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**Light hypernuclei production in Pb-Pb collisions
with ALICE at LHC**

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Riassunto

Questa tesi è dedicata allo studio della produzione di ipernuclei leggeri in collisioni ultra-relativistiche di ioni piombo (Pb) con l'esperimento ALICE (A Large Ion Collider Experiment), uno dei quattro grandi esperimenti del Large Hadron Collider (LHC) del CERN.

Il principale obiettivo scientifico dell'esperimento ALICE è lo studio delle proprietà della materia in condizioni estreme di energia ($> 10 \text{ GeV/fm}^3$) e di temperatura ($\approx 0.2 \text{ GeV}$) mediante lo studio di collisioni di ioni piombo. Calcoli di Cromo Dinamica Quantistica (QCD) su reticolo prevedono, infatti, che in condizioni di alta temperatura e grande energia la materia adronica subisca una transizione di fase verso un "plasma" di quark e gluoni deconfinati (Quark Gluon Plasma, QGP).

Nel primo capitolo della tesi verranno descritte in maniera generale la fisica degli ioni pesanti e le grandezze caratteristiche usate per provare la formazione del QGP (*probes*). Verranno quindi mostrati e discussi i risultati sperimentali che possono provare l'esistenza di uno stato deconfinato della materia nucleare ottenuti agli esperimenti a SPS, RHIC e LHC.

Nel secondo capitolo saranno brevemente presentati il Large Hadron Collider (LHC) e le condizioni sperimentali di lavoro durante i primi tre anni di presa dati; in seguito verrà data un'ampia panoramica dell'esperimento ALICE. Saranno descritti i differenti sotto-rivelatori che formano l'esperimento e verranno inoltre mostrate le loro performance durante l'acquisizione dati; inoltre verrà fornita una descrizione del framework di calcolo utilizzato nell'analisi dei dati.

Il terzo capitolo sarà dedicato alla descrizione dei meccanismi di produzione di (anti)(iper)nuclei in collisioni di ioni pesanti: verranno descritti i due meccanismi di produzione che si ritiene governino la loro produzione (coalescenza e modello termico) e verrà mostrata una panoramica sui risultati ottenuti a diverse energie. Inoltre saranno presentati diversi calcoli teorici, ponendo particolare attenzione ai risultati aspettati all'energia di LHC.

Il quarto capitolo contiene la descrizione del metodo di analisi utilizzato per valutare lo yield di produzione dell'(anti)ipertritone ($(\bar{\Lambda}^3\bar{H})^3\text{H}$) attraverso il suo canale di decadimento mesonico $\bar{\Lambda}^3\text{H} \rightarrow {}^3\text{He} + \pi^-$ ($\Lambda^3\bar{H} \rightarrow {}^3\bar{\text{He}} + \pi^+$) in collisioni Pb-Pb con energia nel

centro di massa $\sqrt{s_{\text{NN}}} = 2.76$ TeV. Inizialmente verrà descritta la tecnica di analisi utilizzata per l'identificazione di particelle e dei vertici secondari, quindi sarà fornita la descrizione dettagliata della tecnica di analisi. L'analisi dei dati è stata suddivisa in due distinte parti: la prima è dedicata alla descrizione della procedura utilizzata per l'analisi dei dati raccolti da ALICE durante la prima acquisizione di collisioni Pb–Pb alla fine del 2010; nella seconda parte, invece, verrà descritta la procedura di analisi dei dati raccolti durante la seconda presa dati nel Dicembre 2011. Verranno quindi descritte in modo dettagliato l'estrazione del segnale, lo studio del fondo combinatoriale e gli errori sistematici. Infine, nella parte finale del capitolo, verrà fornita una stima della vita media dell'ipertritone.

Nel quinto capitolo sarà presentato il metodo usato per ottenere lo spettro in p_T di $({}^3\overline{\text{He}}){}^3\text{He}$. Verranno descritti: la procedura di estrazione del segnale, la stima dell'efficienza in funzione del momento trasverso, la valutazione degli errori sistematici e la procedura usata per sottrarre il feed-down dovuto al decadimento dell'ipertitone (${}^3_{\Lambda}\text{H}$). Lo spettro verrà quindi utilizzato per valutare lo yield di produzione di $({}^3\overline{\text{He}}){}^3\text{He}$.

Infine, nel sesto e ultimo capitolo, i risultati sperimentali ottenuti verranno confrontati con i risultati teorici discussi nel Capitolo 3.

Overview

The subject of the present PhD thesis is the study of the production of light hypernuclei in ultra-relativistic Pb-Pb collisions with ALICE (A Large Ion Collider Experiment), one of the four major experiments at the LHC (Large Hadron Collider).

The main physics goal of the ALICE experiment is the investigation of the properties of the strongly interacting matter at high energy density ($> 10 \text{ GeV}/\text{fm}^3$) and high temperature ($\approx 0.2 \text{ GeV}$) conditions. According to the lattice Quantum Chromo Dynamics (QCD) calculations, under these conditions (i.e. high temperature and large energy density) hadronic matter undergoes a phase transition to a “plasma” of deconfined quarks and gluons (Quark Gluon Plasma, QGP).

In the first chapter of the thesis a general introduction to the heavy-ion physics will be given. Then the main quantities related to QGP formation (i.e. *probes*) will be described. Finally the most important results obtained at SPS, RHIC and LHC experiments will be shown and discussed.

In the second chapter a short description of the LHC and its experimental conditions will be reported and an overview of the ALICE experiment will be given. A description of the different detectors and their performances during data taking will be described; in addition a description of the computing framework will be given.

The third chapter will be devoted to an introduction of the (anti)(hyper)nuclei production in heavy-ion collisions. The two main approaches which are believed to govern nuclei production (i.e. coalescence and thermal models) will be described, and an overview on the results at different energies will be shown. A comparison of the theoretical results will be also shown, with particular regards to the energies at the LHC.

The fourth chapter is devoted to the description of the analysis method used to get (anti)hypertriton production yield in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ with the ALICE experiment via its mesonic decay ${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^-$ (${}^3_{\Lambda}\bar{\text{H}} \rightarrow {}^3\bar{\text{He}} + \pi^+$). In the beginning of the chapter the analysis technique used for particle identification and for the determination of secondary vertices will be described. The analysis will be divided into two distinct parts: the first one based on the data sample collected by the ALICE experiment during the first LHC heavy-ion run held at the end of 2010, while the second one based on data collected at the end of 2011. A detailed description of the study on efficiency

evaluation and signal extraction will be shown for both analysis, together with a study of the systematic uncertainties. The results on the production yield of (anti)hypertriton will also be shown. The estimation of the hypertriton lifetime will be provided in the final section of the chapter.

In the fifth chapter the method used to obtain the p_T spectrum of ${}^3\text{He}$ will be presented. The raw spectra, the efficiency evaluation, systematic errors and feed-down from ${}^3_\Lambda\text{H}$ will be presented. The final spectrum will be used to evaluate the production yield of ${}^3\text{He}({}^3\overline{\text{He}})$ in the whole p_T region, from 0 to ∞ .

Finally, in the last chapter, the present experimental results will be compared with published relevant results and with the most recent theoretical findings. Moreover, the measurement of the “Strangeness Population Factor” [$S_3 = {}^3_\Lambda\text{H}/{}^3\text{He}/(\Lambda/p)$] at the LHC energies will be provided. This quantity is a valuable tool to probe the nature of dense matter created in high-energy heavy-ion collisions and to validate theoretical models.

Heavy ion physics

1.1 Introduction

The framework called the Standard Model is currently the most detailed description of the building blocks of our universe. The model describes our universe in terms of matter (fermions) and forces (bosons) (Fig.1.1a). The fermion group contains six quarks, six leptons, and their anti-particles. The bosons are considered to be the mediators of four fundamental forces: gravity, electromagnetism, weak force and strong force. An atomic nucleus is composed of baryons, namely protons and neutrons, each composed of three quarks. The strong force is responsible for binding the quarks inside of these baryons, and it is mediated by gluons exchange. In addition to quark triplet bound states, there exist particles, called mesons, that essentially contain two quarks. As of yet, no isolated quark has been observed in nature. Quarks (Fig.1.1b) carry a property called color, analogous to electric charge, which requires that they combine to yield colorless objects. A single quark can be detached from a hadron only by producing at least two free objects carrying colour: the quark, and the remainder of the hadron. This phenomenon is therefore called *confinement*.

The quantum field theory that was developed to describe the strong interaction of these coloured objects is called Quantum Chromo-Dynamics (QCD). In addition to describing how the quarks are held together, QCD calculations predict that hadronic matter can undergo a phase transition toward a matter composed of deconfined quarks and gluons (collectively called partons). In order for this to occur the proper conditions of temperature and density must be met, such that distances between quarks get small, and the strong force becomes negligible. In the new phase, the quarks and gluons are the relevant degrees of freedom, not the baryons. The term Quark-Gluon Plasma (QGP) is used to describe such a state.

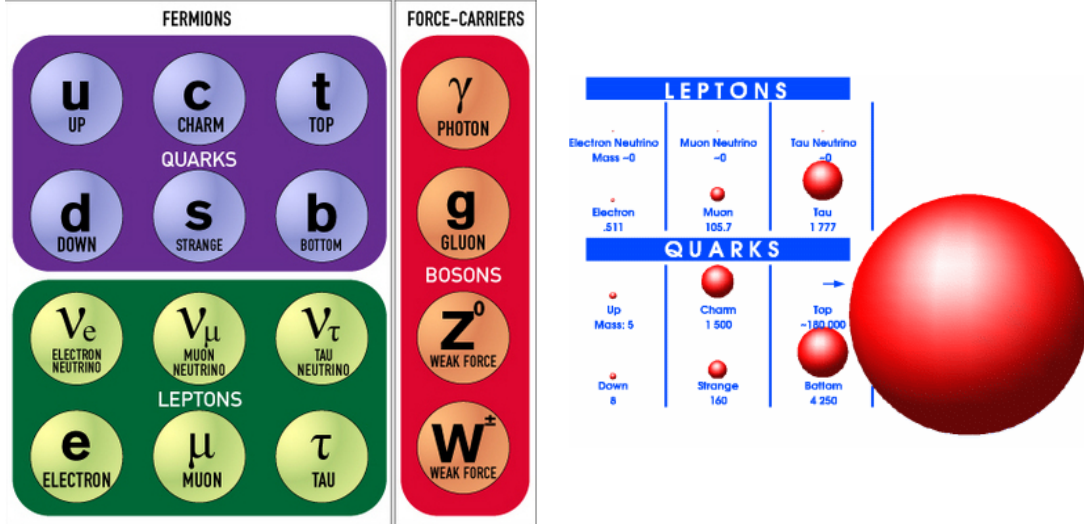


FIGURE 1.1: a): Standard Model families of leptons and quarks as the gauge bosons [1]. b) Masses of different quark flavours [2]

1.1.1 Quantum Chromo-Dynamics

The strong interaction is one of the four fundamental forces in nature, together with gravity, electromagnetism and the weak interaction. Its existence was postulated in the 1970s, to explain how the atomic nucleus was bound together despite the protons' mutual electromagnetic repulsion. This hypothesized force was called the *strong force*, which was believed to be a fundamental force that acted on the nucleons. It was later discovered that protons and neutrons were not fundamental particles, by means of deep inelastic experiments, but were made up of constituent particles (the quarks). The strong attraction between nucleons was the side-effect of a more fundamental force that bounds the quarks together in the protons and neutrons. Nowadays the strong interaction is described through the formalism of a Quantum Field Theory. The particular theory describing this force is the Quantum Chromo-Dynamics (QCD), in analogy to the Quantum Electro-Dynamics (QED) that describes the electromagnetic interaction. In QED the electromagnetic force is mediated by photons, which carry no charge. Similarly, in QCD the gluons are the carriers of the strong force, but unlike the photon they carry color charge, meaning that they can interact with each other. In QED, the electrodynamic coupling constant is $\alpha = 1/137$, whereas the QCD strong coupling constant, α_s , can be 1 or larger. In quantum field theory when a coupling constant is much smaller than 1 the theory is said to be weakly coupled. When the coupling nears 1 the theory is strongly coupled, hence the name "strong" force.

In QCD the strong interaction between two quarks can be described using the following potential:

$$V(r) = -4\frac{\alpha_s}{3r} + kr \quad (1.1)$$

here r is the separation distance between the two quarks, α_s is the strong coupling constant, and k is also a constant that is approximately 1 GeV/fm. The renormalization

scale dependence of the effective QCD coupling $\alpha_s = g_s^2/4\pi$ is controlled by the β -function:

$$\mu \frac{\partial \alpha_s}{\partial \mu} = 2\beta(\alpha_s) = -\frac{\beta_0}{2\pi} \alpha_s^2 - \frac{\beta_1}{4\pi^2} \alpha_s^3 - \frac{\beta_2}{64\pi^3} \alpha_s^4 - \dots \quad (1.2)$$

where

$$\beta_0 = 11 - \frac{2}{3}n_f \quad (1.3)$$

$$\beta_1 = 51 - \frac{19}{3}n_f \quad (1.4)$$

$$\beta_2 = 2857 - \frac{5033}{9}n_f + \frac{325}{27}n_f^2 \quad (1.5)$$

Here n_f is the number of quarks with mass less than the energy scale μ . In solving the differential equation 1.2 for α_s , a constant of integration is introduced. This constant is the fundamental constant of QCD that must be determined from experiment in addition to the quark masses. The most sensible choice for this constant is the value of α_s at a fixed-reference scale μ_0 . It has become standard to choose $\mu_0 = M_Z$. At different values of μ , α_s can be obtained from $\log(\mu^2/\mu_0^2) = \int_{\alpha_s(\mu_0)}^{\alpha_s(\mu)} \frac{d\alpha}{\beta(\alpha)}$. It is also convenient to introduce the dimensional parameter Λ [MeV⁻¹], since it provides a parametrization of the μ dependence of α_s . The definition of Λ is arbitrary. One way to define it [3] is to write the solution of eq.1.2 as an expansion in inverse power of $\ln(\mu^2)$:

$$\alpha_s = \frac{4\pi}{\beta_0 \ln(\mu^2/\Lambda^2)} \left[1 - \frac{2\beta_1}{\beta_0^2} \frac{\ln[\ln(\mu^2/\Lambda^2)]}{\ln(\mu^2/\Lambda^2)} + \frac{4\beta_1^2}{\beta_0^4 \ln^2(\mu^2/\Lambda^2)} \right. \\ \left. \times \left(\left(\ln[\ln(\mu^2/\Lambda^2)] - \frac{1}{2} \right)^2 + \frac{\beta_2\beta_0}{8\beta_1} - \frac{5}{4} \right) \right] \quad (1.6)$$

Experimentally, α_s has been measured at different scales (μ). Fig. 1.2 shows the measurements of α_s as a function of the respective energy scale Q compared to lattice QCD calculations.

Three very important properties of QCD arise from the running constant α_s . They are *confinement*, *asymptotic freedom*, and (hidden) *chiral symmetry*. For large distance scales the second term in the potential equation (eq.1.6) dominates; this means that the coupling between the two quarks is large, making it so that no free quarks are observed in nature, i.e. a quark never exists on its own for longer than $1/\Lambda_{QCD}$, where $\Lambda_{QCD} = 217$ MeV. The up, down, strange, charm, and bottom quarks all hadronize on the time-scale $1/\Lambda_{QCD}$, the top quark decays before it has time to hadronize. Therefore, all but the top quark will be confined inside hadrons. Experimentally, no single quark in a color-triplet state has ever been observed.

Asymptotic freedom arises when the quarks are at a small distance from one another or with a large enough momentum transfer Q ($\alpha_s \rightarrow 0$ as $\mu \rightarrow \infty$). The potential will go like $1/r$ and the effective coupling between the quarks decreases, allowing for a quasi-free quark. The third property is called chiral symmetry, also not observed in nature. It is a symmetry of QCD in the limit of vanishing quark masses. In this limit quarks

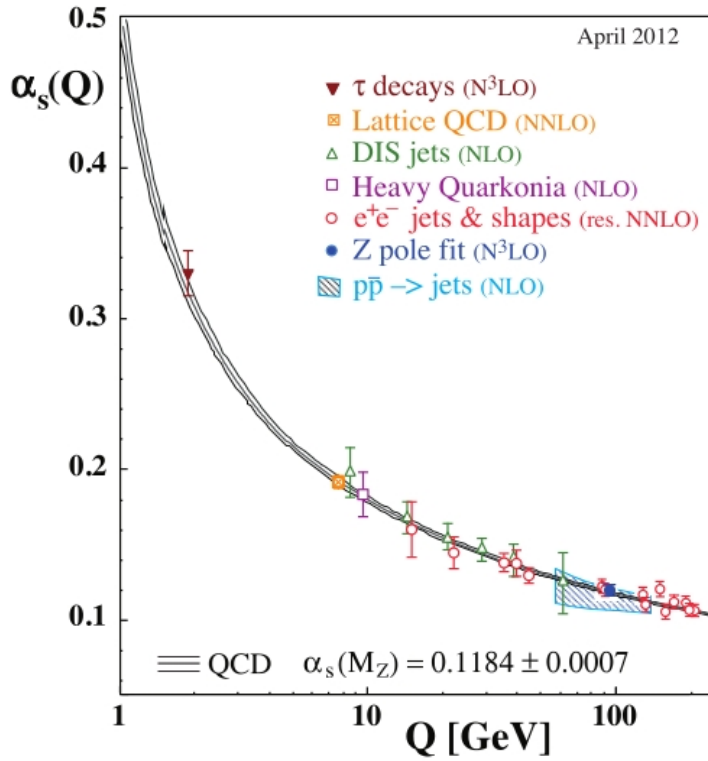


FIGURE 1.2: Summary of measurements of α_s as a function of the respective energy scale Q [4].

are either left or right handed, such that the QCD Lagrangian is symmetric. However, when quarks are confined inside hadrons they have large dynamical masses, called *constituent* or *QCD masses*. Here the chiral symmetry is said to be “broken” (or hidden). In the small α_s limit some quarks will have small mass, called *current mass*. In this limit, chiral symmetry is said to be (partially) restored.

In our world, quarks and gluons are confined inside hadrons. By significantly increasing the temperature and energy density the strong force holding the quarks and gluons together may be reduced, unbinding them from the hadrons. This phenomenon is known as “deconfinement”. Deconfinement implies that there exists a phase transition from a gas of hadrons to a new form of matter of free quarks and gluons, called the Quark-Gluon Plasma (QGP).

1.2 Quark Gluon Plasma (QGP)

Even before the formulation of the QCD, the existence of a phase transition to a new state of matter had been argued from the mass spectrum of resonances produced in hadronic collisions [5]. After the formulation of the QCD as an asymptotically free theory this observation has been related to a phase transition [6]. From lattice QCD predictions [7], the phase transition is expected at a critical temperature $T_c = 175$ MeV,

corresponding to an energy density $\sim 1 \text{ GeV/fm}^3$.

Critical parameters can also be estimated by mapping out the nuclear phase diagram, shown in Fig. 1.3. The diagram demonstrates the transition from a gas of hadrons to a QGP as a function of temperature (T) and baryo-chemical potential (μ_B). The baryo-chemical potential is defined as $\mu_B = \partial E / \partial N_B$, where E is the free Gibbs energy and N_B is the net baryon number of the system ($N_B = N_{\text{baryons}} - N_{\text{anti baryons}}$). μ_B is then an alternative way to express the baryon content of the system.

At normal nuclear densities each nucleon occupies a volume of about 6 fm^3 , whereas the actual volume of a nucleon itself is only about a tenth of this. When the temperature (T) or the baryon density (μ_B) become very high, the force between quarks and gluons weaken and a phase transition to a deconfined state is predicted. The order of the phase transition depends on the hypothesis on the quark masses. In Fig. 1.3 the phase transition is represented in the plane of temperature as a function of the relative nuclear density; the region above the deconfinement band is the quark-gluon plasma. According to the Big Bang theory [8], the state of the Universe a few tenths of μs after the Big Bang was actually a quark-gluon plasma (high temperature and low density in the diagram). The same state of matter is now probably present in the very dense core of neutron stars [9], which can be situated in the bottom right region of the phase diagram.

The hatched region in Fig. 1.3 represents the expected phase boundary between partonic and hadronic matter from lattice QCD calculations. The estimates for LHC and RHIC, and the data points of SPS, AGS, and SIS all sample various regions of the diagram. Results of theoretical predictions based on thermal models [10, 11] show that the chemical potential μ_B and temperatures T place the chemical freeze-out of the system (when inelastic collisions cease) quite close to the currently accepted phase boundary between a plasma of quarks and gluons and a hadron gas. The solid curve, which goes through the low energy data points, is the freeze-out trajectory. This curve closely follows the hatched region, where one expects deconfinement to occur.

1.3 QGP Creation in heavy-ion collisions

Ultra-relativistic heavy ion collisions are thought to allow for the creation of the quark gluon matter that existed right after the Big Bang [12]. The crucial requirements for the system are very high energy density and sufficient collective temperature.

A cartoon of a heavy ion collision can be seen in Fig. 1.4. The ions are travelling at 99.995% the speed of light, causing them to Lorentz contract, so they appear as thin disks. In each reaction a fraction of nucleons participates to the collision, while the rest are spectators. The fraction depends on the impact parameter b ; increasing its value, the

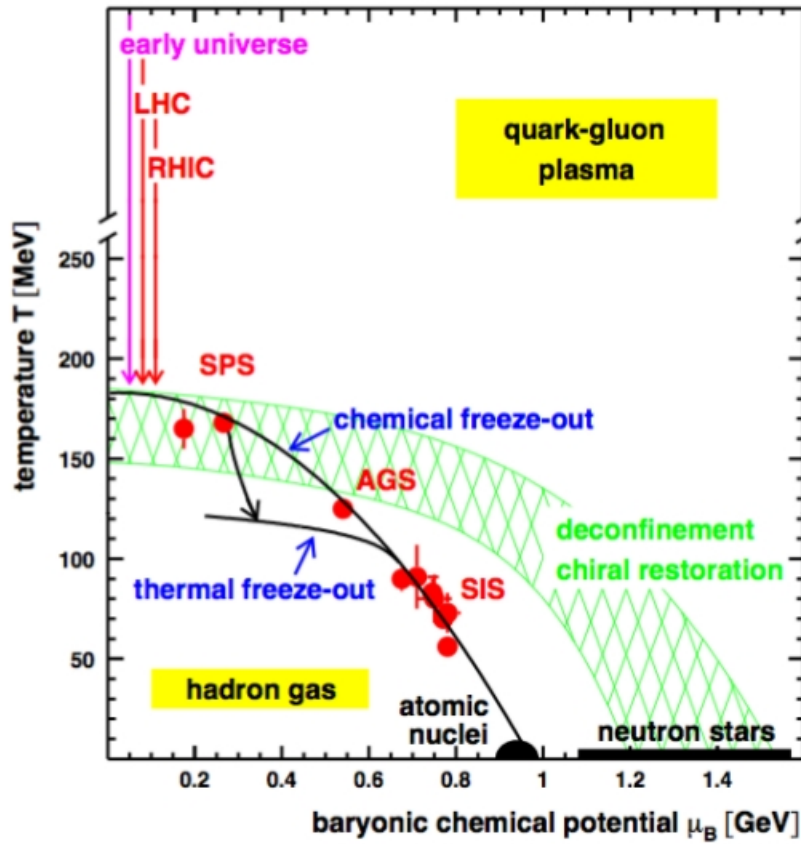


FIGURE 1.3: Phase diagram of hadronic and partonic matter. The chemical freeze out points are determined from thermal models fit to heavy ion data at SIS, AGS, and SPS energies.

number of participating nucleons diminishes, and the collision moves from “central” to “peripheral”.

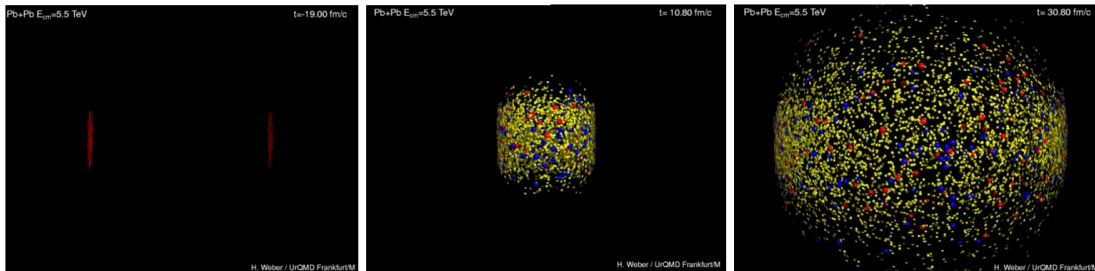


FIGURE 1.4: Three snapshots illustrating a nuclear collision of two nuclei. Left frame: The two incident nuclei (with the incident nucleons in red) are Lorentz contracted as the incident velocities are already close to the speed of light. The middle frame shows the moment of highest compression; the right frame displays the expansion stage, when most of the particles already no longer interact strongly. The final situation is called freeze-out. The pictures resulting from a simulation code calculation are extracted from a movie on <http://urqmd.org/weber/CERNmovies/index.html>.

1.3.1 Heavy-ion observables

1.3.1.1 Kinematic Variables

In high-energy physics, one of the most used kinematic variable is the rapidity y . For a Lorentz transformation along the z -axis, rapidity is defined by:

$$\beta_z = \tanh y \quad (1.7)$$

and it is a convenient variable because it is additive under Lorentz boosts. In this sense, rapidity in relativistic mechanics is analogous to velocity in non-relativistic mechanics, since velocity is additive under Galilean transformations [13]. For a particle with energy E and longitudinal momentum p_z , the rapidity can be written as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (1.8)$$

In the high-energy limit where the particle mass is small compared to its momentum, rapidity can be approximated by pseudorapidity (η) which is defined in terms of the polar angle θ as:

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad (1.9)$$

Note that for a particle travelling precisely along the z -axis, the pseudorapidity is infinite while the rapidity is always finite. For a particle of rest mass m_0 , the momentum transverse to the collision axis, p_T can be used to define a transverse mass $m_T = \sqrt{m_0^2 + p_T^2}$. The following useful relations follow:

$$E = m_T \cosh y \quad (1.10)$$

$$p = p_T \cosh y \quad (1.11)$$

where p is the total momentum of the particle ($E^2 = m_0^2 + p^2$)

1.3.1.2 Impact Parameter and Collision Centrality

As illustrated in Fig. 1.5b, collisions of heavy-ions have as a feature the impact parameter b , which defines the centrality of the collision. At these relativistic collision energies, only nucleons in the overlap region will be involved in the interaction: these are called *participants* while the remaining nucleons are *spectators*. The number of participating nucleons N_{part} is an important way of characterizing a heavy-ion collision: many observables depend on it, and their knowledge could provide the signatures of the underlying dynamics. It is also useful to know the number of binary nucleon-nucleon collisions N_{coll} . N_{part} and N_{coll} are calculated from a Glauber model of the collision [15, 16]. In this picture, a nucleus-nucleus collision is treated as a superposition of individual

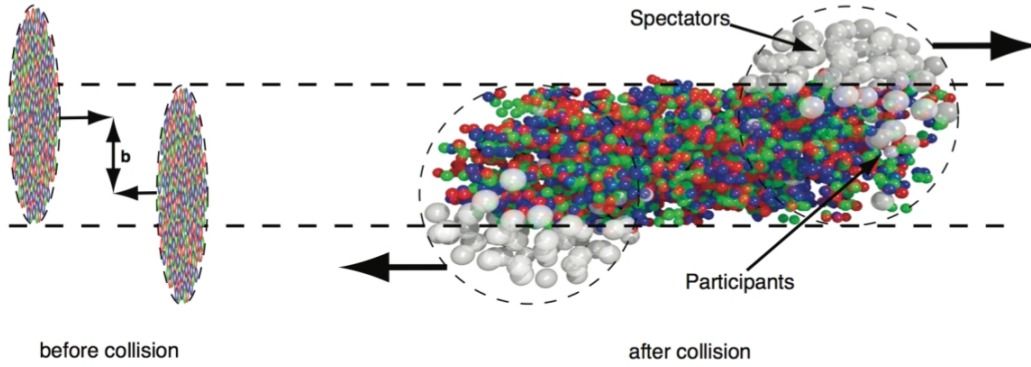


FIGURE 1.5: a) Two heavy-ions before collision with impact parameter b . b) The spectator nucleons continue unscathed, while in the participant zone particle production takes place.

nucleon-nucleon collisions, using the free nucleon-nucleon inelastic cross-section obtained from pp scattering data. The mass density distribution of the nucleus is assumed to follow the Woods-Saxon form of a smoothed square well. Scaling with N_{part} is expected to dominate for “soft” (low- p_T) particle production, according to the wounded nucleon model [17], where it is assumed that a nucleon which has interacted once is unable to interact again. An alternative picture is to regard a nucleus-nucleus collision as an independent superposition of individual nucleon-nucleon collisions. If this was the case, then heavy-ion observables would be expected to scale with N_{coll} . Direct photon production, for example, has been found to exhibit N_{coll} -scaling [18].

1.3.2 Space-time evolution of heavy-ion collision

In the case a QGP is formed, it will eventually expand because of its internal pressure. As the system expands it also cools. The space-time evolution of the expansion can be seen in Fig. 1.6 (right side). A and B represent the two incoming ion beams. After a pre-equilibrium phase a QGP is formed. As it expands, the system will eventually reach what is known as the critical temperature (T_c). At this point partons begin to hadronize and this will continue until the chemical freeze-out (T_{ch}) takes place, when inelastic collisions cease. At this stage the distribution of hadrons is frozen. As cooling and expansion continue the hadrons reach what is called thermal freeze out (T_{fo}). Here the elastic collisions stop and the hadrons carry fixed momenta. The QGP state can not be directly observed, because of its short lifetime. Instead, through experiment we measure the final state hadrons, which have a fixed momentum after T_{fo} . The observables of interest should tell us about the deconfinement and the thermodynamic properties of

the matter. Moreover, experimental measurements include yields and p_T spectra of various particle species, azimuthal studies of high p_T particles, phase space distributions, and particle correlations.

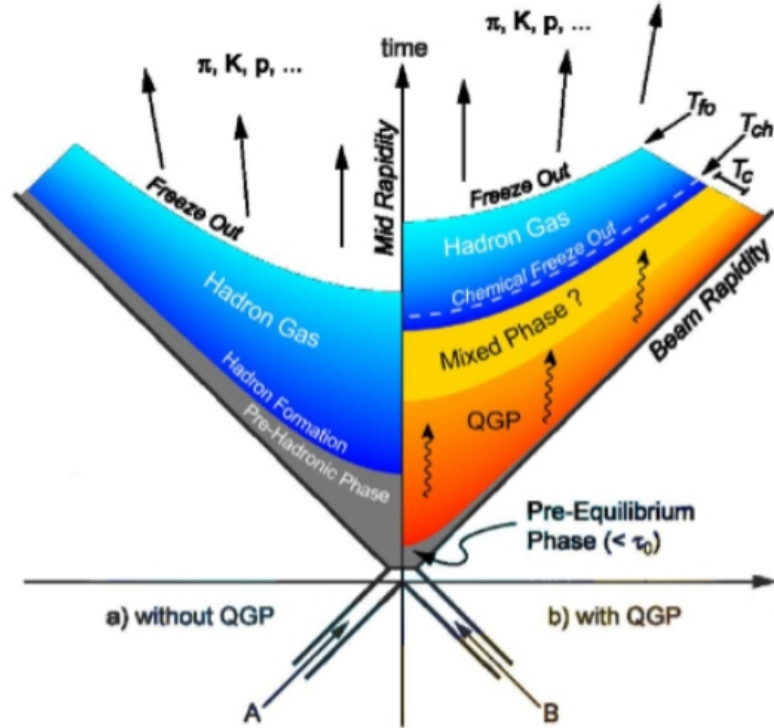


FIGURE 1.6: Hydrodynamic evolution of a heavy ion collision with and without the formation of a QGP. T_{fo} is an abbreviation for the thermal freeze-out temperature and T_{ch} for the chemical freeze-out temperature. Hadronization starts in the region of T_c , known as the critical temperature.

1.4 QGP signatures and results at the LHC

Since the QGP can not be studied directly, the theoretical models must predict which characteristics of the final state of the interactions could provide information on the QGP formation. In other words they should predict which properties are expected to be different in colliding systems where the QGP has formed or not. Such properties are the goal of our investigation: they are called “signatures” of the QGP. Depending on the phase of the collision, these signatures are studied by means of different types of probes.

- **hard probes** are signals produced in the first stages of the collision by the interaction of high momentum partons, such as, production of heavy quarks and of their bound states (charmonium and bottomonium), jet quenching, thermal photons and dileptons;

- **soft probes** are signals produced in the later stage of the collision. Even if they are produced during the hadronization stage, they keep indirect information on the properties of the phase transition and on the QGP. These are momentum spectra, strangeness enhancement, elliptic flow, particle correlations and fluctuations.

Besides the QGP signatures, also the global properties of the A-A collisions, like impact parameter, energy density and entropy are interesting to be studied. Experimentally they can be obtained from charged particle multiplicity and transverse energy distributions.

The purpose of the following section is not to give a detailed description of all the QGP signatures but to report about the most recent results obtained by the LHC experiments from the study of the first Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For more information on QGP experimental results from older experiments one can see e.g. [19]-[24], while for a complete review on the recent results from the LHC experiments see [25].

1.4.1 Soft Probes

Global event properties describe the state and dynamical evolution of the bulk matter created in a heavy ion collision by measuring the characteristics of the majority of particles which have momenta below a few GeV/c, referred as “soft” particles. Such measurement include multiplicity distributions – which can be related to the initial energy density reached during the collision – yields and momentum spectra of identified particles – which are determined by the conditions at and shortly after hadronization – and correlations between particles which measure both size and lifetime of the dense matter state as well as some of its transport properties via collective flow phenomena.

1.4.1.1 Multiplicity distribution

The most basic quantity, and indeed the one measured within days of the first ion collisions, is the number of charged particles produced per unit of (pseudo)rapidity, dN/dy ($dN_{ch}/d\eta$), in a central collision. When the LHC heavy ion program was conceived and detectors had to be designed, predictions for $dN_{ch}/d\eta$ were uncertain, ranging from below 1000 to above 4500, because the predictions were extrapolated from light ions experiment results, which were done at beam energies few order of magnitudes lower than those expected at LHC. With results from RHIC, the uncertainties were substantially reduced, with most predictions concentrating in the range $dN_{ch}/d\eta = 1000 - 1700$. The value finally measured at LHC, $dN_{ch}/d\eta \sim 1600$ [27], was on the upper part of this range. From the measured multiplicity one can derive a rough estimate of

the energy density with the help of the formula proposed by Bjorken [28] which relates the initial energy density ε to the transverse energy E_T :

$$\varepsilon \geq \frac{dE_T/d\eta}{\tau_0 \pi R^2} = \frac{3}{2} \langle E_T/N \rangle \frac{dN_{ch}/d\eta}{\tau_0 \pi R^2} \quad (1.12)$$

where τ_0 denotes the thermalization time, R is the nuclear radius, and $E_T/N \sim 1$ GeV is the transverse energy per emitted particle. The value measured at the LHC implies that the initial energy density (at $\tau_0 = 1$ fm/c) is about 15 GeV/fm³ [29], approximately a factor three higher than in Au+Au collisions at the top energy of RHIC. The corresponding initial temperature increases by at least 30%, with respect to RHIC, to $T \sim 300$ MeV, even with the conservative assumption that the formation time τ_0 , when thermal equilibrium is first established, remains the same as at RHIC. The high multiplicity at LHC, together with the large experimental acceptance of the detectors, allows for a precise determination of the collision geometry (impact parameter and reaction plane orientation) in each event. Events are classified according to “centrality” (Section 1.3.1).

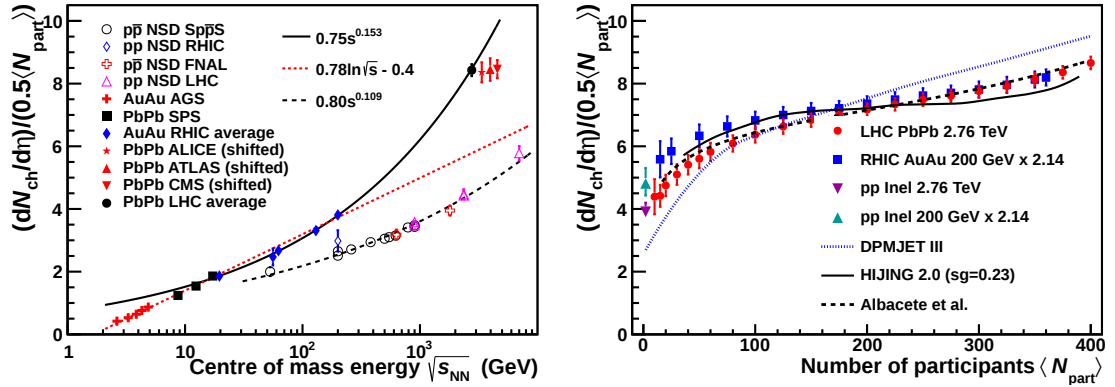


FIGURE 1.7: a): Charged particle pseudorapidity density $dN_{ch}/d\eta$ per colliding nucleon pair ($0.5N_{part}$) versus centre of mass energy for pp and A+A collisions. b): $dN_{ch}/d\eta$ per colliding nucleon pair versus the number of participating nucleons together with model predictions for Pb+Pb at 2.67 TeV [25].

The charged particle multiplicity per participant pair [30, 31, 32] ($dN_{ch}/d\eta/(0.5 N_{part})$), is shown in Fig. 1.7a together with the data for central – typically 0-5% or 0-6% centrality – A+A collisions at lower energies. Particle production is no longer compatible with a logarithmic dependence on $\sqrt{s}$ (red dashed line), as true for the data up to the top RHIC energy [33], but follows a power law $\sim s^{0.15}$ (black full line). Also the pp data are well described by a power law (black dotted line), however with a less steep dependence on energy ($\sim s^{0.11}$). The centrality dependence of the particle production at LHC (red circles) is compared in Fig. 1.7b with the one measured at RHIC (blue squares), normalised to the LHC result at $N_{part} = 350$ by scaling it by a factor 2.14. The results from the three LHC detectors [30, 31, 32] are in excellent agreement with each other (within 1-2%) and have been averaged in this figure using the prescription of [35], i.e. assuming conservatively that the systematic errors in N_{part} are fully correlated between

experiments. The comparison to the averaged and scaled 200 GeV Au+Au data shows a similar shape in both the distributions.

1.4.1.2 Identified particle spectra

Presently, the particle production (π , K, p, Λ ,...) is a non-perturbative process and cannot be calculated directly from first principles (QCD). In the phenomenological QCD inspired event generators, the particle spectra and ratios are adjusted to the data of elementary collisions (pp, e^+e^-) using a large number of parameters. In heavy ion reactions, however, inclusive particle ratios and spectra at low transverse momentum, which, even at LHC energies, include the large majority of all produced hadrons (about 95% of all particles are below 1.5 GeV/c), are consistent with simple descriptions by statistical/thermal [37, 38] and hydrodynamical [39] models, where particle ratios are determined during hadronisation at or close to the QGP phase boundary (“chemical freeze-out”), whereas particle momentum spectra reflect the conditions somewhat later in the collision, during “thermal freeze-out”. A defining characteristic of heavy ion collisions is the appearance of ordered motion amongst the emitted hadrons in the soft part of the momentum spectrum [40, 41] (See section 1.4.1.6). It is called collective flow and implies, in contrast to random thermal motion, a strong correlation between positions and momenta (nearby particles have similar velocities in both magnitude and direction). Flow arises in a strongly interacting medium in the presence of local pressure gradients. Different flow patterns are observed in heavy ion collisions and classified in terms of their azimuthal angle φ dependence with respect to the reaction plane. The isotropic (or angle averaged) component is called *radial flow*. In the framework of hydrodynamic models, the fluid properties (viscosity η/s , equation-of-state, speed of sound) together with boundary conditions both in the initial state (collision geometry, pressure gradients) and in the final state (freeze-out conditions) determine the pattern of collective motions and the resulting momentum spectra $d^2N/dp_T d\varphi$. Fig. 1.8a shows the transverse momentum distributions of identified particles in central Pb+Pb collisions at the LHC [44, 42, 43]. The spectral shapes differ significantly from Au+Au at RHIC (open black symbols), most dramatically for protons at low p_T . The data are compared to hydrodynamic calculations (shown as lines).

The radial flow velocity can be estimated by fitting the combined spectra with a hydrodynamically inspired function called a “blast-wave” fit [46]. The resulting kinetic freeze-out temperatures T_{fo} and average radial flow velocities $\langle\beta\rangle$ are shown in Fig. 1.8b for different centrality selections [42]. The two fit parameters ($T_{fo}, \langle\beta\rangle$) are strongly correlated as indicated by the confidence contours in Fig. 1.9a (each confidence contour corresponds to a different centrality class). However, a relative comparison to a similar fit to RHIC data [56] shows for the most central collisions that the average flow velocity increases significantly at LHC, reaching about 0.65 c and that the kinetic freeze-out temperature drops below the one at RHIC.

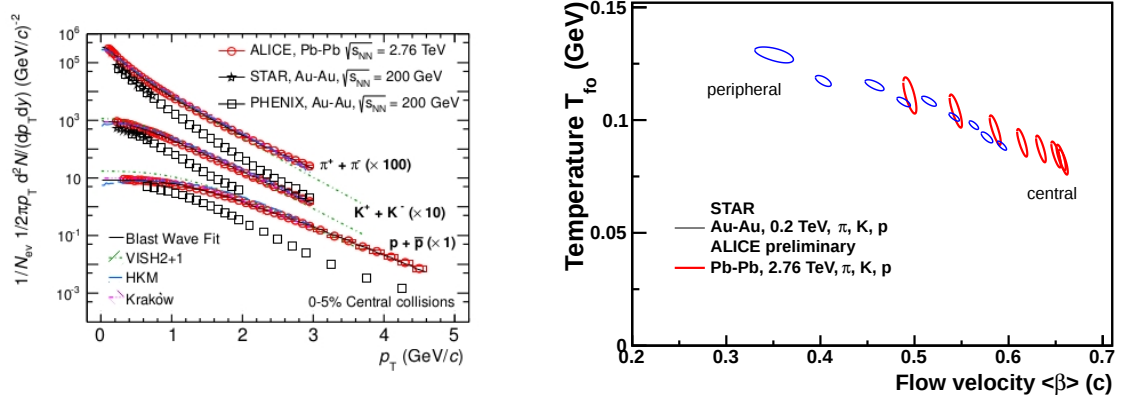


FIGURE 1.8: a): Transverse momentum distributions of the sum of positive and negative particles (π , K and p) for central (0-5%) Pb+Pb collisions measured by the ALICE collaboration [44]. (box: systematic errors; statistical errors smaller than the symbol for most data points). The distributions are fitted individually with a blast wave function and compared to RHIC data and hydrodynamic models. b): Kinetic freeze-out temperatures T_{fo} and average radial flow velocities $\langle\beta\rangle$ extracted from identified particle spectra (π , K, p) at LHC (Pb+Pb) (red contours) and RHIC (Au+Au) (blue contours) for different centralities (Right are peripheral events, left most central events).

1.4.1.3 Identified particle yields

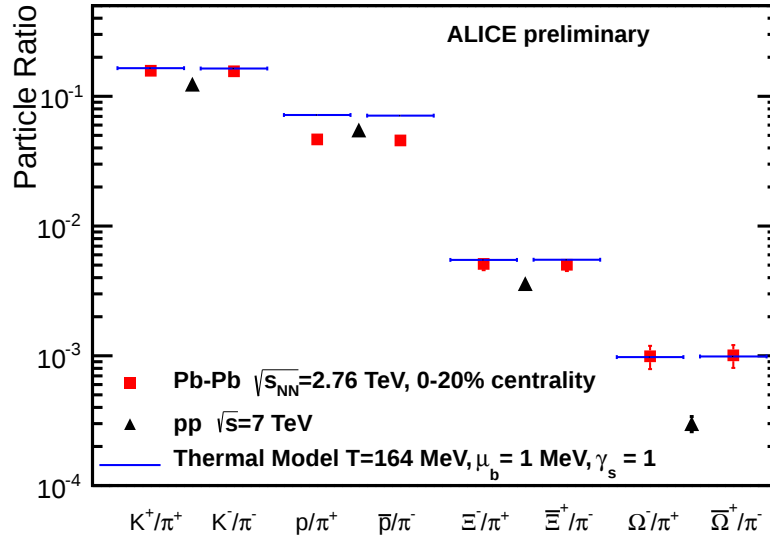


FIGURE 1.9: Particle ratios measured in central Pb+Pb (squares) and pp (triangles) collisions at the LHC at mid-rapidity ($|y| < 0.5$). The full lines are the predictions from a thermal model.

Bulk particle production can be successfully described in the framework of the thermal (statistical) hadronisation model [37, 38]. It assumes that particles are created in thermal (phase space) equilibrium governed by a scale parameter T , interpreted as a temperature. Production of a particle with mass m is suppressed by a Boltzmann factor $e^{-m/T}$. Conservation laws introduce additional constraints, like the baryochemical potential μ_B which accounts for baryon number conservation. An additional parameter γ_s is introduced to describe the observation that in some collision systems particles

containing strange quarks are suppressed compared to the grand canonical thermal expectation. The temperature parameter (T) is found in all high energy collisions (pp, e^+e^- , A+A) to be about 160 - 170 MeV. Fig. 1.9 shows particle ratios from central Pb+Pb collisions (red squares), together with the (particle anti-particle averaged) values measured in pp at 7 TeV (blue triangles) [42, 47], as well as the prediction from a thermal model using the canonical conditions expected for nuclear collisions at the LHC (blue segments)[48]. Within experimental errors, particles and anti-particles are produced in Pb+Pb at mid-rapidity ($|y| < 0.5$) in equal numbers, consistently with the small value of the baryochemical potential μ_B of the thermal model. All strange particle ratios in Pb+Pb are well described by the model, implying that they are produced in accordance with fully thermal ratios (i.e. $\gamma_S = 1$). On the other hand, p/π ratio was found to be unexpectedly strikingly off – too low by a factor of about 1.5 – and well outside predictions. The p/π ratio, which would have been expected to increase from its value measured in pp, stays essentially unchanged or even decreases slightly. The data, which have been checked carefully, seems to indicate that a simple thermal approach is not sufficient to describe the particle production at the LHC energy.

1.4.1.4 Strangeness enhancement

The mass of the hadrons is only partly due to the mass of the constituent valence quarks. Naively speaking, the quarks “dress up” due to the strong interaction that keeps them confined. Once they are free, as in a QGP, the quarks recover their bare masses. It was predicted that, if the QGP is formed, an enhancement of the strange quarks should occur, because the production of $s\bar{s}$ pairs becomes easier due to the lower energy needed. When the QGP cools down, these strange quarks eventually recombine into hadrons favouring also an enhancement of the number of strange hadrons. This effect is larger for hadrons with higher strangeness, with the following scaling for the number type: $N_\Omega > N_\Xi > N_\Lambda$, where $N_\Omega, N_\Xi, N_\Lambda$ are the number of produced Ω, Ξ and Λ . A certain enhancement of strange hadrons can occur also in a hadron gas system, but the processes of hadronization in this case are relatively easy for K and Λ and progressively harder for hadrons with higher strangeness, hence the relation would be: $N_\Omega < N_\Xi < N_\Lambda$. The production of multi-strange hadrons with respect to pp - like collisions is considered to be a signature of the formation of the QGP and it was observed at SPS, RHIC and LHC.(Fig.1.10).

1.4.1.5 Identical particle (HBT) correlations

The freeze-out volume (the size of the matter at the time when strong interactions cease) and the total lifetime of the created system (the time between collision and freeze-out) can be measured by identical particle interferometry (also called Hanbury-Brown–Twiss or HBT correlations) [49]. For identical bosons (fermions), quantum statistics

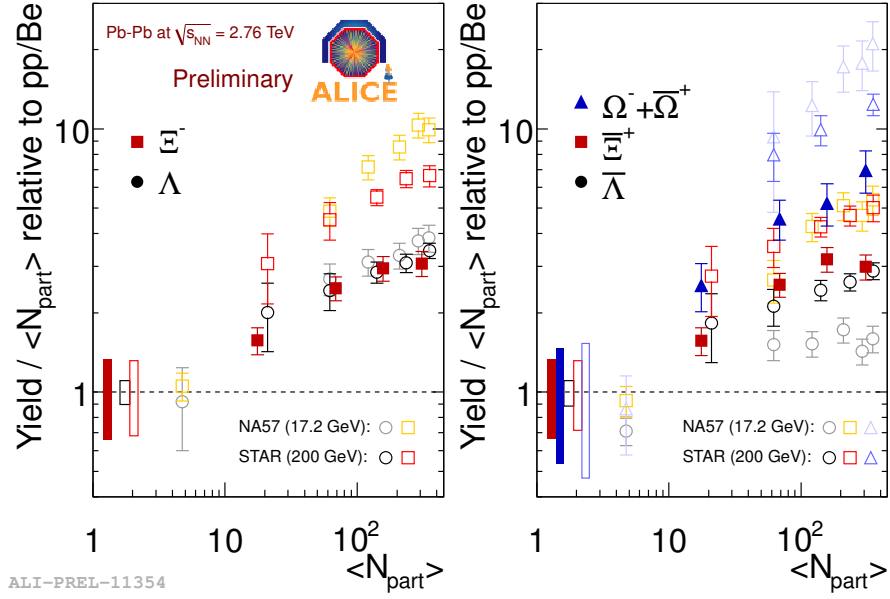


FIGURE 1.10: The observed baryon yields per participant nucleon (full symbols), normalized to the ratio measured in pp (for STAR and ALICE measurements) and p-Be collision (for NA57 experiment) as a function of the number of participants. The energy in the center of mass of the STAR experiment energy is 200 GeV, while the one of NA57 is 17.2 GeV. Open dark symbols are STAR data, while light open symbols are NA57 points.

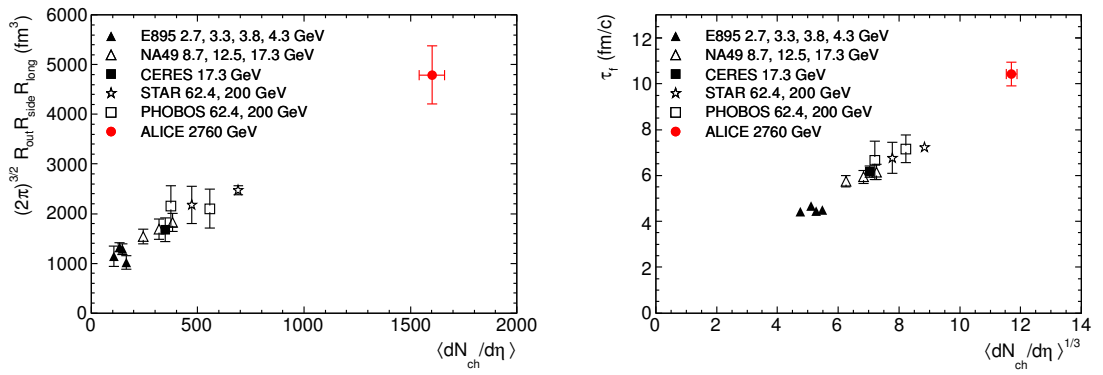


FIGURE 1.11: a): Local freeze-out volume $((2\pi)^{3/2}R_{\text{out}}R_{\text{side}}R_{\text{long}})$ as measured by identical pion interferometry at LHC (full red circle) compared to central gold and lead collisions at lower energies. The energy of the collision is expressed in terms of $dN_{\text{ch}}/d\eta$ (see Section 1.4.1.1) b): The system lifetime (decoupling time) τ_f compared to results from lower energies. Here the energy of the collision is expressed in terms of $(dN_{\text{ch}}/d\eta)^{1/3}$

leads to an enhancement (depletion) for particles emitted close-by in phase space. This modifies the two-particle correlation function, measured in energy and momentum variables, and can be related via a Fourier transformation to the space and time distribution of the emitting source, i.e. the space-time hyper-surface of last rescattering. Results from HBT correlation measurements are shown in Fig. 1.11 for central collisions from very low energies up to LHC as a function of the charged particle density $dN_{\text{ch}}/d\eta$ [50]. The total freeze-out volume is given as the product of a geometrical factor and the radii measured in three orthogonal directions (called R_{long} , R_{side} , and R_{out}), whereas the lifetime was estimated from the pair-momentum dependence of R_{long} . The locally comoving freeze-out volume is directly proportional to the particle multiplicity (Fig. 1.11a) and therefore increases by a factor two compared to top RHIC energy to about 5000 fm^3 . The system lifetime (Fig. 1.11b) is proportional to the cubic root of the particle density and increases by about 30% compared to top RHIC energy to $10 \text{ fm}/c$. The evolution from RHIC to LHC of the individual radius parameters (R_{long} , R_{side} , R_{out}) as well as their pair momentum dependence is in satisfactory agreement with the predictions of hydrodynamical models [66, 50].

1.4.1.6 Azimuthal anisotropy in particle production

The measurement of the particle production in the transverse plane can be more informative about possible asymmetry in the collective motions (*flow*). The azimuthal distribution of particles is isotropic when the mean free path is larger than the size of the system, otherwise the emission pattern is affected by the shape of the system. In non-central collisions, when the impact parameter is different from zero, the overlap zone is anisotropic, featuring an “almond” shape (see Fig.1.12). The spatial anisotropy determines larger pressure gradients along the minor axis of the “almond” with respect to the major one. This reflects on momentum distribution leading to a preferential direction in the particle emission. The effect is self-quenching: in a short time-scale ($\sim 8 \text{ fm}/c$, see Fig.1.13), indeed, the pressure gradients are equilibrated, but the effect on the momenta is visible in the final state azimuthal distributions. The measured anisotropy points directly to the initial QGP state, giving information about its equation of state and the sound velocity. From a measurement of anisotropy it is possible to deduce whether flow originates from partonic or hadronic matter or from the hadronization processes.

A convenient way of characterizing the pattern of the anisotropic flow is to use a Fourier expansion of the triple differential Lorentz invariant distribution:

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\phi - \Psi_{RP})] \right), \quad (1.13)$$

where E is the energy of the particle, p is the momentum, p_T the transverse momentum, ϕ is the azimuthal angle, y the rapidity and ψ_{RP} the reaction-plane angle in the

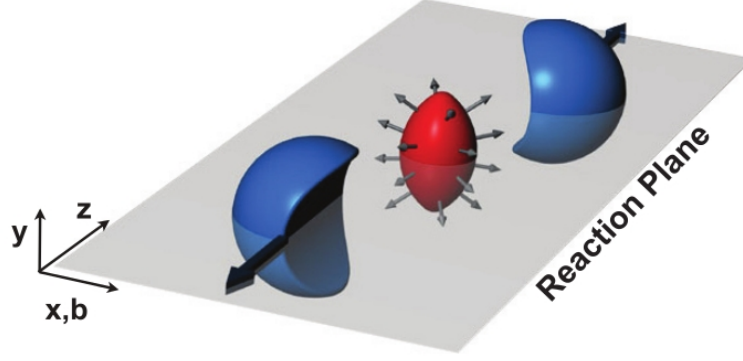


FIGURE 1.12: Almond-shaped interaction volume after a non-central collision of two nuclei. The spatial anisotropy with respect to the $x-z$ plane (reaction plane) translates into a momentum anisotropy of the produced particles (anisotropic flow) [51].

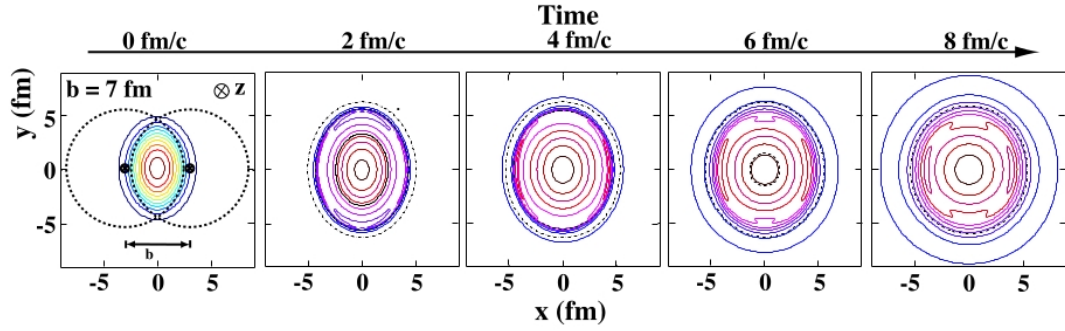


FIGURE 1.13: The created initial transverse energy density profile and its time dependence in coordinate space for a non-central heavy-ion collision [52]. The z -axis is along the colliding beams and the x -axis is defined by the impact parameter.

laboratory frame. The reaction plane (Fig.1.12) is defined by the beam direction and the impact parameter. The sine term in eq.1.13 vanishes due to reflection symmetry with respect to the reaction plane. The Fourier coefficients are given by:

$$v_n(p_T, y) = \langle \cos [n(\phi - \Psi_{RP})] \rangle, \quad (1.14)$$

where brackets denote an average over the particles, summed over all events, in the (p_T, y) region under study. The v_1 coefficient is known as *direct flow*, v_2 as *elliptic flow*, while the v_3 is called *triangular flow*. Elliptic flow has its origin in the amount of re-scattering and in the spatial eccentricity of the collision zone. The amount of re-scattering is expected to increase with centrality, while the spatial eccentricity decreases. The spatial eccentricity is defined as:

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}, \quad (1.15)$$

where x and y are the spatial coordinates in the transverse plane and the brackets denote an average weighted with the initial density. The elliptic flow magnitude increases continuously with $\sqrt{s}$ from SPS to RHIC [40, 41]. At top RHIC energy, v_2 reaches a value

compatible with the one predicted by hydrodynamics for a “perfect fluid”, i.e. a fluid without internal friction and vanishing shear viscosity.

