

Study of $\Lambda(1520)$ resonance production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE at the LHC

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by

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The thesis entitled

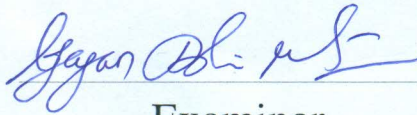
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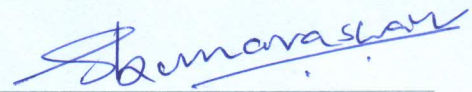
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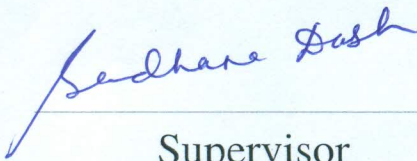
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To my loving family

Abstract

The Large Hadron Collider (LHC) at CERN provides the opportunity to study nuclear matter under extreme conditions, that is at very high temperature and energy density, which are similar to those prevailing just a few microsecond after the Big Bang. At the LHC, a very hot and dense state of partonic matter is created in collisions of heavy ions at very high centre-of-mass energy. In this state of matter, known as Quark-Gluon Plasma (QGP), quarks and gluons become "free" and are no longer confined within hadrons. After formation, the QGP fireball expands and cool down with a typical lifetime of a few fm/c before the partonic phase make a subsequent transition to a hadronic phase (hadronisation) and eventually the produced particles reach the detectors. Hadronic resonances are very short-lived particles, with typical lifetimes ranging from fm/c to a few tens of fm/c. For this reason, hadronic resonances are very good candidates to probe the various stages of the evolution of the fireball and the properties of the dense and strongly-coupled QCD matter created in heavy-ion collisions.

The study of the production of the $\Lambda(1520)$ hadronic resonance is an important measurement in heavy ion collisions due to its characteristic life time of 12.6 ± 1.6 fm/c. The lifetime of the $\Lambda(1520)$ lies between the lifetimes of the $K^*(892)^0$ and $\phi(1020)$ mesons, which are 4.16 ± 0.05 fm/c and 46.3 ± 0.4 fm/c, respectively. From previous measurements of $K^*(892)^0$ production, it is found that the $K^*(892)^0/K$ yield ratio is suppressed in central (head-on) heavy-ion collisions with respect to peripheral heavy-ion collisions and proton-proton collisions. The measurement suggests that the observed suppression might be due to the re-scattering of the $K^*(892)^0$ decay products within the dense hadronic medium, causing a significant reduction of the resonance reconstructible yield. No suppression is observed in the production of the $\phi(1020)$ meson in central heavy-ion collisions where the production yield ratio $\phi(1020)/K$ is almost unaffected with respect to peripheral heavy-ion collisions and proton-proton collisions, indicating that this particle decays outside the fireball due to its longer lifetime. Therefore, the study of $\Lambda(1520)$ production can provide crucial insight on the duration and properties of the evolution of the QCD matter produced in heavy-ion collisions, and in particular on the hadronic phase which exists from the hadronisation (chemical freeze-out) until the moment all interactions among hadrons cease (kinetic freeze-out). The study of $\Lambda(1520)$ complements the results on $K^*(892)^0$ and $\phi(1020)$ production and will help shading light on the lifetime and opacity of the dense hadronic medium. The measurement of $\Lambda(1520)$ resonance production has been performed previously at RHIC in Au–Au, d–Au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV. The $\Lambda(1520)/\Lambda$ was found to be suppressed in Au–Au central collisions as compared to peripheral collisions.

In this thesis, the measurement of $\Lambda(1520)$ production in Pb–Pb collisions at the LHC is presented and is a step forward at a new energy regime. The reconstruction of the $\Lambda(1520)$ signal in heavy-ion collisions is difficult due to its small production cross-section and also because of the very large background caused by the high multiplicity of particle produced. Moreover, as the $\Lambda(1520)$ might decay inside the hadronic medium, the decays products are expected to undergo re-scattering with the other particles of the medium, hence reducing the number of reconstructible $\Lambda(1520)$ resonances. The measurement has been performed in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the hadronic decay channel $\Lambda(1520) \rightarrow K^- + p$ (and charged conjugate), with a branching ratio of $22.5 \pm 0.5\%$. The analysis is performed with the ALICE detector at mid-rapidity ($|y| < 0.5$) in multiple centrality intervals, in the transverse momentum (p_T) range $0.5 < p_T < 6.0$ GeV/ c . In this thesis, the yield ratio of $\Lambda(1520)/\Lambda$ was found to be suppressed in central collisions as compared to peripheral collisions. This yield suppression is qualitatively consistent with predictions from models that include re-scattering of the resonance decay daughters with the dense medium created in the collisions. The mean- p_T , $\langle p_T \rangle$ of $\Lambda(1520)$ is observed to increase from peripheral to central Pb-Pb collisions, in quantitative agreement with the expectations from models of collective hydrodynamical expansion of the created medium. This measurement, which extends STAR results to higher multiplicity and improved accuracy, further supports the existence of a prolonged hadronic phase after the QGP hadronisation, lasting enough to allow for a significant reduction of the production of short-lived resonances.

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Chapter 1

Introduction

"All matter originates and exists only by virtue of a force. . . We must assume behind this force the existence of a conscious and intelligent Mind. This Mind is the matrix of all matter."

– Max Planck

Abstract: This chapter provides a brief theoretical overview of subnuclear particle physics and heavy-ion physics. The Standard Model, the current theory of the fundamental interactions among particles is discussed in Section 1.1. The concepts of Quark Gluon plasma and heavy-ion physics are discussed in Sections 1.2 and 1.3.

1.1 Standard Model

Our diverse universe is formed by fundamental constituents of matter and fundamental forces. Many theoretical and experimental discoveries from the past century have provided a continuous and deeper understanding of its fundamental structure. The Standard Model [1, 2] is one of the most successful and outstanding achievements in the theoretical understanding of the properties of matter and their interactions, which was brought to its current shape following the discoveries by Salam, Glashow and Weinberg [3–5] in 1970. The Standard Model is a very well-tested theory capable of providing insight and predictions to experimental results with very high precision.

In the Standard Model (SM) theory the matter consists of twelve elementary (point-like) particles called "fermions", which have spin = 1/2 and are classified according to their quantum number. The SM includes three of the four known fundamental forces: The Strong, Electromagnetic and Weak force. Although it does not include a theory for the gravitational force. In the fermion category, there are six quarks (q) and six leptons (l), which are divided into three generations depending upon their masses and properties. The first generation of quarks are the constituents of the lightest and stable particles like the protons and the neutrons, whereas the second and third generations are constituents of heavier and unstable particles.

The interaction between particles is described as being mediated by the exchange of gauge bosons. The SM is mathematically a quantized Yang-Mills theory based on the non-abelian symmetry group $U(1) \times SU(2) \times SU(3)$. In total in the theory there are twelve gauge bosons (one photon, three heavy vector bosons and eight gluons) and one scalar boson [6]. The classification

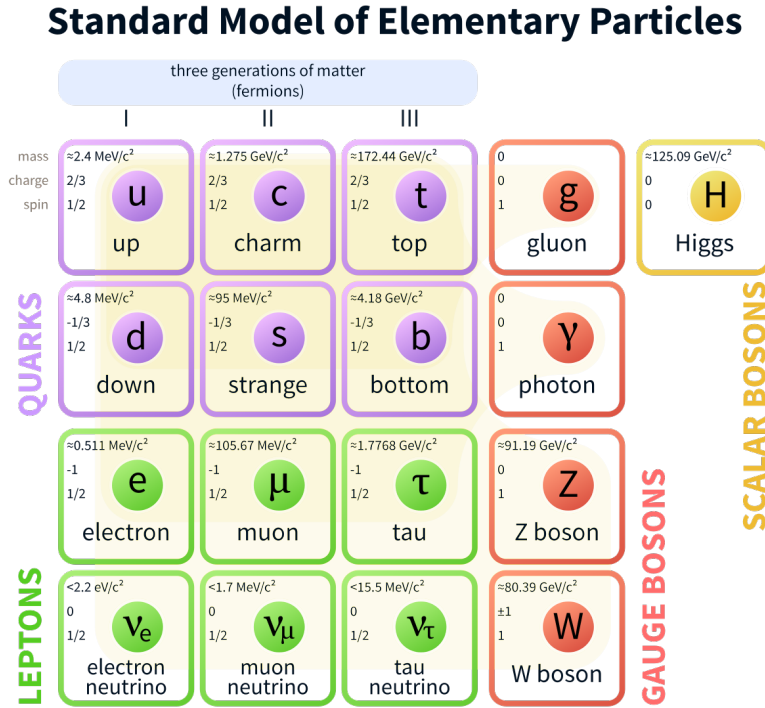


Figure 1.1: Fundamental constituent of the matter in the description of Standard Model.

of all the particles in the SM is shown in Figure 1.1 and Figure 1.2 summarises with an illustration of the fundamental interactions between particles and their characteristics. Particles are classified into four categories according to their interactions as follows

Quarks: The quarks are spin $1/2$ fermions and exist in six different flavours: up (u), down (d), charm (c), strange (s), top (t), bottom (b). Each quark can have three different colour quantum numbers: red, green and blue, which are playing the role of the charge in the strong force. For each quark there exists a corresponding anti-quark partner with opposite of flavour quantum number. Quarks can interact via strong, weak and electromagnetic forces. Quarks are combined into structures with zero net colour quantum number (colourless) to form hadrons: mesons are formed by a quark and an anti-quark pair, baryons are formed by three quarks.

Leptons: There are three leptons, namely the electron (e), muon (μ) and tau (τ) and their corresponding neutrinos: ν_e , ν_μ and ν_τ . Like the quarks, all leptons have their corresponding anti-particles. All leptons can interact via the weak force. The electron, muon and tau leptons have electric charge and can also interact electromagnetically.

Gauge bosons: The gauge bosons are the force carriers of the fundamental interactions: strong, weak and electromagnetic. The strong interaction is the strongest among all the four forces and is mediated by the exchange of massless gluons (spin = 1). The weak interaction is mediated by the exchange of the heavy vector bosons, $W^\pm$ ($m = 80 \text{ GeV}$, spin = 1) and Z^0

Interactions	Charge	Quark	Leptons	Lifetime Range α_i
Strong	Color		--	10^{-23} sec 1fm 1
Electromagnetic	Electric charge (e)			10^{-20} - 10^{-16} sec ∞ 10^{-2}
Weak	Weak charge (g)			10^{-12} sec 10^{-2} - 10^{-1} fm 10^{-6}

Figure 1.2: Fundamental interactions between particles and their characteristics in the description of Standard Model (Figure Source [6]).

($m = 91 \text{ GeV}$, $\text{spin} = 1$), whereas electromagnetic interactions are mediated by the exchange of photons ($m = 0$, $\text{spin} = 1$).

Scalar bosons: The Higgs boson is the only fundamental scalar boson in the SM. It is responsible for providing mass to all particles. The SM was further validated by the recent experimental discovery of the Higgs boson by the ATLAS and CMS experiments at the LHC announced in July 2012 [7, 8], whose existence was originally proposed by Peter Higgs in 1964 [9]. Later in 2013, the Nobel Prize for Physics has been awarded to Peter Higgs and François Englert for their contribution to theoretical discovery of Higgs mechanism.

Quantum Electrodynamics (QED)

Quantum Electrodynamics is the theory of electromagnetic interactions (γ as a mediator particle) and describes the interaction of light with matter. The full agreement between the quantum mechanics and special theory of relativity was achieved in this theory for the first time. This theory was developed by Richard P. Feynmann, Tomonaga Shinichiro and Julian S. Schwinger between 1946 and 1950 and they were later awarded the Nobel Prize in Physics in 1965.

Electroweak Theory (EW)

In particle physics, the Electroweak Theory (EW) is a unified theory of the electromagnetism and the weak interaction. In the Electroweak model, electromagnetic and weak interactions appear as two different aspects of the same force, the electroweak force, due to the spontaneous breaking of a fundamental symmetry at low energy. At the energy of the order of 246 GeV (or

at high temperature $\approx 10^{15} K$), the electromagnetic and the weak forces merge into the unique electroweak force. Sheldon Glashow, Abdus Salam, and Steven Weinberg are the authors of the electroweak unification theory and were awarded the Nobel Prize for Physics in 1979 for their contribution.

In 1983, the predicted W^+ , W^- and Z^0 bosons were discovered by observing their production in the UA1 and UA2 experiments in $p\bar{p}$ collisions at CERN. In the following year, the Nobel Prize for Physics was awarded to Carlo Rubbia and Simon van der Meer for this experimental result. Therefore, the discovery of the W and Z bosons was considered a major success of CERN. Later in 1999, Gerardus't Hooft and Martinus Veltman were awarded the Nobel Prize for their demonstration that the electroweak theory is renormalizable.

Quantum Chromo-Dynamics (QCD)

Quantum Chromo-Dynamics (QCD) is the theory that describes the strong interaction between quarks (q) and gluons (g) in the form of a gauge theory in a very similar manner to the Quantum Electro-Dynamics (QED) does between electrons (e) and photons (γ). Both theories describe spinor matter fields interacting via massless vector gauge fields. In QCD, the colour charge is associated to the non-Abelian gauge group $SU(3)$ instead of the Abelian group $U(1)$ of QED for the electric charge [6]. Three colour charges are carried by the quarks and eight by the gluons, which transform according to the adjoint representation. Compared to the QED, the most striking difference in the QCD is that the gauge fields (gluons) carry an intrinsic colour charge, making interactions among gluons possible: a pure gluon system is an interacting system in contrast to an ideal gas of photons. As a result, the 3D Laplace equation, which in non-relativistic QED leads to the Coulomb potential $V \sim 1/r$, effectively becomes one dimensional for massive quarks with a confining potential $V \sim r$ as a solution [10].

The Lagrangian density of the QCD is given by

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} + \sum_f \bar{\psi}_\alpha^f (i\gamma_\mu \mathcal{D}^\mu)^{\alpha\beta} \psi_\beta^f, \quad (1.1)$$

with

$$F_{\mu\nu}^a = \left(\partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f_{bc}^a A_\mu^b A_\nu^c \right), \quad (1.2)$$

and

$$\mathcal{D}_\mu = \partial_\mu + ig \frac{\lambda_a}{2} A_\mu^a \quad (1.3)$$

The following term needs to be added in Equation 1.1 for the inclusion of massive quarks

$$\mathcal{L} = \sum_f m_f \bar{\psi}_\alpha^f \psi^{\alpha f} \quad (1.4)$$

Here A^a is the gluon field of 8 colour ($a = 1, 2, \dots, 8$) and ψ_α^f is the quark field of 3 colour ($\alpha = 1, 2, 3$) and flavour f and λ_a are the Gell-Mann matrices. Here g is the dimensionless coupling constant, which means Equation 1.1 does not provide any scale [10]. Hence, the QCD can not predict the absolute values in terms of physical units and can provide only the ratio of a physical quantities. The QCD coupling constant " g " provides the strength of the strong force in terms of a running coupling constant α_s which depends on the square of momentum transfer (Q^2) and is defined in terms of number of quarks (n_f) and the QCD scale parameter Λ_{QCD} (expected value is $\simeq 200$ MeV) as

$$\alpha_s(Q^2) \equiv \frac{g(Q^2)}{4\pi} = \frac{4\pi}{(11 - \frac{2}{3}n_f)\ln\frac{Q^2}{\Lambda^2}} \quad (1.5)$$

In QCD, hadrons are color-neutral bound states of quark-antiquark pairs (mesons) or of three quarks (baryons) and thus are the chromodynamic (colour) analog of the positronium or of atoms as electrical-neutral bound states in QED. These two theories are significantly different at large distances because while a finite amount of energy is sufficient to break EM bonds, strong quark binding cannot be broken to let the quark free. This QCD property leads to the concept of "confinement", which means that the quarks and gluons confine themselves inside the hadrons. The coupling constant diverges as the distance between quarks increases and therefore quarks can never be isolated. This implies that the colour force increases significantly with increasing the distance. If very high energy is imparted to a quark in the attempt to isolate it, whenever it is higher than the energy needed to create a quark/antiquark pair, the break-up would result in the creation of new hadrons to preserve colour neutrality.

At very short distances, the QCD coupling constant decreases with decreasing distances. This special property of QCD is known as "asymptotic freedom": partons inside a hadron interact among themselves weakly and can be considered as almost free. In other words, the coupling constant α_s becomes very small at large momentum transfers or at the time when quarks and gluons come closer to each other but at larger distances, α_s becomes large enough to prevent the isolation of quarks from outside the hadrons. At large momentum transfer or at a very short distance, the running coupling constant α_s becomes very small and perturbative QCD (pQCD) calculations can provide reliable results which can be tested experimentally. For QCD processes happening at large distances or at low momentum transfer α_s becomes too large and perturbative calculations stop working. In such cases, QCD calculations on the lattice (lattice QCD) can provide reliable estimates by using a discrete space-time lattice as a tool for non-perturbative QCD calculations.

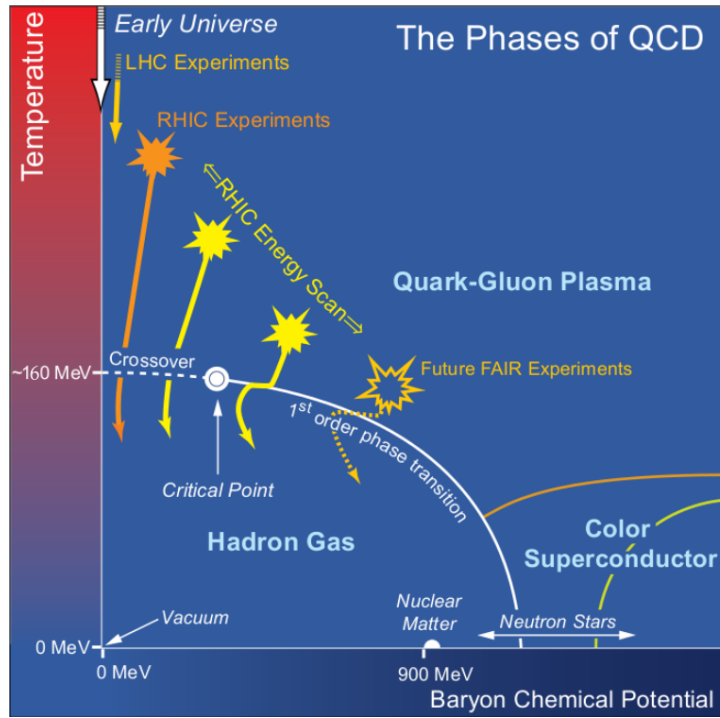


Figure 1.3: Phase diagram of QCD.

1.2 QCD phase diagram and heavy-ion physics

The strongly interacting matter can exist in different phases characterized by given density and temperature as shown by the phase diagram in Figure 1.3 in terms of chemical potential (μ_B) and temperature (T). Ordinary nuclear matter is located in the diagram region at low temperature and low baryochemical potential ($\mu_B \sim 1$ GeV). At higher temperature (on the left of the plot along the y-axis) or at a higher chemical potential (lower part of diagram along the x-axis) a phase of hadronic gas (HG) exist, where the nucleons interact and form other hadrons, resonances and pions. Further increasing the temperature and energy density, a deconfined phase of quark and gluon plasma is predicted to be reached. The number of degrees of freedom increases in the QGP with respect to a hadron gas as they include all the fermionic degrees of freedom ($3 \text{ colours} \times 2 \text{ spin} \times 6 \text{ flavours}$) and gluonic degrees of freedom ($8 \text{ colours gluon state} \times 2 \text{ helicity}$). In the extreme value of μ_B , the nuclear matter is conjectured to exist in a quark-gluon state with characteristics similar to superconductivity. The inner core of neutron stars might be formed of a quark-gluon plasma state, as the condition of very high baryonic density induced by the gravitational force might be reached even at low temperature [11].

The Early Universe following the "Big Bang" was a fireball of fundamental matter at extremely high energy density and temperature. The matter produced in the Big Bang therefore evolved from those very high temperatures and had a very small quark-antiquark excess of about

10^{-9} , corresponding to a vanishing baryon chemical potential ($\mu_B \sim 0$). At zero chemical potential (μ_B) or vanishing baryon number, the properties of the QCD phase transition depend on the quark mass and on the number of active quark flavours. While the most reasonable and quantitative question is at which temperature the transition to high-temperature quark-gluon plasma phase occurs, the nature of the expected transition, namely the order and the details on critical behaviour, are in control of the global symmetries of the QCD Lagrangian. These kind of symmetries exist in the limit of either vanishing quark mass ($m_q \rightarrow 0$) or infinite quark mass ($m_q \rightarrow \infty$).

In fact, the global symmetries are explicitly broken for non-zero value of the quark mass, similarly to what happens in spin models when perturbed by an external magnetic field. Therefore, we do expect that a continuous phase transition, which may exist in the zero or infinite quark-mass limit, will turn into a non-singular crossover behaviour for any value of finite quark mass. On the other hand, the first order transitions may persist for some time before they turn into a continuous transition. In nature, quarks are not massless and in particular, the strange quark whose mass is of the order of the expected phase-transition temperature ($T \sim 170$ MeV) plays a decisive role in determining the transition nature at vanishing chemical potential. The QCD phase transition is supposed to be of the first order until the critical point is reached, predicted to be in the baryon chemical potential range ($200 \leq \mu_B \leq 500$ MeV). The critical point in the phase diagram corresponds to the thermodynamical condition in which the transition process starts changing from the first order to second order. Both hadronic and quark-gluon matter is expected to coexist at the critical point.

In ultra-relativistic heavy-ion collisions at RHIC and LHC, the nuclear matter at the collision point is heated and compressed enough to undergo a transition to the deconfined matter of quarks and gluons, called the Quark Gluon Plasma (QGP), at low chemical potential. The collisions are expected to produce the same conditions present a few microseconds after the "Big Bang". The heavy-ion collision physics program is, therefore, extremely important to understand some of the outstanding mysteries of QCD by studying the properties of the QGP and the equation of state of nuclear matter at a sufficiently large temperature and pressure.

A future experiment, CBM [12] at GSI is planned to study the properties of QGP in the condition of very high baryon density. The LHC [13] at CERN with its ALICE [14, 15], CMS [16] and ATLAS [17] experiments and RHIC at BNL with its STAR [18] and PHENIX [19] experiments are presently investigating the properties of QGP by increasing the temperature of the system beyond the critical temperature predicted by the lattice QCD ($T_c \sim 154$ MeV) at nearly zero baryon density.

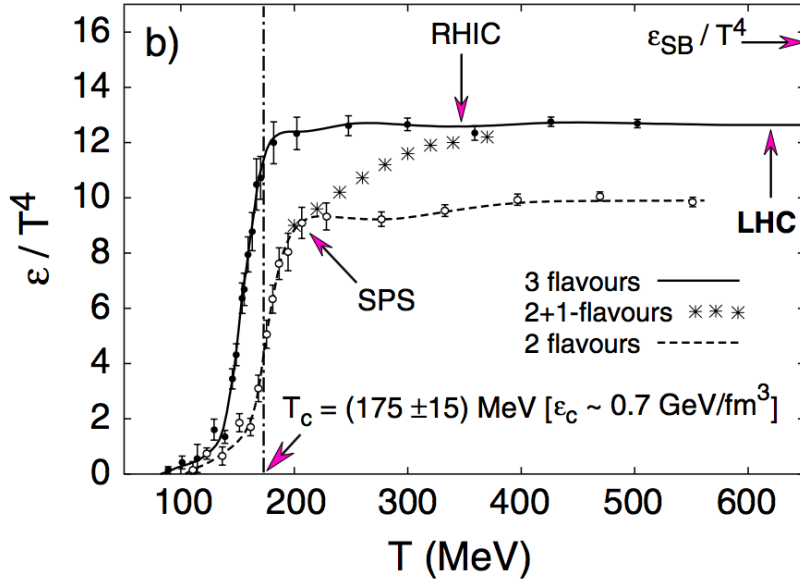


Figure 1.4: Energy density (ϵ) as a function of temperature (T) obtained from Lattice QCD calculation (Figure source [14]).

1.2.1 Lattice QCD

The possibility of the existence of different phases of QCD matter is a fascinating aspect of QCD thermodynamics. The best way to study the phase transition of QCD matter to the QGP state is by QCD calculations within the framework of the lattice-regularized QCD. In the thermal medium, the phase transition is related to large-distance phenomena like collective behaviour, spontaneous breaking of global symmetries and appearance of long-range order. In order to study this kind of mechanisms in QCD, there is the need of a theoretical approach, which is able to deal with non-perturbative aspects of the theory of strong interactions and this is precisely the main purpose of lattice QCD [20].

Lattice QCD is a first principle approach where a discrete space-time lattice is introduced in the QCD formulation and is particularly well suited for numerical calculations. Lattice calculations predicted that the phase transition at high-temperature is continuous and non-singular for a large range of quark masses. In lattice QCD formulation, a definite transition point can be identified by locating the peaks in the susceptibility of the Polyakov loop or the chiral condensate.

In lattice QCD calculations, the transition order and value of the critical temperature depend on the number of flavours and masses of quarks [21–23]. For infinite quark masses (pure $SU(3)$ gauge theory) the critical temperature for a first order phase transition is $T_c^{\text{pure gauge}} = (271 \pm 2) \text{ MeV}$ [21]. A significant decrease in the transition temperature has been observed with the inclusion of light quark masses. In the chiral limit of 2-flavour QCD, the critical temperature

is $T_c = 173 \pm 8$ MeV and about 20 MeV smaller value for 3-flavour QCD [21, 22]. The QCD study with two light flavours and a heavier (strange) quark flavour shows that the transition temperature in the case of physical quark mass is close to the 2-flavour value. The influence on transition temperature due to small chemical potential is estimated and also for the typical value characterising the freeze-out at RHIC ($\mu_B \simeq 50$ MeV) and it has been found that the effect is small [20, 24, 25].

The equation of state by lattice QCD calculation showing the variation of the temperature (T) with an energy density (ϵ) is shown in Figure 1.4. In each flavour study, the variation of temperature (T) with an energy density (ϵ) is always below the Stefan-Boltzmann limit (right-hand arrows). The phase transition of the second order in the chiral limit of 2-flavour QCD and first order in 3-flavour QCD has been estimated and it is found to be only a rapid crossover in the case of physical quark masses. The cross-over takes place at T_c in a narrow temperature range which makes the transition still well localised. It reflects a rapid rise of the energy density (degree of freedom) at critical temperature and possible phase transition of hadronic state to the QGP state.

The partition function (Z) or free energy density is the most fundamental quantity in equilibrium thermodynamics

$$f = -\frac{T}{V} \ln Z(T, V), \quad (1.6)$$

Here T and V are the temperature and volume of the system. All basic thermodynamical observable can be derived by the partition function. In a certain thermodynamic limit, one can directly obtain the pressure, $p = -f$ and subsequently other quantities such as energy (ϵ), entropy densities (s) and velocity of sound (c_s) can also be derived

$$\frac{\epsilon - 3p}{T^4} = \frac{d}{dT} \left(\frac{p}{T^4} \right), \quad (1.7)$$

$$\frac{s}{T^3} = \frac{\epsilon + p}{T^4} \quad (1.8)$$

$$c_s^2 = \frac{dp}{d\epsilon} \quad (1.9)$$

In the infinite temperature limit, according to asymptotic freedom these above observables approach the ideal-gas limit for a gas consist of free quarks and gluons, where the Stefan-Boltzmann constant is a valid quantity to describe the ideal gas behaviour. At high temperature, the following relation is expected

$$\frac{\epsilon_{SB}}{T^4} = \frac{3p_{SB}}{T^4} = \left(16 + \frac{21}{2} n_f \right) \frac{\pi^2}{30}. \quad (1.10)$$

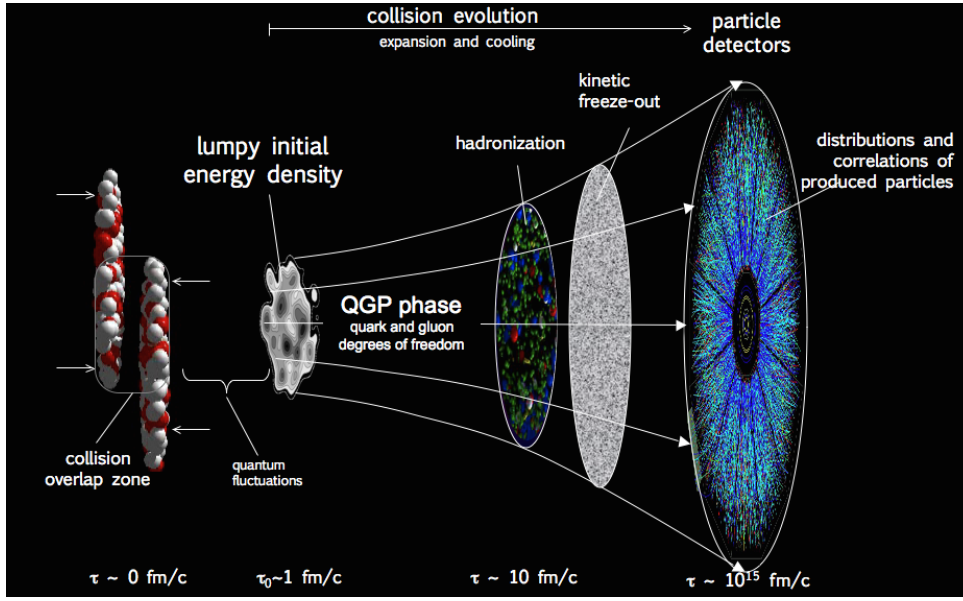


Figure 1.5: The illustration of heavy-ion collision of two Lorentz contracted nuclei (Figure source [26]).

1.2.2 Space time evolution of QCD matter in relativistic high-energy collision

The only practical way to achieve the critical condition in which the ordinary nuclear matter can undergo a phase transition to the deconfined matter of quark and gluons, called as Quark Gluon Plasma (QGP) at high temperature and energy density, is to collide heavy nuclei at ultra-relativistic high energy, which makes it a unique way to study nuclear matter under extreme conditions [27]. Relativistic heavy-ion collisions provides a rich arena of an environment well suited to investigate the primordial matter as well as the interplay of strongly and weakly coupled physics by exploiting the QGP medium properties. A pictorial representation of a heavy-ion collision and its evolution is shown in Figure 1.5. The colliding nuclei travel (in beam direction - z) at 99.995% of the speed of light, such high speed causing the appearance of the nuclei to be Lorentz contracted and represented like a thin disks. When the two nuclei collide with each other, a nuclear overlap region is formed depending upon the impact parameter. The impact parameter, b , is defined as the distance between the centre of two nuclei in the transverse direction to the beam line. The nucleons that lie in the nuclear overlap region in the collision are called "participants" (also called wounded nucleons) and those which lie outside are called as "spectators".

A description that helps in understanding about what should happen in the heavy-ion collision was proposed by J.D. Bjorken in 1983 [28]. He proposed the space-time evolution description of hadronic matter in the ultra-relativistic nucleus-nucleus collision. Figure 1.6 is a schematic

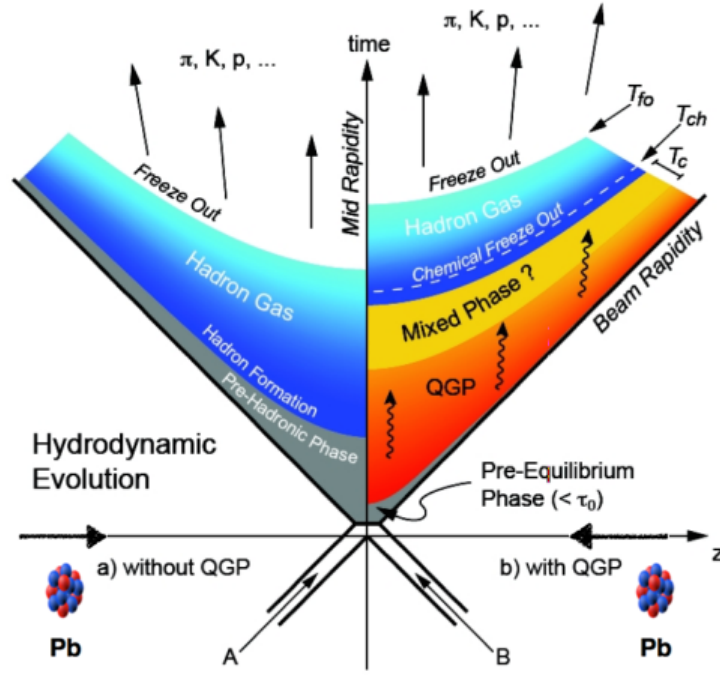


Figure 1.6: Time-space evolution of heavy-ion collision in Bjorken scenario. [28]

representation of the evolution of the system. Two Pb nuclei travel at the speed of light and are made to collide at $z = 0$ at time $t = 0$. Both the nuclei lose their energy in a small nuclear overlap region and this energy is deposited around $z = 0$ in the central rapidity region. The amount of energy density which is deposited in the nuclear overlap region, for a short duration of time, at LHC and RHIC is large enough (should be $> 1 \text{ GeV}/fm^3$ by Lattice QCD calculation) for the transition of nuclear matter to QGP matter to occur. This transition is followed by the following three phases

QGP phase: ($\tau < 10 \text{ fm}/c$) In the initial step, in a time span of a fraction of $1 \text{ fm}/c$ quarks and gluons are produced by the excitation and the system attains an equilibrium state. In a little span of time, $p_T > 1 \text{ GeV}$ -partons are created and at time τ_0 (Figure 1.6) the equilibrated system composed of deconfined quarks and gluons is created, known as quark-gluon plasma state. As the time passes, the system expands and cools down till the temperature of the QGP reaches to the critical temperature T_c . At this temperature, the coupling constant α_s is large enough to confine the partons into hadrons and all the interacting plasma is converted (hadronisation) into hadrons.

Hadron gas: ($10 < \tau < 15 \text{ fm}/c$) The abundance of hadron production is not fixed until hadrons can interact inelastically with each other. As the system expands and cools down, eventually hadrons stop interacting inelastically. When this happens, particle yields are fixed and the system is said to have reached the chemical freeze-out stage, with temperature T_{ch} . The ratio of different particle species can provide information about this stage of evolution of the

system. Despite inelastic collisions have ceased, hadrons can still interact elastically beyond the temperature of the chemical freeze-out and their kinetic properties can be therefore modified. Elastic interactions stop when the distance between hadrons becomes larger than the range of the interaction and at this point the kinetic freeze-out stage is reached with a temperature T_{fo} . As the kinetic distribution of the hadrons is fixed at this stage, the kinetic freeze-out temperature can be extracted from the hadron momentum spectra.

Free hadron system: ($\tau > 15 \text{ fm}/c$) At this stage the hadrons can freely stream out from the collision region to the detectors for their identification.

1.3 Probing the quark-gluon matter

The theory of strong interactions, Quantum Chromo-Dynamics (QCD) predicts a phase transition at sufficient high energy density from normal hadronic matter to a deconfined state of quarks and gluons, the Quark-Gluon Plasma (QGP). Such phase transitions can be achieved in ultra-relativistic heavy-ion collisions [29]. The experimental investigation of the QGP matter needs the identification of appropriate experimental tools to observe its formation and measure its properties.

The observation of the properties of the QGP is the most challenging task for an experimentalist as the size and lifetime of the plasma state are expected to be very small. This study becomes more critical as signals from the QGP phase compete with similar ones emerging from the hot hadronic gas background that follows the hadronization of the plasma and can be modified in the hadronic phase due to final state interactions [30]. In spite of these limitations, a wealth of ideas have been proposed for the investigation and identification of the quark-gluon plasma. In this series, the proposed signatures to probe QGP matter include bulk probes (i.e. enhanced strangeness, strong collective flow) [31] and rare probes. Bulk probes include various experimental observations like the strangeness enhancement, strong collective flow, particle production, transverse momentum spectra, J/ψ suppression and particle correlations. The rare probes mostly correspond to studies of jet modification, heavy flavour production, direct photons and dilepton production. The main aim of this section is to provide an overview of some observables that have been measured in ALICE to probe the matter created by the LHC Pb–Pb collisions.

1.3.1 Kinematic probes and chemical composition

The particle multiplicities, particle yields, transverse momentum spectra and correlations of hadrons emerging from heavy-ion collisions, preferably in the soft sector comprising particles

at transverse momentum $p_T \leq 1.5 \text{ GeV}/c$, carry the properties of the bulk of the matter produced in the collisions.

By theoretical aspects, the global property of the medium produced in the collision is related to the average charged particle multiplicity per rapidity unit ($dN_{\text{ch}}/d\eta$) [32]. This quantity plays an important role in the calculation of many observables which are closely related to the energy density of the collision system. Similarly, the total transverse energy per rapidity unit (dE_t/dy) is another important "day-one" observable. In spite of the experimental and theoretical importance of both the observables, there are no calculations which are able to extract these quantities from Quantum Chromo-Dynamics (QCD) Lagrangian being these observables dominated by soft non-perturbative QCD.

The measured spectra of hadrons are able to reflect the properties of the bulk of the QGP matter just after the elastic collisions among the hadrons cease which happens at the kinetic freeze-out stage. At this stage, the system is relatively dilute and cold as compared to the initial highly dense and hot state. However, some information on the earlier denser and hotter stage can be obtained by the detailed properties of the measured hadronic spectrum. Some of the direct information about the earlier denser and hotter stage can be extracted by the integrated yield of the different hadronic species, which can only be changed via inelastic collisions in the hadronic phase. However, these inelastic collision ceases already at the so-called chemical freeze-out before kinetic freeze-out.

The integrated yields, which reflect the abundances of particle and thus the chemical composition of the fireball, are frozen soon after hadronization and are not affected by the hadronic re-scattering. To some extent, the temperature of the chemical equilibrium can provide constraints on the microscopical reaction processes and their time scales. For example, in case the chemical freeze-out temperature coincides with the phase transition temperature (predicted by lattice QCD calculations), one could conclude that the observed chemical equilibrium cannot originate via hadronic interactions, due to the short time scale. On the other hand, the equilibrium must have been established by the hadronisation process itself: the hadrons are born in equilibrium.

1.3.2 Electromagnetic probes

The identification of the thermal radiation emitted by the system and especially by the QGP medium via $q\bar{q}$ annihilation is one of the famous and important point of interest in the field of relativistic heavy-ion collisions. Such kind of thermal radiation is regarded as a very strong signal of deconfinement, thus the direct evidence of the formation of QGP matter. The plasma temperature can be directly measured via the spectral shape of thermal radiation. The signal from

thermal radiation is expected to be small when compared to the larger background originating from other sources. In principle, thermal radiation can be directly studied via measurements of real dileptons and photon production but this measurement is extremely challenging in practice.

Several mechanisms are present for photon production at various stages of relativistic heavy-ion collisions. In the early stages of the collision, "prompt" photons are produced by parton-parton scattering in the primary A-A collisions. The QGP is expected to be formed in the following stage of the collisions. In the QGP phase, quarks radiate photons following collisions with the nearby quarks and gluons present in the thermal bath. Photons are also produced in the hot and highly dense hadronic phase. Also, photons are produced after the freeze-out by the decay of π^0 and η mesons, which constitute a largely reducible background. On the other hand, "prompt photons" constitute an irreducible background.

In relativistic heavy-ion collisions, dileptons are also an important probe to measure the temperature and the dynamical properties of the QGP matter [33, 34]. Dileptons (lepton-pair) are produced in a similar way as photons. Dilepton production receives contributions from hard nucleon-nucleon collisions, thermal radiation from the plasma and the highly dense and hot hadronic phase together with final-state interactions [35] and the meson decays after the freeze-out (Dalitz decays: $\pi^0 \rightarrow e^+ e^- \gamma$). The range of dilepton mass above the lepton pair mass ~ 2 GeV is mainly contributed by semi-leptonic decays of heavy-flavour mesons and by the process called Drell-Yan, which can be calculated by the perturbative QCD. Like the case of the photon, the challenge of the measurement of dilepton is to discriminate the thermal radiation out of the large prompt background.

1.3.3 Strangeness enhancement

In heavy-ion collisions, enhancement in the strangeness content was proposed by Rafelski and Müller, known as "strangeness enhancement", as one of the signals of the QGP formation [36–38]. The enhancement in the production of strange particles is an important observable due to

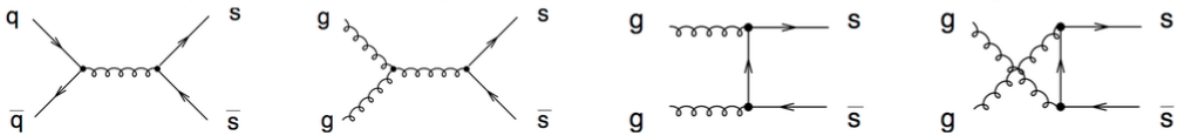


Figure 1.7: Feynman diagrams of the $s\bar{s}$ pair production in the QGP. The first (leftmost) diagram represents the $q\bar{q}$ annihilation and the rest of the three diagrams corresponds to the gluon fusion processes.

the fact that the colliding nuclei do not have strange (s) quarks as valence quarks in the initial stage and there is no net strangeness. This means that the strange quarks must be thermally produced in the hot QCD matter produced in such collisions, which appears as an enhancement in the strangeness into the final stage.

It has been originally proposed that the strangeness production would increase due to the formation of QGP compared to that from a hadronic phase [39, 40]. The main process contributing to the strangeness enhancement is the high production rate of $gg \rightarrow s\bar{s}$ (known as flavour creation) because of the high gluon density. These processes are not present in the hadronic phase and the cross-sections are very low for pp interactions. Figure 1.7 depicts the Feynman diagrams of the processes responsible for producing $s\bar{s}$ pairs inside the QGP medium. The subsequent hadronization of these (anti)strange quark pair is the responsible factor for a significant increase in the strange hadron production.

The observable associated to strangeness enhancement in A–A collisions with respect to pp collisions for a particular hadron species h , is defined as

$$E(h) = \frac{dN/dy(h)^{AA}}{N_{evt}^{AA}\langle N_{part} \rangle^{AA}} \frac{N_{evt}^{pp}\langle N_{part} \rangle^{pp}}{dN/dy(h)^{pp}} \quad (1.11)$$

where dN/dy represents the particle yield per rapidity unit and N_{evt}^{AA} and N_{evt}^{pp} (to account for the increasing reaction volume) is the number of events for A–A and pp collision system.

In the deconfined state, the abundance of a particular particle species quickly reaches their equilibrium values which result in higher abundance of strangeness per participant in Pb–Pb collisions as compared to pp interactions. RHIC has observed the enhancement in the strangeness [41–43] by comparing the production of strange particles in central heavy-ion collision with respect to pp reactions. The observation was originally reported from the SPS in [44–49]. The observed enhancement in the strangeness in RHIC and SPS increases with the strangeness contents of the baryon and increases with collision centrality for all the strange baryons.

Multi-strange hadron production as a function of the mean number of participants i.e. $\langle N_{part} \rangle$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV has been measured in the ALICE experiment and shown in Figure 1.8. The ALICE results are also compared with the results of STAR experiment at RHIC for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV and with NA57 experiment at the SPS for Pb–Pb collision at $\sqrt{s_{NN}} = 17.2$ GeV. It is observed that enhancement increases more for the particles having more strange quark contents. A similar observation has been seen previously in RHIC and SPS energies. This observation is also consistent with the phenomenon of large number of $s\bar{s}$ pairs present inside the hot and dense partonic medium. From Figure 1.8, one can see that for the most central classes, the strangeness enhancement quickly increases with $\langle N_{part} \rangle$ and it seems to indicate the saturation for the most-central collisions.

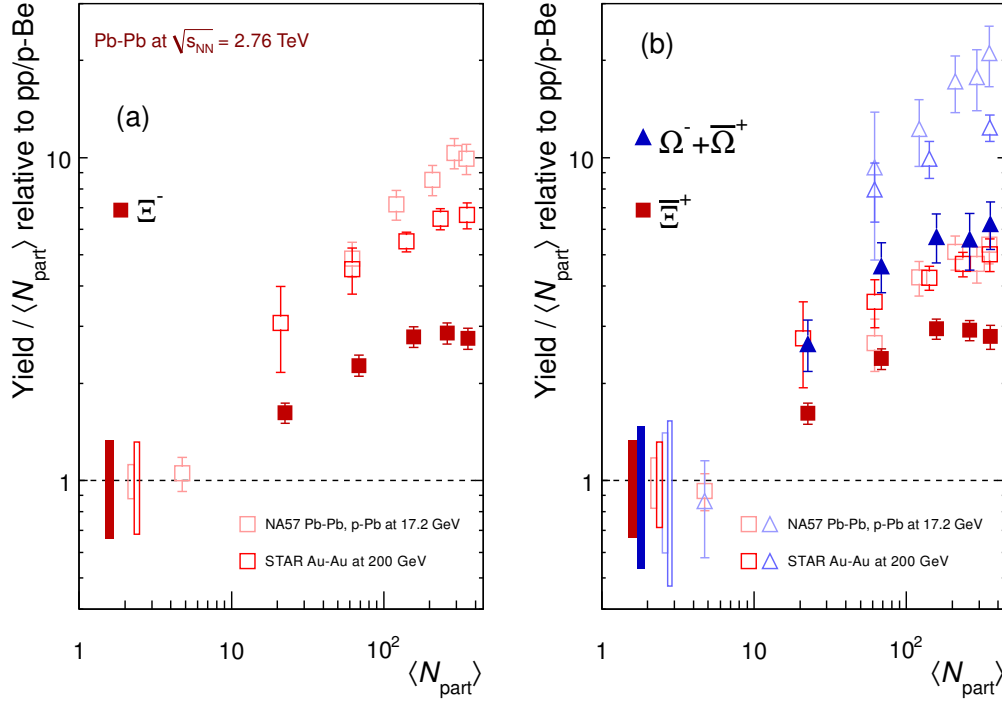


Figure 1.8: The observed enhancement in strange hadron production as a function of mean number of participant $\langle N_{\text{part}} \rangle$ in the ALICE at the LHC (solid symbols). The comparison with the RHIC and SPS results is also shown (open circle). The solid lines and dashed lines are the thermal model predictions from [50] and [51], respectively.

With increasing collision energies, a reduction in strangeness enhancement is observed. This can be understood within a thermodynamical description of the system by statistical models taking into account strangeness conservation in the canonical ensemble. In small systems like pp collisions have small charged-particle multiplicity and the quantum number conservation laws (such as strangeness) have to be applied locally on the event by event basis. On the other hand, in larger systems, like Pb-Pb collisions, conservation laws can be applied on an average basis and the grand-canonical formalism can be used for the thermodynamical description. The quantum number conservation laws reduce the phase space available for particle production and tends to decrease the canonical suppression factor with increasing the centre-of-mass energy of the collision. This phenomenon is able to explain the observation of larger strangeness enhancement at lower energies [52].

1.3.4 Nuclear modification factor

To learn about the particle production mechanism in dense nuclear matter, one efficient way is to compare the particle spectra measured in Pb-Pb collisions to such collisions where one would

not expect QGP, like pp collisions. This can shed some light on the role of the hot and dense partonic medium on the particle production. In the presence of the extended QGP medium, one would expect some energy loss of partons via gluon radiation while traversing through the medium, in particular for the high- p_T partons. This comparison is usually performed by measuring the "nuclear modification factor" known as R_{AA} , defined as

$$R_{AA} = \frac{1}{T_{AA}} \frac{d^2 N^{AA}/dydp_T}{d^2 \sigma^{pp}/dydp_T} \quad (1.12)$$

or

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{(1/N_{evt}^{AA}) d^2 N^{AA}/dydp_T}{(1/N_{evt}^{pp}) d^2 N^{pp}/dydp_T} \quad (1.13)$$

where $d^2 N^{AA}/dydp_T$ and $d^2 \sigma^{NN}/dydp_T$ are the yields measured in A–A and pp collisions, respectively. The T_{AA} is used as a normalisation factor, known as nuclear overlap function and proportional to $\langle N_{coll} \rangle$, which connects it to inelastic A–A collisions. It is estimated for the corresponding centrality class of the A–A collisions via Glauber model [53] by convolution of the nuclear density profiles in A–A collisions.

The production of high- p_T particles is mostly expected to be dominated by the hard processes, this means that high- p_T particle production in A–A collision should scale with the number of binary collisions (N_{coll}), known as binary scaling. In case of the absence of an absorbing QGP medium or for probes not sensitive to it (e.g. photons) the value of R_{AA} should be unity and for high p_T hadrons ($p_T > 2\text{--}3$ GeV/c) the value of R_{AA} should also be unity. One can consider heavy-ion collisions as an incoherent superposition of nucleon-nucleon (pp) interactions. Alternatively, R_{AA} value less than or greater than unity reflects the presence of interactions of high- p_T coloured partons in the QGP medium.

The measurements performed by ALICE and RHIC reveal that the hadron production is affected by the medium created in the heavy-ion collisions. The R_{AA} of unidentified charged hadrons at central rapidity region for central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV has been measured at RHIC. The results show a remarkable suppression of a factor of 3 at high $p_T \geq 4$ GeV/c for central collisions as compared to pp and a factor of 4 as compared to more peripheral collisions [54]. The measurement of R_{AA} of unidentified charged hadrons at central rapidity region for central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is also significantly different from unity. The value of R_{AA} for central collisions is significantly suppressed by a factor of 5 as compared to the peripheral collision for $p_T \leq 7$ GeV/c. A significant rise in the value of R_{AA} by about a factor of 2 is observed in $7 < p_T \leq 20$ GeV/c compared to the value at $p_T \approx 7$ [55]. The comparison of measurement of R_{AA} of unidentified charged hadrons by ALICE experiment at the LHC for the top central Pb–Pb collision to the value measured by PHENIX and STAR experiment at RHIC is shown in Figure 1.9 (upper panel) as a function of p_T , $\langle N_{part} \rangle$ (lower panel left plot) and $dN_{ch}/d\eta$

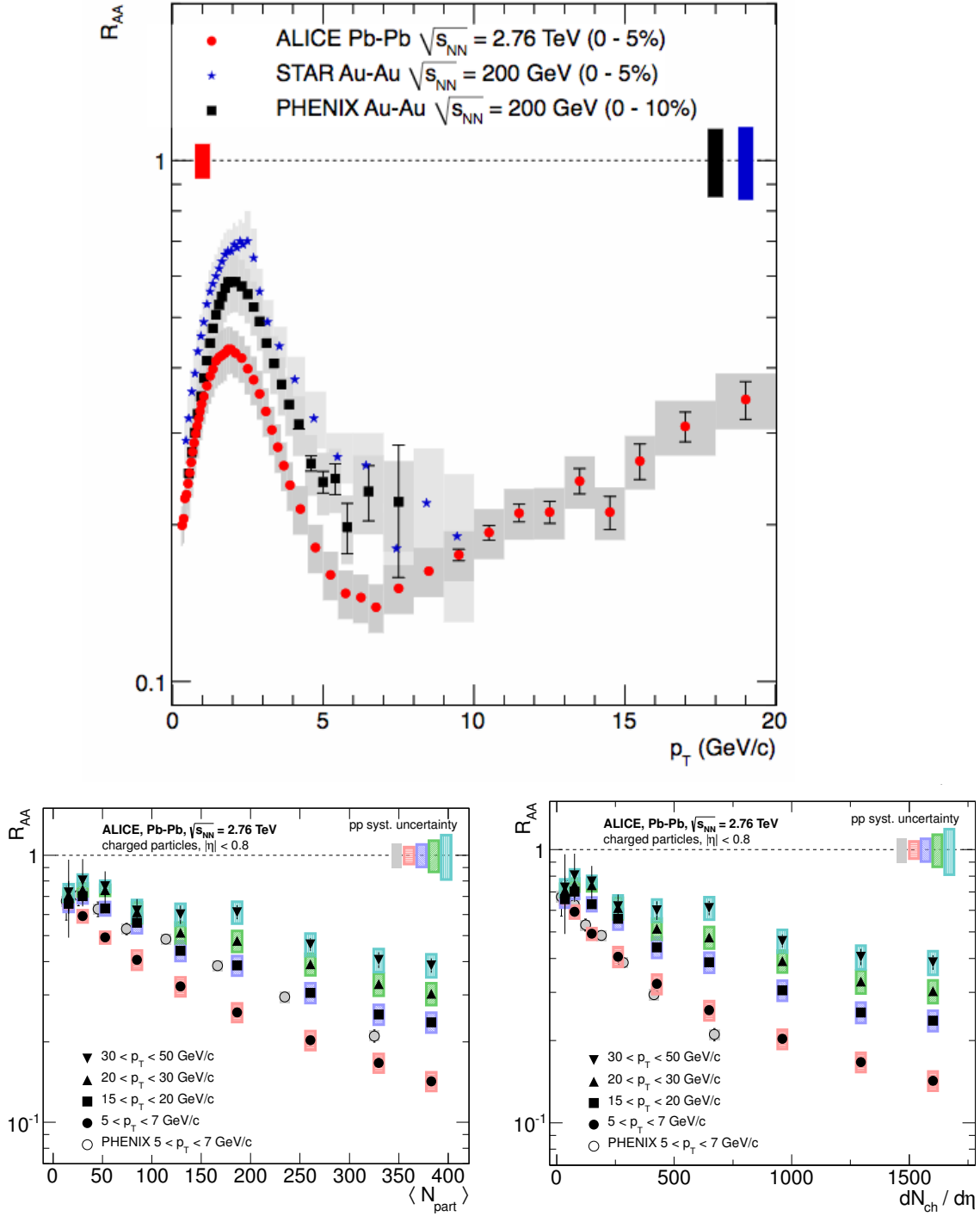


Figure 1.9: Nuclear modification factor, R_{AA} of unidentified charged particles measured as a function of p_T (top figure), $\langle N_{part} \rangle$ (lower panel left plot) and $dN_{ch}/d\eta$ (lower panel right plot) measured by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, in different p_T -intervals and compared to PHENIX results in $5 < p_T < 7$ GeV/c.

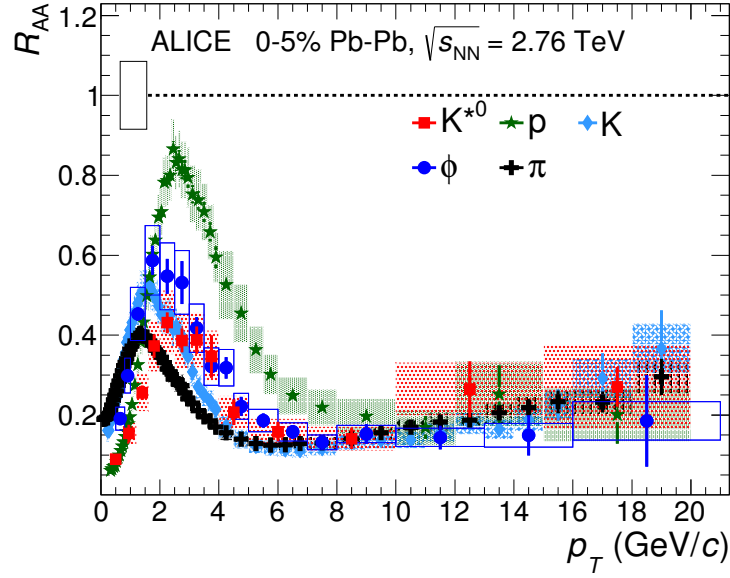


Figure 1.10: The measured R_{AA} of $K^*(892)^0$, ϕ -mesons, π , K and p particle species as a function of p_T for 0–5% centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the ALICE.

