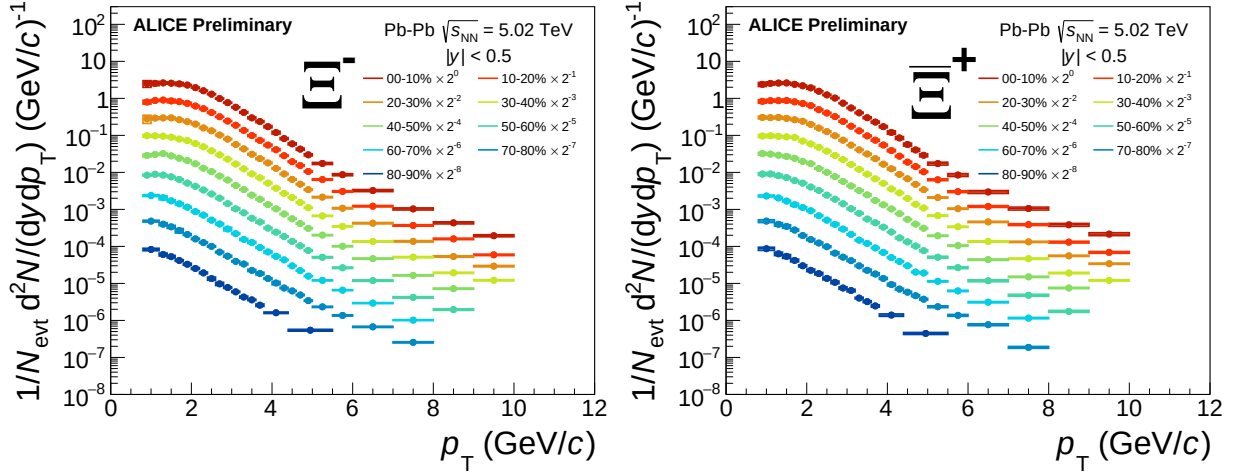


Figure 5.2: Transverse momentum spectra of Ξ^- (left plot) and Ξ^+ (right plot) in centrality intervals in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

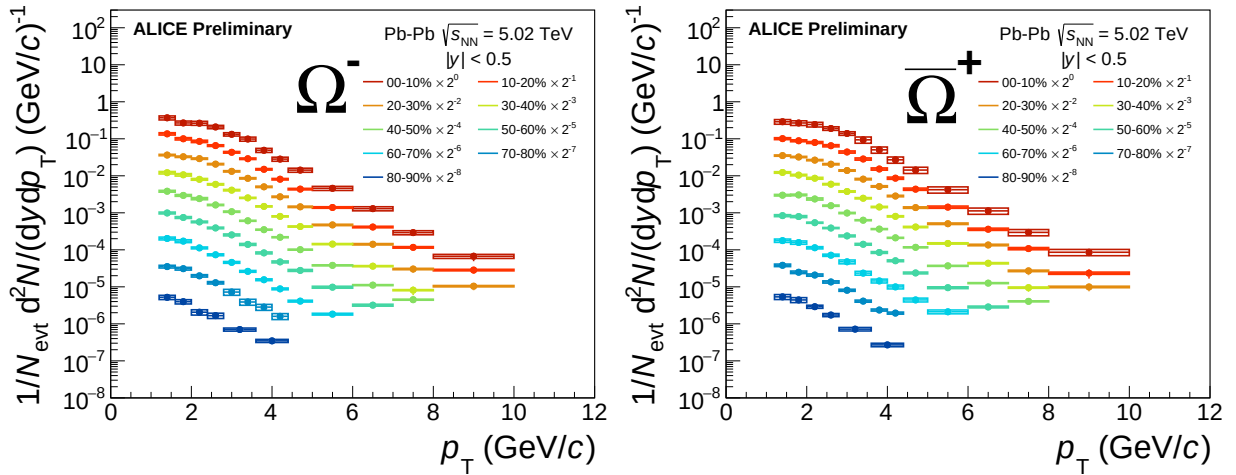


Figure 5.3: Transverse momentum spectra of Ω^- (left plot) and Ω^+ (right plot) in centrality intervals in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

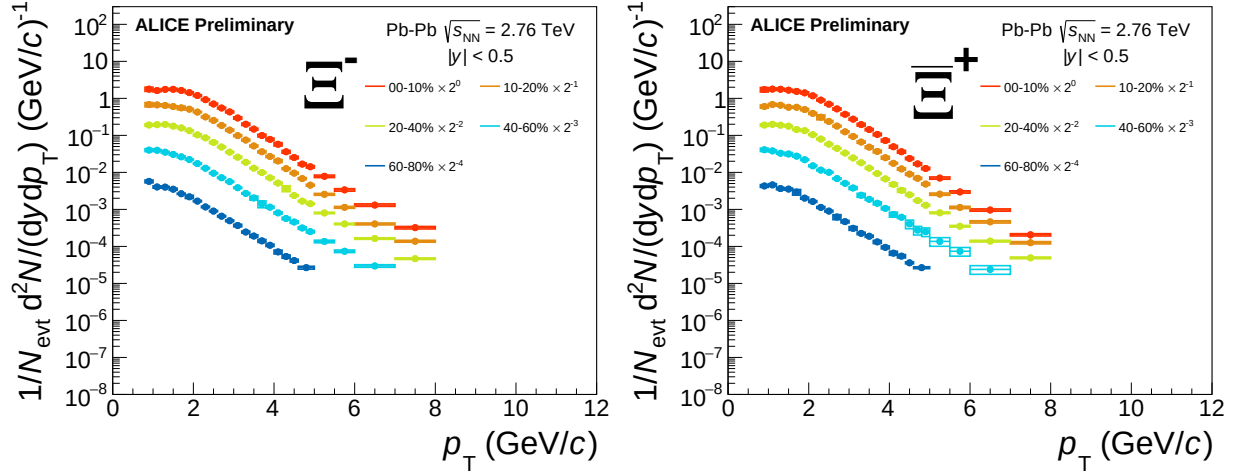


Figure 5.4: Transverse momentum spectra of Ξ^- (left plot) and Ξ^+ (right plot) in centrality intervals in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

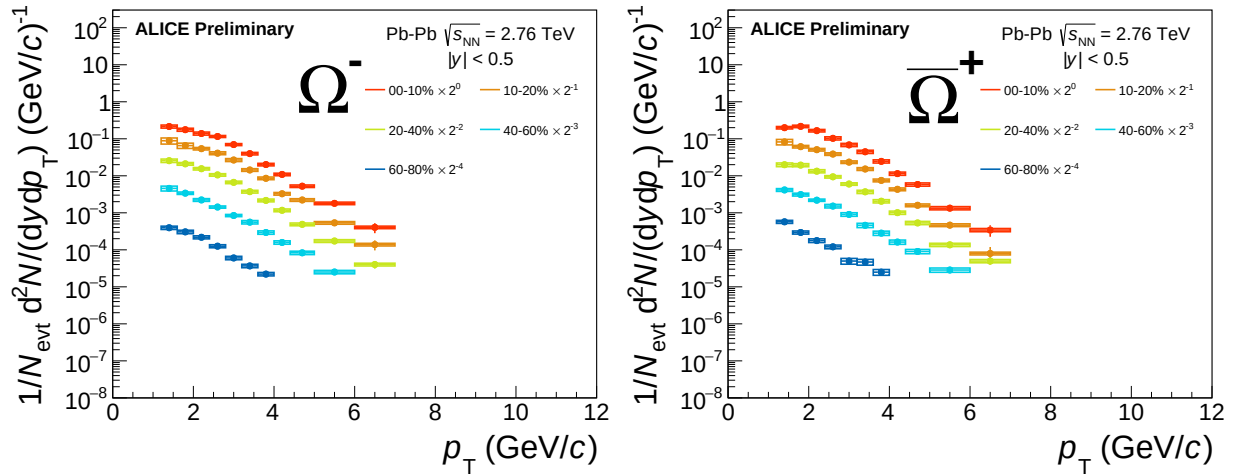


Figure 5.5: Transverse momentum spectra of Ω^- (left plot) and $\bar{\Omega}^+$ (right plot) in centrality intervals in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

5.3 Cascades $\langle p_T \rangle$ and total yields

The evolution of $\langle p_T \rangle$ with $dN_{\text{ch}}/d\eta$ is reported on Fig 5.6 for $\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$ for Pb–Pb collisions at both $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV. As mentioned before, the $\langle p_T \rangle$ of the cascades increases with multiplicity, as expected from the higher stopping power of central collisions. Furthermore, a mass hierarchy is also observed: the $\langle p_T \rangle$ is greater the heavier the particle. This phenomenon, known as radial flow, is understood in the context of a hydrodynamically expanding medium in the early stages of the collision evolution, where particles expand with a common collective velocity [74]. This flow is observed in models that employs an initial hydrodynamical phase (in red and black lines in the figure). The addition of pre-equilibrium dynamics through the KØMPØST code increases the $\langle p_T \rangle$ of cascades in all multiplicity intervals, allowing for a better agreement with data for peripheral collisions. A slight increase of the $\langle p_T \rangle$ with collision energy is also observed for both data and hydro model. The Angantyr model, that lacks this hydro phase, is shown in green and do not reproduce the behaviour observed in data.

The cascade yields are computed as described in section 4.3 and are reported in Tables 5.1 and 5.2 for Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV, respectively. The evolution of the total yield with $dN_{\text{ch}}/d\eta$ is shown in Fig. 5.7. Different models' predictions are show as lines and it is possible to see that the hydro predictions are close to experimental values and the Angantyr model underestimates the cascade production.

5.4 Canonical suppression: hyperon-to- ϕ ratio

As discussed in Sec. 1.2, the strangeness enhancement can be explained within the Canonical Suppression treatment, as shown in Fig. 1.5 for the enhancement of Ξ and Ω . Unlike cascades, the ϕ meson has zero net strangeness and should not be strongly affected by the suspension of the suppression. However, by studying the ratio of Ξ/ϕ as a function of charged multiplicity at mid-rapidity, shown in Fig. 5.8, we observe that this ratio is relatively flat, especially in the more peripheral region. Since we know that the Ξ yield increases with centrality, this

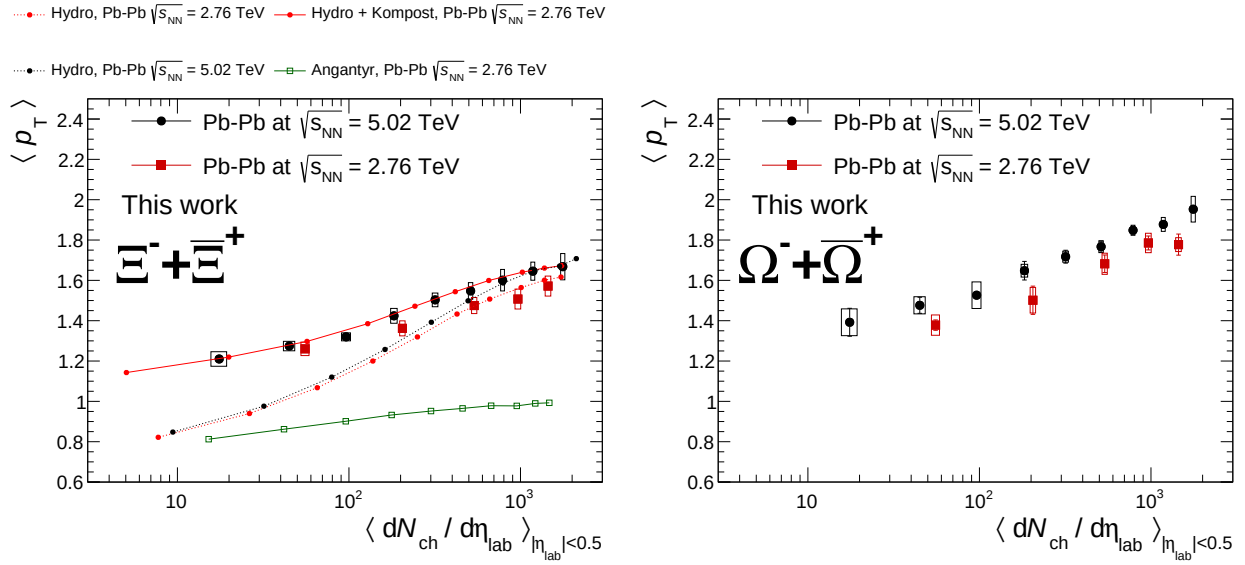


Figure 5.6: Evolution of the $\langle p_T \rangle$ for Ξ (left plot) and Ω (right plot) as a function of $dN_{ch}/d\eta$ for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV in black and at $\sqrt{s_{NN}} = 2.76$ TeV in red. The hydro model predictions are plotted as dashed lines with full circle markers in black ($\sqrt{s_{NN}} = 5.02$ TeV) and red ($\sqrt{s_{NN}} = 2.76$ TeV) and an increase in the $\langle p_T \rangle$ with energy is observed for central collisions. The addition of pre-equilibrium dynamics, through KõMPõST, is observed for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV in the full red line, where we observe an increase of the average momentum of cascades, improving the agreement with data. Predictions from the Angantyr model are shown for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV as the full green line with hollow squares, where we can observe an underestimation of the cascade average transverse momentum across all the measured range.