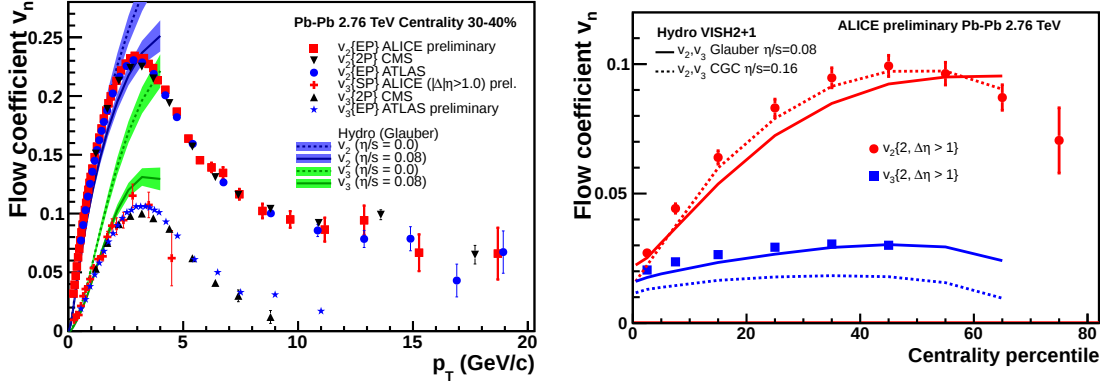


FIGURE 1.14: a): Elliptic flow coefficients v_2 and v_3 as a function of transverse momentum compared to a hydro model using two different values for the viscosity η/s of the fluid ($\eta/s=0$ and $\eta/s=0.08$) b): p_T integrated elliptic flow coefficients (v_2 full red circle and v_3 full blue squares) as a function of collision centrality measured by the ALICE experiment. Results are compared to a hydro calculation using two different models for the initial state geometry. Full line is for a Glauber model with a viscosity $\eta/s=0.08$, while dotted lines are for a CGC model with a viscosity $\eta/s=0.16$; red is for v_2 and blue for v_3 coefficient.

The elliptic (v_2 – red square, blue upside down triangle and blue circle –) and triangular (v_3 – red cross, blue triangle and blue star –) flow coefficients for mid-rapidity ($y;0.5$) Pb-Pb collisions are shown in Fig. 1.14a as functions of p_T . The elliptic flow coefficient rises approximately linearly with p_T to a maximum of $v_2 \sim 0.23$ around 3 GeV/c. The corresponding asymmetry in $dN/d\varphi$ is very large indeed: almost three times as many 3 GeV/c particles are emitted in-plane compared to out-of-plane (see eq 1.13). The coefficient then decreases, at first rapidly then more gradually, but stays finite up to the highest p_T measured. Also the triangular flow coefficient finite out to about 10 GeV/c and similar in shape, reaching about half the value of v_2 at the maximum.

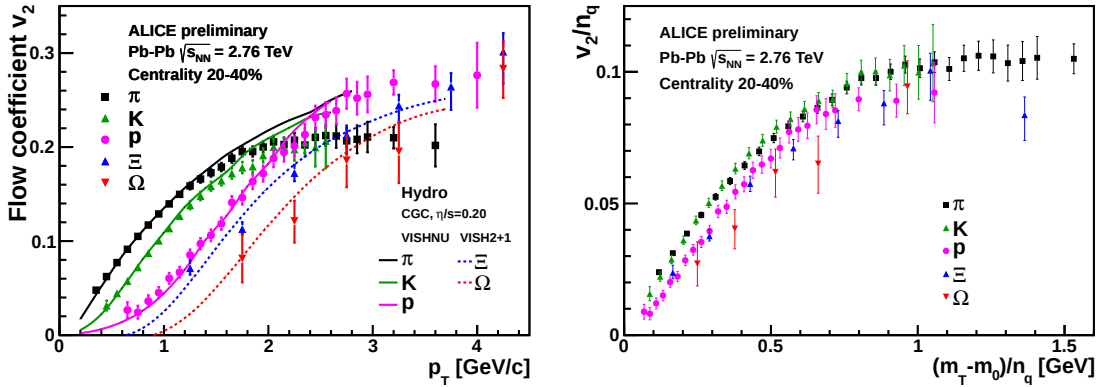


FIGURE 1.15: a): Elliptic flow v_2 as a function of p_T for identified particles compared with a hydrodynamical model [53, 54]. b): Elliptic flow for mesons and baryons, scaled by the respective number of valence quarks n_q , versus scaled transverse kinetic energy.

A more stringent test of the collective flow interpretation of azimuthal anisotropies is the characteristic dependence on particle mass. The LHC data for v_2 for various particles (π, K, p, Ξ, Ω) are shown in Fig. 1.15a. To understand the origin of the characteristic

mass splitting, seen also in v_3 , one needs to keep in mind that collective radial flow tends to equalise the velocities of particles, not their momenta, and therefore shifts heavy particles out to higher p_T than light ones. The effect of a given azimuthal flow asymmetry thus manifests itself at higher momenta for particles with a larger mass. The hydrodynamical model, which incorporates this effect, describes the data very well for all particle species up to intermediate p_T . It also predicted the observation that the mass splitting is larger at LHC than at RHIC as a consequence of the increased radial flow.

1.4.2 Hard Probes

The increased energy of heavy ion collisions at LHC relative to RHIC leads to much larger cross sections for hard processes, i.e. those involving high momentum or high mass scales. Energetic quarks or gluons can be observed as jets or single particles with p_T reaching 100 GeV/ c and beyond. Similarly, high p_T photons, charmonium and bottomonium states (i.e. the J/ψ and Υ families), and even the weak vector bosons W and Z are copiously produced. The details of production and propagation of these high p_T probes can be used to explore the mechanisms of parton energy loss and deconfinement in the medium.

1.4.2.1 Single particle spectra

The single particle production rates at RHIC have shown a large suppression of hadrons in nuclear collisions relative to pp, whereas particles that do not interact strongly, e. g. photons, are not modified. The LHC can significantly extend the accessible p_T range and allows the measurement of additional particles, such as the Z and W . The suppression effects of a given particle are typically expressed in terms of the nuclear modification factor (R_{AA}):

$$R_{AA}(p_T) = \frac{d^2 N_{AA}/dp_T d\eta}{\langle T_{AA} \rangle d^2 \sigma_{NN}/dp_T d\eta}, \quad (1.16)$$

where N_{AA} and σ_{NN} represent the particle yield in nucleus-nucleus collisions and the cross section in nucleon-nucleon collisions, respectively. The nuclear overlap function $\langle T_{AA} \rangle$ is the ratio of the number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, calculated from the Glauber model, and the inelastic nucleon-nucleon cross section ($\sigma_{\text{inel}}^{NN} = (64 \pm 5)$ mb at $\sqrt{s_{NN}} = 2.76$ TeV). In the absence of nuclear effects the factor R_{AA} is unity by construction. As observed at RHIC in 200 GeV Au+Au collisions [55, 56], the yield of 5 – 10 GeV/ c charged particles is suppressed in the most central events by more than a factor of five. Instead of R_{AA} , it can be useful to use the ratio of central over peripheral events, R_{CP} , which takes into account the centrality dependence.

$$R_{CP} = \frac{Yield^{\text{central}}/\langle N_{\text{coll}}^{\text{central}} \rangle}{Yield^{\text{peripheral}}/\langle N_{\text{coll}}^{\text{peripheral}} \rangle} \quad (1.17)$$

While the charged particle R_{AA} is the measurement done with the best statistical and systematic precision [57, 58, 59, 60], it is also interesting to measure the nuclear modification factor for individual particle species to distinguish the exact mechanisms of energy loss. Measurements exist for identified π , K_S^0 , Λ , isolated photons, Z , W , D -mesons, jets [60], J/ψ and Υ . A summary of R_{AA} measurements for different particle species is shown in Fig. 1.16 for the most central events. Fig.1.16a shows the R_{AA} for all the charged particles as full circles, for K_S^0 , Λ as magenta full triangles, for D -mesons as empty squares, and for J/ψ as red diamonds. Fig.1.16b shows the R_{AA} for all the charged particles as full circles, for isolated photons as empty circles and for Z as star open symbols.

The inclusive charged particle R_{AA} follows, up to about 10 – 15 GeV/ c , the characteristic shape discovered at RHIC (1.16a, full circles). The pronounced maximum at a few GeV/ c , which is sometimes attributed to initial or final state interactions in nuclei (“Cronin effect”), is at very high energies more likely to be yet another manifestation of collective flow. This interpretation is also supported by the fact that the apparent “suppression” factor is slightly larger for kaons and significantly larger for Λ ’s. The peak region is followed by a steep decline and a minimum, around 5 – 7 GeV/ c , where the suppression reaches a factor of about seven, very similar to, but slightly larger than, the one measured at RHIC. Heavy quarks, as shown by the R_{AA} of prompt D mesons (open squares) and non-prompt J/ψ (from the decay of bottom quarks, closed diamond) in Fig. 1.16a, are almost as strongly suppressed as inclusive charged particles. The strong suppression found for hadrons containing c - and b -quarks confirms observations made at RHIC and may indicate that the energy loss rate depends less strongly on the parton mass than expected on radiative energy loss.

Above $p_T \sim 8$ GeV/ c , the suppression becomes universal for all particle species. With increasing p_T , R_{AA} rises gradually towards a value of 0.5 (see Fig.1.16 right panel), a feature which was not readily apparent in the RHIC data. Isolated photons and the Z boson are not suppressed, within the currently still large statistical errors (Fig.1.16). This finding is consistent with the hypothesis that the suppression observed for hadrons is due to final-state interactions with the hot medium.

1.4.2.2 Jets

Studying the modification of fully reconstructed jets is a useful tool for probing the properties of the hot quark-gluon plasma. Jets are formed by fragmentation from high p_T partons as they propagate through the produced matter. Measuring the energy of fully reconstructed jets allows one to distinguish between energy redistribution among the leading parton and the remainder of the jet and energy dissipation out of the jet into the thermal medium. One of the most promising channels are dijets, in particular their transverse energy balance and azimuthal angle correlation. The energy dissipation into the medium can be studied by measuring the p_T asymmetry of dijets in heavy ion

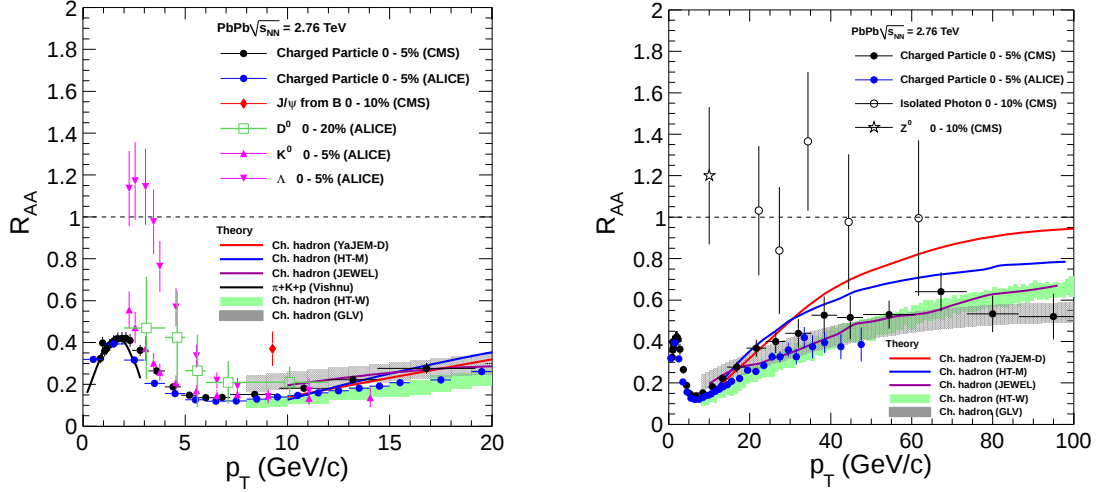


FIGURE 1.16: Nuclear modification factor R_{AA} as a function of p_T for a variety of particle species together with theoretical predictions. Experimental error bars correspond to the total error (statistical and systematic errors added in quadrature). a) Low momentum region $p_T < 20$ GeV; b) Entire momentum range measured at LHC.

collisions as a function of centrality and by comparing them to data from pp collisions. The measurement of the dijet asymmetry $A_J = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$, where “1” and “2” refer to the leading and subleading jet, respectively, was performed by both ATLAS and CMS. Events containing at least two jets, with the leading (sub-leading) jet having p_T of at least 120 (50) GeV/ c for CMS and at least 100 (25) GeV/ c for ATLAS, were selected for further study.

The strong effect of jet quenching is confirmed by the ATLAS measurement of the jet R_{CP} (eq.1.17) [61]. The comparison of number of jet produced between the central and peripheral events indicates that for the most central events the energy loss appears to reduce the number of produced jets by about a factor of two (see Fig. 1.17 upper panel). This shows that the energy lost by the leading parton is not simply redistributed within the jet cone but lost by the reconstructed jet.

1.4.2.3 Quarkonium suppression

Heavy quarkonia are important probes of the QGP since they are produced early in the collision and their survival is affected by the surrounding medium [62]. The bound states of charm and bottom quarks are predicted to be suppressed in heavy ion collisions in comparison with pp, primarily as a consequence of deconfinement (“melting”) in the QGP [63]. The magnitude of the suppression for different quarkonium states should depend on their binding energy, with strongly bound states such as the Υ showing less or no modification. However, J/ψ production, the classical deconfinement signal, has puzzled expectations and interpretations ever since the first nuclear suppression was measured with Oxygen beams at the SPS, now attributed to cold nuclear matter effects rather than deconfinement. The “anomalous” suppression seen later

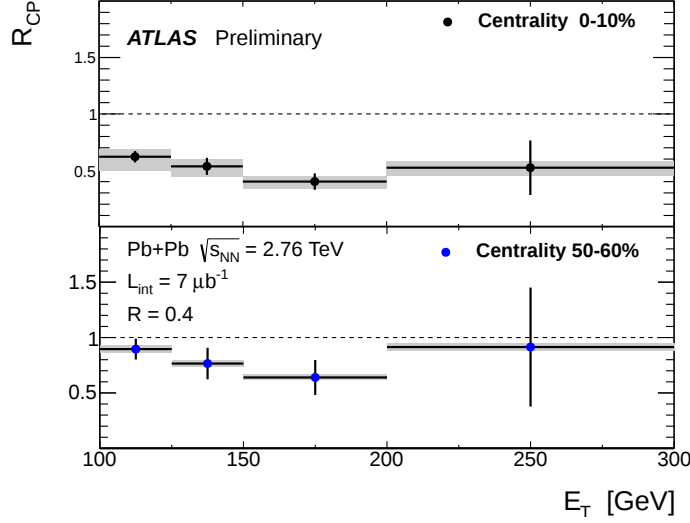


FIGURE 1.17: Jet central-to-peripheral event suppression factor R_{CP} for different centralities.

with heavier beams turned out to be rather similar in magnitude at SPS and RHIC. This could indicate suppression of only the high mass charmonium states ψ' and χ_c , which populate about 40% of the observed J/ψ , and which should dissociate very close to or even below the critical transition temperature. Alternatively, it has been suggested that the increasing (with energy) J/ψ suppression is more or less balanced by enhanced production via recombination of two independently produced charm quarks [64, 65]. A compilation of first LHC results on quarkonia production for both J/ψ (a) and Υ (b) is shown in Fig. 1.18 as a function of centrality (N_{part}), together with data from RHIC. While errors are still large, and the overall amount of suppression at LHC remains qualitatively similar to RHIC, the detailed pattern is quite different and intriguing. The p_T integrated R_{AA} measured for the J/ψ at forward rapidity (closed circles) of about 0.5 depends very little on centrality and is almost a factor of two larger than the one measured at RHIC in central collisions, also at forward rapidity (open circles); the difference is smaller but still significant when comparing with RHIC midrapidity data (open squares). On the contrary, the high p_T data at LHC (full squares), which are compatible with an independent R_{CP} measurement, show a stronger suppression than the high p_T RHIC results (open stars). While such a pattern would be unexpected in a pure suppression scenario, it is qualitatively consistent with the recombination model, which predicts substantial regeneration effects only at low transverse momentum. The Υ suppression (right panel) is very similar at RHIC and LHC. As only about 50% of the observed $\Upsilon(1S)$ are directly produced, and the $\Upsilon(2S/3S)$ states seem to be more suppressed than the ground state, the measured R_{AA} is compatible at both RHIC and LHC with suppression of the high mass bottomonium states only.

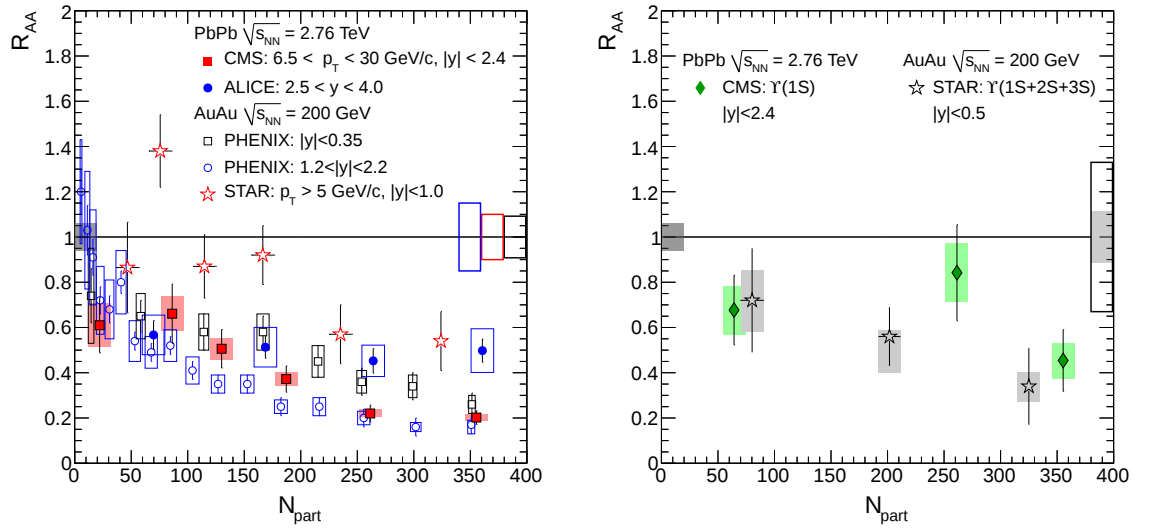


FIGURE 1.18: Nuclear modification factor R_{AA} as a function of centrality for J/ψ (right) and Υ (left).

A Large Ion Collider Experiment at the LHC

2.1 Large Hadron Collider (LHC)

The CERN's LHC complex is located close to the French-Swiss border in the suburb of the city of Geneva, Switzerland. The accelerator components and detectors are placed on average about 100 m beneath the Earth's surface in a circular tunnel spanning 27 km in circumference (see in Fig. 2.1). Main colliding systems are two: proton-proton (pp) and lead-lead (Pb-Pb) opposite beams, but asymmetric proton-ion (p-A) collisions and collisions of lighter ions (e.g. argon) are also foreseen. The design maximum energy for p-p collisions is 7 TeV per beam (or 14 TeV in the centre of mass), while for Pb-Pb collisions the centre of mass energy is 5.5 TeV per nucleon pair (or 1150 TeV total). To achieve the collision energy of 7 TeV for protons in each beam, the protons have to be accelerated to 99.9999991 % of the speed of light, which makes them traverse the LHC accelerator ring 11245 times each second. The protons are grouped within each beam in bunches, where adjacent bunches are separated 25 ns in time (or about 7 m in distance). The design number of bunches per proton beam is 2808, with 1.1×10^{11} protons per bunch, resulting in a design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. When two bunches cross each other, due to the smallness of protons there will be only about 20 collisions between 2.2×10^{11} protons in two intersecting bunches [69]. The average crossing rate of bunches is determined by the total number of bunches in accelerator ring, and the total number of turns the bunch makes within the accelerator ring per second, i.e. $2808 \times 11245 = 31.6 \text{ MHz}$ [69]. This results in a total of $20 \times 31.6 \text{ MHz} \sim 600$ million p-p collisions per second [69].

LHC experiment comprises six detector experiments: ALICE (A Large Ion Collider Experiment) [71], ATLAS (A Toroidal LHC Apparatus) [72], CMS (Compact Muon

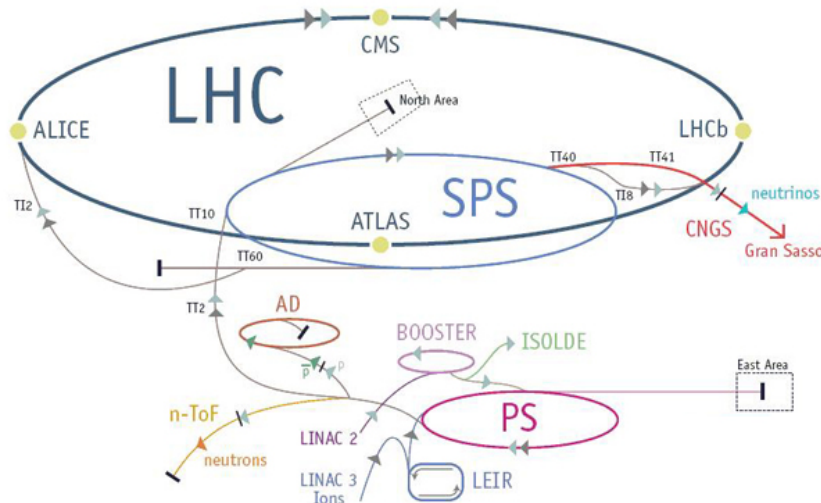


FIGURE 2.1: LHC complex [70].

Solenoid) [73], LHCb (Large Hadron Collider beauty) [74], LHCf (Large Hadron Collider forward) [75] and TOTEM (TOTal Elastic and diffractive cross section Measurement) [76], bringing together more than 10,000 scientists and engineers from the universities and laboratories from more than 100 countries. The primary physical goals at the LHC are addressing some of the most fundamental open questions in physics:

- **Existence of Higgs boson:** The postulated elementary particle whose existence can explain the origin of mass of other elementary particles will be either confirmed or disproved at LHC energies by two general purpose experiments ATLAS and/or CMS. Both the experiments observed a resonance with a mass of $\sim 125 \text{ GeV}/c^2$ in July, 2012: this signal have been interpreted as the observation of the Higgs boson.
- **Properties of Quark-Gluon Plasma:** The Quark-Gluon Plasma was already shortly introduced in Chapter 1. Such study has been in particular pursued by ALICE, a dedicated heavy-ion experiment.
- **Asymmetry between matter and antimatter:** In the observable Universe there is a vast excess of matter over antimatter, while at the time of the Big Bang they were produced at the same rate. Why starting from about 1 second after the Big Bang antimatter had all disappeared will be addressed in a dedicated experiment LHCb, by focusing mainly on physical processes involving B mesons (composite particles containing a bottom (beauty) quark or its antiquark). To create imbalance between matter and antimatter the violation of CP symmetry must be imposed, which was observed in the decays of B mesons in previous experiments BaBar and Belle.

- **Supersymmetry:** Supersymmetry is a hypothesized symmetry which revolves round the idea that for each boson in the Standard Model of elementary particles there exists a corresponding fermion with the same internal quantum numbers and mass, and vice-versa. The reason why the superpartners have not yet been observed in experiments, is that this symmetry is broken, making all superpartners much heavier and much more difficult to produce. If they indeed exist, the lightest of these massive superpartners might be produced in the collisions at LHC energies for the very first time in controlled environment.
- **Origin of Dark Matter and Dark Energy:** Experimental evidence shows that the composition of Universe is only about 4% due to ordinary baryonic matter, which gives rise only to the visible part of Universe, while about 23% and about 73% are due to Dark Matter and Dark Energy, respectively. The details of Dark Matter and Dark Energy remain so far unknown and directly unobservable. Discoveries at LHC energies might in particular shed light on the Dark Matter physics, i.e. one or more of so far only hypothesized Dark Matter candidate particles can be produced at LHC.
- **Extra dimensions:** Currently widespread and popular theories, like for instance String Theory, demand the existence of additional spatial dimensions besides the standard three macroscopic spatial dimensions characterizing the Euclidean space. Such extra spatial dimensions might be detectable at LHC energies.

Although conceived in the early 80's and approved by CERN Council in 1994, the first collisions at LHC occurred only in 2008, due to the various design challenges and the cutting edge technologies required during its development. In particular, the first pp collisions at 900 GeV centre of mass energy were delivered at LHC in September 2008. LHC operations were successfully continued in November 2009 after more than 1 year shut-down due to the serious incident caused by a faulty electrical connection between two magnets, which occurred during the first pp collisions in 2008. At the end of November 2009, by achieving the energy of 1.18 TeV per proton beam, LHC became the most powerful accelerator in the world. The first pp collisions at centre of mass energy of 7 TeV were delivered in March 2010, and the first Pb–Pb collisions at centre of mass energy of 2.76 TeV per nucleon pair in November 2010.

In 2010 the integrated luminosity delivered by the LHC was $\sim 48 \text{ pb}^{-1}$ for pp collisions at $\sqrt{s} = 7 \text{ TeV}$ ($\sim 0.5 \text{ pb}^{-1}$ in ALICE) and $\sim 10 \text{ } \mu\text{b}^{-1}$ for Pb–Pb at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ ($\sim 10 \text{ } \mu\text{b}^{-1}$ in ALICE). In 2011 the beam energy was the same as in 2010 both for pp and Pb–Pb. The performance of the LHC improved in terms of luminosity with $\sim 5.4 \text{ fb}^{-1}$ for pp ($\sim 2 \text{ pb}^{-1}$ in ALICE) and $\sim 150 \text{ } \mu\text{b}^{-1}$ for Pb–Pb collisions ($143.62 \text{ } \mu\text{b}^{-1}$ in ALICE). The 2012 run was even better: the center of mass energy for pp collisions was brought to 8 TeV and the integrated luminosity (up to December 2012) was $\sim 23.3 \text{ fb}^{-1}$ ($\sim 10 \text{ pb}^{-1}$ in ALICE). The delivered luminosity versus time for 2010, 2011, 2012 (including both p-p and Pb-Pb data) is shown in Fig. 2.2 [77]. A pilot p-Pb run operated at $\sqrt{s_{pA}} = 5.02 \text{ TeV}$

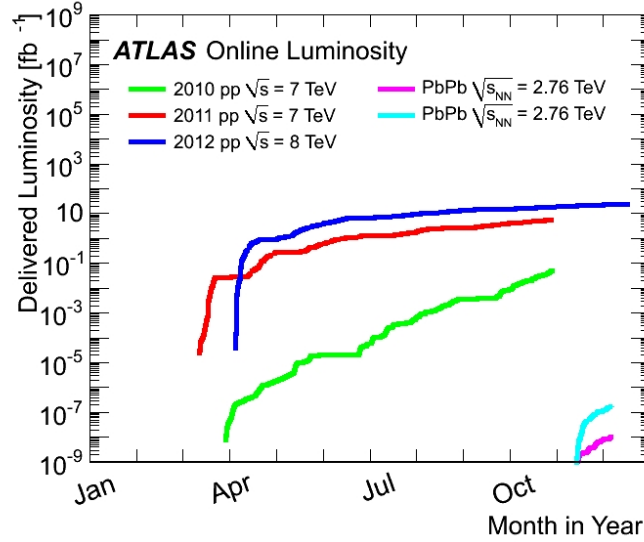


FIGURE 2.2: Cumulative luminosity versus day delivered to ATLAS during stable beams and for p-p and Pb-Pb collisions. This is shown for 2010 (green for p-p, magenta for Pb-Pb), 2011 (red for p-p, turquoise for Pb-Pb) and 2012 (blue) running. The online luminosity is shown. [77]

on September 2012. The p-Pb run is expected before the first long shutdown (LS1) on February 2013. The pp program at the LHC is expected to cast new light upon some of the fundamental open questions in physics, in particular regarding the electroweak symmetry breaking, supersymmetry and CP violation. LHC experiments were able to cope with the increasing luminosity delivered by the LHC. One example of the remarkable performance of the LHC is the Higgs search. The observation of a resonance with a mass near 125 GeV was presented for the first time at CERN on July 2012. Only the high luminosity and good quality of the pp collisions provided by the accelerators have made possible this important achievement [78]. The status of the Higgs search at the time of the summer 2012 (July 2012) is reported in Figure 2.3.

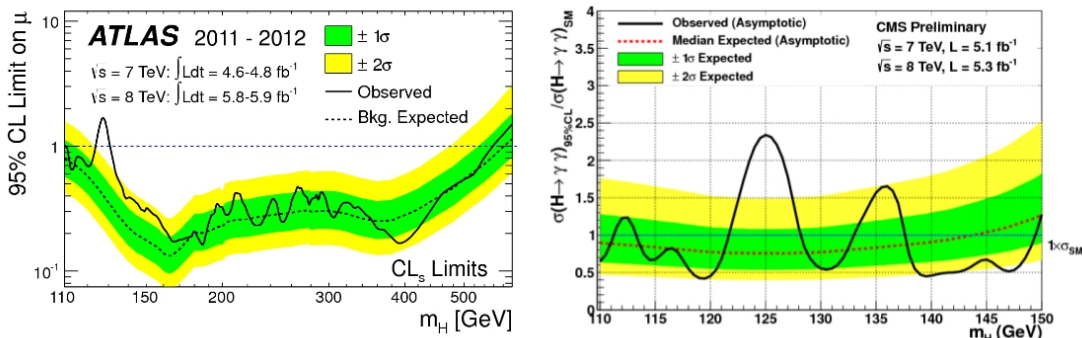


FIGURE 2.3: Higgs search by ATLAS (combined search) and CMS experiments ($H \rightarrow \gamma\gamma$) [78].

2.2 A Large Ion Collider Experiment

ALICE (A Large Ion Collider Experiment) [79] is a general-purpose, heavy-ion detector at the CERN LHC which focuses on QCD, the strong interaction sector of the Standard Model. It is designed to address the physics of strongly interacting matter and the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collisions. It allows a comprehensive study of hadrons, electrons, muons, and photons produced in the collision of heavy nuclei (Pb–Pb), up to the highest multiplicities anticipated at the LHC. The physics programme also includes collisions with lighter ions and at lower energy, in order to vary energy density and interaction volume, as well as dedicated proton-nucleus runs. Data taking during proton-proton runs at the top LHC energy provides reference data for the heavy-ion programme and address a number of specific strong-interaction topics for which ALICE is complementary to the other LHC detectors.

The first conceptual ideas for a general-purpose, heavy-ion detector at the LHC were formulated in a workshop; the ALICE experiment was approved in 1997 and the designs of the different detector systems are described in detail in a number of Technical Design Reports [82, 93]. The expected detector performance and the physics reach, based on detailed simulations, are summarized in the Physics Performance Report [80, 81].

The ALICE detector (Fig. 2.4) was built by a collaboration including currently over 1000 physicists and engineers from 105 Institutes in 30 countries. Its overall dimensions are $16 \times 16 \times 26 \text{ m}^3$ with a total weight of approximately 10,000 t. It is located in an underground cavern with its central axis (beam line) at 44 m below ground level. It consists of a central barrel part, which measures hadrons, electrons, and photons, and a forward muon spectrometer. The central part covers polar angles from 45° to 135° and is embedded in a large solenoid magnet reused from the L3 experiment at LEP.

From the inside out, the barrel contains an Inner Tracking System (ITS) of six planes of high-resolution silicon pixel (SPD), drift (SDD), and strip (SSD) detectors, a cylindrical Time-Projection Chamber (TPC), three particle identification arrays of Time-of-Flight (TOF), Ring Imaging Cherenkov (HMPID) and Transition Radiation (TRD) detectors, and two electromagnetic calorimeters (PHOS and EMCal). All detectors except HMPID, PHOS, and EMCal cover the full azimuth.

The forward muon arm ($2^\circ - 9^\circ$) consists of a complex arrangement of absorbers, a large dipole magnet, and fourteen planes of tracking and triggering chambers. Several smaller detectors (ZDC, PMD, FMD, T0, V0) for global event characterization and triggering are located at small angles.

An array of scintillators (ACORDE) on top of the L3 magnet is used to trigger on cosmic rays.

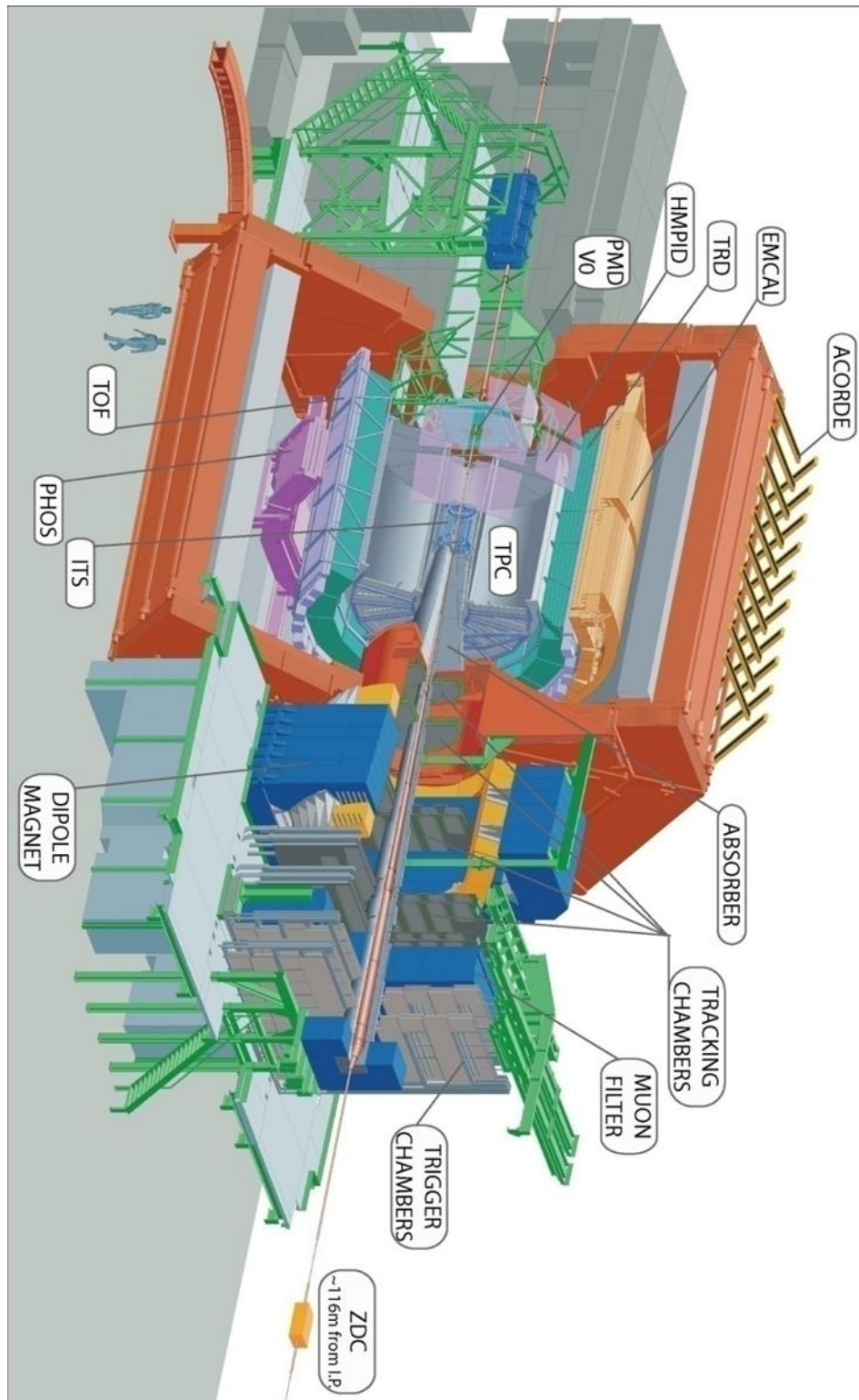


FIGURE 2.4: ALICE detector.

Table 2.1 summarize the acceptance and location of the various detector systems.

Detector	Acceptance (η, ϕ)	Position (m)	Dimension (m ²)	Channels
ITS layer 1,2 (SPD)	$\pm 2, \pm 1.4$	0.039, 0.076	0.21	9.8 M
ITS layer 3,4 (SDD)	$\pm 0.9, \pm 0.9$	0.150, 0.239	1.31	133 000
ITS layer 5,6 (SSD)	$\pm 0.97 \pm 0.97$	0.380, 0.430	5.00	2.6 M
TPC	± 0.9 at $r=2.8$ m ± 1.5 at $r=1.4$ m	0.848, 2.466	readout 32.5 Vol. 90 m ³	557 568
TRD	± 0.84	2.90, 3.68	716	1.2 M
TOF	± 0.9	3.78	141	157 248
HMPID	$\pm 0.6, 1.2^\circ < \phi < 58.8^\circ$	5.0	11	161 280
PHOS	$\pm 0.12, 220^\circ < \phi < 320^\circ$	4.6	8.3	17 920
EMCal	$\pm 0.7, 80^\circ < \phi < 187^\circ$	4.36	44	12 672
ACORDE	$\pm 1.3, -60^\circ < \phi < 60^\circ$	8.5	43	120
Muon Spectrometer				
Tracking Station 1	$-2.5 < \eta < -4.0$	-5.36	4.7	1.08 M
Tracking Station 2		-6.86	7.9	
Tracking Station 3		-9.83	14.4	
Tracking Station 4		-12.92	26.5	
Tracking Station 5		-14.22	41.8	
Trigger Station 1	$-2.5 < \eta < -4.0$	-16.12	64.6	21 000
Trigger Station 2		-17.12	73.1	
ZDC:ZN	$ \eta < 8.8$	± 116	2×0.0049	10
ZDC:ZP	$6.5 < \eta < 7.5$	± 116	2×0.027	10
ZDC:ZEM	$-9.7^\circ < \phi < 7.5^\circ$	7.25	2×0.0049	2
	$4.8 < \eta < 5.7$			
	$-16^\circ < \phi < 16^\circ$			
	$164^\circ < \phi < 196^\circ$			
PMD	$2.3 < \eta < 3.7$	3.64	2.59	2 221 184
FMD disc 1	$3.62 < \eta < 5.03$	inner: 3.2	0.266	51 200
FMD disc 2	$1.7 < \eta < 3.68$	inner: 0.834 outer: 0.752		
FMD disc 3	$-3.4 < \eta < -1.7$	inner: -0.628 outer: -0.752		
V0A	$2.8 < \eta < 5.1$	3.4	0.548	32
V0C	$-1.7 < \eta < -3.7$	-0.897	0.548	32
T0A	$4.61 < \eta < 4.92$	3.75	0.0038	12
T0C	$-3.28 < \eta < -2.97$	-0.727	0.0038	12

TABLE 2.1: Summary of the ALICE detector subsystems. The acceptance in η is calculated from the nominal interaction point and is 360° in azimuth, unless noted otherwise. The position is the approximate distance from the interaction point to the face of the detector and corresponds to the radius for barrel detectors (inner and outer radius for the TPC and TRD) or the position along the beam (z coordinate) for the others. The dimension corresponds to the total area covered by active detector elements. “Channels” is the total number of independent electronic readout channels [79].

2.3 Detector Layout

2.3.1 The magnets

The ALICE experiment includes a solenoid magnet previously used in L3 experiment of LEP, and a dipole magnet situated next to the solenoid one, as a part of the forward muon spectrometer. The value of the uniform field provided by the solenoid magnet is variable up to 0.5 T which is a compromise among the momentum resolution, the acceptance at low p_T , and the efficiency in the track reconstruction. The dipole magnet is placed 7 m from the interaction vertex at 10 cm distance from the solenoid. The field produced by the dipole magnet is perpendicular to the beam direction with a nominal value of $B \sim 0.2$ T.

2.3.2 Inner Tracking System (ITS)

The ALICE Inner Tracking System [82] (Fig. 2.5) consists of 6 silicon layers, grouped in three distinct groups of two layers forming three distinct detectors. The innermost two silicon layers are composed of Silicon Pixel Detector (SPD), the third and fourth layer consist of Silicon Drift Detector (SDD), and the outermost two layers are based on Silicon Strip Detector (SSD). The diameter of beam pipe is 6 cm, providing the lower physical boundary for the innermost radius of ITS. On the other hand, the outermost radius of ITS is bounded by the radius of innermost TPC volume (see Table 2.2 for the summary of the most important sizes of three ITS' detectors).

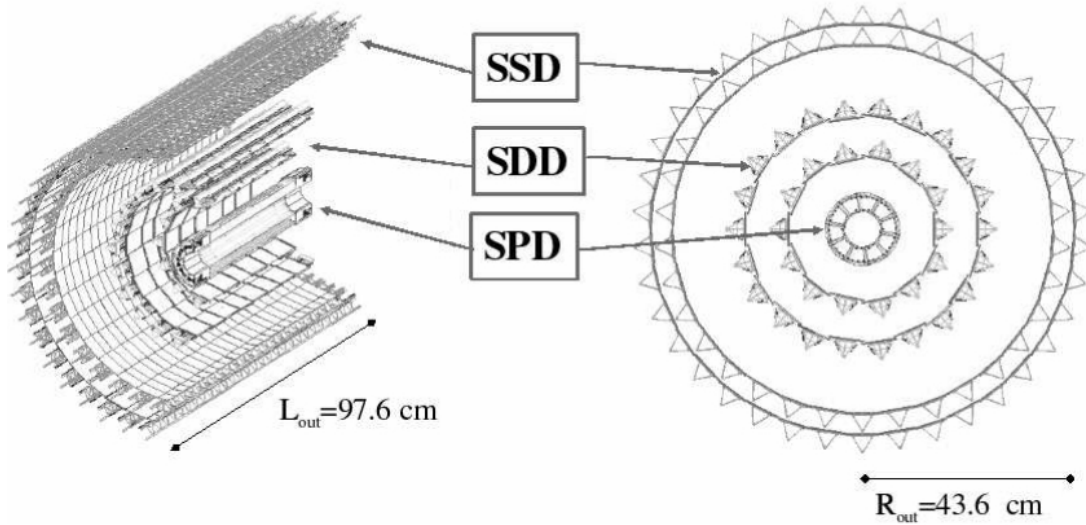


FIGURE 2.5: ALICE Inner Tracking System (ITS). The detector is formed by 6 silicon layers. The two inner most layers are composed of Silicon Pixel Detectors (SPD), in the middle are present two layers of Silicon Drift Detector (SDD), while the two outermost layers are Silicon Strip Detector (SSD).

Layer	Type	r (cm)	$\pm z$ (cm)
1	pixel	3.9	14.1
2	pixel	7.6	14.1
3	drift	15.0	22.2
4	drift	23.9	29.7
5	strip	38.0	43.1
6	strip	43.0	48.9

TABLE 2.2: ITS characteristics: type of detector, radius and length are expressed in cm.

The ITS is being used both for primary vertex reconstruction, with a resolution better than $100 \mu\text{m}$, and for the reconstruction of secondary vertices. Phase space coverage of ITS has the following characteristics:

- Transverse momentum is covered within the range $0.08 < p_T < 3 \text{ GeV}/c$ with a relative momentum resolution better than 2% for pions in this transverse momentum range, while for $p_T > 3 \text{ GeV}/c$ ITS still can be used to improve the transverse momentum resolution for the tracks which also traverse the TPC.
- Coverage in pseudo-rapidity is $|\eta| < 0.9$, while the coverage in azimuth by design is uniform in 360 but in reality due to cooling problems in two innermost layers the resulting azimuthal acceptance is non-uniform. Although ITS has standalone tracking capabilities, which makes it also possible to reconstruct in ALICE the charge particles traversing the dead zones of TPC and to reconstruct the low p_T particles which do not reach the TPC, its main role is the improvement of transverse momentum and the angle resolution of particles reconstructed by TPC.
- The PID capabilities of the ITS rely on standard dE/dx techniques applied in the 4 outer most layers (SDD and SSD). The SPD detector is being used as a centrality estimator, with a resolution of about 0.5% centrality bin width in the most central collisions. Finally, the SPD detector is also used as an online trigger, but more trigger details will be discussed in the 2.3.15.1 section.

2.3.3 Time Projection Chamber (TPC)

The TPC detector [83, 94] is one of the biggest and one of the most important ALICE subsystems. It has a cylindrical shape separated in two volumes with a cathode in the middle (see Fig. 2.25), with a longitudinal length (the length alongside beam direction) of 5 m, the innermost radius of 85 cm and outer radius of 250 cm. It is a gaseous detector filled with a 90 m^3 gas mixture of $\text{Ne}/\text{CO}_2/\text{N}_2$ and it is the main tracking device in

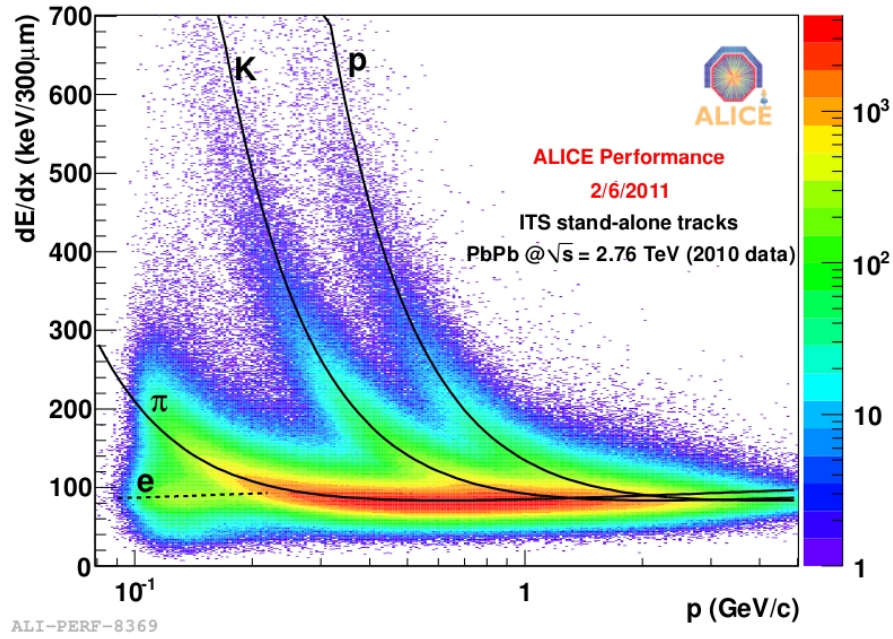


FIGURE 2.6: ALICE ITS performance: The plot shows the dE/dx of charged particles as a function of their momentum, both measured by the ITS alone, in Pb-Pb collisions at 2.76 TeV. The curves are a parametrization of the detector response based on the Bethe-Bloch formula.

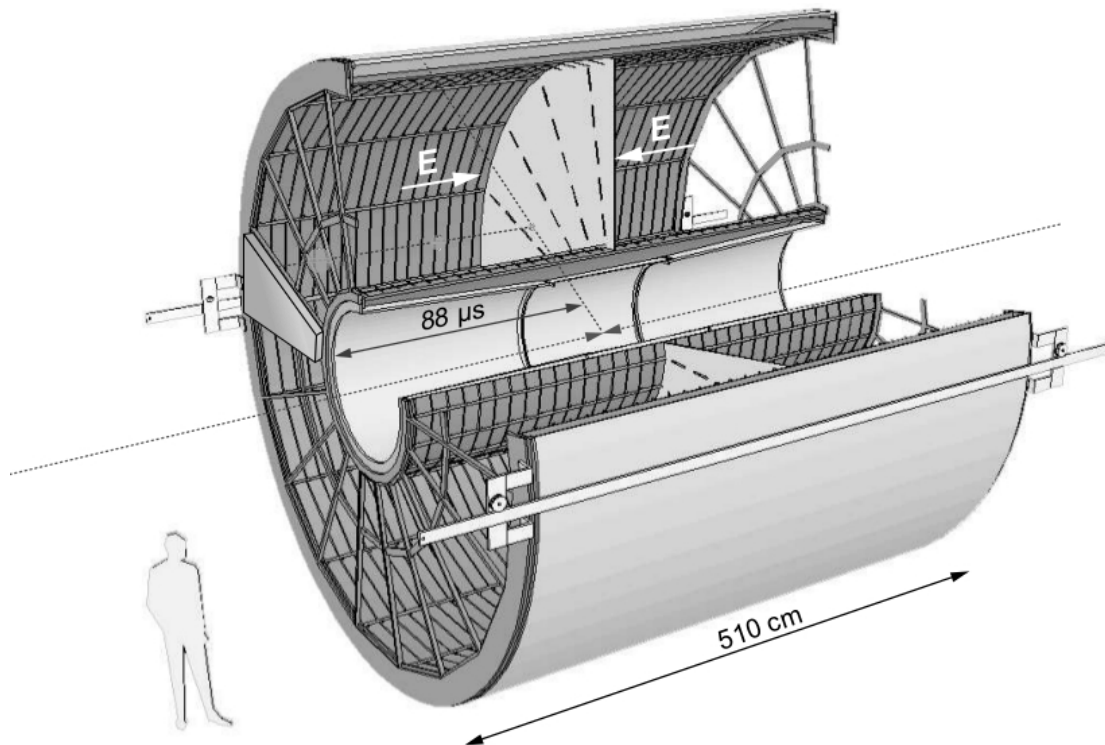


FIGURE 2.7: ALICE TPC.

ALICE. The TPC gas is being ionized by the traversing charged particles, and the liberated electrons drift towards the end plates. The drift time information can be used to determine the z coordinate, while the r and ϕ coordinates are obtained directly from the position of the end plates. It is the TPC's drift time of about $\sim 90 \mu\text{s}$ which is the limiting factor for the maximum luminosity ALICE can handle. The TPC was designed to cope with a large number of particles per event in Pb–Pb collisions, which in the most central collisions was expected to reach about 20,000 primary and secondary particles. When it comes to the phase space coverage, the TPC is capable of detecting the particles in the transverse momentum range $0.1 < p_T < 100 \text{ GeV}/c$, with a transverse momentum resolution in central Pb–Pb collisions, of about 1% for $p_T < 5 \text{ GeV}/c$, 3% for $p_T < 10 \text{ GeV}/c$, 6% for particles $p_T < 20 \text{ GeV}/c$. For higher transverse momenta the resolution worsens, and for instance in interval $60 < p_T < 80 \text{ GeV}/c$ it is about 25% in central Pb–Pb collisions (see Fig. 2.8). On the other hand, the track finding efficiency of TPC saturates at about 90% for particle with $p_T > 1 \text{ GeV}/c$, both in central Pb–Pb collisions and pp collisions, which is essentially determined by the size of the TPC dead zones. The TPC covers full azimuth, with the exception of dead zones between the neighboring sectors (there are 16 sectors altogether), which in total adds up to about 10% of the azimuthal angle. The TPC's azimuthal resolution is about $\Delta\phi = 0.7 \text{ mrad}$ irrespectively of the transverse momentum. Finally, the TPC has a pseudorapidity coverage of $|\eta| < 0.9$ if only the tracks with maximum radial track length are being considered. Besides the primary usage for tracking, the TPC also provides valuable information particle identification (PID) via standard dE/dx technique (2.9).

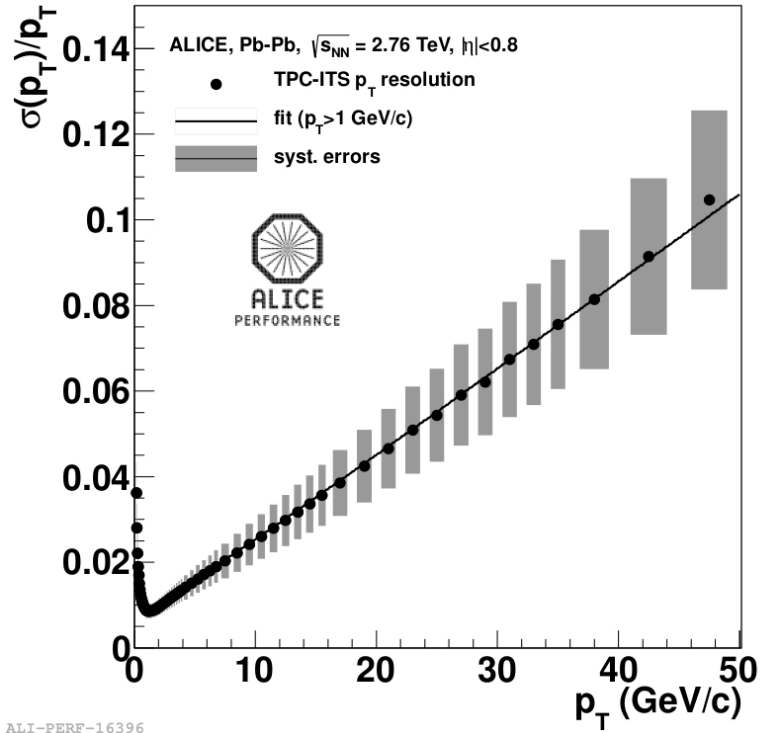


FIGURE 2.8: Relative p_T resolution for TPC+ITS combined tracking ($p_T < 50 \text{ GeV}/c$).

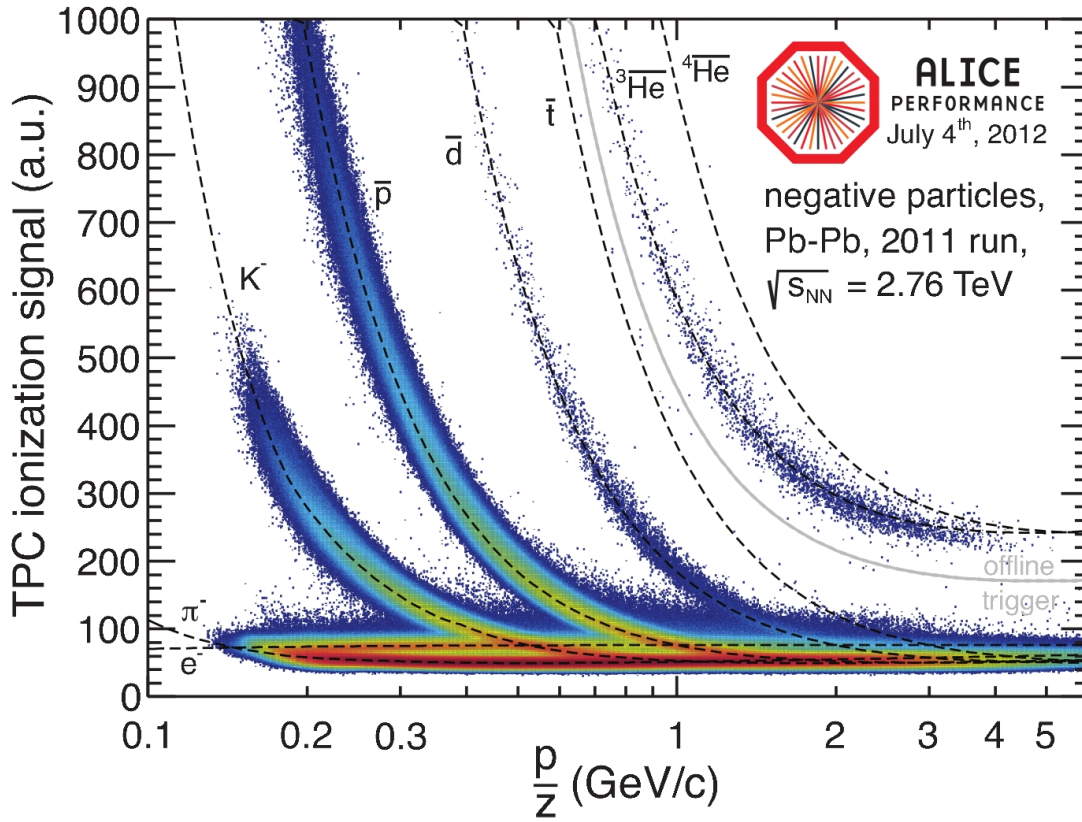


FIGURE 2.9: TPC dE/dx as a function of Rigidity (p/Z) distribution for all events passing the offline trigger selection of events with at least one $Z > 1$ track candidate; only negative charged particles are shown.

