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**Development of the
ALICE Muon Spectrometer:
preparation for data taking
and
heavy flavor measurement**

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Contents

Introduction	iii
1 Heavy flavors and quarkonia in high-energy physics	1
1.1 Nucleon-nucleon collisions: QCD test-bench	2
1.2 Nucleus-nucleus collisions: (hard) probes of the medium . . .	7
1.2.1 Quarks, gluons and Quark-Gluon Plasma	7
1.2.2 The Color Glass Condensate	15
1.2.3 Phenomenology of heavy-ion collisions	17
1.2.4 Probing the medium with heavy flavors	19
1.2.5 Probing the medium with heavy quarkonia	22
2 The ALICE experiment	29
2.1 Overview of the ALICE detectors	31
2.2 The Muon Spectrometer	38
2.2.1 Absorber and shielding	40
2.2.2 Dipole magnet	41
2.2.3 Tracking system	41
2.2.4 Trigger system	46
2.3 The ALICE offline framework: AliRoot	52
3 Muon Spectrometer trigger chamber performance	59
3.1 Misalignment effects	59
3.1.1 Simulation results	60
3.1.2 Latest news from geometrical survey	72
3.2 Efficiency evaluation	76
3.2.1 Method description	76
3.2.2 Systematic errors	82
3.2.3 Integration in the ALICE offline framework	89

4	Physics performance	97
4.1	Open charm and open beauty detection	97
4.1.1	Decay background subtraction	98
4.1.2	Secondary background subtraction	109
4.1.3	Extensive tests on the Grid	116
4.1.4	Discussion	122
4.2	Effects of heavy-quark energy loss in the dimuon continuum .	127
4.2.1	Quenching weights	128
4.2.2	Simulations	131
4.2.3	Discussion	136
5	Conclusions	139
	List of Tables	143
	List of Figures	145
	List of Acronyms	151
	References	153
	Acknowledgments	161

Introduction

The work discussed in this thesis is carried out in the context of ALICE, the experiment at the CERN Large Hadron Collider specifically dedicated to the study of the hot and dense matter which is created in ultra-relativistic heavy-ion collisions. At extreme conditions of energy densities a phase transition is expected to occur from the ordinary hadronic matter to a deconfined state with quark and gluon degrees of freedom: the Quark-Gluon Plasma. The ALICE aim is to investigate the properties of the new state of matter, which can be inferred from the observation of medium-induced modifications affecting a wide number of observables. In this respect the transverse momentum distribution of charm and beauty hadrons and the production of heavy quark $Q\bar{Q}$ bound states, play an important role.

The effects of the interaction with a deconfined system can be disentangled from nuclear matter effects through comparison with results in nucleon-nucleus and nucleon-nucleon collisions: this implies that a detailed p-p program must be carried out by ALICE for the understanding and the interpretation of heavy-ion data. Heavy flavor and quarkonia measurements in p-p collisions are not only a baseline for heavy-ion collisions but can provide a deeper understanding of both perturbative and non-perturbative aspects of QCD.

The ALICE Muon Spectrometer will detect charm and beauty hadrons and heavy quark bound states at forward rapidities, in the semi-muonic and dimuonic decay channel, respectively. The analysis of issues related with such detector is the topic of this thesis.

The work presented is focused on two aspects: the first one is the study of the performance of the muon trigger system, consisting in four planes of gaseous detectors, the Resistive Plate Chambers; the second one is more spe-

cifically dedicated to heavy flavor physics. The synopsis of the manuscript is the following:

- Chapter 1 is a general introduction of heavy quark and quarkonia issues in high-energy physics: the motivations for heavy flavor studies in the different colliding systems, from nucleon-nucleon to nucleus-nucleus, are briefly summarized.
- Chapter 2 is an overview of the ALICE experiment, with a detailed description of the Muon Spectrometer and its trigger system. An introduction to the framework for the analysis and simulations adopted by the collaboration is also included in this section.
- The trigger system performance is analyzed in Chapter 3. The effects on trigger efficiency of a non-perfect alignment of the chambers, as well as a method to measure the intrinsic RPC efficiency are discussed.
- Physics simulations are described in Chapter 4. The possibility of measuring the contribution of the semi-leptonic decay of charm and beauty hadrons in the single muon spectra down to low p_t is taken into account. Results are provided both in Pb-Pb and p-p collisions. Moreover the effects of medium-induced parton energy loss on the dimuon invariant mass continuum from the correlated decay of heavy quark pairs is discussed.
- Finally, the conclusions are drawn in Chapter 5.

Chapter 1

Heavy flavors and quarkonia in high-energy physics

The heavy flavor saga began more than 30 years ago, with the almost simultaneous discovery of the J/ψ meson in 1974 by two different experiments [1, 2]. The resonance was in fact identified as a bound state of the charm quark and its antiquark ($c\bar{c}$), with a mass much higher than the previously known quarks (u, d and s). It is worth noting that the J/ψ itself carries no net charm, since the flavor number cancels between quark and anti-quark. The first baryon with “open” charm, the Λ_c^+ and the first charmed mesons, D^0 and D^+ , were found in 1975 [3] and 1976 [4, 5], respectively, thus definitely confirming the charm hypothesis.

One year later, in 1977, the elementary particle physics picture was further enriched by the discovery [6] of a new resonance, the Υ , which was identified as a bound state of the beauty (or bottom) quark and its antiquark ($b\bar{b}$). Paralleling the charm story, the search for “open beauty” started almost immediately, leading to the observation of the first beauty baryon, the Λ_b in 1981 [7] (though the claim was contested) and of the first beauty mesons, B^0 and B^+ in 1983 [8].

The interest on heavy flavors did not fade away with their discovery: on the contrary it is still lively nowadays. In high-energy nucleon-nucleon collisions, the focus is on heavy flavor and quarkonia production. The former is an intrinsically perturbative phenomenon, allowing to test the perturbative sector of the QCD in a new energy domain. The latter is, at present, not fully understood: the creation of the $Q\bar{Q}$ bound state involves non-perturbative

phenomena which are difficult to describe. Hence the need of new data to constraint the existing models and to provide further information on the production mechanism.

On the other hand, in high-energy nucleus-nucleus collisions, heavy flavors are accounted for as (hard) probes of the high-density medium which is expected to be formed. Heavy quarks are indeed produced at the beginning of the collision, and survive the whole medium expansion, thus carrying information on the crossed high-density matter. Concerning heavy quarkonia, their binding energies are comparable to the mean energies of the plasma, implying a large probability for the quarkonium breakup.

An overview of the heavy quarks and quarkonia issues in the different colliding systems will be provided in the next sections, together with the main experimental results.

1.1 Nucleon-nucleon collisions: QCD test-bench

In the theory of strong interactions, the production of bottom and (to a lesser extent) charm quarks, can be reliably predicted by perturbative QCD, since their masses are large enough to assure the applicability of perturbative calculations. Heavy flavor measurements acquire therefore an important role in testing the ability of perturbative QCD to accurately predict absolute rates in hadronic collisions.

In the past, precise measurements of charm and beauty production cross sections in low energy collisions were limited by statistics, but now heavy quark production has entered the regime of “precision physics”. On the one hand the large center-of-mass energies of the colliders lead to a copious production yield. On the other hand, technological advances such as the introduction of silicon microvertex detectors allow for better tagging of the produced heavy flavors, and hence better measurements. An equally substantial improvement of the theoretical calculations has been needed in order to match this progress and therefore deliver predictions with an accuracy at least as good as that of the experimental measurements. The available calculations are performed by matching the resummation of logarithms of the transverse momentum over the mass of the quark at next-to-leading logarithm (NLL) accuracy with the fixed-order, exact NLO calculation for massive quarks (FONLL).

Perturbative QCD predictions are proved to describe well the beauty production measurements in $p\text{-}\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [9], though they slightly underpredict the charm production [10] (Figure 1.1). It is

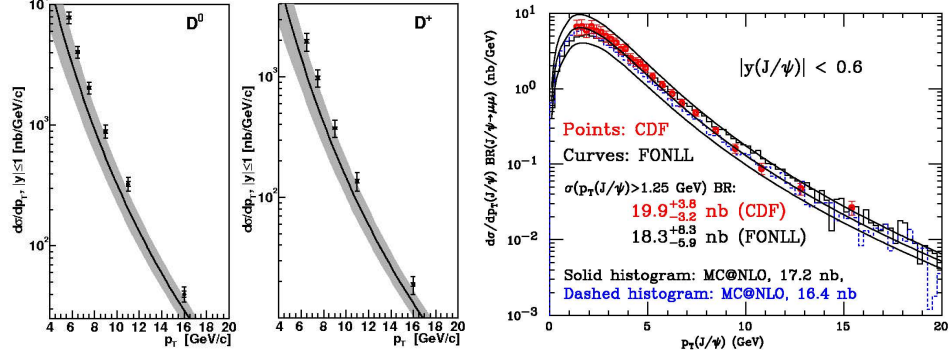


Figure 1.1: D meson production measurements compared to FONLL calculations (left and middle panels) and beauty production measured in the $B \rightarrow J/\psi + X$ decay channel compared with FONLL and MC@NLO calculations (right panel) in $p\text{-}\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at Tevatron.

worth noting that, despite the good accuracy of partonic calculations, the comparison with data is affected by the presence of non-perturbative ingredients needed to parametrize the fragmentation of the heavy quarks into the observed heavy hadrons and by the limited phase space accessible to present detectors. Moreover a breakdown of the standard collinear factorization approach can be expected at low- x .

The short-coming high-energy facilities like the LHC will allow to push forward these studies in a new energy domain ($\sqrt{s} = 14$ TeV), where charm and beauty production is expected to explore Bjorken- x regions down to $x \approx 10^{-6}$.

While the description of the heavy quark pair production at the partonic level rely on solid perturbative treatment of the QCD, the formation of the bound state of quarkonia is a more delicate issue. The production of heavy quarkonium at high-energy colliders involves two distinct scales. The creation of a heavy quark pair is a short-distance process on scales of the order $1/m_Q$ or smaller and can be calculated in perturbation theory. The subsequent non-perturbative transition from the intermediate $Q\bar{Q}$ pair to a physical quarkonium state, on the other hand, involves long-distance

scales of the order of the quarkonium size $1/(m_Q v)$ or larger, where v is the typical heavy-quark velocity in the bound state in the center of mass frame. Provided that these two scales are well separated ($1/(m_Q v) \gg 1/m_Q$), the formation of the bound state should be insensitive to the details of the heavy quark creation process, which is essentially local on the scale of the quarkonium size. It is thus intuitive to expect that long-distance and short-distance physics in quarkonium production can be separated such that binding effects factorize into universal non-perturbative parameters. The factorization approach is common to all models for the description of quarkonium production, which will be briefly reviewed in the following.

The Color Singlet Model (CSM) was first proposed shortly after the discovery of the J/ψ : its fundamental statement is that the production of quarkonia only occurs when the $Q\bar{Q}$ pair generated in the primary collision has the proper quantum numbers and, in particular, is in the color singlet state. The CSM was ruled out by theoretical inconsistencies when dealing with the description of states with non-zero orbital angular momentum, and by the failure to reproduce the Tevatron data in $p\text{-}\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, as shown in Figure 1.2 [11].

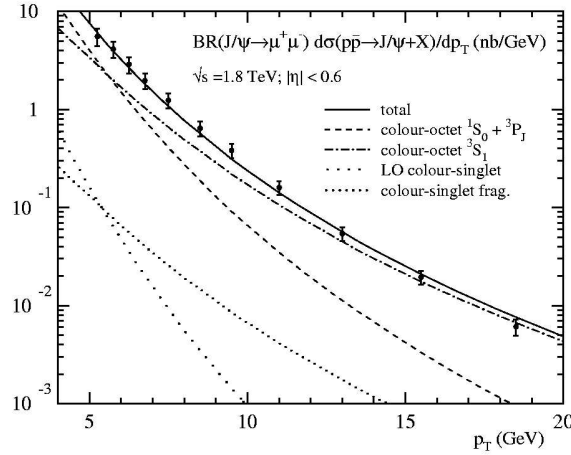


Figure 1.2: Color-singlet and color-octet contributions to direct J/ψ production in $p + \bar{p} \rightarrow J/\psi + X$ at the Tevatron ($\sqrt{s} = 1.8$ TeV, pseudorapidity cut $|\eta| < 0.6$) compared to experimental data from CDF.

The Color Evaporation Model (CEM) [12] is a purely phenomenological approach, stating that the cross section for a quarkonium state C is some fraction F_C of the cross section for producing $Q\bar{Q}$ pairs with invariant mass

below the $M\bar{M}$ threshold, where M is the lowest mass meson containing the heavy quark Q . This cross section has an upper limit on the $Q\bar{Q}$ pair mass but no constraints on the color or spin of the final state. The $Q\bar{Q}$ pair is assumed to neutralize its color by interaction with the collision-induced color field, that is, by “color evaporation”. The fractions F_C are assumed to be universal so that, once they are determined by data, they can be used to predict the cross sections in other processes and in other kinematic regions. The comparison of the Color Evaporation Model at NLO precision with the p_t distributions of quarkonia at Tevatron energies exhibits a reasonable agreement for transverse momenta larger than the quark mass, as shown in Figure 1.3 [13]. However, the CEM prediction for the p_t distributions based

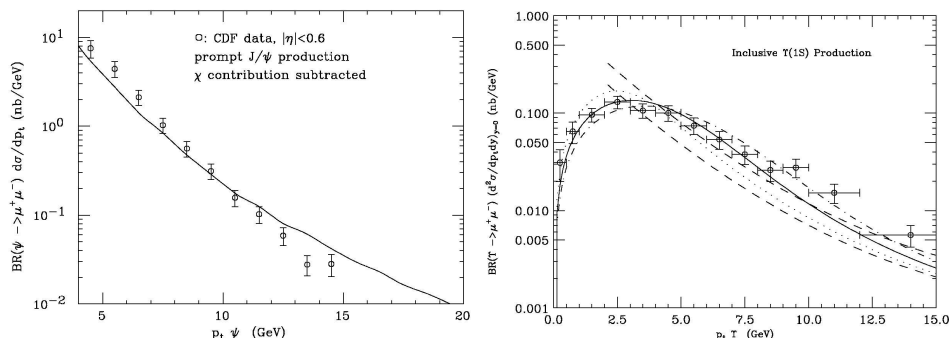


Figure 1.3: Comparison between the transverse momentum distributions of J/ψ (left panel) and Υ (right panel) calculated with the Color Evaporation Model and the CDF data at $\sqrt{s} = 1.8$ TeV. For the Υ case, the effect of an intrinsic transverse momentum of $\langle k_t \rangle = 0$ GeV/c (dashed), 1.25 GeV/c (dotted), 2.0 GeV/c (solid) and 2.5 GeV/c (dot-dashed), is also shown.

on fixed-order perturbation theory cannot be trusted for $p_t \lesssim m_Q$. A correct treatment of the low- p_t region requires soft-gluon resummation which is mimicked through an effective, larger value of the intrinsic transverse momentum $\langle k_t \rangle$. Despite providing useful information on inclusive distributions, the CEM possesses all the limitations of a purely phenomenological approach.

The Non-Relativistic QCD (NRQCD) is an effective theory which accurately reproduces full QCD at momentum scales of order $m_Q v$ and smaller, where v , as already stated, is the typical heavy-quark velocity in the bound state in the center of mass frame ($v^2 \approx 0.3$ for charmonium, and $v^2 \approx 0.1$ for bottomonium). Within the framework of NRQCD, the cross section for

producing a quarkonium state H can be expressed as a sum of terms, each of which factorizes into a short-distance coefficient and a long-distance matrix element:

$$d\sigma(H + X) = \sum_n d\hat{\sigma}(Q\bar{Q}[n] + X) \langle \mathcal{O}^H[n] \rangle$$

The sum includes all color and angular momentum states of the $Q\bar{Q}$ pair, denoted collectively by n : in particular, the color-singlet and color-octet contributions are both taken into account. The short-distance coefficients $d\hat{\sigma}$ are proportional to the cross sections for producing a $Q\bar{Q}$ pair in the state n and with small relative momentum, and can be calculated in perturbation theory. The non-perturbative transition probabilities from the $Q\bar{Q}$ state n into the quarkonium H are given by vacuum expectation values of local four-fermion operators $\mathcal{O}^H[n]$, which are universal and can be determined from data. The NRQCD can correctly reproduce the differential transverse momentum distributions for J/ψ measured in $p\text{-}\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV (see Figure 1.2), but it fails in describing the quarkonium polarization. It predicts in fact a transverse polarization at high p_t , which is not observed neither for J/ψ (left panel of Figure 1.4 [14]) nor for Υ (right panel of same Figure [15]). In the latter case it is worth noting that the results from

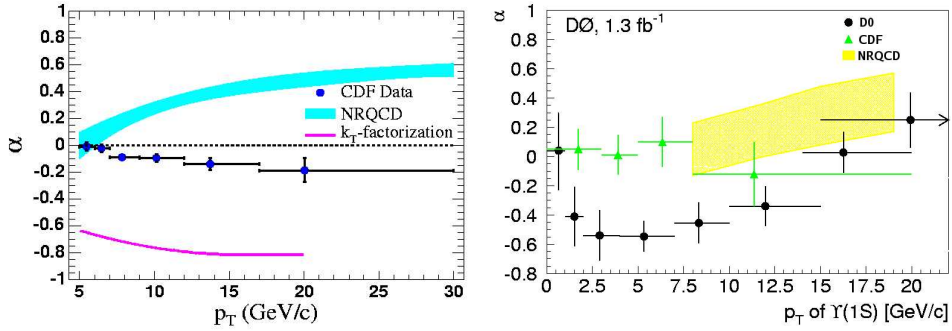


Figure 1.4: J/ψ (left panel) and Υ (right panel) polarization measured in $p\text{-}\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The comparison with the expected polarization from NRQCD calculations is shown.

different experiments are not in agreement: further studies in accelerating facilities like the LHC could probably help to shed light on the issue.

The mechanism of quarkonia production is still an open question which has to be carefully investigated not only for the interest it possesses *per se*,

but also because it can change our understanding of the effects expected in nucleus-nucleus collisions, as will be discussed in the next sections.

1.2 Nucleus-nucleus collisions: (hard) probes of the medium

The particle physics experiments carried out over the last decades allowed to establish and validate a detailed, though still incomplete, theory of elementary particles and their interaction: the Standard Model. The study of fundamental aspects of the theory requires further investigations at high-energy scales, which, from a technical point of view, can be more easily reached through hadron-hadron rather than lepton-lepton or lepton-hadron collisions. The search for new massive particles, where the center of mass energy and the statistics (related with the machine luminosity) are the main experimental requirements, is usually performed through nucleon-nucleon collisions. On the other hand, the application and extension of the Standard Model to complex and dynamically evolving systems is the aim of heavy-ion physics.

The focus of heavy-ion physics is to study and understand how collective phenomena and macroscopic properties, involving many degrees of freedom, emerge from the microscopic laws of elementary particle physics.

In relativistic heavy-ion collisions, because of the Lorentz contraction, the two colliding nuclei appear as thin disks. The elementary nucleon-nucleon collisions between the two nuclei occur nearly at the same time and in close spatial proximity. In consequence, a large amount of energy is deposited in a small region of space in a short amount of time. In this region, the *energy density* is therefore very high, and may exceed by order of magnitudes the typical scale of the ordinary nuclear matter $\epsilon_{\text{nuclear}} \simeq 0.15 \text{ GeV/fm}^3$ [16].

These conditions favor the formation of new states of matter, such as the Quark-Gluon Plasma (QGP).

1.2.1 Quarks, gluons and Quark-Gluon Plasma

In the Standard Model the strong force is described as the interaction between particles with color charge (quarks), mediated by massless bosons

(gluons). The dynamic of the interaction is described by the theory of Quantum Chromo-Dynamics (QCD), in the same way as the Quantum Electrodynamics (QED), explains the interaction between particles with electric charge. However, despite the analogies, the strong and electro-magnetic interactions have some fundamental differences, leading to qualitatively different phenomena. In particular:

- there is only one type of electric charge, while the color charge can appear in three colors;
- the photon, mediator of the electro-magnetic interaction, does not carry a charge, while the gluons are colored and can therefore interact among each others.

As a consequence, while the QED is an Abelian gauge theory, with an infinite range interaction, the QCD is a non-Abelian theory describing a system which is weakly interacting on short distance scales but very strongly interacting on a large distance scale, a property known as “asymptotic freedom” [17]. The QCD coupling constant α is related to the scale of the momentum transfer q by the relation:

$$\alpha(q^2) = \frac{\alpha_0}{1 + \alpha_0 \frac{11N_c - 2N_f}{12\pi} \ln \left(\frac{-q^2}{\mu^2} \right)} \quad (1.1)$$

where α_0 is the coupling constant for the momentum transfer μ and $N_c = 3$ and $N_f = 6$ are the number of colors and flavors, respectively. At small-distance/high-momentum scales, the coupling constant is small and the quarks behave like free particles. On the other hand, at high-distance/low-momentum scales the coupling constant is large and the quarks are subject to confining forces.

Theoretical results from lattice gauge theory indicate that when the distance scale is comparable to the size of the hadron, the quarks interact with an effective strength which goes approximately linearly with the spatial distance. Since the interaction strength increases with the distance, it becomes impossible to isolate a quark by separating it from its partner inside the hadron: hence quarks are confined [18]. However, for sufficiently high energy densities of the order of 1 GeV/fm^3 , the hadrons overlap and get squeezed so tightly that their constituents are free to roam the system without being confined inside baryons and mesons. Moreover, due to the

asymptotic freedom, if the energy density becomes very large, the interaction between the elementary constituents becomes weak: the formed system of deconfined quarks and gluons is called Quark-Gluon Plasma.

The energy density conditions leading to the QGP formation are expected to have taken place in the early universe, few micro-seconds after the Big-Bang, as the system cooled down from the initial temperature of about $T \simeq 10^{19}$ GeV¹ to the temperature of about 200 MeV, when the nucleon formation started (see Figure 1.5).

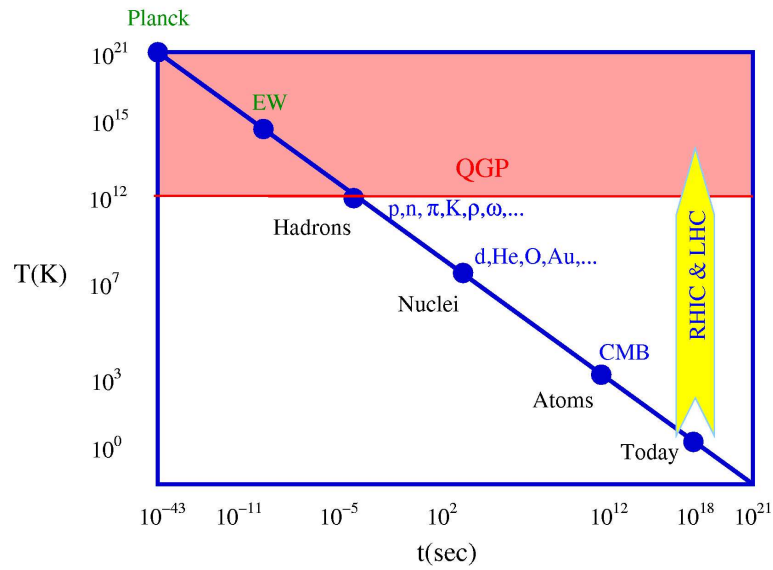


Figure 1.5: Schematic representation of the universe evolution.

Nowadays, energy densities of the order of $1 \text{ GeV}/\text{fm}^3$ could still be found in astrophysical objects and events, such as:

- inside the cores of neutron stars;
- in supernova explosions, leading to the neutron stars formation;
- in collisions of black holes and neutron stars, which can be the origin of the gamma ray bursters, i.e. starlike objects converting an amount of matter of the order of their entire mass into gamma rays.

For these reasons the study of the QGP is of great interest not only in particle physics, but also in astrophysics and cosmology.

¹The temperature in electron volts eV is related with the temperature in Kelvin degrees through the Boltzmann constant $k = 8.617 \times 10^{-5} \text{ eV/K}$

Phase transitions

The onset of deconfinement at the typical energy density scale of $\epsilon_{QGP} \simeq 1 \text{ GeV/fm}^3$, can be explained in an heuristic way with the so called MIT bag model [19], in which quarks are treated as massless particles inside a bag of finite dimension, and are infinitely massive outside the bag. In the model, the confinement is the result of the balance of the bag pressure B , directed inwards, which mimic the fundamental effect of non-perturbative QCD, and the stress arising from the kinetic energy of the quarks. The deconfinement occurs when the pressure of the quark matter inside the bag is increased to become greater than the inward bag pressure. The increase can arise:

1. when the temperature of the matter is high and/or
2. when the baryon number density is high.

The latter case is a consequence of the Pauli exclusion principle: the requirement that no more than one fermion can populate a state with a definite set of quantum numbers leads to the restriction that, as the density of the quarks increases, the quarks must populate states of greater momentum. This is the condition expected in neutron stars.

On the other hand, the QGP formation in a high temperature and low baryon density medium is the expected scenario for high-energy heavy-ion collisions and will therefore be discussed in more details in the following.

At very high energies the coupling constant of QCD becomes weak and a gas of particles should to a good approximation become an ideal gas. If such gas is in thermal equilibrium at the temperature T , its energy density can be easily inferred from the Fermi-Dirac and Bose-Einstein statistics (see for example [18]), resulting:

$$\epsilon_{\text{gas}} = g \frac{\pi^2}{30} T^4 \quad (1.2)$$

where g is the number of particle degrees of freedom. For massless fermions and bosons, the pressure P_{gas} is related to the energy density by

$$P_{\text{gas}} = \frac{\epsilon_{\text{gas}}}{3} \quad (1.3)$$

hence, from Eq. 1.2:

$$P_{\text{gas}} = g \frac{\pi^2}{90} T^4 \quad (1.4)$$

The total energy density and pressure of the system, taking into account the bag pressure, are therefore given by:

$$\epsilon = g \frac{\pi^2}{30} T^4 + B \quad (1.5)$$

and

$$P = g \frac{\pi^2}{90} T^4 - B \quad (1.6)$$

At sufficiently high temperature, the quark matter inside the bag will have a pressure which is bigger than that of the bag pressure: when this happens the quark matter becomes deconfined.

In the model, quark matter at temperatures below deconfinement is assumed to be constituted by (massless) pions. For an ideal gas of pions, the number of degrees of freedom is 3 (the possible values of the third component of the isospin), while for a Quark-Gluon Plasma it is:

$$g_{QGP} = g_g + \frac{7}{8} \times (g_q + g_{\bar{q}}) \quad (1.7)$$

where g_g , g_q and $g_{\bar{q}}$ are the degeneracy number of the gluons, the quarks and the antiquarks, respectively. The 7/8 factor arises from the Fermi-Dirac statistics. The gluon contribution can be evaluated by accounting for the existence of 8 gluons with two possible polarization each, hence:

$$g_g = 8 \times 2 \quad (1.8)$$

The degeneracy number g_q of the quarks depends on the number of colors ($N_c = 3$), the spin states ($N_s = 2$) and the number of flavors taken into account (N_f), which is three if the temperature is below the charm quark mass, hence:

$$g_q = g_{\bar{q}} = N_c \times N_s \times N_f = 3 \times 2 \times 3 \quad (1.9)$$

The total number of degrees of freedom is thus $g_{QGP} = 47.5$, i.e. more than an order of magnitude greater than the equivalent number for a pion gas: this results in a steep rise of the energy density (Eq. 1.2) in the narrow region of temperature corresponding to the phase transition from hadron gas to QGP.

The QCD phase diagram is schematically shown in Figure 1.6. The vertical axis is the temperature, while the horizontal is the quark Fermi level,

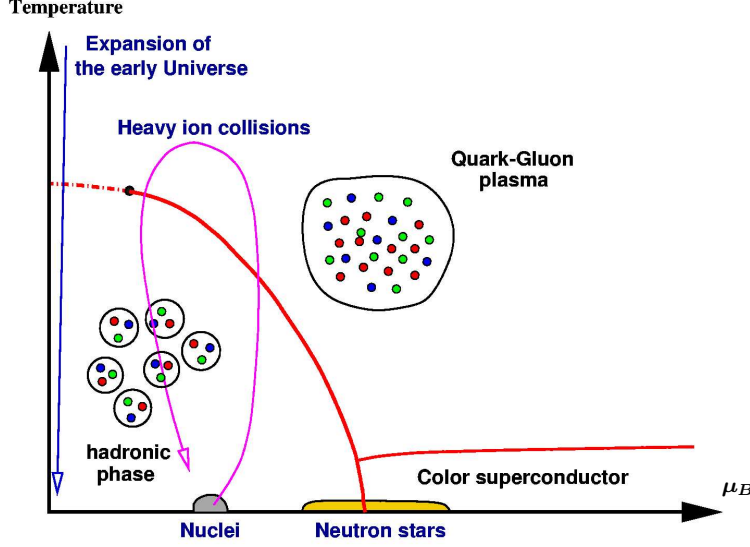


Figure 1.6: Schematic view of the QCD phase diagram.

or chemical potential, which measures the baryon number density. The solid line represents a first order phase transition, the dashed line a rapid crossover while the black point between the two lines is the second order phase transition. We recall that an n^{th} order phase transition is characterized by a discontinuity in the n^{th} derivative of the free energy with respect to a thermodynamic variable, while a crossover is a rapid but continuous transition. The phase diagram region explored by high-energy heavy-ion collisions and by neutron stars is also shown.

At zero chemical potential, our knowledge of the QCD phase diagram is based on lattice calculations. Lattice QCD is a non-perturbative treatment of Quantum Chromo-Dynamics formulated on a discrete lattice of space-time coordinates. The discretization of the space-time continuum provides two main advantages: on the one hand the spacing between the nearest lattice points defines a shortest distance scale which allows a natural regularization of the ultraviolet divergences; on the other hand, using discrete space-time coordinates and going in the domain of imaginary time, the partition function in statistical mechanics can be written in form of a path integral, thus allowing the use of Monte-Carlo methods to find the equilibrium states of the system. The picture arising from recent lattice calculations [20], suggests a critical temperature value for deconfinement of $T_c \simeq 190$ MeV. Around this temperature, the energy density normalized to the fourth power of the

temperature experience a steep rise, reaching about the 80% of the Stefan-Boltzman limit predicted for a gas of non-interacting quarks and gluons, as shown in Figure 1.7.

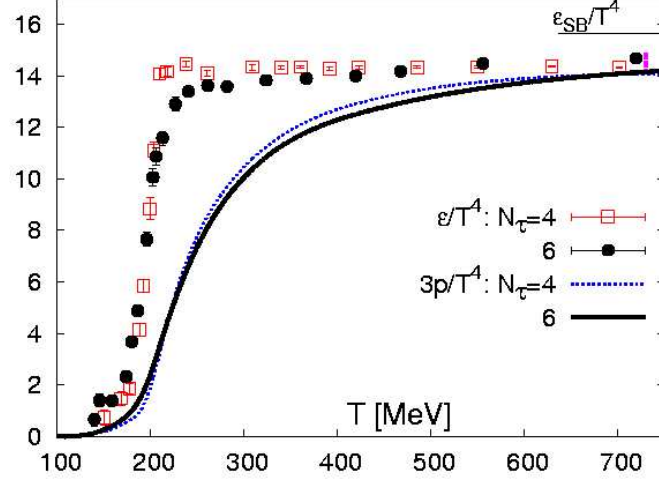


Figure 1.7: Energy density and three times the pressure normalized to the fourth power of the temperature as a function of the temperature. The results are obtained from lattice calculations for a system with two light and one heavy quark species [21]. The resulting transition temperature is $T_c \simeq 190$ MeV.

For non-zero chemical potential, the expectations rely on models interpolating between low-density hadronic matter, described by low-energy effective theories, and high-density quark-gluon plasma, described by perturbative QCD. The uncertainties at high baryon densities are thus relatively large. In this case, the phase transition is expected to occur for baryon densities from three to ten times larger than the standard nuclear density $\rho_0 = 0.15 \text{ fm}^{-3}$.

Finally, it is worth noting that, for vanishing temperature and high baryon densities, the nuclear matter is expected to undergo a phase transition into a color superconductor, a state different from QGP and analogous to the superconducting phase of solid state physics.