(lower panel right plot). A lower value of R_{AA} at ALICE at $p_T = 6-7$ GeV/ c compared to RHIC is observed, which hints of high p_T charged particles suppression due to the larger energy loss of particle in QGP medium and therefore a denser medium.

For further understanding of the particle production mechanism, the R_{AA} of different particles species has been studied in ALICE. The R_{AA} of hadrons like $\pi^+ + \pi^-$, $K^+ + K^-$, $p + \bar{p}$, ϕ -meson and $K^*(892)^0$ as a function of p_T in most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown in Figure 1.10. The first observation from this measurement is that the different behaviour of the shape of R_{AA} for mesons and protons at low and intermediate p_T (< 6 GeV/ c), which can be interpreted as an evidence of baryon to meson anomaly. Secondly, in the high p_T region (> 6 GeV/ c), no difference in the amount of suppression for the different species has been practically observed. Such common behaviour of suppression for mesons and protons suggest that there must be a small effect of flavour dependence on the in-medium parton energy loss for the light flavours.

1.3.5 Collective phenomena

The dynamics of heavy-ion collisions can be studied by measuring the azimuthal distribution of particles with respect to the reaction plane. When two nuclei collide with non-zero finite impact parameter (non-central collisions), the initial shape of the nuclear overlap region is asymmetric and the initial matter distribution is anisotropic (almond shaped) [56]. If the matter is interacting, this spatial asymmetry may be converted via multiple collisions into an anisotropic momentum

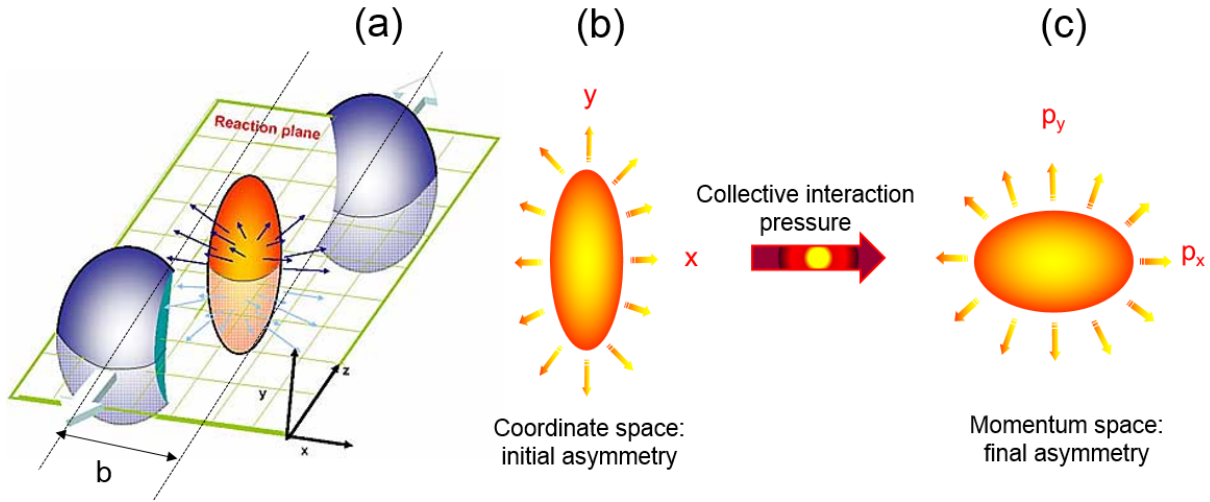


Figure 1.11: Initial collision geometry of colliding nuclei in non-central heavy-ion collisions and responsible for the origin of collective flow (Figure source: [57]).

distribution, which leads to the azimuthal anisotropies in the emission of particles.

The transverse plane of the overlap region is the x - y plane, in which the minor axis (x -axis) is parallel to the vector direction connecting the centre of two colliding nuclei and the major axis (y -axis) is perpendicular to minor axis as illustrated in the Figure 1.11-(a). By convention, the z -axis is the direction of the colliding beam and the x - z plane is known as the reaction plane.

The matter expands faster in the direction where the fireball size is smaller, due to the larger pressure gradients. The elliptic flow is sensitive to the equation of state of the QGP phase as these anisotropies are generated before the critical temperature and the plasma hadronisation. The presence of large anisotropies represent a signal of strong collective behaviour and indicate early local thermal equilibrium inside the fireball. As the partons suffer multiple re-scattering inside the dense and highly interacting matter and because of the spatial anisotropy due to initial collision geometry (almond shape), the partons suffer larger pressure gradients in the minor axis as compared to the major axis as depicted in Figure 1.11-(b). Therefore the initial isotropic local transverse momenta become anisotropic as illustrated in Figure 1.11-(c).

Studies of collective flow can provide insight into the equation of state of QGP matter, therefore it is a powerful tool to study the mechanism and dynamics of the QCD matter produced in heavy-ion collisions. The azimuthal dependence of the particle yield in heavy-ion collision can be decomposed in terms of a Fourier series [58]

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos [n (\phi - \Psi_R)] \right) \quad (1.14)$$

where E , p , p_T , ϕ and y are the energy, momentum, transverse momentum, azimuthal angle and rapidity of the particle and Ψ_R is the reaction plane angle. The Fourier coefficients - " v_n ",

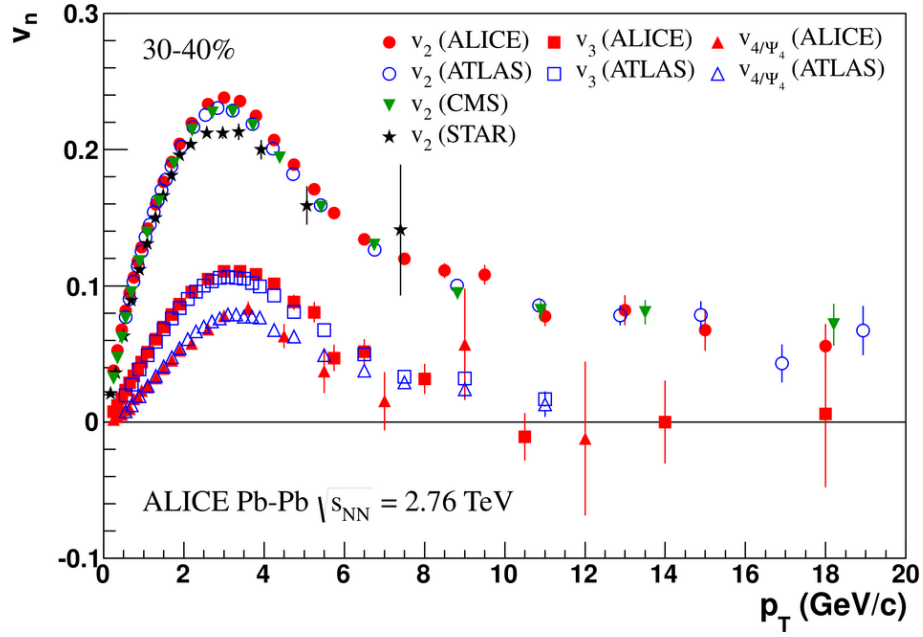


Figure 1.12: Comparison of the ALICE results for 30–40% centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV on $v_n(p_T)$ obtained with the event plane method to the analogous measurements from ATLAS and CMS collaborations, as well as v_2 measurements by STAR.

also known as differential flow, can depend both on p_T and y and measure the strength of the azimuthal anisotropy. They can be expressed as

$$v_n = \langle \cos [n (\phi - \Psi_R)] \rangle \quad (1.15)$$

where the braces denotes an average over all the particles for a particular p_T bin over all the events in a specific centrality bin. The $\phi - \Psi_R = \Delta\phi$ is the difference between the azimuthal angle ϕ of each particle and the reaction plane angle Ψ_R of the event. For $n = 1, 2$ and 3 , the coefficient v_1 , v_2 and v_3 are called as: directed, elliptic and triangular flow, respectively. The magnitude of the anisotropic flow is strongly dependent on the smoothness/friction of the QCD matter and is strongly related to the viscosity over entropy density ratio η/s .

The magnitude of the elliptic flow v_2 for unidentified charged particles has been the measurement by RHIC and was observed to be in agreement with theoretical hydrodynamical model predictions for a "perfect fluid" [59]. Similar measurements have been performed by the ALICE experiment at the LHC in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of centrality and are shown in Figure 1.12. The measured v_2 reaches its maximum value in 30–50% centrality class, as can be seen from Figure 1.14. The v_2 value for charged particles in ALICE is about 30% larger compared to the RHIC value, suggesting that the QGP medium created at the LHC also behaves as a perfect fluid [60,61]. It was previously suggested by thermodynamical models that the p_T -integrated elliptic flow would increase at the LHC due to increase in $\langle p_T \rangle$ from larger

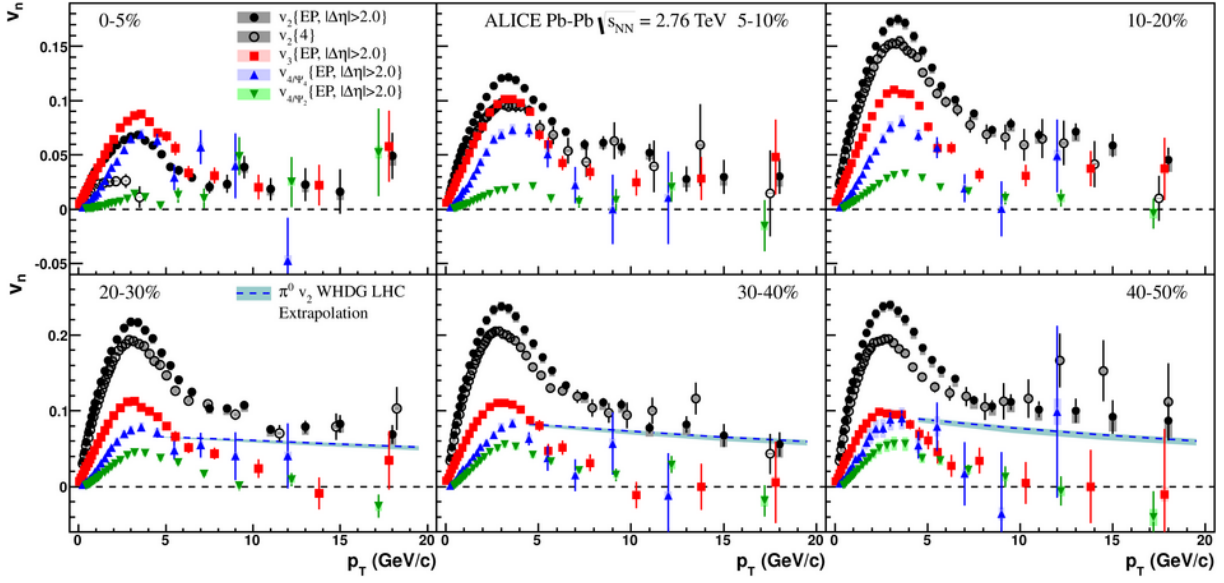
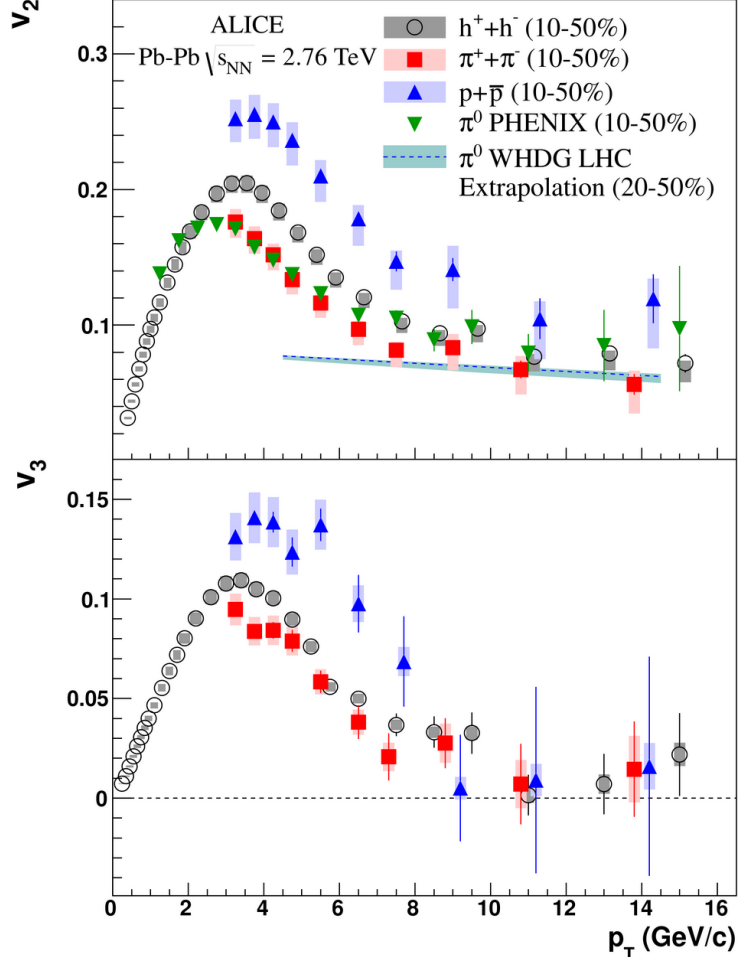


Figure 1.13: The v_2 , v_3 and v_4 measured for unidentified charged particles as a function of p_T for various centrality classes in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the ALICE. The dashed line represents the WHDG model calculations for neutral pions v_2 extrapolated to the LHC collision energy

Figure 1.14: v_2 (top) and v_3 (bottom) of charged π and p as a function of transverse momentum for 10–50% centrality class compared to the unidentified charged particles results from event plane method and PHENIX π^0 v_2 measurements. The dashed line is WHDG model calculations for neutral π extrapolated to the LHC collision energy for the 20–50% centrality class.



radial flow [62].

The ALICE experiment has also measured the triangular flow (v_3) and quadrangular (v_4) with respect to second (Ψ_2) and fourth (Ψ_4) order event plane to provide further physics constraints on the origin of collective flow driven by initial-state fluctuations. The measurements for unidentified charged particles for p_T up to 20 GeV in different centrality classes are shown in Figure 1.13. The elliptic flow and triangular flow of identified charged particles species have also been measured and both shows a mass ordering for $p_T > 3$ GeV/ c as shown in the Figure 1.14 [62]. It is suggested that the mass ordering of flow harmonics could be due to an interplay between the elliptic and radial flow [63].

1.4 Thesis motivation

Measurement of resonance production to probe the evolution of heavy-ion collisions

A resonance states that are of interest to probe the evolution of the matter created in heavy-ion collisions are those with very short characteristic life time and whose decay is therefore governed by the strong interaction. Resonance states of particular interest are those particles whose quark content is identical to a partner long-lived particle, although they might have different set of quantum numbers (charge, spin, isospin and parity etc.). It has to be noted that, given the much shorter lifetime of the resonance state with respect to its stable counterpart, resonances appear as broad states. The width of a resonance state is linked to the uncertainty principle ($E\tau \simeq \hbar c$), namely the shorter the resonance lifetime, the broader is the width of the state. As a consequence, resonances have extremely short decay length, which, depending on the actual lifetime, are on the few fm/ c scale. A brief summary of some of the hadronic resonance states of interest to study the heavy-ion collision phenomenology, along with their lifetime (τ), decay width (Γ), quark contents, decay mode and branching ratio (BR) is presented in Table 1.1.

1.4.1 Medium effects on resonances

In high energy heavy-ion collisions, a very hot and dense state of partonic matter known as QGP is expected to be formed and to persist for a short duration of time (few fm/ c). During the evolution of the QGP fireball across the different stages (see Section 1.2.2), hadronic resonance states are eventually produced at the hadronisation stage and their abundances are in chemical equilibrium with all the other hadrons at the chemical freeze-out stage. As discussed in Section 1.2.2, the chemical freeze-out stage is followed by the dense phase where hadrons continue to interact elastically among each other for a few fm/ c until the kinetic freeze-out stage is reached. After

Table 1.1: Resonance particles with their lifetime, decay width, quark contents, decay mode exploit for the measurements. The branching ratio (BR) [64] is written for the charge particle decay mode to be able to reconstruct in the analysis.

resonances	τ (fm/c)	Γ (MeV)	valance quark contents	decay mode	BR[%]
$\rho(770)^\circ$	1.3	149.1 ± 0.8	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$\pi^+ + \pi^-$	100
$K^*(892)^\circ$	4.2	50.8 ± 0.9	$d\bar{s}$	$K^+ + \pi^-$	66.6
$\phi(1020)$	46	4.26 ± 0.04	$s\bar{s}$	$K^+ + K^-$	48.9
$\Sigma(1385)^\pm$	5.5	36.0 ± 0.7	uus	$p + \pi^- + \pi^+$	87.0
$\Lambda(1520)$	12.6	15.6 ± 1.0	uds	$K^- + p$	22.5
$\Xi(1530)^\circ$	21.7	15.6 ± 1.0	uss	$p + 2\pi^- + \pi^+$	66.7

this latter stage particles stream freely towards the experimental detector. Owing very short lifetime of hadronic resonances, some of them might decay inside the dense hadronic medium before the kinetic freeze-out stage is reached. The decay daughters of short-lived resonances which decay before the kinetic freeze-out might therefore interact with the surrounding hadrons forming such a dense hadronic phase [65]. If the medium present in the hadronic phase is dense and opaque enough, the resonance decay daughter will undergo elastic scattering off the nearby hadrons. Such interaction can therefore alter the momentum of the resonance decay daughters and even more importantly will alter the mother-daughters correlation that is at the basis of the resonance reconstruction technique via invariant mass analysis, preventing the experimental reconstruction of the resonance signal.

In summary, the re-scattering of resonance decay daughters in the hadronic phase results in the loss of a fraction of the reconstructable resonance yield. It has to be noted on the other hand that resonance signal can be produced in the hadronic phase even after the chemical freeze-out stage via pseudo-elastic interactions among the hadrons. This resonance re-generation effect inside the hadronic medium might compensate over the re-scattering loss and the detailed balance is governed by the lifetime and opacity of the hadronic phase and the microscopic hadronic cross-sections of the hadrons involved. The re-scattering and re-generation effect on the baryonic resonance $\Lambda(1520)$ is shown in Figure 1.15. The suppression and re-generation of hadronic resonances in the hadronic medium are therefore sensitive to the different properties of the medium. Moreover, different resonance states with different lifetimes can effectively probe differently the medium, making in general the study of resonances an excellent candidate to provide insight into the evolution of the fireball and the characteristics of the lifetime of the

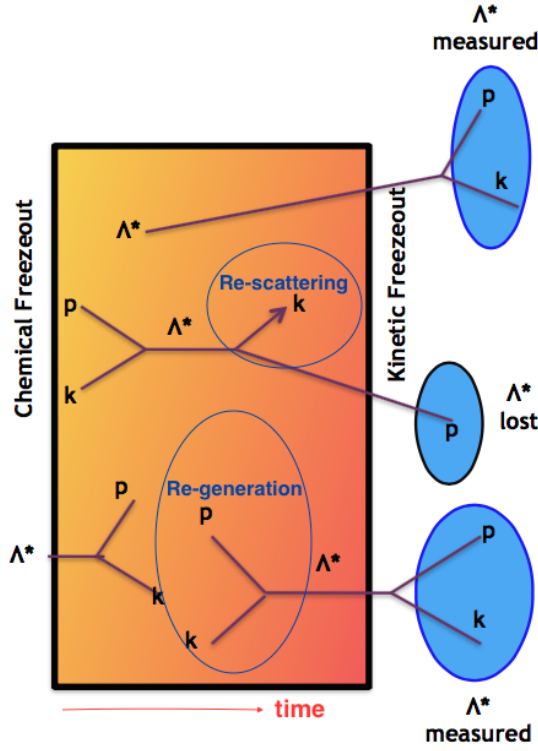


Figure 1.15: The illustration of $\Lambda(1520)$ re-scattering and re-generation effects in dense hadronic medium present between chemical and kinetic freeze-out stage.

hadronic phase, which exists between the chemical and kinetic freeze-out.

1.4.2 $\Lambda(1520)$ baryon as a tool to probe the hadronic medium

In this thesis, the production of the baryonic resonance $\Lambda(1520)$, with $J = 3/2$, is measured in Pb–Pb collisions at 2.76 TeV. The $\Lambda(1520)$ is an excellent candidate due to its short lifetime ($\tau \sim 12.6$ fm/c, which is expected to be comparable to the lifetime of the fireball. Moreover the $\Lambda(1520)$ lifetime is longer than the lifetime of $K^*(892)^0$ resonance $\tau \sim 4.16$ fm/c, which is observed to be suppressed (Figure 1.16), but shorter than the lifetime of the ϕ -meson $\tau \sim 46.3$ fm/c, which is not observed to be suppressed (Figure 1.16) [11]. The observation of $K^*(892)^0$ suppression is interpreted as due to re-scattering effects in the hadronic phase, owing to its short lifetime, whereas the non-suppression of the ϕ -meson might be due to the fact that the lifetime of the hadronic medium is shorter than the ϕ -meson lifetime. The lifetime of the $\Lambda(1520)$ is roughly in between the $K^*(892)^0$ and ϕ -meson lifetimes and makes the $\Lambda(1520)$ an optimal probe to set an upper limit to the lifetime of the hadronic phase.

The $\Lambda(1520)$ produced at chemical freeze-out stage, might decay inside the fireball and re-generate all the way throughout the kinetic freeze-out. The modification of the $\Lambda(1520)$ characteristic properties might also change because of various in-medium effects. These ef-

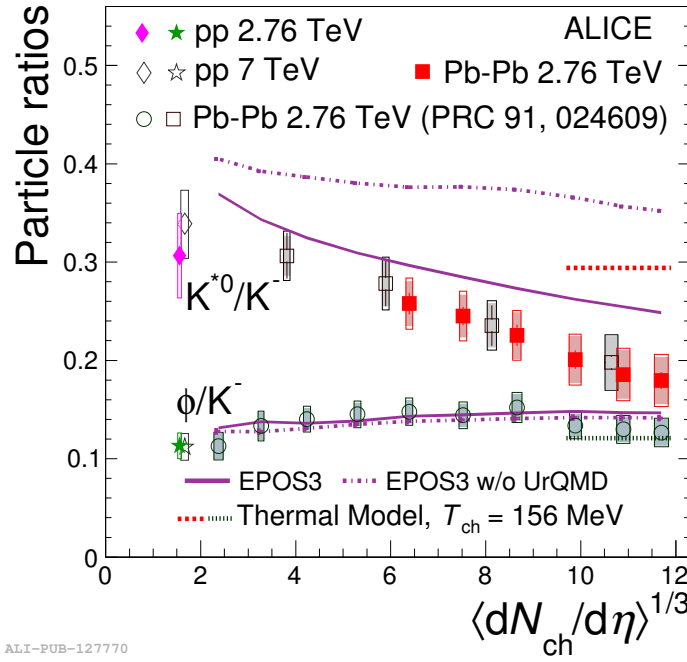


Figure 1.16: The p_T -integrated ratio of $K^*(892)^0/K^-$ and ϕ/K^- as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ measured in mid-rapidity in pp collisions at $\sqrt{s} = 2.76$ TeV and 7 TeV [66], and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in ALICE experiment at LHC.

fects include the high density and high temperature, such as dynamical interactions with the surrounding matter, effects of distortion in phase space due to particle re-scattering and interference between different scattering channels [67]. As a result, the properties of $\Lambda(1520)$ such as mass, width, yield and p_T -spectra can also be modified and can provide valuable insight for the understanding of the dynamical behaviour of the medium created in heavy-ion collisions [68]. The p_T -spectra of $\Lambda(1520)$ which can be affected by the re-scattering and re-generation, reflects a change in $\langle p_T \rangle$ of $\Lambda(1520)$ in different centrality classes.

In heavy-ion collisions, re-scattering and re-generation effects can be best tested by comparing the resonance production yield to the production of its stable counterpart, namely by measuring the particle yield ratio such as $\Lambda(1520)/\Lambda$. This enables one to cancel potential effects related to the quark composition of the resonance state, leaving only the lifetime of the state and its mass as the relevant parameters governing the ratio. According to model predictions [69], it is expected that the re-scattering effect on resonance is dominant at low momenta, whereas high momentum resonances can escape the medium more quickly and hence might not be affected by the re-scattering. The probability to regenerate $\Lambda(1520)$ resonance via proton and kaon interaction in the medium is relatively small as the number of protons available in the hadronic medium is relatively low as compared to the number of kaons. As a consequence, a suppression of the $\Lambda(1520)/\Lambda$ ratio is expected if a dense hadronic medium with sufficiently

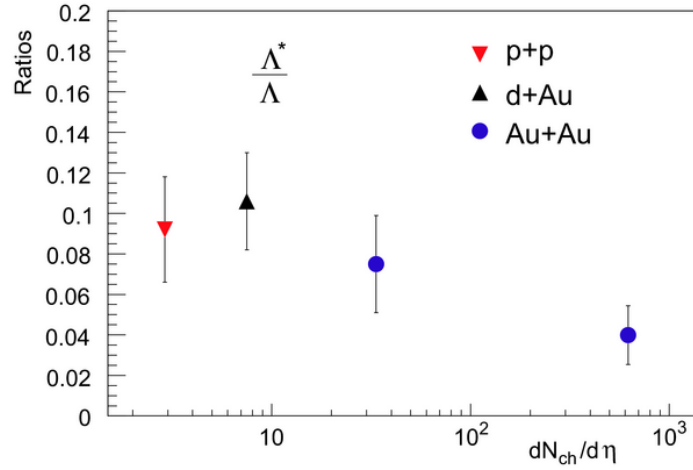


Figure 1.17: The p_T -integrated ratio of $\Lambda(1520)/\Lambda$ as a function of $\langle dN_{ch}/d\eta \rangle$ measured in pp collisions at $\sqrt{s} = 200$ GeV, minimum bias d–Au and two different centralities in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR experiment at RHIC.

long lifetime ($\tau \sim 10$ fm/c) is formed after hadronisation. In the case of only re-scattering effect presence in the hadronic medium, the $\Lambda(1520)/\Lambda$ ratio has to be smaller than the value obtained from pp and this suppression should be larger in central collisions compared to peripheral collisions. Alternatively, if only re-generation effects are present, the ratio should be larger compared to pp and greater in central collisions compared to peripheral ones. Therefore the comparison of the results from heavy-ion data with the elementary pp collisions can be used to estimate the time span between chemical to kinetic freeze-out. The beam energy, system size and centrality dependence of the suppression can be used to investigate the correlation of lifetime with the fireball size.

The STAR experiment at RHIC has measured the $\Lambda(1520)$ production in Au–Au, d–Au and pp collisions at 200 GeV. The measurement of $\Lambda(1520)/\Lambda$ ratio as a function of $\langle dN_{ch}/d\eta \rangle$ by the STAR is shown in Figure 1.17. The observation from STAR experiment suggests the dominance of re-scattering over re-generation effect for $\Lambda(1520)$ and the suppression of $\Lambda(1520)$ yield in central Au–Au collisions [70]. As the LHC has 13 times ($\sqrt{s_{NN}} = 2.76$ TeV) higher centre of mass energy than the RHIC ($\sqrt{s_{NN}} = 200$ GeV), a significantly longer lifetime of the fireball is expected. The lifetime of the hadronic phase formed in central Pb–Pb collisions at the LHC is predicted to be ~ 10 fm/c, therefore the study of $\Lambda(1520)$ resonance with a lifetime of 12.6 fm/c will be very interesting. At such higher energy, this measurement can shed some light on the subject whether the re-scattering effect will dominate or the re-generation will play a dominant role. The double ratio of $\Lambda(1520)/\Lambda$ in central Pb–Pb events with respect to peripheral events can be used to study the effect of a strongly interacting hadronic medium. These studies can be used as a baseline for future analysis in higher energy heavy-ion collisions.

1.5 Organisation of the thesis

In this thesis, the details on the analysis of baryonic resonance $\Lambda(1520)$ production in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ALICE detector at the LHC are reported. As discussed already, the spectral shape of the p_{T} distribution of hadronic resonances is expected to be affected by the hadronic medium as well and will be reflected in a modification of the $\langle p_{\text{T}} \rangle$ of the $\Lambda(1520)$. The thesis is organised as follows, Chapter 2 gives the brief introduction to the LHC and a description of the experimental setup of the ALICE experiment. The various sub-detectors of ALICE are also discussed and categorised in central and forward-backward detectors. Vertex and track reconstruction, as well as the collisions centrality determination methods are also discussed as they are relevant for this analysis. Chapter 3 provides a detailed description of the analysis and methodology utilised for the measurement of $\Lambda(1520)$ production discussed in this thesis. The systematic studies for this analysis are discussed in Chapter 4. The results of the analysis are reported in Chapter 5. Finally, the results are summarised and conclusions are reported in Chapter 6.

Chapter 2

A Large Ion Collider Experiment at the LHC

"It is tribute to how far we have come in theoretical physics that it now takes enormous machines and a great deal of money to perform experiments whose results we can not predict."

– Stephen Hawking

Abstract: The measurement addressed in the dedicated thesis is performed on the data collected by the ALICE experiment at the LHC. The brief history, technical layout and operation of LHC machine are described in this Chapter. The ALICE detector with its various sub-detectors, mainly the detectors used in the concerned analysis are discussed in detail. Some of the initial steps for physics analysis like vertex and track reconstruction, centrality determination are also discussed.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) near Geneva, Switzerland is the most powerful and largest two-ring superconducting hadron accelerator and collider in the world for Particle Physics research. It is installed in an existing tunnel for European Organisation of Nuclear Research (CERN) LEP machine constructed between 1984 to 1989 [71]. This accelerator complex is basically designed to accelerate proton beams to collide at a centre-of-mass energy of 14 TeV with unprecedented peak luminosity $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Although, it is also designed to provide the facility to accelerate the lead ions to collide at a centre-of-mass energy of 5.6 TeV per nucleon pair with a peak luminosity of $\sim 10^{27} \text{ cm}^{-2}\text{s}^{-1}$. The LHC machine is located in an underground circular tunnel of 26.7 km in circumference and consist of superconducting magnets and accelerating devices, installed beneath the Swiss and France border. The basic layout geometry of the LHC tunnel is shown in Figure 2.1. Geometrically, the LHC tunnel is divided into eight arcs and eight straight sections, each containing 154 dipole magnets of 15 meters in length, which bend the beams. Here, each straight section is approximately 528 m in length and can be used for utility insertion or for the experiment purpose. The ATLAS and CMS experiments are the biggest and high luminosity experimental insertions, located at

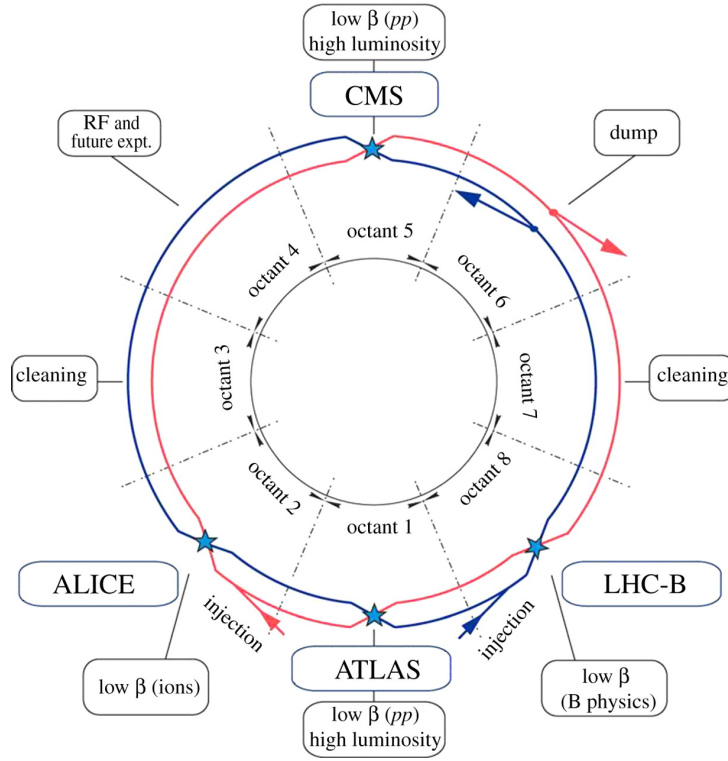


Figure 2.1: The schematic layout of LHC octants and sectors for various operations. The Beam 1 circulates in clockwise and Beam 2 in anticlockwise direction.

diametrically opposite straight sections at Point 1 and Point 5, respectively. The ALICE and LHCb experiments, including the injection system for Beam 1 and Beam 2 are located at Point 2 and Point 8, respectively. The insertions at Point 3 and 7 contain two collimation systems, which cleans the beam by removing those particles which have too large or too low spatial spread from the beam centre. Point 4 contains two Radio Frequency (RF) systems and Point 6 contains the beam dump insertions [71].

The schematic diagram of the Large Hadron Collider and of the CERN accelerator complex is shown in Figure 2.2. The particles are accelerated to increasingly higher energy at different succession stages of the LHC accelerator complex. The beam of the particles boosted from one machine is further injected to next level for higher acceleration. The acceleration of protons (Section 2.1.1) and lead ions (Section 2.1.2) are discussed in the following sections.

2.1.1 Proton acceleration

A hydrogen bottle is the source of protons for the LHC. In the presence of electric field, the protons are obtained by ripping of the electron from the hydrogen atoms. The first acceleration stage is accomplished by the LINAC2 linear accelerator, which accelerates the proton beam up to the energy of 50 MeV. The beam is then fed to the Proton Synchrotron Booster (PSB), a

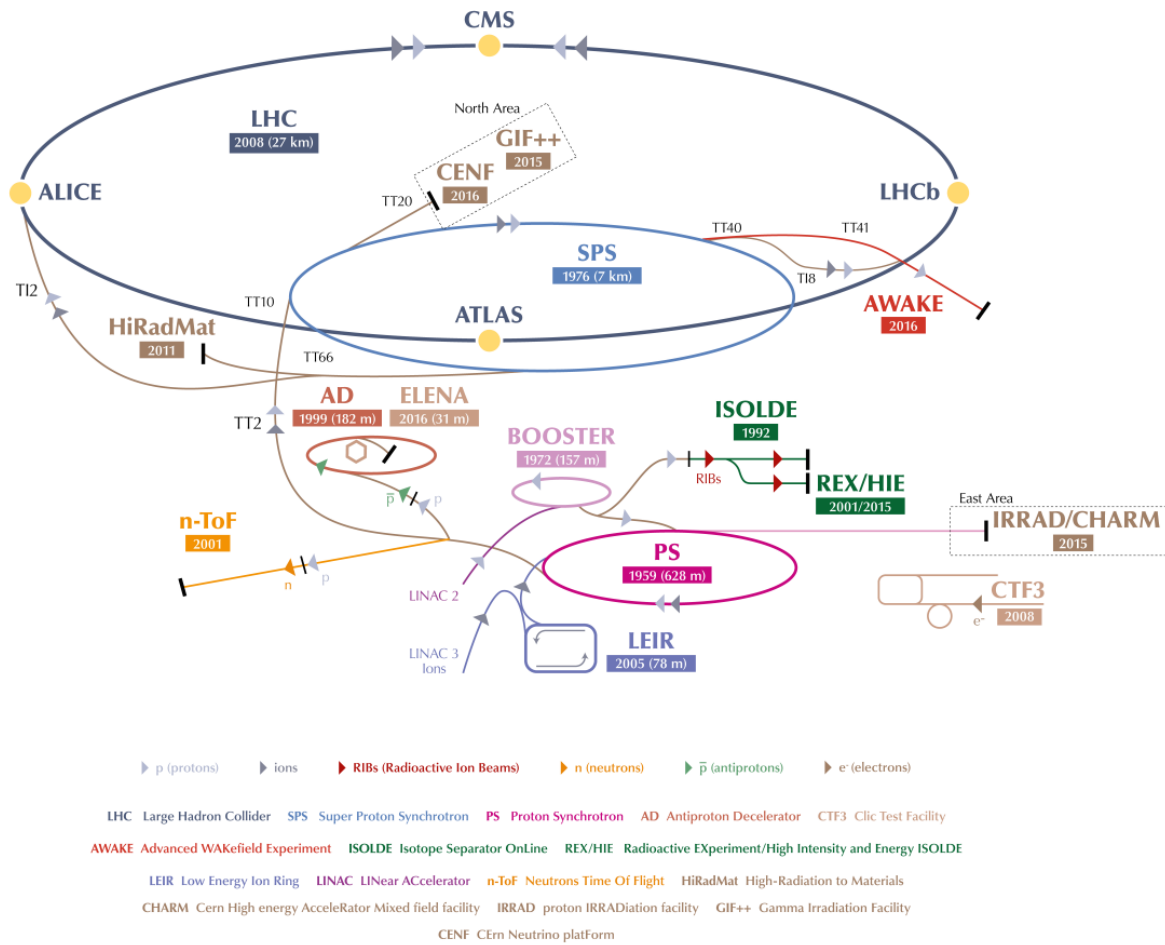


Figure 2.2: The Large Hadron Collider (LHC) ring (dark blue) [72] layout in a complex chain of accelerators for proton/Pb-ion at various stages to help boost their energy to final energy for collisions.

circular synchrotron accelerator of 157 m in circumference, which accelerates the proton beam up to 1.4 GeV. Afterwards, this boosted beam is injected into the Proton Synchrotron (PS) (628 m in circumference), which pushes the beam energy up to 25 GeV. This 25 GeV proton beam is further accelerated into the Super Proton Synchrotron (SPS) (7 km in circumference) up to 450 GeV. Finally, the beam is injected into the two beam pipes of the LHC, the final accelerator of 26.7 km in circumference. The beam circulate clockwise in one pipe and anticlockwise in the second pipe. It takes 4 minutes and 20 seconds to fill each LHC ring with protons and 20 minutes for the LHC to accelerate the protons to attain their maximum energy of 6.5 TeV. Both beams circulate for hours under normal operating conditions and finally collide at centre-of-mass energy $\sqrt{s} = 13$ TeV at the four interaction points where the experimental detectors are located. The detectors installed at four interaction points are ALICE at Point 2, ATLAS at Point 1, CMS at Point 5 and LHCb [73] at Point 8.

2.1.2 Lead ions acceleration

The LHC has so far accelerated only one isotope of Pb, the one that contains 126 neutrons and 82 protons. The lead-ion beam is generated starting from a pure lead piece of 2 cm in length and 500 milligrammes in weight, in the Electron Cyclotron Resonance (ECR) source. In the ECR source, this $^{208}\text{Pb}_{82}$ piece is heated up to 500^0 C to form Pb atom vapors. At the ECR stage, an electric current is used to remove a few electrons from the lead atoms to form Pb^{27+} ions. The newly created ions begin their ride after being transferred into the linear accelerator LINAC 3. At this stage, the Pb^{27+} ions are accelerated up to 4.4 MeV/nucleon and are stripped off more electrons in the carbon foil stripping chamber to convert them into Pb^{54+} ions. These Pb^{54+} ions are then injected into a first circular accelerator, the Low Energy Ion Ring (LEIR) of 78.54 m in circumference, where they are accelerated up to 72 MeV/nucleon. The accelerated Pb^{54+} ions are injected into the PS for further acceleration of up to 5.9 GeV/nucleon, where a stripping Al foil (~ 1 mm in thickness) converts them to fully ionized Pb^{82+} ions. The ion beam is then fed into the SPS for further acceleration of up to 177 GeV/nucleon and finally transferred into the beam pipes of the LHC ring. It takes 10 minutes to fill the LHC ring with Pb^{82+} ions, where the ion beams attain maximum energy of 1.38 TeV/nucleon and finally collide at the interaction points at centre-of-mass energy, $\sqrt{s_{\text{NN}}} = 2.76$ TeV [74, 75]. The LHC parameters for Pb-ions run conditions are summarised in Table 2.1 with the LHC conditions and relevant parameters [71, 76].

Proton–lead collisions

In the year 2012, the protons and lead ions were made to collide with each other at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for the first time and the collision data has been recorded for the physics investigation [77]. The beam preparation for protons and Pb ions are the same as explained in Section 2.1.1 and Section 2.1.2, respectively. In the year 2015, the p–Pb collision data has been recorded at $\sqrt{s_{\text{NN}}} = 8.16$ TeV in the LHC for the second time. The centre-of-mass energy of 5.02 and 8.16 TeV in p–Pb collisions are achieved with the LHC magnet setting for proton beam at 4 and 6.5 TeV, respectively [78].

2.1.3 LHC physics goals

The main aim of CERN is the contribution to the particle physics by studying the fundamental constituents of matter. However the detectors installed at the LHC provides a large arena for physics aspects like, compositeness i.e. to find a possible substructure for subatomic particles, effect of cosmic rays from outer space on the cloud, extra dimensions to explain the weakness of

Table 2.1: The LHC beam parameters used for the Pb-ion collisions scheme at center-of-mass energy ($\sqrt{s_{NN}}$) = 2.76 TeV.

Parameters	Units	Value during collisions
Circumference	[m]	26,659
Dipole operating temperature	[°C]	-271.3 (1.9 Kalvin)
Number of magnet		9593
Lead ion energy	[GeV]	574,000
Lead ion energy per nucleon	[GeV]	2,759
Relativistic "gamma" (γ) factor		2,963.5
Number of ions per bunches		7.0×10^7
Number of bunches		592
Transverse r.m.s beam size	[μm]	16
longitudinal r.m.s beam length	[cm]	7.5
Peak luminosity	[$\text{cm}^{-2}\text{s}^{-1}$]	1.0×10^{27}
Number of collisions per second	[billion]	1

gravitational force, gravitons and tiny black holes, heavy ions and Quark Gluon Plasma (QGP), subatomic particles and their interactions, supersymmetry, which predicts the partner particle for each particle in the Standard Model, search for antimatter, dark matter and Higgs boson.

The LHC has four main detectors, A Toroidal LHC ApparatuS (ATLAS), Compact Muon Solenoid (CMS), Large Hadron Collider beauty (LHCb) and A Large Ion Collider Experiment (ALICE). Three small detectors, TOTal Elastic and diffractive cross section Measurement (TOTEM), Large Hadron Collider forward (LHCf) and Monopole and Exotics Detector at the LHC (MoEDAL) are also installed in LHC, which serve very specialised physics purpose. The general purpose and biggest experiments at LHC, ATLAS and CMS cover the various common physics topics, from the search for extra dimensions to Higgs boson and find the particles that compose dark matter. Both ATLAS and CMS have reported the discovery of the most awaited Higgs boson [7, 8, 79] predicted by the Standard Model, which has been confirmed in July, 2012 and later awarded the Physics Nobel Prize to François Englert and Peter Higgs on 8th October, 2013 for the theoretical proposal of the Higgs particle. The LHCb experiment is mainly focused on CP violation and the rare beauty decays to study the difference between antimatter and

matter. The LHCb has recently reported the measurements of branching fraction and effective lifetime of rare beauty decay [80] and the first observation of baryonic Beauty decay [81] in pp collisions at $\sqrt{s_{NN}} = 7$ and 8 TeV. The fourth main experiment, ALICE is fully devoted to the study of heavy-ion physics, primarily studying the strongly interacting matter and the formation of the Quark-Gluon plasma, a state of matter of deconfined stage of quarks and gluons. The ALICE experiment is also continuously exploring the rich set of physics observations in pp and p-Pb collisions since the start of the experiment in Nov 2009. Recently in April, 2017, ALICE has reported the observation of a novel phenomenon, the enhanced production of multi-strange hadrons in high multiplicity pp collisions [82] at $\sqrt{s_{NN}} = 7$ TeV, as similar to previous observation in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In May, 2016, another major achievement in ALICE was the precise measurement of the mass difference between light nuclei and anti-nuclei (d and $\bar{d}$, ^3He and $^3\bar{\text{He}}$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Various other important measurement like flow of the charged particles [60] and measurement of η/s value [83], size of the fireball [84], di-jet measurement [85], direct photon production to measure the QGP temperature, production of charmed D mesons [86], J/ψ suppression [87] and a rich set of hadronic resonances have also been performed [66, 88–91] by the ALICE collaboration.

2.2 ALICE detector

The ALICE (A Large Ion Collider Experiment) is a heavy ion collider experiment at the Large Hadron Collider (LHC). The systematic view and co-ordinate system of ALICE detector is shown in Figure 2.3. This experiment is originally designed to study the QCD matter created in high-energy heavy ion (lead nuclei) collisions. At high energy density $\varepsilon \geq 1 \text{ GeV/fm}^3$, QCD calculations predict the existence of a deconfined quark and gluon state, accompanied by the chiral symmetry restoration. This state of deconfined quark and gluon matter existed in early universe stage ($10^{-12} - 10^{-5}$ second) after the electroweak phase transition [92]. The ultra-relativistic high energy nucleus-nucleus collisions allow one to reach such energy density regime over an extended volume. The ALICE detector is investigating the non-equilibrium and equilibrium physics of strongly interacting matter in the energy density regime $\varepsilon \simeq 1\text{-}1000 \text{ GeV/fm}^3$. However, ALICE also aims to provide insight into the physics of parton density, very close to the phase space saturation region, together with their collective dynamical evolution close to the hadronization in the highly dense nuclear surroundings. By following the ALICE physics aspects, one can also study the QCD phase diagram structure and the properties of QGP phase.

The ALICE detector has a dimension of $16 \times 16 \times 26 \text{ m}^3$ and weight of 10000 t. It has been built by 1000 physicist/engineers from 105 Institutions across 30 countries. ALICE is

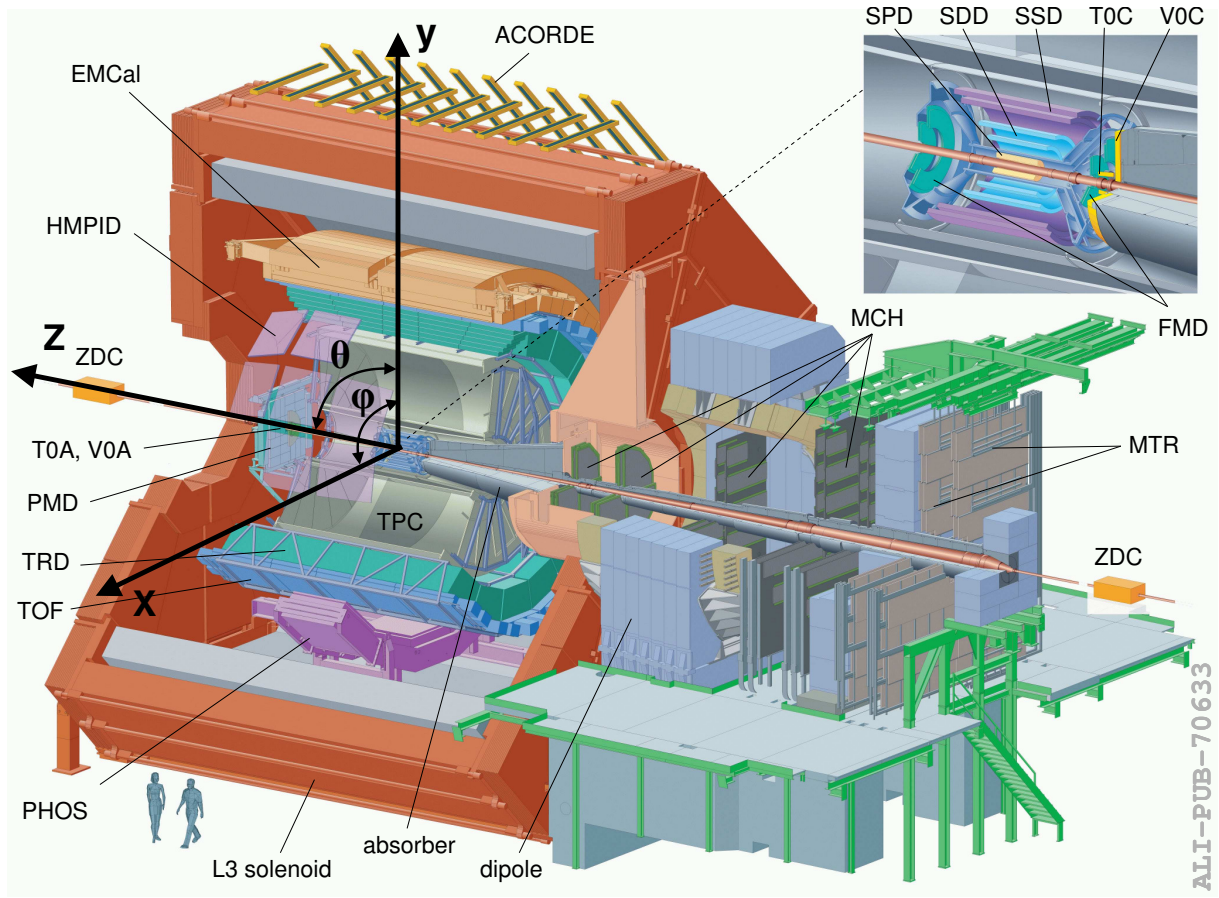


Figure 2.3: The systematic view of the ALICE detector with various detector installed in it.

a high granularity detector, it can handle very high particle multiplicity ≈ 8000 in the Pb–Pb collision at mid-rapidity and has a low $p_T^{\min} \approx 0.15$ GeV/ c threshold, fine particle identification capabilities up to 20 GeV/ c and efficient tracking system from 100 MeV/ c to 100 GeV/ c . The low material budget $\sim 13\%$ of radiation length (X_0) for tracking of this detector, which reduces the multiple scattering at low p_T allows one to study the soft physics ($p_T < 2$ GeV/ c) to the intermediate p_T regime ($p_T < 10$ GeV/ c) and jets ($p_T > 10$ GeV/ c). The sub-detectors of ALICE are categorised in a central and forward-backward region, covering specific pseudorapidity (η) regions and serving specific purposes. All the seventeen detectors of ALICE with the information on polar and azimuthal acceptance region, position, the purpose and the technology used in their fabrication are listed in Table 2.2.

2.3 Central barrel detectors

In this region, the detectors are designed mainly for the tracking purposes and for the identification of hadrons and electrons. They cover the polar angle $45^\circ - 135^\circ$ and are embedded in the

Table 2.2: The sub-detectors of ALICE with their coverage, position, the technology used in detector fabrication and the main physics purpose. The r and z longitudinal co-ordinates are measured w.r.to ALICE Interaction Point (IP2).

Detector	Acceptance		Position (cm)	Technology	detector purpose
	Polar	Azimuthal ($^{\circ}$)			
SPD	$ \eta < 2.0$	full	3.9	Si pixel	tracking, vertex
	$ \eta < 1.4$	full	7.6	Si pixel	tracking, vertex
SDD	$ \eta < 0.9$	full	15.0	Si drift	tracking, PID
	$ \eta < 0.9$	full	23.9	Si drift	tracking, PID
SSD	$ \eta < 1.0$	full	38	Si strip	tracking, PID
	$ \eta < 1.0$	full	43	Si strip	tracking, PID
TPC	$ \eta < 0.9$	full	85–247	Ne drift+MWPC	tracking, PID
TRD	$ \eta < 0.8$	full	290–368	TR+Xe drift+MWPC	tracking, $e^{\pm}$ id
TOF	$ \eta < 0.9$	full	370–399	MRPC	PID
PHOS	$ \eta < 0.12$	220–320	460–478	PbWO ₄	photons
EMCal	$ \eta < 0.7$	80–187	430–455	Pb+scint.	photons and jets
HMPID	$ \eta < 0.6$	1–59	490	C ₆ F ₁₄ RICH+MWPC	PID
ACORDE	$ \eta < 1.3$	30–150	850	scint.	cosmics
PMD	$2.3 < \eta < 3.9$	full	367 (z)	Pb+PC	photons
FMD	$3.6 < \eta < 5.0$	full	320 (z)	Si strip	charged particles
	$1.7 < \eta < 3.7$	full	80 (z/m)	Si strip	charged particles
	$-3.4 < \eta < -1.7$	full	-70 (z/m)	Si strip	charged particles
V0	$2.8 < \eta < 5.1$	full	329 (z)	scint.	charged particles
	$-3.7 < \eta < -1.7$	full	-88 (z)	scint.	charged particles
T0	$4.6 < \eta < 4.9$	full	370 (z)	quartz	time, vertex
	$-3.3 < \eta < -3.0$	full	-70 (z)	quartz	time, vertex
ZDC	$ \eta > 8.8$	full	± 113 m (z)	W+quartz	forward neutrons
	$6.5 < \eta < 7.5$	$\phi < 10$	± 113 m (z)	brass+quartz	forward neutrons
	$4.8 < \eta < 5.7$	$\phi < 32$	7.3 m (z)	Pb+quartz	photons
MCH	$-4.0 < \eta < -2.5$	full	-14.2– -5.4 (z)	MWPC	muon tracking
MTR	$-4.0 < \eta < -2.5$	full	-17.1– -16.1 (z)	RPC	muon tracking

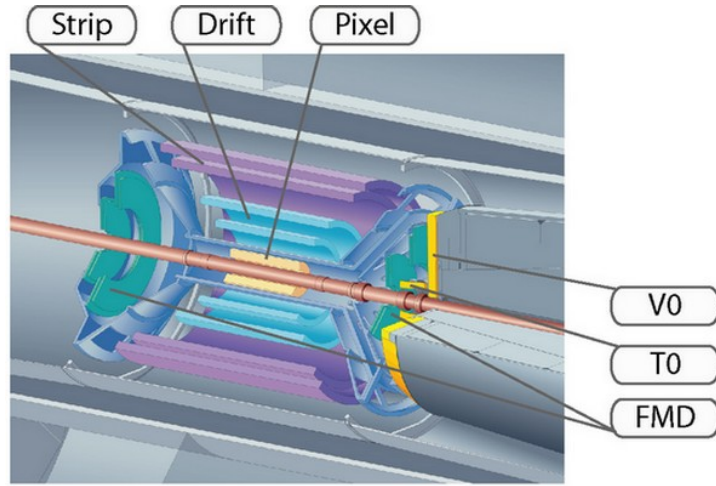


Figure 2.4: The basic layout of ITS detector in ALICE.

large L3 solenoid magnet of magnetic field $B = 0.5$ T. The detectors installed in this region are discussed below.