2.3.4 Transition-Radiation Detector (TRD)

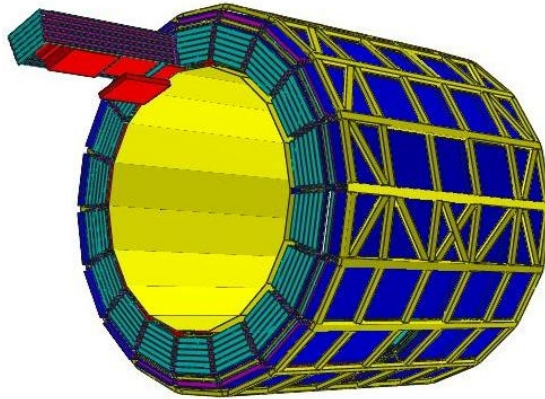


FIGURE 2.10: ALICE TRD: it is composed by 18 supermodules, each containing 30 modules arranged in 5 stacks along z and 6 layers in radius.

The TRD [85] is segmented in 18 super modules in ϕ , each containing 30 modules arranged in 5 stacks along z and 6 layers in radius.

Each detector element consists of a radiator, a drift section and a multi-wire proportional chamber section with pad readout. The layers are placed at a distance of $2.90 \text{ m} < r < 3.68 \text{ m}$ from the beam line, covering the full azimuth and a pseudo-rapidity range

$|\eta| < 0.84$. It identifies electrons with momentum above $1 \text{ GeV}/c$ in the central barrel, where the pion rejection capability of the TPC is no longer sufficient. The working principle of the TRD is shown in Fig. 2.11. The transition radiation is produced only by fast ($\gamma > 1000$) particles at the crossing materials with different dielectric constants. In the momentum range analysed with the TRD ($1 < p < 10 \text{ GeV}/c$) only electrons produce transition radiation, allowing to discriminate between pion and electrons. The PID information provided by the TRD, in addition to that provided by ITS and TPC, allows to the production rates of quarkonia near mid-rapidity (see i.e.2.12), as well as the dilepton continuum in Pb–Pb and in pp data, to be measured. With the impact parameter determination provided by the ITS, it will also be possible to measure open charm and beauty in semi-leptonic decays. With its six layers, the TRD contribute to the global tracking through the central barrel improving the p_T resolution at high momentum.

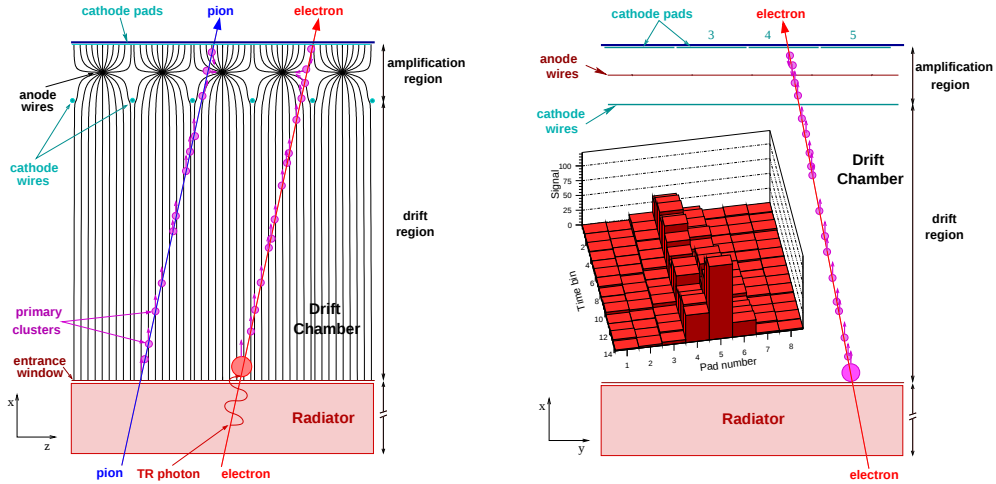


FIGURE 2.11: ALICE TRD working principle.

2.3.5 Time-Of-Flight Detector (TOF)

The TOF [84] is a large area array of Multi-gap Resistive-Plate Chambers (MRPC), a type of gas detector developed to fulfil the requirements of having a large number of channels to keep the occupancy low, an affordable system and a time resolution better than 100 ps. It is positioned on a cylindrical surface that covers the central barrel ($|\eta| < 0.9$) over an area of 140 m^2 with 160.000 individual cells at a radius of about 4 m.

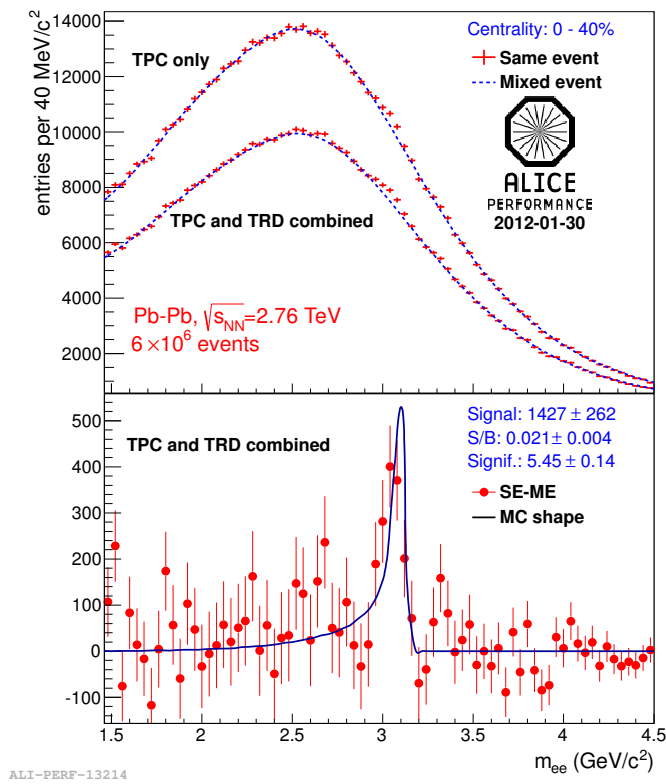


FIGURE 2.12: e^+e^- invariant mass spectrum in central Pb-Pb collisions at 2.76 TeV per nucleon. The case when only TPC-PID is applied is compared to the one where also TRD is used. An improvement on the significance of the reconstructed signal is clearly visible.

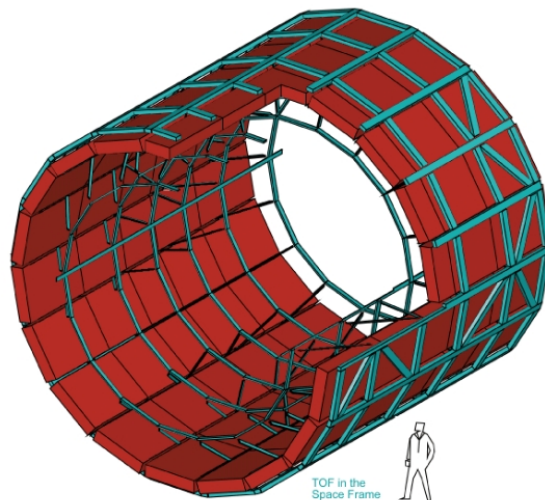


FIGURE 2.13: ALICE TOF: it is a large area array of Multi-gap Resistive-Plate Chambers (MRPC). It is positioned on a cylindrical surface that covers the central barrel ($|\eta| < 0.9$) over an area of 140 m^2 with 160.000 individual cells at a radius of about 4 m.

It identifies hadrons in the momentum range between 2.5 GeV/c (for pions and kaons) to 4 GeV/c (for protons), with a π/K and K/p separation better than 3σ . It provides, together with the tracking system, event-by-event identification of large samples of pions, kaons and protons. Fig. 2.9 shows the PID capabilities of the TOF detector.

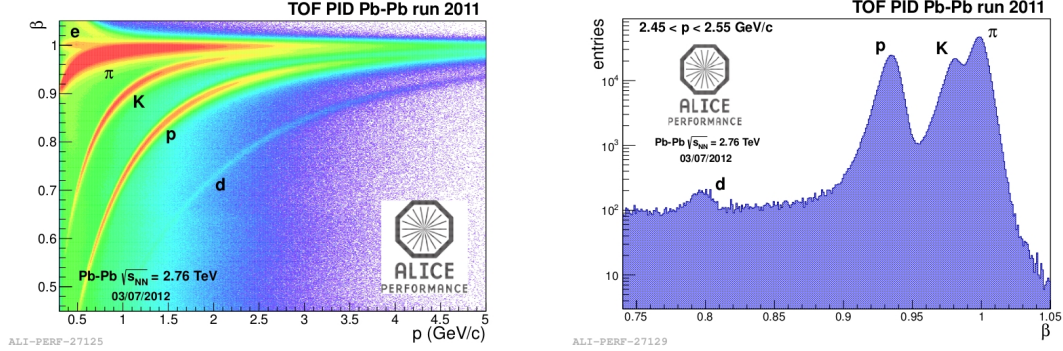


FIGURE 2.14: a) TOF β as a function of the momentum (p) performance in Pb-Pb run 2011. The bands for e , π , K , p and d are clearly visible. Particles outside those bands are tracks wrongly associated with a TOF signal. b) TOF measured particle velocity (β) in Pb-Pb run 2011 for particles in a momentum slice (2.45-2.55 GeV/c).

2.3.6 High-Momentum Particle Identification (HMPID)

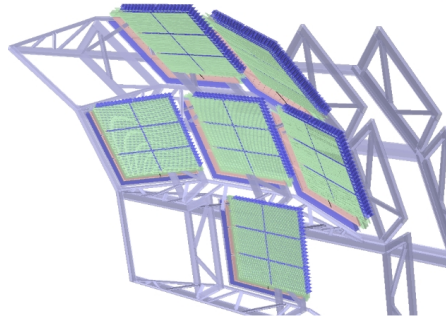


FIGURE 2.15: ALICE HMPID is composed by 7 modules of proximity-focusing ring imaging Cherenkov counters.

HMPID [86] is a 10 m² array of proximity-focusing ring imaging Cherenkov counters with a liquid radiator and a solid CsI photo-cathode, evaporated on the segmented cathode of multi-wire proportional chambers. It consists of 7 modules of 1.5×1.5 m². It is placed at 5 m from the beam line at the 2 o'clock position and has a coverage in pseudo-rapidity of $|\eta| < 0.6$ while the azimuthal coverage is $1.2 < \phi < 8.8$ that results in an acceptance 5% of the central barrel phase space. It extends the inclusive measurement of identified hadrons of the ALICE detector towards momenta $p_T > 1$ GeV/c and the PID capability to particles with high momenta for which the particle identification cannot be performed through energy loss (in TPC and ITS) and time-of-flight measurements (TOF). The detector was optimised to extend the useful momentum range for

π/K and K/p discrimination, on track-by-track basis, up to 3 GeV/c and 5 GeV/c respectively. In Fig. 2.16 the separation (n-sigma) for π/K and K/p as a function of transverse momentum in HMPID is shown. The geometry of the detector has been optimised with respect to particle yields at high p_T in pp and heavy-ion collisions at the LHC energies and with respect to the large opening angle required for two-particle correlation measurements.

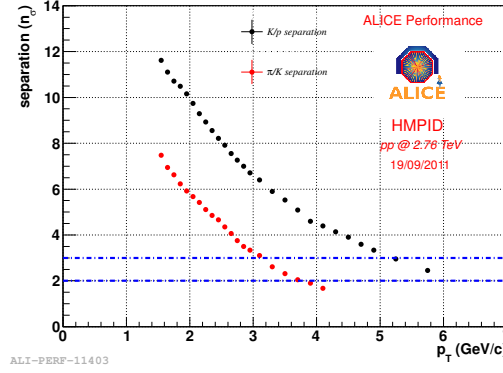


FIGURE 2.16: The separation (n-sigma) for π/K and K/p as a function of transverse momentum in HMPID.

Combining the informations of ITS, TPC, TOF and HMPID it is possible to have a separation for π/K and K/p discrimination from 0.1 up to 7 GeV/c. The result is shown in Fig. 2.17.

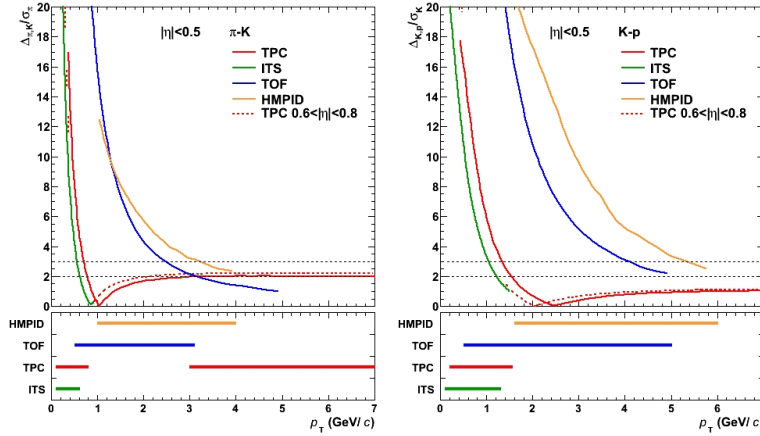


FIGURE 2.17: The separation (n-sigma) for π/K (left) and K/p (right) as a function of transverse momentum in ITS, TPC, TOF and HMPID.

2.3.7 Photon Spectrometer (PHOS)

The PHOS [87] is a high resolution electromagnetic calorimeter dedicated to the detection of photons coming from the interaction point and neutral mesons like π^0 and η through their decay in two photons. Since the main task of the detector is to distinguish

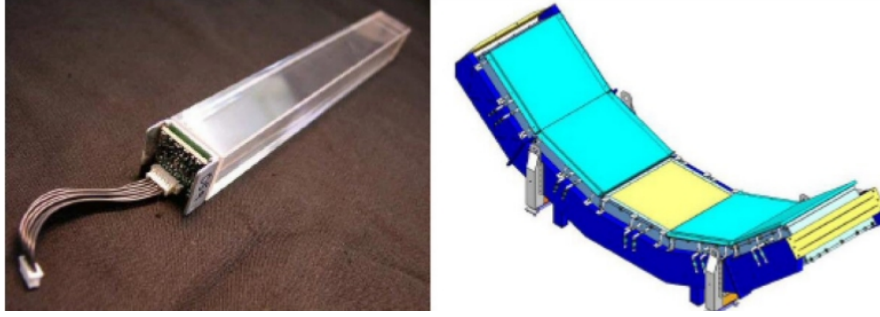


FIGURE 2.18: ALICE PHOS.

between direct photons and photons coming from particle decays, it is characterised by a high granularity and good spatial and energetic resolution. The calorimeter is made of lead crystals, PWO, grouped in five modules; this material has been chosen because of its very small Molière radius of 2 cm. The PHOS is located at 460 cm from the interaction point and covers approximately $|\eta| \leq 0.12$ and $\phi < 100^\circ$ with a total area of about 8 m^2 . The PHOS allows to identify photons with a momentum of $0.5\text{-}10 \text{ GeV}/c$, π^0 of $1\text{-}10 \text{ GeV}/c$ and η mesons of $2\text{-}10 \text{ GeV}/c$ momentum.

2.3.8 Electromagnetic Calorimeters (EmCal)

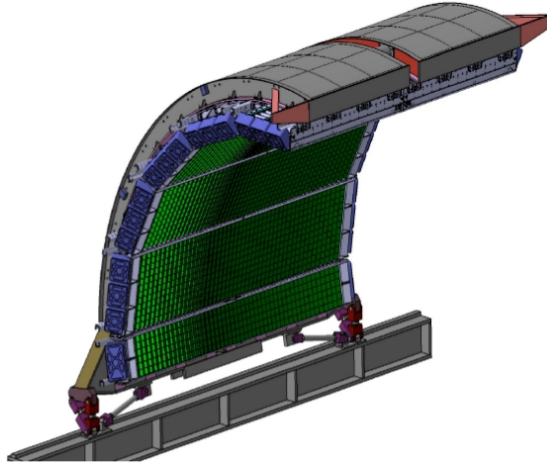


FIGURE 2.19: ALICE EmCal.

The main physics motivations for the EmCal [88] are to improve the ALICE performances for an extensive study of jet quenching, to discriminate between π^0 and γ up to $p_T \sim 30 \text{ GeV}/c$ and to help in the studies of heavy flavour, via detection of electrons. The detector contains 12 modules each consisting of sampling calorimeters made of alternating layers of 1.44 mm Pb and 1.76 mm polystyrene, as scintillating material. The EMCal covers the range $|\eta| \leq 0.7$. Due to the installation of the PHOS and the HMPID respectively below and above the TOF, the EMCal is limited to a region of about 110° in

azimuth adjacent to the HMPID. It is positioned to provide partial back-to-back coverage with the PHOS. Its nominal acceptance is about 25% of the TPC one. The EMCal, coupled with ALICE tracking detectors, enables ALICE to reconstruct large transverse momentum jets. Most quantitative studies of jet quenching to date have relied on observables of high p_T hadrons and their correlations, i.e. leading fragments of jets, in order to suppress the large underlying event backgrounds in heavy ion collisions.

2.3.9 Forward Muon Spectrometer

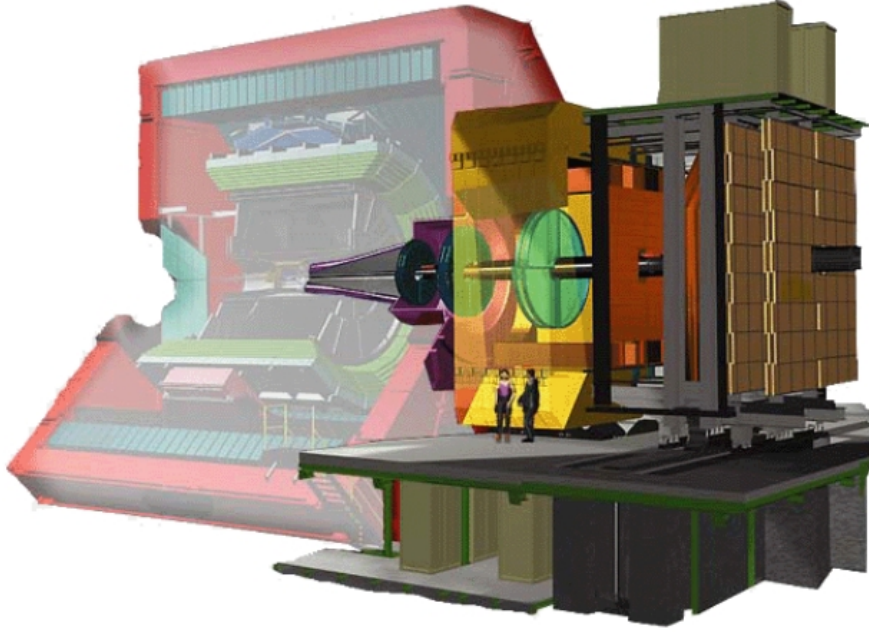


FIGURE 2.20: ALICE Muon Arm.

With the forward muon spectrometer [89], it is possible to study resonances like J/ψ , ψ' , Υ , Υ' , Υ'' through their decay into $\mu^+ + \mu^-$ pairs, and to disentangle them from the continuum given by Drell-Yan processes and semi-leptonic decays of D and B mesons. The study of open heavy flavour production is interesting too and is also accessible through measurements of $e - \mu$ coincidences or single μ approaches. The muon is detected by the muon spectrometer and the electron by the TRD. A resolution of $70 \text{ MeV}/c^2$ in the $3 \text{ GeV}/c^2$ region is needed to resolve J/ψ , ψ' peaks and of $100 \text{ MeV}/c^2$ in the $10 \text{ GeV}/c^2$ region to separate Υ , Υ' , Υ'' .

This detector is located around the beam pipe and covers the pseudo-rapidity range $-0.4 \leq \eta \leq 2.5$. It consists of a passive front absorber to absorb hadrons and photons from the interaction vertex and a muon tracking detector. The material must have a small interaction length in order to absorb hadrons and a large radiation length to absorb γ , and thus small Z , in order to reduce multiple scattering of muons. Muon tracks are reconstructed by tracking chambers consisting of multi-wire proportional chambers with cathode pad readout. They are embedded in a magnetic field generated by a dipole magnet located outside the L3 magnet. The dimuon trigger is provided by four

layers of Resistive Plate Chambers (RPC) operating in streamer mode located behind the muon filter.

In Fig. 2.21 is shown the invariant mass spectrum of $\mu^+\mu^-$ reconstructed with the muon arm. The resolution of reconstructed the J/ψ is $75 \text{ MeV}/c^2$.

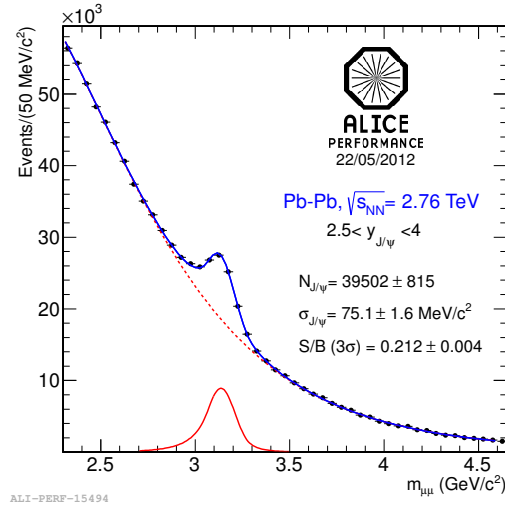


FIGURE 2.21: $\mu^+\mu^-$ invariant mass spectrum (0-90% in centrality). The μ have been reconstructed using the ALICE muon arm.

2.3.10 Zero-Degree Calorimeter (ZDC)

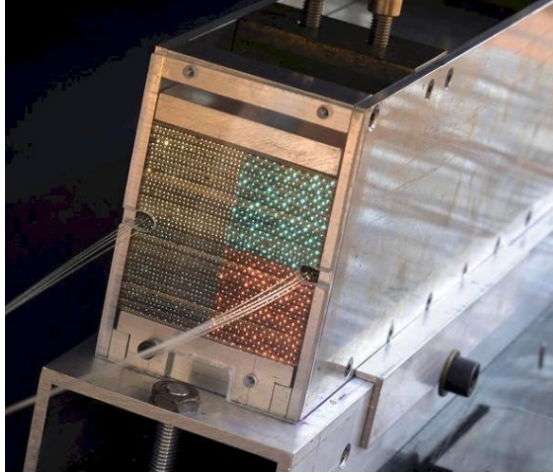


FIGURE 2.22: ALICE ZDC: The ZDC consists of two calorimeters, one for neutrons and one for protons. In the figure is shown the neutron calorimeter.

The experimental apparatus is completed by detectors placed at 0 with respect to the beam axis: the ZDC [90]. It measures the energy of the spectator nucleons and thus provides information on the centrality of the collision, because the zero degree energy decreases with increasing centrality. The ZDC is also used also for flow analysis, because it can estimate the reaction plane through the directed anisotropy of spectator

neutrons. The ZDC consists of two calorimeters, one for neutrons and one for protons. Two ZDCs are symmetrically installed at 116 m from the interaction point. In this detector quartz fibres (active material) are embedded in a dense absorber of Tungsten (passive material). When a particle crosses the passive material creates a shower which produces Cerenkov radiation in the active material. Because of the presence of fragments of the colliding nuclei, the measurement of the zero-degree energy is not enough to determine the centrality of collision. For this reason, the ZDC project includes also an electromagnetic calorimeter (ZEM) to solve the ambiguity due to fragment production. It is a scintillator based detector designed to measure with poor resolution, event by event, the energy of photons emitted at forward rapidity coming from π^0 decays.

2.3.11 Photon Multiplicity Detector (PMD)

The PMD [91] measures the multiplicity and the spatial distribution of photons on an event-by-event basis in the forward region of ALICE. It consists of two planes of multi-wire proportional counters with a honey-comb structure with a thick lead converter in between them. The PMD is placed at 360 cm from the interaction point, on the opposite side of the forward muon spectrometer, covering the region $2.3 \leq \eta \leq 3.5$. The PMD can measure the multiplicity and the spatial (η, η) distribution of photons on an event-by-event basis in the forward pseudo-rapidity region. Providing these pieces of information, the PMD are employed for event-by-event studies as, for example, fluctuations and flow, the estimate of the reaction plane and of transverse electromagnetic energy.

2.3.12 Forward Multiplicity Detector (FMD)

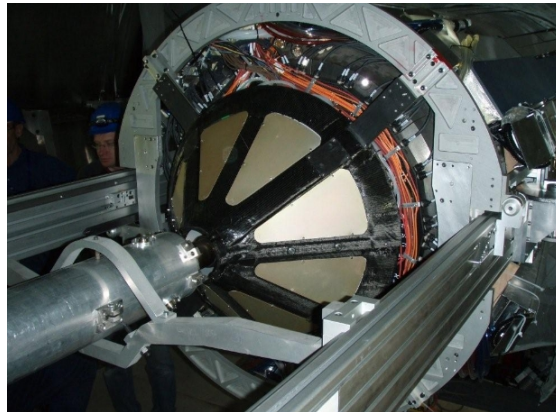


FIGURE 2.23: ALICE FMD.

FMD [92] provides information on the charged particle multiplicity in the pseudo-rapidity ranges $-3.4 \leq \eta \leq -1.7$ and $1.7 \leq \eta \leq 5.1$. With this detector it is possible to extend the η coverage of multiplicity measurements, to study multiplicity fluctuation

on an event-by-event basis and to perform flow analysis. The FMD consists of five rings of Silicon strip detectors, two of which are installed on the muon absorber side where the available space is most restricted; the remaining three are located on the opposite side of the interaction point.

2.3.13 V0

The V0 [92] detector consists of two segmented arrays of plastic scintillator counters, placed around the beam-pipe on either side of the interaction point: one at $z = 90$ cm (in front of the absorber), covering $-3.7 \leq \eta \leq -1.7$, and the other at $z = -340$ cm, covering $2.8 \leq \eta \leq 5.1$. Each array consists of 32 counters distributed in four rings, each divided in eight sectors. The counters are made of scintillator material embedded in Wave Length Shifting fibres. Clear fibres collect and transport the signal to photo-multipliers 3÷5 m far from the detector, inside the L3 magnet. The counters have a time resolution better than 1 ns. Its response is recorded in a time window of 25 ns around the nominal beam crossing time. The V0 is a trigger detector that can provide minimum-bias trigger for all colliding systems to the central barrel detectors and three triggers specifically designed for Pb–Pb collisions. It has an important role in rejecting background from beam-gas collisions exploiting the relative time-of-flight measurement between the two arrays. It can also participate in the measurement of luminosity in pp collisions with a fairly good precision (about 10%). V0 can also be used to measure the particle multiplicity. In Fig. 2.24 is shown the comparison between SPD tracklets, FMD and VZERO $dN/d\eta$ measurement in Pb-Pb at 2.76 TeV

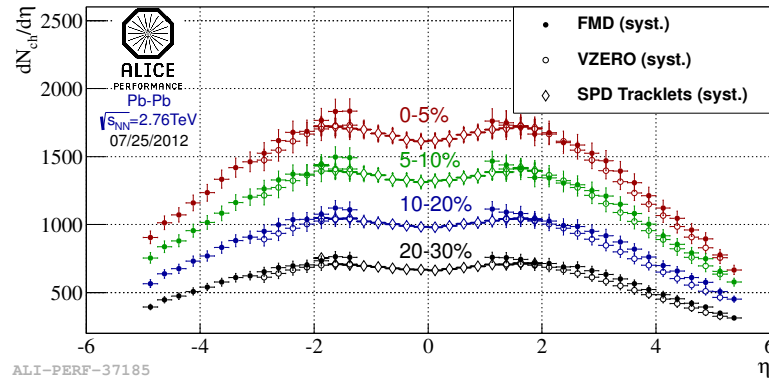


FIGURE 2.24: Comparison between SPD tracklets, FMD and VZERO $dN/d\eta$ measurement in Pb-Pb at 2.76 TeV. FMD and VZERO measurement are performed with the displaced vertex technique

2.3.14 T0

The T0 [92] detector consists of two arrays of 12 Cherekov counters each, mounted around the beam-pipe. One array is placed at $z = -72.7$ cm from the interaction point, the

distance imposed by the layout and position of the muon spectrometer and of the other forward detectors. It covers $-3.28 \leq \eta \leq -2.97$. The other array is placed at $z = 375$ cm on the opposite side of the interaction point, grouped together with other forward detectors. It has a pseudo-rapidity coverage of $4.61 \leq \eta \leq 4.92$. In the radial direction they are placed as close as possible to the beam pipe to maximize the trigger efficiency. The T0 detector, together with the V0, provides fast trigger signals. The main goals of the T0 are:

- measure the event time with a precision better than 25 ps;
- provide the TOF with a start time signal, that is the real time of the collision plus a fixed delay and is independent of the position of the primary vertex;
- measure the interaction vertex position with a precision of ± 1.5 cm and provide a L0 (level zero) trigger when the position is within a predefined window to detect beam-gas interactions;
- provide a wake-up signal to the TRD readout electronics, prior the L0 trigger;
- generate minimum-bias and other trigger signals (based on threshold on multiplicity in heavy-ion collisions).

The T0 contribute to the L0 trigger of the experiment since its dead time is less than the bunch-crossing period in pp collisions (25 ns).

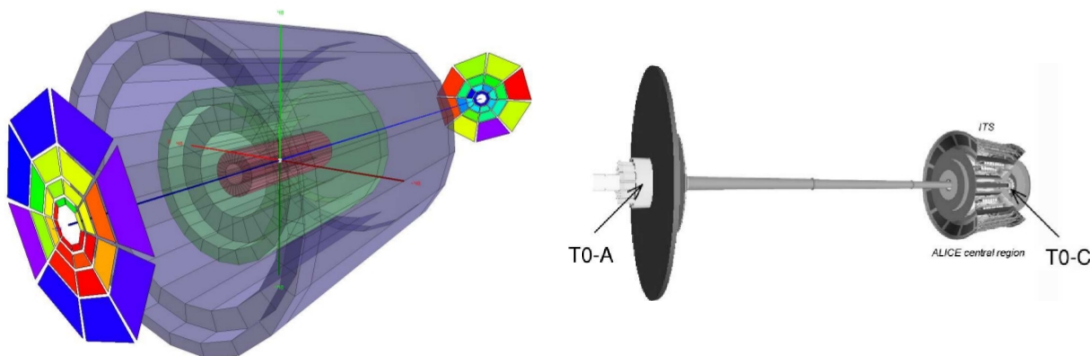


FIGURE 2.25: a): ALICE V0: representation of the V0 detector detector b): ALICE T0: position of the T0 detector inside ALICE

2.3.15 Data Acquisition System (DAQ)

The tasks of the ALICE DAQ [93] system are the assembly of event fragments from individual sub-detectors into complete events (event building) as well as buffering and export of assembled events to permanent storage. The DAQ is designed to process a data rate of up to 1.25 GB/s in heavy-ion runs. Event building is done in two steps. Data

working in the realm of DAQ, DCS (Detector Control System) and High Level Trigger (HLT) and storing their output on so-called File eXchange Servers (FXS) (6-8) in Fig. 2.26. A dedicated programme called SHUTTLE collects these outputs and makes them available for the reconstruction. Furthermore, it retrieves information about the run from the electronic logbook and collects continuously monitored values that are written into the DCS archive. After processing the data, the Shuttle registers the produced condition files in AliEn and stores the data in CASTOR. With the registration of the raw and conditions data the transition from the online to the offline part has taken place. Largely, online denotes all actions and programs that have to run in real time, offline is the subsequent step, like for example event reconstruction, which is executed on worker nodes (WN) of Grid sites located around the world. In fact, this separation between online and offline is not so strict, because during the data taking a first online reconstruction is performed in real time and some calibration information (as the values used for the alignment) are offline extracted and stored in the database in a further step.

2.3.15.1 Trigger system

The trigger system used by ALICE has been studied to select events with different features depending on the physical interests and is optimised to work both in nucleus-nucleus and pp collisions. A dedicated processor combines the signals coming from detectors with fast trigger capability (T0, V0, ZDC, SPD, TOF, TRD, PHOS, EMCal, Muons, ACORDE). It operates at several levels to satisfy the individual timing requirements of the different detectors. A pre-trigger activates the TRD electronics shortly after each interaction (< 900 ns) while two further levels (L0 at $1.2 \mu\text{s}$ and L1 at $6.5 \mu\text{s}$) reduce the event rate depending on the trigger inputs. A final trigger signal called L2 at about $100 \mu\text{s}$ is then issued after the end of the drift time in the SDD, the slowest detector in ALICE (drift time $\sim 6 \mu\text{s}$, but electronic delay of ~ 1 ms). The sub-detectors of ALICE can be grouped in several partitions for the simultaneous data acquisition. For each partition, the active sub-detectors can be grouped in turn into different clusters for which proper trigger classes are defined. The collected data are then merged in a single file. A triggering detector does not have to be necessarily part of the partition. A configuration frequently used during the 2010 data taking consisted of two main clusters, with different trigger classes, in order to have: i) a partition including all the active detectors; ii) a partition (called fast) without the sub-systems with high dead time (namely TPC and SDD) optimised to collected events at forward rapidity (i.e. detected by the muon arm). The trigger includes a protection against pile-up and an event priority scheme which optimizes both the acceptance of rare triggers and the overall throughput of accepted events. In addition to the hardware trigger system, ALICE can select or reject events by means of the so called High-Level Trigger (HLT). It consists of up to 1000 multiprocessor computers which perform a detailed on-line analysis on complete events. The HLT

is also used to reduce the event size by selecting only a fraction of the data for readout (region of interest) or by compressing the complete event information.

2.4 ALICE software

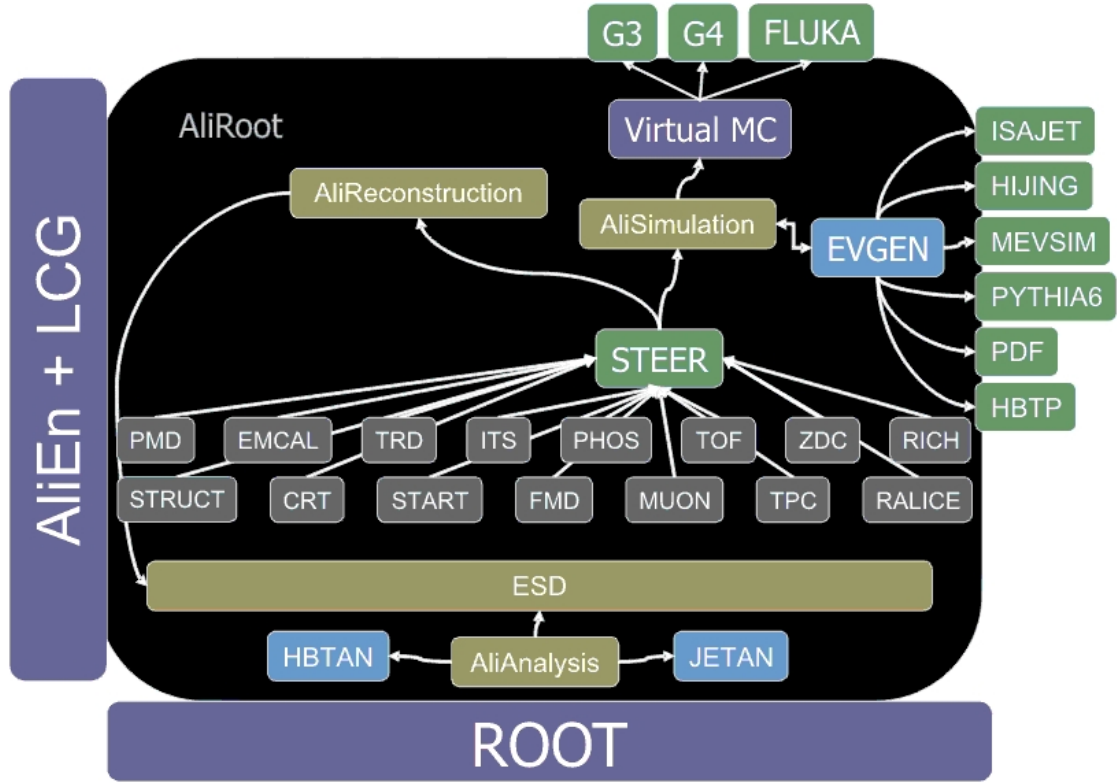


FIGURE 2.27: ALICE software. Scheme of the official framework: AliRoot.

In Fig. 2.27 the ALICE offline framework, AliRoot [95], is schematically shown. Its implementation is based on Object Oriented design and C++ programming by multiple authors, with some external programs (hidden to the user) still in FORTRAN. The ROOT framework, upon which AliRoot is developed, provides an environment for the development of software packages for event generation, detector simulation, event reconstruction, and data analysis. It offers, among other features, integrated I/O with class schema evolution, an efficient hierarchical object store with a complete set of object containers, C++ as a scripting language and a C++ interpreter, advanced statistical analysis tools (multidimensional histograms, several commonly used mathematical functions, random number generators, multiparametric fit, minimisation procedures, cluster finding algorithms etc.), HTML documentation tools and advanced visualisation tools. The ROOT system is interfaced with the Grid Middleware in general and, in particular, with the ALICE-developed AliEn system [96]. AliEn (ALICE Environment) is a lightweight Open Source Grid Framework built around other Open Source components using the combination of a Web Service and Distributed Agent Model. [97]. In

conjunction with the PROOF system, which extends ROOT capabilities on parallel computing systems and clusters, this provides a distributed parallel computing platform for large-scale production and analysis. Since the framework is continuously evolving, a specific release policy has been adopted. The ROOT system was extended with ALICE specific classes and libraries grouped in modules. These libraries are loaded dynamically and the contained classes share the same services with the native ROOT classes, including object browsing, I/O, dictionary and so on. AliRoot has been developed since 1998. This framework is used for simulation, alignment, calibration, reconstruction, visualization and analysis of the experimental data. Initially it was used to carry out simulation studies in order to optimize the design of the ALICE subsystems, then it has been used to study the physics performance of the full ALICE detector and to assess the functionality of the framework towards the final goal of extracting physics results from the data. The processing steps performed with the AliRoot framework starting from Monte Carlo data or from real raw data are shown in Fig. 2.28. Simulated data

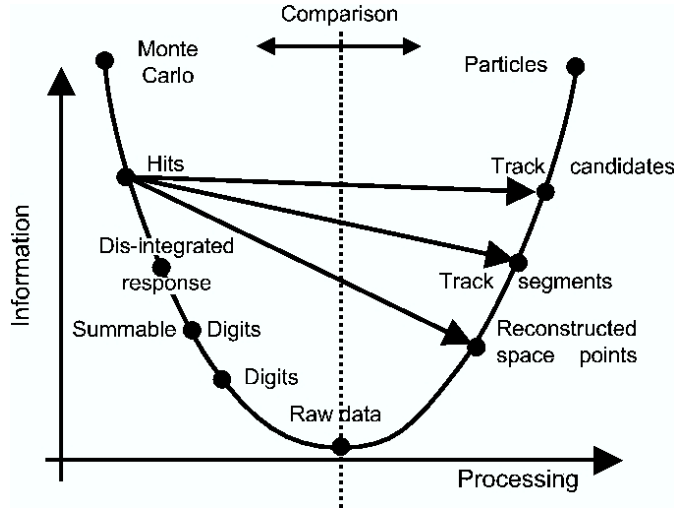


FIGURE 2.28: Scheme of the data processing framework.

are produced using Monte Carlo generators and contain the full information about the generated particles (particle identification and momentum); then the generated tracks are transported through the detector and support geometry using simulation packages such as GEANT3, FLUKA and GEANT4. In order to run simulations with different transport codes, without changing the user code and therefore the input and output format as well as the geometry and detector response definition, the ALICE Software Project developed an interface called Virtual Monte Carlo (VMC) [99, 100]. Nowadays the VMC is the most used interface in particle physics. The energy deposition at a given point and time is stored in the so called hits for each ALICE sub-system. This information is complemented by the so-called track references, corresponding to the location where the particles are crossing user-defined reference planes. Hits are then transformed into an ideal detector response and into the real detector response: digits are produced taking into account the electronic manipulation of the signal performed

by detectors and their electronics, including digitisation. Finally the digits are stored in the specific hardware format of each detector as raw data. From this point on, simulated and real raw data undergo the same processing steps: local reconstruction and tracking. To evaluate the detector and software performance, simulated data are processed throughout the full chain and the final reconstructed particles are compared to the Monte Carlo ones. Shortcuts are possible in the interest of saving computing time, for instance using hits directly for physics studies, instead of producing digitised data and then reconstructing them. The users can intervene in this cycle provided by the framework to implement their own analysis of the data or to replace any part of it with their own code.

Generators: The offline framework was developed for efficient simulation of different colliding systems, that is pp, A-A and p-A collisions. External generators (for example HIJING [98] for nucleus-nucleus interactions, PYTHIA [101] and PhoJet [102] for pp interactions) can be employed. However, since existing generators give different predictions at the same $\sqrt{s}$ or do not correctly simulate some detector features, the ALICE offline framework provides several solutions to reach an efficient simulation: i) simple generators based on parametrised η and p_T distributions that can provide a signal-free event; ii) a tool to merge events from different signal generators; iii) tools for merging underlying events and signal events on the primary particle level (called cocktail); iv) afterburners to introduce ad-hoc particle correlations. In addition, since simulation of small cross-section observables require long campaigns to generate enough events to be compared to the statistics collected in the experiment, rare signals can be generated using the interface to external generators or simple parameterisations of transverse momentum and rapidity spectra, defined in independent libraries.

Detector response: Particles produced by a Monte Carlo generator are transported in the materials of the ALICE sub-system, simulating their interaction and the energy deposition that generates the detector response. Three transport Monte Carlo packages are used to simulate the detector response: GEANT3 [103], GEANT4 [104] and FLUKA [105]. Virtual interfaces have been developed to use them for the simulation of the ALICE geometry within the AliRoot framework. Besides, their native geometry modellers have been replaced by a geometry one provided by ROOT. In this way a unique description of the geometry is used even if the transport code is different. The ALICE experiment is described in the simulation in great detail, including services and support structures, absorbers, beam pipe, flanges and pumps.

Reconstruction: The reconstruction code has a modular design that allows it to be compiled into separate libraries and to be executed independently of the other parts of AliRoot. The input consists of the digits together with some additional information (e.g. module number, readout channel number). The reconstruction can use both digits in special ROOT format (for development and debugging purposes) and digits in the form of raw data, as they are produced by the real detectors. The output of the reconstruction is stored in the Event Summary Data (ESD). It contains the reconstructed tracks together with the particle identification information, the reconstructed primary

vertex, decays and V0, kink and cascade topologies and particles reconstructed in the calorimeters. A main class provides the user with a simple interface to configure the reconstruction procedure, include or exclude a detector from the run and ensure the correct sequence of the reconstruction steps (local reconstruction for each detector, primary vertex reconstruction with SPD, track reconstruction and particle identification, primary and secondary vertex reconstruction from tracks). The space points are reconstructed by a detector-specific cluster-finding procedure. For each point, ALICE also calculate the uncertainty of the position estimation. All of the central tracker detectors (ITS, TPC, TRD) have their own detailed parametrisation of the space-point position uncertainties. The extracted coordinates together with the position uncertainties are then used by the track reconstruction algorithm. This is based on the Kalman filter approach. The detector specific implementations of such algorithm use a set of common base classes, which makes it easy to pass tracks from one detector to another and test various parts of the reconstruction chain. For example in Fig. 2.29 is shown the transverse impact parameter resolution, obtained for the tracks satisfying the standard TPC track quality cuts and having the kITSrefit and 2 points in SPD.

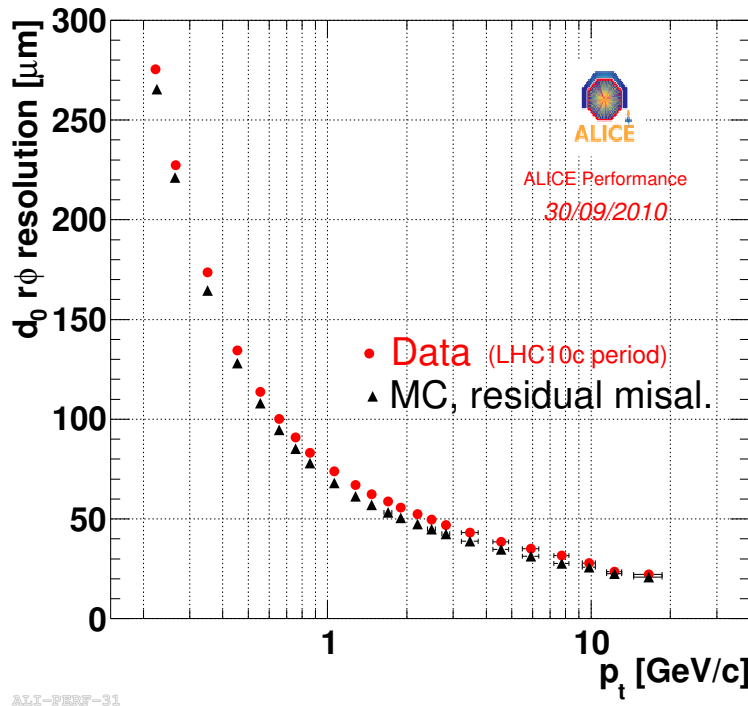


FIGURE 2.29: Transverse impact parameter resolution estimate, obtained for the tracks satisfying the standard TPC track quality cuts and having the kITSrefit and 2 points in SPD. For each track, its impact parameter was estimated with respect to the primary vertex reconstructed without using this track. The primary vertex was reconstructed using the beam constraint. The resulting impact parameter resolution is the convolution of the track-position and the primary-vertex resolutions

Analysis : Analysis is the last step performed on data to extract physics results. It starts from the ESD, whose size is about one order of magnitude lower than the corresponding raw data. Analysis performed on the ESD produces Analysis Object Data

(AOD), that are used by further analysis steps. Analyses can be scheduled (or ordered) or chaotic. Scheduled analysis is performed in a way also indicated as freight train. The ALICE generic analysis framework attaches a number of official algorithms and carries them through data. The advantage is that each event is read only once and the different algorithms are applied to it. Such scheduled analysis has a predictable resource consumption and data access pattern as opposed to chaotic analysis. Chaotic analysis is usually performed during the code developing phase on local systems with a limited amount of data. A general analysis framework has been developed and called *AliAnalysis*. Its scheme has to be employed by users to perform scheduled and chaotic analyses. It has been developed such as the user code is independent of the computing system used (i.e. local computer, local grid of global grid). It also allows Monte Carlo truth to be used for acceptance and efficiency correction studies and calculation.

Offline tools : The computing resources required to store, reconstruct and analyse the present and foreseen amount of data (both real and simulated). It can not be concentrated in a single computing centre. Therefore data processing and storage is distributed onto several centres worldwide located. The Grid Middleware allows a heterogeneous collection of resources to be treated as an integrated computing centre. This is one of the main areas in which the ALICE Offline Project operates. The ALICE interface to the Grid is AliEn (**A**lice **E**nvironment)[96]. It has been developed to offer the ALICE user community a simplified and transparent access to the computing resources distributed worldwide through a single interface. The AliEn system is built around common open source components and on top of the latest internet standards for information exchange and authentication. It provides a virtual file catalogue with transparent access to distributed data sets. Besides, a number of collaborating web services which implement the authentication, job execution, file transport, performance monitor and event logging have been implemented. A detailed description of the architecture and the components of the AliEn system can be found in [106]. Presently the ALICE grid is composed of 60 sites scattered all over the world (Fig. 2.30). The total amount of memory available to store data is ~ 15 PB [107].

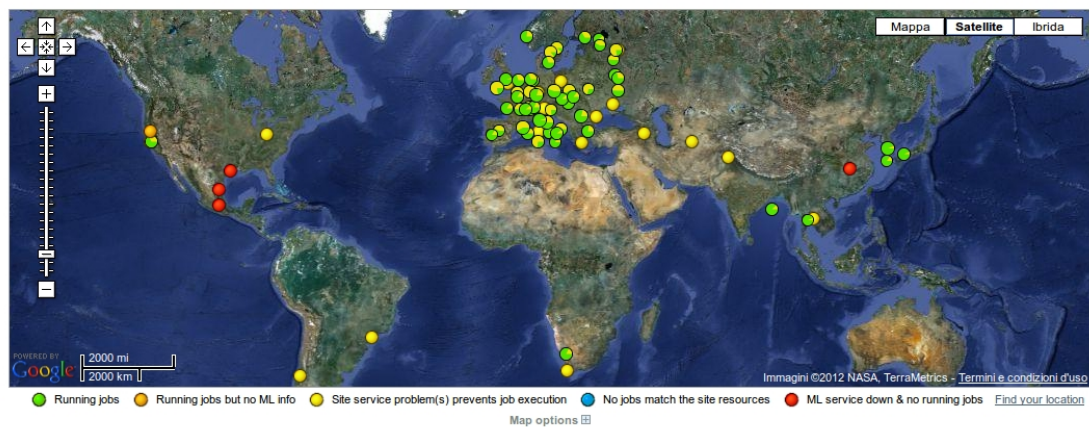


FIGURE 2.30: ALICE Grid sites spotted over a world [107].

The **Parallel Facility (PROOF)** allows the user to run interactive parallel analyses on a local cluster to process large amounts of data minimizing the response time. Parallel means that several nodes process subsets of data at the same time. PROOF itself is not related to Grid but can be used in the Grid. The **CERN Analysis Facility (CAF)** is a cluster at CERN running PROOF for ALICE. Simulated data and measured data are available on the CAF. The aim is conceptually different from analysis on the Grid: due to the limited disk space, only a sub-sample of data taken by ALICE are accessible on the CAF, however it gives much faster feedback than the Grid. The design goal for the CAF is a system with 500 CPUs. At least 50 TB of selected data are available.

(Anti)(Hyper)Nuclei in Heavy Ion Collisions

High-energy heavy-ion collisions offer a unique way to study the behaviour of nuclear matter under conditions of extreme energy and density. One of the remarkable features of the particle production at high energies is the nearly equal abundance of matter and antimatter in the central rapidity region [108, 109]. It is believed that a similar symmetry existed in the initial stage of the universe and it remains to be understood how this symmetry got lost in the evolution of the universe reaching a stage with no visible amounts of antimatter being present.

In relativistic heavy-ion collisions a huge number of particles carrying strangeness is produced. Strangeness can be found not only in elementary particles (i.e. K , Λ , Ξ , Ω), but also in compound particles, such as hypernuclei. A hypernucleus is a nucleus which contains at least one hyperon, namely a baryon containing one or more strange quarks, in addition to nucleons.

Hypernuclear physics was born in 1952 when two Polish scientists, Danysz and Pniewsky observed the first hypernuclear decay in a photographic emulsion exposed to cosmic ray at about 26 km above the ground level [110].

Since the first observation, there has been a constant interest in searching for new hypernuclei and exploring the hyperon-baryon (YN) interaction: the nucleus serves as a laboratory offering the opportunity to study the properties of hyperon interactions. While several Λ -hypernuclei have been found since the first observation, no anti-hypernucleus has ever been observed until the recent discovery of the anti-hypertriton in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at RHIC [111].

The lifetime of hypernuclei depends on the strength of the hyperon-nucleon interaction [112, 113]: the study of this interaction is relevant for nuclear physics and nuclear astrophysics. For example, the YN interaction plays a key role to understand the structure of neutron stars. Depending on the strength of the YN interaction, the collapsed stellar core could consist of hyperons, strange quark matter, or a kaonic condensate [114].

Hypernuclei can be produced and studied in various experimental set-ups. Since 1972 the two-body reactions producing Λ on a nuclear target have been studied. The two-body reactions that led to practically all the present bulk of experimental information on hypernuclei are the following [115]:

1. The “Strangeness Exchange” reaction [116]

$$K^- + \mathcal{N} \rightarrow \Lambda + \pi \quad (3.1)$$

exploited mainly in the $K^- + n \rightarrow \Lambda + \pi^-$ charge state, for evident reasons of easiness of spectroscopy of the π final state. The reaction can be seen as a transfer of the s -quark from the incident meson to the struck baryon.

2. The “Associated Production” reaction [117, 118]:

$$\pi^+ + n \rightarrow \Lambda + K^+. \quad (3.2)$$

This reaction proceeds by the creation of a $(s\bar{s})$ pair by the incident meson.

3. The electroproduction of strangeness on protons in the very forward direction:

$$e + p \rightarrow e' + \Lambda + K^+ \quad (3.3)$$

exploited quite recently [119]. The virtual photons associated to the reaction (3.3) can be regarded as quasi-real and reaction (3.3) is often rewritten as a two-body photoproduction reaction:

$$\gamma + p \rightarrow \Lambda + K^+ \quad (3.4)$$

The production of hypernuclei in heavy-ion collisions has been proposed and studied since a long time [120, 121] and recently studied in Au–Au [111] and Pb–Pb [122]. It is possible to discriminate two distinct mechanisms for hypernuclei formation:

1. the absorption of hyperons on the spectator fragments of non-central heavy-ion collisions [123];
2. emergence of hypernuclei (as well as ordinary nuclei) from the fireball region of the reaction; in this scenario the (hyper)nucleus is formed at, or shortly after, the (chemical)-freeze out of the system.

To estimate the production yield it is possible to employ two distinct approaches. The first one is based on a coalescence model, while the second one is based on the assumption that all the particle species abundance can be described using a thermal model.

In the empirical coalescence model the production of a (hyper)nucleus with mass number A is related to the probability that A nucleons are emitted within a small sphere of

radius p_0 .

On the other hand, the analysis of particle production assessing the degree of thermalization of the particle source has been undertaken since many decades. The first to propose a statistical approach was E. Fermi in 1950 [125], who assumed that particles originated from an excited region occupy all available phase space. This was further developed by Hagedorn [126], who noted that the hadronic mass spectrum has the asymptotic ($m \rightarrow \infty$) form:

$$\rho_H \sim \exp[m/T_H]$$

where m is the mass of the hadron and T_H is the parameter controlling the exponential rise of the mass spectrum. It has been found that the thermalization assumption can be applied successfully to hadrons produced with a large number of particles and nuclear reactions at different energies [127]. With this assumption, it was possible to estimate thermal parameters characterizing the particle source for each colliding system, such parameters are relevant for the understanding of the thermal properties of dense and hot matter and for studies of QCD phase transitions.

Within a thermal model, particle production no longer depends on specific (and in general unknown) cross sections but it is rather governed by the conservation laws and the baryon chemical potential and the temperature of the system at freeze-out, as well as by the mass and quantum numbers of the particles to be produced [120].

Both models predict the possibility to create (anti)(hyper)nuclei in heavy-ion collision experiments. The production of (anti)(hyper)nuclei with atomic mass $A=3$ is favoured with respect to nuclei with $A=4$ according to both the coalescence model and the thermal one, so studies on systems with $A=3$ are experimentally achievable with the statistics collected by the ALICE experiment.

The (anti)hypertriton (${}^3_{\Lambda}\bar{H}$) ${}^3_{\Lambda}H$ is the lightest known hypernucleus and is formed by a (anti)proton, a (anti)neutron and a (anti) Λ . ${}^3_{\Lambda}H$ decays mesonically into the following channels [178]:

$${}^3_{\Lambda}H \rightarrow \pi^-(\pi^0) + {}^3\text{He}({}^3H) \quad (3.5)$$

$${}^3_{\Lambda}H \rightarrow \pi^-(\pi^0) + d + p(n) \quad (3.6)$$

$${}^3_{\Lambda}H \rightarrow \pi^-(\pi^0) + p + n + p(n) \quad (3.7)$$

The study of the production of (hyper)nuclei in heavy-ion collisions is important not only to understand the particles production mechanism, but also to correlate quark and anti-quark production. It has been proposed [129, 130, 131] that the correlation between the strangeness S and the baryon number B provides a useful diagnostic tool for the presence of strong correlations between quarks anti anti-quarks. In lattice QCD calculations [132] the ratio:

$$\chi_{11}^{BS}/\chi_2^B \quad (3.8)$$

where χ_{11}^{BS} is the baryon-strangeness correlation and χ_2^B is the baryon-baryon correlation, is close to unity at high temperature in a deconfined phase, and reaches 0.4 at low temperature in a hadronic phase.