Chiral symmetry restoration

In addition to the onset of deconfinement, another phenomenon may become realized at high temperature: the chiral symmetry restoration. The chiral

symmetry is the invariance of the Lagrangian under an axial transformation of the fermion field:

$$\psi \rightarrow e^{-i\gamma_5 \frac{\vec{\tau} \cdot \vec{\Theta}}{2}} \psi \quad (1.10)$$

where $\vec{\tau}$ are the three Pauli matrices and γ_5 is the chiral operator. A Lagrangian with massless fermions – the limiting case of the light up and down quarks in the physical Lagrangian – possesses chiral symmetry, allowing a decomposition of the quarks into independent left- and right-handed massless spin 1/2 states, which for massive fermions become mixed.

When confined in hadrons, the basic quarks “dress” themselves with gluons to acquire an effective constituent quark mass of about 300 MeV (roughly corresponding to 1/3 of the proton or 1/2 of the ρ mass). This leads to a spontaneous breaking of the chiral symmetry. On the other hand, after the transition to a deconfined phase, the quarks would recover the “bare” mass appearing in the Lagrangian, and the symmetry is restored [22].

In calculations, the order parameter for the transition is the effective quark mass, measured as the expectation value of the corresponding term in the Lagrangian, the chiral condensate $\langle \bar{\psi}\psi \rangle$. The behavior of the order parameter at different conditions of temperature and baryon densities is shown in Figure 1.8: the chiral condensate is non-zero for ordinary nuclear matter and is expected to vanish at higher temperature and density.

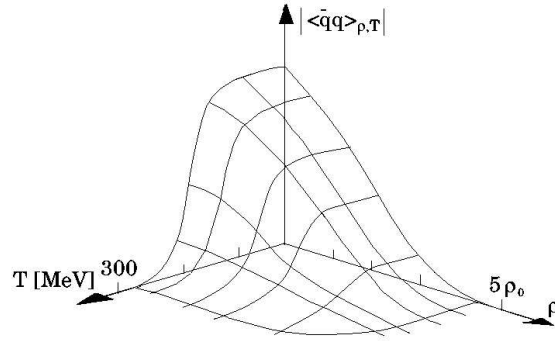


Figure 1.8: Behavior of the chiral order parameter $\langle \bar{\psi}\psi \rangle$ in the $T - \mu_B$ plane.

The chiral symmetry restoration is expected to affect the spectral features of the light vector mesons ρ , ω and ϕ , which therefore constitute an interesting investigation field for experiments.

1.2.2 The Color Glass Condensate

The degrees of freedom involved in the early stages of a nucleus-nucleus collision at sufficiently high energy are partons, mostly gluons, whose density grows as the energy increases (i.e. when x , their momentum fraction, decreases). This growth of the number of gluons in the hadronic wave functions is a phenomenon which has been well established at HERA (Figure 1.9): a “saturation” is however expected when non-linear QCD effects start to play a role.

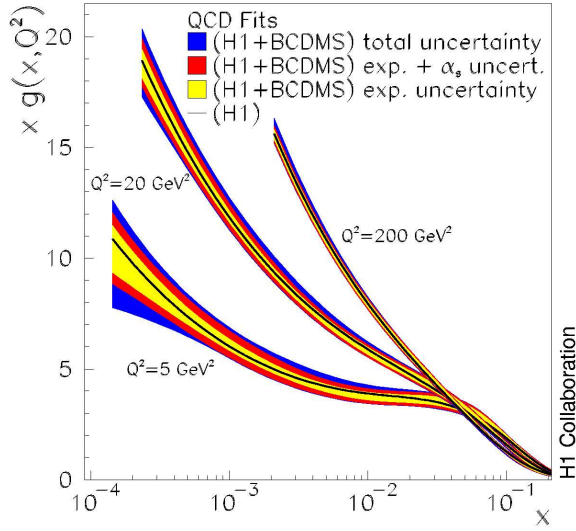


Figure 1.9: Gluon distribution as extracted at HERA, as a function of x in three bins of Q^2 [23].

When the gluon density increases the gluon recombination processes $g + g \rightarrow g$ are expected to gain importance, and eventually balance gluon splitting $g \rightarrow g + g$, thus leading to a saturation of the density number. The momentum scale that characterizes this new regime, Q_s , is called the saturation momentum and can be implicitly defined as [16]:

$$Q_s^2 \approx \alpha_s \frac{xG(x, Q_s^2)}{\pi R^2} \quad (1.11)$$

where $G(x, Q^2)$ is the gluon density and πR^2 is the hadron transverse area.

The dense, saturated system of partons to be found in hadronic wave functions at high energy has universal properties, the same for all hadrons or nuclei. Such system is defined Color Glass Condensate (CGC). The CGC

is *colored* since made of gluons which carry the color charge of QCD; it is a *condensate* since it is characterized by high occupation numbers, or strong classical color fields; finally it is a *glass* since, due to Lorentz time dilation, its internal dynamics is frozen over the natural time scales for high energy scattering (a glass is a disordered system which evolves very slowly relative to natural time scales: it is like a solid on short time scales and like a liquid on much longer time scales).

The theory of CGC predicts that in the saturation region the observables which would depend *a priori* on Bjorken x and the virtuality Q , scale like $Q/Q_s(x)$. This property, known as “geometrical scaling”, was observed in γ^*p Deep Inelastic Scattering at HERA (Figure 1.10).

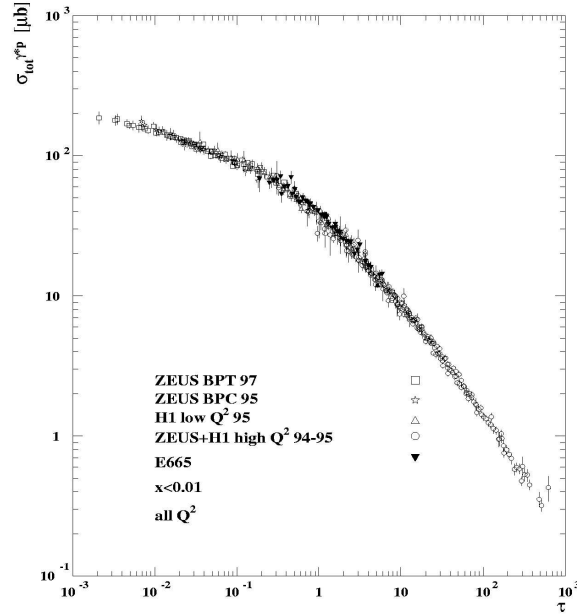


Figure 1.10: The γ^*p cross-section at HERA, plotted against the scaling variable $\tau = Q^2/Q_s^2(x)$ [24].

It is worth noting that the saturation regime is only partially reached at HERA: better conditions for the CGC studies will be created in high-energy heavy-ion collisions, since it is expected that the saturation regime sets in earlier (i.e. at lower energy) in collisions involving large nuclei than in those involving protons [25]. In particular nucleon-nucleus and electron-nucleus collisions seem to be the most promising since they are not affected by final state effects occurring in nucleus-nucleus collisions, that could shadow the

initial state effects of the CGC. Moreover, since the saturation scale exponentially increases with rapidity, it is expected that the saturation regime is reached earlier in the forward rapidity region, rather than at mid-rapidity.

Finally, it has been argued [26] that open charm may have a role in the description of the Color Glass Condensate. When the momentum scale is larger than the quark mass, $Q_s^2 \gtrsim m_Q^2$, the heavy quark production pattern is similar to that of light quarks, which, in case of a CGC at sufficiently high energy and/or rapidity, is suppressed at high p_t . Open charm measurements in p-A collisions in the forward rapidity region will therefore provide useful information in the understanding of the saturation phenomenon.

1.2.3 Phenomenology of heavy-ion collisions

The formation of a new state of matter requires extreme conditions of energy density, which can be re-created in laboratory through nucleus-nucleus collisions. The process of multiple collisions occurring between the constituent nucleons, allows in fact to deposit a large amount of energy in a small region, which is the fundamental requirement for the onset of deconfinement. A detailed description of the new state of matter in terms of thermodynamic properties requires that:

- the number of constituents of the system is large, so that the system can be described by means of macroscopic variables;
- the system is long-lived compared to the typical time-scales of the strong nuclear interactions ($\simeq 1 \text{ fm}/c$) and can thus reach equilibrium.

Hence the need for ultra-relativistic collision energies and the use of large and heavy ions.

Qualitatively speaking, the collision of high-energy heavy-ions can be divided into two different energy regions: the “baryon free” medium region with $\sqrt{s} > 100 \text{ GeV}$ per nucleon, and the “baryon rich” medium region, with $\sqrt{s} \simeq 10 \text{ GeV}$ per nucleon. During the multiple collisions, the nucleons lose a substantial fraction of energy and are therefore slowed-down. At very high energies the slowed-down baryons can still have enough momentum to proceed forward and move away from the interaction region, as shown schematically in Figure 1.11. The energy lost by the baryons is deposited in the collision region, with the consequence that the created matter will

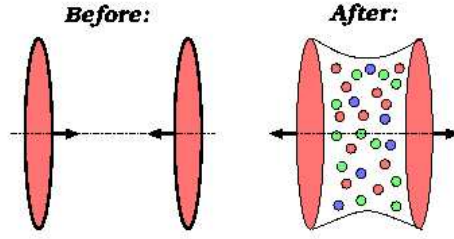


Figure 1.11: The configuration of two colliding nuclei before (left) and after (right) the collision.

have high energy density but a small net baryon content. At lower energies, instead, the baryons are stopped in the collision region, giving rise to a state with a higher chemical potential.

Soon after the collision of the two nuclei, the energy density may be sufficiently high to allow the formation of a Quark-Gluon Plasma in the central rapidity region. If the plasma reaches the thermal equilibrium, the subsequent evolution will follow the laws of hydrodynamics. As the system expands, its temperature drops down and the hadronization takes place: once below the freeze-out temperature, the hadrons stream out of the collision region. The entire process can be summarized as follows [27]:

- pre-equilibrium (proper time $\tau < 1$ fm/c): hard ($\tau \sim 0$ fm/c) and soft ($\tau \sim 0.2$ fm/c) processes occur during the parton scattering, leading to the creation of high- p_t (jets, heavy quarks, photons) and low- p_t particles, respectively;
- thermalization (possibly occurring at $\tau \sim 1 - 2$ fm/c): the multiple scattering among the quark and gluon constituents of the colliding nucleons and the particles produced during the collisions lead to a rapid increase of entropy which could eventually result in thermalization;
- QGP formation ($\tau \sim 10 - 15$ fm/c): at high energy densities the system reaches the deconfinement phase with partonic and gluonic degrees of freedom;
- hadronization ($\tau \sim 20$ fm/c): the temperature of the expanding medium drops down and, below the critical temperature T_c , the quarks and gluons become again confined into hadrons;

- freeze-out ($\tau \rightarrow \infty$): the expansion and the temperature fall lead first to a reduction of the inelastic processes among hadrons, until the relative abundance of hadron species is fixed (chemical freeze-out), and finally to the turn-off of any interaction which fixes the kinematic spectra (kinetic freeze-out).

All the steps of the evolution are schematically represented in Figure 1.12

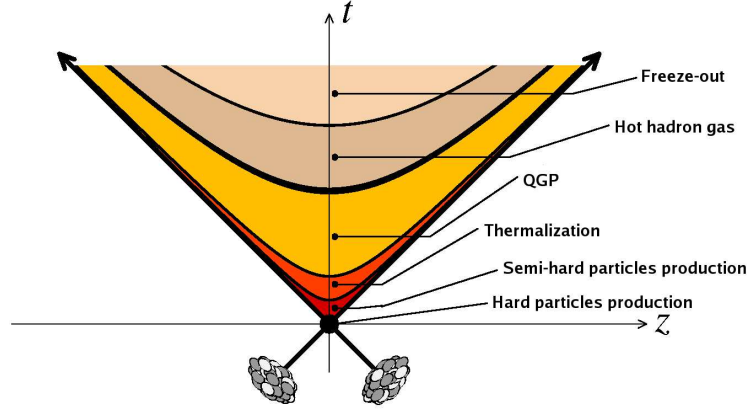


Figure 1.12: Schematic representation of the QGP evolution in a nucleus-nucleus collision.

The strong interactions among the partons and hadrons before freeze-out wipe out much information about their original production processes. Extracting information about the hot and dense early collision stage thus requires to exploit features which are either established early and survive the rescattering and collective expansion or can be reliably back-extrapolated. Correspondingly, one classifies the observables into two classes: early and late signatures. The abundances and spectra of hadrons made of light quarks (u and d) belong to the latter category and can provide useful information on the hadronization and freeze-out of the collision. On the other hand, thermal photons produced in the plasma and heavy flavors and quarkonia constitute early probes of the medium.

1.2.4 Probing the medium with heavy flavors

Heavy quarks are produced in the early stage of the collision in primary partonic scattering with large virtuality Q and, thus, on temporal and spatial scales $\Delta\tau \sim \Delta r \sim 1/Q$, which are sufficiently small for the production to be

unaffected by the properties of the medium. In fact, the minimum virtuality $Q_{\min} = 2m_Q$ in the production of a $Q\bar{Q}$ pair implies a space-time scale of the order of $1/(2m_Q) \simeq 0.1 \text{ fm}/c$ ($0.02 \text{ fm}/c$) for charm (beauty), which is much lower than the expected lifetime of the QGP phase ($\gtrsim 10 \text{ fm}/c$ at LHC energies). Hence, the initially produced heavy quarks experience the full collision history.

For hard processes, in the absence of nuclear and medium effects, a nucleus-nucleus (or proton-nucleus) collision would behave as a superposition of independent nucleon-nucleon (N-N) collisions. The charm and beauty differential yields would then scale from p-p to A-A (or p-A) proportionally to the number N_{coll} of inelastic N-N collisions (binary scaling):

$$\frac{d^2 N_{\text{A-A(p-A)}}^{HQ}}{dp_t dy} = N_{\text{coll}} \frac{d^2 N_{\text{p-p}}^{HQ}}{dp_t dy} \quad (1.12)$$

The effects that can determine the breakdown of the binary scaling are usually divided in two classes:

- Initial-state effects, such as the nuclear shadowing, i.e. the modification of the parton distribution functions in the nucleus due to gluon recombination at small x .
- Final-state effects, due to the interaction of the produced partons with the medium formed in the collisions.

The former can be studied by comparing p-p and p-A collisions, where the formation of a high-density medium is not expected. The latter is investigated in A-A collisions.

One of the most interesting phenomena occurring during the interaction with the medium is the heavy quark energy loss. While traversing the dense matter produced in nucleus-nucleus collisions, the initially-produced heavy partons lose energy, mainly on account of multiple scattering and medium-induced gluon radiation, and become quenched. The average energy loss of the parton travelling a path length L in the medium is estimated to be [28]:

$$\langle E \rangle \propto \alpha_s C_R \hat{q} L^2 \quad (1.13)$$

where $\hat{q} = \langle k_t^2 \rangle_{\text{medium}}/\lambda$, is the average transverse momentum squared transferred to the projectile per unit path length, α_s is the QCD coupling constant

and C_R is the QCD coupling factor (Casimir factor), which is equal to $4/3$ for quark-gluon coupling and to 3 for gluon-gluon coupling. The proportionality to C_R implies that the energy loss is larger by a factor of $9/4$ for gluons than for quarks, thus exhibiting a color-charge dependence. A dependence on the mass (m) of the parton was also argued, since, in the vacuum, the gluon radiation at angles $\Theta < m/E$ is suppressed (“dead-cone” effect) [29].

Heavy flavor energy loss in the medium was recently observed by the PHENIX collaboration at RHIC [30]: the nuclear modification factor for non-photonic electrons, defined as the ratio between the electron yields measured in nucleus-nucleus collisions and the yields measured in nucleon-nucleon collisions, rescaled by the number of binary collisions in the nuclei,

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\frac{d\sigma_{AA}}{dp_t}}{\frac{d\sigma_{NN}}{dp_t}} \quad (1.14)$$

exhibits a depopulation of the high- p_t region in favor of low- p_t one (Figure 1.13).

At the LHC, a promising observable to test the partonic mechanism expected to underlie jet quenching is the heavy-to-light ratio, defined as the ratio of nuclear modification factors of the heavy-flavored mesons (D and B) to that of light-flavored hadrons (h):

$$R_{D(B)/h}(p_t) = \frac{R_{AA}^{D(B)}(p_t)}{R_{AA}^h(p_t)} = \frac{\frac{d^2 N_{AA}^{D(B)}}{dp_t dy}}{\frac{d^2 N_{pp}^{D(B)}}{dp_t dy}} \bigg/ \frac{\frac{d^2 N_{AA}^h}{dp_t dy}}{\frac{d^2 N_{pp}^h}{dp_t dy}} \quad (1.15)$$

Heavy-to-light ratios at the LHC could in fact be sensitive to the color-charge and the mass dependence of the medium-induced parton energy loss [31]. For high transverse momenta ($10 \lesssim p_t \lesssim 20 \text{ GeV}/c$), charm quarks would behave essentially like massless quarks. However, since at LHC energies light flavored hadron yields are dominated by gluon parents, the $R_{D/h}$ would be enhanced with respect to unity as a consequence of the larger color charge of gluons relative to quarks (Figure 1.14, upper panels). This makes the $R_{D/h}$ a sensitive probe of the color-charge dependence of parton energy loss. For B mesons, in contrast, the heavy-to-light ratio would be strongly enhanced due to the large b mass even in the range $10 \lesssim p_t \lesssim 20 \text{ GeV}/c$, thus providing a sensitive test of the mass dependence of parton energy loss (Figure 1.14, lower panels).

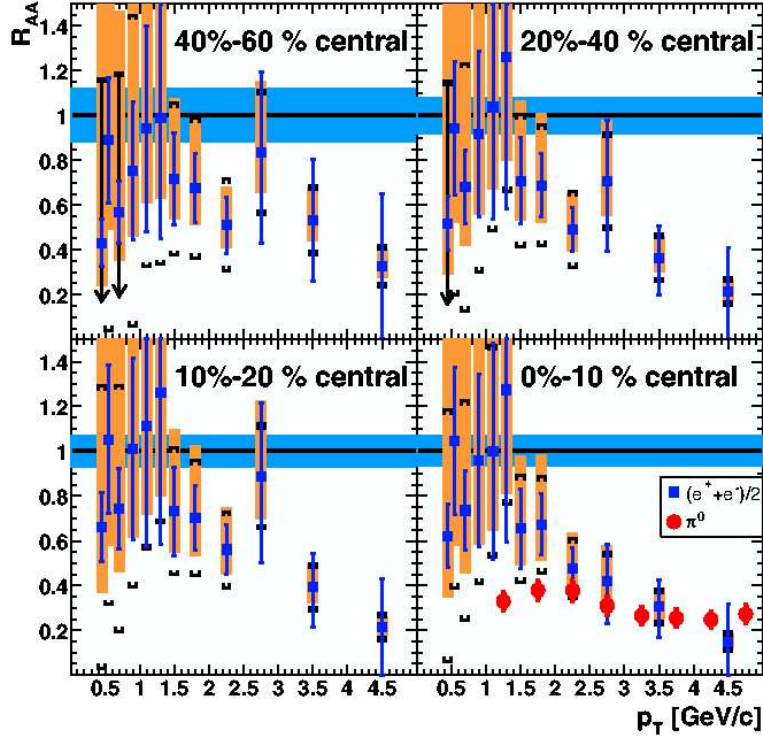


Figure 1.13: Nuclear modification factor R_{AA} for non-photonic electrons as a function of p_t in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the different centrality classes [30].

1.2.5 Probing the medium with heavy quarkonia

The study of quarkonia production in heavy-ion collisions represents one of the most powerful methods to probe the nature of the medium. The quark and anti-quark in the quarkonium states are bound by energies of the order of few hundred MeV, comparable in size to the mean energies of the plasma: this implies a large probability for quarkonium breakup.

Due to the heavy masses of the constituent quarks ($m_c \simeq 1.2 - 1.5$ GeV/ c^2 , $m_b \simeq 4.5 - 4.8$ GeV/ c^2), quarkonium spectroscopy can be studied reasonably well in non-relativistic potential theories. The color potential from the quark Q as seen by the anti-quark $\bar{Q}$ at the point $\vec{r}$ can be represented phenomenologically by the sum of a Coulomb potential and a confining linear potential:

$$V(\vec{r}) = \sigma |\vec{r}| - \frac{\alpha}{|\vec{r}|} \quad (1.16)$$

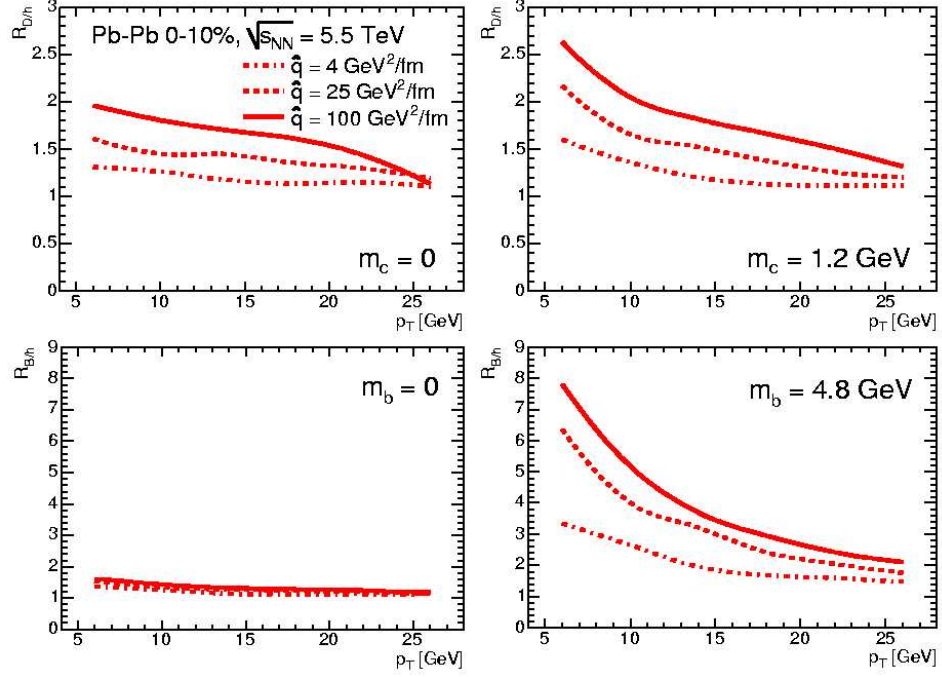


Figure 1.14: Heavy-to-light ratios for D meson (upper panels) and B mesons (lower panels) for the case of a realistic quark mass (right panels) and for a case study in which the quark-mass dependence of parton energy loss is neglected (left panels).

with a string tension $\sigma \simeq 0.2 \text{ GeV}^2$ and a Coulomb gauge coupling $\alpha \simeq \pi/12$ [32].

When the quarkonium is immersed in the Quark-Gluon Plasma, the presence of the quarks, anti-quarks and gluons affects the $Q\bar{Q}$ system. On the one hand, the quark matter alters the string tension σ between Q and $\bar{Q}$, which vanishes at the onset of deconfinement. On the other hand, the presence of quark matter leads to the rearrangement of the densities of quarks, antiquarks and gluons around the heavy quark pair, which results in a screening of the color interaction between Q and $\bar{Q}$.

The effect of the screening is to modify the long-range Coulomb type interaction into a short-range Yukawa type one, with the range given by the Debye screening length which decreases when temperature increases. At high temperatures, the range of the attractive interaction becomes so small as to make it impossible for the $Q\bar{Q}$ pair to form a bound state. When this

happens, the $Q\bar{Q}$ system dissociates into a separate Q and $\bar{Q}$ in the plasma, which subsequently hadronize by combining with light quarks.

Since the binding energy and the corresponding dimensions are different for different resonances, it is expected that the less tightly bound states melt at lower temperatures. In particular, the present understanding is that while the excited states are dissociated just above the critical temperature T_c , the fundamental 1S states melt far above that value, as shown in Table 1.1 (although it is worth noting that the uncertainties are large and previous calculations predict lower values [33]). The dissociation of specific

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon'(2S)$	$\chi_b(2P)$	$\Upsilon''(3S)$
T_d/T_c	2.10	1.16	1.12	> 4	1.76	1.60	1.19	1.17

Table 1.1: Quarkonium dissociation temperatures in the screening theory framework [32].

resonances can thus be used as a measurement of the QGP temperature.

The description of quarkonia dissociation has been improved by finite temperature lattice studies, which allow a direct spectral analysis [34]. The results, schematically represented in Figure 1.15, are only indicative for the moment, since the underlying calculations were generally performed in quenched QCD, i.e. without dynamical quark loops. However, some first calculations in full two-flavor QCD are already available [35] and support the late dissociation of the J/ψ .

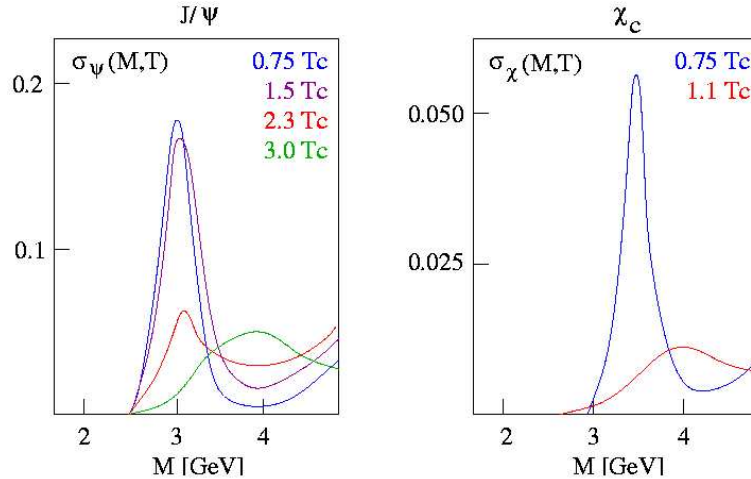


Figure 1.15: J/ψ and χ_c spectral functions at different temperatures.

Experimental results

Experimentally, the information on the suppression mechanism can be extracted from the distribution of quarkonium yields as a function of the collision centrality. The yields are in fact expected to drop in central collisions, when the number of interacting nucleons is high enough to reach temperatures above the threshold for deconfinement.

Quarkonia suppression in a hot and dense medium relies on quite solid theoretical basis, but the direct comparison with data is complicated by the presence of other mechanisms which can modify the resonance yields. In nucleon-nucleus and nucleus-nucleus collisions, quarkonia are in fact expected to breakup in the interaction with the ordinary nuclear matter constituting the nucleus itself. The effect can be described in terms of absorption of the resonance while crossing the nucleus, which depends on the nuclear path length L as:

$$\sigma(AB \rightarrow \text{quarkonia} + X) \simeq AB e^{-\rho_0 \sigma_{\text{abs}} L} \quad (1.17)$$

where A and B are the atomic numbers of the colliding nuclei and ρ_0 is the nuclear density. The absorption cross section σ_{abs} can be extracted from nucleon-nucleus and peripheral nucleus-nucleus collisions, where the number of binary nucleon-nucleon collisions is expected to be too low to release enough energy for the onset of deconfinement. Figure 1.16 shows the J/ψ cross section divided by the Drell-Yan² ($q + \bar{q} \rightarrow l^+ l^-$) cross section, measured in fixed target experiments at the CERN SPS, as a function of the nuclear path length: all data taken in p-A, S-U and peripheral In-In and Pb-Pb collisions can be well reproduced by assuming a nuclear absorption mechanism with $\sigma_{\text{abs}} = 4.18 \pm 0.35$ mb [36]. A different situation occurs instead in central Pb-Pb collisions, where an “anomalous” suppression is observed. This can be related to the formation of a deconfined medium.

Charmonium suppression has been recently studied in Au-Au collisions with $\sqrt{s_{NN}} = 200$ GeV at the Relativistic Heavy Ion Collider (RHIC) [37]. Figure 1.17 shows the J/ψ nuclear modification factor as a function of the

²Whenever possible, it is a common experimental choice to divide the quarkonium yields by an observable which is not strongly interacting with the nuclear medium, and which is therefore independent of the collision centrality. The ratio, indeed, allows to partially cancel the systematic errors of the measurement without affecting the suppression pattern.

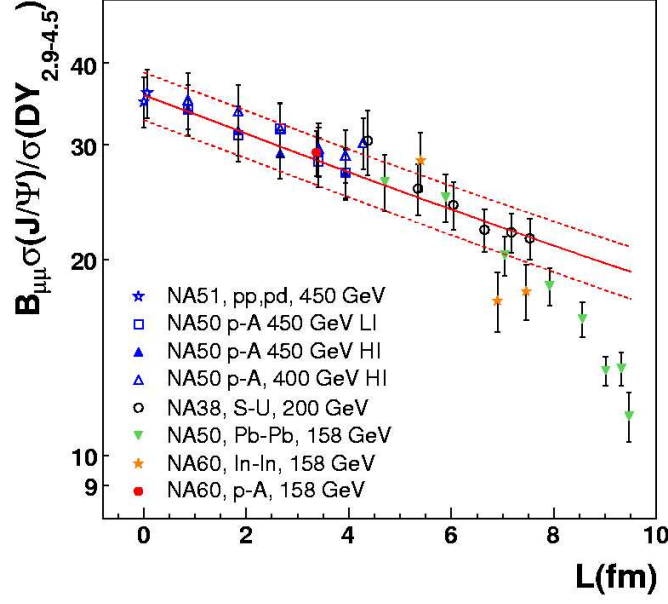


Figure 1.16: Ratio of the J/ψ to Drell-Yan cross sections as a function of the nuclear path length measured at the CERN SPS. Data taken in p-A, S-U and peripheral In-In and Pb-Pb collisions can be well reproduced by assuming $\sigma_{\text{abs}} = 4.18 \pm 0.35$ mb [36].

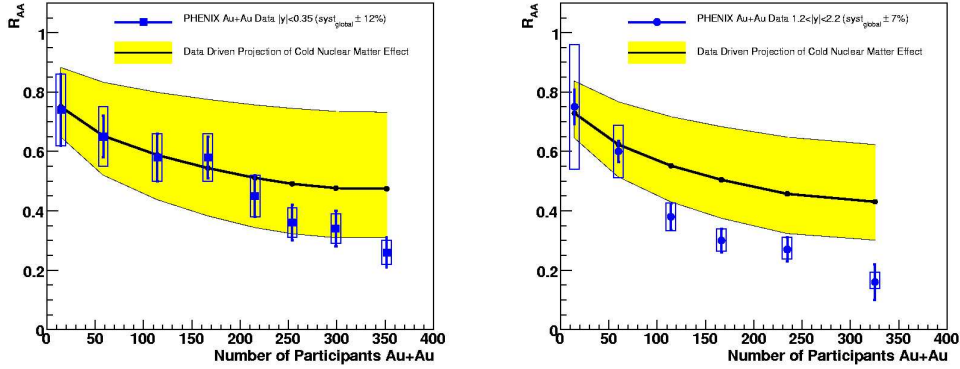


Figure 1.17: J/ψ nuclear modification factor as a function of the number of participants N_{part} measured in Au-Au collisions at RHIC, compared to cold nuclear matter extrapolations [38]. Results at mid (left) and forward (right) rapidities are shown.

number of nucleons participating to the Au-Au collision, for data measured at mid ($|y| < 0.35$) and forward ($1.2 < |y| < 2.2$) rapidities. The comparison with the extrapolations of data at the same energies in d-Au collisions shows

that the nuclear absorption cannot account alone for the J/ψ suppression in central nucleus-nucleus collision.