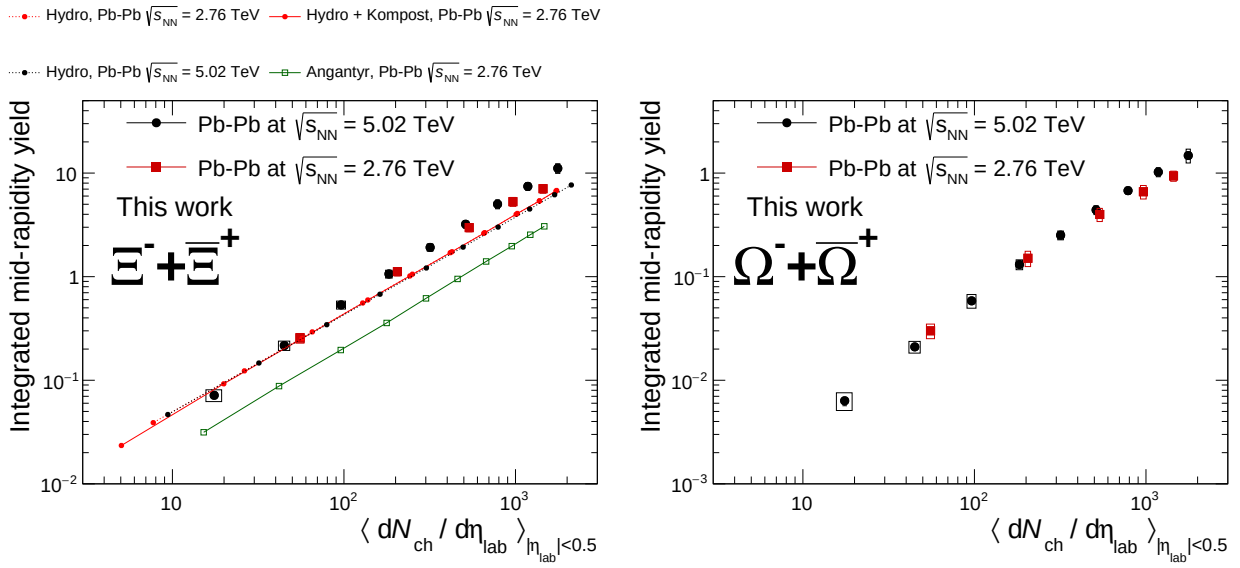


Figure 5.7: Total yield for Ξ (left plot) and Ω (right plot) as a function of $dN_{ch}/d\eta$ for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV in black and at $\sqrt{s_{NN}} = 2.76$ TeV in red. Although close to experimental values, Hydro model predictions underestimate the measured yield, especially for central collisions. We also observe that, for a given multiplicity class, the total yield seems to not depend on the collision energy or the pre-equilibrium dynamics employed in the Hydro simulation. The Angantyr model severely underestimates the reported data, with up to 50% less Ξ per event for the most-central multiplicity class.

indicates that the ϕ yield also increases with approximately the same rate. Suggesting that the enhancement is driven not by the net strangeness, but by the number of strange quarks and antiquarks content of the particle, which is the same for Ξ and ϕ . For reference, the Ω/ϕ ratio is also shown, where an increase can be seen across all multiplicity. This further improves the argument that the enhancement is due to the increase of strangeness content, since the Ω has a higher number of strange quarks.

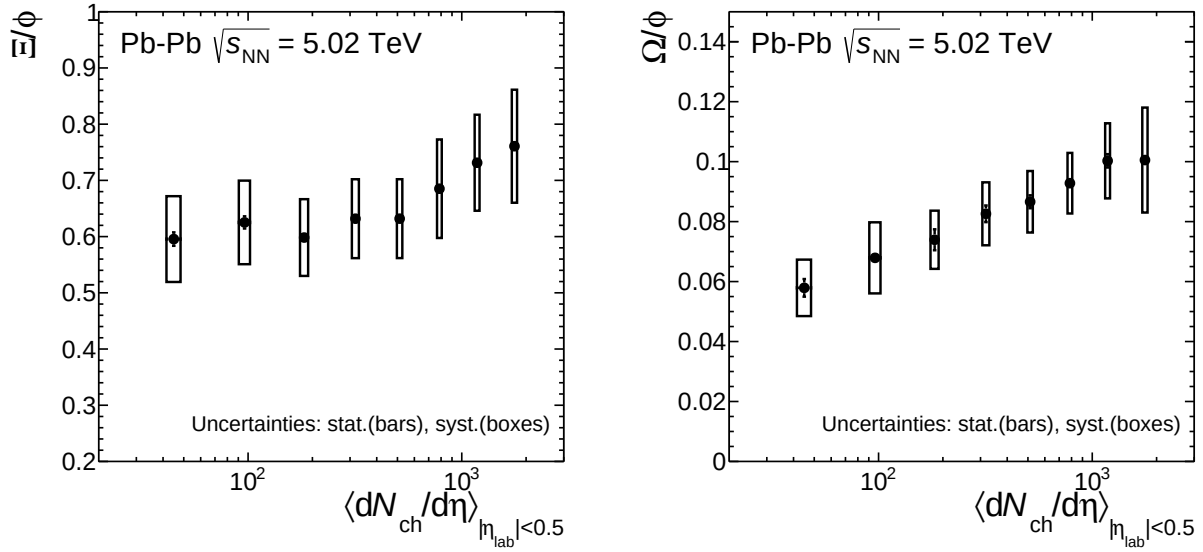


Figure 5.8: Integrated Ξ/ϕ (left plot) and Ω/ϕ (right plot) ratio as a function of $dN_{ch}/d\eta$ for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV.

Therefore, we see that the usual canonical suppression mechanism cannot fully explain the particle production across multiplicity for the strange sector. A better description can be achieved by employing an incomplete equilibration of strangeness and a multiplicity dependent chemical freeze-out temperature [75].

5.5 Strangeness enhancement

The ratio between strange and non-strange particle production rate is shown in Figs. 5.9 and 5.10 as $(\Xi^- + \bar{\Xi}^+)/(\pi^- + \bar{\pi}^+)$ and $(\Omega^- + \bar{\Omega}^+)/(\pi^- + \bar{\pi}^+)$ as a function of $dN_{ch}/d\eta$ for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. For the results of Pb-Pb at

$\sqrt{s_{\text{NN}}} = 5.02$ TeV, preliminary pion yields were used. The plots also include ALICE data from pp collision at $\sqrt{s} = 7$ TeV [29, 76] and p-Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [27, 28]. Predictions from thermal models [77–79] for the 0-10% centrality class of Pb-Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are shown as horizontal grey arrows.

It is important to mention that the statistical thermal model prediction was obtained by fitting the existing data without the inclusion of the Ξ and Ω , hence, the arrows in the figures indicate a prediction of the model, rather than a fit. The Ξ/π ratio shows a higher production of strangeness in central Pb-Pb collisions than predicted by the statistical thermal models that assumes a grand-canonical ensemble and strangeness equilibration. The thermal model predictions of the Ω/π ratio seems to agree better with the data. Since this is a pure strange quark state, the Ω should be less dependent on the results of other particles that affect the thermal model fit. But further discussion of the disagreement between the data and the model would require a more detailed study of the different thermal models available and the associated uncertainties.

Hydro model predictions are shown as lines with full circles symbols and shows a decrease of the to-pion-ratio for both cascades, in disagreement with the data reported in this thesis. Angantyr predictions are shown as the lines with hollow squares and underestimate the relative strange production by a factor of ~ 3 .

The lower ratio value for the most-central multiplicity interval of Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV has been interpreted as an evidence of post-hadronization baryon-antibaryon annihilation [80]. To test this hypothesis, a different simulation was performed for both hydro and Angantyr simulation models, where the post-hadronization stage of the simulation (performed by UrQMD) was turned off. These predictions are shown as green dashed lines and, in the hydro scenario, show a small increase with respect to the default simulation, showing that the baryon-antibaryon annihilation may affect this measurement.

The results presented in Figs. 5.9 and 5.10 show a smooth increase on the relative strangeness productions is observed for all systems, from low multiplicity pp, up to the most-central Pb-Pb collisions. It is also observed that different systems show similar to-pion-ratios for given

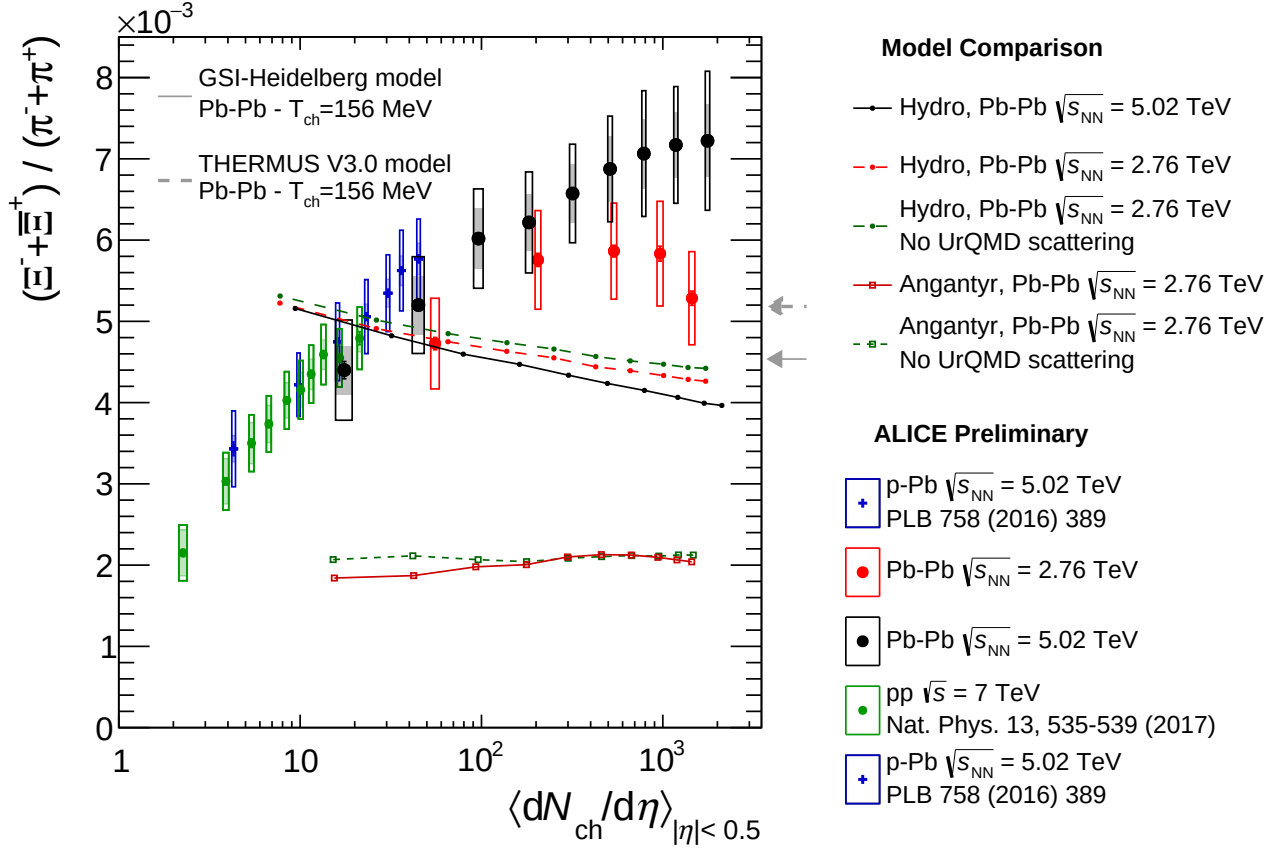


Figure 5.9: Integrated Ξ/π ratio as a function of $dN_{ch}/d\eta$ for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV and re-analysis at $\sqrt{s_{NN}} = 2.76$ TeV shown together with previous data for pp, p-Pb. Predictions from thermal models for the 0-10% centrality class are shown as the horizontal grey arrows right of the plot and shown an underestimation of the total Ξ/π ratio. The hydro simulation predictions are shown as the full black line for Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, dashed red line for $\sqrt{s_{NN}} = 2.76$ TeV and, in order to test the effect of the post-hadronization scatterings, dashed green line for $\sqrt{s_{NN}} = 2.76$ TeV without the UrQMD cascading model. We observe a decrease of the to-pion-ratio across all multiplicity, which is not observed in data. In the models, a small dependence with energy is also observed, with the higher energy producing less strangeness with respect to pions. Finally a small increase in the ratio is observed when turning off the late-stage evolution of the UrQMD, and can be interpreted as the effect of baryon-antibaryon annihilation.