The baryon-strangeness coefficient c_{BS} is defined as:

$$c_{BS} = -3 \frac{\langle BS \rangle}{\langle S^2 \rangle} \quad (3.9)$$

where B and S are the the total baryon number and strangeness; it is supposed to be one of the most robust observables to characterize the nature of the system created in heavy-ion collisions: ideal QGP, strongly coupled QGP or hadronic matter. The proposed observable c_{BS} requires a measurement of the global baryon number and strangeness in each event, so an experimental analysis based on c_{BS} is rather difficult. Hypernuclei, on the contrary, are bound clusters of nucleons and Λ hyperons: if they are produced through a coalescence mechanism by the overlapping of the wave functions of protons, neutrons and hyperons in the final stage of the collision [133], they will provide a measurement of the local correlation between baryons and hyperons (strangeness) on an event-by-event basis [134]. Specifically, the deuteron yield is proportional to the baryon density, while triton and Helium are a measure of baryon correlation [135, 136]. Similarly, the hypertriton is related to the initial $\Lambda - p$ phase space correlation. The ratio $S_3 = {}^3_\Lambda\text{H}/({}^3\text{He} \times \Lambda/p)$, also known as *Strangeness Population Factor*, is sensible to the different model approaches regarding the baryon-strangeness local correlation strength. S_3 is a good representation of χ_{11}^{BS}/χ_2^B [132] since it contains the local baryon-strangeness in the numerator and the baryon-baryon correlation in the denominator. Moreover within the thermal model, S_3 does not depend on the chemical potential of particles, and any correction for strangeness is cancelled out.

3.1 (Anti)(Hyper)Nuclei production in Heavy-ion Collisions

As mentioned in the previous section, the study of the production of (anti)(hyper)nuclei offers a unique opportunity to understand the mechanism of particle production in ultra-relativistic heavy ion collisions. In the following section a description of the two main models which are believed to govern the production of nuclei (e.g. the coalescence and statistical-thermal models) will be given. Predictions for (anti)(hyper)nuclei production will be shown in both models, and a way to discriminate between the two mechanisms will be reported. Finally the prediction of the S_3 ratio in the different models will be shown.

3.1.1 Coalescence Model

In 1961, Butler and Pearson developed a model for deuteron formation in proton-nucleus collisions [137]. According to them, taking into account the p - n strong force and the nuclear optical potential, it is possible to evaluate how protons and neutrons bind together to form a deuteron. Their calculation used second-order perturbation theory to obtain a relation between the density of deuterons in momentum space and the density of protons and neutrons in momentum space. The key result is that, taking into account simple momentum phase space considerations, the deuteron density in momentum space, d^3N_d/dK^3 , is proportional to the proton density in momentum space, d^3N_p/dk^3 , times the neutron density in momentum space, d^3N_n/dk^3 , and can be expressed as:

$$\gamma \frac{d^3N_d}{dK^3} = B_2 \left(\gamma \frac{d^3N_p}{dk_p^3} \right) \left(\gamma \frac{d^3N_n}{dk_n^3} \right) \quad (3.10)$$

where γ is the usual Lorentz factor. Since many experiments measure protons but not neutrons, it is useful to rewrite this equation assuming the neutron and proton densities to be identical:

$$\gamma \frac{d^3N_d}{dK^3} = B_2 \left(\gamma \frac{d^3N_p}{dk^3} \right)^2, \quad (3.11)$$

where

$$B_2 = |V_0|^2 \kappa \left(1 + \frac{m^2}{k^2} \right) J(\kappa R). \quad (3.12)$$

Here m is the nucleon mass, κ^2/m^2 is the binding energy of the final state, $|V_0|$ is the depth of the optical potential and $J(\kappa R)$ is a dimensionless function depending on the optical potential of the target nucleus.

Schwarzschild and Zupancic extended this phase space relation to describe the production of various light nuclei in nucleus-nucleus collisions [138]. However, the constant coefficient B_A was no longer thought to represent an admixture of the binding energy of the deuteron and the nuclear optical potential of the target nucleus. For more violent nucleus-nucleus collisions the optical potential of the colliding nuclei is not a meaningful concept. However, the underlying phase space relationship survives, and is expressed in a form generalized for nuclear species as:

$$\gamma \frac{d^3N_A}{dK^3} = B_A \left(\gamma \frac{d^3N_p}{dk^3} \right)^A, \quad (3.13)$$

where

$$B_A = \left(\frac{2s_A + 1}{2^A} \right) \frac{1}{N!} \frac{1}{Z!} (R_{np})^N \left(\frac{4\pi}{3} p_0^3 \right)^{A-1}. \quad (3.14)$$

Here s_A is the spin of the final bound cluster of mass A , and N and Z are neutron and proton numbers. The factor R_{np} is $R_{np} = (N_p + N_T)/(Z_p + Z_T)$, where N_p, N_T, Z_p and Z_T are the neutron and proton numbers for the projectile and the target nuclei. The formulation assumes that the proton and neutron densities are the same except for a

scale factor R_{np} which accounts for the initial isospin of the colliding system. The proportionality constant B_A is simply reinterpreted as a function of the radius p_0 within which various pairs of nucleons will fuse, and is a phenomenological parameter. However, in this model, it should not change with the beam energy and slightly change with the colliding system.

This rather simple picture was used to describe light nuclei production in A–A collisions at Bevelac energies (from 0.2 up to 1.7 GeV/nucleon) [139], in higher energy p–A data from the CERN SPS ($E_{CM} = 158$ GeV/nucleon)[140], p–A data from Fermilab (p beam energy = 120 GeV)[141], and pp data from the CERN ISR (Maximum energy in the center of mass energy of 62 GeV)[142].

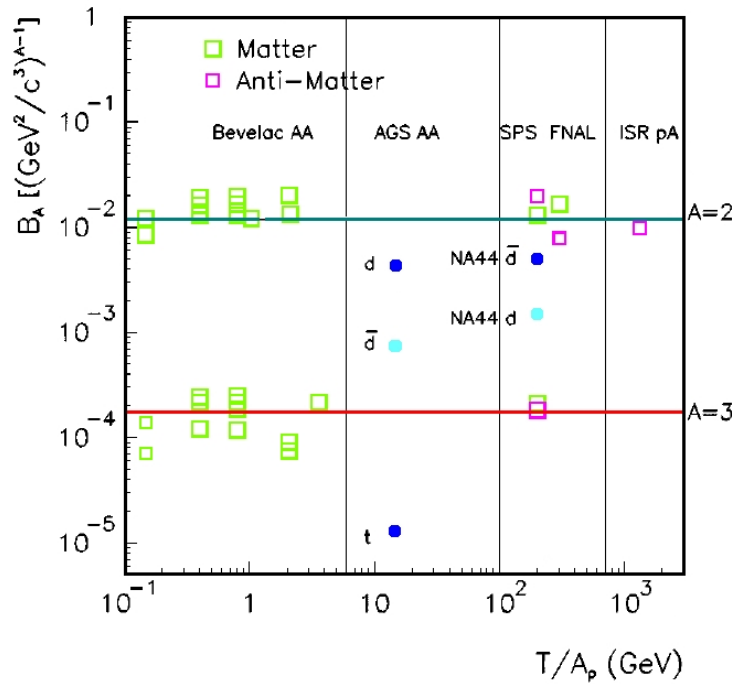


FIGURE 3.1: Coalescence scaling factor B_A for matter and antimatter plotted as a function of the kinetic energy per nucleon T/A (GeV). Data points from [143].

Fig. 3.1 shows the values B_2 and B_3 measured by many experiments for both matter (green squares) and antimatter (magenta squares). The data are consistent with the scale factors being independent of energy. It is important to note that the simple phase space relation described in Eq. 3.13 is applicable to data measured for collisions at a fixed impact parameter, and cannot be applied to impact-parameter-averaged distributions. However, the experimental data looks relatively constant for a wide array of colliding systems: this result is unexpected and probably indicates that the effects of impact parameter averaging are smaller than the precision with which data and calculations have been compared.

Experiment E858 at BNL-AGS [144] measured the scale factor for anti-deuterons and experiment E814 [145] measured B_2 for deuterons and B_3 for tritons in different colliding systems at 14.6A GeV/c (e.g. Si–Pb, Si–Cu and Si–Al); the results are shown as

blue markers in Fig. 3.1. The scale factors are measured at zero degrees as an average over events at different impact parameters (minimum bias), and they reveal significant deviations from the simple coalescence model. Experiment E814 has also measured the scale factor for deuterons as a function of collision centrality and found that B_2 decreases by a factor of 40 and B_3 decreases by a factor two orders of magnitude going from peripheral collisions to the most central. The discrepancy between the AGS data and the simple coalescence model has been attributed to the failure of the model to account for the relative spatial separation of the two nucleons. Preliminary results from the experiment NA44 at CERN-SPS (at Energy 200 A GeV) for B_2 are also shown in Fig. 3.1 (full blue symbols at T/A 200 GeV). Once again significant differences with the simple coalescence model are revealed. It should be noted that the NA44 results are measured over a range of transverse momenta for central collisions. Thus caution is needed when making a comparison between the B_A values obtained at CERN and AGS measurements. Discrepancies with the global scaling can also be found in the Bevalac data for the heavier projectiles [148, 149].

To describe the behaviour of the B_A parameters at different y and centrality, Bond et al. [150] in 1977, and Sato and Yazaki [135] in 1981, introduced a model based on density matrix formulation of many body systems. The model assumes that in the collision a high excited region is formed and decays emitting various particles. The momentum distribution of nucleons within this region, as well as the emitting particles are described by density matrices. The model assumes explicit forms for the wave functions and the spatial distribution of nucleons in the excited region. By choosing a Gaussian spatial distribution for the wave function, the model can be rewritten in the same form as the empirical coalescence model and it is possible to relate the coalescence momentum p_0 to the size parameter of the excited region ν as:

$$\frac{1}{N!Z!} \left(\frac{4}{3} \pi p_0^3 \right)^{A-1} = A^{1/2} \left(4\pi \frac{\nu_A \nu}{\nu_A + \nu} \right)^{3/2(A-1)}, \quad (3.15)$$

where ν_A are parameters of the wave functions and the size parameter ν is related to the root mean square (rms) radius of the excited region as:

$$R_{rms} = \sqrt{\frac{3}{2\nu}} (fm) \quad (3.16)$$

It is then possible to extract the radius parameter from data. The value of the radii calculated by the E814 experiment [145] are shown in Fig. 3.2.

The radius is evaluated as a function of the centrality expressed in terms of C_i , defined as:

$$C_i = \frac{\int_{N_{C_i}}^{\infty} \frac{d\sigma}{dN_c} dN_c}{\int_0^{\infty} \frac{d\sigma}{dN_c} dN_c}, \quad (3.17)$$

where N_{C_i} is the charged particle multiplicity; low C_i corresponds to the most central events.

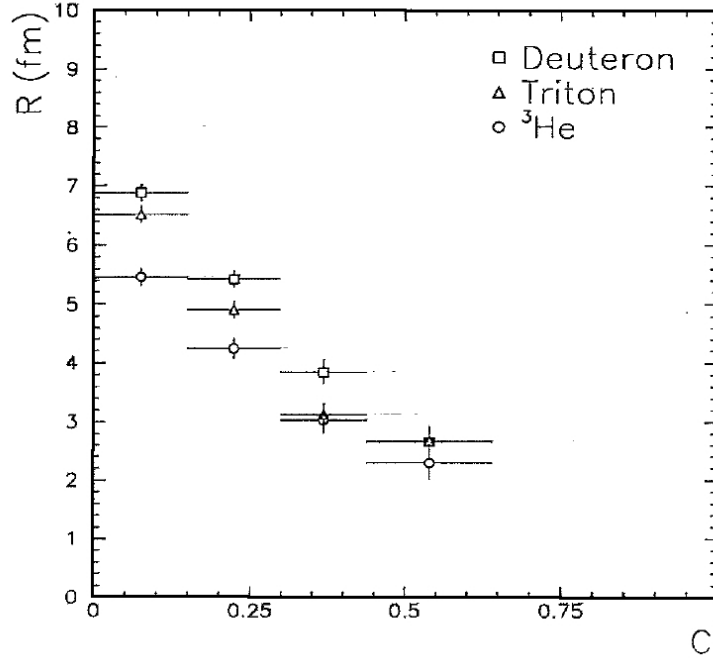


FIGURE 3.2: Rms radius of excited region (E814 data [145]) deduced using the model of Sato and Yazaki [135]. The radius is shown as a function of the centrality for different nuclei: deuterons (squares), tritons (triangles) and ^3He (circle). Low values of C_i correspond to the most central events. The radius values (R) are average values of the rms radius vs centrality represented by the horizontal error bars [145].

Fig. 3.2 shows that the central collisions exhibit much larger radii than the peripheral ones. It also shows some dependence of the radii on the cluster mass, which in this model could be interpreted as different nuclei freezing out at different times. The radius parameters calculated for deuterons (squares) are consistently higher than those calculated for both mass 3 nuclei (triangles and circle). This would imply that the nuclei with mass equal to 3 freeze-out at earlier times. This scenario makes intuitive sense when one considers the fact that the nuclei with $A=3$ have much higher binding energies than deuterons. The binding energy of a deuteron is 2.2 MeV, which makes it barely bound, and it is therefore not likely to survive many collisions before being dissociated.

There are two weak points in the model of Sato and Yazaki. The first is that the model is not relativistic; and the second is that the model makes a Gaussian approximation for the spatial distribution of nucleons inside the source. This might explain why the radius of the source evaluated in this approximation differs from the one evaluated by using other methods, such as two pion HBT (Hanbury-Brown–Twiss) correlation [49]. To take into account the interaction of particles at the initial stage of the collision, a cascade model was then introduced. The advantage of using a cascade calculation is

that many problems related to relativistic considerations, hydrodynamics and different kinematic distributions of protons and neutrons, are taken into account in the dynamics of the cascade, and assumptions about the equilibrium properties and shapes of the system are not necessary. In 1994, Dover and Balz [146], extended the coalescence model by implementing a cascade model into the coalescence one. In their model, for coalesce to occur nucleons must be close to each other in both position and momentum after the interaction is finished. In some sense this is analogous to the basic coalescence model, the main differences being that the cascade based coalescence model considers microscopic levels, where the spatial separations are taken into account. Models which use cascade based coalescence have been successfully used to interpret experimental results [144, 145].

Recently simulations of (anti)(hyper)nuclei production from cascade based coalescence models (i.e. Dubna Cascade Model, DCM [147]) have been performed in a wide range of momenta and energy in the center of mass. These calculations allow to have a prediction of (hyper)nuclei production up to the top-energy of the RHIC collider ($\sqrt{s_{NN}} = 200$ GeV).

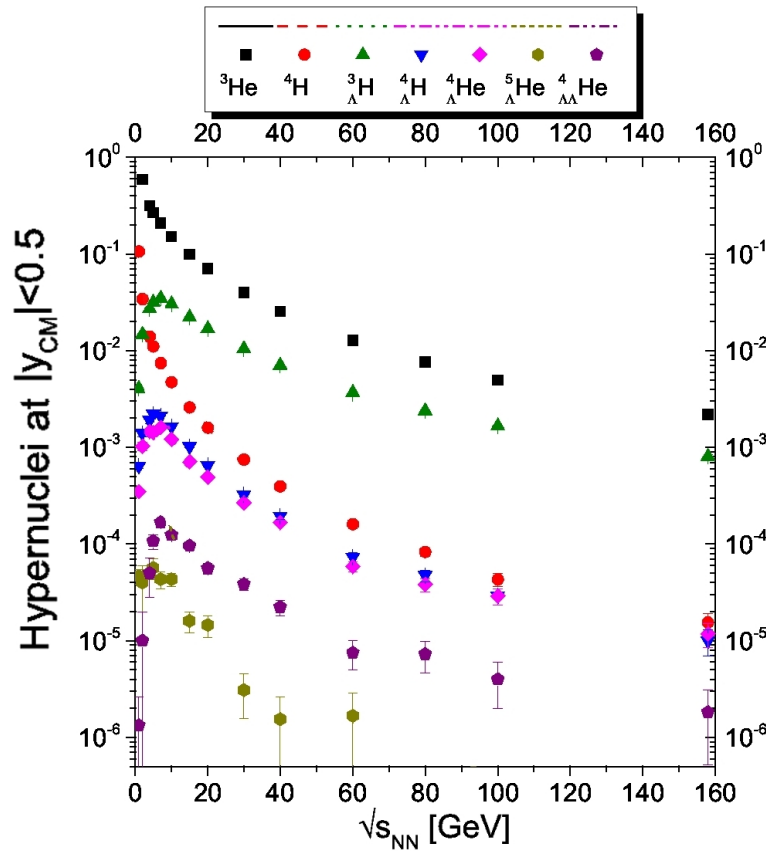


FIGURE 3.3: Yield per event of different (hyper)nuclei at mid-rapidity ($|y_{CM}| < 0.5$) for central events ($b < 3.4$ fm) of Pb–Pb/Au–Au collisions as a function of $\sqrt{s_{NN}}$. The symbols are the results of the DCM (Dubna Cascade Model) coalescence model [147].

Fig. 3.3 shows the expected production yield of (hyper)nuclei at mid-rapidity ($|y_{CM}| < 0.5$)

for central events ($b < 3.4$ fm) of Pb–Pb (or Au–Au) collisions as a function of energy of the collision ($\sqrt{s_{NN}}$). The coalescence results depend on the parameters used in the model. To perform the calculations, the authors of [147] used for the Λ the same parameters of the nucleons. However the hyperon-hyperon and hyperon-nucleon interactions are not well known and it is expected that some parameters should be different for clusters with Λ or even Ξ . Varying the DCM coalescence model parameters could change the production yield even by many orders, but it is argued that ratios of (hyper)nuclei should not change.

In 2010 authors of [131], proposed other calculations based on the coalescence model, but the transport code used was a multiphase transport model (AMPT). AMPT is a Monte Carlo transport model for heavy ion collisions at relativistic energies. It uses the Heavy Ion Jet Interaction Generator (HIJING) for generating the initial conditions, the Zhang’s Parton Cascade (ZPC) for modelling the partonic scatterings, and A Relativistic Transport (ART) model for treating hadronic scatterings. The default version of AMPT treats the initial condition as strings and minijets and uses the Lund string fragmentation model as in HIJING, while the string melting version of AMPT treats the initial condition as partons and uses a simple coalescence model to describe hadronization [151]. Inside AMPT, the (hyper)nuclei are then produced at the final stage of the evolution of the system via Wigner wave-function overlapping of their constituent nucleons (hyperons). The AMPT model used in [131] has a good agreement with data from RHIC, including pions correlations and flow. Up to now, calculations that use the coalescence with the AMPT transport model have been performed only up to the top RHIC energy.

Theoretical calculations based on the simple coalescence models have been recently proposed [152] to interpret results at high energy ($\sqrt{s_{NN}} = 200$ GeV) from the STAR experiment. Measurements of (anti)(hyper)nuclei production yields at the LHC energy ($\sqrt{s_{NN}} = 2.76$ TeV), which are the object of this work, will help to understand if the coalescence is the precess that governs the (anti)(hyper)nuclei production.

3.2 Statistical-Thermal Model

3.2.1 Introduction

The statistical-thermal model treats the fireball, which results from a high-energy collision, as an ideal gas of hadrons including resonances. At freeze-out, these hadrons are assumed to be described by local thermal distributions, typically with freeze-out parameters common to all particle species.

The invariant momentum spectrum of particles species i , with spin-isospin degeneracy g_i , emitted directly from the fireball at freeze-out, is given by the Cooper-Frye formula [153]:

$$E \frac{d^3 N_i}{d^3 p} = \frac{d^3 N_i}{dy dp_T d\phi_P} = \frac{g_i}{(2\pi)^3} \int_{\sigma_f} f_i(x, p) p^\mu d\sigma_\mu \quad (3.18)$$

which involves an integration of the Lorentz-invariant local thermal distribution function $f_i(x, p)$ over the freeze-out surface σ_f . Assuming a grand-canonical ensemble, $f_i(x, p)$ at temperature T is given by,

$$f_i(x, p) = \frac{1}{e^{(p^\mu u_\mu(x) - \mu_i(x))/T(x)} \pm 1} \quad (3.19)$$

where p^μ and $u_\mu(x)$ are, respectively, the 4-momentum and fireball volume-element 4-velocity with respect to the observer frame, and $\mu_i(x)$ is the chemical potential of particle specie i . The plus sign refers to fermions, and the minus sign to bosons.

The freeze-out surface σ_f is a 3-dimensional hypersurface in the space-time $\sigma^0(\sigma^1, \sigma^2, \sigma^3)$, defined by some freeze-out criteria. When parametrized by three mutually orthogonal coordinates u, v and w , its normal vector is given by [154]:

$$d\sigma_\mu = -\epsilon_{\mu\nu\lambda\rho} \frac{\partial\sigma^\nu}{\partial u} \frac{\partial\sigma^\lambda}{\partial v} \frac{\partial\sigma^\rho}{\partial w} \quad (3.20)$$

where $\epsilon_{\mu\nu\lambda\rho}$ is totally antisymmetric and $\epsilon^{\mu\nu\lambda\rho} = +1$ if $(\mu\nu\lambda\rho)$ is an even permutation of $(0,1,2,3)$. In most applications of the statistical-thermal model, T and μ_i are taken as constant over the freeze-out surface.

Particle multiplicities from flowing sources are derived by dividing the Cooper-Frye formula (eq.3.18) by E , and integrating over $d^3 p$:

$$N_i^{(prim)} = \frac{g_i}{(2\pi)^3} \int_{\sigma_f} d\sigma_\mu \int d^3 p \frac{p^\mu}{E} f_i(x, p) \quad (3.21)$$

Provided that the thermal parameters are constant over the freeze-out hypersurface (or else interpreting the freeze-out parameters as global averages) [155],

$$N_i^{(prim)} = \int_{\sigma_f} d\sigma_\mu u^\mu n_i^{0(prim)} \quad (3.22)$$

where $n_i^{0(prim)}$ is the density of hadron species i under the assumption of a stationary fireball. This leads to the identification of $\int_{\sigma_f} d\sigma_\mu u^\mu$ as the dynamical (effective) volume of the system V_{eff} (i.e. the sum of the volumes of each fireball element measured in their own rest frame at freeze-out):

$$V_{eff} = \int_{\sigma_f} d\sigma_\mu u^\mu \quad (3.23)$$

A consequence of this result is that all flow effects (contained in the dynamical volume) cancel in the ratio of fully-integrated particles multiplicities. It is therefore possible to apply a purely thermal model to fully-integrated data, without any consideration of dynamical effects [155, 156].

3.2.2 Choice of the Ensemble

Within the statistical-thermal model there is a freedom regarding the ensemble with which to treat the quantum numbers B (baryon number), S (strangeness), and Q (charge), which are conserved in strong interactions. In order to calculate the thermal properties of a system, the starting point is the evaluation of its partition function. The form of the partition function obviously depends on the choice of the ensemble.

The possible ensembles that can be used are:

- **The Grand-Canonical Ensemble** : The Grand-Canonical Ensemble is the most widely used in heavy-ion collisions applications. Within this ensemble, the chemical potentials for each of the quantum numbers (μ_B , μ_S and μ_Q) are introduced. Conservation laws for energy and quantum or particle numbers are enforced on average through the temperature and chemical potentials;
- **The Canonical Ensemble**: When the number of particles carrying quantum numbers is small (i.e. pp , $p\bar{p}$ and e^+e^- collisions[168, 169]) the canonical ensemble is favoured. Within the canonical ensemble, particle number conservation (or quantum number conservation) is exactly enforced;
- **The Mixed-Canonical (Strangeness-Canonical) Ensemble**: In heavy-ion collisions, the large numbers of baryons and charged particles generally allows baryon number and charge to be treated grand-canonically. However, at low temperatures, the resulting low production of strange particles requires a canonical treatment of strangeness. This is the so-called mixed-canonical approach: within this ensemble the strangeness in the system is fixed exactly by its initial value of S , while the baryon and charge content are treated grand-canonically.

In the following section a description of the Grand-Canonical Ensemble will be given. A detailed description of the other two ensembles can be found in [170, 127] and in the references therein quoted.

3.2.3 The Grand-Canonical Ensemble

The grand-canonical ensemble is the most widely used in applications to heavy-ion collisions and within this ensemble conservation laws for energy and particle numbers

are enforced on average through the temperature and chemical potentials.

Let's consider a gas composed of a single hadron specie i with energy levels $\{\epsilon_i^1, \epsilon_i^2, \dots\}$ and corresponding occupation numbers $\{n_i^1, n_i^2, \dots\}$. With chemical potential μ_i , $\beta \equiv 1/T$, $\hat{H}$ the Hamilton operator, and $\hat{N}$ the particle number operator, the partition function for the gas is given by:

$$\begin{aligned}
 Z_i^{GC} &= \text{Tr} \left(e^{-\beta(\hat{H} - \mu_i \hat{N})} \right), \\
 &= \sum_{\{n_i^j\}} \langle n_i^1, n_i^2, \dots | e^{-\beta(\hat{H} - \mu_i \hat{N})} | n_i^1, n_i^2, \dots \rangle, \\
 &= \sum_{\{n_i^j\}} e^{-\beta[(\epsilon_i^1 n_i^1 + \epsilon_i^2 n_i^2 + \dots) - \mu_i(n_i^1 + n_i^2 + \dots)]}, \\
 &= \prod_{\text{states } j} \left(\sum_{\{n_i^j\}} e^{-\beta(\epsilon_i^j - \mu_i)n_i^j} \right), \\
 &= \prod_{\text{states } j} \left(1 \pm e^{-\beta(\epsilon_i^j - \mu_i)} \right)^{\pm 1},
 \end{aligned} \tag{3.24}$$

where the plus sign refers to a gas of fermions (occupation numbers 0 or 1), and the minus to that of bosons.

Taking into account the logarithm of the partition function,

$$\ln Z_i^{GC}(T, V, \mu_i) = \sum_{\text{states } j} \ln \left(1 \pm e^{-\beta(\epsilon_i^j - \mu_i)} \right)^{\pm 1}, \tag{3.25}$$

which, in the large volume limit, becomes

$$\ln Z_i^{GC}(T, V, \mu_i) = \frac{g_i V}{(2\pi)^3} \int d^3p \ln \left(1 \pm e^{-\beta(E_i - \mu_i)} \right)^{\pm 1}, \tag{3.26}$$

where the degeneracy g_i of hadrons species i has been taken into account, V is the fire-ball volume, and $E_i = \sqrt{p_i^2 + m_i^2}$, where m_i is the particle mass and p_i its momentum. In the case of a multi-component hadron gas of volume V and temperature T , the total partition function is given by:

$$Z^{GC}(T, V, \{\mu_i\}) = \prod_{\text{species } i} Z_i^{GC}(T, V, \mu_i) \tag{3.27}$$

Thus,

$$\begin{aligned}
 \ln Z^{GC}(T, V, \{\mu_i\}) &= \sum_{\text{species } i} \ln Z_i^{GC}(T, V, \mu_i), \\
 &= \sum_{\text{species } i} \frac{g_i V}{(2\pi)^3} \int d^3p \ln \left(1 \pm e^{-\beta(E_i - \mu_i)} \right)^{\pm 1}
 \end{aligned} \tag{3.28}$$

Since in relativistic heavy-ion collisions it is not the individual particle number that is conserved, but rather the quantum numbers B , S and Q , the chemical potential for

particle species i is given by:

$$\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q \quad (3.29)$$

where B_i, S_i and Q_i are the baryon number, strangeness and charge, respectively, of hadrons species i , and μ_B, μ_S and μ_Q are the corresponding chemical potentials for these conserved quantum numbers.

Once the partition function is known, all the thermodynamical quantities can be calculated. Introducing the Grand Potential $\Omega_{GC}(T, V, \{\mu_i\}) \equiv E - TS - \sum_i \mu_i N_i$, the particle multiplicities, entropy and pressure are obtained by differentiation:

$$N_i^{GC} = -\frac{\partial \Omega_{GC}}{\partial \mu_i} \quad (3.30)$$

$$S^{GC} = -\frac{\partial \Omega_{GC}}{\partial T} \quad (3.31)$$

$$P^{GC} = -\frac{\partial \Omega_{GC}}{\partial V} \quad (3.32)$$

as follows from the first law of thermodynamics ($dE = TdS - PdV + \sum_{\text{species } i} \mu_i N_i$), and,

$$\Omega_{GC}(T, V, \{\mu_i\}) = -T \ln Z^{GC}(T, V, \{\mu_i\}) \quad (3.33)$$

Furthermore, the energy is:

$$E^{GC} = T^2 \frac{\partial \ln Z^{GC}}{\partial T}. \quad (3.34)$$

Using the prescription for the particle multiplicity,

$$\begin{aligned} N_i^{GC} &= \frac{g_i V}{(2\pi)^3} \int d^3p \frac{e^{-\beta(E_i - \mu_i)}}{1 \pm e^{-\beta(E_i - \mu_i)}}, \\ &= \frac{g_i V}{(2\pi)^3} \int d^3p e^{-\beta(E_i - \mu_i)} \sum_{k=0}^{\infty} \left(\mp e^{-k\beta(E_i - \mu_i)} \right)^k, \\ &= \frac{g_i V}{(2\pi)^3} \sum_{k=1}^{\infty} (\mp 1)^{k+1} \int d^3p e^{-k\beta(E_i - \mu_i)}, \\ &= \frac{g_i V}{2\pi^2} \sum_{k=1}^{\infty} (\mp 1)^{k+1} \frac{m_i^2 T}{k} K_2 \left(\frac{k m_i}{T} \right) e^{k\mu_i/T}, \end{aligned} \quad (3.35)$$

with similar expressions for the energy, entropy and pressure.

Here K_2 is the modified Bessel function of second kind.

In practice, the Boltzmann approximation, i.e. retaining just the $k = 1$ term in the equation 3.34, is reasonable for all particles but the pions. In this approximation,

$$\ln Z^{GC}(T, V, \{\mu_i\}) = \sum_{\text{species } i} \frac{g_i V}{(2\pi)^3} \int d^3p e^{-\beta(E_i - \mu_i)} = \sum_{\text{species } i} z_i^1 e^{-\beta\mu_i} \quad (3.36)$$

where z_i is the single-particle partition function of hadron species i .

3.2.4 Thermal production of hadrons

The statistical-thermal model has been used to describe the hadron production in heavy-ion collisions from AGS up to RHIC energies. The description of the particle production has been found to be very successful at the RHIC energy. Fig. 3.4 shows the thermal fit to the hadrons yield data at RHIC ($\sqrt{s_{NN}} = 200$ GeV). The value of μ_B is found to be 24 ± 2 MeV, the temperature of the freeze-out is $T=164$ MeV and the volume $V=1960$ fm³ [157]. With these values, the fit at the RHIC energy is found to be $\chi^2/\text{dof}=31.6/12$.

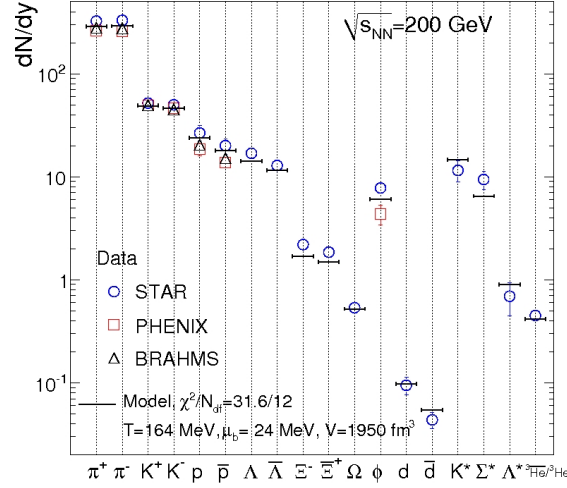


FIGURE 3.4: Hadron yields in comparison with the thermal model fit of combined data (excluding K^* , Σ^* , Λ^*), for the RHIC energy of $\sqrt{s_{NN}} = 200$ GeV. The ratio ${}^3\text{He}/{}^3\overline{\text{He}}$ has been included in the fit. The fit results are: $\mu_B=24 \pm 2$ MeV, $T=164$ MeV and the volume $V=1960$ fm³, with $\chi^2/\text{dof}=31.6/12$ [157].

Fig. 3.5 shows the particle ratios in the most central (0-5%) centrality bin as measured by the ALICE experiment [158] at $\sqrt{s_{NN}} = 2.76$ TeV compared with the results from RHIC experiments [159, 160, 161] at $\sqrt{s_{NN}} = 200$ GeV and the predictions from the thermal models [162, 163].

At the LHC energy the antiparticle to particle ratio is close to unity for all the particle species, consistent with vanishing baryochemical potential μ_B (Fig. 3.5 left panel). For this reason the model predictions have been obtained by using the value $\mu_B = 1$ MeV. This value is much lower than the one estimated at SPS ($\mu_B \sim 225$ MeV) and RHIC ($\mu_B = 24$ MeV). According to the theories that describe the QCD phase diagram, the freeze-out temperature T should be constant above SPS energies. The predictions based on the thermal model were therefore calculated using the T value extracted from fits to the RHIC data ($T=164$ MeV). The ratio $K/\pi = 0.149 \pm 0.001$ is similar to the lower energy values and agrees with the expectations from the thermal model. On the other hand, the ratio $p/\pi = 0.046 \pm 0.003$ is significantly lower than that expected by the model by a factor ~ 1.5 . The thermal model has been very successful in describing particle ratios over a wide energy range so the deviation observed at the LHC was

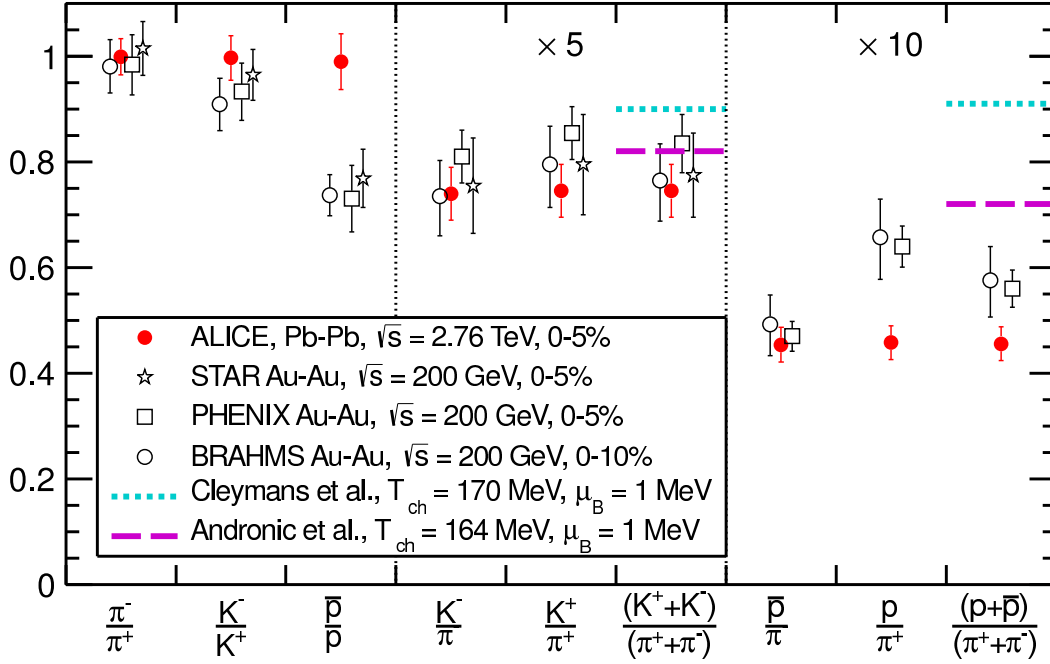


FIGURE 3.5: Mid-rapidity ($|y| < 0.5$) particle ratios, compared to RHIC results and predictions from thermal models for central Pb–Pb collisions at the LHC (combined statistical and systematic errors) [158].

very unexpected. Anyway, it should be noted that a discrepancy of $\sim 20\%$ on the p/π ratio between thermal model and data was already observed at RHIC. The discrepancy was not anyway considered significant because of the large errors due to the secondary particles subtraction and the uncertainties of the model.

In order to extract T from the LHC data, a fit to the particle abundances integrated in p_T has been done (Fig. 3.6.a) by using the preliminary data of the ALICE experiment [164]. In the fit procedure the μ_B has been set at 1 MeV; the freeze-out temperature T from the fit is $T_{ch} = 152$ MeV, which is much lower with respect to what was expected (at STAR it was $T_{ch} = 164$ MeV). The quality of the fit, anyhow, is not high, as the $\chi^2/\text{dof} = 39.6/9$, and the thermal fit fails to describe strange and multi-strange baryons.

Fig. 3.6b shows the particle yields relative to pions at RHIC (empty symbols) [159, 160, 161] and LHC (full symbols) [164] and the predictions from the thermal model [162], assuming $\mu_B = 24$ MeV and $T = 164$ MeV for RHIC data and $\mu_B = 1$ MeV and $T = 152$ MeV for LHC. Looking at the data the only significant modification of the particles ratio when moving from RHIC to LHC is observed in p/π and Λ/π ratios, while all the other particles ratios look unchanged. This could mean that at the LHC energy some processes that at low energy are not important start to be more significant. The value of $T = 152$ MeV is able to reproduce the Λ/π ratio, but is incompatible with the p/π ratio. Moreover using this temperature the estimates of the (multi)strange particles fails.

In conclusion, from the data collected at LHC, it seems that a pure thermal model is not

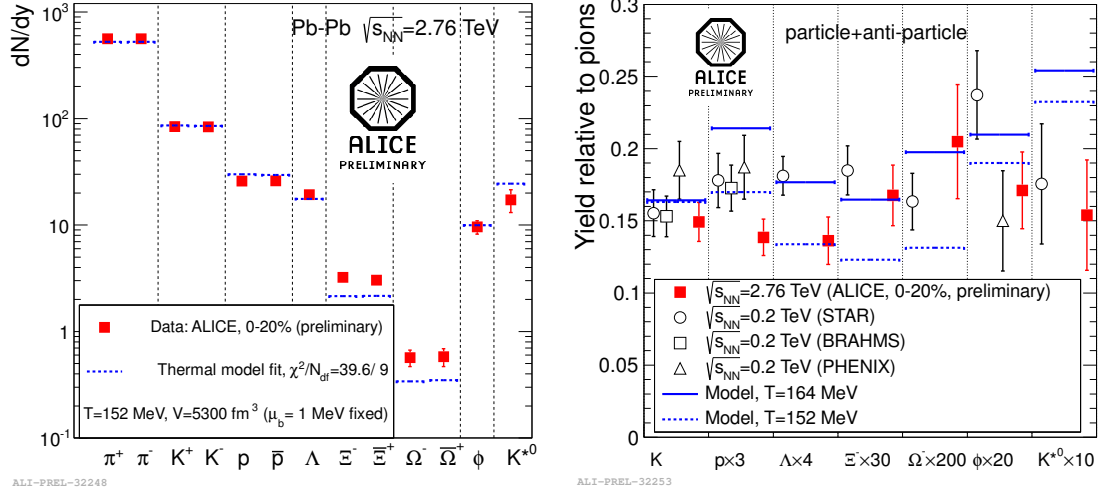


FIGURE 3.6: a): Thermal fit to integrated hadron yields at mid-rapidity $|y| < 0.5$ [164]. b): Yields relative to pions at RHIC [159, 160, 161] and LHC [164]. Prediction from thermal model [162], assuming $\mu_B = 24$ MeV and $T = 164$ MeV for RHIC data and $\mu_B = 1$ MeV and $T = 152$ MeV for LHC.

able to reproduce all the measured particle yields. Alternative scenarios that have been recently proposed are reported below.

- **Interactions in the hadronic phase:**

In this scenario the deviation of particles (i.e. p and Λ) from the thermal model is due to final state interactions of hadrons after the chemical freeze-out. Final state interactions are usually implemented using the UrQMD model [165], which describes the final hadron-resonance cascade. The description of the fireball includes hadronic interactions after the chemical freeze-out, which are neglected in the case of free hadron stream. At low energies these interactions could be too weak to modify the particle production significantly.

- **Non-equilibrium statistical hadronization model:**

In some models, the non-equilibrium of strangeness is quantified by introducing the factor γ_s . The same factor can be introduced for light flavours with the inclusion of γ_u and γ_d . This allows to consider full chemical non-equilibrium statistical hadronisation model [166]. This approach was shown to describe the measured integrated yield at LHC [167]. The freeze-out temperature T from thermal fit decreases when considering more central collisions: ~ 135 MeV in central collisions and ~ 145 MeV in the most peripheral. This has been interpreted as due to more violent transverse fireball expansion leading to a greater and faster cooling of the system. This would also explain the decrease of the freeze-out temperature between LHC and RHIC.

3.2.5 Nuclei production within the thermal model

The use of the thermal model to predict the production yield of (anti)(hyper) nuclei may look inappropriate, since the nuclei binding energy is of a few MeV while the chemical freeze-out temperatures is 100-170 MeV. Albeit, it has been noted [157] that the ratios of particles composed of nucleons is determined by the entropy per baryon, which is fixed at chemical freeze-out and then conserved. This fact has been first recognized about 30 years ago by Siemens and Kapusta [171] and was later confirmed in [172], establishing the basis of thermal analyses of yields of light nuclei [120, 173].

The measurement of the production yields of light (anti)nuclei in central heavy-ion collisions provides significant constraints to the thermal model parameters, since considering their ratios, e.g. $n\bar{\text{He}}/n\text{He}$, they scale like $\exp[-(2n\mu_B/T)]$.

Fig. 3.7a shows the predictions of yields made by using the thermal model for $\bar{p}/p$, $\bar{d}/d$, $\bar{\Lambda}/\Lambda$, ${}^3\bar{\text{He}}/{}^3\text{He}$ and ${}^4\bar{\text{He}}/{}^4\text{He}$ (lines) as a function of the center-of-mass energy compared with experimental data [157]. The calculations have been performed using the parametrizations for T and μ_B established in [174]. The very good agreement between the model and the measurements of the $\bar{d}/d$ ratio (measured at the AGS [175]) extend the range of validity of the thermal model over 8 orders of magnitude. Such analysis have also been extended to light nuclei containing strangeness, the hypernuclei.

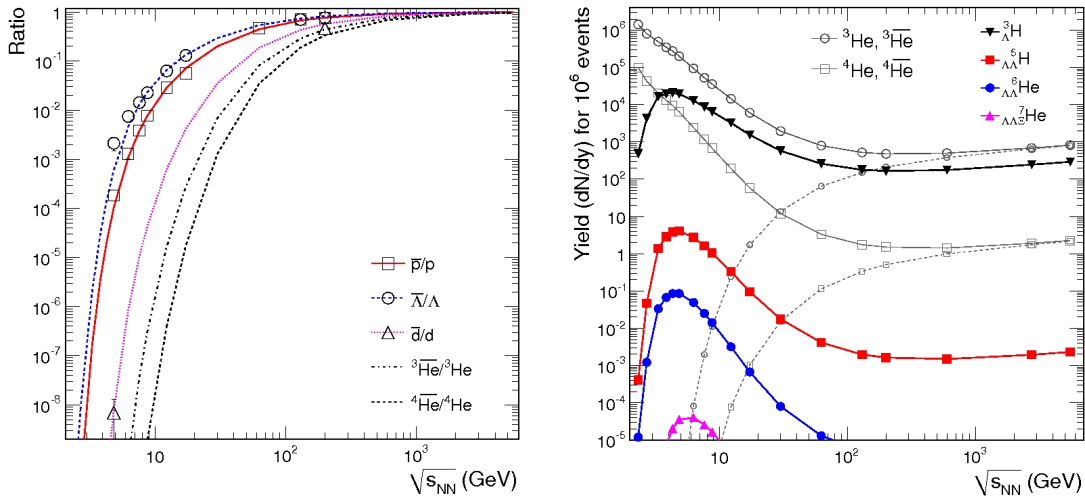


FIGURE 3.7: a): Energy dependence of anti-baryon to baryon yield ratios. The lines are thermal model results, while the symbols represent measured data [157]. b): Energy dependence of predicted hypernuclei yields at mid-rapidity $|y| < 0.5$ for 10^6 central collisions. The predicted yields of ${}^3\text{He}$ and ${}^4\text{He}$ nuclei are included for comparison, along with the corresponding anti-nuclei (dashed lines) [157].

In Fig. 3.7b the predicted yields of (anti)(hyper) nuclei at mid-rapidity $|y| < 0.5$ per million of central events as a function of energy [157] are shown. At the LHC, $({}^4\bar{\text{He}}){}^4\text{He}$ and their corresponding hypernuclei seems to be experimentally accessible. For the LHC energy of 2.76 TeV the authors of [157] predicted ratios ${}^3\text{He}/{}^4\text{He}$ and ${}^3\bar{\text{He}}/{}^4\bar{\text{He}}$ of $2.76 \cdot 10^{-3}$ and $2.70 \cdot 10^{-3}$ respectively. This should allow, at the LHC, to measure the yields of produced (anti)(hyper)nuclei up to mass number 4 in Pb–Pb collisions and

providing a detailed test of thermal model predictions. As mentioned in the previous section, the simple thermal model seems to have some difficulties to describe the particle production at the LHC energies (i.e. at the TeV scale). Some theoretical efforts have been done in order to include a transport code into the thermal model. Authors of [147] recently developed a hybrid approach based on a hydrodynamical evolution inside the UrQMD (Ultra-relativistic Quantum Molecular Dynamics). In this model, the nucleons during the first phase of the evolution are described by UrQMD as hadronic cascade. Once the two nuclei collide and pass through each other, the hydrodynamic evolution starts. While the spectators continue to propagate in cascade, all the other particles are mapped to the hydrodynamical grid. By doing so the system is forced to local thermal equilibrium for each cell. In the hydrodynamical evolution the conservation equations are solved assuming the strange net number to be conserved and equal to zero. At the end of the hydrodynamical phase the fields are mapped to particle degrees of freedom using the Cooper-Frye equation (see Eq.3.18) and the properties of the clusters which serve as input for the computation. The parameters used in the thermal model are: $\mu_B=0$ MeV and $T=170$ MeV. Fig. 3.8 shows the results at mid-rapidity $|y| < 0.5$ of the production of hypernuclei in central events ($b < 3.4$ fm) of Pb–Pb/Au–Au collisions as a function of $(\sqrt{s_{NN}})$, up to the top energy available at RHIC (~ 200 GeV). The values have been evaluated by using the UrMQD-thermal model as described in [147]. Different lines refer to different particles species.

3.3 (Anti)(Hyper) Nuclei production : comparisons among models

The nuclei production in heavy-ion collisions have been predicted both in the coalescence and in the thermal approach. To discriminate among the models, and understand what is the best one to describe the data, it is necessary to find out quantities that allow to discriminate among the two production mechanisms.

The simplest measurement is the absolute production yield of different particles. It has been shown already in 1995 [120], that, e.g. at the AGS energies (i.e. few GeV/nucleon), the absolute predicted yield of production from the thermal model is in most of the times in a reasonable agreement with the one from the coalescence model. The results are summarized in Table 3.1 (from [120]).

This agreement reported for the AGS energies is true also for a wide range of energies. Fig. 3.9 (which is the superimposition of Fig. 3.3 and Fig. 3.8) shows results presented in [147] for the production of (hyper)nuclei in most central ($b < 3.4$ fm) Pb–Pb/ Au–Au collisions at mid rapidity ($|y| < 0.5$) as a function of center of mass energy $\sqrt{s_{NN}}$. UrQMD hybrid model calculations are shown as lines, while the DCM Coalescence results are shown as symbols.

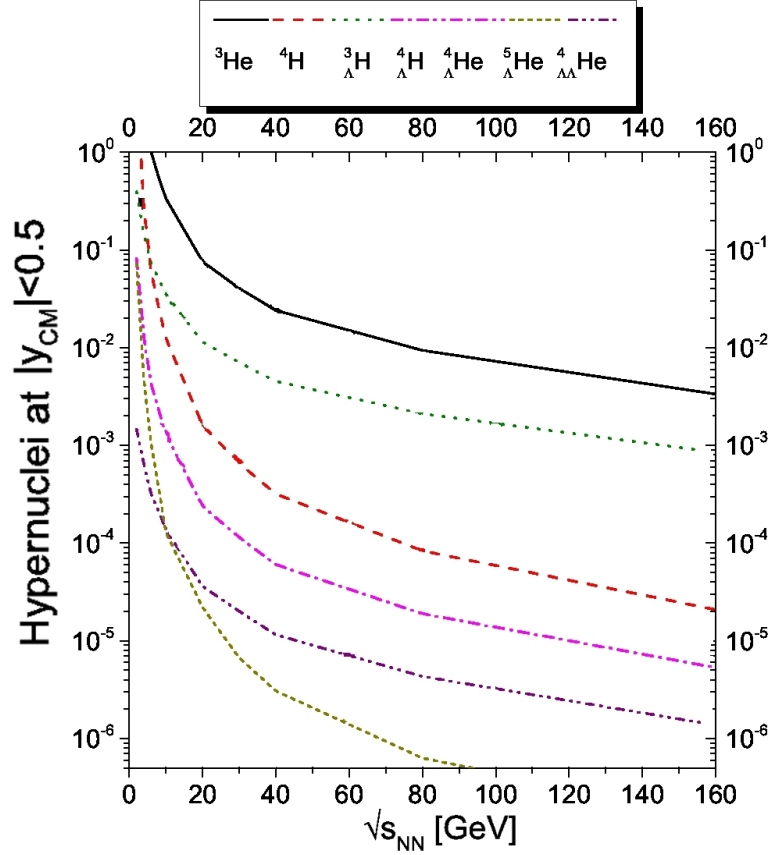


FIGURE 3.8: Yield per event of different (hyper)nuclei at mid-rapidity ($|y_{CM}| < 0.5$) of central events ($b < 3.4 \text{ fm}$) of Pb-Pb/Au-Au collisions as a function of $\sqrt{s_{NN}}$. The lines are the results of the UrQMD hybrid model for different particles. The values used to evaluate the thermal production are : $\mu_B=0 \text{ MeV}$ and $T = 170 \text{ MeV}$ [147].

Particles	Thermal Model	Coalescence Model
	$T=.120 \text{ GeV}$	
d	15	11.7
t+ ^3He	1.5	0.8
α	0.02	0.018
$^5_{\Lambda\Lambda}\text{H}$	$3.5 \cdot 10^{-5}$	$4 \cdot 10^{-4}$
$^6_{\Lambda\Lambda}\text{He}$	$7.2 \cdot 10^{-7}$	$1.6 \cdot 10^{-5}$

TABLE 3.1: Produced number of non-strange and strange clusters and of strange quark matter per central Au-Au collisions at AGS energy, calculated in a thermal model for two different temperatures, baryon chemical potential $\mu_B = 0.54 \text{ GeV}$. The coalescence model predictions are extracted from Table 2 of [177].

Another way to discriminate among particle production mechanisms, is to study the particle ratios. In the simplest coalescence picture the ratios of different (anti)nuclei can be directly related to ratios of hadronic yields. In particular,

$$\frac{\overline{^3\text{He}}}{^3\text{He}} = \frac{\overline{\text{ppn}}}{\text{ppn}} \simeq \left(\frac{\overline{\text{p}}}{\text{p}} \right)^3 \quad (3.37)$$

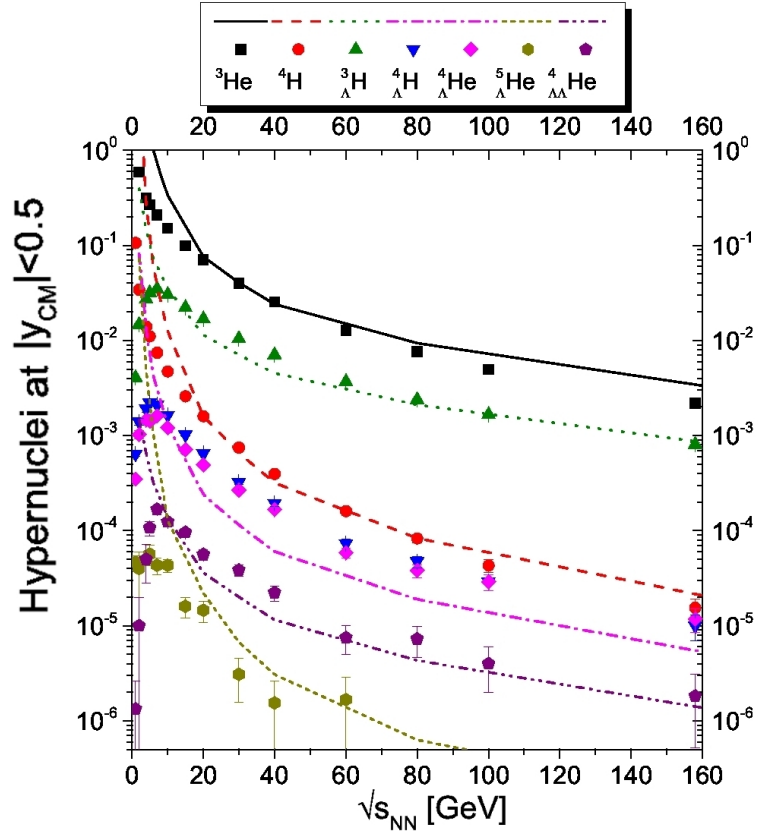


FIGURE 3.9: Yield per event of different (hyper)nuclei at mid-rapidity ($|y_{CM}| < 0.5$) for central events ($b < 3.4 \text{ fm}$) of Pb-Pb/Au-Au collisions as a function of $\sqrt{s_{NN}}$. The lines are the results of the UrQMD hybrid model for different particles. The value used to evaluate the thermal production are : $\mu_B = 0 \text{ MeV}$ and $T = 170 \text{ MeV}$. The symbols are the results of the coalescence model with the DCM (Dubna Cascade Model) model [147].

and

$$\frac{\overline{\frac{3}{\Lambda}\text{H}}}{\frac{3}{\Lambda}\text{H}} = \frac{\overline{pn\Lambda}}{pn\Lambda} \simeq \left(\frac{\bar{p}}{p}\right)^2 \left(\frac{\bar{\Lambda}}{\Lambda}\right) \quad (3.38)$$

In the thermal model, the production depends on μ_B and T ; the $\bar{p}/p$ ratio is:

$$\frac{\bar{p}}{p} = \exp \left[-2 \left(\frac{\mu_B}{T} \right) \right] \quad (3.39)$$

Studying the anti-nuclei/nuclei ratio in the statistical thermal model an extra μ_B factor is added each time the baryon number is increased. Thus, each nucleon adds a factor of μ_B in the exponent of the Boltzmann part. The production of nuclear fragments is therefore very sensitive to the value of the baryon-chemical potential and so it could be used for a precise determination of μ_B . The deuterium has an additional neutron and the anti-deuterium/deuterium ratio in the statistical thermal model is given by

$$\frac{\bar{d}}{d} = \exp \left[-4 \left(\frac{\mu_B}{T} \right) \right] \simeq \left(\frac{\bar{p}}{p} \right)^2 \quad (3.40)$$

so should be similar to the square of the anti-proton/proton ratio if decay contributions of heavier resonances to the nucleon yields are neglected. Therefore this ratio should be very close to the one that can be obtained using the coalescence model. Similarly, the ${}^3\overline{\text{He}}$ has three nucleons and the corresponding anti- ${}^3\text{He}/{}^3\text{He}$ ratio is given by

$$\frac{{}^3\overline{\text{He}}}{{}^3\text{He}} = \exp \left[-6 \left(\frac{\mu_B}{T} \right) \right] \simeq \left(\frac{\overline{p}}{p} \right)^3 \quad (3.41)$$

the ${}^3\overline{\text{He}}/{}^3\text{He}$ ratio should be $\sim(\overline{p}/p)^3$, which again, as long as the feed-down from resonance decays is neglected, make the thermal model and the coalescence model predictions very close.

If the nuclei carry strangeness, this leads to an extra term μ_S and the ratio of antihypertriton/hypertriton yield becomes:

$$\frac{{}^3_{\Lambda}\overline{\text{H}}}{{}^3_{\Lambda}\text{H}} = \exp \left[- \left(\frac{6\mu_B - 2\mu_S}{T} \right) \right] \simeq \left(\frac{\overline{p}}{p} \right)^2 \left(\frac{\overline{\Lambda}}{\Lambda} \right) \quad (3.42)$$

which is equivalent to the coalescence result shown in eq. 3.38. Only by using mixed ratios, i.e. using ratios of different nuclei (or anti-nuclei), differences between the thermal and the coalescence model appear. In the thermal model:

$$\frac{{}^3_{\Lambda}\text{H}}{{}^3\text{He}} = A \exp \left[- \frac{\mu_S}{T} \right]. \quad (3.43)$$

where A is a factor that takes into account the different spin-isospin degeneracy factors and the masses of the considered particles.