However, it is worth noting that the RHIC data and their comparison with the SPS results in the hottest Pb-Pb collisions (Figure 1.18) bring up two striking features:

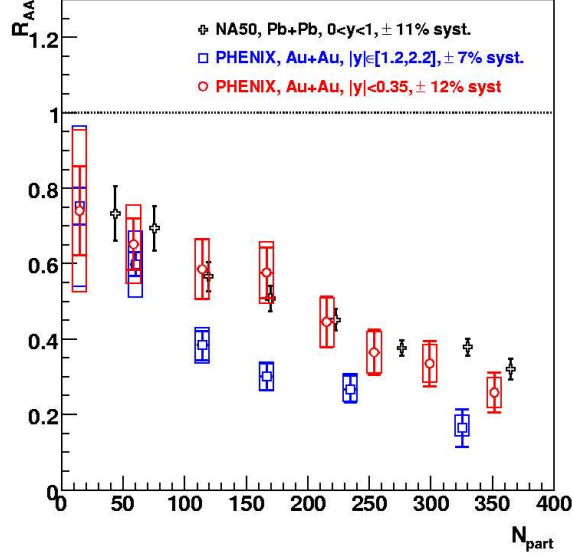


Figure 1.18: J/ψ nuclear modification factor as a function of the number of participants N_{part} measured in the hottest SPS (Pb-Pb) and RHIC (Au-Au) collisions.

- at midrapidity, the amount of suppression is surprisingly similar to the one observed at SPS if plotted as a function of the number of participants N_{part} . Since the energy density should be higher at RHIC and the cold nuclear effects could be drastically different, there is no fundamental reason for this to happen.
- J/ψ 's are more suppressed at forward rapidities than at midrapidities, where the energy density is expected to be higher.

A possible explanation of the first item involves “coalescence” or “recombination” models: due to the high number of $c\bar{c}$ pairs ($\gtrsim 10$) produced in a single central collision at RHIC, the quark of one pair can combine with the anti-quark of another in order to re-form a J/ψ . Qualitatively, this also explains the lower suppression at mid-rapidity, where the number of $c\bar{c}$ pairs is

higher. On the contrary, the higher suppression at forward rapidity could be due to nuclear matter effects: gluon shadowing parameterizations are in fact poorly constrained by data and further saturation effects are not excluded.

The solution to the questions could be hopefully provided by the Large Hadron Collider at CERN.

Chapter 2

The ALICE experiment

Located at the CERN of Geneva, inside a 27 km long tunnel originally built to host the Large Electron Positron Collider (LEP), the Large Hadron Collider (LHC) [1] is at present the biggest and more powerful hadronic accelerating facility in the world. The idea of the LHC began in the early 1980s, when the LEP was not constructed yet: several meetings and working groups were then organized around this idea, leading to the final approval by the CERN Council in 1994. In 1998, the Swiss and French authorities gave the final green light to the beginning of the engineering works. Ten years later, and precisely on the 10th of September 2008, at around 9:30 a.m. (Geneva time) the injection operations starts and leads, about one hour later, to the first circulating beam.

The LHC is designed to accelerate both protons and heavy-ions: the former will reach a maximum energy of 7 TeV; the latter of 2.75 TeV per nucleon. The proton acceleration is performed in many phases: the particles are first injected from the linear accelerator (LINAC2) into the PS Booster and then to the Proton Synchrotron (PS), up to a momentum of 25 GeV/c. Afterwards, the beams circulate in the Super Proton Synchrotron (SPS), where they acquire a momentum of 450 GeV/c, before the final injection at the LHC (see Figure 2.1). Ion acceleration, on the contrary, is complicated by additional stripping and accumulating phases at the beginning of the chain.

Beyond the high energies reached, the other remarkable feature of the LHC is the high luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for p-p and $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ for Pb-Pb collision, allowing the study of rare events. These characteristics will

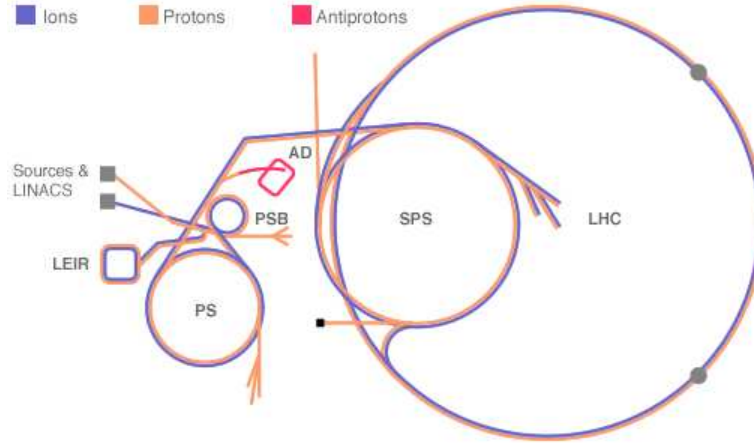


Figure 2.1: The accelerator complex at CERN.

allow to shed light on still unclear topics with strong implications in particle physics and cosmology, such as the nature of dark matter and energy, the Higgs mechanism, the presence of extra dimensions and supersymmetric particles and the study of a new state of matter, the quark gluon plasma.

The two particle beams circulating with opposite directions in the LHC rings collide in 4 different locations, where the scattering products are detected by six experiments:

- ALICE (A Large Ion Collider Experiment), the only experiment specifically dedicated to heavy-ion collisions.
- ATLAS (A Toroidal LHC ApparatuS), a general purpose experiment focused on the searching of the Higgs boson, as well as on physics beyond the Standard Model.
- CMS (Compact Muon Solenoid), with analogous purposes of ATLAS.
- LHCb (Large Hadron Collider beauty), focusing on beauty detection for precise measurements of CP violation and rare decays.
- LHCf (Large Hadron Collider forward), an experiment sharing the interaction point with ATLAS and using the forward particles created at the LHC as a source to simulate cosmic rays in laboratory conditions.
- TOTEM (TOTal and Elastic Measurement), an experiment sharing

the interaction point with CMS for total cross sections, elastic scattering and diffractive dissociation measurements.

Although primarily dedicated to p-p collisions, the ATLAS and CMS experiment foresee an heavy-ion programme as well [2, 3].

2.1 Overview of the ALICE detectors

The ALICE experiment design [4] is driven by the requirements of tracking and identifying particles in a wide transverse momentum range (from about 100 MeV/c up to about 100 GeV/c), of reconstructing short-lived particles such as hyperons, D and B mesons and of performing these tasks in an environment with large charged-particle multiplicities. These features are necessary to achieve a complete and detailed description of the events produced in heavy-ion collisions, from the hard scattering processes to the collective phenomena arising in a complex system. The low- p_t cutoff can be reached by using a magnetic field with the relatively low maximum intensity of 0.5 T.

The ALICE experiment (Figure 2.2) consists of a central detector system, covering mid-rapidity ($|\eta| < 0.9$) over the full azimuth, and several forward systems. The central system include, from inside to outside:

Inner Tracking System (ITS). It consists of six cylindrical layers of silicon detectors, with a radius varying from 4 to 44 cm. Pixel, drift and strip detectors have been chosen for the two innermost, the two intermediate and the two outer layers respectively. The high resolution pixel detectors have an extended coverage ($|\eta| < 1.98$) to provide, together with the forward detectors, a continuous coverage in rapidity for charged particles multiplicity. The six layers will operate together with the central detectors at low frequency (about 100 Hz), while the Silicon Pixel Detector (SPD) can run at higher rate (about 1 kHz) to provide the vertex information for events triggered by the Forward Muon Spectrometer. The ITS is designed to localize the primary vertex with a resolution better than 100 μm , reconstruct the secondary vertexes from the decay of hyperons and D and B mesons, track and identify low momentum particles ($p < 100 \text{ MeV}/c$) and to complete and improve the information provided by the TPC.

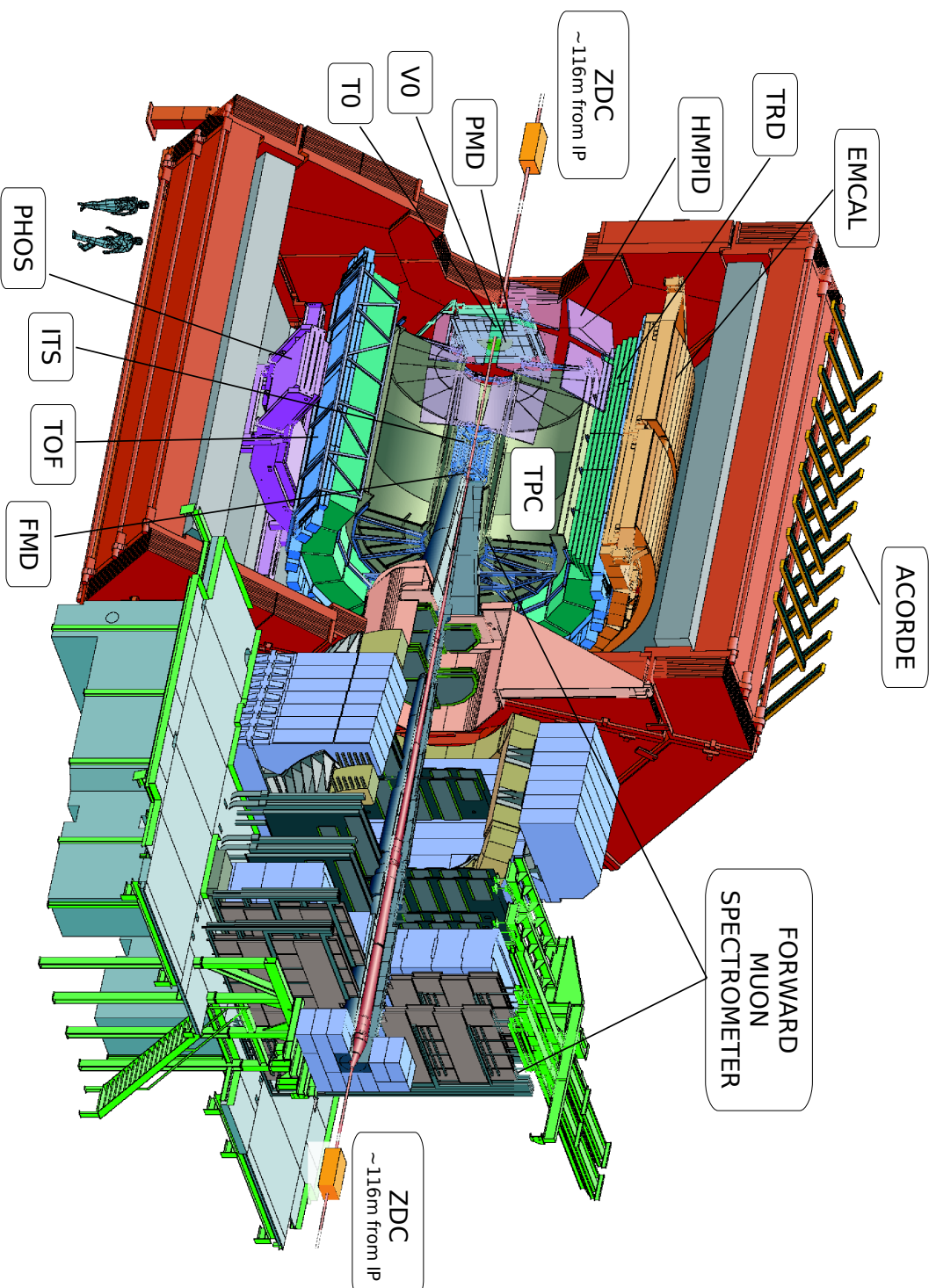


Figure 2.2: Layout of the ALICE experiment.

Time Projection Chamber (TPC) It is the main tracking detector of the ALICE central barrel. The TPC is designed to provide charged-particle momentum measurements up to $p_t = 100$ GeV/ c , with good particle identification and vertex determination in the high multiplicity environment expected in Pb-Pb collisions. The simultaneous detection of high and low momentum particles is achievable with a low magnetic field (≤ 0.5 T) and a large detector volume which allows to measure a large section of the track, thus increasing the sensitivity for the sagitta determination. The Time Projection Chamber has an inner radius of about 85 cm and an outer one of about 250 cm, with a total length of about 500 cm. This however leads to a 88 μ s drift time which is the limiting factor for the luminosity in p-p collisions.

The study of soft hadronic observables requires a resolution of 1% for momenta between 100 MeV/ c and 1 GeV/ c , while the detection of hard probes requires a 10% resolution for tracks with $p_t = 100$ GeV/ c . The latter can be achieved by using the TPC in combination with ITS and TRD. The resolution on the relative momentum between two particles, necessary to measure two-particle correlations, has to be better than 5 MeV/ c . Finally, the TPC can provide particle identification by dE/dx measurement in certain momentum intervals from the low-momentum region up to few tens of GeV/ c , in combination with TOF, TRD and ITS.

Transition Radiation Detector (TRD). It provides electron identification for momenta greater than 1 GeV/ c , where the pion rejection capability through energy loss measurement in the TPC is no longer sufficient. Its use, in conjunction with TPC and ITS, allows to measure the production of light and heavy vector meson resonances and, thanks to the determination of the impact parameter, of open charm and beauty. A similar technique can be used to separate the directly produced J/ψ mesons from those produced by B-decays. The TRD consists of 18 sectors of 6 layers each with a 5-fold segmentation along the beam direction, for a total of $18 \times 5 \times 6 = 540$ detector modules. Each module consists of a radiator of 4.8 cm thickness, a multi-wire proportional readout chamber and its front-end electronic. The TRD increases the ALICE pion rejection capabilities by a factor of 100 for electron momenta above 3 GeV/ c and allows a mass resolution of 100 MeV/ c^2 at the Υ for $B = 0.4$ T.

Time Of Flight (TOF). It is a large area array for particle identification in the intermediate momentum range, from 0.2 to 2.5 GeV/c. Coupled with the ITS and TPC it provides an event-by-event identification of large samples of pions, kaons and protons. The large coverage requires the use of a gaseous detector: Multi-gap Resistive Plate Chambers were chosen, providing an intrinsic time resolution of better than 40 ps and an efficiency close to 100%. The detector is segmented in 18 sectors in φ and 5 segments in z . The whole device is inscribed in a cylindrical cell with an internal radius of 370 cm and an external one of 399 cm.

The central system is completed by two small area detectors:

High Momentum Particle Identification Detector (HMPID). Dedicated to the inclusive measurement of identified hadrons with $p_t > 1$ GeV/c, the HMPID is designed as a single-arm array with a pseudo-rapidity acceptance of $|\eta| < 0.6$ and an azimuthal coverage of about 58° , corresponding to 5% of the central barrel phase space. The detector is based on proximity-focusing Ring Imaging Cherenkov counters and consists of seven modules of about 1.5×1.5 m² each. The HMPID enhances the PID capability of ALICE by enabling the identification of particles beyond the momentum interval attainable through energy loss (in ITS and TPC) and time-of-flight measurements (in TOF). The detector is optimized to extend the useful range for π/K and K/p discrimination, on a track-by-track basis, up to 3 GeV/c and 5 GeV/c respectively.

PHOTon Spectrometer (PHOS). The high resolution electromagnetic spectrometer is designed to provide photon identification as well as neutral meson identification through the two-photons decay channel. The measurement of single photon and di-photon spectra and Bose-Einstein correlations of direct photons will allow testing the thermal and dynamic properties of the initial phase of the collision, while the detection of high- p_t π^0 will allow investigation of jet quenching as a probe of deconfinement. The PHOS is a single arm spectrometer including a highly segmented electromagnetic calorimeter made of lead-tungstenate crystals and a charged particle veto detector consisting of a Multi-Wire Proportional Chamber with cathode-pad

readout. The spectrometer, positioned at the bottom of the ALICE setup at a distance of 460 cm from the interaction point, covers a pseudo-rapidity range of $|\eta| < 0.12$ and 100° in azimuthal angle.

ElectroMagnetic Calorimeter (EMCal). It enhances the ALICE capabilities for jet quenching measurements. The addition of the EMCal enables triggering on high energy jets, reduces significantly the measurement bias for jet quenching studies, improves jet energy resolution and augments existing ALICE capabilities to measure high momentum photons and electrons. The EMCal will be placed between the ALICE spaceframe, supporting the entire central detectors, and the magnet coils. The azimuthal acceptance covered (110°) is limited by the PHOS and the HMPID. The chosen technology is a layered Pb-scintillator sampling calorimeter with alternating layers of 1.44 mm of lead and 1.76 mm of polystyrene scintillator [5]. The EMCal will span $-0.7 < \eta < 0.7$ and will be positioned to provide partial back-to-back coverage with the PHOS calorimeter.

The forward system include:

Muon Spectrometer. The muon detection in the pseudo-rapidity region $-4 < \eta < -2.5$ allows studies of heavy quark vector mesons (ψ and Υ families) in the dimuon channel and of open charm and beauty production in the semi-leptonic decay channel. A detailed discussion of the Muon Spectrometer layout and features is provided in Section 2.2.

Photon Multiplicity Detector (PMD). It is a preshower detector measuring the multiplicity and spatial ($\eta - \varphi$) distribution of photons on an event-by-event basis, in the forward region ($2.3 < \eta < 3.7$). Placed at about 360 cm from the interaction point, in the side opposite to the Muon Spectrometer, the PMD provides estimates of the transverse electromagnetic energy and of the reaction plane on an event-by-event basis. It consists of two identical planes of detectors, made of gas proportional counters with honeycomb structure and wire readout, with a $3X_0$ thick lead converter in between them: the front detector plane is used for vetoing charged particles while the detector plane behind the converter is the preshower plane and registers hits from both photons and charged hadrons.

Forward Multiplicity Detector (FMD). It provides a charged particle multiplicity information in the pseudo-rapidity range $-3.4 < \eta < -1.7$ (Muon Spectrometer side) and $1.7 < \eta < 5.1$ (PMD side). The FMD consists of 51200 silicon strips channels distributed over 5 ring counters of two types: the inner (outer) ring is composed by 20 (40) sectors in azimuthal angle with 512 (256) strips each. The position and dimension of each ring is summarized in Table 2.1. The design ensures, together with the ITS inner

Ring	z (cm)	R_{in} (cm)	R_{out} (cm)	η coverage
FMD3 outer	-75.2	15.4	28.4	$-2.29 < \eta < -1.70$
FMD3 inner	-62.8	4.2	17.2	$-3.4 < \eta < -2.01$
FMD2 outer	75.2	15.4	28.4	$1.7 < \eta < 2.29$
FMD2 inner	83.4	4.2	17.2	$2.28 < \eta < 3.68$
FMD1	320.0	4.2	17.2	$3.68 < \eta < 5.09$

Table 2.1: Summary of the position and sizes of the FMD detector rings. The distance z from the detector and the interaction point, the inner and outer radii and the resulting pseudo-rapidity coverage are shown.

pixel layer, a full pseudo-rapidity coverage in the range $-3.4 < \eta < 5.1$, and an overlap between the FMD and ITS pixel system of about 0.2 pseudo-rapidity units.

T0 and V0. The T0 consists of two arrays of Cherenkov counters, with a time resolution better than 50 ps, asymmetrically placed at 72.7 cm (Muon spectrometer side) and 375 cm (PMD side) from the interaction vertex, with a pseudo-rapidity coverage of $-3.28 < \eta < -2.97$ and $4.61 < \eta < 4.92$, respectively [6]. It is designed to provide a T0 signal for the TOF detector, to measure the vertex position with a precision of ± 1.5 cm, thus providing a L0¹ trigger when the position is within the preset values, and to measure the particle multiplicity and generating a centrality trigger.

The V0 is made of two arrays of scintillator material, located 90 cm (Muon Spectrometer side) and 340 cm (PMD side) from the interaction point. The detectors are segmented into 72 elementary counters distributed in 5 rings, with a pseudo-rapidity coverage of $-3.8 < \eta < -1.7$ and $2.8 < \eta < 5.1$. The

¹The “fast” part of the ALICE trigger is split into two levels: a Level 0 (L0) signal which reaches detectors at 1.2 μ s, but which is too fast to receive all the trigger inputs, and a Level 1 (L1) signal sent at 6.5 μ s which picks up all remaining fast inputs.

measurement of the time-of-flight difference between the detectors allows to identify and reject the beam-gas events, thus providing a minimum bias trigger for the central barrel detectors and a validation signal for the muon trigger. Moreover, the V0 can measure the charged particle multiplicity, thus resulting in a centrality indicator providing two centrality triggers in Pb-Pb collisions.

Zero Degree Calorimeter (ZDC). The ZDC provides a centrality estimation and trigger in Pb-Pb collisions by measuring the energy carried in the forward direction (at zero degrees relative to the beam direction) by non-interacting (spectator) nucleons. The detector consists of two pairs of quartz-fibers hadronic calorimeters (for neutron and protons), placed on both sides of the interaction point, at 116 m from it. The system is completed by two electromagnetic calorimeters (ZEM), both placed at about 7 m from I.P. (PMD side), which allow to resolve ambiguities in the determination of the centrality. Being placed between the beam pipes, the neutron calorimeter (ZN) has the most severe geometrical constraints: the transverse dimensions have to be smaller than 7 cm, requiring a very dense “passive” material (tungsten). The stringent space constraints do not hold for the proton calorimeter (ZP), which is made with a less dense material (lead). The ZN, segmented in four regions, can also provide an estimation of the reaction plane.

The electromagnetic calorimeter (ZEM), made of lead and quartz fibres, is designed to measure the energy of particles, mostly photons generated from π^0 decays, at forward rapidities ($4.8 < \eta < 5.7$). Differently from the ZN and ZP, the ZEM fibres are oriented at 45° , a choice that maximizes the detector response. The ZDCs cannot provide an L0 trigger, since they are located too far from the interaction point, but they will provide an essential L1 trigger for centrality.

A summary of the particle identification with the ALICE detectors can be found in Figure 2.3.

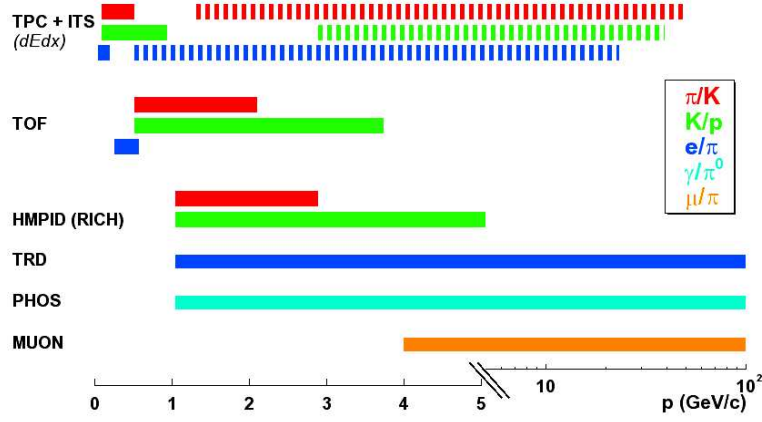


Figure 2.3: Particle identification with the ALICE experiment. Solid (dashed) bands represent the identification capabilities with a 3σ (2σ) cut.

2.2 The Muon Spectrometer

Muon identification in the LHC environment is only feasible for muon momenta above ~ 4 GeV/c because of the amount of absorber material required to reduce the flux of hadrons. Hence the measurement of low- p_t charmonium via dimuon decays is possible only in the forward region, where the muons are Lorentz-boosted. The ALICE Muon Spectrometer (Figure 2.4) is designed to detect muons with a polar angle of $171^\circ < \theta < 178^\circ$ ² with respect to the beam axis, corresponding to a pseudo-rapidity coverage of $-4 < \eta < -2.5$. This will allow the study of heavy quarks and quarkonia in a region complementary to the one explored by the ALICE central barrel and by other LHC experiments, like ATLAS and CMS.

The detector consists of ten planes of tracking chambers with high granularity, a large dipole magnet with a 3 Tm field integral placed outside the L3 magnet, a composite front absorber ~ 10 interaction lengths (λ_{int}) thick, made with layers of both high and low-Z materials, a second absorber ($\sim 7\lambda_{\text{int}}$), made of iron and placed at the about 16 m from the interaction vertex for particle identification, and 4 planes of trigger chambers. The

²The ALICE official coordinate system is a right-handed orthogonal Cartesian system with the z -axis parallel to the beam line and pointing in the direction opposite to the MUON Spectrometer, the x -axis aligned to the local horizon and pointing to the accelerator center and the y -axis perpendicular to the other two and pointing upward. In this reference frame, the angular acceptance of the spectrometer $2^\circ < \theta < 9^\circ$ results in a polar angle of $171^\circ < \theta < 178^\circ$

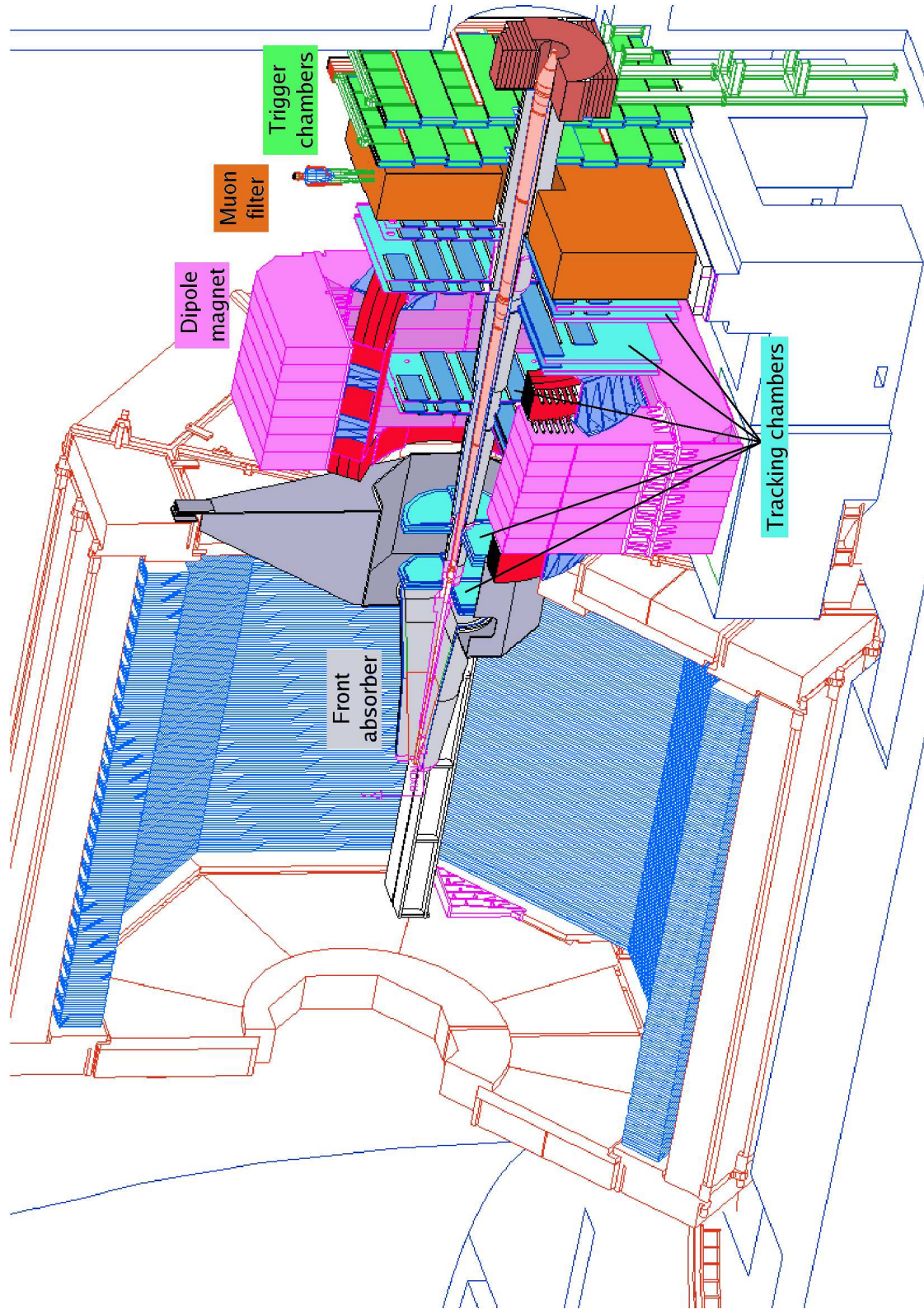


Figure 2.4: Layout of the ALICE Muon Spectrometer.

spectrometer is shielded throughout its length by a dense absorber tube, with a diameter of about 60 cm, which surrounds the beam pipe.

2.2.1 Absorber and shielding

The ALICE Muon Spectrometer design was driven by the requirement of coping with a high multiplicity scenario in Pb-Pb collisions: about 7000 particles produced in the spectrometer acceptance and about 6000 particles intercepting the beam-pipe in the region $-7 < \eta < -4$. The latter will in general interact with the pipe and introduce additional background particles in the acceptance [7].

The front absorber has the double task of attenuating the forward flux of charged particles by at least two orders of magnitude and of decreasing the background of muons from the decay of pions and kaons by limiting the free path for primary π/K . This can be achieved by minimizing the distance between the absorber and the vertex, compatibly with the dimension of the inner tracker and the position of the multiplicity counters: the minimal value imposed by such constraints is 90 cm.

The absorber design and composition are optimized to provide good shielding capabilities on the one hand, and a limited multiple scattering which should not compromise the spectrometer mass resolution on the other. This can be achieved by using low-Z material in the absorber layers close to the vertex and high-Z shielding materials at the rear end. A total thickness of 20 cm of Pb interleaved with layers of boronated polyethylene, which can moderate neutrons by quasi-elastic scattering, was chosen for the front part, while lead and tungsten were selected for the rear end. The absorber is completed by a combination of concrete and carbon, as shown in Figure 2.5. It is worth noting that the use of very dense material at the end of the absorber has an important consequence for the tracking. Since the multiple scattering in this layer is large (about $35X_0$) whereas the distance to the first tracking chamber is small (30 cm), the muon production angle is best defined when the position measurement in the first chamber is combined with the position of the interaction vertex, determined by the ITS.

The small-angle beam shield is made of dense materials (pure tungsten in the most critical region, tungsten-lead mixture elsewhere) encased in a 4 cm thick stainless steel envelope. The latter is “pencil-shaped”: it follows

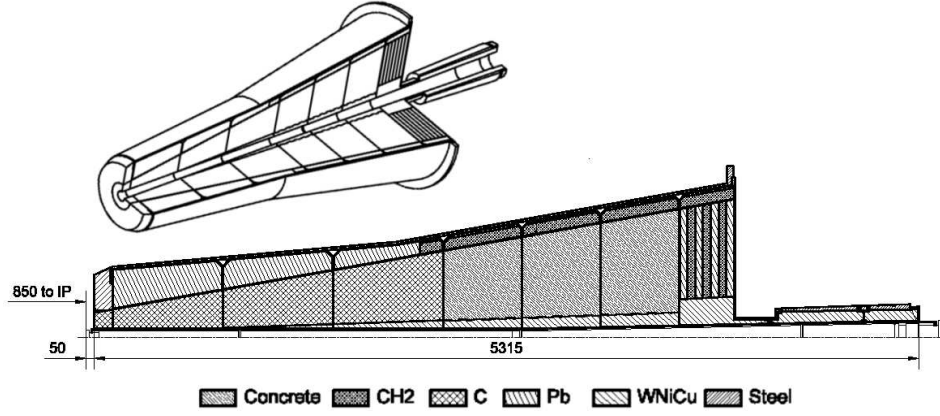


Figure 2.5: Layout of the front absorber.

the 178° acceptance line up to a maximum radius of 30 cm and then stays constant up to the end of the spectrometer. The inner cone opens up till the end of the muon arm (“open geometry” configuration). Within the absorber, the beam shield absorbs primary particles in the region $-5 < \eta < -4$.

2.2.2 Dipole magnet

The Muon Spectrometer dipole magnet (Figure 2.6) is a warm magnet providing a maximum central field of 0.7 T and an integral field of 3 Tm [8]. The general concept of the magnet is based on a window frame return yoke, fabricated from low carbon steel sheets. The saddle type excitation coils are water-cooled with demineralized water, whose inlet temperature can vary between 15 and 25°C . Its overall dimensions are 5 m in length, 7.1 m width and 9 m height, with a total weight of about 890 tons. The dipole has an angular acceptance of $171^\circ < \theta < 178^\circ$ and is designed to provide a horizontal magnetic field perpendicular to the beam axis, whose polarity can be reverted within a short time [4].