2.3.1 Inner Tracking System (ITS)

The ITS detector [14, 93] is the heart of the ALICE and is installed around the beam pipe. It consists of six cylindrical layers of Si-detectors, placed at a radial distance of 3.9, 7.6, 15, 23.9, 38 and 43 cm from the beam pipe with full polar acceptance and maximum pseudorapidity acceptance, $|\eta| < 2$. This allows one to reconstruct vertices located within 10.6 cm along the beam direction. The key role of ITS detector is to perform the following tasks:

1. precisely measure the collision vertex with position resolution better than $100 \mu\text{m}$
2. excellent tracking and identification of charged particles of very low momentum
3. calculate/reconstruct precisely the distance of closest approach (DCA), from primary vertex to secondary vertices produced from decays of hyperons, B and D mesons
4. precisely determine the angular resolution of the first point on the tracks and primary vertex position

The amount of material used in this detector is kept very low in order to achieve the desired performance points discussed above. The main component of ITS is divided into three sub-detector components, where the initial two layers are made of Silicon Pixel Detectors (SPD), the middle two layers are made of Silicon Drift Detectors (SDD) and two outermost layers are made of double sided Silicon Strip Detectors (SSD). The schematic diagram of ITS detector is shown in Figure 2.4.

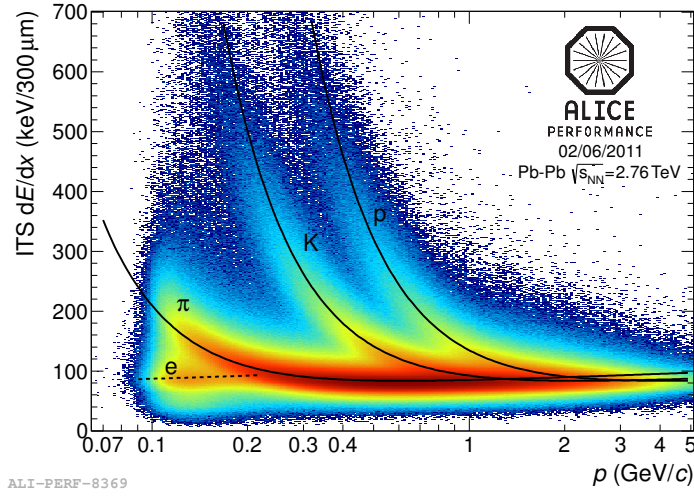


Figure 2.5: The dE/dx of charged particles vs their momentum, both measured by the ITS alone, in PbPb collisions at 2.76 TeV.

The highly precise Silicon Pixel Detector (SPD) layers play an important role in determining primary and secondary vertices, which can operate at track densities greater than 50 tracks/cm². The SPD is based on hybrid silicon pixels, consisting of a two-dimensional matrix (sensor ladder) of reversed-biased silicon detector diodes bound on readout chips. It has 15.7×10^6 high granular pixel cells, each measuring 300 μm in z -direction and 50 μm in $r\phi$ -direction. The SPD barrel is surrounded by an aluminium coated carbon-fibre external shield to prevent radiation of heat towards the SDD layers. The Silicon Drift Detector (SDD) is the intermediate 3rd and 4th layer of the ITS. The SDD provides multi-track capability with dE/dx (specific energy loss) information by its active area $7.25 \times 7.53 \text{ cm}^2$.

It measures the transport time, deposited charge from travelling particle inside it, to localise the impact point in one of the direction. The SSD occupies the two outer-most layers of ITS and is very crucial for the connection of the tracks to TPC through ITS. The basic principle of SSD is to collect the e -hole pairs created by the charged tracks while passing through this detector. It provides PID through specific energy loss and two-dimensional position of the charged tracks.

Particle identification in ITS

The ITS identifies particles with the help of the four layers of SDD and SSD through the measurement of their specific energy loss (dE/dx) while traversing the silicon of the active area of the detector. The dE/dx of each track is calculated using truncated mean, which is defined as the average of the lowest two points in case of four measured points, or weighted sum of the lowest and second lowest points (weight 1 and 1/2, respectively) in a case of 3 measured points. The truncated mean dE/dx measurement as a function of momentum for Pb–Pb collision at

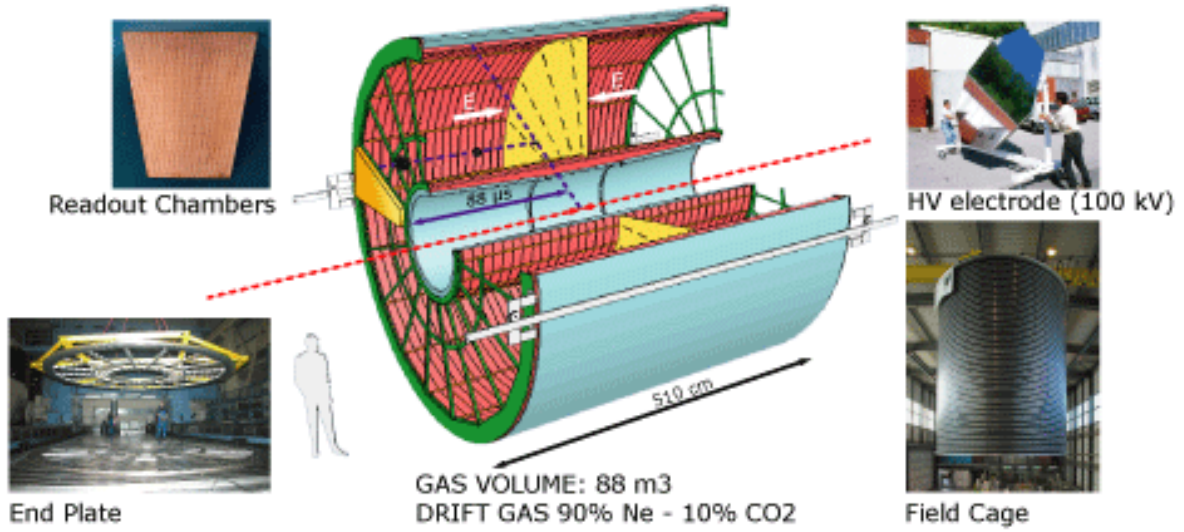


Figure 2.6: The basic layout of ALICE TPC detector.

2.76 TeV by ITS alone is shown in Figure 2.5. The dE/dx resolution of ITS is about 11% which allows good pion to kaon and kaon to proton separation upto 450 MeV/ c and 1 GeV/ c , respectively.

2.3.2 Time Projection Chamber (TPC)

The TPC detector [14, 94] is the main tracking device in ALICE. Along with ITS, TOF and TRD, this detector provides information about the momentum of charged particles, particle identity, two track separation, vertex determination and dE/dx resolution with sufficient momentum resolution. With these excellent capabilities, various kind of studies of hadronic and leptonic signals have been performed. The TPC provides the facility to measure the p_T of charged particles from 100 MeV/ c to 100 GeV/ c , with resolution of 1-2% to 5%, respectively. The TPC can also provide particle identification information at low momentum and also has the capability to statistically separate π , K, p in the relativistic rise region at higher p_T .

TPC is a 510 cm long cylindrical shaped gaseous detector, with the inner and outer radius of 85 and 247 cm, respectively, as shown in Figure 2.6. The TPC has a pseudorapidity coverage, $|\eta| < 0.9$ over full azimuthal acceptance. The field cage of the TPC is designed for expected high particle density in heavy ion collision with minimum systematic error, which does not affect the resolution capability of this detector. The field cage is divided into two detection volume of 2.5 m each with a total detection volume of 88m³ and is filled with 90% of Ne and 10% of CO₂ over the full active volume with a 400 V/cm drift field. This gas mixture provides low material budget, optimum charge transport, transparency for traversing particles and reduces secondary

particle production and multiple scattering. To achieve the desirable detector performance, the field cage is kept at a high central voltage of 100 kV to provide a uniform electric field along the beam direction.

The schematic diagram of the working principle in the TPC is shown in Figure 2.7. The charged particles ionise the gas along their path while traversing the detector. In the presence of a uniform electric field, the liberated e drift towards the cylinder end plates. These end plates are equipped with Multi-Wire-Proportional Chambers (MWPC) to measure the position of the drift electrons. Both end plates have eighteen trapezoidal sectors, containing the Inner and outer Readout Chambers, as shown in Figure 2.8. In order to keep the occupancy as low as possible, to measure precise position resolution and necessarily better dE/dx , about 57000 readout pads of three different size varying from 0.3 cm^2 to 0.9 cm^2 near to inner and outer radius, respectively, are used in these eighteen trapezoidal sectors.

Particle identification in TPC

Each charged particle in the TPC is identified by simultaneously measuring the specific energy loss, dE/dx , inside the TPC gas volume, momentum and charge while traversing through the detector. The energy loss is parameterized by the following Bethe-Bloch formula

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right) \quad (2.1)$$

Here, β is the particle velocity, γ is the Lorentz factor and P_{1-5} are tuned parameters. The measured track dE/dx as a function of the particle momentum by the TPC for Pb–Pb collision at 2.76 TeV is shown in in Figure 2.9, showing clearly separated bands of different particle species. Here, the lines corresponds to the parametrization in 2.1. In the low momentum region, $p \leq 1 \text{ GeV}/c$, particle identification is done on a track by track basis, while at higher momentum particles are separated on a statistical basis with multi gaussian fits. The TPC provides almost constant separation for different particle species in the relativistic rise region over a wide momentum range. The dE/dx resolution of TPC is about 6.5% in the most central (0–5%) Pb–Pb collisions (about 5.2% in pp collisions) and measurement of particle ratio is possible at a p_T of upto 20 GeV/c. The measured and expected dE/dx , parameterized by Equation 2.1 are calculated and used to identify particles via $N\sigma$ cut method explained by the Equation 3.3 in Section 3.5 of Chapter 3.

2.3.3 Time-Of-Flight (TOF)

The TOF detector [14, 95] is a dedicated detector to measure the flight time of charged particles produced in high energy collision in the ALICE experiment. It consists of a large area array

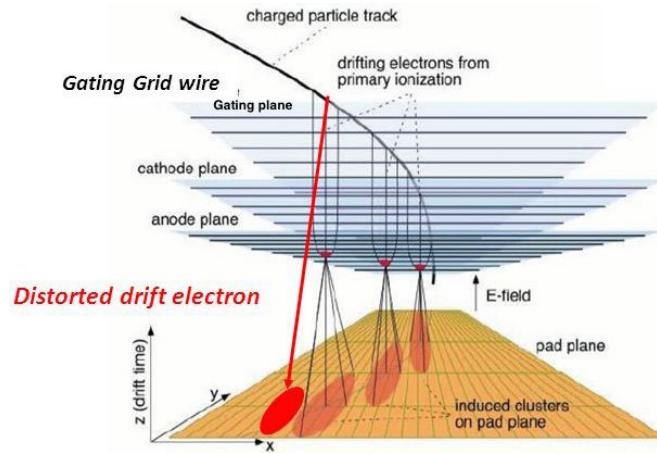


Figure 2.7: The working principle of TPC detector of ALICE.

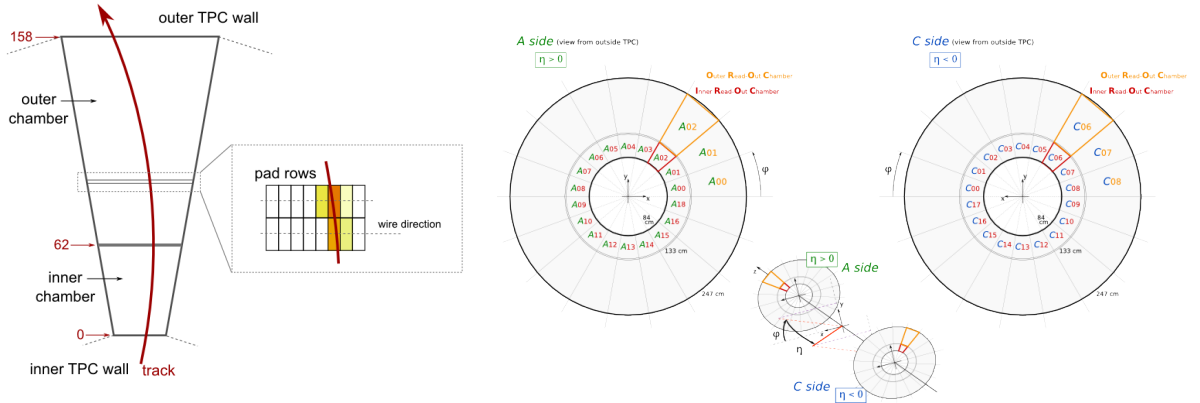
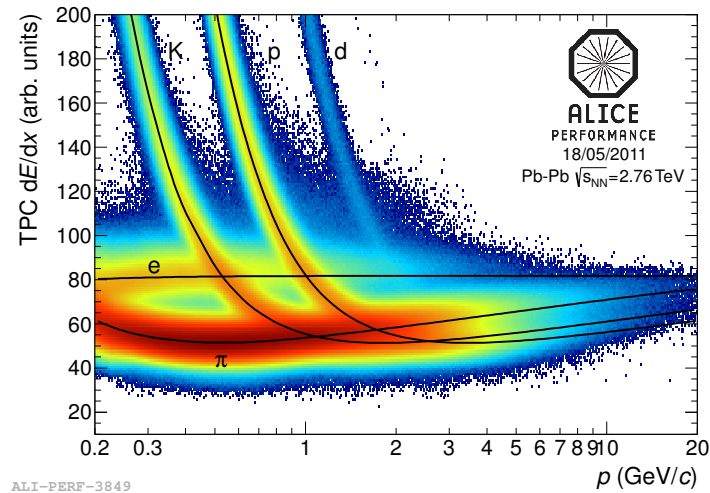


Figure 2.8: The illustration of readout segment into sectors and pad rows in TPC detector.

Figure 2.9: The specific energy loss (dE/dx) inside the TPC as a function of momentum with superimposed bethe-Bloch lines for various particle species, in PbPb collisions at 2.76 TeV.

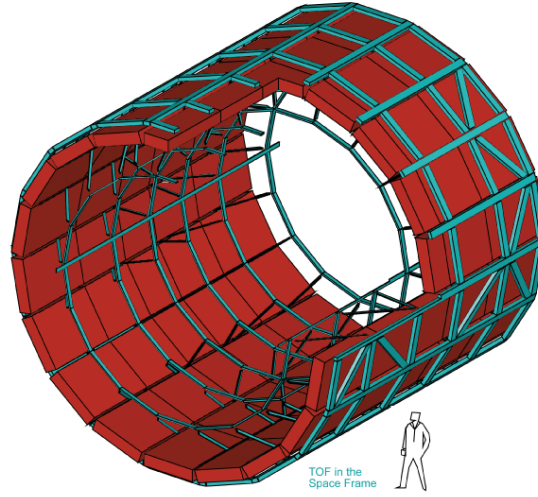


Figure 2.10: The typical layout of ALICE TOF detector.

of Multigap Resistive Plate Chambers (MRPC) of 7.45 m in length, placed at a radial distance of 377-399 cm from the interaction point, covering the pseudorapidity range, $|\eta| < 0.9$ in the full azimuthal region. The TOF system has a modular structure of 18 sectors in the azimuthal plane and five modules along the beam direction. The total read-out channel pads are 157248 of dimension $2.5 \times 3.5 \text{ cm}^2$ with better than 100 ps time resolution. The schematic diagram of ALICE TOF detector is shown in Figure 2.10.

In Pb–Pb collisions, TOF has excellent global time resolution $< 80 \text{ ps}$ for π of about $1 \text{ GeV}/c$ momentum. This resolution includes the contributions from calibration and electronics, intrinsic detector resolution, uncertainty on event start time and momentum and tracking resolution. TOF provides excellent PID performance in the intermediate momentum region, where the TPC capabilities do not allow for accurate particle identification due to the merging of all particle species band. The TOF detector provides 3σ separation of π and K in a momentum range from $0.3 - 2.5 \text{ GeV}/c$ and of p in $0.3 - 4 \text{ GeV}/c$ momentum range with high efficiency.

The key aspect of Multigap Resistive Plate Chambers is that the electric field is uniform and high over the sensitive gas volume inside the detector. The ionisation produced by a travelling charged particle immediately starts the gas avalanche process, generating a signal on the pick-up electrodes. The main advantage of the MRPC technology is that it operates at atmospheric pressure and is constructed with commercially available materials. The TOF measures the charge particle velocity by measuring the time of flight (t) along a known track trajectory length (l) i.e. by the formula, $v = l/t$. The start time to TOF is provided by the T0 detector. In absence of start time by the T0 detector, an average of the arrival time of minimum three particles is used as a start time. If in case, the information from both methods is unavailable, TOF uses the average start time of the run.

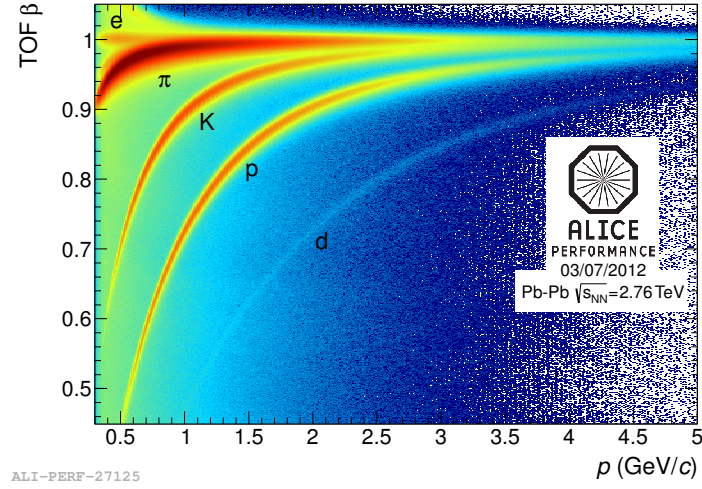


Figure 2.11: The TOF- β performance as a function of momentum in PbPb collisions at 2.76 TeV. The bands for e , π , K, p and d are clearly visible and particles outside those bands are tracks wrongly associated with a TOF signal

Particle identification in TOF

Particle identification in TOF is performed by exploiting the measured and expected time of flight of a particle, where the latter is determined for each mass hypothesis from the track momentum and length. The difference of expected and measured time divide by the TOF-resolution, known as $N\sigma$ method is used for the band separation of each particle species. This method for TOF is discussed in Equations 3.2, 3.4 and 3.5 in Section 3.5 of Chapter 3. The TOF β ($= v/c$), known as particle velocity, as a function of particle momentum for the Pb–Pb collision at 2.76 TeV is shown in Figure 2.11, showing clear separated bands of different particle species. Some background is present due to incorrectly matched tracks to the TOF hits in the high-multiplicity Pb–Pb collisions, whereas the background is lower in pp and p–Pb collisions due to lower track density.

2.3.4 Transition Radiation (TRD)

The TRD [14] is designed for electron identification and is located in the radial gap between TPC and TOF detector. It is placed at a radial distance of 290–368 cm and covering the pseudorapidity range $|\eta| < 0.8$ and full azimuthal region. It has six individual layers, each segmented azimuthally in 18 sectors and each sector between the TPC and TOF is a 5-fold segmented module along the beam direction (z). Each module of the TRD is made of multi-wire proportional readout chambers. The primary goal of the TRD is to provide an improved electron identification at relatively high momentum, $p > 1$ GeV/c in central barrel region.

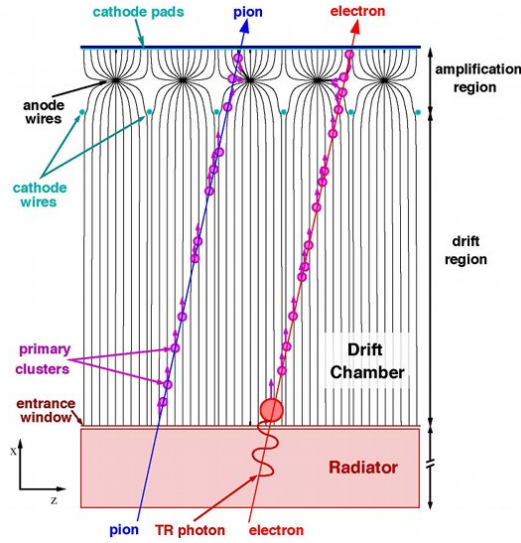


Figure 2.12: The electron and pion identification in TRD inside ALICE.

The working principle of TRD is based on the phenomenon of transition radiation emitted by relativistic charged particle when it passes through the medium consisting of different dielectric medium, as shown in Figure 2.12.

The TRD along with ITS and TPC data, provide efficient electron identification to study light/heavy vector mesons, continuum of di-electron channel, semi-leptonic decays of hadrons and jets with high transverse energy. The TRD is an extremely efficient detector to separate the electrons from pions with high efficiency allowing J/Ψ production measurement through the di-electron decay channel. The pion rejection factor at 90% electron efficiency is about 100.

2.3.5 PHOTON Spectrometer (PHOS)

The PHOS [14] is a high-resolution electromagnetic spectrometer to identify electromagnetic particles in a limited central pseudorapidity acceptance, $|\eta| < 0.12$ and azimuthal coverage of $220\text{-}320^\circ$, located at a radial distance of 460 cm from the interaction point (IP). The high granularity and the choice of the scintillating/absorber material of adequate thickness ($10X_0$) provide a very high-resolution power in the spatial and energy domain. This detector identifies photons and allows one to reconstruct neutral mesons in the two photon decay channel.

The main physics goal of this detector is to test the thermodynamical properties of initial collision phase specially by measuring the QGP temperature and hot zone's space-time dimensions through measuring diphoton spectrum, direct single photons and its Bose-Einstein correlations. It also contributes to study the deconfinement by investigating the jet quenching as a probe through measuring the high transverse momentum π^0 spectra and recognise jets by measuring γ -jet and jet-jet correlations.

2.3.6 High Momentum particle Identification (HMPID)

The HMPID [14] is a Ring Imaging Cherenkov (RICH) detector consisting of a thick layer of liquid C_6F_{14} i.e. perfluorohexane and is located at a radial distance of 490 cm with pseudorapidity and azimuthal coverage of, $|\eta| < 0.7$ and $1 - 59^\circ$, respectively. The Cherenkov electromagnetic radiation is emitted as a cone, while a charged particle traverses through the detector at a velocity greater than that of light in the medium. These cherenkov photons are detected by the photon counter of CsI deposited multi-wire proportional chamber of 12 m^2 active area.

The main role of the HMPID is to enhance the PID capability beyond the momentum range achieved by the ionisation energy loss measurement (in ITS and TPC) and by the TOF. The HMPID detector extends the range for the identification of protons and kaons on a track by track basis, up to $3 \text{ GeV}/c$ and $5 \text{ GeV}/c$, respectively.

2.3.7 Electro Magnetic Calorimeter (EMCAL)

The EMCAL [14, 96] is a layered Pb-scintillator sampling calorimeter located at a radial distance of 4.3 - 4.5 m covering the pseudorapidity range, $|\eta| < 0.7$ and 110° in azimuth electrons. This calorimeter detector is enhancing the capability for jet quenching measurements, high energy jets, high-momentum electrons and photons. It provides improved energy resolution (dE/dx) on jet energies and identified particles by measuring transverse energy E_t from very low (100 MeV) to very high (100 GeV) p_T -region from 19% to 2%, respectively. It also provides efficient and fast trigger (L0, L1) for hard jets, electrons and photons.

2.3.8 ALICE Cosmic Ray Detector (ACORDE)

The ACORDE [14] consists of Cosmic-Ray Trigger (CRT) system of 60 plastic scintillator counters placed at a radial distance of 850 cm on extreme top of the ALICE detector covering pseudorapidity range, $|\eta| < 1.3$ and azimuthal angle $30 - 150^\circ$ with an effective area of $190 \times 20 \text{ cm}^2$. This detector provides precise information of cosmic rays of about $10^{15} - 10^{17} \text{ eV}$ energies. The Cosmic-Ray Trigger system provides a fast L0 trigger signal to the central trigger system during atmospheric muons impinging upon the ALICE. This trigger signal helps in calibration, commissioning, alignment and performance of several ALICE sub-detectors.

2.4 Forward-backward detectors

The backwards and forward detectors are used for trigger configuration, global event characterization and particle production studies. These detectors are the following

2.4.1 Zero Degree Calorimeter (ZDC)

The ZDC [14] is composed of four calorimeters, two for protons and two for neutrons and are placed at ± 113 meter from the Interaction Point (IP) and at zero degree relative to the beam line on both sides, therefore called as zero degree calorimeter. The spectator protons along the beam direction are spatially separated from neutrons by the LHC magnets. Therefore, two calorimeters are used, one is for neutron detection called ZN and one for proton detection, called ZP.

The ZDCs measure the energy of non-interacting spectators nucleons to determine the geometry and nuclei colliding overlap region, hence the number of participant nucleons. The deposited energy in these calorimeters decreases with the increasing collision centrality. It helps to improve the centrality trigger and to estimate the reaction plane angle in A-A collisions.

2.4.2 Photon Multiplicity Detector (PMD)

The PMD [14, 97] is a preshower detector and consists of two identical planes of detectors, a charged particle veto and a pre-shower plane with a $3X_0$ thick Pb convertor in the middle. It is placed at 367 cm far from the IP covering the pseudorapidity region of $2.3 < \eta < 3.9$ in the forward direction. It is mainly designed to measure the multiplicity, η and ϕ -distribution of photons both in pp and Pb-Pb collisions. It can also be used to estimate the reaction plane angle of the collision.

2.4.3 Forward Multiplicity Detector (FMD)

The FMD detector [14, 98] is made of silicon strip detectors and consists of 5 ring counters, three inner and two outer rings divided into 20 and 40 sectors in the azimuthal direction, respectively. The main role of FMD is to provide the precise charged particle multiplicity in the pseudorapidity region of $1.7 < \eta < 5$ and $-3.4 < \eta < -1.7$ in forward and backward direction of the ALICE. The FMD with ITS provides the information of charge particle multiplicity for all the collisions systems in $-3.4 < \eta < 5$ range. This detector allows one to study of the event by event multiplicity fluctuations and flow analysis.

2.4.4 T0

The T0 detector [14, 98] is composed of two arrays of 12 counter each, made of quartz Cherenkov radiator detectors. The first array, T0C is placed 70 cm from the nominal interaction point covering pseudorapidity range $2.9 \leq \eta \leq 3.3$. On the opposite side, the T0A is 3.6 m far

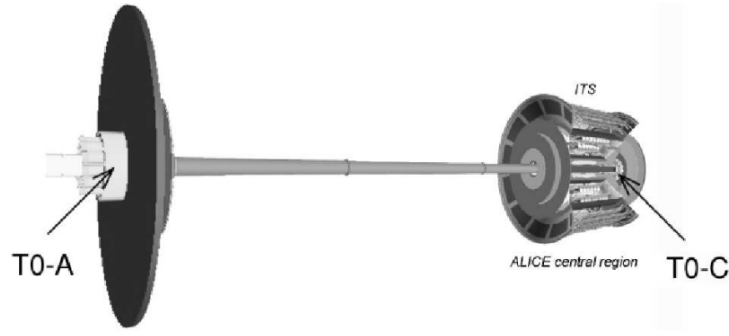


Figure 2.13: The T0 detector position inside ALICE.

from IP and covers pseudorapidity, $4.5 \leq \eta \leq 5$. The schematic diagram and position of both T0 detectors are shown in Figure 2.13. The main role of the T0 detector is to deliver fast timing signal which is used as a reference for TOF detector independent to vertex position and corresponds to real collision time. It also provides an early wake-up call for TRD and L0 trigger signals: $T0_{minbias}$, $T0_{central}$ and $T0_{semicentral}$. This detector has a time resolution better than 50 ps, the trigger efficiency varies from 50% to 100% for pp to A-A collisions. The main trigger signal confirms the vertex position at IP with precision better than 1.5 cm.

2.4.5 V0

The V0 system [14, 98] is composed of 2 disks of the plastic scintillator (V0A and V0C, each of 8 segments) read out by optical fibres. The one which is located at 340 cm from IP in forward direction is known as V0A and the one located at 90 cm in backward direction from IP is called V0C, covering the pseudorapidity $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The sketch of VZERO-A and C detectors is shown in Figure 2.20. This detector sets a threshold on deposited energy to provide an online L0 centrality trigger. It has a capability to provide background rejection for the muon trigger, control over luminosity and reject the asymmetric beam-gas events as additional features. The main role of V0 detector as a centrality indicator is to provide minimum bias trigger and two centrality triggers for Pb–Pb collisions.

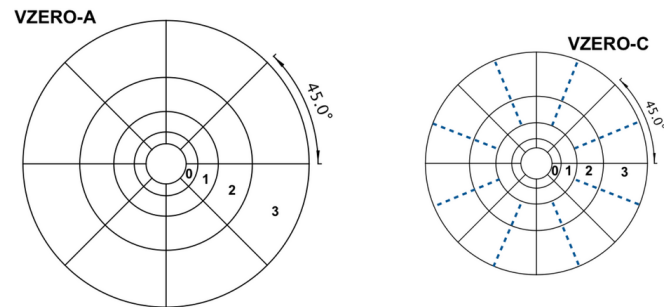


Figure 2.14: Sketches of VZERO-A and VZERO-C detector.

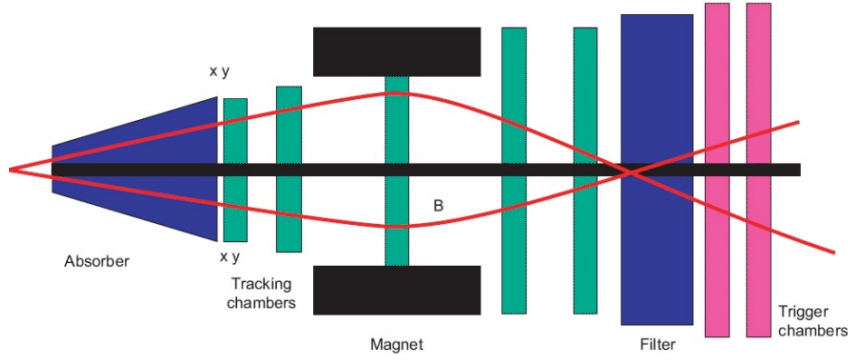


Figure 2.15: main component of muon spectrometer in ALICE.

2.4.6 Muon Spectrometer

The muon spectrometer is a single-arm detector assembly aimed at reconstructing muons of $p_T > 4 \text{ GeV}/c$. It is placed at 14 m in the negative beam (z) direction with acceptance in the pseudorapidity range $-4 < \eta < 2.5$, polar angle of $171^\circ - 181^\circ$ and full azimuth coverage. This apparatus is composed by an absorber made of concrete and steel to filter hadrons complemented by tracking chambers which allow the reconstruction of the muon trajectories, which are bent in a dedicated dipole magnet to allow one to reconstruct their momenta. This spectrometer has its own large dipole magnet with resistive coils and a horizontal field perpendicular to the beam axis as an integral part of muon spectrometer arm. A set of trigger chambers is located at the extreme end of the spectrometer, behind a thick iron wall. A schematic design is shown in Figure 2.15. The spectrometer is shielded by a dense absorber tube which prevents particles emerging from the beam pipe to enter the apparatus.

The muon spectrometer allows one to reconstruct quarkonium resonance in their di-muon decay channel, which are essential tools to study the hot early stage of heavy-ion collisions. In a high-temperature QCD plasma, quarkonium states dissociate due to color screening caused by the surrounding QGP medium, which leads to a suppression of their yield. The ϕ meson and a wide range of heavy quarkonia vector mesons i.e. $J/\psi, \psi', \Upsilon, \Upsilon', \Upsilon''$ are reconstructed by the ALICE muon spectrometer via invariant mass reconstruction in their $\mu^+\mu^-$ decay channel. This study allows one to measure their production rate as a function of collision centrality and transverse momentum.

2.5 Vertex reconstruction

The reconstruction of the primary vertex in ALICE is initially performed by using pairs of reconstructed points in the SPD layers of ITS detector. This allows one to obtain the position

of the primary vertex with very high efficiency. In general, ALICE can reconstruct the primary vertex using three different approaches:

1. VertexerSPD3D
2. SPDz
3. VertexerTracks

The VertexerSPD3D [99] provides the 3D (three dimensional) measurement of the primary vertex based on the SPD tracklets. This method follows three steps which are repeated twice: tracklet finding, tracklet selection and vertex determination. In the first step, the tracklet must cross a cylindrical fiducial region where the interaction point is expected to be localised. In the second step, by using pair of tracklets, the distance of closest approach between the two tracklet < 1 mm is applied. The crossing point of tracklet pair is calculated and only the pairs crossing the fiducial region are selected. In the third step, a first estimate of the position of the primary vertex is calculated from the previous two steps. The coordinates of the vertex are obtained by finding minimum distance point among the tracklets. The primary vertex coordinates are further refined by eliminating the tracklets with a distance of closest approach larger than 1 mm.

The SPDz [99] algorithms provides only the z coordinate of the interaction point with a similar approach, although neglecting the information on x and y coordinates. This is faster algorithm compared to VertexerSPD3D and is used for the reconstruction of events from Pb–Pb collisions. This method measures the z -coordinate of primary vertex when beam position in xy plane is known with an accuracy of $200 \mu\text{m}$. The primary vertex z coordinate is estimated if the correlation of reconstructed points in the first layer to the second layer is within the small azimuthal window. The tracklet i intersecting the beam point z_i is calculated from all the tracks and a "region of interest" (ROI) is defined near the z_i distribution peak. The vertex position is calculated as a weighted mean z_{mean} of z_i values in this region. This calculation is iterated again re-centering the ROI on the previously measured z_{mean} until z_{mean} becomes symmetric in order to minimize bias on asymmetries on the z_i distribution tail.

The VertexerTracks [99] provides the measurement of the primary vertex in three-dimension by using reconstructed tracks. It is used to provide a more accurate measure of the vertex position, which is needed for an efficient reconstruction of secondary vertices. At the initial pre-selection step, reconstructed TPC tracks with a small number of associated TPC cluster or pointing outside the fiducial cylinder $r > 3$ cm and $|z| > 30$ cm are rejected. This algorithm consists of three steps - track selection, vertex finding and vertex filtering. Displaced tracks are rejected in the first step and a first estimate of the vertex position is obtained, when the distance between the accepted tracks is minimum. The second step is based on straight line

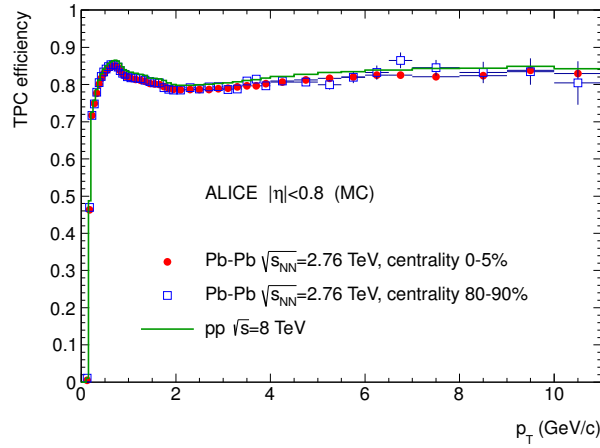


Figure 2.16: TPC track finding efficiency for primary particles in pp and Pb-Pb collisions (simulation).

approximation of the tracks and consists of two iterations, initially, tangent to the track at nominal beam position is performed and secondly, the track is prolonged to vertex estimated from the first iteration. In the third and last step, the tracks are extrapolated to vertex position obtained in the previous step. The best estimate of the vertex position and its covariance matrix is obtained by a fitting algorithm.

2.6 Track reconstruction

The track reconstruction method in ALICE is based on the Kalman filter algorithm [100]. The track reconstruction starts from the outer radius of the TPC detector. For each track, the TPC can provide up to 159 cluster signals. The seeding for the track reconstruction algorithm requires either two clusters and the reconstructed vertex or only three clusters. Only tracks with a minimum number of associated clusters equal or larger than 20 are acceptable, provided that less than 50% of the expected associable clusters are missed by the reconstruction algorithm. The accepted tracks are propagated inwards towards the inner radius of TPC. The TPC efficiency, defined as ratio of reconstructed to generated primary particles, as a function of the transverse momentum measured in Pb–Pb collisions are shown in Figure 2.16. This efficiency shows a drop below the $p_T = 0.5$ GeV/c due to track energy loss in detector material, while the high- p_T efficient trend is due to straight tracks that traverse the dead zones between the readout sectors.

The TPC tracks are further propagated inwards to the outermost ITS layer, which become a seed for the track finding in the ITS and the matching of the ITS-TPC tracks is performed. Matched tracks are propagated further inward and updated at each ITS layers with a proximity cut, which takes into account errors and positions. The updated seeds are marked as new seeds

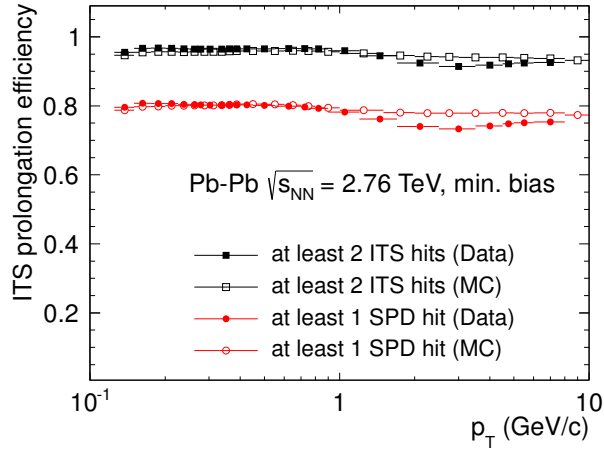


Figure 2.17: ITS-TPC matching efficiency vs. p_T for data and Monte Carlo for Pb-Pb collisions.

for ITS tracking. The ITS tracking can be performed with two options: with or without vertex constraint. With the vertex constraint, the vertex estimated by the SPD is used to guide the track finding and increases the reconstruction efficiency for primary particles. In case of without vertex constraint, tracks are reconstructed with large displacement. The ITS-TPC efficiency as a function of track p_T in Pb-Pb collisions is shown in Figure 2.17.

Tracks with a successfully completed the ITS tracking are extrapolated to the point of the closest approach to the preliminary interaction vertex and then propagate again back to the outward direction. The Kalman filter is used to refit the tracks while propagating in the outward direction by using the clusters found at the previous stage. In every outward step, track length and the time of flight expected for various particle species are integrated for PID in TOF detector. Once the tracks hit the TRD, an attempt is made to match it with a TRD tracklet. Similarly, tracks reaching the TOF detector are matched to TOF clusters. Eventually, the tracks are propagated further outwards to match with EMCal, PHOS and HMPID signals. The tracking steps are schematically shown in Figure 2.18. At the final stage of track reconstruction, all the tracks starting from outer TPC point are propagated to an inward direction to ITS and refitted to the previously found clusters without constraining the SPD primary vertex. Finally, the position, direction and inverse curvature of the track with its associated covariance matrix are determined.

Distance of closest approach

The distance of closest approach is the distance between the reconstructed track trajectory and reconstructed primary vertex at the track's closest point to the vertex. The distance of closest approach is also known as impact parameter. This TPC inward seeds are updated with a proximity cut of all clusters as per the ITS layer. The Figure 2.19 shows schematically the DCA measurement.

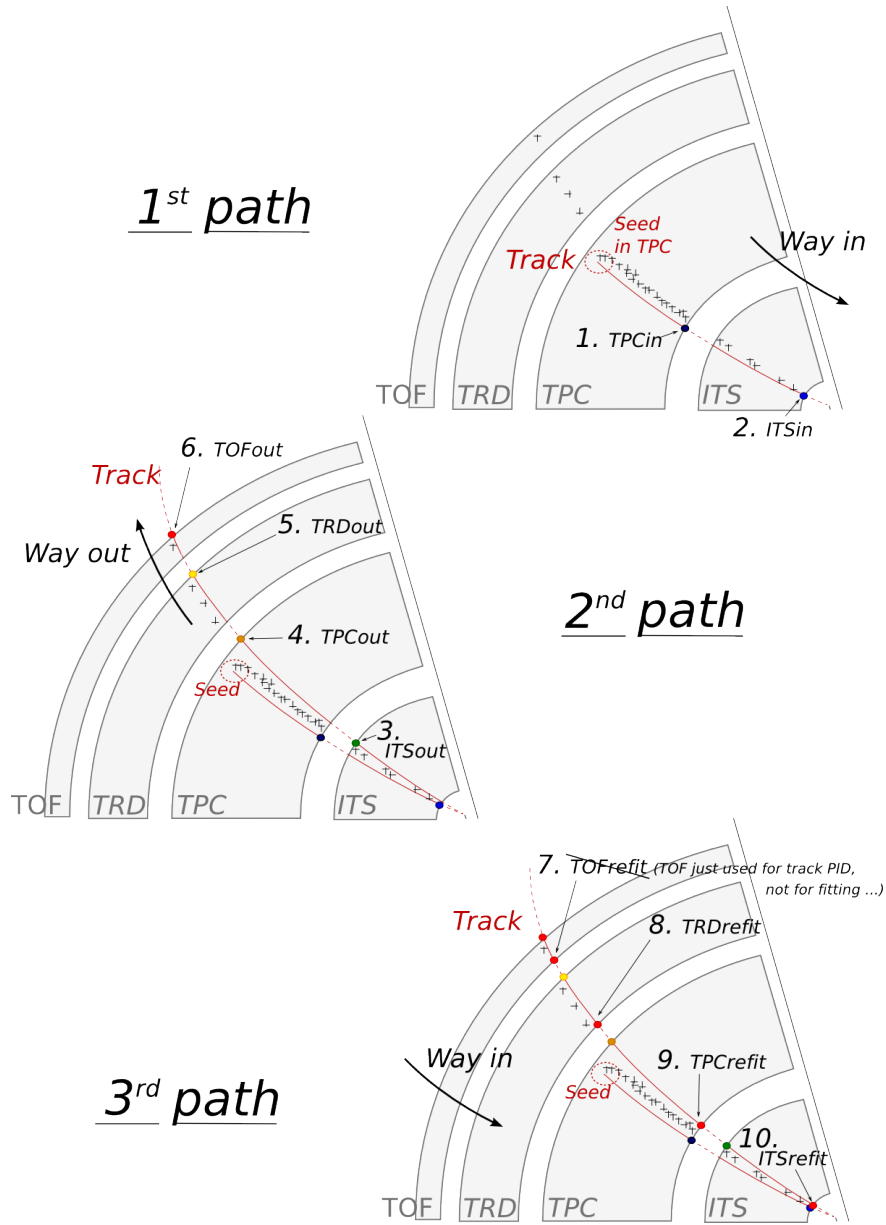


Figure 2.18: Tracking reconstruction steps through various detector.

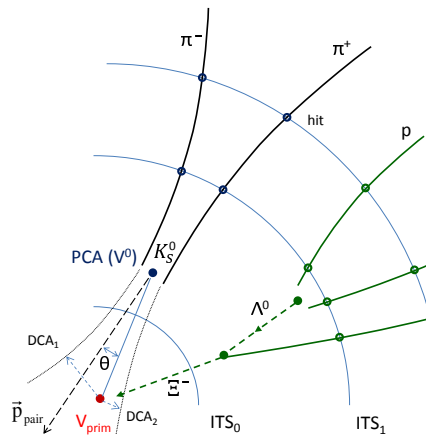


Figure 2.19: DCA measurement during the track and primary vertex reconstruction.

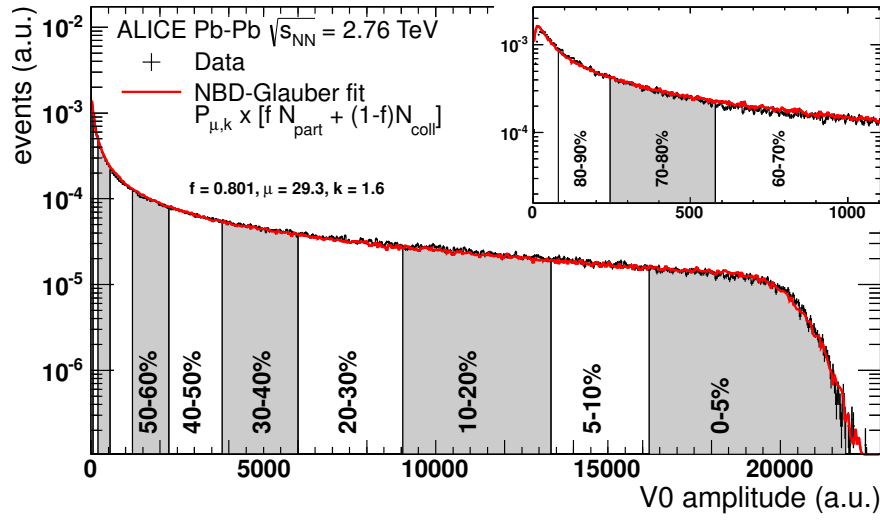


Figure 2.20: The distribution of V0 amplitude in PbPb collisions at 2.76 TeV. The centrality bins are defined by integrating from right to left.

2.7 Centrality determination

The collision centrality is estimated using the amplitude of the signal of the V0 detectors, which is proportional to the charge deposited in the scintillators. The centrality of a nucleus-nucleus collision is related to the impact parameter vector b , which is defined as the distance between the centres of two colliding nuclei. The nucleons that take part in the collision are called "participating" nucleons, while those which do not take part are called "spectators". The number of participating and spectator nucleons are dependent on the impact parameter. The impact parameter can not be estimated directly, although the number of charged particle produced in the collision and spectators nucleons can be directly measured, allowing one to access the information about the collision geometry.

The centrality determination is shown in Figure 2.20, exploiting the charged particle multiplicity from V0 detector (V0A+V0C amplitude) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The high multiplicity part is fitted with the help of the Glauber model [53] and extrapolated to the low multiplicity region. The Glauber model incorporates the nuclear density profile to describe the collision geometry, with the assumption that nucleons follow a straight line trajectory and encounter binary nucleon-nucleon collisions according to an inelastic nucleon-nucleon cross-section σ_{NN} . The number of binary NN collisions N_{coll} and the number of participants N_{part} are determined for a given impact parameter b . The multiplicity distribution is then modeled by assuming $fN_{part} + (1-f)N_{coll}$ particle sources. Each source follows a negative binomial distribution (NBD) for particle production with fit parameters μ and k . The f parameter represents the fraction of the soft process for produced production. The fit gives the integrated number of

events N_{ev} required for absolute centrality scale and relates the binary NN collisions and number of participants to the centrality. For example, the 0-5% centrality bin corresponds to 5% of all events with the highest multiplicity, whereas 90-100% centrality bin corresponds to 10% of all the events with the lowest multiplicity.

2.8 Data Acquisition and trigger system

2.8.1 Trigger system

The ALICE Central Trigger Processor (CTP) is a low-level hardware trigger and most complex among the CTP's of other LHC experiments. The responsibility of CTP is to control over the experiment and to select the interesting physics events on the basis of various trigger detectors in ALICE. These events can be scaled down to suit the bandwidth of Data Acquisition (DAQ) system and the High-Level Trigger (HLT). The optimum use of the detectors is the main challenging task of the ALICE trigger system.

The first response of the trigger system needs to be fast in order to suit the detector requirements. The "fast" part of the trigger is split into Level-0 (L0) and Level-1 (L1). The L0 signal from CTP reach the detector after $1.2 \mu s$, which is too fast to enable trigger inputs from all the detectors and the L1 signal arrives after $6.5 \mu s$ which picks up all the remaining fast inputs. The "past-future" protection is used to avoid the recording of Pb–Pb collisions containing more than one central collision. The CTP decisions are made in 100 ns and a final level of the trigger, Level-2 (L2) waits for the past-future protection interval of $88 \mu s$.

2.8.2 Data Acquisition (DAQ) system

The ALICE DAQ and trigger systems are designed to give different observables a fair share of the trigger and DAQ resources with respect to DAQ bandwidth. They also have to balance the capacity to record Pb–Pb central collisions with the ability to acquire a large fraction of rare events. It has been estimated that a bandwidth of 1.25 GB/s to mass storage is suitable to provide adequate physics statistics, which is consistent with constraints imposed by cost, storage capacity and technology.

The detectors receive the trigger signal and associated information from Central Trigger Processor (CTP) through Local Trigger Unit (LTU). The data produced by the detectors are passed on to the Detector data Link (DDL) by using the same protocol, which is architectural features of the ALICE DAQ. At the receiving end of the DDL, the DAQ Readout Receiver Card (D-RORC, the PCI-X based card) receive and assemble the event fragments into sub-events in

the Local Data Concentrators (LDCs). The LDC ships the sub-events to a form of machine, Global Data Concentrator (GDC) where the whole events are built. The GDC feed the recording system which eventually records the events in the Permanent Data Storage (PDS).

2.8.3 HLT

In a single AA collision (assuming $dN_{\text{ch}}/d\eta = 8000$ at mid-rapidity), the amount of data produced in the TPC alone is estimated to be about 75 MB. While the DAQ archiving rate is about 1 GB/s, the data rate can easily reach up to 25 GB/s. Therefore, the online processing is required to select relevant events to compress data without losing their physics content. The physics requirement of HLT is to accept or reject events on a detailed online analysis and select a physics Region-Of-Interest (ROI) within the event. The HLT also used to reduce the size of the event without losing the important physics information of the accepted and selected data.

Chapter 3

Analysis of $\Lambda(1520)$ production in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

"What we observe is not nature itself, but nature exposed to our method of questioning."

– Werner Heisenberg

Abstract: This chapter describes the strategy and method used in the measurements of the $\Lambda(1520)$ production in Pb–Pb collision at 2.76 TeV. The brief introduction of the present analysis goal is discussed in Section 3.1. The details on data, event, track and particle identification selection are discussed in Section 3.2 to 3.5. The full details on the analysis method, steps starting from signal reconstruction to background estimation and to measure $\Lambda(1520)$ yield are discussed in Section 3.6. The corresponding efficiency correction by the Monte Carlo simulated data, with various correction applied to this efficiency are discussed in Section 3.7.

3.1 Introduction

Hadronic resonances are well-known probes to study the properties of Quark Gluon Plasma (QGP) state of matter produced in ultra-relativistic heavy ion collisions [101] in various experiments of the world [102–104]. The production of hadronic resonances is expected to be sensitive to the properties and evolution of the fireball [105] produced in such collisions. During the QGP expansion, the system cools down and eventually, the plasma of quark and gluons starts hadronizing and turns into ordinary matter. The study of resonance production provides important information on the properties of the dense hadronic phase and its evolution before the complete decoupling of the system. In particular, short-lived hadronic resonances allow one to estimate the time span between the chemical freeze-out stage (hadronisation) to the kinetic freeze-out stage (final decoupling of the system).

At the LHC, heavy Pb nuclei collide at a centre-of-mass energy $\sqrt{s_{\text{NN}}} = 2.76$ TeV per pairs of colliding nucleons and at such extreme high energies, QGP is expected to form. In order to understand this form of matter and its evolution, the $\Lambda(1520)$ baryon resonance is of particular interest as it has a very small life (~ 12.6 fm/c) comparable to the one of fireball

($\sim 10\text{--}11$ fm/c) [84]. Being a short-lived resonance, it can decay inside the hadronic medium, where its decay daughters would experience re-scattering and regeneration processes. The main characteristics of $\Lambda(1520)$ such as mass and width compared to the PDG values [65, 106–108], yield and $\langle p_T \rangle$ can be easily modified inside the hadronic medium. The measurement of this baryonic resonance particle can further aid to understand the properties of the hadronic medium formed in Pb-Pb collisions in ALICE at the LHC energies. Previous results from STAR experiment [70, 109] have shown the dominance of re-scattering effect over re-generation of $\Lambda(1520)$ decay daughters at RHIC energies.

3.2 $\Lambda(1520)$ analysis description

The main focus of this thesis is the measurement of $\Lambda(1520)$ resonance production in Pb-Pb collisions. The analysis is performed using Pb-Pb collision data at $\sqrt{s_{NN}} = 2.76$ TeV, collected with ALICE detector at the LHC. A detailed description of the ALICE detector can be found in Chapter 2. The data have been collected with a minimum bias trigger during the fall of 2010 by the ALICE experiment and corresponds to the LHC data-taking period namely as "LHC10h". Information about the data-taking conditions and trigger settings can be found in Section 3.2.1. Details about the performance of the experiment can be found here [110]. The $\Lambda(1520)$ resonance production in central rapidity ($|y| \leq 0.5$) defined as, ($y = 0.5 \ln [(p_x + p_z)/(p_x - p_z)]$) is measured by reconstructing it in the $\Lambda(1520) \rightarrow pK^-$ and in the corresponding charge conjugate decay channel via invariant mass technique. ITS and TPC detectors are used for the primary vertex and track reconstruction. The TPC and TOF detector are used for particle identification.

The $\Lambda(1520)$ and $\bar{\Lambda}(1520)$ particles are not measured separately due to the large statistical uncertainty in the data for this particle, therefore the sum of $\Lambda(1520)$ and $\bar{\Lambda}(1520)$ is referred collectively as $\Lambda(1520)$ in this thesis unless otherwise specified. This measurement has been performed in 0–20%, 20–50% and 50–80% collision centrality intervals for Pb-Pb data.

3.2.1 Experimental data set

The analysis is based on Pb-Pb collisions data at $\sqrt{s_{NN}} = 2.76$ TeV, collected by the ALICE detector [110] at the LHC during the 2010 data taking period. For this analyzed data, two beams each with 4 bunches with about 10^7 Pb ions per bunch were collided at $\sqrt{s_{NN}} = 2.76$ TeV with an estimated luminosity of $5 \times 10^{23} \text{cm}^{-2} \text{s}^{-1}$ [111]. A minimum bias trigger has been used to select hadronic events with high efficiency, which required at least two conditions out of the following three conditions

1. two-pixel chips hit in the outer layer of the SPD
2. a signal in VZERO-A
3. a signal in VZERO-C

The approximate threshold in the VZERO detector corresponds to the energy deposition of a minimum ionising particle. The luminous region had an r.m.s. width of 5.9 cm and 50 μm in the longitudinal and transverse direction, respectively. The trigger configuration led to a rate of about 50 Hz, where the estimated luminosity corresponds to a hadronic rate of 4 Hz. The remaining 45 Hz was mainly due to electromagnetically induced process like coherent $\gamma\gamma$ and γA interactions in very peripheral collisions [112]. The trigger rate without beam was negligible and the rate in coincidence with bunches of only one beam i.e. beam background was about 1 Hz. In addition, for the offline event selection, the information from two neutron zero degree calorimeters (ZDCs) positioned at ± 114 m from the interaction point has been used. The beam background events are removed from the triggered event sample with the help of VZERO and ZDC timing information, as well as the correlation between the number of reconstructed tracks in TPC and number of hits in the SPD detector. Electromagnetically induced interactions are reduced by requiring an energy deposition above 500 GeV in each of the neutron-ZDCs [113].

Following the above trigger setup, ALICE collected $\sim 56 \times 10^6$ (integrated luminosity of 9 μb^{-1}) minimum bias Pb-Pb events during the data taking period. In this analysis, 87 runs have been used (5 μb^{-1}) following the requirement of having ITS, TPC and TOF detector information in readout to provide additional PID information and their performance were validated by the quality assurance chain and declared them as optimal. After validating these conditions, the events available from these runs, after the offline event selection are about 18×10^6 and tagged as valid collision events. The present analysis uses Analysis Object Data (AOD), which is dedicated to physics objectives from the Event Summary data (ESD). ESD data contain all the information for analysis produced at reconstruction steps. The data used for analysis is the data filtered from the second reconstruction pass (pass 2) and AOD sample used is AOD160.