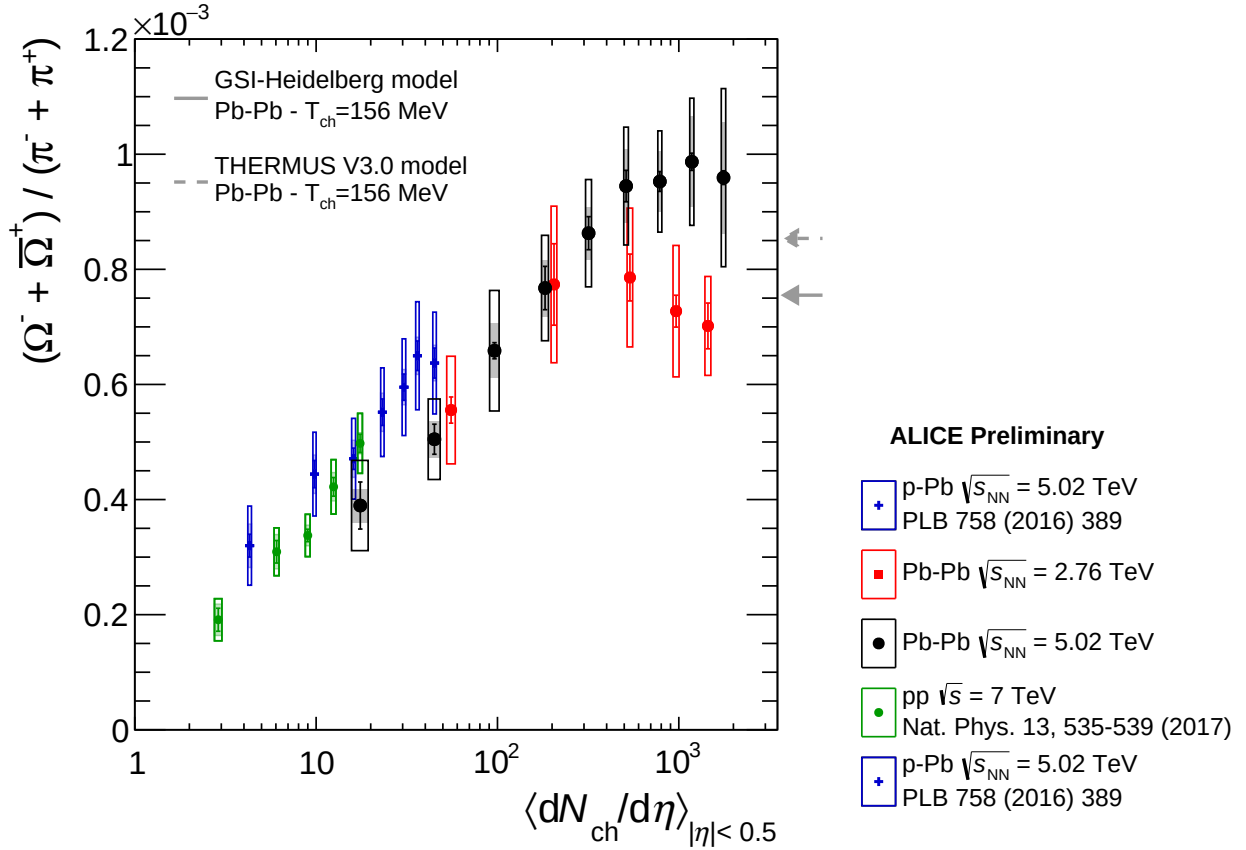


Figure 5.10: Integrated Ω/π ratio as a function of $dN_{\text{ch}}/d\eta$ for Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and re-analysis at $\sqrt{s_{\text{NN}}} = 2.76$ TeV shown together with pp, p–Pb. Predictions from thermal models for the 0-10% centrality class are shown as the horizontal grey arrows right of the plot and a better agreement with data is observed.

Table 5.1: Integrated particle yields for $\Xi^- + \Xi^+$ and $\Omega^- + \bar{\Omega}^+$ in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Both the statistical (first) and systematic (second) uncertainties are reported here.

Centrality	$\Xi^- + \Xi^+$	$\Omega^- + \bar{\Omega}^+$
0-10%	$11.12 \pm 0.07 \pm 1.19$	$1.48 \pm 0.02 \pm 0.23$
10-20%	$7.44 \pm 0.05 \pm 0.65$	$1.02 \pm 0.02 \pm 0.10$
20-30%	$5.02 \pm 0.04 \pm 0.50$	$(6.8 \pm 0.1 \pm 0.5) \times 10^{-1}$
30-40%	$3.21 \pm 0.03 \pm 0.26$	$(4.4 \pm 0.1 \pm 0.4) \times 10^{-1}$
40-50%	$1.92 \pm 0.02 \pm 0.15$	$(2.51 \pm 0.08 \pm 0.25) \times 10^{-1}$
50-60%	$1.06 \pm 0.01 \pm 0.09$	$(1.31 \pm 0.06 \pm 0.14) \times 10^{-1}$
60-70%	$(5.34 \pm 0.06 \pm 0.47) \times 10^{-1}$	$(5.8 \pm 0.1 \pm 0.9) \times 10^{-2}$
70-80%	$(2.16 \pm 0.02 \pm 0.22) \times 10^{-1}$	$(2.1 \pm 0.1 \pm 0.3) \times 10^{-2}$
80-90%	$(7.2 \pm 0.2 \pm 0.9) \times 10^{-2}$	$(6.3 \pm 0.7 \pm 1.2) \times 10^{-3}$

Table 5.2: Integrated particle yields for cascades in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. Both the statistical (first) and systematic (second) uncertainties are reported here.

Centrality	$\Xi^- + \Xi^+$	$\Omega^- + \bar{\Omega}^+$
0-10%	$7.1 \pm 0.1 \pm 0.7$	$(9.4 \pm 0.5 \pm 1.0) \times 10^{-1}$
10-20%	$5.30 \pm 0.08 \pm 0.52$	$(6.6 \pm 0.3 \pm 1.0) \times 10^{-1}$
20-40%	$2.97 \pm 0.04 \pm 0.26$	$(4.0 \pm 0.2 \pm 0.6) \times 10^{-1}$
40-60%	$1.12 \pm 0.02 \pm 0.10$	$(1.5 \pm 0.1 \pm 0.3) \times 10^{-1}$
60-80%	$(2.55 \pm 0.04 \pm 0.27) \times 10^{-1}$	$(3.0 \pm 0.1 \pm 0.5) \times 10^{-2}$

multiplicity. This universality suggests that, at the energies achieved by the LHC, the charged particle multiplicity is a good scaling parameter for the strangeness production mechanisms.

Chapter 6

Conclusion

In this work, we report the measurement of the production rate of multi-strange hadrons: Ξ^- , Ξ^+ , Ω^- and $\bar{\Omega}^+$ in Pb–Pb collisions at the unprecedented energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV. A reanalysis of the already published data of Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV was also performed. The greater number of events recorded for the higher energy dataset allows us to perform the measurement of the p_{T} spectra in narrower multiplicity intervals. Moreover, it is also possible to perform cascades measurements in the 10% most-peripheral multiplicity class, where an overlap with measurements performed in the high-multiplicity pp is possible.

The hardening of the p_{T} spectra with multiplicity and mass observed for the cascades is understood within the context of a hydrodynamically expanding medium during the early stages of the evolution. Comparisons to model predictions where an initial hydrodynamical evolution is present shows the same behaviour, while for the Angantyr model, where no such phase is present, the $\langle p_{\text{T}} \rangle$ is poorly described. We also observe an increase in the $\langle p_{\text{T}} \rangle$ when the system is allowed pre-equilibrium dynamics (KØMPØST), which improves the agreement with the data reported here, especially for low multiplicity centrality classes.

The total yield of the cascades is reported and compared to theoretical model predictions. We saw that, while the hydro model predictions underestimate the cascade production at central collisions, the Angantyr model underestimates the observable for all centralities.

The strangeness enhancement was studied by comparing the relative strangeness production

rate – by evaluating the hyperon-to-pion ratio – as a function of the final multiplicity at mid-rapidity for different colliding systems and energies. A smooth evolution across multiplicity is observed from low multiplicity pp to central Pb–Pb collision. Both hydro and Angantyr model predictions fails to reproduce the observed data. While hydro predictions show a decreasing ratio across all multiplicities, the Angantyr model shows a flat trend that underestimate the data. To understand which mechanism can explain this enhancement, we studied the Ξ/ϕ as a function of multiplicity and saw that the usual canonical suppression mechanism fails to describe the multiplicity dependence of the ϕ meson production rate.

During the years of my Ph.D. studies I was a member of the ALICE Collaboration and, besides working on the measurement reported in this thesis, I have participated in the data taking of both pp and Pb–Pb collisions, working on a total of 37 shift of 8 hours, totalling almost 300 hours inside the ALICE Run Control Center (ARC). During these shifts, I was assigned to the Data Quality Monitoring (DQM) position, being tasked with the monitoring of Quality Assurance (QA) plots for each detector in operation. Crucial for the experiment, this position prevents us from recording bad or low-quality data by alarming the DQM shifter in the ARC of potential problem during the data taking. This position is also responsible for monitoring of the offline system, which takes care of the replication of the data taken. As part of my service task, I worked on the QA and testing of the Multiplicity Selection framework, used in many of analyses within ALICE.

I also had the opportunity of presenting ALICE results in two international conferences. The talks “Multi-strange hadron production at the LHC with ALICE” at the *XVII International Conference on Hadron Spectroscopy and Structure*, in September of 2017 at Salamanca, Spain, and “Hadronic resonances, strange and multi-strange particle production in Xe-Xe and Pb-Pb collisions with ALICE at the LHC” at the *The 27th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions*, in May of 2018 at Venice, Italy. The published proceedings of the second presentation can be found in [81].

The work presented on this thesis is being finalized and will be published together with studies on the production of K_S^0 , Λ and $\bar{\Lambda}$ in a paper entitled “Centrality dependence of strangeness

production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV”.

Being a member of the ALICE experiment, I had the incredible opportunity of working in collaboration with a great number of experienced scientists from different nationalities. Working on the data taking, it was possible to understand just how challenging it is to maintain this whole experiment and, by developing the analysis that culminated in this thesis, I had the great opportunity of achieving a better comprehension of the elementary particle physics. Finally, I hope that this work will further improve our knowledge about nucleus-nucleus collisions, shedding light on the mechanisms of particle production in this extreme condition.

Bibliography

1. Karsch, F. Lattice QCD at high temperature and density. *Lect. Notes Phys.* **583**, 209–249 (2002).
2. Borsanyi, S. *et al.* Full result for the QCD equation of state with 2+1 flavors. *Phys. Lett. B* **730**, 99–104 (2014).
3. Bazavov, A. *et al.* Equation of state in (2+1)-flavor QCD. *Phys. Rev. D* **90**, 094503 (2014).
4. DeTar, C. & Heller, U. M. QCD Thermodynamics from the Lattice. *Eur. Phys. J. A* **41**, 405–437 (2009).
5. Aoki, Y. *et al.* The QCD transition temperature: results with physical masses in the continuum limit II. *JHEP* **06**, 088 (2009).
6. Bazavov, A. *et al.* The chiral and deconfinement aspects of the QCD transition. *Phys. Rev. D* **85**, 054503 (2012).
7. Maire, A. *Production des baryons multi-étranges au LHC dans les collisions proton-proton avec l'expérience ALICE* Ph.D. Dissertation (Strasbourg, IPHC, 2011).
8. Rafelski, J. & Muller, B. Strangeness Production in the Quark - Gluon Plasma. *Phys. Rev. Lett.* **48**. [Erratum: *Phys. Rev. Lett.* 56, 2334 (1986)], 1066 (1982).
9. Koch, P., Muller, B. & Rafelski, J. Strangeness in Relativistic Heavy Ion Collisions. *Phys. Rept.* **142**, 167–262 (1986).
10. Rafelski, J. Melting Hadrons, Boiling Quarks. *Eur. Phys. J. A* **51**, 114 (2015).