In the coalescence model,

$$\frac{{}^3_{\Lambda}\text{H}}{{}^3\text{He}} = \frac{pn\Lambda}{ppn} \simeq \frac{\Lambda}{p}. \quad (3.44)$$

Differences between the model predictions are found for the mixed ratios, ${}^3_{\Lambda}\overline{\text{H}}/{}^3\overline{\text{He}}$ and ${}^3_{\Lambda}\text{H}/{}^3\text{He}$, due to the different nuclear masses. From Eqs. (3.43) and (3.44) it is possible to find out that when the binding energy of nuclei and the feed-down corrections are neglected, the statistical thermal model differs from the coalescence framework by a factor of $(1/3 + 2m_p/3m_{\Lambda})^{3/2}$. Consequently, the statistical thermal model results for ${}^3_{\Lambda}\overline{\text{H}}/{}^3\overline{\text{He}}$ and ${}^3_{\Lambda}\text{H}/{}^3\text{He}$ ratios are lower than those obtained in the coalescence picture [176]. The theoretical predictions for $\overline{p}/p$, $\overline{\Lambda}/\Lambda$, ${}^3_{\Lambda}\overline{\text{H}}/{}^3_{\Lambda}\text{H}$, ${}^3\overline{\text{He}}/{}^3\text{He}$, ${}^3_{\Lambda}\overline{\text{H}}/{}^3\overline{\text{He}}$ and ${}^3_{\Lambda}\text{H}/{}^3\text{He}$ at the RHIC energy ($\sqrt{s_{\text{NN}}} = 200$ GeV) are shown in Fig. 3.10. The green solid lines are the prediction from the thermal model, blue dashed lines are results from coalescence driven by data, while the magenta dash-dotted lines are results of the coalescence model based on thermal model parameters. The red empty squares are the experimental data.

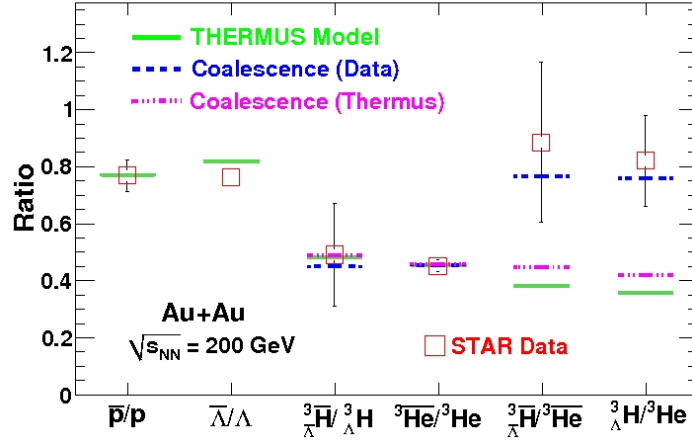


FIGURE 3.10: Comparison of the results from the STAR Collaboration (red empty squares) with the statistical thermal and the coalescence model predictions. For the latter both experimental values (blue dashed lines) and values from the statistical thermal model (magenta dash-dotted lines) have been used [176].

3.4 S_3 predictions in different models

In order for the $\frac{3\bar{H}}{\Lambda}/\frac{3H}{\Lambda}$ ratio to be independent of the differences in the kinematic of different particle species due to collective motions and efficiency, the authors of [121] proposed to use the S_3 ratio already introduced at the beginning of this chapter. S_3 is defined as:

$$S_3 = \frac{\frac{3\bar{H}}{\Lambda}}{\frac{3H}{\Lambda}} \times \frac{\Lambda}{p} \quad (3.45)$$

The authors of [131] proposed S_3 as a valuable tool to probe the nature of the matter created in the heavy-ion collision. According to them, S_3 is sensible to the local correlation of strangeness and baryon number and therefore to the c_{BS} (Eq.3.9) (Baryon-Strangeness coefficient). The S_3 ratio is also interesting since in thermal production, it does not depend on the chemical potential of the particles, and any canonical correction factors for strangeness are cancelled.

The S_3 ratio has been experimentally measured by the AGS-E864 collaboration [121], by using beams of Au and Pt with a momentum of 11.5 GeV/c, and by the STAR collaboration [111] by using Au–Au collisions at $\sqrt{s_{NN}}=200$ GeV. At the AGS, the value obtained was $S_3 = 0.36 \pm 0.26$, while the value achieved at RHIC was $S_3 = 1.1 \pm 0.2$, consistent with unity within the error bars. The evolution of the S_3 ratio as a function of the energy available in the center-of-mass is, therefore, an important quantity to be evaluated.

A quick review of the results obtained for S_3 using the theoretical models discussed in the present chapter is reported below.

3.4.1 Coalescence with a AMPT model

Authors of [131] evaluated the behaviour of S_3 as function of the $\sqrt{s_{NN}}$ by using the AMPT (A Multi Phase Transport) model based on the coalescence model. Fig. 3.11 shows the S_3 results for minimum-bias Au–Au collisions at various beam energies. S_3 increases with beam energy in a system with partonic interactions (melting AMPT, full cyan triangle) while it is almost unchanged in a purely hadronic system (default AMPT, empty red triangles) (Details of the models can be found in [131]). The experimental results ([121],[111]), shown as black squares, are consistent with the melting AMPT calculations and are in contrast to the default AMPT calculations.

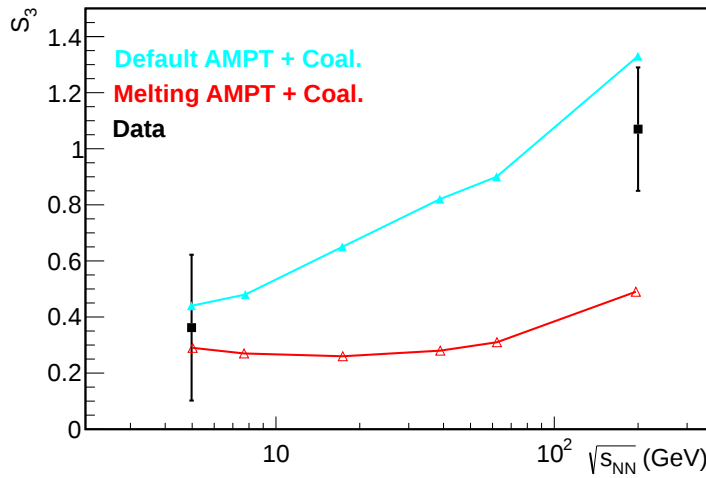


FIGURE 3.11: The S_3 ratio as a function of beam energy ($\sqrt{s_{NN}}$) in minimum-bias Au–Au collisions from default AMPT (open red triangles) and melting AMPT (full cyan triangles) plus coalescence model calculations. The available data from AGS [121] are plotted for reference. Points are taken from [131].

3.4.2 Thermal model

Fig. 3.12 shows the S_3 ratio evaluated by using the thermal model presented in [157]. The *thermal variables* used to perform the calculation are: $T = 164$ MeV and $\mu_B = 1$ MeV. The data come from [121] and [111] and are compared to thermal model predictions. A clear discrepancy between the thermal model predictions (red full line) and the data (full squares) is evident. To compute the red line, the Λ/p ratio contains the feed-down from strong decays of baryonic resonances, while to compute the blue dashed one, the feed-down has been left out. The results from the STAR collaboration indicates a ratio close to 1. This value is above the thermal model prediction by twice the error quoted by the experiment. On the other hand, the results from the E864 collaboration at the AGS energy are, although with large uncertainties, consistent with the thermal model prediction.

Also, Fig. 3.12 shows the measured energy dependence for the ${}^3\text{He}/{}^3\text{H}$ (empty circles); the measured energy dependence of the ${}^3\text{He}/{}^3\text{H}$ is well reproduced by the model calculations (black dotted line) presented in [157].

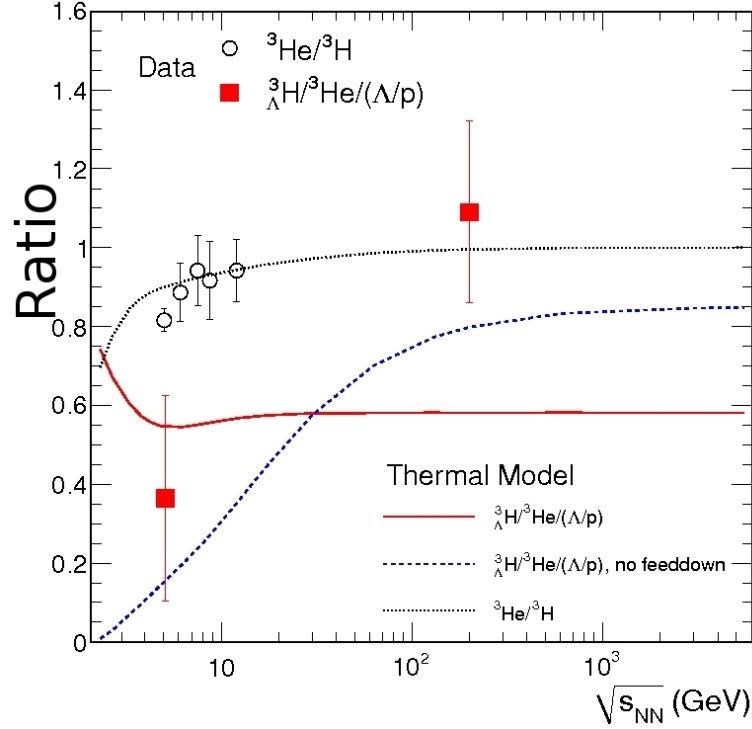


FIGURE 3.12: Energy dependence of nuclei and hypernuclei production ratios. The lines are thermal model calculations [157]. Full squared symbols are data for S_3 measured by E864 collaboration [121] and STAR experiment [111]. Red full line is S_3 vs $\sqrt{s_{NN}}$, when the feed-down from strong decays of baryonic resonances has been included to compute the Λ/p ratio. To calculate the blue dotted line, the feed-down has been subtracted. The empty circles refer to the measured energy dependence of the ${}^3\text{He}/{}^3\text{H}$, while the black dotted line represents the thermal model calculations [157].

3.4.3 Coalescence model with cascade and UrQMD thermal model

Results for S_3 from [147] are shown in figure 3.13 as a function of the beam energy $\sqrt{s_{NN}}$. S_3 is evaluated for the mid-rapidity region ($|y_{CM}| < 0.5$) of most central ($b < 3.4$ fm) heavy ion collisions. The lines are the results from the UrQMD-hybrid model and the symbols are the DCM (Dubna Cascade Model) coalescence results. Experimental data (from AGS-E864 experiment [121] and BNL-STAR experiment ($\sqrt{s_{NN}} = 200$ GeV)[111]) are shown as green symbols with error bars. The *thermal variables* used to perform the calculations of the UrQMD-hybrid model are: $T = 170$ MeV and $\mu_B = 0$ MeV. Because experiments usually cannot distinguish between Λ and Σ^0 , S_3 is shown in the cases where the Λ yield includes Σ^0 (black solid line and squares) and where the yield is corrected for the Σ^0 (red dashed line and circles). The double ratio S_3 from the

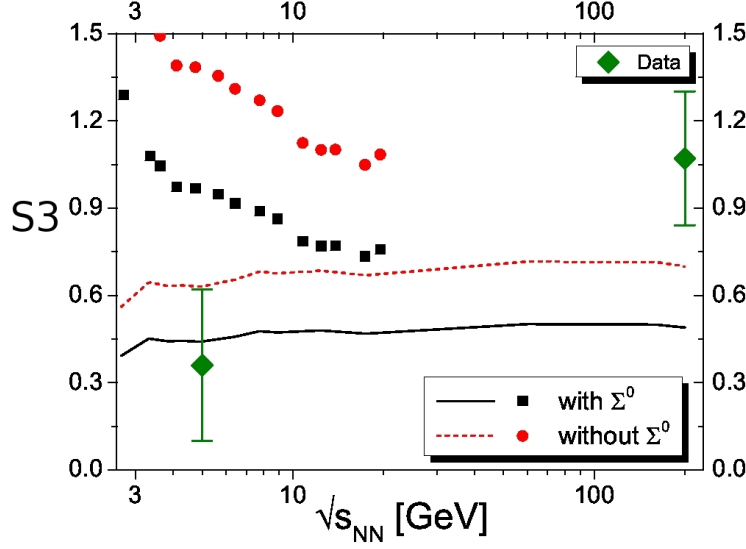


FIGURE 3.13: The Strangeness Population Factor $S_3 = (\frac{3}{\Lambda} H / \frac{3}{He}) \times (p/\Lambda)$ as a function of $\sqrt{s_{NN}}$ for most central collisions ($b < 3.4 fm$) of Pb–Pb(Au–Au). Results from the thermal production in the UrQMD hybrid model (lines) are compared to coalescence results with the DCM model (symbols). The red line and symbols denote values of S_3 where the Λ yield has been corrected for the Σ^0 contribution [147].

UrQMD-hybrid thermal model is almost energy independent, while the coalescence result increases with decreasing beam energy and it is in general larger than the thermal result.

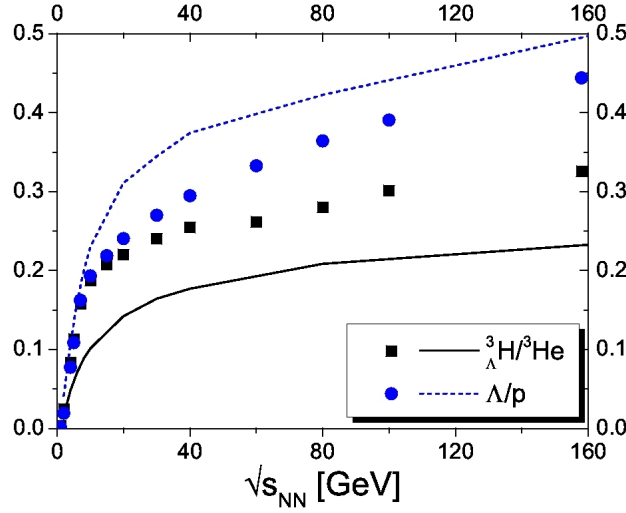


FIGURE 3.14: Single ratios of $(\frac{3}{\Lambda} H / \frac{3}{He})$ (black solid line and circles) and Λ/p (blue dashed line and squares) as a function of $\sqrt{s_{NN}}$ for most central collisions ($b < 3.4 fm$) of Pb–Pb(Au–Au). Results from the thermal production in the UrQMD hybrid model (lines) are compared to coalescence results with the DCM model (symbols) [147].

Fig. 3.14 shows the single ratios $\frac{3}{\Lambda} H / \frac{3}{He}$ and Λ/p from the hybrid thermal model (lines) and the DCM coalescence model (symbols). A stronger correlation seems to be in the transport calculation and in the hydrodynamic description. This observation leads

to the conclusion that the information on correlations of baryon number and strangeness is lost in the thermal calculation because here S_3 essentially depends only on the temperature. On the other hand, in the microscopic treatment the correlation information survives and S_3 follows the trend of c_{BS} .

Study of the production of $(\bar{\Lambda}^3 \text{H})^3_{\Lambda} \text{H}$ with the ALICE detector

4.1 Introduction

Relativistic heavy-ion collisions offer a unique opportunity for hypernuclear studies: it is possible to produce at the same time and with equal abundance matter and anti-matter, i.e. hypernuclei and their associated anti-hypernuclei, as discussed in Chapter 3.

The hypertriton $^3_{\Lambda} \text{H}$ is the lightest known hypernucleus and is formed by a proton, a neutron and a Λ . $^3_{\Lambda} \text{H}$ decays mesonically into the following channels [178]:

$$^3_{\Lambda} \text{H} \rightarrow \pi^{-}(\pi^0) + ^3\text{He}(^3\text{H}) \quad (4.1)$$

$$^3_{\Lambda} \text{H} \rightarrow \pi^{-}(\pi^0) + d + p(n) \quad (4.2)$$

$$^3_{\Lambda} \text{H} \rightarrow \pi^{-}(\pi^0) + p + n + p(n) \quad (4.3)$$

The study of the production of $^3_{\Lambda} \text{H}$ detected via its decay $^3_{\Lambda} \text{H} \rightarrow ^3\text{He} + \pi^{-}$ using ALICE will be presented in this chapter. The analysis is based on the statistics collected by the ALICE experiment during the first two heavy-ion data taking periods at the LHC (see Chapter 2.1).

The data collected at the end of 2010 have been available since April 2011, when they were validated by the collaboration. By April 2012 the data collected at the end of 2011 have been fully reconstructed and validated. For this reason in the present chapter the data analysis is divided in two different parts and two distinct analysis procedures will be described in the present chapter. The 2010 statistics was sufficient to extract an integrated p_{T} yield. Two methods have been studied to extract the signal corrected by the detector's acceptance because the statistics of 2010 inhibits a detailed study of acceptance dependence on p_{T} . The first one is based on the correction of the yield by

means of a mean efficiency, while the second is based on a procedure which uses 2-dimensional histograms. The latter method is based on two 2-dimensional histograms (Invariant Mass vs p_T) for Signal+Background(${}^3\text{He}, \pi^-$)(S+B) and Background (${}^3\text{He}, \pi^+$, Like-Sign background)(B). By their subtraction ((S+B)-B) it is possible to get the Signal (S). The S histogram is corrected for the efficiency calculated in 20 p_T bins and is finally projected to a 1-dim histogram in order to get integral the yield.

On the other hand, the 2011 statistics allows to divide the signal in 3 p_T bins ([2-4],[4-6] and [6-10] GeV/c), therefore the acceptance correction analysis can be performed taking into account directly the signal dependence on p_T . Each signal is corrected for the corresponding efficiency and it will be possible to obtain the ${}^3\Lambda$ H spectrum vs p_T . The same analysis can be performed on anti-matter.

With the 2011 data set it is also possible to extract the lifetime of ${}^3\Lambda$ H. The total invariant mass spectrum can be divided into 3 ct bins and an estimation of the ${}^3\Lambda$ H mean lifetime is provided at the end of this chapter.

4.2 Data Sample and Event Selection

4.2.1 Data Sample

For the present analysis the 2010 and 2011 Pb–Pb data taking have been used. For the 2010 analysis, 93 runs tagged as “good” by the ALICE data quality group have been used while for the 2011 the good runs are 108. To evaluate the efficiency a simulation based on (“anchored to”) the data has been used. The Monte Carlo productions are based on a pure Hijing event simulation enriched with ${}^3\Lambda({}^3\bar{\Lambda})$ and ${}^3\text{He}({}^3\bar{\text{He}})$, because the Hijing generator reproduces many inclusive particle spectra but those of nuclei. Moreover, the injected particle abundance does not correspond to the data, because the purpose of this simulation was to evaluate the efficiency to ${}^3\Lambda$ H and ${}^3\text{He}$ at a reasonable CPU-cost. For each event, 20 ${}^3\Lambda$ H, 20 ${}^3\bar{\Lambda}$ H, 5 ${}^3\text{He}$ and 5 ${}^3\bar{\text{He}}$ have been injected. Besides, the p_T spectra of the injected particles are non realistic: injected particles have a flat p_T ($0 \leq p_T \leq 10$ GeV/c) and a flat rapidity ($|Y| < 1$) distributions.

4.2.2 Event Selection

The ALICE on-line minimum bias (MB) trigger selection is based on the coincidence of the VZEROA and VZEROC signals (V0A && V0C) (see Chap. 2.3.13). In order to get rid of electromagnetically generated background, an additional coincidence of the signals of the zero-degree calorimeters is required ((V0A && V0C) && (ZNA && ZNC)). Additional triggers have been used in the 2011 data taking. For the present analysis only *Minimum-Bias*, *Central* and *Semi-Central* events have been analysed. The on-line

selections used to record Central and Semi-Central events are the same of the minimum bias selections, but an additional trigger on the centrality of the event is imposed: central events must have centrality between 0-10% (Central Events: MB+CVHL), while semi-central events have a centrality between 0-50% (MB+ CVHN). Table 4.1 summarizes the on-line triggers used during the data taking.

Trigger type	Definition
Basic Interaction	V0A && V0C
Minimum Bias (MB)	V0A && V0C && ZNA && ZNC
T0 vertex	$ z_{\text{vertex}} < 10 \text{ cm}, \pm 0.5 \text{ cm at edges}$
Central (v1) (v2)	VZEROA && VZERO C & High threshold (0-10% centrality) v1 + T0 vertex
Semi-Central (v1) (v2)	VZEROA && VZERO C & Low threshold (0-53% centrality) v1 + T0 vertex

TABLE 4.1: 2011 ALICE on-line trigger selection

In the off-line analysis the trigger conditions are recomputed using reconstructed data and an additional cut on the position of the z coordinate of the primary vertex is imposed $|z_{\text{vertex}}| < 10 \text{ cm}$. The off-line procedure of tracks selection is called the “ALICE physics selection”. The “ALICE physics selection” is applied in this analysis.

4.2.3 Centrality Selection

The geometry of the collision for the centrality analysis was studied using the Glauber model, assuming a Woods-Saxon distribution for the nucleon density profile inside the colliding nuclei. The nuclear overlap function T_{AA} [180] is the convolution of the two distributions in the overlap geometrical region. Some centrality classes in the centrality range 0-80% with their corresponding values of average T_{AA} , N_{part} and N_{coll} evaluated in a pure Glauber model are reported in table 4.2. The centrality information can be obtained experimentally by the multiplicity in the VZERO scintillators, the number of tracks in the TPC, the number of clusters in the SPD layers or the number of tracklets¹ in the SPD, the multiplicity in the FMD, the energy deposited in the ZDC calorimeters by the spectator nucleons, which for central events (up to 40% centrality) is correlated to the energy deposited in the ZEM electromagnetic calorimeters to remove the bias from nuclear fragments.

In the present analysis the centrality estimation was done using the multiplicities from the VZERO scintillators (abbreviated as V0M). The distribution of the VZERO amplitudes is shown in Fig. 4.1a for minimum bias events, where the centrality percentiles are also indicated. The centrality percentile 0-5% contains the 5% most central events. The VZERO distribution is compared to the Glauber Monte Carlo simulation

¹In ALICE a tracklet is defined as a track segment measured by the SPD detector

Centrality	b_{min} (fm)	b_{max} (fm)	N_{part}	N_{coll}	T_{AA}
0-2%	0.00		399 ± 3	1824 ± 294	$28 \pm 2.$
2-5%		3.50	372 ± 6	1599 ± 181	$24 \pm 2.$
5-10%	3.50	4.95	330 ± 5	1320 ± 154	$21 \pm 1.$
0-5%	8.55	3.50	383 ± 3	1687 ± 198	$26 \pm 1.$
0-10%	0.00	4.95	356 ± 4	1503 ± 170	23 ± 1
10-20%	4.95	6.98	260 ± 4	923 ± 100	14 ± 0.6
20-30%	6.98	8.55	186 ± 4	559 ± 56	9 ± 0.4
30-40%	8.55	9.88	129 ± 3	321 ± 31	5 ± 0.2
40-50%	9.88	11.04	85 ± 3	172 ± 15	3 ± 0.1
50-60%	11.04	12.09	53 ± 2	85 ± 8	1.3 ± 0.09
60-70%	12.09	13.06	30 ± 1	38 ± 4	0.6 ± 0.04
70-80%	13.06	13.97	16 ± 1	16 ± 1	0.2 ± 0.02
80-90%	13.97	14.96	7 ± 0.4	6 ± 0.5	0.1 ± 0.01
90-100%	14.96	19.61	4 ± 0.1	3 ± 0.1	0.04 ± 0.01

TABLE 4.2: Average values of the minimum (b_{min}) and maximum impact parameter (b_{max}), the number of participating nucleons (N_{part}), the number of binary collisions (N_{coll}), and of the nuclear overlap function (T_{AA}) for the considered centrality classes, expressed as percentiles of the nuclear cross section from the Glauber model.

convoluted with a negative binomial distribution in order to take into account the relation between the number of produced particles $N_{primary}$, the number of participants N_{part} and collisions N_{coll} according to the rule:

$$N_{primary} = f \times N_{part} + (1 - f)N_{coll} \quad (4.4)$$

where the parameter $f = (78.8 \pm 7.8)\%$, which quantifies the relative contributions of N_{part} and N_{coll} , is extracted from the fit to the $dN_{ch}/d\eta/(0.5 \times N_{part})$ distribution. The number of participants per centrality class obtained as percentile of the geometrical cross section from a Glauber Monte Carlo is shown in Fig. 4.1b.

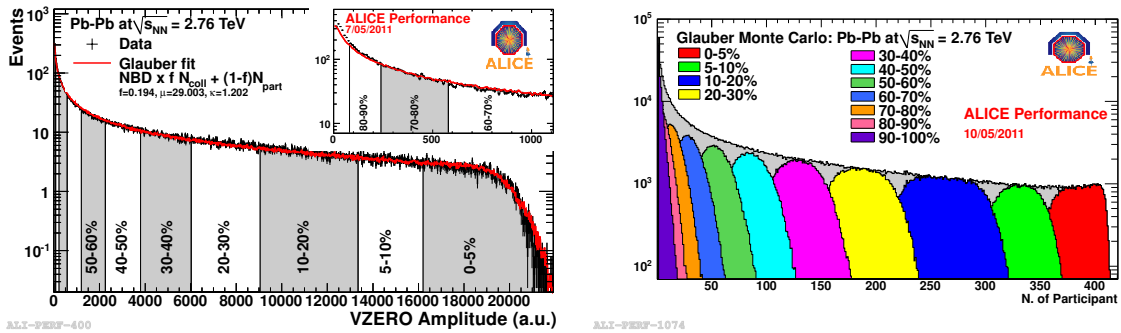


FIGURE 4.1: a) Glauber fit to VZERO distribution b) Number of participants from the Glauber model.

4.2.4 Selected events

Table 4.3 summarizes the event selections used for the analysis. Events to be selected have to pass the standard physics selections.

	Period	Cuts	Trigger	Centrality
2010	LHC10h pass 2 (ESDs)	ITS+TPC vertex $ v_z < 10$ cm	Minimum Bias	0-80%
2011	LHC11h pass 2 (ESDs)	ITS+TPC vertex $ v_z < 10$ cm	Central Semi-Central	0-10% 10-50%

TABLE 4.3: Selections used for the analysis. In addition to the selections listed in this table, the standard physics selections have been applied.

In total, from the 2010 data taking, about 13×10^6 minimum bias events have been selected for the analysis. For the 2011 data ~ 23 millions central events and ~ 20 millions Semi-Central events have been analysed. Moreover, the central events have been divided into 3 centrality classes, and the multiplicity of each class is reported in Table 4.4 under the column “Number of events”.

Centrality	Number of events
0-10 %	2.30×10^7
0-2 %	4.65×10^6
2-5 %	7.23×10^6
5-10 %	1.11×10^7

TABLE 4.4: Number of events for different centrality classes recorded during the 2011 data taking.

Fig. 4.2 shows the charged particle track multiplicity for the selected events. In panel a) the charged track multiplicity for the 2010 data taking is shown, while panel b) shows the track multiplicity distributions of the events selected for the 2011 data analysis.

4.2.5 Charged particles selection

Only tracks which pass quality selections are accepted in the analysis. Table 5.1 summarizes the cuts used to select the tracks in the present analysis. This set of cuts has been used both for the real and the Monte Carlo data.

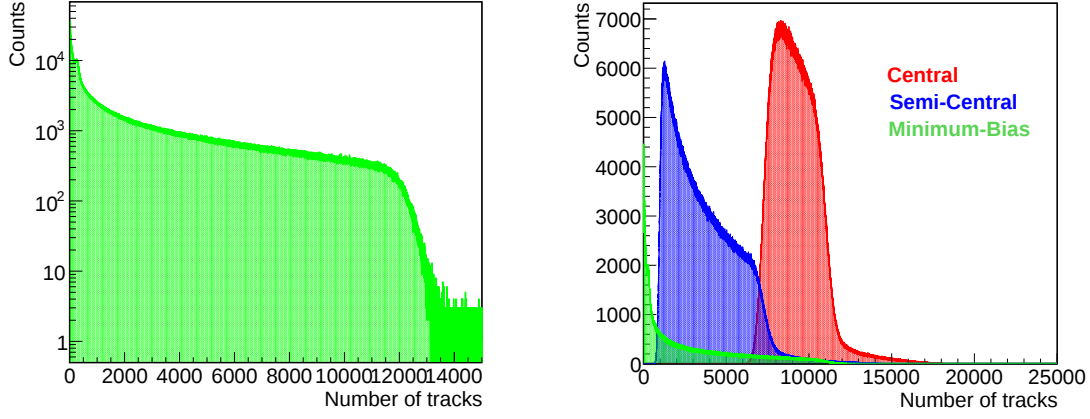


FIGURE 4.2: a) Track multiplicity distribution of MB events from the 2010 data taking. b) Track multiplicity distribution for central (in red), semi-central (in blue) and minimum bias (in green) events from the 2011 data taking.

Track cuts	Value
Kink daughter	reject
TPC refit flag	kTRUE
$n_{cluster}$ TPC	>60
Track χ^2	<5
$ \eta <$	1.2

TABLE 4.5: Cuts used for track selection in the analysis. The same cuts have been applied to real data and Monte Carlo.

4.3 Analysis technique

4.3.1 Particle IDentification

The main ALICE detector used to identify particles in this analysis is the Time Projection Chamber (TPC). The signal in the TPC is given by the energy loss by particles passing through the detector. To identify particles, it is possible to compare the measured dE/dx value with the value of a Bethe-Bloch function that gives the expected energy loss. The Bethe-Bloch function vs p_T depends on the mass of the particle and in ALICE it is usually rewritten using the ALEPH parametrization:

$$\frac{dE}{dx}(m, p) = \left[k_1 - \beta^{k_3} - \log \left(k_2 + \frac{m^{k_4}}{p} \right) \right] \frac{k_0}{\beta^{k_3}} \quad (4.5)$$

The free parameters (k_0, k_1, k_2, k_3, k_4) are determined by fitting the data. Fig. 4.3 shows the measured specific energy loss (dE/dx) versus rigidity $R = p/Z$, where p is the track momentum and Z is the charge number. The superimposed lines are Bethe-Bloch curves parametrized by means of the ALEPH function, for the different particle species.

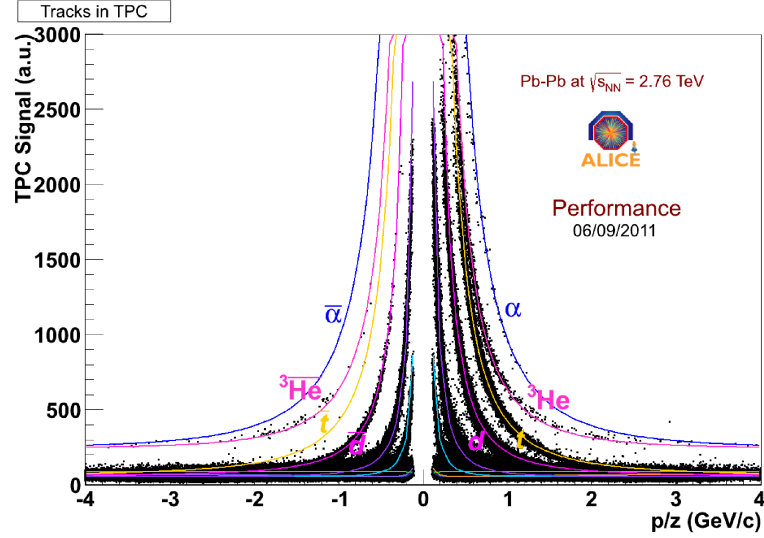


FIGURE 4.3: (dE/dx) in the TPC versus rigidity $R=p/Z$ with Bethe-Bloch curves superimposed.

If the energy lost by a certain track lies within a certain number of σ 's from the expected mean value of the Bethe-Bloch for a certain particle species, then the track is identified as that particle species [181]. Pions are identified by using a 2σ cut, while ${}^3\text{He}$ are identified by using an asymmetric sigma dE/dx cut.

Fig. 4.4 shows the selected tracks for the analysis: pions are in green while ${}^3\text{He}$ are in blue.

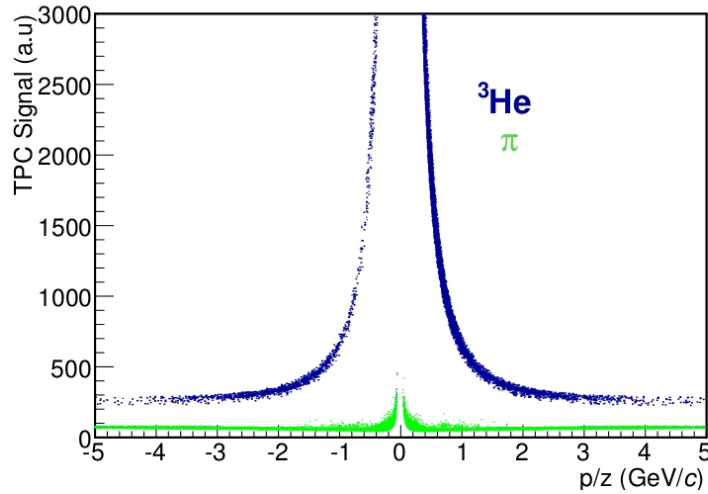


FIGURE 4.4: π (green) and ${}^3\text{He}$ (blue) selected by TPC dE/dx vs p_T analysis.

Nuclei can be produced also by secondary interactions of the particles with the different materials. In order to reduce such a contamination a further cut on the distance of closest approach along the beam axis ($\text{DCA}_Z < 1$ cm) for ${}^3\text{He}$ candidates is applied in addition to the standard track selections. Further details can be found in Chap.5.3.1

4.3.2 Vertex selection

Once both daughter tracks are identified, it is possible to identify the hypertriton signal candidates by reconstructing their decay vertices. Fig. 4.5 shows a pictorial view of the two-body decay of a particle. A set of topological cuts, which are also indicated in the figure, has been implemented in order to reduce the combinatorial background. These cuts include: distance of closest approach (DCA) between the two particle tracks identified as ${}^3\text{He}$ and $\pi^\pm$ in TPC, DCA of the $\pi^\pm$ tracks from the primary vertex, cosine of the pointing angle between the primary and secondary vertex and cut on the lifetime multiplied by c ($ct = \frac{ML}{p}$) of the candidate. In order to reduce the size of the analysed data, a set of loose cuts have been applied to the reconstructed data. These cuts are listed in Table 4.6

Cut	Value
Pion identification	2σ
${}^3\text{He}$ identification	asymmetric σ cut
$ \text{DCA}_Z {}^3\text{He}$	< 1 cm
$\text{DCA}_{\text{tracks}}$	< 1 cm
$\text{DCA}_{\pi \text{ to PV}}$	> 0.1 cm
$\text{Cos}(\text{PointingAngle})$	> 0.9
$\frac{ML}{p}$	< 40 cm
$\frac{ML}{p}$	> 1 cm
p_T	> 2 GeV/c
p_T	< 10 GeV/c

TABLE 4.6: Initial cuts applied to the reconstructed data.

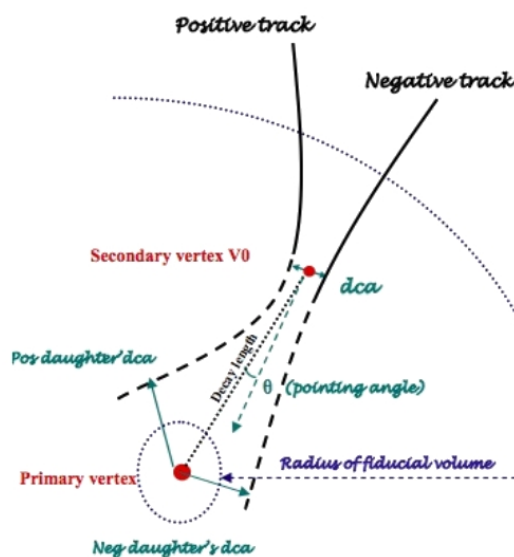


FIGURE 4.5: Pictorial view of a 2-body decay. The observables which have been studied in order to reduce the combinatorial background are shown directly on the figure.

In order to reduce the combinatorial background, tighter topological cuts have been implemented. Fig. 4.6 shows the invariant mass of ${}^3\text{He}$ and π pairs as a function of several observables (i.e. DCA between tracks, DCA of π from the primary vertex, proper lifetime (ct) and cosine of the pointing angle (CPA)) with the Monte Carlo data.

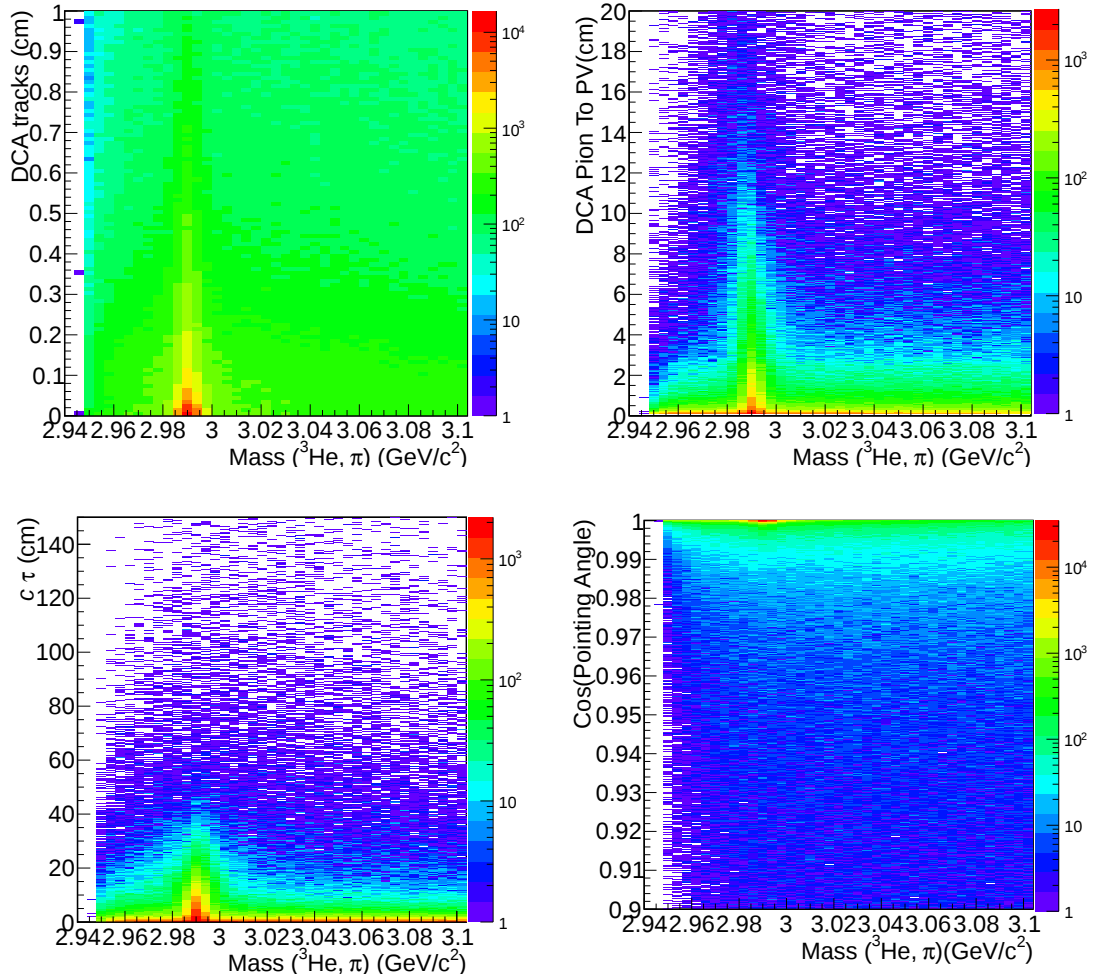


FIGURE 4.6: Invariant mass of MC (${}^3\text{He}, \pi$) pairs vs: a) DCA between tracks, b) DCA of π from the primary vertex, c) proper lifetime (ct) and d) cosine of the pointing angle (CPA). Events satisfied the cuts listed in Table 4.6.

Fig. 4.7 shows the Signal/Background (S/B) ratio on MC data. To perform this plot each cut has been singularly applied and changed while leaving out all the other cuts. The last value (blue bar) corresponds to the best S/N result when applying all the cuts at the same time. The set of cuts which gives the highest S/B and highest significance², is listed in Table 4.7.

In this analysis, tracks from each event are read from ESDs³, then the PID is applied. If in a given event at least one π and one ${}^3\text{He}$ track are present, the secondary vertex algorithm is applied. These pairs become then ${}^3_\Lambda\text{H}$ candidates and the rest of the analysis

²Significance is defined as: $\text{Significance} = S / \sqrt{S + B}$, where S are the counts of the signal and B the ones of the background.

³ESD (Event Summary Data) is the result of massive reconstruction and contains all the information the the analysed event [79]

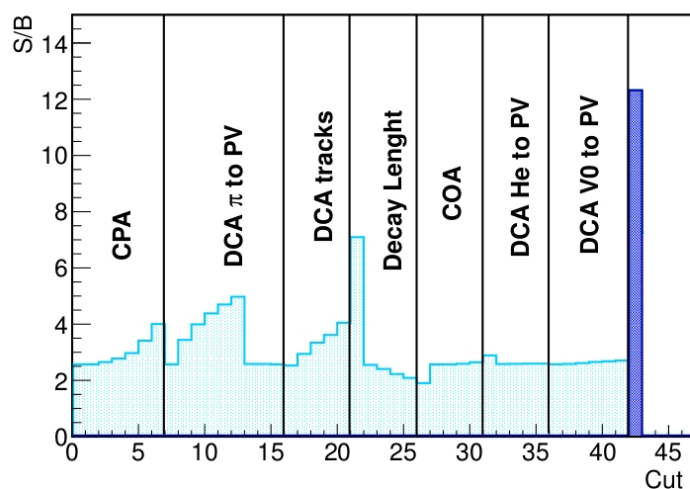


FIGURE 4.7: S/B ratio as a function of the cut indicated by the corresponding label. The cut value is just an index, all the other cuts are excluded. The blue bar is the best results of the combination of different cuts, which are listed in Table 4.7.

Cut	Value
$ DCA_Z \text{ } ^3\text{He}$	$< 1 \text{ cm}$
DCA_{tracks}	$< 0.7 \text{ cm}$
$DCA_{\pi \text{ to PV}}$	$> 0.4 \text{ cm}$
$\text{Cos}(\text{PointingAngle})$	> 0.99

TABLE 4.7: Further selections applied to reconstruct the $\bar{\Lambda}^3\text{H}$ both with real data and MC.

is performed.

4.4 $\bar{\Lambda}^3\text{H}$ yield extraction from 2010 data

4.4.1 Invariant mass spectrum

Fig. 4.8 shows the invariant mass spectrum of $(^3\text{He}, \pi^-)$ pairs that have passed the cuts listed in Table 4.6 and Table 4.7. Experimental data are represented by black circles, while the red histogram is the “like-sign” LS $(^3\text{He}, \pi^+)$ invariant mass spectrum used to evaluate the background. The green curve is the sum of a third degree polynomial (pol3) – used to evaluate the combinatorial background – and a Gaussian function for the signal.

The full circles in the bottom part of the plot are data after the pol3 background subtraction, and the superimposed black line is the Gaussian function.

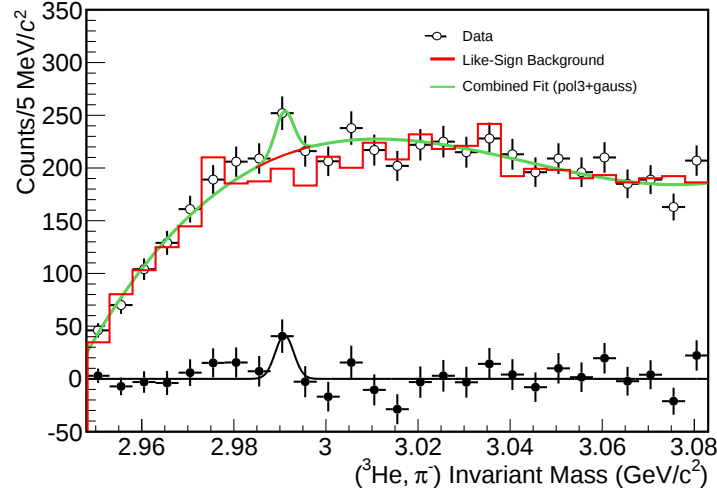


FIGURE 4.8: $(^3\text{He}, \pi^-)$ Invariant mass distribution fitted by (pol3 + Gaussian function) (Green curve). Empty black circles are the data points while the red histogram is the “Like-Sign” LS $(^3\text{He}, \pi^+)$ invariant mass distribution.

4.4.2 Background estimation and Signal extraction

In the present analysis the background has been studied with two different methods. The first one is the “like sign” background which consists of the combination of two tracks with the same sign (i.e. $^3\text{He} + \pi^+$), and the second is the *combined fit* (third degree polynomial function for the background and a Gaussian for the signal) of the invariant mass spectrum.

The like-sign technique is an approach to subtract the background of non-correlated pairs from the “unlike-sign” $(^3\text{He}, \pi^-)$ invariant mass distribution from the same events. The uncorrelated background in the unlike-sign distribution is described by using the invariant mass distributions obtained from uncorrelated $(^3\text{He}, \pi^+)$ from the same events. Compared to other techniques (e.g. mixed-event), the like-sign technique has the advantage that the unlike-sign and like-sign pairs are taken from the same event, so there is no event structure difference between the two distributions resulting from effects such as elliptic flow or centrality. The drawback of this technique is that the like-sign distribution has larger statistical uncertainties compared to the mixed-event spectrum. Therefore, in this analysis, the combined fit method was used in order to avoid the large uncertainties of the like-sign technique. In the combined fit the initial background parameters are extracted by fitting the like-sign invariant mass distribution with the pol3 background function, then a global fit is performed on the unlike-sign distribution with a pol3 plus Gaussian function. From the combined fit (green line in figure 4.8) it is possible to extract the mean μ , width σ , raw yield and significance of the signal.

Table 4.8 shows the value obtained for μ , σ , raw yield.

The mean value from the fit is compatible within 2σ with the one from literature [182].

	2010 Analysis
Total Statistics (events)	12.3 M
Raw Yield (2σ)	68 ± 25
Mean $\mu(\text{GeV}/c^2)$	2.992 ± 0.001
Sigma $\sigma (\times 10^{-3}\text{GeV}/c^2)$	2.1 ± 0.5
Significance	3.65

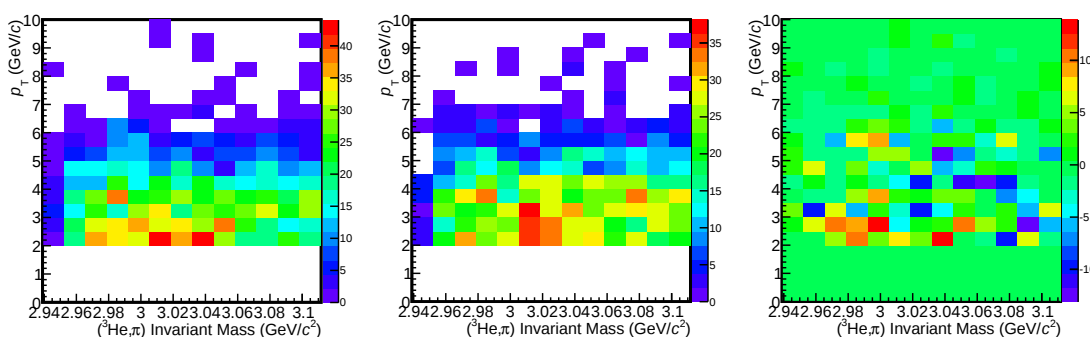
TABLE 4.8: Summary of raw yield, μ , σ of the signal by using 2010 data.

Since the efficiency (see Section 4.4.3) shows a very strong dependence on p_T (see Fig. 4.11c) and since the statistics of the 2010 is not large enough to extract the signal in more than one $(\bar{\Lambda}^3\bar{H})\Lambda^3H$ p_T bin, a method based on 2-dim (Invariant Mass vs p_T) histograms has been studied. This method will be used for the efficiency correction (See Section 4.4.4). After the normalization, the 2-dim Background (Like-Sign) histogram (**B**) is subtracted from Signal+Background histogram (**S+B**), getting the Signal **S** [**S** = (**S+B**)-**B**]. From the projection along the X (invariant mass) axis it is possible to obtain the signal integral. In order to reduce fluctuations the invariant mass axis (X-axis) has less bins w.r.t. the previous histograms shown in Fig. 4.8.

For the analysis based on the 2-dim histograms the bin widths are :

	Bin Width Value
X-axis (Invariant mass)	$13.3 \text{ MeV}/c^2$
Y-axis (p_T)	$0.5 \text{ GeV}/c$

Fig. 4.9 shows the procedure to extract the invariant mass from the 2-dim histograms.

FIGURE 4.9: Signal extraction procedure using 2-dim (Invariant Mass vs p_T) histograms. a):(S+B) b):(B) c):(S=(S+B)-B)

In Fig. 4.10 the projections along the mass axis of the 2-dim histograms of Fig. 4.9 are shown. The blue line is the projection of the (S+B) histogram, the red one is the projection of the Like-sign histogram (B), while the yellow histogram is the result of the subtraction of the two (S).

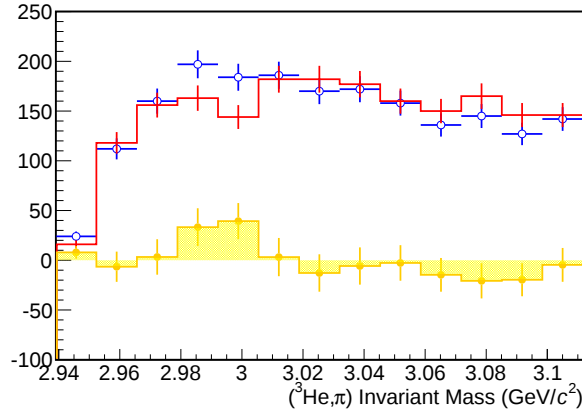


FIGURE 4.10: Projection along the x-axis (mass) of the histograms shown in Fig. 4.9. The blue histogram is the projection of the (S+B) histogram while the red one is projection of the like-sign one (B). The yellow histogram is the subtraction of the two (S).

The raw yield obtained using this method is 73 ± 26 . This number is compatible with the one shown in table 4.8.

In order to validate the method based on 2-dim histograms, a further check was done by using a sub-sample of the MC simulation. To perform this test, the MC sample has been adjusted in order to have a signal over background ratio similar to the one of the data. Two cases have been considered: in the first one the sub-sample used had a high statistics, while in the second one it had the same order of magnitude of the data. The yields resulting after the signal extraction procedure are shown in Table 4.9, together with the MC truth yield ⁴. The method works fine in both cases.

	MC truth	Yield (2-dim method)
High statistics	293	264 ± 100
Low Statistics	30	29 ± 17

TABLE 4.9: Yields extracted by means of the 2-dim method compared to the MC truth in case of high and low statistics.

4.4.3 Monte Carlo Simulation and Efficiency Computation

To evaluate the reconstruction efficiency the Monte Carlo (MC) simulation anchored to the 2010 data has been used. As already mentioned, the simulation is based on a pure minimum-bias Hijing event simulator, where ${}^3_{\Lambda}H$ and ${}^3_{\Lambda}\bar{H}$ signals have been injected flat in p_T , η and centrality. To compute the efficiency two methods have been used. The first one uses the simple MC truth of the reconstructed particle, while in the second one the signal extraction is applied to simulated data using the “like-sign” method. Nevertheless, in both cases, the PID is performed by MC truth instead of TPC dE/dx in order to

⁴The “MC truth yield” is the number of reconstructed pairs identified as “real” ${}^3_{\Lambda}H$ by means of their PDG code.

avoid systematic errors and contaminations due to dE/dx PID in the efficiency determination.

The efficiency⁵ numerator (“reconstructed signal”) is filled in the analysis stage, after all the event selections. The efficiency denominator is filled with MC generated primary $\Lambda^3H(\bar{\Lambda}^3\bar{H})$.

In order to check the stability of the signal extraction method based on the “like-sign” method, the mean (μ) and the width (σ) of the reconstructed signal were checked versus different variables (i.e. p_T , ct , η and the momentum of daughter tracks ${}^3\text{He}$ and π^-), and the efficiency has been evaluated as a function of the same variables.

Fig. 4.11a shows μ vs p_T , while Fig. 4.11b shows σ vs p_T . μ is stable (variation $<0.5\%$); also σ is quite stable and its variation is $\sim 2\%$. In Fig. 4.11c the efficiency as a function of p_T is shown. The efficiency depends strongly on p_T (it varies between 0 and $\sim 50\%$).

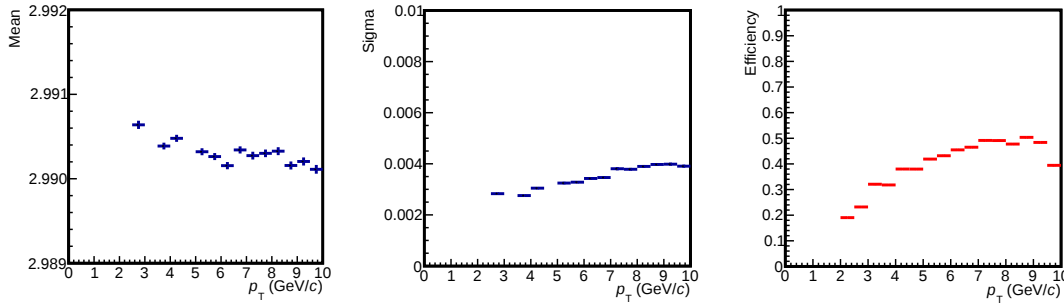


FIGURE 4.11: a) μ b) σ and c) Efficiency as a function of p_T .

Fig. 4.12 shows the μ , σ and efficiency versus ct ($ct = ML/p$). In this case the mean is quite stable, while the width of the signal varies from 3 to 7 MeV/c^2 : this is because the resolution gets poorer if the decay happens far from the primary vertex. Also the efficiency (panel c) shows a quite dependence on ct (it varies between ~ 24 and $\sim 40\%$).

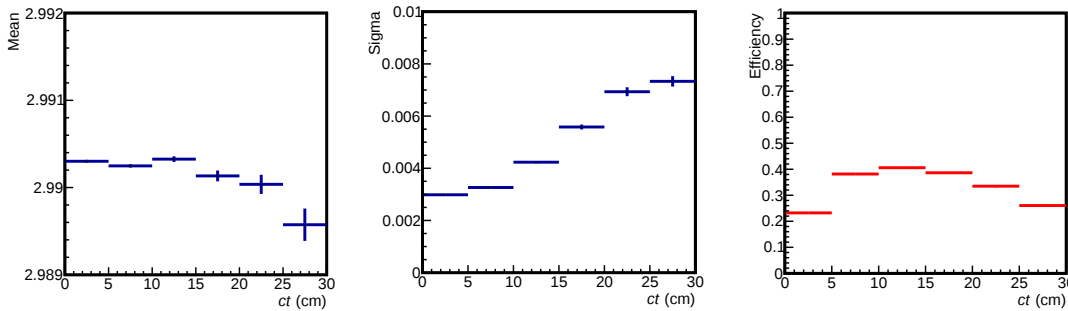


FIGURE 4.12: a) μ b) σ and c) Efficiency as a function of ct .

⁵Efficiency $\epsilon = \frac{\text{Reconstructed events}}{\text{Generated events}}$

Fig. 4.13c shows the ${}^3\Lambda$ H detection efficiency as a function of η , while, respectively, in Fig. 4.13a and Fig. 4.13a μ vs η and σ vs η are shown. The sigma dependence on η is expected: when η is close to ± 1 , ${}^3\text{He}$ particles pass through a larger amount of material and the energy loss becomes larger than for ${}^3\text{He}$ particles with η close to 0. The efficiency depends strongly on η (with $|\eta| > 0.5$). The statistics is too low in order to take into account p_T and η efficiency dependence together. It is possible to reduce the candidates to the $|\eta| < 0.5$ window, where the efficiency is flat, but the statistics strongly decreases (about 40%). Therefore, in the present analysis the efficiency dependence on η is not treated as correction factor but it will be included in the systematic error evaluation.

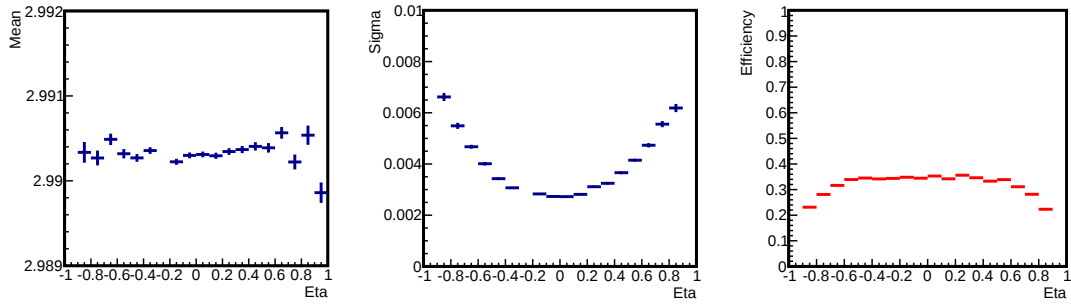


FIGURE 4.13: a) μ b) σ and c) Efficiency as a function of η .

Fig. 4.14a and Fig. 4.14b show the μ and σ of the extracted signal as a function of the ${}^3\Lambda$ H daughter ${}^3\text{He}$ momentum. It is possible to see how the momentum resolution strongly affects the width for rigidity ≥ 5 GeV/c as expected (see Fig. 2.8). Fig 4.14c shows the ${}^3\Lambda$ H reconstruction efficiency as a function of the ${}^3\text{He}$ daughter momentum.