3.2.2 Monte Carlo simulated data set

The corrections to account for acceptance $\times$ efficiency and other performance related quantities are computed by using simulated collision data generated using the HIJING Monte Carlo event generator [114] transported through a GEANT3 [115] simulation of ALICE detectors and material. The centrality definition is adjusted so that the particle density in Monte Carlo is similar to that in real data for the same centrality classes. Two main Monte Carlo productions are used and are identified in the following as

Table 3.1: Information of number of event in Pb-Pb data and Monte Carlo data with the corresponding AliRoot version used in the reconstruction before the event selection, the impact parameter and the number of injected $\Lambda(1520)$ per event in simulated dataset.

	AliRoot version	b selection (fm)	$N_{\Lambda(1520)}/\text{event}$	N_{events} (M)
LHC11a10a_bis	v4-20-Rev-29			1.942
LHC16f2a		0–5	50	0.031
LHC16f2b	v5-08-12-cookdedx-1	5–11	14	0.168
LHC16f2c		11–15	6	0.552
LHC16f2a_bis		0–5	50	0.031
LHC16f2b_bis	v5-08-12-cookdedx-1	5–11	14	0.167
LHC16f2c_bis		11–15	6	0.549

- *General-Purpose Monte Carlo*, production tag LHC11a10a_bis
- *Injected Monte Carlo*, production tags LHC16f2abc and LHC16f2abc_bis (identical productions)

The *General-Purpose Monte Carlo* is a Monte Carlo production performed with the reconstruction code and configurations very close to the ones used for the raw data reconstruction. For this reason, it is supposed to reproduce the performance of the analysed data sample best.

The *Injected Monte Carlo* is a dedicated Monte Carlo production for the $\Lambda(1520)$ analysis presented in this thesis. To enhance the statistics for the corrections, $\Lambda(1520)$ particles are injected in the HIJING event. The configuration of the injection has been optimised in order to achieve insignificant bias on charged-particle multiplicity as well as to achieve the desired performance without demanding high computing needs. For this reason, the *Injected Monte Carlo* production has been split into three subsamples with different HIJING impact parameter (b) selection and a corresponding different level of $\Lambda(1520)$ injection. The details are reported in Table 3.1.

3.3 Event selection

The physics selection has already been applied during ESD filtering in the data sample mentioned in Section 3.2.1 above. The minimum-bias trigger events has been selected to perform this analysis. After trigger selection, the events satisfying the following selection criteria have been selected for this analysis

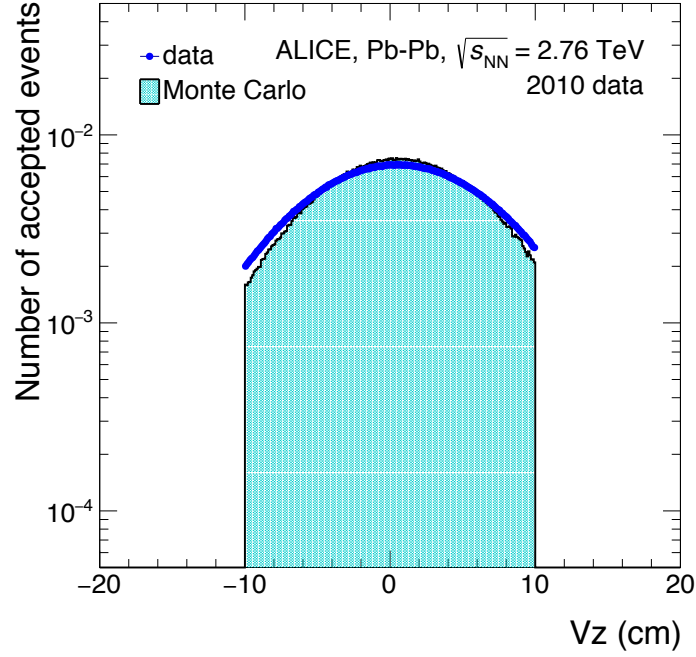


Figure 3.1: z -vertex distribution of selected events after passing the vertex cut in full centrality range 0-100%.

1. the z -position of the primary vertex in beam direction (z) to be within $|z_{vtx}| < 10$ cm with respect to the nominal interaction point
2. centrality range 0 to 80%

The description of vertex reconstruction method in ALICE is discussed in Section 2.5 of the Chapter 2. The event is requested to have a valid reconstructed primary vertex, defined using the information available from the SPD or TPC tracks. For the selected events and for the centrality classes utilised in this analysis ($< 80\%$), a valid vertex is always reconstructed, owing the large number of primary particles produced. Therefore, no vertex-selection corrections are needed. Furthermore, the z -position of the vertex in the beam direction (z) is requested to be within $|z_{vtx}| < 10$ cm with respect to the nominal interaction point to ensure a uniform acceptance in the central pseudo-rapidity region $|\eta| < 0.8$. This reduces the total number of events from initial sample to $\sim 16 \times 10^6$. In Figure 3.1, the z -vertex distribution of the selected events after passing the vertex cut is shown and compared with the Monte Carlo data set.

The determination of centrality estimation in ALICE is discussed in Section 2.7 of Chapter 2. The centrality selection distribution of the events after trigger, vertex and centrality selection is shown in Figure 3.2, which is observed to be flat as expected. The events within 0-80% centrality have been selected and the number of events analysed in the different centrality classes defined are reported in Table 3.2. The events in most peripheral bin (80-90%) have not been

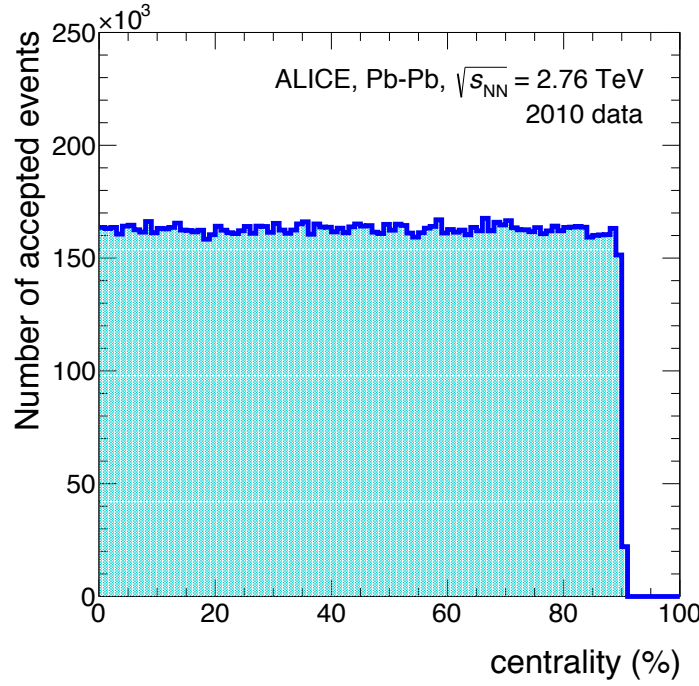


Figure 3.2: Centrality distribution of selected events after passing the centrality selection criteria in the range 0-100%.

included in this analysis due to statistical limitations and larger uncertainty on the centrality determination. The events in 90-100% centrality has been discarded because these events are contaminated by background events and are triggered with an efficiency lower than 100%.

The reaction plane is an event property, defined by the beam axis (z) to the impact parameter direction. The reaction plane angle, Ψ_R is calculated with the help of global tracks and defined as

$$\Psi_R = \frac{1}{2\sqrt{N}} \tan^{-1} \left(\frac{\sum_{i=1}^N \sin(2\phi_i)}{\sum_{i=1}^N \cos(2\phi_i)} \right) \quad (3.1)$$

Here, N is the global tracks number, index i runs over all tracks and ϕ is azimuthal angle associated to each track. The reaction plane angle should be flat because if the event plane reconstruction by the detector is homogeneous, that is important to avoid a bias on event selection. Information of reaction plane angle has not been used for event selection but the event plane information is used for the event-mixing background technique (Section 3.6.2), where it is needed to compute similar shape of invariant mass pairs from different events.

3.3.1 Centrality selection in Monte Carlo

The same selection criteria are applied to the Monte Carlo data analysed. The Monte Carlo was already tuned so that the average number of produced particles for a given centrality class

Table 3.2: Information of Pb–Pb data and corresponding dedicated Monte-Carlo data with the number of events in the measured centrality bins.

data type	data set	centrality class (%)	event counts
Pb–Pb (AOD160)	2010 (Integrated luminosity = $9 \mu\text{b}^{-1}$)	0–20	3.3M
		20–50	4.9M
		50–80	4.9M
Monte-Carlo (AOD)	LHC16f2a	0–10	55.4K
	LHC16f2a_bis		
	LHC16f2b	10–50	300K
	LHC16f2b_bis		
	LHC16f2c	50–80	722.5K
	LHC16f2c_bis		

matches the one in the data. The special Injected Monte Carlo, as mentioned in Section 3.2.2 has been used in this analysis, where some extra $\Lambda(1520)$ particles have been added to enhance the statistical significance of the $\Lambda(1520)$. Due to the additional particles, there is some bias in the multiplicity, with a large number of charged particles in the Monte Carlo than in the data, which is shown in Figure 3.3 (upper right and lower middle). Moreover, the generation of the Monte Carlo events is not performed in a uniform way as a function of the collision centrality, as it can be seen in Figure 3.3 (upper left).

In order to match the performance of the data, the average charged-particle multiplicity of the Monte Carlo should match the data. This has been achieved by adjusting the boundaries of the centrality intervals in the Monte Carlo analysis, so that the average number of reconstructed SPD tracklets (Section 2.3.1) better match the data. The results can be seen in Figure 3.5. The adjusted centrality boundaries are reported in Table 3.3 and are used for the default Monte Carlo analysis. In this analysis, the adjusted centrality boundaries are used to have the best agreement between data and Monte Carlo. On the other hand, it has to be noticed that the measured performance (reconstruction efficiency, resolution) does not change dramatically with multiplicity. The $\Lambda(1520)$ reconstruction efficiency is estimated to change by about 7% for a multiplicity variation of a about a factor of 15 (Section 3.8.1). For this reason, the small differences in the average charged-particle multiplicity, estimated by the average number of reconstructed SPD tracklets, in the selected centrality classes between data and Monte carlo (Figure 3.4) would contribute to a small systematics in the estimated reconstruction efficiency of about 0.5%, in the case where no centrality-boundary adjustment is applied.

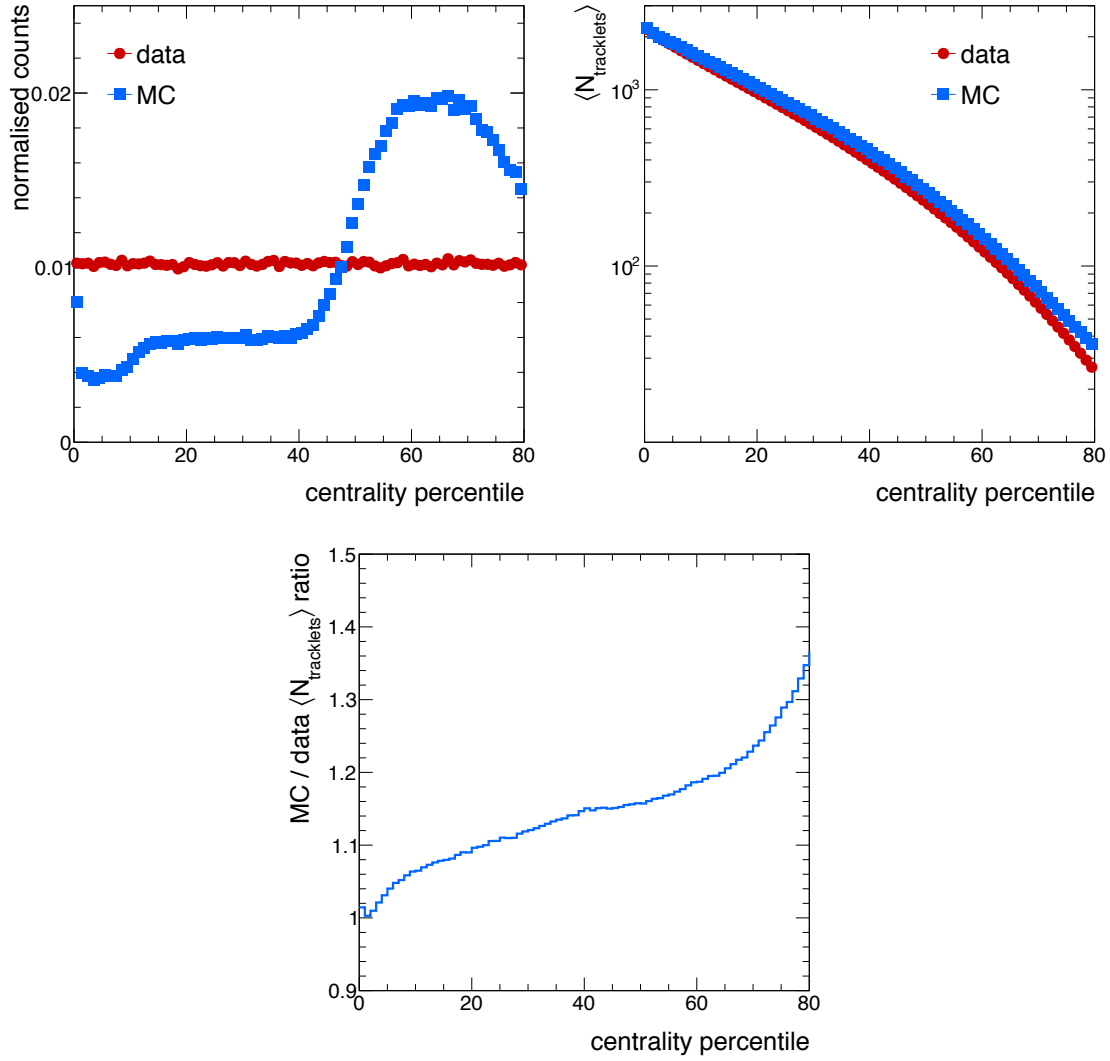


Figure 3.3: (Upper-left) Normalised centrality distribution of selected events in data (Section 3.2.1) and in the *Injected Monte Carlo* (Section 3.2.2). (Upper-right) average number of reconstructed SPD tracklets [110] as a function of centrality. (lower panel) Monte Carlo over data ratio of the average number of reconstructed SPD tracklets as a function of centrality.

Table 3.3: Definition of the centrality classes used for this analysis. The centrality boundaries used in data correspond to the centrality class definition. The centrality boundaries in the *Injected Monte Carlo* (Section 3.2.2) have been adjusted to better match the average number of reconstructed SPD tracklets in the data (Section 3.3.1).

	data	Monte Carlo
0–20%	0–20%	0–22%
20–50%	20–50%	21–51%
50–80%	50–80%	52–85%

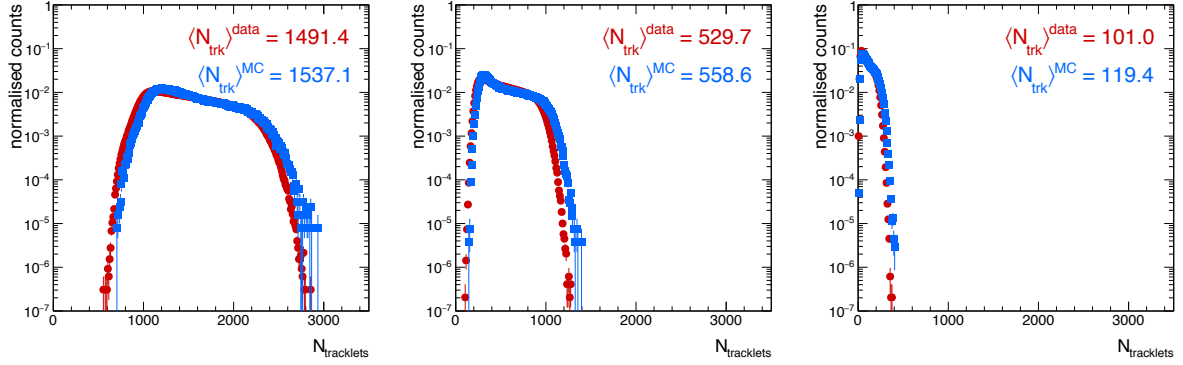


Figure 3.4: Distribution of number of reconstructed SPD tracklets in data and in the *Injected Monte Carlo* (Section 3.2.2) for the centrality classes used in this analysis. The definition of the centrality boundaries for the Monte Carlo is not adjusted to better match the data. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

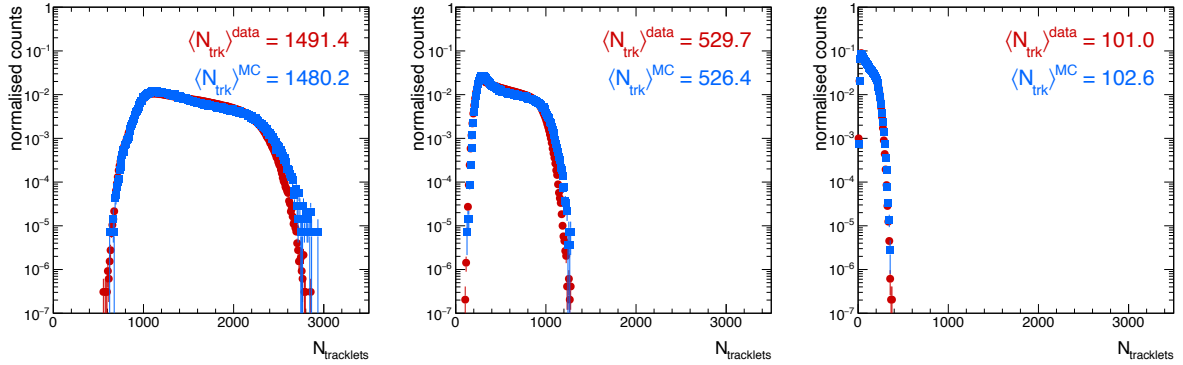


Figure 3.5: Distribution of number of reconstructed SPD tracklets in data and in the *Injected Monte Carlo* (Section 3.2.2) for the centrality classes used in this analysis. The definition of the centrality boundaries for the Monte Carlo has been adjusted to better match the data. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

3.4 Track selection

The $\Lambda(1520)$ has been studied in the hadronic decay channel $\Lambda(1520) \rightarrow pK^-$ (B.R. = 22.5%) [64] and corresponding charge conjugate decay channel at mid-rapidity ($-0.5 < y < 0.5$). Due to the very short life-time of $\Lambda(1520)$ ~ 12.6 fm/c, it decays before the kinetic freeze-out stage after its production and does not make it out of the beam pipe.

In heavy-ion collisions, primary charged particles are produced in bulk, therefore the selection of the daughter candidates, p and K is very challenging for the reconstruction of $\Lambda(1520)$. Therefore, this analysis has been performed by selecting good quality primary tracks from each event. The global tracking is done by using the ITS and TPC detectors.

To select good quality tracks, several selection cuts have been applied to the tracks of those events that pass the event selection cuts. The tracks are selected by the following cuts on the quality of reconstruction

- required successful refit of the reconstruction algorithm from the outer layer of the detector to the primary vertex and vice-versa, through the TPC and ITS detector
- the number of the clusters associated to the track in TPC, $N_{clusters}^{TPC} \geq 70$ out of 159 and at least one hit in SPD *i.e* $N_{clusters}^{SPD} \geq 1$
- the quality of the track fitting with $\chi^2/N_{clusters}^{TPC} < 4$ and $\chi^2/N_{clusters}^{ITS} < 36$ in TPC and ITS respectively by the Kalman filter algorithm [100]
- reject tracks identified as Kink daughters. The kaon decays such as $K^\pm \rightarrow \mu^\pm + \nu_\mu$ inside the active volume of the detectors are defined as "Kinks"
- required component of the distance of closest approach (DCA) to the primary vertex in the direction parallel to the beam is $|DCA|_Z < 2$ cm to get rid of tracks coming from weak decay of strange hadrons and interaction from detector material
- required component of the DCA to the primary vertex in the radial direction (XY-plane) must satisfy the relation $DCA_r(p_T) < (18.2 + 35.0 p_T^{-1.1})(\mu m)$. This takes into account the deflection of the trajectories in the magnetic field
- cut on transverse momentum $p_T > 0.15$ GeV/c, to keep a reasonable momentum resolution
- to stay in uniform acceptance of TPC, cut on η range on each track ≤ 0.8

In order to select the tracks pointing to primary vertex known as primaries, they are required to have at least one associated cluster in any of the SPD layer. Further DCA cuts, which is related to the impact parameter have been applied. The DCA to the primary vertex is the minimum distance between the reconstructed track trajectory when extrapolated to the primary vertex and should be ideally zero assuming the track is coming from the primary vertex point. The resolution on the DCA depends on the primary vertex resolution and on the track reconstruction resolution.

The above tracks cuts are called "*Standard 2010 track quality cuts*" and corresponds to filterbit 5 (standard with tight DCA track cuts). The applied cuts on tracks are summarised in Table 3.4. Finally, a pair rapidity cut, $|y| < 0.5$ on the candidate $\Lambda(1520)$ pairs has been applied.

After applying the track cuts listed in Table 3.4, the quality of each track has been checked by studying the distribution of the various track variable *i.e* φ , η , DCA_{xy} and DCA_z etc. The φ angle

Table 3.4: Track and filterbit 5 selection cuts applied for the 2010 data. The DCA_{XY} and p_T -dependent cuts is expressed in $\mu\text{m GeV}/c$.

Track cuts	2010 data
TPC refit	required
Kink daughter	reject
$N_{clusters}^{TPC}$	≥ 70
$\chi^2 / N_{clusters}^{TPC}$	< 4
$\chi^2_{\text{constrained vs. global}}$	< 36
ITS refit	required
$N_{clusters}^{SPD}$	≥ 1
$\chi^2 / N_{clusters}^{ITS}$	< 36
$DCA_{XY} (\mu\text{m})$	$< (18.2 + 35.0 p_T^{-1.1})$
$DCA_Z (\text{cm})$	< 2
$p_T (\text{GeV}/c)$	> 0.15
$ \eta $	≤ 0.8
$ y_{PK} $	≤ 0.5

is known as azimuthal angle and defined as, $\varphi = \arctan y/x$, which increases counter-clockwise from x ($\varphi = 0$) to y ($\varphi = \pi/2$) with the observer standing at positive z direction.

The φ distribution of the positive and negative tracks has been shown and compared with the Monte Carlo data scaled to data in Figure 3.6. The drop at $\varphi = 230^\circ$ in Figure 3.6 appears due to a chip module from the ITS detector was off during data taking period. Similarly, The η distribution of selected tracks has been shown and compared with the scaled Monte Carlo data in Figure 3.7. From the Figure 3.6 and Figure 3.7, it is clear that the Monte Carlo tracks have the similar φ and η behaviour to the data associated tracks. The applied cuts for DCA_{xy} and DCA_z have been shown and compared with the Monte Carlo data scaled to data in Figure 3.9. From the Figure 3.8, it is clear the DCA cuts on tracks in xy and z direction written in Table 3.4 from the collision interaction point have been successfully applied.

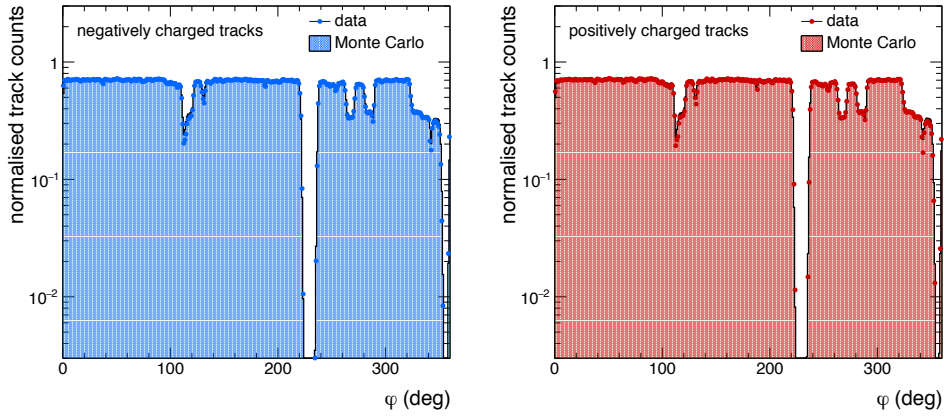


Figure 3.6: φ distribution of selected positive (left) and negative (right) charged tracks in 2010 data and corresponding Monte Carlo (shaded region).

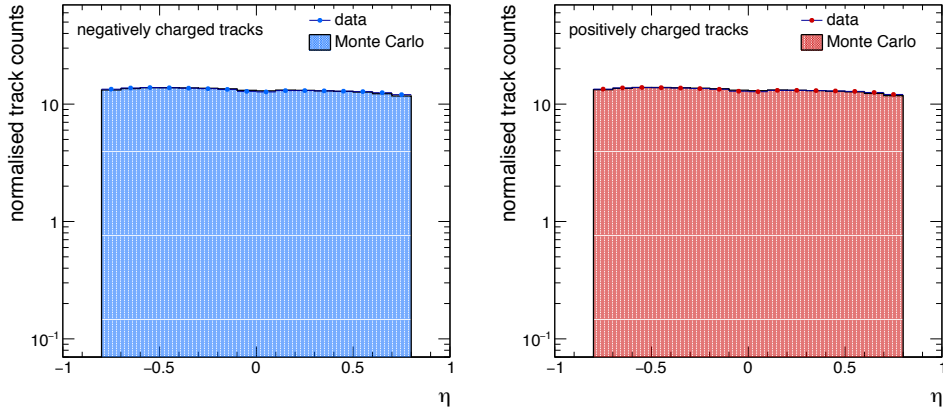


Figure 3.7: η distribution of selected positive (left) and negative (right) charged tracks in 2010 data and corresponding Monte Carlo (shaded region).

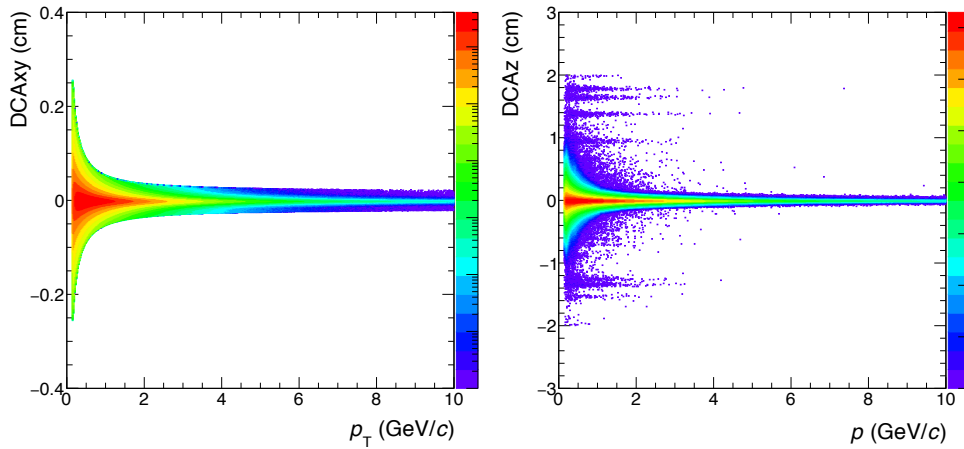


Figure 3.8: DCAxy (left) vs p_T and DCAz (right) vs p distribution of selected charged tracks in 2010 data.

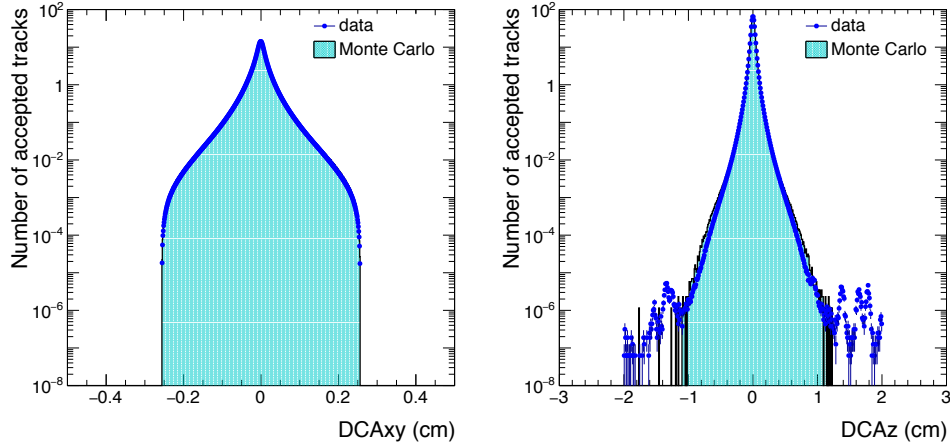


Figure 3.9: DCAxy (left) and DCAz (right) distribution of selected charged tracks in 2010 data and corresponding Monte Carlo (shaded region).

3.5 Kaon and proton identification

The particle identification of kaons and protons is done by the combined information of the TPC and TOF detectors. In order to achieve a successful reconstruction of the $\Lambda(1520)$ signal, it is mandatory to identify kaons and protons with high purity to reduce as much as possible the combinatorial background coming from the association of mis-identified tracks into a candidate pair.

In ALICE, there are several methods to identify charged particle: the measurement of specific energy loss (also charge and momentum, which makes it an excellent PID detector) by TPC detector (Section 2.3.2) and the time-of-flight information in TOF detector (Section 2.3.3). The PID strategy used in this analysis is the " $n\sigma$ -cut" method, discussed in the following.

Let's suppose i indicates the detector used for PID ($i = \text{TPC, TOF}$) and j indicates the particle species hypothesis. The " $n\sigma$ -cut" method is based on the definition of a discriminating variable defined as

$$n_{i,j}^{\sigma PID} = \frac{X_j - X_{i,j}^{exp}}{\sigma_{i,j}^{PID}} \quad (3.2)$$

Here X_j is measured variable in the detector i , $X_{i,j}^{exp}$ is the prediction of that observable's value in the mass hypothesis j and $\sigma_{i,j}^{PID}$ is the resolution on the measurement which depends on detector performance. Afterwards, particle identification is performed by applying an appropriate cut on this discriminating variable. If one would like to exploit the TPC here, X_{TPC} is the specific energy loss, dE/dx by the particle in the detector gas and above equation 3.2 becomes 3.3. With TOF, X_{TOF} is the measured time-of-flight and above equation 3.2 becomes 3.4 [11].

In the TPC detector, the specific energy loss (dE/dx) of the track is compared with the

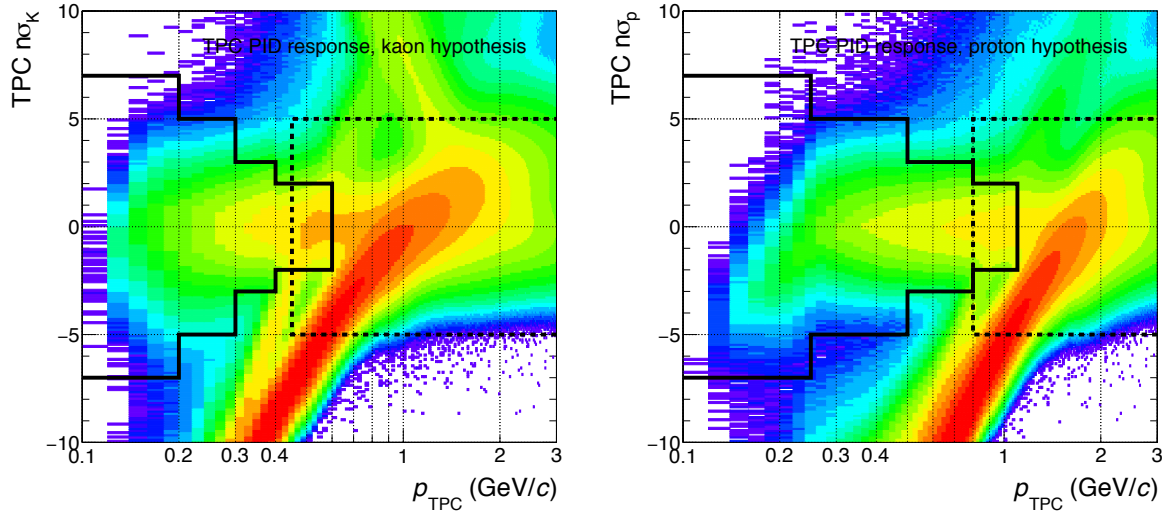


Figure 3.10: $n\sigma$ particle identification of the measured to the expected track energy loss in the TPC as function of the track momentum at the TPC inner wall for kaons (left) and protons (right) for the 2010 Pb-Pb data. The solid and dashed lines represent the TPC selection for TPC-only and TPC-TOF identification, respectively.

expected energy loss (given by Bethe-Bloch formula) for different particle species. The variable $n\sigma$, distance to the expected energy loss for particular particle species hypothesis to identify the tracks in terms of detector resolution is defined as

$$n\sigma = \frac{dE/dx_{measured} - dE/dx_{expected}}{\sigma_{PID(TPC)}} \quad (3.3)$$

Here $dE/dx_{measured}$ is measured energy loss in the TPC gas, $dE/dx_{expected}$ is the expected energy loss for particular particle hypothesis and $\sigma_{PID(TPC)}$ is the TPC dE/dx resolution.

In Time-Of-Flight (TOF) detector, the time of flight of the particle measured by the TOF detector is compared with the expected arrival time of flight for a given particle species hypothesis. The variable $n\sigma$ to identify the particles in the TOF is based on four elements

$$n\sigma = \frac{t_{measured} - t_{expected}}{\sigma_{PID(TOF)}} \quad (3.4)$$

Here $t_{measured} = t_{hit} - startTime$ and t_{hit} is the particle arrival time measured in the TOF detector, $startTime$ is event collisions time (namely the particle start time) and $t_{expected}$ is computed by the ALICE reconstruction taking into account track length, momentum and energy loss in the material. The variable $\sigma_{PID(TOF)}$ is called proper response function, defined as

$$\sigma_{PID(TOF)} = \sqrt{\sigma_{TOF}^2 + \sigma_{starttime}^2 + \sigma_{tracking}^2} \quad (3.5)$$

The $\sigma_{PID(TOF)}$ depends on intrinsic resolution of the TOF detector, on the tracking capabilities of the ALICE and on the precision in the determination of the collision time of the events, which

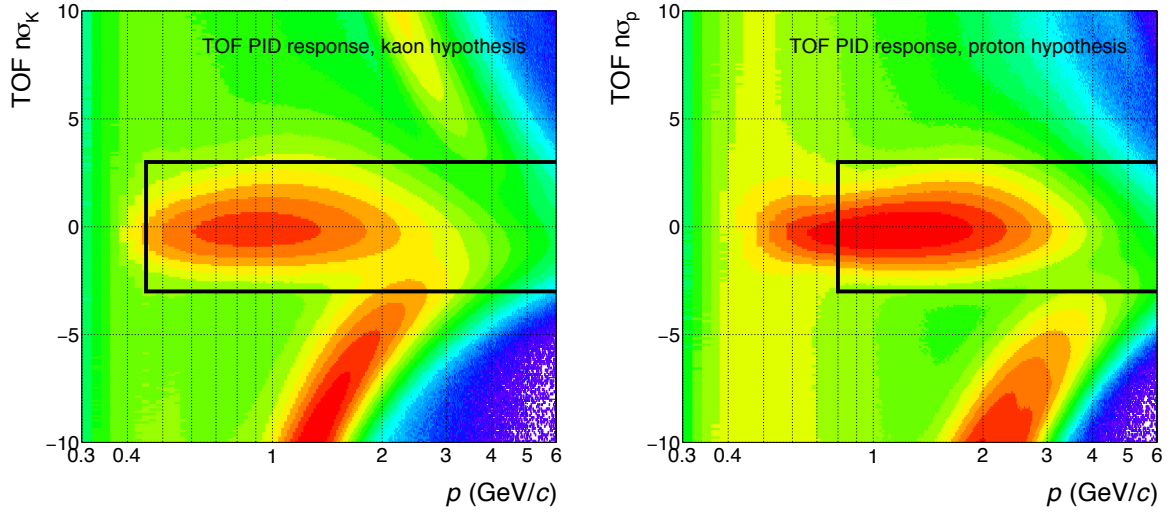


Figure 3.11: $n\sigma$ particle identification of the measured to the expected track time-of-flight in the TOF as function of the track momentum for kaons (left) and protons (right) for the 2010 Pb-Pb data. The solid dashed lines represents the TOF selection.

depends on the "T0" detector resolution, number of tracks reaching the TOF and the spread of the vertex.

The TPC and TOF response for kaon and proton hypothesis are reported in Figure 3.10 and Figure 3.11, respectively, for the tracks selected with the standard cuts, from the full dataset (section 3.2.1) used in this analysis. The response of the TPC is plotted in terms of the $n_{TPC,K}^{\sigma PID}(n_{TPC,p}^{\sigma PID})$ as a function of the momentum reconstructed at its inner radius (p_{TPC}), while the TOF response is given by $n_{TOF,K}^{\sigma PID}(n_{TOF,p}^{\sigma PID})$ as a function of p .

The particle identification in this analysis is performed in such a way to exploit the excellent capabilities of the TOF detector aiming at extending the $\Lambda(1520)$ measurement to higher p_T as much as possible as compared to TPC PID only. Also, TPC pid at low- p_T and TOF pid at intermediate- p_T is used to reduce the systematic uncertainty of the measured $\Lambda(1520)$ parameters. Here, TPC PID is also used as a veto cut in order to reduce the contribution from the combinatorial background coming from low- p_T mismatched tracks in the TOF detector. Table 3.5 represents the particle identification strategy adopted to select kaons and protons.

A large σ cut - 7, 5 and 3 has been applied in the TPC in low momentum region, where the dE/dx separation between different particles is large, up to 200, 300 and 400 MeV/c for kaons, respectively, and up to 250, 500 and 800 MeV/c for protons, respectively, in order to select the largest sample of particles. Further, on TPC PID, a 2σ cut up to 600 MeV/c for kaons and up to 800 MeV/c for protons has been applied, which allows a clean separation of kaons from pions and electrons and protons from kaons and electrons. To clearly identify the

higher momentum tracks, the presence of the TOF signal was set as mandatory imposing a 3σ TOF-matching requirement for kaons from $p > 600$ MeV/ c and for protons from $p > 1.1$ GeV/ c . Also, to reduce the contribution from mismatched tracks in the TOF, an additional 5σ cut (kaons: $p > 450$ MeV/ c , protons: $p > 800$ MeV/ c) on TPC dE/dx has been applied. A track identified within 3σ as a kaon (or a proton) by TOF is rejected if it is not identified as a kaon (or a proton) also from 5σ from the TPC.

Table 3.5: Particle identification selection for charged kaons, protons and antiprotons.

$K^\pm$	$p < 0.2$		$\sigma_{\text{TPC}} < 7$
	$0.2 < p < 0.3$		$\sigma_{\text{TPC}} < 5$
	$0.3 < p < 0.4$		$\sigma_{\text{TPC}} < 3$
	$0.4 < p < 0.45$		$\sigma_{\text{TPC}} < 2$
	$0.45 < p < 0.6$	$\overline{\text{TOF}}$	$\sigma_{\text{TPC}} < 2$
		TOF	$(\sigma_{\text{TPC}} < 5) \wedge (\sigma_{\text{TOF}} < 3)$
	$p > 0.6$	$\overline{\text{TOF}}$	reject
		TOF	$(\sigma_{\text{TPC}} < 5) \wedge (\sigma_{\text{TOF}} < 3)$
$p(\bar{p})$	$p < 0.25$		$\sigma_{\text{TPC}} < 7$
	$0.25 < p < 0.5$		$\sigma_{\text{TPC}} < 5$
	$0.5 < p < 0.8$		$\sigma_{\text{TPC}} < 3$
	$0.8 < p < 1.1$	$\overline{\text{TOF}}$	$\sigma_{\text{TPC}} < 2$
		TOF	$(\sigma_{\text{TPC}} < 5) \wedge (\sigma_{\text{TOF}} < 3)$
	$p > 1.1$	$\overline{\text{TOF}}$	reject
		TOF	$(\sigma_{\text{TPC}} < 5) \wedge (\sigma_{\text{TOF}} < 3)$

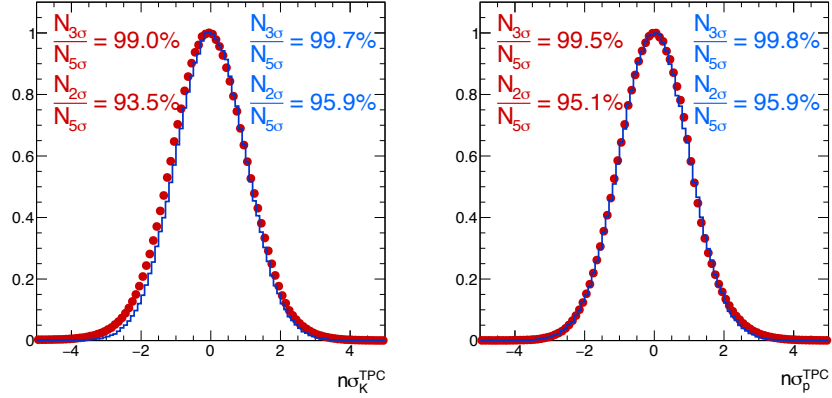


Figure 3.12: PID signal in TPC for kaons at 300 MeV/ c (left) and for protons at 500 MeV/ c (right) compared between data (red points) and Monte Carlo (blue line). The fraction of the signal included within a $3(2)\sigma$ cut with respect to the 5σ integral allows to quantitatively compare the agreement of the PID efficiency between data and Monte Carlo.

3.5.1 Quality assurance of PID

The quality of the PID signals in the analysed data and the agreement with the Monte Carlo have been checked carefully. The PID signal for kaons and protons in the TPC is shown in Figure 3.12 for tracks with momentum 300 and 500 MeV/ c , respectively, where a clean signal can be observed. Similarly, the PID signal for kaons and protons in the TOF is shown in Figure 3.13 for tracks with momentum 1.25 and 2.0 GeV/ c , respectively. As it can be observed, data and Monte Carlo are in very good qualitative agreement.

The agreement between data and Monte Carlo can be evaluated quantitatively by computing the fraction $f_{n\sigma}$ of signal counts which falls within a $n\sigma$ window ($N_{n\sigma}$) over the total signal, that is the counts within a 5σ window ($N_{5\sigma}$)

$$f_{n\sigma} = \frac{N_{n\sigma}}{N_{5\sigma}} \quad (3.6)$$

both for data ($f_{n\sigma}^{\text{data}}$) and for Monte Carlo ($f_{n\sigma}^{\text{MC}}$). This enables one to directly compare the efficiency of a $n\sigma$ PID cut and evaluate possible systematic differences between data and Monte Carlo.

The results are summarised in Table 3.6 where the TPC PID is checked against both 2σ and 3σ , whereas TOF PID is only checked against 3σ cut. The agreement between data and Monte Carlo is quantitatively good, namely, the cut efficiency difference between data and Monte Carlo for kaon and proton ID is about 1%, with the only exception from the $2\text{-}\sigma$ kaon ID in the TPC where the difference is about 2.5%.

From these checks, one can estimate the $\Lambda(1520)$ PID systematic uncertainty corresponding

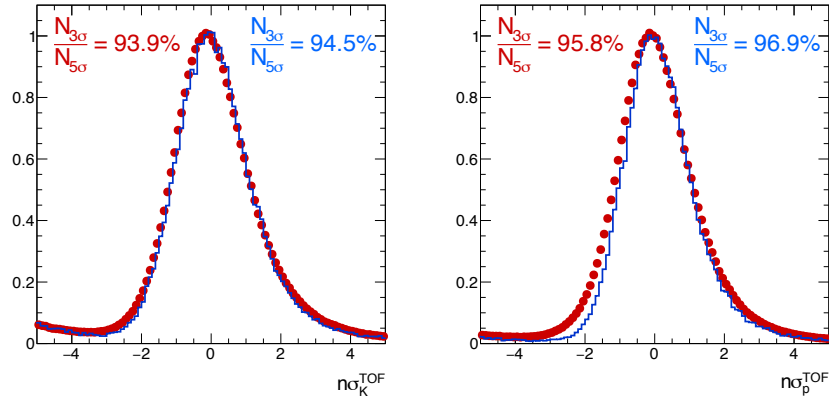


Figure 3.13: PID signal in TOF for kaons at 1.25 GeV/c (left) and for protons at 2 GeV/c (right) compared between data (red points) and Monte Carlo (blue line). The fraction of the signal included within a 3σ cut with respect to the 5σ integral allows to quantitatively compare the agreement of the PID efficiency between data and Monte Carlo.

to the kaon and proton ID in TPC and TOF. The most extreme case that one can have in this analysis is TPC $2\text{-}\sigma$ kaon ID combined with TOF $3\text{-}\sigma$ proton ID. This would result in a $2.5\% + 1.1\%$ PID = 3.6% systematic difference in the PID efficiency in data with respect to the Monte Carlo. On the other hand, this is really the most extreme case, as TPC $2\text{-}\sigma$ PID cuts are only used in a very narrow momentum range (Table 3.5). Most of the PID is performed with $3\text{-}\sigma$ cuts and in this case, the most extreme value for the PID systematics would be about 1.8% .

Table 3.6: The results of the TPC PID checked against both 2σ and 3σ , whereas TOF PID is only checked against 3σ cut for kaons and protons (Section 3.5.1)

	kaon identification		
	$f_{n\sigma}^{\text{data}}$	$f_{n\sigma}^{\text{MC}}$	$f_{n\sigma}^{\text{data}}/f_{n\sigma}^{\text{MC}}$
TPC ($2\text{-}\sigma$)	0.935	0.959	0.975
TPC ($3\text{-}\sigma$)	0.990	0.997	0.993
TOF ($3\text{-}\sigma$)	0.939	0.945	0.994
	proton identification		
	$f_{n\sigma}^{\text{data}}$	$f_{n\sigma}^{\text{MC}}$	$f_{n\sigma}^{\text{data}}/f_{n\sigma}^{\text{MC}}$
TPC ($2\text{-}\sigma$)	0.951	0.959	0.992
TPC ($3\text{-}\sigma$)	0.995	0.998	0.997
TOF ($3\text{-}\sigma$)	0.958	0.969	0.989

3.6 $\Lambda(1520)$ raw yield measurement

The raw yield of $\Lambda(1520)$ is measured via invariant-mass reconstruction technique in the decay channels

$$\Lambda(1520) \rightarrow p + K^- \quad (3.7)$$

$$\bar{\Lambda}(1520) \rightarrow \bar{p} + K^+ \quad (3.8)$$

both with a decay branching fraction [64] of

$$\frac{\Gamma_{\Lambda(1520) \rightarrow pK}}{\Gamma} = 22.5 \pm 0.5\% \quad (3.9)$$

To enhance the statistical significance of the signal, $\Lambda(1520)$ particle and antiparticle states, $\bar{\Lambda}(1520)$ are added together. For this reason, in the following $\Lambda(1520)$ indicates the sum of particle and antiparticle states, unless otherwise specified. The data sample used for this analysis is discussed in Section 3.2.1.

3.6.1 Signal reconstruction

Charged kaons and (anti)protons used in this analysis are requested to pass the track-selection cuts (Section 3.4) and to be identified according to the particle-identification cuts (Section 3.5). It is impossible to build the $\Lambda(1520)$ signal by only selecting the kaon and proton because these decay daughters are indistinguishable from other primary tracks. In order to follow the right approach, the extraction of the signal is done with the help of opposite charge daughter tracks. Therefore, the signal of $\Lambda(1520)$ resonance is reconstructed via the invariant mass technique, which is one of the best and well-known methods for resonance particle reconstruction since a long time.

The technical reconstruction of the invariant mass (m_{Kp}) and the momentum vector in the laboratory frame ($\vec{p}_{Kp}$) for the proton-kaon system is defined as

$$m_{Kp}c^2 = \sqrt{E_{Kp}^2 - |\vec{p}_{Kp}c|^2}, \quad (3.10)$$

$$\vec{p}_{Kp} = \vec{p}_K + \vec{p}_p, \quad (3.11)$$

$$E_{Kp} = E_K + E_p, \quad (3.12)$$

$$E_K(E_p) = m_K^2c^4(m_p^2c^4) + \vec{p}_K^2c^2(\vec{p}_p^2c^2) \quad (3.13)$$

where $\vec{p}$ indicates the momentum vector measured in the laboratory frame. The rapidity of the reconstructed proton-kaon system is requested to be within $|y| < 0.5$. The selected charged kaons

and (anti)proton candidate pairs from the same event contribute to the same-event invariant-mass

$$m_{Kp}^{\text{same}} = m(K + p) \quad (3.14)$$

The same-event invariant mass distributions are constructed for both unlike-sign ($m_{Kp,\text{unlike}}^{\text{same}}$) and like-sign ($m_{Kp,\text{like}}^{\text{same}}$) pairs, for each analysed p_T bins and centrality class. The combinations in the same-event unlike-sign invariant mass distribution are done randomly, the signal from correlated pairs is a very small fraction of a large combinatorial background from uncorrelated pairs, which constitutes the largest part of the distribution.

To ease the signal extraction, an estimate of the combinatorial background distribution (Section 3.6.2) is computed and subtracted from the same-event unlike-distribution to better reveal the signal (Section 3.6.3). There are two possible techniques of estimating combinatorial background

1. event mixing: reconstruct a reference distribution calculated using uncorrelated oppositely charged kaons and protons from different events
2. like-sign: reconstruct a reference distribution calculated using same charged kaons and protons from the same event

3.6.2 Combinatorial background

The combinatorial background from uncorrelated pairs is estimated using the event-mixing approach, thus ensuring that the track combinations are completely uncorrelated. The selected kaons from a given event (event A) are combined to selected protons from a different event (event B) to form the mixed-event invariant mass

$$m_{Kp}^{\text{mix}} = m(K^A + p^B) \quad (3.15)$$

To improve the statistical significance of the event-mixing background, each event is mixed with 15 other events. A more reliable event-mixing description of the same-event combinatorial background is achieved if only events with similar characteristics are mixed. The mixed events are therefore required to have similar

- primary vertex position: $\Delta v_z < 1$ cm
- charged-particle multiplicity: $\Delta N_{\text{ch}} < 10$
- event-plane angle: $\Delta\varphi < 20$ degrees (0.35 rad)

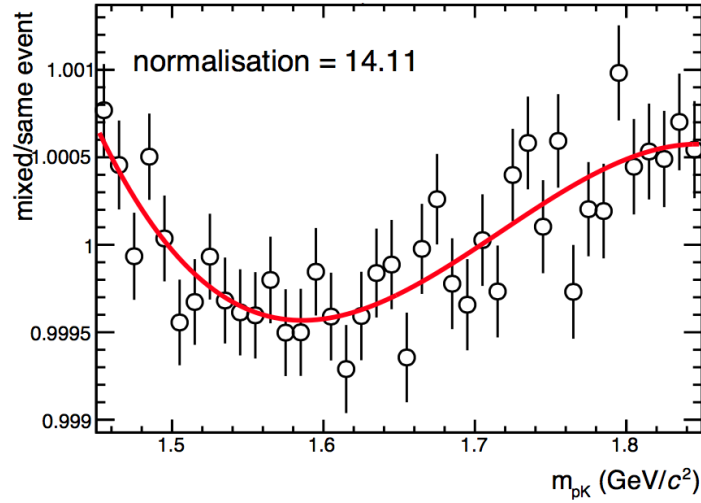


Figure 3.14: Normalisation of event mixing background in 0–20% centrality events in p_T range 0.5 - 1.5 GeV/c.

The vertex reconstruction method is discussed in Section 2.5 of Chapter 2. The information of the reaction plane angle has not been used for the event selection but it is used for the event-mixing background technique (Section 3.6.2), where it is needed to compute similar shape of invariant mass pairs from different events.

The mixed-event invariant mass distributions are constructed for both unlike-sign ($m_{Kp,unlike}^{mix}$) and like-sign ($m_{Kp,like}^{mix}$) pairs. Given the large number of event-mixings requested for each event, the invariant mass distributions obtained have to be properly scaled to match the same-event normalisation. To compute the scaling factor (event-mixing normalisation), the like-sign invariant mass distributions of the same-event ($m_{Kp,like}^{same}$) and of the mixed-event ($m_{Kp,like}^{mix}$) are employed. The event-mixing normalisation factor is defined as

$$F_{mix} = \frac{N_{like}^{mix}}{N_{like}^{same}} \quad (3.16)$$

where N_{like}^{mix} and N_{like}^{same} are the number of counts integrated in the invariant-mass range used for the signal extraction fit (Section 3.6.4) for the mixed-event and the same-event like-sign distributions, respectively. The value shown as "normalisation" obtained in 0–20% centrality in p_T range 0.5 - 1.5 GeV/c is shown in Figure 3.14. The values obtained in each p_T bins are shown as "normalisation" in Figures 3.17, 3.18 and 3.19.

Despite the events to be mixed are requested to be similar, the procedure does not yield perfect results in terms of the description of the same-event combinatorial background. Possible distortions in the shape of the mixed-event background with respect to the same-event combinatorial background are expected. To compute the distortion factor (mixed-event distortion), the like-sign invariant mass distributions of the same-event ($m_{Kp,like}^{same}$) and of the mixed-event

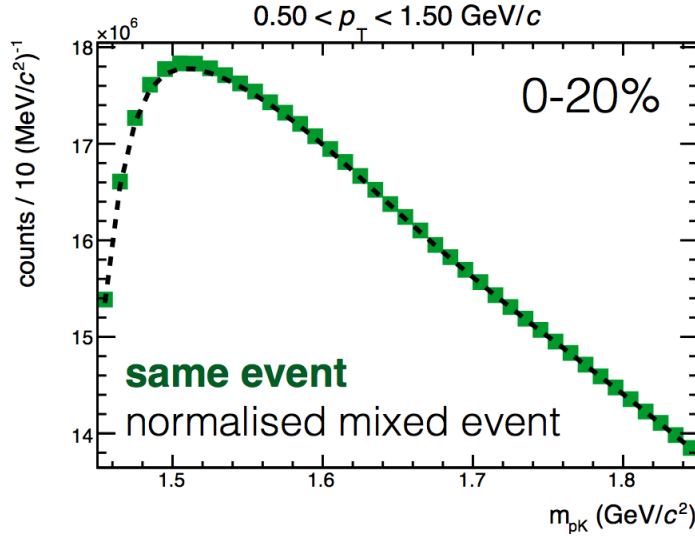


Figure 3.15: Same-event unlike-sign invariant-mass distribution (green marker, Section 3.6) and the estimated combinatorial background (black dotted line, Section 3.6.2) in p_T range 0.5 - 1.5 GeV/c in 0–20% centrality events.