11. Bartke, J. *et al.* Neutral strange particle production in sulphur sulphur and proton sulphur collisions at 200-GeV/nucleon. *Z. Phys. C* **48**, 191–200 (1990).
12. Andersen, E. *et al.* Strangeness enhancement at mid-rapidity in Pb–Pb collisions at 158 AGeV/c. *Phys. Lett. B* **449**, 401–406 (1999).
13. Antinori, F. *et al.* Enhancement of strange and multi-strange baryons and anti-baryons in S W interactions at 200-GeV/c. *Phys. Lett. B* **447**, 178–182 (1999).
14. Antinori, F. *et al.* First results on strange baryon production from the NA57 experiment. *Nucl. Phys. A* **698**, 118–126 (2002).
15. Antinori, F. *et al.* Enhancement of hyperon production at central rapidity in 158-A-GeV/c Pb-Pb collisions. *J. Phys. G* **32**, 427–442 (2006).
16. Abelev, B. I. *et al.* Enhanced strange baryon production in Au+Au collisions compared to p+p at $\sqrt{s} = 200$ -GeV. *Phys. Rev. C* **77**, 044908 (2008).
17. Agakishiev, G. *et al.* Strangeness Enhancement in Cu+Cu and Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. Lett.* **108**, 072301 (2012).
18. Abelev, B. *et al.* Multi-strange baryon production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B* **728**. [Erratum: *Phys. Lett. B* **734**, 409 (2014)], 216–227 (2014).
19. Redlich, K. Strangeness Production as a Signal for Quark-Gluon Plasma Formation in High-Energy Particle Collisions. *Z. Phys. C* **27**, 633–637 (1985).
20. Cleymans, J., Redlich, K. & Suhonen, E. Canonical description of strangeness conservation and particle production. *Z. Phys. C* **51**, 137–141 (1991).
21. Cleymans, J., Elliott, D., Keranen, A. & Suhonen, E. Thermal model analysis of particle ratios at GSI Ni-Ni experiments using exact strangeness conservation. *Phys. Rev. C* **57**, 3319–3323 (1998).
22. Hamieh, S., Redlich, K. & Tounsi, A. Canonical description of strangeness enhancement from p-A to Pb Pb collisions. *Phys. Lett. B* **486**, 61–66 (2000).

23. Sorge, H., Berenguer, M., Stoecker, H. & Greiner, W. Color rope formation and strange baryon production in ultrarelativistic heavy ion collisions. *Phys. Lett. B* **289**, 6–11 (1992).
24. Sorge, H. Flavor production in Pb (160-A/GeV) on Pb collisions: Effect of color ropes and hadronic rescattering. *Phys. Rev. C* **52**, 3291–3314 (1995).
25. Bierlich, C., Gustafson, G., Lönnblad, L. & Tarasov, A. Effects of Overlapping Strings in pp Collisions. *JHEP* **03**, 148 (2015).
26. Andersson, B., Gustafson, G., Ingelman, G. & Sjostrand, T. Parton Fragmentation and String Dynamics. *Phys. Rept.* **97**, 31–145 (1983).
27. Adam, J. *et al.* Multi-strange baryon production in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. *Phys. Lett. B* **758**, 389–401 (2016).
28. Abelev, B. *et al.* Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p-Pb Collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. *Phys. Lett. B* **728**, 25–38 (2014).
29. Adam, J. *et al.* Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions. *Nature Physics* **13**, 535–539 (2017).
30. Sjostrand, T., Mrenna, S. & Skands, P. Z. A Brief Introduction to PYTHIA 8.1. *Comput. Phys. Commun.* **178**, 852–867 (2008).
31. Bierlich, C. & Christiansen, J. R. Effects of color reconnection on hadron flavor observables. *Phys. Rev. D* **92**, 094010 (2015).
32. Pierog, T., Karpenko, I., Katzy, J. M., Yatsenko, E. & Werner, K. EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider. *Phys. Rev. C* **92**, 034906 (2015).
33. Alessandro, B. *et al.* ALICE: Physics performance report, volume II. *J. Phys. G* **32**, 1295–2040 (2006).
34. Aamodt, K. *et al.* The ALICE experiment at the CERN LHC. *JINST* **3**, S08002 (2008).
35. Dobrigkeit Chinellato, D. *Estudo de Estranheza em Colisões próton-próton no LHC* Ph.D. Dissertation (University of Campinas, 2012).

36. Wong, C.-Y. *Introduction to High-Energy Heavy-Ion Collisions* ISBN: 9810202636 (WSPC, 1994).
37. Botta, E. *Particle identification performance at ALICE in 5th Large Hadron Collider Physics Conference (LHCP 2017) Shanghai, China, May 15-20, 2017* (2017).
38. Abelev, B. B. *et al.* Performance of the ALICE Experiment at the CERN LHC. *Int. J. Mod. Phys. A* **29**, 1430044 (2014).
39. Dellacasa, G. *et al.* ALICE: Technical design report of the time projection chamber. *CERN-OPEN-2000-183, CERN-LHCC-2000-001* (2000).
40. Bethe, H. Theory of the Passage of Fast Corpuscular Rays Through Matter. *Ann. Phys. (Berlin)* **397**, 325–400 (1930).
41. Blum, W., Rolandi, L. & Riegler, W. *Particle detection with drift chambers* ISBN: 978-3-540-76684-1 (2008).
42. Collaboration, A. ALICE: Technical proposal for a large ion collider experiment at the CERN LHC. *CERN-LHCC-95-71, CERN-LHCC-P-3* (1995).
43. Abbas, E. *et al.* Performance of the ALICE VZERO system. *JINST* **8**, P10016 (2013).
44. Miller, M. L., Reygers, K., Sanders, S. J. & Steinberg, P. Glauber modeling in high energy nuclear collisions. *Ann. Rev. Nucl. Part. Sci.* **57**, 205–243 (2007).
45. Abelev, B. *et al.* Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE. *Phys. Rev. C* **88**, 044909 (2013).
46. ALICE Collaboration. Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *ALICE-PUBLIC-2015-008* (Dec. 2015).
47. Aamodt, K. *et al.* Charged-particle multiplicity density at mid-rapidity in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. Lett.* **105**, 252301 (2010).

48. Aamodt, K. *et al.* Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. Lett.* **106**, 032301 (2011).
49. Adam, J. *et al.* Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. Lett.* **116**, 222302 (2016).
50. Adam, J. *et al.* Centrality dependence of the pseudorapidity density distribution for charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Lett. B* **772**, 567–577 (2017).
51. Tanabashi, M. *et al.* Review of Particle Physics. *Phys. Rev. D* **98**, 030001 (2018).
52. Kalman, R. A New Approach To Linear Filtering and Prediction Problems. *Journal of Basic Engineering (ASME)* **82D**, 35–45 (Jan. 1960).
53. Gyulassy, M. & Wang, X.-N. HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions. *Comput. Phys. Commun.* **83**, 307 (1994).
54. Brun, R. *et al.* GEANT: Detector Description and Simulation Tool. *CERN-W5013, CERN-W-5013, W5013, W-5013* (1994).
55. Agostinelli, S. *et al.* GEANT4: A Simulation toolkit. *Nucl. Instrum. Meth. A* **506**, 250–303 (2003).
56. Koch, K. π^0 and η measurement with photon conversions in ALICE in proton-proton collisions at $\sqrt{s} = 7$ TeV. *Nucl. Phys. A* **855**, 281–284 (2011).
57. Barlow, R. *Systematic errors: Facts and fictions* in *Advanced Statistical Techniques in Particle Physics. Proceedings, Conference, Durham, UK, March 18-22, 2002* (2002), 134–144.
58. Schnedermann, E., Sollfrank, J. & Heinz, U. W. Thermal phenomenology of hadrons from 200-A/GeV S+S collisions. *Phys. Rev. C* **48**, 2462–2475 (1993).

-
59. Cleymans, J. & Worku, D. Relativistic Thermodynamics: Transverse Momentum Distributions in High-Energy Physics. *Eur. Phys. J. A* **48**, 160 (2012).
60. Adare, A. *et al.* Detailed measurement of the e^+e^- pair continuum in $p + p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and implications for direct photon production. *Phys. Rev. C* **81**, 034911 (2010).
61. Altenkämper, L., Bock, F., Loizides, C. & Schmidt, N. Applicability of transverse mass scaling in hadronic collisions at energies available at the CERN Large Hadron Collider. *Phys. Rev. C* **96**, 064907 (2017).
62. Bass, S. A. *et al.* Microscopic models for ultrarelativistic heavy ion collisions. *Prog. Part. Nucl. Phys.* **41**, 255–369 (1998).
63. Bleicher, M. *et al.* Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model. *J. Phys. G* **25**, 1859–1896 (1999).
64. Heinz, U. & Snellings, R. Collective flow and viscosity in relativistic heavy-ion collisions. *Ann. Rev. Nucl. Part. Sci.* **63**, 123–151 (2013).
65. Bernhard, J. E., Moreland, J. S., Bass, S. A., Liu, J. & Heinz, U. Applying Bayesian parameter estimation to relativistic heavy-ion collisions: simultaneous characterization of the initial state and quark-gluon plasma medium. *Phys. Rev. C* **94**, 024907 (2016).
66. Nunes da Silva, T. *et al.* Testing a best-fit hydrodynamical model using PCA. *MDPI Proc.* **10**, 5 (2019).
67. Moreland, J. S., Bernhard, J. E. & Bass, S. A. Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions. *Phys. Rev. C* **92**, 011901 (2015).
68. Kurkela, A., Mazeliauskas, A., Paquet, J.-F., Schlichting, S. & Teaney, D. Effective kinetic description of event-by-event pre-equilibrium dynamics in high-energy heavy-ion collisions. *Phys. Rev. C* **99**, 034910 (2019).
69. Schenke, B., Jeon, S. & Gale, C. (3+1)D hydrodynamic simulation of relativistic heavy-ion collisions. *Phys. Rev. C* **82**, 014903 (2010).

-
70. Schenke, B., Jeon, S. & Gale, C. Higher flow harmonics from (3+1)D event-by-event viscous hydrodynamics. *Phys. Rev. C* **85**, 024901 (2012).
 71. Bierlich, C., Gustafson, G., Lönnblad, L. & Shah, H. The Angantyr model for Heavy-Ion Collisions in PYTHIA8. *JHEP* **10**, 134 (2018).
 72. Sjöstrand, T. *et al.* An Introduction to PYTHIA 8.2. *Comput. Phys. Commun.* **191**, 159–177 (2015).
 73. Bierlich, C., Chinellato, D. D., Vieira, A. & Takahashi, J. Studying the effect of the hadronic phase in nuclear collisions. *The 18th International Conference on Strangeness in Quark Matter* (2019).
 74. Voloshin, S. A., Poskanzer, A. M. & Snellings, R. Collective phenomena in non-central nuclear collisions. *Landolt-Bornstein* **23**, 293–333 (2010).
 75. Vovchenko, V., Dönigus, B. & Stoecker, H. Canonical statistical model analysis of p-p, p-Pb, and Pb-Pb collisions at the LHC (2019).
 76. Acharya, S. *et al.* Multiplicity dependence of light-flavor hadron production in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. C* **99**, 024906 (2019).
 77. Wheaton, S. & Cleymans, J. THERMUS: A Thermal model package for ROOT. *Comput. Phys. Commun.* **180**, 84–106 (2009).
 78. Petran, M., Letessier, J., Rafelski, J. & Torrieri, G. SHARE with CHARM. *Comput. Phys. Commun.* **185**, 2056–2079 (2014).
 79. Stachel, J., Andronic, A., Braun-Munzinger, P. & Redlich, K. Confronting LHC data with the statistical hadronization model. *J. Phys. Conf. Ser.* **509**, 012019 (2014).
 80. Becattini, F., Grossi, E., Bleicher, M., Steinheimer, J. & Stock, R. Centrality dependence of hadronization and chemical freeze-out conditions in heavy ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. C* **90**, 054907 (2014).

-
81. Albuquerque, D. S. D. Hadronic resonances, strange and multi-strange particle production in Xe-Xe and Pb-Pb collisions with ALICE at the LHC. *Nucl. Phys. A* **982**, 823–826 (2019).

Appendix A

Improvements on finder algorithms

This section summarizes the improvements made on the V0 and cascades algorithms and the corresponding effect on the raw counts of reconstructed cascades studied in this analysis, at both Pb–Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV. These improvements were motivated by discussions between Prof. Dr. David D. Chinellato (UNICAMP) and Prof. Dr. Iouri Belikov (IPHC) and implemented in the default ALICE analyses during the development of this analysis. Therefore, we worked on the necessary comparisons and documentation of such improvements.

During the analysis of the $\sqrt{s_{\text{NN}}} = 5.02$ TeV data, it was found that topological selections associated to the cascade decay vertex were chosen to be rather tight in past analyses of Pb–Pb data, causing a significant loss in signal. In addition, the usage of tight cuts was shown to have a non-negligible impact on corrected spectra, because simulations would not adequately describe the extreme signal losses caused by these selections.