2.2.3 Tracking system

The tracking chamber design was driven by two main constraints: to achieve the spatial resolution of $100\ \mu\text{m}$ necessary for an invariant mass resolution of $100\ \text{MeV}/c^2$ at the Υ mass and to operate in a maximum hit density of about $5 \times 10^{-2}\ \text{cm}^{-2}$ expected in central Pb-Pb collisions. Less stringent criteria are required for the resolution along the non-bending plane (parallel

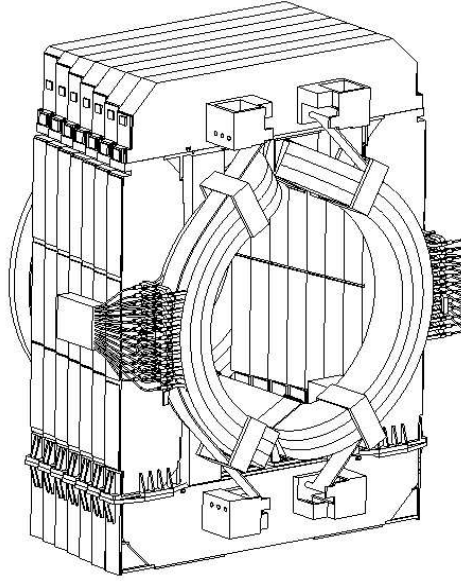


Figure 2.6: Layout of the dipole magnet.

to the magnetic field), which should be better than about 2 mm to allow an efficient track finding. An additional constraint is imposed by the large area (about 100 m²) covered by the tracking system.

All these requirements can be fulfilled by the use of Multi-Wire Proportional Chambers (MWPC) with cathode pad readout. The detectors are arranged in five stations: two are placed before, one inside and two after the dipole magnet. Each station is made of two chamber planes, with two cathode planes each, which are readout in order to provide bi-dimensional information. The segmentation of the cathode pads is designed to keep the occupancy at a 5% level: since the hit density decreases with the distance from the beam pipe, larger pads are used at larger radii. This enables to keep the total number of channels at about one million.

Multiple scattering of the muons in the chamber is minimized by using composite material, such as carbon fibres. The chamber thickness corresponds to about $0.03X_0$. Although based on standard MWPC design, the individual chambers have been adapted to meet the particular constraints on the different tracking stations. The first two are based on a quadrant structure [9]: Figure 2.7 shows a layout of the cathode plane for one of the quadrants of Station 1. The readout electronics is distributed over the sur-

face, as displayed in Figure 2.8. For the other stations a slat architecture

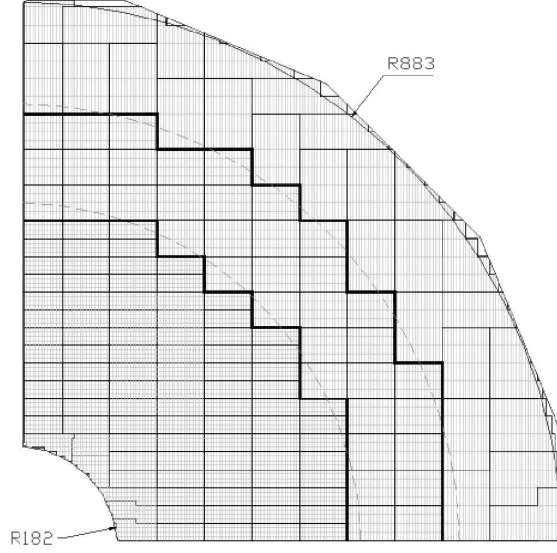


Figure 2.7: The cathode plane layout of Station 1.

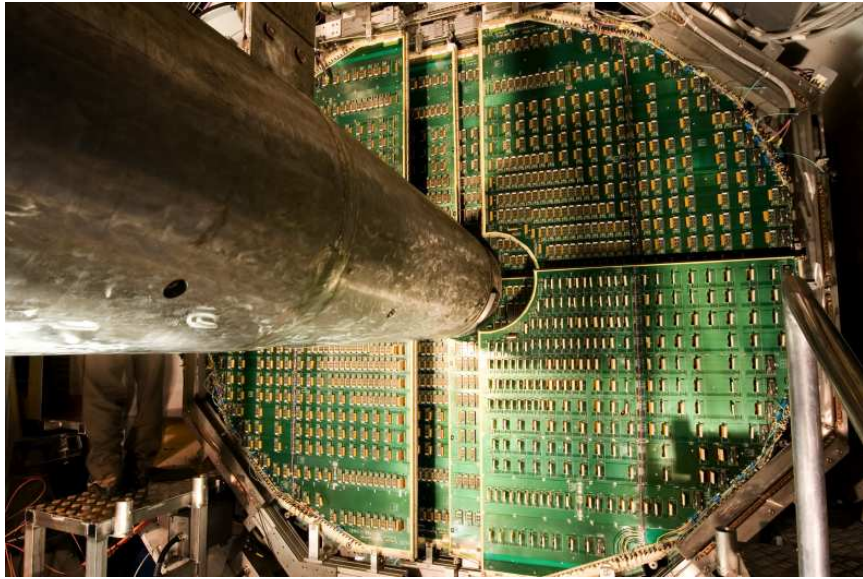


Figure 2.8: Layout of the tracking system Station 2, installed in the ALICE cavern.

was chosen (Figure 2.9), with the electronics implemented on the side of the slats, as shown in Figure 2.10. The slats and quadrants overlap to avoid dead zones in the detector.

For all the stations the front-end electronics is based on a 16-channel chip called MANAS (Multiplexed ANALogic Signal processor) including the functionality of charge amplifier, filter, shaper and track & hold. The signal digitization is performed on board. The channels of four of these chips are

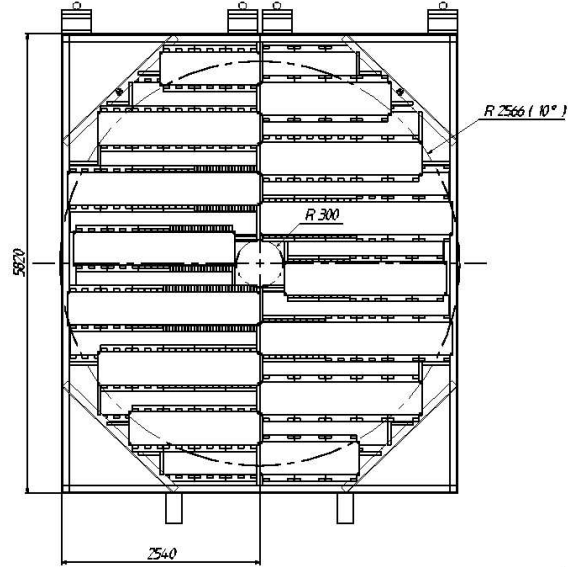


Figure 2.9: Scheme of a station with slat architecture.



Figure 2.10: Layout of the tracking Stations 4 and 5, installed in the ALICE cavern.

fed into a 12-bits ADC, read out by the Muon Arm Readout Chip (MARC), whose functionalities include zero suppression. The entire chain is mounted on a front-end board, the MANas NUMérique (MANU): the 1.08 million channels of the tracking system are treated by about 17000 MANU cards.

The Protocol for the ALICE Tracking CHamber (PATCH) buses provide the connection between the MANUs and the Cluster ReadOut Concentrator Unit System (CROCUS) crate. Each chamber is readout by two CROCUS, which concentrate and format the data, transfer them to the DAQ and dispatch the trigger signals, coming from the Central Trigger Processor (CTP). These crates allow also the control of the FEE and of the calibration processes.

The Geometry Monitoring System

The requirement of a mass resolution of 1% at the mass of the Υ puts strict constraints on the alignment of the tracking chambers. During the installation phase the chambers are positioned according to theodolite measurements and with photogrammetry, with a spatial accuracy of few tenths of a millimeter [10]. At the beginning of each data taking period, dedicated runs without magnetic field will be carried out in order to align the ten tracking chambers with straight muon tracks, thus determining the initial geometry of the system. However, after switching on the magnet and electronic power supplies, such initial positioning will be disturbed by the forces of the L3 and dipole magnetic fields, as well as by the thermal expansion of the chambers and their support. The displacements and deformations are measured and recorded during data taking by the Geometry Monitoring System (GMS), with a resolution better than 40 μm .

The GMS is an array of about 460 optical sensors which are placed on platforms located at each corner of the tracking chambers. Two different types of optical devices were used: the Boston CCD Angle Monitor (BCAM) and the Proximity [11]. In both cases the image of an object is projected on a CCD sensor through a lens: the analysis of the captured image provides a displacement measurements. The most relevant difference between the devices is represented by the luminosity object used: a pair of point-like LEDs for the long range system BCAM and a coded mask for the short distance system Proximity.

The BCAM are used to monitor the relative longitudinal distance be-

tween two neighboring chambers in different stations, the flatness of the chamber supports and the absolute displacement of the entire spectrometer, through eight optical lines linking chamber 9 to the ALICE cavern walls. The longitudinal distance between two chambers of the same station is measured by the Proximity device. The resulting optical lines are shown in Figure 2.11.

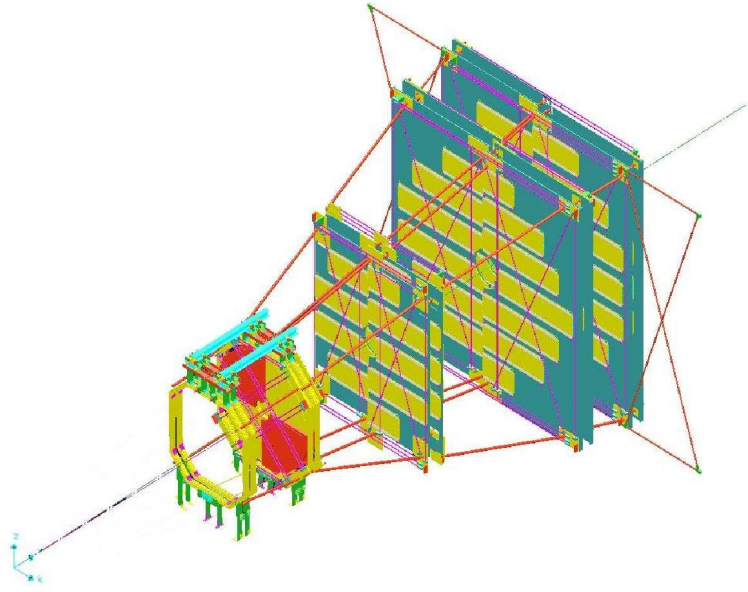


Figure 2.11: General view of the GMS setup: the red lines in the figure represent the optical lines.

2.2.4 Trigger system

The trigger system of the ALICE Muon Spectrometer consists of two trigger stations (MT1 and MT2) located at about 16 m from the interaction point and 1 m apart from each other, placed behind an iron muon filter, as shown in Figure 2.12. The filter has a thickness of 120 cm, corresponding to 7.2 interaction lengths, and performs muon selection by stopping the low-energy background particles and hadrons escaped from the front absorber.

Each station is constituted by two planes of 18 Resistive Plate Chambers. RPCs are large area detectors, made up of high resistivity ($\sim 4 \times 10^7 \Omega\text{m}$) Bakelite electrodes separated by 2 mm wide gas gap. The surface of the Bakelite foils on the gap side is painted with linseed oil, while the exter-

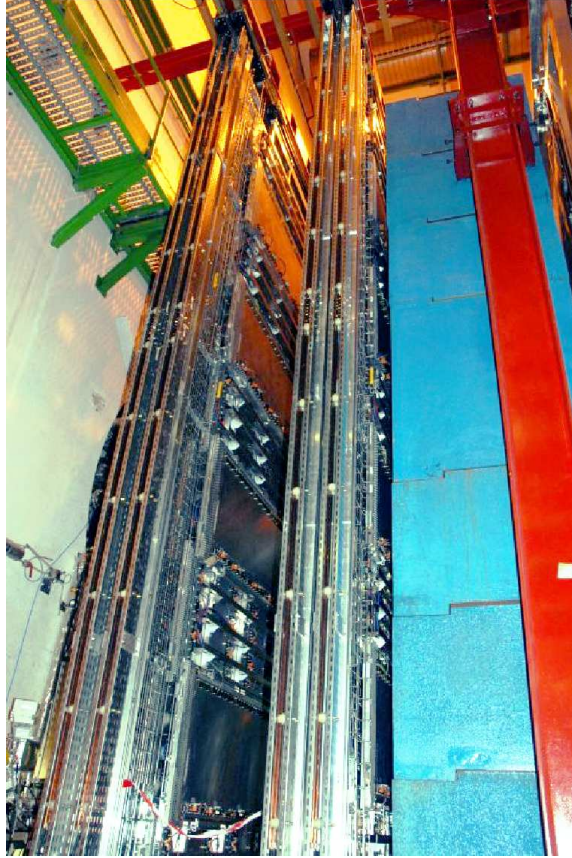


Figure 2.12: Layout of the trigger stations and the iron wall, installed in the ALICE cavern.

nal surface is painted with graphite, with one layer connected to the high voltage and the other to the ground (Figure 2.13). The signal is picked up by read-out strips connected with the Front-End Electronics (FEE), which basically consists of a leading-edge discriminator stage followed by a shaper. The strips are placed on both sides of the chambers, in order to provide a bi-dimensional information. The horizontal strips measure the bending deviation due to the dipole magnetic field, while vertical strips measure the non-bending direction. The two layers of read-out pads are therefore called “bending” and “non-bending” plane respectively.

The signals coming from the FEE, consisting in the x and y fired strip patterns of the four detection planes, are sent to the local trigger electronics. The whole system is divided in 234 detection areas, each of them associated with a local trigger board. Figure 2.14 shows a schematic view of the local

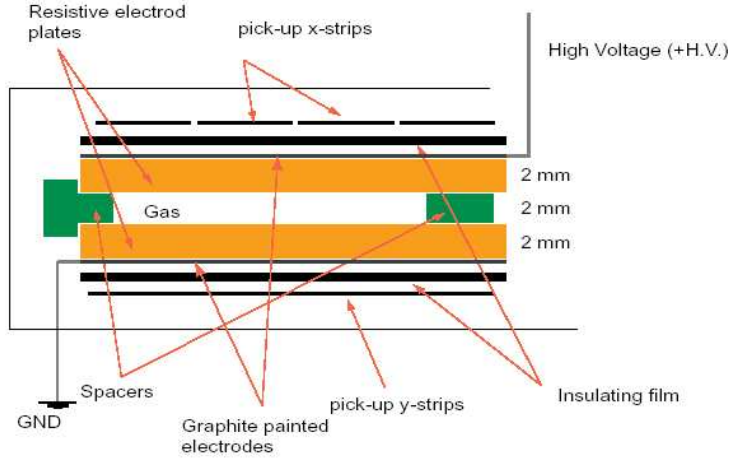


Figure 2.13: Resistive Plate Chamber scheme.

board position in one plane of trigger chambers, as seen from the interaction point. The local board density reflects the strip segmentation which is finer in the region close to the beam pipe, where a higher particle multiplicity is expected: in particular, moving from the beam pipe outwards, the strip pitch is about 1, 2 and 4 cm in the bending plane and about 2 and 4 cm in the non-bending plane.

The main aims of the local electronics are to perform the local trigger algorithm and deliver the trigger decision on single tracks, and to backup strip patterns and trigger decision in a pipeline memory which is read-out on occurrence of an ALICE trigger sequence.

The geometry of the detection elements is projective: straight tracks from the interaction point cross the strip with the same ID number in all chambers. The principle of the p_t cut with the trigger relies on the use of an estimated deviation of the measured track with respect to the track of a muon with infinite momentum (see Figure 2.15). The estimation is performed by the local boards. The maximum measurable deflection has been fixed, for practical reasons, to ± 8 strips in the vertical direction and ± 1 in the horizontal direction. This defines the maximum width of the open “roads” between MT1 and MT2.

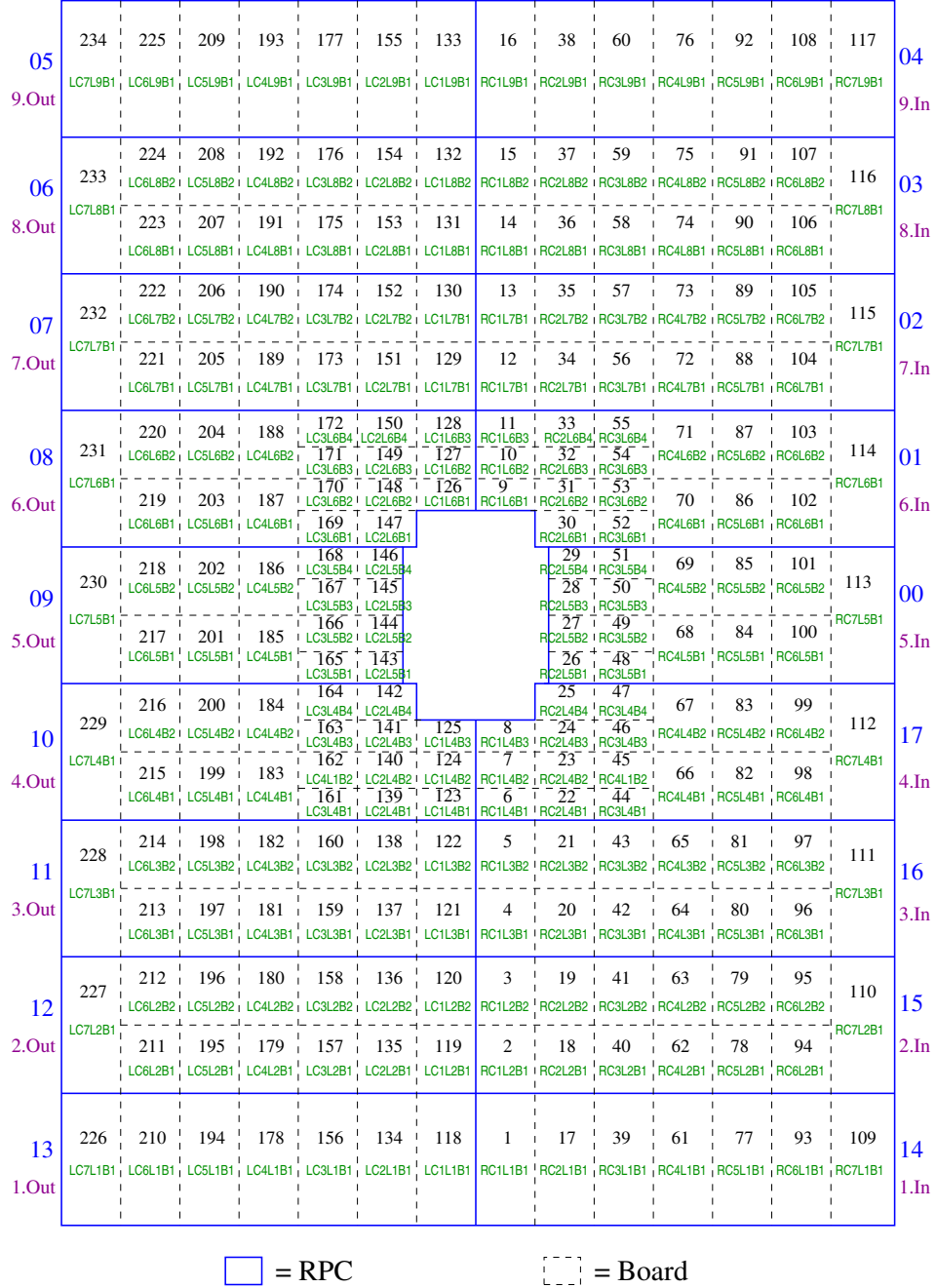


Figure 2.14: View of one of the trigger chambers (looking from the interaction point) showing the 18 RPCs and the 234 trigger boards. The board enumeration, both in labels and numbers (more suitable for interfacing with the analysis software) is also shown.

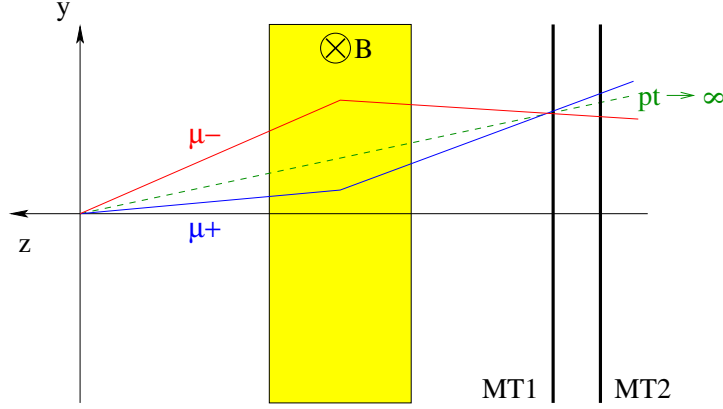


Figure 2.15: The muon arm trigger principle, based on the estimation of the transverse momentum of the track: the larger the deviation, with respect to the $p_t \rightarrow \infty$ straight line, the lower the p_t of the track.

The trigger algorithm

The local trigger algorithm performs operations separately on the bending and non-bending plane, eventually applying the p_t cut.

In the bending plane, each board collects 16+16 strip information from plane 1 and 2 in station MT1 and 32+32 from plane 1 and 2 in station MT2. The information collected undergoes first a “declustering” process, consisting in doubling the real bit-patterns by insetring a (virtual) bit between two real bits (corresponding to strips) [12]. A new bit pattern is then filled following the procedure shown in the examples of Table 2.2. When the number of adjacent fired strips is $N=1$ or $N=2$, the center of the cluster is selected, while for $N \geq 3$ a reduction with a $2N-1$ algorithm is applied. Since the cluster size of 2 is usually due to the passage of a particle between two strips, the described procedure enhances the position resolution of the trigger chambers.

Cluster size	N=1	N=2	N=3	N=4	N=5
Real strip pattern	0 0 1 0 0	0 0 1 1 0	0 1 1 1 0	0 1 1 1 1	1 1 1 1 1
After declustering	0000 1 0000	00000 1 000	0000 1 0000	0000 11 100	00 1111 100

Table 2.2: Examples of declustering for bit pattern with cluster size from $N=1$ to $N=5$.

The bit pattern after declustering is analyzed by the trigger algorithm, in search of the hits associated with the passage of a single particle. A “mini-road” ± 1 strip wide (corresponding to 2 bits after declustering) is opened

between the two planes of the same station. This is needed to account for the particle deflection, since the two planes of a station are placed 17 cm away from each other. If at least one bit per plane is found within a mini-road, the result is called “Double”. Otherwise, the result is a Single. The initial bit pattern is then substituted with the pattern of Singles and Doubles. If both the S and D bits are on, the bit of Singles is reset (DS reduction). In this way it is possible to reduce the effect of the soft-background hits, without compromising the signal detection efficiency. All of these operations are shown in the examples of Table 2.3.

Pattern plane 1	00000 1 000	00000 1 000	000000000	00 1 000 1 0 0	00 1 000000
Pattern plane 2	00000 1 000	000000000	00000 1 000	000000 1 0 0	00000 111 0
Singles	000000 000	00000 S 000	00000 S 000	00 S 00000 0	00 S 00 SSS 0
Doubles	00000 D 000	000000000	000000000	000000 D 00	000000000
DS reduction	00000 D 000	00000 S 000	00000 S 000	000000 D 00	00 S 00 SSS 0

Table 2.3: Examples of conversion of the bit patterns into mini-road Singles and Doubles, and the subsequent DS reduction.

For any Single or Double on MT1, a road is opened with a fixed width of ± 8 strips (± 15 bits after declustering). The triggerability condition is satisfied if hits in at least three out of four chambers are found within the defined road (3/4 condition), namely with the configurations D-D, S-D, or D-S on MT1-MT2. In case of ambiguity, the track with the minimum deviation (corresponding to the higher p_t) is selected among all the valid roads of a local board circuit.

In the non-bending plane each trigger board collects the information of either 8 or 16 strips according to a scheme that depends on the strip pitch and the board width: in general the local boards group 16 strips with a ~ 2 cm pitch and 8 strips with a ~ 4 cm pitch, with few exceptions (see [12] for further details). The 16 strips bit pattern is left untouched while the 8 strips one is doubled. The determination of Singles and Doubles, as well as the DS reduction is then performed as described for the bending plane. It is worth noting that the mini-road and declustering steps are not necessary in this case since the track deflection due to the magnetic field is not effective in the x direction. Finally, the 3/4 coincidence condition can be applied to a road of ± 1 strip. The road is introduced to account for any possible deviation due to multiple scattering in the muon filter or misalignment of the strips. If more than one valid road is found within a local board circuit,

the one with the less significant bit on MT1 is chosen, which corresponds to the the point closer to the beam pipe.

A particle satisfying the 3/4 condition on both bending and non-bending plane is “triggerable”. In order to be triggered it still has to pass the p_t cut. The choice of the maximum deviation of ± 8 strips in the bending plane roughly defines a minimum threshold on the corresponding transverse momentum, but the actual estimation of the p_t is performed through the Look-Up Tables (LUT). The main principle is based on the correspondence between the triplet of x and y position and y deviation, and the track transverse momentum.

The LUT are filled according to GEANT [13] simulations of muon tracks, in which a realistic description of all detectors as well as their segmentation and the field map of the dipole are taken into account.

The trigger electronics can provide two different thresholds, the Low and High- p_t cuts, which can be optimized for the detection of two different resonance families. In this way, it is possible to choose on which of the resonances to trigger, without re-programming each time the corresponding LUT. Cut values of $p_t \simeq 1$, and 2 GeV/ c are selected for the J/ψ and Υ detection, respectively. Lower thresholds are foreseen for the detection of lower mass resonances. It is worth noting that the L0 trigger cut is not sharp: the cut values refer to the transverse momentum magnitudes at which the trigger efficiency reaches the 50%. The effect of the cut can be later improved with a High-Level Trigger.

2.3 The ALICE offline framework: AliRoot

The project for the ALICE offline framework³, AliRoot [14], started in 1998 [15] and has been continuously developed by the offline core team and collaboration members. AliRoot is entirely based on Object Oriented technology (C++) and depends on the ROOT [16] framework, which provides an environment for the development of software package for event generator, detector simulation, event reconstruction and data acquisition and analysis.

The final objectives of the AliRoot framework are:

- the simulation of the primary hadronic collisions and the resulting detector response.

³A framework is a set of software tools that enables data processing.

- the reconstruction of the physics data (raw-data) coming from simulated and real events.
- the (distributed) analysis of reconstructed data.

The AliRoot design was guided by the basic principles of re-usability and modularity, which minimize the amount of user code unused or rewritten and maximize the participation of the physicists in its development. A schematic picture of the framework layout is shown in Figure 2.16: the core of the system is the STEER module, which provides steering, run management, interface classes and base classes. The codes from the different detectors

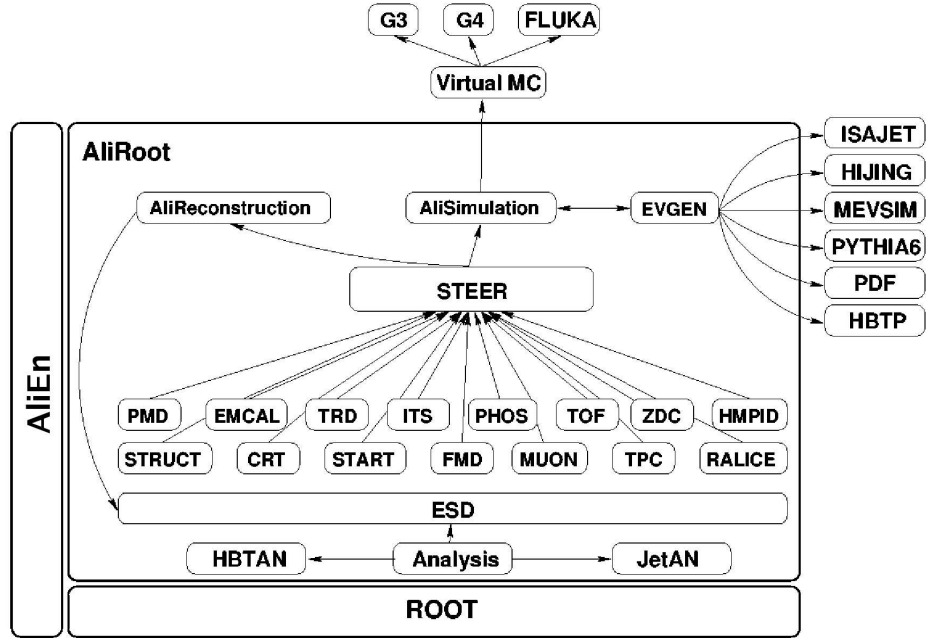


Figure 2.16: Schematic view of the AliRoot framework.

are independent so that different detector groups can work concurrently on the system while minimizing the interference. The use of an Object Oriented programming language, allowing a defined class hierarchy, realizes the modularity structure in a natural way.

The hadronic collision can be simulated with different Monte Carlo event generators, like, for example, PYTHIA [17] and Hijing [18], which are interfaced to the framework in a completely transparent way to the users. The detector response simulation follows the same logic, allowing the user to switch among different transport packages like GEANT3 [19], GEANT4 [20]

and FLUKA [21], without changing the code: only a different shared library has to be loaded.

The role of the framework is shown schematically in Figure 2.17. The left branch of the curve represents the simulation phase: the Monte Carlo truth is degraded to reproduce the detector response. On the contrary, the right branch is the reconstruction phase: the real or simulated data are reconstructed in order to retrieve back the kinematics of the detected particles.

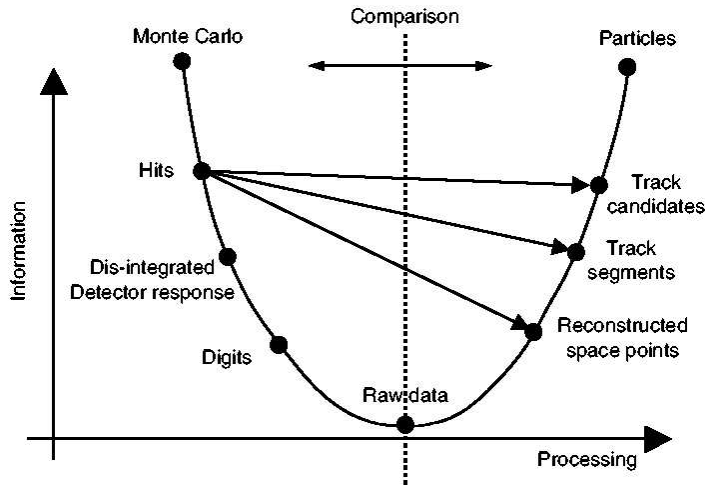


Figure 2.17: Data processing framework.

The primary interactions are simulated via event generators and the resulting kinematic tree is then used in the transport package. The tree contains the produced “particles”, defined through a set of kinematic variables, such as momenta and energies, and keeps track of the production history (in terms of mother-daughters relationship and production vertex). Each particle is then transported into the set of detectors: the point where the energy is deposited together with the amount of such energy constitutes an *hit*. The hits contain also information about the particle that generated them.

At the next step the detector information is taken into account. The hits are “dis-integrated”: the information on the parent track is lost and the spatial position is translated into the corresponding detector readout element (e.g. strips, pads, etc.), thus generating the *digits*. There are two types of digits: the “summable digits”, where zero-thresholds are used and

the results can be summed when different events are superimposed (event merging), and the “digits”, where real thresholds are used and the result is similar to what one would get in a real data taking. The “digits” are eventually converted in raw-data, which are stored in binary format as a “payload”.

The reconstruction chain can then start, allowing the creation of track candidates. The final output is an Event Summary Data (ESD), a root file containing all the output of the reconstruction relevant for physics studies. Metadata information of reconstructed events in the ESD file (like, for instance, the muon multiplicity) are stored in the Tag database of AliRoot: this is important in the analysis since it allows to select only those events of interest for the specific analysis considered, with a fast query to the database. The selection, performed through a train of “analysis tasks”, results in the creation of Analysis Object Data (AOD) files, which contains all the information needed for a specific analysis and can be more easily handled by end users.

Distributed computing and the Grid

With a data acquisition rate of 1.25 GB/s in heavy-ion, about 5 PB/year of data stored on tape and an amount of CPU power equivalent to about 25000 PCs of the year 2003, the ALICE experiment represents a challenge for data storage and processing. The picture is further complicated by the fact that, in an international collaboration, the computing resources and competences are naturally distributed, thus making a centralized solution almost impossible.