$(m_{Kp,like}^{mix})$ are employed again. The mixed-event distortion factor is defined as the mass-dependent ratio

$$f_{mix} = \frac{m_{Kp,like}^{mix}}{m_{Kp,like}^{same}} \quad (3.17)$$

The obtained ratio is fitted with a 3rd order polynomial function to smoothen the statistical fluctuations, hence defining the event-mixing distortion factor f_{mix}^{fit} . The ratios and fits obtained in each p_T bin are shown in Figures 3.17, 3.18 and 3.19.

Finally, the combinatorial background m_{Kp}^{bkg} is defined as the unlike-sign event-mixing invariant mass corrected for event-mixing normalisation and event-mixing distortion, namely

$$m_{Kp}^{bkg} = \frac{m_{Kp,unlike}^{mix}}{F_{mix} f_{mix}^{fit}} \quad (3.18)$$

Event-mixing has not been performed in the Monte Carlo as raw yield extraction has not been performed in the MC as the environment is completely biased wrt. to the data given the injection.

3.6.3 Signal

The estimated combinatorial background (Section 3.6.2) is subtracted from the same-event unlike-sign invariant-mass distribution (Section 3.6) to obtain the invariant-mass distribution of the signal

$$m_{Kp}^{signal} = m_{Kp,unlike}^{same} - m_{Kp}^{bkg} \quad (3.19)$$

This operation is performed individually for each analysed p_T bin and centrality class. An example of same-event unlike-sign invariant mass distribution and the estimated combinatorial background in p_T range 0.5 - 1.5 GeV/c for 0–20% centrality is shown in Figure 3.15. The same-event unlike-sign invariant-mass distribution and the estimated combinatorial background in all measured p_T bins in 0-20%, 20-50% and 50-80% are shown in Figures 3.20, 3.21, and 3.22, respectively. The resulting background-subtracted invariant mass distributions in all measured p_T bins in 0-20%, 20-50% and 50-80% are shown in Figures 3.23, 3.24, and 3.25. The estimated background is effective in describing the combinatorial background. The event mixing technique is effective in reconstructing resonance signals in heavy ion collisions where the topological method used in Λ and K_s^0 is not possible [116].

However, mixed event combinatorial background does not perfectly reproduce the background for the same event spectrum because it only takes care of the combinatorial background obtained from the uncorrelated pair of kaons and protons. Hence, subtracting this mixed event background, there is always a possibility of certain amount of residual background (correlated) remaining under the signal. This residual background in signal comes from the three dominant sources

1. elliptic flow in non-central Pb-Pb collisions
2. correlated real K–p pair from particle decay.
3. correlated but misidentified particles.

3.6.4 Fit to Signal

The signal extraction is performed by fitting the combinatorial background-subtracted invariant-mass distributions (Section 3.6.3) with the following function

$$f_{\text{total}}(m_{pK}) = f_{\text{signal}}(m_{pK}) + f_{\text{background}}(m_{pK}), \quad (3.20)$$

where m_{pK} is the reconstructed proton-kaon invariant mass. The signal, f_{signal} is parameterized by the Voigtian function, the convolution of the non-relativistic Breit-Wigner function $f_{\text{BW}}(x, M, \Gamma)$ and a Gaussian function $f_{\text{gauss}}(x, \mu, \sigma)$,

$$f_{\text{signal}}(m_{pK}) = S \int_{-\infty}^{+\infty} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(m_{pK} - m')^2}{2\sigma^2}\right] \frac{1}{2\pi} \frac{\Gamma}{(m' - M)^2 + (\Gamma/2)^2} dm' \quad (3.21)$$

$$(3.22)$$

$$f_{\text{signal}}(m_{pK}) = S \frac{\Gamma}{(2\pi)^{3/2}\sigma} \int_{-\infty}^{+\infty} \exp\left[-\frac{(m_{pK} - m')^2}{2\sigma^2}\right] \frac{1}{(m' - M)^2 + (\Gamma/2)^2} dm' \quad (3.23)$$

Table 3.7: Configuration of default fit parameters. The values of mass (M), width (Γ), resolution (σ) and low-mass cutoff (m_{cutoff}) are expressed in (GeV/c^2). The p_T -dependence of the resolution (σ) is determined from the Monte Carlo analysis (Section 3.7.2).

parameter	value	limits	default status
signal normalization (S)		$[0, \infty]$	FREE
mass (M)	1.5195	$[1.51, 1.53]$	FREE
width (Γ)	0.0156		FIXED
sigma (σ)	p_T -dependent		FIXED
background normalization (B)		$[0, \infty]$	FREE
low-mass cutoff (m_{cutoff})	1.431949	$[1.422, 1.442]$	FREE
(n)	1	$[0.5, 2.0]$	FREE
$1/kT$ (C)		$[0, \infty]$	FREE

where S is a normalization factor, M and Γ are the mass and width of the resonance, respectively and σ is the invariant-mass resolution (Section 3.7.2).

The residual background, $f_{\text{background}}$ is described by an exponential function, which is inspired from the Maxwell-Boltzmann distribution

$$f_{\text{MB}}(E) = 2 \sqrt{\frac{E}{\pi}} \left(\frac{1}{kT} \right)^{3/2} \exp \left[-\frac{E}{kT} \right] \quad (3.24)$$

and defined as

$$f_{\text{background}}(m_{\text{pK}}) = B \sqrt{(m_{\text{pK}} - m_{\text{cutoff}})^n} C^{3/2} \exp \left[-C (m_{\text{pK}} - m_{\text{cutoff}})^n \right], \quad (3.25)$$

with the following substitution from Equation 3.24 for Equation 3.25

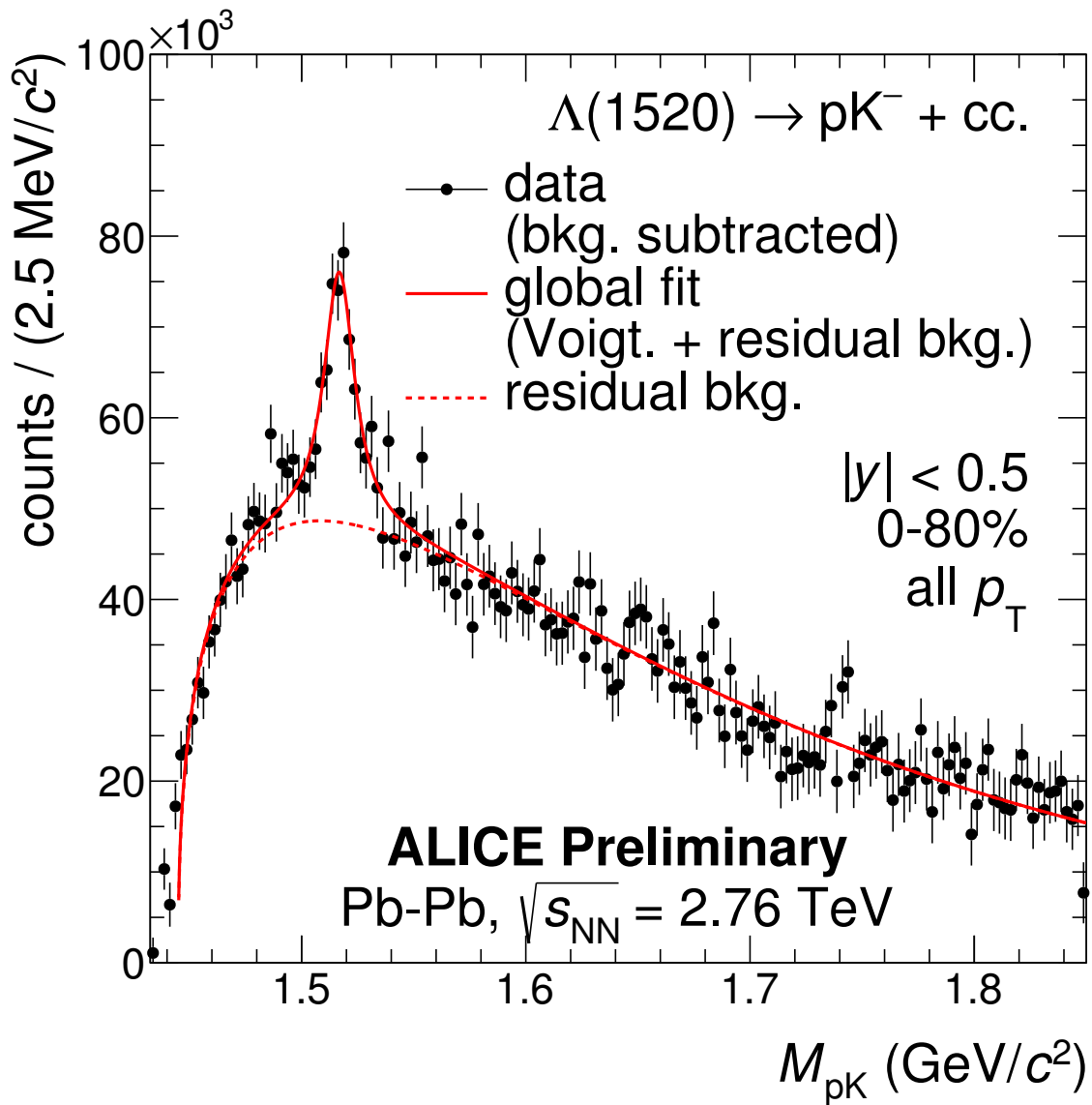
$$E = (m_{\text{pK}} - m_{\text{cutoff}})^n \quad (3.26)$$

$$\frac{1}{kT} = C \quad (3.27)$$

where B is a normalization factor, m_{cutoff} is a shifting parameter which acts as a low-mass cutoff. It can be noticed that for $m_{\text{cutoff}} = 0$ and $n = 1$, Equation 3.25 is equivalent to Equation 3.24. The default fit is performed in the invariant mass range $1.45 < m_{\text{pK}} < 1.85 \text{ GeV}/c^2$ with the configuration shown in Table 3.7.

The idea to use a function similar to Maxwell-Boltzmann distribution function for background shape assumes that the background comes from correlated K-p pairs, emitted from thermal-like sources. This is strictly not true although it is a better choice than polynomial function and has proved to describe the residual background shape nicely over a larger invariant

mass range. The resolution is fixed to the value obtained from the Monte Carlo, as this is the expected resolution. The resonance width is fixed to the PDG value to avoid extra fluctuations, given the large statistical uncertainty of the invariant mass plots. This enables a more reliable determination of the residual background. The invariant mass integrated over centrality and p_T is shown in figure 3.16. The results of fit are shown in Figures 3.23, 3.24, and 3.25.



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Figure 3.16: The Kp invariant mass distribution fitted to extract the $\Lambda(1520)$ integrated over centrality and p_T . The solid curve stands for the fit function using Equation 3.20 and the dashed lines stands for the linear residual background.

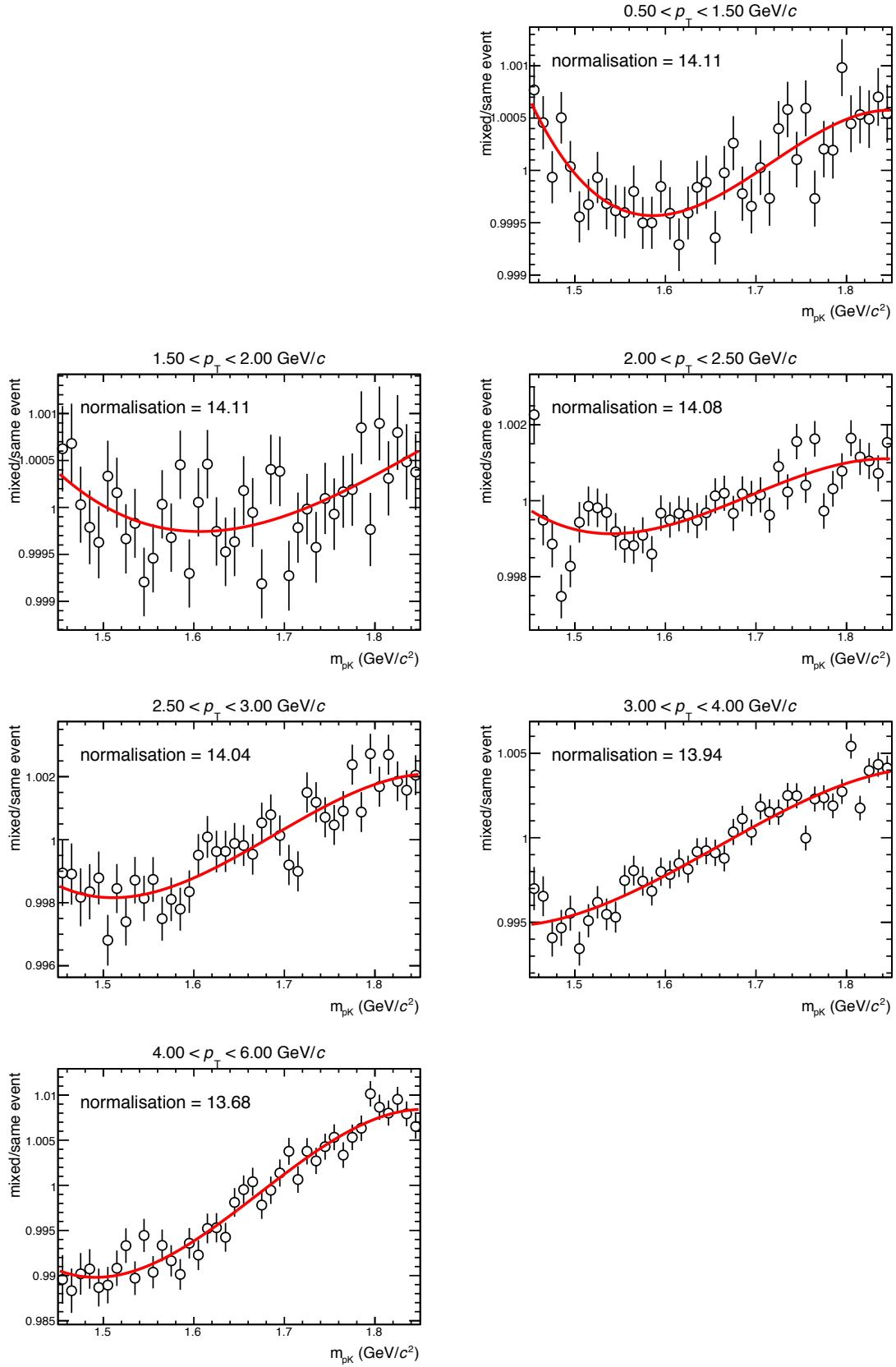


Figure 3.17: Event-mixing distortion factor and normalisation of event mixing background for various p_T bins in 0–20% centrality events.

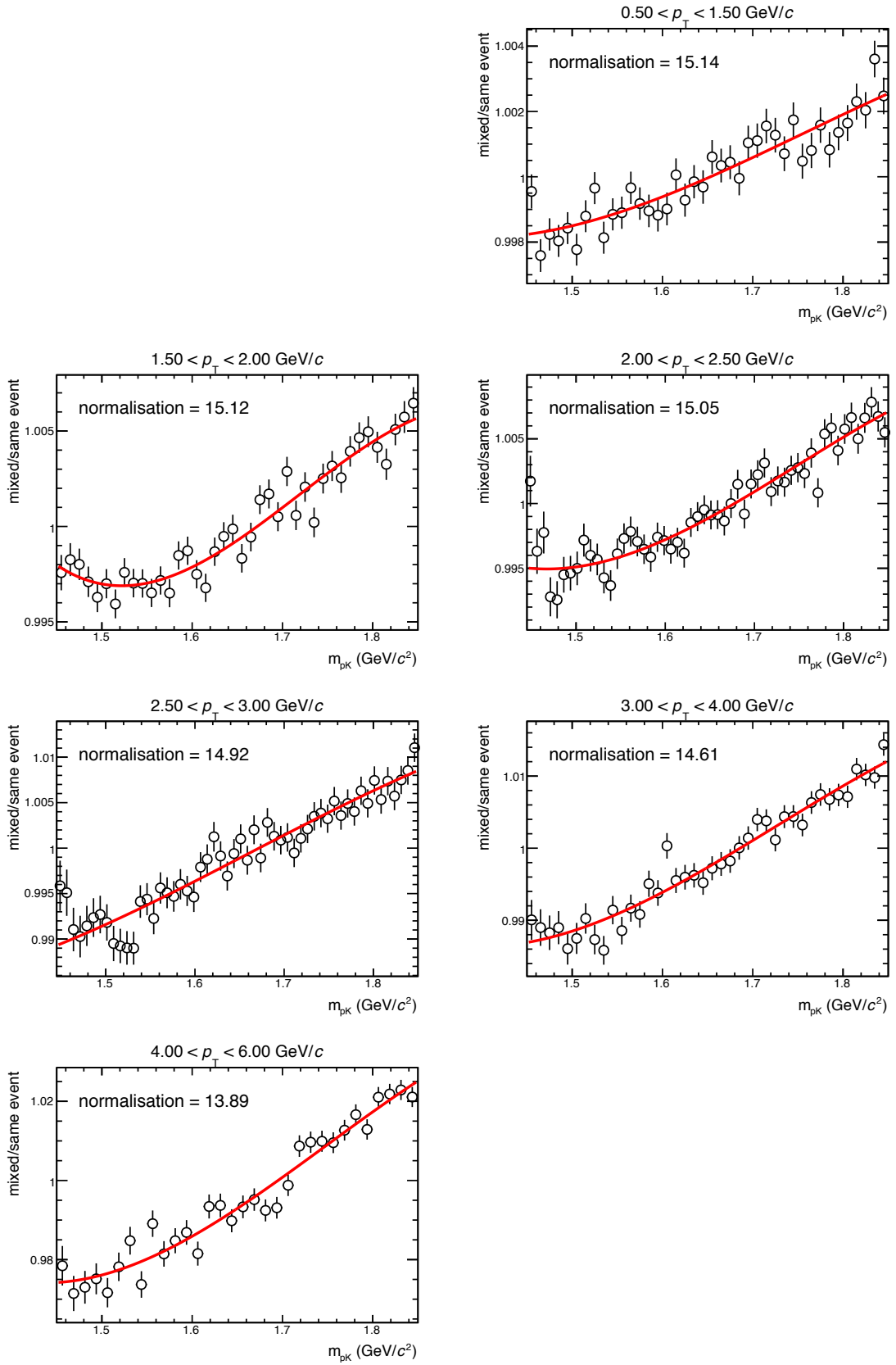


Figure 3.18: Event-mixing distortion factor and normalisation of event mixing background for various p_T bins in 20–50% centrality events.

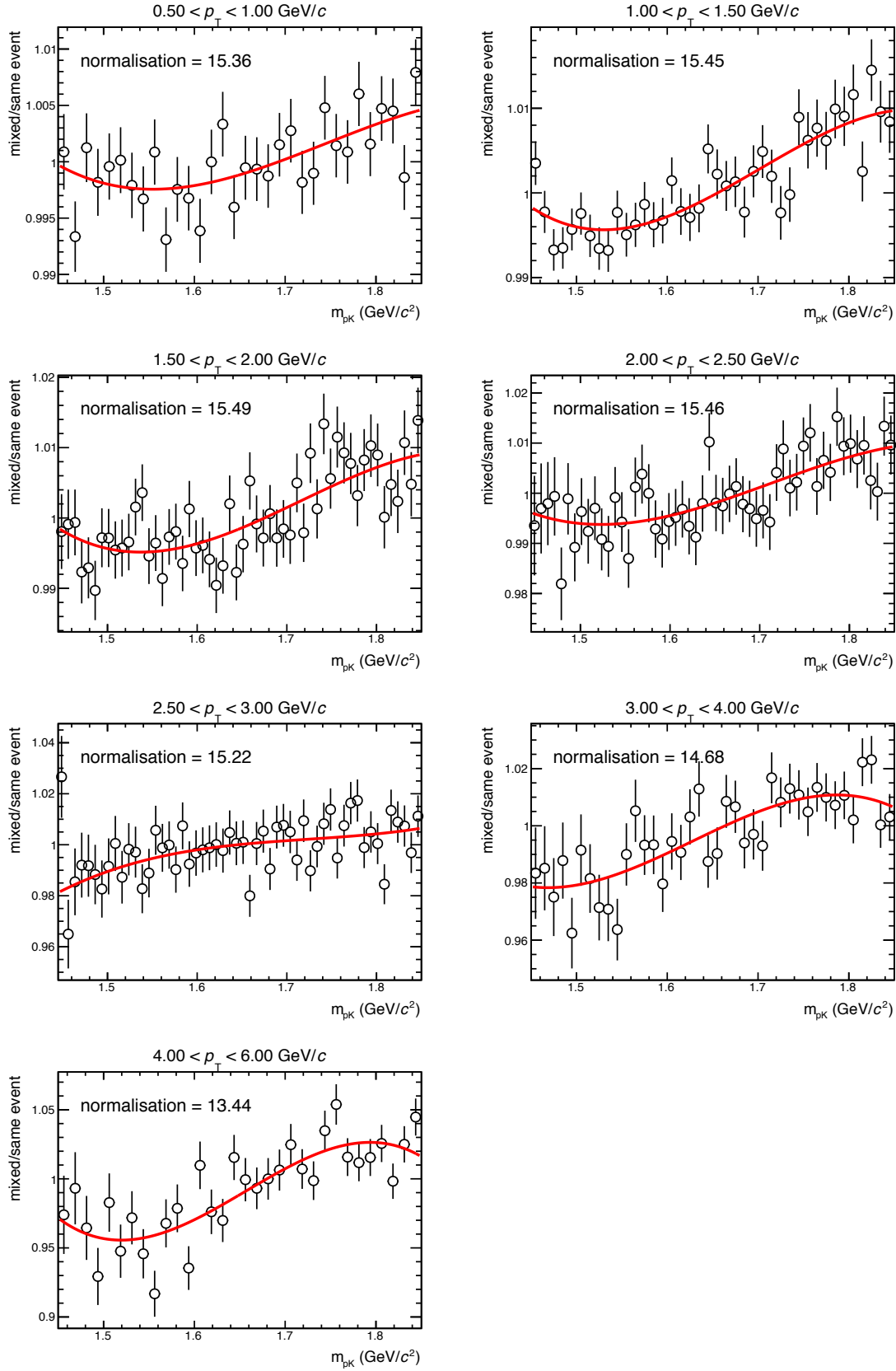


Figure 3.19: Event-mixing distortion factor and normalisation of event mixing background for various p_T bins in 50–80% centrality events.

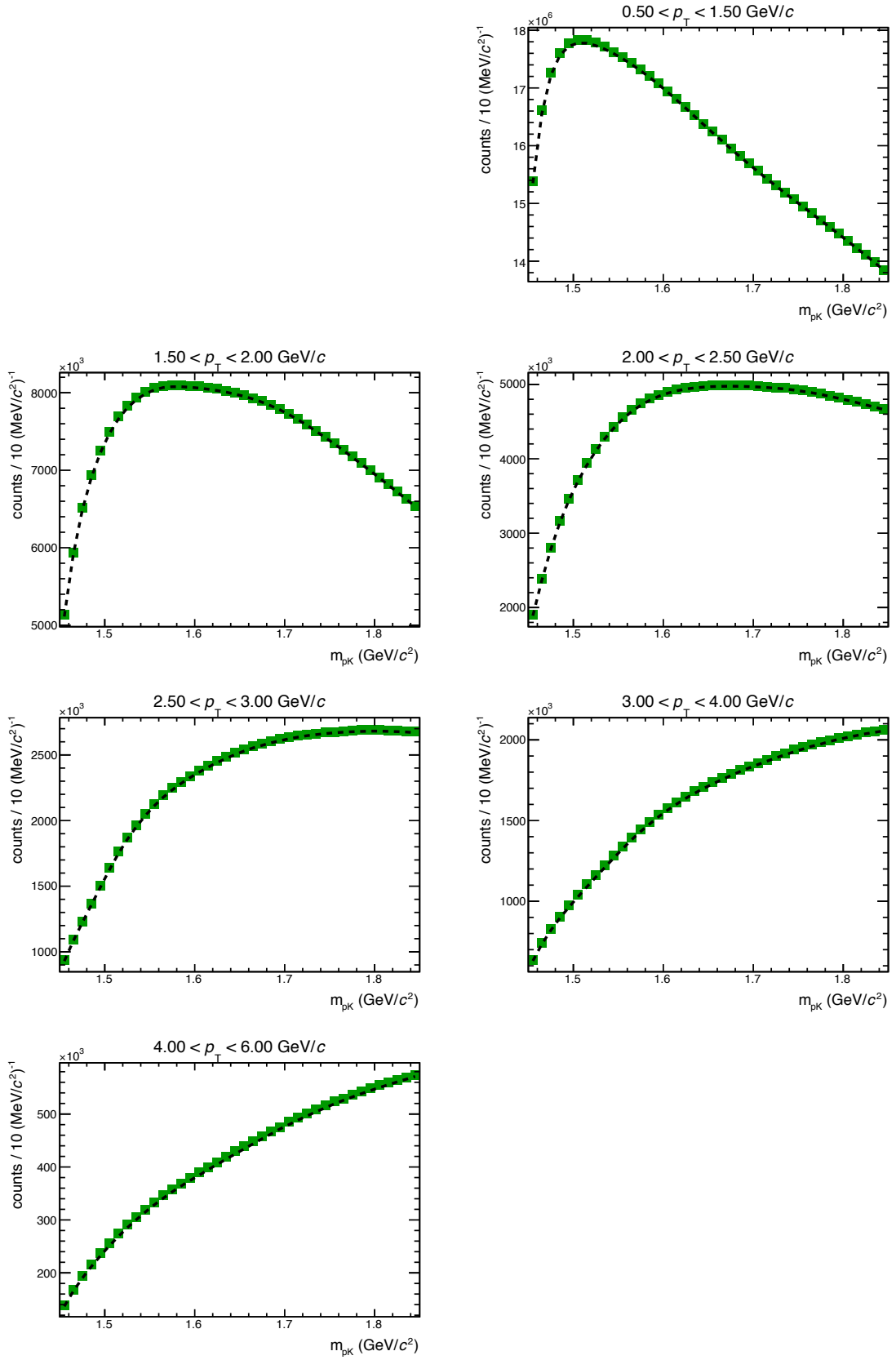


Figure 3.20: Same-event unlike-sign invariant-mass distribution (green marker, Section 3.6) and the estimated combinatorial background (black dotted line, Section 3.6.2) for various p_T bins in 0–20% centrality events.

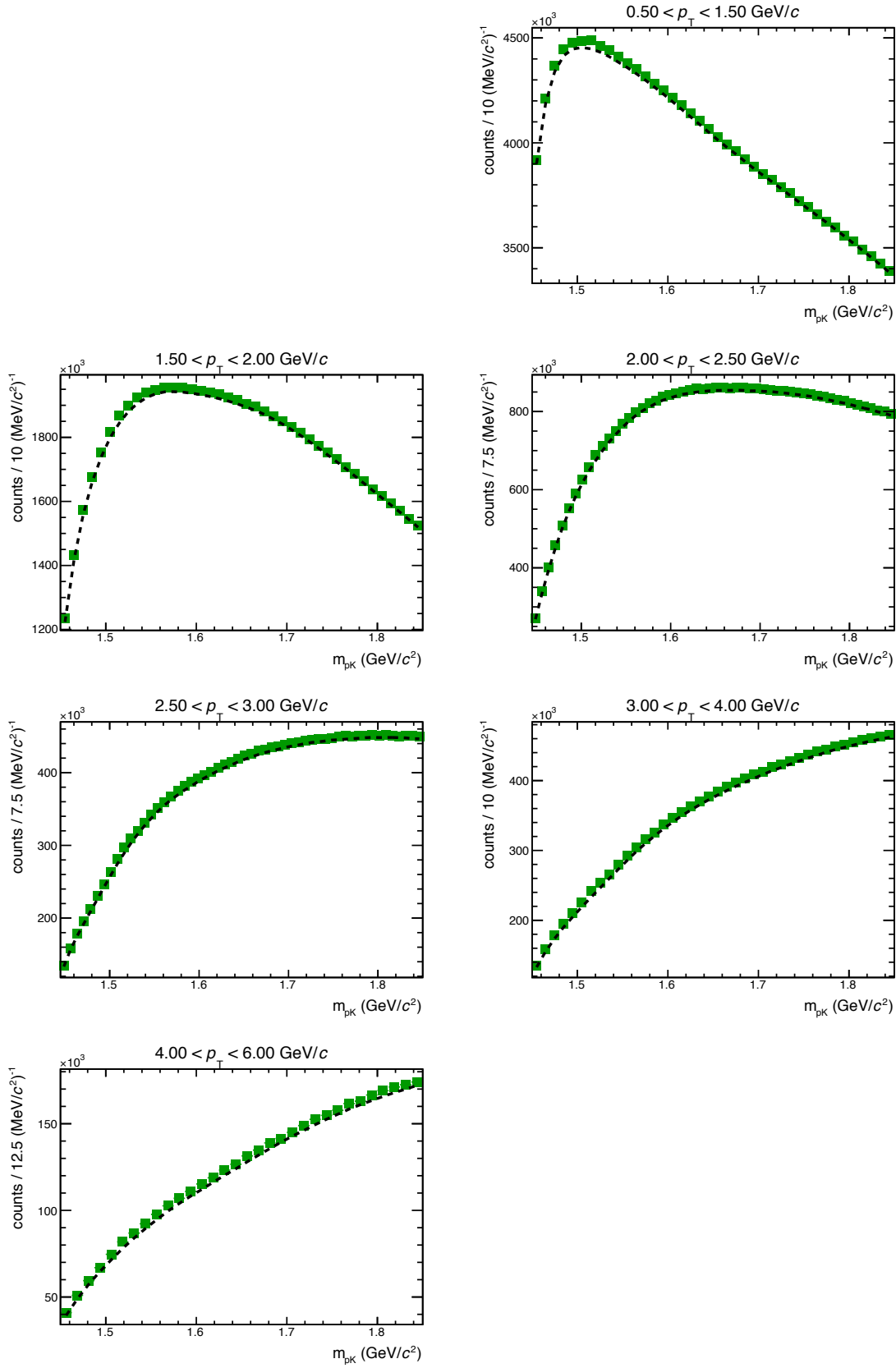


Figure 3.21: Same-event unlike-sign invariant-mass distribution (green marker, Section 3.6) and the estimated combinatorial background (black dotted line, Section 3.6.2) for various p_T bins in 20–50% centrality events.

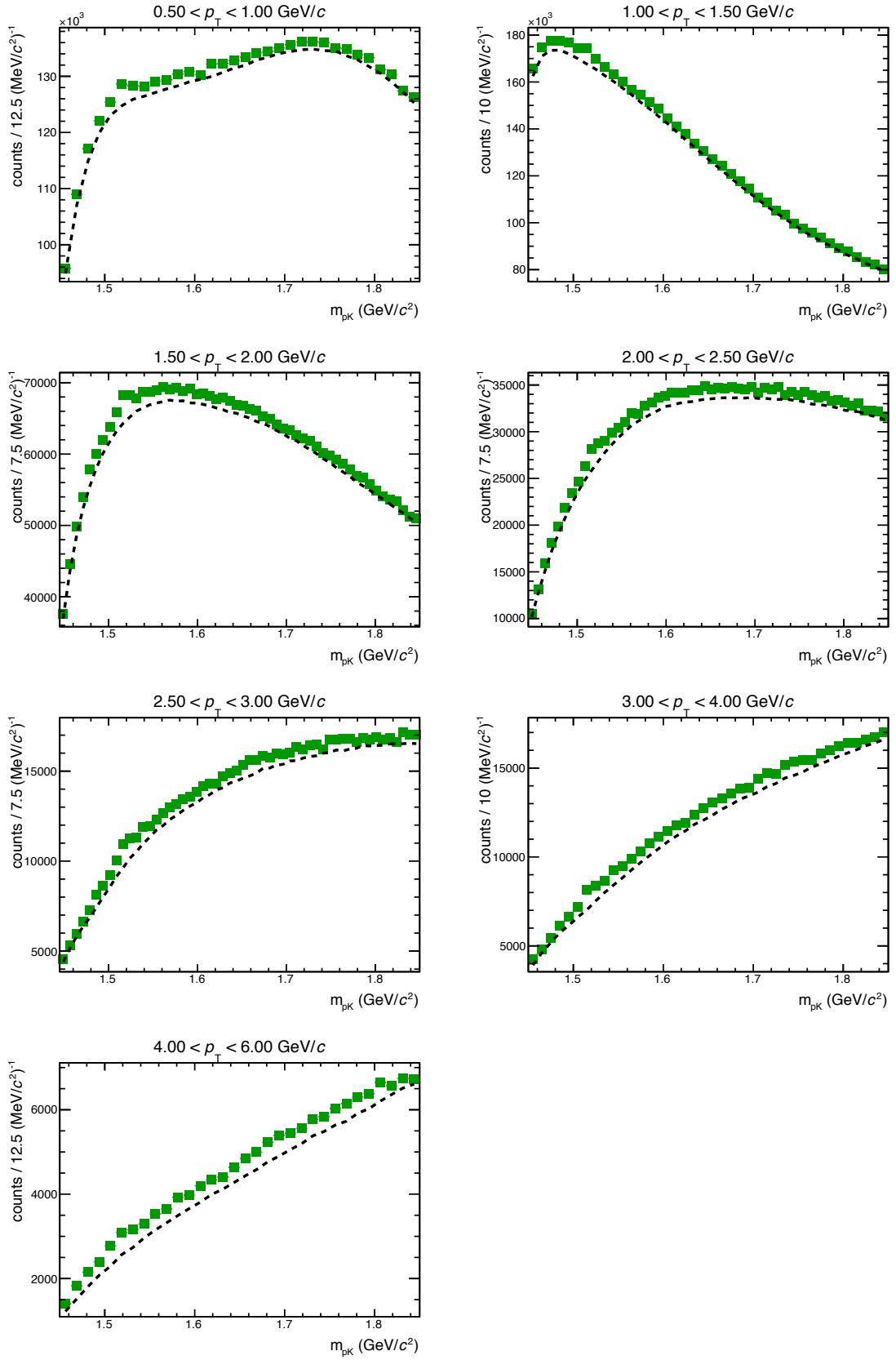


Figure 3.22: Same-event unlike-sign invariant-mass distribution (green marker, Section 3.6) and the estimated combinatorial background (black dotted line, Section 3.6.2) for various p_T bins in 50–80% centrality events.

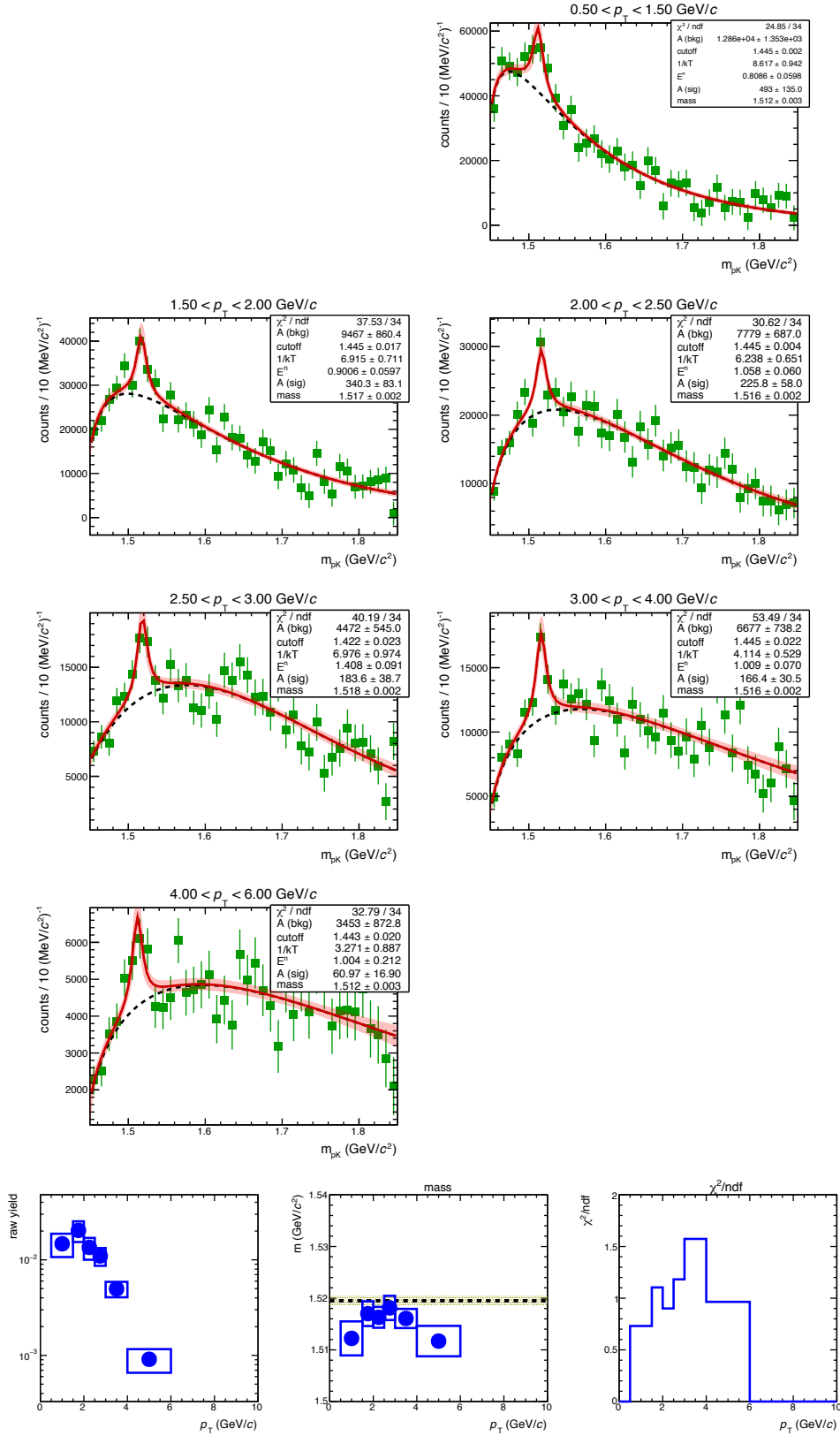


Figure 3.23: Results of the default fit in various p_T intervals for 0–20% centrality events. The solid curve stands for the fit function using Equation 3.20 and the dashed lines stands for the linear residual background. Lower panel, first (left) figure shows the extracted raw yield from fits, middle figure shows the mass from fit and third (right) shows the χ^2/ndf of the fits.

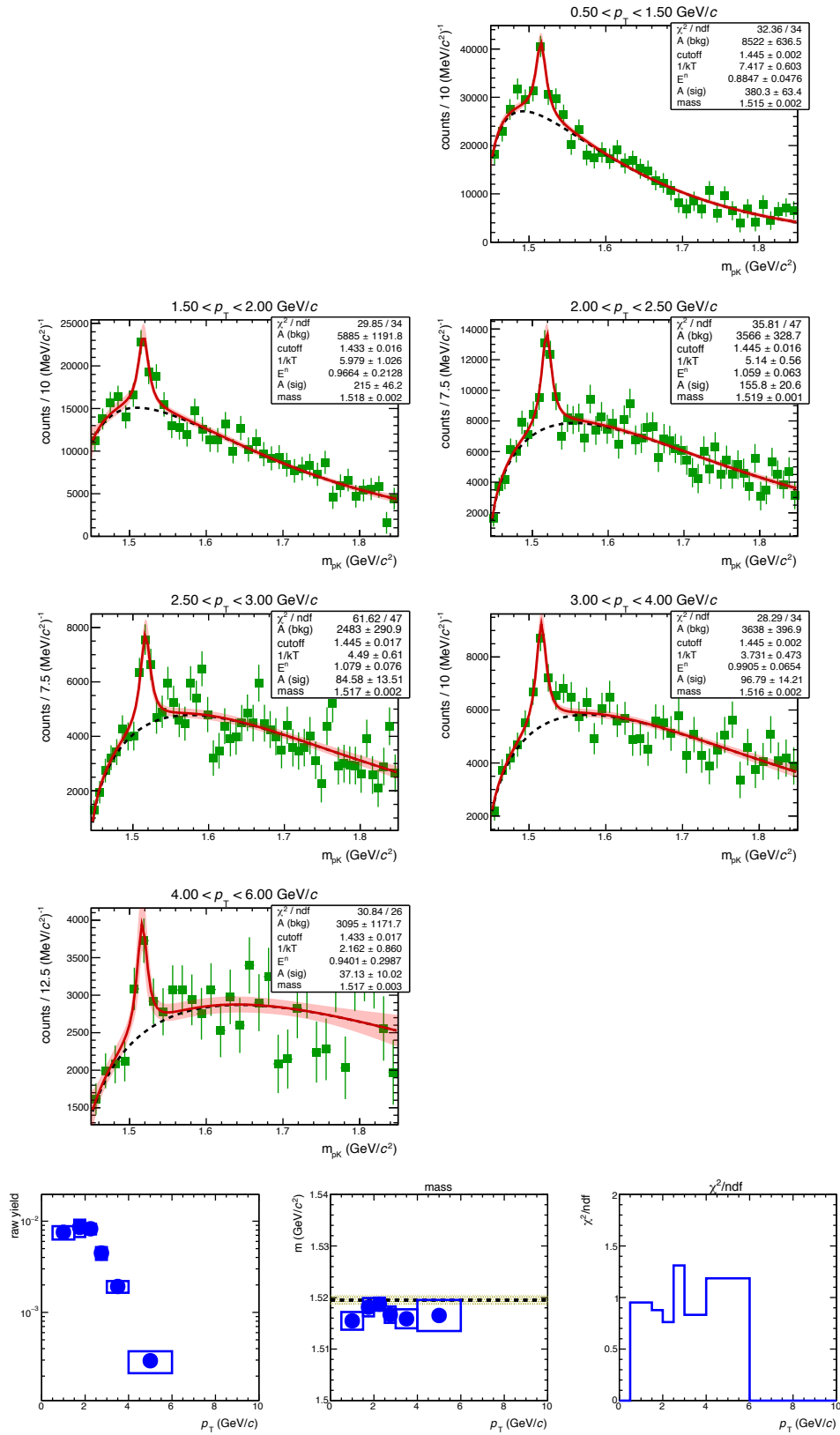


Figure 3.24: Results of the default fit in various p_T intervals for 20–50% centrality events. The solid curve stands for the fit function using Equation 3.20 and the dashed lines stands for the linear residual background. Lower panel, first (left) figure shows the extracted raw yield from fits, middle figure shows the mass from fit and third (right) shows the χ^2/ndf of the fits.

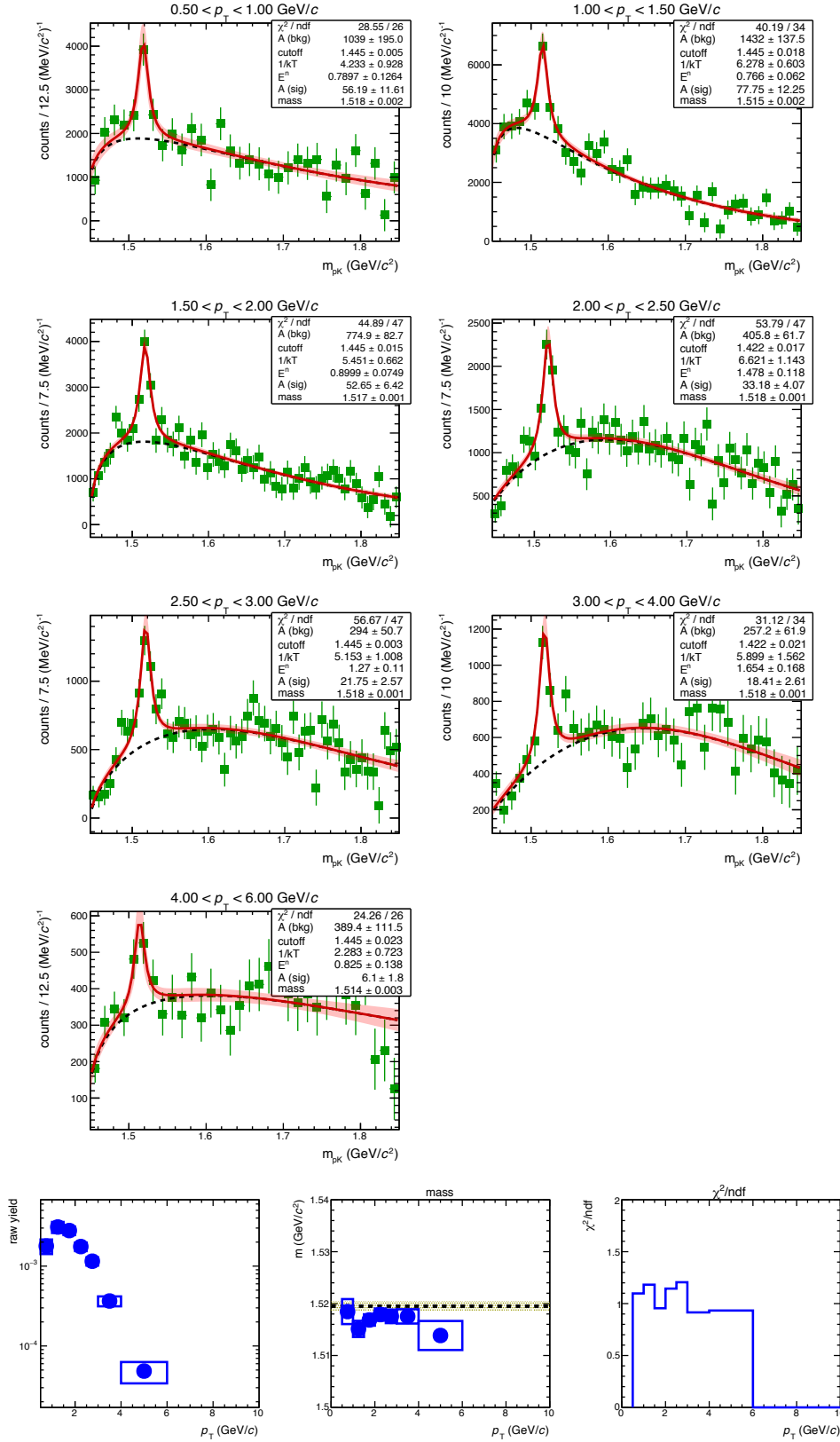


Figure 3.25: Results of the default fit in various p_T intervals for 50–80% centrality events. The solid curve stands for the fit function using Equation 3.20 and the dashed lines stands for the linear residual background. Lower panel, first (left) figure shows the extracted raw yield from fits, middle figure shows the mass from fit and third (right) shows the χ^2/ndf of the fits.

3.7 Efficiency correction by Monte Carlo data

The Monte Carlo analysis is performed using dedicated simulation data (Section 3.2.2). The utilised Monte Carlo production is based on events generated using HIJING, with the addition of injected $\Lambda(1520)$ signals to enhance the statistical significance of the corrections.

3.7.1 Acceptance $\times$ efficiency

Acceptance $\times$ efficiency (ε), a p_{T} -dependent correction due to detector acceptance and reconstruction efficiency is measured via Monte Carlo analysis. This correction includes the contribution of the tracking and candidates selection cuts and defined for each p_{T} bin as

$$\varepsilon = \frac{N_{\text{rec}}}{N_{\text{gen}}} \quad (3.28)$$

where N_{gen} is the number of $\Lambda(1520) \rightarrow \text{K}^- + \text{p}$ generated within the rapidity interval $|y| < 0.5$ and N_{rec} are the ones reconstructed after all selection cuts (Sections 3.4 and 3.5). The definition of the efficiency does not include the $\Lambda(1520)$ decay branching ratio in the analysed decay channel.

The results, obtained integrating over 0–80% event centrality, are shown in Figure 3.26 and 3.27. Several corrections are applied to the efficiency obtained from the Monte Carlo analysis and are discussed in the following (Section 3.8).

3.7.2 Resolution and mass shift

In a perfect detector, the resolution and mass shift should be zero. For $\Lambda(1520)$ measurement, the resolution and mass shift of reconstructed $\Lambda(1520)$ resonances due to detector effects are measured via Monte Carlo analysis. They are defined for each p_{T} bin as the standard deviation and mean of the distribution of

$$\Delta_M = M_{\text{rec}} - M_{\text{gen}} \quad (3.29)$$

respectively, where M_{rec} is the mass obtained via invariant-mass analysis of reconstructed $\Lambda(1520)$ decay daughter tracks (Section 3.6.3) and M_{gen} is the actual invariant-mass of the decay daughters at the generator level.

The results, obtained integrating over 0–80% event centrality, are shown in Figure 3.26 and 3.27. The corresponding Δ_M distributions are shown in Figures 3.28 and 3.29.

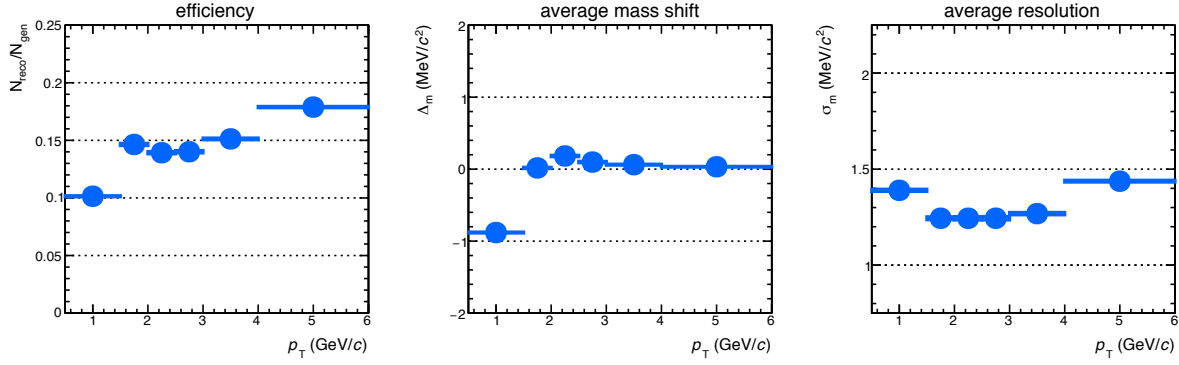


Figure 3.26: Results of the Monte Carlo analysis (Sections 3.7.1 and 3.7.2) for 0–80% centrality events in the p_T binning used for 0–20% and 20–50% centrality events, showing the $\Lambda(1520)$ reconstruction efficiency (left), average mass shift (center) and resolution (right).

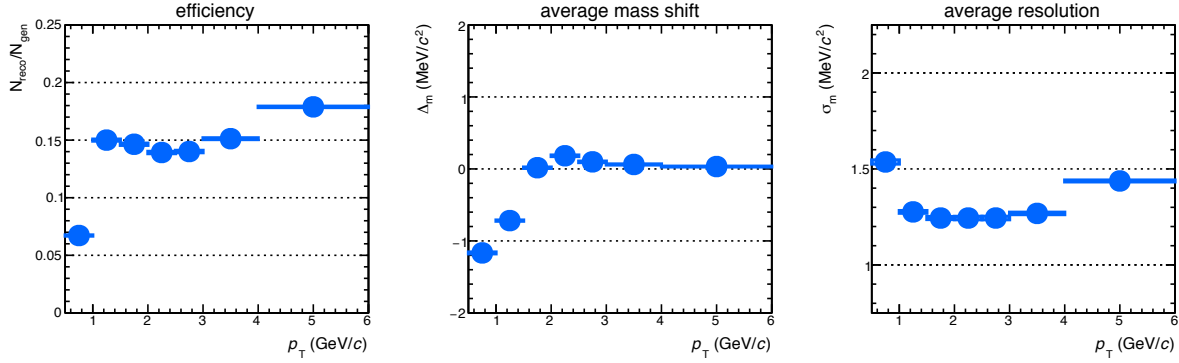


Figure 3.27: Results of the Monte Carlo analysis (Sections 3.7.1 and 3.7.2) for 0–80% centrality events in the p_T binning used for 50–80% centrality events, showing the $\Lambda(1520)$ reconstruction efficiency (left), average mass shift (center) and resolution (right).

3.8 Corrections to efficiency

The following three corrections have been applied before considering the correction factor, efficiency $\times$ acceptance (ε) for the reconstruction of $\Lambda(1520)$ to be final.

1. Multiplicity correction (Section 3.8.1)
2. Input p_T distribution correction (Section 3.8.2)
3. Single-track efficiency (Section 3.8.3)

After applying these corrections, the final efficiency $\times$ acceptance (ε) of $\Lambda(1520)$ reconstruction is shown in Figure 3.40.

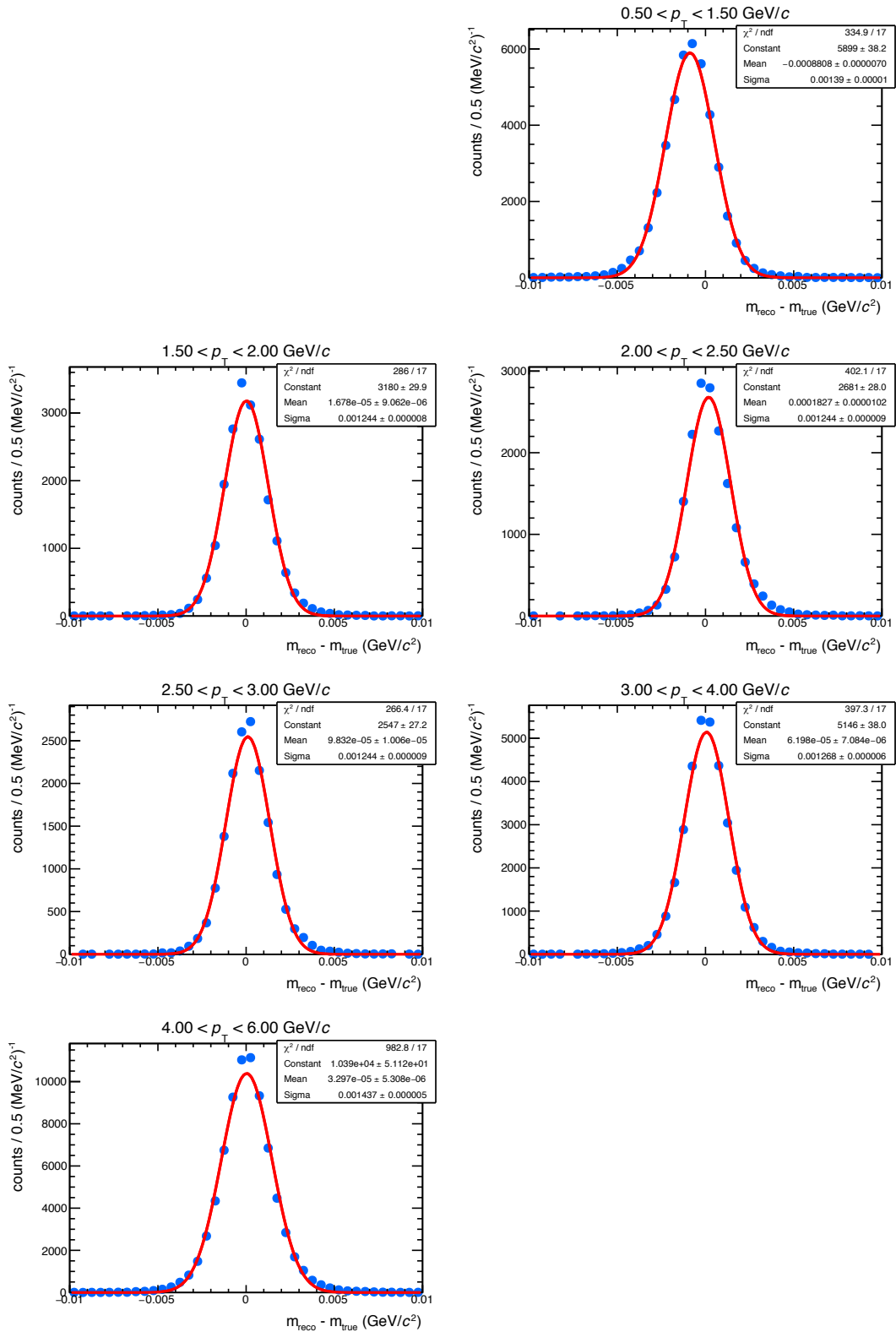


Figure 3.28: Results of the Monte Carlo analysis (Section 3.7.2) for 0–80% centrality events in the p_T binning used for 0–20% and 20–50% centrality events, showing the $\Lambda(1520)$ mass distributions for Δ_M calculation.