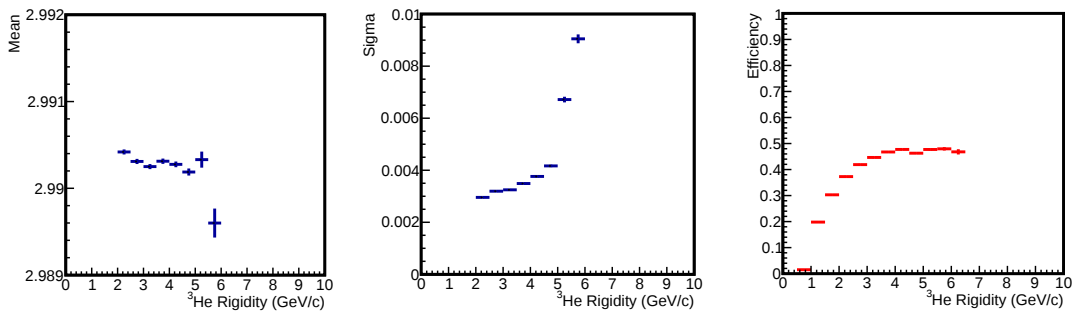


FIGURE 4.14: a) μ b) σ and c) Efficiency as a function of ${}^3\text{He}$ daughter rigidity.

Finally, Fig. 4.15a and Fig. 4.15b show the μ and σ of the extracted signal as a function of the ${}^3\Lambda$ H daughter π momentum. It is possible to see that the mean and sigma are quite stable once the statistics is big enough to extract a signal. Fig 4.15c shows the ${}^3\Lambda$ H reconstruction efficiency as a function of π daughter momentum. Efficiency depends strongly on daughters momenta, and will be included in the ${}^3\Lambda$ H efficiency corrections.

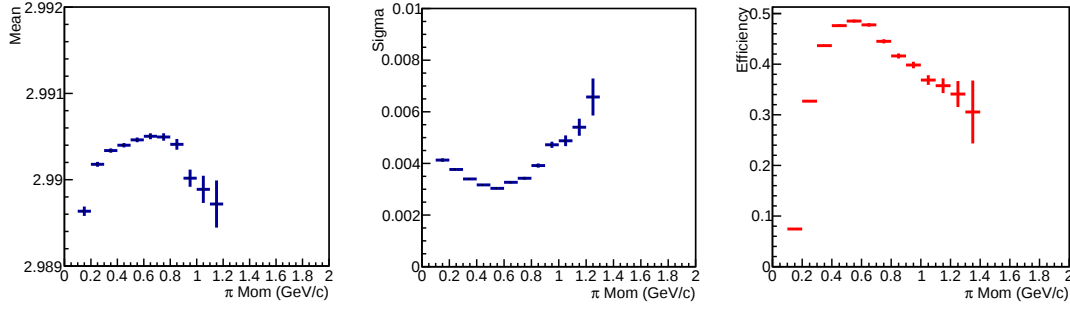


FIGURE 4.15: a) μ b) σ and c) Efficiency as a function of the daughter π momentum.

From Fig. 4.14 and Fig. 4.15 it is possible to observe also that the momenta of the two daughter tracks of $\bar{\Lambda}^3\text{H}$ are quite different. In fact the masses of $\bar{\Lambda}^3\text{H}$ and ${}^3\text{He}$ are similar (Mass (${}^3\text{He}$) = 2.808 GeV/ c^2 and Mass($\bar{\Lambda}^3\text{H}$) = 2.991 GeV/ c^2), while the mass of the pion is a factor 20 smaller (Mass(π) = 0.139 GeV/ c^2). Due to the large mass difference of the daughter particles, in the laboratory frame most of the momentum of the initial particle is carried away by the heavier particle. This can be seen in a phase-space diagram, shown in Fig. 4.16. The $\bar{\Lambda}^3\text{H}$ is generated with a initial flat p_T distribution and the momentum of the two daughter tracks is used to fill the phase-space histogram.

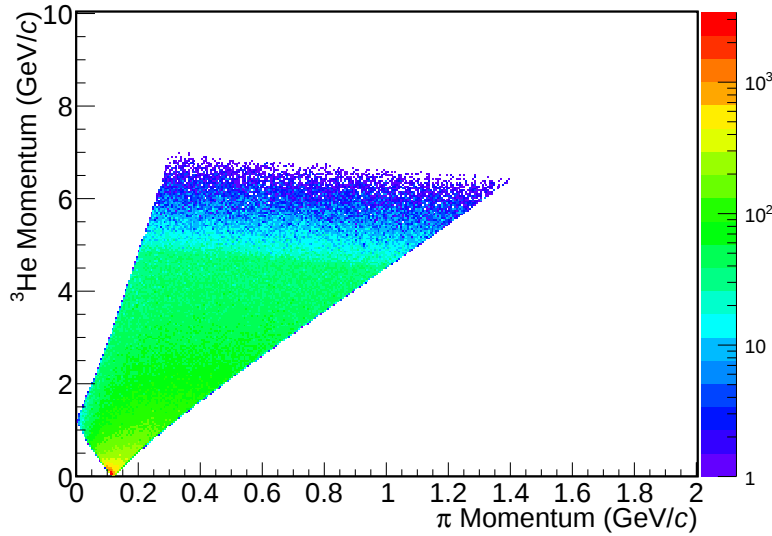


FIGURE 4.16: The momenta of the daughter tracks of $\bar{\Lambda}^3\text{H}$ generated with a flat p_T distribution are used to generate the phase-space shown in this figure.

Another important dependence which has to be taken into account is the connection between the efficiency reconstruction and the centrality of the event. Central events are expected to have a lower efficiency since the multiplicity is so high that the inefficiencies of tracks reconstruction become evident. Fig. 4.17a shows the efficiency vs p_T evaluated for different centrality bins. A dependence on the centrality can be seen. To quantify this dependence, the ratios of the efficiency in different centrality bin over

the 0-80% one has been evaluated (Fig. 4.17b). The efficiency in the 0-5% centrality bin (in cyan) is $\sim 30\%$ lower with respect to the one in the 0-80% centrality bin (in red), while efficiencies evaluated in the others centrality classes differs from the one at 0-80% by a factor less than 10%.

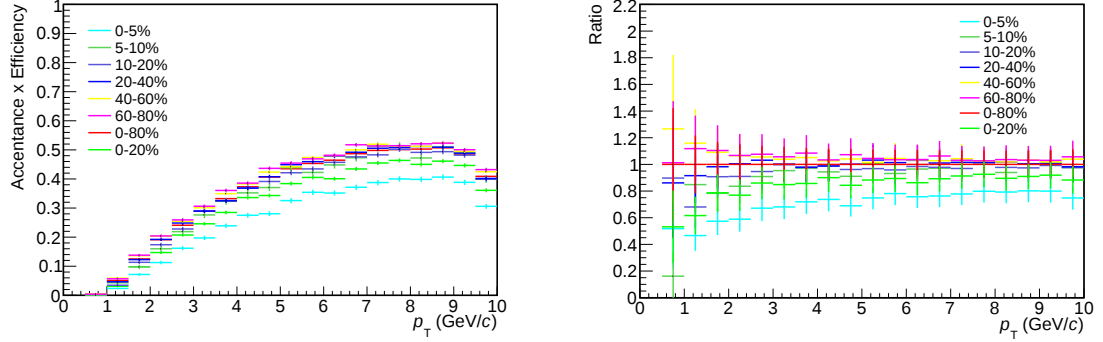


FIGURE 4.17: a) Efficiency vs p_T for different centrality. Different colors refer to different centrality classes as shown in the legend. b) Ratio of the efficiency vs p_T in different centrality bins over the one in the 0-80% centrality bin. Colours are the same as in the left panel, and are shown in the legend.

To take into account this dependence, a method to weight the efficiencies has been used. In the simulation the ${}^3_\Lambda\text{H}({}^3_\Lambda\bar{\text{H}})$ is injected with a flat distribution in centrality. However, assuming the Glauber model, particle production scales with the number of participants N_{part} . It means that in central collisions the number of produced ${}^3_\Lambda\text{H}$ is expected to be larger with respect to the peripheral ones; the scaling factor can be extracted from Table 4.2. For instance, in events with 0-5% centrality $N_{\text{part}}=382$, while in a event with a centrality 60-80% $N_{\text{part}}=22$; so, taking into account also the centrality bin width, to evaluate the mean efficiency, a weight of 1 is assigned to the 60-80% centrality bin, while a weight of 4.34 is assigned to the 0-5% bin. Fig. 4.18 shows the result (in green) which is compared to the efficiency in the 0-80% centrality bin (in red) and mean efficiency (in magenta).

The comparison between the two methods used to extract the efficiency (i.e. like-sign and MC truth) is shown in Fig. 4.19 for 0-80% of the centrality: the two methods are consistent in the whole p_T range of interest ($p_T > 2$ GeV/c) and for each centrality class.

4.4.4 Yield Correction

As already mentioned in Section 4.4.2, the 2010 statistics was not enough to extract the signal in more than one p_T bin. Therefore, two methods to extract the absolute yield have been studied.

The first method is based on a “ p_T mean efficiency” correction assuming the p_T distribution of ${}^3_\Lambda\text{H}$ is a Blast-Wave. Although it is not possible to use the efficiency shown in Fig. 4.18, as it has been obtained from an initial flat p_T distribution, it is possible to extract a mean p_T dependent efficiency by using the convolution of the efficiency with

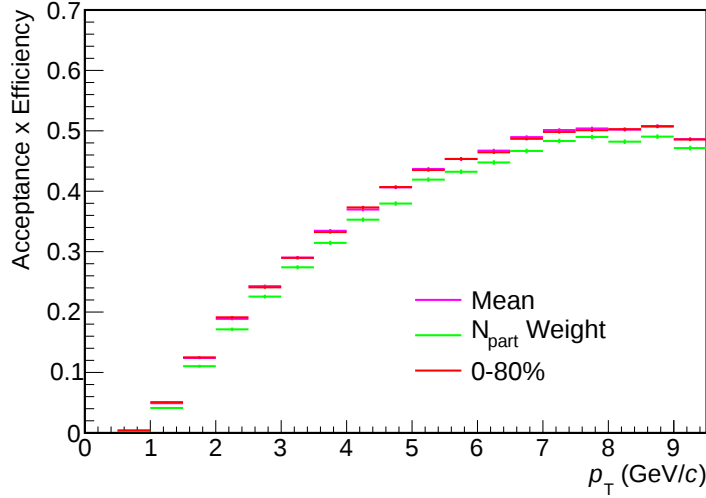


FIGURE 4.18: Efficiency vs p_T . In red the result for the 0-80% centrality bin, in magenta the mean efficiency, while in green the efficiency weighted for N_{part} .

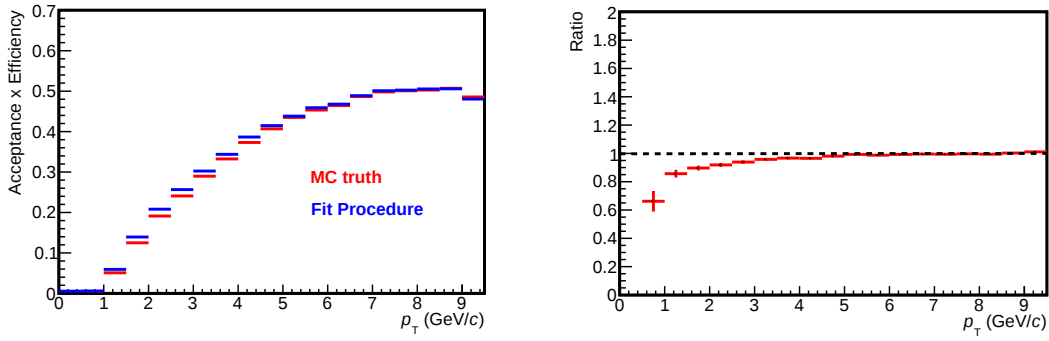


FIGURE 4.19: a) Efficiency vs p_T . Comparison of the two methods used to extract the efficiency (i.e. like-sign and MC truth). b) Ratio of the two efficiencies .

different p_T shapes. Usually the function used to describe the p_T shape of the different particles generated in the collisions is a Blast-Wave function (described in Appendix A), but other functions, such as Boltzmann, Bose-Einstein, Fermi-Dirac and Levi-Tsallis distributions (also described in Appendix A) can be used to evaluate the systematic error connected to this procedure. Each function depends on different parameters, which have been extracted from the fit to the ${}^3\text{He}$ p_T spectrum (described in Chapter 5). In Fig. 4.20 the different p_T shapes used to evaluate the mean efficiency are shown.

The value of the mean efficiency in the region [2-10] GeV/c after the convolution with a Blast-Wave function, is 0.228. This value implies that the absolute yield in the region [2-10] GeV/c is:

$$\text{Yield}_{2-10 \text{ GeV/c}} = 297 \pm 110 \quad (4.6)$$

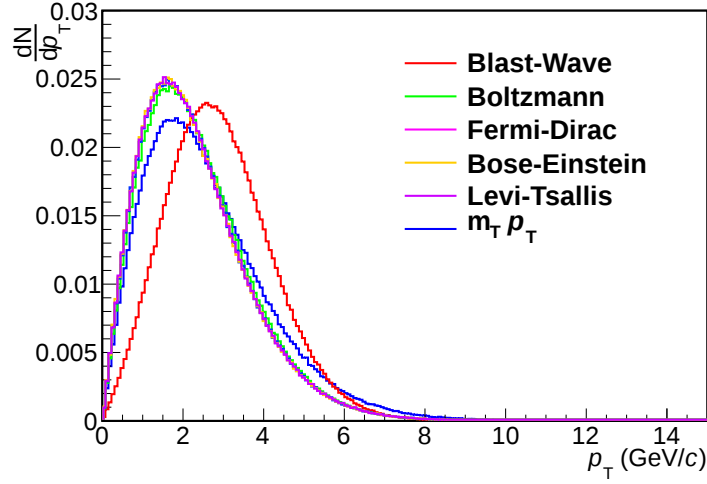


FIGURE 4.20: Different functions used to evaluate the mean p_T dependent efficiency.

This yield has to be corrected for the ${}^3\text{H} \rightarrow {}^3\text{He} + \pi^-$ branching ratio (B.R. = $35 \pm 4\%$) [179]. The yield after the BR correction becomes:

$$\text{Yield}_{2-10 \text{ GeV/c}} = 849 \pm 314 \quad (4.7)$$

To get the ${}^3\text{H}$ yield integrated over the full p_T range, it is necessary to know the shape of the ${}^3\text{H}$ p_T distribution; in this way it will be possible to extrapolate the “missing” yield in the regions where the efficiency is 0 (i.e. $p_T \leq 2 \text{ GeV/c}$ and $p_T \geq 10 \text{ GeV/c}$.)

The integral of the red histogram shown in Fig. 4.20, which corresponds to a Blast-Wave distribution, in the $[0-2] \text{ GeV/c}$ region, is 26.7% of the total, while for $p_T > 10 \text{ GeV/c}$ is less than 1%. These contributions can be added to the yield shown in eq. 4.7 to give the following result:

$$\text{Yield}_{0-10 \text{ GeV/c}}^{0-80\%} = 1158 \pm 428 \quad (4.8)$$

The second method used to obtain the absolute yield is based on 2-dim (Invariant Mass vs p_T) histograms, as explained in Section 4.4.2. After the normalization, the 2-dim Background (Like-Sign) histogram (**B**) is subtracted from Signal+Background histogram (**S+B**), getting the Signal **S** [**S** = (**S+B**)-**B**]. From the projection along the X (mass) direction it is possible to obtain the signal integral.

After the subtraction, the **S** histogram is corrected by applying the efficiency correction as a function of p_T . At this point, projecting along the X-axis the 2-dim histogram, the absolute yield with the associate error can be extracted.

The MC simulation has been used to test the goodness of this method. First of all, the efficiency vs p_T has been calculated (as described in Section 4.4.3) by using a sub-sample of the available MC sample ($\sim 1/6$ of the overall statistics). The same sample used to evaluate the efficiency is then corrected with the method described above.

Results are listed in Table 4.10.

	Value
Total MC Yield	18911
absolute yield	19215 ± 369

TABLE 4.10: Comparison between MC truth sample and absolute yield done by using the method described in Section 4.4.4. The corrected sample is the same used to evaluate the efficiency.

The absolute yield is comparable with the MC sample within 1% (and is inside the statistical error). The same test has been done with other sub-samples obtaining comparable results, but absolute yield overestimates the MC truth yield of about 1-2%. A second test was done using all the available MC statistics ($\sim 30K$ events) to calculate the efficiency, and then using this efficiency to correct a sub-sample of data. Results are listed in Table 4.11.

	Value
Total MC Yield	18911
absolute yield	19685 ± 327

TABLE 4.11: Comparison between MC truth sample and absolute yield done by using the method described in Section 4.4.4. The efficiency is computed using the full MC statistics, while only a sub-sample is corrected.

The absolute yield is compatible with the MC sample within 5%. The same test has been done with other sub-samples obtaining comparable results. The absolute yield varies with respect to the MC truth yield by about 6%. This error will be taken into account in the systematic uncertainty evaluation).

Once tested with the MC simulation the method was applied to the real data. The histograms of the invariant mass distribution of $({}^3He, \pi^-)$ with $2 \leq p_T \leq 10$ GeV/c, before (yellow) and after (violet) the efficiency correction are shown in Fig. 4.21.

The yield, calculated as the bin counts in a region that corresponds to a 3σ interval around the mean value of the peak, after the p_T correction ($2 \leq p_T \leq 10$ GeV/c) is:

$$\text{Yield}_{2-10 \text{ GeV/c}} = 274 \pm 111 \quad (4.9)$$

Again, this value has to be corrected for the B.R.; the yield after the correction is:

$$\text{Yield}_{2-10 \text{ GeV/c}} = 783 \pm 319 \quad (4.10)$$

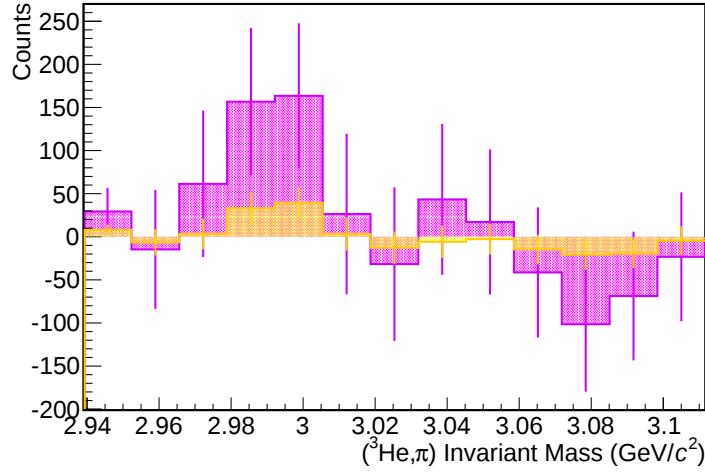


FIGURE 4.21: $(^3\text{He}, \pi^-)$ with $2 \leq p_T \leq 10$ GeV/c invariant mass distribution. The histograms are the projections along the x-axis of the 2-dim histogram (I.M. vs p_T) after the LS background subtraction. The yellow histogram is the $(^3\text{He}, \pi^-)$ I.M. distribution before the p_T correction, while the violet one is shown after the correction. The yield is calculated as the bin counts in a region that correspond to a 3σ interval around the mean value of the signal listed in Table 4.8.

Thus far, no assumption on the initial p_T shape of $^3_\Lambda\text{H}$ has been done. Anyway, to extract the integrated yield in the whole p_T range, it is necessary to make an assumption about the p_T shape. Again, assuming a Blast-Wave distribution, the missing strength is about 26.7%. This contribution can be added to the yield shown in eq. 4.10 getting the result:

$$\text{Yield}_{0-10 \text{ GeV/c}}^{0-80\%} = 1068 \pm 435 \quad (4.11)$$

Results shown in eq.4.8 and in eq.4.11 are compatible within 1σ . The $^3_\Lambda\bar{\text{H}}$ analysis is not described here because its significance is 2. Therefore more statistics is needed for a proper assessment (See next section).

4.4.5 Systematic Errors

Several sources of systematic uncertainties were considered, namely those affecting the $^3_\Lambda\text{H}$ extraction as the analysis cuts and all the correction factors applied to obtain the integrated yield.

- Topological cuts: some topological cuts (i.e, $\cos(\text{Pointing Angle})$, $\text{DCA}_{\pi \text{ to PV}}$ and $\text{DCA}_{\text{tracks}}$) were varied in order to evaluate the systematic errors associated to the choice of the topological cuts. In Table 4.18 the values which have been varied are shown.

The evaluation of the systematic error related to topological cuts is very sensitive to the statistics of the analysed sample. The systematic error was evaluated with

	Nominal Value	Value
$\cos(\text{Pointing Angle})$	0.990	0.992, 0.994, 0.995
$\text{DCA}_{\pi \text{ to PV}}$	0.4 cm	0.3, 0.5 cm
$\text{DCA}_{\text{tracks}}$	0.7 cm	0.4, 0.5, 0.9 cm

TABLE 4.12: Topological cuts used to evaluate the systematics errors. The nominal value column refers to the value of the cut used in the analysis.

the help of the MC simulation with the method described in Section 4.5.6. The error associated to the topological cuts is $\pm 9.8\%$.

- Efficiency dependence on η : Fig. 4.13a shows the efficiency as a function of η ; in order to take into account also this number an error of 6% will be added to the systematic error evaluation.
- Correction error: as explained in Section 4.4.4 the method used to correct the yield introduces an error on the absolute yield of $\pm 6\%$.
- Choice of the p_T shape: to evaluate the corrected yield with the first method described in Section 4.4.4, a Blast-Wave function has been chosen for the p_T shape. The systematic error related to the choice of different p_T distributions was evaluated to be $\pm 5\%$.

The errors are then combined in quadrature. The total systematic error when the first method described in Section 4.4.4 is used to obtain the absolute yield is evaluated to be $\pm 14\%$, while when the second method is used, the systematic error becomes $\pm 13\%$.

4.5 ${}^3\Lambda$ H yield extraction from 2011 data.

4.5.1 Invariant mass spectrum

The 2011 statistics allows to extract both the ${}^3\Lambda$ H and ${}^3\bar{\Lambda}$ H signal. Fig. 4.22a (b) shows the invariant mass spectrum of $({}^3\text{He}, \pi^-)({}^3\bar{\text{He}}, \pi^+)$ pairs passing the cuts listed in Section 4.3. Black points are the data while the red histogram is the “like-sign” LS $({}^3\text{He}, \pi^+)({}^3\bar{\text{He}}, \pi^-)$ invariant mass spectrum. The green curve is the fitting function which is the sum of a pol3, used to evaluate the combinatorial background, and a Gaussian function for the signal, as already explained in section 4.4.2. The black line is the signal extracted after the pol3 background subtraction. Full circles in the bottom part of the plot are the data after the pol3 background subtraction.

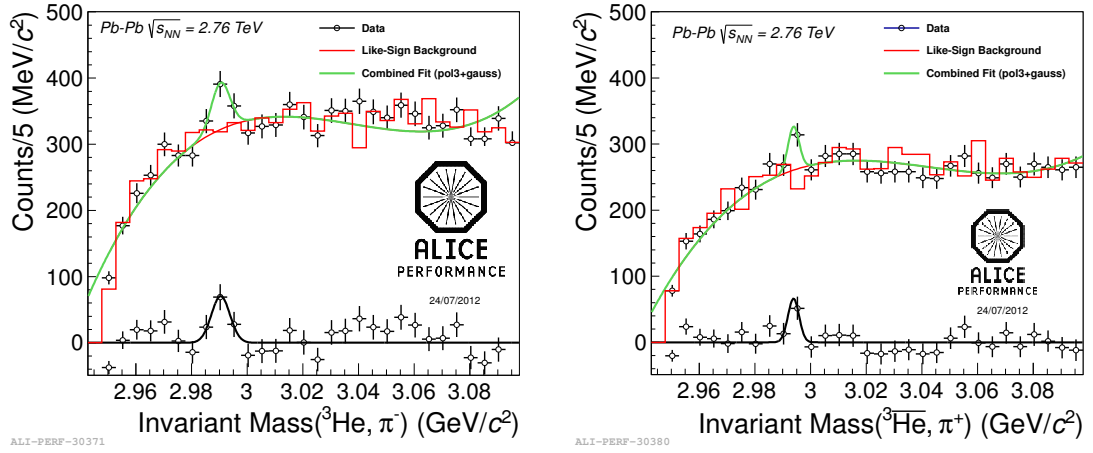


FIGURE 4.22: a) $(^3\text{He}, \pi^-)$ Invariant mass b) $(^3\bar{\text{He}}, \pi^+)$ Invariant mass. The distributions are fitted with a function which is the sum of a pol3 + Gaussian function (Green curve). Black points are data points while the red histogram is the LS invariant mass distribution. Open circles in the bottom part of the plot are data after the pol3 background subtraction, and the superimposed black line is the Gaussian function.

4.5.2 Background estimation and Signal extraction

The background has been evaluated by using the invariant mass spectrum fitted with a function which is the sum of a pol3 and a Gaussian; the method is the same applied to 2010 data and discussed in 4.4.2. From the fit it is possible to evaluate the mean (μ), width (σ), raw yield and significance, both for $^3_\Lambda\text{H}$ and $^3_\Lambda\bar{\text{H}}$ candidates. Results are listed in Table 4.13.

	$^3_\Lambda\text{H}$	$^3_\Lambda\bar{\text{H}}$
Raw Yield (3σ)	74 ± 30	68 ± 25
Mean $\mu(\text{GeV}/c^2)$	2.992 ± 0.001	2.993 ± 0.001
Sigma $\sigma (\times 10^{-3}\text{GeV}/c^2)$	2.02 ± 0.5	2.01 ± 0.4
Significance	3.85	3.67

TABLE 4.13: Summary of raw yield, μ , σ for the $^3_\Lambda\text{H}$ and $^3_\Lambda\bar{\text{H}}$ signals obtained with the data from 2011 data-taking.

For this analysis the $^3\text{He}(^3\bar{\text{He}})$ rigidity range ($p/Z > 1.2\text{GeV}/c$) has been considered. The raw yields of $^3_\Lambda\text{H}$ and $^3_\Lambda\bar{\text{H}}$ are comparable. The $^3_\Lambda\text{H}$ and $^3_\Lambda\bar{\text{H}}$ mean values (μ) are compatible with the value from the literature [182].

4.5.3 Efficiency Computation

To evaluate the efficiency in detecting and reconstructing the $^3_\Lambda\text{H}$ signal the Monte Carlo (MC) simulation anchored to the 2011 data has been used. The simulation is based on a pure central Hijing event simulator, where $^3_\Lambda\text{H}$ and $^3_\Lambda\bar{\text{H}}$ signals have been injected flat in p_T , rapidity and centrality. As already described in 4.4.3, two different methods have

been used to evaluate the efficiency. The first one uses the MC truth of the reconstructed particle, while in the second one the signal extraction is applied to simulated data by using the “like-sign” method; in both cases the PID is performed by MC truth instead of TPC dE/dx .

The efficiency numerator (“reconstructed signal”) is filled in the analysis stage, after all the event selections have been applied. The efficiency denominator is filled with MC generated primary $\Lambda^3H(\bar{\Lambda}^3\bar{H})$.

To have a quality check of the stability of the signal extraction method based on the “like-sign” method, the mean (μ) and the width (σ) of the reconstructed signal were checked versus different variables (i.e. p_T , ct and η), and the efficiency was evaluated as a function of the same variables.

Fig. 4.23a shows μ vs p_T of the extracted signal, while Fig. 4.23b shows σ vs p_T . μ is stable (variation $<0.5\%$); σ shows a dependence which can be attributed to the worsening of the resolution with increasing p_T . Fig. 4.23c shows the efficiency as a function of p_T . Also for the 2011 simulation a strong dependence of the efficiency on p_T is observed, as already discussed in section 4.4.3.

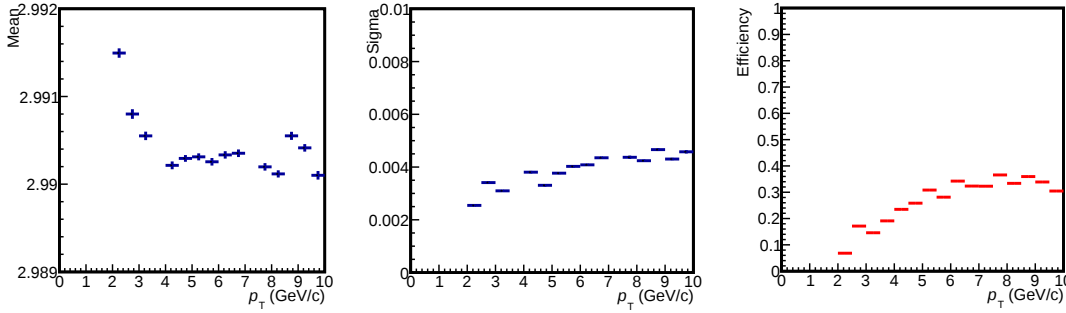
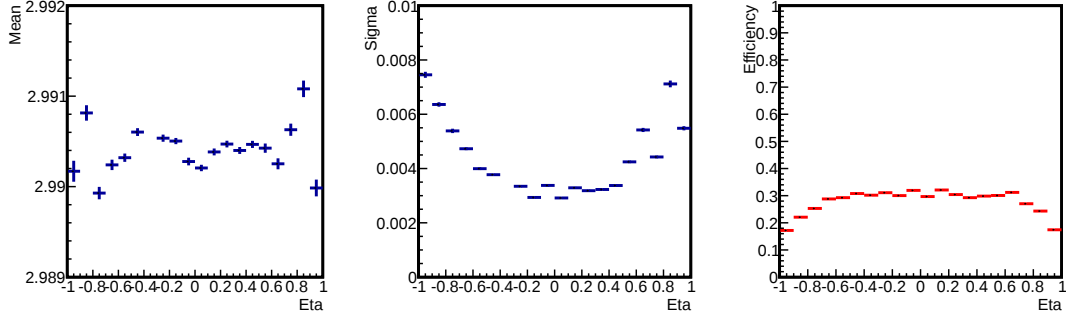
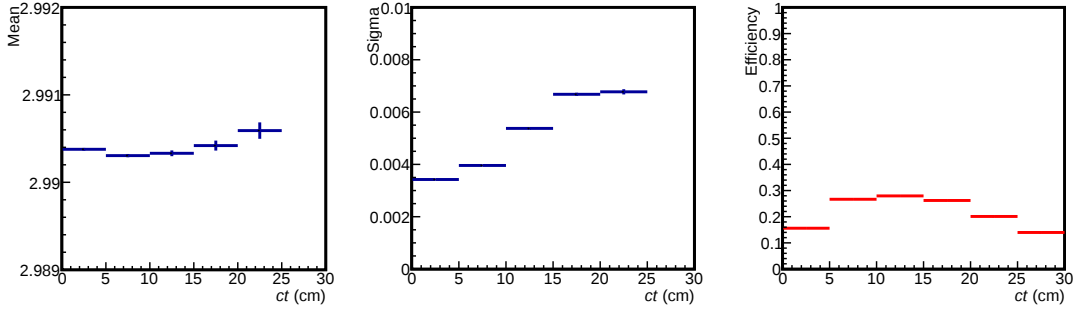


FIGURE 4.23: a) μ b) σ and c) Efficiency as a function of p_T .

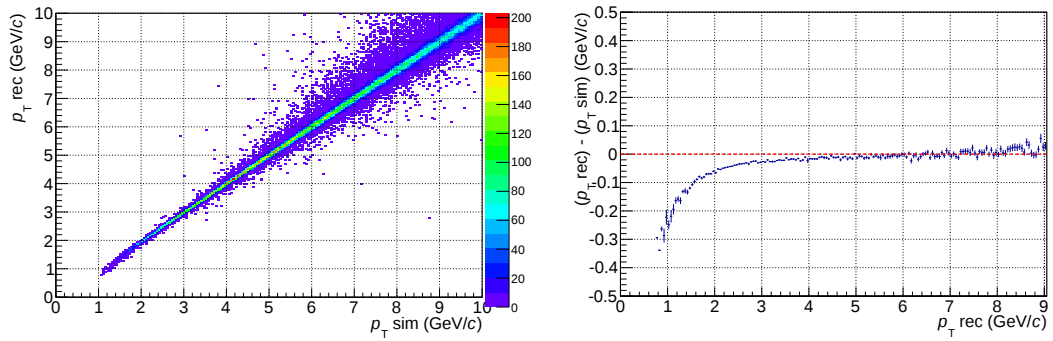
Fig. 4.13c shows the Λ^3H detection efficiency as a function of η , while, respectively, in Fig. 4.13a and Fig. 4.13a μ vs η and σ vs η are shown. The efficiency depends quite strongly on η . In order not to spoil the signal strength this dependence will be included in the systematic evaluation without determining the efficiency as a function of η (already discussed in 4.4.3).

Fig. 4.25c shows the efficiency as a function of ct . The behaviour is similar to that observed for the data coming from the 2010 data-taking and it is possible to draw the same conclusions. Section 4.6 will be devoted to extract an efficiency corrected Λ^3H lifetime from 2011 data.

The effect of the Λ^3H transport correction in Geant3 has also been checked. The left panel of Fig. 4.26 shows the Λ^3H p_T generated momentum vs the reconstructed one, while the right panel shows the difference of the generated and reconstructed momenta versus the reconstructed one. An effect connected to the transport correction

FIGURE 4.24: a) μ b) σ and c) Efficiency as a function of η .FIGURE 4.25: a) μ b) σ and c) Efficiency as a function of ct .

is clearly seen: the ${}^3_{\Lambda}\text{H}$ reconstructed momenta are underestimated at low p_T values, because the reconstruction program during the refit procedure does not take into account the proper mass and charge of the ${}^3\text{He}$ daughter particles. The larger effect is observed for $p_T < 2 \text{ GeV}/c$, which is not analysed in this work. Anyway, in order to take into account this effect, all the efficiencies will be evaluated using the generated momentum instead of the reconstructed one. In this way all transport corrections are embedded in the calculated efficiency.

FIGURE 4.26: a) ${}^3_{\Lambda}\text{H}$ generated p_T vs reconstructed p_T . Profile of reconstructed-generated momentum vs reconstructed momentum.

4.5.4 Determination of the yield versus p_T

The 2011 statistics allows to extract a signal in 3 p_T bins: [2-4], [4-6] and [6-10] GeV/c. Fig. 4.27 shows $[(^3\text{He}, \pi^-) + (^3\bar{\text{He}}, \pi^+)]$ invariant mass spectra for 3 p_T bins. In the present analysis only central events with centrality range 0-10% have been considered, while the minimum ct considered is 1 cm. For each bin it is possible to extract a signal and the related yield, μ and σ .

The same analysis can be repeated for both $(^3\text{He}, \pi^-)$ and $(^3\bar{\text{He}}, \pi^+)$ separately, as shown in Fig. 4.28 and Fig. 4.29.

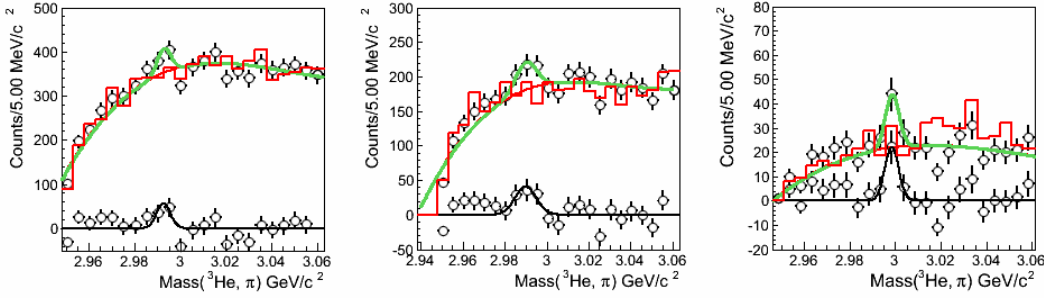


FIGURE 4.27: $[(^3\text{He}, \pi^-) + (^3\bar{\text{He}}, \pi^+)]$ invariant mass distribution for 3 p_T bins: a) [2-4] GeV/c; b) [4-6] GeV/c and c) [6-10] GeV/c.

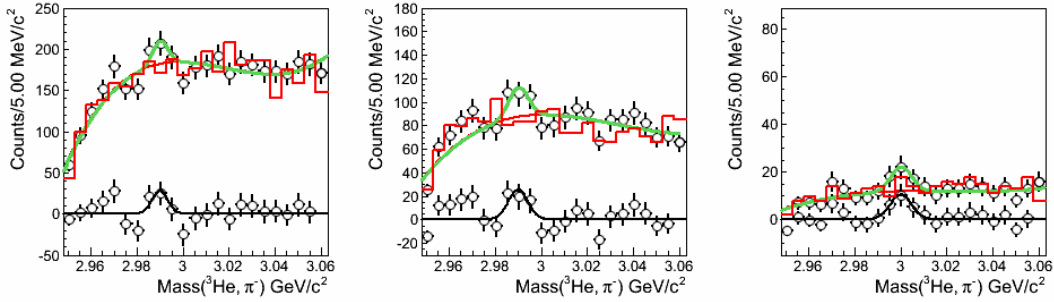


FIGURE 4.28: $(^3\text{He}, \pi^-)$ invariant mass distribution for 3 p_T bins: a) [2-4] GeV/c; b) [4-6] GeV/c and c) [6-10] GeV/c.

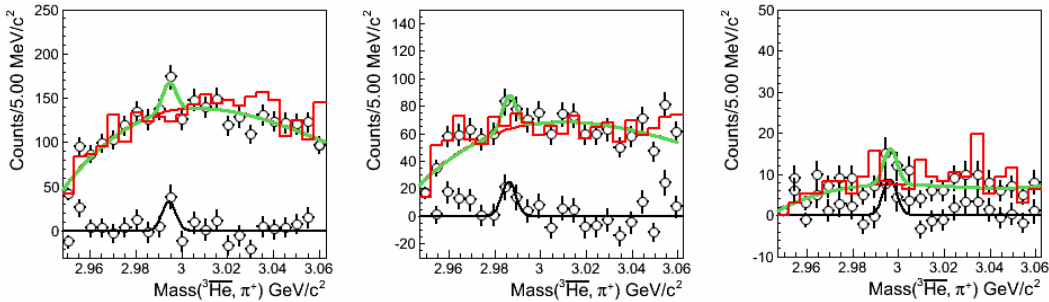


FIGURE 4.29: $(^3\bar{\text{He}}, \pi^+)$ invariant mass distribution for 3 p_T bins: a) [2-4] GeV/c; b) [4-6] GeV/c and c) [6-10] GeV/c.

Table 4.14 shows the raw yields in 3 p_T bins for $[(^3\text{He}, \pi^-) + (^3\overline{\text{He}}, \pi^+)]$ and $(^3\text{He}, \pi^-)$ and $(^3\overline{\text{He}}, \pi^+)$ separately.

	$^3_\Lambda\text{H} + ^3_\Lambda\overline{\text{H}}$	$^3_\Lambda\text{H}$	$^3_\Lambda\overline{\text{H}}$
$2 \leq p_T < 4 \text{ GeV}/c$	100 ± 34	67 ± 25	53 ± 23
$4 \leq p_T < 6 \text{ GeV}/c$	46 ± 26	35 ± 20	30 ± 17
$6 \leq p_T < 10 \text{ GeV}/c$	28 ± 10	16 ± 8	13 ± 7

TABLE 4.14: Summary of raw yield for 3 p_T bins

The results of the raw yield determination in the three cases are shown in Fig. 4.30. The errors shown in figure are statistical only.

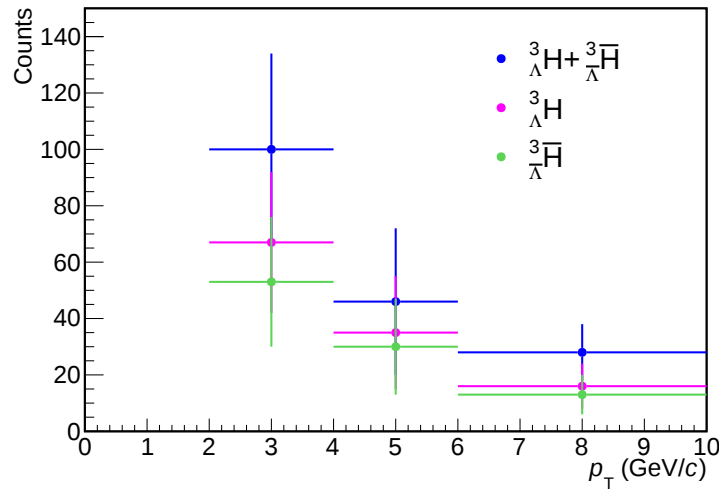


FIGURE 4.30: The raw yield vs p_T for $(^3_\Lambda\text{H} + ^3_\Lambda\overline{\text{H}})$ in blue, for $(^3_\Lambda\text{H})$ in magenta and for $(^3_\Lambda\overline{\text{H}})$ in green. The errors shown in figure are statistical only.

Fig. 4.31 shows the ratio of the raw yield of $^3_\Lambda\overline{\text{H}}$ over $^3_\Lambda\text{H}$ is shown. Although the ratio cancels out many systematic effects, correction factor which are different between matter and anti matter survive. To draw any conclusion the efficiency corrections are needed.

4.5.4.1 Efficiency studies

In this section the methods to calculate the efficiency vs p_T will be described. As in the raw data analysis both $^3_\Lambda\text{H}$ and $^3_\Lambda\overline{\text{H}}$ are investigated, the dependence of the efficiency vs p_T on the charge of the selected particle is checked. Fig. 4.32 shows the efficiency vs p_T for $^3_\Lambda\text{H}$ (in green), $^3_\Lambda\overline{\text{H}}$ (in magenta) and for the sum of the two channels (in red). No significant dependence on the charge of the analysed particle can be observed.

Another quantity that needs to be checked is the dependence of the efficiency of p_T on the centrality. The MC sample has been divided in 3 centrality classes (0-2%, 2-5% and

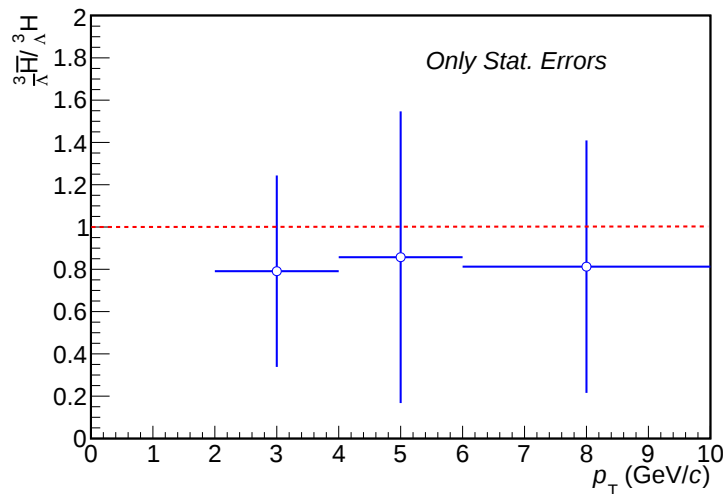


FIGURE 4.31: Ratio of the raw yield of ${}^3_{\Lambda}\bar{H}/{}^3_{\Lambda}H$ vs p_T . The ratio is consistent with unity in the each p_T bin within 2σ s.

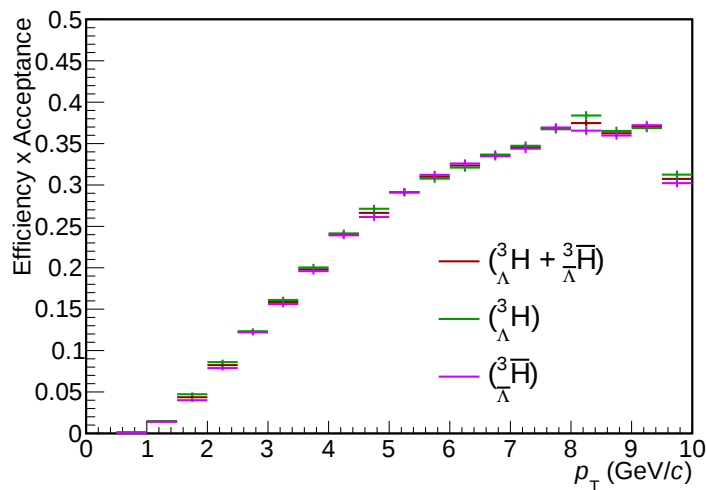


FIGURE 4.32: Comparison of efficiency vs p_T for ${}^3_{\Lambda}H$ (in green), ${}^3_{\Lambda}\bar{H}$ (in magenta) and for the sum of the two charges (in red).

5-10%) and the results, shown in Fig. 4.33a have been compared to the result in the whole investigated range, i.e. 0-10% centrality bin: a dependence on the centrality can be seen. To quantify this dependence the ratio of the results in different centrality bins over the 0-10% centrality bin was computed; the final result is shown in Fig. 4.33b. In the most central bin (0-2%) the efficiency is $\sim 10\%$ lower than the one in the 0-10% bin; on the other hand, the results in the 2-5% and 5-10% centrality bin are $\sim 10\%$ higher.

To take into account this effect a method that takes care of the width of the bin, the multiplicity of tracks in the real data and the number of participants in each centrality class has been studied.

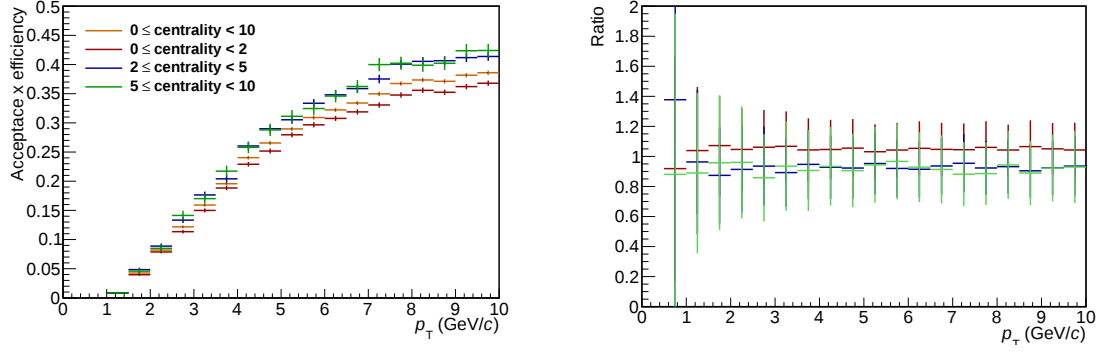


FIGURE 4.33: a) Efficiency vs p_T for different centrality bin; each bin is identified by a color as shown in the legend. b) Ratio of the efficiency vs p_T in different centrality bin over the one in the 0-80% centrality. Colours used to identify the centrality bin are the same as shown in the left panel.

Considering a flat centrality distribution,

$$w_{0-2\%}^1 = 2$$

$$w_{2-5\%}^1 = 3$$

$$w_{5-10\%}^1 = 5$$

where w is the weight of each centrality bin. Taking into account the multiplicity of events recorded in the real data, listed in Table 4.4, the weights that should be applied are:

$$w_{0-2\%}^2 = w_{0-2\%}^1 * 4.65$$

$$w_{2-5\%}^2 = w_{2-5\%}^1 * 7.23$$

$$w_{5-10\%}^2 = w_{5-10\%}^1 * 11.1$$

In the simulation the multiplicity of injected ${}^3_{\Lambda}\text{H}({}^3_{\Lambda}\overline{\text{H}})$ is flat in centrality; assuming that the particle production scales with N_{part} an additional factor due to this has to be taken into account. By using the N_{part} values listed in Table 4.2 the weights become:

$$w_{0-2\%}^3 = w_{0-2\%}^2 * 399$$

$$w_{2-5\%}^3 = w_{2-5\%}^2 * 372$$

$$w_{5-10\%}^3 = w_{5-10\%}^2 * 330$$

Finally, the weights that will be applied are the following: 4.93 to the [5-10%] centrality events, 2.17 to [2-5%] centrality events and 1 to [0-2%] centrality events. The result of the weighted efficiency is shown in Fig. 4.34 as green points and compared to the one from a simple arithmetical mean (in red) and the result from the 0-10% centrality bin (in orange).

Another thing to deal with is the fact that in the data it is possible to divide the signal only in 3 p_T bins: without any assumption of the initial p_T shape the error that has to

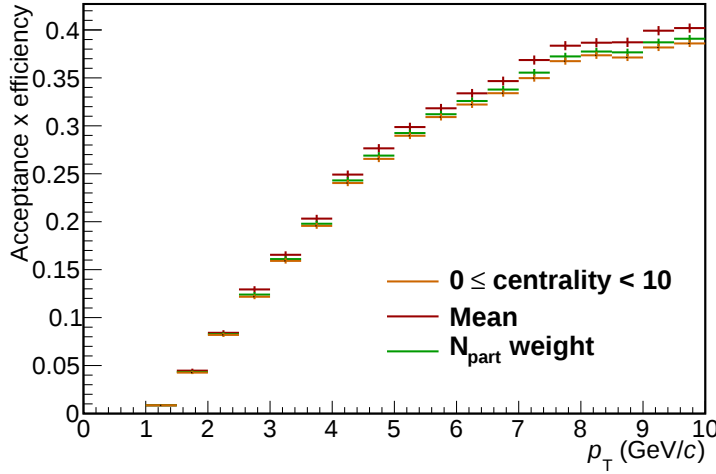


FIGURE 4.34: Green points: efficiency vs p_T , when the weight procedure described in the test to mediate efficiencies from different centrality classes is applied. The result is compared to the simple arithmetical mean (in red) and the result from the 0-10% centrality bin. The weight factor is described in the text.

be assigned to each point is the maximum variation between the edge bins (Fig. 4.35), which gives rise to rather large errors, especially in the first bin, as reported in Table 4.15.

p_T (GeV/c)	Mean Efficiency	Error
2-4	0.16	50%
4-6	0.29	13%
6-10	0.36	7%

TABLE 4.15: Mean efficiency and associated errors considering 3 p_T bins for an initial flat p_T distribution.

In order to avoid the error due to the unknown p_T shape, it is possible to assume the p_T distribution as known. If a Blast-Wave distribution (shown in Fig. 4.20) is used, the weighted efficiency, shown as an orange line in Fig. 4.36, is provided.

4.5.4.2 Results

At this point it is possible to obtain the absolute yield in each p_T bin for $(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\bar{\text{H}})$, $\bar{\Lambda}^3\text{H}$ and $\bar{\Lambda}^3\bar{\text{H}}$ separately.

Results are summarized in Table 4.16 and shown in Fig. 4.37, after multiplying them for the $\bar{\Lambda}^3\text{H} \rightarrow \bar{\Lambda}^3\text{He} + \pi^-$ branching ratio, (B.R. = 35 ± 4)% [179].

The yields obtained are:

$$\text{Yield}_{2-10\text{GeV}/c}^{0-10\%}(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\bar{\text{H}}) = (2.83 \pm 0.81) \times 10^3 \quad (4.12)$$

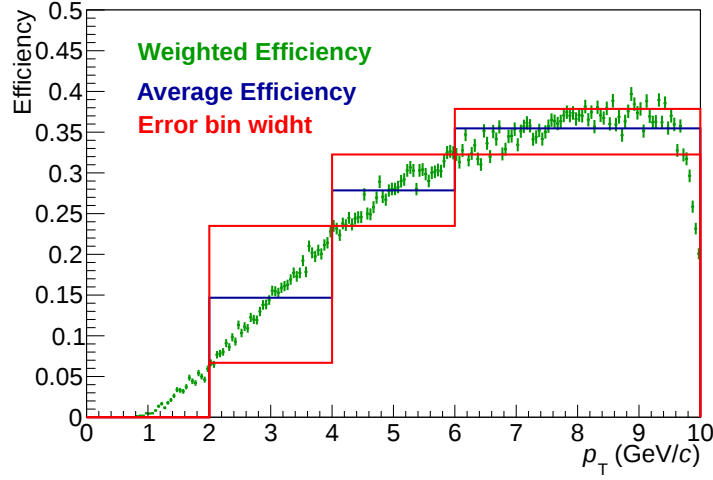


FIGURE 4.35: In green the efficiency vs p_T is shown, in blue the average of the efficiency when the initial p_T shape is unknown and in red the error due to the differences between the edge bins.

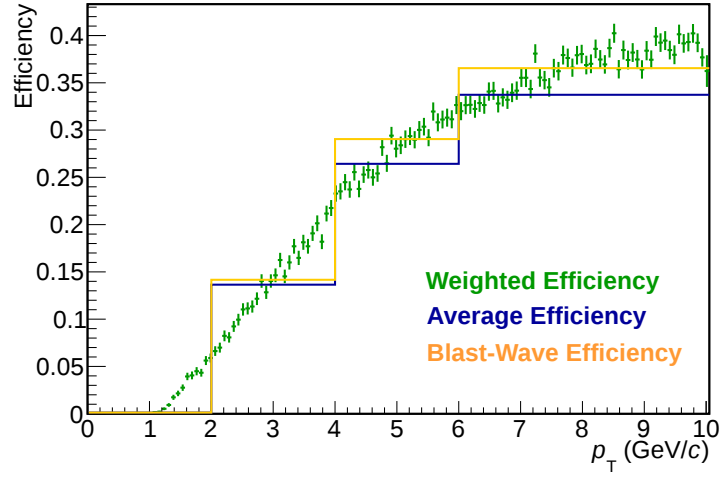


FIGURE 4.36: In green the efficiency vs p_T is shown, in blue the average of the efficiency when the initial p_T shape is unknown and in orange the average when a Blast-Wave distribution is assumed as initial p_T shape.

	${}^3_{\Lambda}\text{H} + {}^3_{\Lambda}\bar{\text{H}}$	${}^3_{\Lambda}\text{H}$	${}^3_{\Lambda}\bar{\text{H}}$
$2 \leq p_T < 4 \text{ GeV}/c$	734 ± 247	491 ± 187	385 ± 171
$4 \leq p_T < 6 \text{ GeV}/c$	172 ± 98	132 ± 75	114 ± 64
$6 \leq p_T < 10 \text{ GeV}/c$	83 ± 30	48 ± 23	40 ± 20

TABLE 4.16: Summary of yields (${}^3_{\Lambda}\text{H} + {}^3_{\Lambda}\bar{\text{H}}$), ${}^3_{\Lambda}\text{H}$ and ${}^3_{\Lambda}\bar{\text{H}}$ in 3 p_T bins after efficiency correction.

$$\text{Yield}_{2-10 \text{ GeV}/c}^{0-10\%}({}^3_{\Lambda}\text{H}) = (1.92 \pm 0.60) \times 10^3 \quad (4.13)$$

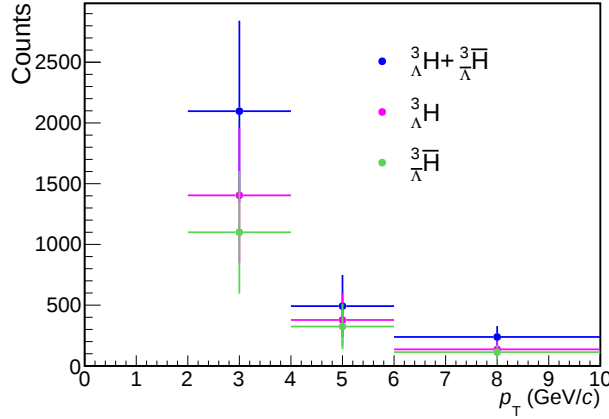


FIGURE 4.37: Absolute yield vs p_T for $(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\text{H})$ (in blue), $\bar{\Lambda}^3\text{H}$ (in magenta) and $\bar{\Lambda}^3\text{H}$ (in green). Shown errors are statistical only.

$$\text{Yield}_{2-10 \text{ GeV}/c}^{0-10\%}(\bar{\Lambda}^3\text{H}) = (1.54 \pm 0.54) \times 10^3 \quad (4.14)$$

To get the $\bar{\Lambda}^3\text{H}$ yield integrated over the full p_T range, it is necessary to know the shape of the $\bar{\Lambda}^3\text{H}$ p_T distribution; in this way it will be possible to extrapolate the “missing” yield in the regions where the efficiency is 0 (i.e. $p_T \leq 2 \text{ GeV}/c$ and $p_T \geq 10 \text{ GeV}/c$). In order to understand if the assumptions made on the p_T shape of the $\bar{\Lambda}^3\text{H}$ are reasonable, a Blast-Wave distribution has been superimposed to the data. Since this function has 4 free parameters, and in the analysis only 3 points are available, it is not possible to make a proper fit to the distribution, however it could be interesting to see if the p_T shape and the data are consistent. The Blast-Wave parameters have been fixed by using the ^3He corrected spectra, leaving only the normalization free. The result of the one-parameter fit is shown in Fig. 4.38. The points correspond to the data $(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\text{H})$, while the red curve is the Blast-Wave distribution. Even if this is only a qualitative check, the data points look close to the function ($\chi^2 = 1$); this makes all the assumptions done up to this point more reliable.