The issue was addressed by the High Energy Physics (HEP) community with the so called Monarc model: computing resources are concentrated in a hierarchy of centers called *Tiers*, where Tier-0 is CERN, Tier-1’s are the major computing centers, Tier-2’s the small regional centers, Tier-3’s the university departmental local clusters or the user’s workstations (see Figure 2.18). In such model the raw-data are stored at CERN, where a Tier-1 center for each experiment is hosted. Tier-1 centers not at CERN collectively store a large portion of the raw-data, possibly all, providing a natural backup. All Tier-1’s share the reconstruction task, while subsequent data reduction, analysis and Monte Carlo production are a collective operation

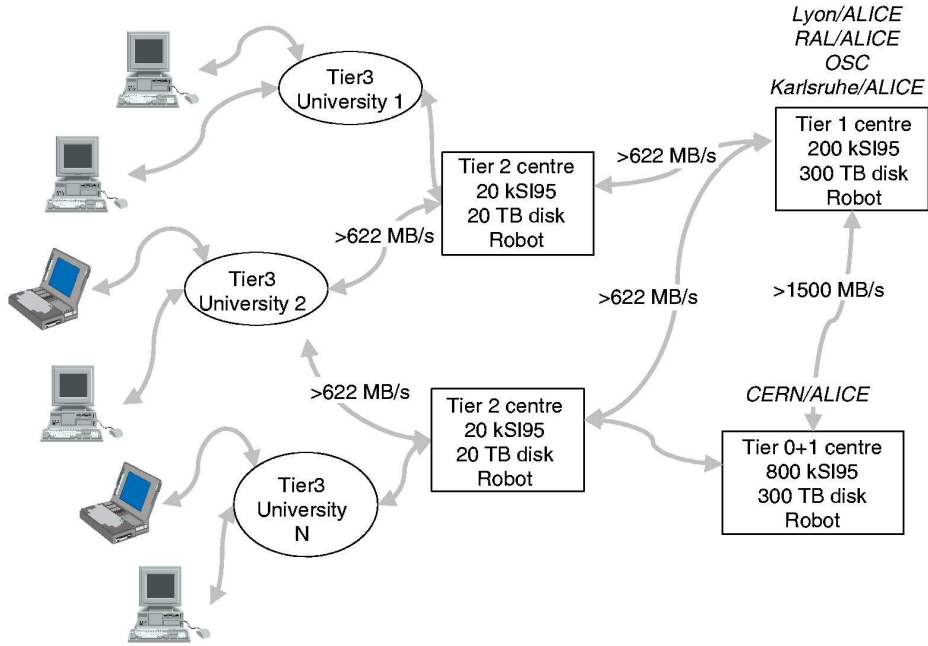


Figure 2.18: The Tiers structure.

where all Tiers participate, with Tier-2's being particularly active for Monte Carlo and analysis.

The basic principle of the model is that every physicist should have in principle equal access to the data and resources. The resulting system, of extreme complexity, was developed in the Grid project [22].

In order to provide a transparent access to the Grid resources distributed worldwide, the ALICE ENvironment (AliEn) [23] framework was developed. AliEn provides a functional computing environment that fulfills the needs of the experiment in the preparation phase and defines stable interface to the end users, shielding the ALICE core software from the inevitable changes in the technology that makes distributed computing possible. In the AliEn framework, a central service manages all the tasks, while computing elements are defined as “remote queues”. Input and output associated with any job can be registered in the AliEn file catalogue, a virtual file system in which a virtual file name is associated to a file. The catalogue allows to put in relation the Logical File Name with the Physical File Names on real storage systems, providing the full path to the storage element in which the local file is placed.

In a typical analysis process, a subset of the datasets from the virtual file catalogue can be extracted using metadata conditions provided by the user. Then the tasks are automatically split according to the location of datasets, after a trade-off between best use of available resources and minimal data movements. At the end of the task execution, the output files are then moved to a storage element and registered to the file catalogue, thus made available to the user.

During the last few years the whole system underwent extensive tests, with more and more end users getting involved in the analysis of both Monte Carlo grid production and real data. Today AliEn and the Grid are well established realities, allowing to cope with the LHC data challenge.

Chapter 3

Muon Spectrometer trigger chamber performance

3.1 Misalignment effects

The trigger algorithm, presented in Section 2.2.4, relies on the determination of the deflection (due to the magnetic field) of a track with respect to the trajectory of a particle with an infinite momentum. By construction, an infinite momentum muon from the interaction vertex would fire the strip with the same ID number in all trigger chamber planes: any deviation, measured in strips, is therefore related with the (transverse) momentum and sign of the particle. The correspondence between deflection and p_t has been determined through simulations and tabulated in the Look-Up Tables, which are read during the trigger decision phase.

From this picture, it is clear that any misalignment of the detection elements would spoil the projective geometry of the system, resulting in a systematic error in the determination of the particle p_t and, consequently, on the efficiency of the trigger selection. Due to the relatively large pitch of the strips (from about 1 cm to about 4 cm), the effects of misalignment is not as critical as in the tracking chambers. However it is important to understand what are its effects on trigger efficiency and what is the maximum error on alignment that can be tolerated during installation.

3.1.1 Simulation results

The effects of trigger chamber misalignment on quarkonia detection efficiency have been studied. J/ψ and Υ are generated from parameterizations of rapidity and transverse momentum distributions. The former is provided by the Color Evaporation Model [1], while the latter is obtained by rescaling the quarkonia p_t distributions measured by the CDF experiment, as explained in [2]. Quarkonia are then forced to decay into muon pairs, which are reconstructed. The resonance is “triggerable” if each muon of the pair fires at least three chambers out of four; it is “triggered” if it satisfies the requirements of the trigger algorithm which searches for at least one unlike-sign pair of tracks above the p_t threshold. The efficiency is then given by the ratio triggered/triggerable. In the simulations, the trigger chambers are assumed to be fully efficient, with a cluster-size of 1. The latter condition represents a conservative approach: misalignment effects are expected to be reduced with a bigger cluster-size.

Due to the intrinsic features of the trigger algorithm, the misalignment of a chamber plane within a station or the misalignment of one entire station relative to the other may have different effects on the measured efficiency. For the same reason, also the direction along which the misplacement occurs could be important. The aim of the present study is to provide a detailed understanding of such effects, thus individuating the most critical ones.

The first case analyzed is the impact on efficiency obtained by moving one plane of chambers within a station. In particular, MT12 was shifted along the x -axis (i.e. non-bending direction), as shown in Figure 3.1. The

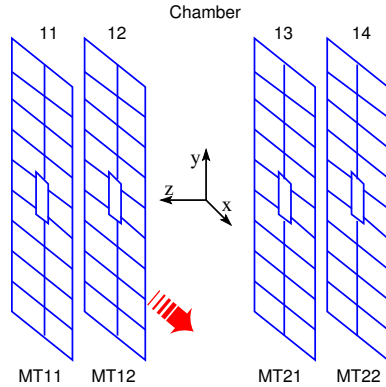


Figure 3.1: Chamber plane MT12 moved along the non-bending direction x .

entire plane was shifted by 20 mm, with steps of 1 mm. Figure 3.2 shows the trigger efficiency as a function of misalignment for J/ψ and Υ . The yellow band represents a variation of $\pm 1\%$ around the efficiency obtained with a perfect alignment.

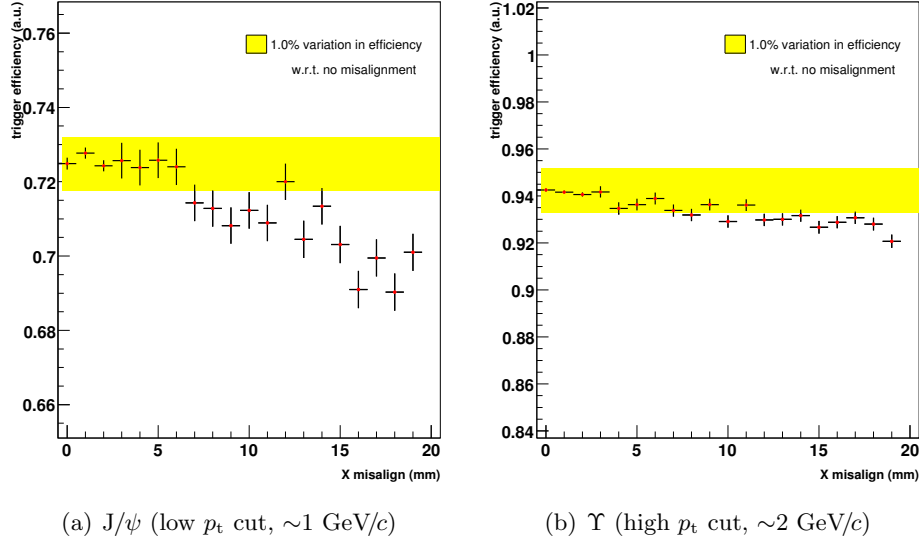


Figure 3.2: Trigger efficiency as a function of the misalignment of chamber MT12 along the non-bending direction x .

The reduction of efficiency with chamber misalignment, can be explained by taking into account the trigger algorithm working principle. As explained in Section 2.2.4, the algorithm searches for fired strips in mini-roads of defined width opened between the two planes of each station¹. The positive match is called Double, while the negative is a Single. The occurrence of a trigger requires the presence of a fired strip within the opened road in at least three chamber planes out of four, which is equivalent of requiring a Double in one station and a Single in the other (D-S and S-D) or a Double in both stations (D-D).

The misalignment of a chamber spoils the projective geometry of the detector: a straight line from the interaction point could indeed cross strips with a different number inside the different chamber planes. This would

¹In fact the algorithm is applied to the virtual bit-pattern, which is built out of the real fired strips after the declustering process. However, for the following considerations concerning chamber misalignment, it is more intuitive to identify the bit-pattern with the real strip position rather than with the result of the doubling of bits: the simplification does not affect the validity of the conclusions.

lead to a modification of the strip pattern. The behavior is summarized in the example of Table 3.1. The bit pattern of a hypothetical track from the

	Example 1		Example 2	
Misalignment	No	Yes	No	Yes
Strip pattern MT11	0 0 1 0 0	0 0 1 0 0	0 0 1 0 0	0 0 1 0 0
Strip pattern MT12	0 0 1 0 0	0 0 0 1 0	0 0 1 0 0	0 0 0 1 0
MT1	D	S S	D	S S
MT2	D	D	S	S
Triggered	Yes (4/4)	Yes (3/4)	Yes (3/4)	No

Table 3.1: Example of strip pattern modification due to the misalignment of MT12 plane along x . The modification leads to an incorrect response of the trigger algorithm and to a consequent loss in efficiency.

interaction point is considered: if chambers are aligned the bit pattern in MT11 and MT12 is the same, otherwise it can change. In the former case, the algorithm correctly identifies the configuration as a Double, while in the latter it finds two Singles. If a Double is found also in MT2 (example 1), the track satisfies the triggerability condition in both cases, but in case of a Single on MT2 (example 2) the track, which would be triggered with a correct alignment, is lost. The efficiency loss is expected to increase with the amount of misalignment, as it is observed in the simulations (Figure 3.2).

The second case considered is the misalignment of MT12 along the y direction, as sketched in Figure 3.3. The simulation inputs and methods, as

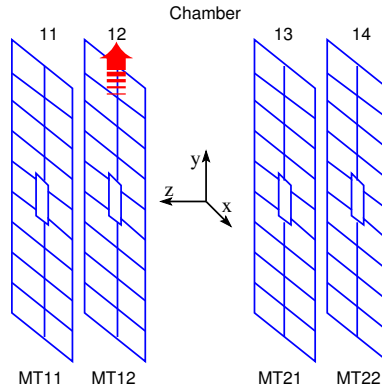


Figure 3.3: Chamber plane MT12 moved along the bending direction y .

well as the efficiency determination are the same explained before, but the results show significant changes. In particular, while increasing the shift of

the chamber along y , the measured trigger efficiency is first enhanced ($5 \lesssim \Delta y \lesssim 12$ mm), and only later suppressed ($\Delta y \gtrsim 12$ mm), as clearly visible in Figure 3.4. The changes are due to the different ways in which the trigger

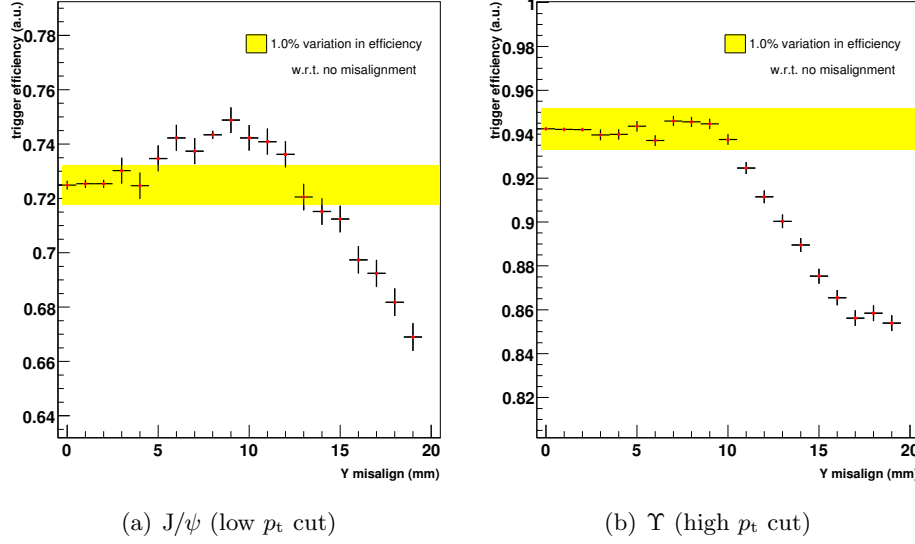


Figure 3.4: Trigger efficiency as a function of the misalignment of chamber MT12 along the bending direction y .

algorithm handles the non-bending (x) and the bending (y) direction. On the one hand, the ± 1 strip mini-road which is opened (only in the bending plane) between the two chambers planes inside each station, reduces the effects of efficiency loss due to the mechanism described in Table 3.1. On the other hand, the measurement of the muon p_t thorough the track deflection between stations MT1 and MT2 introduces variations in the efficiency which do not have an analogous in the misalignment along x , such as the efficiency enhancement. Indeed the effect disappears when the p_t cut is not taken into account as shown in Figure 3.5. When a bit pattern of a track is not seen as a Double but as two Singles, the trigger algorithm opens two different roads between stations, corresponding to two (hypothetical) distinct particles. If both match a Double in the second station, the one with the highest p_t is chosen (see Table 3.2). This leads to a systematic overestimation of the track transverse momentum. The consequence is that, particles that should fail the p_t cut are instead accepted, thus increasing the trigger efficiency. The enhancement applies to low p_t muons which bend in the direction opposite to the chamber shift: with the magnetic field directed as in Figure 2.15, if

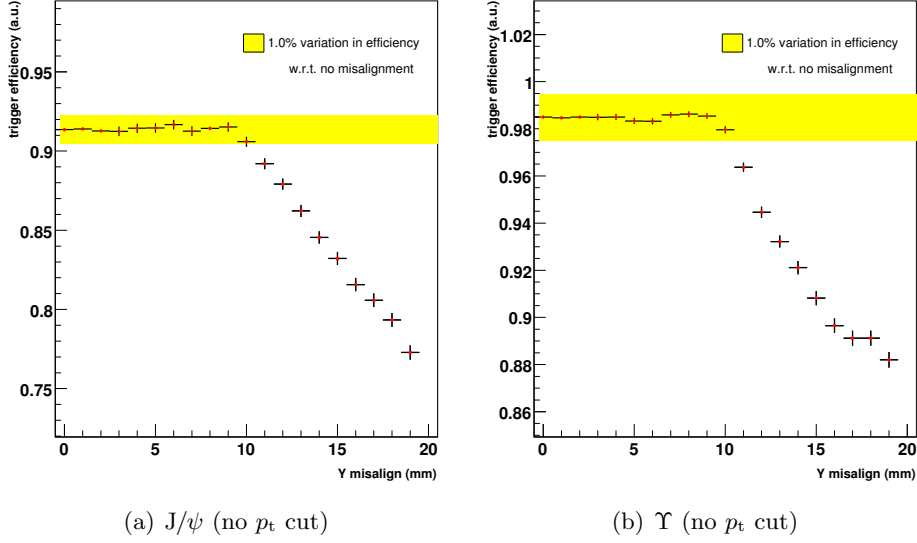


Figure 3.5: Trigger efficiency as a function of the misalignment of chamber MT12 along y : no p_t cut is performed.

	Example 1		Example 2	
Misalignment	No	Yes	No	Yes
Strip pattern MT11	0 1 0 0 0	0 1 0 0 0	0 1 0 0 0	0 1 0 0 0
Strip pattern MT12	0 0 1 0 0	0 0 0 1 0	0 0 1 0 0	0 0 0 1 0
MT1	D	S S	D	S S
MT2	D	D	D	D

Table 3.2: Example of strip pattern modification due to the misalignment of one plane along y . The modification introduces systematics in the determination of the track transverse momentum. The solid line represent the chosen road (providing the highest p_t) while the dotted line represent the real one (shown when the roads do not coincide).

$\Delta y > 0$ ($\Delta y < 0$) it affects μ^- (μ^+). The statement is demonstrated in Figure 3.6, showing the ratio between the trigger efficiency for single-muons measured with MT12 shifted by 8 mm and the one without misalignment, as a function of the track p_t .

The efficiency loss observed at high values of misalignment is related with the muon sign mis-identification. The trigger system is designed in such a way that an infinite momentum particle crosses the strips with the same ID number in all chambers. Finite momentum muons undergo a deflection from this straight line: the amount in strips of the deviation can be related

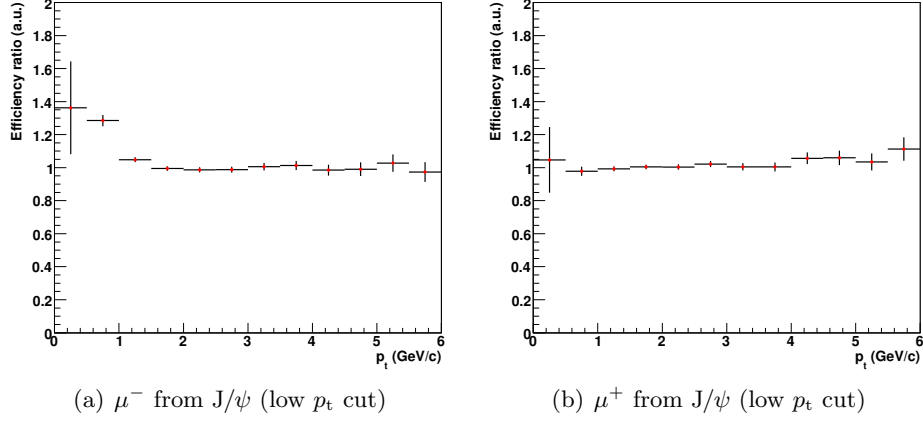


Figure 3.6: Ratio between trigger efficiency measured with MT12 shifted by 8 mm along y and the value measured without misalignment as a function of the muon p_t .

to the particle p_t , while its direction allows to identify the muon sign. If the chamber misalignment is significant, it can happen that the (small) positive deviation of high momentum particles becomes a negative one, with a consequent mis-identification of the sign of the particle. If the muon comes from a resonance, the unlike-sign muon pair is wrongly considered as a like-sign one, and rejected by the trigger, as shown in Figure 3.7.

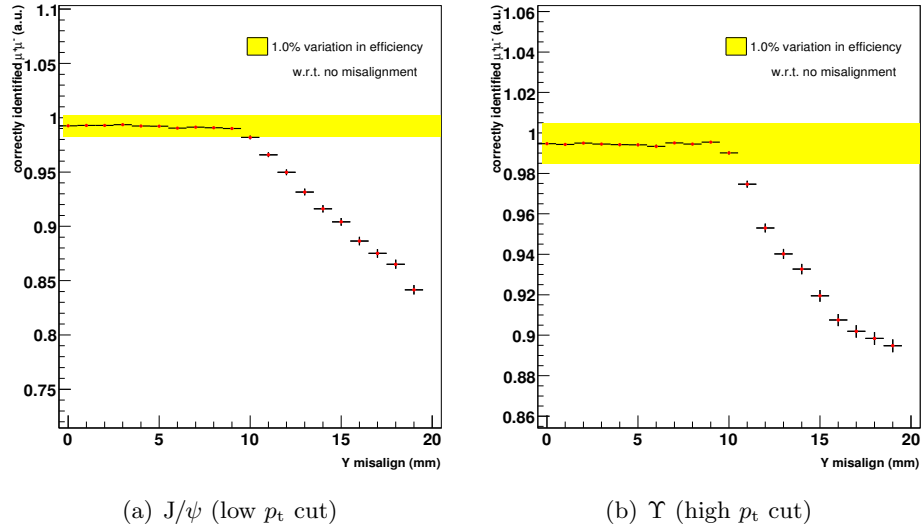


Figure 3.7: Probability of correctly identifying the $\mu^+\mu^-$ as an unlike-sign muon pair, as a function of the misalignment of chamber MT12 along y .

The third case considered is the misalignment of one entire station along x (see Figure 3.8). Similarly with what obtained when moving only one

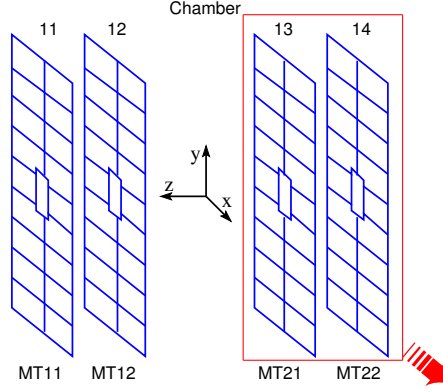


Figure 3.8: Station MT2 moved along x .

plane inside a station, the result is an efficiency loss increasing with the MT2 shift (Figure 3.9), and it is related to the ± 1 strip road opened between the stations (Table 3.3).

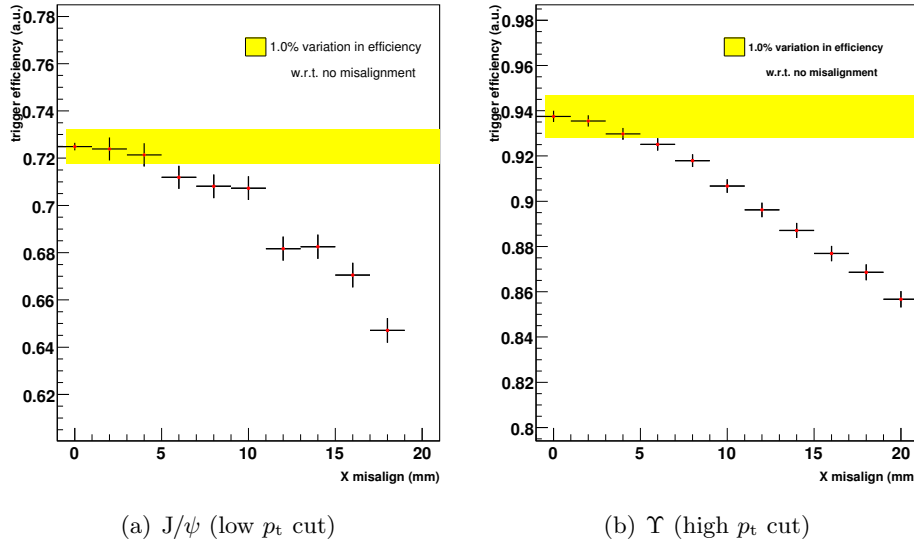


Figure 3.9: Trigger efficiency as a function of the misalignment of station MT2 along x .

The analogous study in the bending direction (see Figure 3.10) leads to the results shown in Figure 3.11. In this case, the road opened between the stations is wide enough (± 8 strips) to avoid the effects described in

	Example 1				Example 2			
Misalignment	No		Yes		No		Yes	
MT1	0	D	0	0	0	S	0	0
MT2	0	0	D	0	0	0	D	0
Triggered	Yes (4/4)		No		Yes (3/4)		No	

Table 3.3: Example of strip pattern modification due to the misalignment of one station along x . The modification leads to an incorrect response of the trigger algorithm and to a consequent loss in efficiency.

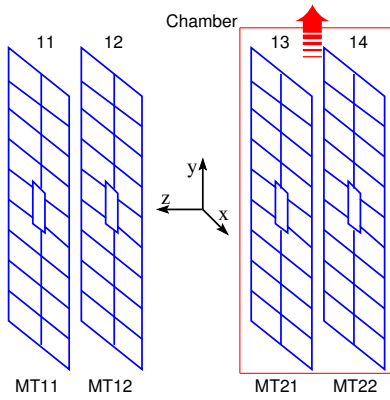


Figure 3.10: Station MT2 moved along y .

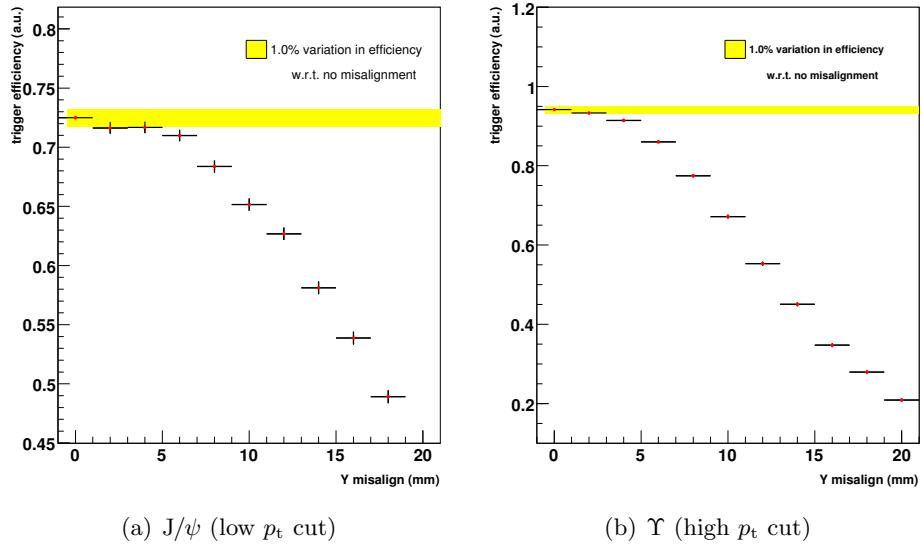


Figure 3.11: Trigger efficiency as a function of the misalignment of station MT2 along y .

Table 3.3. The efficiency loss for big shifts of the stations are related with the mis-identification of the particle sign, in the same way previously described for the misalignment of chamber MT12.

Finally, the combined misalignment of MT12 and MT22 is taken into account (Figure 3.12). Figure 3.13 refers to shifts along the y direction: it

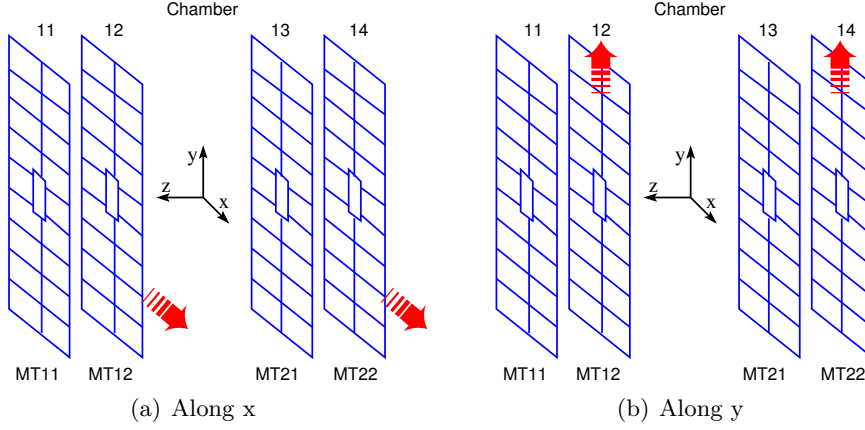


Figure 3.12: Combined shift of chamber plane MT12 and MT21.

shows the J/ψ (left panels) and Υ (right panels) trigger efficiency as a function of the MT22 shift when MT12 is misaligned by 1 mm (top panels) and 3 mm (bottom panels). The presence in the trigger algorithm of mini-roads between the chambers inside a station reduces the effects of misalignment: shifts up to few millimeters on chamber planes do not provide any substantial modification on trigger efficiency.

The analogous study in the non-bending direction is shown in Figure 3.14. In this case, despite the larger strip pitch, the effect of chamber misalignment on trigger efficiency is more important. This is due to the features of the trigger algorithm, and, in particular, to the fact that, differently from the bending-plane, in the non-bending plane no mini-road is opened between the chambers of the same station. Simulation results suggest that, in order to limit efficiency loss, the shift with respect to the nominal position should be lower than about 2 mm.

During the installation of the trigger chambers, a small variation of the z position of some RPCs with respect to the nominal one was applied for practical reasons. The geometrical configuration of the trigger system, ac-

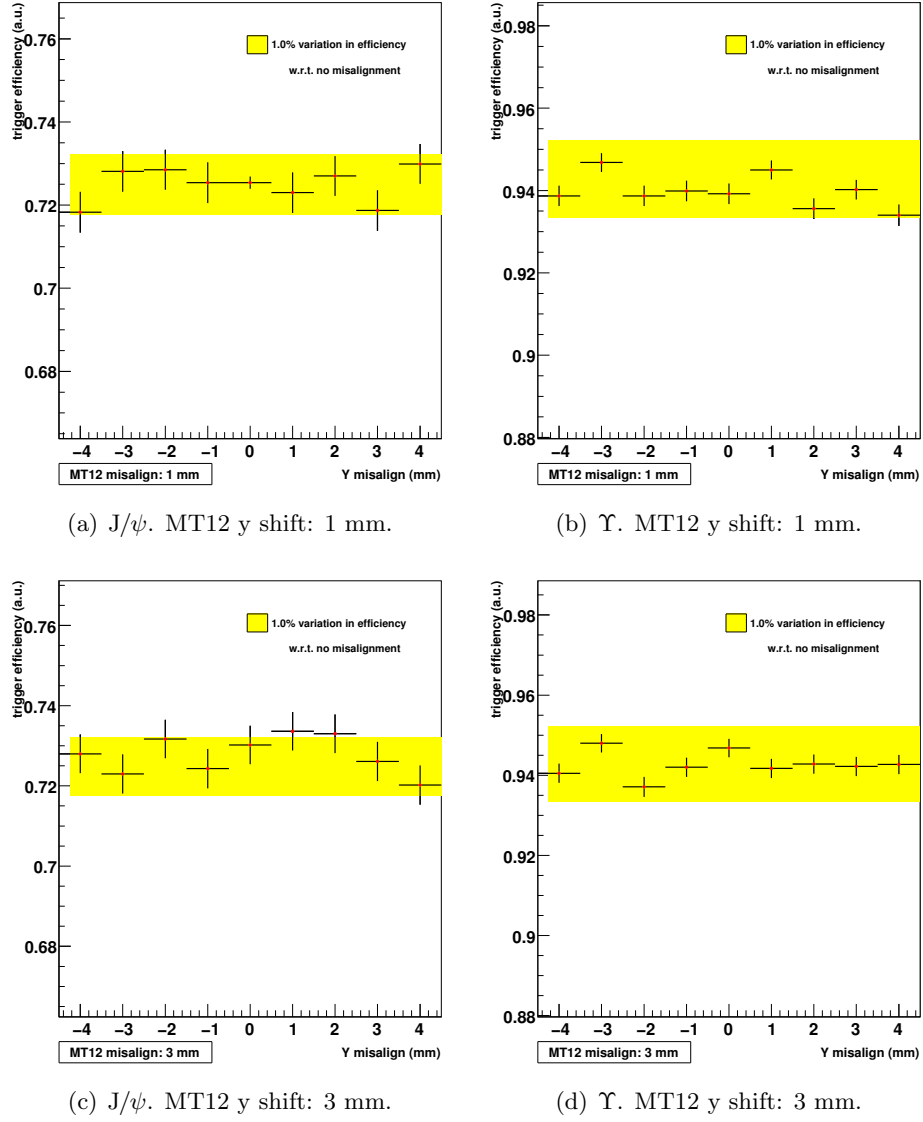


Figure 3.13: Trigger efficiency for J/ψ and Υ as a function of the misalignment of chamber MT22 along y , with two different misalignments for MT12.