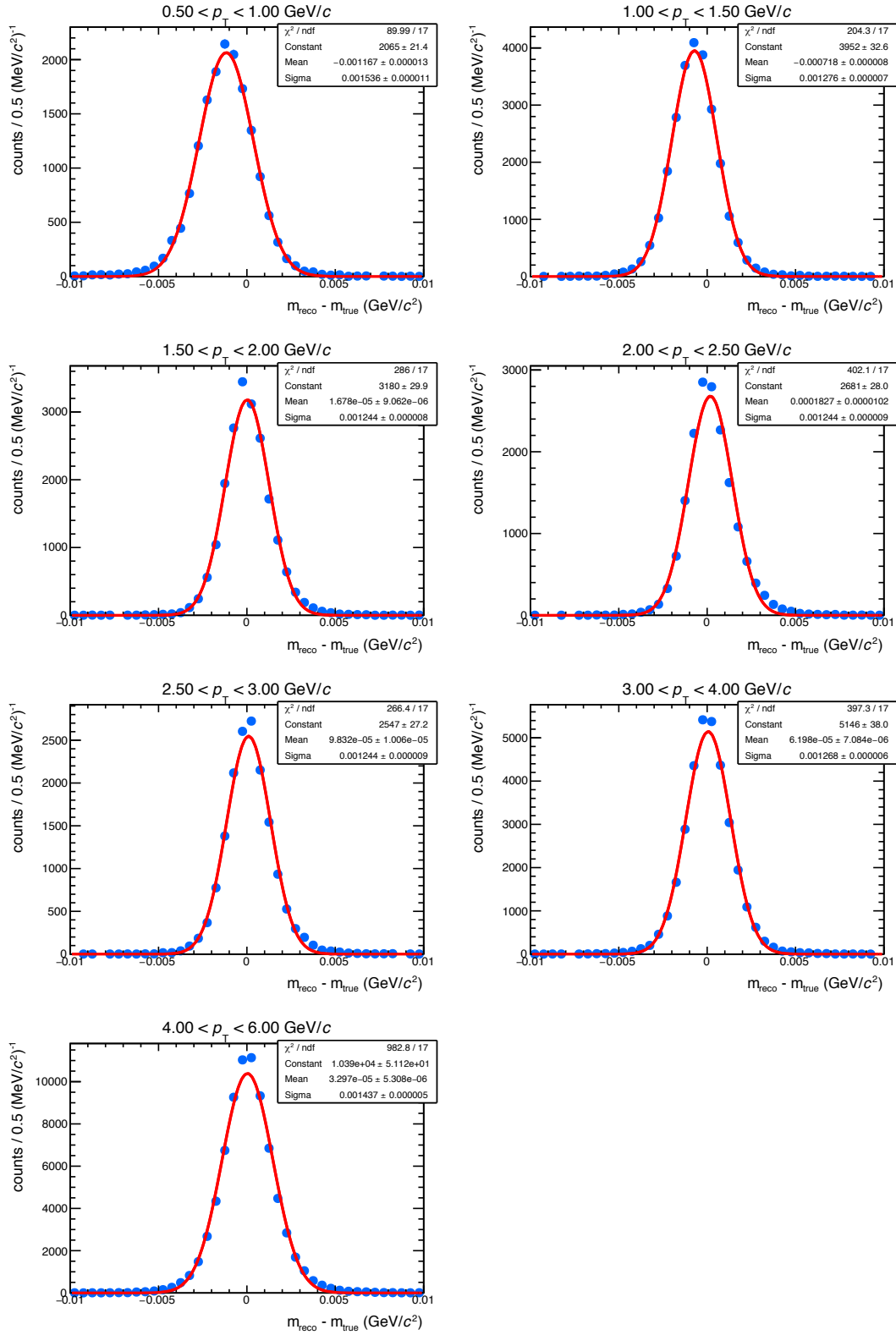


Figure 3.29: Results of the Monte Carlo analysis (Section 3.7.2) for 0–80% centrality events in the p_T binning used for 50–80% centrality events, showing the $\Lambda(1520)$ mass distributions for Δ_M calculation.

3.8.1 Multiplicity correction

To study and correct for any multiplicity dependence of the $\Lambda(1520)$ reconstruction performance, the Monte Carlo analysis to measure efficiency and resolution (Sections 3.7.1 and 3.7.2) is performed both in the inclusive centrality class 0–80% and in the centrality classes defined for the analysis. The results obtained for 0–20%, 20–50% and 50–80% centrality classes are compared to the inclusive ones in Figures 3.30, 3.31 and 3.32, respectively. The relative deviation of the results obtained for 0–20%, 20–50% and 50–80% centrality classes with respect to the inclusive 0–80% ones are shown in Figures 3.33, 3.34 and 3.35, respectively.

To reduce the fluctuations due to the limited statistics available for this comparison, a constant fit is performed to quantify the deviation of the results from the inclusive 0–80% class. The efficiency in the inclusive 0–80% centrality class is corrected for the deviation quantified by the constant fit to determine the efficiency of each of the centrality classes used in the analysis. A systematic uncertainty is assigned to this correction, as discussed in Section 4.5.2.

There is no significant deviation observed for the mass shift. The deviation observed for the resolution is also not considered to be significant and the same resolution is used for all centrality classes. This is justified by the fact that the width of the resonance is much larger than the reconstruction resolution, whose actual value plays little role in the final results. In fact, in one of the systematic checks performed (see Section 4.4) the resolution is changed by $\pm 30\%$ with no significant deviations in the results.

3.8.2 Input p_T distribution correction

When large p_T bins are used, the efficiency measured via Monte Carlo analysis might depend on the input p_T distribution. The p_T distribution of the $\Lambda(1520)$ generated in the Monte Carlo is substantially different from the expected one. The shape in the Monte Carlo data is determined by the shape used in HIJING generator [114] and by the shape generated from HIJING and injected on top of HIJING background.

Figure 3.36 compares the p_T distribution in the Monte Carlo to the one from the Blast-Wave parametrisation [117] fitted to the data (Section 5.3.1), which gives a more reliable description of the real p_T distribution. A correction to the efficiency is computed as

$$C_{\text{shape}} = \frac{\varepsilon_{\text{BW}}}{\varepsilon_{\text{MC}}} \quad (3.30)$$

where ε_{BW} and ε_{MC} are the binned $\Lambda(1520)$ efficiencies obtained using as input the p_T distribution from the Blast-Wave parametrisation and from Monte Carlo, respectively. The results are shown in Figure 3.37. A systematic uncertainty is assigned to this correction, as discussed in Section 4.5.7.

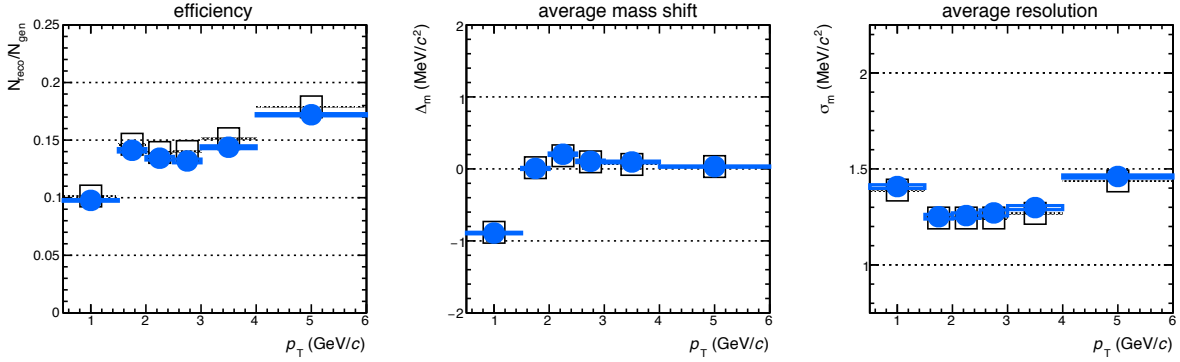


Figure 3.30: Results of the Monte Carlo analysis for 0–20% centrality events. The open points show the 0–80% centrality values.

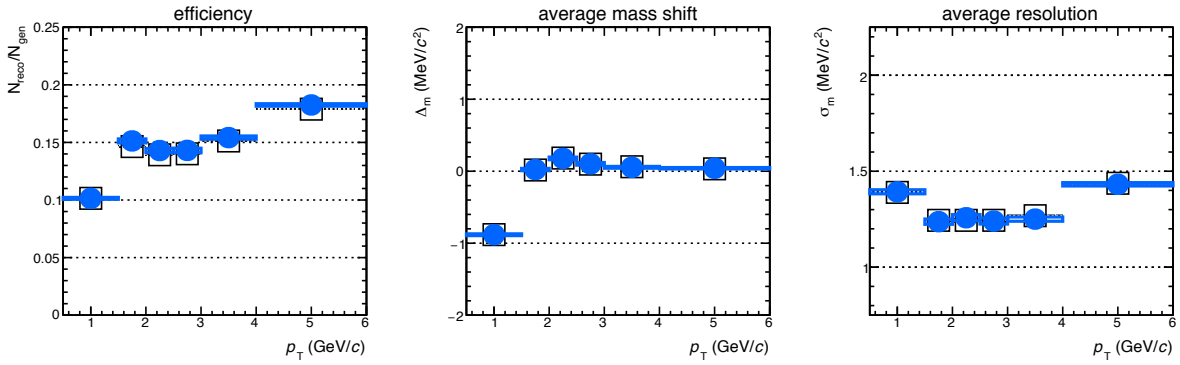


Figure 3.31: Results of the Monte Carlo analysis for 20–50% centrality events. The open points show the 0–80% centrality values.

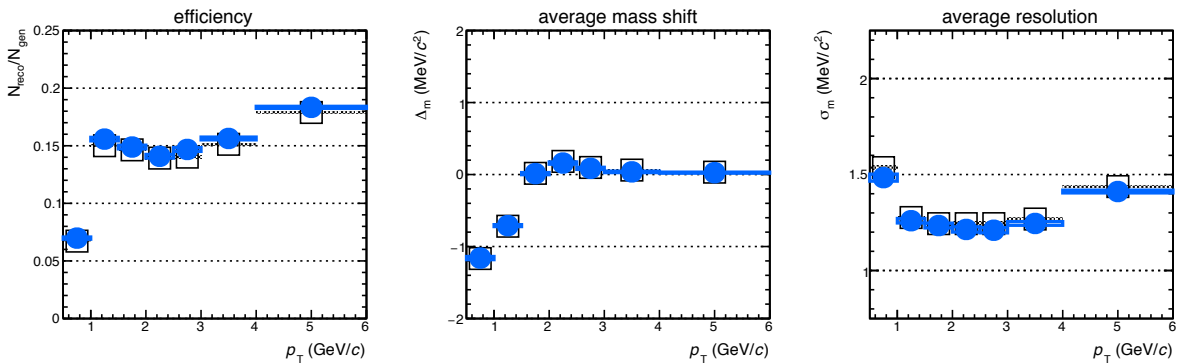


Figure 3.32: Results of the Monte Carlo analysis for 50–80% centrality events. The open points show the 0–80% centrality values.

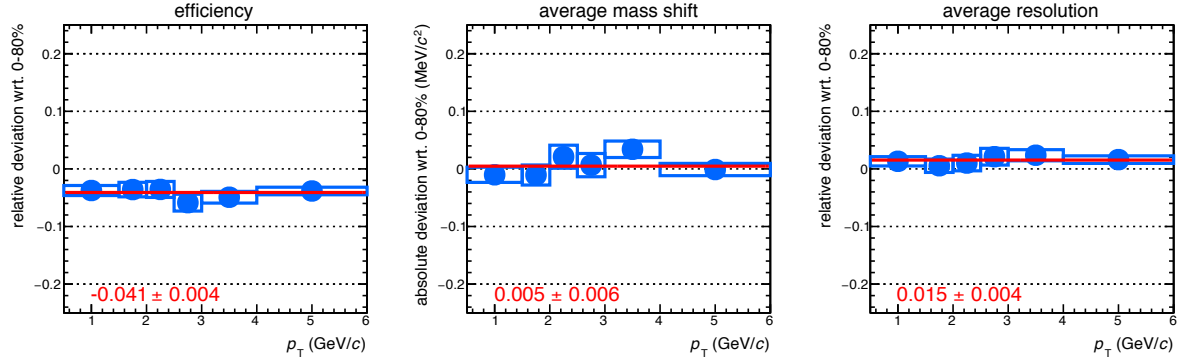


Figure 3.33: Relative deviation of the results of the Monte Carlo analysis for 0–20% centrality events to the 0–80% centrality values.

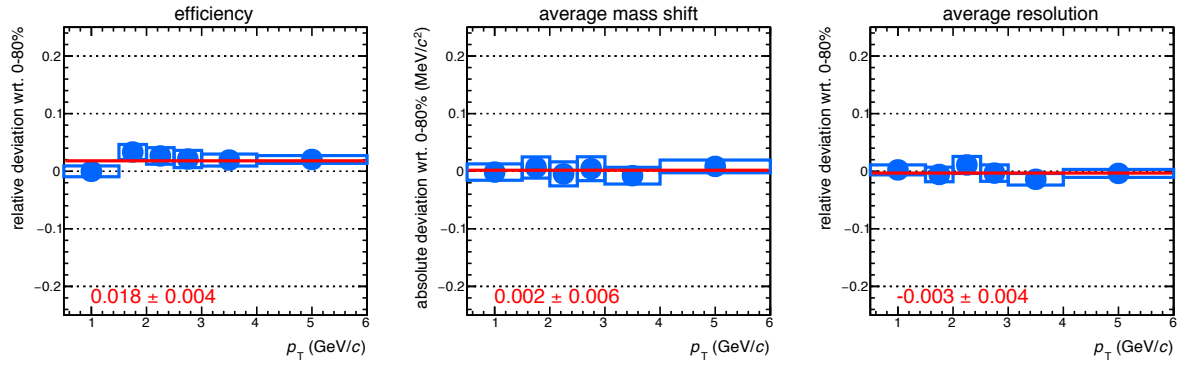


Figure 3.34: Relative deviation of the results of the Monte Carlo analysis for 20–50% centrality events to the 0–80% centrality values.

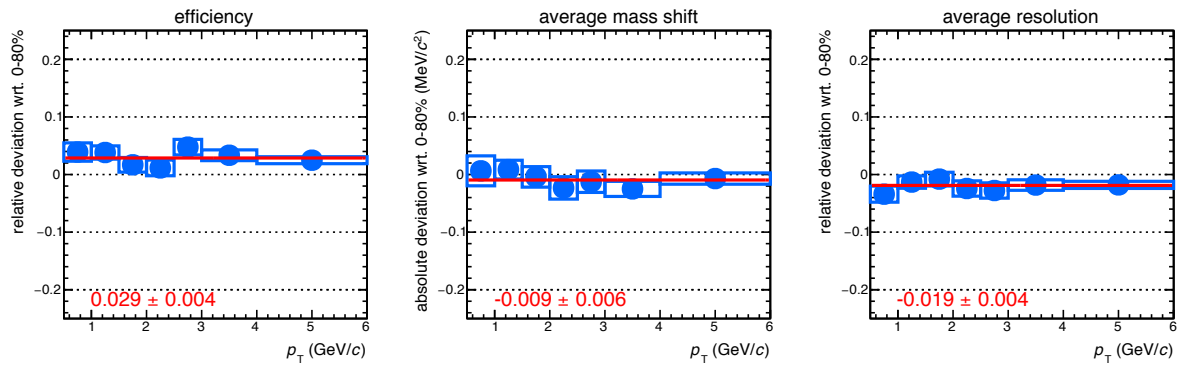


Figure 3.35: Relative deviation of the results of the Monte Carlo analysis for 50–80% centrality events to the 0–80% centrality values.

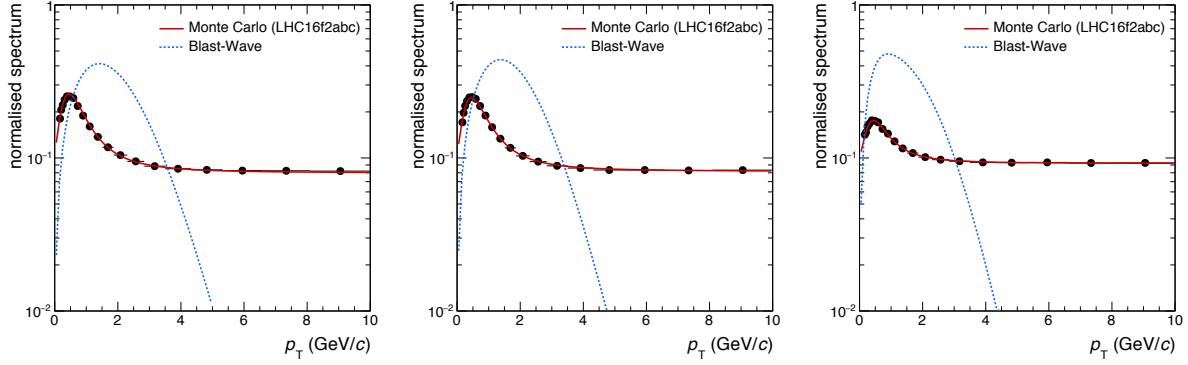


Figure 3.36: p_T distributions of $\Lambda(1520)$ generated in the Monte Carlo sample compared to the Blast-Wave parametrisation fitted to the data (Section 3.8.2). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

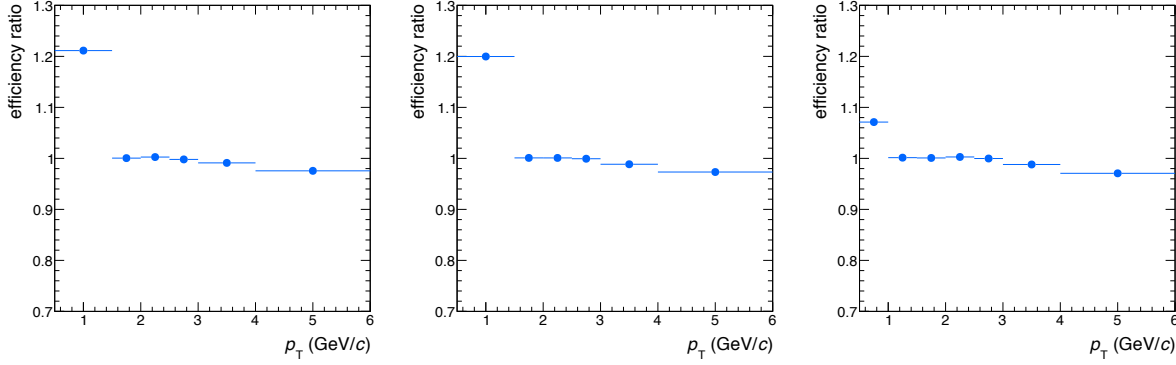


Figure 3.37: Ratio of the $\Lambda(1520)$ efficiency determined using the Blast-Wave p_T distribution fitted to the data with respect to the one determined using the p_T distribution generated by the analysed Monte Carlo sample (Section 3.8.2). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

3.8.3 Single-track efficiency

The Monte Carlo data used for efficiency calculation has been processed with a different reconstruction code than the one used for data reconstruction. Some differences in the performance might be expected and they have been checked by comparing the single-track reconstruction performance.

The efficiencies of kaons and protons obtained with the Injected Monte Carlo (LHC16f2abc and LHC16f2abc_bis, Section 3.2.2) are compared to the ones obtained with the General-Purpose Monte Carlo (LHC11a10a_bis, Section 3.2.2) in Figure 3.38. Special care has been used in the comparison of the antiproton efficiency, as the parametrisation of the corresponding interaction cross-section has been modified as well. The antiproton efficiency in the General-Purpose Monte Carlo was corrected for the so-called *Geant/Fluka correction factor*. This correction is

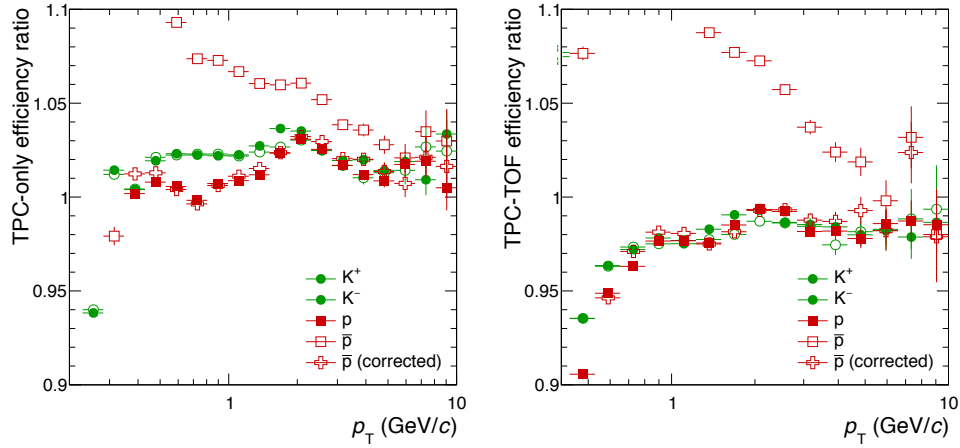


Figure 3.38: Ratio of the kaon and proton efficiency in the Injected Monte Carlo with respect to the ones in the General-Purpose Monte Carlo (Section 3.8.3). The shown ratio for antiproton (*corrected*) is after applying the *Geant/Fluka correction factor* to the General-Purpose Monte Carlo.

not needed in the Injected Monte Carlo, which uses a more recent GEANT3 version where the antiproton interaction cross-section has been updated. A correction to the efficiency is computed as

$$C_{\text{track}} = \frac{\varepsilon_{\text{Injected}}}{\varepsilon_{\text{General-Purpose}}} \quad (3.31)$$

where $\varepsilon_{\text{Injected}}$ and $\varepsilon_{\text{General-Purpose}}$ are the binned $\Lambda(1520)$ efficiencies obtained using the single-track efficiencies from the Injected Monte Carlo and from the General-Purpose Monte Carlo, respectively. The results are shown in Figure 3.39. A systematic uncertainty is assigned to this correction, as discussed in Section 4.5.8.

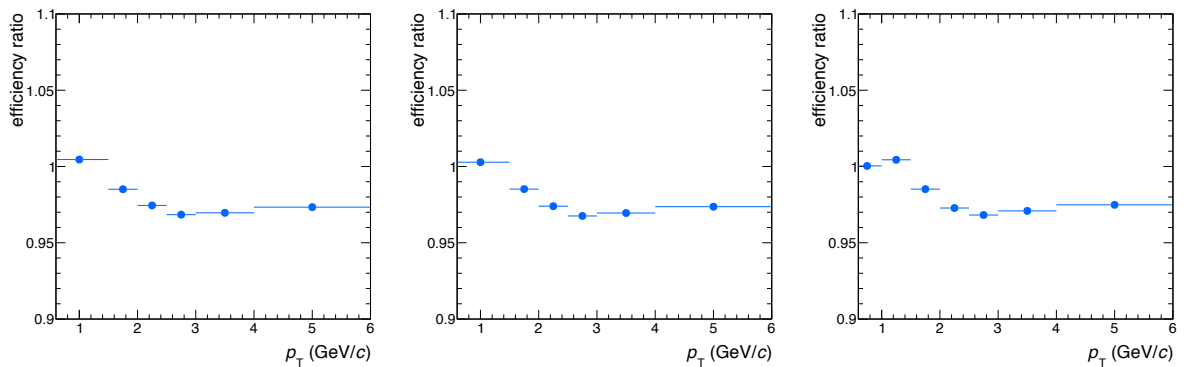
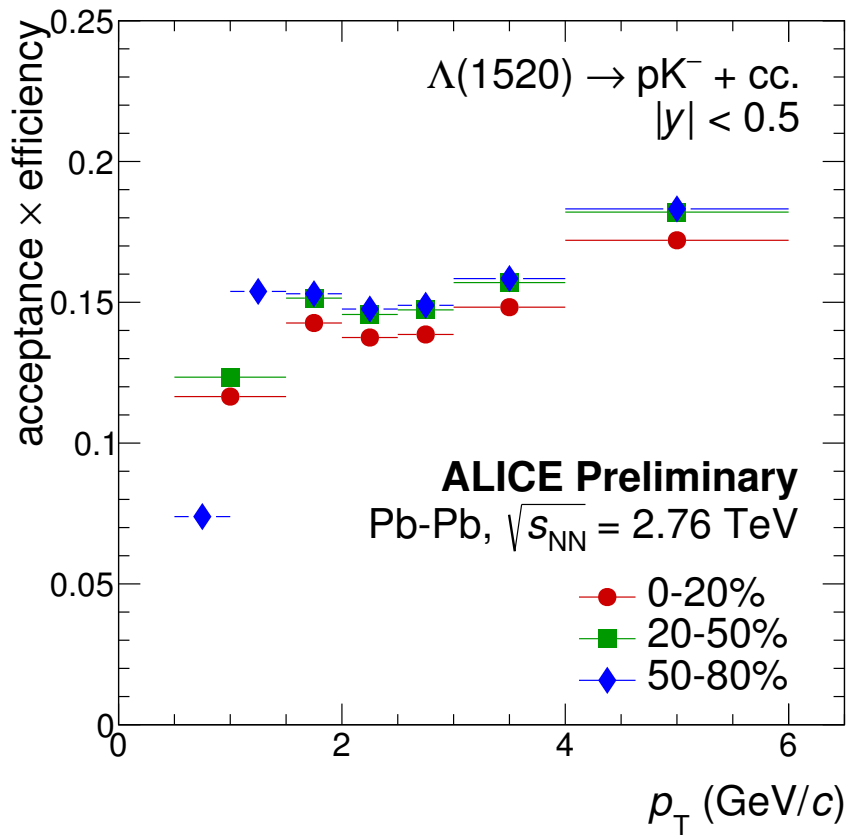


Figure 3.39: Ratio of the $\Lambda(1520)$ efficiency determined using the kaon and proton efficiency in the Injected Monte Carlo with respect to the one determined using the kaon and proton efficiency of the General-Purpose Monte Carlo (Section 3.8.3). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.



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Figure 3.40: The reconstruction efficiency $\times$ acceptance correction factor (Section 3.7.1) as a function of p_T for $\Lambda(1520)$ for different centralities after applying the corrections discussed in Section 3.8.

Chapter 4

Estimation of systematic uncertainties

"Insanity is doing the same thing over and over again and expecting different results."

– Albert Einstein

Abstract: This chapter describes the study of systematic uncertainty on the $\Lambda(1520)$ measurements. In this systematic uncertainty study various sources are considered and discussed in Section 4.2 to 4.8. Finally, the total and uncorrelated systematics uncertainty are discussed in Section 4.7.

4.1 Systematics studies

There are systematic uncertainties in the $\Lambda(1520)$ measurement due to experimental techniques in the measurement, design of the measurement device (e.g. detector calibration), non-perfect knowledge of background estimation and methods to compute the measurement values. To study the $\frac{dN}{dy}$ and $\langle p_T \rangle$ of $\Lambda(1520)$, various sources of systematic uncertainties related to the measurement performed have been considered. The complete analysis procedure is repeated for each of the systematic sources and studied carefully. Finally, the systematic uncertainty is evaluated by comparing the results of the checks performed with the ones obtained from the default settings of the analysis.

4.1.1 Sources of systematics

The systematic uncertainties from all the sources are classified into two classes, separating the contributions that are common to all centrality classes (correlated) from the ones which are not (uncorrelated). All uncertainties are calculated individually and combined in quadrature to obtain total uncertainty. The sources of systematic uncertainties which have been evaluated are grouped into these main contributions

1. Raw yield (Section 4.2)
2. Efficiency (Section 4.5)

3. Normalisation (Section 4.6)

4. Low- p_T extrapolation (Section 4.8)

and are discussed in details in the following sections.

4.2 Raw yield

The raw yield of $\Lambda(1520)$ has been extracted following the procedure discussed in Section 3.6. Several checks are performed to estimate the systematic uncertainty related to the raw yield extraction. Although a clear determination of this systematics is challenging owing the large statistical uncertainties of the fitted invariant mass distribution, the main contributions to the raw yield systematic uncertainty originate from the limited knowledge of

- Background description (Section 4.3)
- Signal description (Section 4.4)

and are discussed in the following paragraphs.

4.3 Background description

The $\Lambda(1520)$ signal is extracted by subtracting the same event invariant mass distribution through mixed event invariant mass distribution. The residual background shape needs to be fitted well for the proper signal extraction. The shape of residual background is not known a priori and in this analysis, it is fitted with a parametric function of the form of a Maxwell-Boltzmann distribution function (Section 3.6.4) which reproduces the data well.

The good description of the data confirms that the use of a parametric function to fit the residual background is a good approximation but the procedure can lead to systematic effects on the estimated background. To estimate the uncertainty related to the choice of the background description and of the details of the fitting procedure, the following checks have been performed

1. Modification of the fit parameters (Section 4.3.1)
2. Variation of the fit range (Section 4.3.2)
3. Variation of the number of mixed events (Section 4.3.3)
4. Variation of the procedure for event-mixing normalisation (Section 4.3.4)
5. Variation of the histogram bin width of the invariant-mass (Section 4.3.5)

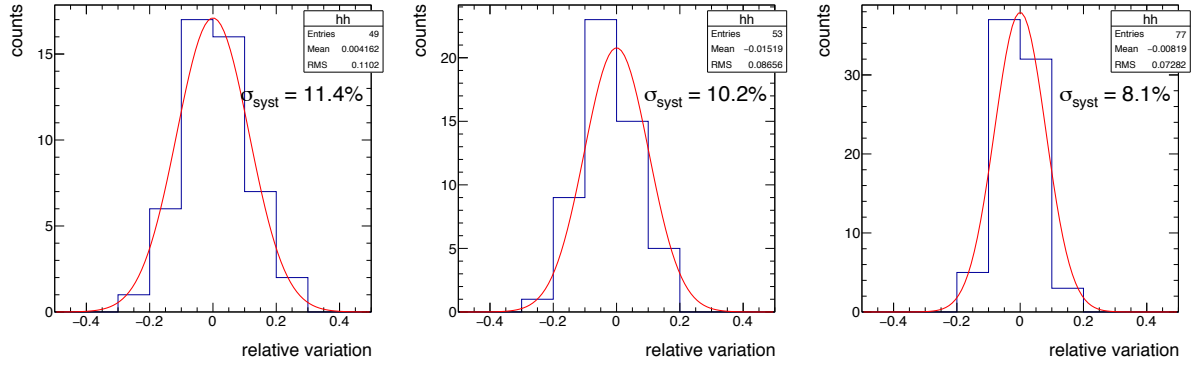


Figure 4.1: Distribution of the systematic deviations from the systematic checks related to the background description (Section 4.3), integrated over p_T . 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

These checks are discussed separately in the following sections for the clarity of discussion and visualisation and they all are assumed to relate in similar manner to the uncertainty of the background description. The systematics uncertainty derived from these checks cannot be estimated as the quadratic sum of the individual contribution. A reliable estimate of the individual contributions is difficult because of very large statistical fluctuations. Therefore, an estimation based on the quadratic sum of the individual contributions would result in an overestimation of systematics uncertainties.

In order to provide a satisfactory estimate of this systematic uncertainty, the results of the systematic checks listed above are grouped together, integrated over p_T , to form a distribution of the systematic deviations (Figure 4.1). The systematic uncertainty assigned to the background description is taken to be

$$\sigma_{\text{sys}} = \sigma_{\text{RSM}} + |\mu| \quad (4.1)$$

where σ_{RSM} is the RMS of the distribution and $|\mu|$ is the absolute value of the mean of the distribution. The choice to add the absolute value of the mean to the RMS to the assigned systematics is justified by the cases where the distribution is not perfectly centred at zero. This allows extending the coverage of the Gaussian probability to include the full distribution of the observed deviations.

In order to avoid a bias from the large number of small-deviation results from the checks, we used the Barlow [118] approach to reject those which do not result in a significant variation. The measured deviations are defined as

$$\Delta_i = \frac{v_i - v_{\text{ref}}}{v_{\text{ref}}} \quad (4.2)$$

where v_i is the value measured after given systematic check i and v_{ref} is the reference default

value. The uncertainty assigned to the deviation, according to the Barlow [118] criterion, is

$$\sigma(\Delta_i) = \frac{\sqrt{\sigma(v_i)^2 - \sigma(v_{\text{ref}})^2}}{v_{\text{ref}}} \quad (4.3)$$

where $\sigma(v_i)$ and $\sigma(v_{\text{ref}})$ are the statistical uncertainties of v_i and v_{ref} , respectively. Significant variations, thus contributing to the above-mentioned distribution for the estimate of the systematic uncertainty, are considered the ones that deviate from zero by more than one sigma

$$|\Delta_i| > \sigma(\Delta_i) \quad (4.4)$$

The assigned systematic uncertainty is about 11.4%, 10.2% and 8.1% for 0–20%, 20–50% and 50–80% centrality classes, respectively. From visual inspection of the plots relative to the systematic checks listed above, these estimates appear to be reasonable: the largest deviations (which are only a few) are included within the 3σ confidence level.

The distributions are also visually compared with Gaussian distribution with $\mu = 0$, $\sigma = \sigma_{\text{sys}}$ and normalisation such that the integral matches the integral of the distribution. As it can be seen, the Gaussian gives a reasonable description of the distribution of measured deviations, which points to the fact that the σ_{sys} is a good estimate for the $1\text{-}\sigma$ systematic uncertainty.

4.3.1 Modification of the fit parameters

The fits for raw yield extraction have been repeated varying the strategy for invariant-mass fitting function parameters reported in Table 3.7. The parameters controlling the shape of the background and the position of the signal (Section 3.6.4) are fixed and released, while keeping all other settings to the DEFAULT values (Table 3.7). Here, DEFAULT values represent the values of fitting parameters stick to the values, which has been used during the baseline fit of signal and written in Table 3.7. During the DEFAULT fit, the value of mass (M) is fixed to $1.5195 \text{ GeV}/c^2$, low-mass cutoff (m_{cutoff}) is allowed to vary from 1.422 to $1.442 \text{ GeV}/c^2$ and n , the power of parameter E in background function is allowed to vary from 0.5 to 2.0 .

In order to estimate the uncertainty due to these three parameters, the default values are changed depending on the sensitivity of the fit to the signal. The configuration of the fits used to estimate the background description uncertainty is reported in Table 4.1. The results for variation of the raw yields when changing the strategy for invariant-mass fitting are shown in Figure 4.2.

4.3.2 Variation of the fit range

The default range of the function to fit the invariant mass signal is 1.45 to $1.85 \text{ GeV}/c^2$. The fits for raw yield extraction have been repeated varying the range of the fit (Section 3.6.4) while

Table 4.1: Configurations used for the systematic checks done varying the strategy for invariant-mass fitting (Section 4.3.1). The values for mass (M) and low-mass cutoff (m_{cutoff}) are in GeV/c^2 .

	mass (M)	low-mass cutoff (m_{cutoff})	(n)
DEFAULT	1.5195	[1.422, 1.442]	[0.5, 2.0]
FREEMASS	[1.51, 1.53]	DEFAULT	DEFAULT
MASSPLUS	1.5205	DEFAULT	DEFAULT
MASSMINUS	1.5185	DEFAULT	DEFAULT
FIXEDCUTOFF	DEFAULT	1.431949	DEFAULT
FIXEDPOWER	DEFAULT	DEFAULT	1
FIXEDCUTOFF, FIXEDPOWER	DEFAULT	1.431949	1

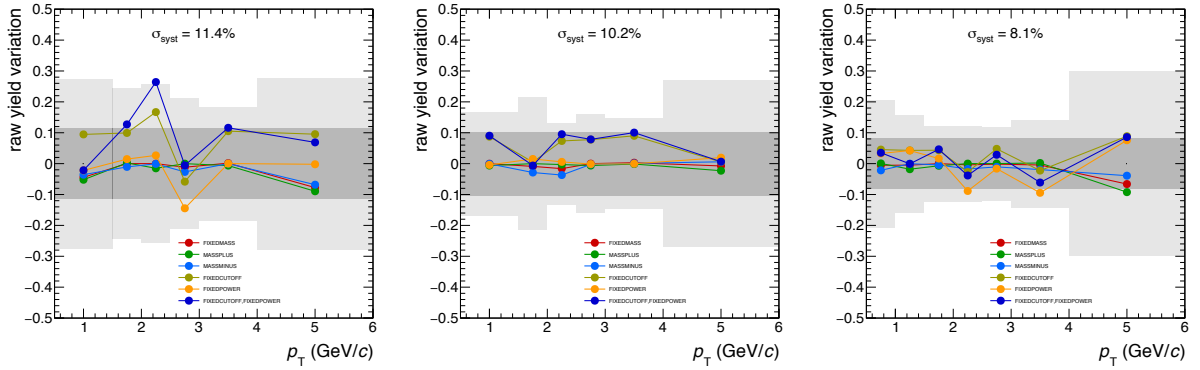


Figure 4.2: Variation of the raw yields when changing the strategy for invariant-mass fitting (Section 4.3.1). The light-shaded band shows the statistical uncertainty of the default values. The dark-shaded band shows the systematic uncertainty assigned to the background description (Section 4.3). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

keeping all other settings to the DEFAULT values. To estimate the uncertainty due to the fitting range, the default values is changed depending on the sensitivity of the fit to the signal. The configurations of the fits are reported in Table 4.2. The results for variation of the raw yields when changing the fit range are shown in Figure 4.3.

4.3.3 Variation of the number of mixed events

In this analysis, the default number of events which were mixed to produce the combinatorial background is 15. The full analysis has been repeated by changing the number of events mixed to obtain combinatorial background (Section 3.6.2). The event-mixing settings are reported

Table 4.2: Configurations used for the systematic checks done varying the range of the fits (Section 4.3.2). The values for fit minimum and maximum are in GeV/c^2 .

	fit minimum	fit maximum
DEFAULT	1.45	1.85
FITMINPLUS	1.46	DEFAULT
FITMINMINUS	1.44	DEFAULT
FITMAXPLUS	DEFAULT	1.90
FITMAXPLUSPLUS	DEFAULT	1.95
FITMAXPLUSPLUSPLUS	DEFAULT	2.00
FITMAXMINUS	DEFAULT	1.80
FITMAXMINUSMINUS	DEFAULT	1.75
FITMAXMINUSMINUSMINUS	DEFAULT	1.70

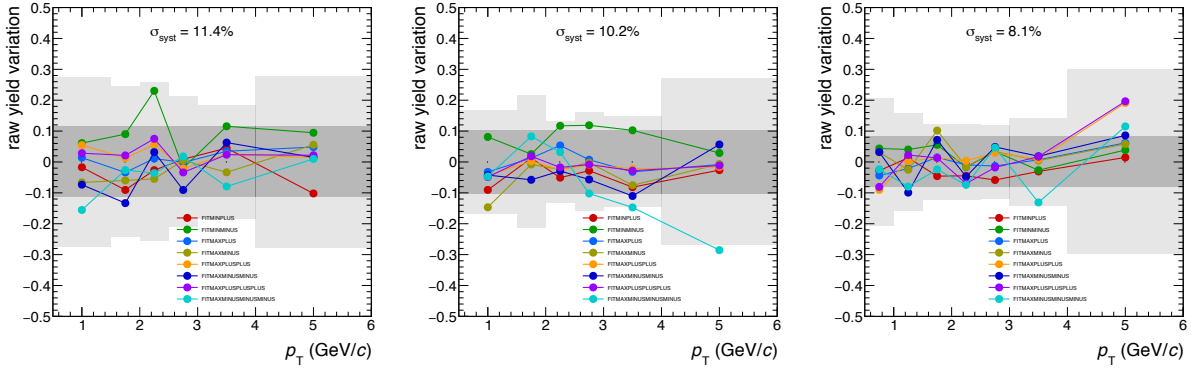


Figure 4.3: Variation of the raw yields when changing the fit range (Section 4.3.2). The light-shaded band shows the statistical uncertainty of the default values. The dark-shaded band shows the systematic uncertainty assigned to the background description (Section 4.3). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

in Table 4.3. The fits for raw yield extraction are performed with DEFAULT settings and the results for variation of the raw yields when changing the number of mixed events are shown in Figure 4.4.

4.3.4 Variation of the procedure for event-mixing normalisation

The fits for raw yield extraction have been repeated varying the strategy for event-mixing normalisation (Section 3.6.2). Third order polynomial function is used as a default function to fit the event-mixing normalisation. The function used to fit the estimated distortion of the

Table 4.3: Configurations used for the systematic checks done varying the number of mixed events (Section 4.3.3).

	number of mixed events
DEFAULT	15
MIX10TIMES	10
MIX20TIMES	20

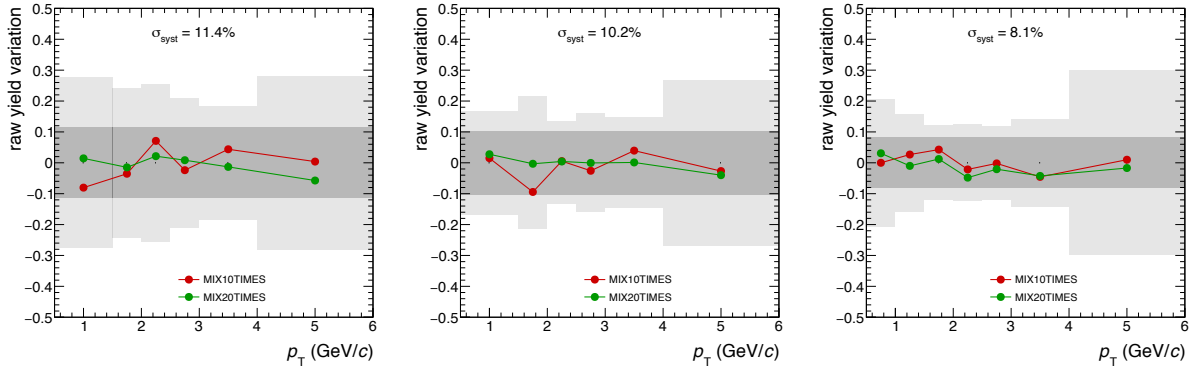


Figure 4.4: Variation of the raw yields when changing the number of mixed events (Section 4.3.3). The light-shaded band shows the statistical uncertainty of the default values. The dark-shaded band shows the systematic uncertainty assigned to the background description (Section 4.3). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

event-mix background is changed, while keeping all other settings to the DEFAULT values. The configurations of the fits are reported in Table 4.4. The results for variation of the raw yields when changing the strategy for event-mixing background normalisation are shown in Figure 4.5.

4.3.5 Variation of the histogram bin width of the invariant-mass

The fits for raw yield extraction have been repeated varying the binning of the invariant-mass distribution histogram with respect to the nominal bin width. The default bin width in 0–20% for each p_T bin is 10 MeV/ c^2 , while bin width varies from 7.5 to 12.5 MeV/ c^2 in different p_T bins for 20–50% and 50–80% centrality classes. An increment and decrement of 2.5 MeV/ c^2 from the DEFAULT bin width has been used for the systematic check. The results for variation of the raw yields when changing the bin width of the invariant mass histograms are shown in Figure 4.6.

Table 4.4: Configurations used for the systematic checks done varying the strategy for event-mixing normalisation (Section 4.3.4).

	fit function
DEFAULT	3 rd order polynomial
MIXEDPOL1	1 st order polynomial
MIXEDPOL2	2 nd order polynomial
MIXEDPOL4	4 th order polynomial

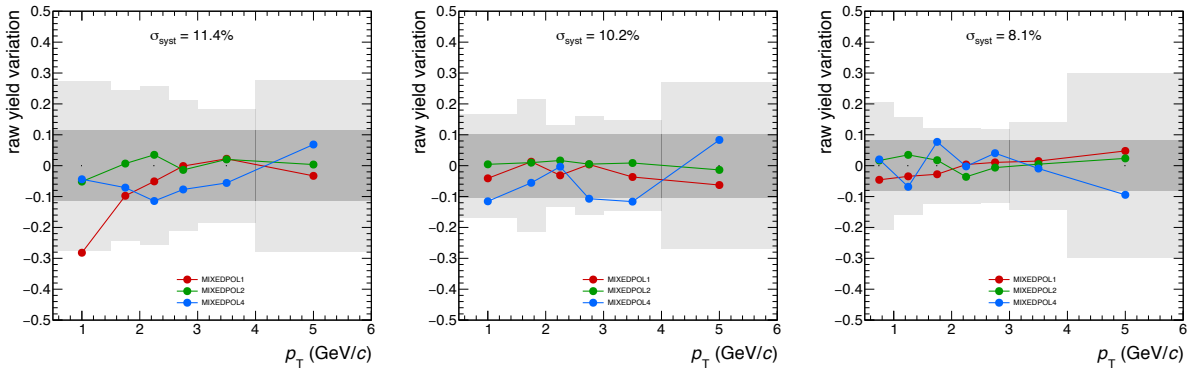


Figure 4.5: Variation of the raw yields when changing the strategy for event-mixing background normalisation (Section 4.3.4). The light-shaded band shows the statistical uncertainty of the default values. The dark-shaded band shows the systematic uncertainty assigned to the background description (Section 4.3). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

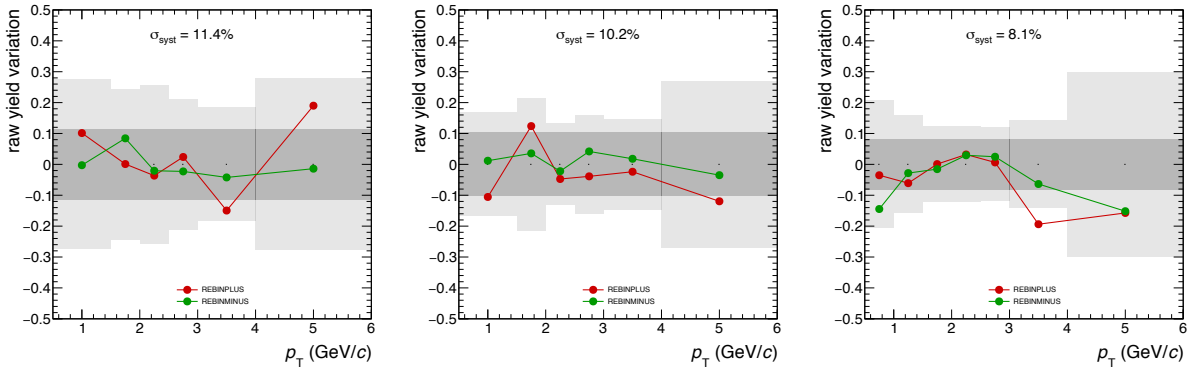


Figure 4.6: Variation of the raw yields when changing the bin width of the invariant mass histograms (Section 4.3.5). The light-shaded band shows the statistical uncertainty of the default values. The dark-shaded band shows the systematic uncertainty assigned to the background description (Section 4.3). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

Table 4.5: Configurations used for the systematic checks done varying the parameters that control the width of the signal (Section 4.4). The values for width (Γ) and sigma (σ) are in GeV/c^2 .

	width (Γ)	sigma (σ)
DEFAULT	0.0156	p_T - dependent
SIGMAPLUS	DEFAULT	+30%
SIGMAMINUS	DEFAULT	-30%
WIDTHPLUS	0.0166	DEFAULT
WIDTHMINUS	0.0146	DEFAULT

4.4 Raw yield systematics due to signal description

The fits for raw yield extraction have been repeated varying the parameters that control the width of the signal (Section 3.6.4), while keeping all other settings to the DEFAULT values. The default value of width is $15.6 \text{ MeV}/c^2$ and corresponds to the central value of the resonance width as quoted in the PDG [64]. The first set of systematic checks has been performed varying the width used for the fit by $\pm 1 \text{ MeV}$ (1σ), namely by the uncertainty on the resonance width quoted in the PDG. The resolution value of the Voigtian function for each p_T bin has been calculated by Monte Carlo analysis, as discussed in Section 3.7.2. A variation of the resolution of $\pm 30\%$ from the value obtained from the Monte Carlo has been tested as a systematic check. The configuration of the fits is reported in table 4.5.

The results of the variation of the raw yields when changing the width and resolution of the Voigtian function to fit the signal are shown in Figure 4.7. A systematic uncertainty of about 4% is eventually assigned as due to the description of the signal. Given the fact that the signal description is linked to the physical characteristics of the resonance, which are the same for all p_T bins, this source of systematic uncertainty is assumed to be common to all centrality classes and does not contribute to the multiplicity-uncorrelated systematics.

4.5 Systematics due to efficiency

The details on the $\Lambda(1520)$ reconstruction efficiency are discussed in Section 3.7. There are many factors associated to the measurement of reconstruction efficiency, which plays an important role for particle tracking and identification. These factors are associated to the detectors hardware and their performance, on the knowledge of the detector description and of the interaction of the

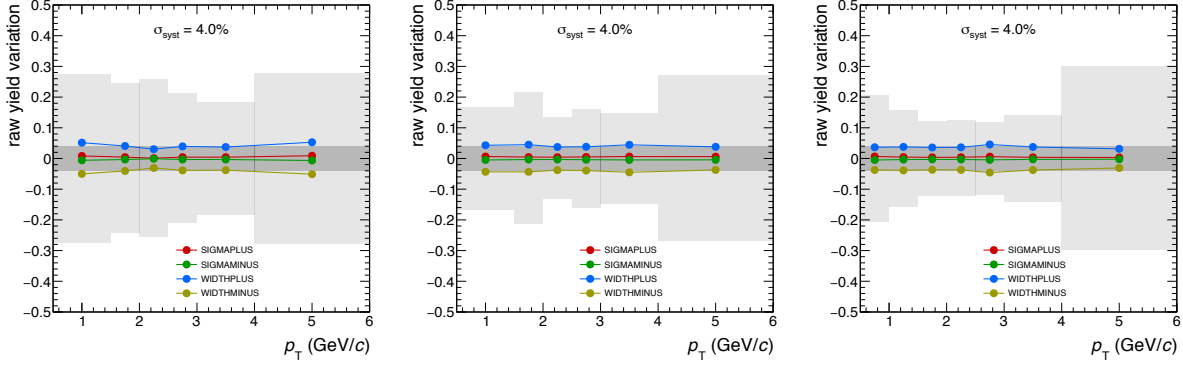


Figure 4.7: Variation of the raw yields when changing the width and resolution of the Breit-Wigner to fit the signal (Section 4.4).

particles with the detector material.

In order to estimate the uncertainty due to the estimated efficiency $\times$ acceptance, the following sources are considered

1. Track reconstruction and selection (Section 4.5.1)
2. Multiplicity dependence (Section 4.5.2)
3. Particle identification (Section 4.5.3)
4. TOF matching (Section 4.5.4)
5. Hadronic cross-section (Section 4.5.5)
6. Material budget (Section 4.5.6)
7. p_T shape correction (Section 4.5.7)
8. Single-track correction (Section 4.5.8)

The details of the above sources are discussed in the following sub-sections.

4.5.1 Track reconstruction and selection

The systematic uncertainty arising from the track reconstruction and track selection has been evaluated from the corresponding systematic uncertainty of primary kaons and protons. The track reconstruction and track selection systematic uncertainties of primary kaons and protons have been estimated in preceding analyses [119] and amounts to about 4% for both kaons and protons. A systematic of about 8% would result, conservatively assuming that the contributions of kaons and protons are fully correlated. Previous analyses on resonance production [88] have

followed a similar approach and have estimated the uncertainty of about 10% for the cases of resonance reconstruction via invariant-mass technique in the two daughter decay channel.

In this analysis, the systematic uncertainty assigned for track reconstruction and selection uses the more conservative value of 10% as estimated by previous analysis on resonance production in ALICE. As the reconstruction efficiency does not depend significantly on multiplicity and this source of uncertainty is mostly related to the accuracy of the Monte Carlo simulation in the description of the actual detector characteristics and algorithmic performance, this uncertainty is assumed to be common to all centrality classes and does not contribute to the multiplicity-uncorrelated systematics.

4.5.2 Multiplicity dependence

A systematic uncertainty is assigned to the multiplicity-dependence of the efficiency correction. The $\Lambda(1520)$ reconstruction efficiency in the inclusive 0–80% centrality sample is corrected for the observed variation in the centrality classes measured in this analysis (Section 3.8.1). The maximum observed variation and applied correction is 4%. Half of the maximum correction (2%) is assigned as a conservative estimate of the multiplicity-dependent uncertainty of the reconstruction efficiency.

4.5.3 Particle identification

The systematics due to the PID selection cuts can be inferred from the PID Quality Assurance checks performed on kaon and proton selection (Section 3.5.1). The direct comparison of data and Monte Carlo in regions where the PID signal is clear allows one to estimate uncertainty by using the same experimental approach used in analysis in order to check the efficiency of the PID selection cut. As discussed in Section 3.5.1, the most extreme case is when TPC 2- σ kaon ID is combined with TOF 3- σ proton ID and would result in a 3.6% systematics for the $\Lambda(1520)$. On the other hand, most of the PID is performed with 3- σ cuts, where the most extreme PID systematics would be 1.8%. To be conservative, we assigned a 3% systematic uncertainty due to the PID.

The PID systematics has also been checked by running the analysis with slightly different $n\sigma$ cuts ($\pm 10\%$). The results are shown in Figure 4.8 for 0–20%, 20–50% and 50–80%. Besides the large statistical uncertainty that affects the measurement, the deviations are observed to be small and within the conservatively-assigned 3% systematic-uncertainty band.