The integral of the Blast-Wave function (shown Fig. 4.20) which corresponds to a in the $[0-2] \text{ GeV}/c$ region is the 26.7% of the total, while the integral of the region $p_T > 10 \text{ GeV}/c$ is less than 1%. These contributions are used to evaluate the $\bar{\Lambda}^3\text{H}(\bar{\Lambda}^3\text{H})$ production yield.

The yields obtained are:

$$\text{Yield}_{0-10 \text{ GeV}/c}^{0-10\%}(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\text{H}) = (3.86 \pm 1.11) \times 10^3 \quad (4.15)$$

$$\text{Yield}_{0-10 \text{ GeV}/c}^{0-10\%}(\bar{\Lambda}^3\text{H}) = (2.62 \pm 0.82) \times 10^3 \quad (4.16)$$

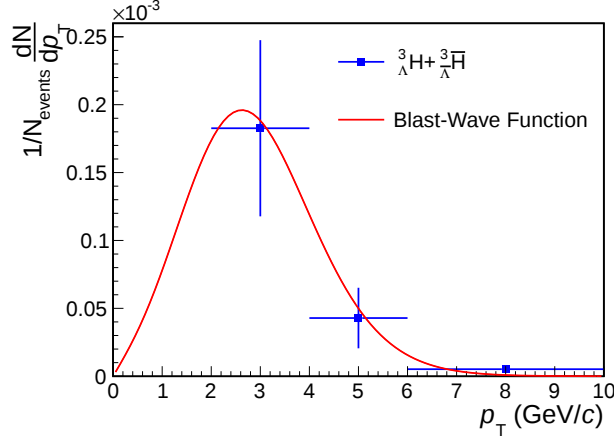


FIGURE 4.38: Blue points:corrected yield vs p_T for $(^3_\Lambda \text{H} + ^3_\Lambda \bar{\text{H}})$; red curve: Blast-Wave distribution used to evaluate the missing fraction of yield.

$$\text{Yield}_{0-10 \text{ GeV}/c}^{0-10\%} (^3_\Lambda \bar{\text{H}}) = (2.10 \pm 0.74) \times 10^3 \quad (4.17)$$

4.5.5 Analysis of Semi-Central events

The analysis described up to this point has been applied to central events only. In central collisions a higher number of particles is produced, so the probability to observe a (anti)(hyper)nucleus is higher, but also the combinatorial background is higher, making the analysis very challenging. During the 2011 data taking a dedicated trigger selected also a significant number of semi-central events. In this kind of events, the number of produced particles is much lower which makes the production of (hyper)nuclei less probable, but, on the other side, generates a smaller combinatorial background. An attempt to look for $^3_\Lambda \text{H} (^3_\Lambda \bar{\text{H}})$ in this kind of events was performed. The cuts used for the analysis are the same listed in section 4.3. In panel a) of Fig. 4.39 the invariant mass of $[(^3\text{He}, \pi^-) + (^3\bar{\text{He}}, \pi^+)]$ is shown, while in panel b) and c) the invariant mass of, respectively, $(^3\text{He}, \pi^-)$ and $(^3\bar{\text{He}}, \pi^+)$ is shown. A signal can be clearly seen in each panel. Black empty points are the data points while the red histogram is the “like-sign” LS invariant mass spectrum. The green curve is the sum of a pol3, used to evaluate the combinatorial background, and a Gaussian function for the signal.

The full circles at the bottom of the plot are data after the pol3 background subtraction, and the superimposed black line is the Gaussian fit. In Table 4.17 the raw yield calculated in a region of 3σ around the mean value, the mean (μ) and the sigma σ from the fit and the significance are reported.

To correct the raw yield the method based on “ p_T mean efficiency” has been used, as explained in Section 4.4.4. The efficiency is weighed with a Blast-Wave distribution and the integral of the resulting function is used as mean efficiency. The value of the mean efficiency in the region $[2-10] \text{ GeV}/c$ after the convolution with the Blast-Wave function,

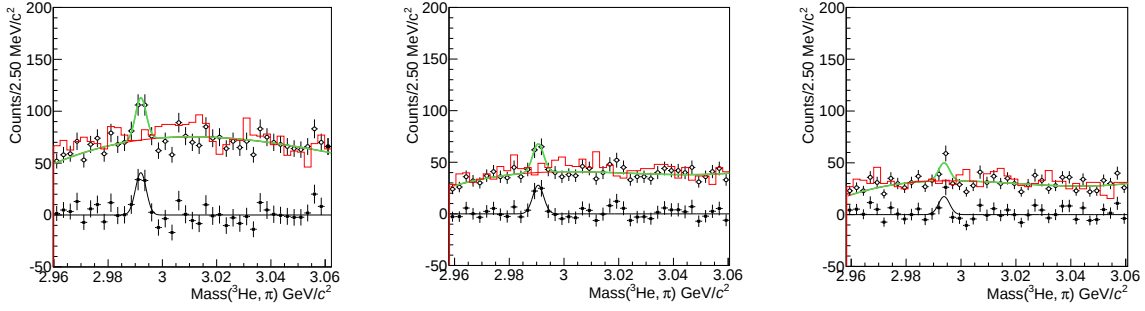


FIGURE 4.39: Invariant mass of $[(\bar{\Lambda}^3\text{He}, \pi^-) + (\bar{\Lambda}^3\text{He}, \pi^+)]$ (a), $(\bar{\Lambda}^3\text{He}, \pi^-)$ (b) and $(\bar{\Lambda}^3\text{He}, \pi^+)$ (c). Black empty points are the data points while red histogram is the “like-sign” LS invariant mass spectrum. The green curve is a sum of a pol3, used to evaluate the combinatorial background, and a Gaussian function for the signal. The full circles in the bottom of the plot are data after the pol3 background subtraction, and the superimposed black line is the Gaussian function.

Total Statistics (events)	$\sim 20 \text{ M}$		
	$(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\bar{\text{H}})$	$\bar{\Lambda}^3\text{H}$	$\bar{\Lambda}^3\bar{\text{H}}$
Raw Yield (3σ)	81 ± 18	55 ± 13	35 ± 12
Mean $\mu(\text{GeV}/c^2)$	2.992 ± 0.001	2.994 ± 0.001	2.990 ± 0.001
Sigma $\sigma (\times 10^{-3} \text{GeV}/c^2)$	2.08 ± 0.5	2.01 ± 0.06	2.0 ± 0.9
Significance	3.94	3.53	2.5

TABLE 4.17: Summary of raw yield, μ , σ of the signal by using 2011 semi-central data.

is 0.170. This value implies that the absolute yields in the region $[2-10] \text{ GeV}/c$ after the $\bar{\Lambda}^3\text{H} \rightarrow \bar{\Lambda}^3\text{He} + \pi^-$ branching ratio (B.R. = $35 \pm 4\%$) [179] correction are:

$$\text{Yield}_{2-10 \text{ GeV}/c}^{10-50\%}(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\bar{\text{H}}) = 1373 \pm 333 \quad (4.18)$$

$$\text{Yield}_{2-10 \text{ GeV}/c}^{10-50\%}(\bar{\Lambda}^3\text{H}) = 853 \pm 246 \quad (4.19)$$

$$\text{Yield}_{2-10 \text{ GeV}/c}^{10-50\%}(\bar{\Lambda}^3\bar{\text{H}}) = 796 \pm 211 \quad (4.20)$$

Finally to get the $\bar{\Lambda}^3\text{H}$ yield integrated over the full p_T range, it is necessary to know the shape of the $\bar{\Lambda}^3\text{H}$ p_T distribution. As already explained in Section 4.4.4, an additional 26.7% yield has to be added in order to extrapolate the total missing part of the p_T spectrum. The results are:

$$\text{Yield}_{0-10 \text{ GeV}/c}^{10-50\%}(\bar{\Lambda}^3\text{H} + \bar{\Lambda}^3\bar{\text{H}}) = 1873 \pm 454 \quad (4.21)$$

$$\text{Yield}_{0-10 \text{ GeV}/c}^{10-50\%}(\Lambda^0 \text{H}) = 1163 \pm 336 \quad (4.22)$$

$$\text{Yield}_{0-10 \text{ GeV}/c}^{10-50\%}(\Lambda^0 \bar{\text{H}}) = 796 \pm 288 \quad (4.23)$$

As expected, the yields of semi-central events are about half of the central events and their comparison could be used to test models versus number of participants.

4.5.6 Systematic Errors evaluation

The systematic uncertainties originate from different sources and are separately evaluated for each source, as discussed in the following:

- Topological cuts: some topological cuts (i.e, $\cos(\text{Pointing Angle})$, $\text{DCA}_{\pi \text{ to PV}}$ and $\text{DCA}_{\text{tracks}}$) were varied in order to evaluate the systematic errors associated to the choice of the topological cuts. In Table 4.18 the values which have been varied are shown.

	Analysis Value	Value
$\cos(\text{Pointing Angle})$	0.990	0.992, 0.994, 0.995
$\text{DCA}_{\pi \text{ to PV}}$	0.4 cm	0.3, 0.5 cm
$\text{DCA}_{\text{tracks}}$	0.7 cm	0.4, 0.5, 0.9 cm

TABLE 4.18: Topological cuts used to evaluate the systematics errors. The nominal value column refers to the value of the cut used in the analysis.

The error is evaluated, after efficiency correction, as the maximum deviation in the extracted yield. The results are shown in Table 4.19.

p_T bin	Relative systematic error (%)
[2-4]GeV/c	20
[4-6]GeV/c	34
[6-10]GeV/c	22

TABLE 4.19: Relative systematic error in 3 p_T bins

The systematic errors associated to the topological cuts are large. Since the statistics analysed is quite small, the extraction of the yields by means of the Gaussian fit (see Section 4.4.2) is affected by the poor statistics. The errors obtained in this way may therefore contain a relevant contribution of statistical origin. In order to understand if this is right, the Monte Carlo simulation has been used. The simulation has been modified in order to have a S/B ratio comparable to the one of the data; then the systematic errors evaluation varying with the topological cut has

been repeated 3 times. In the first one the overall statistics is similar to that of the data; in the second and third is 5 and 8 times bigger, respectively. To evaluate the yields two methods have been used: the MC truth and the fit procedure as used to evaluate the signal from the data. Using the fit procedure it is possible to evaluate also the systematics related to the procedure. When the MC statistics is similar to the data statistics the evaluated errors are comparable with those obtained with the data. When the statistics increases the errors decrease (see Fig.4.40, blue points). This indicates that errors evaluated with the data are not purely systematic, but contain also relevant statistical errors (as well those evaluated with the MC with the same procedure and using similar statistics). In order to disentangle the statistical error from the systematic one, the Monte Carlo truth together with the sample with higher statistics has been used. When the MC truth is used, the systematic error is essentially independent on the statistics of the analysed sample (red points in Fig. 4.40). It essentially represents the (systematic) error related to the efficiency correction. The systematic error associated with the topological cut can be extracted by subtracting in quadrature the error related to the efficiency correction from the systematic error evaluated with the MC when the statistics is 8 times that of the data. Results are listed in Table 4.22.

Relative systematic error (%) (MC)						
	Fit procedure			MC truth		
(MC/Data)statistics	1x	5x	8x	1x	5x	8x
[2-4] GeV/c	20	17	15	8	12	7
[4-6] GeV/c	34	14	10	7	7	7
[6-10] GeV/c	22	10	11	7	6	7

TABLE 4.20: Relative systematic error in several p_T bins

p_T bin	Relative systematic error (%)
[2-4]GeV/c	13
[4-6]GeV/c	9
[6-10]GeV/c	8.5
[2-10]GeV/c	9.7

TABLE 4.21: Relative systematic error related to topological cuts in different p_T bins. The procedure to extract these value is explained in the text.

- Dependence of the efficiency evaluation: as explained in the previous point an error of 7% is added to take into account the error related to the efficiency evaluation varying the cuts applied.
- η dependence of the efficiency: Fig. 4.24a shows the efficiency as a function of η : in order to take into account this dependence an error of 5% will be added to the systematic error evaluation.

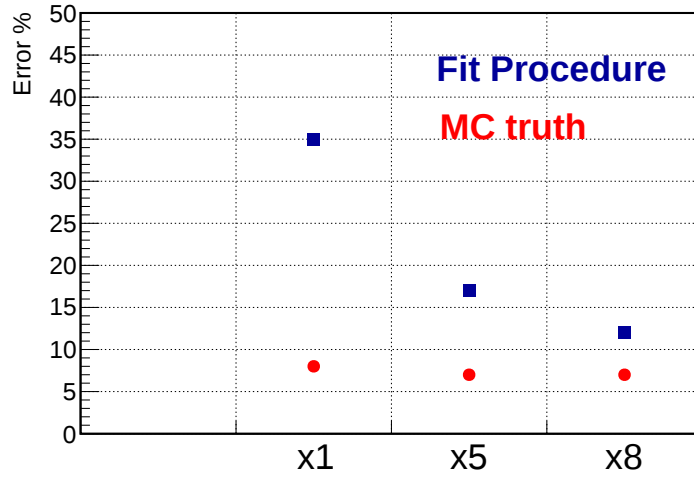


FIGURE 4.40: Relative systematic errors related to topological cuts as a function of the MC/data statistics for the [2-4]GeV/c p_T bin. Blue squares: results of the fit procedure to extract the signal. Red circles: MC truth.

- Choice of the p_T shape: to evaluate the corrected yield with the semi-central events, a Blast-Wave function has been chosen for the p_T shape. The systematic error related to the choice of different p_T distributions was evaluated to be $\pm 5\%$.

Finally the errors are combined in quadrature. The total relative systematic errors are shown in Table. 4.22.

Relative systematic error (%)	
p_T bin	
[2-4]GeV/c	15.6
[4-6]GeV/c	12.5
[6-10]GeV/c	12
Semi-Central Events	14.5

TABLE 4.22: Relative systematic errors related to topological cuts in different p_T bins. The procedure to extract these values is explained in the text.

4.6 ${}^3_{\Lambda}\text{H}$ Lifetime determination

With the 2011 statistics (${}^3_{\Lambda}\text{H} + {}^3_{\Lambda}\bar{\text{H}}$ candidates) it is possible to determine the lifetime of the hypertriton, assuming the ${}^3_{\Lambda}\text{H}$ and the ${}^3_{\Lambda}\bar{\text{H}}$ lifetimes are the same. For this analysis central and semicentral events with 0-50% centrality and candidates with $p_T > 2$ GeV/c have been used.

The proposed method is to divide the total ct distribution into three bins, extract the signal, correct it by using the efficiency versus ct , and finally fit the corrected spectrum

with an exponential function:

$$N(t) = A_0 \cdot e^{-\frac{t}{A_1}} \quad (4.24)$$

where $t = \frac{L}{\beta\gamma c}$, $\beta\gamma c = p/M$, A_0 is a normalization parameter and A_1 is the $1/c\tau$ parameter.

The definition of ct is:

$$ct = \frac{ML}{p} \quad (4.25)$$

where M is the nominal value of the $\Lambda^3\text{H}$ mass $= 2.991 \text{ GeV}/c^2$, L is the measured decay length and p is the total momentum of the $\Lambda^3\text{H}$ candidate.

Usually, the decay length is defined as:

$$L = \sqrt{(x_{PV} - x_{SV})^2 + (y_{PV} - y_{SV})^2 + (z_{PV} - z_{SV})^2} \quad (4.26)$$

Where (x_{PV}, y_{PV}, z_{PV}) and

(x_{SV}, y_{SV}, z_{SV}) are the coordinates of the primary and secondary vertex, respectively. For neutral particles, the decay length is equal to the track length, while for charged particles inside the ALICE detector it is an helix segment. The definition of the length of an helix track segment is:

$$Trk \text{ length} = \sqrt{(Arc \text{ length})^2 + (z_{PV} - z_{SV})^2} \quad (4.27)$$

where

$$Arc \text{ length} = 2R \arcsin \left(\frac{\sqrt{(x_{PV} - x_{SV})^2 + (y_{PV} - y_{SV})^2}}{2R} \right) \quad (4.28)$$

R is the curvature radius of the track defined as:

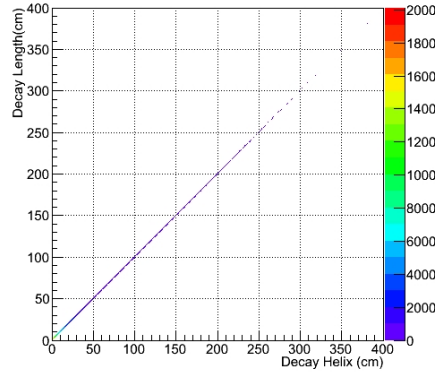
$$R = \frac{p_T}{qB} \quad (4.29)$$

When p_T is in GeV/c and the magnetic field B is in T, R can be rewritten as:

$$R = \frac{1}{B} p_T \frac{10}{3} \quad (4.30)$$

In the case of $\Lambda^3\text{H}$, which is a charged particle, the decay length is not equal to the track length. Inside the ALICE detector the magnetic field is 0.5 T, so the curvature radius of a particle with a p_T of 2 GeV/c is $R \sim 13 \text{ m}$ and the helix track segment can be approximated with a straight line. Fig. 4.41 shows the $\Lambda^3\text{H}$ track length versus the $\Lambda^3\text{H}$ decay length: for $\Lambda^3\text{H}$ s with a p_T distribution in the interval $(0 < p_T < 10 \text{ GeV}/c)$ no visible effects can be seen; so in the following analysis the “decay length” (eq.4.26) will be used.

Since the available $\Lambda^3\text{H}$ candidates have a ct from 2 to 11 cm, the ct range is divided in three bins with the same width: [2-5]cm, [5-8]cm and [8-11]cm. For each bin the signal

FIGURE 4.41: ${}^3_{\Lambda}\text{H}$ track Length versus ${}^3_{\Lambda}\text{H}$ decay length.

is extracted by fitting the ct data distribution with a sum function of pol3 and gaussian. Fig. 4.42 shows the $({}^3\text{He}, \pi)$ invariant mass spectrum divided into three bins (Fig. 4.42 a: [2-5]cm, b: [5-8]cm and c: [8-11]cm).

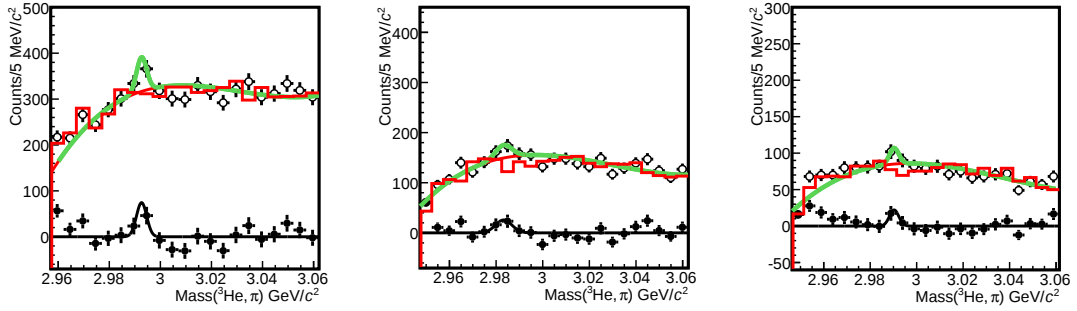
FIGURE 4.42: $[({}^3\text{He}, \pi^-) + ({}^3\overline{\text{He}}, \pi^+)]$ invariant mass spectra for 3 ct bins. a): [2-5]cm b): [5-8]cm c): [8-11]cm.

Table 4.23 shows the mean and the sigma of the Gaussian fit and the raw yield, determined as the integral of the Gaussian function in a region of $\pm 3\sigma$ around the mean value.

	Mean (GeV/c^2)	Sigma (GeV/c^2)	Raw Yield (3σ)
$2 < ct \leq 5 \text{ cm}$	2.993 ± 0.001	$(2.91 \pm 1.94) \pm 10^{-3}$	74 ± 31
$5 < ct \leq 8 \text{ cm}$	2.984 ± 0.002	$(4.56 \pm 1.74) \pm 10^{-3}$	45 ± 26
$8 < ct \leq 11 \text{ cm}$	2.990 ± 0.012	$(2.49 \pm 1.72) \pm 10^{-3}$	22 ± 17

TABLE 4.23: Summary of the mean, sigma and raw yield values for the $({}^3_{\Lambda}\text{H} + {}^3_{\Lambda}\overline{\text{H}})$ signal relative to 3 different ct bins. The mean and the sigma are extracted from the Gaussian fit; the raw yield is determined as the integral of the Gaussian function in a region of $\pm 3\sigma$ around the mean value.

4.6.1 Efficiency dependence on ct

The same studies done for the efficiency versus p_T have been repeated also for the efficiency vs ct . The first thing that can be checked is if in the Monte Carlo differences between $\Lambda^3\text{H}$ and $\bar{\Lambda}^3\text{H}$ are present. Fig. 4.43 shows the efficiency vs ct for $\Lambda^3\text{H}$ (in green), $\bar{\Lambda}^3\text{H}$ (in magenta) and for the sum of the two channels (in red). No significant dependence on the charge of the $\Lambda^3\text{H}$ can be seen within the used Monte Carlo simulation.

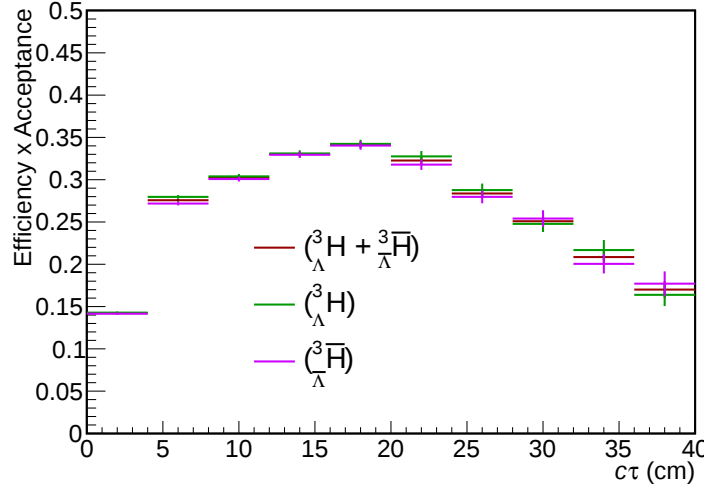


FIGURE 4.43: Efficiency vs ct of $\Lambda^3\text{H}$ (in green), $\bar{\Lambda}^3\text{H}$ (in magenta) and the sum of the two channels (in red).

Another item which has been studied is the dependence of the efficiency vs ct for different centrality bins. Fig. 4.44a shows the efficiency vs ct evaluated in several centrality bins. A dependence on the centrality can be seen. To quantify this dependence, the ratios of the efficiency in different centrality bin over the 0-10% one have been evaluated (Fig. 4.44b). The efficiency in the 0-2% centrality bin (in red) is $\sim 7\%$ lower with respect to the one in the 0-10% centrality bin (in orange), while efficiencies evaluated in the centrality bins 2-5% and 5-10% (in blue and green respectively) are $\sim 10\%$ higher.

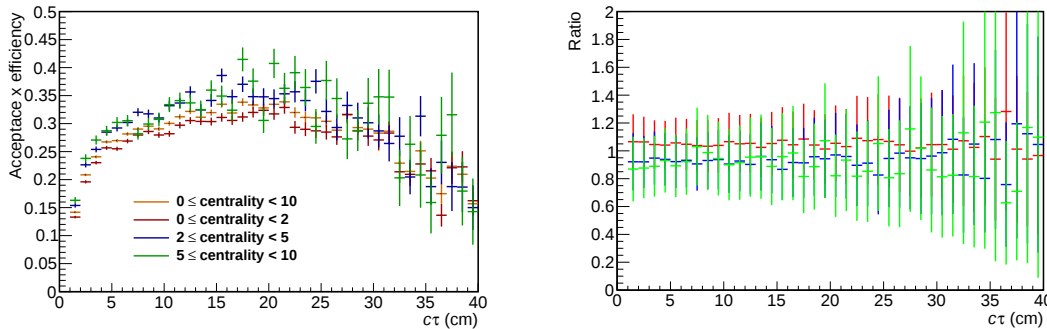


FIGURE 4.44: a) Efficiency vs ct for different centrality. Orange is for 0-10%; red for 0-2%, blue for 2-5% and green for 5-10% centrality bin. b) Ratio of the efficiency vs ct in different centrality bin over the one in the 0-10% centrality bin. Colours are the same as in the left panel.

To take into account this dependence, the same method already explained in section 4.5.4.1 has been applied. This method takes into account the number of events recorded in each centrality bin and the N_{part} in each class. This leads to weight the 5-13% centrality bin by a factor 4.9, the 2-5% bin by a factor 2.17 and the 0-2% bin by 1. Fig. 4.45 shows the result (in green) which is compared to the simple arithmetic mean (in red) and the efficiency in the 0-10% centrality bin in orange.

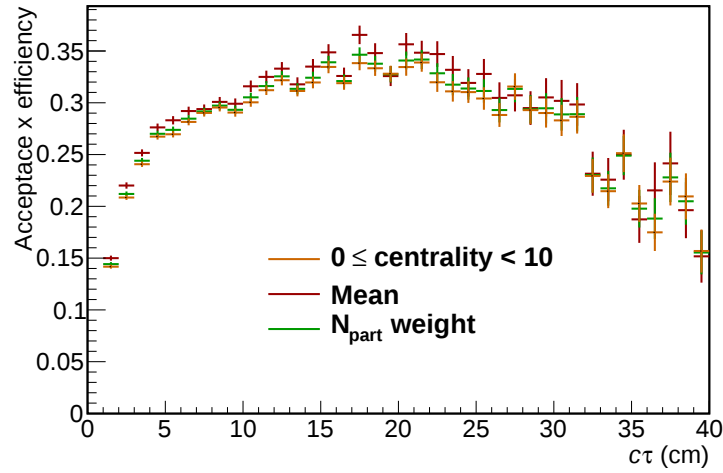


FIGURE 4.45: Efficiency vs ct . In orange the result in the 0-10% centrality bin, in red the simple arithmetic mean of the different efficiencies in several centrality bins, while in green is shown the weighed mean. The procedure to get this efficiency is explained in the text.

Finally, the dependence of the efficiency has been evaluated changing the injected lifetime of ${}^3\Lambda$ H.

The STAR collaboration presented [111, 183] preliminary results where ${}^3\Lambda$ H lifetime $\sim$ half of the free Λ one. In the left panel of Fig. 4.46 it is shown (in green) the efficiency when the injected lifetime is equal to the free Λ , together with the efficiency when the injected lifetime is equal to half that of the free Λ (in red). The ratio between the efficiencies is shown in the right panel; the ratio is compatible with 1.

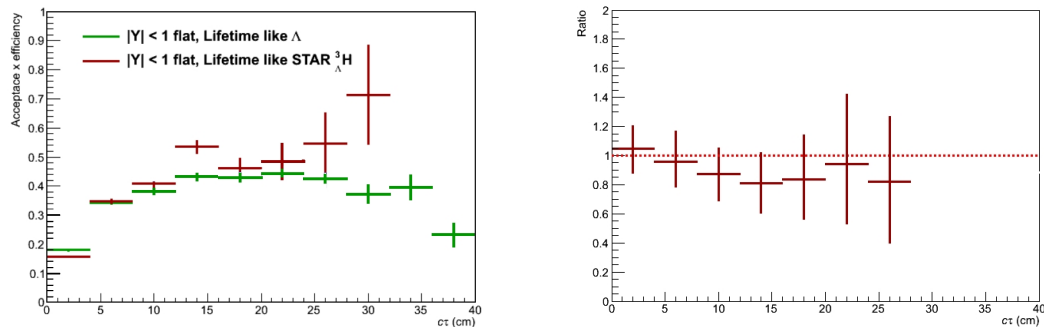


FIGURE 4.46: a) Efficiency for an injected ${}^3\Lambda$ H lifetime equal to the free Λ (green points) and for an injected lifetime equal to 1/2 of the free Λ (red points). b) Ratio between the efficiencies in the left panel.

4.6.2 Systematic Errors

Several sources of systematic uncertainties were considered, namely those affecting the $\bar{\Lambda}^3\text{H}$ lifetime extraction as the analysis cuts and all the correction factors applied to obtain the p_T differential cross sections. A summary of the estimated relative systematic errors and the investigated cuts is given in the following:

- Efficiency determination: since the efficiency has been evaluated with a ct bin width of 1 cm, while in the data the bin width is 3 cm, the mean efficiency has to be taken into account. The spread between the mean and the minimum and between the mean the maximum will be taken into account as a systematic error source. The systematic error associated is $\sim 13\%$. Fig. 4.47 shows (in black) the efficiency evaluated in 1 cm bins and (in red) the mean when a 3 cm bin is used. The error associated to the mean value is shown as a rectangle. The systematic error is evaluated as the maximum deviation in the extracted yield.

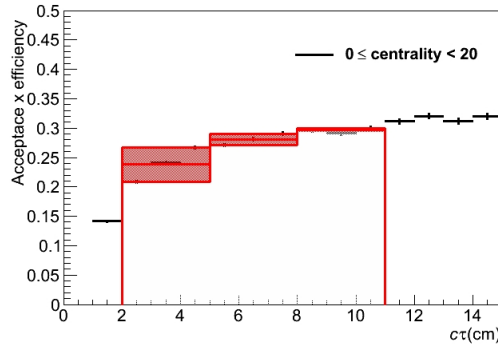


FIGURE 4.47: The efficiency evaluated in 1 cm bin is shown in black, while in red the mean value when a 3 cm bin is used. The error associated to the mean value is shown as a rectangle. The systematic error associated to this effect is $\sim 13\%$

- Topological cuts: some topological cuts (i.e, $\cos(\text{Pointing Angle})$, $\text{DCA}_{\pi \text{ to PV}}$) are varied in order to evaluate the related systematic errors. Table 4.24 summarizes the studied cuts.

	Value
$\cos(\text{Pointing Angle})$	0.992, 0.994, 0.996
$\text{DCA}_{\pi \text{ to PV}}$	0.3, 0.50 cm

TABLE 4.24: Values of topological cuts used to evaluate the systematic errors.

Varying the topological cuts, the extracted lifetime varies itself. As already explained in 4.4.5, the evaluation of systematic errors is affected by the lack of statistics. Again, the Monte Carlo simulation has been used to evaluate the systematic errors. First, the simulation has been modulated in order to reproduce the S/B

ratio measured in data; then the systematic errors evaluation varying topological cuts has been repeated 4 times. In the first one the overall statistics is similar to the one of the data; in the second one it is 2 times bigger, in the third one it is 7 times bigger while in the latter it is 10 times bigger. To evaluate the yields in each ct bin two methods have been used: the MC truth and the fit procedure as used to evaluate the signal from the data. The extracted yields have then been used to evaluate the ct . Changing the topological cuts, ct slightly varies, but the values are all consistent within 1σ (see Fig. 4.48). When the MC truth is used, ct is almost independent from the statistics and its error slightly varies: this error is related only with the acceptance correction. On the other hand, when the signal is extracted by using the fit procedure, the measured ct 's are still compatible, but their error increases when the statistics decreases since the fit results are very sensitive to the underlying events statistics.

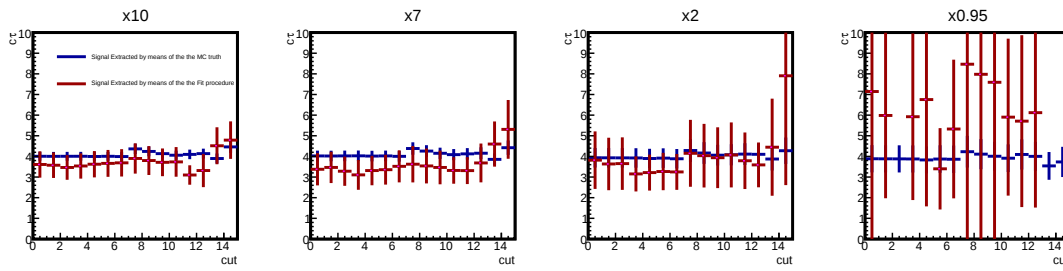


FIGURE 4.48: ct versus the topological cut applied. Each panel refers to different statistics, as indicated in each histogram title, by a factor which is a multiplying factor with respect to the experimental data statistics. Magenta points have been evaluated using the fit procedure, while blue points by using the Monte Carlo truth.

The systematic error associated to ct is then defined as the mean value of the relative errors associated with different topological cuts. It is possible to define the “acceptance error” as the error related to the produce associated to the MC truth signal, the “Statistical + Fit + Acceptance” error as the one associated to the signal extracted by means of the combined fit and the “fit + statistical” error the subtraction in quadrature of the previous two defined errors. These three errors are shown, as a function of the statistics utilized in the analysis, in Fig. 4.49: the “fit + statistical” error is shown in red triangles, the acceptance error in blue circles and the “Statistical + Fit + Acceptance” error in green squares. The “fit + statistical” error can be used to extract the systematic error in the data. The “Statistical + Fit + Acceptance” error in data is evaluated in the same way as for the Monte Carlo, i.e. as the mean of the mean value of the relative errors related to different topological cuts. By subtracting in quadrature the error obtained from the experimental data to the (MC) “fit + statistical” error, it is then possible to evaluate the relative systematic error in the experimental data. The total systematic error due to topological cuts is evaluated to be 19%.

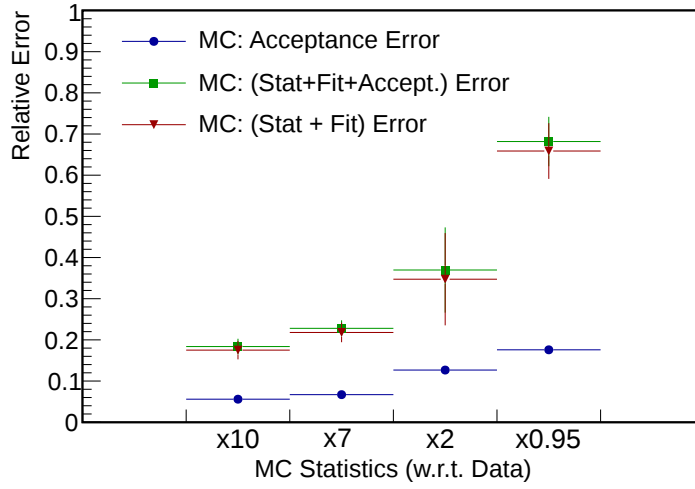


FIGURE 4.49: Relative ct error versus the Monte Carlo statistics used to evaluate the ct . Green squares: “Statistical+Fit+Acceptance” error, red triangles: “fit+statistical” component and blue circles: acceptance error.

- η dependence of the efficiency: Fig. 4.24a shows the efficiency as a function of η : in order to take into account this dependence an error of 5% will be added to the systematic error evaluation.

The uncertainties are summed in quadrature. The total systematic error is evaluated to be $\pm 24\%$.

4.6.3 Results

Fig. 4.50 shows the corrected yields, fitted with the exponential function (eq.4.24).

The errors associated with ct are determined by using the χ^2 function as a function of A_1 . (See Fig. 4.51).

The results are:

$$c\tau = 4.69^{+1.52}_{-1.85} \pm 1.40 \text{ cm} \quad (4.31)$$

$$\tau = 159^{+52}_{-62} \pm 48 \text{ ps} \quad (4.32)$$

Fig. 4.52 shows the obtained value of the ${}^3_{\Lambda}H$ lifetime (τ) compared to the world results up to summer 2012. The references are shown directly in the plot.

The lifetime of ${}^3_{\Lambda}H$ obtained in this analysis is: $159^{+52}_{-62} \pm 48$ ps. With the present statistics it is not possible to exclude any previous measurement, but the result presented seems to support a hypertriton lifetime shorter than that of the free Λ .

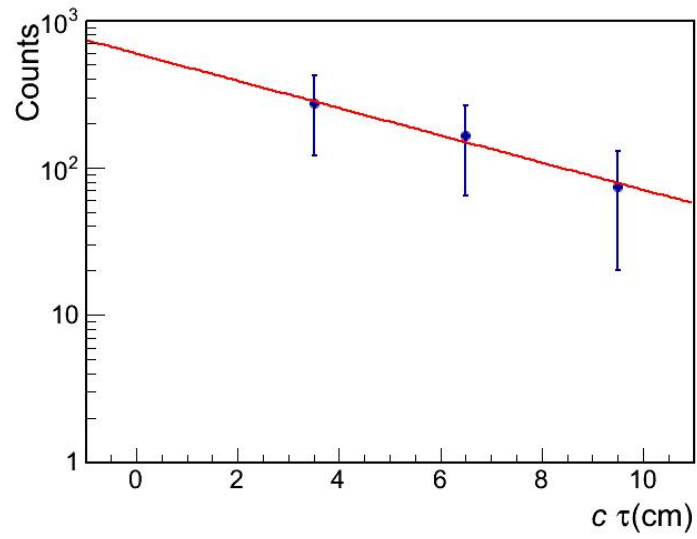


FIGURE 4.50: Corrected(${}^3_{\Lambda}\text{H} + {}^3_{\Lambda}\overline{\text{H}}$) yields vs ct . Points are fitted with function 4.24. The results are shown in eq. 4.31 and 4.32.

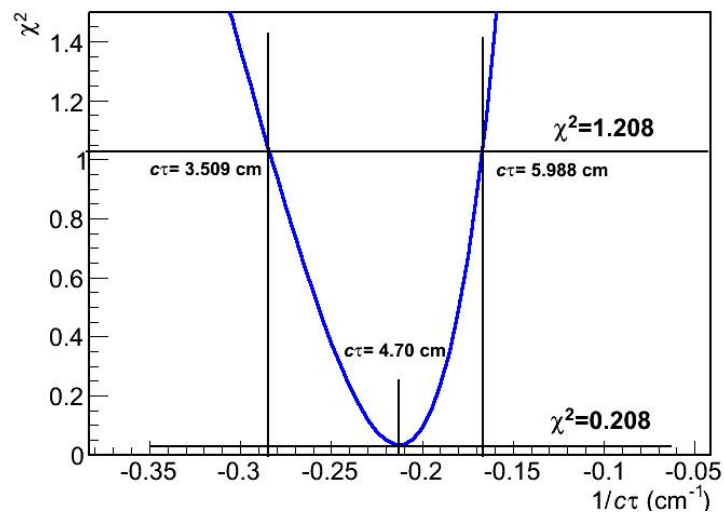


FIGURE 4.51: χ^2 vs $1/ct$

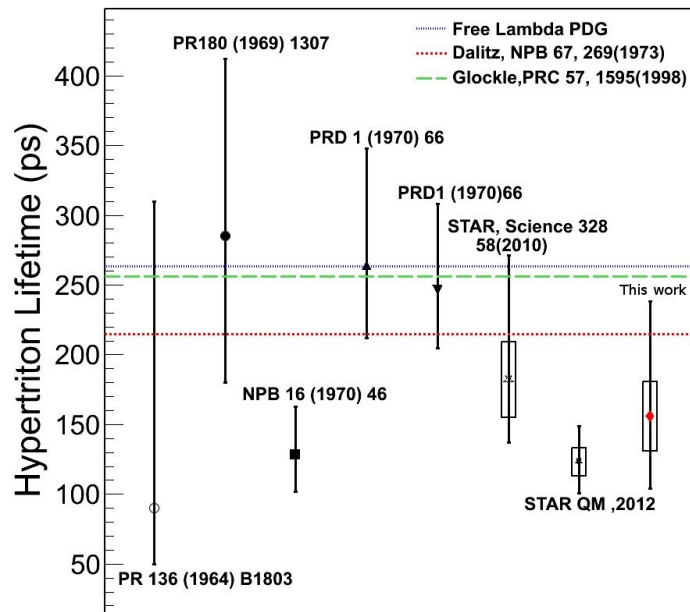


FIGURE 4.52: ${}^3_\Lambda H$ proper lifetime as measured by various experiments. The red full diamond marker refers to results presented in this note.

Measurement of the ^3He transverse momentum spectra

5.1 Introduction

In this chapter the method used to evaluate the $^3\text{He}(^3\overline{\text{He}})$ production yield will be described.

To evaluate the total production yield, the spectrum as a function of the transverse momentum (p_T) will be used. First of all, the data sample and the event selection used in the analysis will be shortly described; then, the raw yields as a function of p_T for central and semi-central events will be shown and the efficiency and systematic errors evaluations will be described. Furthermore, the effect of the feed-down of ^3He from $^3_\Lambda\text{H}$ will be discussed. Finally, the fully corrected spectra will be shown and the total yield will be extracted by fitting the spectra with different functions.

5.2 Data Sample and Event Selection

5.2.1 Data Sample

For the present analysis the data from 2011 Pb–Pb data taking at 2.76 TeV has been used. The data sample is composed by 108 runs tagged as “good” by the ALICE collaboration. To evaluate the efficiency a simulation based on the 2011 data sample has been used; in total about 24 million central events and about 21 million semi-central events has been analysed.

The Monte Carlo production is based on a pure Hijing event simulation enriched with

${}^3_\Lambda\text{H}({}^3_\Lambda\overline{\text{H}})$ and ${}^3\text{He}({}^3\overline{\text{He}})$; the simulation is not fully realistic: the injected particles abundances do not correspond to the data since the purpose of this simulation was to evaluate the detection and reconstruction efficiency of the ${}^3_\Lambda\text{H}$ and ${}^3\text{He}$ with a reasonable CPU-cost. For each event, 20 ${}^3_\Lambda\text{H}$, 20 ${}^3_\Lambda\overline{\text{H}}$, 5 ${}^3\text{He}$ and 5 ${}^3\overline{\text{He}}$ have been injected. Moreover, the p_{T} spectra of the injected particles are non realistic: the injected particles have both $p_{\text{T}}(0 \leq p_{\text{T}} \leq 10 \text{ GeV}/c)$ and rapidity ($|Y| < 1$) flat distributions.

5.2.2 Track Selection

${}^3\text{He}$ and ${}^3\overline{\text{He}}$ tracks are identified using the specific energy loss dE/dx in the TPC. Only tracks which pass particular selections are accepted in the analysis. Table 5.1 summarizes the cuts used to select the tracks for the analysis. This set of cuts has been used both for real and Monte Carlo data.

Track cuts	Value
Kink daughter	reject
TPC refit flag	kTRUE
ITS refit flag	kTRUE
$n_{\text{cluster}}^{\text{TPC}}$	>80
Track χ^2	<5
$ \eta <$	1.2

TABLE 5.1: Cuts used for the track selection in the present analysis. The same cuts have been applied to real data and Monte Carlo.

5.3 Measurement of the ${}^3\text{He}$ p_{T} spectrum

5.3.1 Particle Identification

The main ALICE detector used to identify ${}^3\text{He}$ in this analysis is the Time Projection Chamber (TPC). The signal in the TPC is given by the energy loss of charged particles passing through the detector. Fig. 5.1 shows the specific energy loss versus the rigidity ($R=p/Z$) of tracks identified as ${}^3\text{He}$ and ${}^3\overline{\text{He}}$ (blue points). The superimposed lines are Bethe-Bloch curves for different particle species. In particular, the lines correspond to Bethe-Bloch functions for ${}^3\text{He}$ and ${}^3\overline{\text{He}}$ (in green) and ${}^4\text{He}$ and ${}^4\overline{\text{He}}$ (in magenta).

In addition to the production from the primary vertex, nuclei can be produced by secondary interactions of the outgoing particles with the different materials crossed in their way out. In order to reduce such a contamination it is needed to apply further cuts on the tracks used for the analysis. On the contrary to nuclei, the distribution of the distance of closest approach to the primary vertex along the beam axis (DCA_Z) for

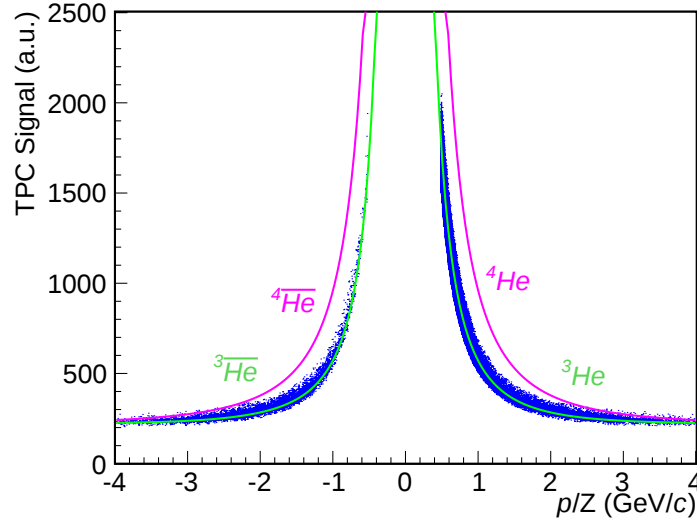


FIGURE 5.1: (dE/dx) of particles identified as ${}^3\text{He}({}^3\overline{\text{He}})$ in the TPC versus rigidity $R=p/Z$ (blue points) with Bethe-Bloch curves for ${}^3\text{He}({}^3\overline{\text{He}})$ and ${}^4\text{He}({}^4\overline{\text{He}})$ superimposed.

anti-nuclei, which has essentially no contribution from secondary interactions, shows a negligible number of tracks with a DCA_Z value greater than 0.5 cm (Fig. 5.2b).

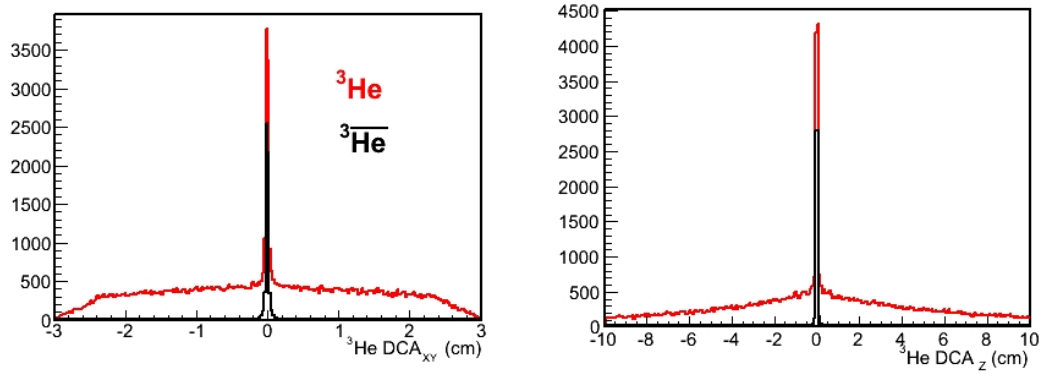


FIGURE 5.2: a) DCA_{XY} distribution of identified ${}^3\text{He}$ (in red) and ${}^3\overline{\text{He}}$ (in black).
b) DCA_Z distribution of identified ${}^3\text{He}$ (in red) and ${}^3\overline{\text{He}}$ (in black).

In order to reduce ${}^3\text{He}$ tracks from secondary production an additional cut on the DCA_Z ($|\text{DCA}_Z| < 0.5$ cm) is added. Fig. 5.3a shows the effect of such a cut on the DCA_{XY} : the total number of ${}^3\overline{\text{He}}$ is not changed, while the number of secondary ${}^3\text{He}$ is significantly reduced if compared to the red distribution in Fig. 5.2a.

A small contamination is still present, which is anyhow limited to the lower p_T bins. This is visible in Fig. 5.4 which shows the DCA_{XY} for nuclei (in red) and anti-nuclei (in black) in different p_T bins for central collisions after the DCA_Z cut. The contamination above 3 GeV/c is negligible. As GEANT3 is not able to reproduce such a behaviour it is

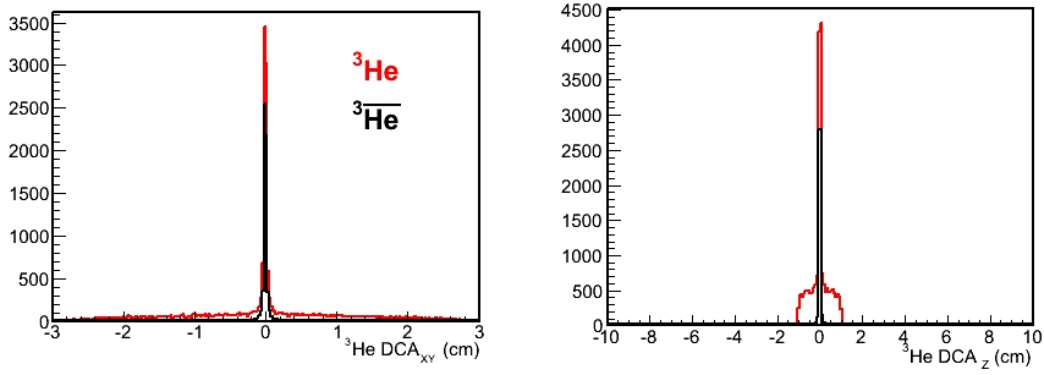


FIGURE 5.3: a) DCA_{XY} distribution of identified ^3He (in red) and $^3\bar{\text{He}}$ (in black) after applying the $|\text{DCA}_Z| < 0.5$ cm applied. b) DCA_Z distribution of identified ^3He (in red) and $^3\bar{\text{He}}$ (in black). The total number of $^3\bar{\text{He}}$ is not changed, while the number of secondary ^3He is significantly reduced, if compared to the red distribution in Fig. 5.2

not possible to correct for it. Therefore, the spectra will be analysed only for tracks with $p_T > 3$ GeV/c.

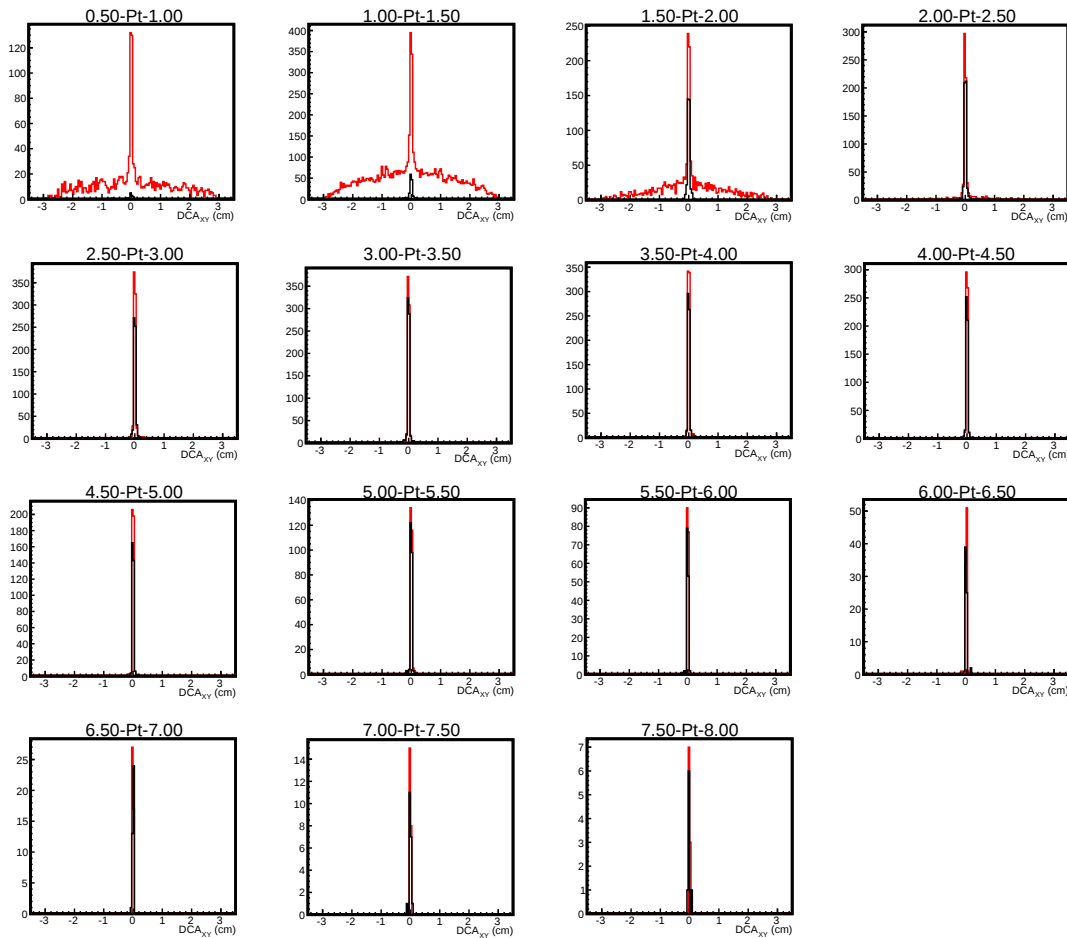


FIGURE 5.4: DCA_{XY} distribution of identified ^3He (in red) and $^3\bar{\text{He}}$ (in black) in different p_T bins.

5.3.2 ^3He and $^3\overline{\text{He}}$ raw spectra

Fig. 5.5 shows the raw spectra for ^3He (red points) and $^3\overline{\text{He}}$ (black points) as a function of p_T . The bin width is 0.500 GeV/c. For $p_T \leq 3\text{ GeV}/c$ the secondary production of ^3He and the annihilation of $^3\overline{\text{He}}$ can be appreciated as an excess and, respectively, a depletion of strength in the low p_T region. In the following, only the region with $p_T > 3\text{ GeV}/c$ will be considered to compute the production yield of $^3\text{He}(^3\overline{\text{He}})$.

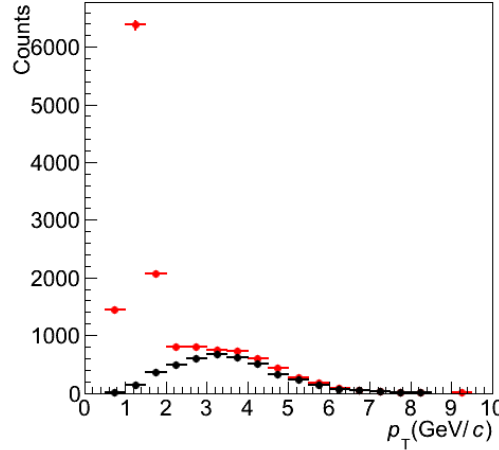


FIGURE 5.5: ^3He (red points) and $^3\overline{\text{He}}$ (black points) raw p_T spectra. For $p_T \leq 3\text{ GeV}/c$ the secondary production of ^3He and the annihilation of $^3\overline{\text{He}}$ can be appreciated as an excess and, respectively, a depletion of strength in the low p_T region.

5.3.3 Efficiency Evaluation

To compute the efficiency, the particle identification is performed via the Monte Carlo truth instead of the TPC dE/dx . The details of MC truth PDG code are +1000020030 for ^3He and -1000020030 for $^3\overline{\text{He}}$.

The efficiency numerator (“reconstructed signal”) is filled in the analysis stage, after all event selections. The efficiency denominator is filled with generated MC primary $^3\text{He}(^3\overline{\text{He}})$.

First of all, the effect of the ^3He transport correction in Geant3 has been checked. The left panel of Fig. 5.6 shows the ^3He p_T generated momentum vs the reconstructed one, while in the right panel it is shown the difference of the generated and reconstructed momenta versus the reconstructed one. An effect connected to the transport correction can be clearly seen: as all particles heavier than a proton are treated as protons, the ^3He low reconstructed momenta are underestimated because the reconstruction program during the refit procedure does not take into account the proper mass and charge of the particle. The larger effect is observed for $p_T < 3\text{ GeV}/c$, which are not analysed in this work. Anyway, in order to take into account this effect, all the efficiencies will

be evaluated using the generated momentum instead of the reconstructed one. In this way all transport corrections are embedded in the calculated efficiency.

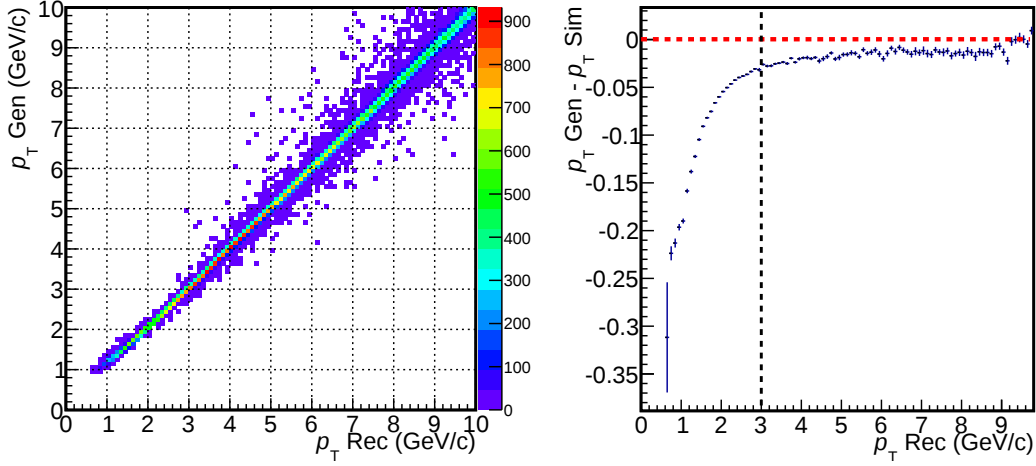


FIGURE 5.6: a) ^3He generated p_T vs reconstructed p_T . b) Profile of (generated – reconstructed) p_T vs reconstructed p_T . The vertical black line is the lower p_T used in the present analysis.

