

Dissertation for the degree of Doctor of Philosophy

Study on Hadron Phase
via Hyperon Resonance and Light Nuclei
Produced in Elementary and Heavy Ion Collision

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Study on Hadron Phase via Hyperon Resonance and Light Nuclei Produced in Elementary and Heavy Ion Collision

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Abstract

The properties of the Quark-Gluon Plasma and its evolution, even its existence itself, always have been one of the most curious puzzles in nature. A hadronic phase, which is the part of the evolution of the matter, also has been studied to find its properties, such as size, lifetime, condition, and so on. This thesis will investigate one of its properties, the size of the phase generated in proton-proton collisions and Pb-Pb collisions by using the measurement of hadronic resonance and light nuclei.

The production of hyperon resonances, $\Sigma(1385)^\pm$ and $\Xi(1530)^0$, in proton-proton collisions at $\sqrt{s}=13$ TeV, and light nuclei, deuteron and ^3He , in Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV was measured using the ALICE detector at the LHC. The transverse momentum p_T differential yields $d^2N/dydp_T$ have been measured at midrapidity, $|y| < 0.5$. The following findings such as integrated yield dN/dy and average transverse momentum $\langle p_T \rangle$ are obtained based on the p_T differential yields. Finally, the invariant yield ratio between the measured particles and the others will be discussed with phenomenological models.

Chapter 1

Introduction

The object of high-energy nuclear physics is to understand the state of matter under extremely high temperatures and high densities that are estimated to have existed in the early universe. Quantum Chromodynamics (QCD), which describes the strong interaction, predicts an extreme nuclear matter at high temperature and density where quarks and gluons are not confined, the so-called Quark-Gluon Plasma (QGP). Such an extreme matter can be reproduced by ultra-relativistic heavy-ion collisions. Some of the new interesting findings highlighted in small systems as a function of the charged-particle multiplicity imply the possibility of a small QGP droplet. This chapter will introduce the basic properties of the QGP and fundamental characteristics of heavy-ion collision including the time evolution of the created volume, especially focusing on the hadronic phase and major hadronic interactions. In general, the natural system of units with $\hbar = c = k_B = 1$ is used in this thesis.

1.1 The Quark-Gluon Plasma and QCD Phase Transition

Quantum chromodynamics (QCD), the theory of the strong interaction, suggests that the strongly interacting matter can exist in different phases based on the temperature (T) and the density (chemical potential, μ_B) of the system. This matter could exist in the early universe from 10 ps until 10 μ s after the big bang, and might still exist in the core of dense neutron stars.

The fundamental matter units of QCD are *Quarks*, which carry a colour charge. Like virtual photons mediating the electromagnetic interaction in QED, *Gluons* act as exchange bosons of the interaction, in with carrying colour charge and interacting with each other. The intensity of the QED coupling constant α_{em} gives the value of the fine-structure constant $\alpha \approx 1/137$ when the momentum transfer Q^2 is small. And it only gets a little larger as an increase of Q^2 owing to the vacuum polarization. Cross-sections can be calculated based on the perturbation methods ($\alpha \ll 1$), and it is expressed in expansion powers of α .

However, unlike QED, the effective coupling constant for a strong interaction α_s , increases with increasing distance. And, it has a large variation as a function of the transferred momentum Q^2 as shown in Fig. 1.1.

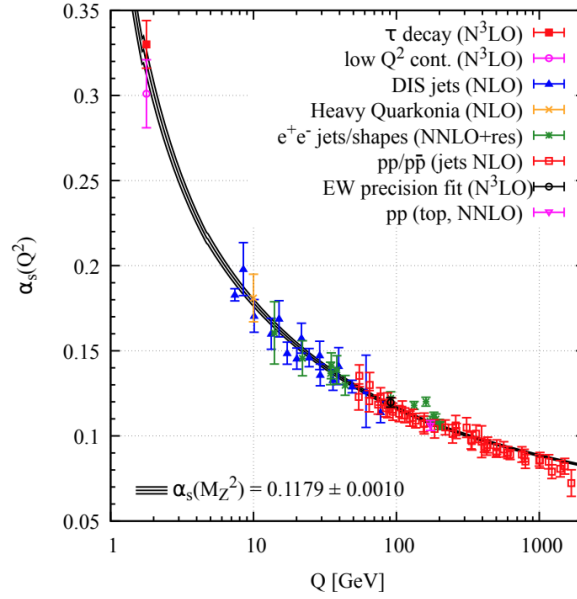


Figure 1.1. Summary of measurements of $\alpha_s(Q)$ as a function of respective scale of momentum transfer Q . The curves are obtained from QCD predictions for the combined world average value of $\alpha_s(M_Z^2)$ [1]

In QCD, the dependence of α_s on Q^2 in first order perturbation is given by

$$\alpha_s(Q^2) \approx \frac{4\pi}{\beta_0 \cdot \ln(Q^2/\Lambda^2)} \quad (1.1)$$

where $\beta_0 = \frac{11}{3}N_c - \frac{2}{3}N_f$ with N_c and N_f being the number of colors and participating quark flavors, respectively. The QCD scaling parameter is given by $\Lambda \approx 200$ MeV obtained from experiments.

Confinement The strong coupling constant α_s becomes larger at large distances and small values of Q^2 ($\alpha_s > 1$). In this state, the quarks are bound in neutral color states- *hadron*-, such as meson ($q - \bar{q}$) and baryon (qqq). Since it's impossible to apply the perturbation theory in this state, non-perturbative theories (lattice QCD) or effective models are used.

Asymptotic freedom At short distances (large values of Q^2), the constant gets weaker until the quarks behave as quasi-free particles, $\alpha_s \rightarrow 0$ for $Q^2 \rightarrow \infty$. The perturbative QCD (pQCD) only can be applicable to describe phenomena involving high energy quarks and gluons when the $Q^2 \gg \Lambda$.

The quark-antiquark potential in confinement sate is often approximated in a phenomenological way as

$$V_s(r) \approx -\frac{\alpha_s}{r} + \kappa r \quad (1.2)$$

where the string tension constant $\kappa \approx 1$ GeV/fm. The first term comes from the single-gluon exchange as like the single-photon exchange in Coulomb potential in QED. The force is obtained by taking the derivative of $V_s(r)$, so the first term becomes similar to the electromagnetic interactions. The second term, a linear increase at a larger distance r , arises from the self-interaction between gluons.

Figure 1.2 shows a QCD phase diagram. The ordinary nuclear matter is located at low temperature and low baryon chemical potential region of the diagram. As the temperature is increasing following the y -axis or A baryon chemical potential is increasing through the x -axis, the system becomes a phase of hadronic gas (HG). In hadronic gas, nucleons interact with other hadrons, resonances, and pions. A deconfined phase on *asymptotic freedom*, QGP, is expected to be reached as increasing the temperature and chemical potential further.

The QCD phase transition can be studied in the laboratory by reproducing similar conditions, such as temperature, pressure, and density, that lead to the QGP formation with the help of ultra-relativistic heavy-ion collisions.

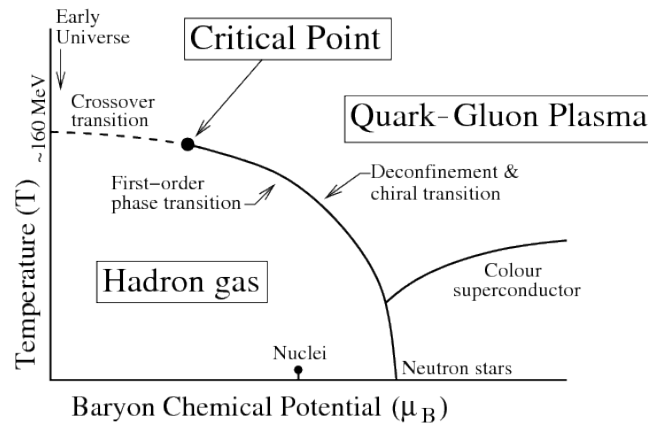


Figure 1.2. QCD phase diagram [2]

1.1.1 Ultrarelativistic Heavy-Ion Collisions

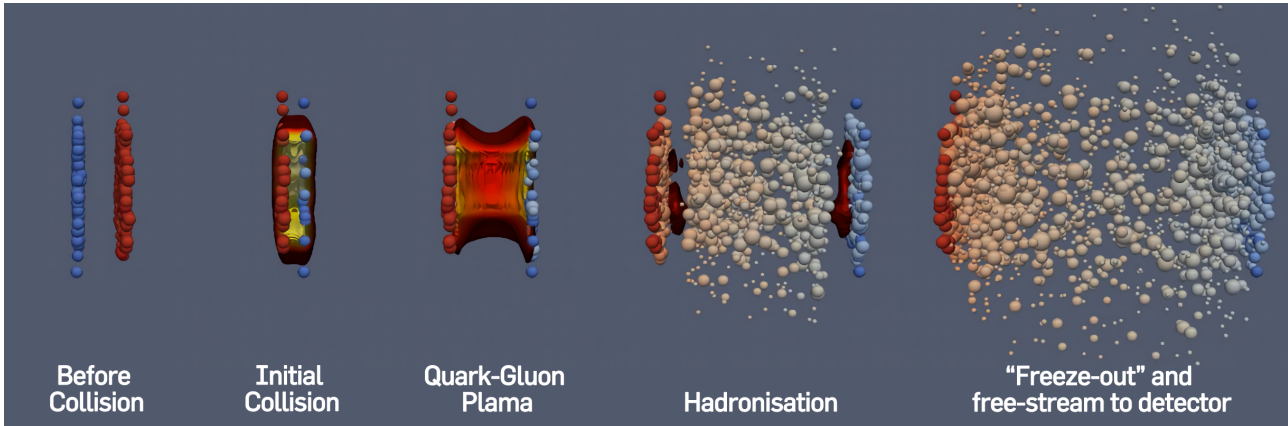


Figure 1.3. Simulation of the evolution of the heavy-ion collision, time flows from left to right [3].

The collisions of heavy ions at ultra-relativistic energies can represent a unique experimental tool to produce the matter with extremely high temperature and vanishing baryon chemical potential, quark-gluon plasma, in the laboratory. The five snapshots in Fig. 1.3 show the collision process in the ultrarelativistic heavy-ion collision.

Before Collision The two heavy-ion are approaching the speed of light along the beam axis (horizontal axis in the figure), showing flattened along the beam axis due to the Lorentz contraction.

Initial Collision After the heavy-ion collide, a "soup" of deconfined QCD matter is produced in the overlap region of the two discs, known as participants. At this moment, the rest of the nucleus, known as spectators, are not participating in the collision, instead of travelling in the longitudinal direction (beam direction).

Quark-Gluon Plasma After $\sim 0.1 - 1$ fm, the overall space-time evolution of the deconfined QCD matter can begin to be described with relativistic hydrodynamics. This phase can be referred to as the strongly-coupled quark-gluon plasma (sQGP).

Hadronisation As the volume expands and becomes more dilute (after a time of the order of ~ 10 fm/c [4]), the strongly-coupled quark-gluon plasma begins to reconfine into a hadron gas at a certain critical temperature, T_{ch} . The reconfinement of quarks and gluons in QGP proceeds locally in the overall region and usually, from the edge of the plasma to the central regions. At T_{ch} , Most particle species are determined at this level, thus the time where all particle species are frozen is called the chemical freeze-out. The hadronisation can be described via two main mechanisms: fragmentation-like processes and a coalescence picture. The coalescence picture [5] will be handled in Section 1.5.2. In this phase, although the particles are again confined in hadrons, the density is still so large that interactions continue to happen. Unstable hadrons decay, such as resonances, and hadrons go through (pseudo-)elastic collisions that change the momenta and species composition. This will be discussed in Section. 1.4.1.

Freeze-Out As the hadron gas becomes so dilute that hadronic interactions do not occur, hadrons continue their way to the detectors at a certain critical temperature, T_{fo} [3].

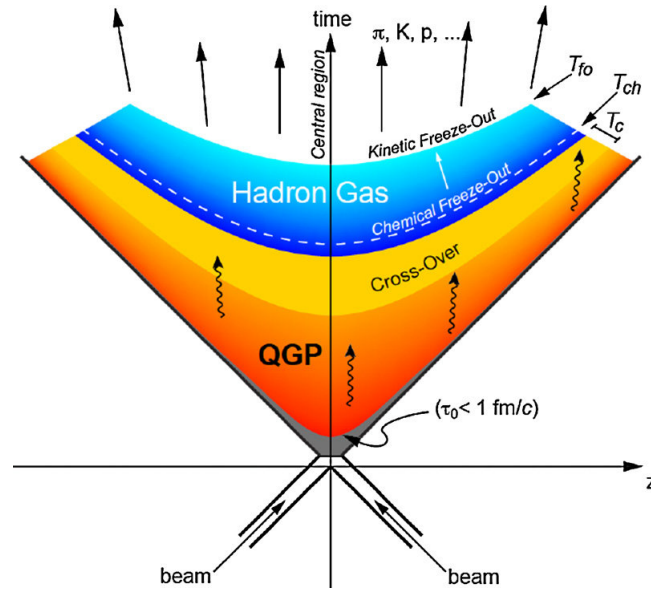


Figure 1.4. Space-time diagram of a heavy-ion collision of two nuclei colliding at time $t = 0$ and longitudinal position $z = 0$ (transverse direction not shown). The evolution goes from a hot-fireball in a pre-equilibrium phase through the formation of a QGP, followed by a cross-over phase transition to a hadron gas. [6]

Figure 1.4 shows the diagram describes the overall processes of the heavy-ion collisions in space-time axes.

1.2 Charged Particle Multiplicity and System Size

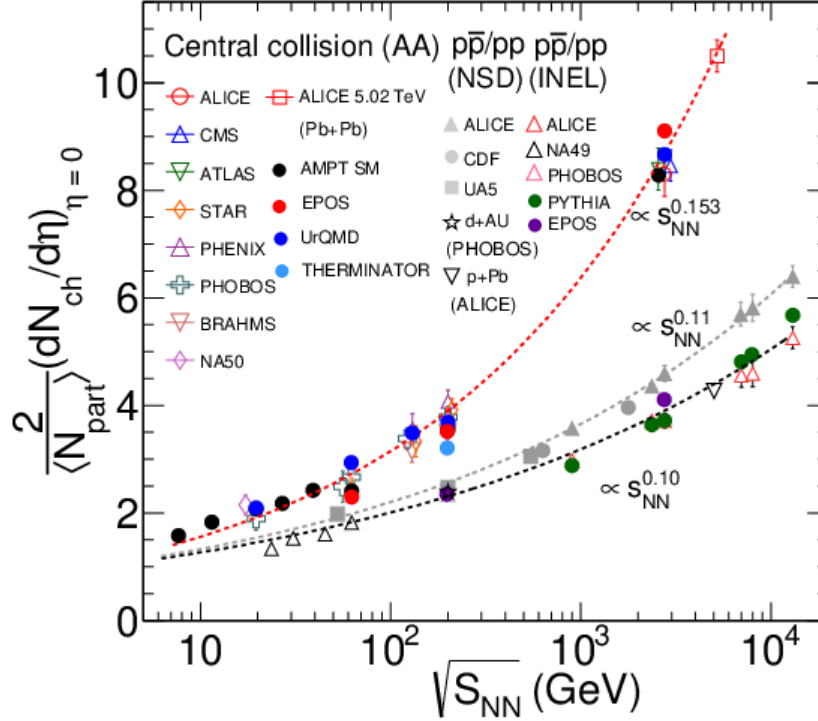


Figure 1.5. Compilation of measurements of the beam-energy dependence of charged particle multiplicity density at mid-rapidity, scaled by the average number of participating nucleon pair ($\langle N_{\text{part}} \rangle / 2$). Data from pp, p $\bar{p}$, d–Au, p–Pb, Au–Au, and Pb–Pb collisions are parameterized with power-law fits (dash-lines) and compared to calculations from event generators. [7].

Charged particle multiplicity $dN_{\text{ch}}/d\eta$, "Multiplicity", indicates the number of charged particles produced in a unit rapidity, and is one of the most accessible observables for heavy-ion collisions. Fig. 1.5 shows multiplicity as a function of centre-of-mass energy $\sqrt{s_{\text{NN}}}$ for various experiments and collision systems. To compare the collision systems, the dependence on the average number of participant pairs is taken out. This $\langle N_{\text{part}} \rangle$ normalization is chosen as particle production in heavy-ion collisions is expected to scale with the number of participating nucleons.

The centrality of a Pb–Pb collision is estimated from multiplicity with the relationship between the impact parameter b and multiplicity on Glauber Model [8]. It helps to control the source size in different collision geometries. The radius of the collision system R is usually estimated by using the Hanbury Brown–Twiss (HBT) method with two-particle correlations [9]. As in Ref. [10], the HBT radius can be parameterised as a function of multiplicity as:

$$R = a(dN_{\text{ch}}/d\eta)^{1/3} + b \quad (1.3)$$

where R is the source radius, $a = 0.473$ fm and $b = 0$ which is obtained from a fit. Fig. 1.6 shows some examples of the HBT radius parameterisation as a function of multiplicity.

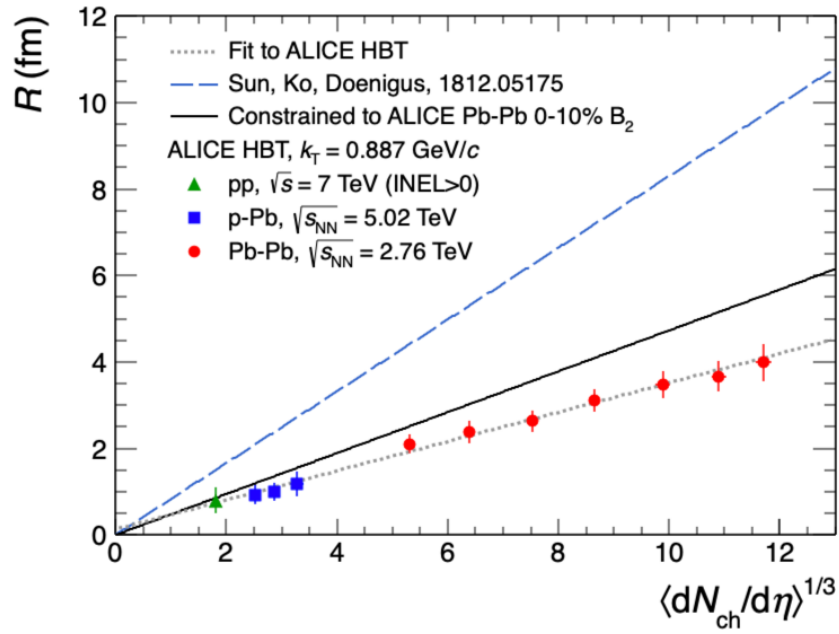


Figure 1.6. Comparison of different source volume parameterisations. The dotted gray line is the result of a linear fit to the ALICE HBT data [11–13], according to Eq. 1.3 with $a = 0.339$ fm and $b = 0.128$ fm. The dashed blue line represents the parameterisation used in [14], corresponding to $a = 0.83$ fm and $b = 0$. The solid black line represents the parameterisation used in the study ($a = 0.473$ fm and $b = 0$) and obtained by a constraint from the B_2 measured in central (0-10%) Pb–Pb collisions [10].

1.3 Strangeness Enhancement

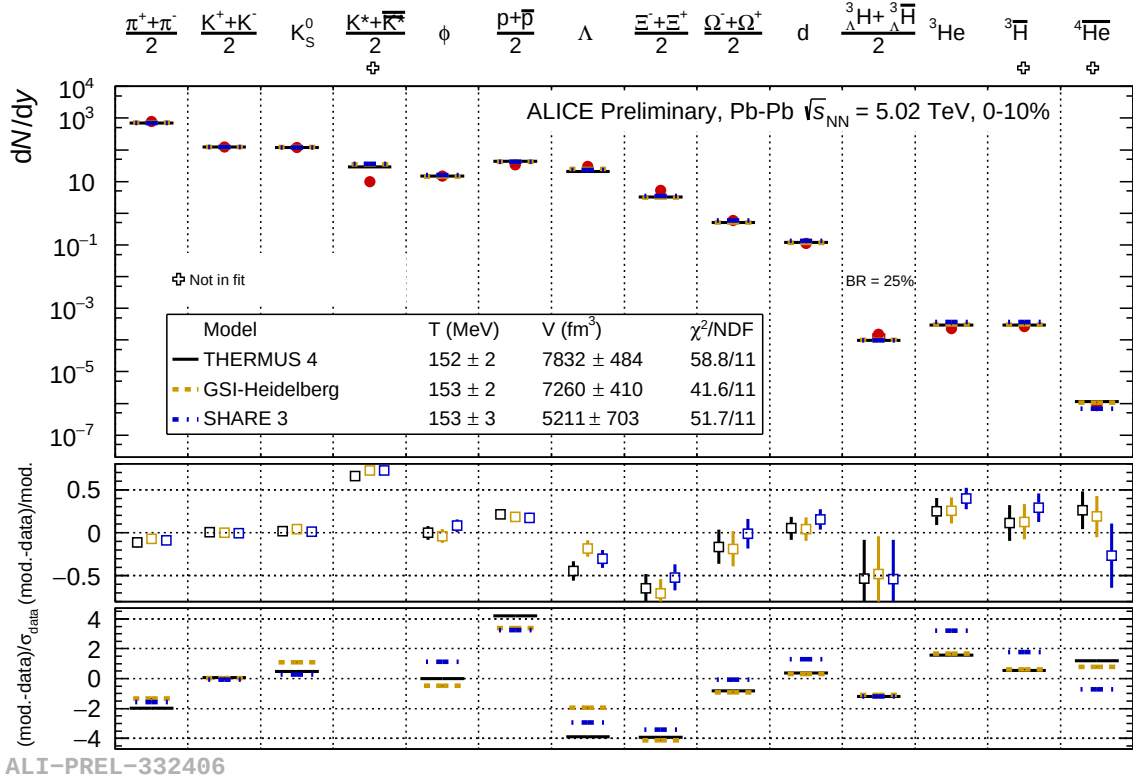


Figure 1.7. Grand canonical thermal fit for light hadrons and nuclei of 0–10% central Pb-Pb collisions at 5 TeV, with 3 models (THERMUS [15], GSI, SHARE).

The enhanced production of strange particle, *Strangeness enhancement*, was originally suggested as a signature of the formation of QGP in 1982 [16]. It explains that the strange quark production is enhanced in the QGP since it can only depend on the mass of the quarks, such as u, d, s, while the same product in a hadron gas needs to take into account the confinement mass of the produced particle.¹ Moreover, the overall productions seem not to be affected in the hadronic phase in view of that the light hadrons (i.e. hadrons consisting of u, d, and s quarks) measured in heavy-ion collisions are well described by the thermal model. Figure 1.7 shows that the thermal model fits worked well in describing not only the production of the hadrons consisting of u and d quarks, such as π and p , but also the strange hadrons, such as Λ , Ξ , Ω . It means that the equilibrated QGP, which can be described by the thermal model, is formed in collisions. In addition to that, the model suggests that the multi-strange baryons are fully thermalised from their saturated yields at high multiplicity.

In contrast to the classical view of *strangeness enhancement*, a similar enhancement has been observed also in p–Pb and high-multiplicity pp collisions [17]. Figure 1.8 shows a smooth scaling of the strangeness hadrons to π with multiplicity without significant dependence of the collision system or the centre-of-mass energy. The statistical model with a strangeness *canonical suppression* [18] and core-corona superposition model [19, 20] predicts, with the correct trend and orders of magnitude, the suppression of strangeness production in small systems.

¹**REACTION THRESHOLD:** In case of the production $p + p \rightarrow p + K^+ + \Lambda$, $Q = m_\Lambda + m_K - m_p \approx 670$ MeV needed in a hadron gas while $Q_{\text{QGP}} \approx m_s \approx 200$ MeV needed in QGP.

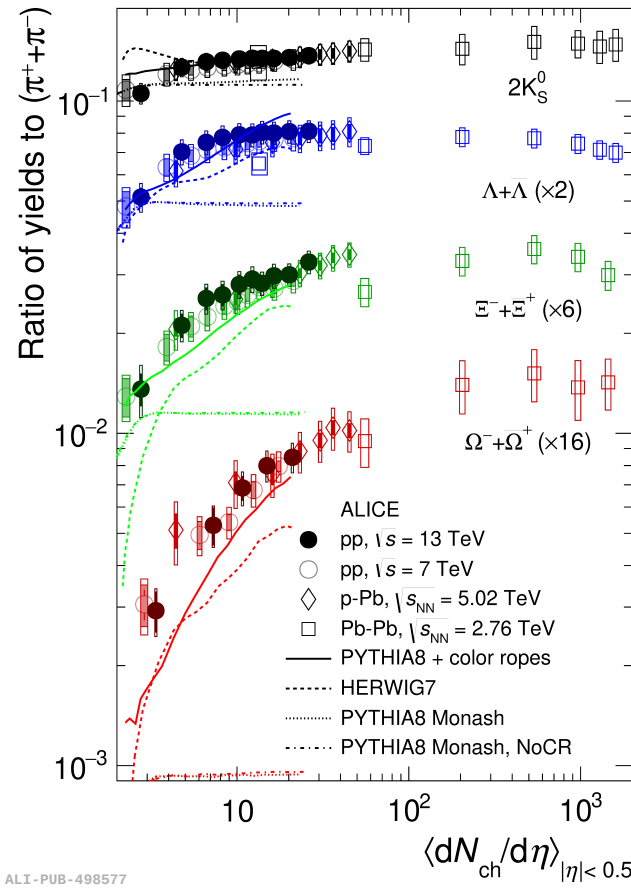


Figure 1.8. Integrated strange hadron-to-pion ratios as a function of $dN_{ch}/d\eta$ measured in pp, p-Pb, and Pb-Pb collisions. The open (shaded) boxes around markers represent full (multiplicity uncorrelated) systematic uncertainties. Different lines represent predictions from different MC generators for pp collisions at $\sqrt{s} = 13$ TeV [21].

1.4 Resonances

Hadronic resonances are the hadron which has the same quark contents of its ground state particle but has a different excited quantum state. Resonance particles are having an extremely short lifetime, the order of 10^{-23} seconds or $c\tau \approx 1$ fm, and decay via the strong interaction. The lifetime of the QGP evolution is a time of the order of ~ 10 fm/ c as discussed in Section.1.1.1, resonances can be influenced by interactions in the hadronic phase, thus can be a useful tool to probe the characteristic of the hadronic phase. The list of resonances that have been studied can be found in the Tab. 1.1.

Table 1.1. Properties of the resonances [22] Antiparticles are not listed for conciseness.

Resonances	Valence quarks	Mass (MeV/ c^2)	Width (MeV/ c^2)	$c\tau$ (fm)	Decay mode	B.R (%)
$\rho(770)^0$	$(u\bar{u} + d\bar{d})/\sqrt{2}$	775.26 ± 0.25	147.8 ± 0.9	1.3	$\pi^+ + \pi^-$	100
$K^*(892)^0$	$d\bar{s}$	895.81 ± 0.19	47.4 ± 0.6	4.2	$K^- + \pi^+$	66.6
$\Sigma(1385)^+$	uus	1382.80 ± 0.35	36.0 ± 0.7	5.48	$\Lambda + \pi^+$	87.0
$\Sigma(1385)^-$	dds	1387.2 ± 0.5	39.4 ± 2.1	5.48	$\Lambda + \pi^-$	87.0
$\Lambda(1520)^0$	uds	1519.54 ± 0.17	15.73 ± 0.29	12.6	$p^+ + K^-$	22.5
$\Xi(1530)^0$	uss	1531.80 ± 0.32	9.1 ± 0.5	22	$\Xi^- + \pi^+$	66.7
$\Phi(1020)^0$	$s\bar{s}$	1019.455 ± 0.020	4.26 ± 0.04	44	$K^+ + K^-$	48.9

1.4.1 Medium Effects in Hadronic Phase

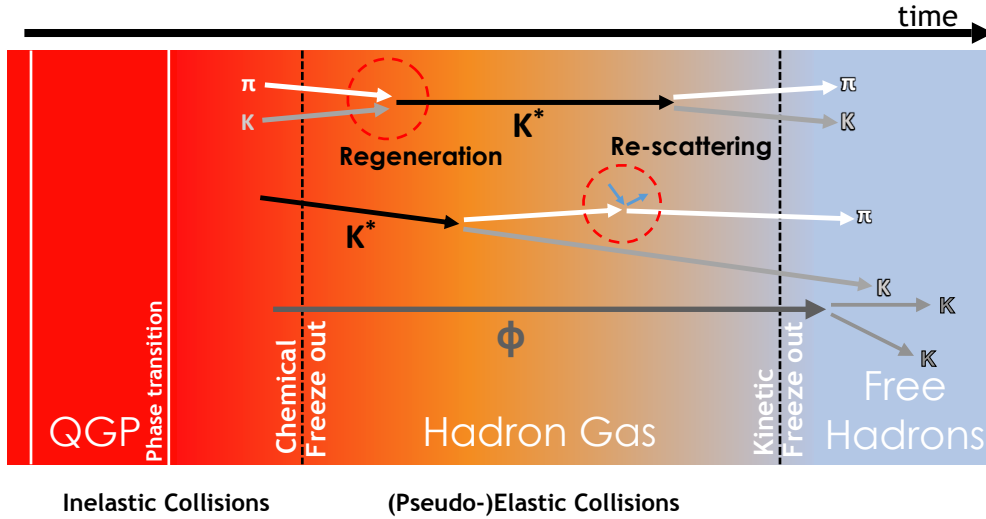


Figure 1.9. Sketch of the possible interactions in Hadronic Phase. Yields of the short-lived resonance, such as K^* ($c\tau \approx 4.2$ fm), can be affected by re-scattering and regeneration in hadronic phase while long-lived resonance, such as Φ ($c\tau \approx 44$ fm) can pass through the phase.

After the heavy-ion collision, hadronic resonance states are produced and their abundances are determined in chemical equilibrium with all the other hadrons at the chemical freeze-out temperature T_{ch} . In the hadronic phase, most hadron yields are fixed and their momenta change. (Pseudo-)Elastic collisions are continuing and some hadrons can be generated. After the kinetic freeze-out, the hadron yields and moment are fixed eventually [23] and particles stream freely towards the experimental detector.

Due to the very short lifetime of hadronic resonances, some of them can be decay inside the dense hadronic medium before the kinetic freeze-out stage is reached. The decay daughters of the resonance might interact with the surrounding hadrons forming such a dense hadronic phase [24]. If the circumstance present in the hadronic phase is dense and opaque enough, the decay daughters can interact with the nearby hadrons in an elastic collision. Such interaction can change the momenta of the decay daughters, and this process could prevent the invariant mass analysis technique used to reconstruct the resonance based on the correlation between mother and daughter particles by smearing the resonance peak in the invariant mass distribution. As a result, it reduces the reconstructable yields of the resonance relative to the primordial resonance yield is called *Re-scattering* in the hadronic phase. Conversely, the resonance signal can be produced via pseudo-elastic interactions among the hadrons in the medium. This *regeneration effect* inside the hadronic medium can compensate for the re-scattering loss. The interactions depend on the scattering cross-sections of the decay products, the density of the produced medium, the lifetime of resonances and the hadronic phase duration. [23]

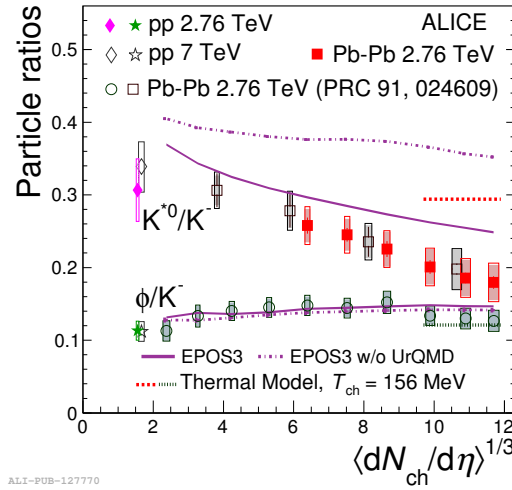


Figure 1.10. K^*/K , Φ/K ratios as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ measured at mid-rapidity in pp collisions at 2.76 TeV and 7 TeV, and Pb–Pb collisions at 2.76 TeV. The expectations from a thermal model calculation with chemical freeze-out temperature of 156 MeV for the most central collisions are shown. The EPOS3 calculation of the ratios are also shown as a violet band for different centrality intervals [25].

Figure 1.10 shows the ratios of p_T -integrated particle yields K^*/K , Φ/K in pp and Pb–Pb collisions at different energies. The ratios of K^*/K in Pb–Pb collisions show the clear decreasing trend in high multiplicity events. When recalling the good accuracy of the thermal model on light hadron yields, it is surprising that the thermal model overestimates the ratio of the K^*/K while the ratio Φ/K shows a constant behaviour along with the multiplicity and matches well with the thermal model expectation. The solid purple line, EPOS3 model, follows the decreasing trend of K^*/K ratio qualitatively but fails to describe when it turns off the UrQMD [26], which describes the rescattering effect, in purple dashed line. One can notice that the difference between the expectation from EPOS3 and EPOS3 without UrQMD of Φ/K is negligible. Comparing the lifetime of 2 resonances in Tab. 1.1, it suggests *Re-scattering* of decay products in hadronic phase.

In addition to that, the fact that re-scattering of the decay products of K^{*0} in the hadronic phase is dominant over K^{*0} regeneration suggests that $K^{*0} \leftrightarrow K\pi$ is not in balance [27].

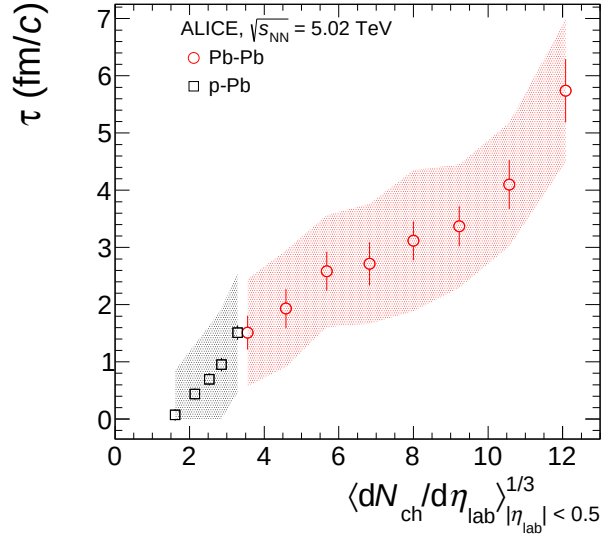


Figure 1.11. Lower limit on the hadronic phase lifetime between chemical and kinetic freeze-out as a function of $dN_{\text{ch}}/d\eta$ in p-Pb and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The bars and bands represent the statistical and systematic uncertainties, respectively, propagated to the lifetime from the uncertainties associated with the measured K^{*0}/K ratios in Pb-Pb (p-Pb) and pp collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Ref. in [27].

Therefore, in Pb-Pb the K^{*0}/K^- ratio can be used to calculate a rough estimate of the duration of the hadronic phase between chemical and kinetic freeze-out, τ as:

$$\left. \frac{K^{*0}}{K^-} \right|_{\text{kinetic}} = \left. \frac{K^{*0}}{K^-} \right|_{\text{chemical}} \times e^{\tau/\tau_{K^{*0}}} \quad (1.4)$$

where $\tau_{K^{*0}}$ is the lifetime of K^{*0} . One can substitute 4.16 fm/c for $\tau_{K^{*0}}$ for a rough calculation. By assuming a special case that all decayed K^{*0} are lost due to the re-scattering effect and there is no re-generation effect in hadronic phase based on AMPT simulation [28], The value of $K^{*0}/K^-|_{\text{chemical}}$ can take from measured data in pp collisions and the value of $K^{*0}/K^-|_{\text{kinetic}}$ can be estimated from data in Pb-Pb collisions. Figure 1.11 shows the estimation of the lower limit of the lifetime of the hadronic phase.

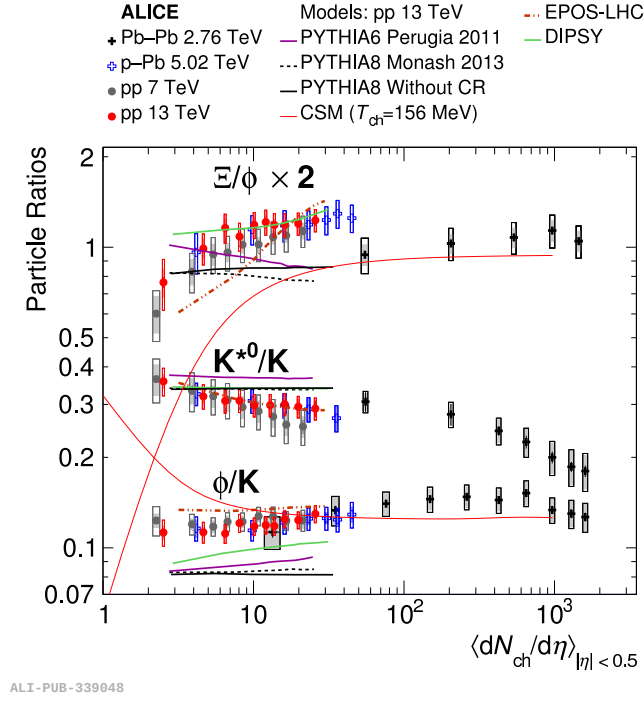


Figure 1.12. Ratios of p_T -integrated particle yields K^*/K , Φ/K , and Ξ/Φ in pp collisions at $\sqrt{s} = 13$ TeV as functions of $\langle dN_{ch}/d\eta \rangle$ [29]. These measurements are compared with data from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [30, 31] and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [25, 32], as well as results from common event generators [33–36] and a Canonical Statistical Model calculation [37]. Ref: [38]

On the other hand, as like recent findings of strangeness enhancement showed a smooth scaling of the strangeness hadrons to π with multiplicity without significant dependence of the collision system in Fig. 1.8, latest study of K^*/K ratios in high multiplicity classes in pp collisions show a hint of re-scattering effect in small systems in Fig. 1.12. The ratio of K^*/K in the highest multiplicity class is below the low-multiplicity value at the 2.3σ level. EPOS-LHC [35] describes almost perfectly the trend of the K^*/K ratio in pp collisions at $\sqrt{s} = 13$ TeV. PYTHIA [33, 34] and DIPSY [36] tend to overestimate the ratio for large multiplicities and do not describe the decreasing trend with increasing multiplicity. The Φ/K ratio also follows a similar trend in the three collision systems. It shows an almost constant value as a function of $\langle dN_{ch}/d\eta \rangle$.

1.5 Light Nuclei Production

Table 1.2. Properties of nuclei and hyper-nuclei with mass number $A \leq 3$. The nucleus size is given in terms of the (charge) rms radius of the wave-function, λ_A . The size parameter of the wave-function of the harmonic oscillator potential, r_A , is chosen to approximately reproduce the measured/expected rms, $\lambda_{rmA}^{\text{meas}}$ (fm). The proton rms charge radius $\lambda_p = 0.879(8)$ is subtracted from $\lambda_{rmA}^{\text{meas}}$ according to $\lambda_A = \sqrt{(\lambda_{rmA}^{\text{meas}})^2 - \lambda_p^2}$ to account for the finite extension of the constituents. It assumes $\lambda_\Lambda \approx \lambda_n \approx \lambda_p$. Ref. in [10]

Mass Number	Nucleus	Composition	Binding Energy (MeV)	Spin	$\lambda_{rmA}^{\text{meas}}$ (fm)	r_A (fm)
$A = 2$	d	pn	2.224575 (9)	1	2.1413 ± 0.0025	3.2
$A = 3$	^3H	pnn	8.4817986 (20)	1/2	1.755 ± 0.086	2.15
	^3He	ppn	7.7180428 (23)	1/2	1.959 ± 0.030	2.48
	$^3_\Lambda\text{H}$	p Λ n	0.13 ± 0.05^2	1/2	$4.9 \sim 10$	$6.8 \sim 14.1$

Light (anti-)nuclei are abundantly produced in heavy ion collisions, but their production mechanism is still not understood well. While the chemical freeze-out temperature in heavy-ion collision is $T_{\text{ch}} \approx 150$ MeV, nucleons in the light (anti-)nuclei are combined by a binding energy of the order of 1 MeV per nucleon [39]. This leads to a major puzzle: how these loosely bound objects can be produced and survive in such extreme conditions, like ‘snowballs in hell’ [40]. There are 2 major phenomenological models that try to describe such a strange phenomenon: the Statistical Hadronisation Model (SHMs) [41] and the coalescence model [42].

1.5.1 Statistical Hadronisation Models

The Statistical Hadronisation Model (SHM) is developed to describe the abundances of different hadrons produced in particle collisions. The main idea that tries to apply the statistical method in particle production was introduced by Enrico Fermi in 1950 [43] and evolved by Rolf Hagedorn to the Hagedorn formulation [44] that could describe the production rate in proton-proton collisions successfully.

The general idea of the statistical model-*Thermal Model*- is that the final state of the interaction is composed of all the particle states compatible with the conservation laws imposed by the underlying theory of interaction (Standard Model, in SHM), and the relative abundance of different particle states is determined to maximise the total phase space filled by the system, to which each particle species contributes according to its partition function. The SHM is particularly interesting in heavy-ion collisions since it is expected to present a large volume that eventually reaches the thermal equilibrium. The system created in a relativistic HIC is large enough to be modelled using the Grand Canonical ensemble [45].

In the Grand Canonical ensemble approach, the system under interest is in contact with an energy and charge reservoir. Since the region of interest in heavy ion collision is meet with the condition, i.e. the mid rapidity region in the case of the ALICE detectors, this formalism can be applied. This small portion of the system, mid rapidity region, is in equilibrium with a thermal reservoir, the rest of the medium in the collision, and quantities such as system energy, baryon number, and charges are conserved on average.

²For the hypertriton, the separation energy of the Λ from the other two nucleons is reported.

The statistical properties of the system at thermodynamic equilibrium are described by the grand partition function Z :

$$Z(T, V, \mu) = \text{Tr} \left[e^{-\beta(H - \sum_i \mu_i Q_i)} \right] \text{ with } \mu = \sum_i \mu_i Q_i \text{ and } \beta = \frac{1}{T} \quad (1.5)$$

where H is the Hamiltonian of the system, T is the temperature of the system, V is the volume of the system at equilibrium (*canonical volume*), Q_i are the conserved charges and μ_i are their respective chemical potentials. For a strongly interacting medium, the main conserved charges are the electric charge Q , the strangeness content of the system S and the baryon number B . The Hamiltonian H of a Hadron Resonance Gas (HRG) is used since it can describe the interaction of a strongly interacting medium and it can reproduce over a wide temperature range the equation of state obtained with Lattice QCD before the transition to a deconfined state.

The partition function Z of the system is obtained from the product of the partition functions Z_i of all the particle states in HRG:

$$Z(T, V, \mu) = \prod_i Z_i(T, V, \mu_i) \rightarrow \log Z(T, V, \mu) = \log \sum_i Z_i(T, V, \mu_i) \quad (1.6)$$

The partition functions Z_i , defined as:

$$\log Z_i(T, V, \mu_i) = \frac{Vg_i}{2\pi^2} \int_0^\infty \pm p^2 dp \log(1 \pm \lambda_i(T, \mu_i) e^{-\beta\epsilon_i}) \quad (1.7)$$

where $-$ sign is for Bose-Einstein and $+$ sign is for Fermi-Dirac partition functions for bosons and fermions respectively. The constant g_i is the *spin-isospin degeneracy factor*, which means number of spin and isospin degenerate state for the species i and ϵ_i is the energy of one particle of the species with momentum p ($\epsilon_i = \sqrt{p^2 + m_i^2}$). The dependence on the chemical potential is included in the fugacity λ_i , defined as:

$$\lambda_i(T, \mu_i) = e^{\beta(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)} = e^{\beta\mu_i} \quad (1.8)$$

where B_i, S_i and Q_i are respectively the baryon number, the strangeness content and the electric charge of the particle species i . If one performs a Taylor expansion of the logarithm and integrates over the momentum [46], the partition function for the species i becomes

$$\log Z_i(T, V, \mu_i) = \frac{VTg_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k^2} \lambda_i^k m_i^2 K_2(\beta k m_i) \quad (1.9)$$

where $+$ sign for bosons and $-$ sign for fermions and K_2 is the second modified Bessel function.

From the partition function, the average number $\langle N_i \rangle^{th}$ of the particle species i for a system described by the Grand Canonical ensemble is defined as

$$\langle N_i \rangle^{th}(T, V, \mu_i) = \frac{1}{\beta} \frac{\partial}{\partial \mu_i} \log Z_i(T, V, \mu_i) = \frac{VTg_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k^2} \lambda_i^k m_i^2 K_2(\beta k m_i) \quad (1.10)$$

But it is not sufficient to describe the particle production measured in a HIC. To compare the theoretical prediction with a real measurement of the yield, one should consider the feed-down contributions of other species j (resonances) that decay in a final state containing a particle of the species i :

$$\langle N_i \rangle^{th}(T, V, \mu) = \langle N_i \rangle^{th}(T, V, \mu_i) + \sum_j \Gamma_{j \rightarrow i} \langle N_j \rangle^{th}(T, V, \mu_j) \quad (1.11)$$

where $\Gamma_{j \rightarrow i}$ is the branching ratio of the species j decaying into the species i .

This definition of particle yields has a limitation in that it works only in a low-density system, where the repulsive and attractive interactions are negligible. The repulsive corrections by introducing an eigenvolume for each particle state in the system [47] is currently a matter of study but, Eq. 1.11 already shows the crucial five dependencies of the observed particle yields: the temperature T , volume V and the three chemical potentials (μ_B , μ_Q and μ_S). Among them, two chemical potentials μ_Q , μ_S are constrained from the HIC conditions, since μ_Q is fixed by the isospin asymmetry of the initial stage and μ_S is fixed to zero by the no net strangeness is present in the colliding nuclei. However, μ_B is not constrained by initial conditions because the "amount of baryonic number" transported in the equilibrium region can be different with the energy of the collision. Lastly, the dependence on the volume of the system can be removed considering the ratio between the yields of different particle species rather than the yields themselves.

The statistical thermal model is used to predict hadron yields in a collision from π to light nuclei. By adding some extensions to the thermal model, the model can predict the emission of some particle species such as strange particles out of the Grand Canonical equilibrium. Statistical HAdronization with REsonances (*SHARE*) [48] is one of the examples that introduce some additional phase space occupancy factors that are useful to describe systems where the suppression of the production rate for some particle species, like strange particles in small systems, is observed.

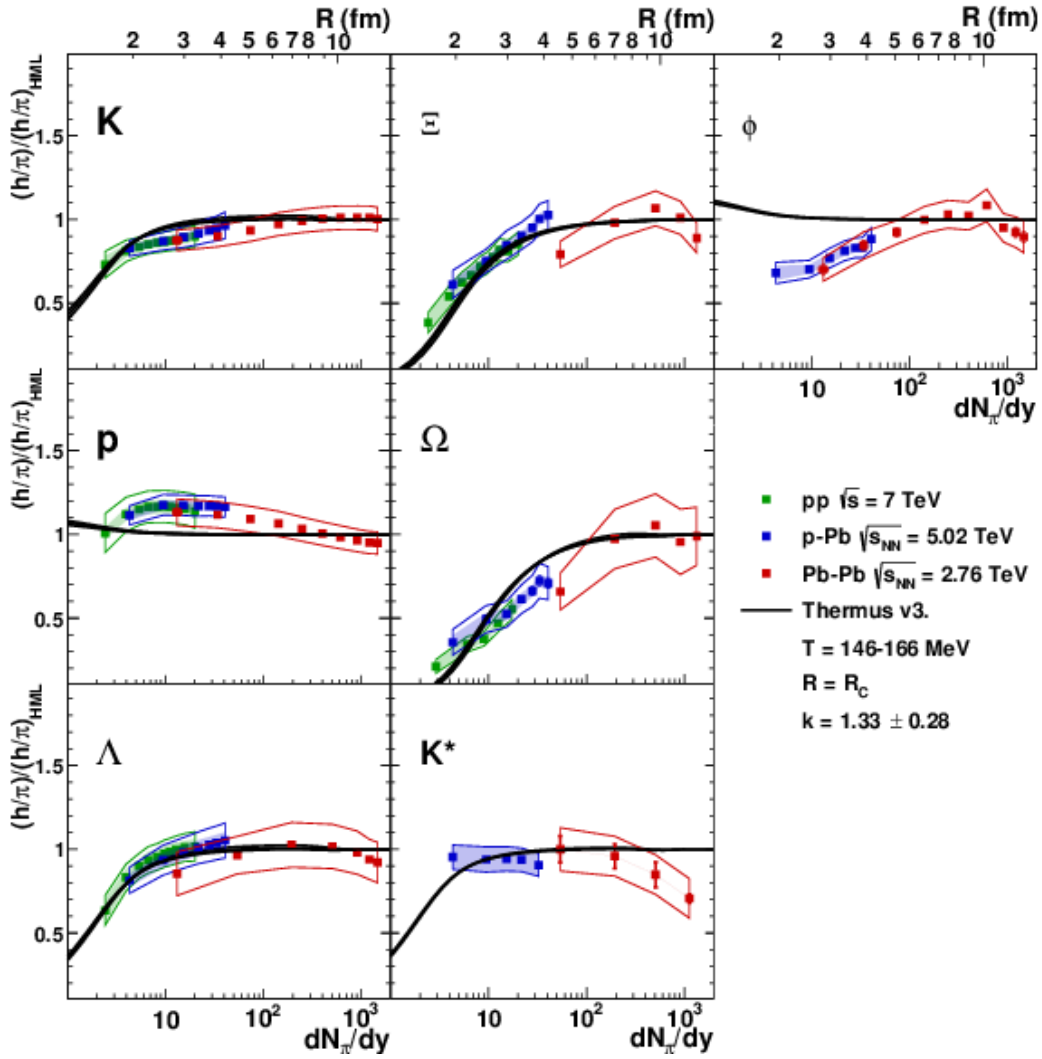


Figure 1.13. Ratios of several particle species measured by the ALICE collaboration as a function of the midrapidity π yields for pp, p-Pb and Pb-Pb colliding systems compared to the THERMUS strangeness canonical suppression model prediction (black line), in which only the system size is varied. The upper axis shows the radius R of the correlation volume $V = R^3$ which corresponds to the predicted particle ratios. The width of the model prediction line corresponds to a variation of the chemical freeze-out temperature between 146 MeV and 166 MeV. Ref in [49]

Canonical Suppression Following to the Sec. 1.3, Figure 1.13 shows the successful description of the SHM (THERMUS [15]) to the increasing trend of the yield of the strangeness hadrons with regard to the yields of π as a function of charged particle multiplicity. The deviations observed for the K^* meson in central Pb-Pb collisions can be explained with the re-scattering effect in the hadronic phase.

Snowballs in hell In the view of the thermal models, light nuclei yields are determined naturally when the chemical freeze-out temperature and the baryon chemical potential are fixed. However, note that the thermal model does not consider the internal structure of hadron and the hadron yields are the result of their distribution in phase space. One of the suggested explanations on how the light nuclei can survive the extreme condition is related to the entropy conservation [50] that the relative yield of particles composed of nucleons is determined by the entropy per baryon, which is fixed at chemical freeze-out. As the system

expansion after the chemical freeze-out, the entropy density is supposed to conserve, such conservation could steer the mechanism for the nuclei production in HIC.

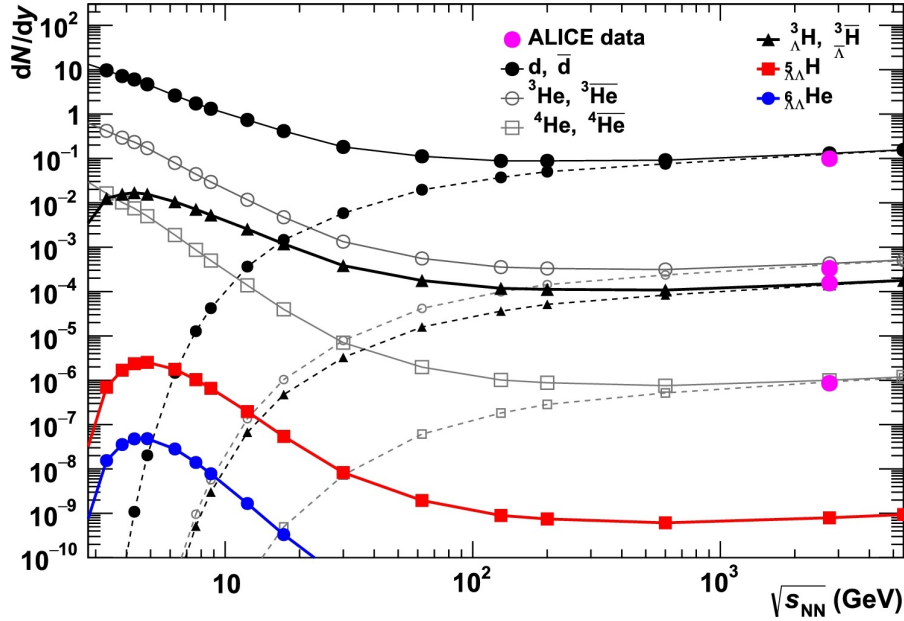


Figure 1.14. Energy dependence of predicted hypernuclei yields at midrapidity for 10^6 central collisions. The predicted yields of ${}^3\text{He}$ and ${}^4\text{He}$ nuclei are included for comparison. The ALICE results of Run1 are shown in magenta. Similar figure as in [50] Ref in [6]

Figure 1.14 shows the thermal model prediction of the yields of (hyper-)(anti-)nuclei at the LHC energy. One can find that At low collision energy, the baryon chemical potential differs significantly from zero and the $e^{\beta B_i \mu_B}$ term in the particle yield makes a difference between matter (solid line) and anti-matter (dashed line). As the energy increases, μ_B decreases and the difference disappear.

Figure 1.7 shows the thermal model fit to all the light-flavoured hadrons measured in central (0 – 10%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV up to hypertriton ${}^3_\Lambda\text{H}$. The fits are performed with three different implementations of the thermal model: THERMUS, GSI-Heidelberg [51] and SHARE [48]. They differ in the list of resonances included in the Hamiltonian and the hadron volume is taken account in THERMUS and GSI-Heidelberg while SHARE assumes point-like hadron. These fits to the hadron yields provide a common chemical freeze-out temperature $T_{\text{ch}} = 156$ MeV, thus it means that light nuclei are produced at statistical equilibrium at the same temperature as the other hadrons.

1.5.2 Coalescence Model

The coalescence model was first developed by Butler and Pearson for proton-nucleus collisions [52]. The model suggests a deuteron production mechanism that nucleons, like protons and neutrons, that are close to each other in phase space after chemical freeze-out can bind together and form a nucleus via coalescence. In such a static model, the nuclei are created at the kinetic freeze-out and there is no attempt to give a detailed description of the interactions that lead to their formation, like SHMs. But, the coalescence models give a clear prediction about the momentum distribution of the produced light nuclei as a function of the production spectra of the constituent nucleons.

The key parameter of the coalescence model is the coalescence parameter B_A when A constituent nucleons form a nucleus of the species i , defined as:

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \bigg|_{p_p=p_n=\frac{p_A}{A}} \quad (1.12)$$

where $p_{p,n}$ are the proton and neutron momenta and $E_{p,n}$ their energies. The number of produced protons and neutrons at mid rapidity as well as their momentum distributions are expected to be equal at LHC energies (Fig. 1.14). Moreover, the invariant spectrum of protons is evaluated at $p_T^p = p_T^A/A$, because the nucleus momentum is the sum of the momenta of A nucleons. With this simplification, it is possible to test the value of the coalescence parameter, B_A , of nuclei with the same A but different nucleon content³.

One of the first implementations of the coalescence model is the simple coalescence models, also referred to as *naive* coalescence model [53], considering only the momentum space and not the space-time, so that the coalescence parameter can be expressed, neglecting the nucleon spin, as

$$B_A = \left(\frac{4\pi p_0^3}{3} \right)^{A-1} \frac{m_i}{m_P^A} \quad (1.13)$$

where A is the nucleus mass number, m_i is the mass of the species i , m_i is the proton mass, p_0 is the maximum distance in momentum-space at which coalescence can happen. This is the only dependence of the coalescence parameter foreseen by this formulation of the model, which is the most commonly used for the comparison with the data. In view of the naive coalescence model, B_A should not depend either on transverse momentum p_T or on the system volume.

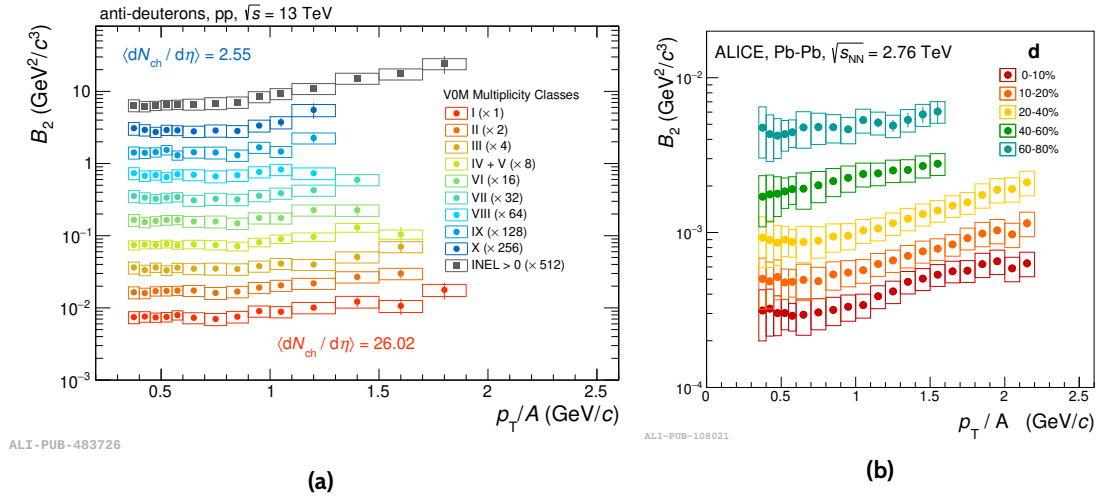


Figure 1.15. Measured B_2 in pp collisions at $\sqrt{s} = 13$ TeV [54] (a) and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [55] (b)

Figure 1.15 shows, however, even if B_A is flat as a function of transverse momentum in pp collisions [54], it increases with transverse momentum in large systems, such as Pb-Pb collisions [55]. Moreover, the B_A decreases not only with the centrality but also with the multiplicity. Indeed, the coalescence probability

³For example, ^3H , ^3He and $^3_\Lambda\text{H}$ have the same $A = 3$.

decreases for nucleons with similar momentum that are distant in space and this is not applied in the simple coalescence model. Due to this, advanced extensions of the model predicting a dependence on the geometry of the system is considered to reproduce the trend observed in the data.

Advanced Coalescence Model:

The key concept of the advanced coalescence model [10] is the overlap of the Wigner function, which is replaced from the classical definition of phase space, with the phase-space distributions of the nucleons.

The wave-functions of the (hyper-)nuclei, from here on focus to deuteron, are approximated by the ground-state wave-functions of an isotropic spherical harmonic oscillator with one single characteristic-size parameter, r_d :

$$\psi_d(\vec{r}) = (\pi r_d^2)^{-3/4} \exp\left(-\frac{r^2}{2r_d^2}\right) \quad (1.14)$$

Based on the relation between r_d and the rms of the charge wave-function λ_d is derived in Ref [56], once can obtain $r_d = \sqrt{8/3}\lambda_d$. By introducing the average correction factor $\langle C_d \rangle$ accounting for the quantum-mechanical nature of the coalescence products, the nucleus size implemented in the calculation of the coalescence parameter B_2 :

$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R_\perp^2(m_T) R_\parallel^2(m_T)} \quad (1.15)$$

where $R_\perp^2(m_T), R_\parallel^2(m_T)$ are the homogeneity radii of the source, and correction factor $\langle C_d \rangle$ is:

$$\langle C_d \rangle \approx \frac{1}{\left[1 + \left(\frac{r_d}{2R_\perp(m_T)}\right)^2\right] \sqrt{1 + \left(\frac{r_d}{2R_\parallel(m_T)}\right)^2}} \quad (1.16)$$

In Eq. 1.15, the coalescence parameter decreases as volume ($R_\perp^2 R_\parallel$) increases. $\langle C_d \rangle$ it brings in a length scale defined by the size of the deuteron with regard to the source. This can be further simplified when we assume the sphere shape of the volue that $R_\perp \approx R_\parallel \approx R$.

$$\langle C_d \rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)}\right)^2\right]^{-3/2} \quad (1.17)$$

and

$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R^3(m_T)} \quad (1.18)$$

Figure 1.16 shows the source radius (R) dependence of $\langle C_d \rangle$ and B_2 , calculated assuming (a.) $r_d = 0$, (b.) $r_d = 0.3$ fm, (c.) the actual value $r_d = 3.2$ fm [57], (d.) a larger, unrealistic $r_d = 10$ fm. One can find that $\langle C_d \rangle$ inhibits remarkably the production of objects, deuterons at here, with a radius larger than the source here.

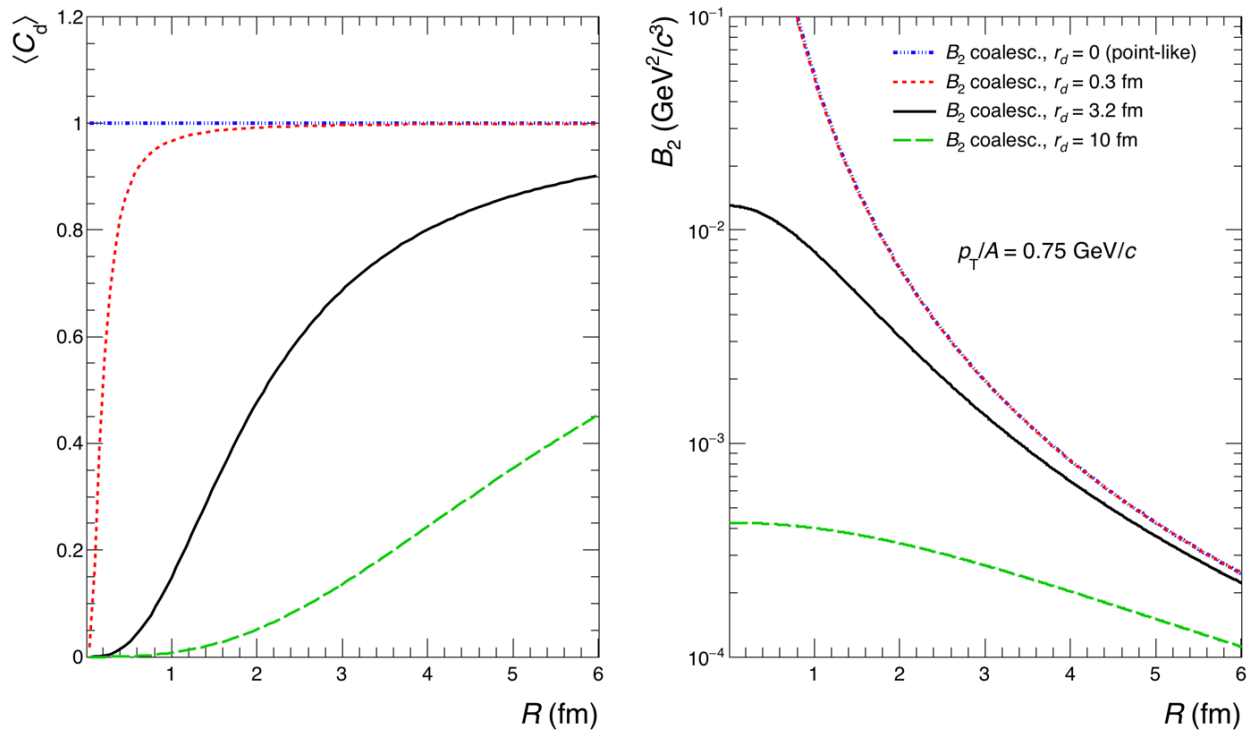


Figure 1.16. The quantum mechanical correction factor $\langle C_d \rangle$ (left panel, see Eq. 1.17) and the coalescence parameter B_2 for deuteron (right panel, see Eq. 1.18) as a function of the radius of the source, R , calculated assuming a size parameter for the deuteron $r_d = 0, 0.3, 3.2$ and 10 fm. Ref. in [10]

Chapter 2

Experimental Setup

The analysis of this thesis has been done based on the data collected using the ALICE detector at the Large Hadron Collider (LHC) of the CERN laboratory in Geneva, Switzerland. ALICE is one of the four major experiments installed at LHC, dedicated to heavy-ion physics and the characterisation of the Quark-Gluon Plasma. In this chapter, the overall experimental setup will be discussed. In section 2.1, the LHC main features will be introduced along with some parameters that are relevant for the proton and heavy-ion beams which have been used in this analysis. Section 2.2 presents the overview of the ALICE experimental setup. In section 2.3.4, Centrality and charged particle multiplicity which is one of the main observables of the analysis will be handled.

2.1 A Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest and highest energetic particle accelerator of the CERN laboratory located at the border of French-Swiss near Geneva, Switzerland. The collider is contained in a circular tunnel, with two parallel beam pipes that have a circumference of 27 km at a depth ranging from 50 to 175 m underground. LHC is the last component of the acceleration complex consisting the sub accelerators for sequential acceleration chain (Fig. 2.1). The accelerator is designed to accelerate the protons up to $\sqrt{s} = 14$ TeV and heavy ions including lead, argon, xenon up to $\sqrt{s_{NN}} = 5.5$ TeV.

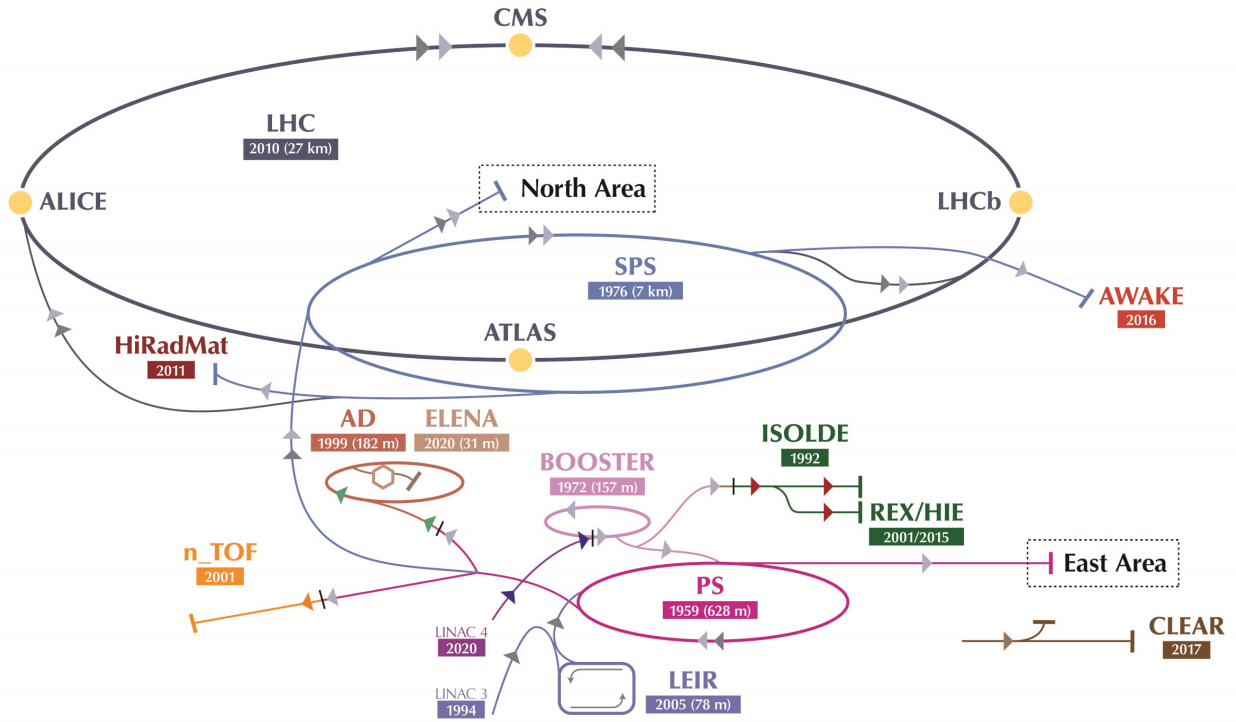


Figure 2.1. CERN Accelerator Complex [58]

Along with the energy, luminosity is an essential parameter in high energy physics, basically expressing the interaction rate normalised to the intensity of the interacting fluxes of particles in the collider. The luminosity of the collider, L , can be simply expressed as

$$L = R/\sigma \quad (2.1)$$

where R is the collision rate and σ is the cross section for the collision process. The luminosity in the particle collider can be measured by the experimental technique named *Van der Meer scan* [59]. By using this, the luminosity can be defined as

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F \quad (2.2)$$

where N_b is the number of particles per bunch, n_b is the number of bunches per beam, f_{rev} the revolution frequency, γ is the relativistic factor, ϵ_n the transverse beam emittance, β^* the beta function at the interaction point (IP) and F is a correction factor due to the crossing angle at the interaction point.

The target peak luminosity of each experiment is different by their experimental aim. For ATLAS and CMS, the peak luminosity requirement is about $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in pp collisions while the one of ALICE is about $L = 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ in Pb–Pb collisions. In general, ALICE takes less beam than ATLAS and CMS due to the limit of the detector capacity designed for Pb–Pb collisions. Figure. 2.2 shows the integrated luminosity of ALICE during Run2 period, especially for pp collisions in $\sqrt{s} = 13 \text{ TeV}$ (a) and Pb–Pb collisions $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ in 2018 (b).

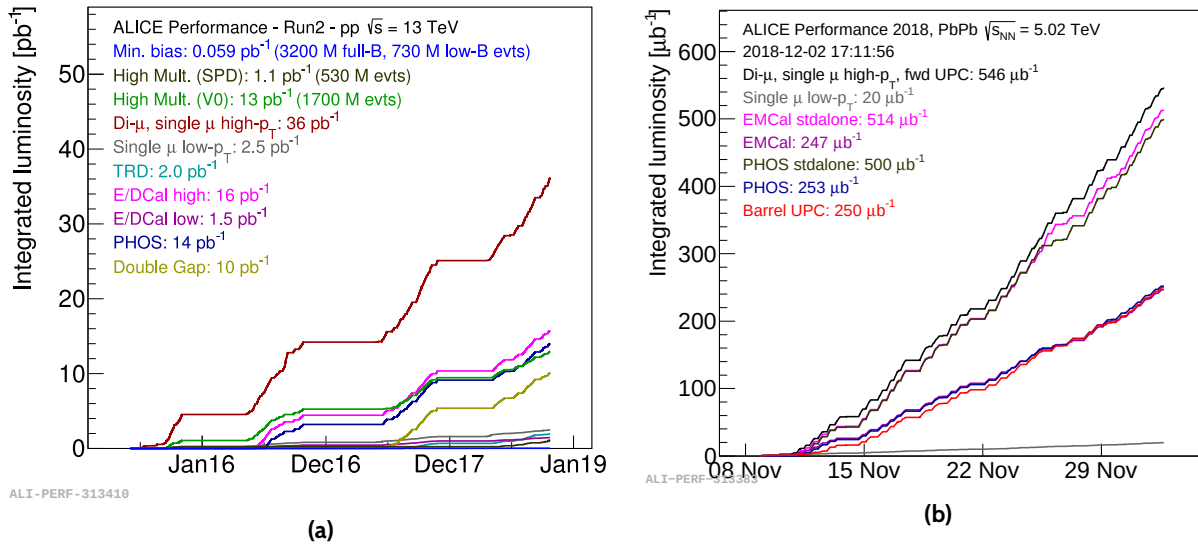


Figure 2.2. Integrated luminosity for various rare triggers in pp collisions at $\sqrt{s} = 13$ TeV during from 2015 to 2018 (a) and Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV in 2018 (b)

There are four main experiments on the interaction points which two beams are colliding at LHC: ATLAS, CMS, ALICE, LHCb.