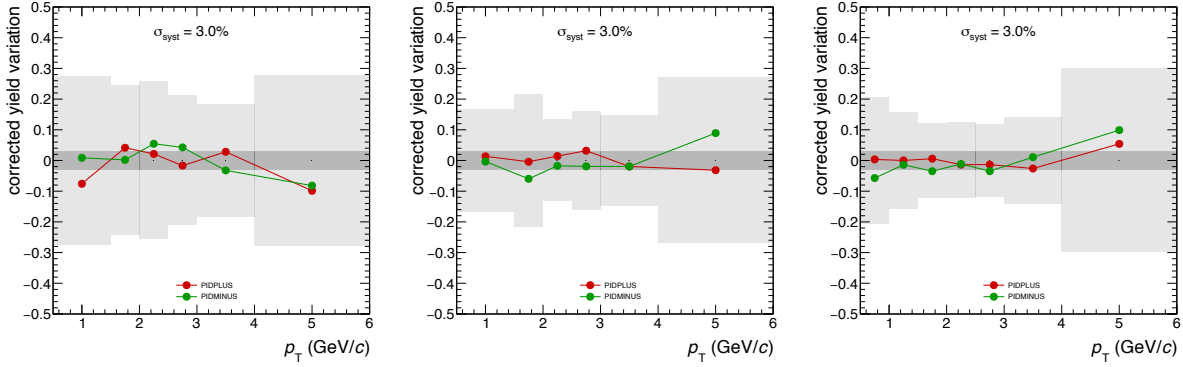


Figure 4.8: Variation of the corrected yields when changing the cuts for particle-identification.

4.5.4 TOF matching

The systematic uncertainty arising from the uncertainty of the TOF matching efficiency has been evaluated employing the simplified resonance model. The nominal efficiency of kaons and protons have been varied according to their TOF-matching systematic uncertainties, allowing one to evaluate the corresponding $\Lambda(1520)$ systematic uncertainty. The TOF-matching systematic uncertainties of primary kaons and protons have been estimated in preceding analyses [119] (Figure 4.9).

The results from the simplified resonance model are shown in Figure 4.10. The assigned systematic uncertainty (Figure 4.11) is taken as the sum of all the contributions, which are conservatively assumed to be fully correlated. This is justified by the fact that the behaviour of the TOF detector in terms of matching efficiency is largely independent from the type of the hitting particle and is mostly due to imperfections in the description of the actual characteristics in the Monte Carlo simulation. For the same reason, this uncertainty is assumed to be common to all centrality classes and does not contribute to the multiplicity-uncorrelated systematics.

4.5.5 Hadronic cross-section

The systematic uncertainty arising from the uncertainty of the hadronic cross-section of kaons and protons with the detector material has been evaluated employing the simplified resonance model. The nominal efficiency of primary kaons and protons have been varied according to their hadronic cross-section systematic uncertainties, allowing one to evaluate the corresponding $\Lambda(1520)$ systematic uncertainty. The hadronic cross-section systematic uncertainties of primary kaons and protons have been estimated in preceding analyses [119] (Figure 4.12).

The results from the simplified resonance model are shown in Figure 4.13. The assigned systematic uncertainty (Figure 4.14) is taken as the quadratic sum of all the contributions, which

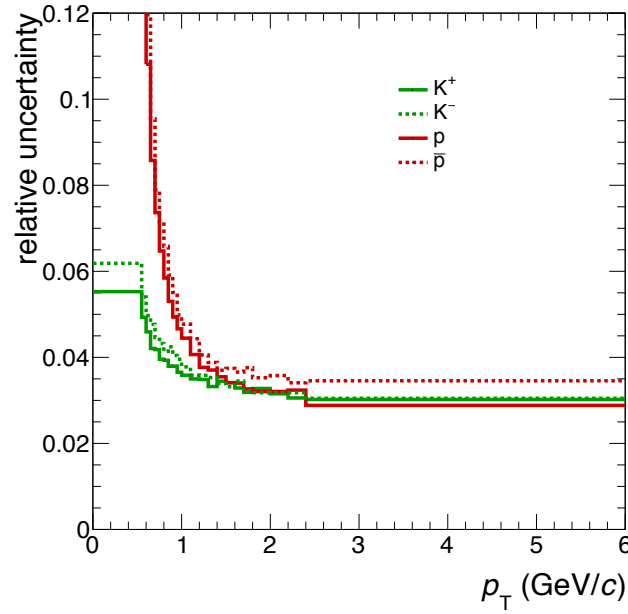
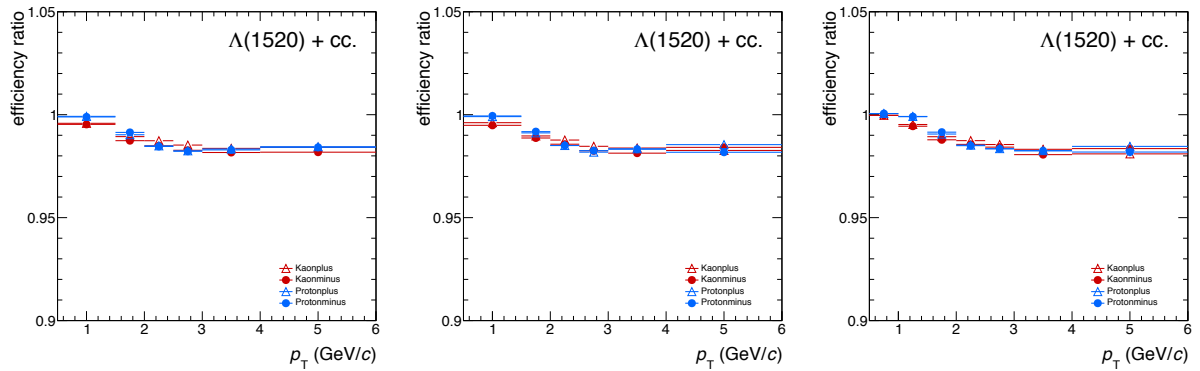
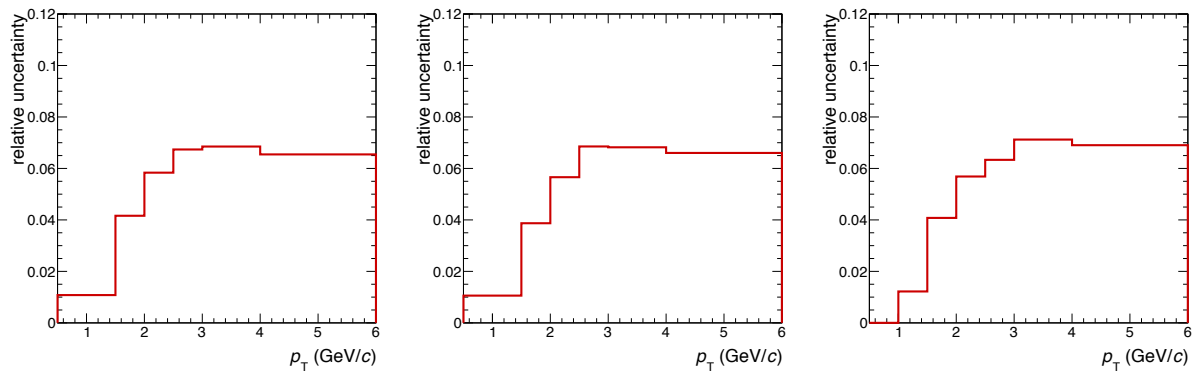


Figure 4.9: TOF-matching systematic uncertainties of primary kaons and protons.

Figure 4.10: Ratio of the $\Lambda(1520)$ efficiency to the nominal value after the variations on kaon and proton efficiency. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.Figure 4.11: TOF-matching systematic uncertainty assigned to the $\Lambda(1520)$. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

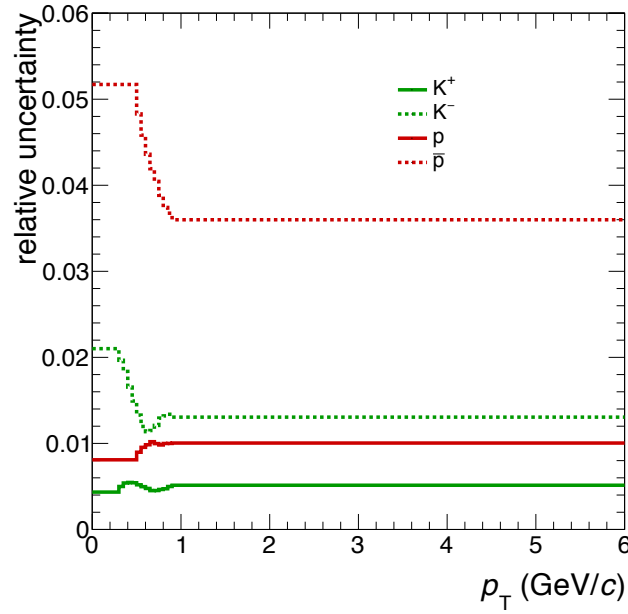


Figure 4.12: Hadronic cross-section systematic uncertainties of primary kaons and protons.

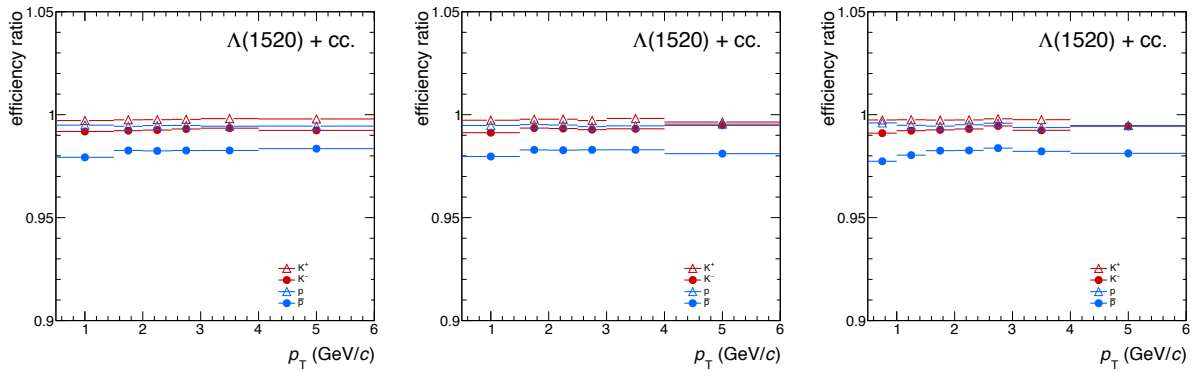


Figure 4.13: Ratio of the $\Lambda(1520)$ efficiency to the nominal value after the variations on kaon and proton efficiency. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

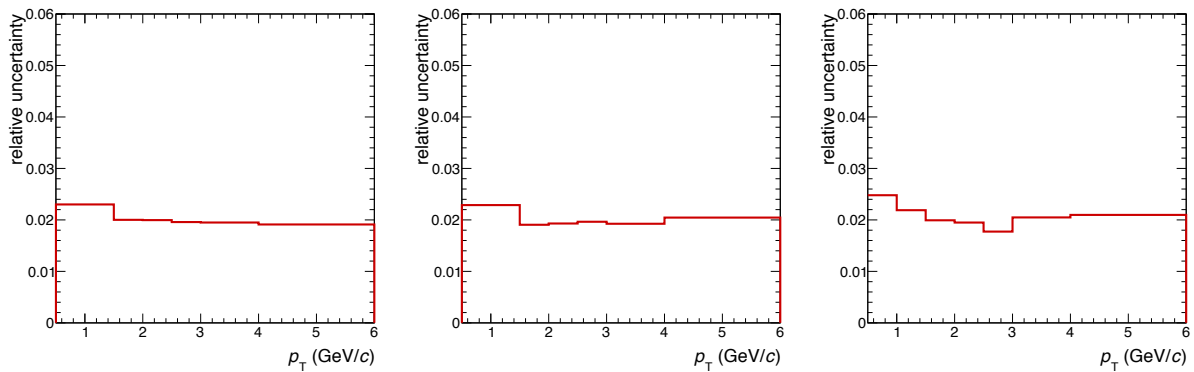


Figure 4.14: Hadronic cross-section systematic uncertainty assigned to the $\Lambda(1520)$. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

are assumed to be uncorrelated. As this systematic uncertainty is related to the properties of the hadronic interaction cross-section of kaons and protons with the detector material, this source of systematic uncertainty is common to all centrality classes and does not contribute to the multiplicity-uncorrelated systematics.

4.5.6 Material budget

The systematic uncertainty arising from the uncertainty of the detector material budget has been evaluated employing the simplified resonance model. The nominal efficiency of primary kaons and protons have been varied according to their material-budget systematic uncertainties, allowing one to evaluate the corresponding $\Lambda(1520)$ systematic uncertainty.

The material-budget systematic uncertainties of primary kaons and protons have been estimated in preceding analyses [119] (Figure 4.15). The results from the simplified resonance model are shown in Figure 4.16. The assigned systematic uncertainty (Figure 4.17) is taken as the sum of all the contributions, which are assumed to be fully correlated. This is justified by the fact that a deviation in the material budget would cause a deviation in the estimated efficiencies for all particles simultaneously, regardless of particle specie. Thus, this source of systematic uncertainty is related to the knowledge and description of the detector and is therefore, common to all centrality classes and does not contribute to the multiplicity-uncorrelated systematics.

4.5.7 p_T shape correction

As discussed in Section 3.8.2, the measured efficiency is corrected to take into account the difference in the input p_T distribution of the analysed Monte Carlo with respect to the expected one. A systematic uncertainty to this correction is estimated using different p_T distributions like m_T -exponential, Fermi Dirac, Boltzmann, Levy-Tsallis and constrained Blast-Wave after fitting them to the measured spectra. The ratio of the resulting p_T shape corrections with respect to the default one are shown in Figure 4.18. The systematics uncertainty is estimated from the largest observed deviation. The resulting systematic uncertainties are shown in Figure 4.19

4.5.8 Single-track correction

As discussed in Section 3.8.3, the measured efficiency is corrected to take into account the differences in the reconstruction performance of the analysed Monte Carlo with respect to the General-Purpose one. The systematic assigned due to the single-track correction is 0.5 times to the correction factor (Figure 3.39).

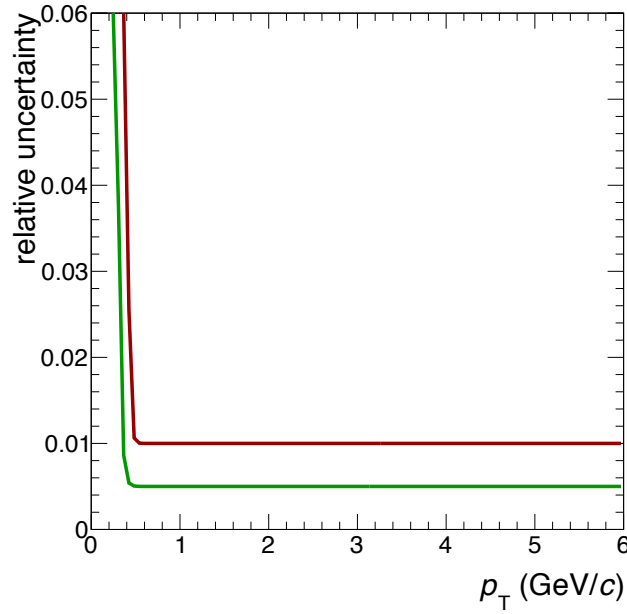


Figure 4.15: Material-budget systematic uncertainties of primary kaons and protons.

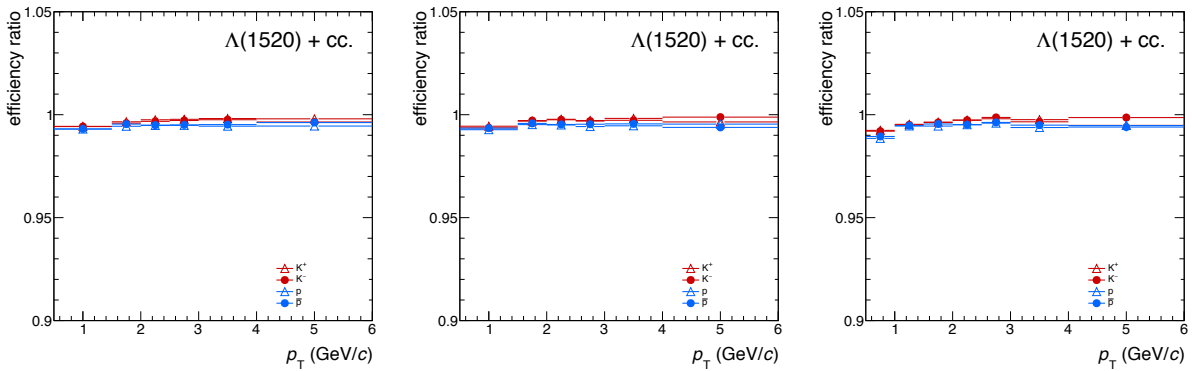


Figure 4.16: Ratio of the $\Lambda(1520)$ efficiency to the nominal value after the variations on kaon and proton efficiency. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

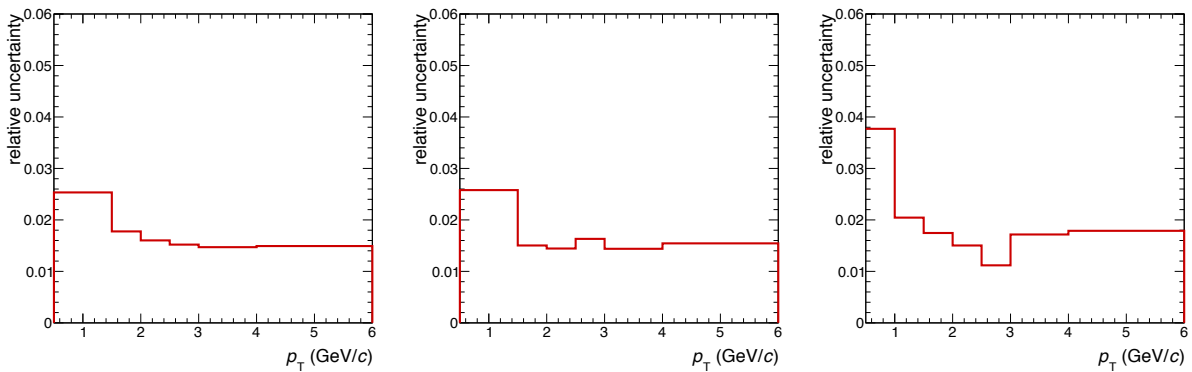


Figure 4.17: Material-budget systematic uncertainty assigned to the $\Lambda(1520)$. 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

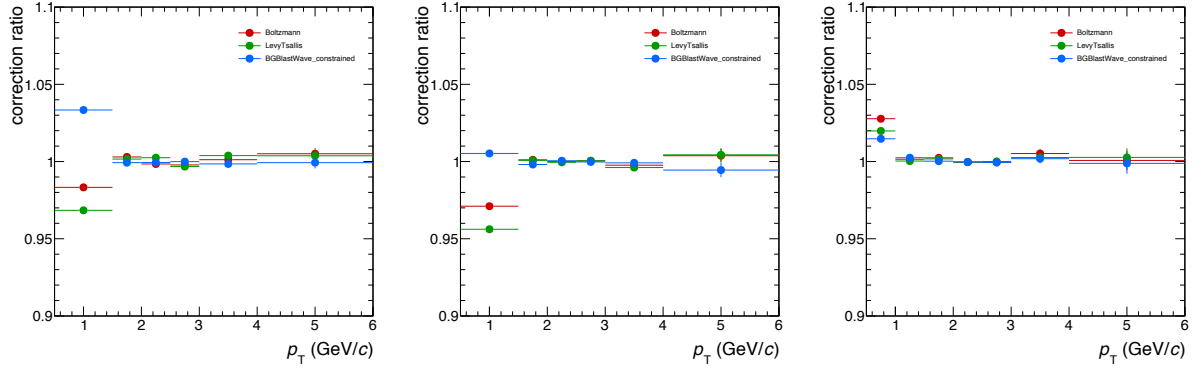


Figure 4.18: Ratio of the p_T shape correction computed with different p_T distributions fitted to the data with respect to the default correction (Section 4.5.7). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

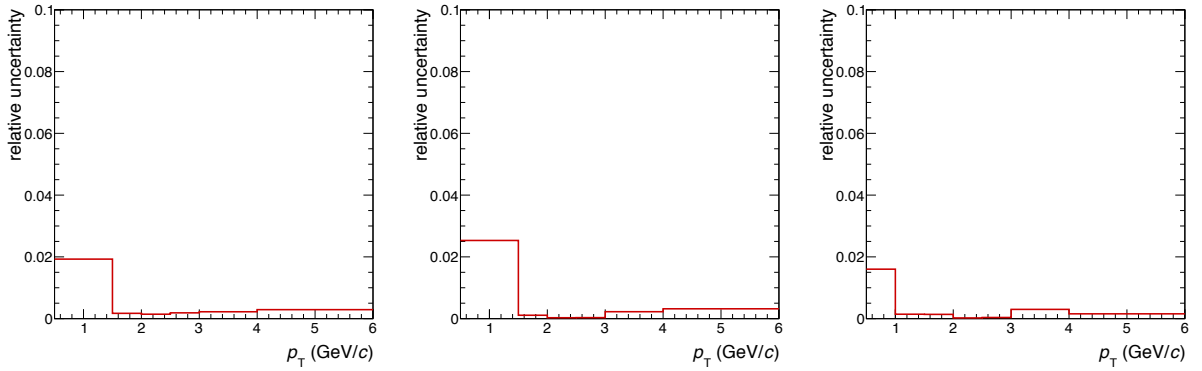


Figure 4.19: Systematic uncertainty assigned to the p_T shape correction procedure (Section 4.5.7). 0–20%, 20–50% and 50–80% centrality classes are shown from left to right.

4.6 Normalisation

The systematics for the centrality selection and normalisation in the centrality classes used in this analysis is derived from the values published in preceding analysis [119]. The values, which are published in narrower centrality classes are averaged to obtain the ones in the centrality classes used for this analysis, using the charged-particle multiplicity density as weight. The uncertainties are averaged assuming they are fully correlated, which is the correct assumption as a shift in the centrality determination affects all centrality bins in the same direction. The values in 0–20%, 20–50% and 50–80% centrality classes are reported in Table 4.6.

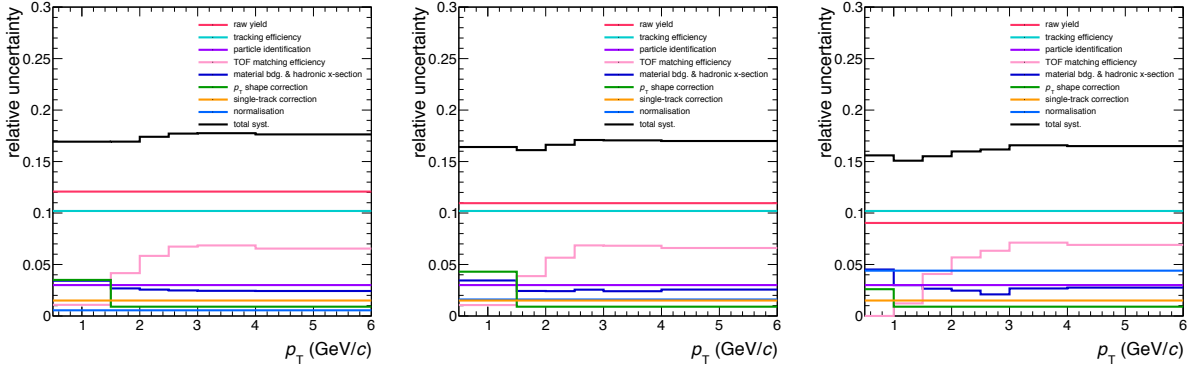


Figure 4.20: The total systematics uncertainties and corresponding sources are shown in different colours for 0–20% (left), 20–50% (middle) and 50–80% (right) centrality events in the 2010 data sample.

4.7 Total systematic uncertainty

The total systematic uncertainty in the measurement of baryonic resonance $\Lambda(1520)$ is calculated as the quadratic sum of all the contributions, namely:

- Background description (Section 4.3)
- Signal description (Section 4.4)
- Track reconstruction and selection (Section 4.5.1)
- Particle identification (Section 4.5.3)
- TOF matching (Section 4.5.4)
- Hadronic cross section (Section 4.5.5)
- Material budget (Section 4.5.6)
- p_T shape correction (Section 4.5.7)
- Single-track correction (Section 4.5.8)
- Normalisation (Section 4.6)

The result is summarised in Table 4.6 and in Figure 4.20.

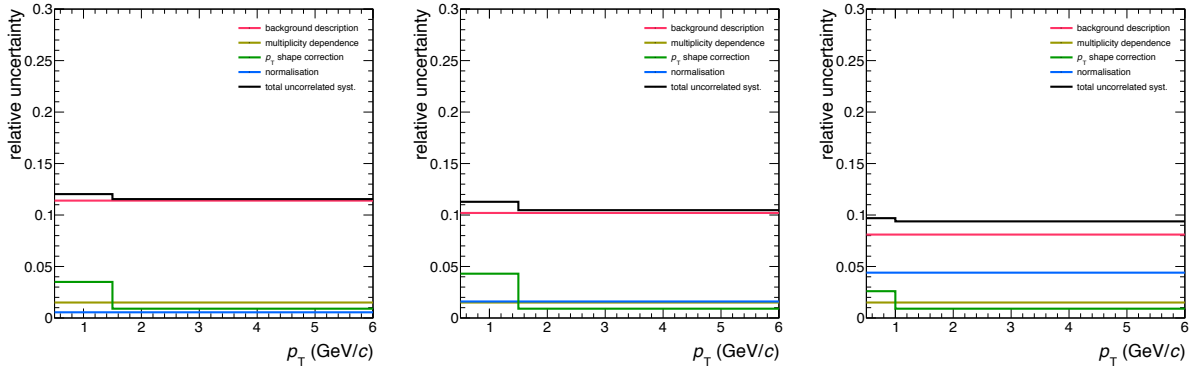


Figure 4.21: The uncorrelated systematic uncertainties and corresponding sources are shown in different colours for 0–20% (left), 20–50% (middle) and 50–80% (right) centrality events in the 2010 data sample.

4.7.1 Total uncorrelated systematic uncertainty

The systematic uncertainty in the measurement of baryonic resonance $\Lambda(1520)$, which is uncorrelated across different centrality classes has been estimated removing all contributions which are common to all centrality classes, namely:

- Signal description (Section 4.4)
- Track reconstruction and selection (Section 4.5.1)
- Particle identification (Section 4.5.3)
- TOF matching (Section 4.5.4)
- Hadronic cross section (Section 4.5.5)
- Material budget (Section 4.5.6)
- Single-track correction (Section 4.5.8)

The remaining contributions have been summed in quadrature to define the uncorrelated systematic uncertainty, as summarised in Table 4.6 and in Figure 4.21.

Table 4.6: Sources contributing to the systematic uncertainty of the p_T -differential yield of the $\Lambda(1520)$. The values are the relative uncertainties, expressed in %. Whenever two values are reported, they indicate the uncertainty in the first and in the last measured p_T bin, respectively. Sources of uncertainty which are common to all centrality classes are marked with the symbol (*). The *Total* row reports the total systematic uncertainty, which is the quadratic sum of all the contributions. The *Uncorrelated* row reports the systematic uncertainty which is uncorrelated across centrality, which is the quadratic sum of all contributions, but the ones common to all centrality classes. The uncertainty of the yield extrapolation in the unmeasured p_T region is also reported.

	0–20%	20–50%	50–80%
Background description	11.4	10.2	8.1
Signal description (*)	4	4	4
Tracking (*)	10	10	10
Multiplicity dependence	2	2	2
PID (*)	3	3	3
TOF matching (*)	1 - 6.5	1 - 6.5	0 - 6.5
Hadronic cross-section (*)	2.3 - 2.0	2.3 - 2.0	2.5 - 2.0
Material budget (*)	2.5 - 1.5	2.5 - 1.5	3.8 - 1.5
p_T shape correction	3.5 - 0.9	4.3 - 0.9	2.6 - 0.9
Single track correction (*)	0 - 1.5	0 - 1.5	0 - 1.5
Normalisation	0.55	1.6	4.4
Total	16.8 - 17.7	16.4 - 16.9	15.5 - 16.2
Uncorrelated	12.0 - 11.6	11.3 - 10.5	9.8 - 9.4
Extrapolation function	2.7	3.4	2.2

Table 4.7: The fraction of the low- p_T extrapolated $\Lambda(1520)$ yield with different p_T distribution fitting function in measured centrality bins.

p_T distribution fitting function	low- p_T extrapolation		
	0–20%	20–50%	50–80%
Blast-Wave	6.07%	6.13%	11.41%
Constrained Blast-Wave	4.02%	5.66%	10.70%
Boltzmann	7.32%	8.13%	9.52%
Levy-Tsallis	8.32%	9.10%	10.61%
m_T -exponential	8.31%	9.08%	10.59%
Fermi-Dirac	8.00%	8.81%	10.34%

4.8 low- p_T extrapolation systematic uncertainty

In order to determine the fully integrated $\Lambda(1520)$ yield, the yield in the unmeasured p_T region has to be estimated. The measured p_T -differential yields (Section 5.3.1) are fitted using p_T distributions like, m_T -exponential, Fermi-Dirac, Boltzmann, Levy-Tsallis and constrained Blast-Wave. The values of the Blast Wave parameterisation utilised is same as discussed in Section 5.1.1 and reported in Table 5.1 with the normalisation factor being varied to fit the data. On the other hand, the default fit for the low- p_T extrapolation is performed with a *Free Blast-Wave* parameterisation, where all the parameters are allowed to vary. The results of the default fit is shown in Figure 5.1. The results of the fits to compute the yield systematic in the unmeasured p_T region are shown in Figure 4.23, 4.24 and 4.25.

The total systematic uncertainty is obtained by repeating the fits by taking into account the highest/lowest possible spectrum allowed by the systematic uncertainties of data and is shown in Figure 4.25. A summary showing all fits is shown in Figure 4.8. The $\frac{dN_{\text{low}}}{dy}$ and $\frac{dN_{\text{high}}}{dy}$ values have been calculated by varying the functional form of p_T distribution fitting function. The fraction of low- p_T extrapolation yield to total integrated yield for different p_T distribution fitting function is reported in Table 4.7. Similarly, the fraction of high- p_T extrapolation yield to total integrated yield from various p_T distribution fitting function is reported in Table 4.8.

The total p_T -integrated yield ($\frac{dN_{\text{low}}}{dy} + \frac{dN_{\text{data}}}{dy} + \frac{dN_{\text{high}}}{dy}$) is calculated for each p_T distribution function and is reported in Table 4.9. The ratio of the resulting p_T -integrated yields (Section 5.3) to the default ones are shown in Figure 4.22. The systematic uncertainty is estimated from the largest observed deviation. The assigned systematic uncertainties are shown in Table 4.6.

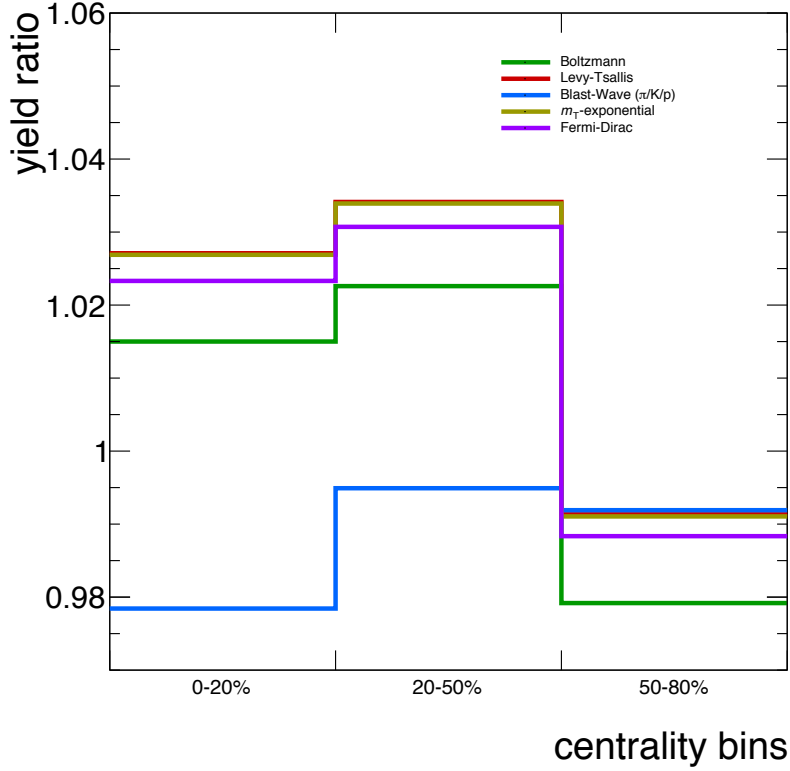


Figure 4.22: Uncertainty in total integrated yield with different p_T -distribution fitting function w.r.t Blast-Wave function.

4.9 $\langle p_T \rangle$ systematic

The details on the $\langle p_T \rangle$ of $\Lambda(1520)$ extraction are discussed in Section 5.4. The systematic uncertainty on $\langle p_T \rangle$ is estimated, firstly by fitting various p_T -distribution functions like m_T -exponential, Fermi-Dirac, Boltzmann, Levy-Tsallis and constrained Blast-Wave to p_T -differential yield spectra, secondly by repeating the default fit to the hardest/softest possible spectrum allowed by the systematic uncertainties of data in the system.

The $\langle p_T \rangle$ value obtained by these p_T -distributions are reported in Table 4.10. The values of the Blast Wave parameterisation utilised is same as discussed in Section 5.1.1 and reported in Table 5.1 with the normalisation factor being varied to fit the data. On the other hand, the default fit for the $\langle p_T \rangle$ calculation is performed with a *Free Blast-Wave* parameterisation, where all the parameters are allowed to vary. The results of the default fit are shown in Figure 5.1. The results of the fits to compute the $\langle p_T \rangle$ systematic are shown in Figure 4.23, 4.24 and 4.26.

Table 4.8: The fraction of the high- p_T extrapolated $\Lambda(1520)$ yield with different p_T distribution fitting function in measured centrality bins.

p_T distribution fitting function	high- p_T extrapolation		
	0–20%	20–50%	50–80%
Blast-Wave	0.1%	0.04%	0.01%
Constrained Blast-Wave	0.06%	0.04%	0.01%
Boltzmann	0.22%	0.12%	0.04%
Levy-Tsallis	0.30%	0.17%	0.05%
m_T -exponential	0.30%	0.17%	0.05%
Fermi-Dirac	0.30%	0.16%	0.05%

Table 4.9: Total $\Lambda(1520)$ yield with different p_T distribution fitting function in measured centrality bins.

p_T distribution fitting function	$\Lambda(1520)$ yield $\pm$ (stat)		
	0–20%	20–50%	50–80%
Blast-Wave	1.5637 ± 0.2047	0.7029 ± 0.0649	0.2203 ± 0.0195
Constrained Blast-Wave	1.5299 ± 0.1872	0.6994 ± 0.0572	0.21854 ± 0.0148
Boltzmann	1.5871 ± 0.1887	0.7188 ± 0.0579	0.2157 ± 0.0149
Levy-Tsallis	1.6061 ± 0.1892	0.7269 ± 0.0581	0.2184 ± 0.0149
m_T -exponential	1.6057 ± 0.1891	0.7268 ± 0.0581	0.2184 ± 0.01499
Fermi-Dirac	1.6001 ± 0.1891	0.7246 ± 0.0581	0.2178 ± 0.01498

Table 4.10: $\langle p_T \rangle$ of $\Lambda(1520)$ production with different p_T distribution fitting function in measured centrality bins.

p_T distribution fitting function	$\langle p_T \rangle \pm$ (stat) (GeV/c)		
	0–20%	20–50%	50–80%
Blast-Wave	1.847 ± 0.093	1.763 ± 0.057	1.497 ± 0.047
Boltzmann	1.832 ± 0.093	1.736 ± 0.056	1.524 ± 0.049
Levy-Tsallis	1.820 ± 0.090	1.723 ± 0.054	1.510 ± 0.049
m_T -exponential	1.820 ± 0.089	1.723 ± 0.058	1.511 ± 0.047
Fermi-Dirac	1.824 ± 0.094	1.727 ± 0.054	1.514 ± 0.046

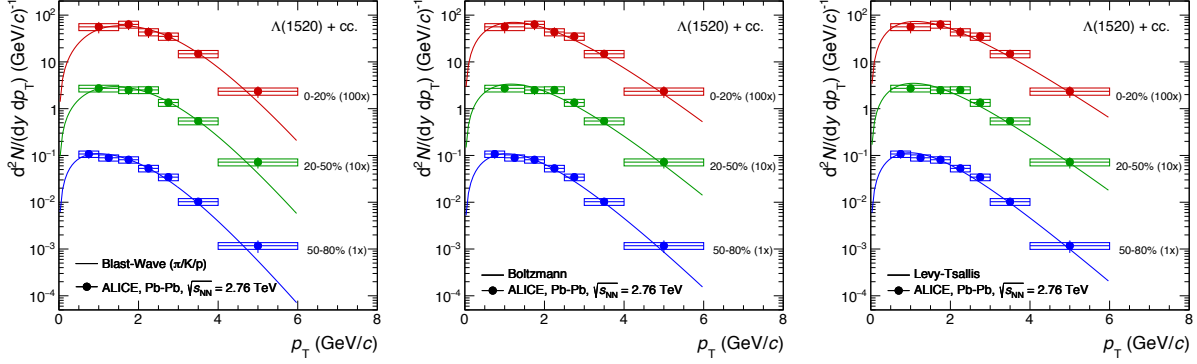


Figure 4.23: Measured $\Lambda(1520)$ p_T -differential yields in 0–20%, 20–50% and 50–80% centrality events. The solid lines represent the *constrained Blast-Wave*(left) parametrisation fitted to Table 5.1, *Boltzmann*(middle) and *Levy-Tsallis*(right) parametrisation fitted to the data. Predictions from the EPOS3 model are also shown (Section 5.1.2).

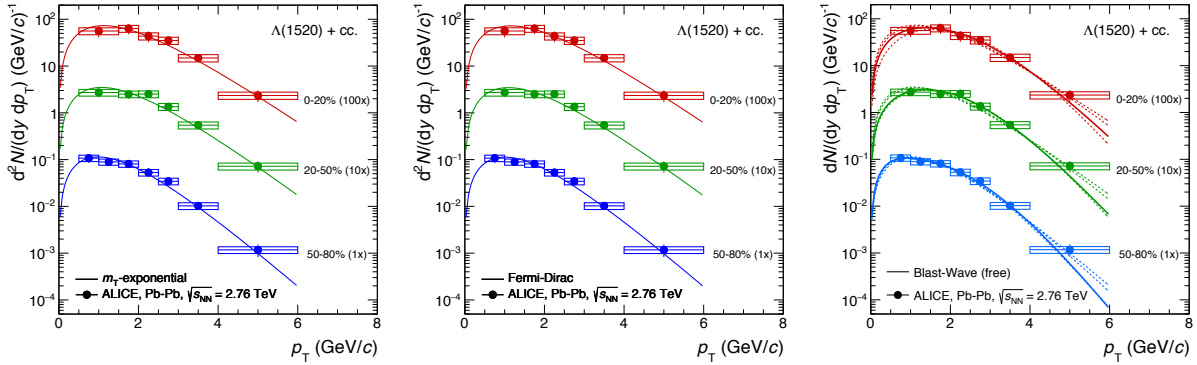


Figure 4.24: Measured $\Lambda(1520)$ p_T -differential yields in 0–20%, 20–50% and 50–80% centrality events. The solid lines represent the m_T -exponential(left), *Fermi Dirac*(middle) parametrisation fitted to the data. Predictions from the EPOS3 model are also shown (Section 5.1.2). In right hand plot, The solid line represent the Free Blast-Wave parametrisation fitted to the data, whereas the dashed lines show the fits with the other functions used for the estimated of the low- p_T extrapolation systematics 4.8

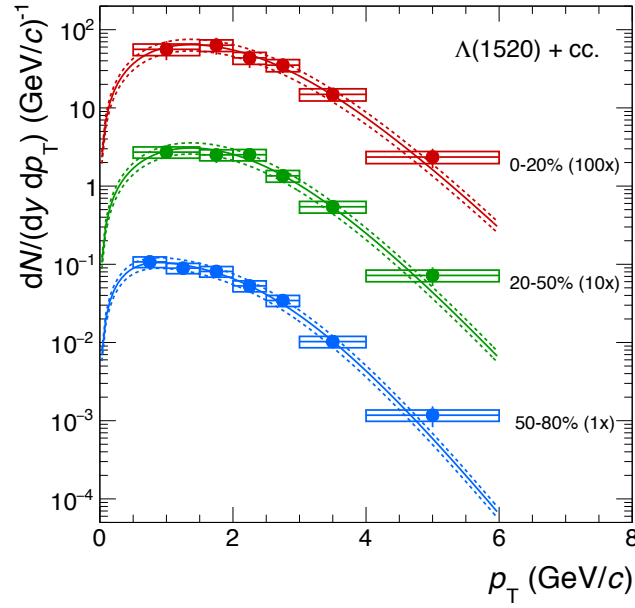


Figure 4.25: Measured $\Lambda(1520)$ p_T -differential yields in 0–20%, 20–50% and 50–80% centrality events. The solid lines represent the *Free Blast-Wave* parametrisation fitted to the data and dotted lines represents the highest/lowest possible spectrum allowed by the system to calculate the integrated yield systematics.

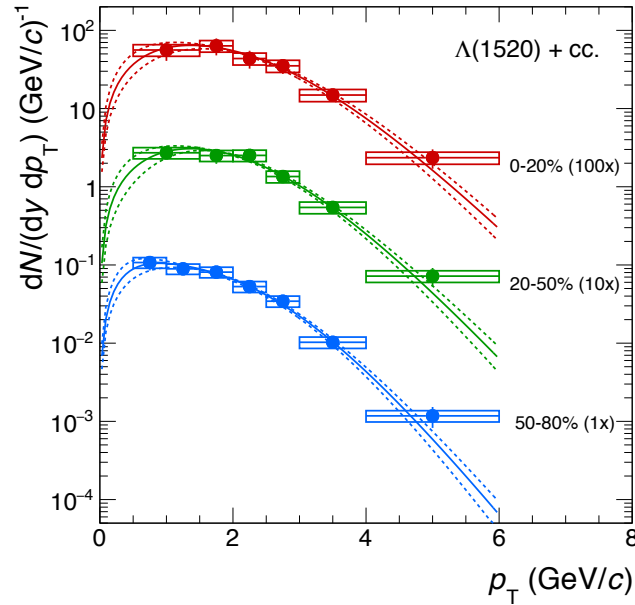


Figure 4.26: Measured $\Lambda(1520)$ p_T -differential yields in 0–20%, 20–50% and 50–80% centrality events. The solid lines represent the *Free Blast-Wave* parametrisation fitted to the data and dotted lines represents the hardest/softest possible spectrum allowed by the system to calculate the $\langle p_T \rangle$ systematics.

Chapter 5

Results and comparison to Models

"Success can come to you by courageous devotion to the task lying in front of you."

– CV Raman

Abstract: This chapter describes the results of the analysis, namely the measurement of the p_T -differential and integrated $\Lambda(1520)$ yield, $\langle p_T \rangle$ of $\Lambda(1520)$ and $\Lambda(1520)/\Lambda$ ratio in details.

The $\Lambda(1520)$ resonance analysis method and the estimation of systematic uncertainties are described in detail in Chapter 3 and 4, respectively. In this chapter, the results of the analysis related to the measurement of $\Lambda(1520)$ production is reported and the results are compared to various model predictions. In particular, the transverse momentum spectrum of $\Lambda(1520)$ and its derived experimental observables (such as integrated yields, mean p_T and particle ratios) are presented and discussed in Section 5.1, Section 5.3, Section 5.4 and Section 5.6. The comparison with the model predictions provides a mean for the understanding of the possible phenomena occurring during after the hadronisation of the QGP fireball which depends on important details of the final state, such as system size and thermal conditions. The results of $\Lambda(1520)$ measurements are discussed in detail in the following sections.

5.1 p_T -differential yield

The p_T differential yields measured at mid-rapidity are obtained from the measured raw yields (Section 3.6) after applying all the corrections (Section 3.7) as a function of p_T in three centrality classes, 0-20%, 20-50%, 50-80% in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The p_T differential yields have also been corrected for the $\Lambda(1520)$ decay branching ratio [64] in the analysed decay channel.

$$BR = \frac{\Gamma_{\Lambda(1520) \rightarrow pK}}{\Gamma} = 22.5 \pm 0.5\% \quad (5.1)$$

The corrected and normalised p_T -differential yields are obtained for each centrality and each p_T bin as

$$\frac{d^2 N}{dy dp_T} = \frac{1}{N_{ev}} \frac{N_{raw}}{\Delta y \Delta p_T} \frac{1}{\epsilon} \frac{1}{BR} \quad (5.2)$$

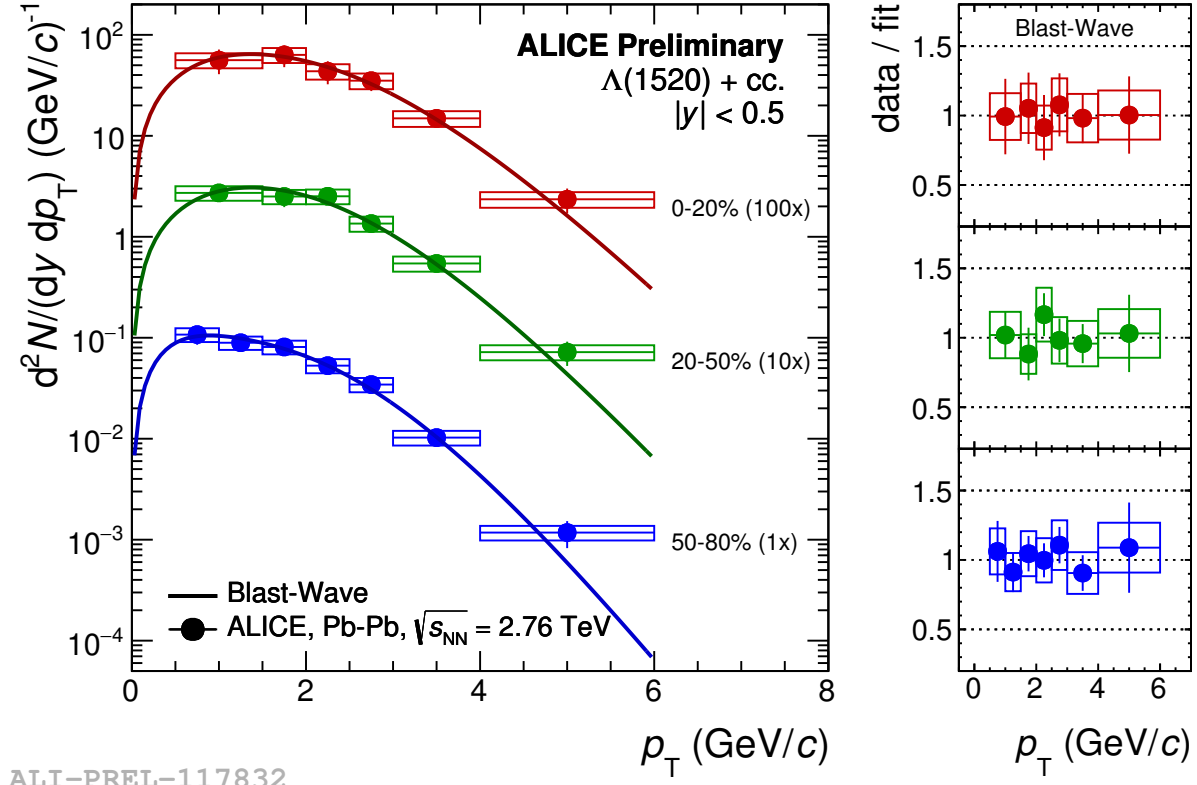


Figure 5.1: Measured $\Lambda(1520)$ p_T -differential yields in 0–20%, 20–50% and 50–80% centrality events. The solid lines represent the *Free Blast-Wave* parametrisation fitted to the data (Section 5.1.1). Predictions from the EPOS3 model are also shown (Section 5.1.2). The right panel shows the ratio of the measured $\Lambda(1520)$ p_T -differential yields to the *Free Blast-Wave* parametrisation fitted to the data (Section 5.1.1). 0–20%, 20–50% and 50–80% centrality classes are shown from top to bottom.

where N_{ev} is the number of events analysed in the centrality class, N_{raw} is the measured raw yield, Δp_T is the width of the p_T -bin, Δy is the width of the rapidity window, ε is the efficiency correction factor and BR is the branching ratio in the analysed decay channel. The p_T distributions for different centrality classes are shown in Figure 5.1. The data points of the top 0–20% and 20–50% centralities are scaled by a factor 100 and 10, respectively in order to optimise the visualisation of the p_T -spectrum.

5.1.1 Comparison to Blast-Wave Model

The p_T spectral shape of $\Lambda(1520)$ can be predicted from the hydrodynamical inspired Boltzmann-Gibbs Blast Wave (BW) model [117] with the assumption that $\Lambda(1520)$ undergoes the same hydrodynamical expansion as pions, kaons and protons. The solid lines on Figure 5.1 show the

Blast-Wave (BW) model prediction for the measured centralities, 0-20%, 20-50% and 50-80%. In the simple Blast-Wave model, based on the Boltzmann-Gibbs statistics, the transverse momentum spectrum is computed by boosting the thermal sources in the transverse direction, hence assuming that the thermal sources are collectively expanding in a hydrodynamical fashion. The transverse velocity distribution of a thermal source located at radius r in the hydrodynamically-expanding fireball is

$$\beta_T(r) = \beta_s \left(\frac{r}{R} \right)^n \quad (5.3)$$

where β_s is the surface velocity, R is the radius of the fireball and n is the velocity profile. The resulting transverse momentum distribution of the particles emanating from the fireball is

$$\frac{d^2N}{dydp_T} \propto p_T \times \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{\text{kin}}} \right) \quad (5.4)$$

where ρ is

$$\rho = \tanh^{-1} \beta_T = \tanh^{-1} \left(\left(\frac{r}{R} \right)^n \beta_s \right) \quad (5.5)$$

and $m_T = \sqrt{m^2 + p_T^2}$ is the transverse mass, I_0 and K_1 are the modified Bessel functions, R is the radius of the fireball, r is the radial distance in the transverse plane, β_T is the transverse expansion velocity and β_s is the transverse expansion velocity at the surface, T_{kin} is the temperature of the thermal sources and n is the velocity profile in the fireball. The advantage of using the Blast-Wave function is related to its relatively simple and analytical formula, which provides a good approximation in a simplified hydrodynamic picture. The Blast Wave model hence allows one to describe the spectral shape of many particles with only a few parameters under the assumption of collective hydrodynamic expansion and to evaluate whether collectivity actually applies.

The corrected spectra in the measured centralities are compared to the Blast Wave predictions from Equation 5.4, where the model parameters are fixed to the ones obtained from fits to pion, kaon and protons spectra [119]. The BW parameters obtained from pion, kaon and proton spectra were measured in narrower centrality classes than the one utilised in $\Lambda(1520)$ analysis. For this reason, the parameters corresponding to the centrality classes used for the $\Lambda(1520)$ analysis have to be derived. The Blast-Wave parameters in $\Lambda(1520)$ measured centrality classes have been obtained by averaging the measured BW parameters, by using the measured charged particles multiplicity density [113] as a weight factor, namely as

$$p_{ABC} = \frac{p_A \omega_A + p_B \omega_B + p_C \omega_C}{\omega_A + \omega_B + \omega_C} \quad (5.6)$$

$$\omega_i = (dN_{\text{ch}}/d\eta)_i \quad (5.7)$$

where p_{ABC} is a given Blast-Wave parameter averaged over the centrality class A, B and C. p_A is the Blast-Wave parameter in the centrality class i and $(dN_{\text{ch}}/d\eta)_i$ is the corresponding charged-particle multiplicity density. The Blast-Wave parameters measured from the pion, kaon and

Table 5.1: Measured Blast-Wave parameters from pion, kaon and proton spectra [119] and the ones derived for the centrality classes used in this analysis (Section 5.1.1). The charged-particle multiplicity density for the centrality classes of the pion, kaon and proton results [113] are also shown.

	$dN_{\text{ch}}/d\eta$	$\langle\beta_T\rangle$	T_{kin} (GeV/c)	n
0–5%	1601 ± 60	0.651	0.095	0.712
5–10%	1294 ± 49	0.646	0.097	0.723
10–20%	966 ± 37	0.639	0.099	0.738
20–30%	649 ± 23	0.625	0.101	0.779
30–40%	426 ± 15	0.604	0.106	0.841
40–50%	261 ± 9	0.574	0.112	0.944
50–60%	149 ± 6	0.535	0.118	1.099
60–70%	76 ± 4	0.489	0.129	1.292
70–80%	35 ± 2	0.438	0.139	1.578
0–20%	1207 ± 46	0.646	0.097	0.722
20–50%	445 ± 16	0.608	0.105	0.831
50–80%	87 ± 4	0.508	0.124	1.220

proton spectra and the ones derived with the procedure discussed above for the $\Lambda(1520)$ in the derived centrality classes 0–20%, 20–50% and 50–80% are shown in Table 5.1. The Blast-Wave model expectations based on these parameters is mentioned as *Constrained Blast-Wave* in the following sections.

The p_T distribution of $\Lambda(1520)$ measured in this analysis are compared to the Blast-Wave expectations in Figure 5.2 after fitting the model normalisation to the data. A direct comparison with the data is shown in the right panel of Figure 5.2, where the ratio of the values measured in the data and model is computed for each measured p_T bin. To compute the ratio in a specific p_T bin the BW predicted yield is determined by integrating the model in the p_T bin width that matches the data measurement. The spectral shapes of $\Lambda(1520)$ in each measured centrality are observed to be very well in agreement with the *Constrained Blast-Wave*, whose spectral shape prediction is only based on the parameters obtained from $\pi/K/p$ [119] as can be seen from Figure 5.2. This suggests that the $\Lambda(1520)$ experiences the same hydrodynamical expansion and kinetic freeze-out conditions as those of the bulk of the produced matter, namely pions, kaons and protons.