The efficiency versus p_T for events with a centrality between 0 and 20% is shown in Fig. 5.7. Red circles are for ^3He , while black triangles are for $^3\overline{\text{He}}$.

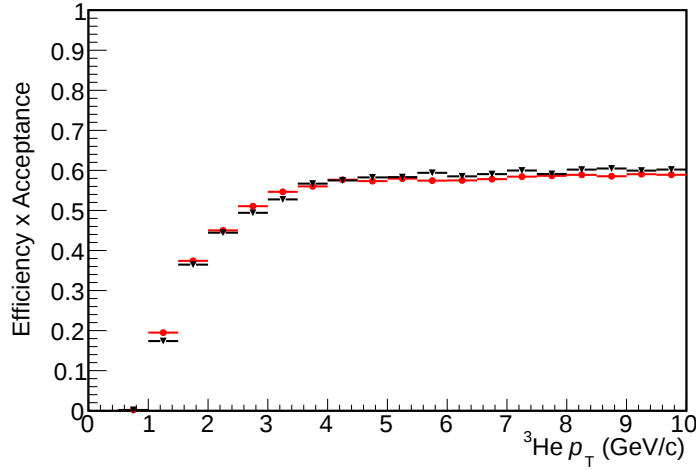


FIGURE 5.7: ^3He (red circles) and $^3\overline{\text{He}}$ (black triangles) efficiency times acceptance vs p_T .

The efficiency has been evaluated also as a function of the centrality of the event. Fig. 5.8 shows the efficiency as a function of p_T for different centrality bins (0-2% in red; 2-5% in green and 5-10% in violet). A dependence of the efficiency from the centrality is clearly visible. To take into account this effect, the different efficiencies have been weighted with the total number of participant (N_{part}) and the number of events recorded in each centrality bin. The details of this procedure are explained in Section 4.5.3. The assigned weights varies from 5.20 for the most peripheral (5-10%) events

to 1.40 for the centrality between 2 and 5%, while the weight is 1 for the most central bin (0-2%). The efficiency that will be used to evaluate the correction of ${}^3\text{He}({}^3\overline{\text{He}})$ is shown in Fig. 5.8 as a black line.

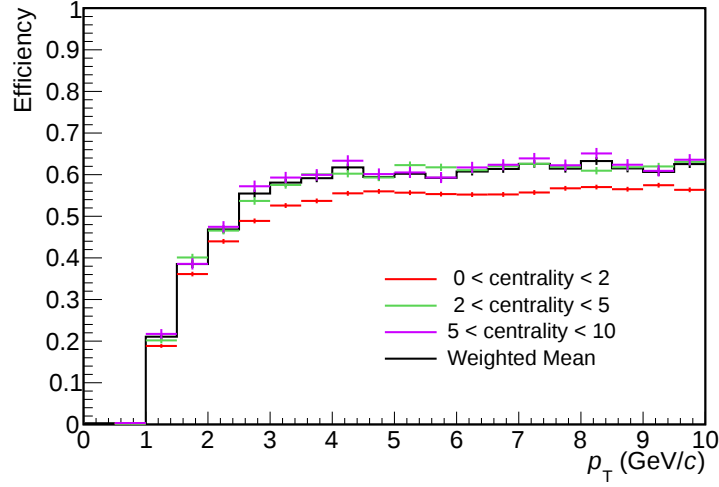


FIGURE 5.8: ${}^3\text{He}$ efficiency $\times$ acceptance vs p_T in several centrality bins (0-2% in red; 2-5% in green and 5-10% in violet). The black line refers to the weighted efficiency that will be used in the following analysis.

5.3.4 Systematic Errors evaluation

Several sources of systematic uncertainties were considered, namely those affecting the ${}^3\text{He}$ extraction. A summary of the the investigated cuts is given in Table 5.2.

	Value
Number of TPC clusters	60,80,90
DCA_Z	0.5, 2 cm
DCA_{XY}	0.1, 0.5 cm

TABLE 5.2: Modified track cuts used to evaluate the systematic errors.

The systematic errors induced by selection cuts were evaluated by repeating the analysis with looser and with tighter selections w.r.t. the ones used in the analysis.

The systematic errors on the tracking efficiency of ${}^3\text{He}$ is mainly due to the minimum number of TPC clusters that are connected to a track. In the present analysis a requirement of a minimum of 80 clusters should be satisfied in order to be considered. For the systematic error evaluation a tighter (i.e. 90) and lower (i.e. 60) cut has been applied.

The systematic error induced by the particle identification selection and the contamination reduction has been evaluated by investigating the PID and DCA selections. The effect of varying the DCA_{XY} and DCA_Z values around the nominal one has been used as an addition systematic source. All the errors have been summed in quadrature.

Fig. 5.9 shows the relative error as a function of p_T for ${}^3\text{He}$ and ${}^3\overline{\text{He}}$ in central (Fig. 5.9 left and right top panels) and semi-central (Fig. 5.9 left and right bottom panels) events.

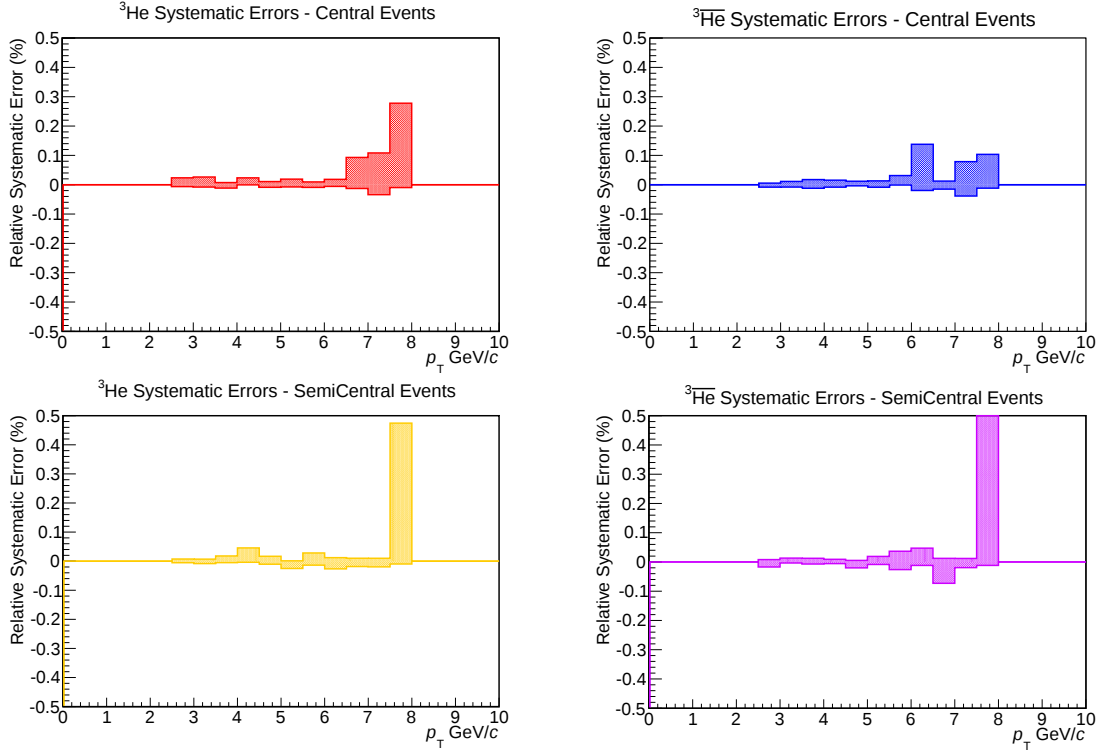


FIGURE 5.9: Relative systematic errors vs p_T for a) ${}^3\text{He}$ central events b) ${}^3\overline{\text{He}}$ central events c) ${}^3\text{He}$ Semi-Central events and d) ${}^3\overline{\text{He}}$ Semi-Central.

5.3.5 Feed-Down from ${}^3_\Lambda\text{H}$

The measured ${}^3\text{He}$ and ${}^3\overline{\text{He}}$ are not only primaries since a fraction of them, which has to be evaluated, may come from ${}^3_\Lambda\text{H}$ and ${}^3_\Lambda\overline{\text{H}}$ decays. In order to subtract this fraction, it is possible to define a “feed-down matrix” as:

$$F_{ij} = \frac{N_{reco}({}^3\text{He})_{\text{from } {}^3_\Lambda\text{H in bin } j}^{\text{in bin } i}}{N_{gen}({}^3_\Lambda\text{H})_{{}^3_\Lambda\text{H bin } j}} \quad (5.1)$$

The matrix represents a detection efficiency of a ${}^3\text{He}$ ($N_{reco}({}^3\text{He})$) with a momentum in bin i from ${}^3_\Lambda\text{H}$ in a given bin j , which passes all the cuts, coming from ${}^3_\Lambda\text{H}$ in a momentum bin j . The dominator is filled with the number of generated ${}^3_\Lambda\text{H}$ ($N_{gen}({}^3_\Lambda\text{H})$). Only the statistical error is considered for the matrix elements F_{ij} . The “feed-down matrix” from the presented analysis is shown in Fig. 5.10.

The feed-down subtraction in each i -th p_T bin for the ${}^3\text{He}$ is computed in the raw counts by using the formula:

$${}^3\text{He}_{primary}^{raw} = {}^3\text{He}_{measured}^{raw} - \sum_j F_{ij} \int_{p_T \text{ (bin)}} \frac{dN}{dp_T} ({}^3_\Lambda\text{H}) \quad (5.2)$$

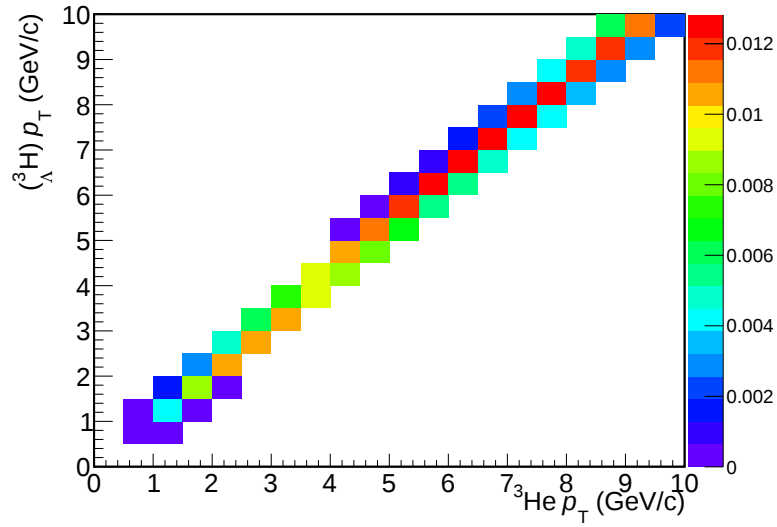


FIGURE 5.10: Feed-down matrix for ${}^3\text{He}$ from ${}^3_{\Lambda}\text{H}$. In x-axis it is shown the p_T distribution of ${}^3\text{He}$ from ${}^3_{\Lambda}\text{H}$; the y-axis shows the p_T distribution of ${}^3_{\Lambda}\text{H}$, while the z-axis is filled with the F_{ij} element, as described in eq.5.1.

As the p_T distributions of ${}^3\text{He}({}^3\overline{\text{He}})$ and ${}^3_{\Lambda}\text{H}({}^3_{\Lambda}\overline{\text{H}})$ is gerated flat in the Monte Carlo simulations, it is necessary to make some assumptions on the p_T shape of the particles in real data. The function which is usually used to describe the particle spectra in Pb–Pb collisions is the Blast-Wave function [184]:

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r \, dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{\text{kin}}} \right) \quad (5.3)$$

Where the dependence of the velocity profile is described by:

$$\rho = \tanh^{-1} \left(\left(\frac{r}{R} \right)^n \beta_T \right) \quad (5.4)$$

Here, $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass, I_0 and K_1 the modified Bessel functions, r is the radial distance in the transverse plane, T_{kin} is the freeze-out temperature, β_T is the average transverse velocity and n is the exponent of the velocity profile. This function has been used successfully to fit the p_T distributions of all particle species over the whole measured p_T range by the ALICE collaboration. However, it should be noted that the fit parameters have not any physics meaning because the formula is empirical. The Blast-Wave parameters which are used for the ${}^3\text{He}$ spectra have been extracted from the fit to the acceptance corrected p_T spectrum, see Section 5.4 for the acceptance calculation details. The same parameters, except for the mass and the normalization which are extracted by fitting the corrected ${}^3_{\Lambda}\text{H}$ spectra, are used to evaluate the $dN({}^3_{\Lambda}\text{H})/dp_T$ shown in eq.5.2.

Finally, the ${}^3\text{He}/{}^3_{\Lambda}\text{H}$ ratio is needed to be evaluated in order to get the total fraction of ${}^3\text{He}$ from ${}^3_{\Lambda}\text{H}$. The evaluation of this value changes considering different particle production mechanisms (see Chapter 3). Since the production mechanism is unknown, in

the present analysis different values of this ratio have been considered to evaluate the systematic uncertainties due to feed-down.

The dark red dashed line in Fig. 5.11a represents the raw ^3He counts after the feed-down correction for central collisions, while the dark blue dashed line in Fig. 5.11b is the ^3He raw spectra corrected for the $^3_{\Lambda}\bar{\text{H}}$ feed-down for central collisions. This spectra have been computed assuming a $^3\text{H}/^3\text{He}$ equal to 1.

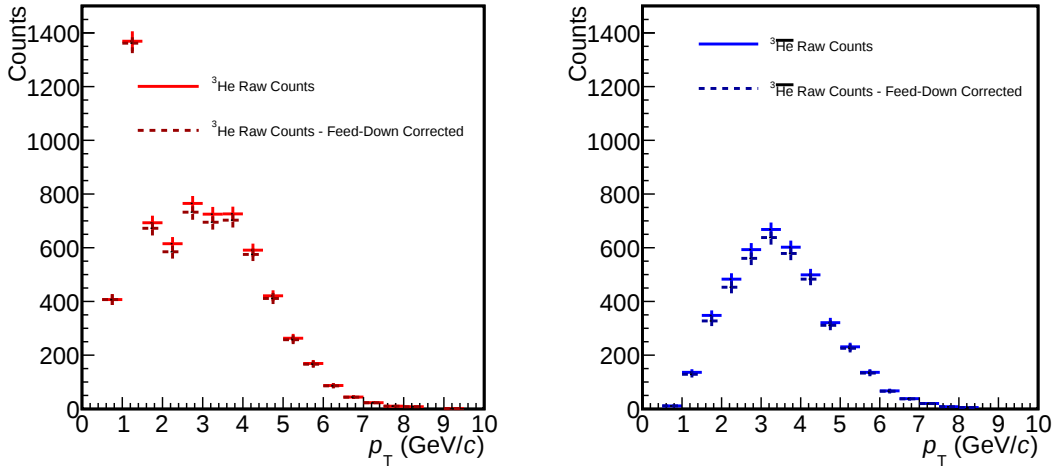


FIGURE 5.11: a) Raw ^3He p_T spectrum with (dashed lines) and without (full lines) the feed-down correction from $^3_{\Lambda}\bar{\text{H}}$. b) Raw ^3He p_T spectrum with (dashed lines) and without (full lines) the feed-down correction from $^3_{\Lambda}\bar{\text{H}}$.

Fig. 5.12a shows the ratio of ^3He spectra without the feed-down correction over the spectra corrected for the feed-down when the $^3\text{H}/^3\text{He}$ ratio is equal to 1. Fig. 5.12b shows the same ratio, but for ^3He . The same ratios are reported also in case $^3\text{H}/^3\text{He} = 0.5$ in Fig. 5.13 and $^3\text{H}/^3\text{He} = 0.3$ in Fig. 5.14.

The maximum fraction of the spectra removed due to the feed-down correction is about 5% both for ^3He and ^3He when the $^3\text{H}/^3\text{He} = 1$, is $\sim 2\%$ when the $^3\text{H}/^3\text{He} = 0.5$ and is $\sim 1.5\%$ when the $^3\text{H}/^3\text{He} = 0.3$. It has to be noted, however, that the maximum is reached for a p_T of about 2 GeV/c, while in the analysis only $p_T > 3$ GeV/c have been considered. In this region the fraction of the spectra removed looks stable versus p_T and lower than 1%. This value is smaller than the statistical error. With the present statistics, the effect of the feed-down of $^3\text{He}(^3\text{He})$ from $^3_{\Lambda}\text{H}(^3_{\Lambda}\bar{\text{H}})$ can be neglected. The same analysis has been repeated also for semi-central events with comparable results.

5.4 Results

Fig. 5.15 shows the p_T corrected spectra, normalized for the number of events. In the left panel, the spectra of ^3He and ^3He for central events (centrality between 0-13%) are shown: blue markers are for ^3He , while red markers are for ^3He . In the right panel the

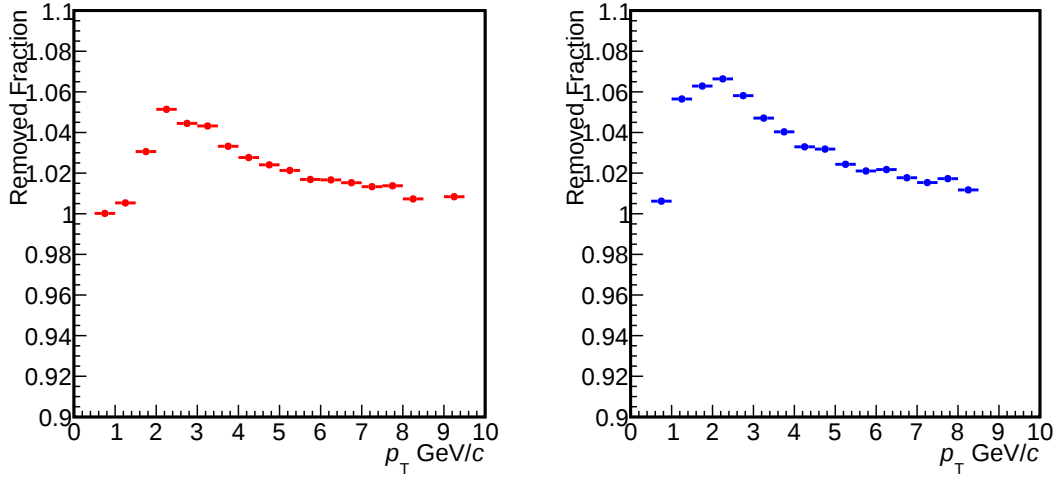


FIGURE 5.12: Ratio of feed-down uncorrected over feed-down corrected spectra for a ${}^3\text{He}/{}^3\text{H}$ ratio equal to 1, for ${}^3\text{He}$ left panel and ${}^3\overline{\text{He}}$ right panel.

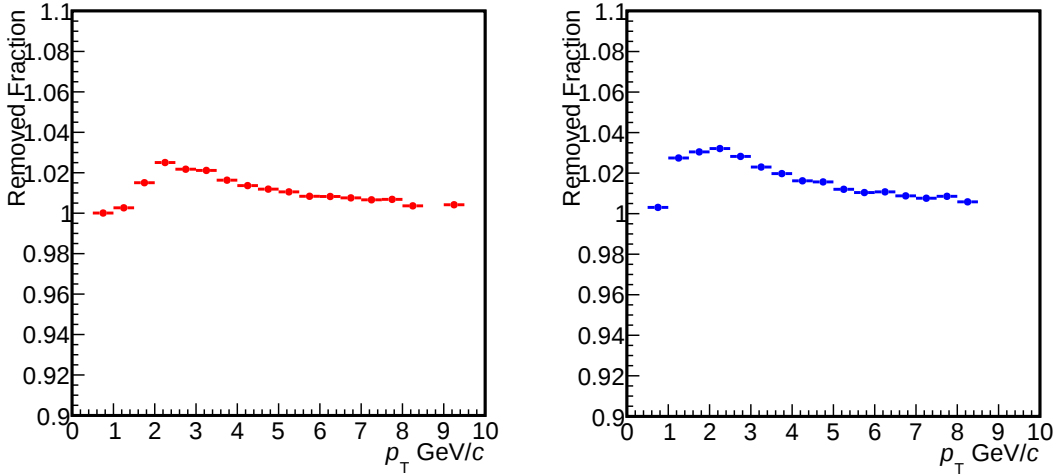


FIGURE 5.13: Ratio of feed-down uncorrected over feed-down corrected spectra for a ${}^3\text{He}/{}^3\text{H}$ ratio equal to 0.5. ${}^3\text{He}$ left panel and ${}^3\overline{\text{He}}$ right panel.

results for semi-central (centrality between 10-50%) events are shown: ${}^3\text{He}$ spectrum is in violet, while ${}^3\overline{\text{He}}$ is in orange. Statistical errors are represented as lines, while boxes are systematic errors.

In order to extrapolate the p_T spectrum from zero to ∞ and obtain the integrated yields, the spectra have been fitted with different distributions: Boltzmann, Fermi-Dirac and Blast-Wave. The functions are shown in Appendix A. Table 5.3, 5.4, 5.5, 5.6, summarize the results of the fit to the ${}^3\text{He}({}^3\overline{\text{He}})$ spectrum when different p_T distributions are used. The best results (i.e. lower χ^2/NDF and χ^2/NDF closer to 1) is obtained with the Blast-Wave function in all four cases. Fig. 5.16 shows the 4 spectra fitted with the Blast-Wave function. (a) ${}^3\text{He}$ central, b) ${}^3\overline{\text{He}}$ central c) ${}^3\text{He}$ semicentral d) ${}^3\overline{\text{He}}$ semicentral).

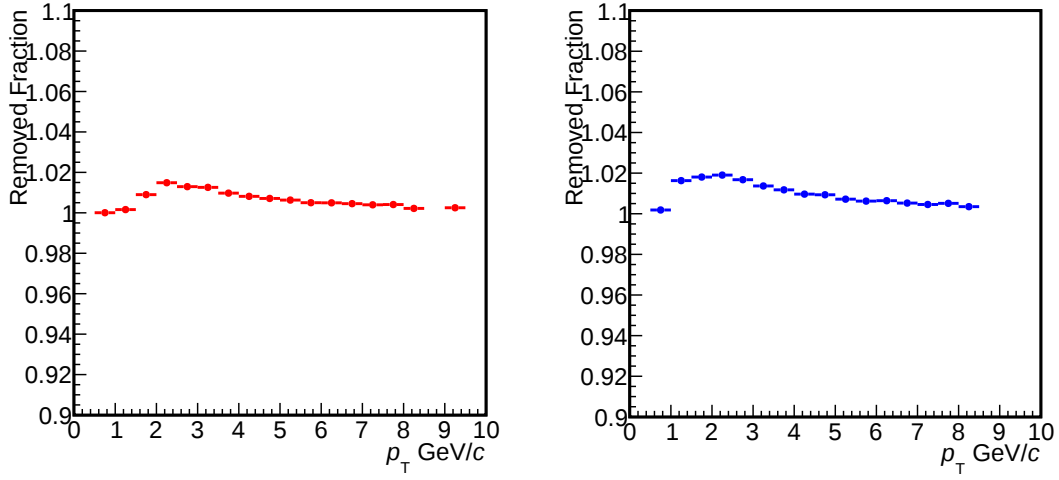


FIGURE 5.14: Ratio of feed-down uncorrected over feed-down corrected spectra for a $^3\text{He}/^3\text{H}$ ratio equal to 0.3. ^3He left panel and $^3\bar{\text{He}}$ right panel.

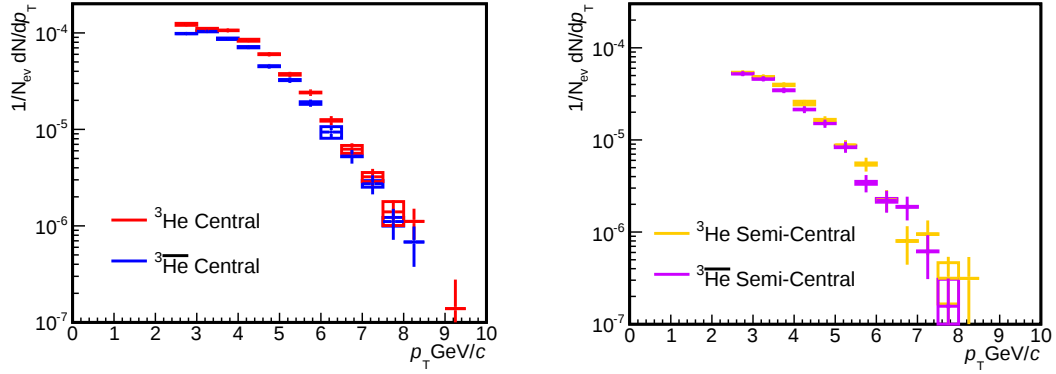


FIGURE 5.15: a) ^3He (in blue) and $^3\bar{\text{He}}$ (in red) spectra with statistic (lines) and systematic (boxes) errors in central (0-13%) events. b) ^3He (in orange) and $^3\bar{\text{He}}$ (in violet) spectra with statistic (lines) and systematic (boxes) errors in central (0-13%) events.

The production yield of ^3He in central collisions, in a rapidity window $|Y| < 1$ is:

$$\left. \frac{dN(^3\text{He})}{dp_T} \right|_{\text{Central}} = (4.13 \pm 0.42 \pm 0.11) 10^{-4} \quad (5.5)$$

The production yield of $^3\bar{\text{He}}$ in central collisions is:

$$\left. \frac{dN(^3\bar{\text{He}})}{dp_T} \right|_{\text{Central}} = (3.24 \pm 0.29 \pm 0.02) 10^{-4} \quad (5.6)$$

while, in semi-central collisions:

$$\left. \frac{dN(^3\text{He})}{dp_T} \right|_{\text{Semi-Central}} = (1.52 \pm 0.15 \pm 0.02) 10^{-4} \quad (5.7)$$

and

$$\left. \frac{dN(^3\overline{\text{He}})}{dp_T} \right|_{\text{Semi-Central}} = (1.57 \pm 0.16 \pm 0.05) 10^{-4} \quad (5.8)$$

The systematic errors have been evaluated by fitting the spectra taking into account the systematic errors associated with the different points. Assuming particle production scales with the number of participants, condition verified for other particle species [44], it is possible to compare the production yields obtained in the two different analyses (i.e. the based on central and semi-central events).

The number of participants in central collisions is $N_{\text{part}} = 356$, while in semi-central collisions is $N_{\text{part}} = 165$. In the most central collisions (0-5%) the number of participant is $N_{\text{part}} = 383$. If we want to normalize the results to the most central events, a factor 1.1 has to be used to multiply to “central” results, while a factor 2.3 has to be multiplied to the “semi-central” results. This leads to:

$$\left. \frac{dN(^3\text{He})}{dp_T} \right|_{\text{Central} \rightarrow 0-5\%} = (4.54 \pm 0.46 \pm 0.12) 10^{-4} \quad (5.9)$$

$$\left. \frac{dN(^3\overline{\text{He}})}{dp_T} \right|_{\text{Central} \rightarrow 0-5\%} = (3.56 \pm 0.32 \pm 0.05) 10^{-4} \quad (5.10)$$

$$\left. \frac{dN(^3\text{He})}{dp_T} \right|_{\text{Semi-Central} \rightarrow 0-5\%} = (3.50 \pm 0.40 \pm 0.06) 10^{-4} \quad (5.11)$$

$$\left. \frac{dN(^3\overline{\text{He}})}{dp_T} \right|_{\text{Semi-Central} \rightarrow 0-5\%} = (3.61 \pm 0.43 \pm 0.12) 10^{-4} \quad (5.12)$$

These results will be discussed more in details in Chapter 6.

Function	Parameters	χ^2/NDF	Yield	% Below
Boltzmann	norm: 2.17e-3 T : 0.767e-1	173/11	$(6.11 \pm 0.001) \times 10^4$	0.655
Bose-Einstein	norm: 4.53e-3 T: 0.887	273/11	$(6.52 \pm 0.10) \times 10^4$	0.68
Fermi-Dirac	norm : 4.68e-3 T: 0.884	210/11	$(6.40 \pm 0.10) \times 10^4$	0.67
Blast-Wave	mass: 2.808 β : 0.833 T: 0.138 n: 0.532 norm: 1.22e6	9.25/9	$(4.13 \pm 0.05) \times 10^4$	0.455

TABLE 5.3: Summary of the fit results of ^3He spectrum in central collisions. In the table are shown the parameters from the fit together with the production yield, extracted as integral of the fitting function from $0 < p_T \infty$. The % Below is the percentage of the total yield which is not covered by the experimental points.

Function	Parameters	χ^2/NDF	Yield	% Below
Boltzmann	norm: 1.93e-3 T : 0.766e-1	136/10	$(5.15 \pm 0.09) \times 10^4$	0.656
Bose-Einstein	norm: 3.76e-3 T: 0.890	169/10	$(5.48 \pm 0.09) \times 10^4$	0.679
Fermi-Dirac	norm : 3.89e-3 T: 0.887	163/10	$(5.38 \pm 0.09) \times 10^4$	0.672
Blast-Wave	mass: 2.808 β : 0.805 T: 0.161 n: 0.352 norm: 3.85e4	4.0/8	$(3.24 \pm 0.04) \times 10^4$	0.420

TABLE 5.4: Summary of the fit results of $^3\overline{\text{He}}$ spectrum in central collisions. In the table are shown the parameters from the fit together with the production yield, extracted as integral of the fitting function from $0 < p_T \infty$. The % Below is the percentage of the total yield which is not covered by the experimental points.

Function	Parameters	χ^2/NDF	Yield	% Below
Boltzmann	norm: 2.15e-3 T : 0.664e-1	31/10	$(2.62 \pm 0.09) \times 10^4$	0.733
Bose-Einstein	norm: 4.06e-3 T: 0.664	38 /10	$(2.78 \pm 0.09) \times 10^4$	0.750
Fermi-Dirac	norm : 4.13e-3 T: 0.758	37/10	$(2.75 \pm 0.09) \times 10^4$	0.766
Blast-Wave	mass: 2.808 β : 0.722 T: 0.195 n: 0.197 norm: 6.84e2	4.38/8	$(1.52 \pm 0.03) \times 10^4$	0.508

TABLE 5.5: Summary of the fit results of ^3He spectrum in semi-central collisions. In the table are shown the parameters from the fit together with the production yield, extracted as integral of the fitting function from $0 < p_T \infty$. The % Below is the percentage of the total yield which is not covered by the experimental points.

Function	Parameters	χ^2/NDF	Yield	% Below
Boltzmann	norm: 2.29e-3 T : 0.651e-1	20 / 9	$(2.49 \pm 0.009) \times 10^4$	0.744
Bose-Einstein	norm: 4.31e-3 T: 0.744	273/9	$(2.64 \pm 0.10) \times 10^4$	0.761
Fermi-Dirac	norm : 44.39-3 T: 0.742	25/9	$(2.60 \pm 0.10) \times 10^4$	0.758
Blast-Wave	mass: 2.808 β : 0.730 T: 0.200 n: 0.371 norm: 4.75e2	5.28/7	$(1.57 \pm 0.03) \times 10^4$	0.574

TABLE 5.6: Summary of the fit results of $^3\overline{\text{He}}$ spectrum in semi-central collisions. In the table are shown the parameters from the fit together with the production yield, extracted as integral of the fitting function from $0 < p_T \infty$. The % Below is the percentage of the total yield which is not covered by the experimental points.

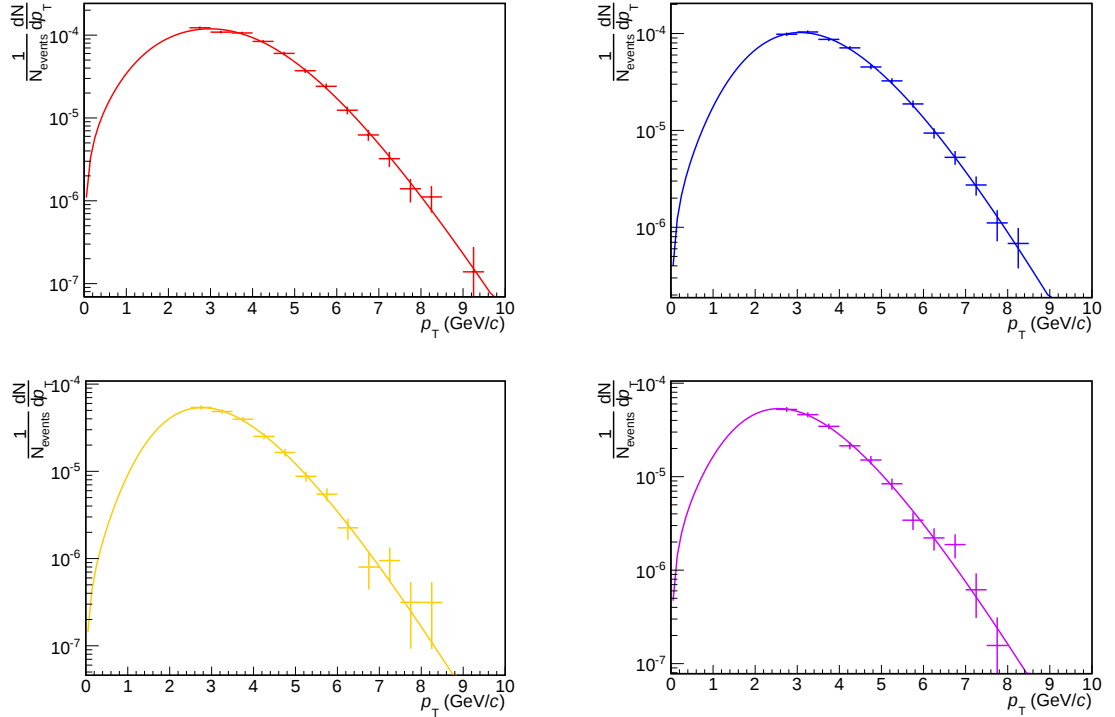


FIGURE 5.16: Corrected p_T spectra fitted with a Blast-Wave distribution for a) ^3He central events (red) b) $^3\overline{\text{He}}$ central events (blue) c) ^3He Semi-Central events (orange) and d) $^3\overline{\text{He}}$ Semi-Central (violet).

Discussion

In this chapter the results shown in Chapter 4 and Chapter 5 are summarized and compared to theoretical models. Theoretical predictions are usually given in terms of $\frac{dN}{dY}$ (production yield per unit of rapidity normalised to the number of events), so the yields presented in Chapter 4 and Chapter 5 have to be normalised by a factor 2, which is the rapidity window (Y) used in the analysis:

$$\frac{dN}{dY} = \frac{1}{2} \frac{1}{N_{\text{events}}} \text{Yield} \quad (6.1)$$

The results of the present analysis are the following:

$$\left. \frac{dN}{dY} (\Lambda^3 \text{H} + \Lambda^3 \bar{\text{H}}) \right|_{0-10\%} = (0.84 \pm 0.24 \pm 0.20) 10^{-4} \quad (6.2)$$

$$\left. \frac{dN}{dY} (\Lambda^3 \text{H}) \right|_{0-10\%} = (0.57 \pm 0.16 \pm 0.11) 10^{-4} \quad (6.3)$$

$$\left. \frac{dN}{dY} (\Lambda^3 \bar{\text{H}}) \right|_{0-10\%} = (0.46 \pm 0.16 \pm 0.11) 10^{-4} \quad (6.4)$$

$$\left. \frac{dN}{dY} (\Lambda^3 \text{H} + \Lambda^3 \bar{\text{H}}) \right|_{10-50\%} = (0.48 \pm 0.12 \pm 0.07) 10^{-4} \quad (6.5)$$

$$\left. \frac{dN}{dY} (\Lambda^3 \text{H}) \right|_{10-50\%} = (0.30 \pm 0.09 \pm 0.05) 10^{-4} \quad (6.6)$$

$$\left. \frac{dN}{dY} (\Lambda^3 \bar{\text{H}}) \right|_{10-50\%} = (0.20 \pm 0.08 \pm 0.04) 10^{-4} \quad (6.7)$$

$$\left. \frac{dN}{dY}({}^3_{\Lambda}\text{H}) \right|_{0-80\%} = (0.43 \pm 0.18 \pm 0.07)10^{-4} \quad (6.8)$$

Here, the subscript indicates the centrality window used in the analysis. The results are shown in Fig. 6.1: the blue points are the production yields of ${}^3_{\Lambda}\text{H}$ and ${}^3_{\Lambda}\bar{\text{H}}$ in central collisions (eq. 6.3 and eq. 6.4), red points are for semi-central collisions (eq. 6.6 and eq. 6.7), while the green point is the result for the minimum-bias events (shown in eq. 6.8). The minimum-bias result is the result of the 2010 data analysis. The points are different because central and semi-central events are characterised by a different number of participants.

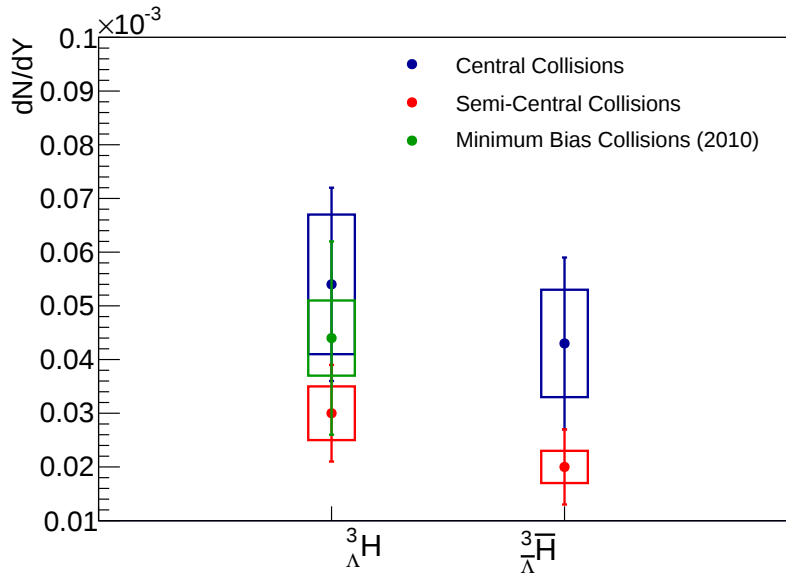


FIGURE 6.1: dN/dY of ${}^3_{\Lambda}\text{H}$ and ${}^3_{\Lambda}\bar{\text{H}}$. Blue points are the results for central collisions, red points for semi-central collisions, the green point for the minimum-bias events (i.e. analysis with the 2010 data).

Assuming particle production scales with the number of participants (N_{part}) – hence with centrality – it is possible to scale the production yield by taking into account the ratio between different N_{part} . For central (0-10%) collisions $N_{\text{part}} = 356$, for semi-central (10-50%) $N_{\text{part}} = 165$ while for minimum bias (0-80%) events it is 139. The results after the scaling “a la Glauber” are shown in Fig 6.2. The results from central and semi-central analysis match well, while the result from the minimum-bias analysis differs by a factor 2. It should be noted, anyway, that the minimum-bias yield is the result of the 2010 analysis, which is based on a lower statistics and partially different analysis.

It is also possible to assume that particle production scales like $N_{\text{ch}}/d\eta$ instead of N_{part} . For central (0-10%) collisions $N_{\text{ch}} = 1447$, for semi-central (10-50%) $N_{\text{part}} = 966$ while for minimum bias (0-80%) events it is 501 [185]. The results after the “ N_{ch} scaling” are shown in Fig 6.3. Again, the results from central and semi-central analysis match well, while the result from the minimum-bias analysis differs by a factor ~ 2 .

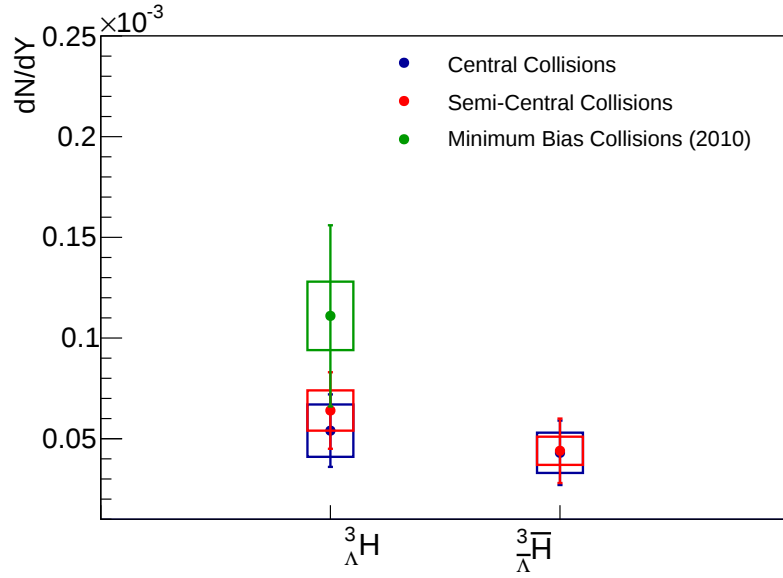


FIGURE 6.2: $1/N_{\text{part}} dN/dY$ of ${}^3_{\Lambda}\text{H}$ and ${}^3_{\Lambda}\bar{\text{H}}$ after the “a la Glauber” scaling. Blue points are the results for central collisions, the red points the ones for semi-central collisions, while the green point is the results for the minimum-bias events.

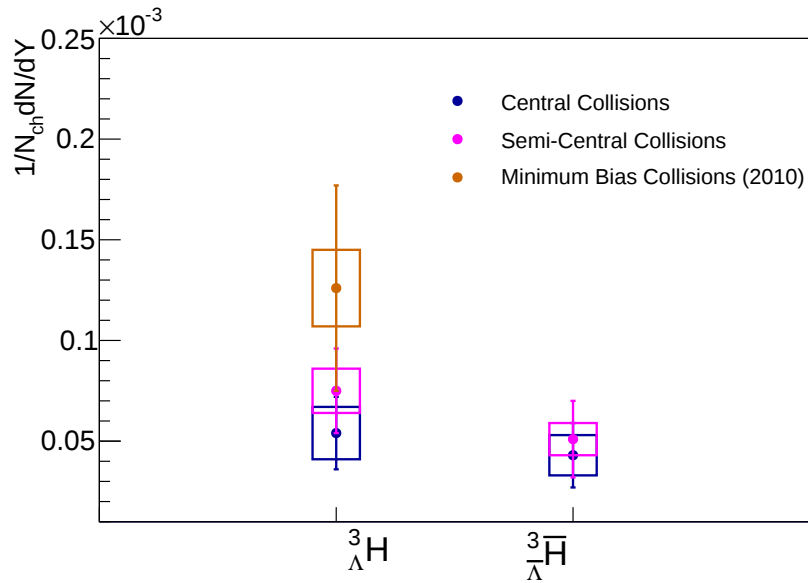


FIGURE 6.3: $1/N_{\text{ch}} dN/dY$ of ${}^3_{\Lambda}\text{H}$ and ${}^3_{\Lambda}\bar{\text{H}}$ after the “ N_{ch} ” scaling. Blue points are the results for central collisions, the red points the ones for semi-central collisions, while the green point is the results for the minimum-bias events.

The total production yield of ${}^3_{\Lambda}\text{H}$ and ${}^3\text{He}$ can be compared to that of other particles in order to extract some information about the initial stage of the collisions (e.g. the Temperature). The coloured segments in Fig. 6.4 show the predictions of the thermal model for the ratios of particles with different masses, assuming chemical freeze-out temperature (T) between 110 MeV and 170 MeV. It can be noted that the particle ratios are very sensitive to the freeze-out temperature. The calculations [186] have been performed for

Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the grand canonical approach of the THERMUS code [170, 176]. The ratio of production yields ${}^3_\Lambda\text{H}/d$, ${}^3\text{He}/p$ and ${}^3\text{He}/d$ are shown in Fig. 6.4, as full black squares. The ${}^3\text{He}/d$ and ${}^3_\Lambda\text{H}/d$ ratios suggest that the chemical freeze-out temperature is ~ 150 MeV, while the ${}^3\text{He}/p$ ratio suggest a chemical freeze-out temperature between 130 and 150 MeV. These results look in agreement with the freeze-out temperature at LHC extracted from the fit to lighter particles: a temperature $T=152$ MeV (when $\mu_B=1$ MeV) was in fact obtained from the fit of particles ratios (See Section 3.2.4).

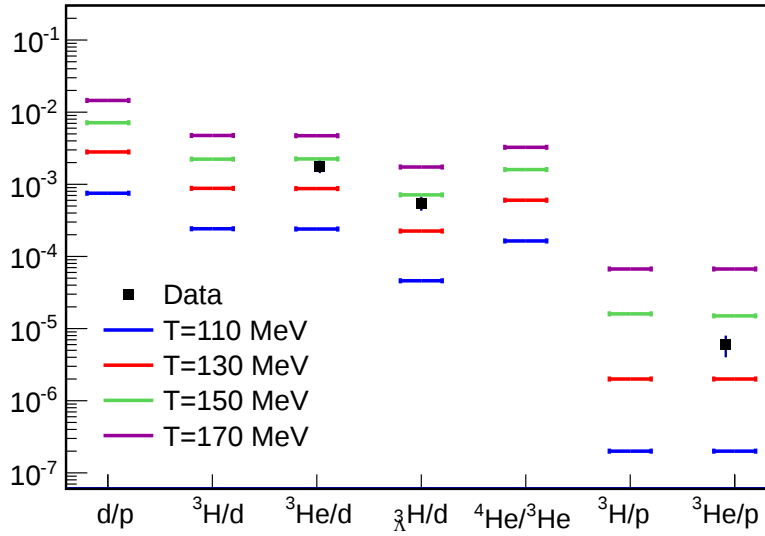


FIGURE 6.4: Ratios of particles with different masses. The predictions [186] are obtained by using the THERMUS code [170, 176], a framework which uses the statistical thermal model to describe particles production.

The production ratios of ${}^3_\Lambda\text{H}/{}^3\text{He}$ and ${}^3_\Lambda\bar{\text{H}}/{}^3\bar{\text{He}}$ are shown in Fig. 6.5. In the figure, the ${}^3_\Lambda\text{H}/{}^3\text{He}$ for central events is shown in blue, while the same ratio for semi-central events is shown in red. The resulting ratios are consistent with each other, and the mean value between results from central and semi-central events are:

$${}^3_\Lambda\text{H}/{}^3\text{He} = 0.31 \pm 0.07 \pm 0.05 \quad (6.9)$$

$${}^3_\Lambda\bar{\text{H}}/{}^3\bar{\text{He}} = 0.25 \pm 0.06 \pm 0.04 \quad (6.10)$$

These results are shown as blue and magenta squares in Fig. 6.6, and are compared to different theoretical models. The green and red dotted lines (from [157]) are results from a simple thermal model where a $T=164$ MeV has been used. Black full circles are theoretical predictions from the DCM coalescence model ([147]), while the cyan full line is extracted by using a thermal model where the UrQMD is implemented ([147]). Unfortunately, only [157] provides predictions up to the LHC energy; this calls for a theoretical

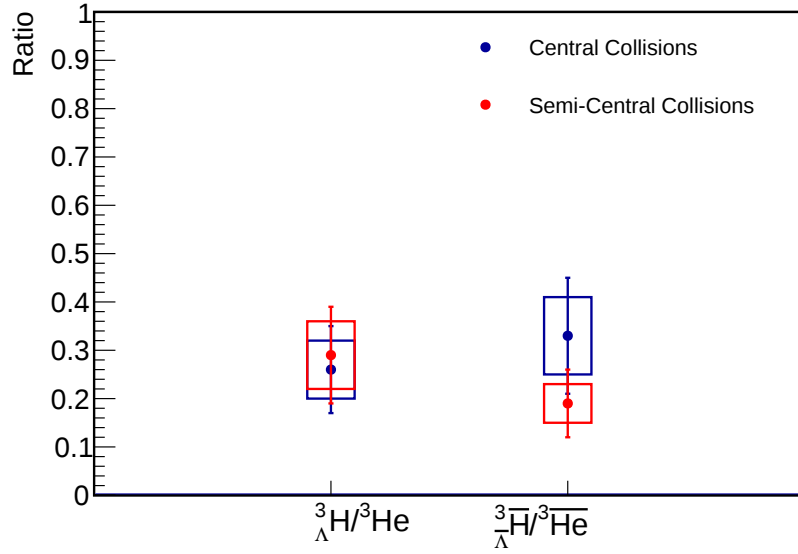


FIGURE 6.5: $\frac{3}{\Lambda}\text{H}/\frac{3}{\Lambda}\text{He}$ and $\frac{3}{\Lambda}\bar{\text{H}}/\frac{3}{\Lambda}\bar{\text{He}}$ determined by the present analysis for central (in blue) and semi-central (in red) events.

effort to extend the present predictions to energies one order of magnitude higher. Although the present analysis statistics is not rich and the relative statistical error is $\sim 25\%$, the energy of the collision makes the present analysis unique and worthwhile. In particular the present results seem to support the validity of the thermal model prediction; in such an hypothesis the STAR results (blue triangle and orange circle in Fig. 6.6) would overestimate the $(\frac{3}{\Lambda}\bar{\text{H}}/\frac{3}{\Lambda}\bar{\text{He}})\frac{3}{\Lambda}\text{H}/\frac{3}{\Lambda}\text{He}$ ratio by more than a factor 2.

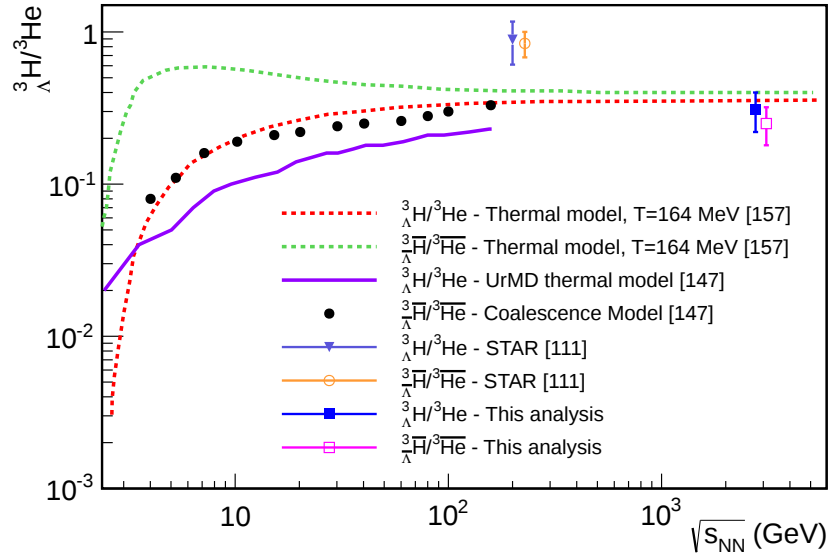


FIGURE 6.6: $\frac{3}{\Lambda}\text{H}/\frac{3}{\Lambda}\text{He}$ and $\frac{3}{\Lambda}\bar{\text{H}}/\frac{3}{\Lambda}\bar{\text{He}}$ determined by the present analysis (blue full square for matter and empty magenta square for anti-matter) compared to STAR results [111] and theoretical predictions.

Finally, the ratio:

$$S_3 = \frac{{}^3_{\Lambda}\text{H}}{{}^3_{\text{He}}}\times\frac{p}{\Lambda}$$

has been evaluated. The ratio Λ/p used here is $\Lambda/p=1.35 \pm 0.19$ and has been extracted from measurements of Λ and p yields which are still preliminary [164]. The results obtained are:

$$\frac{{}^3_{\Lambda}\text{H}}{{}^3_{\text{He}}}\times\frac{p}{\Lambda} = 0.41 \pm 0.13 \quad (6.11)$$

and

$$\frac{{}^3_{\Lambda}\bar{\text{H}}}{\bar{{}^3_{\text{He}}}}\times\frac{\bar{p}}{\bar{\Lambda}} = 0.33 \pm 0.11 \quad (6.12)$$

These results are shown in Fig.6.7 as blue (magenta) full (empty) squares for the (anti) particles ratio and are compared to different theoretical models (described in section 3.4 and shown directly on the figure) and to the results from older experiments at BNL-AGS [121] and RHIC [111] shown as full green squares.

It can be noted that the present result at $\sqrt{s_{\text{NN}}} = 2.76$ TeV is comparable to that measured in [121] at $\sqrt{s_{\text{NN}}} \sim 3$ GeV. This result suggests the validity of the thermal model approach, which predicts that above few GeV the S_3 value should stay constant. Under this assumption, the measured point at $\sqrt{s_{\text{NN}}} = 200$ GeV [111] would be $\sim 2 \sigma$ above the theoretical prediction.

Presently, only the thermal model [157] gives a prediction at the the measured energy, making it difficult to extract any further information. This calls for a theoretical effort to extend also the predictions for the strangeness population factor S_3 to LHC energies. The present analysis results will be a benchmark for theoretical models.

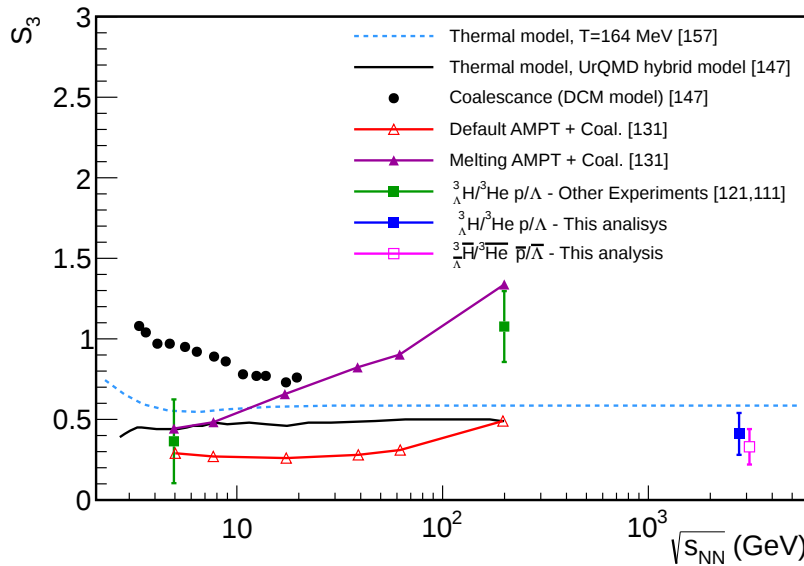


FIGURE 6.7: S_3 ratio measured in this analysis (blue full square for matter and empty magenta square for anti-matter) compared to previous experiments ([121, 111], full green squares) and theoretical models indicated in the legend.

Different Distributions

To fit the p_T spectra of ${}^3\text{He}$, ${}^3\overline{\text{He}}$, ${}^3_\Lambda\text{H}$ and ${}^3_\Lambda\overline{\text{H}}$ different functions have been used. In this appendix the functions used are shortly described.

A.1 m_T exponential

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto N \times p_T \times \exp\left(-\frac{\sqrt{p_T^2 + m_T^2}}{T}\right) \quad (\text{A.1})$$

where N is the normalization factor, p_T is the transverse momentum, m_T is the transverse mass and T is a parameter usually identified as the temperature.

A.2 Boltzmann

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto N \times p_T \times \sqrt{p_T^2 + m^2} \exp\left(-\frac{\sqrt{p_T^2 + m^2}}{T}\right) \quad (\text{A.2})$$

where N is the normalization factor, p_T is the transverse momentum, m_T is the transverse mass and m is the mass of the particle and T is a parameter usually identified as the temperature.

A.3 Bose-Einstein and Fermi-Dirac

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto N \times p_T \times \frac{1}{\left(\exp\left(\frac{\sqrt{p_T^2 + m^2}}{T}\right) \pm 1\right)} \quad (\text{A.3})$$

Here the plus is for a Fermi-Dirac distribution, while the minus sign is used for the Bose-Einstein distribution. N is the normalization factor, p_T is the transverse momentum, m is the mass of the particle and T is a parameter usually identified as the temperature.

A.4 Blast-Wave

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r \, dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{kin}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{kin}} \right) \quad (A.4)$$

Where the dependence on the velocity profile is described by:

$$\rho = \tanh^{-1} \left(\left(\frac{r}{R} \right)^n \beta_T \right) \quad (A.5)$$

Here, $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass, I_0 and K_1 the modified Bessel functions, r is the radial distance on the transverse plane; T_{kin} is the freeze-out temperature, β_T is the average transverse velocity and n is the exponent of the velocity profile.

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