2.2 ALICE: Detector Overview

THE ALICE DETECTOR

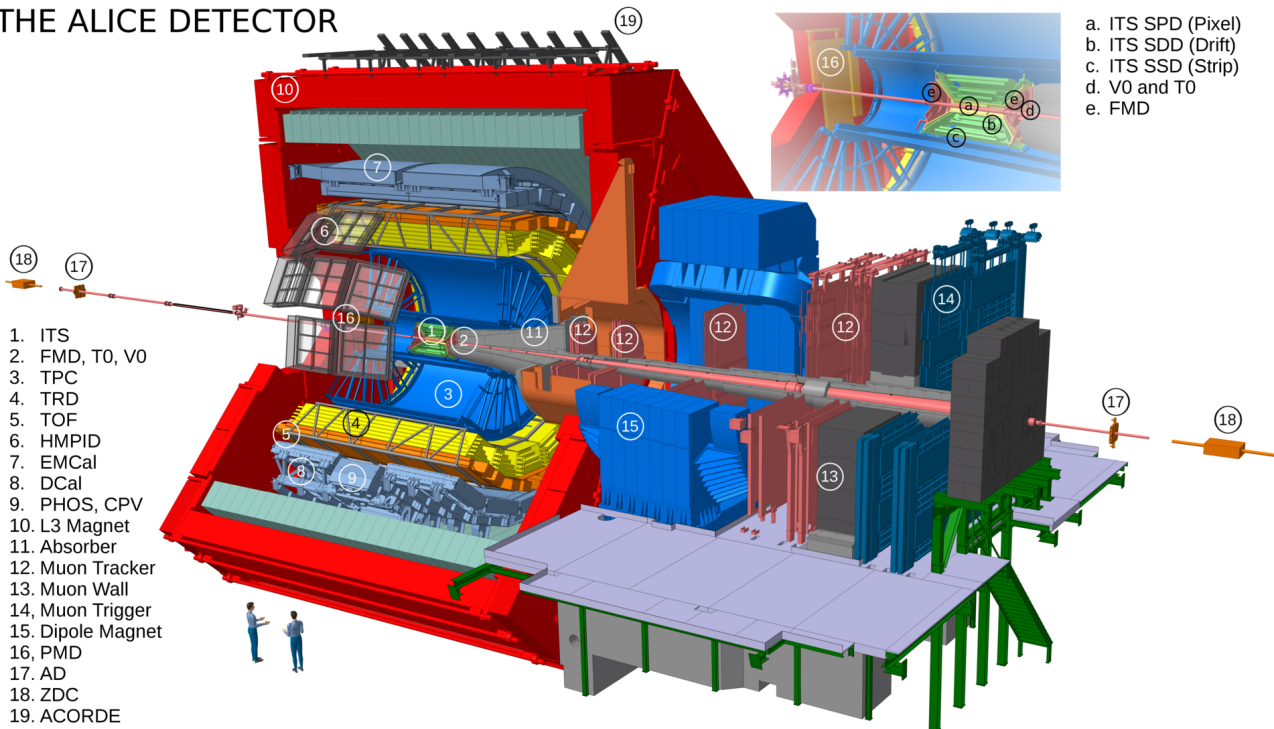


Figure 2.3. The ALICE Schematic for RUN2 with Description. The top right inset shows a zoom on the V0, TO, FMD, ITS detectors.

The ALICE experiment [60] is a general-purpose experiment specifically designed and optimised for the heavy ion experiment. The main object of the ALICE experiment is studying the properties of the QGP and it is necessary to provide particle tracking and identification on all the particles produced in the heavy ion collisions for that purpose. Therefore, ALICE detectors are designed to be able to operate in a circumstance when the charged particle multiplicity is up to $dN_{\text{ch}}/dy \approx 8000$ at mid rapidity [61]. In order to that, ALICE adopted relatively slow detectors with high granularity and low material budget, such as the Time Projection Chamber and the Silicon Drift Detector.

Figure 2.3 shows the schematic view of the ALICE detectors. The detector systems of ALICE can be grouped into two parts depending on whether they are placed in: *Central detectors* which is housed in L3-magnet operating 0.5 T and *Muon Arm* located outside the central magnet. Among them, only specific detectors which is used for the analysis focused in this thesis will be discussed in following section.

2.2.1 Inner Tracking System

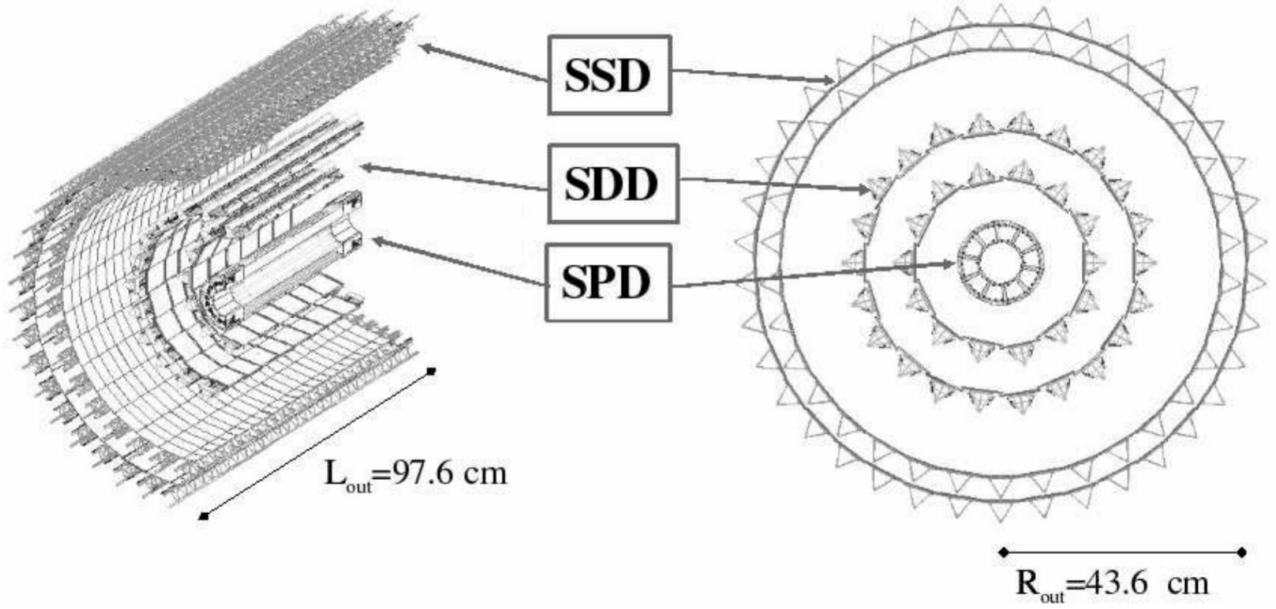


Figure 2.4. ITS schematic layout used in RUN2 period.

The Inner Tracking System (ITS) [62] made up of six silicon layers is the innermost detector of ALICE. The first two layers of the ITS consist of Silicon Pixel Detectors (SPD), locating at an average radial distance r of 3.9 and 7.6 cm from the beam pipe, which covers the pseudorapidity range $|\eta| < 1.4$ and the full azimuth around the interaction point. The SPD is used to reconstruct a short track segment that is called the SPD tracklet. The SPD tracklet is reconstructed by extending two hits on each layer linearly to the interaction point of the two beams. The next two layers and outermost two layers are also sub-detectors of the ITS are the Silicon Drift Detector (SDD) and the Silicon Strip Detector (SSD), respectively, with the outermost layer having a radius $r = 43.6 \text{ cm}$.

The main task of the ITS is the reconstruction of primary and secondary vertices with a resolution better than $100 \text{ }\mu\text{m}$. With the close space points of the silicon layers, the ITS can provide tracking even for low p_T particles down to $p_T = 80 \text{ MeV}/c$. To achieve even higher resolution and low material budget along with the fast readout, the ITS system has been upgraded for RUN3 period [63]. A dedicated section for the effort participating the upgrade project is discussed in Appendix A.

2.2.2 Time Projection Chamber

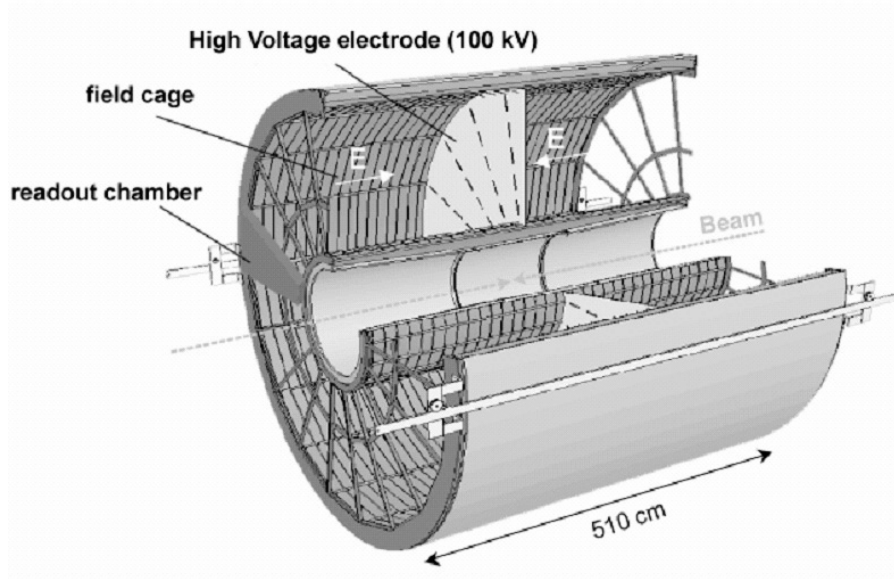


Figure 2.5. TPC schematic layout used in RUN2 period

The Time Projection Chamber (TPC) [62] is the main detector for track reconstruction and particle identification via specific energy loss in ALICE. TPC is located just outside the ITS and provides excellent momentum and spatial resolution for tracking of charged particles. The radial and longitudinal size of the TPC is about $85 < r < 250$ cm and $-250 < z < 250$ cm, respectively. It covers the pseudorapidity range $|\eta| < 0.9$ with respect to $z = 0$ and the full azimuthal angle. It is a 90 m^3 cylindrical drift chamber filled with an mixture of active gas (Ar, Ne, CO_2 , N_2) and has a large number of readout channels (570 000).

The initial gas in the central barrel was chosen to be a 90%-10% mixture of Ne- CO_2 . This mixture was modified during the RUN2 data taking campaign to an initial use of N_2 and a later transition to Ar instead of Ne in 2016 and 2018. This change was necessary in order to reduce distortions in tracking by reducing the space charge buildup in the TPC.

Besides the tracking, the TPC is used for particle identification by measuring the specific ionization energy loss (dE/dx) in the gas. When a charged particle passes through the gas volume of the TPC, it ionizes gas atoms. Therefore, it loses an amount of energy per unit track length (dE/dx) which is specific for each particle type. Figure 2.6 shows the clear separation of the dE/dx in the given momentum region.

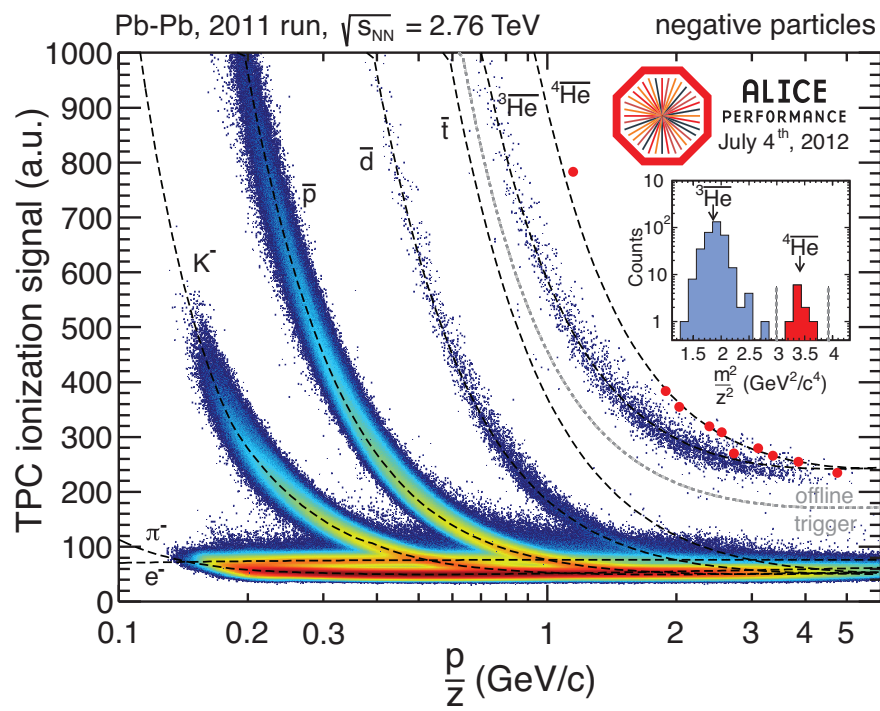


Figure 2.6. Example of TPC dE/dx vs Rigidity distribution for all events passing the offline trigger selection of events with at least one $Z > 1$ track candidate. ONLY NEGATIVELY CHARGED PARTICLES ARE SHOWN. Ten anti-alpha candidates are indicated in this plot. Ref. in [64]

2.2.3 Time of Flight Detector

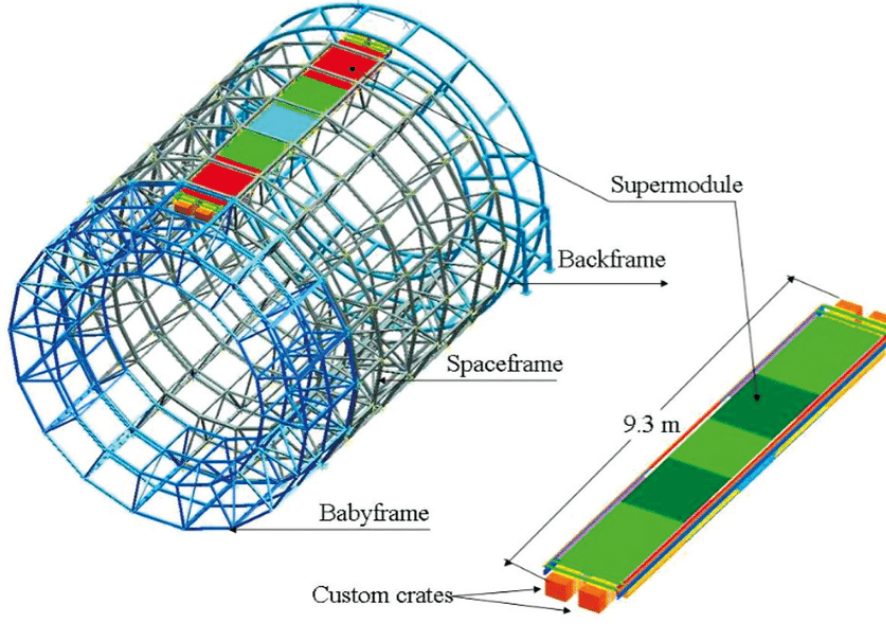


Figure 2.7. TOF schematic layout used in RUN2 period [65]

The ALICE Time of Flight (TOF) [62] detector is a cylindrical detector located about 3.7 m from the interaction point covering $|\eta| < 0.9$ in pseudorapidity and the full azimuth. It consists of 1593 Multi-gap Resistive Plate Chambers (MRPC), with a sensitive area of $7.4 \times 120 \text{ cm}^2$ each and an intrinsic resolution of about $\sim 40 \text{ ps}$. TOF is designed for particle identification by measuring the flight time in momentum regions where energy loss measurements in TPC are no longer being used as efficient discriminators (Fig. 2.8).

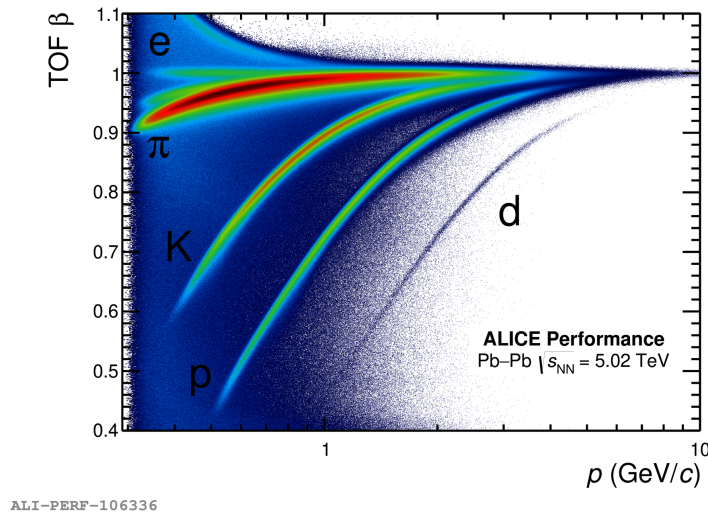


Figure 2.8. TOF β vs Momentum performance plot in Pb-Pb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

2.2.4 VO Detector

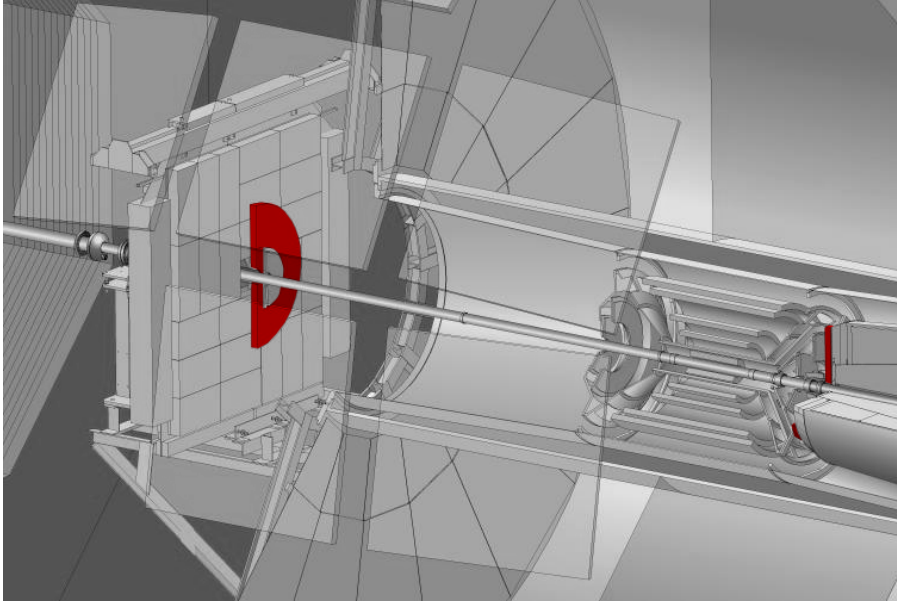


Figure 2.9. VO Location in Central Barrel of ALICE

The VO detector [66, 67] consists of two arrays (VOA and VOC) of 32 scintillating counters. The VOA (VOC) is located at a distance of 329 cm (-88 cm) away from the nominal interaction point ($z = 0$) along the beamline (z -axis in the *coordinate* system). The VOA (VOC) covers the pseudorapidity range $2.8 < \eta < 5.1$ ($-3.7 < \eta < -1.7$) and the full azimuth.

VO is used for triggering, the rejection of beam-gas events, and the determination of the Centrality (Multiplicity) classes of the Pb–Pb (pp) collisions by measuring the sum of the signals (VOM amplitude) deposited in the VOA and VOC. The detailed description of the Centrality (Multiplicity) will be discussed in Section 2.3.4.

2.2.5 Trigger

ALICE Trigger decision is generated by the Central Trigger Processor (CTP) [68] based on detector signals and information about the LHC bunch filling scheme. decision in $\sim 0.9 \mu\text{s}$. A 3-level trigger system is deployed for triggering. The Level 0 trigger decision (LO) is made $\sim 0.9 \mu\text{s}$ after the collision using **fast detectors**, such as VO, TO, EMCal, PHOS, and MTR. The L1 trigger decision is made after 260 LHC clock cycles ($\sim 6.5 \mu\text{s}$) for the event passing LO trigger selection due to the latency caused by the computation time (TRD and EMCal) and propagation times (ZDC, 113 m from IP2). The Level 2 (L2) decision, taken after $\sim 100 \mu\text{s}$ (the drift time of the TPC) and all the events passing L2 selection are sent to the Data Acquisition (DAQ) machines and the High Level Trigger (HLT), which is implemented as a pure software trigger.

The minimum bias triggers (MB_{AND}) is used for all pp and Pb–Pb data taking on RUN2. In addition to that, high-multiplicity (HM) Trigger for pp and Central, Semi-Central Trigger for Pb–Pb is used for the data taking.

2.3 ALICE Offline Framework

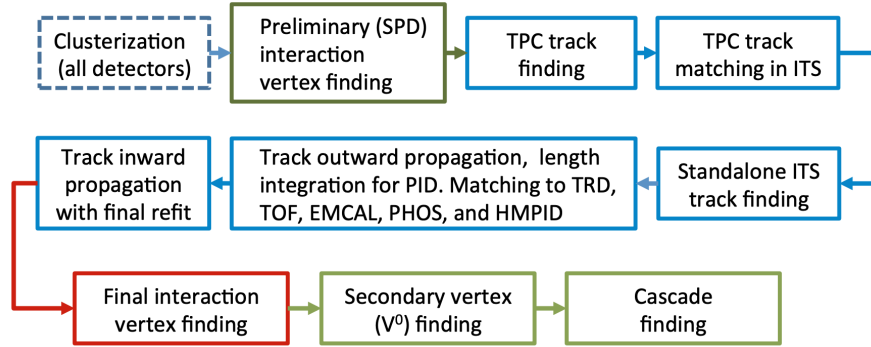


Figure 2.10. Event reconstruction flow. Ref. in [69]

After data acquisition, ALICE performs an event reconstruction as the schematics of the flow shown in Fig. 2.10. At this stage, the raw data is relevant to the signals produced by the same kind of interaction within the detector. The subsequent reconstruction is identical, both for Monte-Carlo simulation as well as real data. It consists of the following steps:

Clusterization: The detector data are converted into *clusters* characterized by positions, signal sizes, signal times, etc., along with their associated errors. This process is performed separately for each detector.

Track Reconstruction: The preliminary interaction vertex is estimated using clusters in the first two ITS layers (SPD). After that, track finding and fitting are performed in TPC and ITS using the Kalman filter technique. [70]. The tracks founded based on the ITS-TPC detectors are matched to the other central barrel detectors and fitted. The final interaction vertex is established using the reconstructed tracks. See section 2.3.1, 2.3.2 for details.

Secondary Vertex Finding: Once primary vertex and all tracks are available, ALICE can find the secondary vertex generated by strange hadrons. This is the final step of the central-barrel tracking procedure.

2.3.1 Vertex Finding

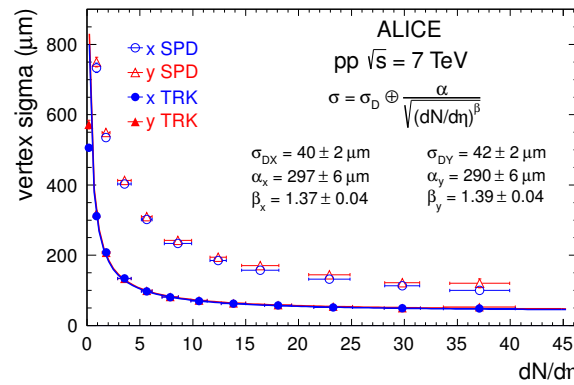


Figure 2.11. Transverse width of the final vertex distribution (solid points), decomposed into the finite size of the luminous region σ_D and the vertex resolution $\alpha/\sqrt{(dN_{\text{ch}}/d\eta)^\beta}$. For comparison, the widths of the preliminary (SPD) interaction vertices are shown as open points. Ref. in [71]

Primary Vertex is the point where the two-beam particles are estimated to collide. Although the best estimation of the PV can be obtained by using the full track information, the first estimation of PV position, *SPD Vertex*, is obtained by using the first two layers of the ITS (SPD) for the usage in the tracking algorithm to increase the search speed of valid track candidate.

SPD Vertex is obtained from the point where minimise the distance among all the *tracklets*, connecting the clusters on each layer of SPD within the same azimuthal acceptance window. The reconstruction of the 3D position of the primary vertex requires at least two tracklets. But this condition is not always satisfied in pp collisions, where often just one tracklet is found in an event. In such a case, the algorithm tries to find the maximum in the z -distribution of closest approach (PCA) of tracklets to the nominal beam axis.

Similarly, the final PV is reconstructed by minimising the distance among the full reconstructed tracks after the track reconstruction, which will be discussed in Sec. 2.3.2. The difference of the resolution between the SPD Vertex and the Primary Vertex can be found in Fig. 2.11 obtained in pp collisions at $\sqrt{s} = 7$ TeV. Note that the resolution depends on the charged particle multiplicity: in Pb–Pb collisions, characterised by a higher multiplicity than pp collisions, a resolution of 10 μm is obtained while the average resolution of 150 μm in pp collisions.

2.3.2 Track Reconstruction

Figure 2.14 shows the schematic view of the track reconstruction. Track finding and fitting is performed in three stages, following an inward–outward–inward scheme [72, 73].

TPC Track Reconstruction The first stage of the tracking algorithm starts finding tracks in the TPC at a large radius. Track seeds are built with two TPC clusters and the vertex point (SPD Vertex), then with three clusters without the vertex constraint. The seeds are propagated inward, at each step, the proximity cut is applied to check. Only those tracks that have at least 20 clusters (out of maximum 159 possible) and that miss no more than 50% of the clusters expected for a given track position are accepted. Figure 2.12a shows the TPC track finding efficiencies for pp $\sqrt{s} = 8$ TeV and Pb–Pb $\sqrt{s_{\text{NN}}} = 2.76$ TeV. While the drop at $p_{\text{T}} < 0.5$ GeV/c is caused by energy loss in the detector material, the characteristic shape at larger p_{T} is determined by the loss of clusters in the p_{T} - dependent fraction of the track trajectory projected on the dead zone between readout sectors.

ITS-TPC Track Reconstruction The reconstructed TPC tracks are matched to the hits in the outermost SSD layer and become the seed for the track reconstruction in the ITS. The seeds are propagated inward and are updated at each ITS layer by all clusters within a proximity cut, saving the results of each update as a new seed. A penalty factor of its χ^2 is added whenever a seed in the extrapolation does not find a compatible cluster unless the extrapolation happened to be in the dead zone of the layer where no cluster should be expected. As a result, each TPC track produces a tree of track hypotheses in the ITS. The candidates are selected to ITS+TPC track in the reconstructed event according to their χ^2 . Figure 2.12b shows the comparison between the fraction of tracks in TPC that have a prolongation in the ITS, in data and MC for Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

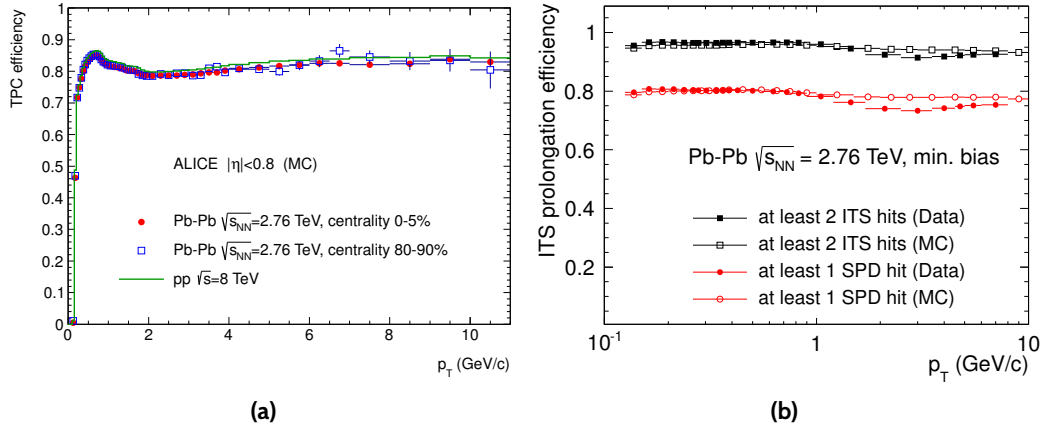


Figure 2.12. TPC track finding efficiency for primary particles in pp and Pb-Pb collisions (simulation). The efficiency does not depend on the detector occupancy (a) and ITS-TPC matching efficiency vs. p_T for data and Monte Carlo for Pb-Pb collisions (b). Ref. in [69]

Re-fitting and Finalisation The ITS-TPC tracks are then back-propagated outwards to match the clusters in the TRD and in the TOF and the signals in other detectors outside of TOF as shown in *2nd path* of Fig. 2.14. Finally, all the tracks are propagated back to the innermost ITS layer in one last Kalman Filter refit pass, using the information of all the attached clusters and completing the three passes fit of the track parameters. Figure 2.13 shows the resolution on $1/p_T$ for tracks of TPC tracks and ITS-TPC tracks with and without vertex constrain in p-Pb $\sqrt{s_{NN}} = 5.02$ TeV. The $1/p_T$ resolution of the track related to the p_T resolution is expressed by the simple formula:

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_{1/p_T}}{1/p_T} \quad (2.3)$$

The $1/p_T$ is directly obtained from the covariance matrix of the Kalman filter fit. The resolutions vary from 1% to 10% in the p_T range between 0.1 and 100 GeV/c.

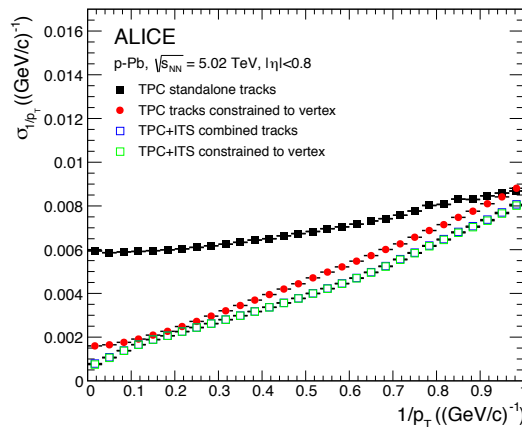


Figure 2.13. The p_T resolution for standalone TPC and ITS-TPC matched tracks with and without constraint to the vertex. The vertex constrain significantly improves the resolution of TPC standalone tracks. For ITS-TPC tracks, it has no effect (green and blue squares overlap). Ref. in [71]

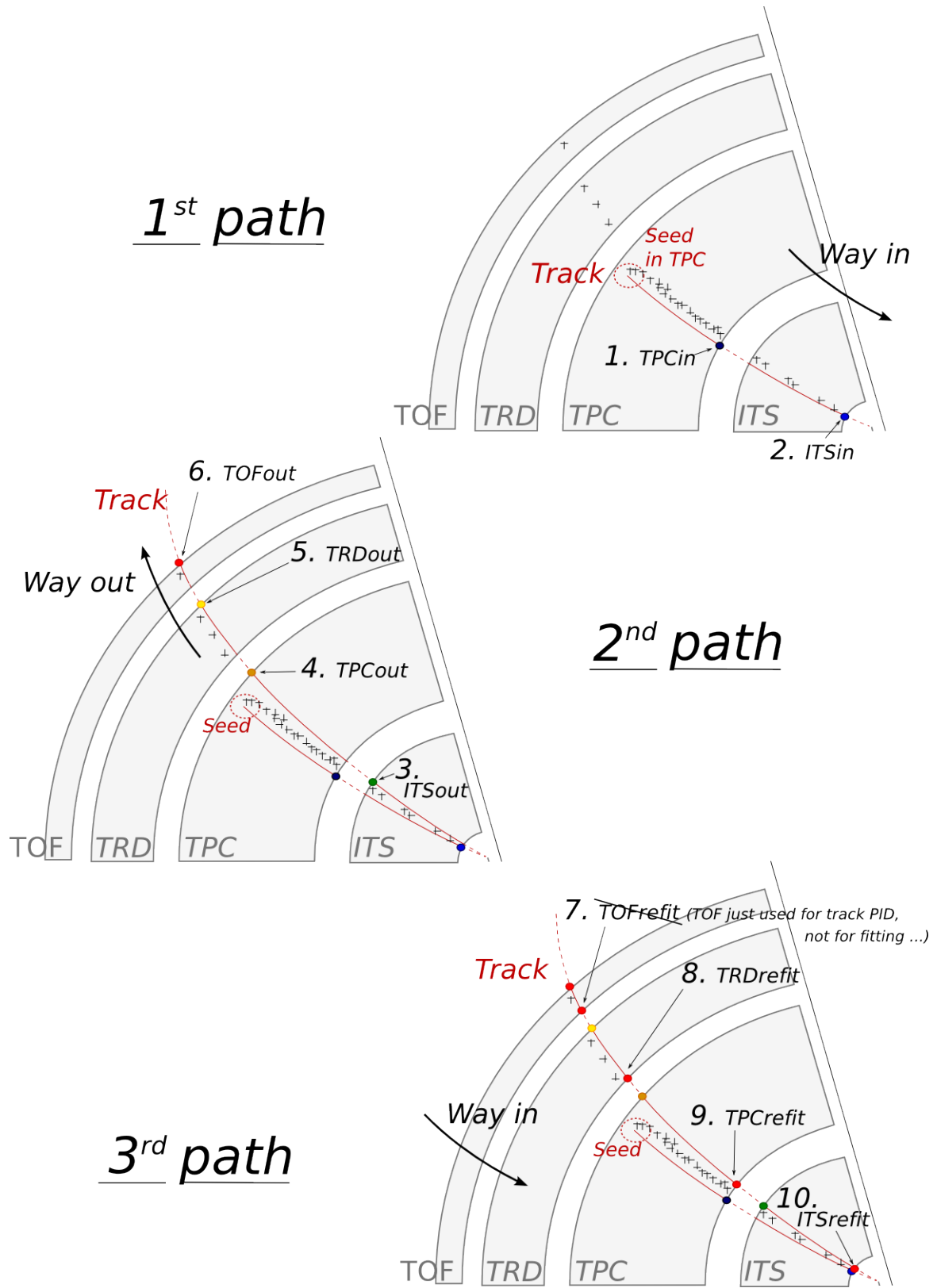


Figure 2.14. Principles of tracking for an ALICE event, showing the three successive paths allowing to build a track and refine its parameters. Numbers ranging from 1 to 10 mention the bits that are activated in case of success during the propagation of the Kalman filter at the considered stage. Ref. in [71]

2.3.3 Secondary Vertex Finding using Weak Decay Topology

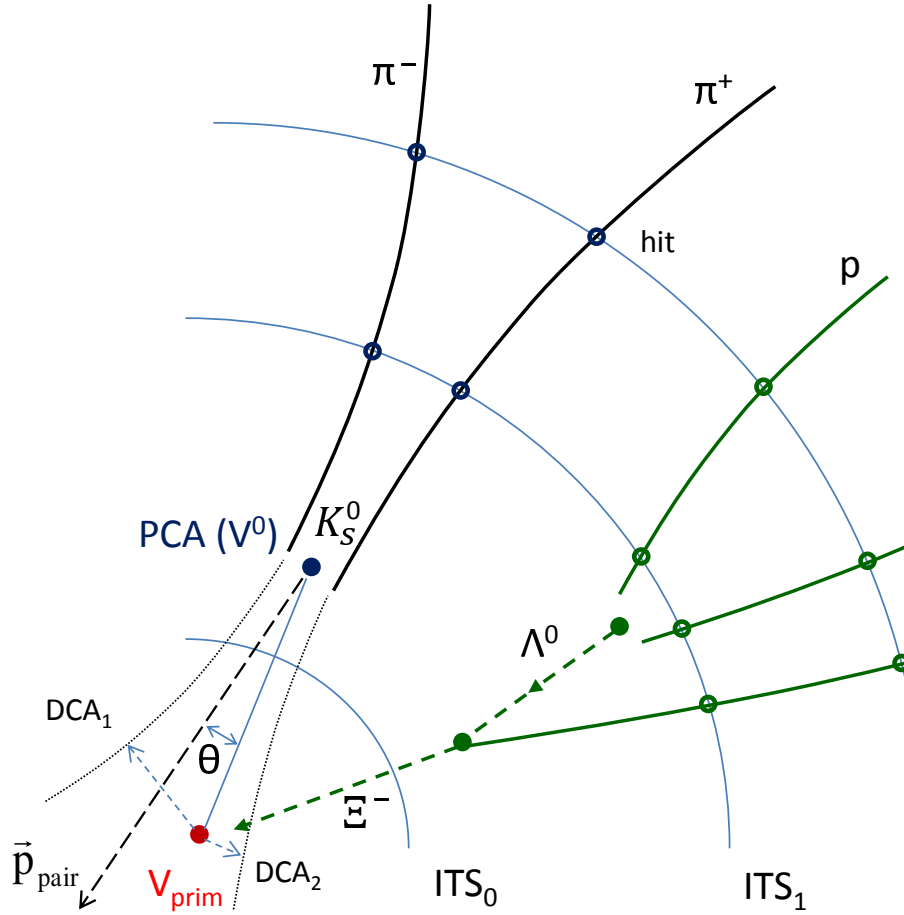


Figure 2.15. Secondary vertex reconstruction principle, with K_S^0 and Ξ^- decays shown as an example. For clarity, the decay points were placed between the first two ITS layers (radii are not to scale). The solid lines represent the reconstructed charged particle tracks, extrapolated to the secondary vertex candidates. Extrapolations to the primary vertex and auxiliary vectors are shown with dashed lines. Ref. in [69]

In addition to the primary vertex reconstruction and global tracking, also secondary vertices from particles, that either have a long decay length or that interact with the detector material, are reconstructed in ALICE. Figure 2.15 shows the example of the topological selection of K_S^0 and Ξ^- .

Tracks with a distance of closest approach (DCA) to the interaction vertex exceeding a certain minimum value (0.5 mm in pp and 1 mm in Pb–Pb) are selected first. For each unlike-sign pair of selected tracks (called *VO candidate*), the point of closest approach (PCA) between the two tracks is calculated. The VO candidates are then subjected to further cuts:

- The distance between the two tracks at their PCA is less than 1.5 cm
- The PCA is closer to the interaction vertex than the innermost hit of either of the two tracks
- The cosine of the angle (CPA) θ between the total momentum vector of the pair $\vec{p}_{\text{pair}}$ and the straight line connecting the primary (interaction) and secondary vertices exceed 0.9

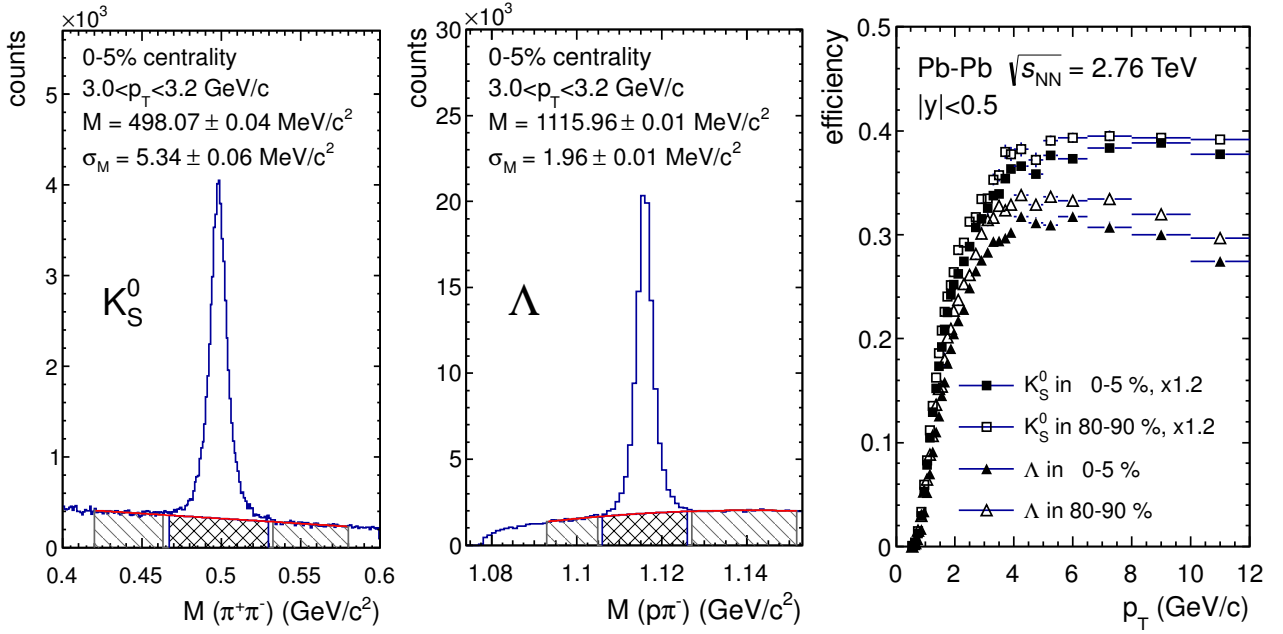


Figure 2.16. Invariant mass distributions of $\pi^+\pi^-$ (left panel) and $p\pi^-$ (middle panel) pairs in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The hatched areas show the regions of the K_S^0 and Λ peaks and of the combinatorial background. The right-hand panel shows the reconstruction efficiencies (including the candidate selection cuts) as a function of transverse momentum for central (0 – 5%) and peripheral (80 – 90%) collisions. Ref. in [69]

Figure 2.16 shows K_S^0 (left) and Λ (center) peaks obtained in central Pb–Pb collisions. Proton, daughters of Λ , with $p_T < 1.5$ GeV/c were identified by their energy loss dE/dx in the TPC detector (Sec. 2.2.2). The right plot shows the K_S^0 and Λ reconstruction efficiencies in central (0-5%) and peripheral (80-90%) collisions as a function of their p_T . The drop in Λ reconstruction efficiency at high p_T is due to the smaller probability of decay in the fiducial volume ($r < 100$ cm) of the VO search at higher momenta.

After finding VO candidates, the search for the cascade (Ξ^-) decays is performed as shown schematically in Fig. 2.16. VO candidates with an invariant mass in the vicinity of the Λ are matched with a secondary track by cutting on their mutual distance at the PCA and requesting that the latter is outside of a cylindrical volume around the interaction vertex ($r > 0.2$ cm).

These VO and cascade candidates are saved in the data files for analysis and used in Chapter 3 for Reconstruction of the resonances decaying into them.

2.3.4 Centrality Estimation and Multiplicity

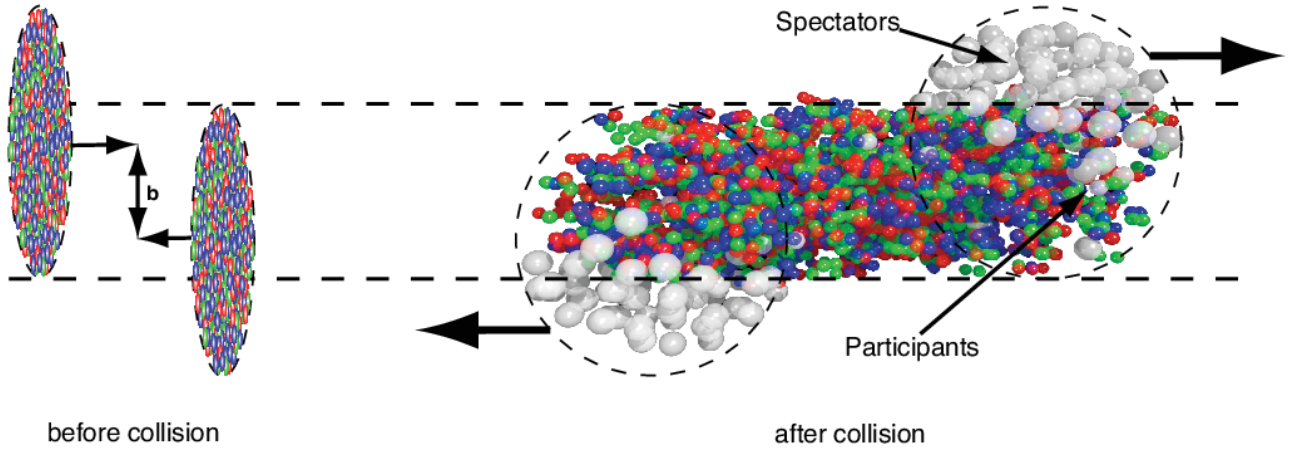


Figure 2.17. Left: The two heavy-ions before collision with impact parameter b . Right: The spectators continue unaffected, while in the participant zone particle production takes place [74]

The geometry of heavy-ion collisions is characterized by the impact parameter vector $\mathbf{b}$ connecting the centres of the two colliding nuclei in the plane transverse to the beams as shown in Fig. 2.17. In the experiment, the impact parameter cannot be measured directly but it can be estimated by using the zero-degree energy measured in ZDCs [69] or the charged particle multiplicity (Sec. 1.2) with the Glauber Model [8].

It is customary to express the centrality of nuclear collisions not in terms of the impact parameter b but via a percentile of the total hadronic interaction cross-section σ_{AA} . The centrality percentile c of an AA collision with impact parameter b is defined as:

$$c(b) = \frac{\int_0^b \frac{d\sigma}{db'} db'}{\int_0^\infty \frac{d\sigma}{db'} db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db' \quad (2.4)$$

where, it is based on the assumption that, on average, the particle multiplicity at mid rapidity (the zero-degree energy) has the monotonic dependence on the impact parameter. Experimentally, the centrality is defined as the fraction of cross section with the largest detected charged particle multiplicity N_{ch} or the smallest zero-degree energy E_{ZDC} as:

$$c \approx \frac{1}{\sigma_{AA}} \int_{N_{ch}}^\infty \frac{d\sigma}{dN'_{ch}} dN'_{ch} \approx \frac{1}{\sigma_{AA}} \int_0^{E_{ZDC}} \frac{d\sigma}{dE'_{ZDC}} dE'_{ZDC} \quad (2.5)$$

The cross-section σ_{AA} may be replaced with the number of observed events n , corrected for the trigger efficiency and for the non-hadronic interaction background:

$$c \approx \frac{1}{N_{ev}} \int_{N_{ch}}^\infty \frac{dn}{dN'_{ch}} dN'_{ch} \approx \frac{1}{N_{ev}} \int_0^{E_{ZDC}} \frac{dn}{dE'_{ZDC}} dE'_{ZDC} \quad (2.6)$$

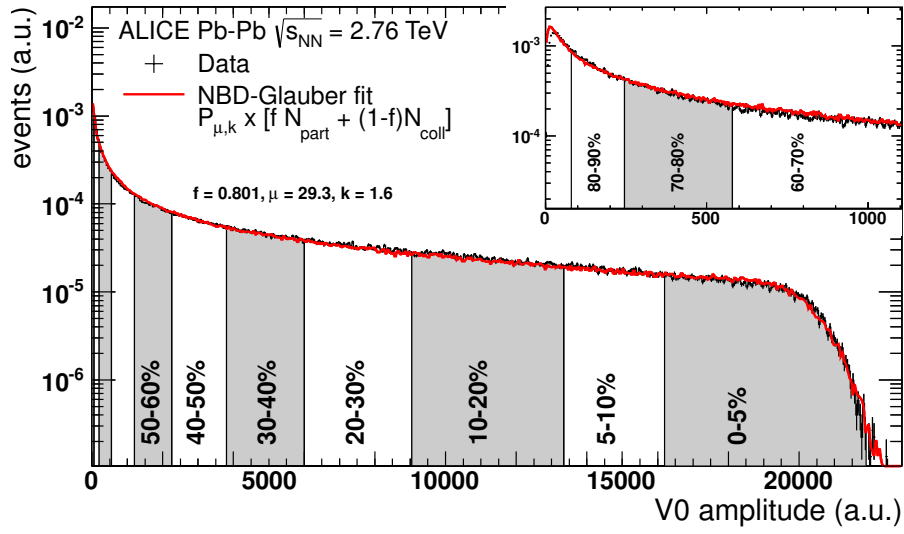


Figure 2.18. Distribution of the VO amplitude (sum of VOA and VOC). The centrality bins are defined by integrating from right to left following Eq.(5). The absolute scale is determined by fitting to a model (red line), see below for details. The inset shows a magnified version of the most peripheral region. Ref. in [69]

The centrality determination via the VO amplitude (sum of VOA and VOC amplitudes) is illustrated in Fig. 2.18. The VO amplitude distribution was obtained in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, requiring a coincidence of VO and SPD, and using ZDC to reduce the electromagnetic dissociation background. The analysis is restricted to events with a vertex position within $|z_{vtx}| < 10$ cm. The centrality bins are defined by integrating the charged-particle multiplicity distribution following Eq. 2.6, and the absolute scale is determined by fitting to a model as described in Ref [69]. It creates the connection between the experimental observable and the geometrical model of HIC used in the Glauber Monte Carlo. The impact parameter b distribution and the number of participant nucleons N_{part} distribution obtained from the Glauber Monte Carlo simulation are shown in Fig. 2.19.

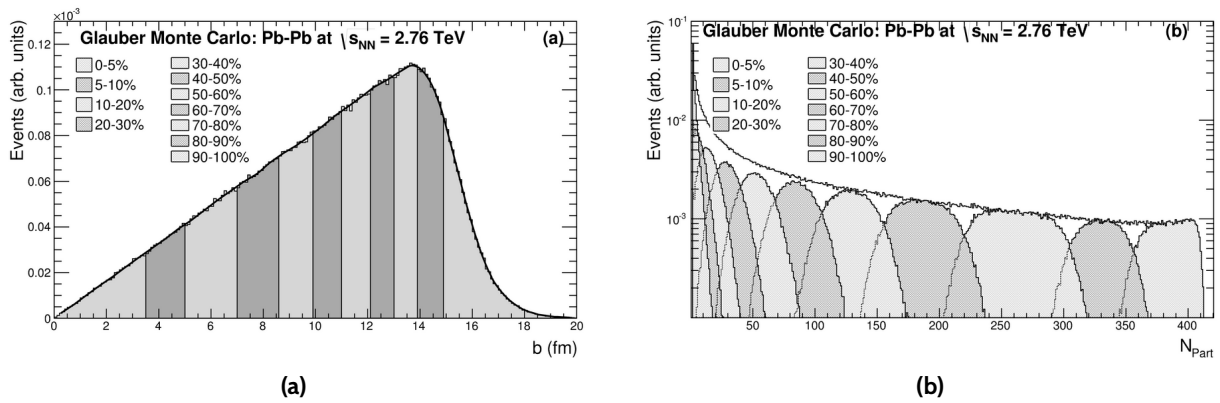


Figure 2.19. Geometric properties of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV obtained from a Glauber Monte Carlo calculation: Impact parameter distribution (a), sliced for percentiles of the hadronic cross section, and distributions of the number of participants (b) for the corresponding centrality classes. Ref. in [75]

Multiplicity in proton-proton collisions As used on the centrality in Pb–Pb collisions, the VOM amplitude (VOM stands for VOA+VOC) is used to determine the charge particle multiplicity in pp collisions. Similarly, *Multiplicity* is defined as the percentile of the distribution of the VOM signal amplitude as shown in Fig. 2.20. The events in pp collisions are divided into ten multiplicity classes. Each multiplicity class is labelled by a roman number, going from I for the highest multiplicity class (0-1%) to X for the lowest multiplicity class (70-100%).

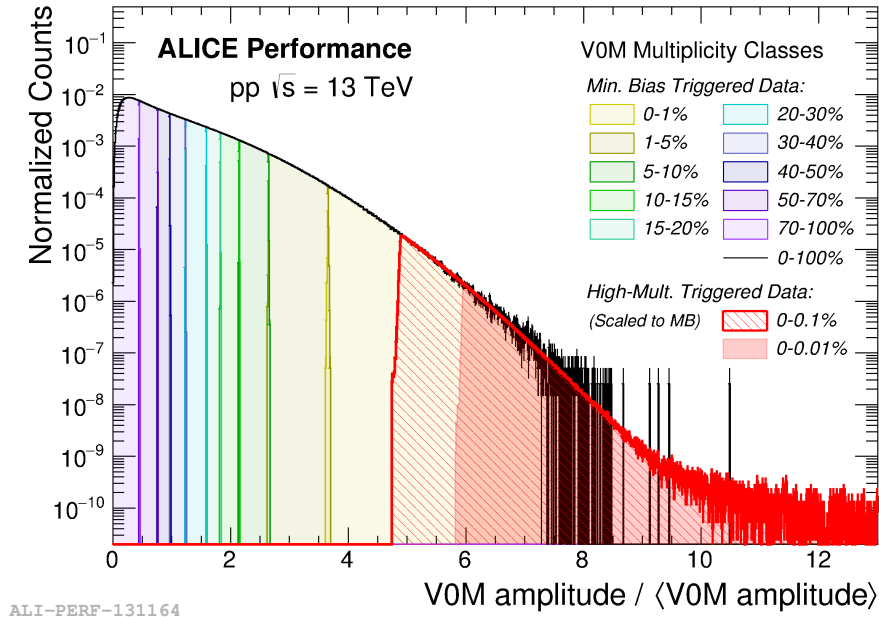


Figure 2.20. VOM signal distribution with given charged particle multiplicity.

2.4 Coordination System and Kinematic Variables

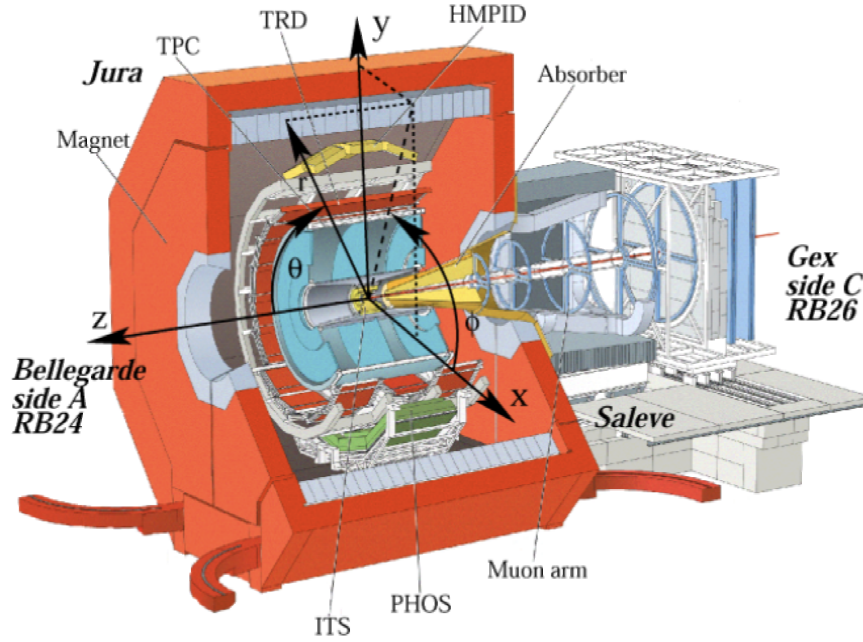


Figure 2.21. Definition of the ALICE coordinate system axis, angles and detector sides. Ref. in [76]

The observables reported in the thesis are based on the ALICE Coordinate System [76] referred to a right-handed Cartesian system, centred in the collision point, with the z axis parallel to the beam direction, the x axis aligned with the accelerator plane, pointing towards the centre of the ring, and the y axis pointing upwards, according to the chirality of the system. The z direction is referred as longitudinal dimension and the xy plane as the transverse plane. For example, the momentum $\vec{p}$ of a particle can be decomposed into its longitudinal momentum with module p_z and its transverse momentum with module $p_T = \sqrt{p_x^2 + p_y^2}$. The polar angle θ is expressed with respect to the z axis.

The rapidity of a particle is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (2.7)$$

where E means the energy of the particle and p_z is its longitudinal momentum.

The pseudorapidity η is instead defined as:

$$\eta = -\ln \tan \frac{\theta}{2} = \frac{1}{2} \ln \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \quad (2.8)$$

At high energy, $E \sim |\vec{p}|$ so $\eta \sim y$.

Chapter 3

Measurement of $\Sigma^{*\pm}$ and Ξ^{*0} in pp Collisions at $\sqrt{s} = 13$ TeV

The hyperon resonance, $\Sigma(1385)^\pm$ and $\Xi(1530)^0$, are measured in pp at $\sqrt{s} = 13$ TeV for investigating the particle production mechanism in a small system with several events divided by the charged-particle multiplicity. The data sample used to the study is provided in 3.1, the extracted signals are shown in 3.4. The corrections for the number of event and number of obtained yields are presented in Section 3.4. Finally, the corrected spectra can be found in Section 3.6 with integrated yield and mean p_T .

The charged $\Sigma(1385)$ and $\Xi(1530)^0$ are reconstructed via their hadronic channels. The two charged states $\Sigma(1385)^+$, $\Sigma(1385)^-$ and their anti-particles ($\bar{\Sigma}(1385)^-$, and $\bar{\Sigma}(1385)^+$) are separately reconstructed via

$$\begin{aligned}\Sigma(1385)^+ &\rightarrow \Lambda + \pi^+ \rightarrow (p + \pi^-) + \pi^+ \\ \bar{\Sigma}(1385)^- &\rightarrow \bar{\Lambda} + \pi^- \rightarrow (\bar{p} + \pi^+) + \pi^- \\ \Sigma(1385)^- &\rightarrow \Lambda + \pi^- \rightarrow (p + \pi^-) + \pi^- \\ \bar{\Sigma}(1385)^+ &\rightarrow \bar{\Lambda} + \pi^+ \rightarrow (\bar{p} + \pi^+) + \pi^+ .\end{aligned}\tag{3.1}$$

Likewise, $\Xi(1530)^0$ and its antiparticle ($\bar{\Xi}(1530)^0$) are reconstructed via

$$\begin{aligned}\Xi(1530)^0 &\rightarrow \Xi^- + \pi^+ \rightarrow (\Lambda + \pi^-) + \pi^+ \rightarrow ([p + \pi^-] + \pi^-) + \pi^+ \\ \bar{\Xi}(1530)^0 &\rightarrow \bar{\Xi}^+ + \pi^- \rightarrow (\bar{\Lambda} + \pi^+) + \pi^- \rightarrow ([\bar{p} + \pi^+] + \pi^+) + \pi^- .\end{aligned}\tag{3.2}$$

3.1 Data sample and Event Selection

The data sample for this study was collected by ALICE during Run 2 (2015–2018) in pp collisions at $\sqrt{s} = 13$ TeV. The minimum-bias trigger (MB_{AND}) requires logical AND hits in both the VOA and VOC detectors. In addition to the MB_{AND} trigger, at least one charged particle track in the SPD detector is required ($INEL > 0$). Meanwhile, background events are rejected by using the correlation between the number of clusters and the multiplicity of tracklets in the SPD. Events having the reconstructed primary vertex within the range $|v_{vtx}| < 10$ cm with respect to the nominal interaction point along the beam axis are considered.

The event selection was done with the following criteria:

1. Standard Physics Selection with pileup rejection option

- `AliTriggerAnalysis::IsSPDClusterVsTrackletBG`
- `AliTriggerAnalysis::IsVOMOnVsOfPileup`
- `AliTriggerAnalysis::IsSPDOnVsOfPileup`
- `AliTriggerAnalysis::IsVOPFPileup`
- `AliTriggerAnalysis::IsSPDVtxPileup`

2. kINT7 trigger (Minimum Bias trigger) used.

3. `!AliEvent::IsIncompleteDAQ`

4. Vertex cuts

- Good AOD vertex selection
 - Difference z position between TPC vertex and AOD vertex $\geq 1 \times 10^{-6}$
 - Difference χ^2_{NDF} between TPC vertex and AOD vertex $\geq 1 \times 10^{-6}$
- SPD Vertex contributors > 0 || Track Vertex contribution > 1
- Vertex position
 - | SPD Vertex z position | ≤ 10
 - | Track Vertex z position | ≤ 10
 - | Vertex z position | ≤ 10
- Vertex quality
 - Difference z position between TPC vertex and SPD vertex < 0.5
 - SPDvertex Resolution < 0.25

5. Pileup cuts

- `!AliAODEvent::IsPileupFromSPD`
 - Basically same with `AliAODEvent::IsPileupFromSPDInMultBins`
- `!AnalysisUtils::IsSPDClusterVsTrackletBG()`
- `!AnalysisUtils::IsPileUpMV()`

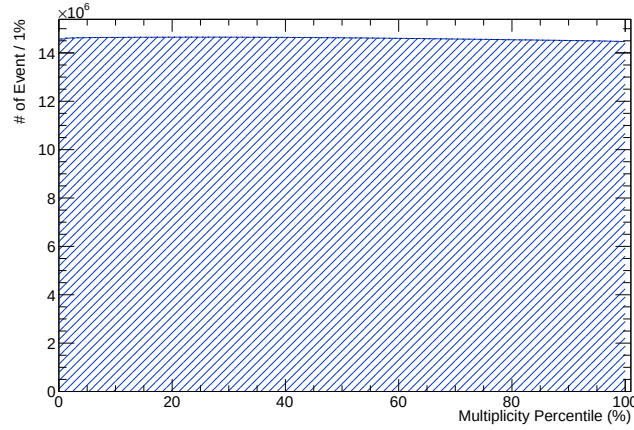
6. $INEL > 0$ check; the event must have a least one tracklet in SPD. (Not applied in the inelastic study)

The total number of minimum-bias pp events analysed is 1.82×10^9 corresponding to an integrated luminosity $\mathcal{L}_{int} = 31.5 \text{ nb}^{-1}$ [77].

Multiplicity classes are determined by uniformly slicing the number of MB_{AND} events with at least one SPD tracklet in $|\eta| < 1$ ($MB_{AND>0}$) as described in Sec. refSec:Centrality. ALICE presents charged-particle multiplicities averaged within $|\eta| < 0.5$, denoted as $\langle dN_{ch}/d\eta \rangle$ for given multiplicity classes [78], as shown in Table 3.1.

Table 3.1. The multiplicity classes used in this Analysis $P(MB_{AND>0}) = \Delta\sigma/\sigma_{MB_{AND>0}}$ and their corresponding mean charged particle multiplicity, $\langle dN_{ch}/d\eta \rangle$ [78, 79].

$P(MB_{AND>0})$ (%)	Event Class	$\langle dN_{ch}/d\eta \rangle$
0 – 10	I+II+III	18.16 ± 0.54
10 – 30	IV+V+VI	10.94 ± 0.30
30 – 50	VII+VIII	7.02 ± 0.15
50 – 70	IX	4.36 ± 0.06
70 – 100	X	2.67 ± 0.04

**Figure 3.1.** VOM Multiplicity Percentile Distribution after all event cuts.

3.2 Track and Topological Selection

Table 3.2. Summary of the track selection criteria applied to the daughter tracks and primary tracks.

Common selection	
$ \eta_{lab} $	< 0.8
p_T	$> 0.15 \text{ GeV}/c$
Number of TPC clusters	> 70
$N_{crossed}/N_{findable}$	> 0.8
TPC dE/dx	$< 3\sigma$
Primary track selection	
DCA_z to PV	$< 2 \text{ cm}$
DCA_r to PV	$< 7\sigma DCA(p_T) \text{ cm}$

For the reconstruction of resonances, all primary and secondary charged tracks are selected in the range of $p_T > 0.15 \text{ GeV}/c$ and $|\eta_{lab}| < 0.8$ based on Ref. [62]. To ensure the quality, tracks are required to have at least 70 out of 159 rows crossing the TPC, in addition of more than 80% of ratio of the number of the crossed rows $N_{crossed}$ to the findable cluster $N_{findable}$ in the TPC, and χ^2 per TPC cluster has to be less than 4 to assure their quality. Finally, Particle Identification (PID) is based on the requirement that the specific energy loss in the TPC (dE/dx) is measured within 3 standard deviations ($3\sigma_{TPC}$) from the expected value (dE/dx_{exp}). The first emitted pions (π_{First} in Fig.3.2) should be constrained to the Primary Vertex (PV), so they are selected based on the condition that the distance of closest approach (DCA) to the Primary Vertex (PV) along the z direction (DCA_z) is less than 2 cm and the p_T -dependent transverse DCA (DCA_r) and on

a p_T -dependent requirement that corresponds to a 7 standard deviations away. Track selection criteria is summarised in Table. 3.2.

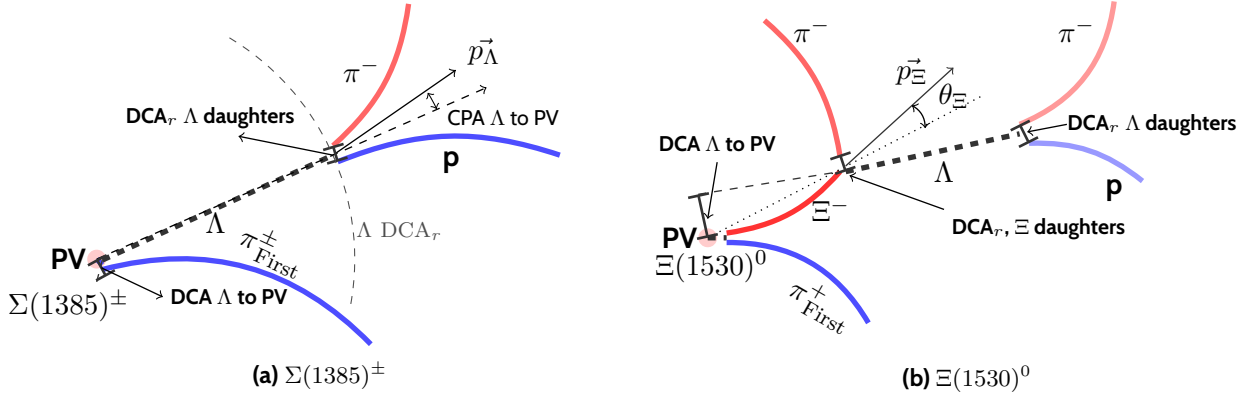


Figure 3.2. Sketch of the decay modes for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ and depiction of the main/some track and topological selection criteria.

Based on the pre-selection, discussed in Sec. 2.3.3, the secondary vertices of Λ ($c\tau = 7.89$ cm [22]) and Ξ^- ($c\tau = 4.91$ cm [22]) are reconstructed from the charged tracks based on the TPC PID as described in Ref. [62]. Since their charged decay products are produced away from the PV, specific topological and track selection criteria, as summarized in Table 3.3, are applied [29, 80–82]. $\Lambda(\bar{\Lambda})$ from $\Sigma(1385)$ are selected when the distance of closest approach (DCA) between the two daughter tracks (DCA Λ daughters in Fig.3.2(a)) is less than 1.6 cm and the DCA of Λ in xy -plane to the PV (Λ DCA_r in Fig.3.2(a)) is larger than 0.05 cm to ensure that those tracks are not primary charged particles from the PV. In addition, the DCA of Λ to the PV is set to be less than 0.3 cm to remove as much as reasonably possible the case of Λ decaying from Ξ^- or Ξ^+ [81]. The invariant mass of Λ ($m_{p\pi^-}$) is required to be within ± 10 MeV/ c with respect to the value provided from the Particle Data Group (PDG) [1]. The cosine of the pointing angle (θ_Λ) between the direction of the momentum of Λ and the line from the decay vertex to the PV (CPA Λ to PV in Fig.3.2(a)) is set to be larger than 0.99. The radius of the transverse radius $r(\Lambda)$ (the distance between the PV and decay vertex) is requested to be between 1.4 and 100 cm. After the Λ selection, the first emitted π ($\pi_{\text{First}}^\pm$ in Fig.3.2(a)) is used to reconstruct the invariant mass signal of $\Sigma(1385)^\pm$.

Ξ^- from $\Xi(1530)^0$ are selected by requiring the DCA between π and Λ (DCA Ξ daughters in Fig.3.2(b)) to be less than 1.9 cm and the DCA_r of π from Ξ^- to the PV larger than 0.015 cm. The DCA between the Λ decay products, π and p (DCA Λ daughters in Fig.3.2(b)) is required to be less than 1.4 cm. The DCA_r of Λ to the PV (DCA Λ to PV in Fig.3.2(b)) is required to be larger than 0.06 cm. Selections on the invariant masses of the daughter particles, the cosines of the pointing angles (θ_Λ and θ_Ξ) and the transverse radius $r(\Lambda)$ and $r(\Xi)$ from PV in Table. 3.3 are applied to optimize the balance of purity and efficiency of each particle sample.

Table 3.3. Topological selection criteria for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$.