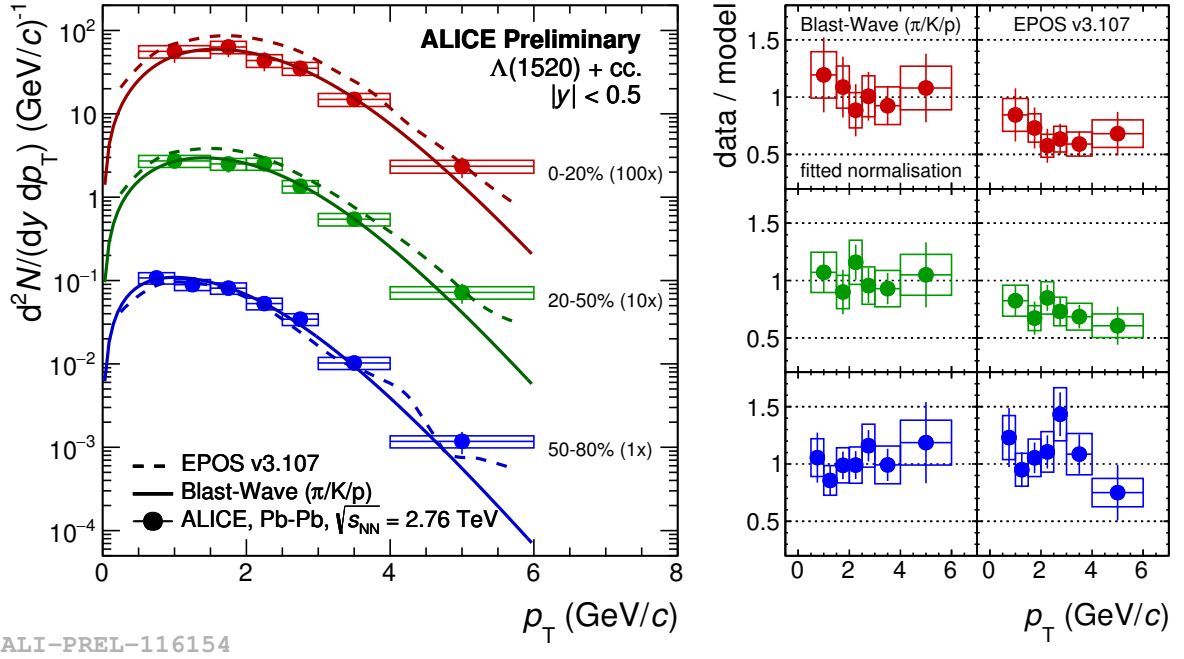


Figure 5.2: Measured $\Lambda(1520)$ p_T -differential yields in 0–20%, 20–50% and 50–80% centrality events. The solid lines represent the *Constrained Blast-Wave* parametrisation fitted to the data. Predictions from the EPOS3 model are also shown (Section 5.1.2). Right, first panel shows the ratio of the measured $\Lambda(1520)$ p_T -differential yields to the *Constrained Blast-Wave* parametrisation fitted to the data. Right, second panel shows ratio of the measured $\Lambda(1520)$ p_T -differential yields to the predictions from the EPOS3 model (Section 5.1.2). 0–20%, 20–50% and 50–80% centrality classes are shown from top to bottom.

5.1.2 Comparison to EPOS3 Model

The production of hadronic resonances can be studied using the EPOS3 model [69], a detailed Monte Carlo event generator for the study of hadronic and nuclear collisions. The motivation for using the EPOS3 model is related to the fact that it provides a complete description of the full evolution of the heavy-ion collision (Section 1.2.2). The model includes hydrodynamical calculations to describe the evolution of the partonic matter, coupled with the UrQMD model for the description of the hadronic phase after hadronisation. The UrQMD model describes in a microscopic way the hadronic interactions including binary elastic and $2 \rightarrow n$ inelastic scattering, string excitations, resonance creation and decays, strangeness exchange reactions and particle + antiparticle annihilations.

The p_T distributions of $\Lambda(1520)$ in the measured centrality classes are compared to the predictions from the EPOS3 model in the left panel of Figure 5.2. The direct comparison of the EPOS3 predictions with the measurement in data is shown in the right-most panel of Figure 5.2,

where the ratio of data to model is computed for each measured p_T bin. The spectral shapes of $\Lambda(1520)$ in each measured centrality are observed to be in rather good agreement with the EPOS3 predictions as can be seen from Figure 5.2. However, it has to be noticed that EPOS3 over-predicts the $\Lambda(1520)$ yield for the central collisions but works reasonably well for the peripheral collisions. The disagreement in the normalisation of the production yield for central collisions might be related to the parameters of the model that control the QGP hadronisation, where a larger freeze-out temperature might cause a large resonance yield without affecting the spectral shape.

5.2 Estimation of charged-particle multiplicity

The $\Lambda(1520)$ measurement has been performed in three wide centrality classes. The charged-particle multiplicity density has been published in narrower centrality classes [113]. Hence, the charged-particle multiplicity density values corresponding to 0–20%, 20–50% and 50–80% centralities have been determined from the published values [113], by using the centrality bin width as a weight factor, as follows

$$\langle dN_{ch}/d\eta \rangle_{ABC} = \frac{\langle dN_{ch}/d\eta \rangle_A \Delta_A + \langle dN_{ch}/d\eta \rangle_B \Delta_B + \langle dN_{ch}/d\eta \rangle_C \Delta_C}{\Delta_A + \Delta_B + \Delta_C} \quad (5.8)$$

where $\langle dN_{ch}/d\eta \rangle_{ABC}$ is the $dN_{ch}/d\eta$ value averaged over the centrality classes A, B and C, $\langle dN_{ch}/d\eta \rangle_i$ is the $\langle dN_{ch}/d\eta \rangle$ value in the centrality class i and Δ_i is the corresponding width of the centrality bin. The systematic uncertainty of the average values is computed by assuming that the uncertainties are fully-correlated across centrality. The published $\langle dN_{ch}/d\eta \rangle$ values are reported in Table 5.1. The $\langle dN_{ch}/d\eta \rangle$ values derived for the $\Lambda(1520)$ measured centrality classes 0–20%, 20–50% and 50–80% are shown in both Table 5.1 and 5.2

5.3 $\Lambda(1520)$ integrated yield

The $\Lambda(1520)$ integrated yield ($\frac{dN}{dy}$) is defined as

$$\frac{dN}{dy} = \frac{dN_{data}}{dy} + \frac{dN_{low}}{dy} + \frac{dN_{high}}{dy} \quad (5.9)$$

Where $\frac{dN_{data}}{dy}$ is the $\Lambda(1520)$ yield computed integrating the measured p_T -differential yields (Section 5.1), $\frac{dN_{low}}{dy}$ and $\frac{dN_{high}}{dy}$ are the low and high- p_T yields extrapolated from the data with the help of spectral fits (Section 5.3.1), respectively. The integrated yield in the measured p_T range is calculated as

$$\frac{dN_{data}}{dy} = \sum_i \frac{d^2 N_i}{dy dp_T} \Delta p_{T,i} \quad (5.10)$$

where i runs over all the measured p_T bins in a particular centrality interval, $\frac{d^2 N_i}{dy dp_T}$ is the measured p_T -differential yield in a given p_T bin and $\Delta p_{T,i}$ is the width of the corresponding p_T bin. The corresponding statistical uncertainty is computed as the quadratic sum of each p_T -differential statistical uncertainties

$$\sigma_{\text{stat}} \left[\frac{dN_{\text{data}}}{dy} \right] = \sqrt{\sum_i \sigma_{\text{stat}}^2 \left[\frac{d^2 N_i}{dy dp_T} \right] \Delta p_{T,i}^2} \quad (5.11)$$

In order to estimate the systematic uncertainty, the total and centrality un-correlated systematic uncertainties are computed as sum of the corresponding p_T -differential systematic uncertainties by assuming that they are fully correlated across p_T , as

$$\sigma_{\text{syst}} \left[\frac{dN_{\text{data}}}{dy} \right] = \sum_i \sigma_{\text{syst}} \left[\frac{d^2 N_i}{dy dp_T} \right] \Delta p_{T,i} \quad (5.12)$$

The $\Lambda(1520)$ total integrated yields are reported in Table 5.2. The corresponding statistical, total systematic and total centrality un-correlated uncertainties are also reported in Table 5.2. The $\frac{dN}{dy}$ value of $\Lambda(1520)$ increases from peripheral to central collisions.

Table 5.2: $\Lambda(1520)$ integrated yields and corresponding uncertainties (Section 5.3). Total systematic uncertainties (syst) include all contributions, whereas the centrality-uncorrelated systematic uncertainties (uncor) do not include the contributions common to all centrality-classes. The fraction of the extrapolated yield (Section 5.3.1), as well as the average charged-particle multiplicity density derived in the measured centrality classes (Section 5.2) is also shown.

	$\langle dN_{\text{ch}}/d\eta \rangle$	$\frac{dN}{dy} \pm (\text{stat}) \pm (\text{syst}) \pm (\text{uncor})$	extrapolation
0–20%	1207 ± 46	$1.5637 \pm 0.2047 \pm 0.2685 \pm 0.1933$	6.17%
20–50%	445 ± 16	$0.7029 \pm 0.0649 \pm 0.1159 \pm 0.0806$	6.17%
50–80%	87 ± 4	$0.2203 \pm 0.0195 \pm 0.0344 \pm 0.0226$	10.42%

5.3.1 Low- and high- p_T extrapolation

In order to determine the total production yield of $\Lambda(1520)$ yield (Section 5.3), the yield in the unmeasured p_T region needs to be estimated. The measured p_T distribution is fitted with the Blast-Wave parameterisation (Section 5.1.1), where all the parameters are allowed to vary. This is called *Free Blast Wave* in the following. The parameters of the BW formula are released to allow the best adjustment of the function to the data and avoid biases in the obtained results. The results of the fits and ratio of data to fit are shown in the left and right panel of Figure 5.1,

respectively. In order to obtain the low- p_T integrated yield i.e. $\frac{dN_{\text{low}}}{dy}$, the fitted function is integrated at low- p_T , starting from zero till the low boundary of the first measured p_T bin. Similarly, to obtain the high- p_T integrated yield i.e. $\frac{dN_{\text{high}}}{dy}$, the fitted function is integrated at high- p_T , starting from the high boundary of the last measured p_T bin to 10 GeV/c. As the high- p_T extrapolation corresponds to a very negligible fraction of the total yield, the high- p_T integration is not performed up to infinity, thus allowing the numerical calculation of the integral to quickly converge. A statistical uncertainty is assigned to the low- and high- p_T extrapolation measurement according to the covariance matrix of the fit. The fraction of the low- and high- p_T integrated yields ($\frac{dN_{\text{low}}}{dy} + \frac{dN_{\text{high}}}{dy}$) from the extrapolation are reported in Table 5.2.

5.4 $\langle p_T \rangle$ of $\Lambda(1520)$

The $\langle p_T \rangle$ of $\Lambda(1520)$ in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 2.76$ TeV has been obtained in 0–20%, 20–50% and 50–80% centrality classes. The $\langle p_T \rangle$ of $\Lambda(1520)$ is defined as

$$\langle p_T \rangle = \frac{\int_{-\infty}^{\infty} p_T f(p_T) dp_T}{\int_{-\infty}^{\infty} f(p_T) dp_T} \quad (5.13)$$

where $f(p_T)$ is the transverse momentum distribution of $\Lambda(1520)$. The value of the $\langle p_T \rangle$ is calculated as follows

$$\langle p_T \rangle = \frac{\langle p_T \rangle_{\text{low}} \frac{dN_{\text{low}}}{dy} + \sum_i p_T^i dp_T^i \frac{dN_{\text{data}}^i}{dy} + \langle p_T \rangle_{\text{high}} \frac{dN_{\text{high}}}{dy}}{\frac{dN_{\text{low}}}{dy} + \frac{dN_{\text{data}}}{dy} + \frac{dN_{\text{high}}}{dy}} \quad (5.14)$$

Where, p_T^i is the i th bin centre, dp_T^i is the corresponding p_T bin width and $\frac{dN_{\text{data}}^i}{dy}$ is $\Lambda(1520)$ yield in i th measured bin. $\frac{dN_{\text{low}}}{dy}$ and $\frac{dN_{\text{high}}}{dy}$ are the total yields of $\Lambda(1520)$ per unit rapidity in low and high p_T extrapolated range. The statistical uncertainty of $\langle p_T \rangle$ is estimated by assuming to be fully correlated in low- p_T , measured and high- p_T region. The statistical uncertainty in $\langle p_T \rangle$ is calculated as follows

$$\sigma_{\langle p_T \rangle} = \frac{\langle p_T \rangle_{\text{low}} \sigma_{\frac{dN_{\text{low}}}{dy}} + \sqrt{\sum_i (p_T^i dp_T^i \frac{dN_{\text{data}}^i}{dy})^2} + \langle p_T \rangle_{\text{high}} \sigma_{\frac{dN_{\text{high}}}{dy}}}{\frac{dN_{\text{low}}}{dy} + \frac{dN_{\text{data}}}{dy} + \frac{dN_{\text{high}}}{dy}} \quad (5.15)$$

The results of $\langle p_T \rangle$ are shown as a function of $\langle dN_{\text{ch}}/d\eta \rangle^{1/3}$ in Figure 5.3 and are reported in Table 5.3.

The observed value of $\langle p_T \rangle$ of $\Lambda(1520)$ in central Pb–Pb collisions (0–20%) is found to be higher as compared to the one obtained in mid-peripheral (20–50%) and to the peripheral collisions (50–80%). In this measurement, it is observed that $\langle p_T \rangle$ shows a strong dependence

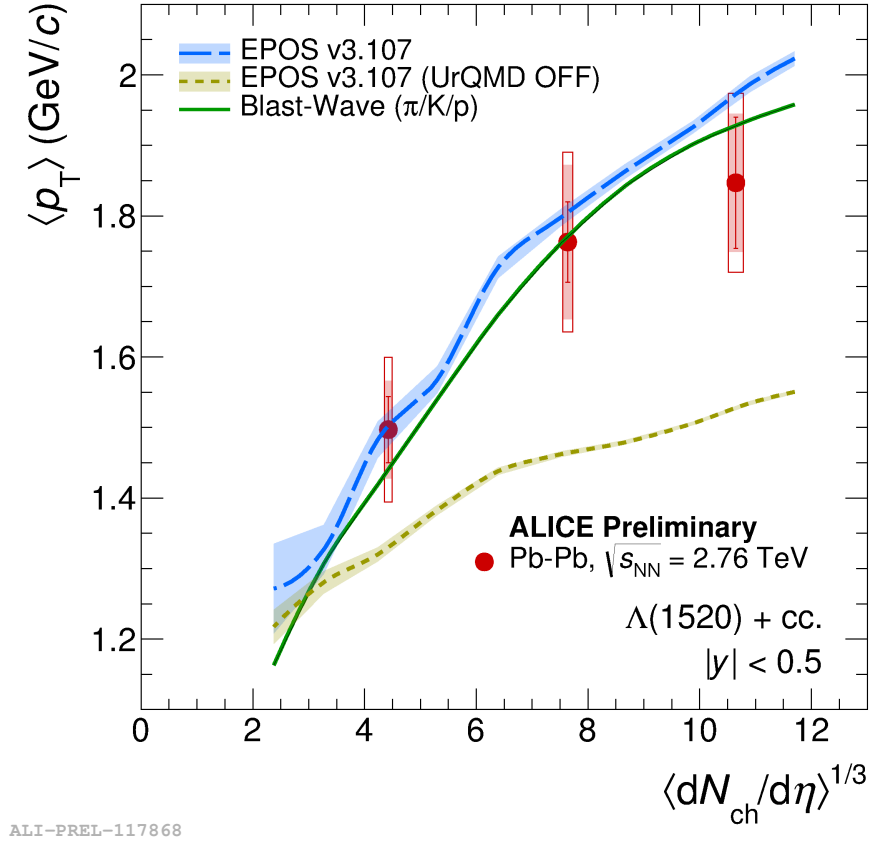


Figure 5.3: Measured $\langle p_T \rangle$ of $\Lambda(1520)$ production in 0–20%, 20–50% and 50–80% centrality events. The solid green line represent the $\langle p_T \rangle$ measured from *Constrained Blast-Wave*, where parametrisation is fitted to the data. Predictions from the EPOS3 model are also shown (Section 5.1.2), blue solid line represents the $\langle p_T \rangle$ measured from EPOS3+UrQMD and dark yellow solid line represents the $\langle p_T \rangle$ measured from EPOS3 without UrQMD modelling.

on the collision centrality. The mean p_T of $\Lambda(1520)$ in central collisions (0–20%) is about 23% higher than the value measured in peripheral (50–80%) collisions, and in mid-peripheral (20–50%) is about 18%. This observation is in agreement with a progressively increasing radial flow with centrality as it has also been concluded based on previous measurements of pion, kaon, and proton p_T distributions [119].

The mean p_T of $\Lambda(1520)$ is compared to the mean p_T of $K^*(892)^0$ and ϕ -meson [88] in central collisions (0–20%) and reported in Table 5.4. The mean p_T of $\Lambda(1520)$ in central collisions (0–20%) is found to be about 40% higher as compared to both the $K^*(892)^0$ and ϕ -meson. The $K^*(892)^0$ and ϕ -meson have similar $\langle p_T \rangle$ because these particles have similar mass whereas $\Lambda(1520)$ has higher $\langle p_T \rangle$ because it has larger mass as compared to $K^*(892)^0$ and ϕ -meson. This is in agreement with the hydrodynamic expansion picture, where particles with larger mass obtain a larger boost, hence a larger $\langle p_T \rangle$.

Table 5.3: $\langle p_T \rangle$ of $\Lambda(1520)$ production (Section 5.4) and corresponding $\langle dN_{ch}/d\eta \rangle^{1/3}$.

	$\langle dN_{ch}/d\eta \rangle^{1/3}$	$\langle p_T \rangle \pm (\text{stat}) \pm (\text{syst}) \pm (\text{uncorr}) \text{ (GeV}/c)$
0–20%	10.65 ± 0.13	$1.847 \pm 0.093 \pm 0.127 \pm 0.098$
20–50%	7.63 ± 0.09	$1.763 \pm 0.057 \pm 0.127 \pm 0.110$
50–80%	4.43 ± 0.07	$1.497 \pm 0.047 \pm 0.103 \pm 0.069$

Table 5.4: $\langle p_T \rangle$ of $K^*(892)^0$ and ϕ -meson production (Section 5.4) in Pb–Pb (0–20)% and corresponding $\langle dN_{ch}/d\eta \rangle^{1/3}$ [88].

	$\langle dN_{ch}/d\eta \rangle^{1/3}$	$\langle p_T \rangle \pm (\text{stat}) \pm (\text{syst}) \pm (\text{uncorr}) \text{ (GeV}/c)$
$K^*(892)^0$ (Pb–Pb 0–20%)	10.65 ± 0.13	$1.31 \pm 0.04 \pm 0.11$
ϕ -meson (Pb–Pb 0–20%)	10.65 ± 0.13	$1.33 \pm 0.04 \pm 0.06$

5.4.1 Comparison to RHIC data

The $\langle p_T \rangle$ of $\Lambda(1520)$ has been measured at RHIC (Relativistic Heavy-Ion Collider) by the STAR experiment (Solenoidal Tracker at RHIC) in pp and d–Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ [70, 109]. The results from STAR are compared to the measured ALICE data in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ and are shown in Figure 5.3. The $\langle p_T \rangle$ of $\Lambda(1520)$ from STAR data are reported in Table 5.5. The observed value of $\langle p_T \rangle$ of $\Lambda(1520)$ as a function of charged-particle multiplicity in central collisions (0–20%) is about 71% higher than that from STAR pp and about 58% higher than that from STAR d–Au collisions, as shown in Figure 5.4. The $\langle p_T \rangle$ of $\Lambda(1520)$ in Au–Au collisions in 0–10% and 60–80% centralities are not used for the comparison with the ALICE measurements because these values have been derived from the data by considering the fixed spectral shapes of $\Lambda(1520)$ [70].

5.4.2 Comparison to Models

The $\langle p_T \rangle$ values of $\Lambda(1520)$ from EPOS3 [69] and Blast-Wave models [117] have been calculated and compared to the values obtained by the ALICE data (Section 5.4). The $\langle p_T \rangle$ values from the Blast-Wave model prediction are shown in Figure 5.3. From Figure 5.3, it is clearly seen that the $\langle p_T \rangle$ of $\Lambda(1520)$ is in agreement with the Blast-Wave model predictions. The $\langle p_T \rangle$ values from the EPOS3 model are also shown in Figure 5.3 and reported in Table 5.6. It is observed that the $\langle p_T \rangle$ of $\Lambda(1520)$ is in agreement with the EPOS3 model predictions. It is important to notice the relevance of the UrQMD stage for the successful description of heavy-ion data by EPOS3,

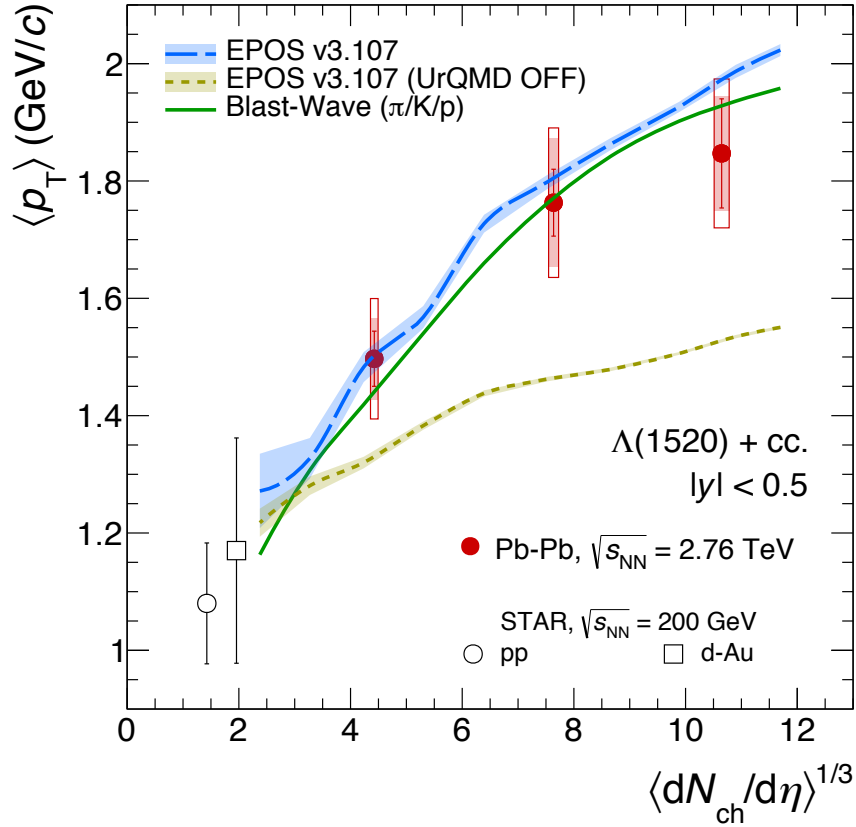


Figure 5.4: Measured $\langle p_T \rangle$ of $\Lambda(1520)$ production in 0–20%, 20–50% and 50–80% centrality events. The solid green line represent the $\langle p_T \rangle$ measured from *Constrained Blast-Wave*, where parametrisation is fitted to the data. The $\langle p_T \rangle$ values measured from pp and d–Au collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR experiment at RHIC are shown in black circle and square marker, respectively. Predictions from the EPOS3 model are also shown (Section 5.1.2), blue solid line represents the $\langle p_T \rangle$ measured from EPOS3+UrQMD and dark yellow solid line represents the $\langle p_T \rangle$ measured from EPOS3 without UrQMD modelling.

which fails to reproduce the data if the UrQMD stage is not enabled. This observation suggests that the $\langle p_T \rangle$ of $\Lambda(1520)$ might increase due to interactions in the hadronic phase and stresses the importance of such a phase for the best understanding of heavy-ion reactions at the LHC.

5.5 Λ yield

In order to measure the $\Lambda(1520)/\Lambda$ ratio, the Λ yield is estimated in the $\Lambda(1520)$ centrality classes to match the centrality bins. The Λ yield has been previously measured and the results are published in [120] in narrower centrality classes, which are not same as the $\Lambda(1520)$ centrality classes. In particular, the $\Lambda(1520)$ measured centrality classes 0–20%, 20–50% and 50–80% can

Table 5.5: $\langle p_T \rangle$ of $\Lambda(1520)$ production measured by STAR in pp and d–Au collisions at $\sqrt{s_{NN}} = 200$ GeV (Section 5.4) and corresponding $\langle dN_{ch}/d\eta \rangle$. The data are obtained from <https://drupal.star.bnl.gov/STAR/files/starpublications/110/data.html>.

	$\langle dN_{ch}/d\eta \rangle$	$\langle dN_{ch}/d\eta \rangle^{1/3}$	$\langle p_T \rangle$ (GeV/c)
pp (NSD)	2.9	1.426	1.08 ± 0.103
d–Au (minimum bias)	7.5	1.957	1.17 ± 0.192
Au–Au (0–10%)	620.4	8.529	$1.2 \pm 0.2_{\text{fixed}}$
Au–Au (60–80%)	33.55	3.225	$1.2 \pm 0.2_{\text{fixed}}$

Table 5.6: $\langle p_T \rangle$ of $\Lambda(1520)$ production (Section 5.4) measured by EPOS3 model [69] and corresponding $\langle dN_{ch}/d\eta \rangle^{1/3}$.

	$\langle dN_{ch}/d\eta \rangle^{1/3}$	$\langle p_T \rangle$ (GeV/c)
0–20%	10.65 ± 0.13	1.973 ± 0.006
20–50%	7.63 ± 0.09	1.813 ± 0.007
50–80%	4.43 ± 0.07	1.509 ± 0.014

not all be directly derived averaging the centrality bins used in Λ measurement [120]. Therefore, the Λ yield in the three centralities 0–20%, 20–50% and 50–80% of $\Lambda(1520)$ measurement, have been interpolated by fitting the measured values of Λ with the following parametrisation

$$a + b\langle N_{\text{part}} \rangle^c \quad (5.16)$$

The mean number of participants $\langle N_{\text{part}} \rangle$ values corresponding to the 0–20%, 20–50% and 50–80% centrality classes have been determined from the published values [121], by using the centrality bin width as weight, as follows

$$\langle N_{\text{part}} \rangle_{\text{ABC}} = \frac{\langle N_{\text{part}} \rangle_A \Delta_A + \langle N_{\text{part}} \rangle_B \Delta_B + \langle N_{\text{part}} \rangle_C \Delta_C}{\Delta_A + \Delta_B + \Delta_C} \quad (5.17)$$

where $\langle N_{\text{part}} \rangle_{\text{ABC}}$ is the $\langle N_{\text{part}} \rangle$ value averaged over the centrality classes A, B and C. $\langle N_{\text{part}} \rangle_i$ is the $\langle N_{\text{part}} \rangle$ value in the centrality class i and Δ_i is the corresponding centrality bin width. In order to extract the uncertainty of the interpolated values, the same fit has been performed by shifting (up/down) the measured Λ data points by their corresponding systematic uncertainties. The results of the fits to Λ yield vs. $\langle N_{\text{part}} \rangle$ by the Equation 5.16 is shown in Figure 5.5, where the quality of the fits can also be appreciated. The measured Λ yields and the ones derived with the procedure explained above for the centrality classes 0–20%, 20–50% and 50–80% are shown in Table 5.7.

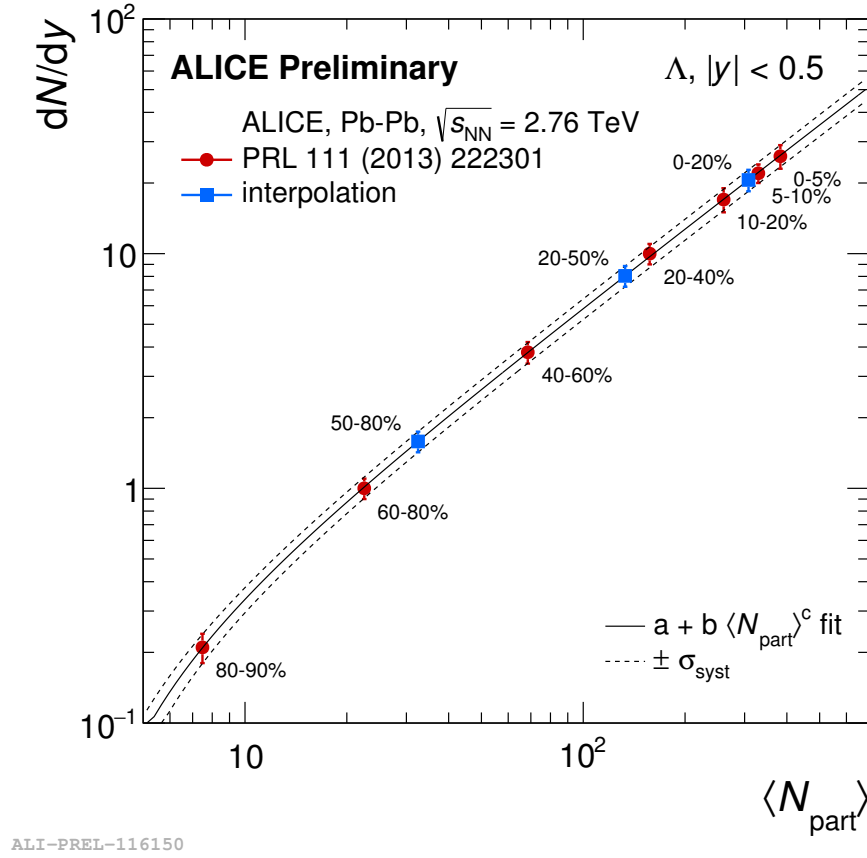


Figure 5.5: Λ yield as a function of $\langle N_{part} \rangle$. The red points show the measured data [120, 121] whereas the blue points show the values interpolated in the centrality classes used for this analysis (Section 5.5). The solid line shows the function (Equation 5.16) fit to the data for interpolation of the central values, whereas the dashed lines show the same function fit to the extreme of the data error bars to determine the uncertainty of the interpolated values.

5.6 $\Lambda(1520)/\Lambda$ ratio

The production of $\Lambda(1520)$ resonances can be affected by the late hadronic phase present in heavy-ion collisions. As the lifetime of $\Lambda(1520)$ is comparable to that of the fireball produced in heavy-ion collisions, the decay daughters of $\Lambda(1520)$ might suffer interactions with the other hadrons present around them during the hadronic phase. These phenomena could affect the measured yield of $\Lambda(1520)$, but does not affect the yield of its stable counterpart Λ owing its much longer lifetime. If $\Lambda(1520)$ decays inside the hadronic medium while traversing through it, the decay daughters could be re-scattered by the neighbouring hadrons present inside the medium. This would change the daughter's momentum and as a result, one would not be able to reconstruct the actual $\Lambda(1520)$ through invariant mass analysis of the decay daughters. In this re-scattering scenario, the $\Lambda(1520)$ signal is lost and the $\Lambda(1520)$ yield is observed to be suppressed. As the

Table 5.7: Λ yields and $\langle N_{\text{part}} \rangle$ of the corresponding measured centrality classes [120, 121] and the ones derived for the centrality classes used in this analysis (Section 5.5). The Λ yield in 0–20% centrality class has been derived also with a centrality-weighting method and it is consistent with the interpolated value.

	$\langle N_{\text{part}} \rangle$	Λ yield
0–5%	382.7	26 ± 3
5–10%	329.4	22 ± 2
10–20%	260.1	17 ± 2
20–40%	157.2	10 ± 1
40–60%	68.56	3.8 ± 0.4
60–80%	22.52	1.0 ± 0.1
80–90%	7.485	0.21 ± 0.03
0–20%	308.1	20.6 ± 2.15
20–50%	133.0	8.04 ± 0.82
50–80%	32.48	1.58 ± 0.16

size of the hadronic medium increases with collision centrality, the suppression can be expected to be more prominent in the most central Pb–Pb collisions. Alternatively, kaons and protons inside the hadronic medium could also go through pseudo-elastic interactions with neighbouring hadrons and produce $\Lambda(1520)$ particles. In this re-generation scenario, the $\Lambda(1520)$ yield would be enhanced. These two possible and competing processes i.e. re-scattering and re-generation can be better investigated by comparing the $\Lambda(1520)$ yield to its stable counterpart $\Lambda(1520)/\Lambda$.

The $\Lambda(1520)/\Lambda$ ratio can be studied as a function of centrality in the heavy-ion collisions and then it can be compared to the value obtained from pp collisions. Due to small and short-lived medium expected to be create in pp collisions [82], the decay daughters of resonances are expected to be less likely affected inside the hadronic medium. In the $\Lambda(1520)/\Lambda$ measurement, if the re-scattering effect is prominent compared to re-generation effect inside the hadronic medium, one would expect the suppression of the $\Lambda(1520)/\Lambda$ ratio in the most central Pb–Pb collisions compared to Pb–Pb peripheral and minimum bias pp collisions. On the other hand, if the re-generation effect is prominent compared to re-scattering effect, it would lead to an increase in the $\Lambda(1520)/\Lambda$ ratio in the most central Pb–Pb collisions compare to the Pb–Pb peripheral and minimum bias pp collisions. The p_T -integrated ratios of $\Lambda(1520)/\Lambda$ are derived from the $\Lambda(1520)$ (Section 5.3) and Λ (Section 5.5) p_T -integrated yields in three measured centrality

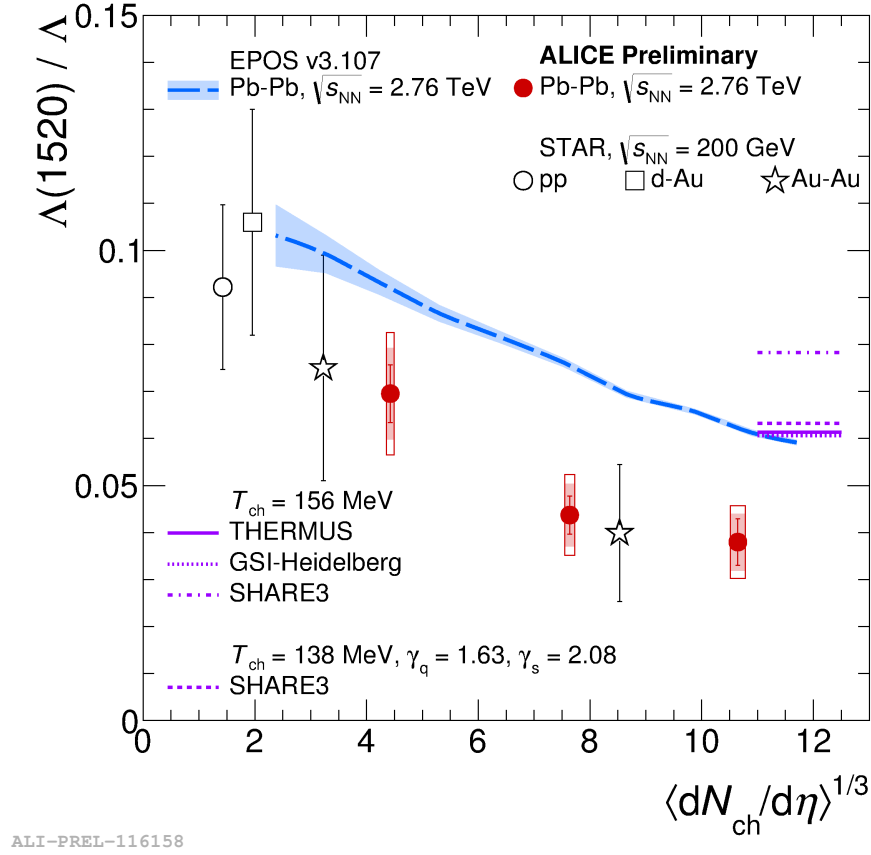


Figure 5.6: p_T -integrated ratio of $\Lambda(1520)/\Lambda$ production (Section 5.6) as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$. Predictions from several SHM models (Section 5.6.2) as well as the prediction from EPOS3 (Section 5.6.3) are compared to the data.

classes, 0–20%, 20–50%, 50–80%. In this analysis, the definition of $\Lambda(1520)/\Lambda$ ratio is

$$\Lambda(1520)/\Lambda = \frac{\Lambda(1520) + \bar{\Lambda}(1520)}{2\Lambda} \quad (5.18)$$

Only Λ particle state is used in $\Lambda(1520)/\Lambda$ ratio in Equation 5.18 due to the availability of results in ALICE for Λ productions for the particle state and not for its antiparticle state. Although, no differences in the production of particles and antiparticles are expected because the baryochemical potential at the LHC is small which justifies the choice of using only Λ in the $\Lambda(1520)/\Lambda$ ratio calculation.

From HBT [122] studies, it has been observed that the radius of the fireball produced in heavy-ion collisions increases approximately linearly with the $\langle dN_{ch}/d\eta \rangle^{1/3}$ and hence $\langle dN_{ch}/d\eta \rangle^{1/3}$ can be used as a proxy to the size of a system formed in heavy-ion collisions. The variation of $\Lambda(1520)/\Lambda$ is shown as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ in Figure 5.6 and the values are reported in Table 5.8. The ratio $\Lambda(1520)/\Lambda$ in central Pb–Pb collisions (0–20%) is smaller than that in mid-peripheral (20–50%) by 13% and peripheral collisions (50–80%) by 45.5%. This observed

Table 5.8: p_T -integrated ratio of $\Lambda(1520)/\Lambda$ production (Section 5.6) and corresponding $\langle dN_{ch}/d\eta \rangle^{1/3}$.

	$\langle dN_{ch}/d\eta \rangle^{1/3}$	$\Lambda(1520)/\Lambda \pm (\text{stat}) \pm (\text{syst}) \pm (\text{uncor})$
0–20%	10.65 ± 0.13	$0.0379 \pm 0.0049 \pm 0.0077 \pm 0.0061$
20–50%	7.63 ± 0.09	$0.0437 \pm 0.0040 \pm 0.0086 \pm 0.0067$
50–80%	4.43 ± 0.07	$0.0695 \pm 0.0061 \pm 0.0130 \pm 0.0097$

suppression of $\Lambda(1520)/\Lambda$ ratio in central collisions with respect to peripheral collisions may be due to the dominance of re-scattering of the decay daughter particles over re-generation effects. Moreover, the suppressed value of $\Lambda(1520)/\Lambda$ at the highest $\langle dN_{ch}/d\eta \rangle^{1/3}$ might be attributed to the larger fireball size and life-time accessible at the LHC energies. In this measurement, the statistical uncertainty of the ratio is determined only from the statistical uncertainty of $\Lambda(1520)$ yield because the statistical uncertainty of Λ yield are considered to be negligible, as stated in the corresponding paper [120]. In order to estimate the systematic uncertainties, the calculation has been performed by assuming that the systematic uncertainties of $\Lambda(1520)$ and Λ are fully uncorrelated. The assumption of systematic uncertainties of $\Lambda(1520)$ and Λ are fully uncorrelated is based on the fact that Λ measurement uses secondary-vertex reconstruction whereas $\Lambda(1520)$ comes from a primary vertex. Also, the PID techniques used differ substantially for Λ and $\Lambda(1520)$ reconstruction.

5.6.1 Comparison to RHIC data

The $\Lambda(1520)/\Lambda$ ratio in Pb–Pb collisions from ALICE at $\sqrt{s_{NN}} = 2.76$ TeV has been compared to pp collisions, d–Au and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR [70, 109] experiment. This comparison is shown in Figure 5.6. The minimum bias results in pp and d–Au collisions and 60–80%, 0–10% Au–Au collisions have been used for this comparison. It is observed from Figure 5.6 that the $\Lambda(1520)/\Lambda$ ratio in central Pb–Pb collisions from ALICE experiment at LHC is suppressed as compared to the pp, d–Au and peripheral Au–Au collisions from STAR experiment at RHIC. However, similar $\Lambda(1520)/\Lambda$ ratio value in central Pb–Pb and Au–Au collision has been observed which might be due to the presence of large regeneration effect in central Pb–Pb collisions. The values of $\Lambda(1520)/\Lambda$ ratio measured by STAR in minimum bias pp, d–Au and 60–0%, 0–10% Au–Au collisions have been reported in Table 5.9.

The suppression trend of $\Lambda(1520)/\Lambda$ ratio in ALICE follows the trend of STAR results, confirming the observation of the phenomenon of $\Lambda(1520)$ suppression in central nucleus-nucleus collisions. It has to be noted that the ALICE results extend STAR finding to a higher

Table 5.9: p_T -integrated ratio of $\Lambda(1520)/\Lambda$ production measured by STAR in pp, d–Au and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV (Section 5.6) and corresponding $\langle dN_{ch}/d\eta \rangle$. The data are obtained from <https://drupal.star.bnl.gov/STAR/files/starpublications/110/data.html>.

	$\langle dN_{ch}/d\eta \rangle$	$\langle dN_{ch}/d\eta \rangle^{1/3}$	$\Lambda(1520)/\Lambda$
pp (NSD)	2.9	1.426	0.092 ± 0.026
d–Au (minimum bias)	7.5	1.957	0.106 ± 0.024
Au–Au (60–80)%	33.55	3.225	0.075 ± 0.024
Au–Au (0–10)%	620.4	8.529	0.0399 ± 0.0145

charged-particle multiplicity and significantly improved the accuracy of the measurement.

5.6.2 Comparison to thermal models prediction

The $\Lambda(1520)/\Lambda$ ratio in Pb–Pb collisions from ALICE at $\sqrt{s_{NN}} = 2.76$ TeV has been compared with the calculations from the several Statistical Hadronisation Models (SHM) in the Grand Canonical Ensemble description, and with one non-equilibrium model. The comparison with these SHM models to the data is shown in Figure 5.6.

In SHM, the ratio $\Lambda(1520)/\Lambda$ is defined as

$$\Lambda(1520)/\Lambda = \frac{\Lambda(1520) + \bar{\Lambda}(1520)}{\Lambda + \bar{\Lambda}} \quad (5.19)$$

The SHM values are obtained at a given chemical freeze-out temperature $T_{ch} = 156$ MeV and at zero baryon-chemical potential $\mu_B = 0$. The SHM values for $\Lambda(1520)/\Lambda$ ratio is reported in Table 5.10.

The value of $\Lambda(1520)/\Lambda$ ratio in central Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV is $\sim 40\%$ smaller than the predictions from Statistical Hadronisation Models (SHM). Owing the vast success of SHM models in describing and predicting the particle yields and ratios in heavy-ion collisions, this observation suggests that the measured $\Lambda(1520)/\Lambda$ suppression occurs because of phenomena happening after the QGP hadronisation stage.

5.6.3 Comparison to EPOS3 model

The $\Lambda(1520)/\Lambda$ ratio value and its evolution with multiplicity is predicted by the EPOS3 model [69], which employs the UrQMD model for the description of the hadronic phase following

Table 5.10: Predictions for the $\Lambda(1520)/\Lambda$ ratio from several Statistical Hadronisation Models (Section 5.6.2)

	$\Lambda(1520)/\Lambda$
GSI-Heidelberg [123]	0.0606
THERMUS [124]	0.0613
SHARE3 [125]	0.0783
SHARE3 (non equilibrium) [125]	0.0632

QGP hadronisation. In this model, the $\Lambda(1520)/\Lambda$ is defined as

$$\Lambda(1520)/\Lambda = \frac{\Lambda(1520) + \bar{\Lambda}(1520)}{\Lambda + \bar{\Lambda}} \quad (5.20)$$

and it is compared to the measured data as shown in Figure 5.6. From this comparison, the trend of the $\Lambda(1520)/\Lambda$ suppression from peripheral to central collision in Pb–Pb collision is reproduced by EPOS3 reasonably well. However, the EPOS3 model overestimates the $\Lambda(1520)/\Lambda$ ratio value as compared to the data. The higher value of $\Lambda(1520)/\Lambda$ ratio observed by EPOS3 might be related to the parameters of the model that control the QGP hadronisation, where a larger freeze-out temperature might cause a large resonance yield without affecting the spectral shape, which is leading to an offset of $\Lambda(1520)/\Lambda$ ratio to the data.

5.7 $\Lambda(1520)/\Lambda$ suppression

The suppression of $\Lambda(1520)/\Lambda$ ratio in central Pb–Pb events with respect to peripheral events is better quantified as the double ratio with respect to some reference value. This enables one to remove common uncertainties and therefore enhance the statistical significance of the result. The quantitative $\Lambda(1520)/\Lambda$ suppression in central Pb–Pb collisions (0–20%) with respect to peripheral Pb–Pb collisions (50–80%) is evaluated as follows

$$S_{CP} = \frac{[\Lambda(1520)/\Lambda]_{0-20\%}}{[\Lambda(1520)/\Lambda]_{50-80\%}} \quad (5.21)$$

The uncertainties which are common to both centralities cancel in this ratio. For this reason, only the uncertainties which are uncorrelated for these centralities are used for the calculation of the systematic uncertainty of the ratio. The result of the double ratio (Equation 5.21) is

$$S_{CP} = 0.545 \pm 0.085(stat) \pm 0.117(syst) \quad (5.22)$$

$\Lambda(1520)/\Lambda$ production in 0–20% central Pb–Pb collisions is measured to be suppressed with respect to 50–80% collision events by about 45% at 3.1 σ confidence level.

The observed suppression of the $\Lambda(1520)/\Lambda$ ratio in central Pb–Pb collisions with respect to peripheral collisions is significant and supports the existence of a hadronic phase lasting enough to allow for a significant reduction of the short-lived hadronic resonance production after hadronisation.

5.7.1 Quantitative estimation of suppression by thermal models

The suppression of $\Lambda(1520)/\Lambda$ ratio in central Pb–Pb events with respect to peripheral events is measured as the double ratio in data, as explained in Section 5.7. A similar suppression is also computed with respect to the several Statistical Hadronisation Models (SHM) expectations. The results of the double ratio (Equation 5.21) with respect to the SHM models are

$$S_{\text{GSI-Heidelberg}} = 0.625 \pm 0.081(\text{stat}) \pm 0.125(\text{syst}) \quad (5.23)$$

$$S_{\text{THERMUS}} = 0.618 \pm 0.079(\text{stat}) \pm 0.124(\text{syst}) \quad (5.24)$$

$$S_{\text{SHARE3}} = 0.484 \pm 0.063(\text{stat}) \pm 0.097(\text{syst}) \quad (5.25)$$

$$S_{\text{SHARE3,non-eq.}} = 0.599 \pm 0.078(\text{stat}) \pm 0.120(\text{syst}) \quad (5.26)$$

In this measurement, the full (total) systematic uncertainty is used for the systematics of the ratio. The $\Lambda(1520)/\Lambda$ production in 0–20% central Pb–Pb collisions is measured to be suppressed with respect to GSI-Heidelberg [123], THERMUS [124], SHARE3 [125] and non-equilibrium SHARE3 [125] by about 37%, 38%, 52% and 40% at 2.5, 2.6, 4.5 and 2.8 σ confidence level, respectively.

The thermal models, which can successfully describe particle production in heavy-ion collisions for many hadronic states, predict the $\Lambda(1520)/\Lambda$ i.e. resonance to stable particle ratio at the chemical freezeout stage. The deviation for the $\Lambda(1520)/\Lambda$ ratio observed in the data encodes effects related to interactions (rescattering of the resonance decay daughters) happening after hadronisation. The measured deviation from SHM predictions can be used to estimate the timespan between the chemical and kinetic freezeout.

Chapter 6

Summary and Outlook

"You must never be fearful about what you are doing when it is right."

– Marie Curie

The work presented in this thesis has led to a better understanding of the evolution and the properties of the hadronic medium created in heavy-ion collisions at the LHC energies. This has been done by measuring and studying the $\Lambda(1520)$ resonance. $\Lambda(1520)$ resonance was chosen because the ALICE detector with its excellent tracking and particle identification capabilities out of all the four experiments is best suited for such measurements. In the analysis reported in this thesis, the production of $\Lambda(1520)$ resonance has been measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with data collected by the ALICE experiment at the LHC in the year 2010. The analysis has been performed in 0–20%, 20–50% and 50–80% centrality classes. The $\Lambda(1520)$ has been reconstructed via the invariant mass analysis through its hadronic decay channel, $\Lambda(1520) \rightarrow p + K^-$ and $\bar{\Lambda}(1520) \rightarrow \bar{p} + K^+$. The decay daughters, K and p were identified with the information provided by the TPC and TOF detector. In order to extract the signal of $\Lambda(1520)$, the combinatorial background was obtained by event mixing technique. After removal of the combinatorial background $\Lambda(1520)$ resonance signal still had a residual background. The signal and residual background were appropriately fitted to extract the $\Lambda(1520)$ yield. The transverse momentum distributions at mid-rapidity ($|y| < 0.5$) have been obtained in the range $0.5 < p_T < 6$ GeV/c. This yield is further corrected for efficiency and limited detector acceptance for the measured p_T bin of the resonance. Statistical uncertainty has been estimated from the data and systematic uncertainty due to various sources has been estimated in each measured p_T bin for the three measured centrality classes.

The analysis presented in this thesis is the first ever measurement of the production of the $\Lambda(1520)$ resonance in heavy-ion collisions at the LHC energies. The $\Lambda(1520)$ invariant yield $\frac{dN}{dy}$ at mid rapidity ($|y| < 0.5$) has been extracted from the transverse momentum (p_T) spectrum in the three measured centrality classes. The p_T -spectral shapes are found to be well described by the hydrodynamical inspired Boltzmann-Gibbs Blast-Wave (BW) model for all the centralities, with the assumption that the $\Lambda(1520)$ undergoes the same hydrodynamical expansion as pions, kaons and protons. The p_T -spectral shapes are also observed to be in good qualitative agreement

with EPOS3 coupled with UrQMD model. EPOS3 is a Monte Carlo event generator, which describes the full evolution of the heavy-ion collision while the UrQMD model has been used for the description of the hadronic medium. The $\langle p_T \rangle$ of $\Lambda(1520)$ has been extracted from the data by using the above spectra extrapolated to the unmeasured regions for three centrality classes. It is observed that the $\langle p_T \rangle$ shows a strong dependence on the collision centrality and increases as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$. The reason behind this observation is the progressively increasing radial flow with centrality and has already been confirmed by measured pions, kaons and protons p_T distributions. Moreover, due to large hadronic medium present in central collisions, the large re-scattering of decay daughters can reduce the probability of detection of low p_T resonances and could further enhance the effect. The increasing behaviour of $\langle p_T \rangle$ is in quantitative agreement with the predictions from the Blast-Wave and EPOS3 model with UrQMD indicating that the $\Lambda(1520)$ resonance experiences the same hydrodynamical expansion as pions, kaons and protons. The disagreement of the data with respect to the EPOS3 model without UrQMD indicates the importance of the hadronic phase, where a non-negligible radial flow component builds up. The $\langle p_T \rangle$ of $\Lambda(1520)$ is observed to be larger as compared to both the $K^*(892)^0$ and ϕ -meson, in agreement with the hydrodynamical expansion picture, where higher mass particle obtains larger boost and therefore larger $\langle p_T \rangle$. The observed value $\langle p_T \rangle$ of $\Lambda(1520)$ in central collisions is also found to be higher than the STAR measurement for pp and d–Au collisions.

Finally, the $\Lambda(1520)$ yield to its non-resonance particle yield, $\Lambda(1520)/\Lambda$ ratio has been calculated as a function of centrality. If the hadronic medium created in central collision lived long enough then the $\Lambda(1520)$ could decay inside the medium and its particles would interact with the other particles inside the hadronic medium. The re-scattering of decay daughters depends on the hadronic cross-sections σ_{KK} and σ_{pp} , and on the hadronic densities inside the medium. They are in competition with the σ_{Kp} cross-section, which is responsible for re-generation. The measured $\Lambda(1520)/\Lambda$ ratio is found to be suppressed in central Pb–Pb collisions (0–20%) as compared to peripheral Pb–Pb collisions (50–80%), suggesting the dominance of re-scattering over re-generation effect of decay daughter particles in the hadronic phase. Moreover, the suppressed value of $\Lambda(1520)/\Lambda$ ratio at the highest $\langle dN_{ch}/d\eta \rangle^{1/3}$ could be attributed to a larger fireball size and life-time accessible at the LHC energies. The suppression trend of $\Lambda(1520)/\Lambda$ ratio from peripheral to central Pb–Pb collisions is reproduced by the EPOS3 model with UrQMD reasonably well. This suppression trend predicted by EPOS3 is observed to be qualitatively in agreement with the data. The overestimation of the ratio value as compared to the data might be due to large value of freeze-out temperature used in the model. The $\Lambda(1520)/\Lambda$ ratio in Pb–Pb collision from ALICE at $\sqrt{s_{NN}} = 2.76$ TeV has been compared to pp collisions, d–Au and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR experiment. This ratio in central

Pb–Pb collisions from ALICE experiment is observed to be suppressed as compared to the pp, d–Au and peripheral Au–Au collisions from STAR experiment at RHIC. It has been found that the suppression trend of $\Lambda(1520)/\Lambda$ ratio in ALICE follows the trend of STAR results and confirms the observation of the phenomenon of $\Lambda(1520)$ suppression in central nucleus-nucleus collision. Moreover, these ALICE results extends STAR finding to a higher charged-particle multiplicity as well as significant improvement in the accuracy of the measurement. Further, the $\Lambda(1520)/\Lambda$ ratio in central Pb–Pb collisions has been compared and found to be smaller with the calculations from the several Statistical Hadronisation Models (SHM) in Grand Canonical description and one non-equilibrium model. The deviation of $\Lambda(1520)/\Lambda$ ratio in the data as compared to the SHM models are useful to encode effects related to the interactions in hadronic medium and also to estimate the time span between the chemical and the kinetic freezeout. These results further support the existence of a hadronic phase lasting long enough to cause a significant reduction of the reconstructible yield of short lived resonances. The results from this analysis have been approved by the ALICE collaboration along with the corresponding publication which is currently in preparation.

6.1 Future prospects

Due to limited statistics, the measurement of $\Lambda(1520)$ resonance production could only be performed in three wide centrality classes (0–20%, 20–50% and 50–80%) by using the data taken by the ALICE experiment in the year 2010 for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. This measurement can be performed in narrower centrality bins by using the data taken by ALICE experiment in the year 2015 for the Pb–Pb collisions at 5.02 TeV with seven times larger statistics as compared to 2010 Pb–Pb data. The 2015 data can also be beneficial to gain more control over the statistical uncertainty (almost 2.5 times) in similar centrality classes. However, no significant difference in the charged particle multiplicity in the measured centrality classes has been observed in Pb–Pb 5.02 TeV data as compared to 2.76 TeV, so one does not expect a significant change with respect to the analysis reported in this thesis. However, with a similar statistical precision, one can study the $\Lambda(1520)$ production in much narrower and more central, 0–2.5% class in 5.02 TeV data for significantly larger charged-particle multiplicity as compared to 0–20% class in 2.76 TeV data. In the coming year 2018, ALICE will be collecting 10 times higher statistics of 5.02 TeV Pb–Pb data as compared to year 2015, which will allow to reduce the statistical uncertainty by a factor of three for the measurement of $\Lambda(1520)$ production in the ultra-central 0–2.5% class, as compared to what one can achieve with 2015 Pb–Pb data. Future measurements in the narrow centrality class, 0–2.5% would provide the study of $\Lambda(1520)$ production in the largest possible system achieved in Pb–Pb collisions and can provide a more

precise description of the details of the QGP expansion and the interactions within the hadronic phase. This measurement along with the variation in the ratio of $\Lambda(1520)$ to Λ for many centrality classes will be helpful in confirming the phenomena observed by the other analysis measurement as well as can provide the best tuned input for many theoretical model simulations, whose results is being used to understand the process involved in the full evolution of the QGP produced in the heavy ion collisions at ultra relativistic energies.

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A handwritten signature in black ink, reading 'Neelima Agrawal' with a stylized flourish at the end.

Neelima Agrawal

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