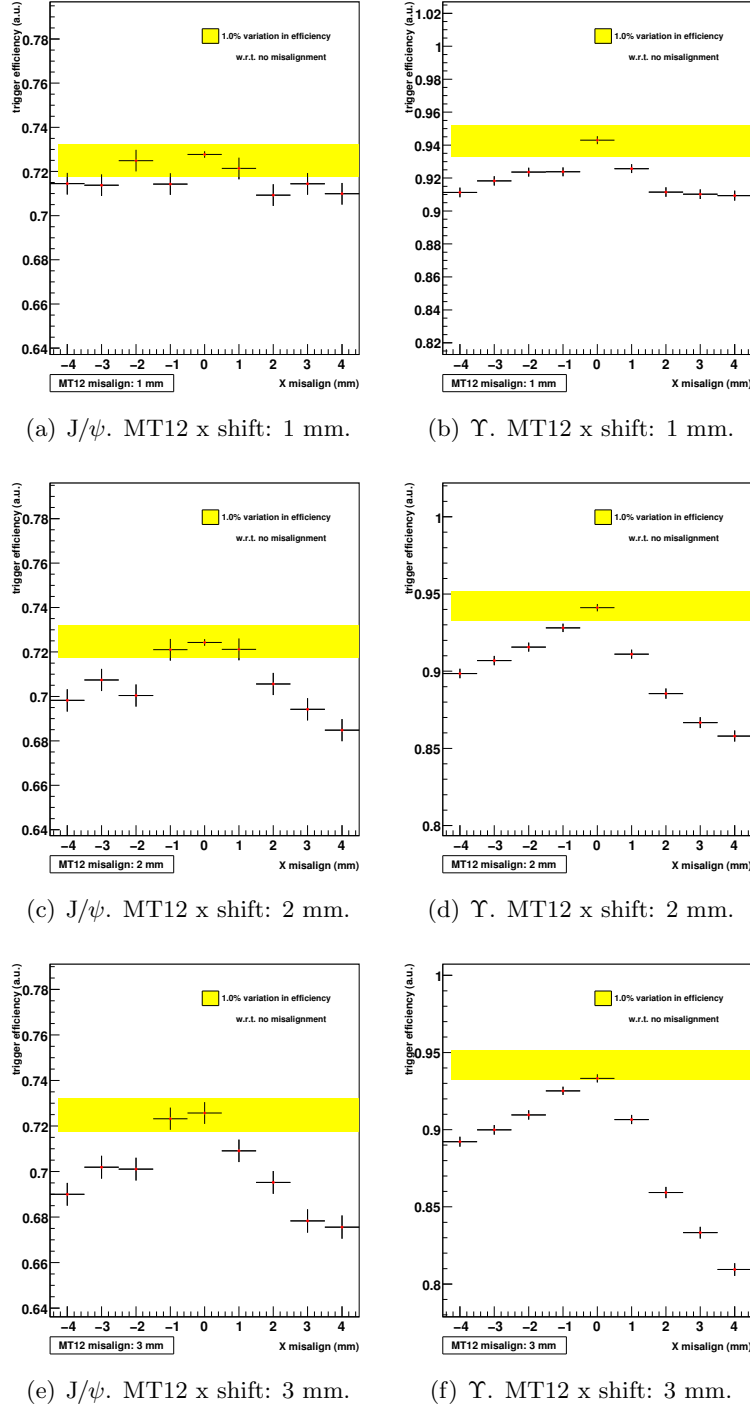


Figure 3.14: Trigger efficiency for J/ψ and Υ as a function of the misalignment of chamber MT22 along x , with three different misalignments for MT12.

cepting tracks at small polar angles, considerably reduces the effects due to the misalignment of the chambers along the beam pipe direction compared with the ones in the transverse plane. However further simulations were performed to determine any effects on the trigger efficiency.

The RPCs are placed alternatively on one side or the other of the support structure, at about 3.6 cm from the mean plane, as clearly shown in Figure 3.15. In the region where the RPCs on different sides superimpose



Figure 3.15: Detail of the trigger chambers installation: RPCs are placed in an alternated sequence on both sides of the supports. The red arrows show how the RPCs facing the center of the stations are moved (of about 1 cm) to better fit the electronics. For simplicity, the arrows are plotted only for MT1 but analogous considerations apply to the station MT2, shown in the “open” configuration on the left.

in the $x - y$ plane, the space for the electronics is small, resulting in a possible partial contact with the RPC on the opposite side of the structure. To

avoid any problems, the chambers facing the inner side of each station, i.e. the ones closer to the iron wall in MT12 and MT22 and the further in MT11 and MT21, were moved away from the support by an additional 1 cm, as indicated by the red arrows (Figure 3.15). Figure 3.16 shows the trigger efficiency for J/ψ and Υ detection in case of nominal position (configuration 0) and of misaligned RPCs: in both cases the efficiency variation is within errors.

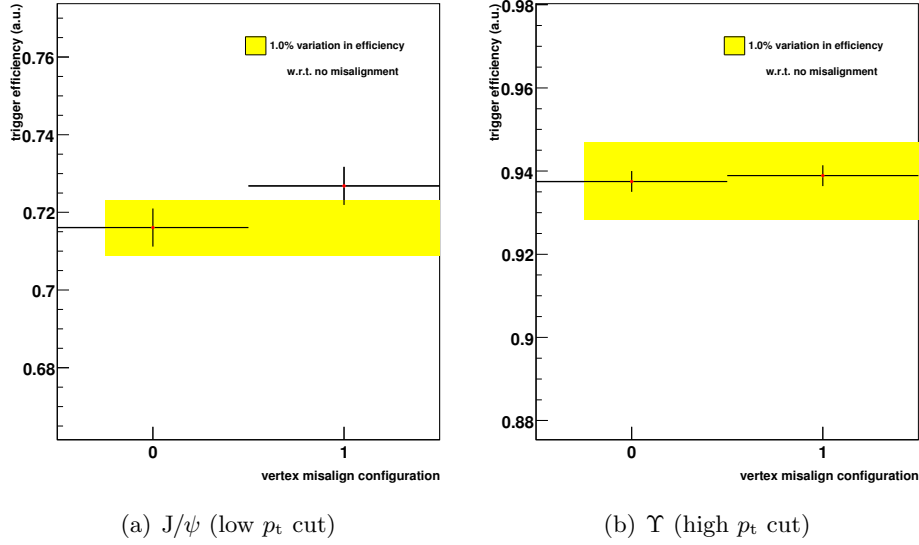


Figure 3.16: Trigger efficiency as a function of the misalignment of chamber MT12 along z . Configuration 0 refer to no misalignment while configuration 1 is obtained by shifting of 1 cm the RPCs facing the inner part of the station, as explained in the text.

3.1.2 Latest news from geometrical survey

The positioning of the trigger chambers is performed through measurements with theodolite and photogrammetry of targets placed at the corners of each RPC (Figure 3.17).

From the point of view of the support elements, the trigger system consists of eight half-planes, accommodating nine Resistive Plate Chambers each. The structures can slide along the x direction, so that each half-plane can be moved away from the beam pipe. This configuration is called “open position”, while the configuration for normal operations of the detector is called “closed position”, as shown in Figure 3.18. The position measurement

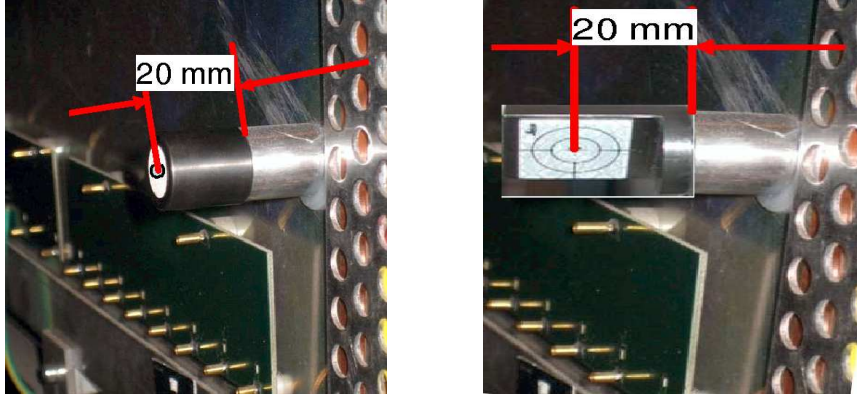


Figure 3.17: Target equipment for photogrammetry (left) and theodolite (right) measurements.

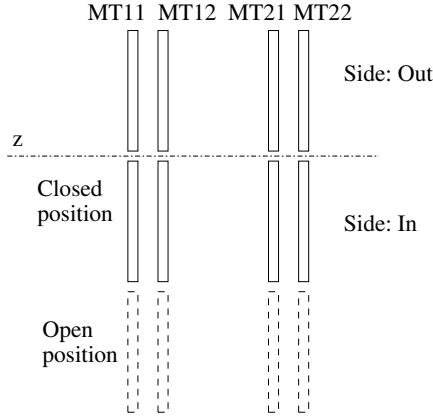


Figure 3.18: Open position and Closed position of trigger chamber half-planes.

can be summarized in the following steps:

- measurement by theodolite in closed position: the absolute position in the ALICE coordinate system of the visible external targets is provided.
- measurement by photogrammetry in open position: the relative position of targets in an arbitrarily defined coordinate system is defined.
- measurement by theodolite in open position.

The coordinates measured by photogrammetry can be best-fit transformed in the ALICE coordinate system by using common points measured by

theodolite. The measurements of common points by theodolite in open and closed position can then be used to transform the photogrammetry measurements in both positions. It is worth noting that the global precision in x , y and z directions of the ALICE coordinate system is 1 mm at 1 sigma level [3]. Further errors can arise from the mechanical positioning of the targets (see Figure 3.17), which can be estimated in about 1 mm. Hence, the precision of the whole position measurement method is expected to be of the order of 1.5 – 2 mm.

The measurement of the trigger chamber x and y position was completed only recently, in late September [4]. The distribution of the difference between the measured positions of the targets and their nominal value in all chamber planes is shown in Figure 3.19. The presence of large tails in the dis-

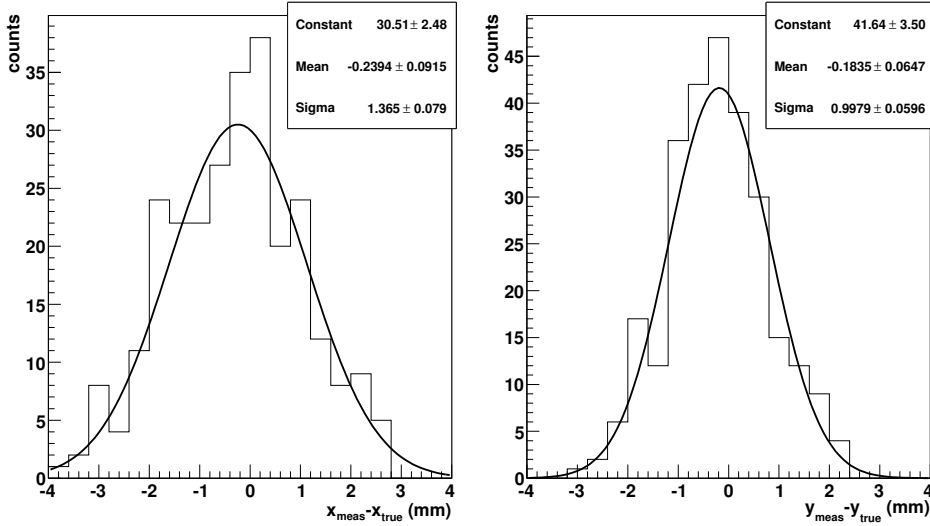


Figure 3.19: Distribution of the measured trigger chamber position with respect to the nominal one along x (left panel) and y (right panel).

tribution is given by targets with sensitive mechanical misplacement, which can be excluded in the determination of the chamber position. A Gaussian fit of the distribution provide a width of about 1 mm in y and about 1.4 mm in x .

These values can be compared with the results of Figure 3.14 and Figure 3.13. The comparison shows that the amount of chamber misplacement along y does not sensitively reduce the trigger efficiency, while the misalignment along x could slightly affect the efficiency for Υ . It is worth

noting that the simulation results provide a somehow pessimistic estimation of the misalignment effect, since this affects all the RPCs in one plane, without allowing the possibility of partial compensation among some chambers. Hence, a more realistic simulation based on the measured data points was performed. Differently from the previous cases, the x and y position of each RPC is shifted independently of a quantity sampled by the distributions of Figure 3.19. The result is shown in Figure 3.20: the trigger efficiency in case of nominal position (configuration 0) and of misaligned RPCs (configuration 1) is provided. The variation in the efficiency introduced by misalignment is limited: within 1% for the J/ψ and 2% for Υ .

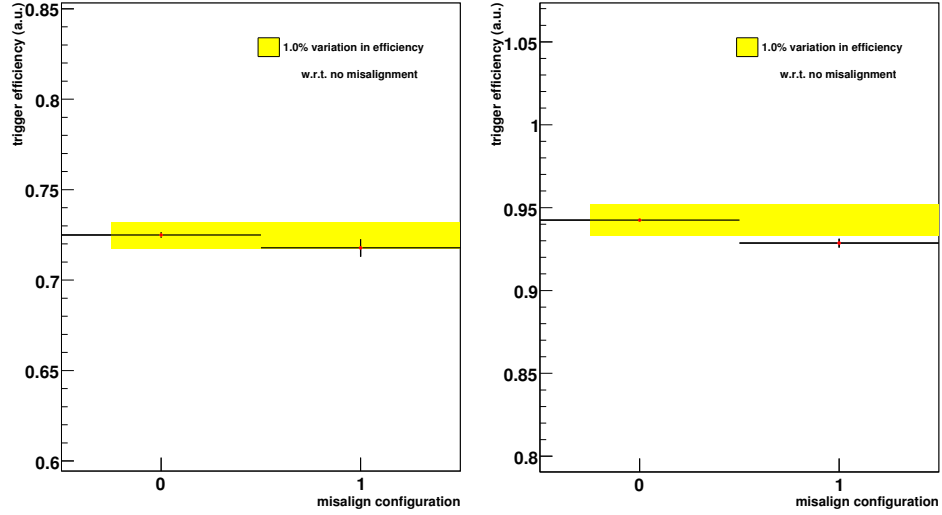


Figure 3.20: Trigger efficiency for J/ψ (left panel) and Υ (right panel) with a realistic chamber misalignment from data. The configuration 0 refers to results with no misalignment, while the configuration 1 refers to the results obtained when the position of each RPC is shifted from the nominal value by a quantity sampled by the measured distributions of Figure 3.19.

3.2 Efficiency evaluation

A detailed knowledge of the detector features is a central point in an experiment. The determination of physical quantities, such as the inclusive or differential cross sections, requires acceptance and efficiency corrections to measured data, which have to be properly determined, either by simulations or direct measurements.

The efficiency of each detection element is usually measured during the commissioning phase, before the final installation “in situ”. However, for detectors designed to work for a period of some years, the possibility that the initial efficiency can undergo some variations with time has to be taken into account: it is therefore important to develop methods and tools allowing to monitor the detector status during the experiment life-time. This acquires a particular importance at the beginning of data taking, since it can be a powerful tool to check the correct functionality of the hardware.

The ALICE Muon Spectrometer will provide a level 0 trigger for heavy quark and quarkonia measurements in the forward region. The spectrometer response function can be calculated through simulations, provided the efficiency map of the Resistive Plate Chambers of which it is constituted. The nominal efficiency of each RPC was measured and proved to be above 95% [5], but since the detector has to work for about 10 years in a high radiation environment, it is important to monitor any possible modification with respect to the nominal value. Moreover, due to the large area covered by each chamber, the possible variation in efficiency might be not homogeneous, so the maps should be measured with the highest granularity achievable.

3.2.1 Method description

The signal on RPCs is collected by strips positioned on both sides, read out by the Front-End Electronics (FEE). Strips on the so called “bending plane” lie horizontally and provide information on the position of the crossing particle in the direction along which muons are bent due to the dipole magnetic field. Analogously, strips on the “non-bending plane” lie vertically and provide information on the position along the direction orthogonal to the one previously described. The trigger algorithm searches, separately in the bending and non-bending plane, for fired strips which lie within a region

of defined width (see [6] for further details): a particle is “triggerable” if it fires the strips in at least three out of four chambers in both planes.

If the triggerability condition is satisfied, a track can be defined out of the trigger response. Given a sample of N_{tot} particles, the number of reconstructed tracks firing all the chambers is:

$$N_{4/4} = N_{tot} \prod_{11 \leq i \leq 14} \varepsilon_i$$

where the chambers are conventionally numbered from 11 to 14 in order to distinguish them from the 10 tracking chambers.

Analogously, the number of muons that would be triggered even if the information of the chamber ch is not taken into account is:

$$N_{3/3}^{ch} = N_{tot} \prod_{\substack{11 \leq i \leq 14 \\ i \neq ch}} \varepsilon_i$$

Hence, the efficiency of the chamber ch can be calculated as:

$$\varepsilon_{ch} = \frac{N_{4/4}}{N_{3/3}^{ch}} \quad (3.1)$$

It is worth noting that the efficiency can be calculated separately for the bending and non-bending plane, since the 3/4 condition has to be satisfied by both independently.

The algorithm for the chamber efficiency measurement, analyzes the reconstructed tracks searching for the presence of the associated fired strips in all chambers: in this way it is possible to determine $N_{4/4}$ and $N_{3/3}^{ch}$, and hence the chamber efficiency according to Eq. 3.1. The procedure can be summarized as:

- determination of the intersection point between the reconstructed trigger track and the trigger chamber.
- identification of the strip corresponding to that point according to the chamber plane geometry and segmentation.
- search for a fired strip in the region of ± 1 strip around the intersected one. If the strip pitch is smaller than 2 cm, which happens only for

the strips in the bending plane closest to the beam pipe, the region is set to ± 2 cm.

It is worth noting that the track reconstruction in the trigger chambers is not as accurate as the one in the tracker. The choice of the maximum value between the dimension of 1 strip and 2 cm, was introduced in order to account for any residual between the reconstructed impact point and the real one. The default value can be changed at the beginning of the reconstruction (see Section 3.2.3 for further details).

In some cases the muons can interact with the iron wall, giving rise to a shower of particles, resulting in many strips fired in a restricted region. Under these circumstances the reconstructed track may be biased and the probability of mismatch between the track and the corresponding fired strips increases. These difficulties can be overcome by requiring that the track entering the algorithm:

- matches a reconstructed track in the tracker;
- crosses the trigger chambers in a region with at most 2 fired strips in an area of ± 3 strips around the intersection point.

Again, the definition of the searching area is fully customizable (Section 3.2.3).

This simple method can be applied to all available data, with no need of dedicated runs. In this way the chamber efficiency can be constantly monitored with high statistics.

Without any further constraint, the calculated efficiency is an average over the efficiencies of all RPCs belonging to chamber ch . However, the projective geometry of the Muon Spectrometer allows to determine the efficiency for each RPC. It is enough to apply the explained method to a sub-sample of tracks that cross the RPCs placed at the same position in each chamber. The final result is a set of 18 $N_{4/4}$ and $N_{3/3}^{ch}$ values, whose ratio gives the efficiency for each RPC, ε_{ch}^{RPC} .

The developed method was tested on simulated events. A realistic description of the cluster size distribution is included in all simulations. A random efficiency value, ranging from 70%² to 95%, is assigned to the bending and non-bending plane of each RPC. Single muons are then generated

²It is worth noting that efficiency values down to 70% are not realistic: the values were chosen in order to test the validity of the algorithm in a wide efficiency region.

according to a flat distribution in polar angle and momentum and the detector response is evaluated. The algorithm is applied during the standard reconstruction. The calculated efficiency of the different RPCs of each plane and the corresponding input value are shown in Figure 3.21 and Figure 3.22 for the bending and non-bending plane, respectively. The error on the reconstructed efficiency is statistical and is derived from the number of successes, which follows a binomial distribution. The total number of triggerable muon tracks providing such results is around 5.2×10^5 .

The dispersion of the reconstructed efficiencies around the input values is shown in Figure 3.23 and fitted with a Gaussian. The mean value of such Gaussian gives an estimate of the systematic errors involved. In both planes the systematic error on the trigger chamber efficiency is a fraction of percent.

The efficiency determination can be repeated for the smallest part of the detector entering the trigger algorithm: the trigger local boards. The method adopted is the same used to determine the efficiency for each RPC: since local boards are disposed in a projective geometry it is possible to calculate the ratio $N_{4/4}/N_{3/3}^{ch}$ for the sub-sample of tracks crossing the boards placed at the same position in all chambers. In this way it is possible to measure up to 234 efficiency points for both bending and non-bending planes in each chamber. Moreover, due to the detector segmentation (see Figure 2.14), the number of measured points is higher in the region closer to the beam pipe. The results of simulations are shown in Figure 3.24 and Figure 3.25, for the bending and non-bending plane, respectively. The dispersion of the reconstructed efficiency around the input efficiency is shown in Figure 3.26. For a better understanding of the method accuracy, the difference between the reconstructed and input efficiency divided by the statistical error of each measure is shown in Figure 3.27.

In order to get a 1% statistical error on each local board, assuming a nominal efficiency of 95% and a uniform hit distribution on chambers, around 500 tracks are needed per local board, which means a total number of $500 \times 234 \sim 1.2 \times 10^5$ tracks. Such statistics will be collected in few minutes of p-p data taking at the nominal luminosity of $3 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, with an expected single muon trigger rate of about 1.8 kHz (see [7]). It is worth noting that the value provided is meant to be a mere guideline, since the board occupancy changes with the distance from the beam pipe. Although

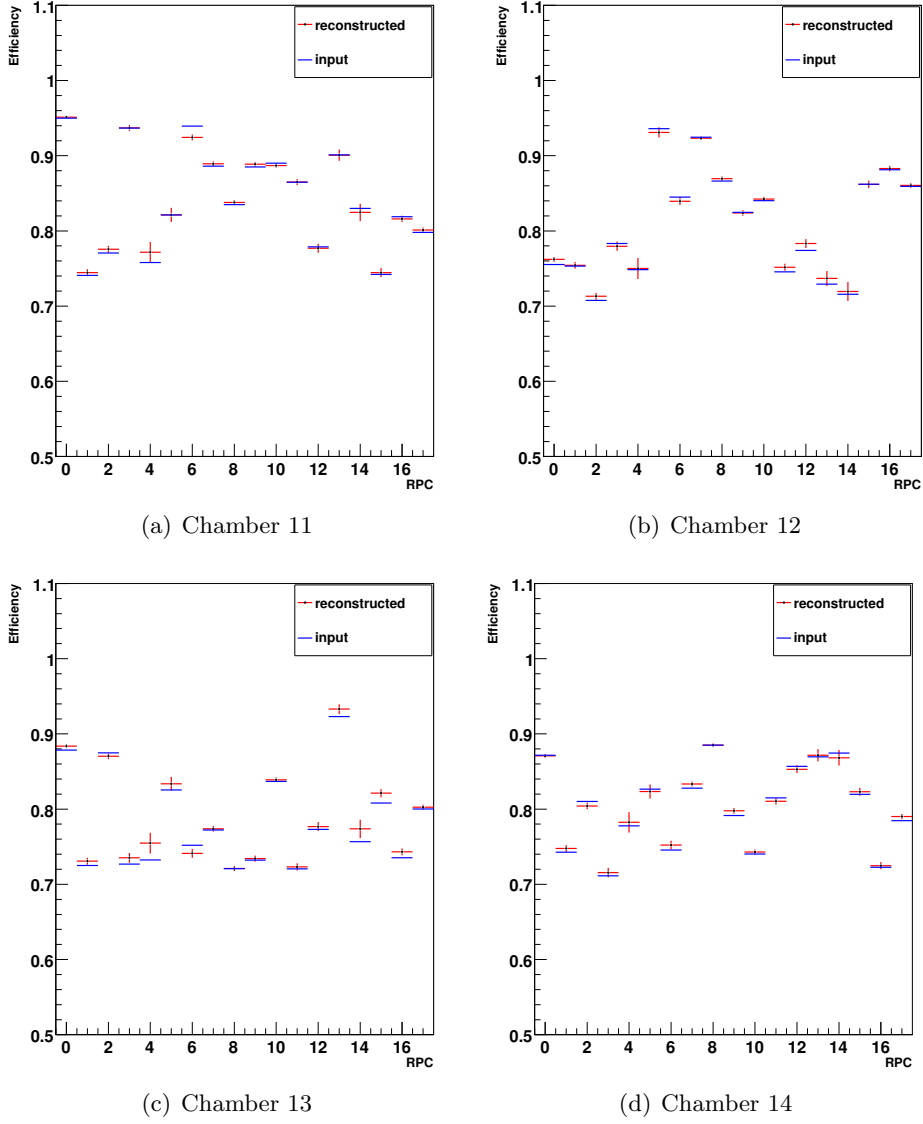
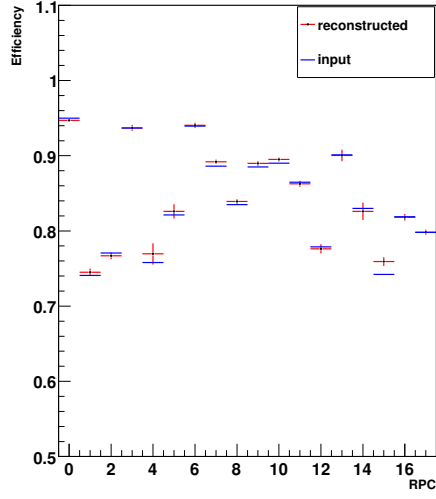
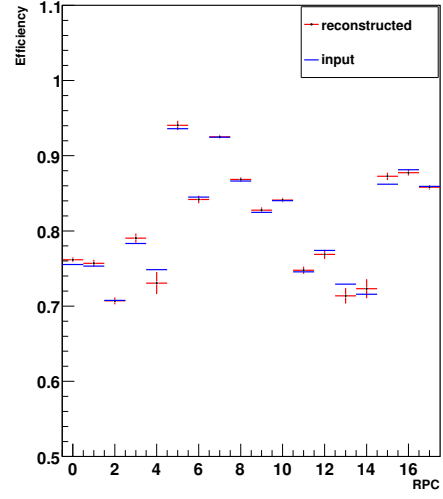


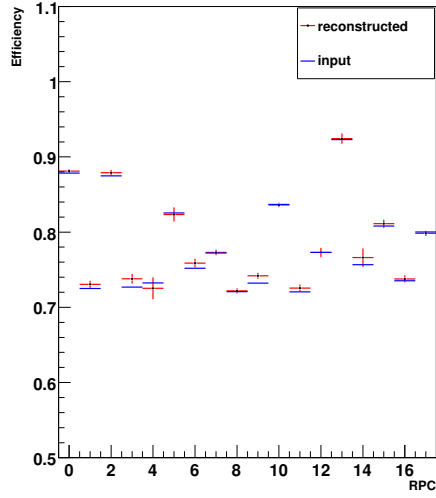
Figure 3.21: Reconstructed and input efficiencies per RPC in the bending plane. Simulations were obtained by shooting single muons from a flat phase space distribution.



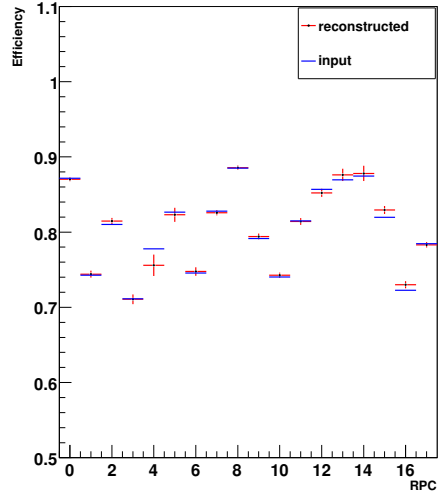
(a) Chamber 11



(b) Chamber 12



(c) Chamber 13



(d) Chamber 14

Figure 3.22: Reconstructed and input efficiencies per RPC in the non-bending plane. Simulations were obtained by shooting single muons from a flat phase space distribution.

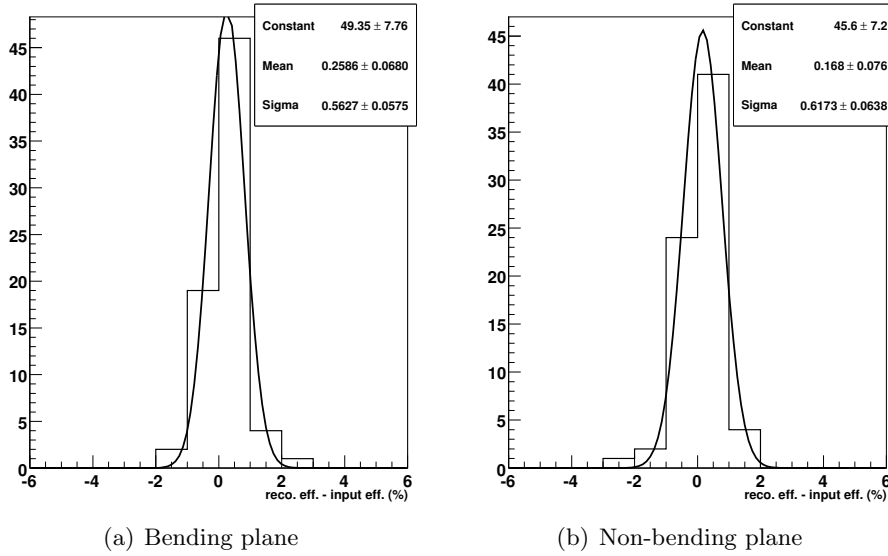


Figure 3.23: Difference between the reconstructed efficiency and input for all RPCs in bending (left) and non-bending (right) plane. The efficiency is expressed in percents. Distributions refer to results obtained with the simulation of single muons shot from a flat phase space distribution.

the given numbers are reasonable for almost all RPCs, a slightly higher number of tracks should be probably needed to determine the efficiency with a 1% statistical error for the boards furthest from the center.

3.2.2 Systematic errors

The method presented can provide an accurate measurement of the trigger chamber efficiency in a low-multiplicity environment typical of p-p collisions. A more challenging situation is represented by heavy-ion collisions. Indeed, in a high multiplicity environment, an overestimation of the calculated efficiency is expected, due to two main reasons:

- the muon can cross the chamber without being detected, but the corresponding strip can be nevertheless fired due to the passage of another particle.
- the muon crosses a strip which gives no signal, but another particle fires the neighbor strip which is wrongly assigned by the trigger efficiency algorithm to the muon track.