Topological selection criteria	$\Sigma(1385)^\pm$	$\Xi(1530)^0$
DCA between π and p decaying from Λ [cm]	< 1.6	< 1.4
DCA of Λ to the PV [cm]	< 0.3	> 0.07
$\cos \theta_\Lambda$	> 0.99	> 0.97
$r(\Lambda)$ [cm]	$1.4 < r < 100$	$0.2 < r < 100$
$ m_{p\pi} - m_{\Lambda, \text{PDG}} $ [MeV/ c^2]	< 10	< 7
DCA _r of pions decaying from Ξ^- to the PV [cm]		> 0.015
DCA between Λ and π decaying from Ξ^- [cm]		< 1.9
$\cos \theta_\Xi$		> 0.97
$r(\Xi^-)$ [cm]		$0.2 < r < 100$
$ m_{\Lambda\pi} - m_{\Xi, \text{PDG}} $ [MeV/ c^2]		< 7

3.3 Signal Extraction

3.3.1 Invariant mass distribution

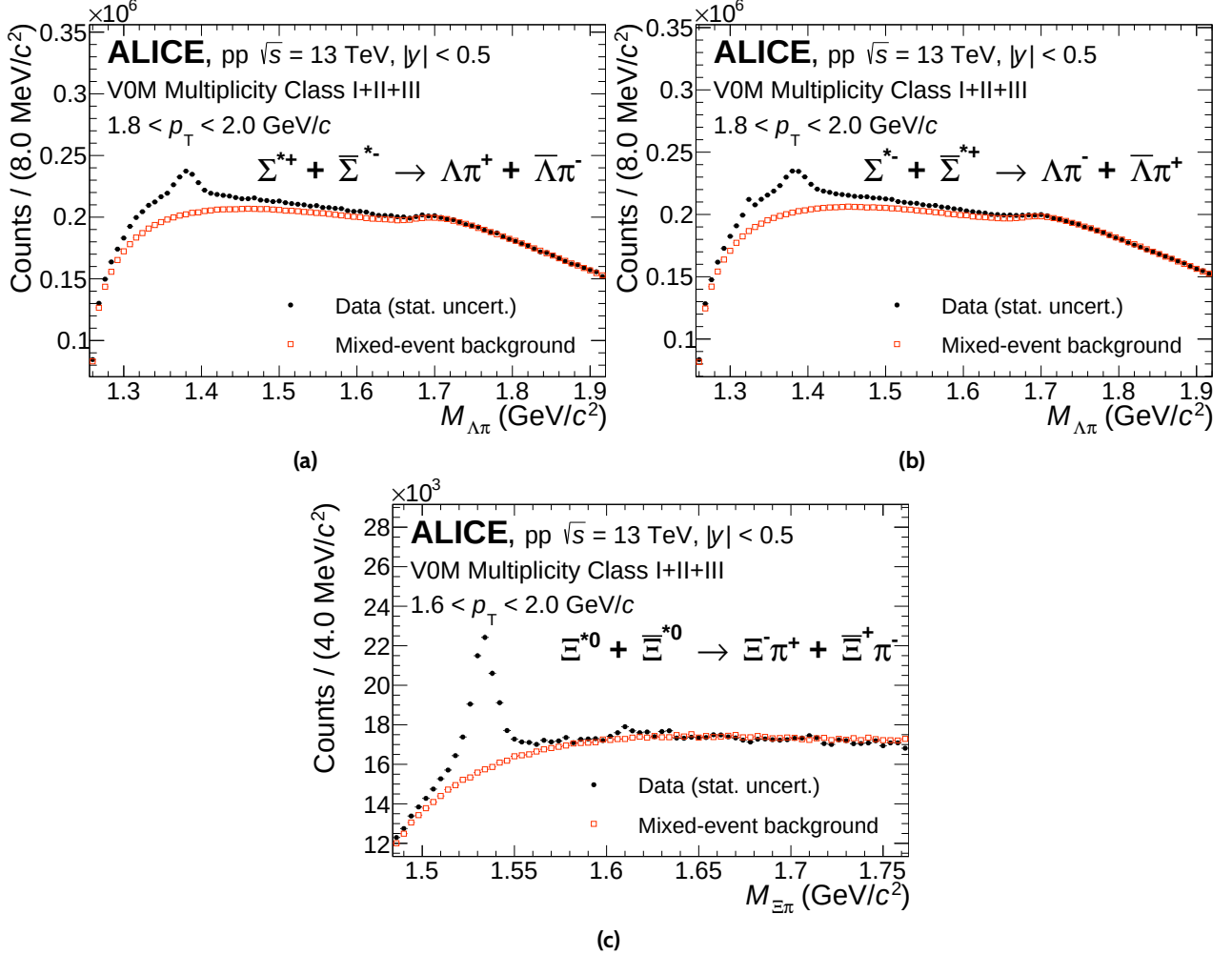


Figure 3.3. Example of invariant mass distributions of $\Lambda\pi^+(\bar{\Lambda}\pi^-)$ pairs (a) and $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ pairs (b) for $1.8 < p_{T,\Lambda\pi^+} < 2.0$ GeV/c and of $\Xi^-\pi^+$ ($\Xi^+\pi^-$) pairs for $1.6 < p_{T,\Xi\pi} < 2.0$ GeV/c in the I+II+III (0–10%) multiplicity class. Full black point represents the data and open red squares indicates the assessment of the combinatorial background via event mixing technique.

The invariant mass distributions of $\Lambda\pi$ ($\Xi\pi$) for $1.8 < p_T < 2.0$ GeV/c ($1.6 < p_T < 2.0$ GeV/c) are shown in Fig. 3.3, where the resonance peak is located at the m_{PDG} [22].

In $\Sigma(1385)^\pm$ ($\Xi(1530)^0$) study, p_T bin is selected as [0.7, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.4, 3.2, 4.0, 4.8, 6] ([0.8, 1.2, 1.6, 2.0, 2.4, 3.2, 4.0, 4.8, 5.6, 8.8]) as they have the same p_T binning with the 7 TeV study [81] so that the result can be compared.

In order to increase the significance of the signal extraction, the invariant mass distribution of $\Sigma(1385)^+$ and $\bar{\Sigma}(1385)^-$ are merged although they are reconstructed separately. Similarly, $\Sigma(1385)^-$ and $\bar{\Sigma}(1385)^+$, and $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ are merged. The background distributions in the figures are estimated through an event-mixing technique where π - Λ (Ξ) pairs are formed by combining π belonging to different events. Each event is combined with nine other ones. To minimise distortions due to the different positions of the PV and to ensure a similar event structure, only events entering the pool for mixing are requested to

be i) with similar PV positions in the z-direction ($|\Delta z_{PV}| < 1$ cm) and ii) of the same multiplicity class. The mixed-event background is normalised with the region where the mixed-event background and the invariant mass distribution from the data have similar slopes.

As an alternative description for the background shape, a different range of the normalisation region is considered for $\Sigma(1385)^\pm$. For $\Xi(1530)^0$ analysis, in addition to the different range of normalisation region, a like-sign background which takes $\Xi^\mp$ and $\pi^\mp$ in a same event is considered (Fig. 3.8). Furthermore, background fit is tried to describe the background shape by using the second order polynomial function without background subtraction (Fig. 3.9).

Figure 3.4 (Fig. 3.5) shows the invariant mass distribution of the $\Sigma(1385)^+$ (top) and $\Sigma(1385)^-$ (bottom) in most high multiplicity bin (0–10%) and low multiplicity bin (70–100%). Similarly, Fig. 3.6 (Fig. 3.7) shows the invariant mass distribution of the $\Xi(1530)^0$ in most high multiplicity bin (0–10%) and low multiplicity bin (70–100%).

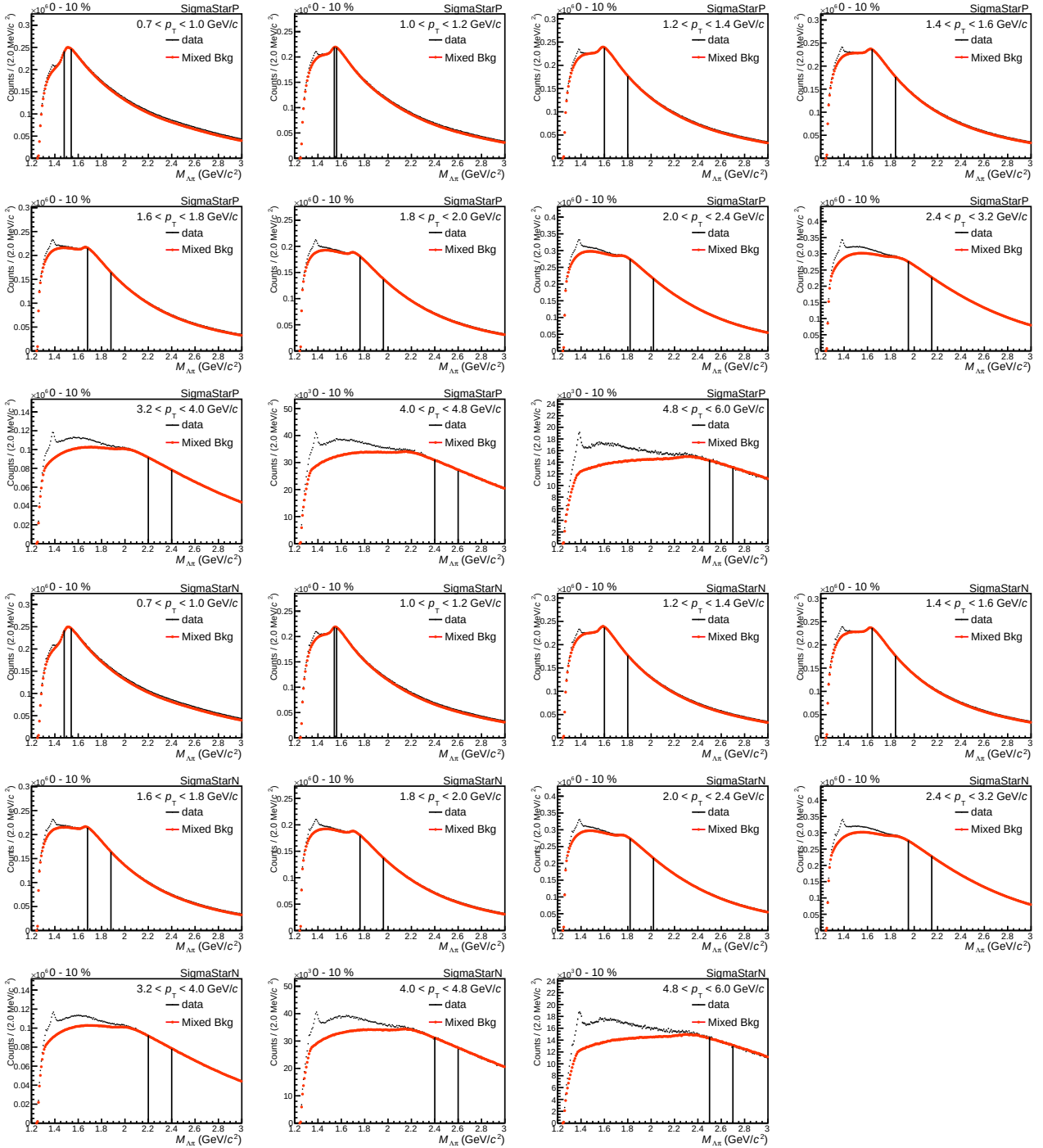


Figure 3.4. Raw signal(black) and Event mixing background(red) of $\Sigma(1385)^+$ (top) and $\Sigma(1385)^-$ (bottom) in 0–10% multiplicity class. The 2 vertical black line indicates the normalisation range.

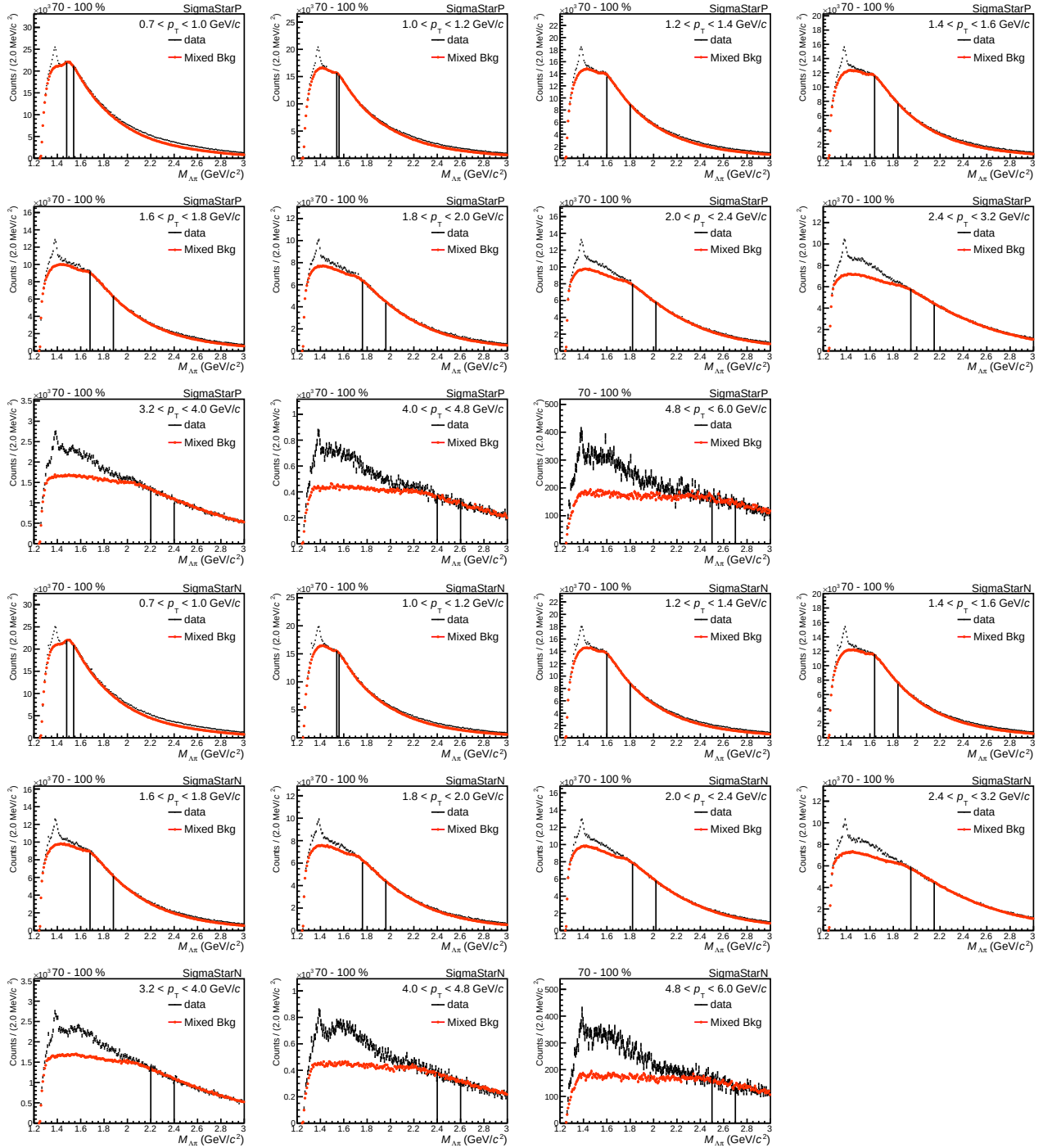


Figure 3.5. Raw signal(black) and Event mixing background(red) of $\Sigma(1385)^+$ (top) and $\Sigma(1385)^-$ (bottom) in 70–100% multiplicity class. The 2 vertical black line indicates the normalisation range.

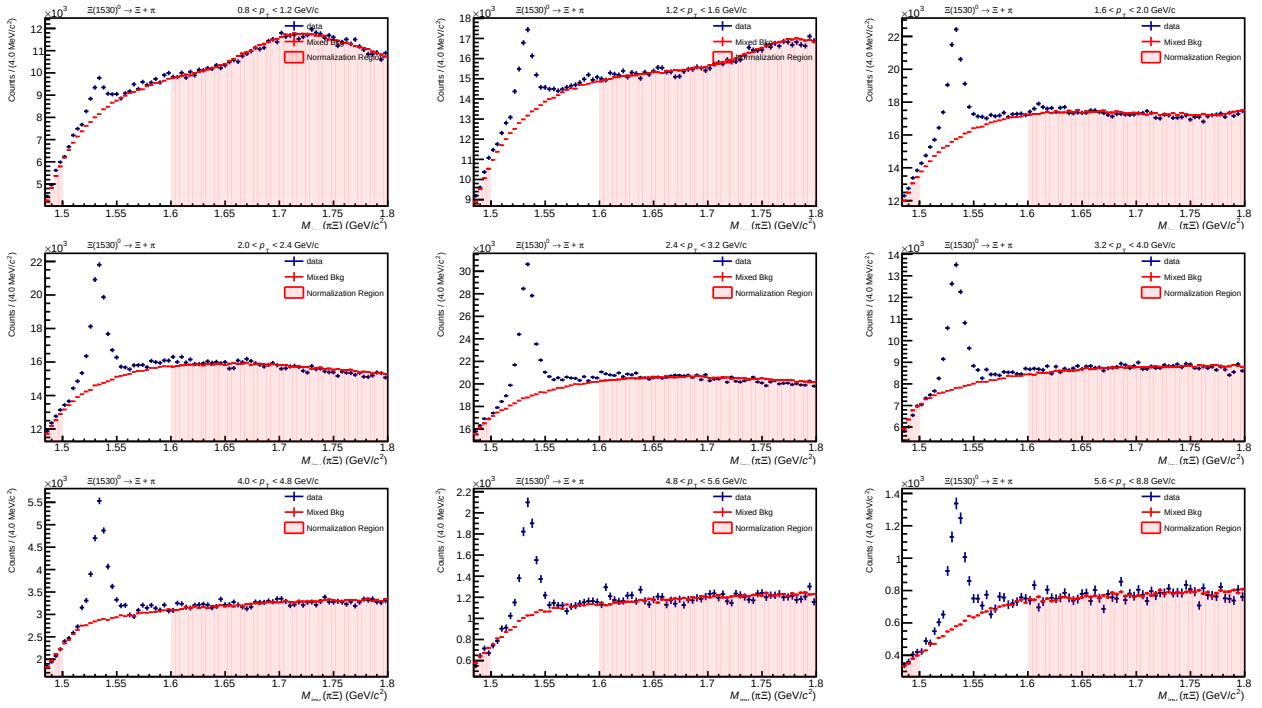


Figure 3.6. Raw signal(blue) and Event mixing background(red) of $\Xi(1530)^0$ in 0 – 10% Multiplicity class. The red colored region indicates the normalisation region.

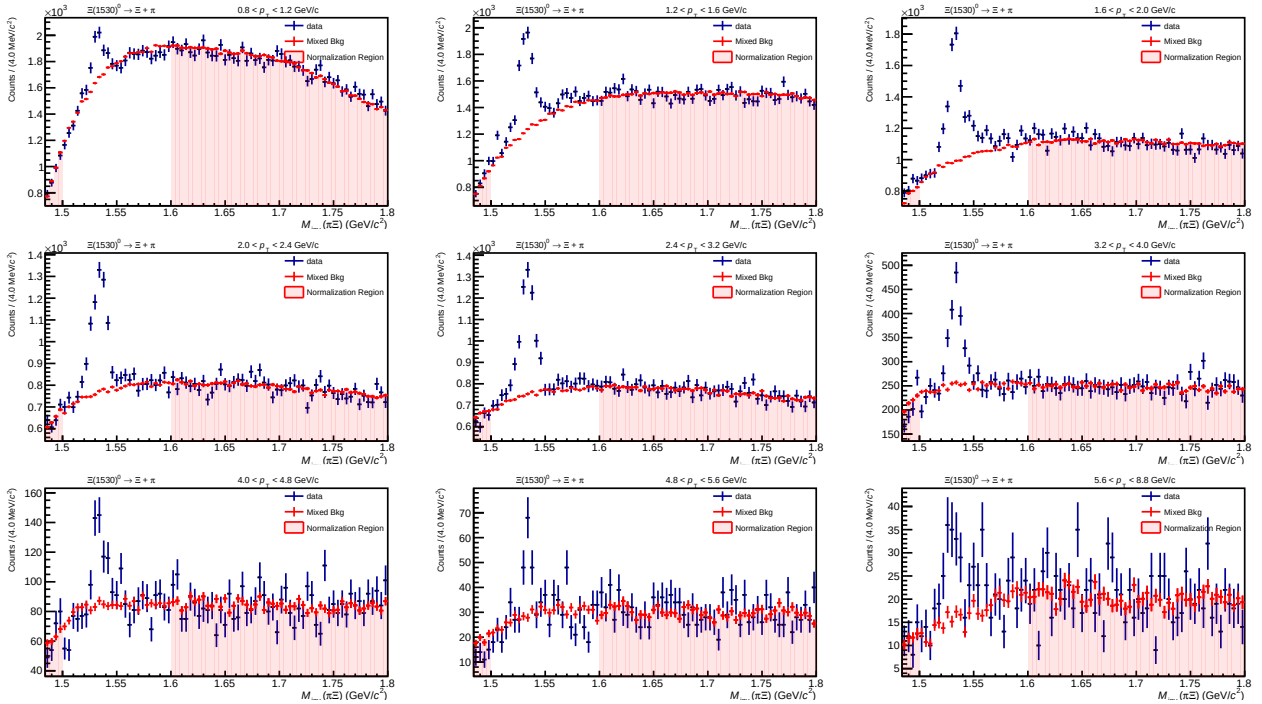


Figure 3.7. Raw signal(blue) and Event mixing background(red) of $\Xi(1530)^0$ in 70 – 100% Multiplicity class. The red colored region indicates the normalisation region.

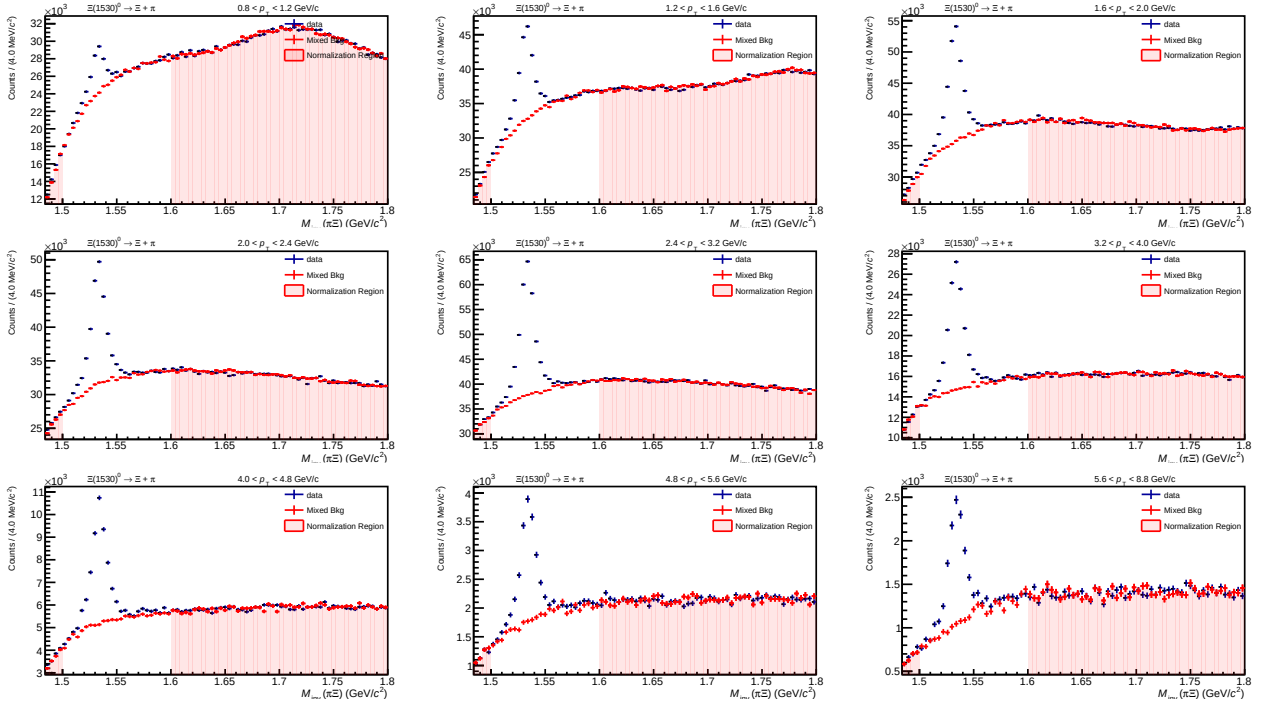


Figure 3.8. Raw signal(blue) and Like-sign background(red) in 0 – 100% Multiplicity Percentile

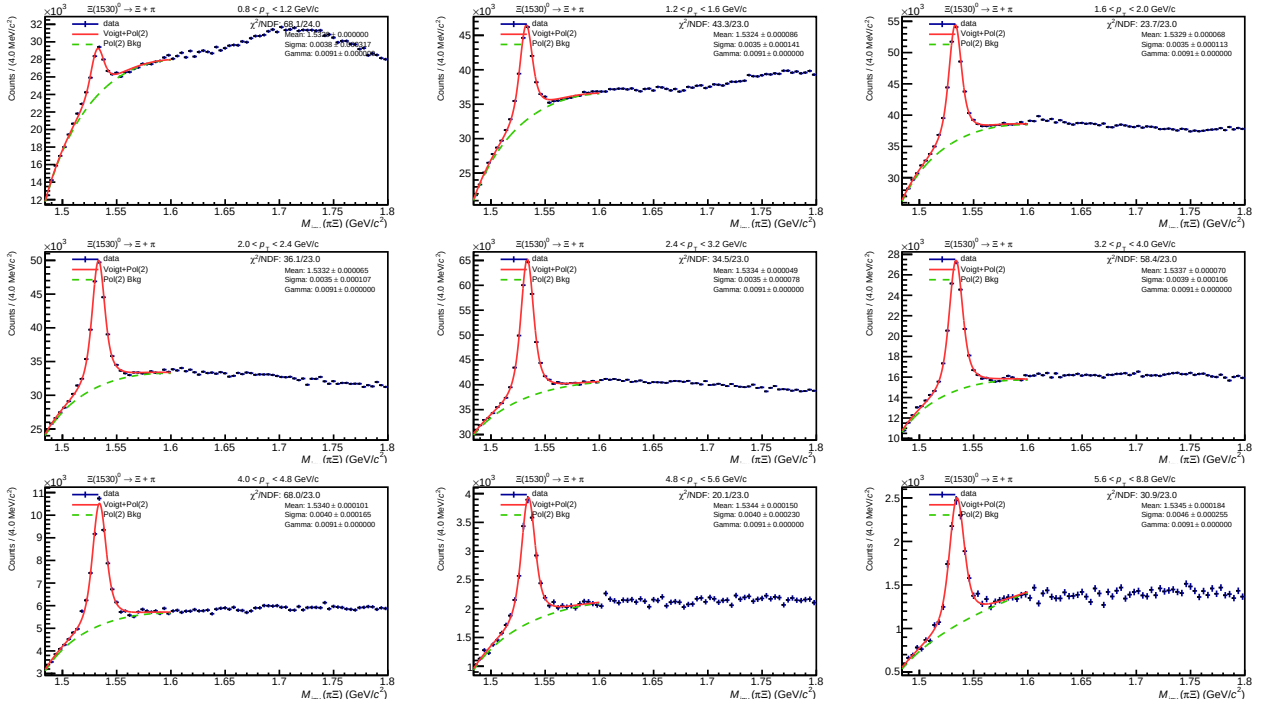


Figure 3.9. Fitted invariant mass without background subtraction in 0 – 100% Multiplicity Percentile

3.3.2 Raw yield extraction

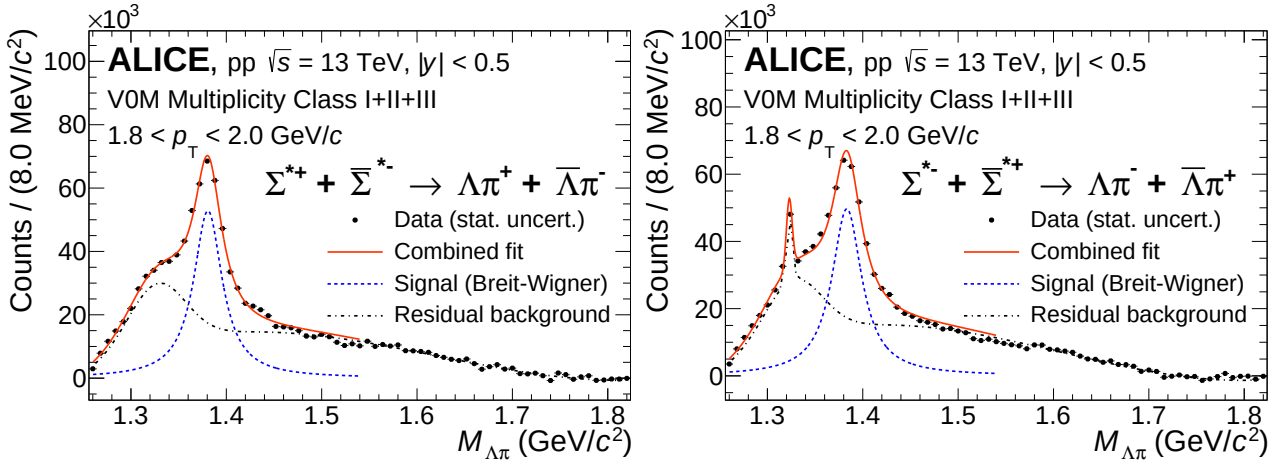


Figure 3.10. Example of invariant mass distribution of $\Lambda\pi^+(\bar{\Lambda}\pi^-)$ pairs (left) and $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ pairs (right) after combinatorial background subtraction together with the fits to the signal and residual background contribution for $1.8 < p_{T, \Lambda\pi^+} < 2.0$ GeV/c and the I+II+III (0–10%) multiplicity class. The solid red curve is the result of the combined fit and the dashed black line represents the residual background.

Figure 3.10 is the fitted invariant mass distribution of $\Sigma(1385)^+$ (left) and $\Sigma(1385)^-$ (right) obtained by subtracting the mixed-event background from the data (black full circle). For $\Sigma(1385)^\pm$ analysis, the Breit-Wigner function is applied to describe the signal with a free parameter of Breit-Wigner width Γ as shown in Fig. 3.10.

Especially for $\Sigma(1385)^-$ analysis, the peak from $\Xi^- \rightarrow \Lambda + \pi^-$ is visible in Fig. 3.10 (right), while the amount of the Ξ^- is expected as much as $\Sigma(1385)^-$ but suppressed because of the topological selection to the PV. Such a parasitic species is accounted for as an additional component entering the residual background shape for $\Sigma(1385)^-$ candidates.

$$P_{BW}(m; m_0, \Gamma) = \frac{1}{\pi} \frac{\Gamma/2}{(m - m_0)^2 + \Gamma^2/4}$$

The residual background is represented by the black dashed line. It consists set of a gaussian function and a third-order polynomial function, which describes $\Lambda\pi$ pairs coming from the decays of other particles and $\Lambda\pi$ pairs which come from the dynamics of the collision, respectively. See [81] for the detailed description of the residual background. One example of the correlated background coming from the dynamics of the collision studied with MC can be found at Fig. 3.11. The distribution was fitted with a third-order polynomial function successfully. Figure 3.12 presents a invariant distribution of π - Λ pair from the same event regardless the true signal peak from MC (black) and the mixed event pair (red). The difference of these distributions become the correlated background and fitted with the polynomial function. The fit values obtained with the MC are used to fit the data.

To make fit converge, Fit parameters of the gaussian function are fixed as a value from MB (0–100% multiplicity class) $\Sigma(1385)^+$ case as shown in Tab. 3.4. As a systematic study, the gaussian function describing $\Lambda\pi$ pairs coming from the decays of other particles is replaced to the tailed gaussian ($G_{\text{tailed}}(m; m_0, a, b)$).

$$G_{\text{tailed}}(m; m_0, a, b) = N \times e^{\frac{-(x-m_0)^2}{2 \times (a + b \times (\frac{m-m_0}{m_0})^2)}}$$

Overall fitting value distribution can be found in Fig. 3.15. The fitting results (mean, width) with p_T , multiplicity can be found in Fig. 3.13 and Fig. 3.14

Table 3.4. Fixed Parameters for the Gauss fitting of $\Sigma(1385)^\pm$

p_T -bin [GeV/c]	Gauss Mean	Gauss Width
0.7 – 1.0	1.33157	0.0251698
1.0 – 1.2	1.33018	0.0266685
1.2 – 1.4	1.32753	0.0266511
1.4 – 1.6	1.32763	0.0276483
1.6 – 1.8	1.32733	0.0294612
1.8 – 2.0	1.32733	0.0293154
2.0 – 2.4	1.32551	0.0282499
2.4 – 3.2	1.32395	0.0273428
3.2 – 4.0	1.32544	0.0304059
4.0 – 4.8	1.32317	0.0316147
4.8 – 6.0	1.32110	0.0334169

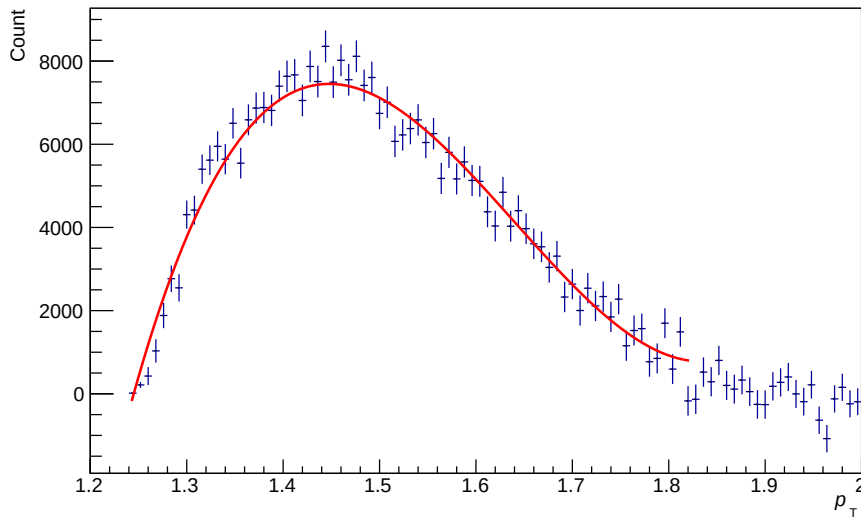


Figure 3.11. Correlated Background: Invariant mass distribution from MC without the true signal peak after subtracting Mixed-Event Background of $\Sigma(1385)^\pm$. Red: fitting with a third-order polynomial function

The raw yield of $\Sigma(1385)^+$ is finally calculated by integrating the Breit-Wigner function from 1.335 to 1.7 GeV/ c^2 for each p_T interval.

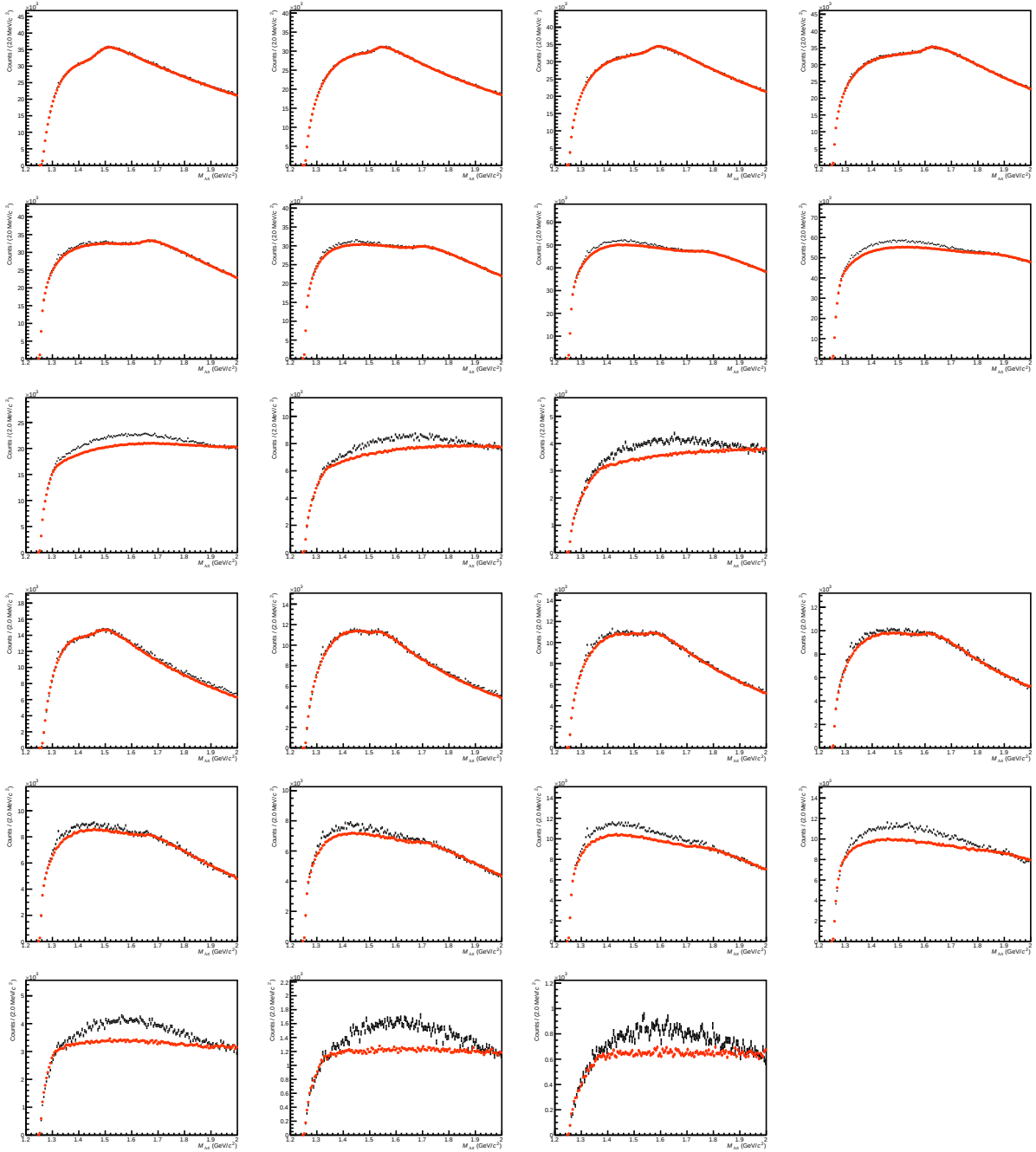


Figure 3.12. Correlated Background: Invariant mass distribution for different p_T bins from MC **without** the true signal peak. Black: π - Λ pair from the same event, Red: π - Λ pair from mixed-event. The difference will make a correlated background, which is described with a third-order polynomial function. Top: 0 – 10% Multiplicity, Bottom: 50 – 70% Multiplicity

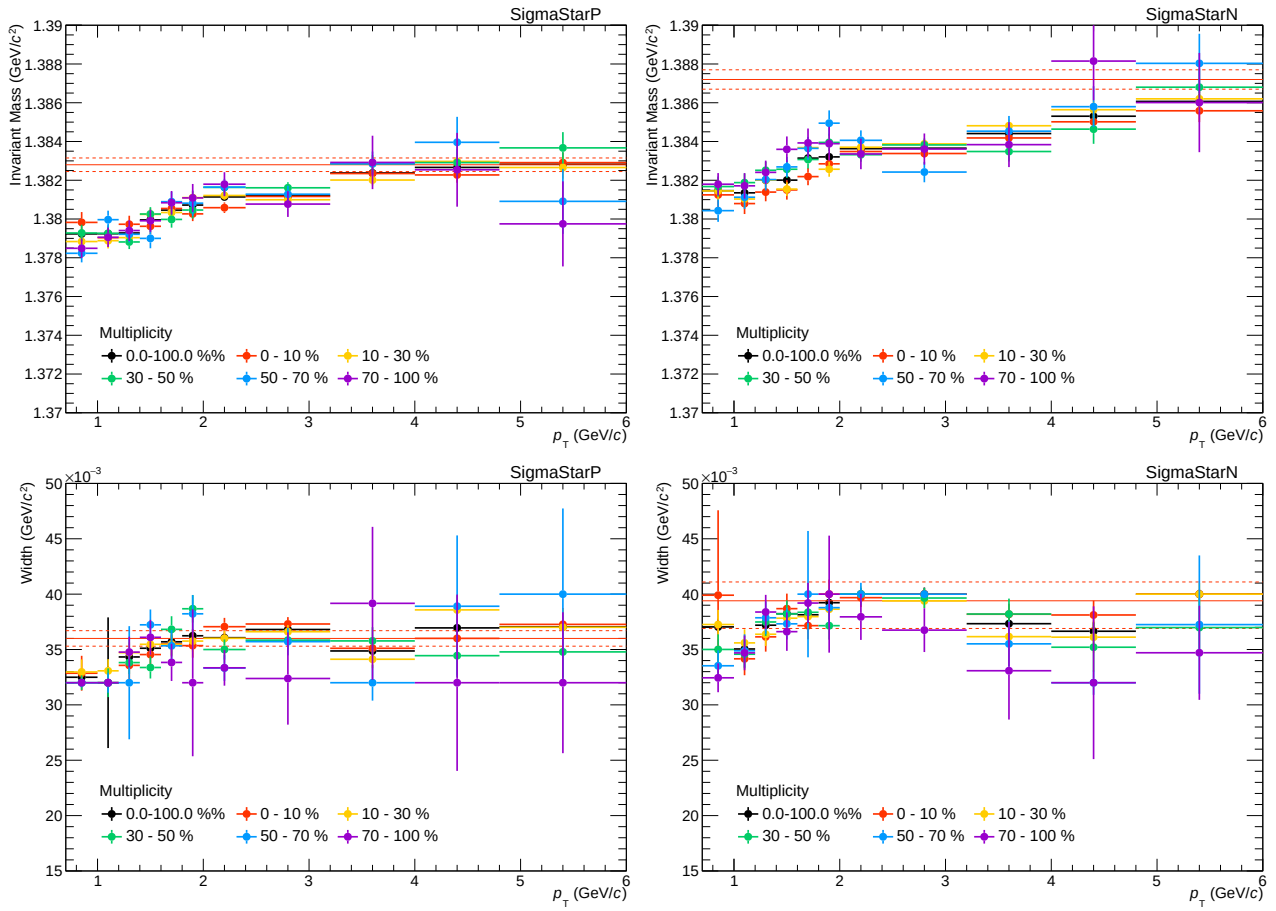


Figure 3.13. Mean(m_0 , Top) and Width(Γ , Bottom) of Breit-Wigner function. The red line shows PDG value and dashed line shows 1 σ range.

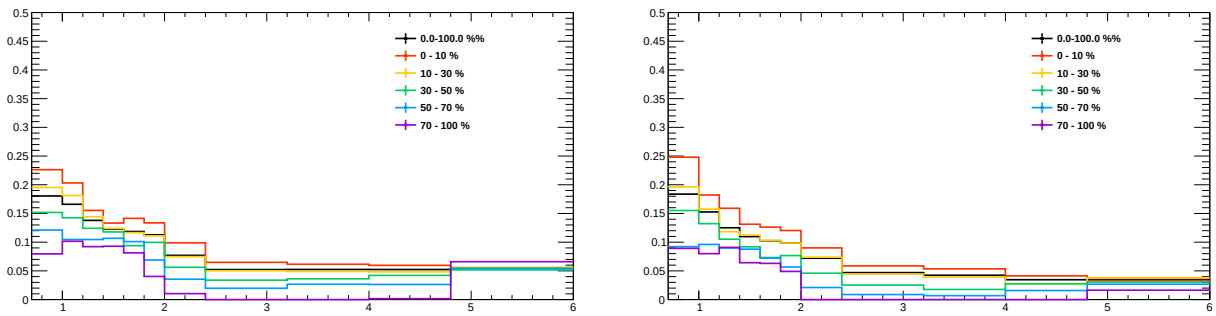


Figure 3.14. Fraction of the yield of the bump to the signal (Left: $\Sigma(1385)^+$, Right: $\Sigma(1385)^-$)

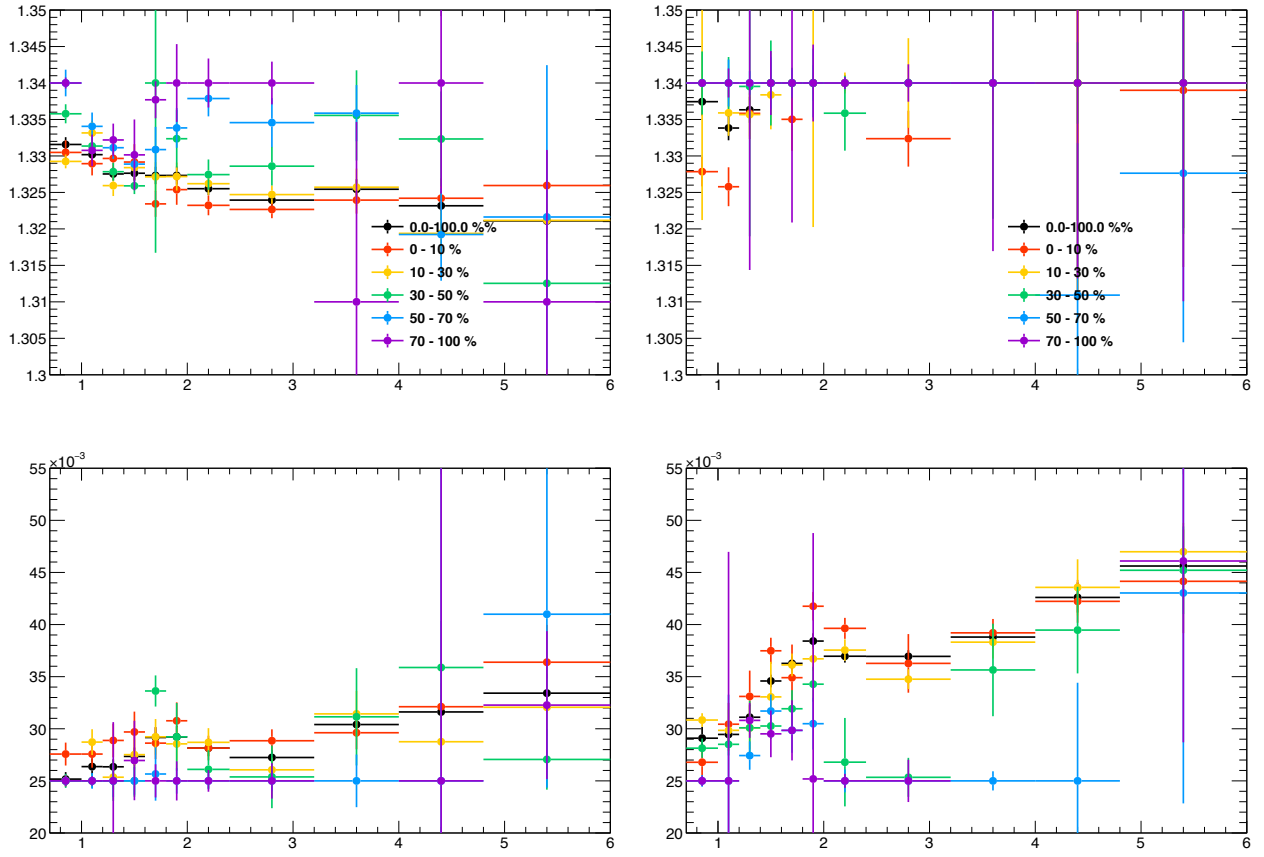


Figure 3.15. Mean(m_0 , Top) and Width(Γ , Bottom) of the gauss function. Left: $\Sigma(1385)^+$, Right: $\Sigma(1385)^-$ Only MB(0 – 100%) values from $\Sigma(1385)^+$ is used as a fixed value for all multiplicities. (X-axis: p_T)

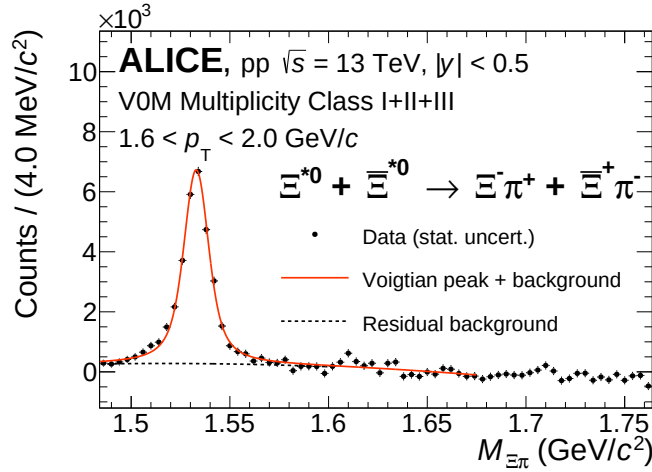


Figure 3.16. Example of invariant mass distribution of $\Xi^- \pi^+ (\Xi^+ \pi^-)$ after combinatorial background subtraction together with the fits to the signal and residual background contribution for $1.6 < p_{T, \Xi\pi} < 2.0$ GeV/c and the I+II+III (0–10%) multiplicity class. The solid red curve is the result of the combined fit and the dashed black line represents the residual background.

For $\Xi(1530)^0$ analysis, the distribution is fitted with a Voigtian function with a fixed width Γ to $9.1 \text{ MeV}/c^2$ to describe the signal and a second-order polynomial function for the remaining background. The width of the $\Xi(1530)^0$ is about $9.1 \text{ MeV}/c^2$, which has a similar scale of the detector resolution reported as around few MeV/c^2 [81]. Therefore, the Voigtian ($P_{Voigt}(x; x_0, \sigma, \Gamma)$) which is the convolution of the Breit-Wigner ($P_{BW}(m; m_0, \Gamma)$) describing the invariant mass signal and Gaussian function describing the detector resolution is used to fit the $\Xi(1530)^0$.

$$P_{Voigt}(x; x_0, \sigma, \Gamma) = \int_{-\infty}^{+\infty} P_{Gauss}(x'; x_0, \sigma) P_{BW}(x - x'; x_0, \Gamma) dx'$$

The invariant mass of Ξ^{*0} (x_0) as a function of p_T in Fig. 3.17. The red line on the figure shows PDG mass. The σ in minimum bias events are presented as a function of p_T in Fig. 3.17. Though σ shows good agreement with MC, the fitted mass has slightly shifted value $\approx 1 \text{ MeV}/c^2$. Detector resolution (σ) is expected to be $\approx 2 \text{ MeV}/c^2$ in previous study [81]

The raw yield of $\Xi(1530)^0$ is obtained by integrating the Voigtian function from 1.4 to 1.7 GeV/c^2

Figure 3.18 (Fig. 3.19) shows the fitted invariant mass distribution after background subtraction of the $\Sigma(1385)^+$ (top) and $\Sigma(1385)^-$ (bottom) in most high multiplicity bin (0–10%) and low multiplicity bin (70–100%). Similarly, Fig. 3.21 (Fig. 3.22) shows the fitted invariant mass distribution after background subtraction of the $\Xi(1530)^0$ in most high multiplicity bin (0–10%) and low multiplicity bin (70–100%).

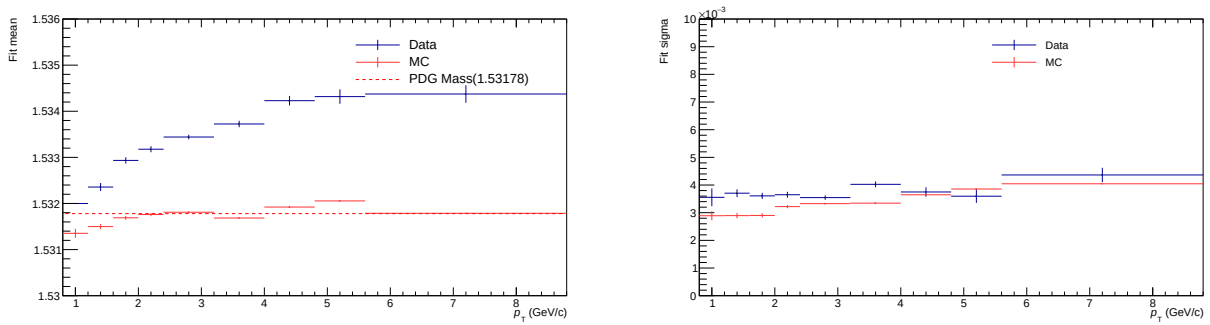
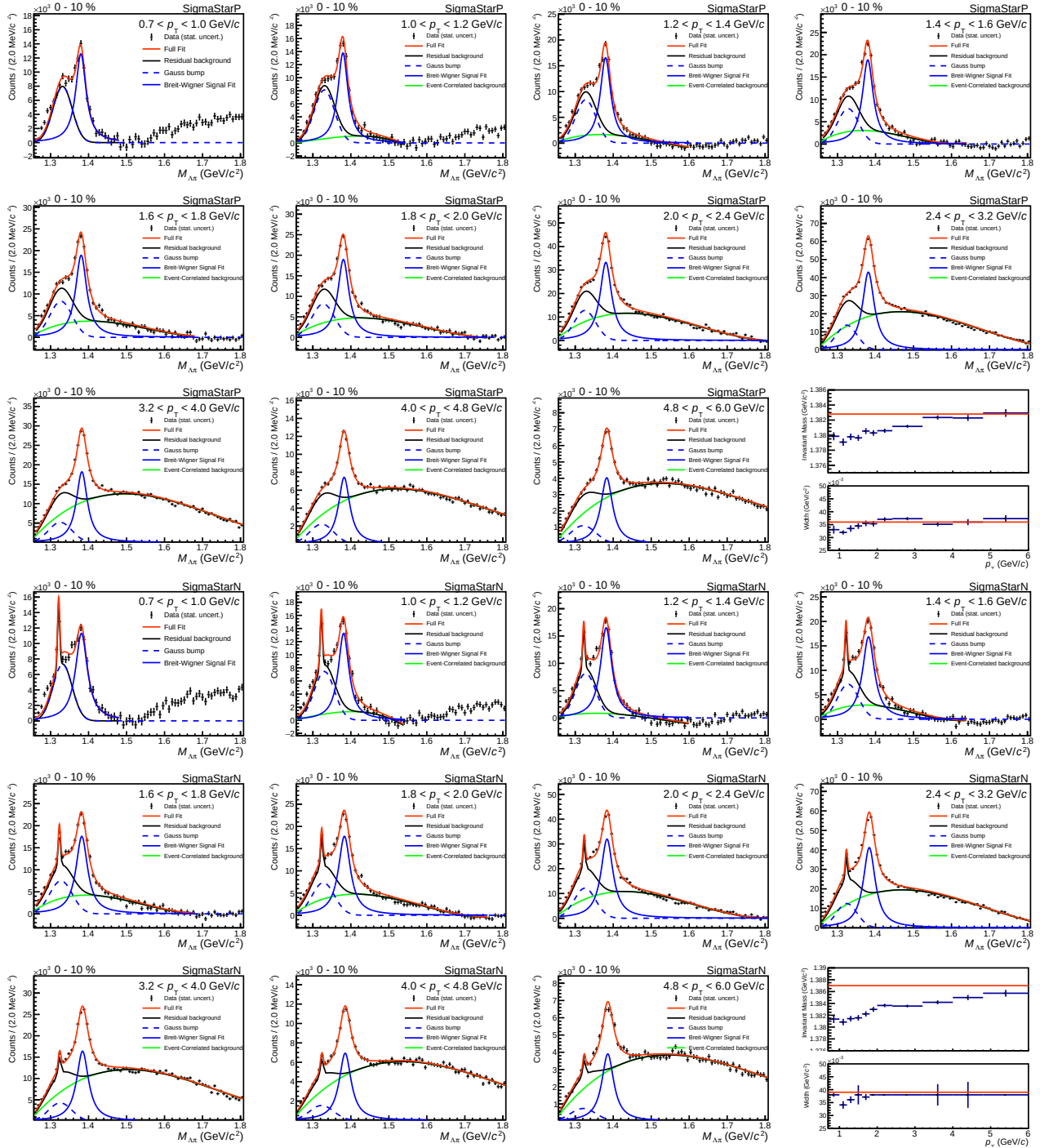
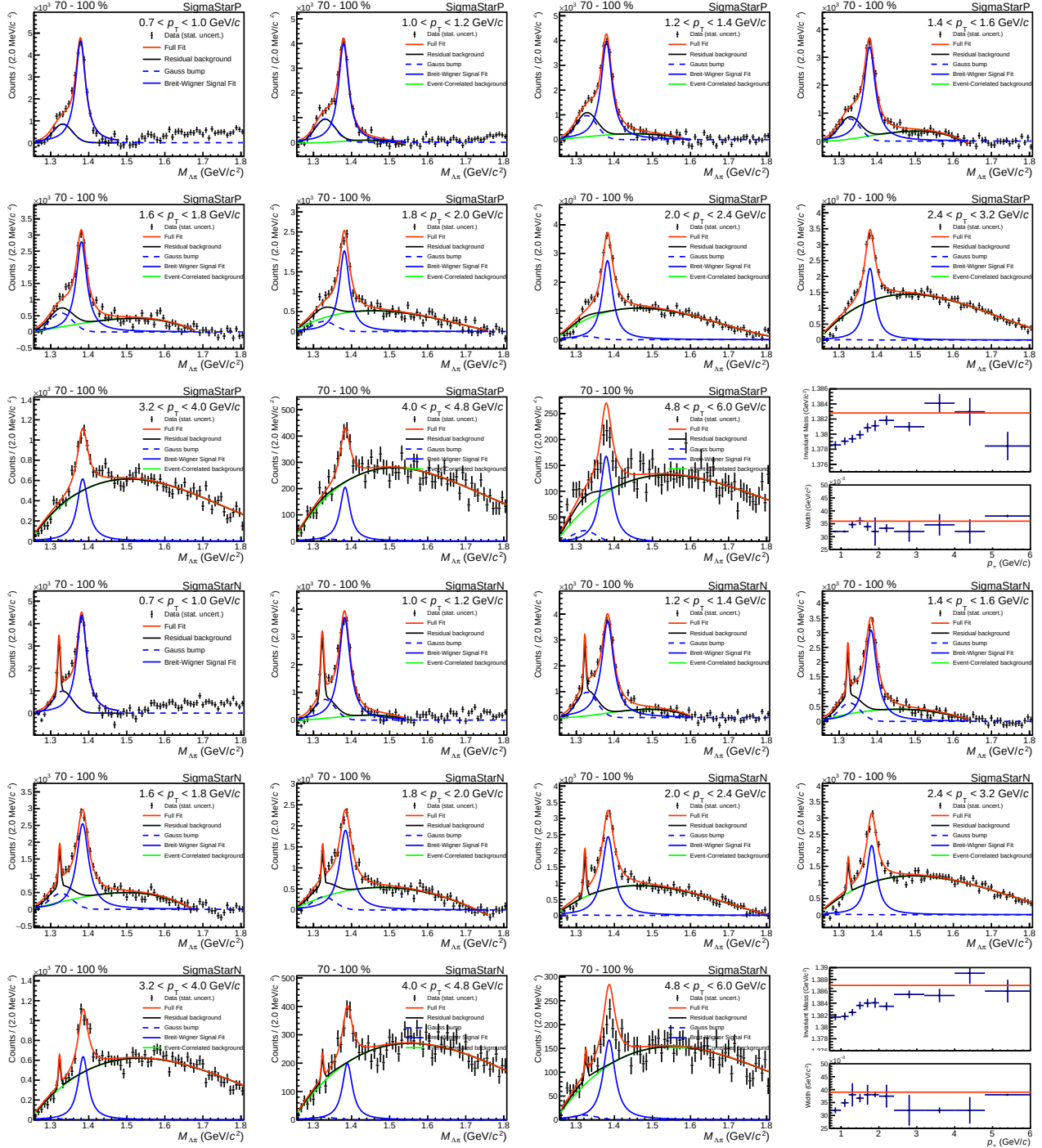
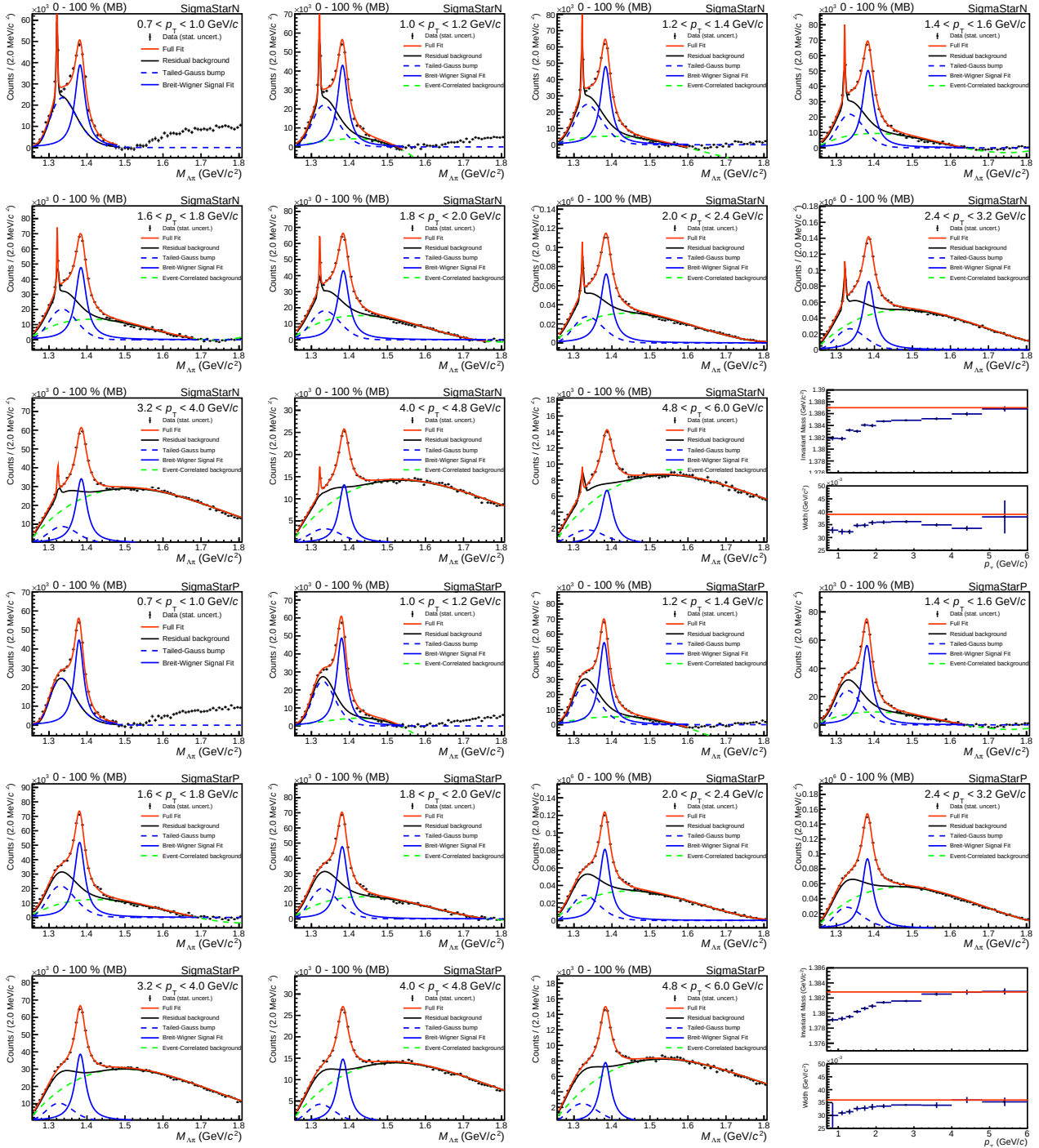


Figure 3.17. Fitted mass (left) and σ (right) versus p_T in MB (0-100). The PDG mass value is drawn as dashed red line in fit mean figure (left)

Figure 3.18. Fitted signal in 0–10% multiplicity class Top: $\Sigma(1385)^+$, Bottom: $\Sigma(1385)^-$

Figure 3.19. Fitted signal in 70–10% multiplicity class Top: $\Sigma(1385)^+$, Bottom: $\Sigma(1385)^-$

Figure 3.20. Alternative fit function(Tailed-Gauss) signal fitting Top: $\Sigma(1385)^+$, Bottom: $\Sigma(1385)^-$ of MB event.

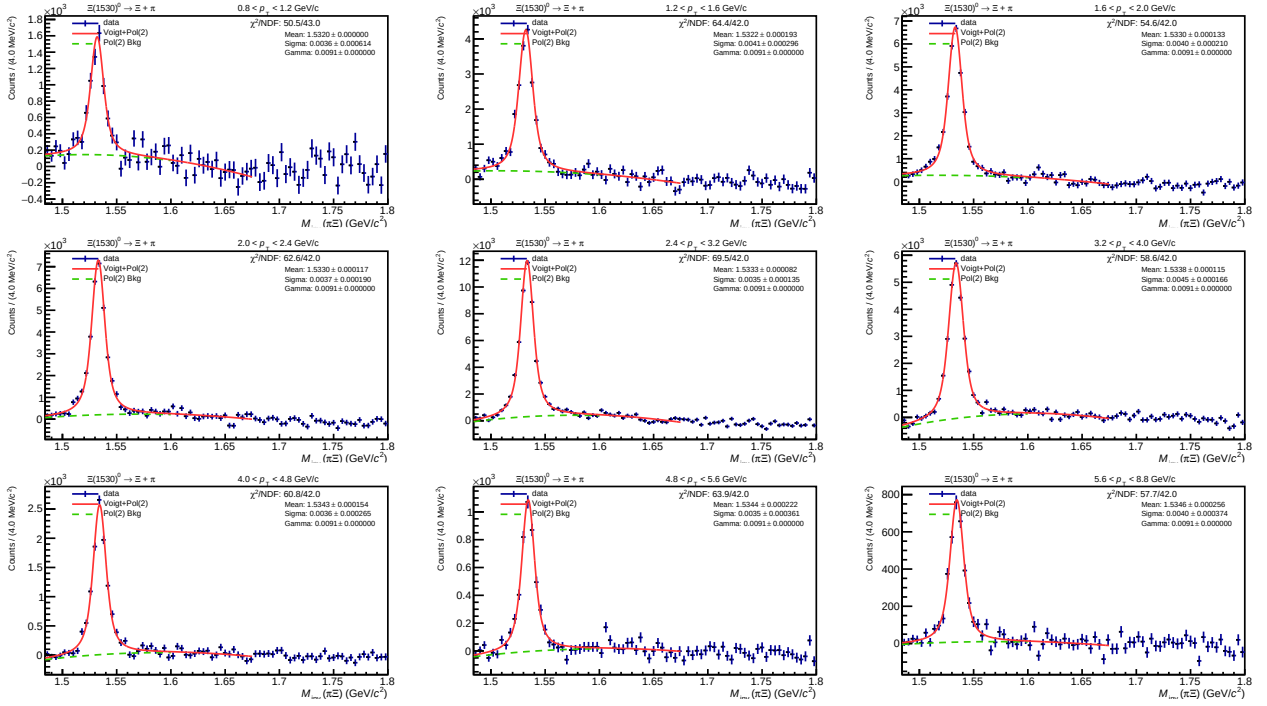


Figure 3.21. Fitted invariant mass after background subtraction in 0 – 10% Multiplicity Percentile

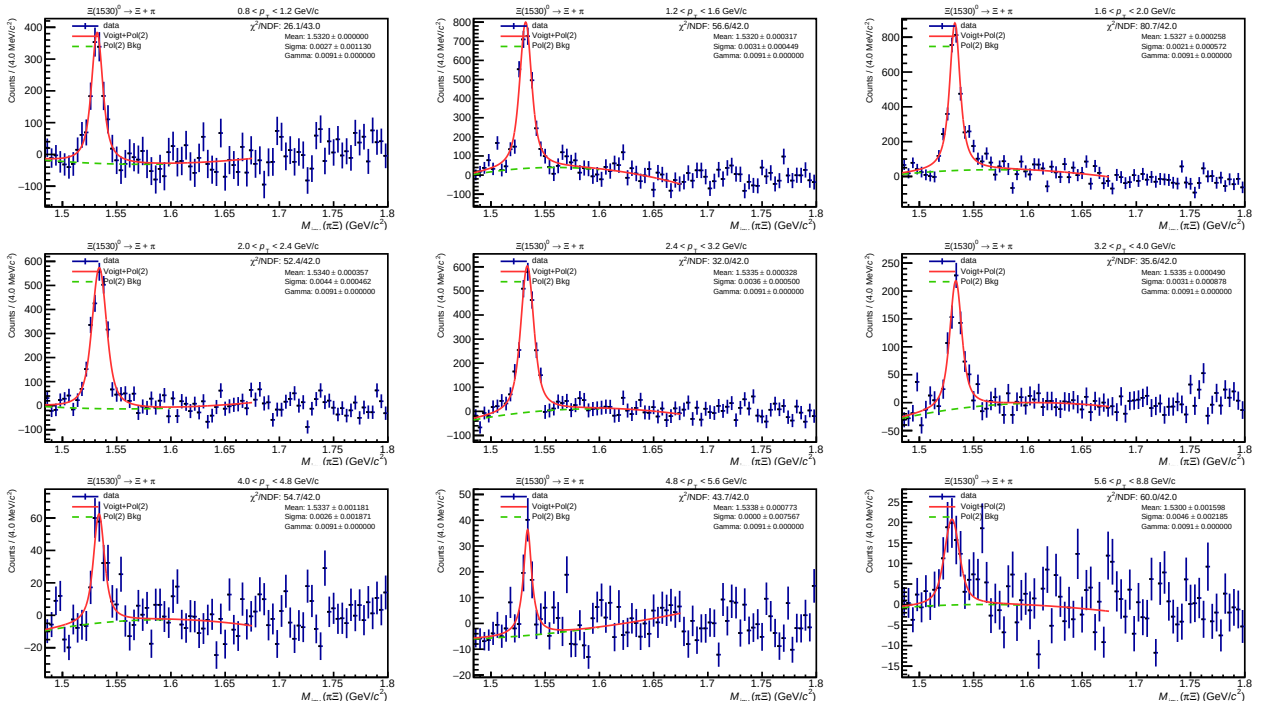


Figure 3.22. Fitted invariant mass after background subtraction in 70 – 100% Multiplicity Percentile

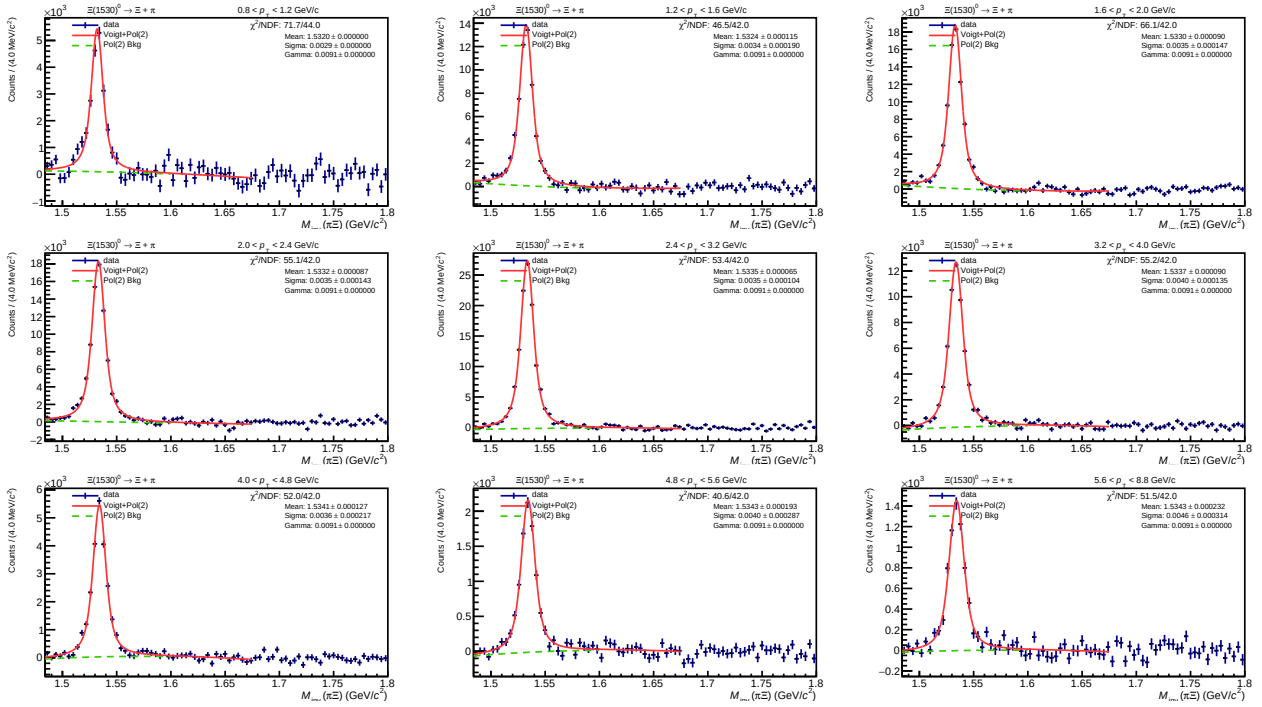


Figure 3.23. Fitted invariant mass after Like-sign background subtraction in 0 – 100% Multiplicity Percentile

3.4 Monte-Carlo Correction

The raw yields of $\Sigma(1385)^+$, $\Sigma(1385)^-$ and $\Xi(1530)^0$ for each p_T interval are corrected for the geometrical acceptance and the reconstruction efficiency of the detector and normalised for the branching ratios.