This knowledge prompted the use of significantly looser selection criteria for the data analysis at $\sqrt{s_{\text{NN}}} = 5.02$ TeV which, however, also increase the combinatorial background rather significantly. In order to get background levels under better control, one of the explored options was the improvement of both V0 and cascade finder algorithm, denoted here as vertexer. The objective was to boost resolution in the relevant variables and possibly enable the use of topological selections that are only moderate, as opposed to completely loose, while still keeping

any corrected results as stable as possible. This section outlines these improvements and their effect on the relevant topological variables. All of these improvements were implemented in a dedicated, improved vertexing class called `AliAnalysisTaskWeakDecayVertexer`.

A.1 V0 finding: Introduction

In the ALICE V0 finding algorithm used thus far, the following procedure is used:

1. All positive and negative particle tracks are pre-filtered based on their DCA to primary vertex, which has to be above a certain threshold.
2. All unlike-sign pairs are studied, and their distance of closest approach is calculated with a method contained in `AliExternalTrackParam` called `GetDCA`. This function employs a multi-dimensional implementation of Newton's method to minimize the distance between two helix-like trajectories.
3. The track pair is only accepted if the DCA is below a certain threshold in effective centimeters¹.
4. The V0 decay position is estimated as being a weighted combination of the point of closest approach of the V0 and the point of closest approach of the bachelor track, with the relevant weights being determined based on the track uncertainties of the positive and negative tracks.
5. The track pair is only accepted if the cosine of its pointing angle (to the primary vertex) is above a certain threshold.
6. The track pair is only accepted if the estimated decay position is within a certain range in R_{2D} which includes both a lower and an upper limit.

¹the distance unit for this selection is indeed centimeters. However, the XY and Z directions are re-scaled according to the ratio of the corresponding track uncertainties during this procedure and this is why the DCA selection isn't really performed in pure centimeters.

One of the main items that could benefit from improvement in the list above is step 2, in which the minimum track distance is determined with a numerical method. This is because, while the minimization algorithm used is quite efficient computationally, it is also rather unprotected as far as local minima are concerned. While in many situations the local minimum will already be the global one, there are conditions in which two oppositely-charged tracks may exhibit two distance minima, as outlined in the next section.

A.2 V0 finding: Improved distance minimization

In order to avoid the situation in which the track distance minimizer finds only a local minimum, an improved distance minimizer has been studied and implemented into a method called `GetDCAVODau` contained in the base vertexing class `AliAnalysisTaskWeakDecayVertexer`². In this method, we include a pre-processing stage in which the minimization problem is first considered only in the XY plane as opposed to in three dimensions. Depending on the distance between the helix centers of the two trajectories $\vec{r}_1$ and $\vec{r}_2$ and the two radii of curvature R_1 and R_2 , one of the following occurs:

- If $|\vec{r}_2 - \vec{r}_1| > R_1 + R_2$: then there is only one distance minimum in the XY plane. Even so, to save computing resources, the two tracks are already propagated to the location corresponding to where they are closest together in the XY plane before moving to a final, three-dimensional minimization using the traditional procedure as described in step 2 in the previous section.
- If $|R_1 - R_2| < |\vec{r}_2 - \vec{r}_1| < R_1 + R_2$: then there are two distance minima in the XY plane. In this case, we calculate the three-dimensional distance between the two tracks at each of these minima and choose the minimum at which this 3D distance is smallest to start a final three-dimensional minimization using the same procedure described in step 2 in the previous section.

²This improvement is used whenever this weak decay vertexer is used with the flag `fkDoImprovedCascadeVertexFinding` set to `kTRUE`, which can be set via the dedicated setter `SetDoImprovedCascadeVertexFinding(flag)`.

- If $|R_1 - R_2| > |\vec{r}_2 - \vec{r}_1|$: then the two circles corresponding to the XY projection of the two helix-like trajectories are such that one of them is fully contained within the other. In this case, there is only one distance minimum in the XY plane and no further steps are needed. The usual three-dimensional minimization described in step 2 in the previous section is employed without any change in the starting position.

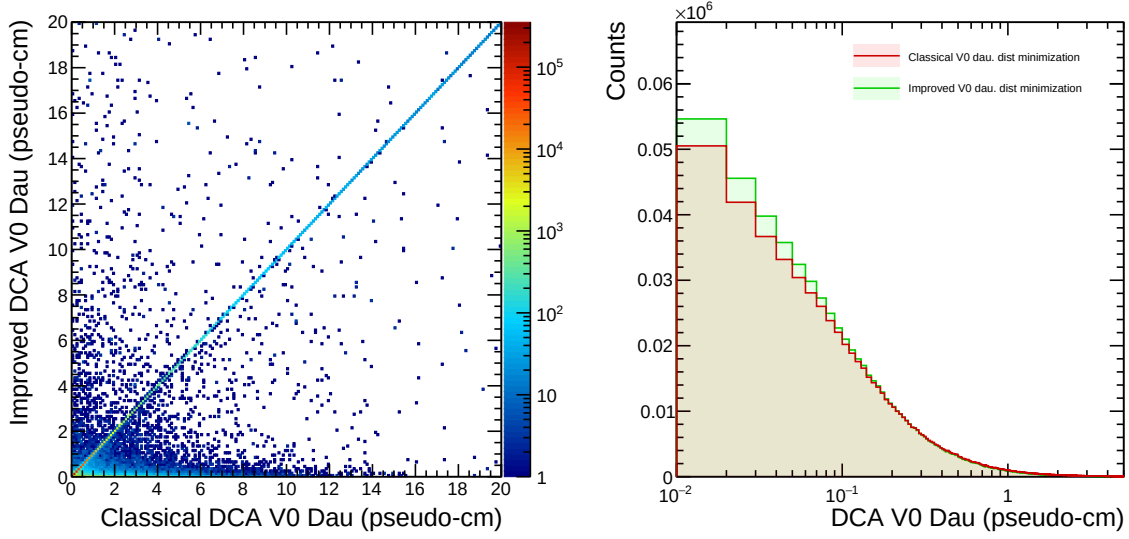


Figure A.1: (Left plot) Correlation between V0 daughter DCAs as calculated by the default ALICE algorithm (X axis) and the improved V0 daughter DCA calculated with the XY-plane preprocessing enabled. (Right plot) DCA distribution for the original DCA (in red) and the improved DCA (in green). These plots consider all findable cascade candidates for all p_T and may not perfectly match the effects observed in analysis conditions.

Because this procedure contemplates all mathematical possibilities for local minima, it is able to recover a certain amount of true V0 candidates for which the usual ALICE methods would not have recovered the correct decay position, as can be seen in Fig. A.1. This improved distance minimization effectively increases the number of correctly reconstructed candidates by up to 5%, depending on transverse momentum and analysis conditions.

A.3 Cascade Finding: Introduction

The standard ALICE cascade finding algorithm, as contained in the `AliCascadeVertexer` class, finds cascade candidates by combining V0s and potential bachelor tracks into $\Lambda\pi$ pairs according to the following procedure:

1. All positive and negative particle tracks are pre-filtered based on their DCA to the primary vertex, which has to be above a certain threshold, and a list of candidate bachelor tracks is filled.
2. All V0 candidates within the same event are studied and are selected for combining with the bachelors from the first step if the V0 mass under the Λ or $\bar{\Lambda}$ hypothesis is sufficiently close to the Λ or $\bar{\Lambda}$ mass.
3. For all possible V0-bachelor combinations, the distance of closest approach is determined with a method contained in `AliCascadeVertexer` called `PropagateToDCA`. This method assumes that both bachelor and V0 trajectories are straight lines.
4. The V0-bachelor pair is only accepted if the DCA calculated in the previous step is below a certain threshold.
5. The Cascade decay position is estimated as being exactly halfway between the point of closest approach of the V0 and the point of closest approach of the bachelor track.
6. The V0-bachelor pair is only accepted if the cosine of its pointing angle (to the primary vertex) is above a certain threshold.
7. The track pair is only accepted if the estimated cascade decay position is within a certain range in R_{2D} which includes both a lower and an upper limit.

A.4 Cascade Finding: Bachelor propagation

As described in step 3 above, the point of closest approach between the V0 trajectory and the bachelor trajectory is determined in the function `PropagateToDCA`, which makes use of an

analytical formula to propagate two straight trajectories, which is an approximation because of the fact that the bachelor track is charged and therefore actually exhibits a curved, helix-like trajectory in the presence of a magnetic field.

A clear improvement to this algorithm would be to propagate the bachelor tracks to their point of closest approach to the V0 trajectory with a proper helix-like parametrization for bachelor trajectory. This can be done using adaptations of algorithms such as the numerical minimization procedure employed in `AliExternalTrackParam::GetDCA` in which, as mentioned above, a three-dimensional version of Newton's method is used to determine the point of closest approach between two helix-like trajectories. A minor modification of the `GetDCA` method in which a magnetic field of zero intensity is passed to obtain the curvature of one of the tracks is enough to ensure that this method is applicable to the V0-bachelor distance minimization problem. This improved minimization has been implemented in the method³

`AliAnalysisTaskWeakDecayVertexer::PropagateToDCA`

Because this change affects the propagation of bachelors to their point of closest approach to the V0 in the V0-bachelor pairing, the variable most affected by this is the DCA between cascade daughters. Testing revealed that, as can be seen in Fig A.2, the resulting p_T -integrated cascade daughter DCA distribution is significantly more peaked at zero. As a side product, this improvement also results in a better estimation of the cascade decay point since a smaller DCA indirectly means less ambiguity in determining the decay position.

A.5 Cascade finding: Decay point estimation

In the default reconstruction, the cascade vertex is defined as the average of the V0 and the bachelor position at DCA, regardless of track uncertainties. In this section we propose a better solution, improving the decay point estimation with information from the covariance matrices.

Fig. A.3 shows a schematic of the cascade decay point estimation. The points of DCA for the bachelor and the V0 are shown in red circles, the vector $\vec{A}$ is defined by the distance

³This improvement is used whenever this weak decay vertexer is used with the flag `fkDoImprovedCascadeVertexFinding` set to `kTRUE`, which can be set via the dedicated setter `SetDoImprovedCascadeVertexFinding(flag)`.

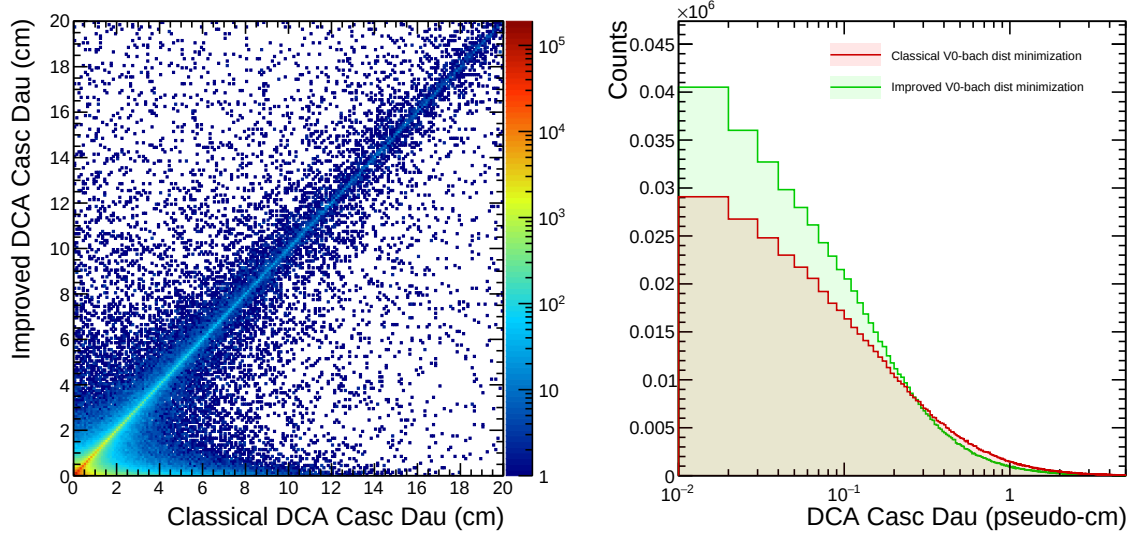


Figure A.2: (Left plot) Correlation between cascade daughter DCAs as calculated by the default ALICE algorithm (X axis) and the improved cascade daughter DCA calculated with the XY-plane preprocessing enabled. (Right plot) DCA distribution for the original DCA (in red) and the improved DCA (in green). These plots consider all findable cascade candidates for all p_T and may not perfectly match the effects observed in analysis conditions.

between these two points and the vector $\vec{B}$ (only accessible in the simulation) is defined by the distance of the true decay point to the bachelor track position at DCA.