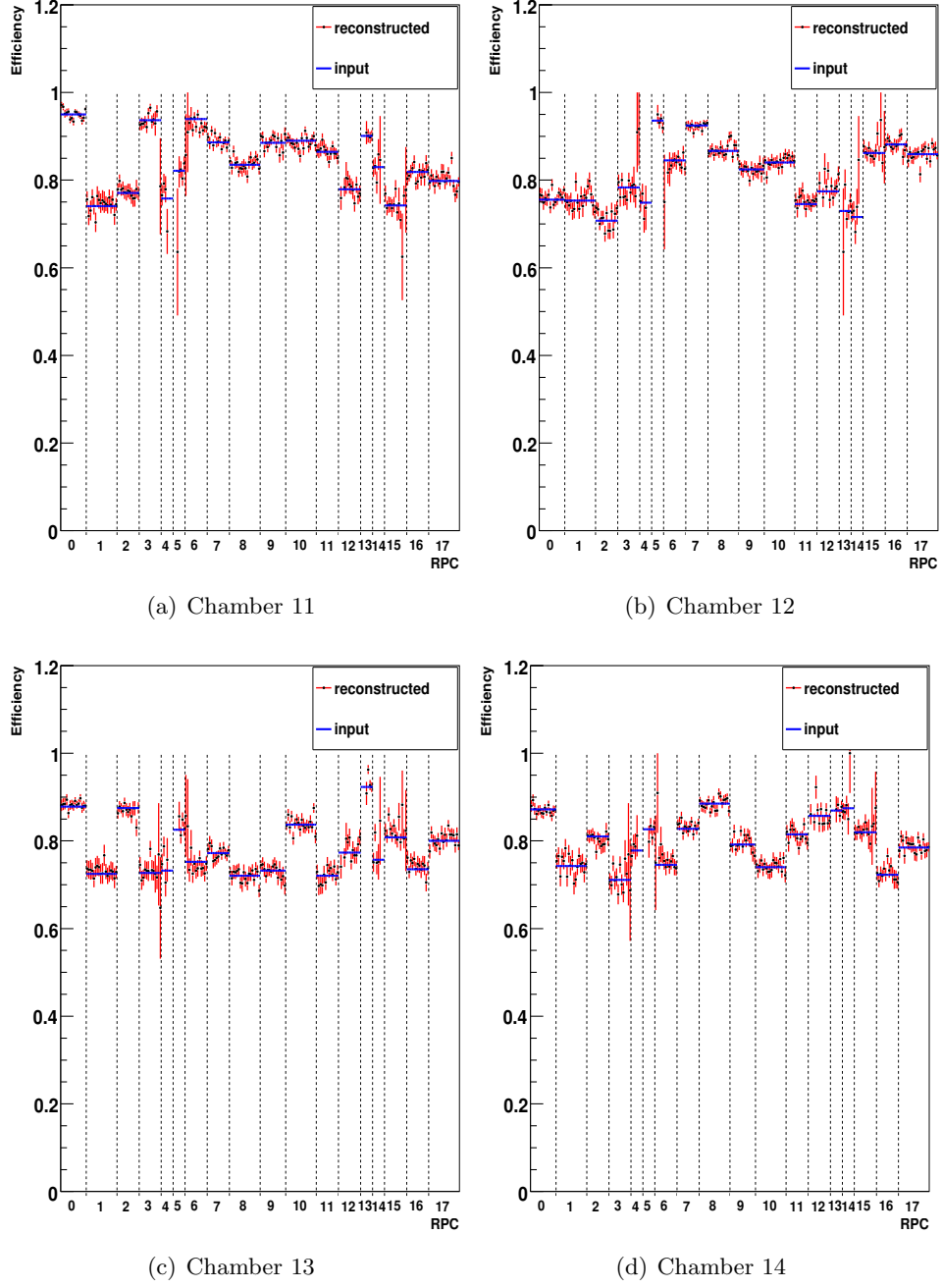


Figure 3.24: Reconstructed and input efficiencies per board in the bending plane. Points with bigger error bars correspond to boards in the most peripheral RPCs, far away from the beam pipe, where the statistics is lower. Simulations were obtained by shooting single muons from a flat phase space distribution.

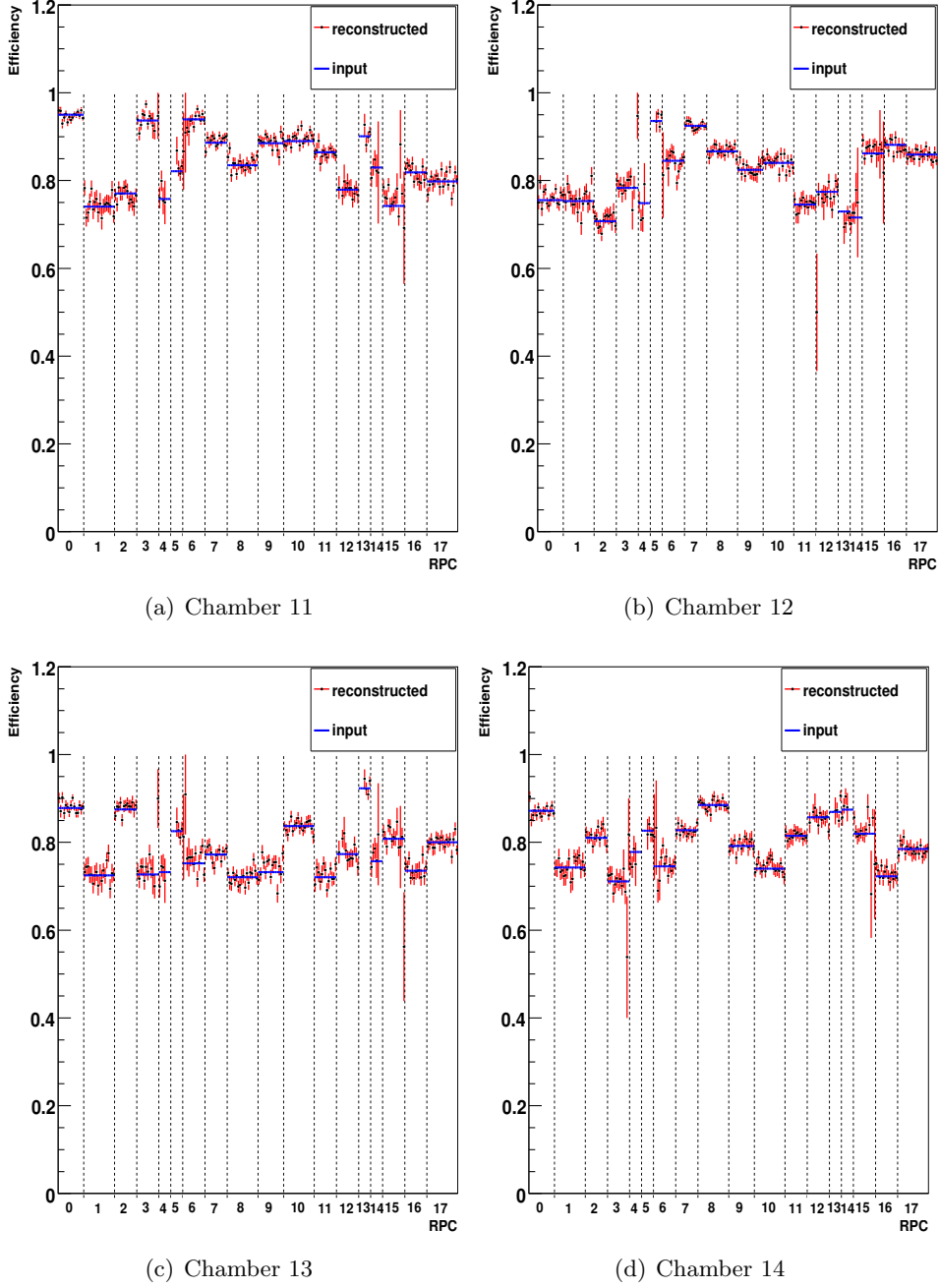


Figure 3.25: Reconstructed and input efficiencies per board in the non-bending plane. Points with bigger error bars correspond to boards in the most peripheral RPCs, far away from the beam pipe, where the statistics is lower. Simulations were obtained by shooting single muons from a flat phase space distribution.

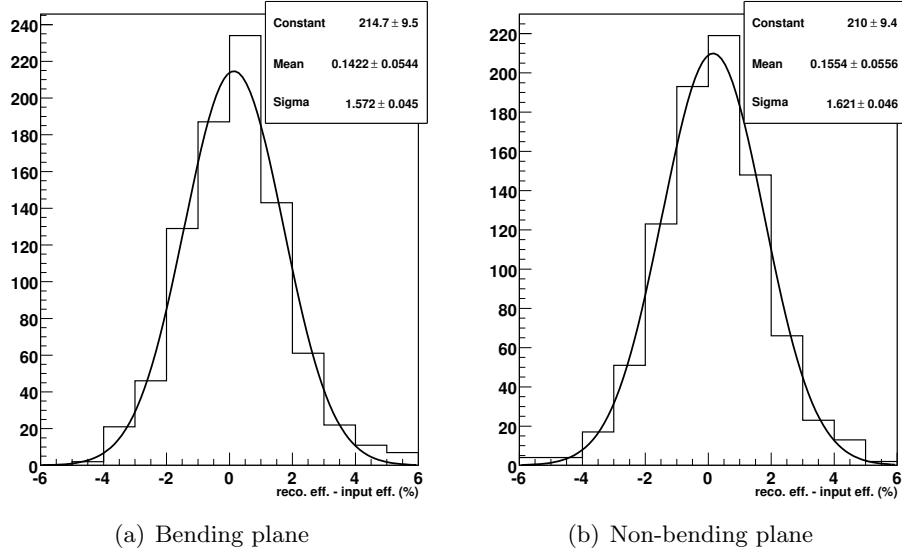


Figure 3.26: Difference between the reconstructed efficiency and input for all boards in bending (left) and non-bending (right) plane. The efficiency is expressed in percents. Distributions refer to results obtained with the simulation of single muons shot from a flat phase space distribution.

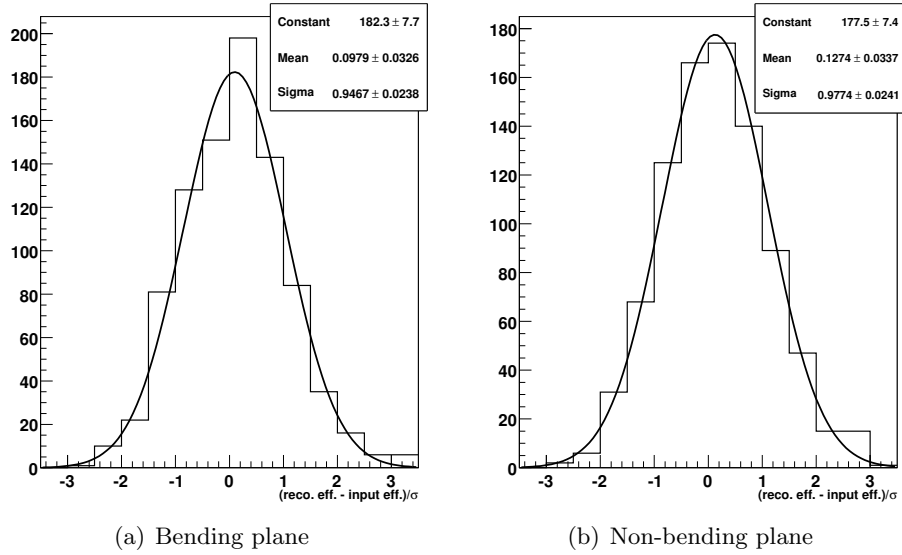


Figure 3.27: Difference between the reconstructed efficiency and input divided by the statistical error for all boards in bending (left) and non-bending (right) plane. Distributions refer to results obtained with the simulation of single muons shot from a flat phase space distribution.

The effects increase with the particle multiplicity and the strip area.

The arising systematic errors were investigated in different scenarios of muon multiplicity and soft background levels. In each event, a fixed number of muons is shot in a polar angle window of $170^\circ < \theta < 180^\circ$, slightly wider than the muon spectrometer acceptance in order to take edge effects into account. The high multiplicity environment due to soft background is simulated with random hits in the chambers, sampled from the hit distribution provided in [8]. The number of muons and the background level for each scenario is summarized in Table 3.4.

Scenario	1	2	3	4
Generated μ /event	1	5	5	10
μ /chamber/event	0.7	3.5	3.5	7.0
bkg. hits/chamber/event	0	25	50	50

Table 3.4: Multiplicity scenarios adopted in simulations. The numbers in the third line refer to muons crossing at least 3 chambers out of 4 and with $p_t > 0.5$ GeV/ c .

The systematic error as a function of the multiplicity ranges from 0.14% (0.16%) to about 0.8% (2%) in the bending (non-bending) plane, as shown in Figure 3.28 (full circles).

It is worth noting that the conditions in scenario 4 of Table 3.4 describe an extremely conservative situation. Further simulations were performed to determine the expected multiplicity in Pb-Pb collisions at 5.5 TeV. Pions and kaons were produced through parameterizations of the p_t and pseudo-rapidity distributions obtained from HIJING [9]. Since results from RHIC [10] suggest a low multiplicity scenario for the LHC, the simulation was tuned in order to get 2000 charged particles per units of pseudo-rapidity at $\eta = 0$. Charm and beauty hadrons were instead obtained through parameterization of PYTHIA p_t and rapidity distributions [7]. The expected muon multiplicity per event is shown in Table 3.5. The produced particles

	from π /K	from charm/beauty
μ /chamber/event	1.5	1.2

Table 3.5: Muon multiplicity per event in the trigger chambers. The numbers refer to muons crossing at least 3 chambers out of 4 and with $p_t > 0.5$ GeV/ c .

are then transported through the detector and the hit density on trigger

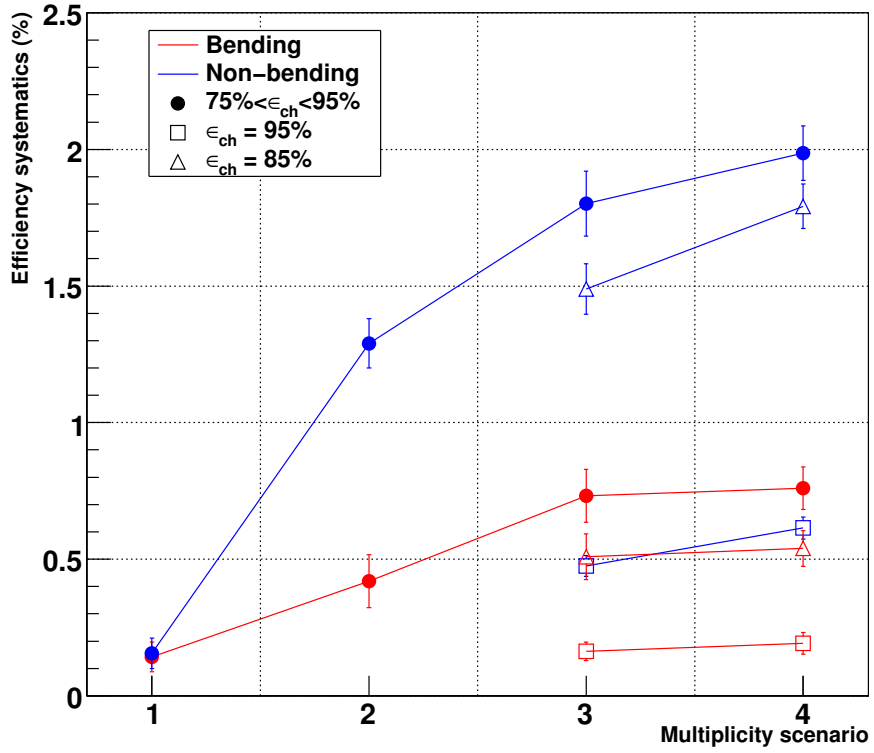


Figure 3.28: Systematics in trigger chamber efficiency evaluation as a function of multiplicity (see text). Full circles refer to results obtained with an input RPC efficiency ranging from 70 to 95%. Open triangles (squares) refer to results obtained with a constant input efficiency of 85% (95%) for all RPCs. The systematic error is in the direction of an overestimation of efficiency, as expected from general considerations (see text).

chambers is calculated. Since it was shown [11] that simulations underestimate the soft-background contribution of about 50%, the soft-background yield is multiplied by a safety factor of 2, consistently with the given reference. The results are shown in Figure 3.29 and summarized in Table 3.6.

	Ch 11	Ch 12	Ch 13	Ch 14
Hits/chamber/event	12	12	15	15

Table 3.6: Total number of hits (from muons and background) per event on trigger chambers.

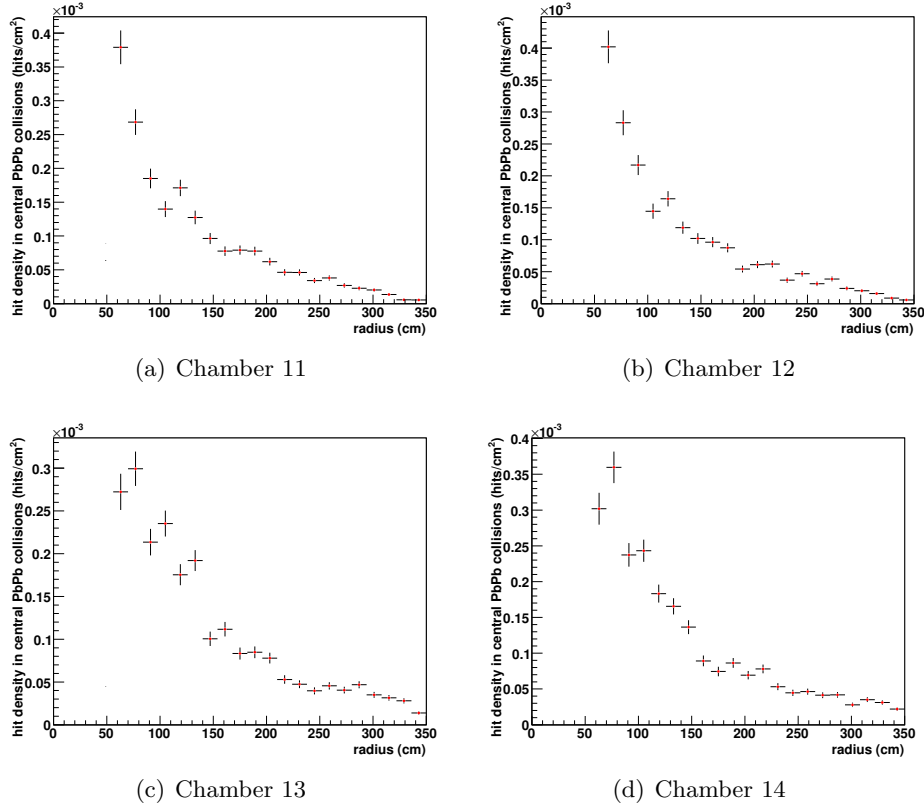


Figure 3.29: Hit density on trigger chambers. Results are obtained from HIJING parameterizations of p_t and pseudo-rapidity distributions, with an expected charged particle yield of $\left. \frac{dN}{d\eta} \right|_{\eta=0} = 2000$ (see text).

The simulation results suggest that, among the scenarios proposed in Table 3.4, the most realistic is the number 2.

Finally, it has to be pointed out that the systematic error is a function of the chamber efficiency. In particular, it goes to zero when ε_{ch} goes to unit. Such dependence was studied through simulations in which the input efficiency is set to a constant value for all RPCs in all chambers. The open triangles and squares in Figure 3.28, refer to the results obtained with an efficiency of 85% and 95% respectively, and with the conditions of scenarios with the highest multiplicity (3 and 4, Table 3.4). Since the nominal RPC efficiency is around 95%, the expected systematic error is below 1%.

3.2.3 Integration in the ALICE offline framework

The aim of ALICE offline framework, AliRoot, consists in providing all the needed features for the simulation of the detector response and the data reconstruction and analysis. The development of the common packages, constituting the core of the framework, is entrusted to the “offline core team”, while the detector modules are independently updated by the detector working groups. From the point of view of the simulation, the final goal is a description as detailed as possible of the characteristics of the detectors, from their layout to their performances.

At the time when the current work on the Muon Spectrometer trigger chamber efficiency begun, the possibility to describe a RPC with an efficiency different than 1 was not yet implemented in the code: consistent efforts were therefore made in this direction.

Due to the large area covered, small inhomogeneities could arise in different regions of the RPC, hence a realistic description of the chamber efficiency should provide maps with a good segmentation inside the chamber itself. A reasonable choice was to allow the setting of one efficiency value per local board: this defines the segmentation of the efficiency map.

A class (`AliMUONTriggerEfficiencyCells`) was created to handle the map information. The maps can either be provided in the form of ASCII files, or they can be generated by the class itself starting from a root file containing the histograms with the $N_{3/3}^{ch}$ and the $N_{4/4}$ per local board (see Section 3.2.1). As will be explained below, such root file is automatically created by an analysis task which implements the trigger efficiency determination from real data.

Once initialized, the class can be written in the Offline Calibration DataBase (OCDB), containing all the relevant information for the hard-

ware (dead-channels map, efficiencies, gains, pedestals, etc.): in this way the measured map can be made available at any time to the user. The main method of the class is called `IsTriggered`: given the ID of the chamber plane, and the local board ID number, it checks the efficiency in the map and returns two booleans (for the bending and non-bending planes) with value “true” if the pad was fired or “false” in the opposite case. In the simulation workflow, the method is called during the dis-integration process, namely when the hits on the chambers are converted into summable digits (see Section 2.3). From the hit position, the identification number of the fired local board is extracted, and then passed to the `IsTriggered` method: if the response is true, the corresponding digit is created, otherwise the pad is lost. This is performed before the clusterization process, so that, if the board is inefficient, none of the digits that would form a cluster is stored.

The option to account for a chamber efficiency lower than 1 can be easily turned on (default is off) at the beginning of the simulation, in the configuration file, with the command:

```
AliMUON *MUON = new AliMUONv1("MUON", "default");
MUON->SetTriggerEffCells(1);
```

The developed code can also be used to exclude a local board or an entire Resistive Plate Chamber from the simulation, since a switched-off board is equivalent to a board with null efficiency. This, together with a map of the dead-channels, allows to account for any hardware malfunctioning during the data taking (like boards or RPCs temporarily off during a run), without modifying the code.

Finally, some display methods are added to the class, after an explicit request from the users. The efficiency is naturally provided through histograms whose abscissa represent the RPC or board number id. However, the detection elements numbering (see Figure 2.14) follows a logic which fits the needs of a computer algorithm, but it does not provide immediate visualization for human beings (local boards in the same RPC have non-contiguous numbers). Since the detection element efficiency is a basic diagnostic tool for the detector, it is important, especially for offline shifters, to have histograms allowing to catch the status of the chamber at a glance.

This is implemented with the method `DisplayEfficiency`, which provides bi-dimensional histograms showing the position of each local board

in the chamber planes. The method, in fact, uses an instance of the more general class `AliMUONTriggerDisplay`, specifically created to convert histograms as a function of local board, RPC, or even strip ID, into graphical representations of the real position of such elements in space. Some examples are shown in Figure 3.30.

The class is intensively used in the creation of the Quality Assurance (QA) objects, which are histograms automatically built during the reconstruction of raw-data, with the aim of providing basic distributions (fired strips/pad multiplicity, local trigger multiplicity, etc.) easily-readable by shifters, to check the status of current data.

Trigger chamber efficiency determination in AliRoot

The algorithm for the determination of the chamber efficiency is fully integrated in the standard reconstruction, which starts from the detector raw-data. The Muon Spectrometer digits are re-created and the pads in the tracking chambers are grouped to form the clusters, out of which the (tracker) tracks are created. Afterwards, the trigger tracks are built out of the trigger response. At this point the tracker and trigger information, which so far were treated separately, are put in relation: tracker tracks are extrapolated beyond the muon filter in search of matching with the trigger ones. The algorithm for trigger chamber efficiency determination from data is performed at this level.

The process is handled by the class `AliMUONTrackHitPattern`. For each trigger track matching the tracker, it computes the intersection point on the trigger chambers and searches for fired strips in a region of $\pm N_{\text{match}}$ strips around it, as described in Section 3.2.1. The tracks crossing the chamber in a region where more than 2 strips are fired in an area of $\pm N_{\text{reject}}$ strips around the impact point could be due to particle showers: to avoid bias, they are flagged as “not good” for efficiency calculation. The choice of the number of strips in the matching ($\pm N_{\text{match}}$) and rejection region ($\pm N_{\text{reject}}$) is a parameter of the reconstruction. It can be set through:

```
AliMUONRecoParam *muonRecoParam =
    AliMUONRecoParam::GetLowFluxParam();

// Set N_match. Default 1
```

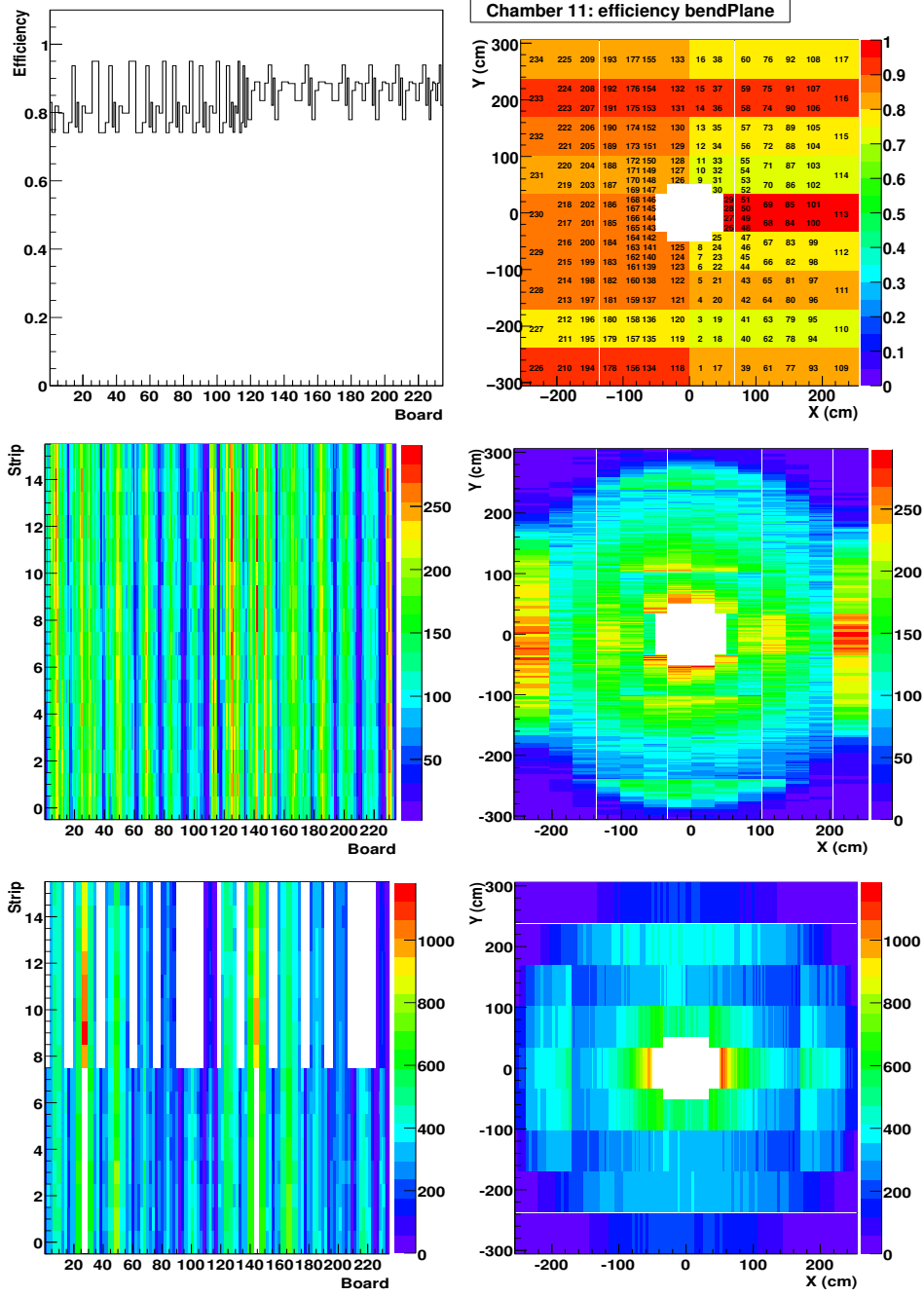


Figure 3.30: Examples of conversion of histograms used in calculation (left panels), and the corresponding human-readable display (right panels). Trigger chamber efficiency per local board (upper panels) and counts per strip in the bending (middle panels) and non-bending (lower panels) plane are shown.

```
muonRecoParam->SetStripCutForTrigger(double);
```

```
// Set N_reject. Default 3
```

```
muonRecoParam->SetMaxStripAreaForTrigger(double);
```

The result of the algorithm is a 16-bits word containing:

- the hit pattern for the bending and non-bending planes, indicating whether the track matched (1) or not (0) a strip in each chamber.
- the number of the crossed RPC.
- a 2-bits flag indicating that the track:

00 should be rejected during efficiency determination.

01 crosses RPCs with different ID numbers in the four chambers.

10 crosses RPCs with the same ID number in all chambers, but local boards with different ID numbers.

11 crosses local boards with the same ID number in all chambers.

The word, which is built as indicated in Table 3.7, is attached to the matching tracker track stored in the ESD and available for analysis.

0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1
void	RPC (0–17)					flag (0–3)	Bend plane Match chamber				Non-bend plane Match chamber				
							11	12	13	14	11	12	13	14	

Table 3.7: Explanation of the 16 bits word associated to an ESD track with the results of the trigger chamber efficiency determination algorithm.

The obtained word, together with the ID number of the fired local board, provides all the information needed to calculate the trigger chamber efficiency. At the end of reconstruction, a train of analysis tasks is submitted: ESD files are first converted into AODs, selecting the interesting events for generic analysis categories. AOD files can be further processed with selection cuts for more specific analyses. This step is extremely important for the Muon Spectrometer, since the extraction of the events with at least one muon at forward rapidities allows to considerably reduce the file size, which

is dominated by events with particles detected in the central barrel, particularly by the TPC. User analyses can then be performed on this specific files. In parallel, the detector efficiency is calculated from the ESD. The entire process is schematically depicted in Figure 3.31.

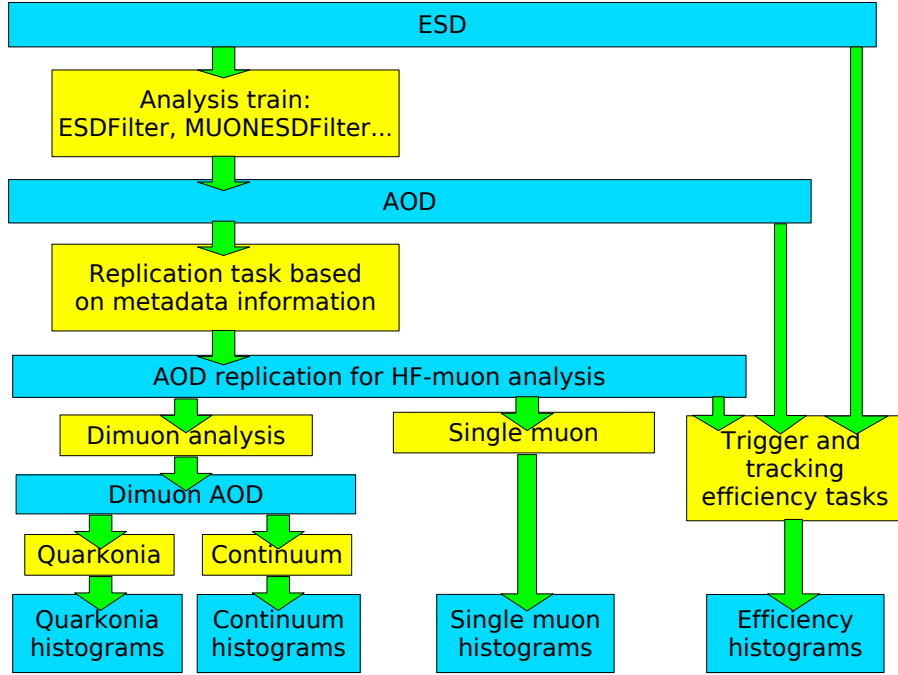


Figure 3.31: Schematic view of the analysis task train. Trigger chamber efficiency is computed from the ESDs.

The analysis task for the trigger chamber efficiency calculation, called `AliAnalysisTaskTrigChEff`, was created and it is now part of the standard AliRoot code. As already stated, the result is a root file containing the histograms of $N_{3/3}^{ch}$ and the $N_{4/4}$ per local board and RPC. An `AliMUONTriggerEfficiencyCells` can be created taking such file as input and eventually inserted into an Offline Calibration DataBase. An equivalent method is under development to provide the same maps for the tracking chambers [12].

The final goal is to provide efficiency and acceptance correction to the measured data. The details of the procedure are still under study, but the main steps are:

- Build an OCDB with the measured trigger and tracking chamber efficiency, dead-maps, pedestals and electronic gain.
- Plug the OCDB into a simulation which will allow a realistic description of the detector status at the data taking conditions.
- Change the simulations inputs with different hypotheses on particle kinematic distributions, and compare with data: when a good agreement is found, it can be argued that the simulations describe in a reasonable way the detector performances.
- Efficiency and acceptance corrections to the data can be obtained directly from the simulations (with as many as possible cross-checks with quantities directly measured from data).