3.4.1 Acceptance x Reconstruction Efficiency

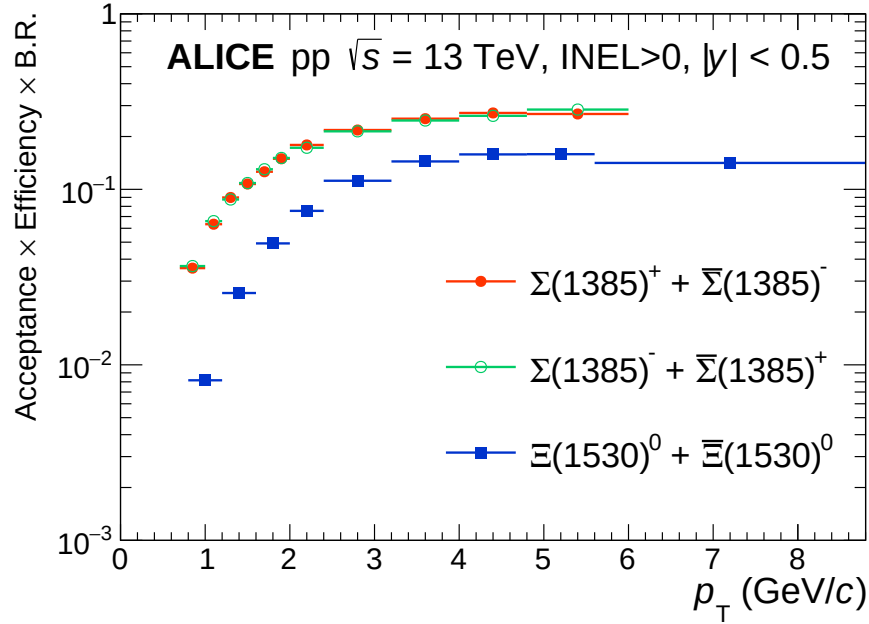


Figure 3.24. The product of geometrical acceptance, reconstruction efficiency of the detector and branching ratio for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ obtained with PYTHIA 8 Monash 2013 [34] and GEANT 3 [83], as a function of p_T in $|y| < 0.5$.

The correction factors are estimated by Monte Carlo simulations based on PYTHIA 8 Monash 2013 [34] for particle generation and GEANT 3 [83] for the transport of particles through the ALICE subdetectors. $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ are reconstructed in Monte Carlo by applying the same track, topological and PID selection criteria as for the data. The generated and reconstructed resonances in PYTHIA 8 are used to calculate the correction factors. The acceptances and efficiencies including the branching ratio, $A \times \epsilon \times \text{B.R.}$ for $\text{INEL} > 0$ events are shown in Fig. 3.24 from 0.7 GeV/c for $\Sigma(1385)^\pm$ and 0.8 GeV/c for $\Xi(1530)^0$. Since no strong multiplicity dependence is observed as like Ref [29], the values from the $\text{INEL} > 0$ events are used for the correction of the raw yields from any of the multiplicity classes, with a 2% systematic uncertainty from $A \times \epsilon \times \text{B.R.}$, constant for all p_T bins.

3.4.2 Signal Loss Correction and Trigger Efficiency

All selected events are required to have at least one charged particle track in the pseudo-rapidity region $|\eta| < 1$ ($\text{INEL} > 0$). However, due to the incompleteness of the trigger, some $\text{INEL} > 0$ events are missing, therefore, all the $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ produced in those events are lost as well. So, there is an additional correction for the missed events, called signal loss correction $f_{\text{S.L.}}$, that is more important for the lower multiplicity classes. The signal loss correction is applied to the yields.

Signal Loss correction factor is defined as:

$$f_{\text{S.L.}} = \frac{N_{\text{MCtrue;EventSelection}}^{\Xi^{*0}}}{N_{\text{MCtrue}}^{\Xi^{*0}}}$$

Figure 3.25 (Fig. 3.26, $1/f_{\text{S.L.}}$ drawn) shows the Signal Loss correction factor of $\Sigma(1385)^\pm$ ($\Xi(1530)^0$) as a function of p_T in each multiplicity classes.

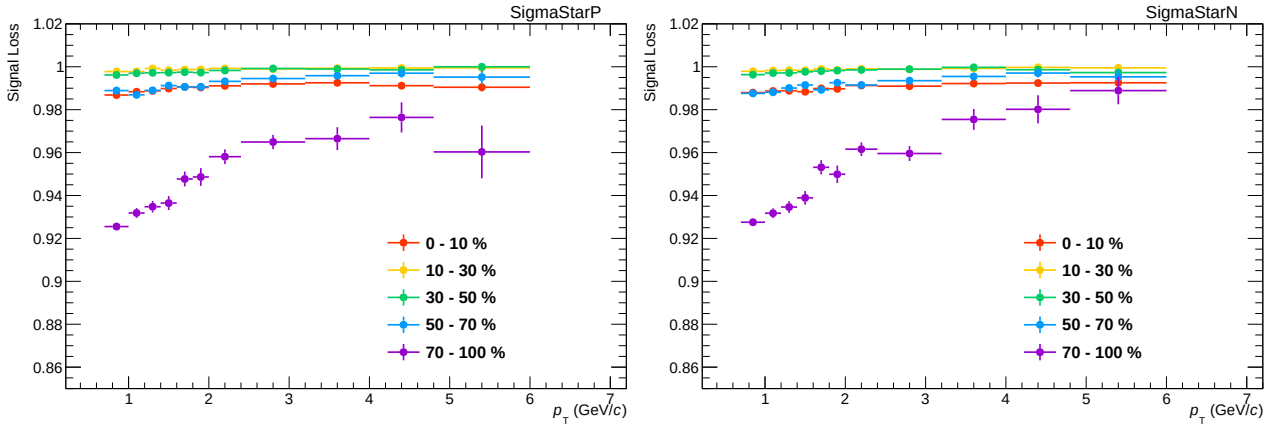


Figure 3.25. Signal Loss correction factor of $\Sigma(1385)^+$ (left) and $\Sigma(1385)^-$ (right)

Along with the correction of the yield, the number of events also needs to be corrected due to the incompleteness of the trigger and event selections such as good primary vertex selection. The trigger efficiency f_{Trig} and the good vertex selection efficiency f_{Vertex} are more relevant for the lower multiplicity classes while it is negligible at the higher multiplicity[29]. In case of the inelastic study, the trigger efficiency is replaced to the normalisation factor 0.7448 ± 0.0190 used in [80].

Trigger Efficiency f_{Trig} is defined as

$$f_{\text{Trig}} = \frac{N_{\text{Trig|TrueINEL}>0}^{\text{Event}}}{N_{\text{TrueINEL}>0}^{\text{Event}}}$$

where denominator is a number of MC event with True $\text{INEL} > 0$ and numerator is a number of MC event which triggered in Trig trigger AND passes the same check with the denominator.

Similarly, Vertex Selection Efficiency is defined as

$$f_{\text{vtx}} = \frac{N_{\text{vtx|TrueINEL}>0}}{N_{\text{trig|TrueINEL}>0}}$$

where numerator is the number of MC event after good vertex selection described in Sec. 3.1.

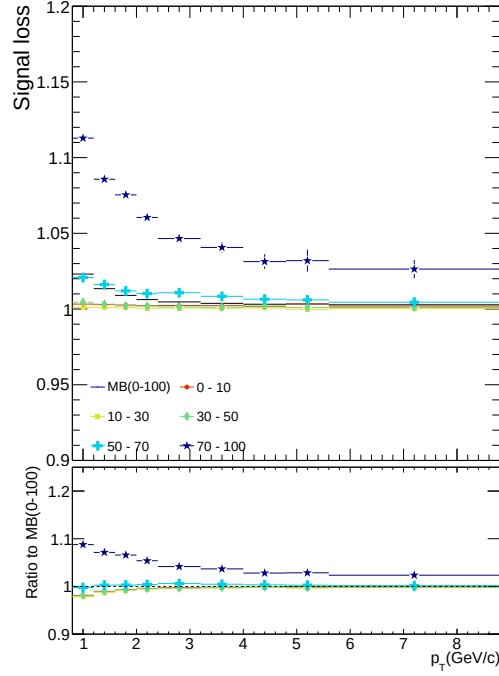


Figure 3.26. Signal Loss Correction $1/f_{S.L.}$ for $\Xi(1530)^0$ with multiplicity bin and ratio of the values to the one at MB (bottom)

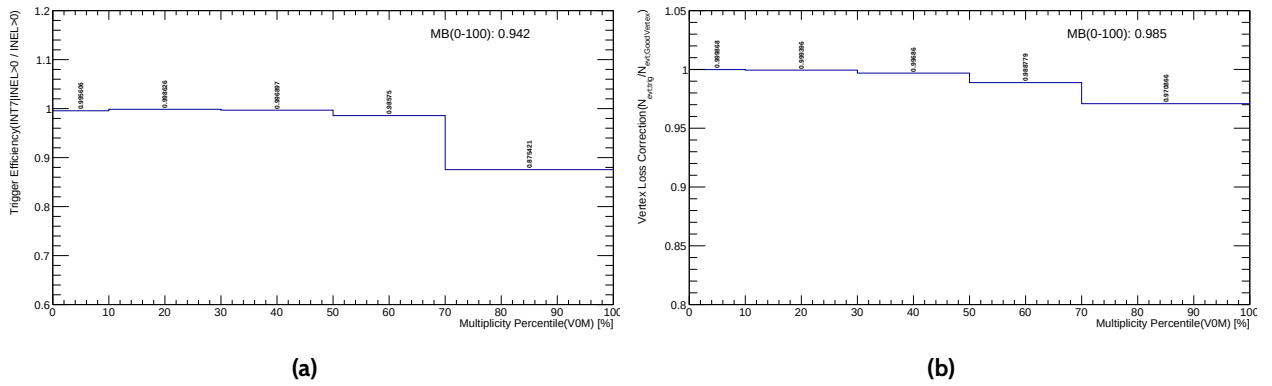


Figure 3.27. Trigger Efficiency f_{Trig} (a) and Vertex Selection Efficiency f_{vtx} (b) with multiplicity bin

3.5 Systematic Uncertainties

The systematic uncertainty has been studied with several groups: Signal Extraction (Sec. 3.5.1), Topological Selection (Sec. 3.5.2), TPC dE/dx PID Selection (Sec. 3.5.3), p_T independent Uncertainties (Sec. 3.5.4). For each group, an enough variation has been tried to get the uncertainties and check the trend of variation in function of p_T .

Basic principle is below:

1. Check the corrected yield(Y_{def}) of each p_T bin in default configuration as a default value.
2. Change one cut parameter and check corrected yield(Y_{var})
3. Calculated relative error of these variation($|Y_{\text{var}} - Y_{\text{def}}| / Y_{\text{def}}$)

For the topological cut variation and TPC PID variation, a barlow criterion[84] has been applied to prevent an effect to systematic uncertainty from statistical fluctuation since their results are coming from a subset of the another, certainly, in which we can use "subtract of statistical uncertainty" of them.

$$\begin{aligned}\Delta Y &= |Y_{\text{var}} - Y_{\text{def}}| \\ \Delta \sigma &= \sqrt{|\sigma_{\text{var}}^2 - \sigma_{\text{def}}^2|} \\ n &= \Delta Y / \Delta \sigma\end{aligned}$$

If the barlow criteria(n) is less than 1, we can regard that differences could be coming from a statistical fluctuation, we will not accept it as a systematic error. Detail of this procedure is described in Sec. 3.5.5.

The total uncertainties are shown in Sec. 3.5.6.

3.5.1 Signal Extraction Variations

In signal extraction of $\Xi(1530)^0$, alternative background descriptions are applied as described in Sec 3.3.1, such as like-sign background ($\Xi^- + \pi^-$, $\Xi^+ + \pi^+$, Fig. 3.8) and background fitting without using event mixed background as shown in Fig. 3.9. Unlike-sign background variations are impossible to apply in $\Sigma(1385)^\pm$ because unlike-sign of $\Sigma(1385)^+$ makes $\Sigma(1385)^-$. The signal extraction uncertainty includes the uncertainty from the fitting procedure quantified by varying the fit range and the initial values of the parameters, and the normalisation range of the invariant mass distributions from the real and the ME background. In case of $\Sigma(1385)^\pm$, the signal extraction is the main contribution to the total systematic uncertainty of $\Sigma(1385)^\pm$, originated by the bump structure located on the left-side of the signal peak (Figure. 3.10). The left bump structure of $\Sigma(1385)^\pm$ is described with the Gauss function as default and tailed-Gauss function as an alternative.

3.5.2 Topological Variations

The topological cut variation has been checked with loose/tight cut on various cut options. The full details about the topological cut values are in Table 3.6 (Tab. 3.5). Figure 3.28 (Fig. 3.29, left) shows the example of the corrected spectra of each topological cut variation and its ratio to the default configuration for $\Sigma(1385)^\pm$ ($\Xi(1530)^0$).

Table 3.5. Variations in topological/PID cuts applied in $\Xi(1530)^0$

Analysis cut(Topological/TPC PID)	Default value	Variation(loose)	Variation(tight)
Xi(1530) primary π vertex-z cut (cm)	<2.0	<2.5	<1.5
DCA Lambda daughters(π, p) (cm)	<1.4	<1.5	<1.3
DCA Cascade daughters(π, Λ) (cm)	<1.6	<2.0	<1.2
DCA Lambda to PV (cm)	<0.07	<0.05	<0.09
VO Cosine of Pointing Angle	>0.97	>0.96	>0.98
Cascade Cosine of Pointing Angle	>0.97	>0.96	>0.98
Cascade Mass Window (MeV/c^2)	<0.007	<0.008	<0.006
TPC PID response for Xi(1530) primary π (σ)	<3	<3.5	<2.5
TPC PID response for Xi daughters π, p (σ)	<3	<3.5	<2.5

Table 3.6. Variations in topological/PID cuts applied in $\Sigma(1385)^\pm$

Analysis cut(Topological/TPC PID)	Default value	Variation(loose)	Variation(tight)
$\Sigma(1385)^\pm$ primary π vertex-z cut (cm)	<2.0	<2.2	<1.8
$\Sigma(1385)^\pm$ primary π vertex-r cut (σ)	<7.0	<8.0	<6.0
DCA Lambda daughters(π, p) (cm)	<1.6	<0.67 (tight)	<0.35 (tighter)
DCA Lambda to PV (cm)	>0.3	>0.22	>0.4
Λ Cosine of Pointing Angle	>0.98	>0.97	>0.99
Λ Lifetime	<30	<32	<28
Λ Mass Window (MeV/c^2)	<0.010	<0.013	<0.0076
TPC PID response for $\Sigma(1385)^\pm$ primary π (σ)	<3	<3.5	<2.5
TPC PID response for Λ daughters π, p (σ)	<3	<3.5	<2.5

3.5.3 TPC dE/dx PID Selection

To achieve better significance of the signal, TPC PID signal has been used in this study. Uncertainty for TPC PID variation was studied by variegating cut value from 2.5σ to 3.5σ for all daughters tracks. Details are in Table 3.6 (Tab. 3.5). In final systematic error from TPC PID selection was chosen as a maximum value of each p_T bin. Since one source must have one systematic error, only the largest error from loose/tight cut is considered for the final error. Figure 3.28 (Fig. 3.29, right) shows the example of the corrected spectra of each topological cut variation and its ratio to the default configuration for $\Sigma(1385)^\pm$ ($\Xi(1530)^0$).

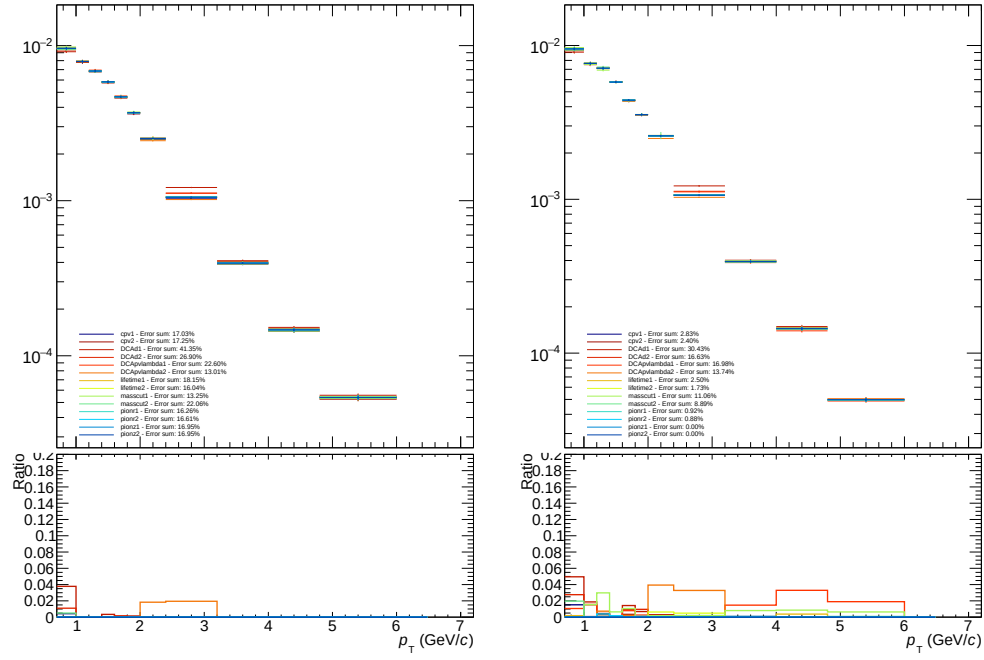


Figure 3.28. Example of corrected spectra of each topological cut variation and its ratio to the default configuration. Left: $\Sigma(1385)^+$, Right: $\Sigma(1385)^-$ in MB event

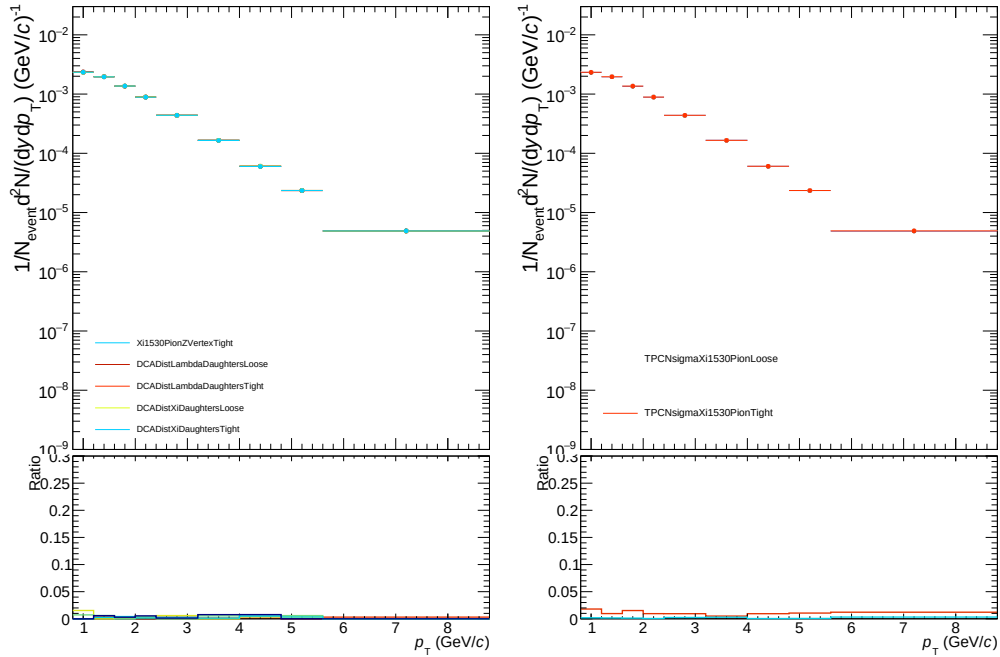


Figure 3.29. Example of corrected spectra of each topological cut variation (left) and TPC dE/dx PID (right), and their ratio to the default configuration in 0 – 100% (MB)

3.5.4 p_T independent uncertainty

As a p_T independent error, these errors are considered:

$$U_{\text{MB}}^2, U_{\text{TE}}^2, U_{\text{Multi}}^2$$

U_{MB}^2 is the uncertainty from the material budget, which is applied as p_T independent value of 4% from study on strange particle [79]. U_{TE} stands for the ITS-TPC tracking efficiency which have 3% of p_T independent value. U_{Multi} is uncertainty from the MC reconstruction efficiency of different multiplicity bins, $\approx 2\%$ value is applied as p_T independent error.

3.5.5 Consistency Check

Although the Barlow criteria is useful tool to avoid to add a statistical fluctuation to the systematic uncertainty, the Barlow criteria itself can be affected by statistical fluctuation. To verify that, a consistency check is performed. if we check the value in many different conditions, it can be expected that it would have a standard distribution ($N(\mu, \sigma)$) with $\mu \approx 0$ and $\sigma \approx 1$, and also 68% of entries in the distribution will be in the range of ± 1 ($I1$), and 98% will be in ± 2 region ($I2$), if the variation is consistent with the original.

Here are some evaluation factors:

- $|\mu| < 0.8$
- $|\sigma| < 1.3$
- $I1 > 0.55$
- $I2 > 0.75$

The values are chosen to have 80% value of its expected value in $N(\mu \approx 0, \sigma^2 \approx 1)$. For example, a Gaussian distribution with $\mu = 0.8, \sigma = 1$ will have 80% same distribution with the ideal case ($|\mu| < 0.8$). In a same context, 0.55 is the 80% value of ideal $I1$ value (66%).

if the distribution satisfy all of the evaluation above, we can accept that the variation is consistent with the original. In $\Sigma(1385)^\pm$ analysis, the uncertainty from 11 p_T bins in 6 different multiplicity bins, 2 different particles, which compose 132 entries are used to the test. In Ξ^{*0} analysis, the uncertainty from 9 p_T bins in 6 different multiplicity bins, which compose 54 entries are used to the test.

In $\Sigma(1385)^\pm$ analysis, None of these variations are passed the consistency check.

In Ξ^{*0} analysis, the Normalisation region variation (Fig. 3.30a), Fitting Background without subtraction (Fig. 3.30b left), DCA Lambda to PV (Fig.3.30c) and Lambda CPA are passed (Fig.3.30e) the test, so they are not included in final systematic uncertainty as shown in Fig. 3.30.

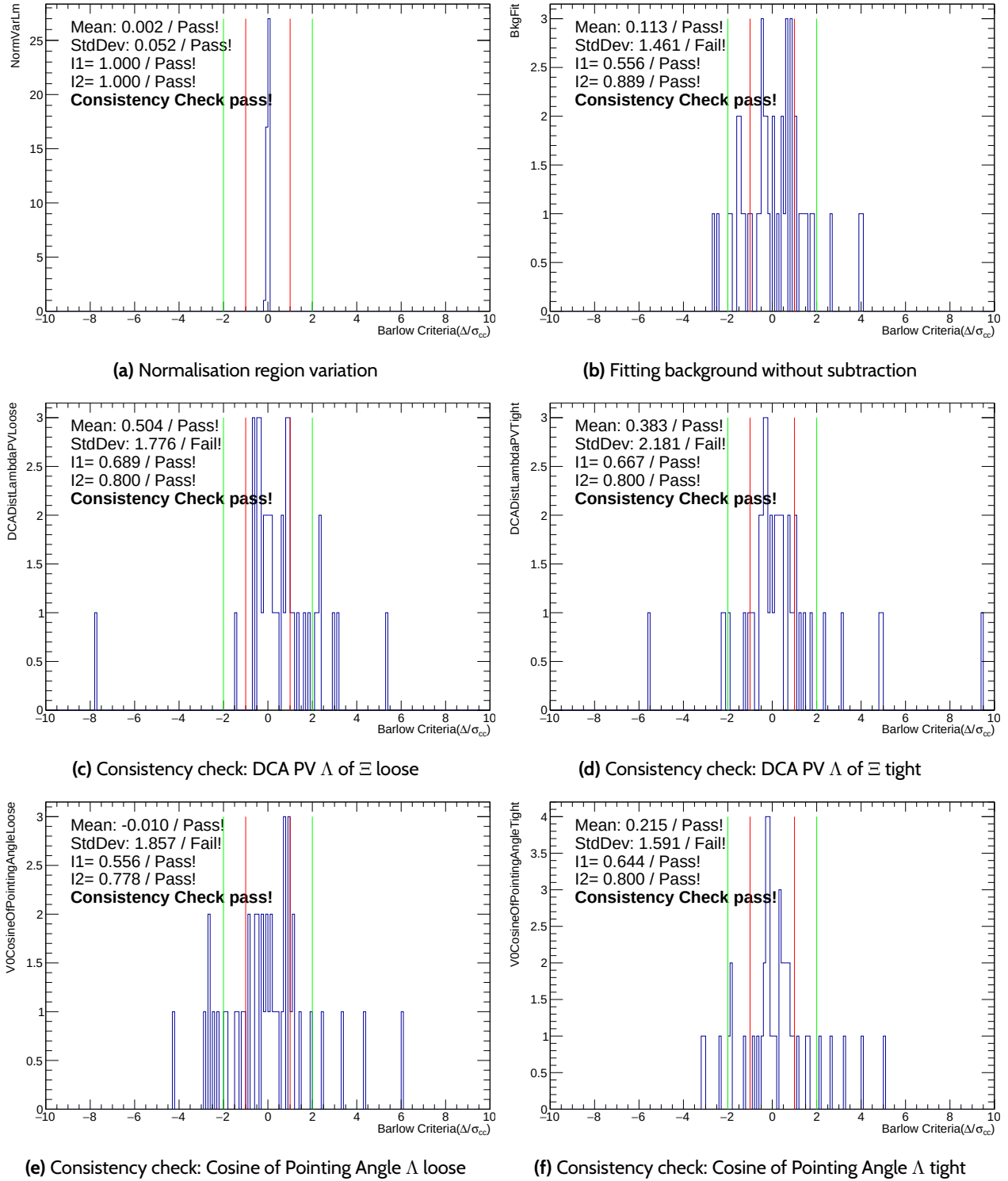


Figure 3.30. The variation of $\Xi(1530)^0$ which passed consistency check

3.5.6 Total Systematic Uncertainties

$$U_{\text{Total}} = \sqrt{U_{\text{sig}}^2 + U_{\text{topol}}^2 + U_{\text{PID}}^2 + U_{\text{MB}}^2 + U_{\text{TE}}^2 + U_{\text{Multi}}^2}$$

The systematic uncertainties from each groups are merged via quadrature sum. Figure 3.31 (Fig. 3.32, Fig. 3.33) shows the total systematic uncertainty of $\Sigma(1385)^+$ ($\Sigma(1385)^-$, $\Xi(1530)^0$) in highest multiplicity class (0–10%, I+II+III) and lowest multiplicity class (70–100%, X). Table. 3.7 shows the summary of systematic uncertainties.

Table 3.7. Summary of systematic uncertainties.

Source of uncertainty	$\Sigma(1385)^+$	$\Sigma(1385)^-$	$\Xi(1530)^0$
p_T -dependent			
Topological selection	1–10%	1–10%	1–3%
TPC particle identification	1–3%	1–3%	1–3%
Signal extraction	1–10%	8–15%	1–17%
p_T -independent			
Material budget	4%	4%	4%
ITS-TPC matching	3%	3%	3%
Multiplicity-independent efficiencies	2%	2%	2%
Total	7–18%	9–18%	7–20%

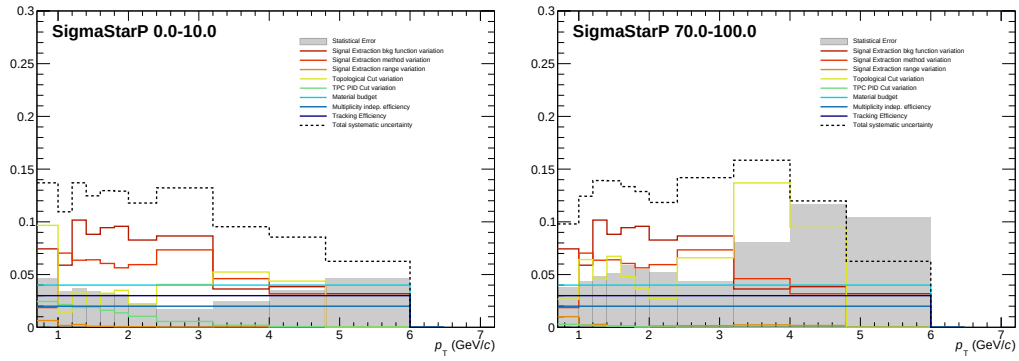


Figure 3.31. Systematic Errors from each source in 0–10% (Left) 70–100% (Right) event $\Sigma(1385)^+$

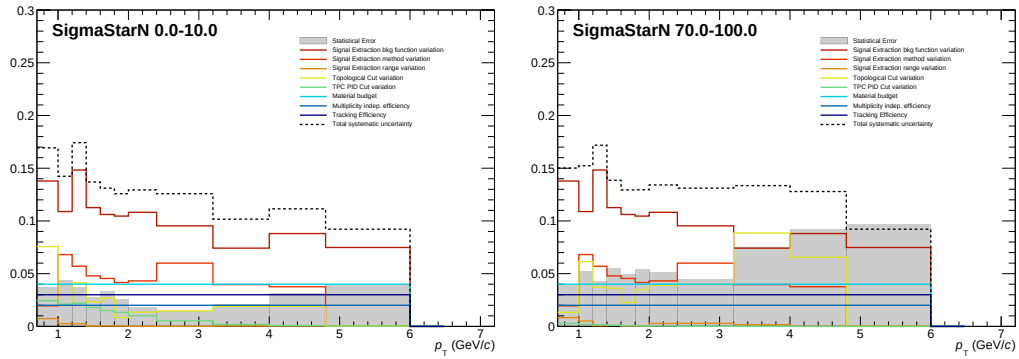


Figure 3.32. Systematic Errors from each source in 0–10% (Left) 70–100% (Right) event $\Sigma(1385)^-$

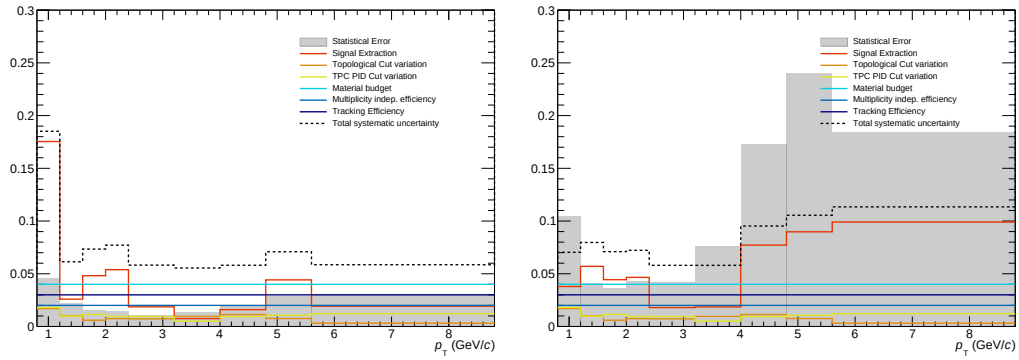


Figure 3.33. Ξ^{*0} Systematic Errors from each source in 0 – 10% (Left) and 70 – 100% multiplicity

3.6 Results

3.6.1 Normalisation

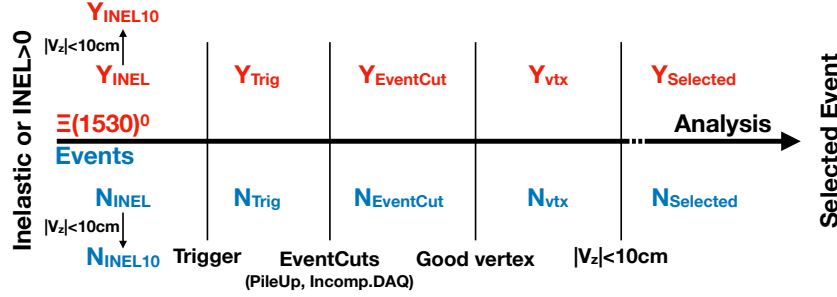


Figure 3.34. Number of Signal/Event with Event cuts

Combining the raw yields and the all the corrections, the production spectra of resonances is evaluated as:

$$\frac{1}{N_{INEL>0}^{ev}} \frac{d^2N}{dydp_T} = \frac{1}{N_{ev}} \frac{N_{raw}}{\Delta p_T \Delta y} \frac{1}{\epsilon_{rec} \times A} \times f_{Trig} \times f_{vtx} \times f_{S.L.} \quad (3.3)$$

To correct the spectra for inelastic event, following normalisation has been applied:

$$\begin{aligned} \frac{Y_{INEL}}{N_{INEL}} &= \frac{Y_{Selected}}{N_{Selected}} \times f_{INEL.norm} \times f_{vtx} \times f_{S.L} \\ &= \frac{Y_{Selected}}{N_{Selected}} \times \left(\frac{N_{trig}}{N_{INEL}} \right) \times \left(\frac{N_{vtx}}{N_{trig}} \right) \times \left(\frac{Y_{INEL10}}{Y_{Selected}} \right) \\ &= \frac{Y_{vtx}}{N_{vtx}} \times \left(\frac{N_{trig}}{N_{INEL}} \right) \times \left(\frac{N_{vtx}}{N_{trig}} \right) \times \left(\frac{Y_{INEL}}{Y_{vtx}} \right) \\ &= \frac{Y_{vtx}}{N_{vtx}} \times \left(\frac{N_{trig}}{N_{INEL}} \right) \times \left(\frac{N_{vtx}}{N_{trig}} \right) \times \left(\frac{Y_{INEL}}{Y_{vtx}} \right) \\ &= \frac{Y_{INEL}}{N_{INEL}} \end{aligned} \quad (3.4)$$

Since the physics will be not changed by the z-vertex position, we can convert $\frac{Y_{Selected}}{N_{Selected}}$ to $\frac{Y_{vtx}}{N_{vtx}}$ and $\frac{Y_{INEL10}}{Y_{Selected}}$ to $\frac{Y_{INEL}}{Y_{vtx}}$ (after/before z-vertex cut). Figure 3.34 illustrates the number of event N and number of signal Y with the several step of the event selection, such as trigger selection and vertex cut.¹

For the multiplicity dependent study ($INEL>0$), the $f_{Trig} = \frac{N_{Trig}^{Event} | TrueINEL>0 }{N_{TrueINEL>0}^{Event}}$ is used instead of the f_{norm} so that the result is normalised to $\frac{Y_{INEL>0}}{N_{INEL>0}}$.

3.6.2 p_T -differential Yields

Figure 3.35 shows the p_T spectra for $\Sigma(1385)^+$, $\Sigma(1385)^-$, and $\Xi(1530)^0$ (and their antiparticles) in the various multiplicity classes, as well as the ratios of these spectra to the inclusive $INEL>0$ spectrum.

For $p_T < 4$ GeV/c, the hardening of the p_T spectra from low to high-multiplicity events is clearly visible, while at higher p_T the spectra have the same shape regardless the multiplicity class, indicating that the

¹The "vtx" means the state the good vertex selection is done. The "INEL10" means inelastic event with vertex- z cut.

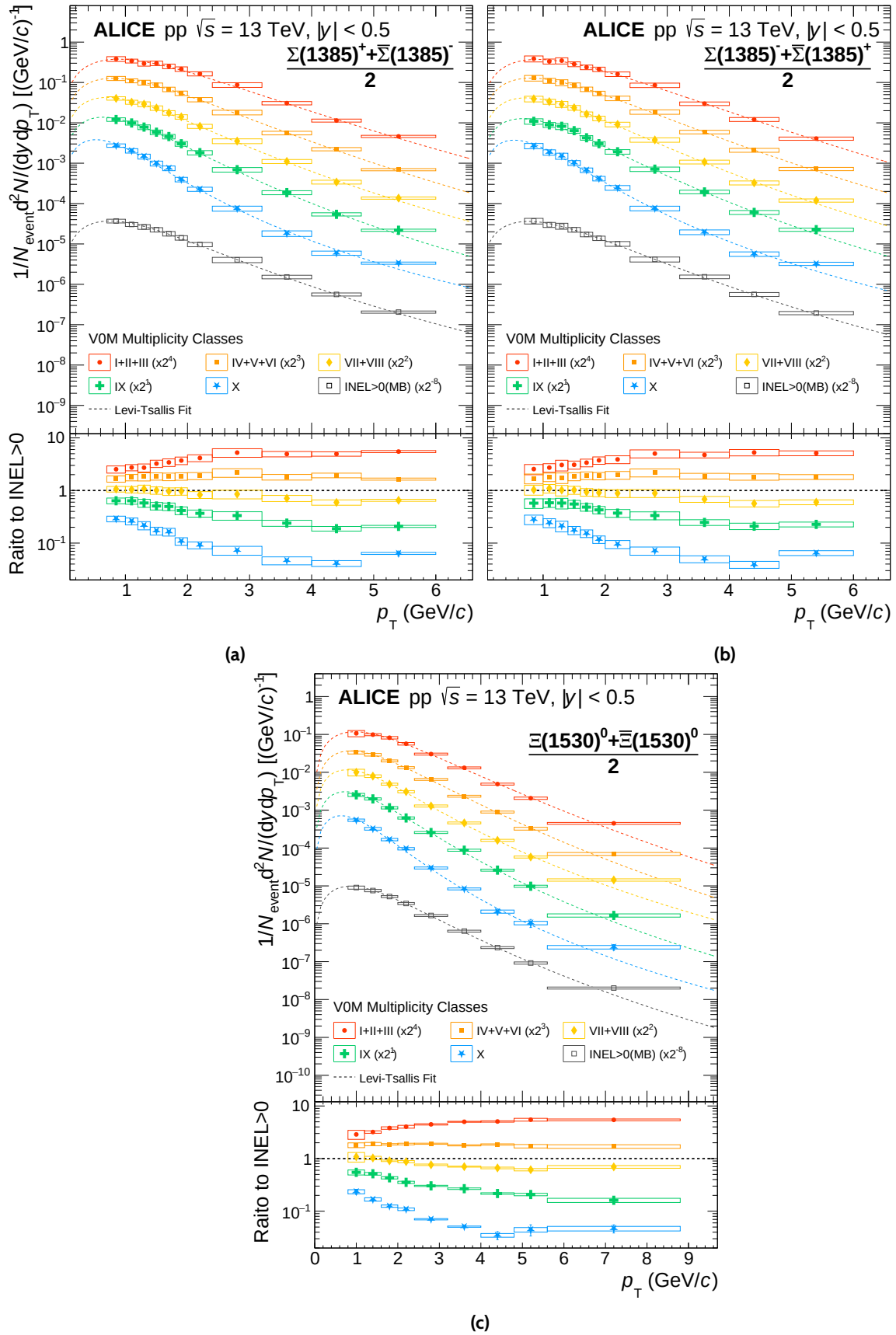


Figure 3.35. Invariant yields of $\Sigma(1385)^+$ (a), $\Sigma(1385)^-$ (b) and $\Xi(1530)^0$ (c) in pp collisions at $\sqrt{s} = 13$ TeV in multiplicity classes and the inclusive case ($\text{INEL} > 0$). Statistical and total systematic uncertainties are shown by error bars and boxes, respectively. The bottom panels show the ratios of the multiplicity dependent spectra to $\text{INEL} > 0$. The systematic uncertainties on the ratios are obtained by considering only contributions of uncorrelated uncertainties. The dashed lines represent the fits to the spectra with the Lévi-Tsallis function.

processes that change the shape of the p_T spectra in different multiplicity classes are dominant at low p_T . Similar behaviour was reported for other hadrons [85].

Each spectrum is fitted with a Lévi–Tsallis function [86]

$$\frac{1}{N_{\text{event}}} \frac{d^2N}{dp_T dy} = p_T \frac{dN}{dy} \frac{(n-1)(n-2)}{nC [nC + m_0(n-2)]} \left[1 + \frac{\sqrt{p_T^2 + m_0^2} - m_0}{nC} \right]^{-n}, \quad (3.5)$$

where N_{evt} is the number of events in the given multiplicity class, m_0 is the PDG mass of the particle, and n , C and the integrated yield dN/dy are free parameters of the fit. This function is successfully used to describe most of the identified particle spectra in pp collisions [29, 80]. For each multiplicity class, the corresponding Levi-Tsallis function is drawn as a dashed line Fig. 3.35.

3.6.3 Integrated Yield and Mean p_T

Fits of the spectrum

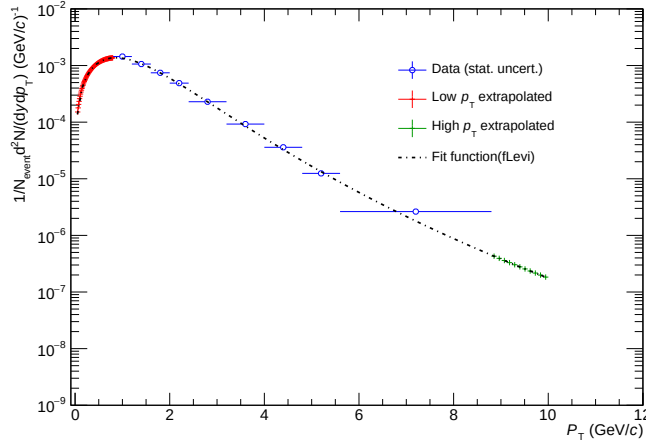


Figure 3.36. Low/high- p_T extrapolated spectra by using Levi-Tsallis distribution. Red point show the low- p_T extrapolated histogram and green points for high- p_T extrapolation.

The p_T -integrated dN/dy and $\langle p_T \rangle$ can be extracted from the corrected spectra with several fitting function. For the integrated yield, use the measured yield by counting the bin contents and error as a base, and use the integration of the fitted function in low p_T region ($0 - 0.7$ GeV/ c for $\Sigma(1385)^\pm$, $0 - 0.8$ GeV/ c for $\Xi(1530)^0$) and higher p_T region ($6.0 - 10.0$ GeV/ c for $\Sigma(1385)^\pm$, $8.8 - 10.0$ GeV/ c for $\Xi(1530)^0$).

For the resonance study, Levy-Tsallis function, m_T exponential function, p_T exponential function, Boltzmann distribution [87], Fermi-Dirac distribution, Boltzmann-Gibbs blast wave function was used to fit the final result. the p_T exponential function is not used in $\Sigma(1385)^\pm$ fitting since the fit does not converge. They are fitted in several p_T region, but some functions are fitted only in limited range since some functions are fit well only in low p_T region. All fitting variation is shown at table 3.8 for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$.

Table 3.8. Spectra fitting function with several fitting range

Distributions	$\Xi(1530)^0$ Fit Range		$\Sigma(1385)^\pm$ Fit Range	
	p_T start	p_T end	p_T start	p_T end
m_T exponential				
Boltzmann				
Fermi-Dirac	0.8	2.0, 2.4, 3.2	0.7	2.0, 2.4, 3.2
p_T exponential			Not used	Not used
Levy-Tsallis				
Blast wave	0.8	2.4, 3.2, 4.0, 4.8, 5.6, 8.8	0.8	2.0, 2.4, 3.2, 4.0, 4.8, 5.6, 8.8

Figure 3.36 shows an example of low/high- p_T extrapolated spectra of $\Xi(1530)^0$. One can easily find that the red points corresponding to the low- p_T extrapolated histogram and green points for high- p_T extrapolation.

Statistical uncertainty Statistical uncertainty of the fit is estimated by following procedure:

1. Get low/high- p_T extrapolated spectra using fitted Levi-Tsallis distribution. The uncertainty of these histograms are determined from `TF1::IntegralError()`
2. Generate 1000 spectra which has randomly shifted points
 - Set bin content to $y + k \times \sigma$ where y is original bin content and σ is statistical uncertainty.
 - the random factor k is obtained from standard deviation ($N(0, 1)$)
 - this modification is done for all bins separately, different k factor.
 - Same random factor k is used in low/high- p_T extrapolated spectra.
3. Fill a histogram of obtained total dN/dy value from the 1000 random spectra.
4. Take RMS value of the histogram as a statistical uncertainty (Fig.3.37, left)

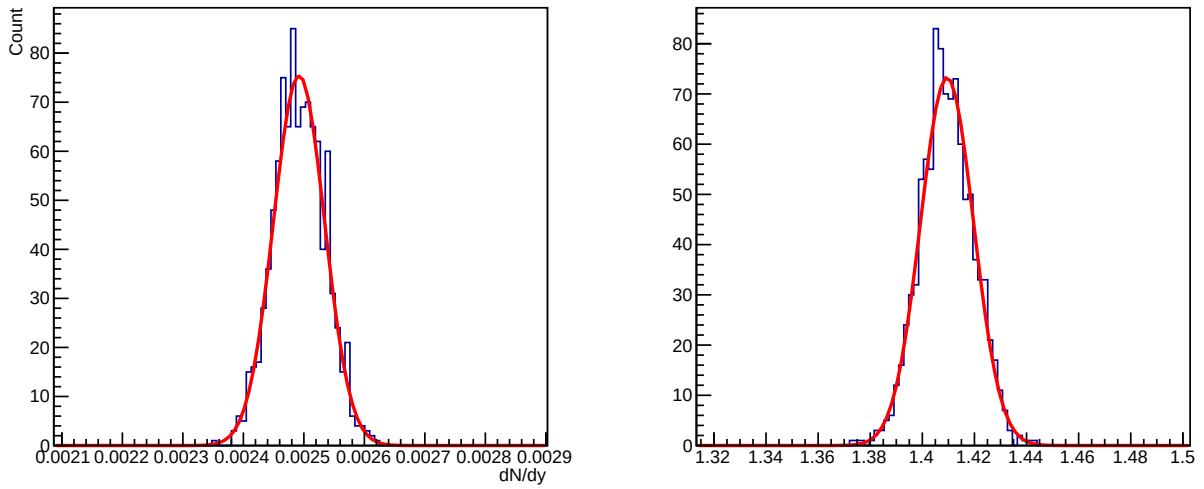


Figure 3.37. Example of the distribution of dN/dy and $\langle p_T \rangle$ from 1000 randomly generated spectra. The distribution is fitted with the Gaussian distribution and the σ of the fit is used as a statical uncertainty.

Systematic Uncertainty It has 3 different sources of systematic uncertainties:

- Choosing fit functions to extrapolate low/high p_T part.
- Uncertainty from grouped systematic study.
- p_T -independent uncertainties (Section 3.5.4)

For the first, fitting function variation uncertainty is calculated by using many fitting function with various fit range which was explained in section 3.6.3. Figure 3.38 shows the example of the extrapolated functions. The RMS value from the obtained values is used as a systematic uncertainty of fitting variation.

And second, the grouped systematic uncertainty of spectra is used to get the extreme spectra in the `YieldMean` macro. The extreme high spectra has all point with plus each systematic uncertainty and the extreme low spectra has minus. Fig 3.39 shows the example of the extreme histogram. the ratio to the default histogram is under the histogram. The calculated dN/dy values by using these histograms are used as a upper/lower uncertainty, and finally average value of them is used as a systematic uncertainty from the grouped systematic uncertainty.

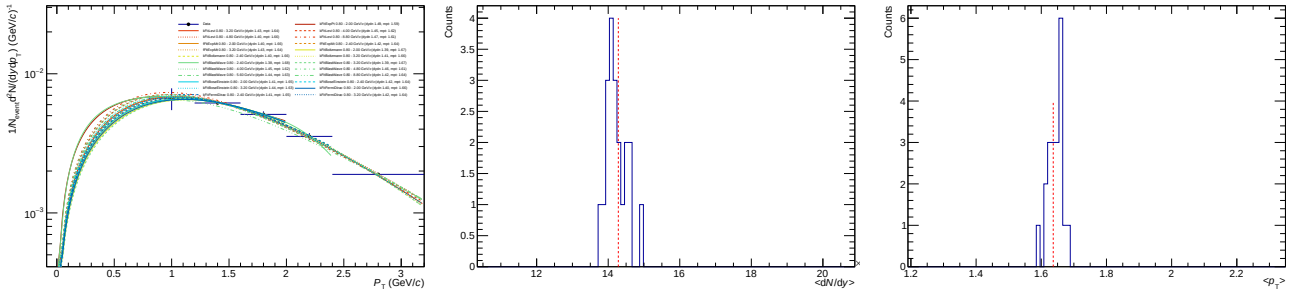


Figure 3.38. $\Xi(1530)^0$ spectra with various fit function in 0–10% multiplicity bin (left), obtained total dN/dy (center) and $\langle p_T \rangle$ (right). Red dashed line in center, right figure indicates the central value from Levy-Tsallis fit.

Finally, p_T -independent uncertainties are added by quadrature sum.

The results from different fit functions are used to calculate the systematic uncertainty from low- p_T extrapolate yield extraction. (Fig 3.38) Levi-Tsallis function with some fit region, which has best χ^2/NDF value, is used to central value.

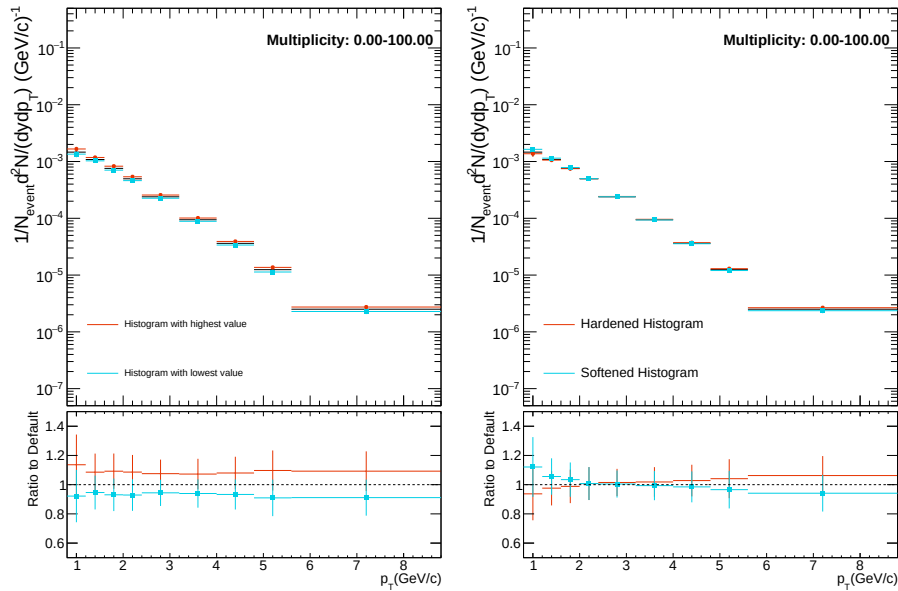


Figure 3.39. Examples of the extreme high/low histograms (left) and hard/soft histograms (right) of $\Xi(1530)^0$. The bottom figures show the ratio to the default histogram. The extreme high/low histograms are evenly larger/lower than the default. The extreme hard/soft histograms are lower/higher at lower p_T but higher/lower at high p_T region than the default.

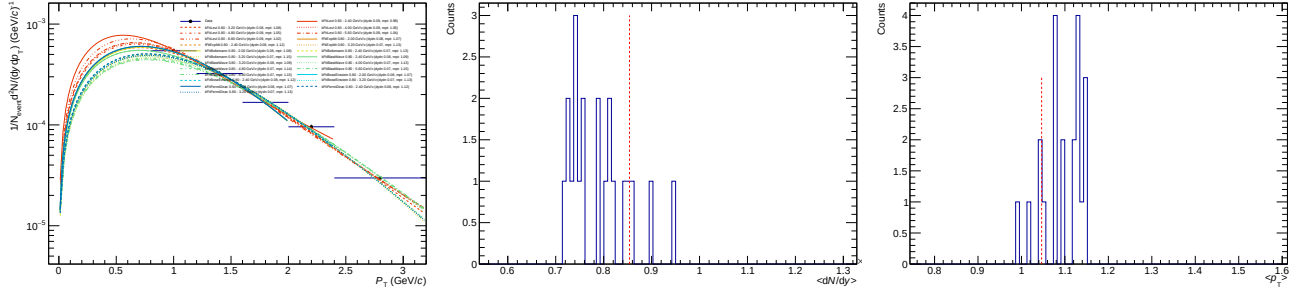


Figure 3.40. $\Xi(1530)^0$ spectra with various fit function in 70 – 100% multiplicity bin (left), obtained total dN/dy (center) and $\langle p_T \rangle$ (right). Red dashed line in center, right figure indicates the central value from Levy-Tsallis fit.

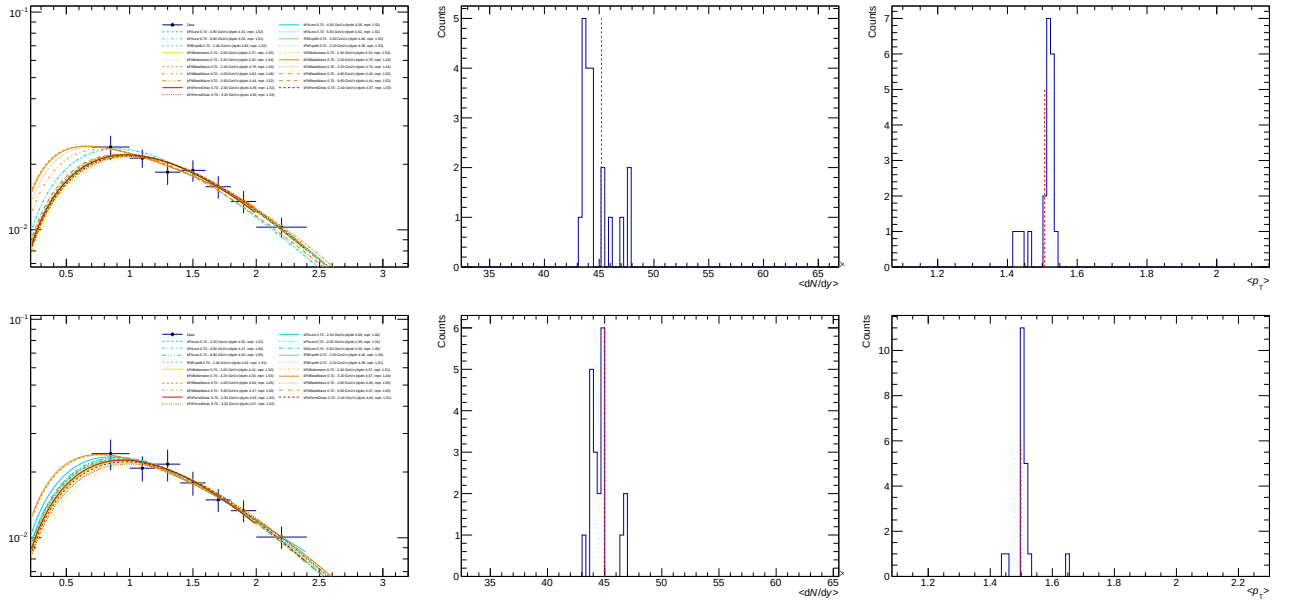


Figure 3.41. Spectra with various fit function in 0 - 10% Multiplicity bin (left), obtained total dN/dy (center) and $\langle p_T \rangle$ (right) Top: $\Sigma(1385)^+$, Bottom: $\Sigma(1385)^-$. Red dashed line in center, right figure indicates the central value from Levy-Tsallis fit.

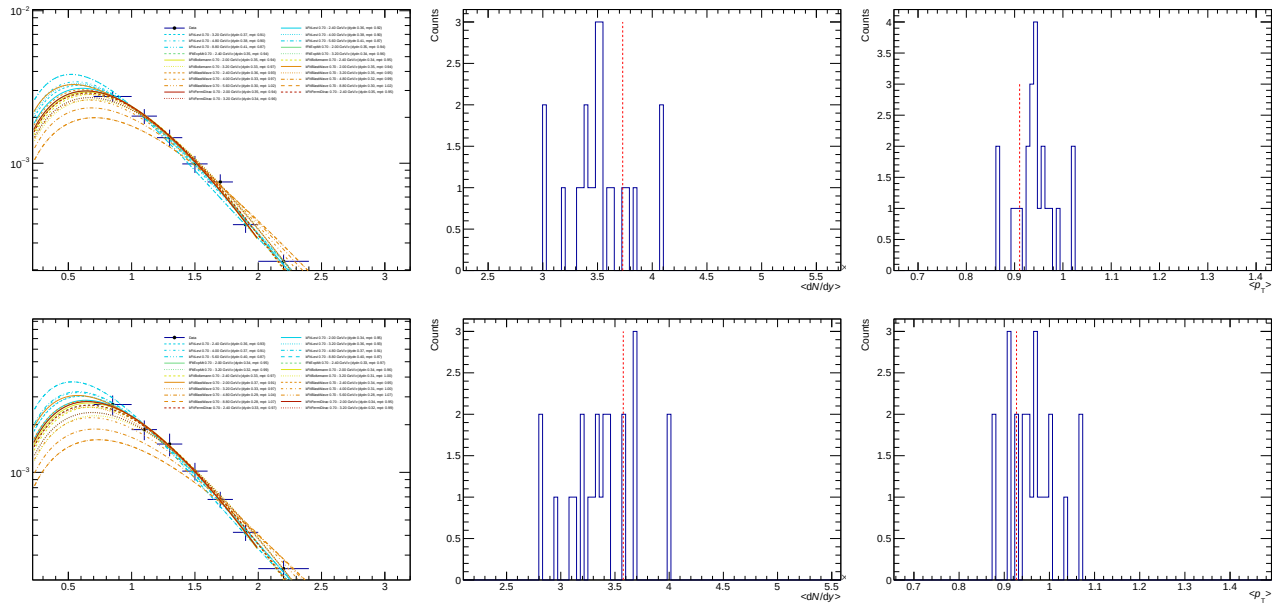


Figure 3.42. Spectra with various fit function in 70 - 100% Multiplicity bin (left), obtained total dN/dy (center) and $\langle p_T \rangle$ (right) Top: $\Sigma(1385)^+$, Bottom: $\Sigma(1385)^-$. Red dashed line in center, right figure indicates the central value from Levy-Tsallis fit.

3.6.4 Final Results

Table 3.9. The summary of the values of dN/dy and $\langle p_T \rangle$ of the resonances for each multiplicity class. Statistical (first one), total systematic (second one) and uncorrelated systematic (third one) uncertainties are quoted.

Baryon	Event Class	$dN/dy (\times 10^{-3})$	$\langle p_T \rangle$
$\Xi(1530)^0$	INEL > 0 (MB)	$4.27 \pm 0.04 \pm 0.28 \pm 0.23$	$1.44 \pm 0.01 \pm 0.08 \pm 0.08$
	I+II+III	$14.24 \pm 0.15 \pm 0.90 \pm 0.77$	$1.64 \pm 0.01 \pm 0.09 \pm 0.09$
	IV+V+VI	$7.94 \pm 0.11 \pm 0.47 \pm 0.43$	$1.44 \pm 0.01 \pm 0.08 \pm 0.08$
	VII+VIII	$4.39 \pm 0.08 \pm 0.33 \pm 0.24$	$1.30 \pm 0.01 \pm 0.08 \pm 0.07$
	IX	$2.13 \pm 0.09 \pm 0.14 \pm 0.12$	$1.22 \pm 0.03 \pm 0.07 \pm 0.07$
	X	$0.85 \pm 0.05 \pm 0.06 \pm 0.05$	$1.05 \pm 0.03 \pm 0.06 \pm 0.06$
	Inelastic	$2.97 \pm 0.07 \pm 0.17 \pm 0.16$	$1.45 \pm 0.02 \pm 0.08 \pm 0.08$
$\Sigma(1385)^\pm$	INEL > 0 (MB)	$14.81 \pm 0.11 \pm 1.23 \pm 0.80$	$1.28 \pm 0.01 \pm 0.09 \pm 0.07$
	I+II+III	$45.21 \pm 0.52 \pm 3.30 \pm 2.43$	$1.51 \pm 0.01 \pm 0.09 \pm 0.08$
	IV+V+VI	$26.43 \pm 0.34 \pm 2.03 \pm 1.42$	$1.33 \pm 0.01 \pm 0.08 \pm 0.07$
	VII+VIII	$15.20 \pm 0.25 \pm 1.20 \pm 0.82$	$1.18 \pm 0.01 \pm 0.07 \pm 0.06$
	IX	$8.67 \pm 0.18 \pm 0.65 \pm 0.47$	$1.07 \pm 0.01 \pm 0.06 \pm 0.06$
	X	$3.73 \pm 0.01 \pm 0.30 \pm 0.20$	$0.91 \pm 0.01 \pm 0.05 \pm 0.05$
	Inelastic	$11.04 \pm 0.08 \pm 0.67 \pm 0.59$	$1.27 \pm 0.01 \pm 0.08 \pm 0.07$

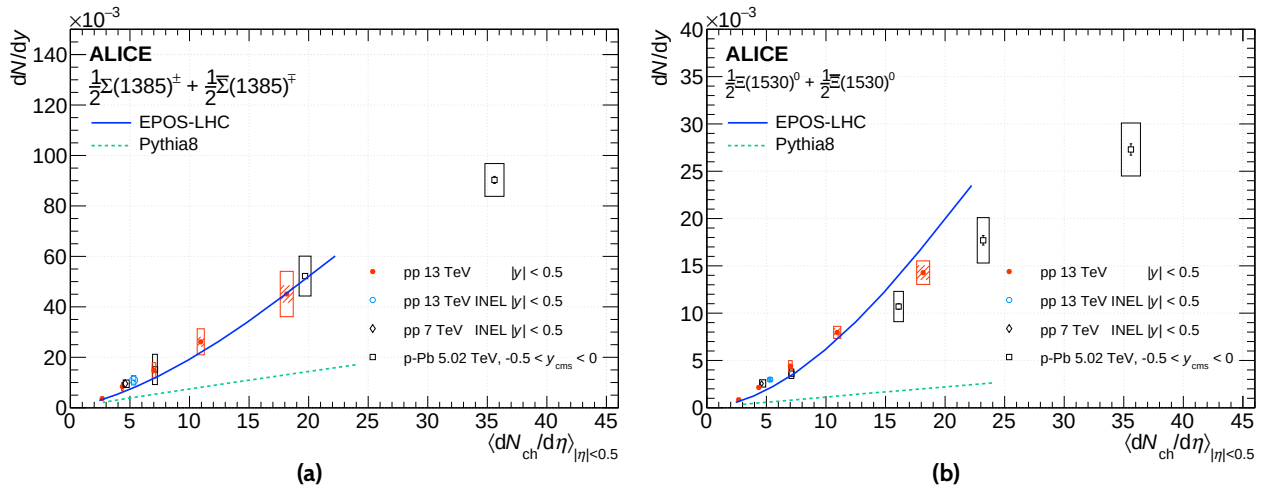


Figure 3.43. The values of dN/dy as a function of multiplicity $\langle dN_{ch}/d\eta \rangle$ for $\Sigma(1385)^\pm$ (a) and $\Xi(1530)^0$ (b). The open and shaded boxes represent the total and p_T -correlated systematic uncertainties, respectively. Solid blue lines indicates the model prediction from EPOS LHC [35] and green dashed-lines from PYTHIA 8 [34].

Table 3.9 summarises the values of the mid-rapidity yield integrated over p_T (dN/dy) and the mean transverse momentum ($\langle p_T \rangle$) for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ assessed in each multiplicity class. The relative amounts of the yield in the unmeasured low- p_T region compared to the measured region are about 26–43% and 21–43% for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$, respectively. The amounts from the high- p_T region are negligible. Fit functions such as Boltzmann and Fermi-Dirac, m_T -exponential, and p_T -exponential are alternatively hired to estimate the systematic uncertainty due to the choice of the fit functions, which gives 3–4% of uncertainty for both particles.

Figure 3.43 shows the mid-rapidity yield integrated over p_T , dN/dy , as a function of the multiplicity and in comparison with the values at a different energy like $\sqrt{s} = 7$ TeV and in a different collision system like p–Pb, previously measured by ALICE [88, 89]. The integrated yields depend on multiplicity only, irrespective of the collision energy and system. This is consistent with previous findings at the LHC [79], highlighting the fact that the mechanisms of particle production are related only to the variables that determine the multiplicity. The increasing trend of dN/dy versus $\langle dN_{ch}/d\eta \rangle$ of both $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ is reproduced by Monte Carlo models; Pythia8 (green curve in Fig. 3.43), however, predicts a much milder increase, whereas EPOS LHC [35] (blue curve in Fig. 3.43) is in perfect agreement with data for $\Sigma(1385)^\pm$ and only slightly overestimates the data for $\Xi(1530)^0$ at the highest multiplicity.

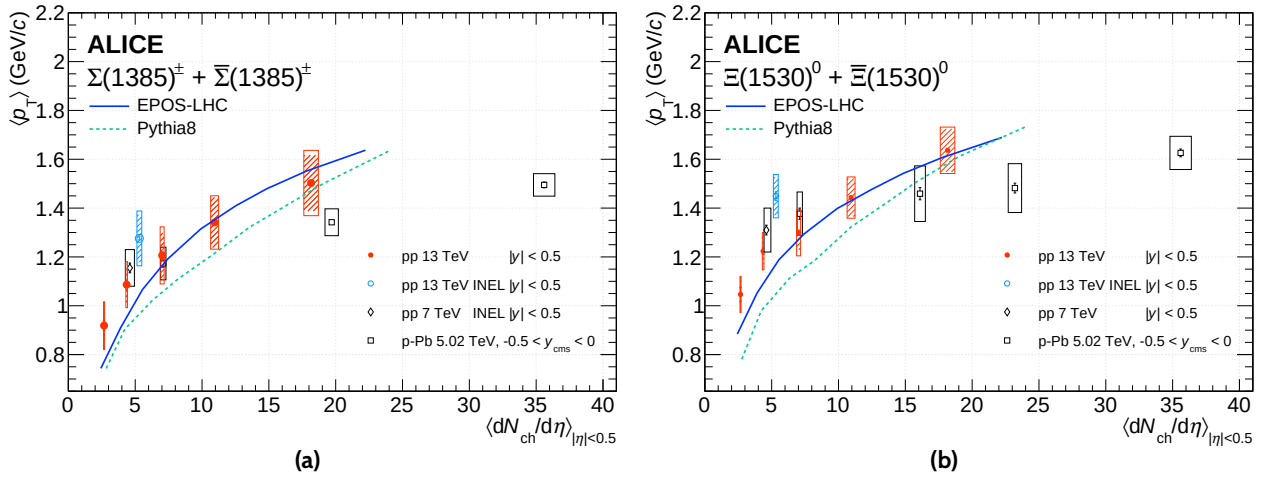


Figure 3.44. $\langle p_T \rangle$ as a function of multiplicity for $\Sigma(1385)^\pm$ (a) and $\Xi(1530)^0$ (b). The open and shaded boxes represent the total and p_T -correlated systematic uncertainties, respectively. Solid blue lines show the model prediction from EPOS LHC and green dashed-lines from PYTHIA 8.

Figure 3.44 shows the mean transverse momentum $\langle p_T \rangle$ for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ as a function of the charged-particle multiplicity. Those are compared with the values in pp collisions at $\sqrt{s} = 7$ TeV and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, which were previously measured by ALICE [88, 89]. The increasing trend of the $\langle p_T \rangle$ as a function of the system size in pp collisions is steeper than the one in p–Pb collisions for both $\Sigma(1385)^\pm$ and $\Xi(1530)^0$, consistently with the previous findings in pp collisions at $\sqrt{s} = 7$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [90]. The increasing trend and the predicted values are well described by EPOS LHC (blue curve). PYTHIA 8 reproducing the increasing trend, however, it underestimates the data for lower $\langle dN_{ch}/d\eta \rangle$.

Chapter 4

Measurement of d and ^3He in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

The analyses of the (anti-)deuteron production and of the (anti-) ^3He production spectra have been carried out only in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. Based on the study of the light nuclei production in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$, this study will give the new measurement in higher energy and better resolution on ^3He measurement thanks to the bigger data sample obtained in 2018. The data sample used to the study is provided in Section 4.1, the extracted signals are shown in Section 4.3.2. Finally, the corrected p_{T} spectra is presented in Section 4.6 with integrated yield and mean p_{T} .

4.1 Data sample and Event Selection

The analyses presented in this chapter are based on the data sets of Pb–Pb collisions in 2018 at $\sqrt{s_{\text{NN}}}=5.02 \text{ TeV}$. The events were collected whenever a coincidence of signals of both sides of the VO detector was found (MB trigger). Moreover, the timing information of the VO detector paired with the timing information from the ZDC is used as a further offline rejection for events triggered by the interactions of the beams with the residual gas in the LHC vacuum pipe (Beam-Gas background). After the offline event selection, the data sample consists of about 360M events of Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

Figure 4.1 shows the distribution of the centrality percentile for the selected events. This distribution shows two bumps at 0–10% and 30–50% region due to the trigger strategy adopted during the 2018 Pb–Pb data taking that was enhancing the 0-10% (CENT) and the 30-50% (SEMI-CENT) centrality ranges. In order to have a flat centrality distribution in the ranges 20-30% and 50-90% only the events with INT7 trigger (MB trigger) are used for the analysis.

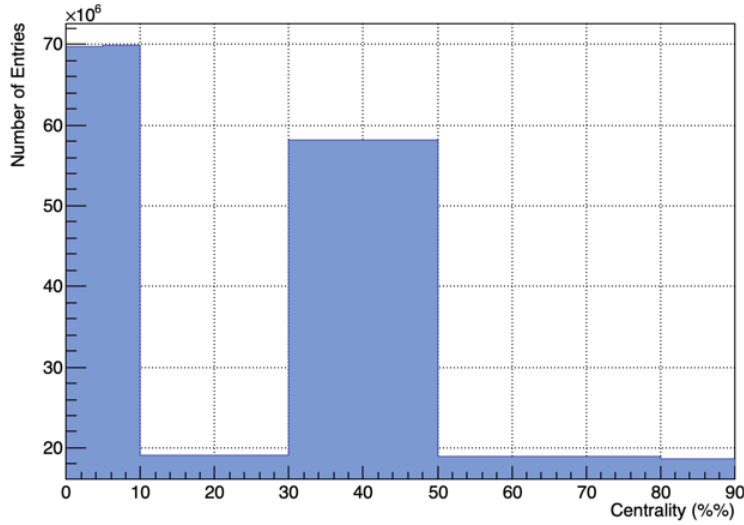


Figure 4.1. VOM centrality percentile distribution in the 2018 data sample after all event cuts. The centrality estimation, as well as the definition of the VOM estimator, are discussed in Sec. 2.3.4

The Monte Carlo (MC) samples used to compute the efficiency, acceptance and momentum shift corrections were generated using the HIJING event generator [91] with GEANT4. The conditions of data taking are applied in the MC by reproducing the actual configuration of the different detectors in the runs used for the analysis. Since the HIJING event generator used to simulate Pb–Pb collisions does not provide light (anti-)nuclei, dedicated MC samples which have injected nuclei on top of a HIJING event was used. The kinematics of the injected nuclei is chosen randomly by picking their transverse momentum p_T from a flat distribution in the range between 0 and 10 GeV/ c , their azimuthal angle from a distribution between 0 and 2π , and their rapidity from a flat distribution in the range $|y| < 1$.