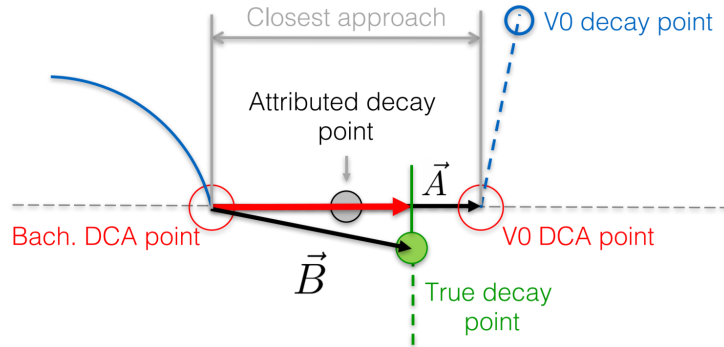


Figure A.3: Cascade decay point estimation diagram. Bachelor track in blue solid line, V0 trajectory in dashed blue line. Closest approach distance denoted by the vector $\vec{A}$. ALICE default attributed decay point represented by the grey circle and true decay point, by the green one. Vector $\vec{B}$ denotes the distance between the bachelor DCA point and the cascade true decay point. The DCA between cascade daughters above has been greatly exaggerated for illustration purposes.

In order to understand how much in between the bachelor and the V0 DCA points should

the attributed cascade decay point be, we define f as follows:

$$f = \frac{\vec{A} \cdot \vec{B}}{|\vec{A}|^2}. \quad (\text{A.5.1})$$

By definition, $f = 0$ when the true decay point of the cascade is the same as the bachelor position at DCA and $f = 1$ when the true decay point is the same as the V0 position at the DCA point. As mentioned before, the default cascade finding algorithm defines the cascade vertex as the midpoint of the bachelor and V0 DCA points, this being equivalent to set $f = 0.5$. The distribution of f can be accessed in the simulation and is shown in Fig. A.4 for Ξ . It is noted that the distribution has two local maxima, around the bachelor and V0 DCA points, suggesting that the assumption of $f = 0.5$, although correct in the average, fails to describe the decay in a case-by-case study.

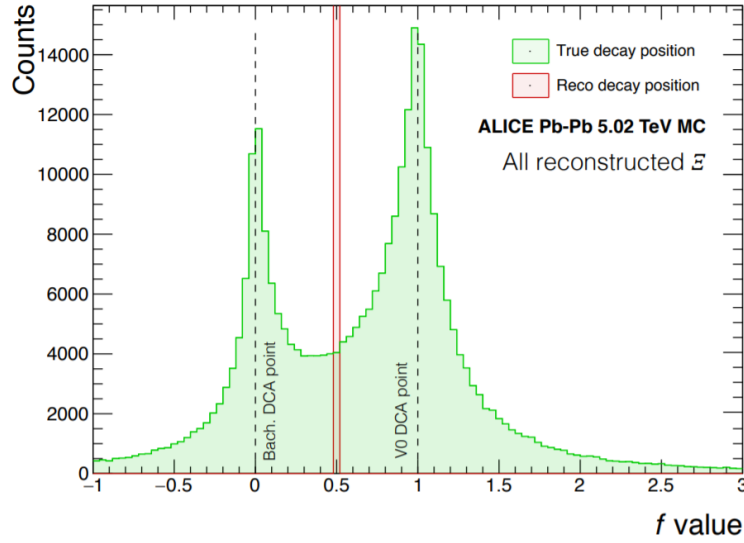


Figure A.4: Distribution of f from MC simulations for Ξ . The distribution shows two local maxima, around the bachelor and the V0 DCA points. The ALICE default assumption of $f = 0.5$ (shown in red) is also shown.

The estimation of the cascade decay point can be improved by taking the uncertainties of the bachelor and V0 DCA points into consideration.

The components that need to be taken into consideration here are:

- Position of the bachelor track at DCA
 1. **Position of bachelor at decay vertex**
Covariance matrix, C_{bach} , acquired using `AliV0vertexer::GetWeight()`.
- Position of the V0 at DCA

2. **Position of V0 decay vertexer**

Position covariance matrix, C_{V0} , acquired from `AliESDv0::Refit()`.

3. **Extrapolate back to V0 DCA point**

Angular uncertainties on momentum multiplied by lever arm (distance between cascade and V0 decay point). This was tested to be $\sim$ negligible and will be disregarded for now.

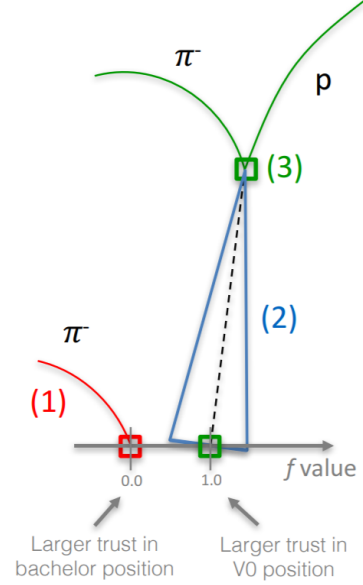


Figure A.5: Components used in the improved estimation of the cascade decay point. The DCA between cascade daughters above has been greatly exaggerated for illustration purposes.

In the default ALICE reconstruction, we have:

$$\vec{r}_{\text{decay}} = 0.5\vec{r}_{\text{bach}} + 0.5\vec{r}_{V0}.$$

The new proposed estimation takes into consideration the covariance matrix mentioned above and defines the decay point as:

$$\vec{r}_{\text{decay}} = \left[C_{\text{bach}}^{-1} + C_{V0}^{-1} \right]^{-1} \times \left[C_{\text{bach}}^{-1} \vec{r}_{\text{bach}} + C_{V0}^{-1} \vec{r}_{V0} \right].$$

This procedure is hereafter referred as the cascade “refit”. In Fig. A.6, it is possible to

see the effect of this refit for the Ξ . The effect is stronger in the low- p_T region, with up to 20–30% more true- Ξ accepted, while for the high- p_T region, where the pointing angle resolution is already good enough, little effect is observed.

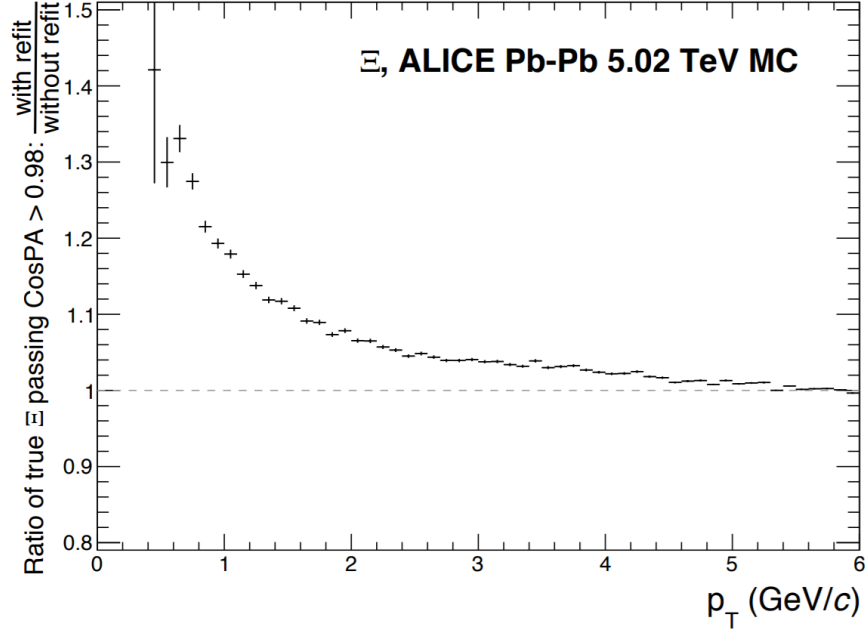


Figure A.6: Effect of the cascade refit for true (MC association) Ξ when a selection in the cosine of pointing angle of 0.98 is applied.

A.6 Improvements effect on cascades

Fig. A.7 shows the effect of all the combined improvements on the Ξ^- raw counts as a function of p_T for both $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV energies. The improved vertexer accepts up to 50% more candidates in the high- p_T region. It is also important to note that the effects are period dependent, as can be seen in the lower pad of Fig. A.7.

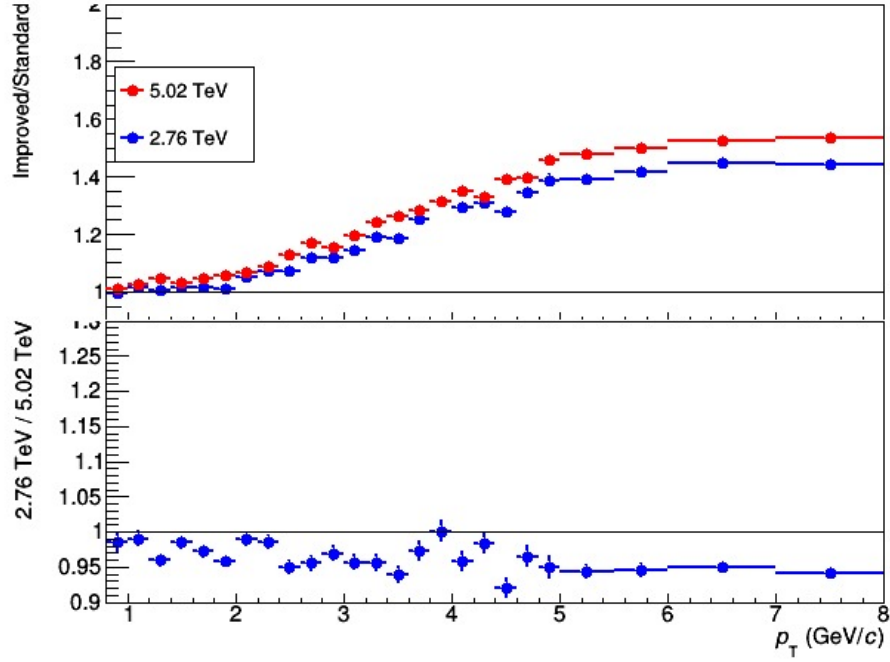


Figure A.7: (Top pad) Effect of all combined improvements discussed in this appendix on the raw counts of Ξ^- in Pb-Pb collisions at both $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV. At both energies, an increase of up to 50% candidates is observed in the high p_T region. (Bottom pad) Ratio between the effect of the new vertexer at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV, showing that the effects of this improvement are period dependent.

Appendix B

Pile-up rejection event selection

Due to the high luminosity at which the ALICE detector operates, multiple Pb–Pb collisions can occur within the same trigger window, resulting in what we define as pile-up events. These events are usually rejected by requesting the event to have only one valid vertex reconstructed by the ITS, as mentioned in 3.1. However, considering the long drift time of the electrons inside the TPC, it is possible to have tracks still traversing the TPC when a new collision is triggered, even if it has only one ITS valid vertex. This rejection of this second type of pile-up is the focus of this appendix.

B.1 Further details on the new event selection

In order to remove events with bad reconstruction properties or events containing pile-up, a new event selection was proposed, based on the correlation between the multiplicity measured by the VZERO detector and the total number of ESD tracks with the flag `TPCout`¹ on, denoted here as N_{Tracks} for simplicity. This selection rejects events where the N_{Tracks} is greater than a threshold, N^{THR} , that is dependent on the VZERO amplitude. The corresponding formula that relates the event VZERO amplitude and the threshold value used in this analysis is:

$$\text{VZERO amplitude} = 2 \times 10^{-5} (N^{\text{THR}})^2 + 2.5 N^{\text{THR}} - 2200.$$

¹This flag is attributed to particle tracks that extend until the outer walls of the TPC.

The correlation between the VZERO amplitude and the N_{Tracks} inside the TPC can be seen in Fig. B.1. We see that, for a given VZERO amplitude, the distribution of N_{Tracks} has a tail, with low multiplicity (measured by the VZERO) events producing a huge number of particles inside the TPC. This is an indication of pile-up events, with the TPC recording tracks from other collisions that are still traversing the detector.