Moreover, a number of additional MC production with no injected light (anti-)nuclei states, as known as *General Purpose MC*, are used to extract the DCA_{xy} templates for nuclei coming from secondary interactions.

4.1.1 Event Selection

After the online event selection, a further offline selection of the events is applied to reduce possible biases from particular conditions of the data taking, such as high interaction rate and events which has parts of detectors switched off. The typical selection used in Pb–Pb collision to obtain a symmetric acceptance is the rejection of events with the primary vertex outside the fiducial region of $\pm 10 \text{ cm}$ in the beam direction from the nominal collision point ($|z_{\text{vtx}}| \leq 10 \text{ cm}$).

Because of the high interaction rate observed in the 2018 data taking, a fraction of the triggered events contains data corresponding to more than one collision (pile-up event). To remove the pile-up event, a number of SPD vertex cut is applied. It rejects the event when it has more than n contributors in SPD vertex, where n is a parameter of the selection. From previous analyses, looking at the multiplicity dependence of the false-positive pile-up tagging, the n parameter was set to 5 for events with more than 50 tracklets, to 3 for events with less than 20 tracklets and it was set to 4 for the remaining events (adaptive pile-up rejection).

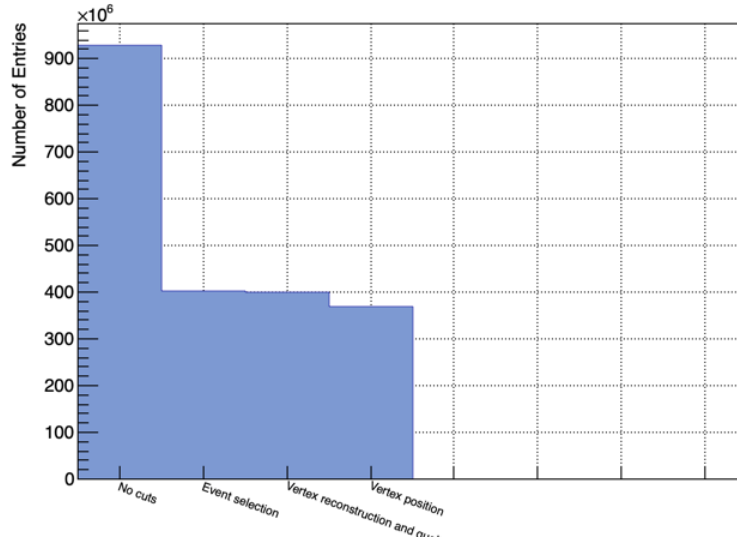


Figure 4.2. A number of event after the trigger selection, event selection and vertex selection in the 2018 data sample

This method removes only the pile-up of collisions occurring either during the same bunch crossing¹ or out of bunch pile-up within the SPD readout time (300 ns). The pile-up tagging method based on the SPD vertex finding can't reject if collisions spaced along the beam axis coordinate by less than 8 mm due to the SPD resolution. A visible effect due to the very high multiplicity events, for instance, those containing two piled up central collisions, is in the distribution of the z_{vtx} . In such conditions, the vertex finding algorithm using the reconstructed tracks fails to find the correct primary vertex. As a result, the distribution of the primary vertex z_{vtx} shows some spikes. To achieve the best condition, the selection described in Tab. 4.1 are applied to the event finally. Figure 4.2 shows the number of event accepted in each event selection step.

Table 4.1. Summary of the event selection applied for the different data samples analysed in this work. See the text for the description of the used variables.

Data sample	Selections
Pb–Pb 2018 (data + MC)	$ V_z \leq 10\text{cm}$
	Reject multiple SPD vertices with more than 5 contributors
	$ \Delta V_z \leq 20\sigma_{\text{track}}, \Delta V_z \leq 10\sigma_{\text{SPD}}$ and $ \Delta V_z \leq 0.2\text{ cm}$

To compare the result of (anti-)deuteron with other light flavoured particles, such as proton, the event is sliced with the centrality 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80% and 80-90% as used in proton analysis in Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02\text{ TeV}$. On the same reason, but having an issue with limited statistics on ^3He , the centrality interval of ^3He is selected in five bins: 0-10%, 10-30%, 30-50% and 50-90%.

¹The bunch crossing is defined as the instant when the two LHC beams cross at the ALICE interaction point. The time windows separating two bunch crossings are always multiple of 25 ns, that is the period of the LHC clock.

4.2 Track Selection

The main object of the analyses presented in this thesis is to measure the primary light (anti)nuclei produced in the collision or in the evolution stages of the system created in a HIC, in the mid-rapidity region ($|y| < 0.5$). Therefore, only tracks in the pseudorapidity region $|\eta| < 0.8$ are used in these analyses to use the best possible PID information and full tracking performance in ALICE.

Moreover, tracks are selected to have at least 70 clusters in the TPC and two points in the ITS (out of which at least one in the SPD²) for the 2% of momentum resolution and 6% of dE/dx resolution.

Table 4.2. Summary of the track selections applied in deuteron and ${}^3\text{He}$ analyses.

Track selections
$ \eta \leq 0.8$ and $ y \leq 0.5$
$n_{\text{TPCclusters}} \geq 70$, $n_{\text{ITSclusters}} \geq 2$ and $n_{\text{SPDclusters}} \geq 1$
$ \text{DCA}_z \leq 1 \text{ cm}$
$ \text{DCA}_{xy} \leq 0.1 \text{ cm}$
$\chi^2_{\text{TPC}}/n_{\text{TPCclusters}} \leq 4$
$\chi^2_{\text{ITS}}/n_{\text{ITSclusters}} \leq 36$
Reject kink topologies
3σ Tracking PID in TPC for (anti-) ${}^3\text{He}$
A hit machied in the TOF for (anti-)deuteron

In order to suppress the contribution of secondary nuclei only tracks with $|\text{DCA}_z| \leq 1 \text{ cm}$ are selected. The main secondary deuteron contribution comes from the knock-out deuterons produced by the interaction of primary particles with the material of the beam-pipe and of the detector materials and it is relevant for the production spectra and the elliptic flow measurements for $p_T \leq 1.4 \text{ GeV}/c$. It is known that weak decays comes from the charged three-body decay of the hypertriton (${}^3_{\Lambda}\text{H} \rightarrow d + p + \pi^-$) and of the anti-hypertriton (${}^3_{\Lambda}\bar{\text{H}} \rightarrow \bar{d} + \bar{p} + \pi^+$) give a negligible contribution to the secondary (anti-)deuterons, so it's ignore in deuteron analysis. The contribution of hypertriton to ${}^3\text{He}$ is known that it gives $\sim 1.8\%$ of uncertainties. Therefore, it is accounted for when the total systematic uncertainty is calculated. Tracks of weak-decay products (kink) are rejected as the deuteron is a stable nucleus. Finally, 3σ cut of the track PID, which is performed in data taking with online information, is applied to ${}^3\text{He}$ analysis to suppress the contamination from ${}^3\text{H}$. When the TOF PID is used, a hit matched to the track extrapolation in the TOF sensitive area is required.

Table 4.2 summarises the total track selection criteria applied to the (anti)deuteron and (anti) ${}^3\text{He}$.

²The requirement of at least one point in the SPD assures a resolution better than $300 \mu\text{m}$ [92] on the distance of closest approach to the primary vertex in the plane perpendicular (DCA_{xy}) and parallel (DCA_z) to the beam axis for the selected tracks.

4.3 Raw Spectra Extraction

(anti-)deuteron and (anti-) ^3He are identified in the TPC and TOF detectors as described in Sec. 2.2.2 and Sec. 2.2.3. For ^3He analysis, only TPC PID while deuteron analysis uses both TPC and TOF PID for effective selection.

4.3.1 Signal Extraction for ^3He using TPC PID

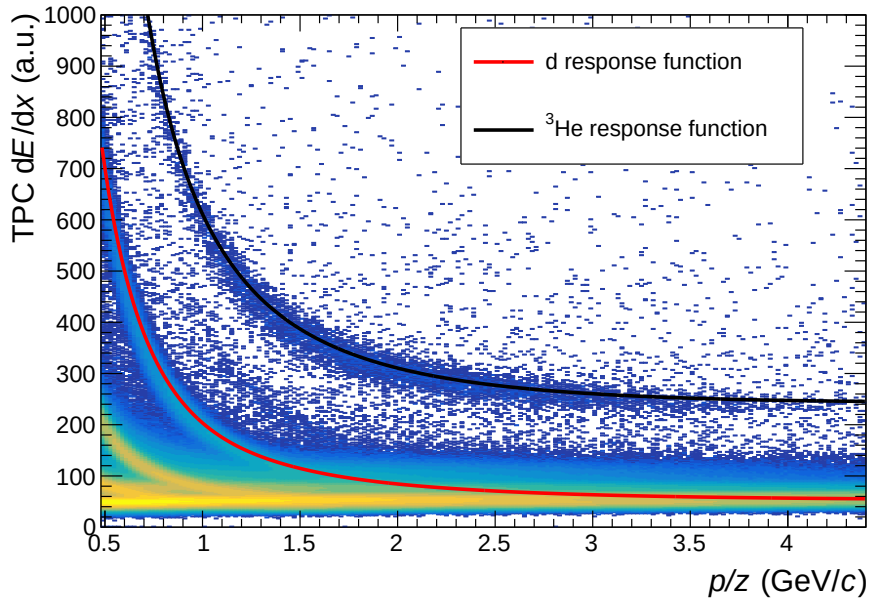


Figure 4.3. An example of specific energy loss dE/dx in the TPC active volume for negative particles as a function of the particle rigidity in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV recorded in 2015. The solid lines represent the expected TPC response for deuterons (red) and ^3He (black).

Figure 4.3 shows the specific energy loss dE/dx for negative particles in the TPC active volume and the expected signal for deuterons and ^3He for the 2015 Pb–Pb data sample. The solid red line (deuteron) shows a good separation at low momentum but overlaps with the other particles at $p_T \sim 2.0$. For sake of simplicity, (anti-)deuteron analysis is performed using the combined TPC and TOF PID as described in Sec. 4.3.2. On the other hand, for the ^3He , which has charge $z = 2e$, the TPC PID information provides a clear identification as shown in solid black line in Fig. 4.3.

^4He which has charge $z = 2e$ as like ^3He , might contaminate the TPC PID distribution but it can be neglected in this analysis since its expected production rate is approximately 300 times smaller. In the low momentum region, the specific energy loss dE/dx of ^3He becomes similar to the one of the ^3H . So this is the main contamination of ^3He analysis.

The TPC PID $n\sigma$ distribution is used to count the number of produced ^3He in a particular transverse momentum interval. The TPC PID $n\sigma$ is obtained as:

$$n\sigma = \frac{(dE/dx)_{\text{measured}} - (dE/dx)_{\text{expected}}^{^3\text{He}}}{\sigma^{^3\text{He}}} \quad (4.1)$$

where $(dE/dx)_{\text{measured}}$ is the measured specific energy loss in TPC volume, $(dE/dx)^{^3\text{He}}_{\text{expected}}$ is the expected specific energy loss for the ^3He and $\sigma^{^3\text{He}}$ is the detector resolution for the ^3He .

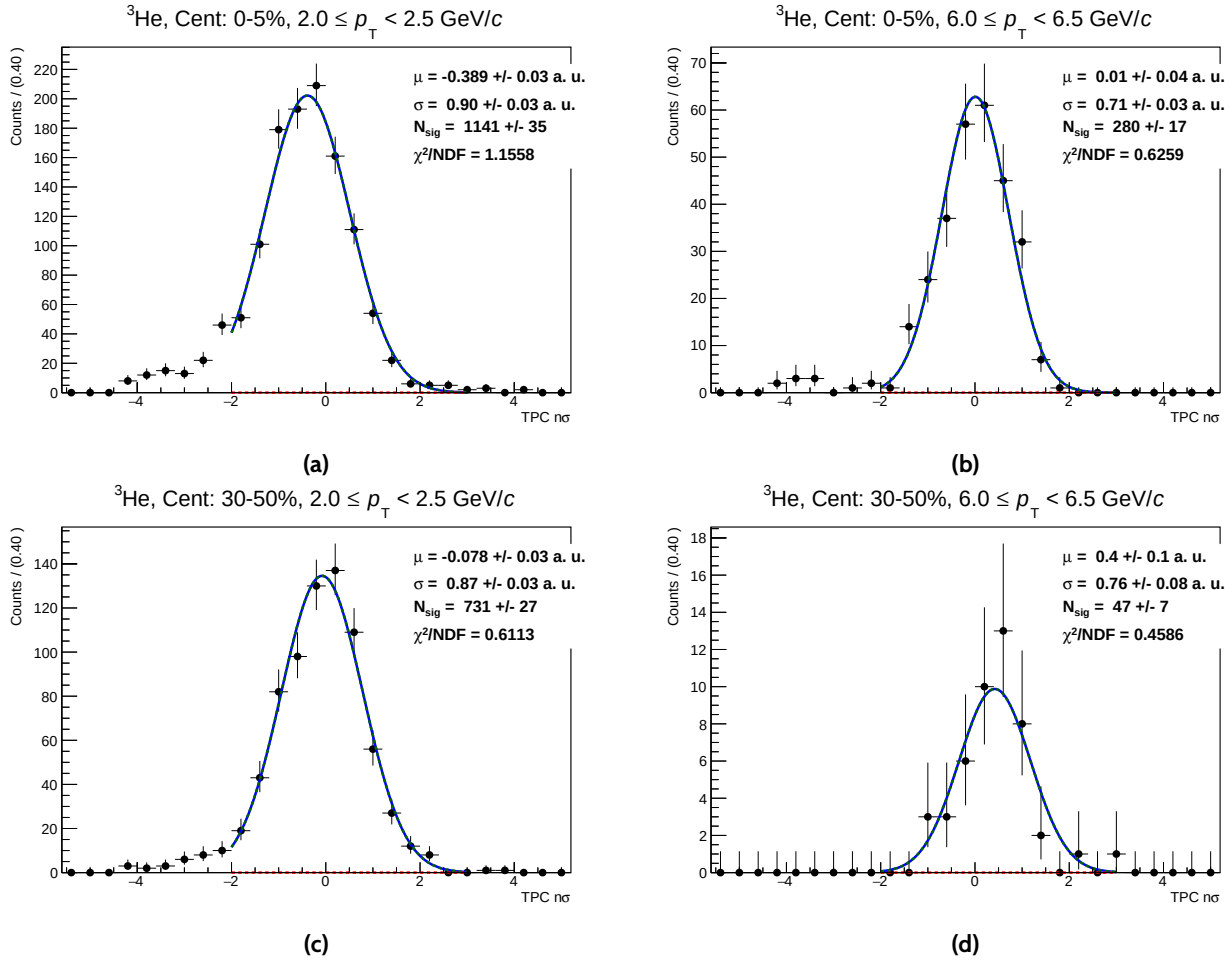


Figure 4.4. $n\sigma$ distributions for ^3He in the $2.0 \leq p_{\text{T}} < 2.5 \text{ GeV}/c$ bin. The blue lines show the fitted function which was used to determine the bin counting range for the signal extraction.

Figure 4.4 shows the $n\sigma$ distributions for ^3He in two p_{T} bins and centrality bins. The $n\sigma$ of the ^3He is expected to be placed around 0σ but, as shown in Fig. 4.4, a shift to negative direction is observed. For the purpose of the yield computation for the spectra analysis, this shift can be ignored as the entries can be computed starting from the mean of the observed distribution within a 3σ interval.

Although the tracking PID was applied in track selection in order to reduce the contamination from ^3H , one can find rest of ^3H in Fig. 4.4a around left tail of the distribution. The reason of the contamination from ^3H is due to secondary ^3H nuclei from knock-out interactions of other primary particles with the experiment material. For this reason, such a contamination is not present in the $n\sigma$ distributions for the $^3\overline{\text{He}}$.

The $n\sigma$ is fitted with the double gaussian function for the better estimation of the yield. The raw yield of ^3He is obtained by integrated the fitting function. Error is obtained from the fit result. As a systematic variation, bin-counting method with several variation of range widening and shifting are considered.

Finally, Figure 4.5a and Figure 4.5b show the raw counts extracted with the procedure mentioned above.

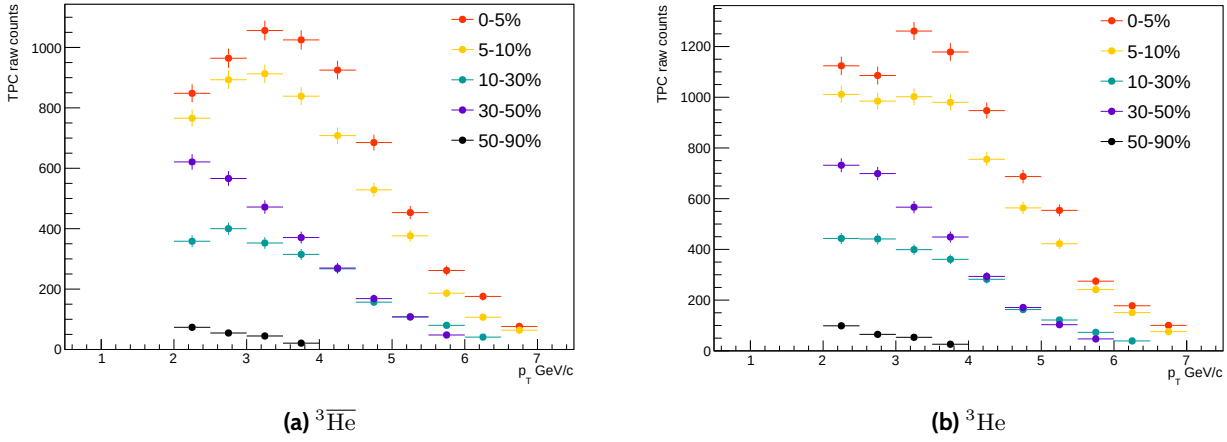


Figure 4.5. Raw counts for ${}^3\text{He}$ and ${}^3\overline{\text{He}}$ in the p_T range where the procedure for the signal extraction described in the text was feasible.

4.3.2 Signal Extraction for Deuterons using TPC+TOF

The signal extraction for (anti)deuterons is performed by combining the information of the specific energy loss dE/dx measured by the TPC with that of the time of flight measured by the TOF. For this reason, an additional track requirement is set for the deuteron analysis: a hit matched in the TOF detector that provides.

The Lorentz β of the particle can be calculated from the timing information $t_{\text{TOF}c}$ and the track length L measured in the tracking procedure:

$$\beta = \frac{L}{t_{\text{TOF}c}}, \quad (4.2)$$

where c is the speed of light.

By combining this with the measured particle momentum p , the particle mass can be estimated as:

$$m = \frac{\sqrt{1 - \beta^2}}{\beta} p. \quad (4.3)$$

(anti)deuterons can be discriminated from lighter species over a wide momentum range thanks to the excellent TOF timing resolution (≈ 80 ps in Pb–Pb collisions) as shown in Fig 2.8.

Even though one can use the excellent discrimination from TOF β , it is impossible to get a clean identification without a background in Pb–Pb events since the background from mismatched TOF hits: in high multiplicity events, the TOF resolution can be not enough to possible match more than one hit. And when more than one hit can be associated, the closest to the track extrapolation is chosen. The probability of TOF miss matching is not negligible ($\sim 20\%$ for pions at $1 \text{ GeV}/c$ in the most central Pb–Pb collisions [93]) and it is higher for low momentum particles. The presence of mismatched hits can be seen in the PID plots (Fig. 2.8) as hits which does not correspond to any particle species expected signal. Additional 3σ of TPC PID cut is applied to (anti-)deuteron analysis to remove mismatched TOF signal effectively. This additional TPC PID cut helps to reduce the background from mismatched TOF hits in the p_T region where the TPC provides a good separation of deuteron from the lighter species (up to $p_T \sim 1.8 \text{ GeV}/c$).

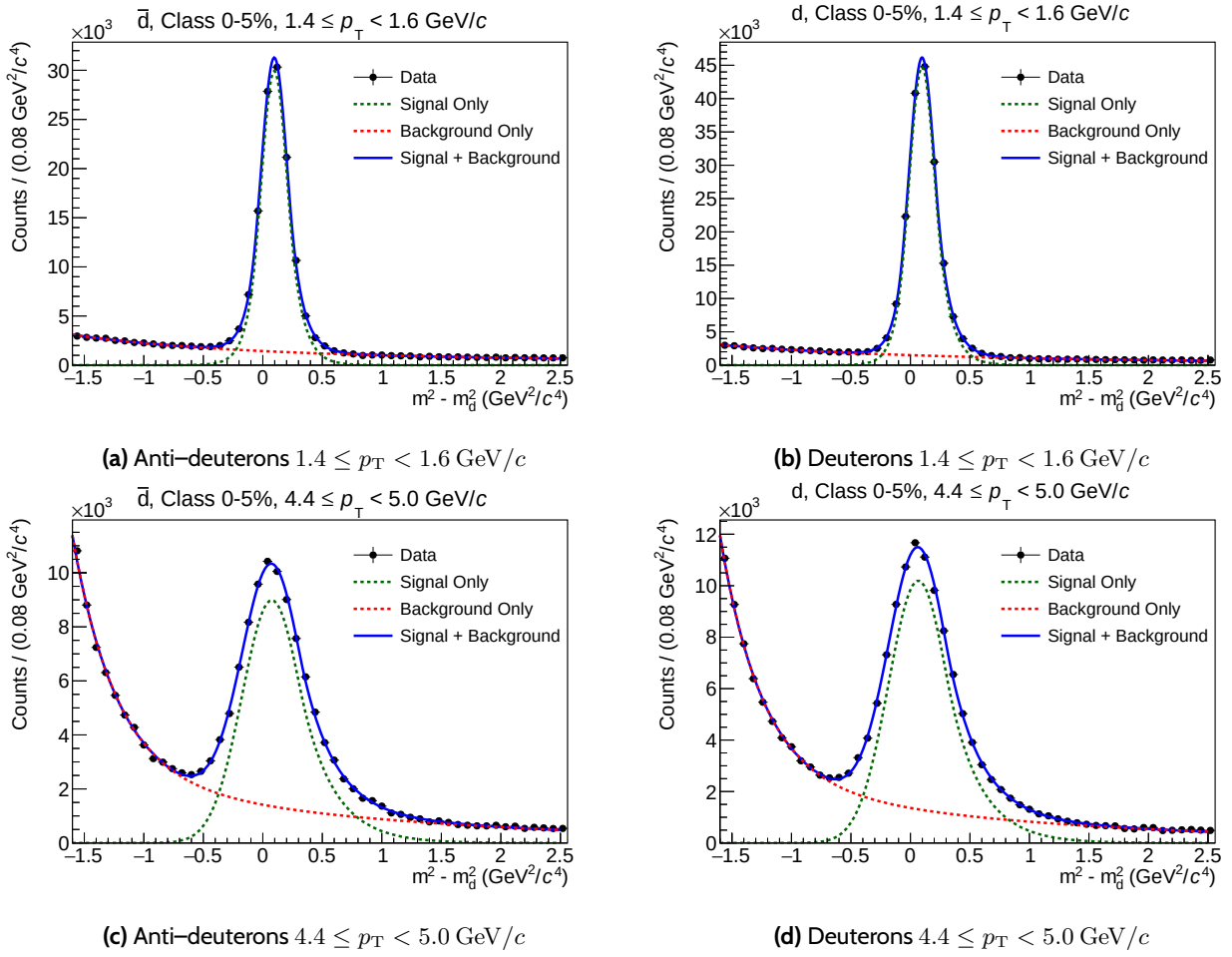


Figure 4.6. $m^2 - m_{\text{PDG}}^2$ distributions for anti-deuterons (left) and deuterons (right) in two p_T bins (top and bottom) extracted in the 0-5% centrality interval of the 2018 dataset. The dashed line and the dotted line are the background and signal components of the model respectively. The blue line represents the total fit to the distributions.

Figure 4.6 shows two examples of the distribution of the measured mass squared m^2 shifted by the squared nominal mass of the (anti)deuteron m_{PDG}^2 at low p_T and the other at higher p_T .

The (anti)deuteron signal S is fitted by using a Gaussian distribution with an exponential tail:

$$S(x; N_{\text{raw}}, \mu, \sigma, n) \propto N_{\text{raw}} \begin{cases} \exp \left[-\frac{1}{2} \left(\frac{x-\mu}{\sigma} \right)^2 \right] & \text{for } x \leq \mu + n\sigma \\ \exp \left[-n \left(\frac{x-\mu}{\sigma} - \frac{n}{2} \right) \right] & \text{for } x > \mu + n\sigma \end{cases} \quad (4.4)$$

where N_{raw} is the number of signal counts, μ and σ is the mean and the standard deviation of the gaussian respectively, while n is the number of σ s at which S becomes an exponential function.

All parameters of the distribution are free in the fitting procedure, therefore, the shift in the $m^2 - m_{\text{PDG}}^2$ distribution can be easily recovered by the determination of the μ parameter in the fit. The slope of the exponential is defined such that the S function and all its derivatives are continuous and differentiable.

For the background description, a sum of two exponentials are used: one exponential for mismatched TOF hits shape around the signal peak, and the other for the tail of the proton distribution at high p_T (e.g.

Figure 4.6c). The raw yields and errors are taken from the fit directly since they are in the parameters of the fit. As a systematic variation, bin-counting method with several variation of range widening and shifting are considered.

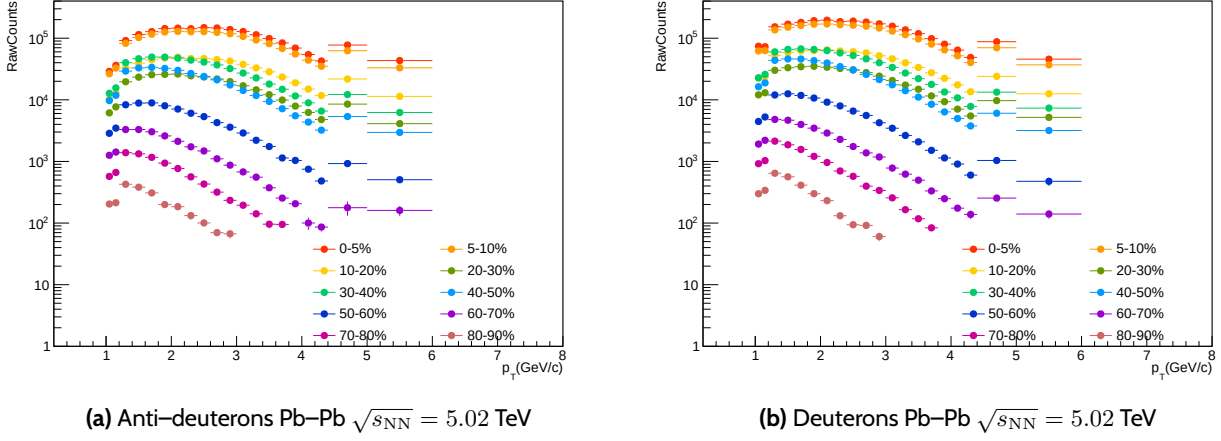


Figure 4.7. Raw yields for anti-deuterons (left) and deuterons (right) represented with different colours for the different centrality classes.

Figure 4.7 show the raw yield spectra for deuterons and anti-deuterons in the different centrality classes. The main factor that limits the p_T region of the raw yield extraction is the available amount of events and the stability of the corrections applied to the raw spectra.

Signal distributions from all p_T bins used in this analysis can be found in from Fig. 4.8 to Fig. 4.11 for (anti-)deuterons in most central (0–5%) event and most peripheral (80–90%) event. Figure 4.12 and Fig. 4.13 shows the signal distribution from all p_T bins for (anti-) ^3He in most central (0–5%) event and most peripheral (50–90%) event.

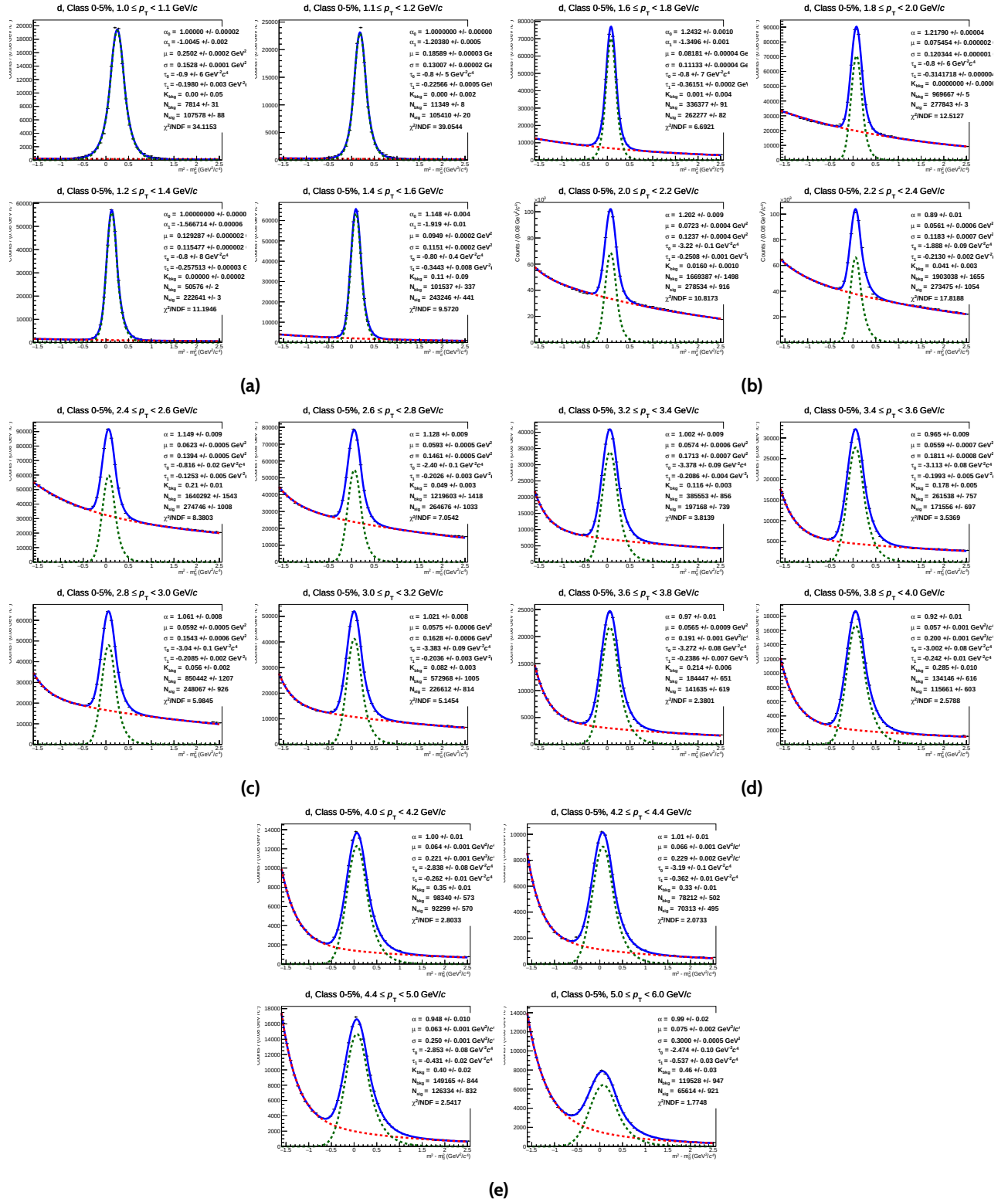


Figure 4.8. Signal Extraction of deuteron in 0–5% centrality bin

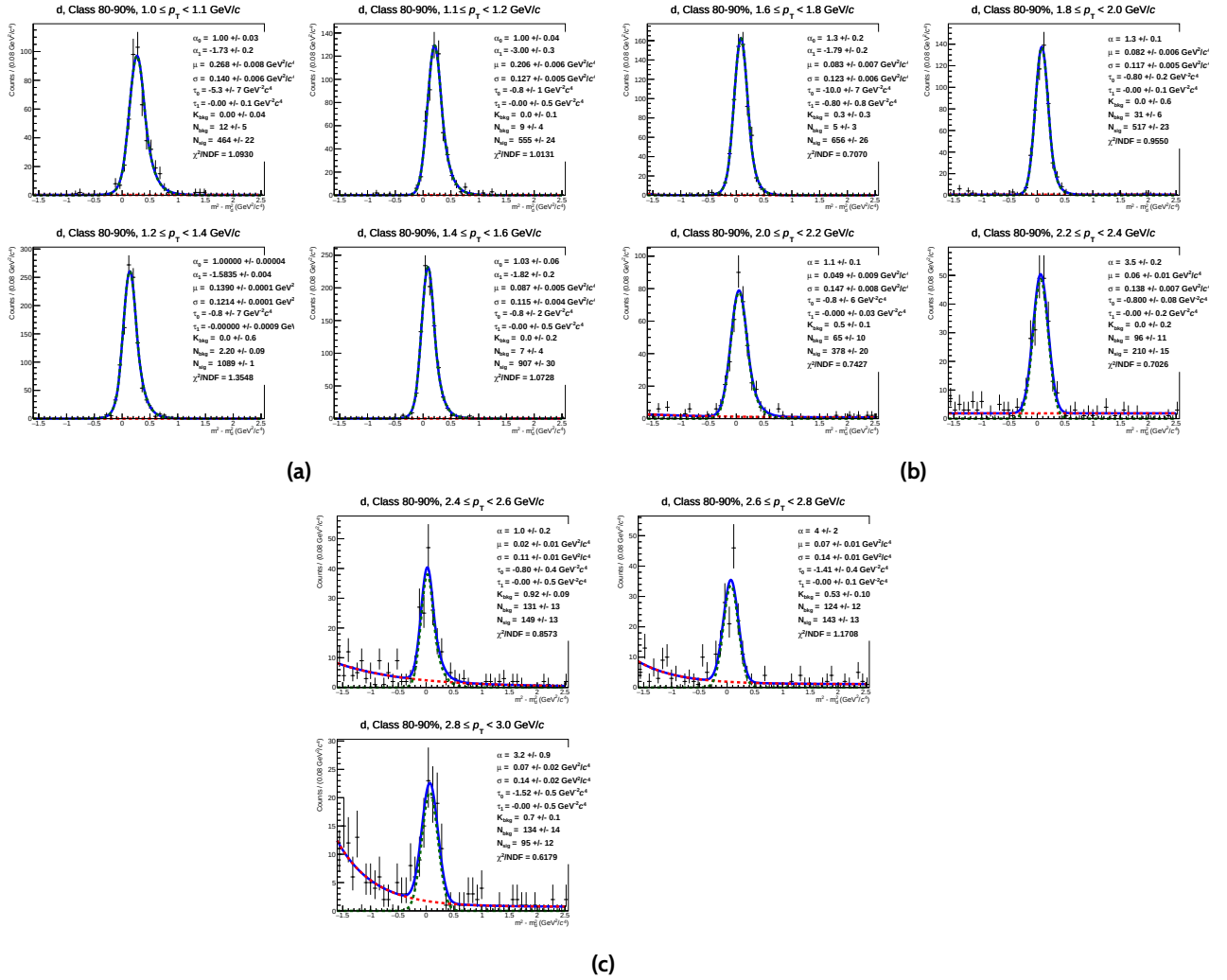


Figure 4.9. Signal Extraction of deuteron in 80–90% centrality bin

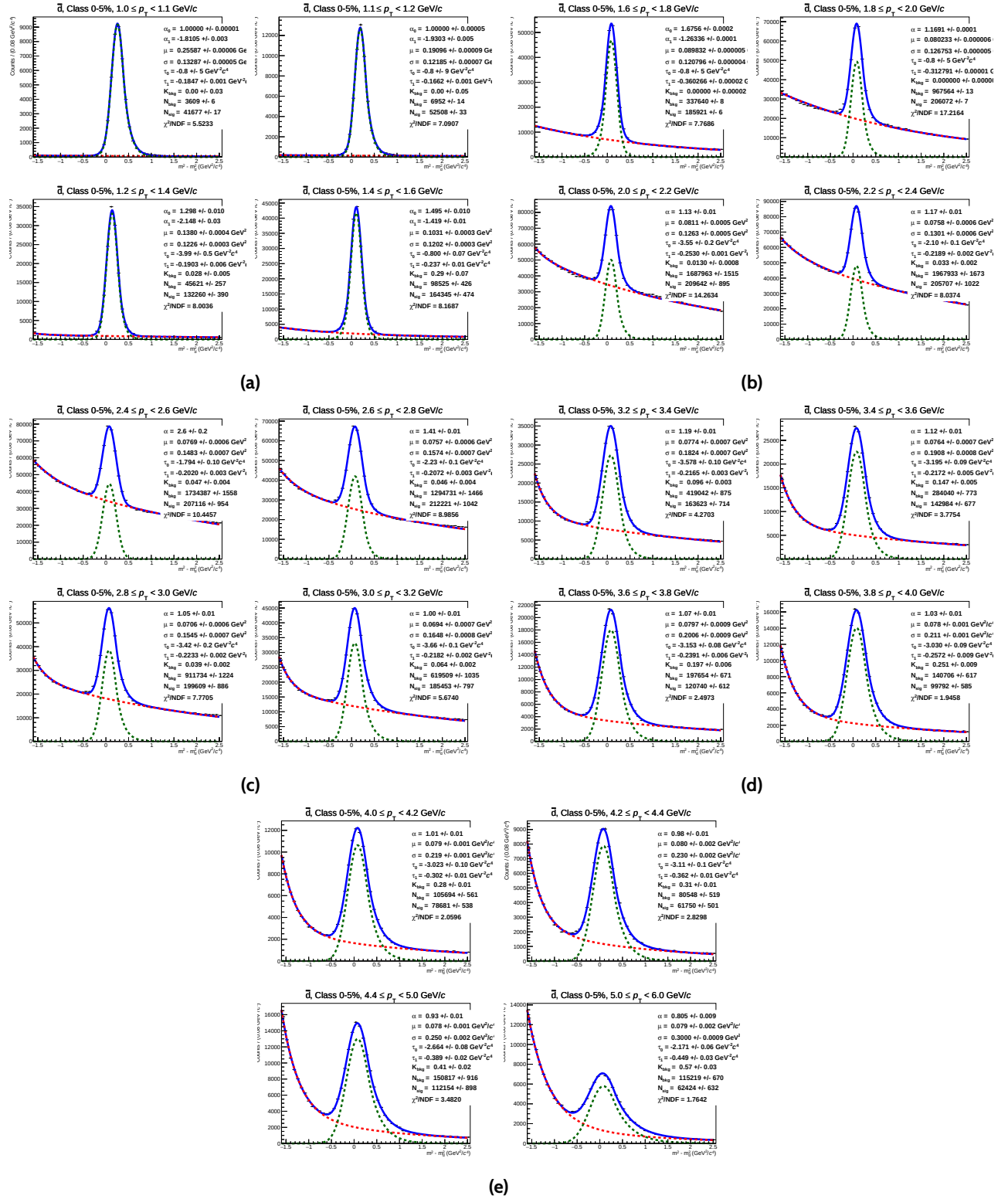


Figure 4.10. Signal Extraction of anti-deuteron in O–5% centrality bin

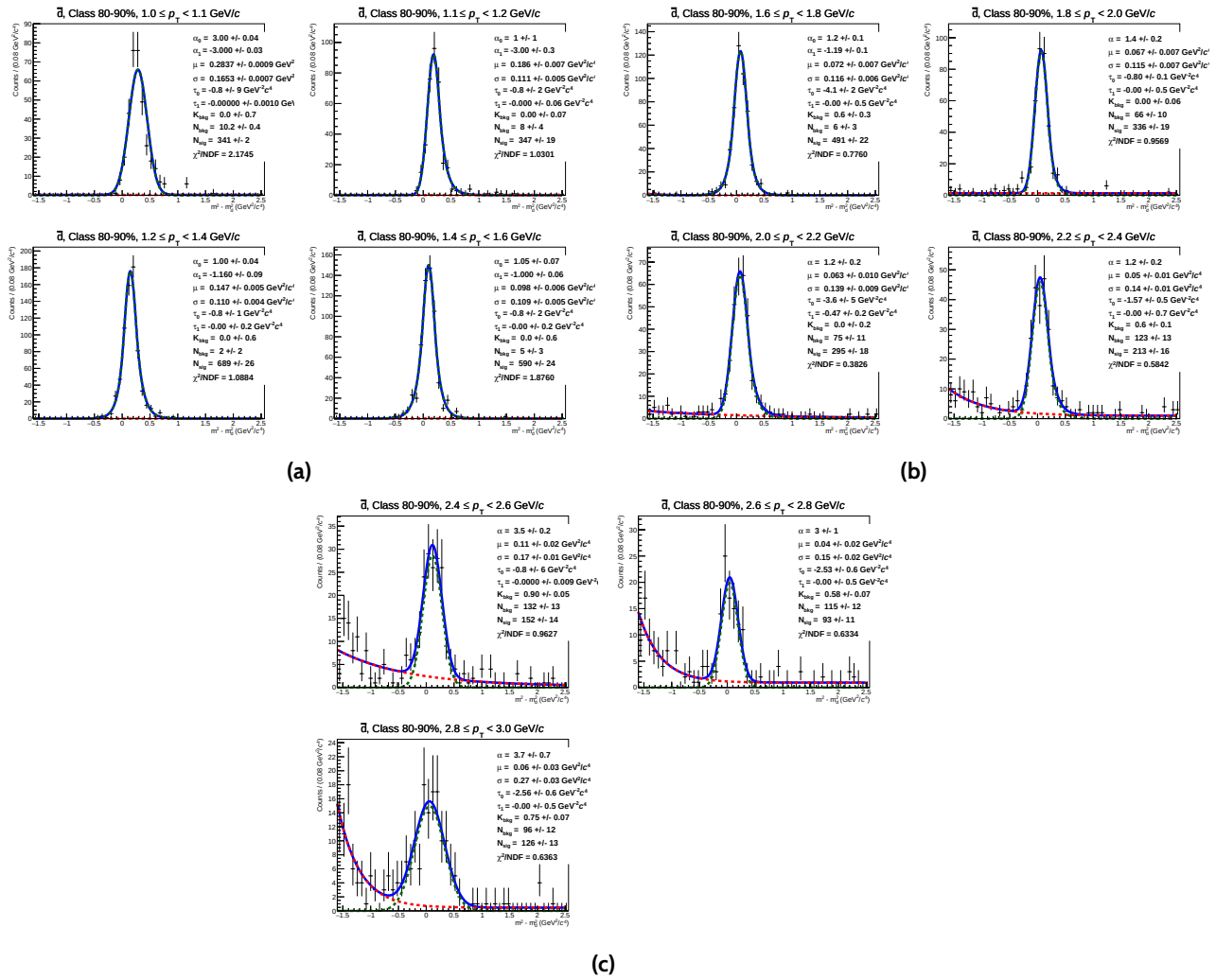
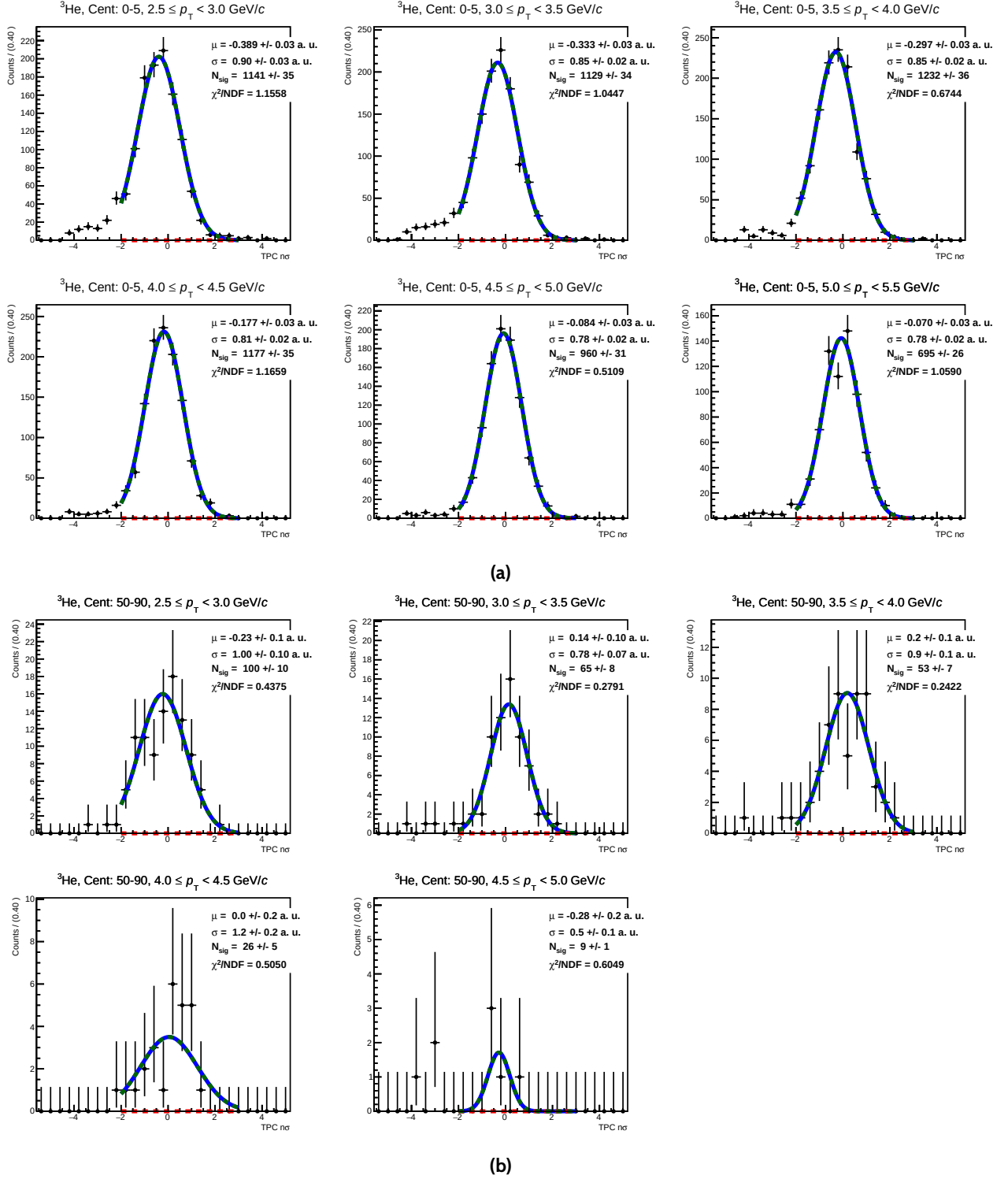
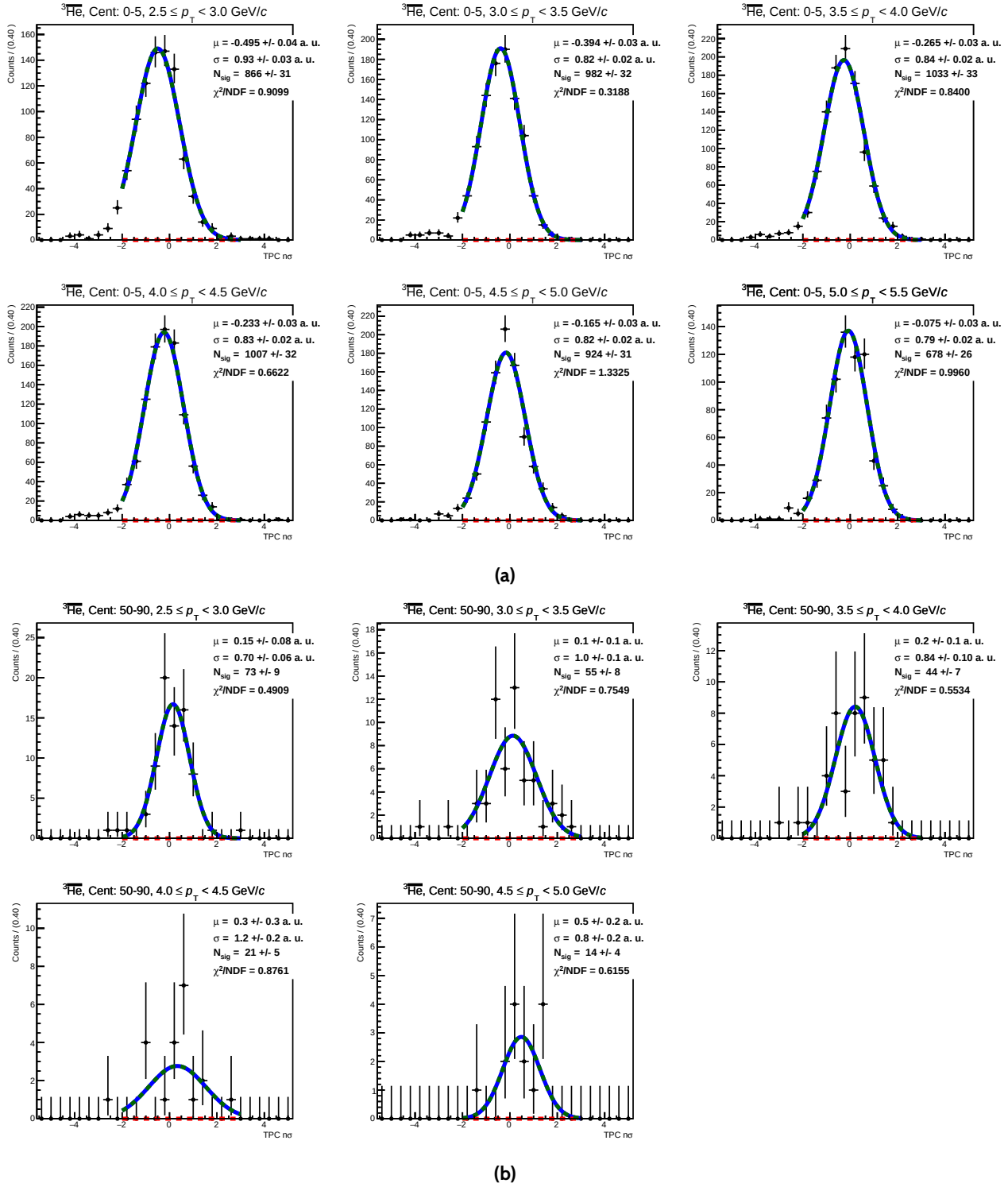


Figure 4.11. Signal Extraction of anti-deuteron in 80–90% centrality bin

Figure 4.12. Signal Extraction of ${}^3\text{He}$ in 0–5% (a) 50–90% (b) centrality bin

Figure 4.13. Signal Extraction of anti- ^3He in 0-5% (a) 50-90% (b) centrality bin

4.4 Monte-Carlo Correction

The raw yields of (anti-)deuterons and (anti-) ${}^3\text{He}$ are corrected to obtain the real production spectra. The tracking efficiency with the detector acceptance and the contamination from secondary particles will be discussed in Sec. 4.4.1 and Sec. 4.4.2, respectively.

4.4.1 Efficiency $\times$ Acceptance

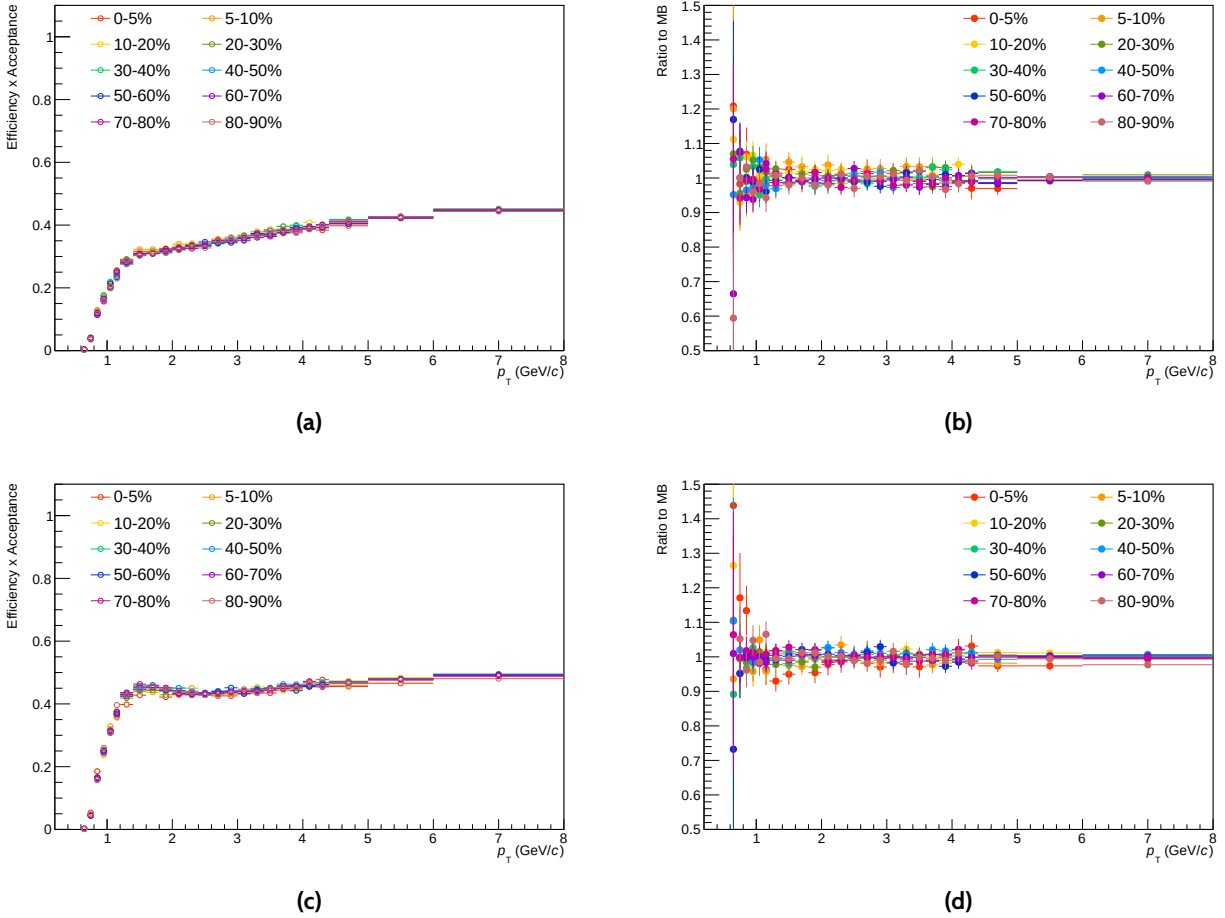


Figure 4.14. On the left: anti-deuteron (top) and deuteron (bottom) efficiency times acceptance computed as a function of the centrality for the 2018 datasets. On the right: ratio between the efficiency times acceptance computed in centrality bins and the one computed without any centrality selection for (anti)deuterons (top) and deuterons (bottom).

As discussed in the ALICE track reconstruction section, Sec. 2.3.2, the reconstructed tracks are not fully efficient (Fig. 2.12). In addition to this, the analyses have applied a lot of further cuts in Sec. 4.2. Therefore, the number of raw yields needs a correction for their inefficiency. It is corrected by using a MC simulation where the full geometry and data taking conditions are reproduced.

The number of particles crossing the detector is known when using a MC simulation and the efficiency can be defined as:

$$\epsilon \times A(p_T^{\text{rec}}) = \frac{N_{\text{rec}}(p_T^{\text{rec}})}{N_{\text{gen}}(p_T^{\text{gen}})}, \quad (4.5)$$

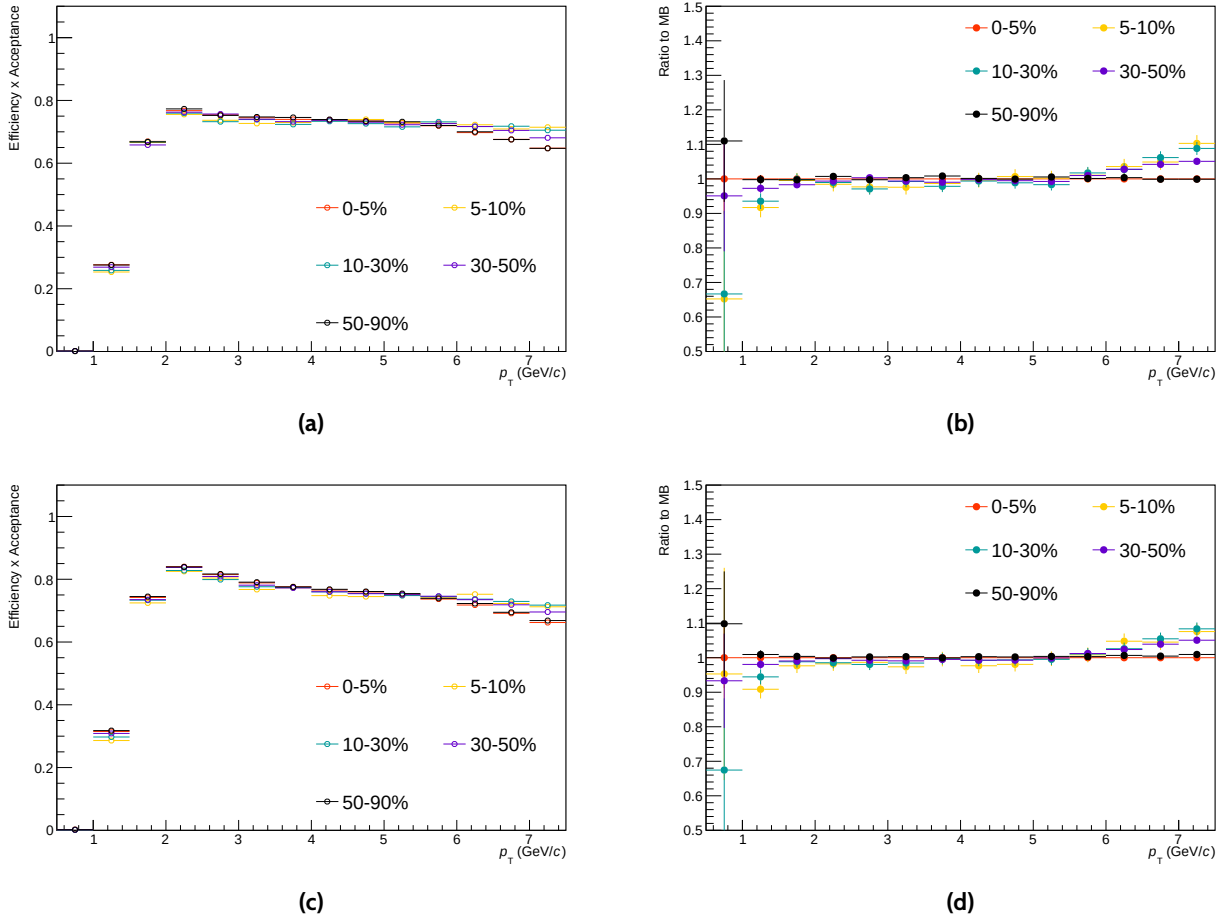


Figure 4.15. On the left: anti- ^3He (top) and ^3He (bottom) efficiency times acceptance computed as a function of the centrality for the 2018 datasets. On the right: ratio between the efficiency times acceptance computed in centrality bins and the one computed without any centrality selection for (anti) ^3He (top) and ^3He (bottom).

where ϵ is Efficiency, A is Acceptance, p_T^{gen} and p_T^{rec} are the p_T generated by the event generator and the p_T measured by the tracking algorithm respectively; N_{gen} is the number of particles generated in the azimuthal region $0 \leq \phi < 2\pi$ and in the rapidity region $|y| < 0.5$. N_{rec} is the number of tracks corresponding to one of the particle species of interest satisfying the selection criteria summarised in Table 4.2.

Based on Fig. 4.14b and Fig. 4.14d, no centrality dependence is observed for (anti)deuteron in the Pb-Pb at $\sqrt{s_{\text{NN}}}=5.02$ TeV sample. Hence, the efficiency from MB (0–90%) event is used for the correction of (anti)deuteron to have better statistics on the MC events. This is not possible for (anti) ^3He , since the acceptance $\times$ efficiency for these particles shows a trend with centrality (Figure 4.15 and its subfigures).

Nuclei Absorption Correction Efficiency $\times$ Acceptance obtained with GEANT4 is needed to be corrected because the measured inelastic cross sections of (anti)nuclei are different compared to the default parametrizations implemented in GEANT4. A dedicated study [94] has been performed based on the relationship using two parameters: the relative uncertainty on the inelastic cross section and the detector thickness in units of hadronic interaction length. Table 4.3 summarises the correction parameters applied in the

Efficiency $\times$ Acceptance. The systematic uncertainty on this absorption correction has to be added in the total systematic uncertainty.

Table 4.3. Summary of the correction factors obtained in the nuclei absorption study.

Particle	Correction Function
deuterons (TOF)	$0.99653 \cdot \text{TMath::Power}(\text{pt}, 0.00068)$
antideuteron (TOF)	$1.06380 \cdot \text{TMath::Power}(\text{pt}, -0.02353)$
helium-3 (TPC)	$0.99274 \cdot \text{TMath::Power}(\text{pt}, 0.00143)$
antihelium-3 (TPC)	$1.04948 \cdot \text{TMath::Power}(\text{pt}, -0.01525)$

4.4.2 Secondary Particle Background

The secondary nuclei, such as coming from the interactions of other primary particles with the detector material, is one of the main sources of background in nuclei analysis. The typical momentum of, for instance, deuterons produced with the knock-out processes with the detector material is less than $1.4 \text{ GeV}/c$.

Although it is important to correct for the knock-out production for the deuteron production spectra, the p_{T} region in which the ${}^3\text{He}$ productions is studied is less affected by this source of background. This correction is only applied to nuclei, not to anti-nuclei since the baryon number conservation sets a very high energy threshold for the production of secondary anti-nuclei with similar processes.

Other processes, such as the decay of (anti-)hypernuclei, represent a negligible fraction of the observed (anti)deuterons as discussed in Sec. 4.2. On the contrary, the decay of (anti)hypernuclei represents a significant systematic uncertainty for the (anti) ${}^3\text{He}$ production as no effective correction can be put in place in this case, as it will be discussed in the next Section.

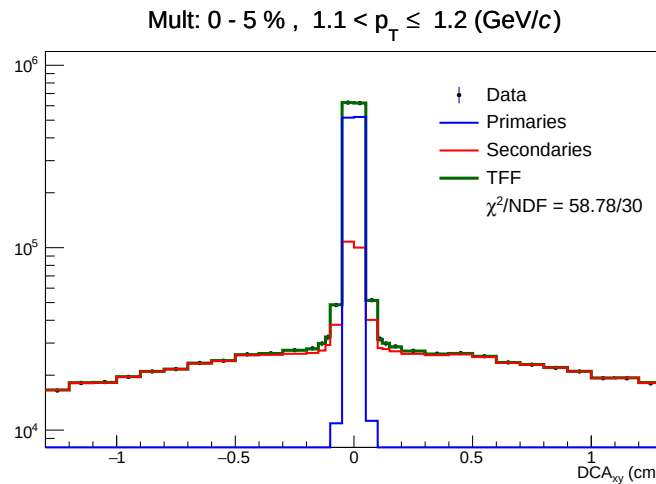


Figure 4.16. Fit to the DCA_{xy} distribution (black points) of deuteron candidates. The green line is the fit result and it represents the sum of the primary particle component (blue line) and secondary particle one (red line).

To remove the contamination of secondary deuterons, it is possible to study the Distance-Of-Closest (DCA) approach distributions on the transverse plane (DCA_{xy}) of the deuteron candidates. Primary particles are expected to have a distribution with a clear peak around $\text{DCA}_{xy} = 0 \text{ cm}$, which is the expected value

for particles coming from the primary vertex. On the other hand, secondary particles are expected to have a flat DCA_{xy} distribution at the first order, which means no dependency in the transverse plane.

Wrong SPD Cluster Extrapolation Unfortunately, not only the knock-out production was the source of the secondary contamination, but also there was an additional effect that originated from the detector algorithm: There are fake primary tracks distributed around $DCA_{xy} \approx 0$ in the case of the tracks corresponding to secondary particles are associated with a wrong cluster in the SPD, which makes a wrong extrapolation pointing to the primary vertex since the track pointing is mostly given by the SPD clusters. It happens to less than 10% tracks in the most central Pb–Pb collisions.

For this reason, the *primary fraction* of observed deuterons is extracted by fitting the observed DCA_{xy} distribution using histogram templates for the primary particles and secondary particles component. Since anti-deuterons are known to be produced only in the primary collision, they can be used to build a realistic DCA_{xy} distribution also for the deuterons. Thus, this was used as the histogram template of the primary deuterons. The histogram template of the secondary deuterons used for the fit is filled from MC production, where both the identity and the origin of every particle are known. For the template of the secondary deuteron, more than 90M events of general purpose MC is used to achieve better statistics. Moreover, the binning of DCA_{xy} distribution is re-binned to use only 4 bins around $DCA_{xy} = 0$ region. This helps to improve the fitting result.

An example of a fit to the DCA_{xy} distribution is shown in Figure 4.16, where it is possible to see that the secondary particle component (red line) has a peak structure at $DCA_{xy} = 0$ cm. The fit is done in a range of DCA_{xy} wider than the actual track selection criterium (< 0.1 cm Table 4.2) to better constrain the fit of the component of the secondary particle, that populates mostly the tails of the DCA_{xy} distribution. One can find the broad binning around $DCA_{xy} = 0$ as describe before.

TFractionFitter The fraction of primary deuterons is computed using the methods implemented in the class of fraction fitter, `TFractionFitter` [84], which is included in the framework ROOT [95]. This algorithm enables the possibility of fitting an experimental distribution using some of the templates obtained from MC generated samples, keeping into account the statistical uncertainties on the MC histograms in the likelihood maximisation. This is attained by considering the true value of each bin of the MC samples as one fit parameter. As a result, the MC components fitted to the data will not have exactly the same shape they had before being fed to the fitting algorithm. For this reason, `TFractionFitter` has to be applied only if the statistical uncertainties of the MC samples are small, otherwise, the likelihood maximisation can almost adapt any input shape to the data. The primary and secondary templates used in this analysis have small statistical uncertainties, thus it is suitable for the fitter.

Figure 4.17 shows the fraction of primary particles as a function of p_T computed in all the centrality bins covered by this analysis. It is possible to see a clear dependence of the fraction of primary deuterons with centrality: in peripheral events (i.e. low multiplicity events, purple colour) the fraction of primary deuterons is higher than in central events (i.e. high multiplicity events, red colour). This can be easily explained since the higher flux of particles in the detector material makes a higher fraction of secondary particles.

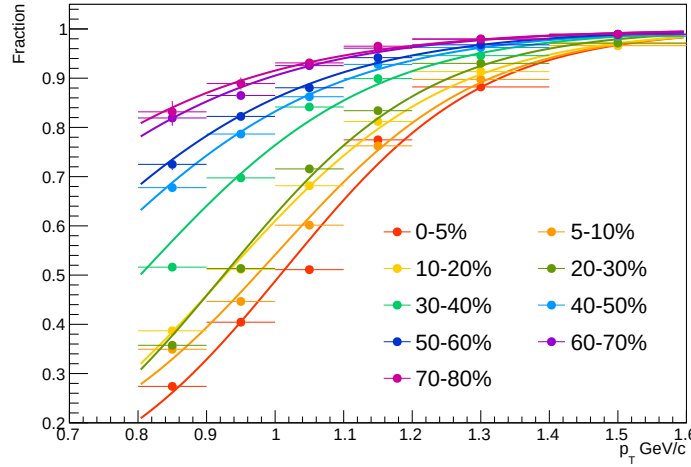


Figure 4.17. Primary fraction of selected deuterons as a function of the transverse momentum. The different colours correspond to different centrality classes. The solid lines represent the fits to the distributions.

To have a smooth evolution of the primary fraction as a function of p_T , the final correction $f_p(p_T)$ is obtained by fitting the distribution with the sigmoid function to minimise the statistical fluctuations:

$$f(p_T) = a + \frac{1 - a}{1 + be^{cp_T}}, \quad (4.6)$$

with $0 \leq a < 1$, $b > 0$ and $c < 0$. The resulting fits are shown as solid lines in Figure 4.17.

The systematic contribution of secondary particles is evaluated by varying the DCA_z track selection, which is particularly sensitive to the presence of secondary deuterons, as it will be shown in the section 4.5.

4.5 Systematic Uncertainties

A set of systematic studies is performed with six groups to evaluate if and how much the results presented in this work are affected by systematic uncertainties:

1. **Signal Extraction:** Checks on the raw yield extraction by using bin-counting method.
2. **Track Selection:** Checks on the track selection criteria, carried out by varying the selection parameters and studying how they affect the final results.
3. **Material Budget:** Checks on the efficiency $\times$ acceptance correction, done by varying the material budget used in the MC simulation of the ALICE apparatus.
4. **Hadronic Interaction:** Check the interaction of the particles with the detector and of the weak decay of unstable particles.
5. **ITS-TPC Matching Efficiency:** Check the matching between tracks in the ITS and in the TPC and how it is reproduced in MC.
6. **Weak decay from Hypertriton:** Check the possible weak decay from hypertriton to (anti-)deuterons.

When one of these checks finds a discrepancy in the obtained results, this discrepancy is kept into account to quantify the systematic uncertainty. The standard deviation of the distribution of each possible systematic uncertainty source is used as a systematic uncertainty of these variations. The last three checks are discussed in Sec 4.5.5.

4.5.1 Signal Extraction

The first contribution to the systematic uncertainties is the signal extraction. This systematic uncertainty is evaluated through the direct count of the candidates, known as *bin counting*.

bin counting is performed by default in the region $[\mu - 3\sigma, \mu + 5\sigma]$ for (anti-)deuterons and $[\mu - 3\sigma, \mu + 3\sigma]$ for (anti-) ^3He , where μ and σ are the parameters of the fit function used for the signal extraction. For the (anti-)deuteron analysis, an asymmetric range is used to take into account the exponential tail that characterises the signal shape. The bin counting method is evaluated by varying the width of bin counting interval of 1 or 2 bins and by shifting the interval by 1 or 2 bins. For the bins where the background is present (higher p_T), the background is fitted first by using the range of the side-bands next to the signal peak. Then the integral of the background function in the bin counting region is subtracted.

The standard deviation of all these checks is taken as the systematic uncertainty of the signal extraction.

4.5.2 Track Selection

The second source of the systematic uncertainty is the track selection. The track selection criteria variation is performed with looser/tighter track cut option as summarised in Tab. 4.4. When the track selection is done, only one parameter is varied from its original value in Tab. 4.2. The Barlow criteria, discussed in Sec. 3.5 is applied for the track selection variation study.

The total systematic uncertainty due to the track selection variation is then the sum in quadrature of each of these contributions.

Table 4.4. Track selection variations with respect to the standard selections quoted in Table 4.2 (replicated here in the column of the default values).

Description	Default values	Other values
# TPC clusters	70	60,65,75,80
DCA _z (cm)	1	0.5,0.75,1.5,2
PID (σ_{TPC}), only for (anti)d	3	3.25,3.5

4.5.3 Material Budget

The third source of systematic uncertainty is based on the imperfect reproduction of the detector material budget in MC simulations. This check is performed by computing $\epsilon \times A$ as like discussed in Sec. 4.4 but using difference MC simulations in which the material budget is changed from its nominal value. Two additional MC samples were used, one with the material budget increased by 4.5%³ and one with the material budget decreased by the same amount.

The average ratio between the $\epsilon \times A$ from the original value to the increased/decreased material budget is used as a systematic uncertainty from the material budget study. Therefore, it shows non-constant value as a function of p_{T} , which shows a larger value at low p_{T} . In the p_{T} region studied with the (anti)³He analysis, instead, an uncertainty of the 3% of constant is used as a systematic uncertainty from the material budget.

4.5.4 p_{T} -correlated and centrality-correlated systematics

All the source of the systematic uncertainty has the p_{T} -correlated and centrality-correlated systematics. The fractions are needed to evaluate the centrality-correlated uncertainties of the p_{T} -integrated yield and the $\langle p_{\text{T}} \rangle$.

The p_{T} -correlated fractions are evaluated based on the MB spectrum of the deuterons. The p_{T} -correlated fractions for all sources are reported in Tab. 4.5. Systematic uncertainty from material budget, hadronic interaction are assumed fully p_{T} -correlated and centrality-correlated.

For the other sources, the fraction of p_{T} -correlation is obtained from the correlation coefficient of the scatter plots with the spectra of different selections. The scatter plots are reported in Fig. 4.18 with variation (X-axis) and yield ratio between varied spectra (S_{var}) and default spectra (S_{ref}) from MB.

The centrality-correlated fractions are evaluated through the R ratio, defined as:

$$R^i_{\text{var}} = \frac{\frac{S^i_{\text{var}}}{S^i}}{\frac{S^{\text{MB}}_{\text{var}}}{S^{\text{MB}}}} = \frac{1 + \frac{\Delta S^i_{\text{var}}}{S^i}}{1 + \frac{\Delta S^{\text{MB}}_{\text{var}}}{S^{\text{MB}}}} \quad (4.7)$$

where R^i_{var} is the R coefficient for the multiplicity class i corresponding to the variation var under study. S^i and S^{MB} are the nominal spectra for the centrality class i and the MB sample, respectively. S^i_{var} and $S^{\text{MB}}_{\text{var}}$ are the varied spectra, corresponding to the variation var under study, for the centrality class i and MB sample, respectively.

³The value 4.5% corresponds to the uncertainty on the determination of the material budget by measuring photon conversions.

This R ratio is the comparison between the varied spectra of specific centrality and the MB spectra in each centrality class. If the uncertainty is fully correlated, R ratio will be 1 ($R_{var}^i = 1$). For this reason, the fraction of uncorrelated uncertainty can be evaluated as:

$$f_{uncorr} = |1 - R_{var}^i| \quad (4.8)$$

and The correlated fraction will be:

$$f_{corr} = 1 - |1 - R_{var}^i| \quad (4.9)$$

The R value for the 2 extreme centrality classes are shown in Fig. 4.20. These values are very close to 1 and it means that the uncertainties are almost fully correlated with the centrality.

Table 4.5. p_T -correlated fraction for each source of systematic uncertainty of deuterons and ^3He

Source	p_T -correlated fraction (%) of d	p_T -correlated fraction (%) of ^3He
Material budget	100	100
Hadronic interaction	100	100
DCA _z (cm)	32.7	31.6
TPC clusters	4.5	22.1
PID	16.7	20.3
Width bin counting	9.8	81.9
Shift bin counting	6.2	55.0

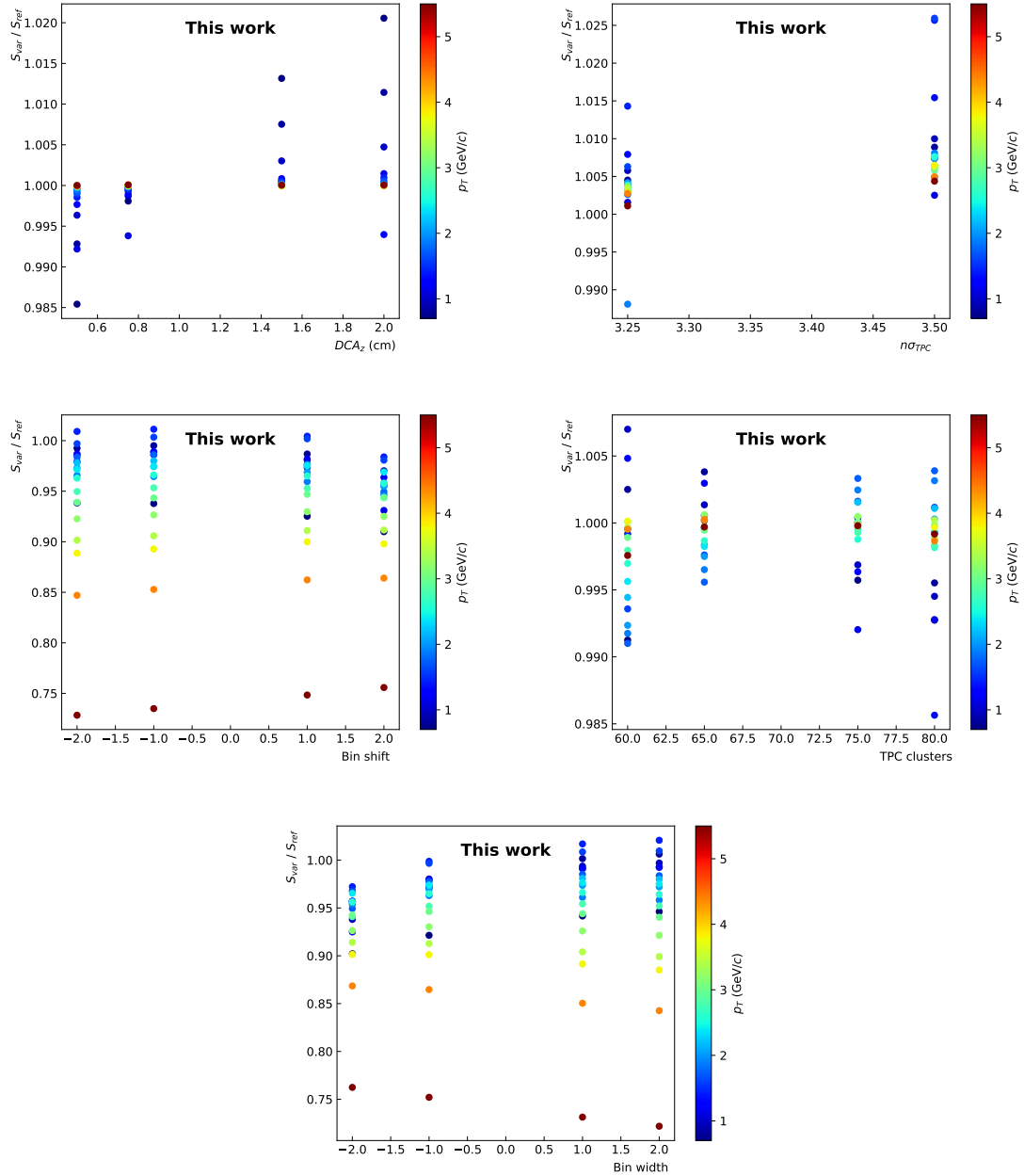


Figure 4.18. Scatter plot of the ratio between the varied yield S_{var} and the reference one S_{ref} for different selection criteria of deuteron measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

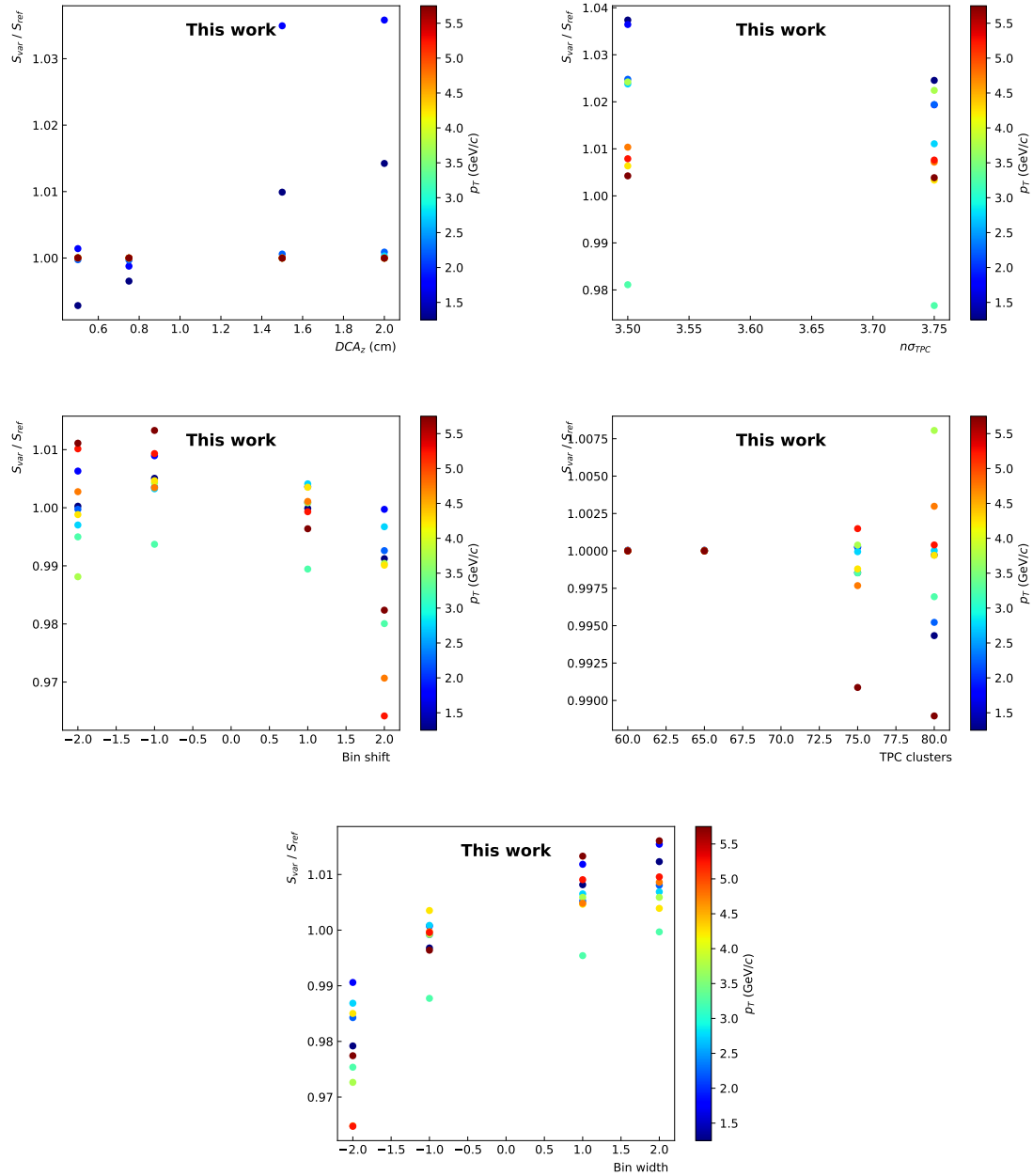


Figure 4.19. Scatter plot of the ratio between the varied yield S_{var} and the reference one S_{ref} for different selection criteria of ${}^3\text{He}$ measured in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV.

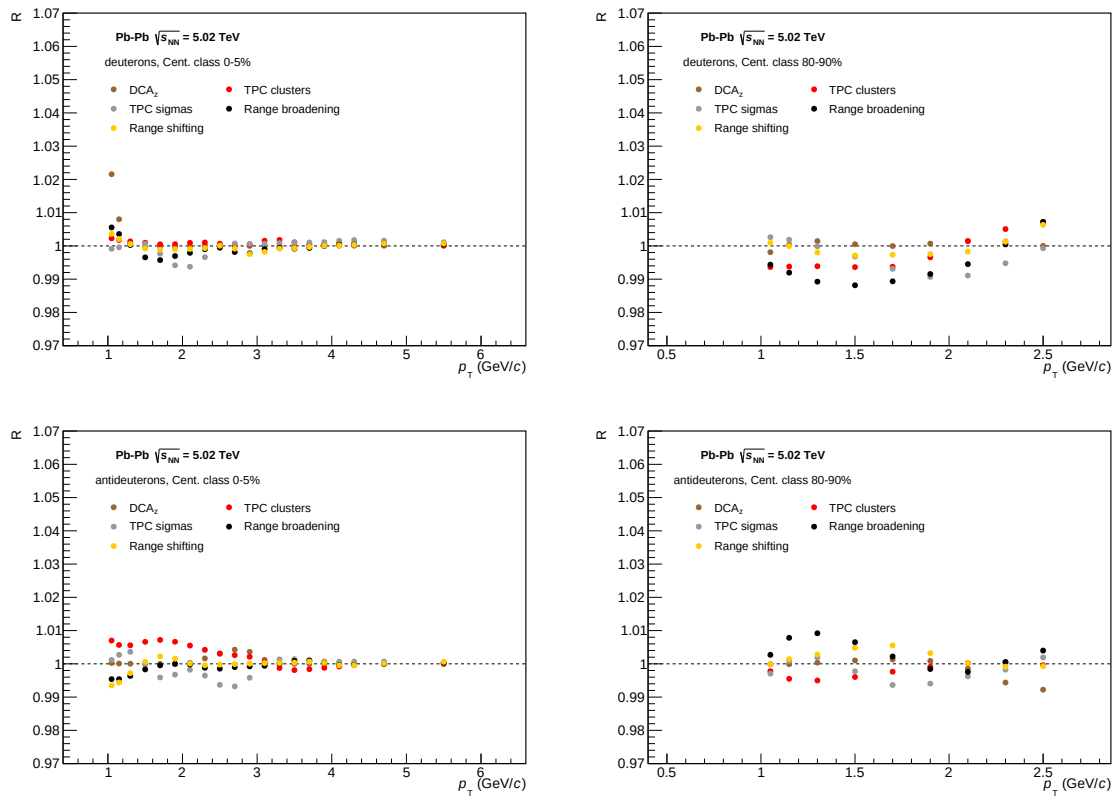


Figure 4.20. R value for different sources of systematic uncertainty for the two extreme centrality classes of deuteron (top) and anti-deuteron (bottom) measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

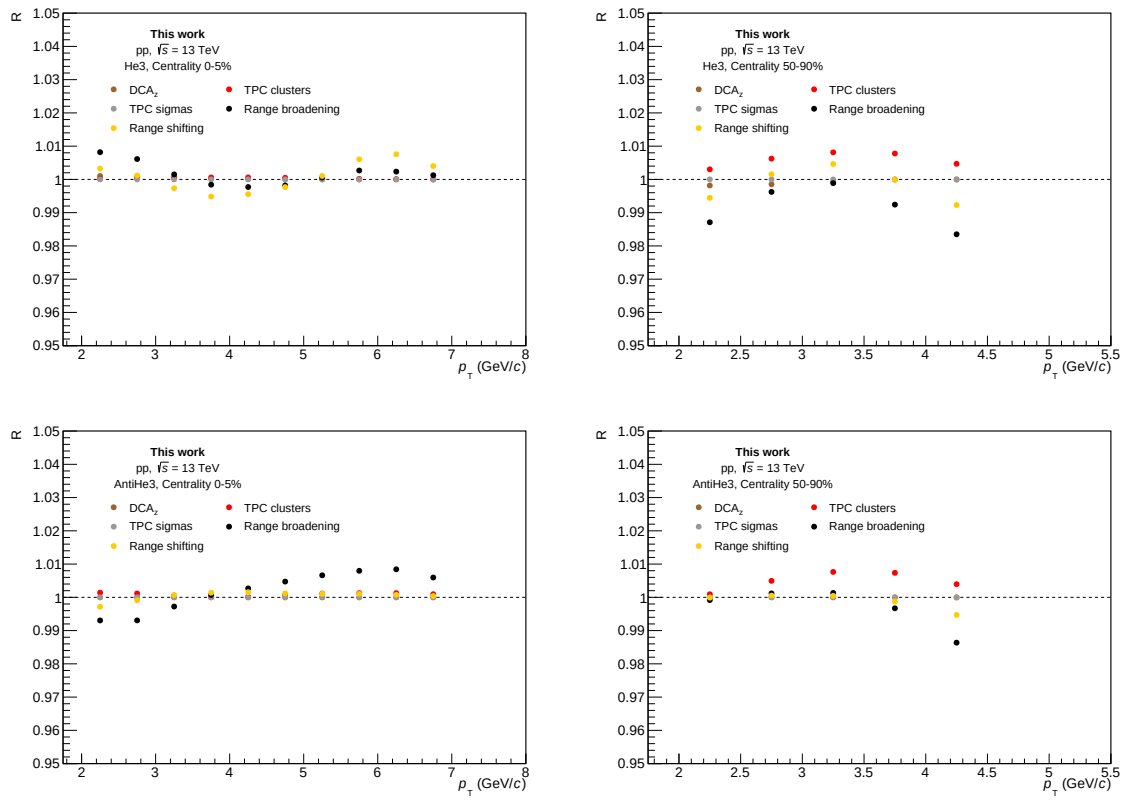


Figure 4.21. R value for different sources of systematic uncertainty for the two extreme centrality classes of ^3He (top) and $^3\overline{\text{He}}$ (bottom) measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV.

4.5.5 Total Systematic Uncertainties

Finally, the total systematic uncertainty has been computed summing in quadrature the contributions from all the checks mentioned above. For uncertainties from the ITS-TPC matching efficiency, 5% of constant value is used based on the proton study in 2018 dataset. The uncertainty of the weakdecay from hypertriton to ${}^3\text{He}$ is 1.8% [96] of constant value in the p_{T} range in this study. In addition to that, the uncertainties from the absorption correction for efficiencies are obtained as shown in Tab. 4.7.

Figure 4.22 shows examples of the systematic uncertainties for the light nuclei studied. It is shown well the hadronic interaction uncertainties of the anti-matter in figure. The full figure of the systematic uncertainties can be found from Fig. 4.23 to Fig. 4.26.

Table 4.6 summarises the overall systematic uncertainties of light nuclei produced in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

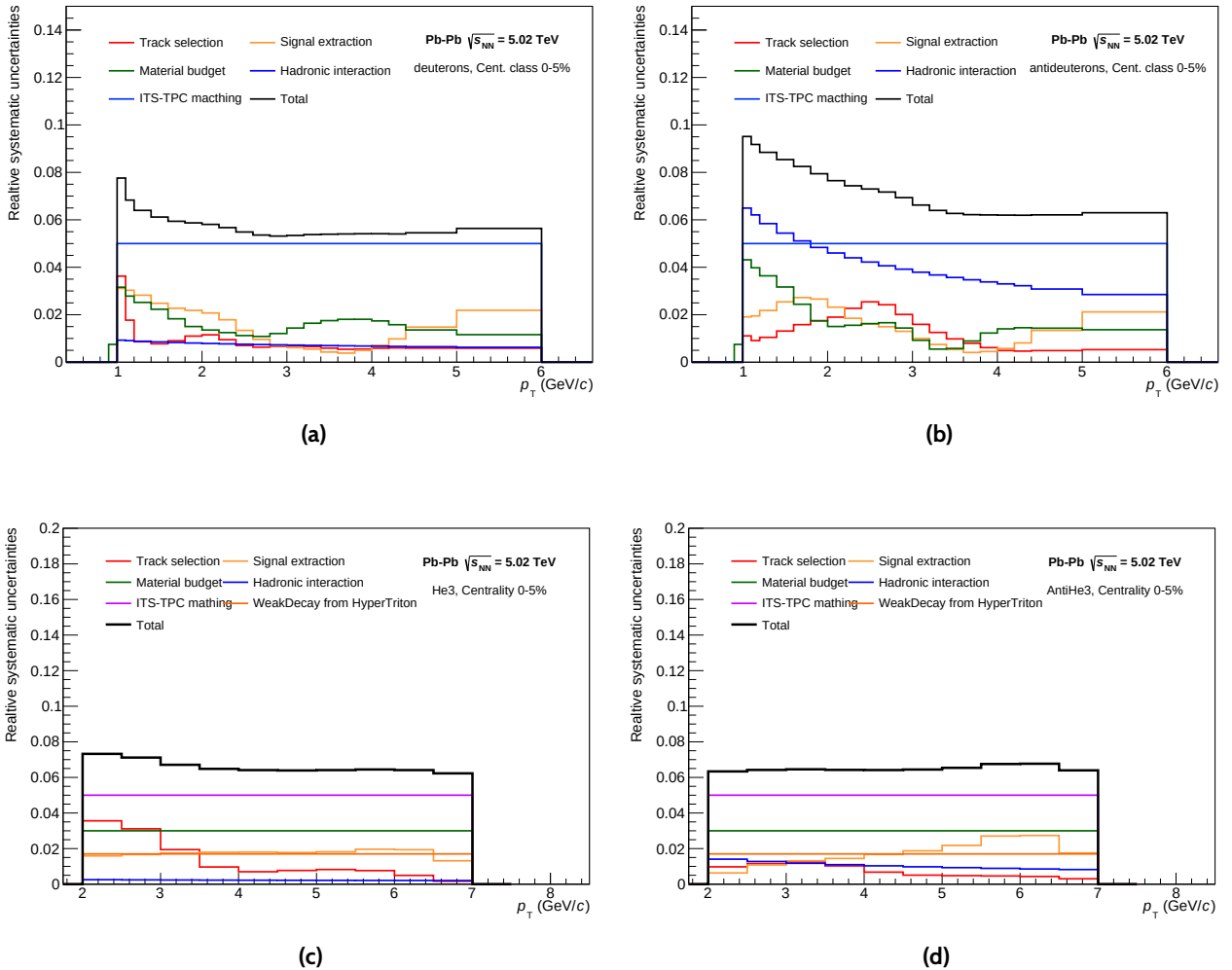


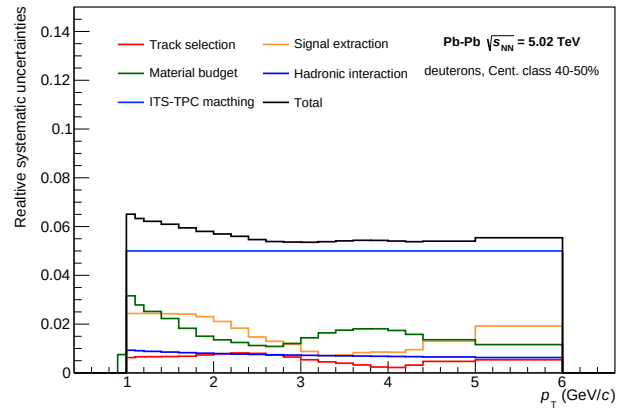
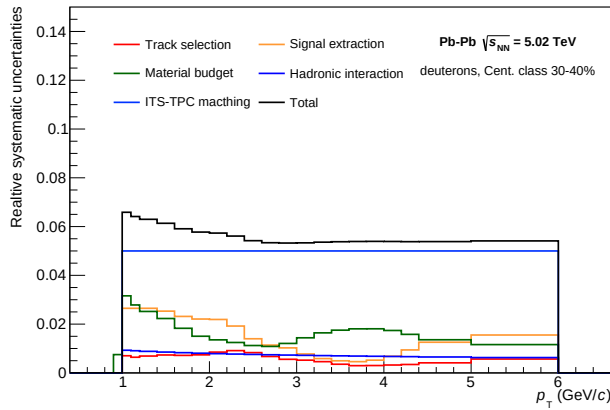
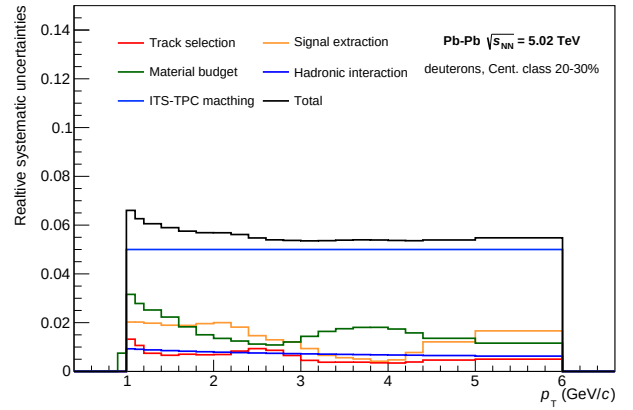
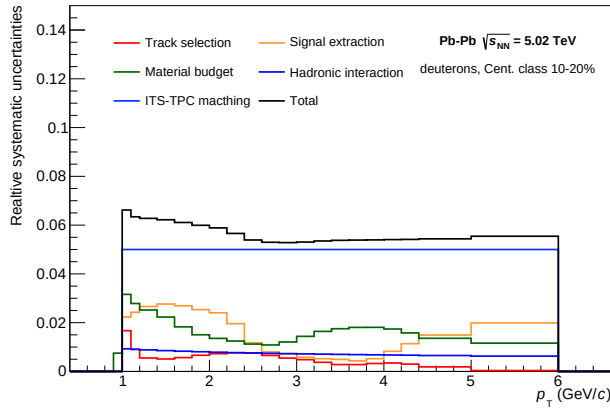
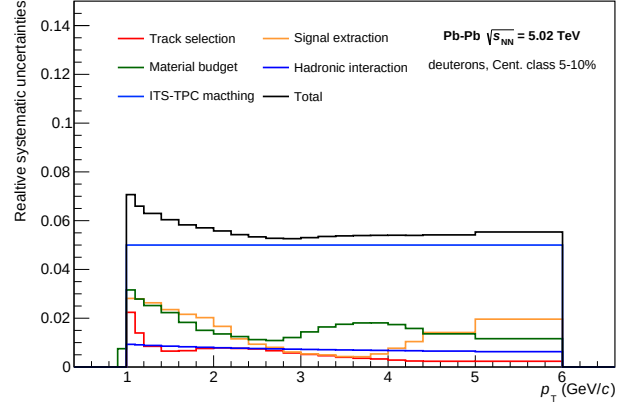
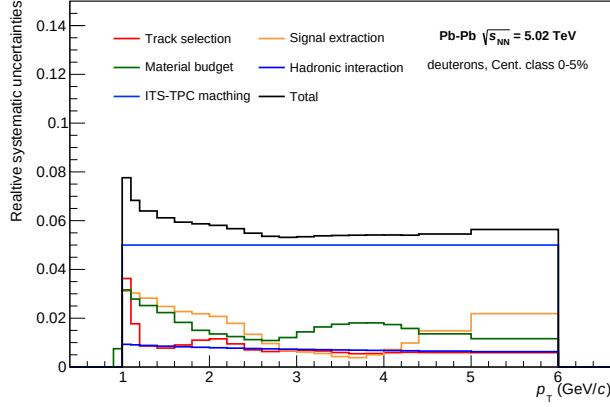
Figure 4.22. Example of the systematic uncertainties for deuteron (a), anti-deuteron (b), ${}^3\text{He}$ (c), anti- ${}^3\text{He}$ (d) in the most central event (0–5%) of Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

Table 4.6. Summary of the systematic uncertainties contribution for the (anti-)deuteron and the (anti-) ^3He analysis in the Pb–Pb at $\sqrt{s_{\text{NN}}}=5.02$ TeV data sample. This table refers to all the centrality classes analysed in this thesis.

Contribution	Deuteron	Anti-deuteron	^3He	Anti- ^3He
Signal Extraction	$\leq 4\%$	$\leq 3\%$	$\leq 4\%$	$\leq 3\%$
Track Selections	$\leq 4\%$	$\leq 4\%$	$\leq 4\%$	$\leq 2\%$
Material Budget	$\leq 4\%$	$\leq 5\%$	3%	3%
Hadronic Interaction	$\leq 1\%$	$\leq 7\%$	$\leq 1\%$	$\leq 2\%$
ITS-TPC Matching	5%	5%	5%	5%
Weakdecay from Hypertriton	-	-	1.8%	1.8%

Table 4.7. Summary of the systematic uncertainties from the correction factors obtained in the nuclei absorption study.

Particle	Uncertainty
deuterons (TOF)	$0.00939 \cdot \text{TMath::Power}(\text{pt}, -0.23572)$
antideuterons (TOF)	$0.06654 \cdot \text{TMath::Power}(\text{pt}, -0.49699)$
helium-3 (TPC)	$0.00294 \cdot \text{TMath::Power}(\text{pt}, -0.19483)$
antihelium-3 (TPC)	$0.02088 \cdot \text{TMath::Power}(\text{pt}, -0.48766)$



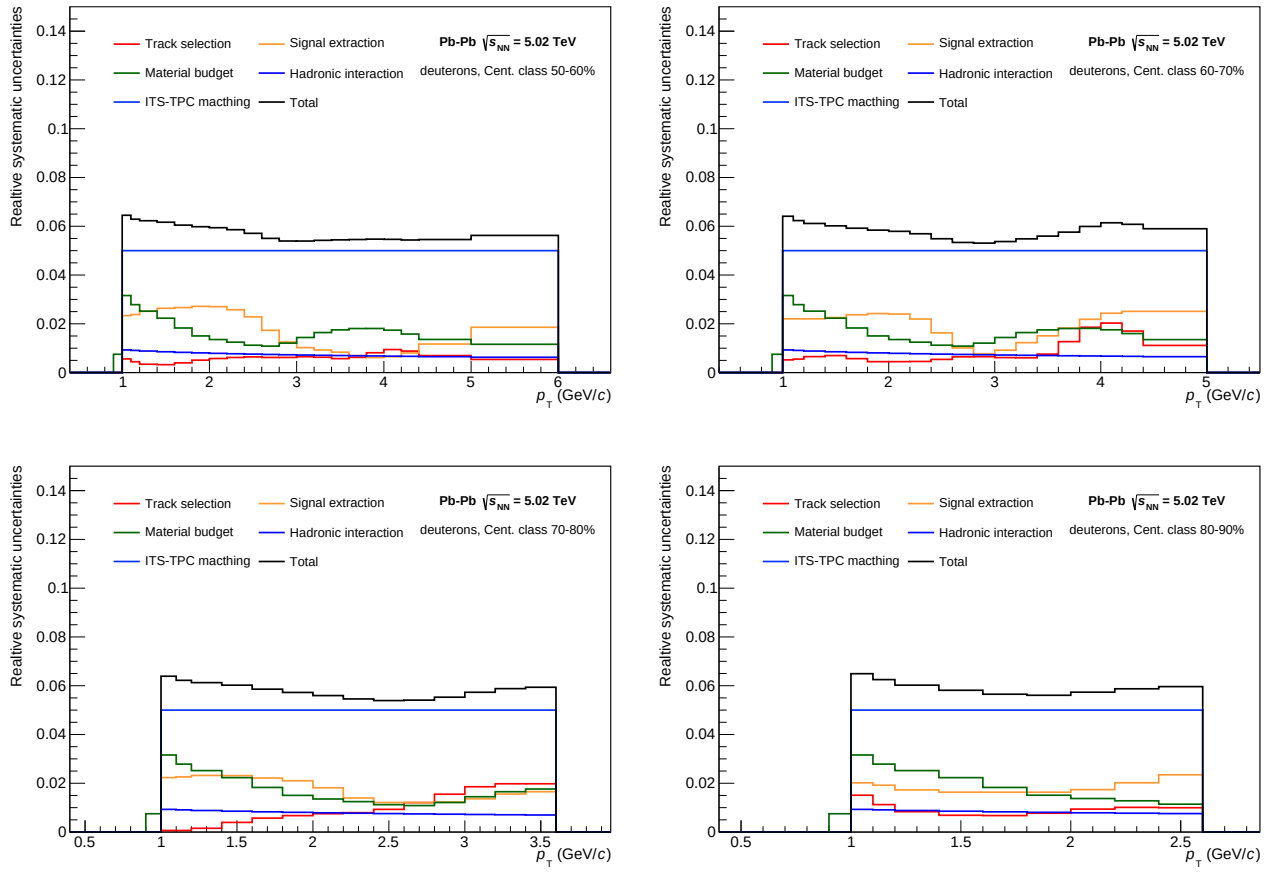
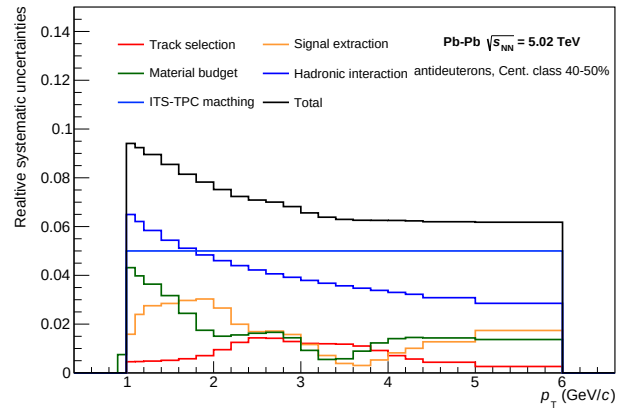
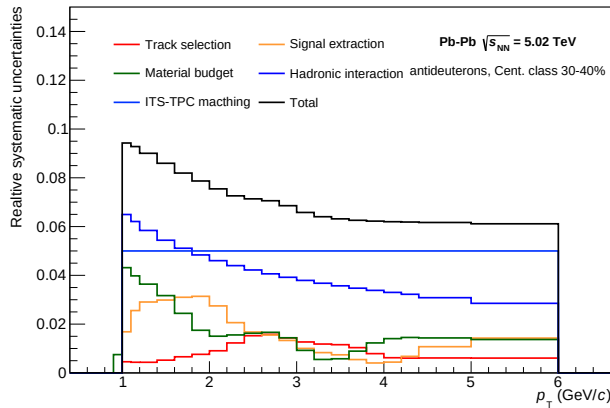
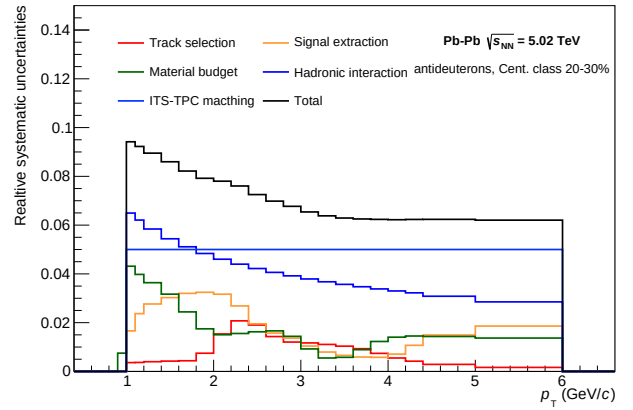
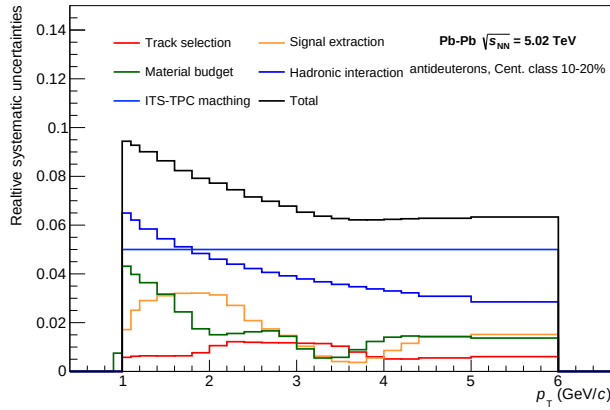
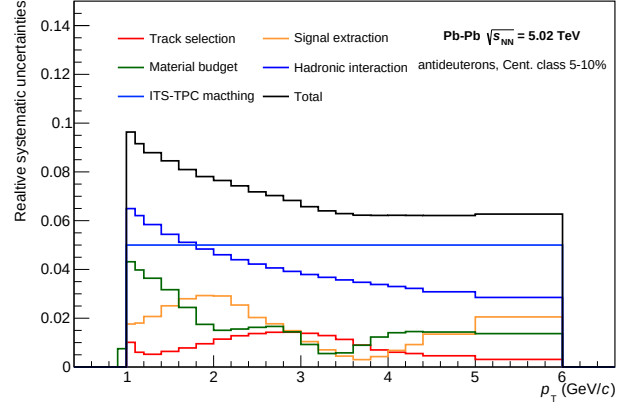
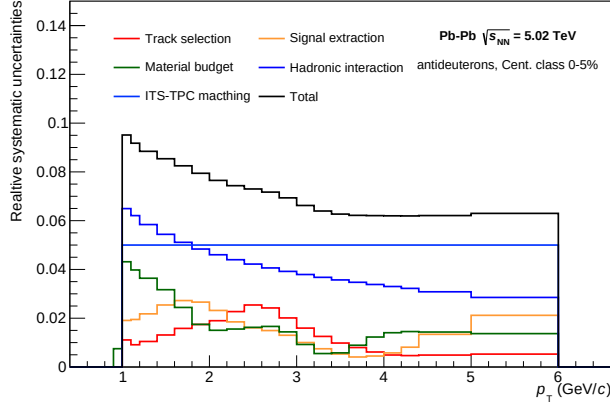


Figure 4.23. Summary of the systematic uncertainties evaluated for the deuteron spectra in the different central-ity classes of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The thick black line represents the sum in quadrature of the systematic uncertainties contributions.



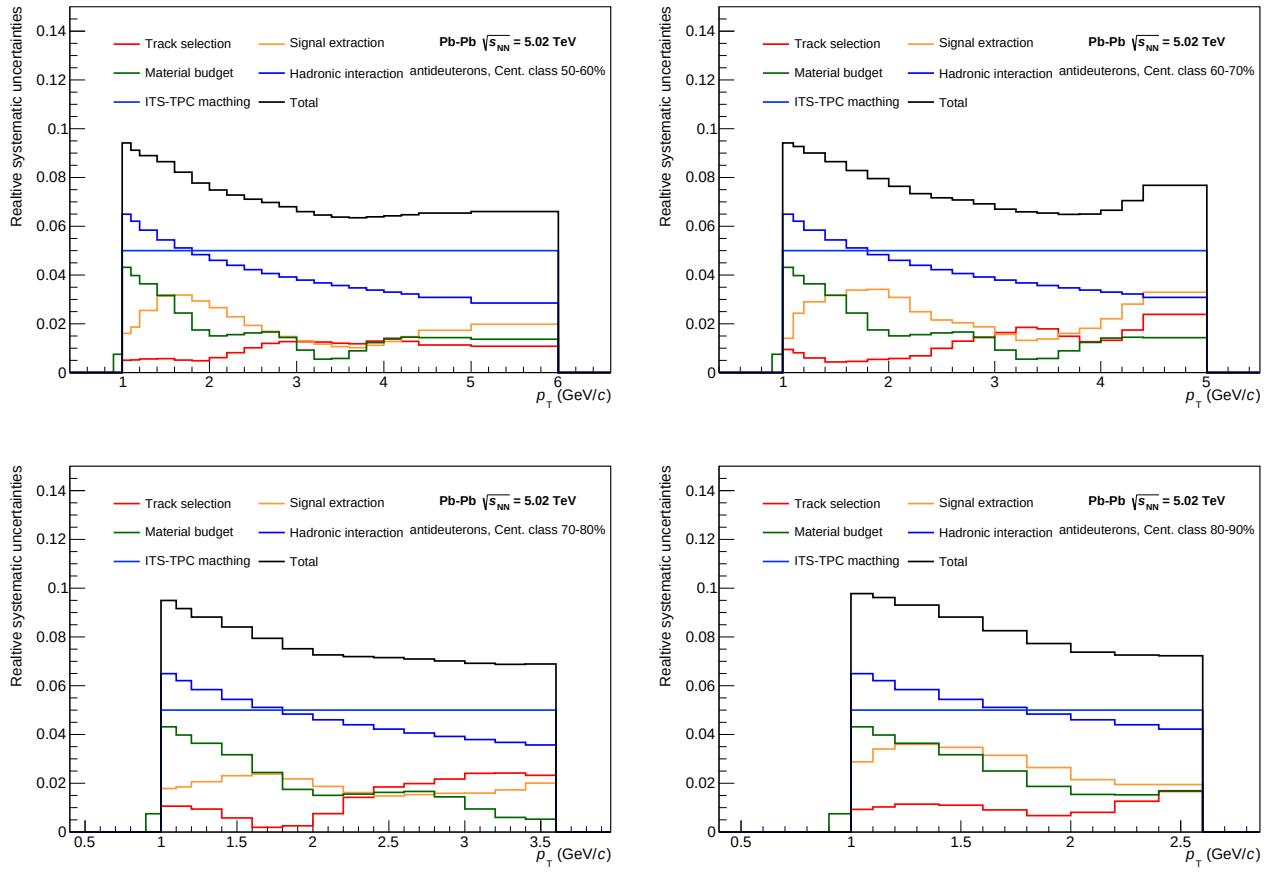


Figure 4.24. Summary of the systematic uncertainties evaluated for the anti-deuteron spectra in the different centrality classes of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The thick black line represents the sum in quadrature of the systematic uncertainties contributions.

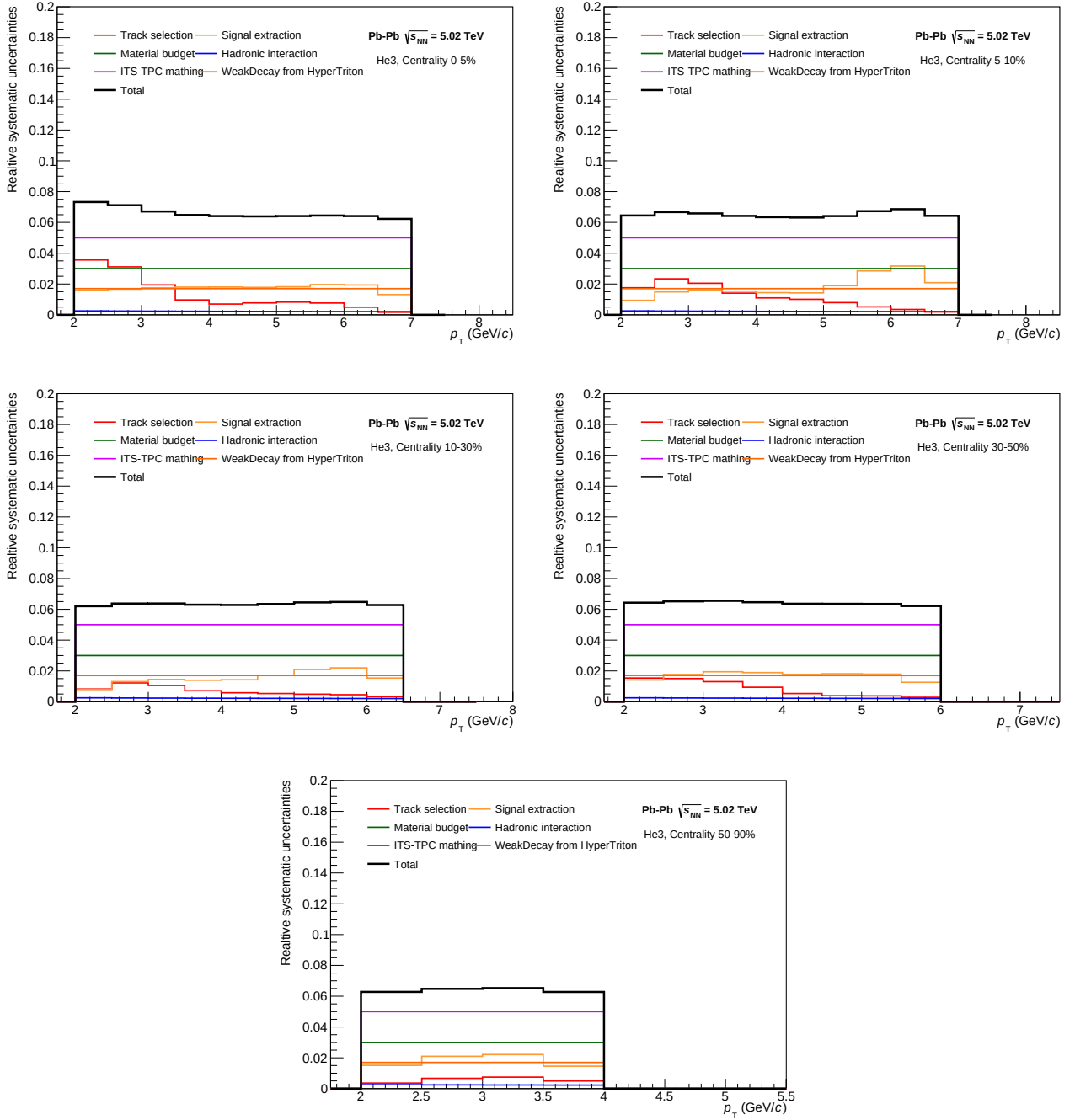


Figure 4.25. Summary of the systematic uncertainties evaluated for the ^3He spectra in the different centrality classes of Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The thick black line represents the sum in quadrature of the systematic uncertainties contributions.

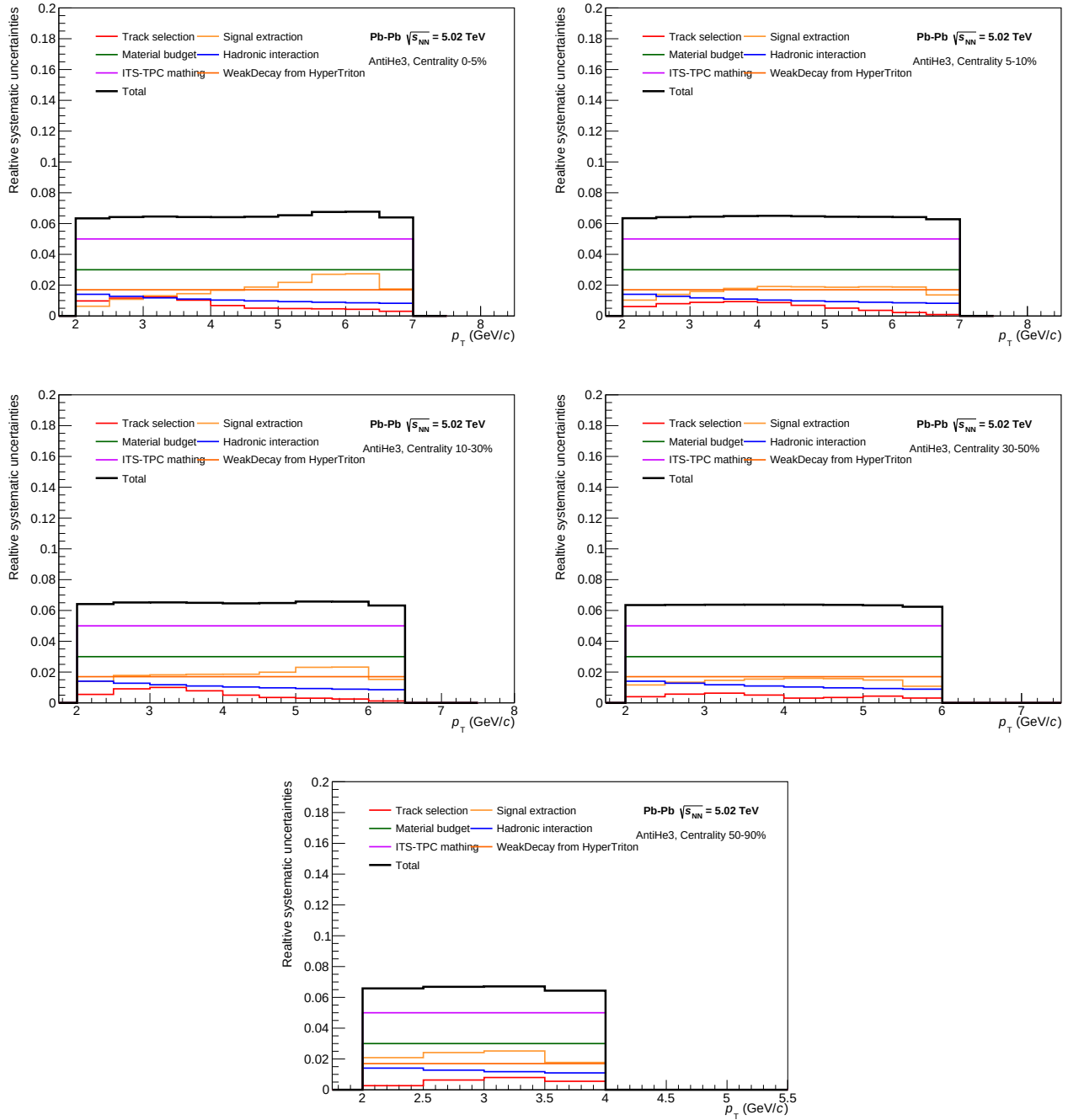


Figure 4.26. Summary of the systematic uncertainties evaluated for the ${}^3\text{He}^-$ spectra in the different centrality classes of Pb-Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The thick black line represents the sum in quadrature of the systematic uncertainties contributions.

4.6 Results

4.6.1 p_{T} -differential Yields

Combining the raw yields and the all the corrections, the production spectra of light nuclei is evaluated as:

$$\frac{1}{N_{\text{ev}}} \frac{d^2N}{dy dp_{\text{T}}} = \frac{1}{N_{\text{ev}}} \frac{f_{\text{primary}}}{\epsilon \cdot \epsilon_{\text{Absorption}}} \frac{dN_{\text{raw}}}{dp_{\text{T}}}, \quad (4.10)$$

where N_{ev} is the total number of events, ϵ is the acceptance $\times$ efficiency correction, f_{primary} is the estimated fraction of primary particles (Sec. 4.4.2) and $\epsilon_{\text{Absorption}}$ is the correction due to the nuclei absorption.

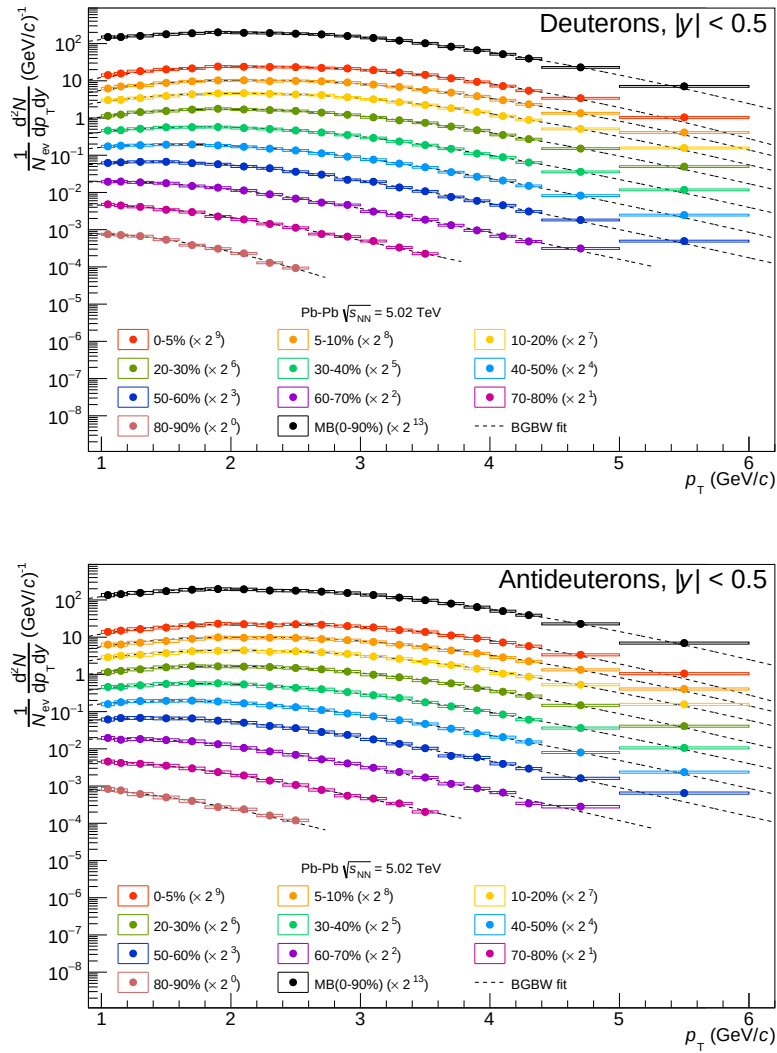


Figure 4.27. Deuteron (top) and anti-deuteron (bottom) spectra measured in this analysis on the Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The boxes represent the systematic uncertainties while the vertical lines are the statistical ones. The dashed lines represent the individual Blast Wave fit to the spectra.

Figure 4.27 shows the p_{T} spectra for (anti-)deuteron.

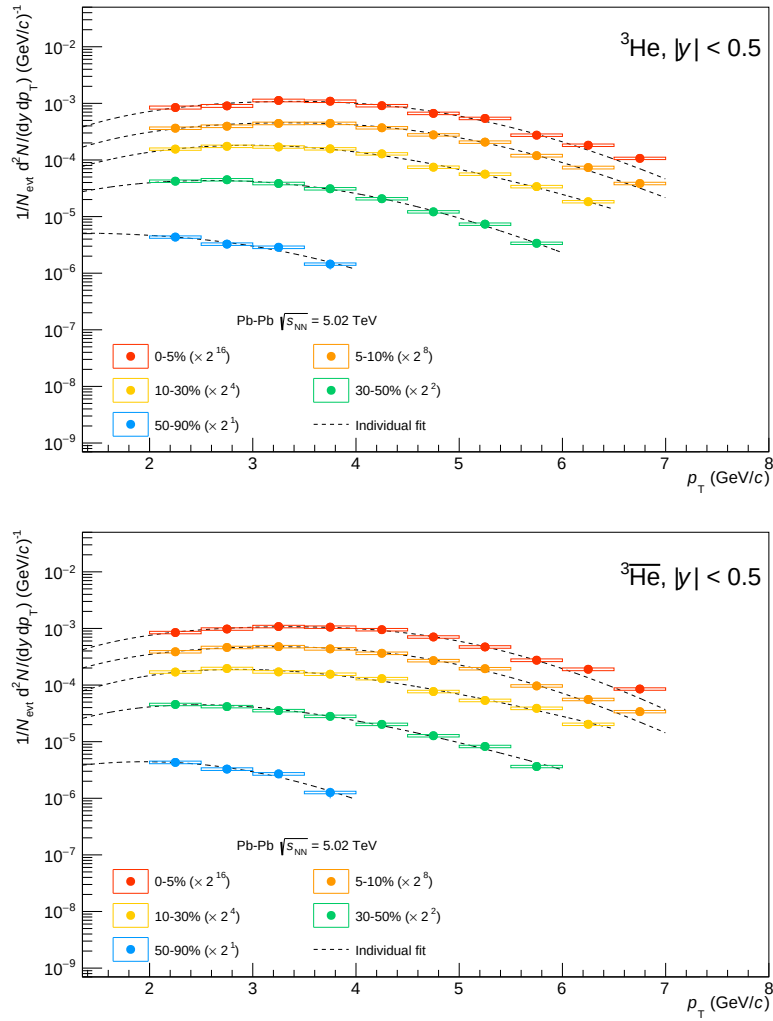


Figure 4.28. ${}^3\text{He}$ (top) and $\bar{{}^3\text{He}}$ (bottom) spectra measured in this analysis on the Pb–Pb at $\sqrt{s_{\text{NN}}}=5.02$ TeV. The boxes represent the systematic uncertainties while the vertical lines are the statistical ones. The dashed lines represent the individual Blast Wave fit to the spectra.

Similarly, Figure 4.28 shows the p_T spectra for $(\bar{\text{anti}}-){}^3\text{He}$. Thanks to the higher statistics measured in 2018, the centrality bin could be split up to 0–5%, 5–10% which are the same with the (anti-)deuteron analysis.

4.6.2 Integrated Yield and Mean p_T

Fits of the spectrum

The integrated yield dN/dy and average transverse momentum $\langle p_T \rangle$ are extracted from the fit of the spectra with the Blast Wave function. Blast Wave describes the measured spectra features assuming a thermal production of particles from an expanding source:

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r m_T I_0 \left(\frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{\text{kin}}} \right) dr, \quad (4.11)$$

Table 4.8. Summary of the measured dN/dy and $\langle p_T \rangle$ for deuterons and ^3He in the centrality classes analysed in the Pb–Pb at $\sqrt{s_{\text{NN}}}=5.02 \text{ TeV}$. The last column reports the fitting χ^2/ndf for the Blast Wave fits.

Centrality	dN/dy	$\langle p_T \rangle$ (GeV/ c)	χ^2/ndf
d (0-5%)	$(1.31 \pm 0.00 \pm 0.05 \pm 0.04) \times 10^{-1}$	$2.47 \pm 0.00 \pm 0.04 \pm 0.02$	1.19
d (5-10%)	$(1.13 \pm 0.00 \pm 0.04 \pm 0.03) \times 10^{-1}$	$2.43 \pm 0.00 \pm 0.03 \pm 0.02$	1.47
d (10-20%)	$(9.68 \pm 0.01 \pm 0.29 \pm 0.30) \times 10^{-2}$	$2.35 \pm 0.00 \pm 0.03 \pm 0.02$	0.68
d (20-30%)	$(7.09 \pm 0.01 \pm 0.17 \pm 0.22) \times 10^{-2}$	$2.25 \pm 0.00 \pm 0.02 \pm 0.02$	0.68
d (30-40%)	$(4.55 \pm 0.00 \pm 0.08 \pm 0.18) \times 10^{-2}$	$2.09 \pm 0.00 \pm 0.02 \pm 0.02$	0.93
d (40-50%)	$(2.94 \pm 0.00 \pm 0.04 \pm 0.11) \times 10^{-2}$	$1.91 \pm 0.00 \pm 0.01 \pm 0.02$	0.41
d (50-60%)	$(1.83 \pm 0.00 \pm 0.03 \pm 0.08) \times 10^{-2}$	$1.75 \pm 0.00 \pm 0.02 \pm 0.02$	1.18
d (60-70%)	$(9.80 \pm 0.02 \pm 0.09 \pm 0.38) \times 10^{-3}$	$1.51 \pm 0.00 \pm 0.01 \pm 0.02$	1.23
d (70-80%)	$(4.02 \pm 0.02 \pm 0.03 \pm 0.15) \times 10^{-3}$	$1.35 \pm 0.00 \pm 0.02 \pm 0.02$	1.64
d (80-90%)	$(1.16 \pm 0.08 \pm 0.02 \pm 0.07) \times 10^{-3}$	$1.17 \pm 0.05 \pm 0.03 \pm 0.05$	1.71
^3He (0-5%)	$(3.12 \pm 0.08 \pm 0.34 \pm 0.22) \times 10^{-4}$	$3.91 \pm 0.06 \pm 0.32 \pm 0.09$	1.07
^3He (5-10%)	$(2.51 \pm 0.06 \pm 0.22 \pm 0.17) \times 10^{-4}$	$3.75 \pm 0.06 \pm 0.25 \pm 0.08$	0.17
^3He (10-30%)	$(1.72 \pm 0.04 \pm 0.09 \pm 0.12) \times 10^{-4}$	$3.15 \pm 0.05 \pm 0.04 \pm 0.06$	0.23
^3He (30-50%)	$(7.74 \pm 0.17 \pm 0.05 \pm 0.05) \times 10^{-5}$	$2.6 \pm 0.03 \pm 0.10 \pm 0.04$	0.81
^3He (50-90%)	$(1.34 \pm 0.12 \pm 0.01 \pm 0.10) \times 10^{-5}$	$1.93 \pm 0.07 \pm 0.01 \pm 0.04$	0.76

where I_0 and K_1 are the modified Bessel functions, r is the distance from the centre of the expanding system, R is the limiting radius of the system expansion, T_{kin} is the temperature of the kinetic freeze-out and ρ is the velocity profile. The velocity profile can be expressed in terms of the transverse expansion velocity at the system surface, β_S , and an exponent n :

$$\rho = \tanh^{-1} [\beta_S (r/R)^n]. \quad (4.12)$$

Since the production spectra of nuclei and anti-nuclei are compatible in LHC energy (Fig. 1.14) and the anti-nuclei spectra have relatively larger systematic uncertainties than the nuclei, the measurement of the yield is performed using the nuclei spectra only.

The Blast-Wave function was used to extract the central value and the statistical uncertainties of the dN/dy and $\langle p_T \rangle$, but the systematic uncertainty due to the extrapolation in the unmeasured region at high and low transverse momenta was evaluated by fitting the spectrum using three additional functions:

1. an m_T exponential function
2. a Levy–Tsallis model
3. a Boltzmann distribution

The detailed extrapolation procedure, fitting variation and statistical uncertainty is the same as discussed in the Sec. 3.6.3. For the systematic uncertainty, Half of the difference between the maximum and the minimum dN/dy and p_T computed with the different functions were added in quadrature. The measured $\langle p_T \rangle$ and dN/dy with their statistical and systematic uncertainties are reported in Table 4.8.

Final Results

Figure 4.30 shows the evolution of the $\langle p_T \rangle$ with the average charged particles multiplicity in the pseudo-rapidity region $|\eta| < 0.5$. The centrality classes adopted in the extraction of the spectra were translated in

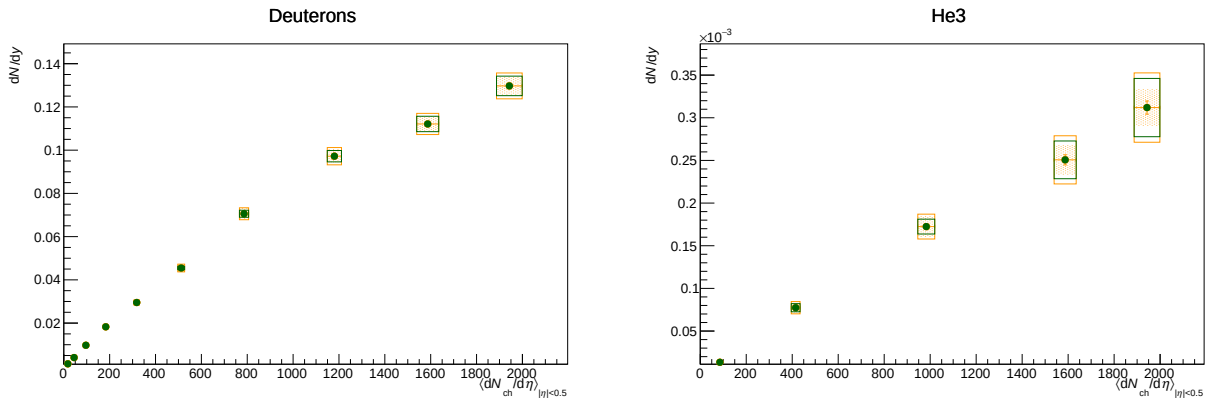


Figure 4.29. Integrated Yields for deuterons (left) and ${}^3\text{He}$ (right) as a function of the measured charged particle multiplicity in the pseudorapidity region $|\eta| < 0.5$. The vertical lines and the boxes represent the statistical and systematic uncertainties respectively.

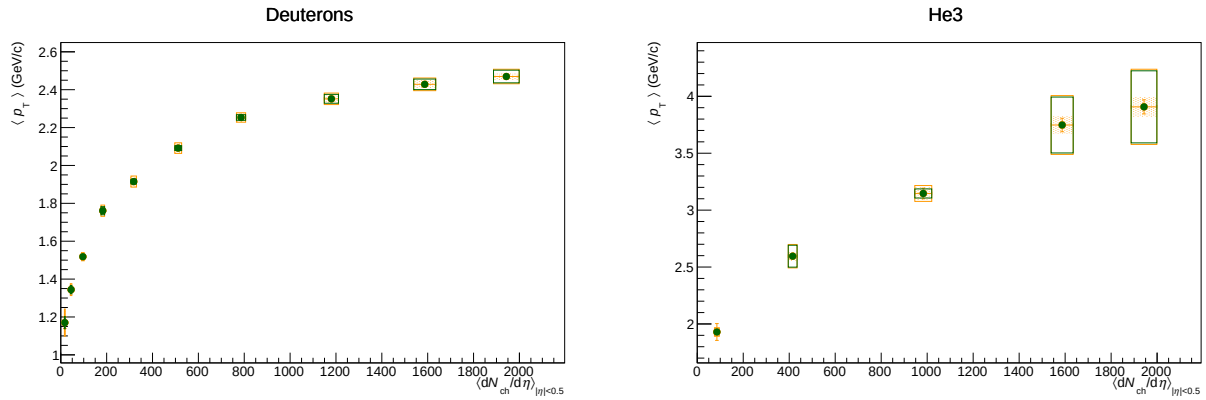


Figure 4.30. Mean transverse momentum for deuterons (left) and ${}^3\text{He}$ (right) as a function of the measured charged particle multiplicity in the pseudorapidity region $|\eta| < 0.5$. The vertical lines and the boxes represent the statistical and systematic uncertainties respectively.

$\langle dN/d\eta \rangle$ using the values tabulated in [97].

Chapter 5

Discussions and Conclusion

In this chapter, the results respectively obtained in the chapter 3 for the production of the hyperon resonances and chapter 4 for the production of the light nuclei will be compared to the other results produced in various systems and energies. The results are mainly compared with the charged particle multiplicity $\langle dN_{\text{ch}}/d\eta \rangle$ that is used as a proxy of the system size [9, 10] to bridge from a heavy ion collision to a small system [21]. It enables us to have another point of view in the model of the heavy ion collision. Finally, the thesis is summarised in Section 5.7.

5.1 Energy Dependence of the Resonance Production

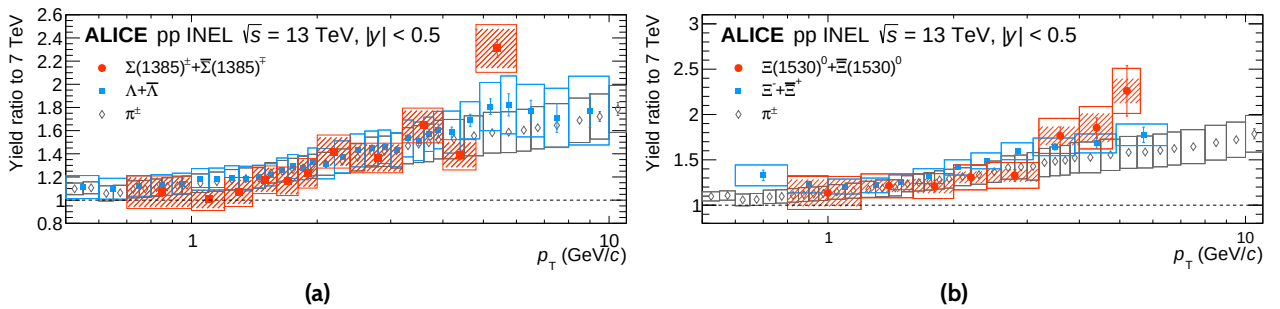


Figure 5.1. Ratios of transverse-momentum spectra of $\Sigma(1385)^\pm$ (a) and $\Xi(1530)^0$ (b) in inelastic events at $\sqrt{s} = 13$ TeV to the transverse-momentum spectra in pp collisions at $\sqrt{s} = 7$ TeV compared with Ξ , Λ and π . The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively. The shaded box represents the uncorrelated uncertainties.

Figure 5.1 shows the ratios of the p_T -differential yields in inelastic events of pp collisions at $\sqrt{s} = 13$ TeV to those at $\sqrt{s} = 7$ TeV for $\Sigma(1385)^\pm$ (left) and $\Xi(1530)^0$ (right), respectively. For both $\Sigma(1385)^\pm$ and $\Xi(1530)^0$, a clear increasing trend can be observed by increasing p_T , that we can call p_T hardening effect.

Similar behaviour was observed for π , Λ and Ξ [98], those ratios are overlaid for comparison in the same figure. For both $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ up to $p_T \approx 2$ GeV/c, the yield ratios appear independent of the centre of mass energy within the systematic uncertainties. This suggests that the particle production mechanism in the soft scattering region (up to $p_T \approx 2$ GeV/c) is independent of the collision energy over the measured energy range. The slope of $\Xi(1530)^0$ in the right-hand-side plot is compatible within uncertainties with the slope of Ξ and there is a hint that it is higher than the slope of π , suggesting a sharper energy dependence for double-strange particles. The slope of $\Sigma(1385)^\pm$ is consistent within uncertainties with the slope of Λ and π .

5.2 Strangeness Enhancement

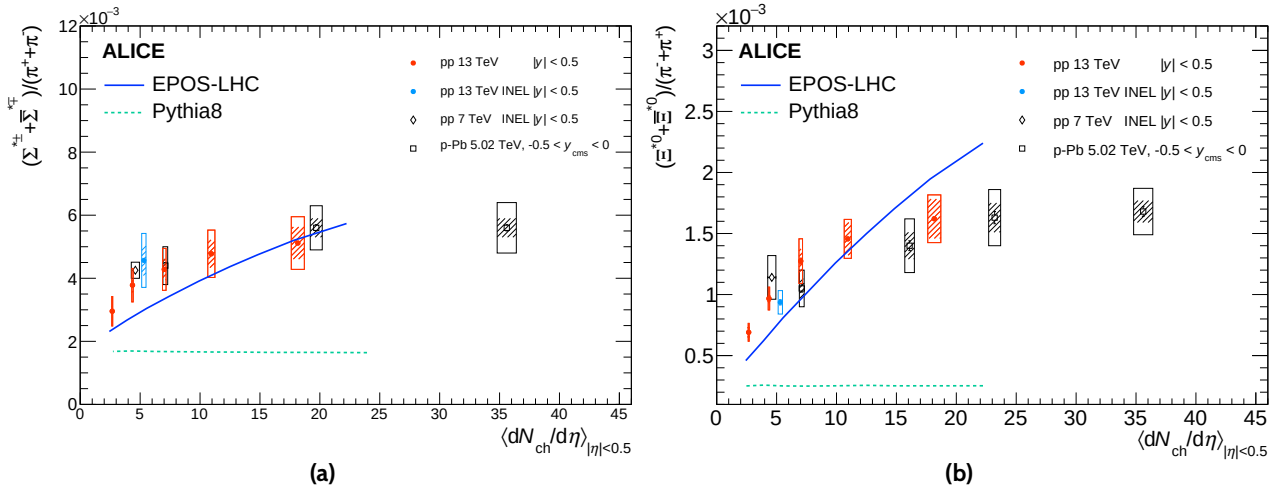


Figure 5.2. Ratio of the resonances to pions as a function of the charged-particle multiplicity for $\Sigma(1385)^\pm$ (a) and $\Xi(1530)^0$ (b). The open and shaded boxes represent the total and p_T -correlated systematic uncertainties, respectively. Solid blue lines show the model prediction from EPOS LHC and green dashed-lines from PYTHIA 8.

The integrated yield ratios of hyperon resonances to pions are shown in Fig. 5.2. They represent the evolution of the relative strangeness production yields with increasing collision system size regardless of energy and collision system. One can observe increasing yields of excited hyperons to pions by 60 and 120%¹ in high multiplicity pp collisions compared to lower multiplicity events for $\Sigma(1385)^\pm$ and $\Xi(1530)^0$, respectively.