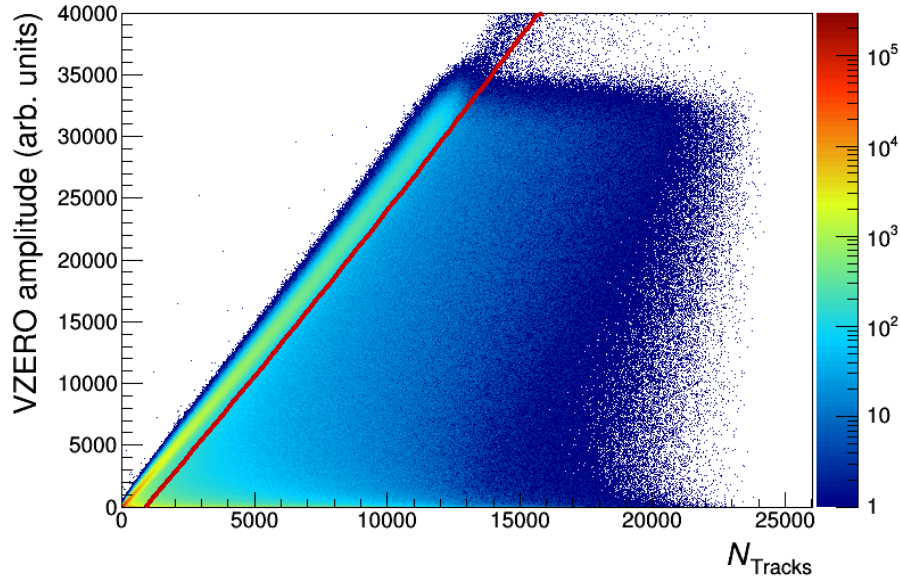


Figure B.1: Correlation between the number of tracks, N_{Tracks} , and the VZERO amplitude in a given event. The red line represents the value of the threshold, N^{THR} for given VZERO amplitude. This way, the new event selection rejects events to the right of the red line.

This study was performed in two different subset of the LHC15o dataset: the low Interaction Rate (IR) and the high IR runs. Runs in the low IR dataset have a small number of expected colliding bunch pairs inside the ALICE detector, with 8 or less colliding bunch pairs. On the other hand, the high IR runs have expected colliding bunch pairs ranging from 362 to 444. This difference results in higher pile-up probability for the high IR runs.

By studying the correlation between $N_{\text{Tracks}} - N^{\text{THR}}$ and the VZERO amplitude (in such a way that accepted events are on the negative- x region), it is possible to better visualise the tail on the N_{Tracks} distribution. This is shown in Fig. B.2. By integrating this histogram in different VZERO multiplicity intervals, we can construct distributions of the N_{Tracks} for each centrality class studied in this thesis. In Fig. B.3, we see this distribution for the most-central and most-

peripheral centralities used in this analysis for both IR datasets and for MC simulation (where no pile-up is present). The distributions are normalized to have the same value at the maximum as the high IR dataset.

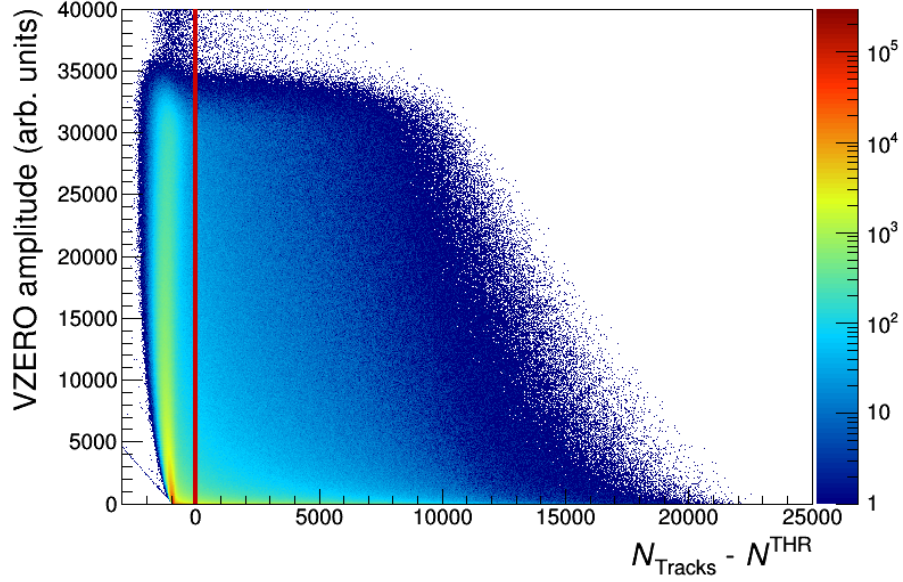


Figure B.2: Correlation between the number of tracks shifted by the selection threshold, $N_{\text{Tracks}} - N^{\text{THR}}$, and the VZERO amplitude in a given event. The events accepted by the new event selection are the ones in the negative x region..

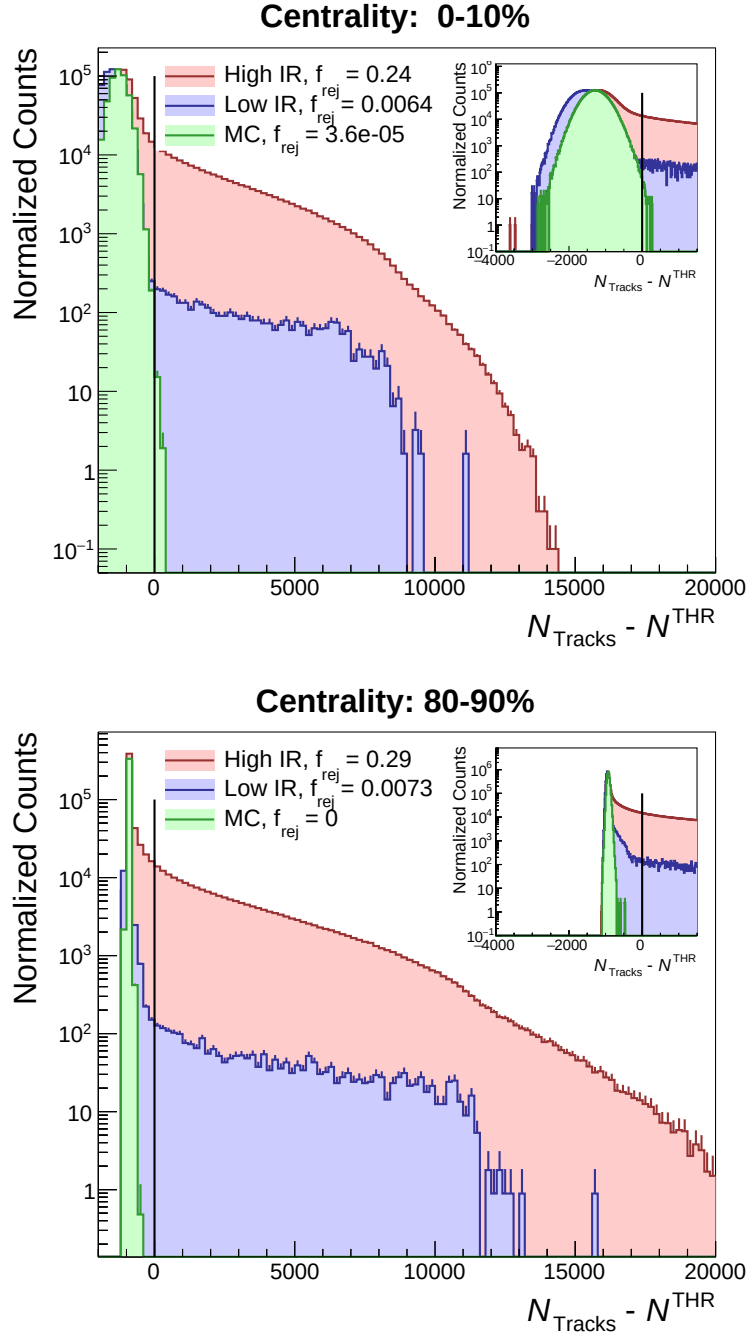


Figure B.3: Distribution of the $N_{\text{Tracks}} - N^{\text{THR}}$ for the 10% most central (top plot) and peripheral collisions (bottom plot). Three datasets are shown here: LHC15o high interaction rate in red, low interaction rate in blue and the Monte Carlo production in green. In both plots, the distributions are normalized such that the maximum value are equal for the three productions. A zoom of the region close to the peak is also shown.

We see that this selection rejects $25 \sim 30\%$ of events for the high interaction rate dataset, $< 1\%$ for the low interaction rate, while for the associated MC production (where there is no

pile-up) the rejection rate is negligible. Fig. B.4, shows the evolution of the fraction of accepted events as a function of centrality, for the centralities used in the cascade analysis. Here other event selections used in the analysis are also applied.

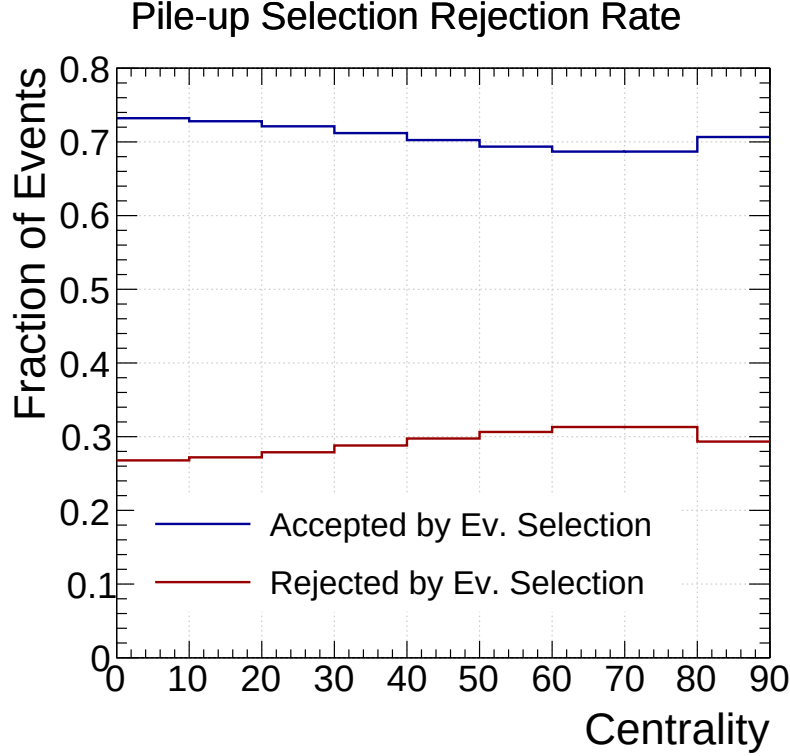


Figure B.4: Fraction of events accepted/rejected by the event selection for all centralities used in the analysis. Here other event selections used in the analysis are also applied.

When considering the other event selections, described in 3.1, this selection reduces the trigger efficiency by $\sim 30\%$ in all centralities.

B.2 Event selection effect on cascades

Cascades and V0 candidates in the rejected events seem to have worse reconstruction properties. This can be observed in the widening of the invariant mass peak of the K_S^0 (used here since its the systematic uncertainty in the signal extraction is lower), see Fig. B.5.

It is also noteworthy that, when studying the number of candidates per event, V0 and cascade yields are smaller ($\lesssim 10\%$ smaller) for candidates in the rejected events and that, for peripheral events, most of the original background comes from the rejected events. Figure B.6

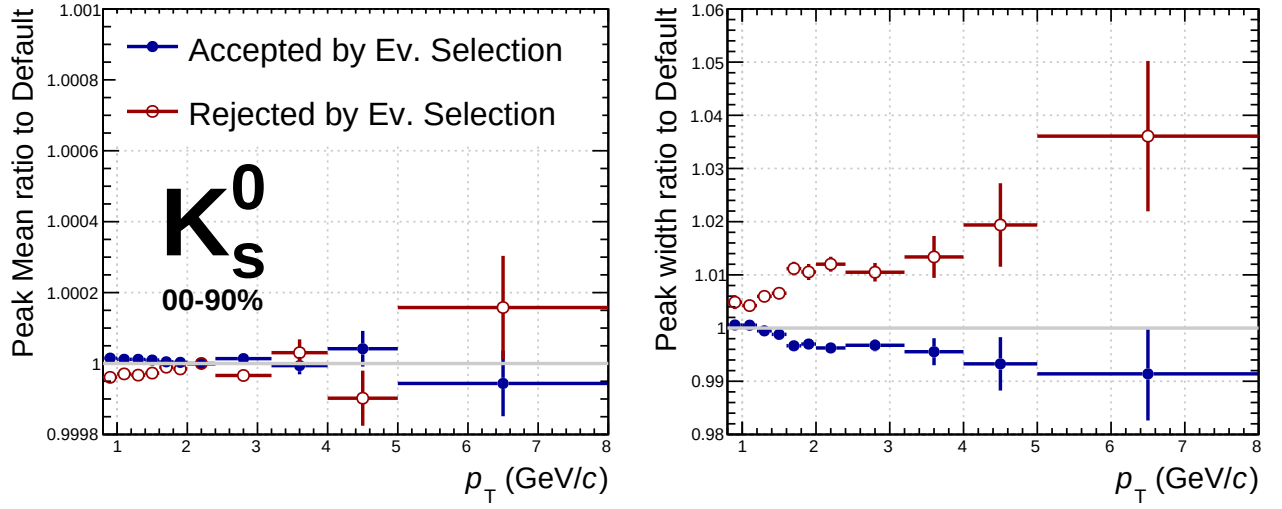


Figure B.5: Mean (left plot) and width (right plot) of the K_S^0 peaks as a function of p_T ; the fit consists of a Gaussian + a 1st degree polynomial. A widening of the peak can be observed for the rejected events, suggesting worse reconstruction quality.

shows an invariant mass distribution normalized by the number of events for Ξ^- for the intermediate p_T region and peripheral centrality class, illustrating the removal of the background achieved by this selection. This is of extreme importance for this study, since the measurement of the Ω in the 80-90% centrality class is only possible after this pile-up rejection. The peripheral collisions are of great interest since it is where the measurements of Pb-Pb collisions overlap with high multiplicity pp, as discussed in Sec. 5.5.