The increasing trend of the hyperon resonances to pions confirms the strangeness enhancement [17] in a small system as a function of the multiplicity. When it compares with the increasing trend of Ξ in Ref [17], the increasing trend of Ξ is steeper than $\Sigma(1385)^\pm$ although $\Sigma(1385)^\pm$ is heavier than Ξ . It also implies that the strangeness enhancement predominantly depends on the strangeness content, rather than on the hyperon mass in small collision systems.

¹for $\Sigma(1385)^\pm$, first multiplicity bin start at 3×10^{-3} and it ends over 5×10^{-3} at most highest multiplicity, which shows $(5 - 3)/3$, $\sim 60\%$ of increasing. For $\Xi(1530)^0$, it starts at 0.7×10^{-3} and ends with 1.6×10^{-3} , which shows $(1.6 - 0.7)/0.7$, $\sim 130\%$ of increasing.

These results are consistent with previous measurements of ground-state hyperons to pion ratios at ALICE [79]. The EPOS LHC describes the $\Sigma(1385)^\pm/\Lambda$ ratios quantitatively well while it overestimates the increasing trend for the $\Xi(1530)^0/\Xi$ ratios. PYTHIA 8 does not describe the data at all.

5.3 Ratios of Resonances to Stable Hyperons

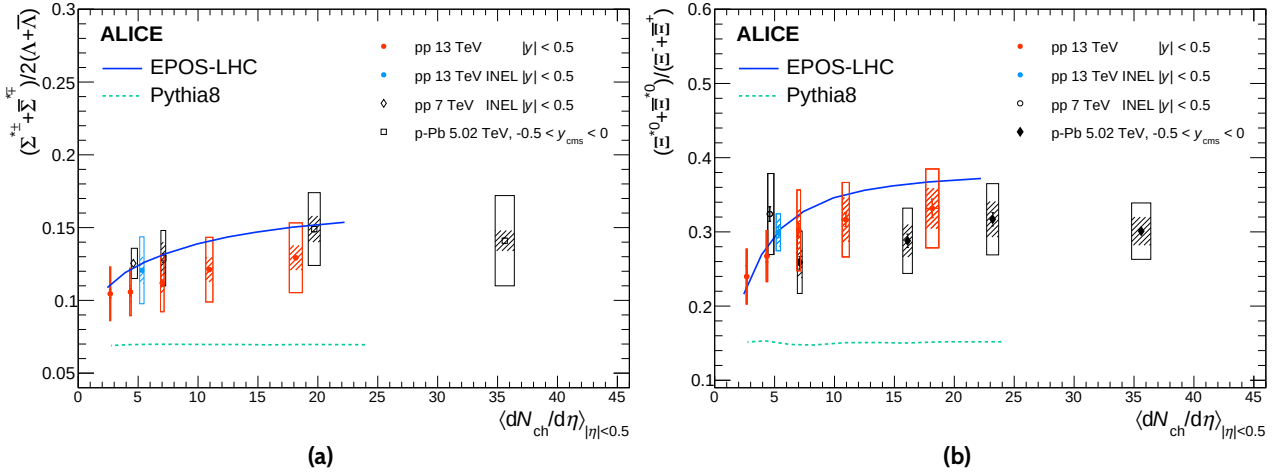


Figure 5.3. Ratio of the resonances to the hadrons having the same quark contents as a function of multiplicity for $\Sigma(1385)^\pm$ (a) and $\Xi(1530)^0$ (b). The open and shaded boxes represent the total and p_T -correlated systematic uncertainties, respectively. Solid blue lines show the model prediction from EPOS LHC and green dashed-lines from PYTHIA 8.

The integrated yield ratios of excited to ground-state hyperons [79, 88, 89] with the same strangeness content for different collision systems and center-of-mass energies as a function of $\langle dN_{ch}/d\eta \rangle$ are shown in Fig. 5.3. Similar flat behaviour for $\Sigma(1385)^\pm/\Lambda$ and $\Xi(1530)^0/\Xi$ is observed. The flat behaviours shown here are not confirming those for the K^*/K ratio in pp and p–Pb [31, 38] where a decrease was observed at high multiplicity in pp collisions, that followed a common decreasing trend from Pb–Pb collisions, hinting at collective behaviours in small systems. The results are compared with model predictions, PYTHIA 8 and EPOS LHC in pp collisions at $\sqrt{s} = 13$ TeV. The EPOS LHC describes the $\Sigma(1385)^\pm/\Lambda$ and $\Xi(1530)^0/\Xi$ ratios well. An increasing trend at the low multiplicity region is observed, however, the uncertainties are too large to conclude anything. PYTHIA 8 presents constant for all multiplicities while it seriously underestimates the data by about a factor of 2.

The $\Lambda(1520)/\Lambda$ ratio showed a constant behaviour at the similar multiplicity region as well while $\Lambda(1520)$ has a lifetime $c\tau = 12.6$ fm [99].

5.3.1 Summary: Ratio of Resonances to Long-lived Particles

The integrated yield ratios of excited to ground-state hyperons can be compared with various resonances introduced in Introduction (Chapter 1.4). Figure 5.4 shows the summary of the ratio of resonance yields to the ground state hadrons: ρ^0/π , K^{*0}/K , $\Sigma^{*\pm}/\Lambda$, $\Lambda(1520)/\Lambda$, Ξ^*/Ξ , and Φ/K .

Starting from the ρ^0/π ratio in Fig. 5.4, it shows a clear decreasing trend from small to large systems as multiplicity increases. As the lifetime of ρ meson is shorter than the one of K^{*0} , this trend can be originated

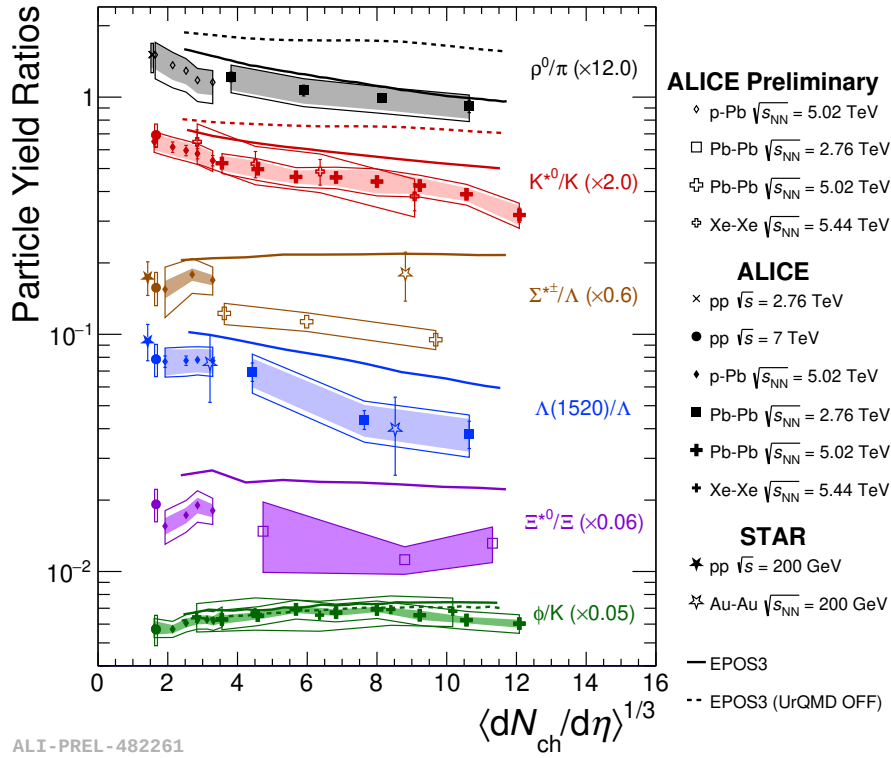


Figure 5.4. Summary of particle yield ratios ρ^0/π , K^{*0}/K , $\Sigma^{*\pm}/\Lambda$, Λ^*/Λ , $\Xi(1530)^0/\Xi$, and Φ/K as a function of multiplicity for pp, p-Pb, Xe-Xe, and Pb-Pb collisions, with comparisons to EPOS3 predictions and STAR data.

from the re-scattering effect in the hadronic phase. It can be supported by the prediction of EPOS with UrQMD describing its trend while the EPOS without UrQMD can't.

The ratio of $\Lambda(1520)/\Lambda$ shows an interesting result. Although the other resonances have a common flat/decreasing trend as a function of multiplicity, it has different behaviour. $\Lambda(1520)/\Lambda$ ratio shows a flat behaviour in a small system (pp, p-Pb) and decreases at higher multiplicities in central Pb-Pb collisions. The result from STAR also confirms this decreasing trend, and EPOS3 with UrQMD only describes the slope qualitatively.

In addition to the result studied in this thesis, ratios of $\Sigma^{*\pm}/\Lambda$ and Ξ^*/Ξ have an interesting point from the preliminary results in Pb-Pb collisions [100]. The lifetime of Ξ^* is long enough with regard to the lifetime of the hadronic phase even in Pb-Pb collisions. Thus, none of the suppression is expected. But the preliminary result of Ξ^* in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV shows a hint of suppression with regard to the model expectation in central Pb-Pb collisions. In addition to that, the ratio of $\Sigma^{*\pm}/\Lambda$ from Pb-Pb collisions also shows deep suppression with regard to the model expectation in the overall region of Pb-Pb collisions. The EPOS3 prediction expects a flat behaviour through the whole multiplicity region and the STAR result of $\Sigma(1385)^\pm$ matches with the model prediction.

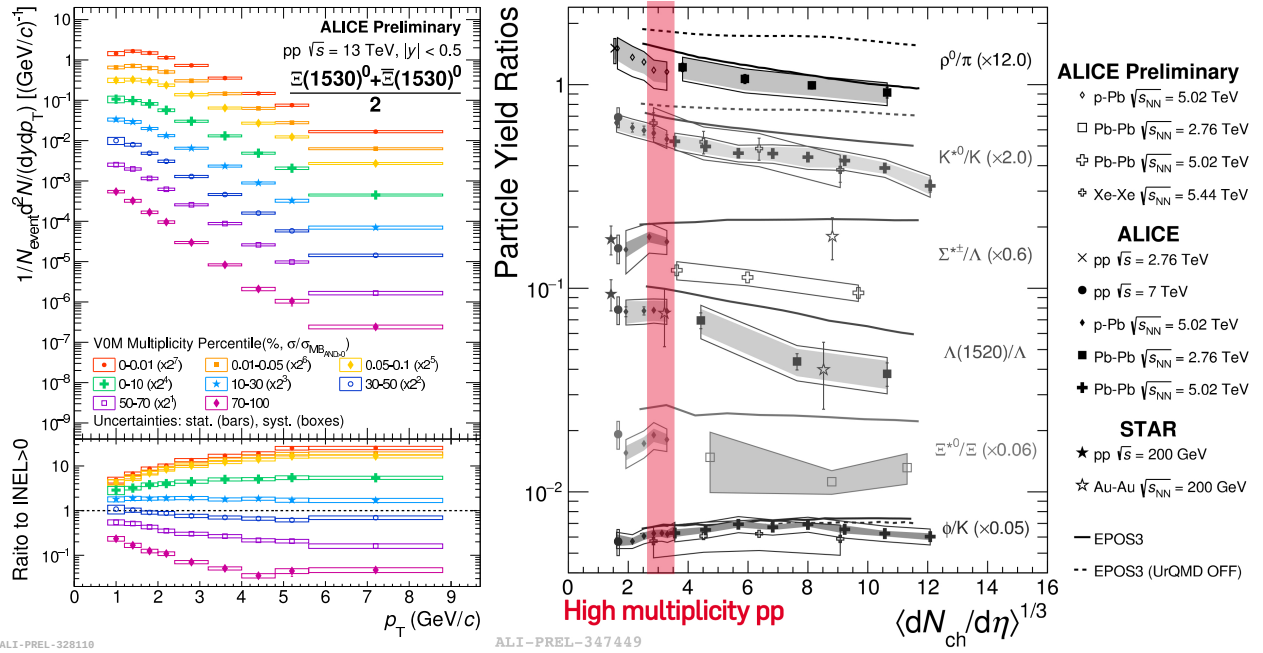


Figure 5.5. Invariant yields of $\Xi(1530)^0$ in pp collisions at $\sqrt{s} = 13$ TeV in multiplicity classes and the inclusive case ($INEL > 0$) including the result from the dedicated high multiplicity pp trigger (0–0.01, 0.01–0.05, 0.05–0.1%). Statistical and total systematic uncertainties are shown by error bars and boxes, respectively. The bottom panels show the ratios of the multiplicity dependent spectra to $INEL > 0$. (Left) Summary of particle yield ratios as a function of multiplicity for pp, p–Pb, Xe–Xe, and Pb–Pb collisions. The highlighted region is the range of the multiplicity which can be measured with the high multiplicity pp trigger (right).

For those preliminary results which shows the suppression, it can be also interesting to check the connection region between the p–Pb and Pb–Pb multiplicities. If there is a certain decreasing in Pb–Pb collisions, it may possible to see the hint of the trend in the region between p–Pb and Pb–Pb as well. For this, datasets recorded with a dedicated trigger for the high multiplicity pp collisions that covers whole p–Pb region can be used in ALICE. Figure 5.5 shows the preliminary result of Ξ^* from the high multiplicity region (left) and the region of High multiplicity triggered event in pp collisions in the resonance summary figure (right). Three p_T spectra from HM triggered event, 0–0.01, 0.0–0.05, 0.05–0.1% multiplicity classes are shown.

5.4 Chemical Freeze-out Temperature in SHM

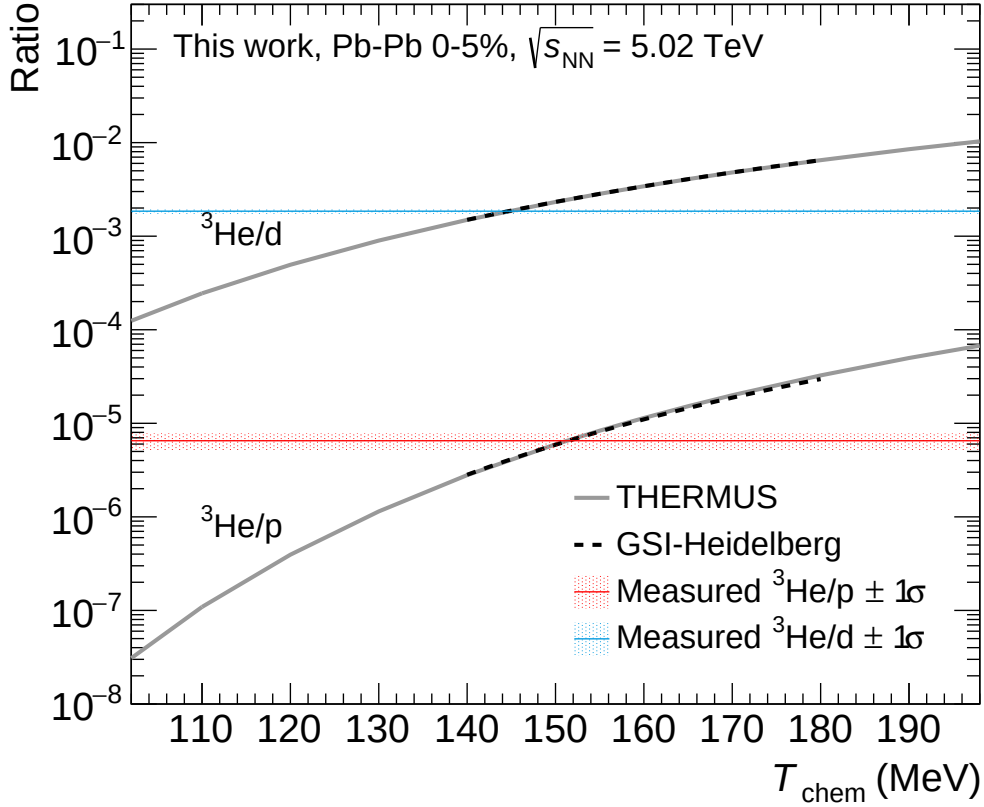


Figure 5.6. Measured ^3He over deuteron ratio (blue line) and ^3He over proton ratio (red line) compared with the predictions of the THERMUS (grey line, [15]) and GSI-Heidelberg (dashed line, [50]) SHM models. The shaded areas correspond to the 1σ uncertainty (statistical + systematic) interval from the measurements.

In the thermal model framework, the yield of a particle species i , $\langle N_i \rangle$, is proportional to the volume of the system V as shown in Eq. 1.11. Therefore, one can remove the dependence on the system size V by dividing the yield of the particle species to other particle species. Hence, it is possible to investigate directly the chemical freeze-out temperature of the system.

Figure 5.6 shows the comparison between the measured ratios, ^3He over deuteron (blue line) and ^3He over proton (red line), and the prediction from two different implementations of the SHM [15, 50, 101] as a function of the chemical freeze-out temperature. The range of chemical freeze-out temperatures compatible within 2σ with the measurements is between 144 (blue line) and 150 (red line) MeV, where the lines are crossing to the model expectation.

5.5 Coalescence Approach of Light Nuclei

Following the thermal model approach [43–45], it will be interesting to see the coalescence model approach [10, 52, 53] to the light nuclei. This can be easily comparable by computing the coalescence parameter, B_2 and B_3 for deuterons and ${}^3\text{He}$ respectively. In experiment, the coalescence parameter can be obtained via:

$$B_A = E_i \frac{d^3 N_i}{dp_i^3} \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^{-A}. \quad (5.1)$$

By definition, the proton spectra used in the equation above has to be the proton spectra formed before the nuclei since it will be used to form the nuclei by coalescence. In the experiment, since the yield of nuclei is less than 1/300 of the one of the proton, the nuclei with mass number A is suppressed by a factor of $(300)^A$ with respect to the proton yield [102] as shown in Fig. 5.7. Therefore, the experimental computation of the coalescence parameters (Eq. 5.1) will have a negligible effect even though we use the measured proton spectrum for the computation.

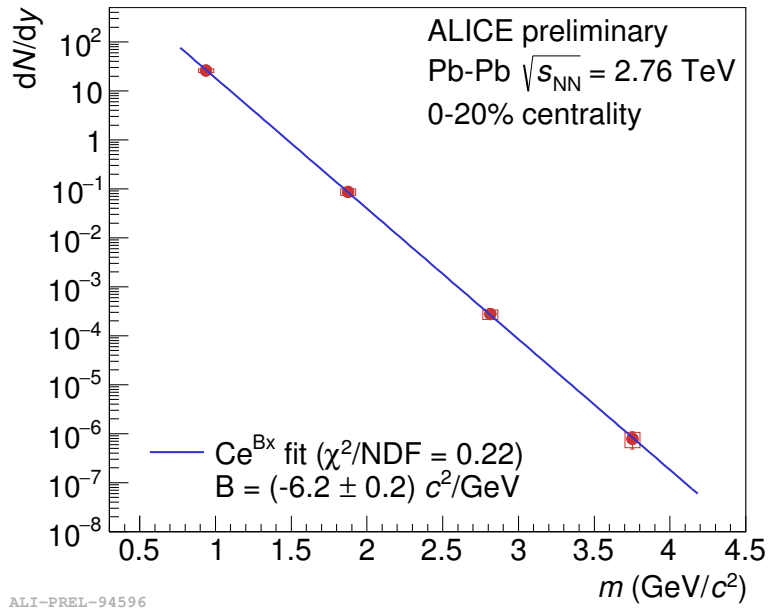


Figure 5.7. dN/dy of protons, deuterons, ${}^3\text{He}$ und anti-alphas. The blue line represents a exponential fit, with a $\chi^2/\text{NDF} = 0.22$. The resulting fit parameters are: constant = 9.1 and slope = -6.2 . [102]

5.5.1 Coalescence Parameter as a function of p_T

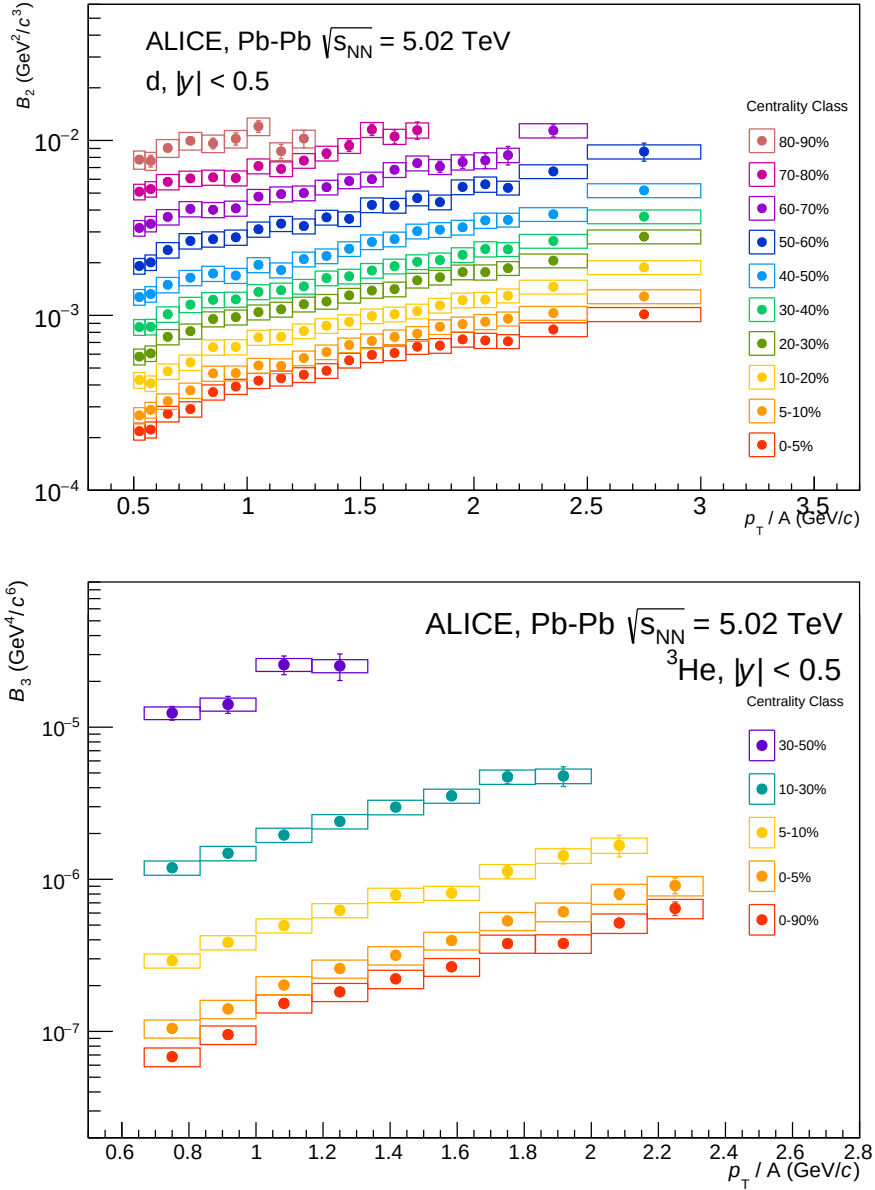


Figure 5.8. Coalescence parameters B_2 (top) and B_3 (bottom) measured in Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV as a function of the transverse momentum scaled by the mass number of the nucleus.

Figure 5.8 shows the extracted coalescence parameters B_2 and B_3 from deuteron and ^3He as a function of the transverse momentum scaled by the mass number A for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

The figure shows a clear centrality ordering of the coalescence parameters, which vary from higher B_A values in peripheral collisions to lower B_A values in the central ones. This means the coalescence mechanism is less efficient at the central collisions due to the larger volume V_{eff} of the source in central collisions as discussed in Introduction (Chapter 1.5.2) [53]. If the V_{eff} is bigger, the probability of having two nucleons close enough in the phase space to form a bound state is lower, thus the coalescence parameters are smaller.

In addition to the centrality dependence, it shows a significant increase with the p_T , especially in the central collision, which can not be intuitively explained by the simple coalescence model [53]. One of the possible explanations could be the position-momentum correlations which are caused by a radially expanding source [103].

5.5.2 Coalescence Parameter as a function of $\langle dN_{ch}/d\eta \rangle$

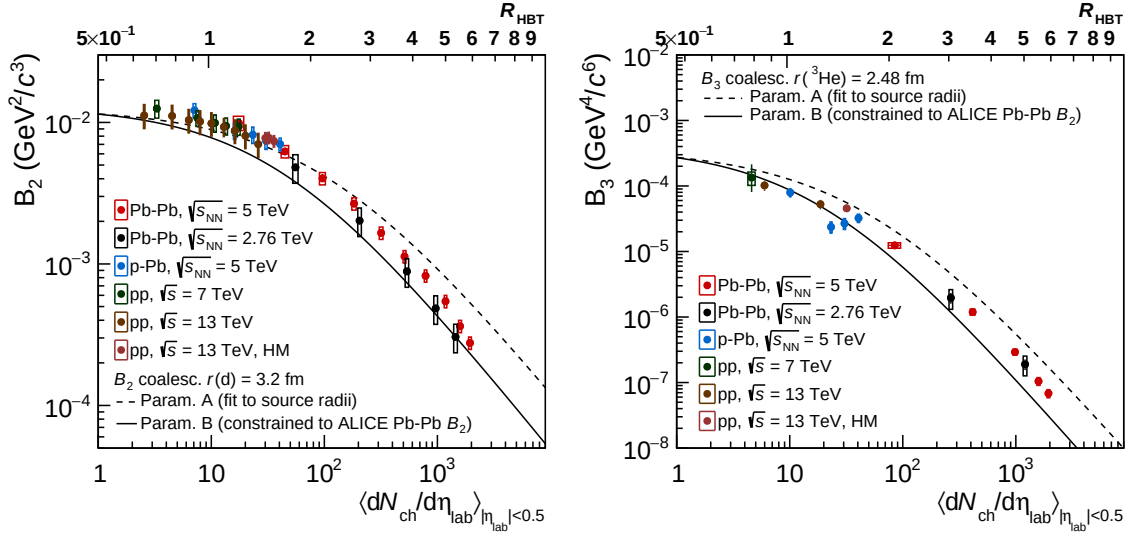


Figure 5.9. Coalescence parameters B_2 (left) and B_3 (right) measured in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV as a function of the charged particle multiplicity $\langle dN_{ch}/d\eta \rangle$. B_2 and B_3 at a fixed momentum $p_T/A = 0.75$ GeV/c are plotted to compare the value across different collision systems. The upper axis shows the HBT radii R_{HBT} calculated with Eq. 1.3 when $a = 0.473$ fm and $b = 0$. Ref. [10]

Figure 5.9 shows the coalescence parameters B_2 and B_3 from deuteron and ^3He when the specific scaled transverse momentum $p_T/A = 0.75$ GeV/c² as a function of the charged particle multiplicity $\langle dN_{ch}/d\eta \rangle$ for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. To compare the coalescence parameters B_2 and B_3 with the other collisions systems, the parameter is selected at a specific momentum $p_T/A = 0.75$ GeV/c since the coalescence parameters increase with increasing momentum in Pb–Pb collisions (Fig. 5.8).

The figure represents the evolution of the coalescence parameters with increasing charged particle multiplicity regardless of energy and collision systems. This trend is basically same with the centrality scaling, that is qualitatively discussed in previous section. Considering that the charged particle multiplicity can be a proxy to the size of the system (Section. 1.2, this smooth evolution can be interpreted as a hint of a common particle production mechanism that depends on the system size produced in the collision.

The results are also compared with the prediction of a coalescence model. The black lines in Fig. 5.9 represent the coalescence model prediction parameterised with the HBT radius as a function of multiplicity, where the relation between HBT radius and multiplicity is fixed for reproducing the B_2 measured in the central collision in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (Eq. 1.3 with $a = 0.339$ fm and $b = 0.128$). The black dashed lines are the prediction with the relation between HBT radius obtained by fitting the HBT radii measurements as a function of multiplicity (Eq. 1.3 with $a = 0.473$ fm and $b = 0$).

²Any momentum range can be selected but $p_T/A = 0.75$ GeV/c is used commonly for comparing with various systems.

The results can be discussed by dividing them into two regimes along with the charged particle multiplicity: Low multiplicity regime up to $\langle dN_{\text{ch}}/d\eta \rangle \approx 50$, where B_A is slightly decreasing, and high multiplicity regime, where B_A is deeply decreasing. In the case of the deuteron, at a low multiplicity regime, the probability to form a deuteron via coalescence is relatively high since the system size is smaller or comparable with the deuteron size. According to the advanced coalescence approach, Eq. 1.18 [10], the length scale factor defined by the deuteron size relative to the source size $\langle C_d \rangle$ will be much effective than the source volume $R^3(m_T)$ here.

However, at a higher multiplicity regime, the size of the system becomes larger than the one of the deuteron. Hence, the probability to form a deuteron via coalescence becomes lower. In view of the advanced coalescence model, the length scale factor approaches 1 and the source volume $R^3(m_T)$ becomes the dominant term on the coalescence parameter B_A as shown in Fig. 1.16.

5.6 Particle ratio of light nuclei to proton

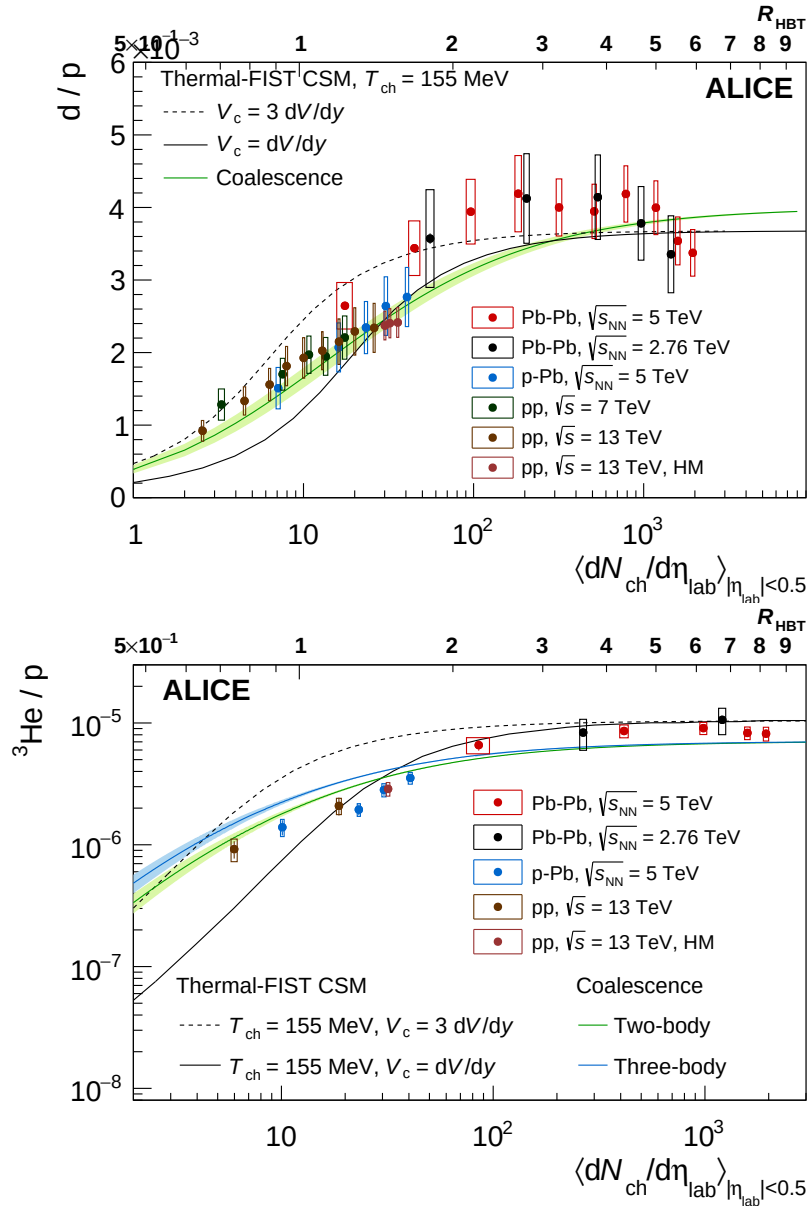


Figure 5.10. Ratios of nuclei to pions as a function of the charged particle multiplicity. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively. The red points are the measured point in this analysis.

The ratio between the p_T -integrated yields of nuclei and protons $R(A)$ is a benchmark for the models for the nuclei production mechanism: SHM and coalescence model. The ratio between nuclei and protons dN/dy defined as

$$R(A) = \frac{dN/dy|_A}{dN/dy|_p} \quad (5.2)$$

Figure 5.10 shows the $R(A)$ of the deuteron (top) and ^3He (bottom) as a function of charged particle multiplicity together with all measurements in various energies at different systems³.

The figure represents the evolution of the $R(2)$ (top) and $R(3)$ (bottom) with increasing charged particle multiplicity regardless energy and collision systems. Considering that the charged particle multiplicity can be a proxy to the size of the system (Section. 1.2, this smooth evolution also can be interpreted as a hint of a common production mechanism that depends on the system size produced in the collision.

The figure includes the model predictions of the SHM and the coalescence model. The solid green line corresponds to the coalescence model and two black lines correspond to the Thermal-FIST [104] canonical statistical model (CSM) for a chemical freeze-out temperature $T_{\text{ch}} = 155$ MeV with two limit configurations, where a correlation volume V_C spanning from 1 (solid line) to 3 (dashed line) rapidity units.

According to the SHM, the ratio of the particle yields $R(A)$ should be fixed when the temperature of the source is determined. However, when the reaction volume is small, for example in a case that the number of particles with a particular conserved charge is small, then the canonical treatment of the corresponding conserved charge(s) is necessary. The conserved charges are conserved exactly in every microscopic state in the canonical ensemble. Therefore, *canonical suppression* rose, which is the yields of particles carrying conserved charges are suppressed relative to their grand-canonical values. The black solid (dashed) line in Fig. 5.10 shows the decreasing trend as charged particle multiplicity drops while it's constant at higher multiplicity region in Pb–Pb collisions. All measured points in the Fig. 5.10 are distributed between two correlation volume limits (solid/dashed black line) of Thermal-FIST CSM.

On the other hand, based on the coalescence model, the raise with multiplicity in the low multiplicity region is explained by the interplay between the system size and the proton yield since the system size is comparable with the nuclei size. In the high multiplicity region, the $R(A)$ saturates like SHM. It becomes less likely to find a proton and a neutron close to each other for the coalescence even if the nucleon yield, such as a proton, increases since the system size of this region is larger than the size of nuclei.

At the highest multiplicity, Both $R(2)$ from $\sqrt{s_{\text{NN}}} = 5.02$ TeV and $\sqrt{s_{\text{NN}}} = 2.76$ TeV shows a decreasing trend. One of the possible explanations is the different re-scattering conditions in the hadronic phase as observed a similar effect in Ξ/p ratio [105]. In addition to that, the advanced coalescence approach gives the dependency of the system volume R^3 in Eq. 1.18. Thus, the production of deuteron can be suppressed due to the small coalescence parameter in the highest multiplicity.

³proton yields are obtained as an average yield of proton and anti-proton.

5.7 Summary and Outlook

The aim of this thesis was to study the characteristics of the hadronic phase produced in heavy ion collisions. For that, the aspect of the phase were studied based on the measured hyperon resonances and light nuclei.

For the first, the measurement of $\Sigma^{*\pm}$ and Ξ^{*0} produced in pp collisions at $\sqrt{s} = 13$ TeV were analysed. The study has been performed based on the data collected by the ALICE detector from 2016 to 2018, consisting of about 1.8 billion minimum bias (MB) pp collisions provided by the LHC. Thanks to the large data sample, it was possible to study the hyperon resonance production in five multiplicity classes. The analysis method to reconstruct the hyperon resonances via the invariant mass technique based on the topological reconstruction of weak decays into charged particles has been presented. The transverse momentum spectra of hyperon resonance, $\Sigma^{*\pm}$ and Ξ^{*0} , are measured as shown in Fig. 3.35. Their p_T -integrated yields dN/dy and average transverse momenta $\langle p_T \rangle$ are evaluated based on the transverse momentum spectra.

Secondly, the measurement of deuteron and ^3He produced in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV were analysed with their anti-matters. The production was measured using the data collected by the ALICE detector in 2018, consisting of about 280 million minimum bias (MB) Pb–Pb collisions. 10 fine centrality bins were able to use for studying the light nuclei production, thanks to the large data sample. The light nuclei were reconstructed based on the particle identification in TPC and TOF detectors. The transverse momentum spectra of light nuclei, deuteron and ^3He , are measured. Following that, their p_T -integrated yields dN/dy and average transverse momenta $\langle p_T \rangle$ are evaluated based on the transverse momentum spectra.

The measurements of the hyperon resonances were compared with the previous findings. The ratio of p_T -differential yields of resonances in pp collisions between 13 TeV and 7 TeV showed a clear p_T hardening. The yield ratio of the hyperon resonances to the long-lived particles in pp collisions didn't show any clue of decreasing trend observed in K^*/K in small systems. However, it might be interesting to see the results from events measured with the dedicated pp high-multiplicity trigger which covers the whole p–Pb multiplicity region, since the two preliminary results of hyperon resonances in Pb–Pb collisions showed a suppression with regard to the model predictions.

The Light nuclei measurements were compared with two different models: Statistical Hadronization Models and Coalescence Models. The yields ratio between measure nuclei and nuclei over proton present a simple check for the chemical freeze-out temperature between 144 to 160 MeV. The coalescence parameter B_A was extracted as a function of the p_T/A , which is the transverse momentum scaled by the mass number of the nucleus. A clear ordering of the parameter with centrality was observed as the coalescence model predicts less efficient nuclei production in the larger volume of the source in central collisions. The parameters are also showed an increasing trend with p_T/A , which can be understood based on the position-momentum correlation of the source expansion. The coalescence parameter is also compared with the charged particle multiplicity $\langle dN_{ch}/d\eta \rangle$ on a fixed momentum. The parameter is deeply decreasing in the high multiplicity region on Pb–Pb collisions while it is gently decreasing in the low multiplicity region. The system size of the phase can be comparable with the size of the nuclei at the low multiplicity region, hence the coalescence parameter showed larger values. The particle ratio of light nuclei and proton is plotted as a function of charged particle multiplicity. The SHM explains a contestant behaviour in Pb–Pb collisions with a grand canonical ensemble while the decreasing trend towards the small systems with canonical suppression. The results showed a decreasing trend in the high multiplicity region of Pb–Pb

collisions which can be explained by a small coalescence parameter in the advanced coalescence model, therefore, it will be interesting to study this region with finer centrality bins.

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Appendix A

ALICE ITS Upgrade Project in Pusan

The ALICE detector has been upgraded during the Long Shutdown 2 (LS2) of the LHC for better physics capabilities. It includes the upgrade of the innermost detector of the ALICE, Inner Tracking System (ITS). In this Appendix, dedicated efforts of the "Pusan" Team for participating in the production chain of the Outer Barrel (OB) of the new ITS, especially focused on the preparation and early production period of the series chip test (MCT) will be discussed with a brief introduction of the new ITS upgrade project.

A.1 The ITS Upgrade Project

A.1.1 Design Concepts of the new ITS

The main object of the ITS upgrade was to improve the vertex-reconstruction capabilities by enhancing the pointing resolution by a factor three at low p_T (Fig. A.1) with respect to the old ITS and to record Pb–Pb collisions at up to 100kHz and pp collisions at 400kHz [63]. A better pointing resolution can be obtained by small inner radii and low material budget, especially for the innermost layer and the beam pipe. In summary, the following design objectives were specified:

- **First detection layer closer to the beam line:** The distance between the first layer and the interaction point is reduced from 39 mm to 22 mm.
- **Reduction of material budget:** The material budget is reduced from 1.14% to 0.3% x/X_0 per layer for the innermost layers and to 1.0% x/X_0 per layer for the outer layers.
- **Geometry and segmentation:** The pixel size of the sensor is reduced from $50\text{ }\mu\text{m} \times 425\text{ }\mu\text{m}$ to about $30\text{ }\mu\text{m} \times 30\text{ }\mu\text{m}$. The number of layers is increased from currently six to seven. Thus, the standalone tracking efficiency and p_T -resolution at low p_T region is improved.
- **Read-out time:** The readout rate is increased from currently maximum 1 kHz to up to 100 kHz for Pb–Pb collisions and 400 kHz for pp collisions.

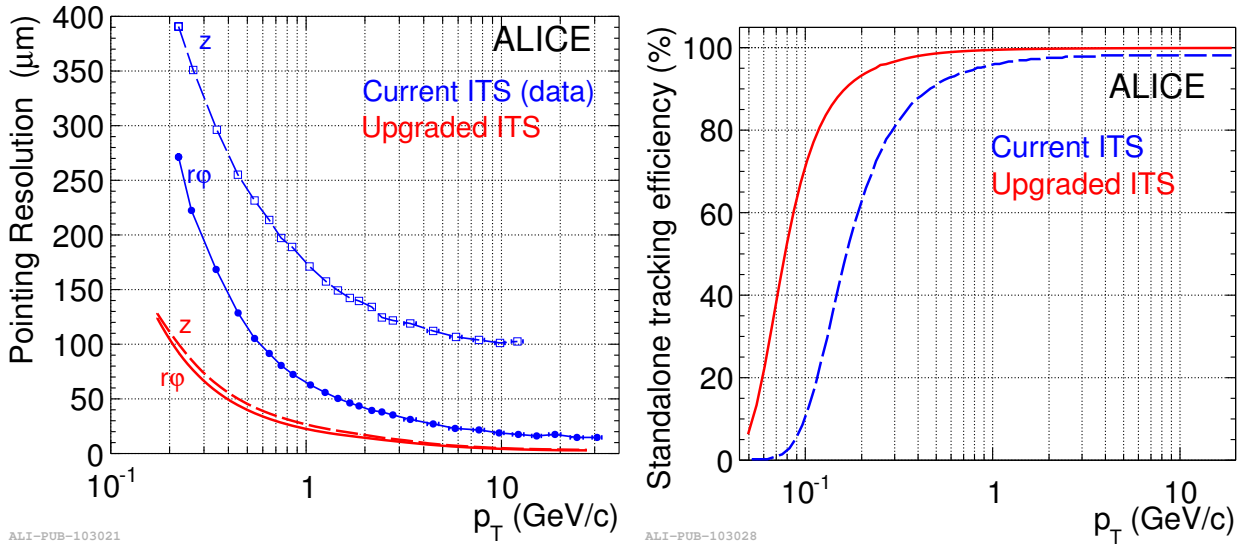


Figure A.1. Pointing resolution (left) and tracking efficiency (right) of the upgraded ITS obtained from MC simulations compared to the old ITS [63].

- **Maintenance:** The new structure consisting of several detector parts is implemented for the efficient removal and insertion during the yearly shutdown period.

A.1.2 Layout of the new ITS

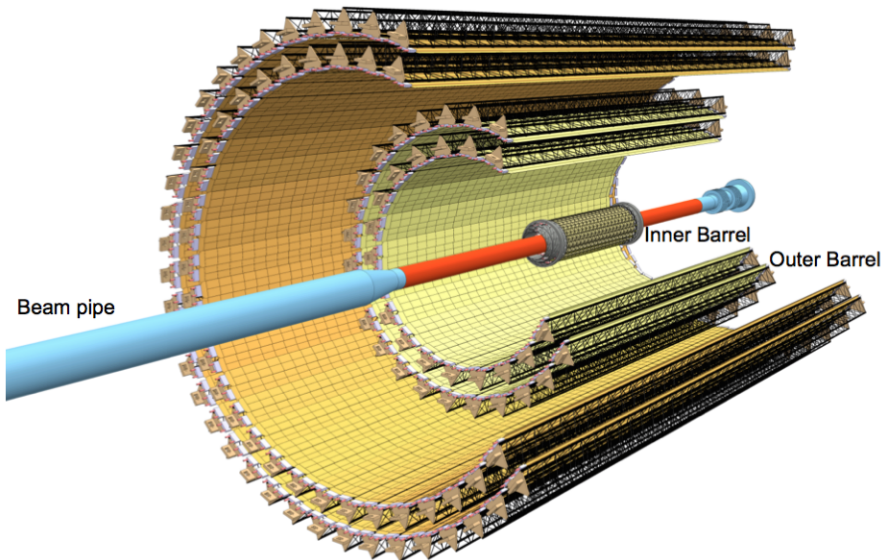


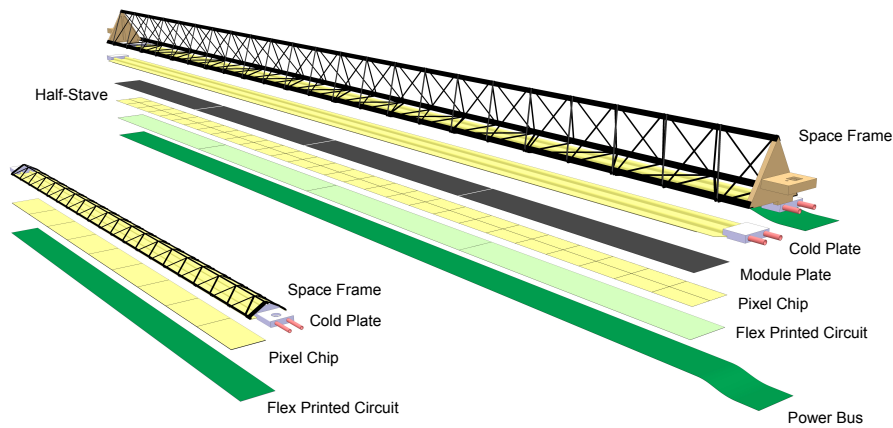
Figure A.2. Layout of the upgraded ITS [63].

Figure. A.2 shows a layout of the new ITS consisting of seven layers. The set of the innermost three layers is named Inner Barrel (IB). The middle and the outer layers form together the Outer Barrel (OB). The detailed specification of the layout parameters is summarised in Tab. A.1. The new ITS has $\sim 10 \text{ m}^2$ of total active area with $\sim 24,000$ pixel chips (12.5 giga pixels).

Table A.1. Layout parameters of the new ITS [63].

	Inner Barrel			Outer Barrel			
	Inner Layers			Middle Layers		Outer Layers	
	Layer 0	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Length [mm]	271			843		1475	
Radial position (min.) [mm]	22.4	30.1	37.8	194.4	243.9	342.3	391.8
Nr. pixel chips	108	144	180	2688	3360	8232	9408
Nr. modules	12	16	20	192	240	588	672
Nr. staves	12	16	20	24	30	42	48
Chip size [mm ²]				15 x 30			

Stave

**Figure A.3.** Schematic of the Inner Barrel (left) and Outer Barrel (right) Stave [63].

The ITS layers are azimuthally segmented in units named Staves, which are mechanically independent. The *Stave* is the complete detector element containing all structural and functional components, which consists of the following main components:

- **Space frame:** The space frame is a truss-like lightweight mechanical support structure for the single stave based on the carbon fibre material.
- **Cold plate:** The cold plate is a carbon ply that embeds the cooling pipes.
- **Hybrid integrated circuit (HIC):** HIC is an assembly consisting of the polyimide flexible printed circuit (FPC) on which the Pixel Chips (2×7) and some passive components are bonded with the wire-bonding technique.

IB stave contains a single HIC with nine pixel chips. On the other hand, the OB stave hosts two *Half-Stave*, which is subdivided in longitudinal direction into a number of HIC modules. Figure A.3 show the schematic of the IB stave and OB stave.

A.1.3 ALICE Pixel Detector (ALPIDE)

ALICE Pixel Detector (ALPIDE) is a silicon pixel sensor chip that features very thin sensors and very high granularity. In order to cover a considerably large area of about 10 m^2 with pixels, CMOS Monolithic Active

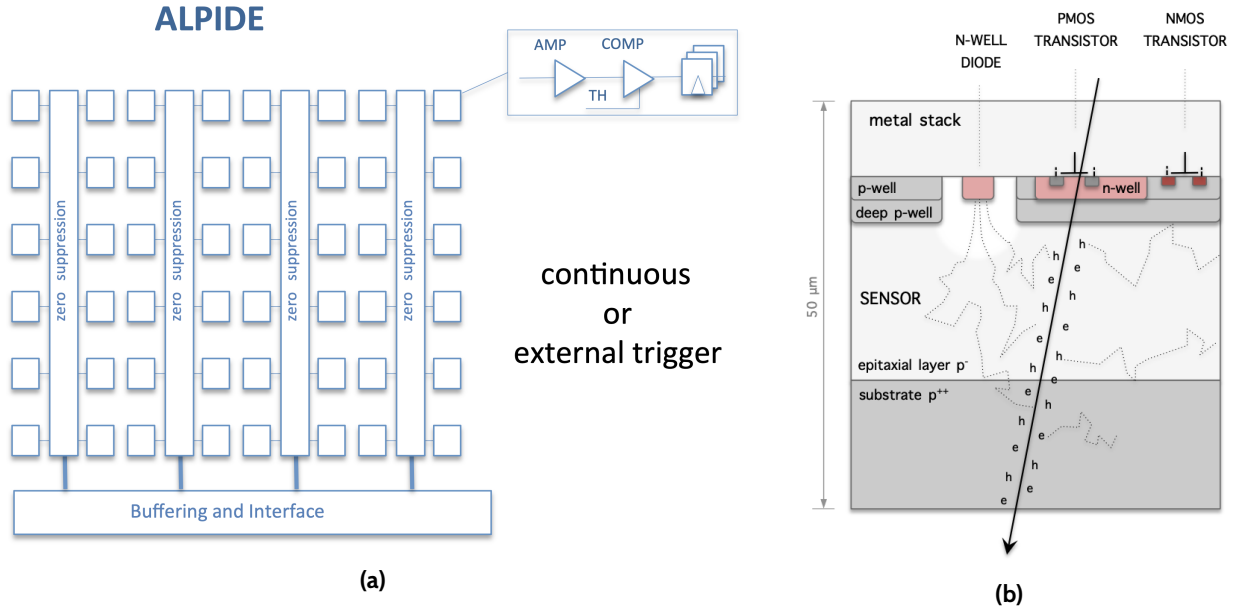


Figure A.4. Schematic layout of the ALPIDE pixel chip architecture (a) and Schematic cross sections through pixel sensors of CMOS Monolithic Active Pixel Sensors (MAPS) technology (b) [106].

Pixel Sensors (MAPS), which integrates both sensor and readout electronics on the same die, is chosen as the technology for all layers. ALPIDE can be operated in two modes: the *triggered mode* and the *continuous mode*. In the triggered mode, the sensors will take the data based on the arrival of the ALICE level zero (LO) trigger, which has a latency of about 1.2 μs. In continuous mode, data will be continuously taken to the readout. The pixel pitch of ALPIDE is 28 μm × 28 μm.

Figure. A.4a shows a schematic layout of the architecture of ALPIDE. The basic idea of the ALPIDE structure is to put complexity as much as needed into the pixel or matrix. Each ALPIDE pixel has its own amplifier, discriminator and (multi-)hit buffers. By implementing the in-pixel discriminator, it can produce only the digital output including the address of hit pixels, as we called *Zerosuppression* performed in the matrix. An Address-Encoder Reset-Decoder (AERD) circuit is employed for the Zerosuppression. It propagates the addresses of hit pixels to the end-of-column logic and resets the corresponding in-pixel hit buffers. This architecture allows to read all pixels in a global-shutter mode rather than the traditional rolling-shutter mode. ALPIDE has high speed output serial link which operates upto 1.2 Gbit/s for IB and 400 Mbit/s for OB.

Monolithic Active Pixel Sensor (MAPS)

Monolithic Active Pixel Sensor (MAPS, Fig A.4b) is the technology that allows building a Pixel Chip that integrates the sensor matrix and the read-out electronics in one silicon wafer, unlike the traditional Hybrid pixel detectors which are produced by implementing the sensor and the front-end electronics in two separate silicon chips. Due to this configuration, MAPS are typically thinner than hybrid pixel sensors. The high-resistivity ($> 1\text{ k}\Omega\text{ cm}$) p-type epitaxial layer (25 μm) is placed on highly doped, high-resistivity ($\sim 10\Omega\text{ cm}$), p-type substrate, serving as sensitive volume by generating a partially depleted region. The generated charge by the passing particles is constrained by potential barriers at the boundary until it reaches the collection diodes. By implanting the n-well and p-well on the top of the epitaxial layer, it shapes the PMOS

and NMOS transistors of the CMOS circuit. In addition to that, additional **deep p-wells** are embedded under the n-wells of PMOS transistors in order to prevent the n-well to collect the generated charge inside the sensitive volume, thus preserving the charge collection efficiency of the collection diode.

A.1.4 Production Workflow of the OB of the new ITS

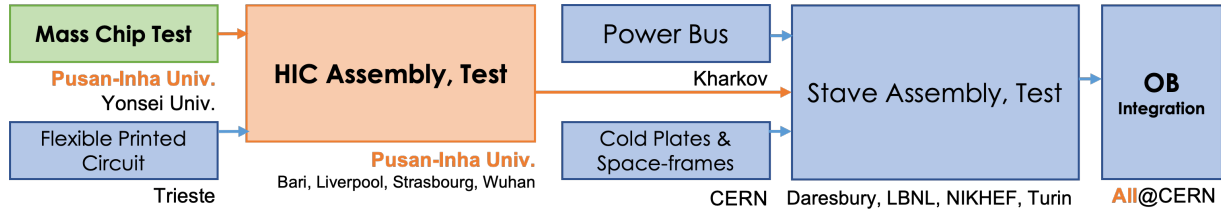


Figure A.5. Overall production workflow of the ITS OB. The parts where Pusan group participated are highlighted.

The new ITS IB was produced and assembled at CERN only. Besides, the production of the OB of the new ITS was distributed in several sites as shown in Fig. A.5. All ALPIDEs produced at TowerJazz have been transferred to the company for thinning and dicing in Korea. Among them, the ALPIDEs for IB are sent to CERN for the operational test, the other ALPIDEs for OB is sent to two testing sites, Pusan National University (Pusan¹) and Yonsei University (Yonsei). Pusan and Yonsei had to test all produced ALPIDEs for the OB production, which consists of 60k pixel chips including spares. A dedicated Automatic Test Equipment (ATE) designed and developed for the ITS upgrade project, *ALICIA*, was prepared for the series chip test in Pusan. The test includes not only the electrical test but also the optical test. Once the ALPIDE is tested, they are sent to CERN for the shipping management and distributed to the OB module assembly site consisting of Pusan (KR), Bari (IT), Liverpool (GB), Strasbourg (FR), Wuhan (CN). The module assembly sites take the ALPIDE from CERN and Flexible Printed Circuit (FPC) from Trieste (IT). In the module assembly site, the detector module (HIC) is produced by assembling the 14 ALPIDEs to FPC by using *ALICIA* and the glue. All tested HICs are sent to CERN for the shipping management and sent to the stave assembly sites together with the power bus from Kharkov (UK) and the cold plates & the space-frame produced at CERN, in Daresbury (GB), LBNL (US), NIKHEF (AN) and Turin (IT). All produced staves are finally sent to CERN and assembled on the ground for the final test and the commission.

¹The operation was done by Pusan-Inha joint team for the ITS upgrade project, which consists the member of Pusan National University and Inha University.

ALICE Integrated Circuit Inspection and Assembly Machine (ALICIA)

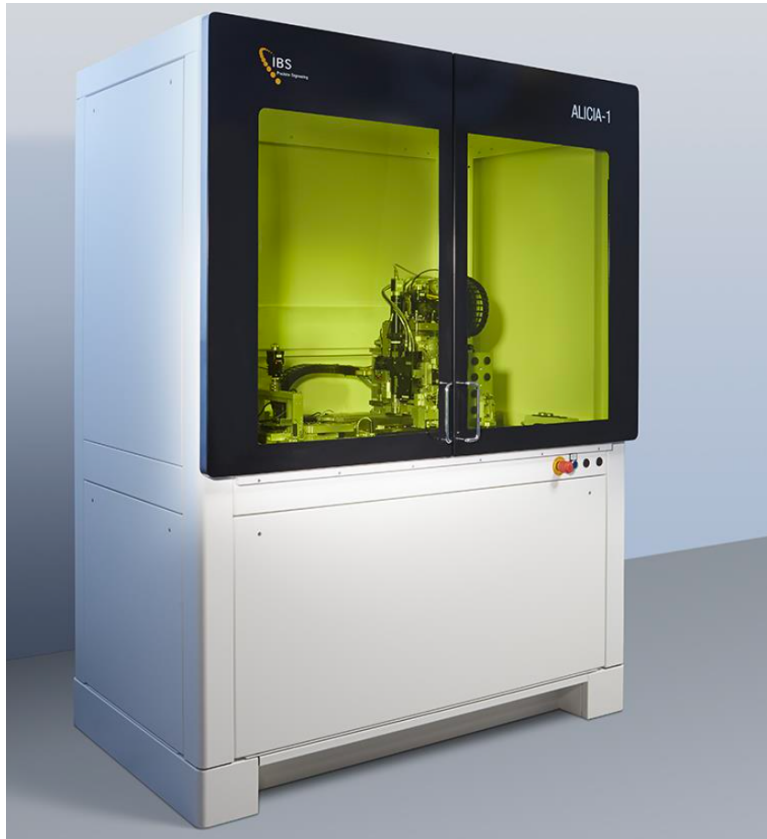


Figure A.6. ALICE Integrated Circuit Inspection and Assembly Machine (ALICIA)

The ALICIA is an automatic inspection and assembly system for mounting these chips on an FPC within the required accuracy, co-developed by CERN and IBS Precision Engineering [107]. ALICIA is the acronym of ALICE Integrated Circuit Inspection and Assembly Machine. The positioning accuracy of chips of $< 5 \mu\text{m}$ with respect to external reference features was required for the ALICIA.

The ALICIA manipulates the chip of sub-micron accuracy based on the metrology capability provided by a high-resolution vision system that measures the position of each chip with respect to reference fiducials for the chip manipulation. It can measure and check the dimension of the chip, cleanliness of the chip contact pads and edge quality of the chips with the same vision system. The machine uses a vacuum gripper to handle the chip and brings it to three different regions: Chip Tray, Pre-Position Chuck, HIC Assembly Table. A Pre-Position Chuck is used for the initial alignment of chips and electrical testing using the probecard. The HIC Assembly Table is used for the final assembly of the Hybrid Integrated Circuits (HICs).

Figure A.7 shows the sub-assemblies of ALICIA (top) and a schematic overview of the ALICIA components (bottom). To install and operate the ALICIA, the below requirement has to be fulfilled:

System Requirements

- Pneumatic System: 7 bar of pressurized air plant supply with 80 nl/min flow
- Electrical Supply: 3 P+N+G (phases + neutral + ground) of 400 V (50 Hz) of electricity with 16 A

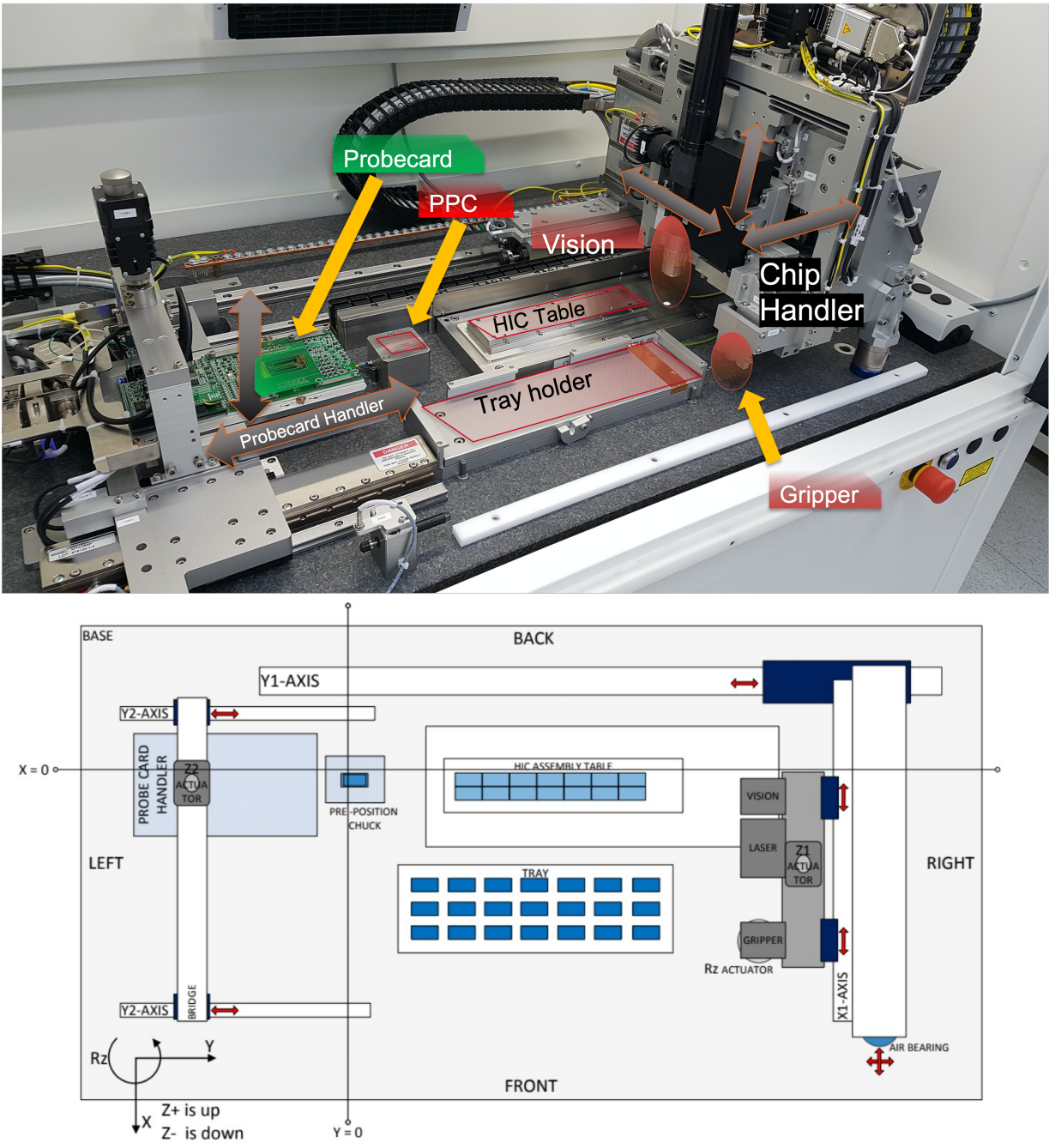


Figure A.7. Sub-assemblies of ALICIA (top) and Schematic overview of ALICIA main components and coordinates (bottom)

A.1.5 Series Chip Test

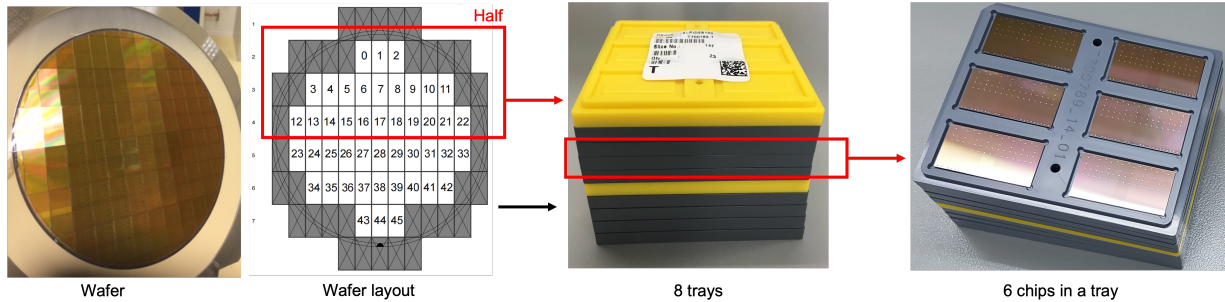


Figure A.8. ALPIDE: Wafer to chip tray

A series test of the ALPIDE chips for the whole ITS upgrade project was planned and performed at Pusan and Yonsei groups as we called Mass Chip Test (MCT). Total 60k chips were planned for testing using the dedicated ATE, which is the ALICIA with the probecard extension for Pusan and Corea-YS-01 for Yonsei. The pixel chips are sent from the company in Korea to Pusan after the post-processing of the silicon chip production, such as thinning (grinding), dicing and packaging to the trays. Figure A.8 shows the flow of the chip from a wafer to the chip trays. Each wafer contains 46 chips. A half of them, 26 chips, are put in a set of tray consisting a yellow cover tray and four gray mini trays. Each mini tray contains 6 chips, consequently, the last mini tray will contains 5 chips ($6+6+6+5$, 23 chips). They are managed with a unique number, based on the number of lot, wafer and chip. The unique number is converted to the QR code so that it can be handled efficiently in every site where the chip will be used. All transferred chip trays are inserted into ALICIA and tested under human monitoring.

Automatic Test Procedure

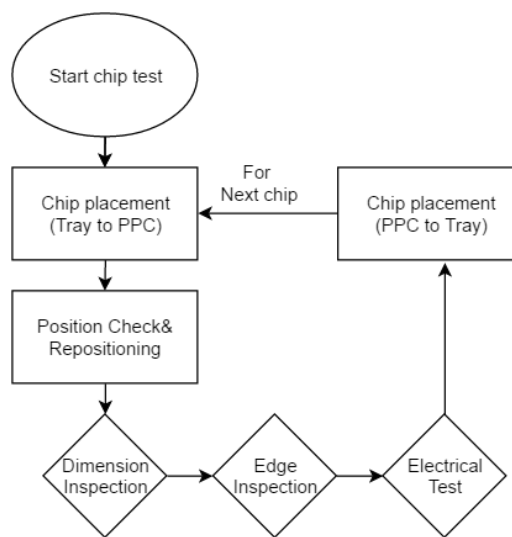


Figure A.9. Flowchart of the chip test

The ALICIA performs several steps of testing for each chip (Fig. A.9). The test includes Chip placement, Position check, Re-positioning, Dimension inspection, Edge inspection and finally, Electrical test.

Figure A.10 shows the time consumption of the each process. ~ 80 chips are used for the average calculation. The test results are classified into two states: OK for good chips and NK for bad chips. There are two most time demanding test procedure, Edge inspection and Electrical test. Figure A.11 show the test time distribution for OK and NK chips. NK chips tend to have relatively short test time while OK chips are taking more than twice the time than NK. This is due to the fact that NK chips stop the test at a point where the test result shows a bad result. In particular, it happens during the electrical test as shown in Fig. A.10. A total of ~ 2.5 hour is taken for testing one set of trays, 23 chips.

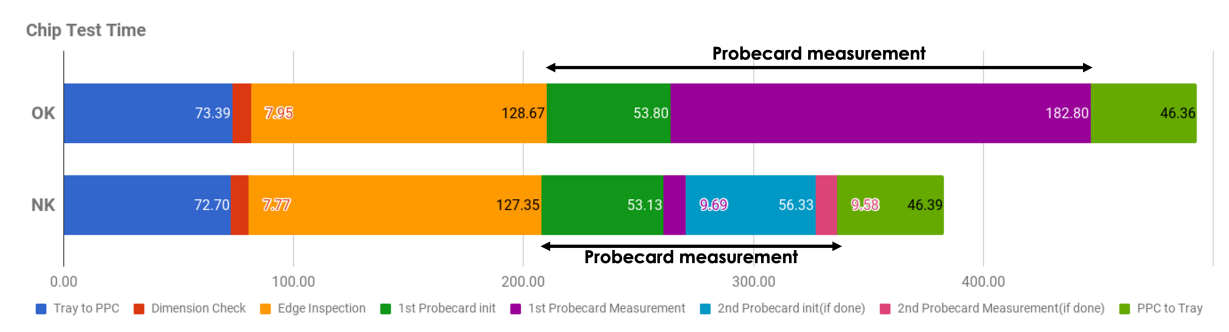


Figure A.10. Time consumption of the each test (bottom)

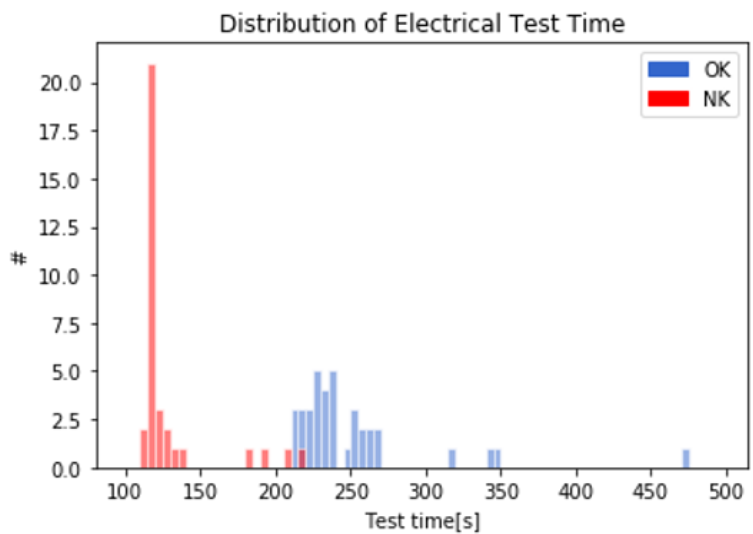


Figure A.11. Histogram of the time consumption of the test for OK and NK chips

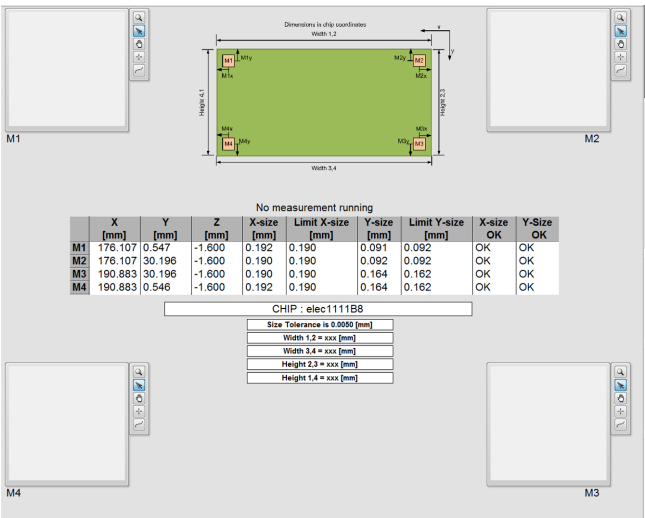


Figure A.12. Dimension Inspection window on ALICIA software

Dimension inspection In dimension inspection, the machine takes four photos of each corner, where the distance between marker and chip edge is measured in both X and Y directions. The dimension measurement screen (Fig. A.12) shows the measurement result of the chip dimension measurement. By comparing the measured dimension with the design value, the machine can reject the chip in case it overs the limit.

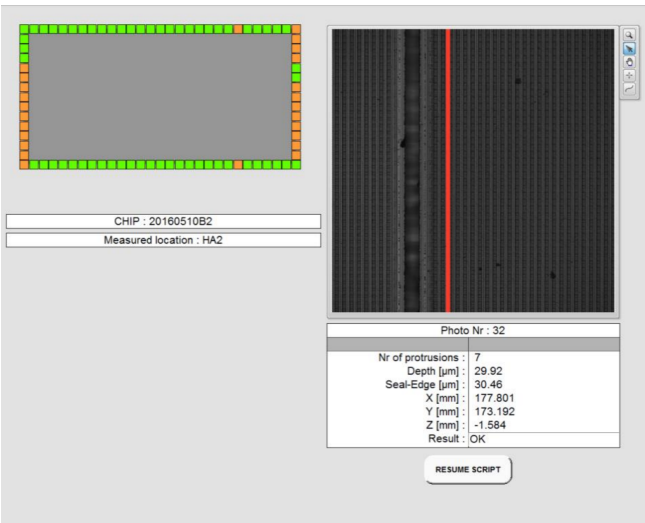


Figure A.13. Edge Inspection window on ALICIA software

Edge inspection In the Edge inspection, ALICIA takes 84 overlapping photos, where each image is analyzed on cracks and defects, along with the edge of the chip. In the screen of Edge Integrity of ALICIA software (Fig. A.13), it provides direct insight into the results of the edge integrity of the chip. During the edge inspection, the squares on the rim of the figure on the top left corner will be filled. Once the test is finished, a measurement of each section can be selected by clicking on one of the squares. The result of the test on the point and the corresponding photo is displayed. If the color changes as orange, the operator should check if it is due to the crack or just dust.

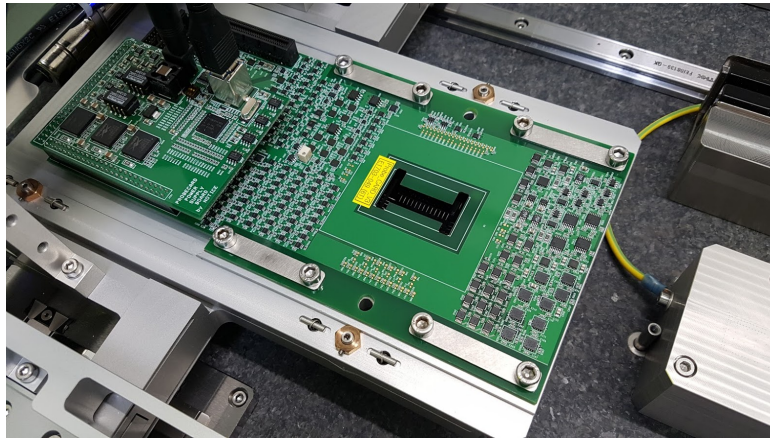


Figure A.14. Probe card for electrical test

Electrical test The electrical test evaluates the chip using the *Probe Card* installed at the left inside of ALICIA as shown in Fig. A.14. Probe card can interact with the chips by connecting its needles to the pad on the chip. The electrical connection between the chip and the probe card is established by the physical connection of needles under the probe card and pads on the chip. Fig. A.15 shows the needles under the probe card and the pad map of ALIPDE. Once the electrical test is triggered, the probe card will be placed over the chip on the PPC, and gently land the needles on the chip. The probe card is connected by a USB cable to the DB PC, which is used not only for executing the electrical test script in the command-line interface but also for connecting the central DB of the ITS upgrade project.

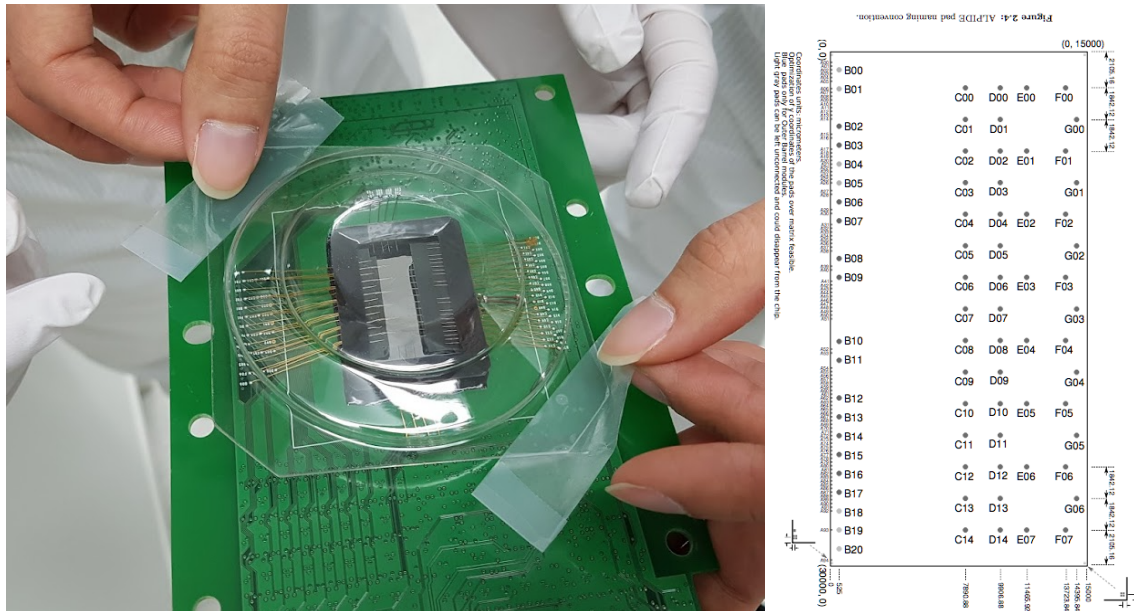


Figure A.15. Needle of the probe card (Left) and Pad on the chips [108] (Right)

The electrical test contains several tests as listed below:

- **Powering Test:** Apply nominal voltages without any attempt of communicating the the chip.
- **V_{bb} I-V Test:** Apply the reverse substrate bias, *back bias*, is swept from 0 V down to -6 V.
- **DAC Scan:** Verify that each DAC is working by sweeping through all its code words, and the bias network is not shorted.
- **Power on Reset test:** Check the functionality of power on reset.
- **Chip ID test:** Check the response of the ALPIDE by changing the input of different operation modes.
- **SEU check:** Monitor the SEU counter and the flag bits on idle operation.
- **Register test:** Check all registers by write and read back to find stuck bit.
- **FIFO test:** Check all of the generated memory blocks for stuck bits, broken bit or word lines as well as addressing failures.
- **Data Port test:** Verify its functionality to send quasi-static patterns for getting additional information in case of the readout test failure.
- **Digital Scan:** Test the 'testing functionality' of ALPIDE, and then inject single hits directly into the in-pixel memories.
- **Fake Hit Rate:** Measures the number of pixels with a non-Gaussian behavior as well as faulty front-ends.
- **Analogue Scan DP:** Exercises the analogue front-end and the full readout chain of ALPIDE
- **Threshold Scan:** Test all analogue front-ends/pixels by using the analogue pulse injection.
- **High Speed Link check:** Check the functionality of HS Link.

Details of each function can be found in Ref. [108]. The average time consumption of each test was studied as shown in Fig. A.16. The average time consumption of the full test process was 3 min 7s for OK chips, 26s for NK chips. The most time demanding test was the Threshold scan.

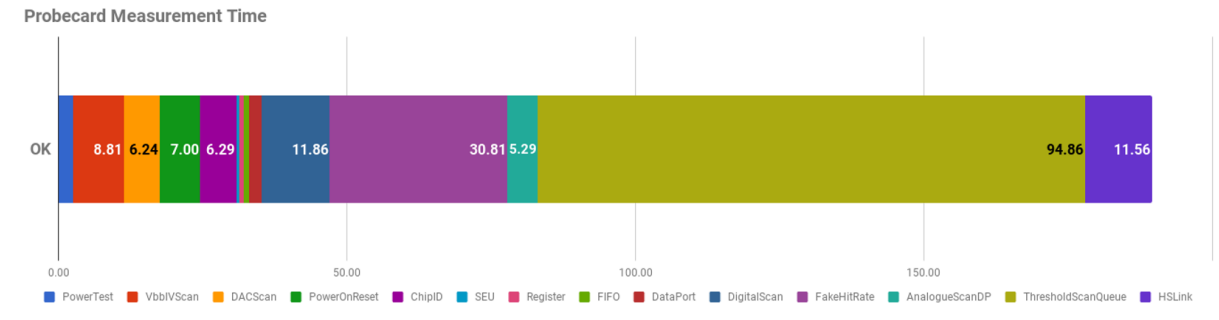


Figure A.16. Detailed time consumption in the electrical test

Shipment

After all test procedures, the tray is collected from the machine and stored in a desiccator until shipment. Vacuum packing is adopted to prevent any potential contamination and to achieve tight sealing.



Figure A.17. Vacuum packing (left) and Packed tray for the shipment

A.1.6 Module Assembly

Hybrid Integrated Circuit (HIC) is the core part of the new ITS consisting of the flexible printed circuit (FPC) and 14 pixel chips. Total 2k of OB HIC including 20% of spares have to be produced by five sites, Pusan (KR), Bari (IT), Liverpool (GB), Strasbourg (FR) and Wuhan (CN). By sharing these amounts of required HIC equally, ~ 400 working HICs have been expected to be produced in each site.

Chip placement HIC assembly is performed in ALICIA. 14 Pixel chips are precisely aligned in two parallel rows of seven chips with $\pm 5 \mu\text{m}$ of accuracy on the HIC Table as shown in Fig. A.18. (Figure missing one chip at the left top side.) Placement of the chip in ALICIA including the procedure of edge inspection takes around 1.5 hours if there is no error during the operation. It's an automatic procedure, therefore, the operator can prepare the FPC meanwhile.

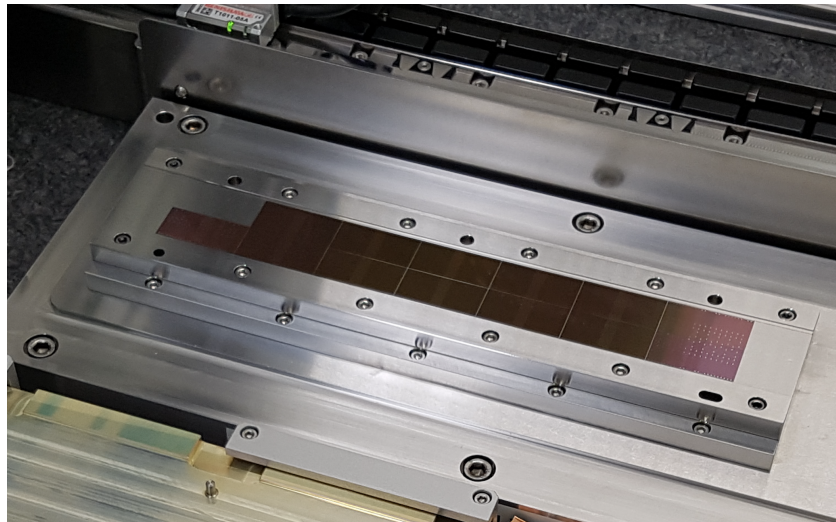


Figure A.18. Placing chips on the HIC table in ALICIA.

FPC preparation The second component of HIC, FPC (Fig. A.19) is shipped on the OB HIC carrier as shown in Fig. A.21a. Six power connections for the HIC electrical test can be found together. When opening the FPC, a visual inspection is carried out. To glue the FPC with chips, an adhesive is distributed on the FPC using the glue mask and glue mask gripper. After glue distribution, a specific pattern of glue can be seen as shown Fig. A.22. Figure A.21 shows main procedures described above.

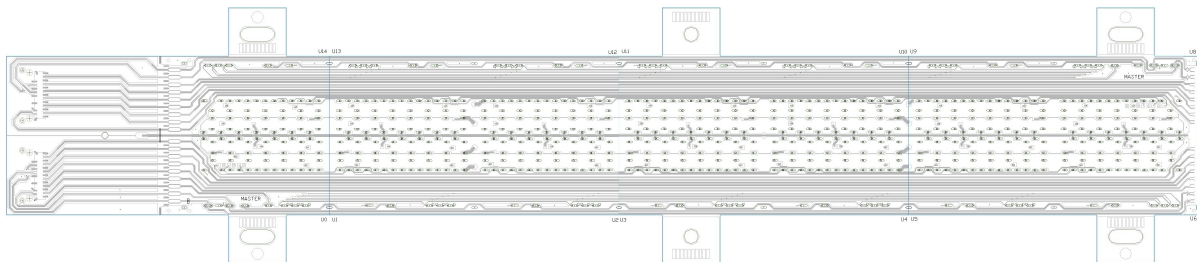
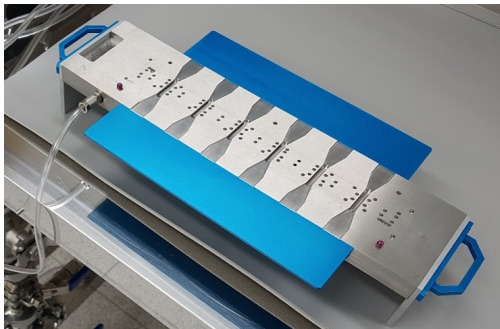


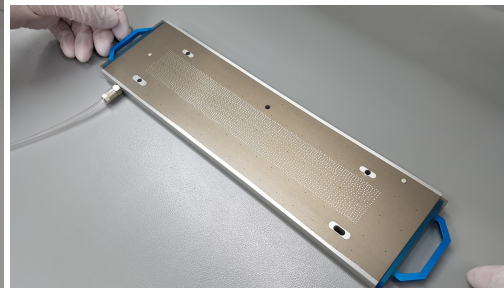
Figure A.19. Top view of FPC



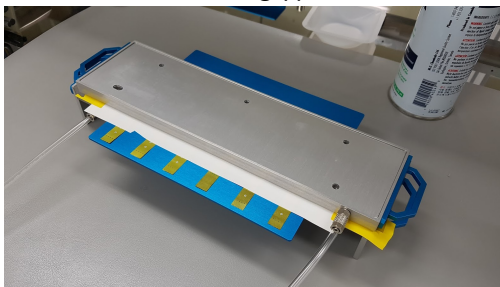
Figure A.20. FPC with OB HIC carrier



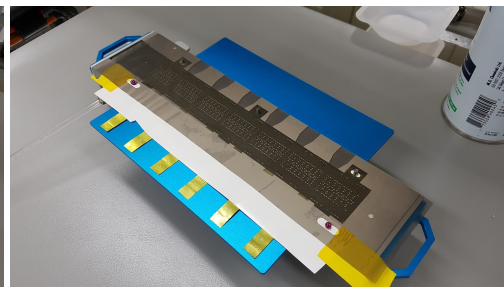
(a) FPC gripper



(b) Glue mask on glue mask gripper



(c) Coupling of FPC and glue mask



(d) Glue mask on FPC

Figure A.21. FPC preparation with glue

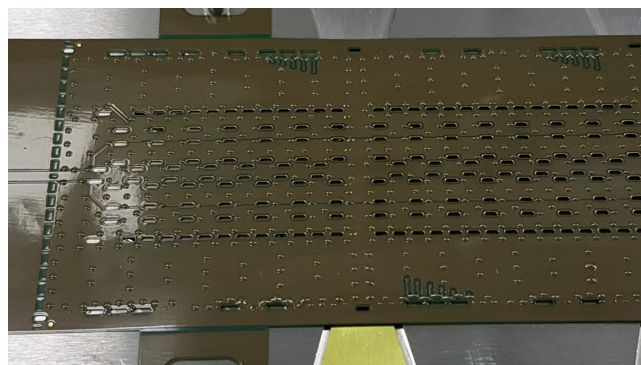


Figure A.22. Glue patterns on FPC

Coupling FPC and chips After glue distribution, FPC is ready to couple with chips. The FPC is gone down gently on the top of the chips as it is attached to the FPC gripper based on the ruby position marker. Once the coupling is completed, ~ 5 hours of curing time is needed. After curing, the HIC can be removed from the table by using the FPC gripper. It is stored to HIC carier again to wait the wire-bonding.

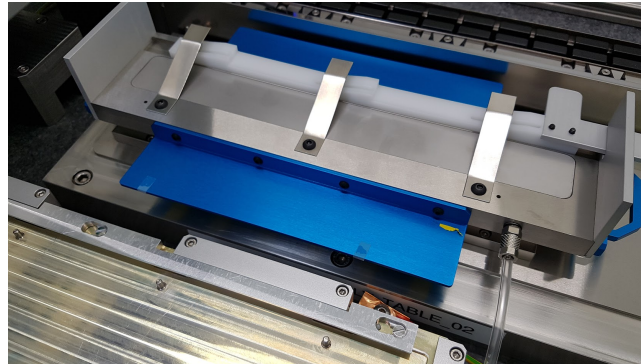


Figure A.23. FPC under the FPC gripper coupled with chips.

Wire-bonding An ultrasonic wedge bonding is used as a connection technology between the FPC and the chips. The connection is established between the pad over the chip and the metalised crown surrounding the vias of the FPC. Figure A.24 shows the connection points after wire-bonding (top) and the cross-section view of the connection point. For the wire-bonding, $25\ \mu\text{m}$ Al wire is used for more than 2 points of bonding on each pad. To ensure the quality of the bonding, the Bonds Pull Force Test (BPT) is performed periodically. Figure A.25 presents a top view of FPC after the wire-bonding, in which one can easily find 3 bonding points per each connection.

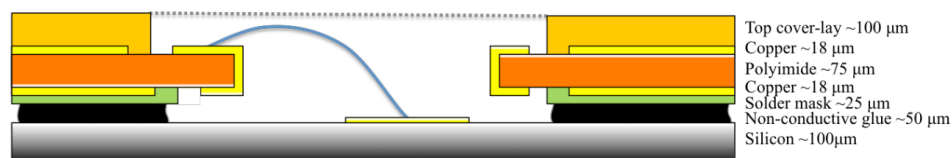


Figure A.24. Cross-section view of the connection point between FPC and chip

HIC Electrical Test After the wire-bonding, the HIC takes three electrical tests. Figure A.26 represents a OB HIC test setup. The big black box placed at the left of the table in Fig. A.26 is the setup for the endurance test, and the small black box at the right side shows the qualification test setup. For the OB HIC test, three electrical tests are adopted: **Impedance Test** for identifying any shorts that occur between the voltage supplies of the HIC, **Qualification Test** for the main working test of the HIC with similar tests specified in the electrical test on Sec. A.1.5 and, finally, **Endurance Test** for the long-term stability of the HICs that tests 10 HICs for a week.

Based on the test result, the produced HICs are classified into: gold, silver, bronze, partially working, partially working category B, no back-bias, no back-bias category B or not working. The fully tested HICs are sent to CERN for the next production site, stave assembly site.

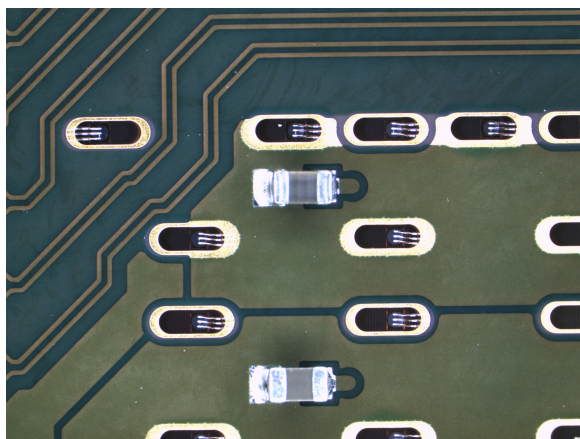


Figure A.25. Wire-bonding between FPC connection and chip pad

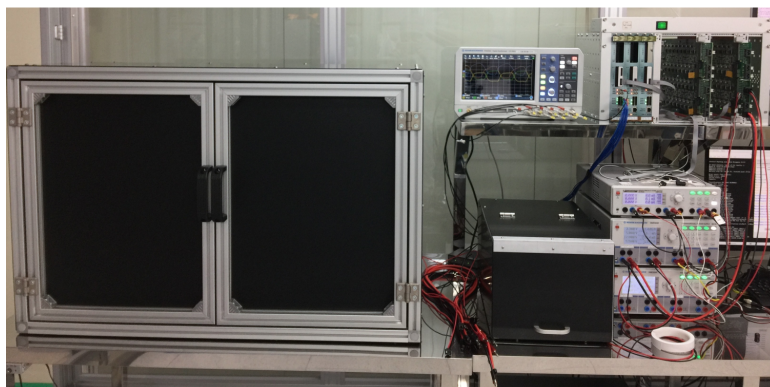


Figure A.26. OB HIC Test Setup



Figure A.27. Qualification Test setup for single HIC (left) and Endurance Test setup for 10 HICs

A.2 Lab Preparation

To handle the semiconductor for test and assembly, an appropriate environment is required. The clean room with a proper level of cleanliness is needed to prevent any potential contamination to the devices. In addition to that, floor vibration must be controlled in specific vibration criteria. Finally, electrostatic discharge(ESD) should be prevented.

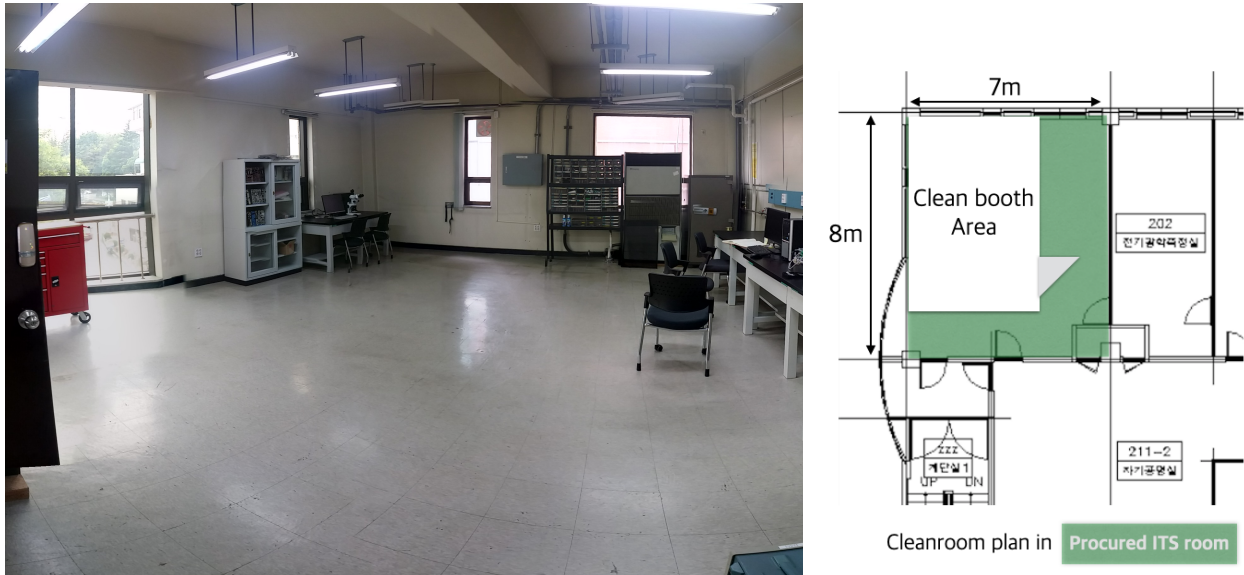


Figure A.28. The ITS lab in Pusan at the beginning (Left, taken at 10th of June, 2014) and blueprint of the room (Right).

The lab preparation was started from the scratch. The size of the room was about 55 m². There are some requirements for the HIC assembly sites:

- Environmental conditions:
 - Temperature: $(20 \pm 2) ^\circ\text{C}$
 - Humidity: 30–60 %
 - Floor Vibration Level: Compliant with vibration criteria C
 - Heat in (to machine): Machine should not be placed in vicinity of radiating heat sources.
- Supplies (for ALICIA):
 - Pressurized air: 7 bar with 80 nl/min flow
 - Electricity: 3 P+N+G (phases + neutral + ground) of 400 V (50 Hz) of electricity with 16 A

Temperature and Humidity were controlled based on the thermo-hygrostat machine in the room, which has 21, 000 W power². In addition to that, a large window area where it can be found in the left bent side of Fig. A.28 had to be blocked for the better thermal insulation of the room. Figure A.29 shows the temperature and humidity monitoring graph with requirements. Gases are supplied with 30 L gas bottles, and the

²For an active area, the appropriate power of air conditioner per square meter: $\sim 125 \text{ W/m}^2$

pressure and flow are controlled by regulators on the bottle. Due to the high air consumption of the ALICIA, the gas bottles had to be replaced every 2.5 working days. Therefore, 2 gas bottles for the pressurized air are placed, one for active while the other for backup. The electricity given in the facility was 380 V with 60 Hz, but it was confirmed that the machine can be operated.

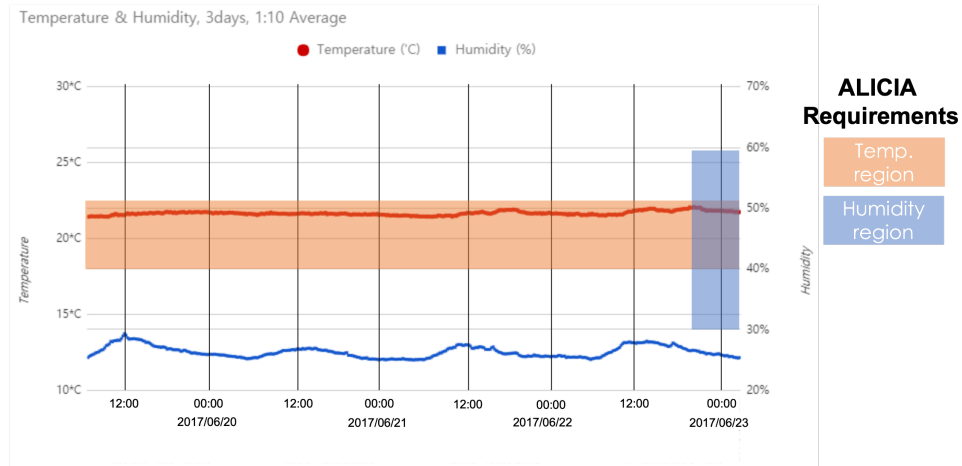


Figure A.29. Measured Temperature and Humidity for four days with requirements

A.2.1 Cleanliness: Clean Room

Table A.2. Cleanroom Classification (US FED STD 209E)

Class	Maximum Particles/ft ³					ISO Equivalent
	≤ 0.1 μm	≤ 0.2 μm	≤ 0.3 μm	≤ 0.5 μm	≤ 5 μm	
1	35	7	3	1		ISO 3
10	350	75	30	10		ISO 4
100				100		ISO 5
1,000				1,000	7	ISO 6
10,000				10,000	70	ISO 7
100,000				100,000	700	ISO 8

To prevent any potential contamination to chips and modules, a cleanroom environment was required to be installed in the lab. A 100,000 class of Cleanliness was recommended for the HIC Assembly site, which is the appropriate class for semi-conductor assembly. Since Pusan has to perform the series chip test together, better class (~10,000 class) of the cleanroom was considered. Based on the consideration that the room size was limited and the cleanroom has to be maximised in the given room, the *Clean Booth* was adopted to install. A clean booth is a cleanroom based on a booth structure that the vertical unidirectional airflow of the filtered air is provided. The airflow outs to the bottom slit of the wall of the clean booth. It has benefits for: fast construction, easy installation, easy modification, low cost, easy maintenance and ease to control.

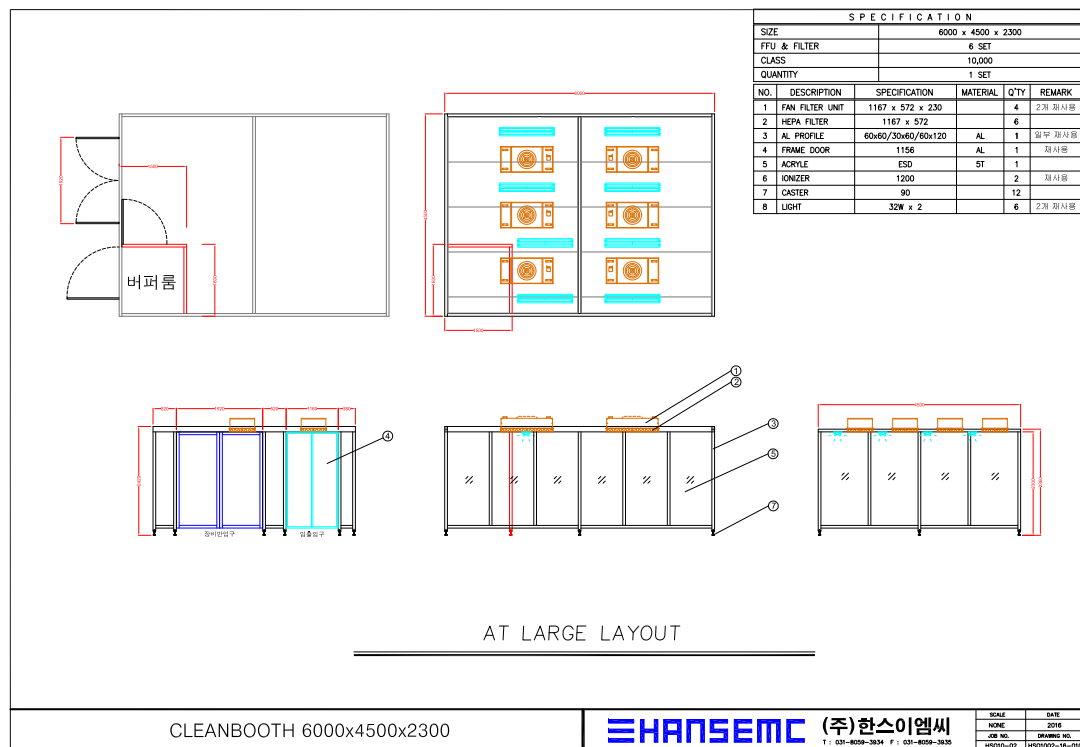


Figure A.30. A blueprint of the clean booth installed in lab.

Figure A.30 shows the blueprint of the clean booth installed in the lab. The size of clean booth is $6.0 \times 4.5 \times 2.3 \text{ m}^3$ ($W \times D \times H$) including the 2.4 m^3 of buffer room inside. Six Fan Filter Units (FFU) are installed

at the top. The ESD acrylic wall is used to prevent any adhesion of dirt on the wall. Two doors are installed: one for the human, the other for the machine.

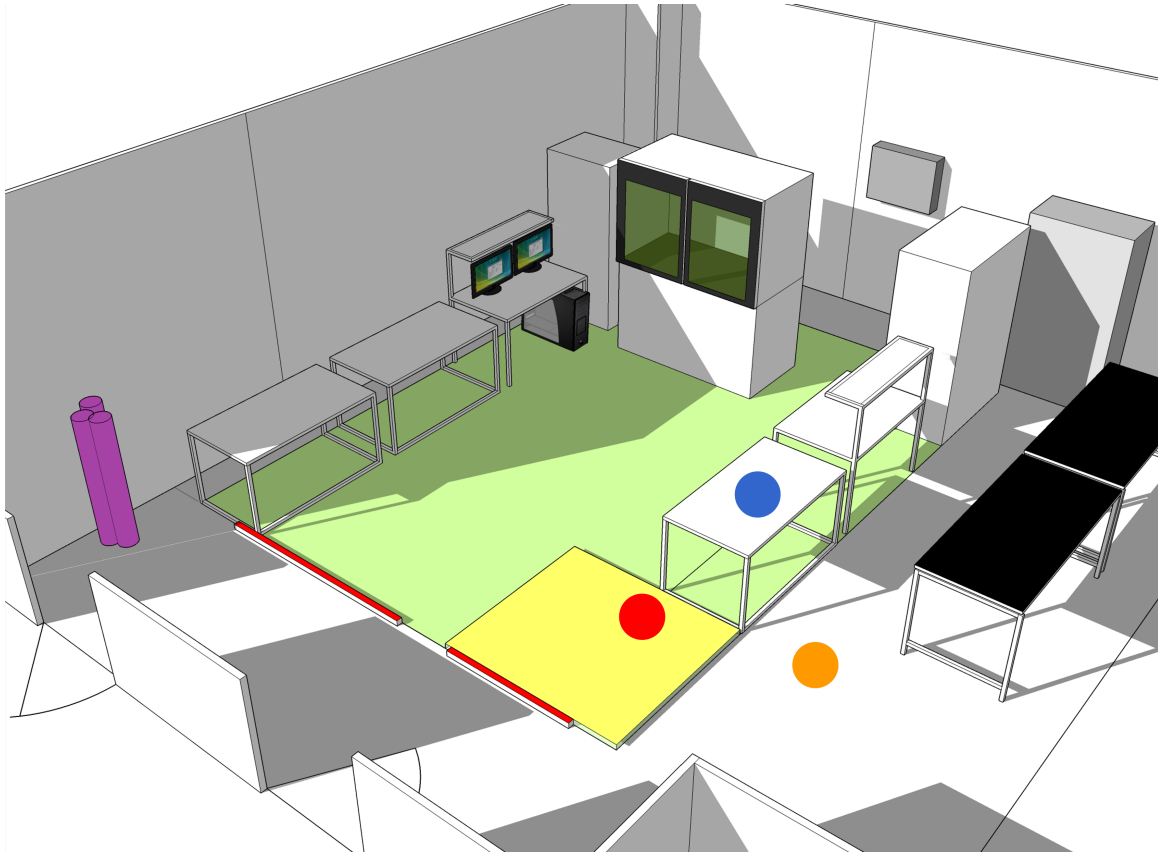


Figure A.31. 3D schematic view of the clean booth. 3 points coloured red, blue, orange are the place where the number of particle was measured.

Figure A.31 illustrates the arrangement of the clean booth in the lab and some of major materials inside. The green coloured area represents for the cleanroom area and yellow coloured area for the buffer room. Two red bars indicate the door of the clean booth. Inside the cleanroom, anti-dust tables built with aluminium and 120 L size of desiccators for storing the chips and modules are placed.

To check the quality of the clean booth, a number of particles are counted using the particle counter³ on three different positions in the room. The three coloured points in Fig. A.31 represent the position inside the clean booth (blue), buffer room (red) and outside of the clean booth (orange). The three histograms in Fig. A.32 show the histogram of the number of measured $0.5 \mu\text{m}$ particles in 1 ft^3 , which correspond to the Cleanness Level. On average, 46 ± 30 particles for the clean booth, 1524 ± 1137 for the buffer room and 14380 ± 11678 outside of the clean booth are measured. The measurement was performed between 21st June to 17th July in 2016, total of 23 times. A bottom graph in Fig. A.32 shows the time evolution of the Cleanness Level with a clear separation of three different places. Consequently, around 1,000 class of well managed clean booth is constructed although 100,000 class of Cleanliness was recommended.

³Airy Technology P311 is used.

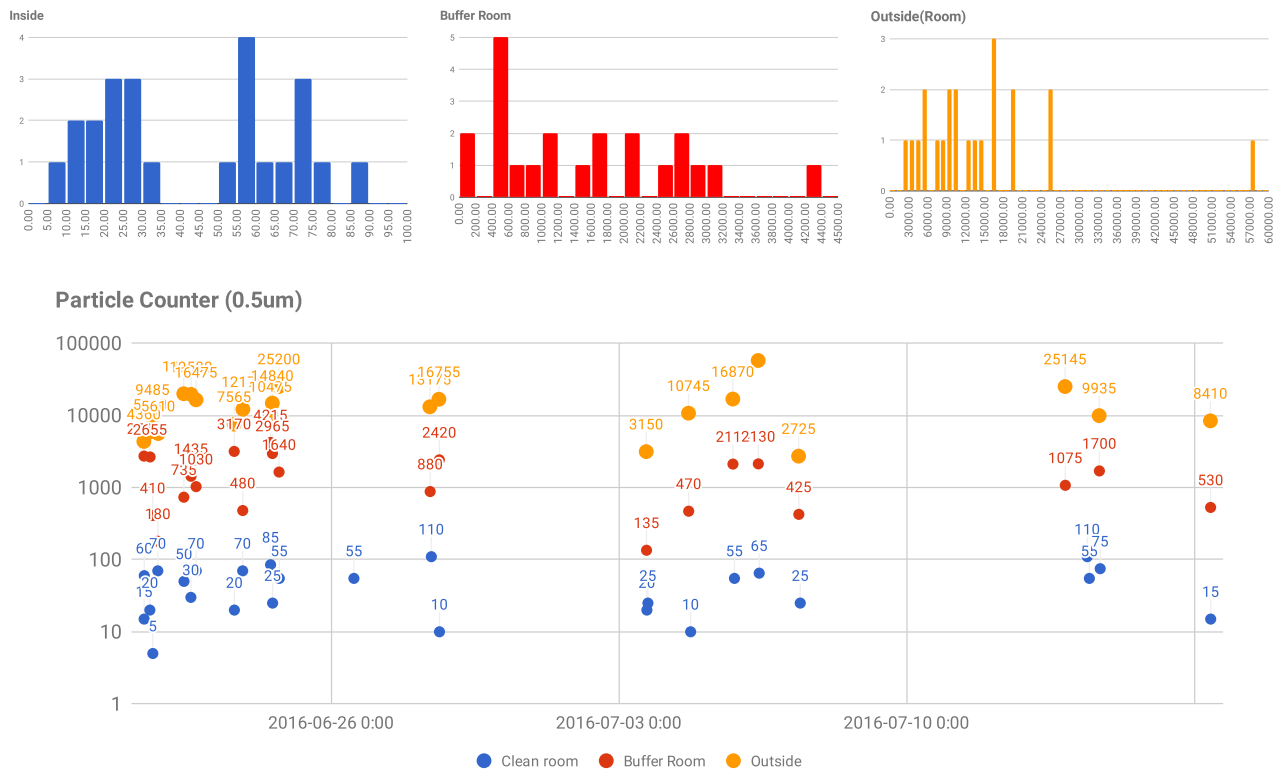


Figure A.32. Measured number of particle at clean booth (blue), Buffer room (red), outside of the clean booth (orange).

A.2.2 Floor Vibration

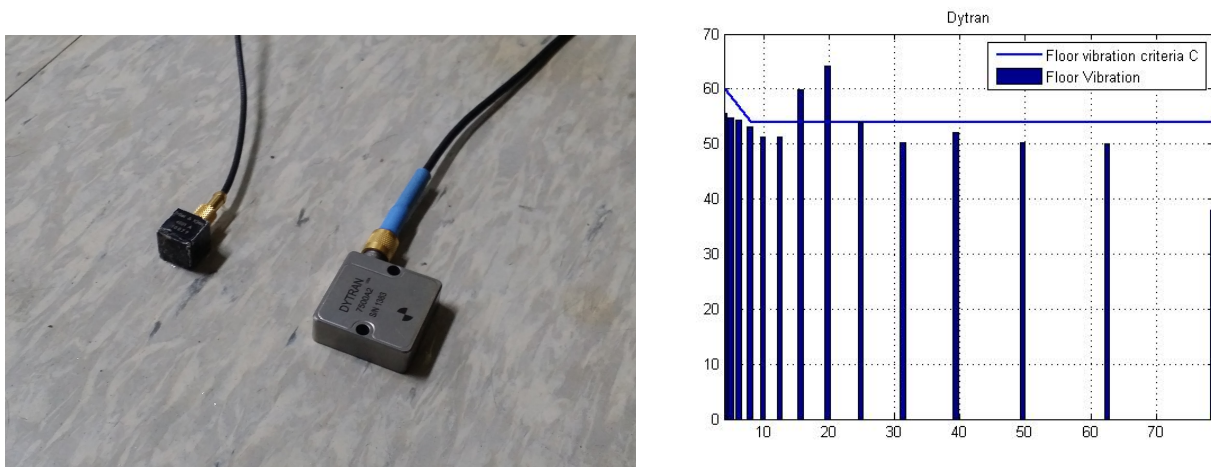


Figure A.33. Measuring the floor vibration using Dytran 7500A2 (left) and measured floor vibration level of 1/3 octave band (Right). The blue horizontal line indicates the floor vibration criteria C.

Floor vibration is one of the major factors disturbing position accuracy. To achieve the position accuracy of $< 5 \mu\text{m}$, the floor vibration criteria C is required. The floor vibration measurement was performed by help of VibroNoise Lab. in PNU [109] using Dytran 7500A2 device. Figure A.33 shows the result of the first measurement of the floor vibration. It shows a 1/3 octave band of the frequency response of the vibration

acceleration. The blue horizontal line indicates the floor vibration criteria C. The first measurement of done before the machine delivery to check the current status of the room. It clearly shows that 2 bands are over the criteria and one band touches it. The problematic frequency range is used to be related to the fan vibration. Thus, one could find the result without any issue when the clean booth (FFU) was turned off. A common solution for the vibration noise from the fan is anti-vibration rubber pad.



Figure A.34. Anti-vibration rubber pad installed under ALICIA (left) and clean booth (right).

Figure A.34 shows the photo of the anti-vibration rubber pad installed under the ALICIA (left) and the clean booth (right). For the rubber pad installed under the ALICIA, the calculation of the effect of the pad was performed by the company [110]. The weight of the ALICIA is 1,200 kg and it has four feet with ~ 70 mm of diameter. If we use 25 mm pad, it will press about 2.7 mm with 10.6 Hz of natural frequency. The effect of the pad is calculated based on the physical model of a harmonic oscillator with a mass-less spring on a solid and plane foundation. The calculation program FreqCalc [111] made calculations based on the assumption of a rigid mass in the centre of gravity. As a result shown in Fig. A.35, the damping is starting from 14 Hz, has 21% of effect at 16 Hz and 77% for 25 Hz.

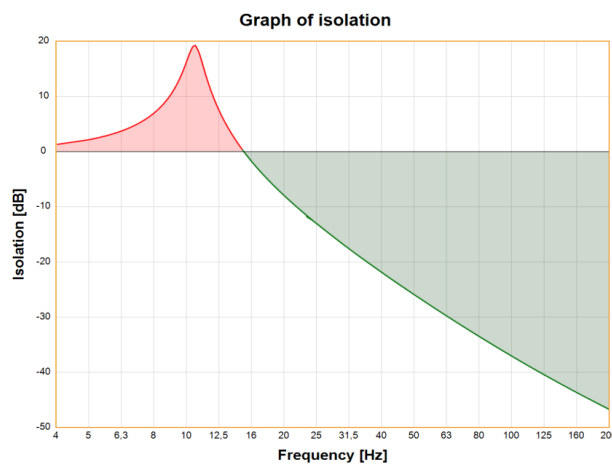


Figure A.35. Calculation of the isolation from the anti-vibration rubber pads under ALICIA [110]

After installation, the floor vibration was measured again, and it showed a good result under the criteria as shown in Fig. A.36.

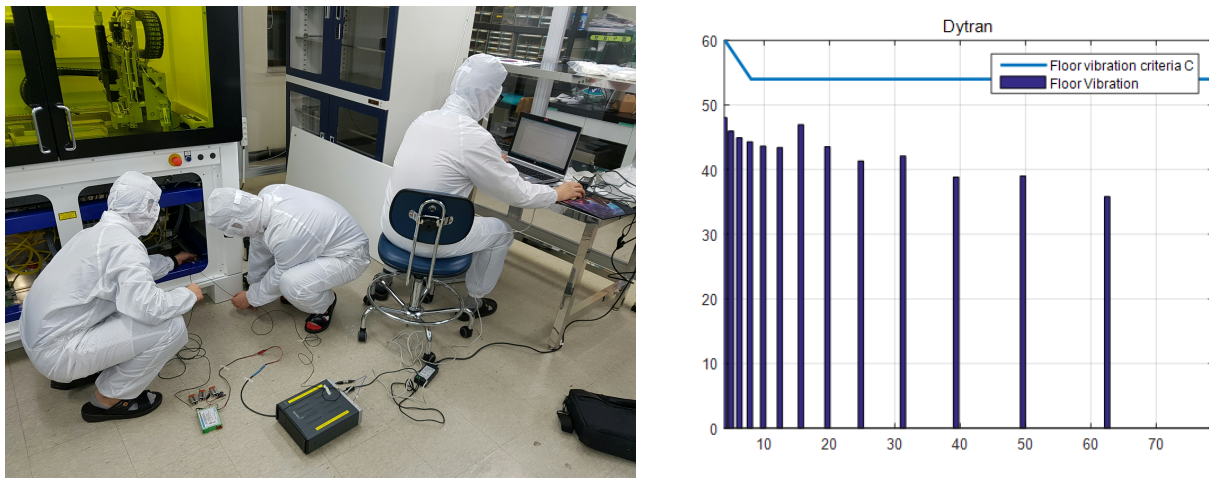


Figure A.36. Measuring the floor vibration with VibroNoise Lab. in PNU [109] (left) and measured floor vibration level of 1/3 octave band (Right). The blue horizontal line indicates the floor vibration criteria C.

A.2.3 Electrostatic Discharge (ESD)

Static electricity is one of the potential sources of damage to semiconductors. Thus, the environment where handling the semiconductor must prepare Electrostatic Discharge (ESD) configurations in the lab. It can be prepared based on grounding all risky parts of the lab. Therefore, all the tables are grounded by connecting the line from the ground. Figure A.37 shows the schematic of the grounding line connected to the tables. The ground line are arranged with the small bus bar placed in each tables. Further lines to the ESD wrist strap and the ESD tile are extended from the ground bus bar.

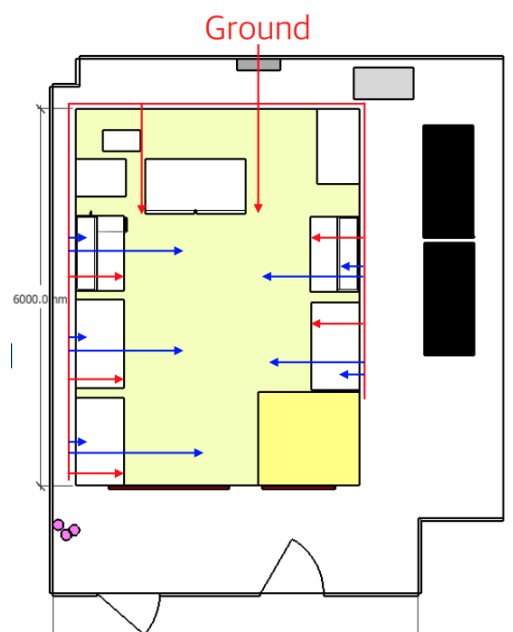


Figure A.37. The grounding line to the tables in the clean booth. The red line stands for the ground line. Blue lines stand for the further connection to the ESD wrist strap and the ESD tile.

The ESD tiles are installed on the floor of the clean booth. Figure A.38 shows two photos before/after installation of the ESD tile. To achieve the best protection, cleanroom shoes with ESD protection are adopted. In addition to that, ESD pad for table is installed to all tables in the clean booth.



Figure A.38. Installation of the ESD tile in the clean booth , before (left) and after (right).



Figure A.39. Inside of the clean booth after all installation

Finally, the clean booth in the ITS lab is prepared as shown in Fig. A.39.

A.2.4 Site Acceptance Test

ALICIA is the main device to perform the series chip test and the module assembly. Therefore, the perfect operation of ALICIA has to be confirmed at the installation phase. The Site Acceptance Test (SAT) is one of the processes that ensure the performance of the machine.

Shipment ALICIA was delivered on the pallet, two engineers from IBSPE accompanying the shipment. Due to the limited space of the building where the ITS lab is located, the ALICIA had to be transferred in a thoughtful plan. Exact sizes of the width of the aisle, a place for the rotation and the size of the door are measured. The wheel under the machine was installed since the handy forklift was not suitable for transfer inside the building. Figure A.40 describes the transfer plan inside the building. The machine was rotated in the placed named A in Fig. A.40 and moved in to the clean booth through the door for the machine (Fig. A.31).

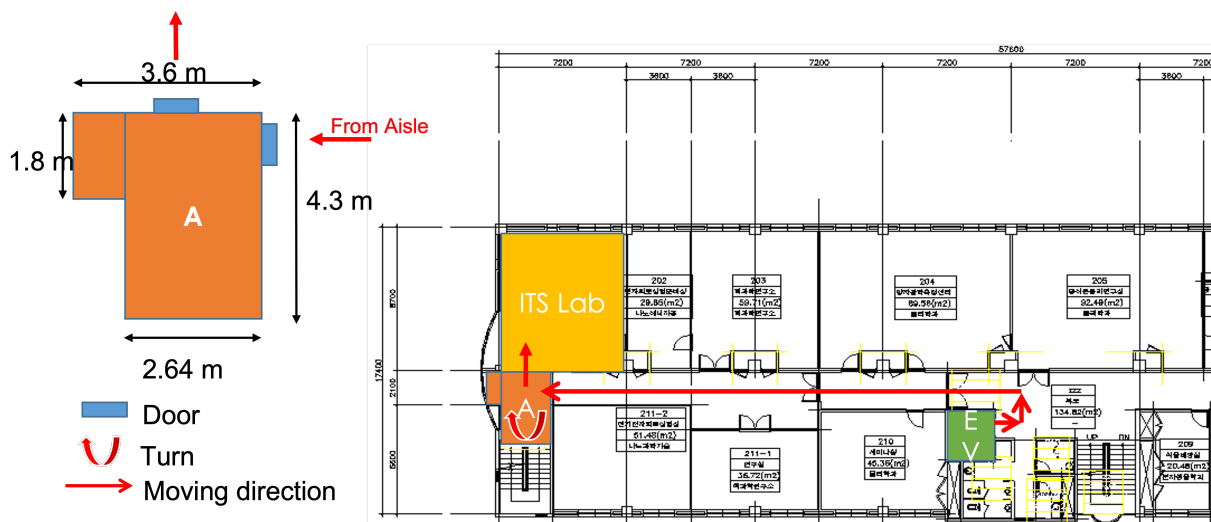


Figure A.40. Moving plan in the building aisle

SAT The site acceptance test was performed by two engineers from IBSPE. The test includes the operator training, the functional test of the probe card including the alignment procedure, the chip placement to the OB HIC Table and DB connection to the production DB⁴ of the ITS project. The document of the test procedure is signed together, with taking a photo of SAT as shown Fig. A.41.

⁴At SAT stage, ITS upgrade project used a development DB.



Figure A.41. Site Acceptance Test of ALICIA-2 (pusan)

A.3 Operation

The mission of Pusan contained both MCT and HIC assembly. The MCT was officially started with 2.5 wafers/day (115 chips/day) speed on 1st August 2017 with Pusan-Inha Team, suspended at End of April 2018 due to the probe card accident, and finished in August 2018 for shifting to HIC Assembly. Total ~ 10,800 chips of the 30,000 target (36%) are tested, and the rest was shared to Yonsei. While being under the backup site of MCT after repairing the probe card, Pusan started HIC assembly in February 2018 with the commissioning of production. The HIC production speed had been increased to one HIC/s until April 2018 and bumped to two HICs/day in May 2018. The HIC Assembly in Pusan was finalised in End of May 2019. Total 241 HICs of the 400 target (60%) are assembled.

A.3.1 Planning

The MCT was planned to test 115 chips from five wafers per day, which consists of 2.5 wafers per shift of the two shifts per day. The shift is divided into the morning shift for 09:00–15:00 (6H) and the night shift for 15:00–21:00 (6H). Two shifters are assigned for each shift for monitoring the machine activity and potential malfunction. The shifter has to be inside of the clean booth wearing dustproof clothes, a mask and gloves during their shift. Each shift, at least one shift leader (SL) had to participate, who is trained for the detailed manipulation of the machine and takes responsibility for the test during his/her shift. The SL was promoted from those who had at least two weeks of stable shift. This means a shifter pool can be filled with SL only in case. The shifts were divided into the same ratio to Pusan and Inha group since the ratio of the participant were the same. Total 11 (PhD. and MSc) students participated in the beginning.

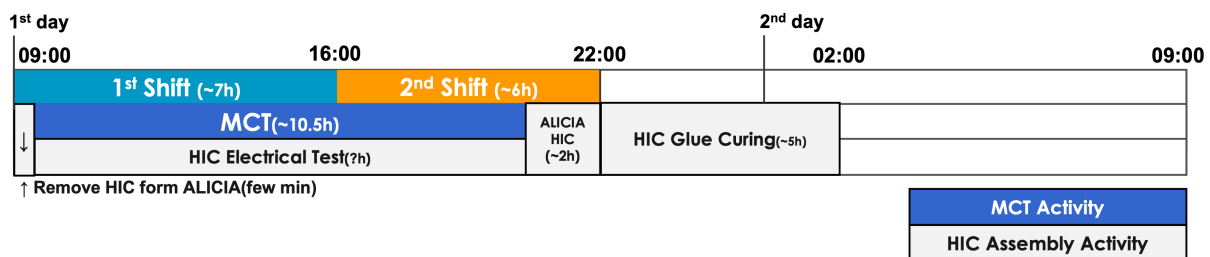


Figure A.42. Prototype Shift Timeline of MCT and HIC assembly

Figure A.42 shows the prototype plan of the Shift timeline for MCT and HIC assembly considered based on the four wafer tests per day and one HIC production per day. Two shifters start the morning shift at 09:00 and remove the HIC produced by the last shifter. Then one shifter starts MCT using ALICIA, and the other shifter starts the test of wire-bonded HIC. At 15:00, the morning shifter change to the night shifter. In case that they have a running chip test, the test is not interrupted but taken over to the next shifter. At 20:00, the night shifter stops the ongoing chip test for the HIC assembly. A shifter triggers the chip placement in ALICIA and they start to prepare the FPC and glue.

A.3.2 Actual Operation



Figure A.43. Timeline of MCT and HIC assembly

As a result, this plan was completely revised. The HIC assembly was not started at the beginning stage of MCT. Therefore, the part of the HIC assembly was not considered and the MCT part was focused. And the MCT was planned to start from June/July 2017 but it was postponed until August since there was a delay from the post-processing company. At the end of 2017, the HIC assembly had to follow the production status of the sites since the sites in Europe already started the early production in November 2018. And the expected total number of HIC production also updated from ~ 2000 to ~ 2500 , consequently, each site should produce ~ 400 HICs. Pusan changed the plan to produce HIC from the end of 2017 while modifying the MCT as test 2 wafers. But there was a delay in purchasing a vacuum for the assembly jigs, actual production was delayed to April 2018. At the end of April 2018, there was an incident during the probe card alignment, in which the needle of the probe card crashed to the PPC, the MCT was suspended. On the situation that the testing capability in Yonsei had risen rapidly and HIC production was urgent, Pusan decided to stop the MCT and shift to focus to produce HIC. The HIC production was finished at the end of May 2018.

A.4 Discussion

During the series production, a number of small prompt R&D of the procedure was discussed and performed. Among them, only some of the examples will be discussed in this section. These studies are generally based on the output from the machine during the production.

A.4.1 Study on Dimension Inspection Failure

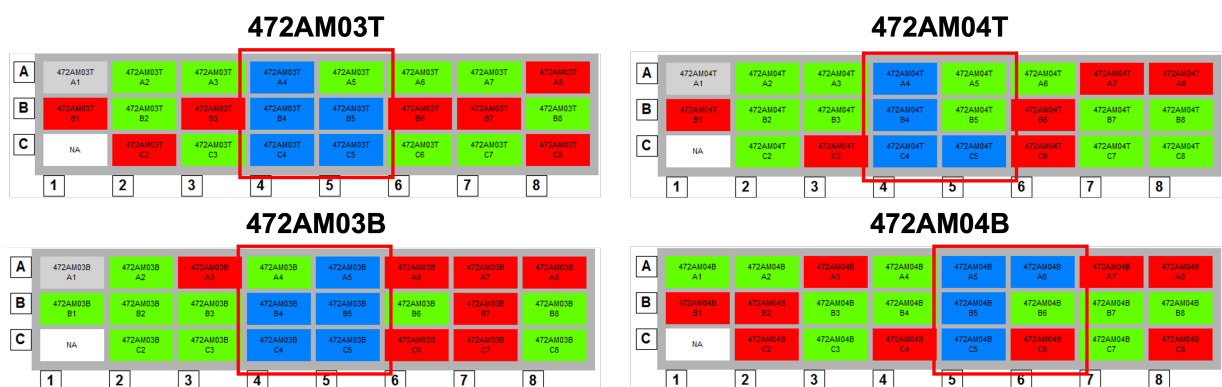


Figure A.44. Failed chips in Dimension Inspection. (Blue chips)

As described in Sec. A.1.5, ALICIA tests the dimension of the chips for the first. When the first batch of ALPIDE was tested in July 2017, strange behaviour of the test result was observed and reported as shown in Fig. A.44. The four sections in the figures mean the test result from four different half wafers. The title on each result shows the name of the wafers. T stands for Top, B stands for Bottom part of each wafer. The colours green and red represent their test results OK and NK, respectively. The point is blue coloured chips. The blue means this chip has not been tested yet, and they are actually not tested due to the failure in the stage of the dimension inspection. The chips that failed in dimension inspection are rare since the inspection actually tests the quality of the dicing procedure at the post-processing company. The industrial company, especially in semi-conductor areas, uses the well-defined machine. So if they even actually have any issue with the process, the issue must appear randomly. However, the failed chips were observed only in the specific area on the trays.

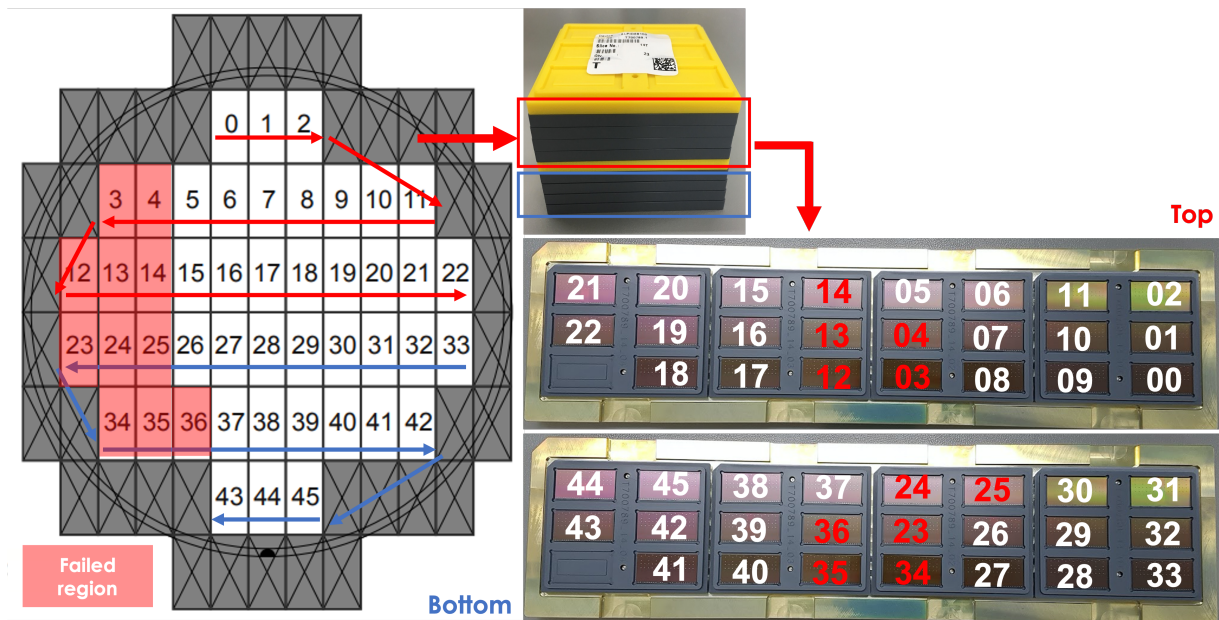


Figure A.45. Actual chip position on the wafer. The regions where the failed chips are placed are highlighted.

Based on the picking procedure given by the company, this strange position can be inference as shown in Fig A.45. The chips are not arranged in order of numbers. Rather, they are placed as the efficient path of the picking machine. The figure also shows the area highlighted in red on the wafer. Now, some of the rules can be found. The failed chips are distributed in a specific area, which implies a systematic effect of the machine.

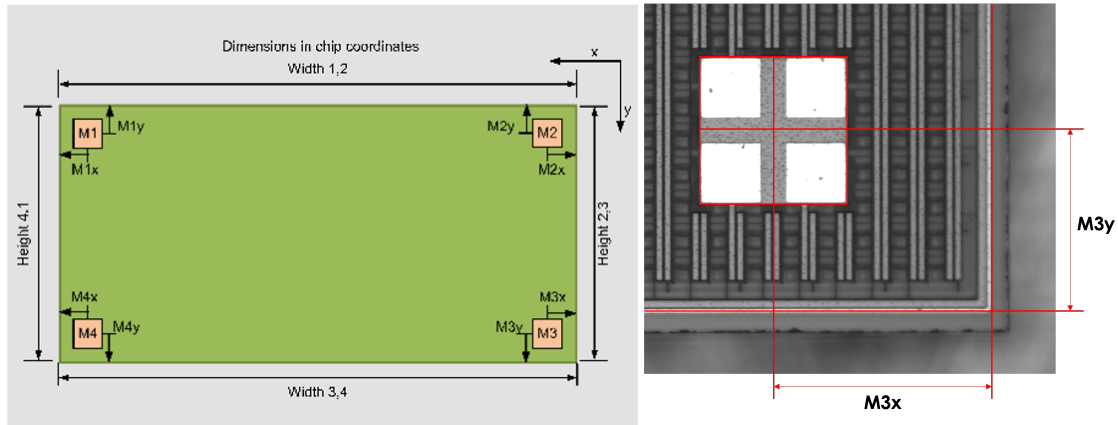


Figure A.46. Measured values in Dimension Inspection (left) and Example of the measurement (right)

This leads a further study on such chips. For the first, The measured values can be investigated. Figure A.46 shows the guide of the values measured in the dimension inspection, M1x, M1y, M2x, M2y, M3x, M3y, M4x, M4y. The distance between the chip markers and edges are measured as an example of M3x, M3y shown in Fig. A.46. During the dimension inspection, the vision system of ALICIA measures each value, and compare it with the position tolerance. If the value exceeds the limit, the test failed⁵.

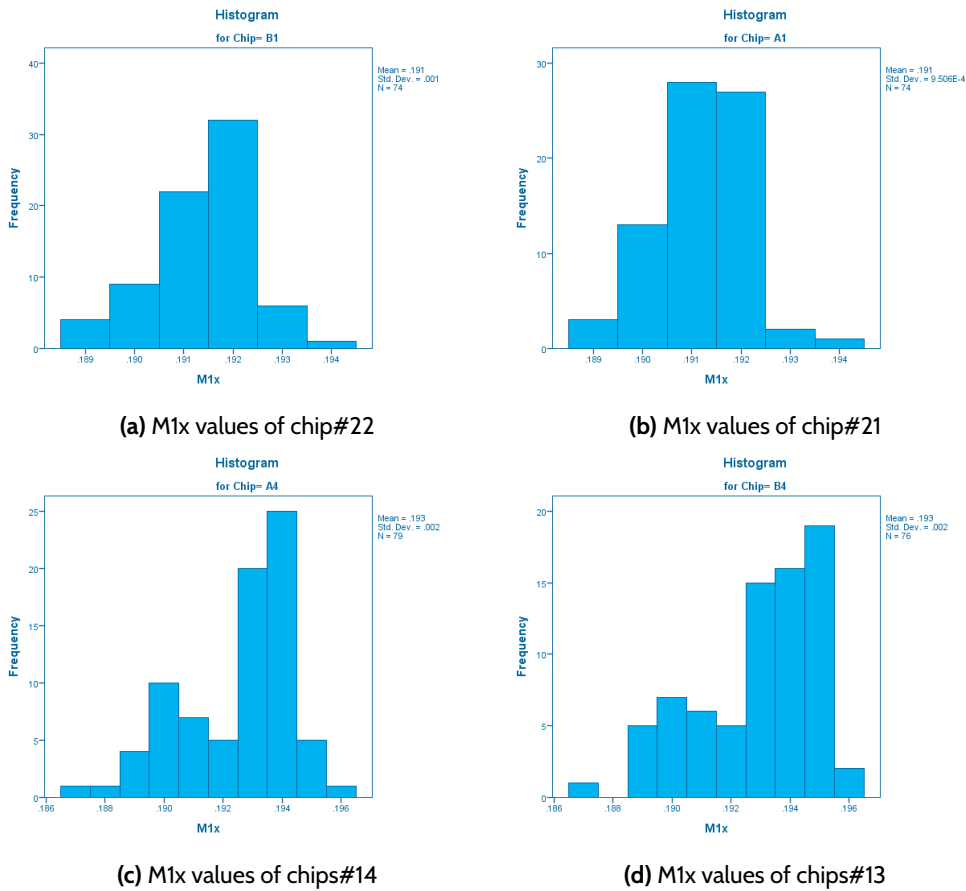


Figure A.47. Histogram of M1x values from several chips

⁵Note that the failure in the dimension test doesn't make the chip as NK as red chips shown in Fig. A.44. It just passes the test and the chip is left as like not tested.

The histogram of the measured M1x value of several chips is presented in Fig. A.47. Here, outliers such as the values having extremely larger or smaller values were not included since they are apparently coming from the malfunction of the vision system. Two top histograms are obtained from the chips placed at the right side on the wafer while two bottom histograms are from at the right side. One can easily find that the bottom plots are showing the histogram that is biased to the right while the top figures look normal. And, since the size tolerance is 0.05 from 0.19 of central value, bottom plots have a lot more statistics of the value that cannot pass the test.

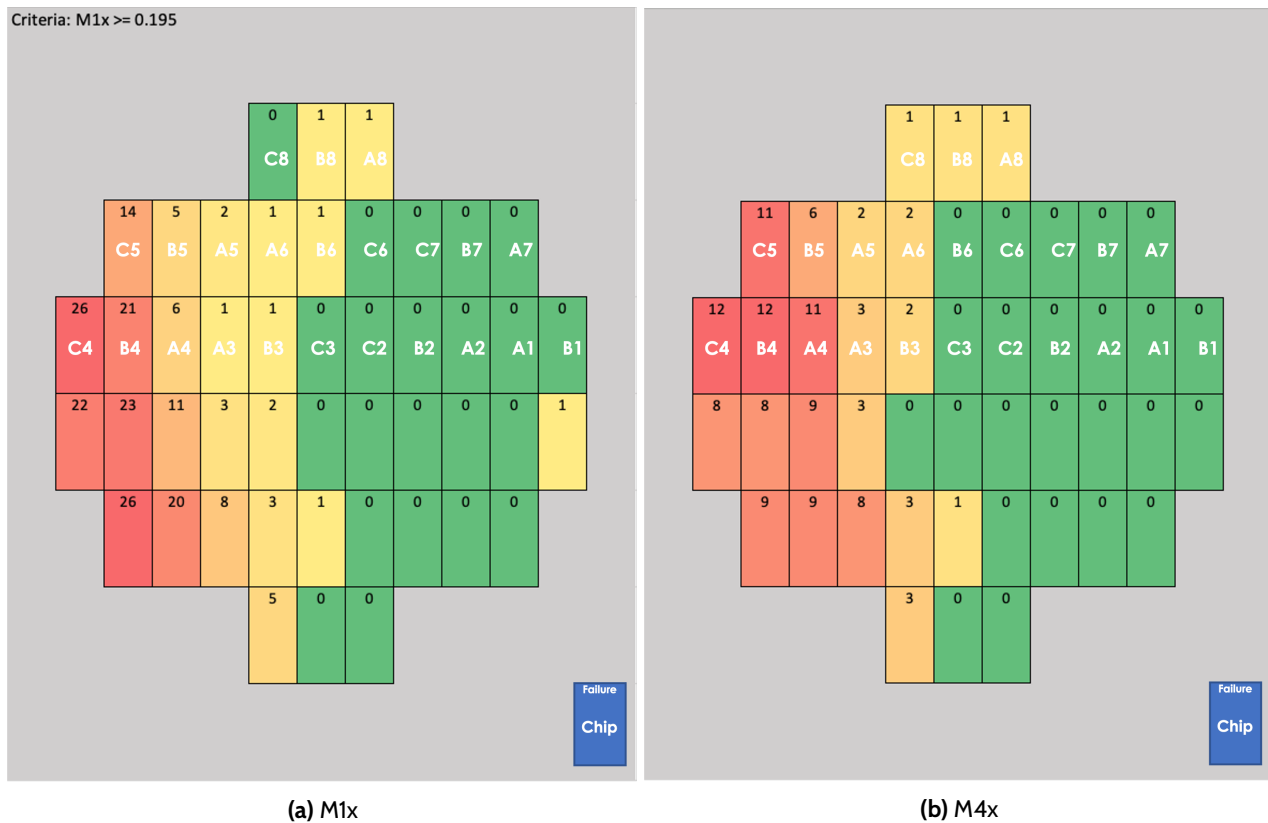
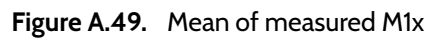


Figure A.48. Number of chips that failed in dimension test on each values.

Figure A.48 represents the number of failed chips on M1x (top) and M4x (bottom) value. It shows a clear tendency that the number of chips that failed in the test is increasing from right to left. One of the possible scenarios is that the wrong alignment of the dicing blade can affect this. This hypothesis can be confirmed by plotting the mean value of each chip on the wafer.

Figure A.49 shows the mean value of M1x. The mean values are increasing from ~ 0.191 (left) to ~ 0.193 (right). This implies that the dicing blade could be well-positioned at the right position but it deviates as it goes to the right.

The study of the dimension inspection was reported to the company for the correction of the dicing procedure. Meanwhile, the series test had to be continued and the deviation of chip dimension was small. So the configuration of the limit was increased to 10 μm from 5 μm so that the values up to 0.200 mm can be passed.



Pusan group has participated in the ITS upgrade project. The new ITS features up to five times better position resolution in low p_T with a low material budget. The series chip test (MCT) was introduced with a brief explanation of the HIC assembly as a part of OB HIC series production. A detailed preparation process considered for constructing the semi-conductor handling laboratory in Pusan was discussed. It includes a clean booth, floor vibration check and ESD treatment. A study performed in the early production related to the chip dimension was introduced.

중이온충돌실험에서의 생성도 하이퍼론 공명입자 및 가벼운 핵자 생성을 통한 강입자 상의 특성 연구

임 봉 휘

부산대학교 대학원 물리학과

요약

쿼크-글루온 플라즈마에 대한 특성 및 그것의 진화과정, 심지어 그것의 존재 여부 자체 까지도, 자연계의 풀리지 않은 수수께끼의 하나로 연구되었다. 그 진화 과정 중 한 상인, 강입자 상에 대한 연구 또한 그것의 수명, 크기, 상태 등의 특성을 찾기 위해 연구되었다. 이 논문은 강입자 상의 특성 중 하나인 크기에 집중하여, 13TeV 양성자-양성자 충돌 및 5.02 TeV 납-납 충돌에서 생성되는 공명 입자 및 가벼운 핵자의 생성량을 통해 그것의 특성 중 하나인 크기에 대해 다룰 것이다.

대형이온충돌실험 검출기를 이용하여, 중심에너지가 13 TeV 인 양성자-양성자 충돌에서의 하이퍼론 공명입자, $\Sigma(1385)^{\pm}$, $\Xi(1530)^0$ 의 생성량 및 핵자 당 에너지가 5.02 TeV 인 납-납 충돌에서 생성되는 가벼운 핵종, 중수소 및 헬륨-3 생성량을 측정하였다. 횡방향 운동량 p_T 에 따른 생성량 $d^2N/dydp_T$ 가 중간영역, $|y| < 0.5$ 에서의 생성량을 기준으로 측정되었으며, 총 생성량 dN/dy , 평균 횡방향 운동량 $\langle p_T \rangle$ 이 함께 도출되었다. 마지막으로, 얻어진 생성량은 대형이온충돌실험에서 얻어진 다른 입자들과 비를 현상학적 모형과 함께 비교하여본다.

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