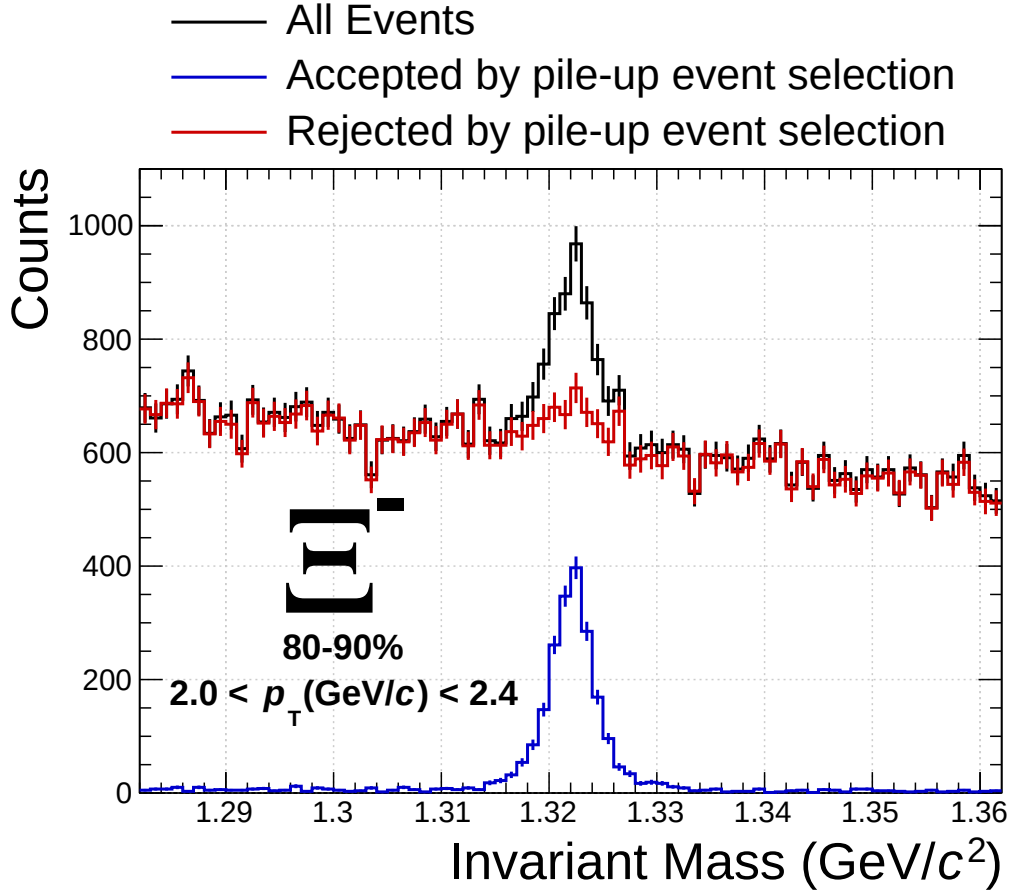


Figure B.6: Invariant mass spectra normalized by the number of events for Ξ^- candidates in the 10% most-peripheral events with $2.0 < p_T \text{ (GeV/c)} < 2.4$.

The evolution with p_T of the signal per event, background per event and peak significance ($S/\sqrt{S+2B}$), with respect to not applying the selection, is shown in Fig. B.7 for Ξ^- and Fig. B.8 for Ω^- , for central and peripheral centralities. For Ω^- , the peripheral centrality used is 70 – 80%, since without this selection the signal extraction at 80 – 90% is not possible. There is an increase of the significance of ~ 2 for the peripheral events, motivating the addition of this event selection for the cascade analysis in Pb-Pb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$.

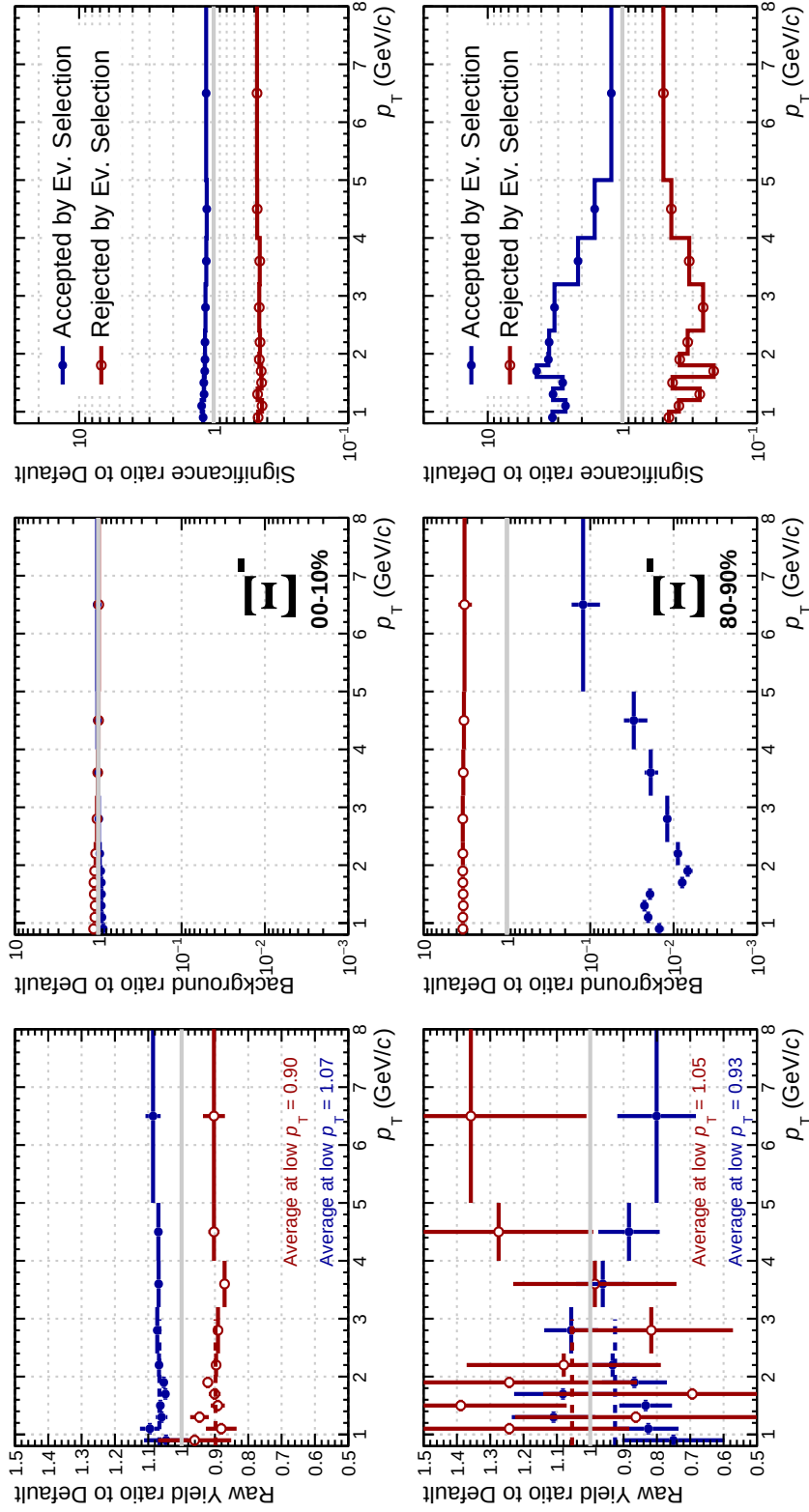


Figure B.7: Signal per event (left column plots), background per event (middle column plots) and peak significance (right column plots) of Ξ^- candidates in the 0-10% (top row plots) and 80-90% (bottom row plots) multiplicity classes. Rejected events have yield per event smaller than the default (no rejection). A constant fit is done up to 3 GeV/c to estimate the effect on the final yield.

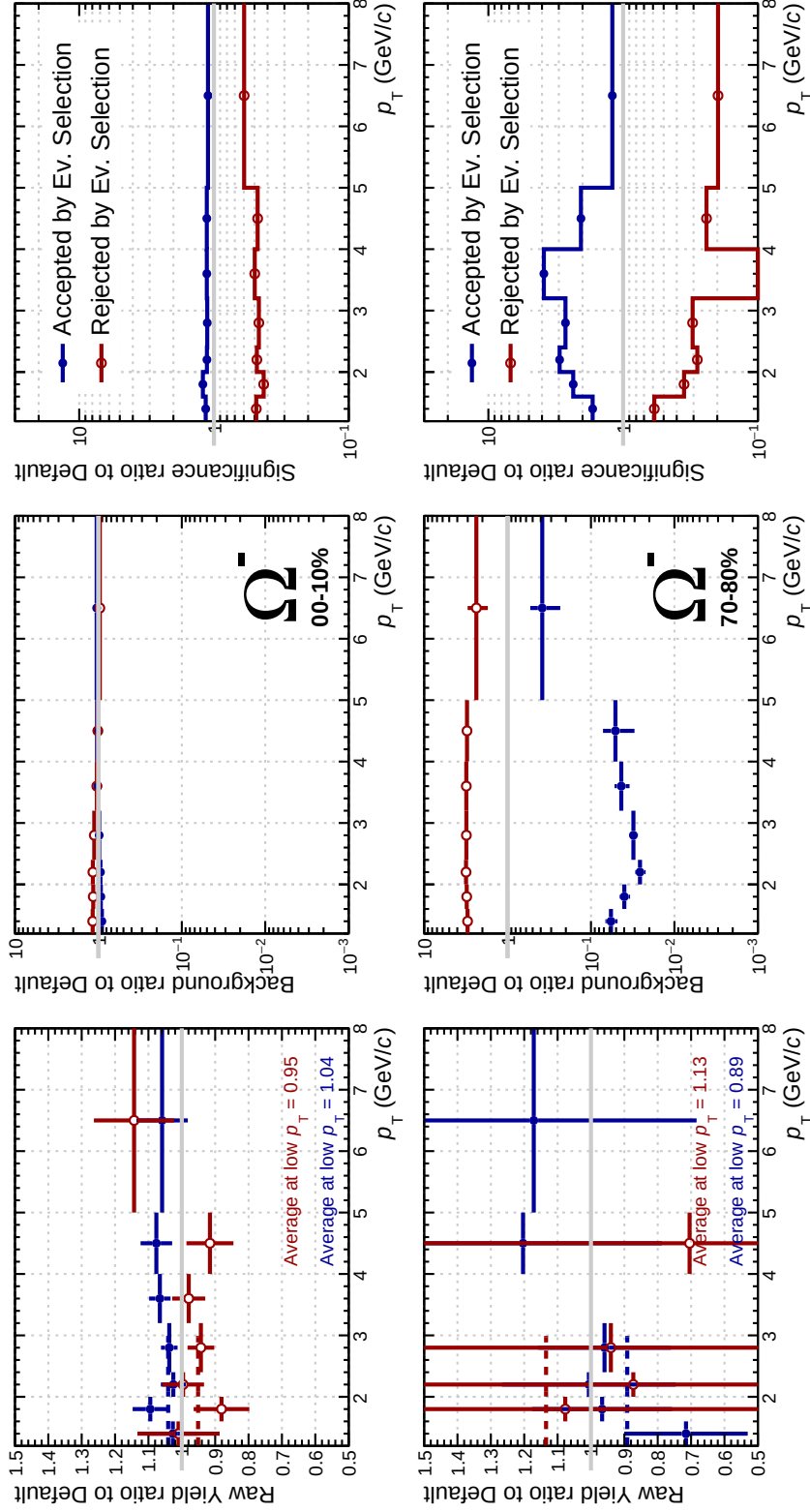


Figure B.8: Signal per event (left column plots), background per event (middle column plots) and peak significance (right column plots) of Ω^- candidates in the 0-10% (top row plots) and 70-80% (bottom row plots) multiplicity classes. Rejected events have yield per event smaller than the default (no rejection). A constant fit is done up to 3 GeV/c to estimate the effect on the final yield.