The entire chain will allow to go from the reconstructed data to the input distributions, providing the statistical and systematic errors of the process.

Chapter 4

Physics performance

The ALICE Muon Spectrometer detects single muons emitted in the forward region, with a polar angle of $171^\circ < \theta < 178^\circ$. Its main goals are the measurement of heavy quarkonia and of heavy flavored mesons (“open charm” and “open beauty”) decaying in the dimuon and semi-muonic channel, respectively.

Quarkonia resonances are selected by an unlike-sign dimuon trigger with two levels of p_t cuts for the charmonia and bottomonia states. The extraction of the signal from the background is performed by a fit of the dimuon invariant mass spectra, which show clear structures around the mass values of the resonances. The fit of the dimuon continuum in the high mass region can provide also useful information on the open beauty yields [1].

Open heavy flavors can be measured from the analysis of single muon spectra, selected with the single muon trigger. In this case the subtraction of background is a more tricky problem which requires careful considerations on physics properties of the decaying particles and the merging of the information of different detectors.

4.1 Open charm and open beauty detection

The main contributions to the single muon spectra are the decay of heavy flavored hadrons on the one hand and the decay of pions and kaons on the other. Due to the high number of light hadrons produced in the primary collisions (especially between heavy ions), the latter constitutes the main source of background in the detector. The Muon Spectrometer front absorber was

specifically designed to cope with such background: its composition, with layers of high and low Z materials, reduces the multiple scattering and particle leakage on the chambers, while its placement at only 90 cm from the interaction point, limits the free decay length of pions and kaons, and consequently the probability of generating background muons in the spectrometer. The interaction of particles with the absorber can, nevertheless, produce a small fraction of secondary leptons which has to be taken into account.

Hence, the muons in the spectrometer acceptance can be divided in three typologies:

- “Heavy flavor muons”, from the semi-leptonic decay of heavy flavored mesons.
- “Decay muons”, from the free decay of π/K produced in the primary collision.
- “Secondary muons”, from the decay of π/K produced inside the front absorber.

Muons belonging to the three categories are produced at rather different distances from the interaction point: closer than 1 mm in the first case; closer than about 90 cm in the second and between about 90 and 503 cm in the third. This is schematically shown in Figure 4.1.

However this information is not enough to identify the muon typologies for two main reasons:

- Muon tracks are measured only after the absorber, so any extrapolation is affected by multiple scattering whose importance grows for low momentum particles.
- Muons in the spectrometer acceptance are very close to the z direction ($171^\circ < \theta < 178^\circ$), which results in a bad resolution on the reconstruction of the z position of the decay vertex.

Nevertheless, the three muon sources have different features that should be exploited to extract the contribution of the signal from the background.

4.1.1 Decay background subtraction

The main difference between heavy flavors and π/K -decays is their decay length: of the order of hundreds of micrometers for the former and of me-

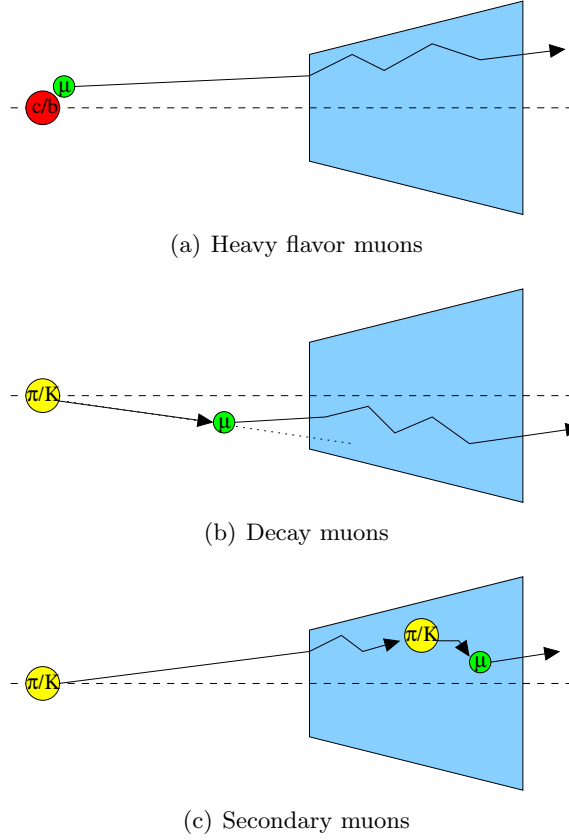


Figure 4.1: Schematic view of the production point of the three muon sources with respect to the Muon Spectrometer front absorber (trapezium). The dashed line represent the beam axis.

ters for the latter (see Table 4.1). The semi-muonic decay of heavy flavors

Source	$c\tau$
B mesons	491.1 μm
D mesons	311.8 μm
π	7.8045 m
K	3.713 m

Table 4.1: Muon sources decay lengths [2].

takes place very close to the interaction point, while the most of pions and kaons are absorbed (by the front absorber) before producing background muons. The suppression depends on the distance between the absorber and the interaction point, whose position changes event-by-event. The intersection region between the beams is indeed diamond shaped, due to non-zero

angle between the beam lines, with a dimension of few centimeters along the beam axis (z) and of the order of a hundred micrometers in the transverse plane. The collision can take place at different points of such region, with a probability which is Gaussian distributed along z , with a standard deviation of $\sigma_z \simeq 5.3$ cm.

The spectrum of muons from π/K decays can be obtained from the spectrum of π/K through:

$$\frac{dN_{\mu}^{\pi/K}}{dp_t} = \int dp'_t P_{\pi/K}(p_t, p'_t) \frac{dN_{\pi/K}}{dp'_t}$$

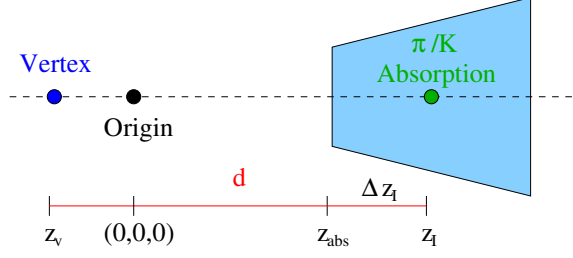
where $P_{\pi/K}(p_t, p'_t)$ is the probability to produce a muon with transverse momentum p_t from a π/K of transverse momentum p'_t . Provided a uniform detector acceptance for muons produced in the region spanned by the interaction vertex (within $\pm 2\sigma_z$ from the origin), the rate dependence on the vertex position can be written in the following way:

$$\begin{aligned} \frac{dN_{\mu}^{\pi/K}}{dp_t} = \int d\theta \int dp'_t P_{\pi/K}(p_t, p'_t) \frac{d^2 N_{\pi/K}}{dp'_t d\theta} \times \\ \int dz_v \rho(z_v) \left[1 - \exp\left(-\frac{d m_{\pi/K} \tan \theta}{c\tau p'_t}\right) \right] \end{aligned}$$

where θ , τ and $m_{\pi/K}$ are the polar angle, mean life and mass of the pion or kaon, respectively. The variable d is the free path that the π/K can travel before interaction. It can be written as (see Figure 4.2):

$$d = |z_{\text{abs}} + \Delta z_I - z_v| \quad (4.1)$$

where z_v is the position of the interaction vertex with respect to the axis origin, distributed as a Gaussian $\rho(z_v)$ with mean value 0 and $\sigma_z \simeq 5.3$ cm, $z_{\text{abs}} = 90$ cm is the distance between the origin and the absorber front face, and Δz_I is the mean path travelled by π/K in the absorber before interaction, which, on average, corresponds to an interaction length $\langle \Delta z_I \rangle = \lambda_I \simeq 40$ cm.


 Figure 4.2: Definition of the π/K free path length.

The bi-dimensional distribution can be written as:

$$\frac{d^2 N_{\mu}^{\pi/K}}{dp_t dz_v} = \rho(z_v) \int d\theta \int dp'_t P_{\pi/K}(p_t, p'_t) \frac{d^2 N_{\pi/K}}{dp'_t d\theta} \times \left[1 - \exp\left(-\frac{d m_{\pi/K} \tan \theta}{c\tau p'_t}\right) \right]$$

The π/K decay probability, $\exp\left(-\frac{d m_{\pi/K} \tan \theta}{c\tau p'_t}\right)$, is small by construction and can be expanded in series, thus reading:

$$\begin{aligned} \frac{d^2 N_{\mu}^{\pi/K}}{dp_t dz_v} &\simeq d \rho(z_v) \int d\theta \int dp'_t P_{\pi/K}(p_t, p'_t) \frac{d^2 N_{\pi/K}}{dp'_t d\theta} \frac{m_{\pi/K} \tan \theta}{c\tau p'_t} \\ &= \rho(z_v) A_{\pi/K}(p_t) d \end{aligned}$$

The corresponding distribution for charm and beauty, under the assumption of constant acceptance as a function of the vertex position, drops the dependence on d :

$$\frac{d^2 N_{\mu}^{c/b}}{dp_t dz_v} \simeq \rho(z_v) \int dp'_t P_{c/b}(p_t, p'_t) \frac{dN_{c/b}}{dp'_t} = \rho(z_v) B_{c/b}(p_t)$$

The behavior of the secondary muons is somehow opposite with respect to the decay ones. Indeed it depends on the probability that the π/K interacts with the absorber before decaying:

$$\begin{aligned} \frac{dN_{\mu}^{\text{sec}}}{dp_t} &= \int d\theta \int dp'_t P_{\text{sec}}(p_t, p'_t) \frac{d^2 N_{\pi/K}}{dp'_t d\theta} \times \\ &\quad \int dz_v \rho(z_v) \exp\left(-\frac{d m_{\pi/K} \tan \theta}{c\tau p'_t}\right) \end{aligned}$$

where $P_{\text{sec}}(p_t, p'_t)$ is the probability that a pion or kaon produced in the

interaction vertex with transverse momentum p'_t , interacting with the front absorber generates a π/K decaying in a muon with transverse momentum p_t .

The expansion in series reads:

$$\begin{aligned} \frac{d^2 N_{\mu}^{\text{sec}}}{dp_t dz_v} &= \rho(z_v) \int d\theta \int dp'_t P_{\text{sec}}(p_t, p'_t) \frac{d^2 N_{\pi/K}}{dp'_t d\theta} \left(1 - \frac{d m_{\pi/K} \tan \theta}{c\tau p'_t} \right) \\ &= \rho(z_v) [B_{\text{sec}}(p_t) - d A_{\text{sec}}(p_t)] \end{aligned}$$

Hence, the bi-dimensional muon spectrum can be written as:

$$\frac{d^2 N_{\mu}}{dp_t dz_v} = \rho(z_v) [B_{c/b}(p_t) + B_{\text{sec}}(p_t) + d (A_{\pi/K}(p_t) - A_{\text{sec}}(p_t))] \quad (4.2)$$

If the contribution of secondary muons is subtracted with other methods, Eq. 4.2 would read:

$$\frac{d^2 N_{\mu}}{dp_t dz_v} = \rho(z_v) [B_{c/b}(p_t) + A_{\pi/K}(p_t) d] \quad (4.3)$$

Therefore, after eliminating the secondary muons (see Section 4.1.2), the contribution of the muons from heavy flavors at a given p_t , $B_{c/b}(p_t)$, can be determined with a linear interpolation of the bi-dimensional single muon distribution of Eq. 4.3.

Simulation results

The method was first tested on simulations of heavy-ion collisions, where the contribution of the decay background at low p_t is important [3]. Nevertheless, it will be shown in Section 4.1.3 that the same considerations apply to p-p collisions as well.

The full simulation of Pb-Pb collisions requires a huge amount of computing time, due to the big number of particles per event produced and the long time needed to track the particles in the absorber. The difficulty can be overcome by performing a fast simulation, which is based on the parameterization of the whole spectrometer response at the single muon level [3]. Given a muon of momentum p generated at the interaction point with polar and azimuthal angles θ and φ , the fast simulation applies the smearing of the apparatus and gives the reconstructed p' , θ' and φ' together with the detection

probability. It is worth noting that, despite providing a good description of the heavy flavor and decay muons in the spectrometer, the fast simulation cannot properly reproduce the secondary background contribution, which will be neglected in the following. A proper treatment of secondaries will be provided in Sections 4.1.2 and 4.1.3: the aim of the current section is to show the capability of the method for primary background subtraction.

The particle spectra in pseudorapidity and p_t are generated through parameterizations of HIJING [4] and PYTHIA [5] results, tuned to provide 8000 charged particles per unit of rapidity at mid-rapidity. Although recent data from RHIC [6] suggest a lower multiplicity scenario for the LHC, a conservative approach is adopted. The statistics expected in one year of Pb-Pb data taking ($\sim 10^6$ s), with a luminosity of $5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ is generated.

The vertex position follows a Gaussian distribution centered at 0 and with a standard deviation of 5.3 cm [7]. Muons coming from the decay in flight of pions and kaons are weighted according to the decay probability, depending on the distance between the vertex and the absorber.

Figure 4.3 shows the distribution of muons in p_t and z_v , expected in the data taking scenario previously explained and collected with the single-muon Low- p_t trigger cut ($\sim 1 \text{ GeV}/c$). The vertex profile, obtained by integrating

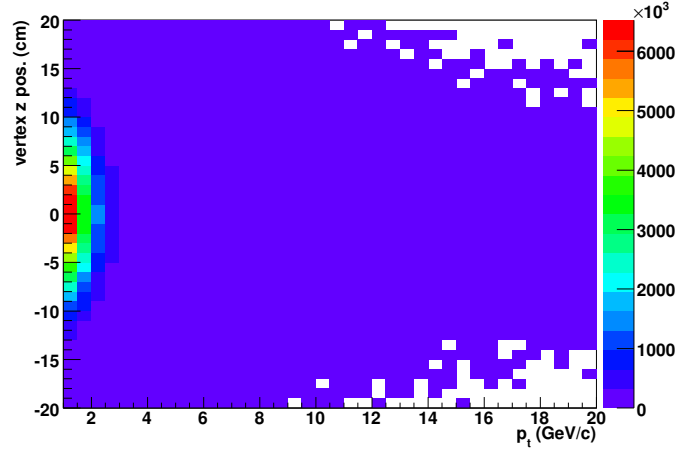


Figure 4.3: Bi-dimensional distribution ($\frac{d^2 N^\mu}{dp_t dz_v}$) of reconstructed muons.

the bi-dimensional distribution over the whole transverse momentum range ($p_t > 1 \text{ GeV}/c$), is the product of a Gaussian and a straight line (Figure 4.4).

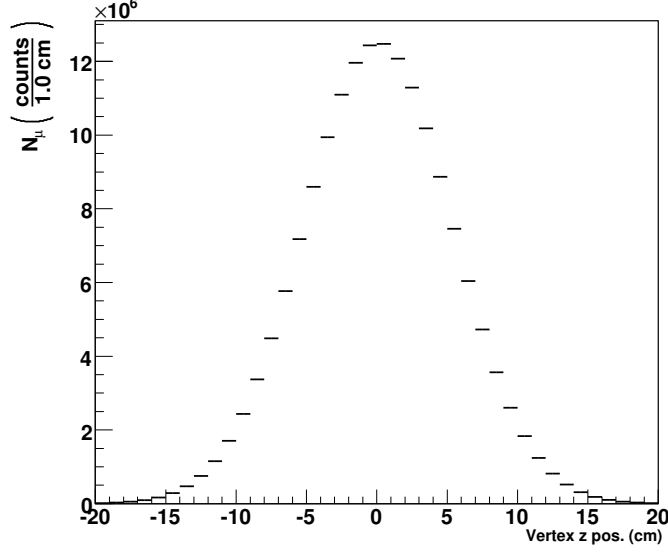


Figure 4.4: Vertex distribution ($\frac{dN^\mu}{dz_v}$) of reconstructed muons with $p_t > 1$ GeV/c.

For each p_t bin, the distribution of the longitudinal vertex position,

$$\frac{dN^\mu}{dz_v} = \int_{p_t^{\text{low bin edge}}}^{p_t^{\text{high bin edge}}} \frac{dN^\mu}{dp_t dz_v}$$

is created and the resulting histograms are then divided by the Gaussian distribution of the vertex, $\rho(z_v)$, normalized to 1. The Gaussian parameters can be obtained directly from data, by fitting the vertex spectrum $\frac{dN^\mu}{dz_v}$ obtained from the integration of $\frac{d^2N^\mu}{dp_t dz_v}$ at high transverse momenta ($p_t \gtrsim 6$ GeV/c). In this region the contribution of muons from pions and kaons should be negligible and, consequently, the one-dimensional distribution is purely Gaussian. The final results are shown in Figure 4.5. The slope of each one-dimensional vertex distribution at fixed p_t can be related to the yields of muons from π/K decays, while their values extrapolated to $d = 0$ (i.e. to $z_v = z_{\text{abs}} + \Delta z_1$) give the yields of muons from charm and beauty (see Eq. 4.3).

The reconstructed p_t distributions of muons from the heavy flavor decay are shown in Figure 4.6 together with input for comparison: the reconstructed data well reproduce the generated signal, even in the region of low p_t , where the contribution from background is dominant.

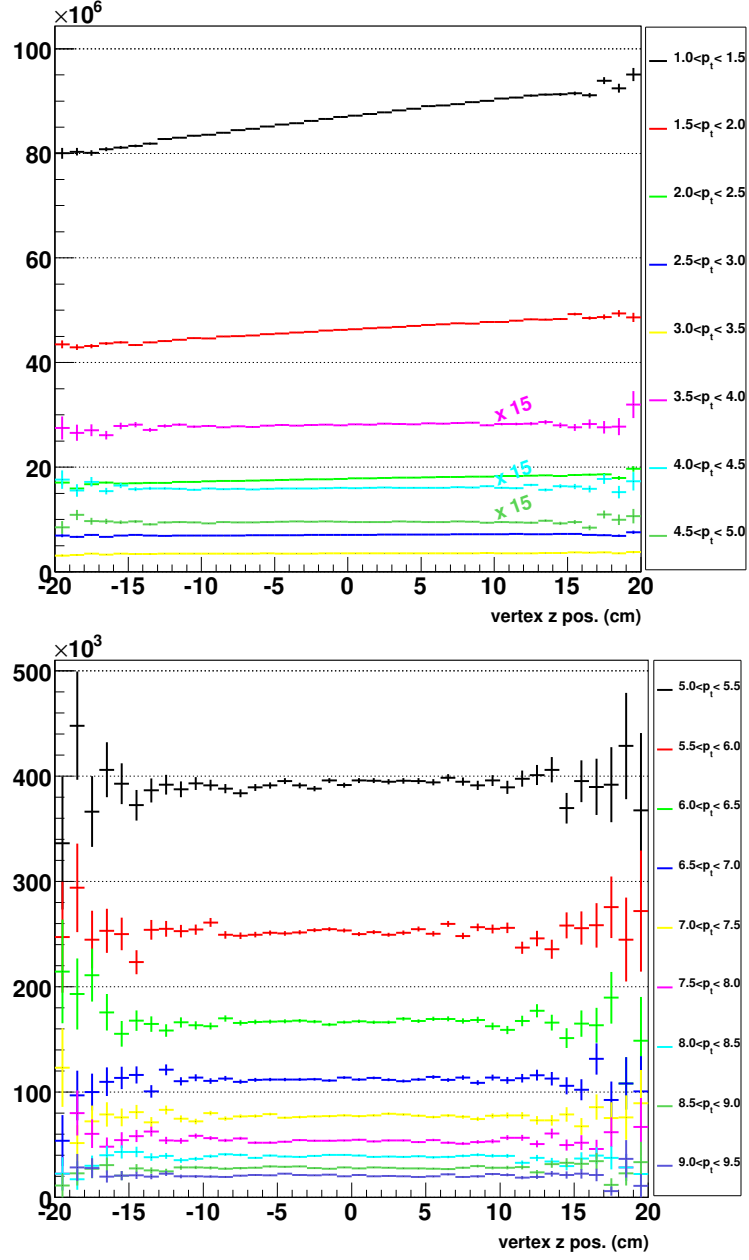


Figure 4.5: Plots of $\frac{1}{\rho(z_v)} \frac{d^2 N^\mu}{dp_t dz_v}$, obtained at different values of p_t . The distributions show a linear dependence on the longitudinal vertex position, as stated in Eq. 4.3.

Robustness test

The result shown in Figure 4.6, is obtained with a reasonable assumption on the relative abundance between π/K and charm/beauty. Obviously the

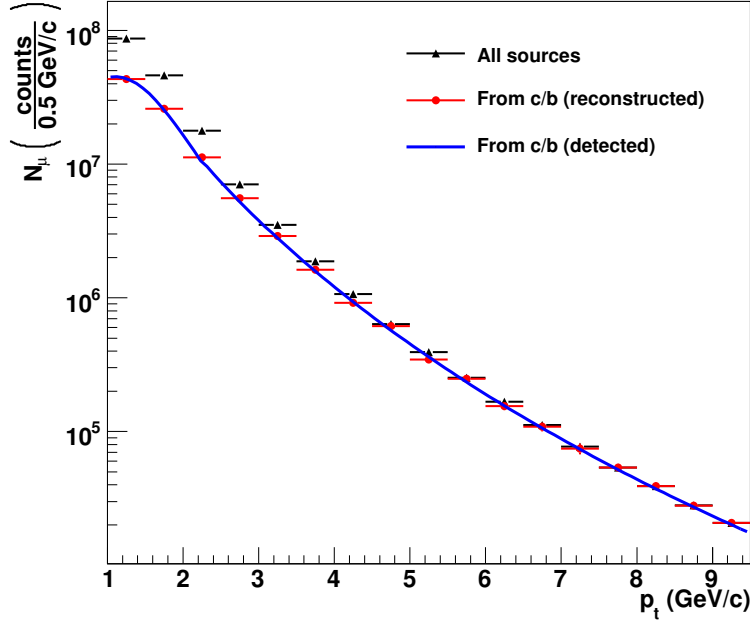


Figure 4.6: Transverse momentum distributions of muons from all sources (black triangle histogram), and contribution of muons from heavy flavors (red circle histogram) reconstructed with the described method. The comparison with the detected muons provided by the simulation (solid blue line) shows a good agreement.

fitting procedure must be completely independent on the muon sources relative yields. This was tested by modifying the amount of pions and kaons, while keeping the heavy flavor muon number fixed. The results are shown in Figures 4.7(a) and (b): the accuracy of the method still holds.

Single muon trigger statistics

The study performed requires data taken triggering on single muons. The ALICE detector schedule foresees collection of data with triggers on both single-muon and muon pairs, but the length of the running periods in either mode is to be decided yet. Moreover, in case of single-muon trigger, a pre-scaling of data could occur, of an amount to be further discussed. Figure 4.8 shows the results obtained in one year of data taking at the LHC when the single-muon trigger is applied in the 10% (left panel) and 1% (right panel) of cases respectively: the method seems to be effective even with a low one-year statistics.

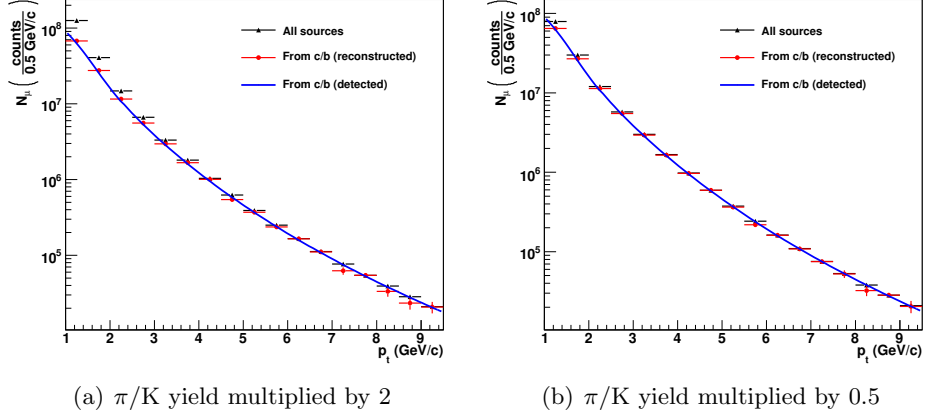


Figure 4.7: Reconstructed p_t distributions. The relative abundance of muons from π/K and heavy flavors is multiplied by a factor of 2 (a) and 0.5 (b)

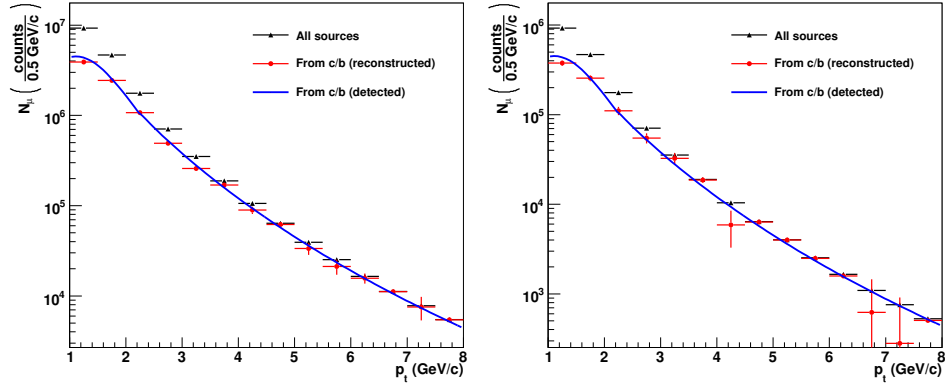


Figure 4.8: Same as Figure 4.6 with the 10% (left panel) and 1% (right panel) of the statistics expected in one year of data taking at $5 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$.

Systematic errors

The systematic errors of the method come from theoretical and experimental uncertainties. In the first category, the most important is the event by event fluctuation of the free decay length. As already stated, the free decay distance is the sum of the measured vertex position, the fixed distance between the front absorber and the nominal interaction point and the travelled path in the absorber before interaction. The latter is distributed as an exponential:

$$\frac{dP}{d\Delta z_I} = \frac{1}{\lambda_I} \exp(-\Delta z_I/\lambda_I)$$

The systematic error is minimized by setting $\Delta z_I = \langle \Delta z_I \rangle = \lambda_I$ in the calculations (Eq. 4.1). The statistical error on the mean value $\langle \Delta z_I \rangle$ decreases with the square root of the number of events:

$$\sigma_{\langle \Delta z_I \rangle} = \sigma_{\Delta z_I} / \sqrt{N} = \lambda_I / \sqrt{N}$$

The second source of systematics is related with the detection of muons. In particular, any dependence of the Muon Spectrometer geometrical acceptance and efficiency on the vertex position would spoil the precision of the method. Such dependence can, however, be studied in detail through simulations. The tracking and trigger efficiencies as well as the acceptance as a function of the vertex position is shown in Figures 4.9(a), (b) and (c) respectively. The horizontal band represents a $\pm 1\%$ variation with respect to the value measured at the nominal vertex position equal to (0,0,0). The results show a very limited dependence of the acceptance and efficiencies on the vertex position, with a variation lower than 1%.

The method presented is a very powerful tool to subtract the contribution of the muons from the decay in flight of pions and kaons. However, the obtained results are partially biased when the secondary muons are taken into account in simulations. The dependence of such particles on the vertex position introduces two new terms in Eq. 4.3, one independent on d and the other decreasing when the distance between the interaction point and the absorber increases, as shown in Eq. 4.2. The extrapolation to $d = 0$ removes the latter contribution, but the result is not simply the heavy flavor muon yield, and reads:

$$\left. \frac{d^2 N}{dp_t dz_v} \right|_{d=0} = B_{c/b}(p_t) + B_{\text{sec}}(p_t)$$

Among the background sources, the fraction of secondary muons is not the main one, being of the order of 20% of the decay contribution. Moreover, the characteristics of secondary muons, produced inside the absorber, show many kinematic differences with respect to the heavy flavor and decay muons, whose parents are produced in the interaction point. Such differences can be used to further reduce their contribution through other methods.

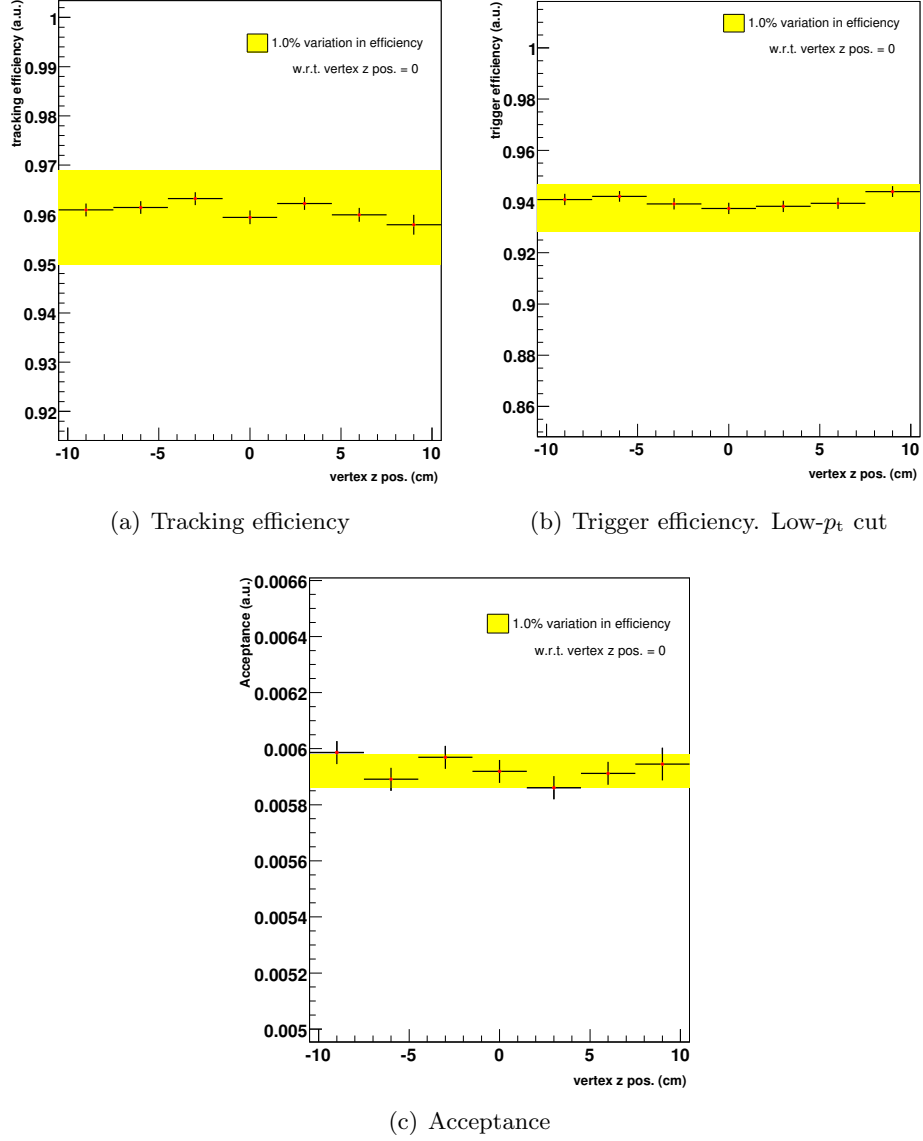


Figure 4.9: Efficiencies and acceptance dependence on vertex position. The horizontal band represent the $\pm 1\%$ variation with respect to the value measured at the nominal vertex position.

4.1.2 Secondary background subtraction

The secondary muons come from the decay of pions and kaons which are generated by the interaction of particles with the front absorber, at a distance ranging between 90 and 503 cm from the interaction point.

The Muon Spectrometer is designed to detect particles approximately

pointing to the primary collision vertex, a feature that minimizes the number of secondary muons in the acceptance. Therefore, the fraction of background particles that are reconstructed have a direction similar to the muons from other sources, also taking into account the uncertainties introduced by the multiple scattering in the absorber. It is however possible to find observables which enhance the differences between secondary muons from the one hand and decay and heavy flavor muons from the other, thus allowing to subtract the contribution of the former.

Cut on Transverse Distance at Vertex

During standard reconstruction, the track parameters measured at the first tracking station are extrapolated to the vertex. The extrapolation involves momentum corrections for the energy loss and multiple scattering in the absorber, which are performed by using the interaction vertex as an additional point of the track [8]. This obviously introduces a bias for secondary muons, which does not come from the interaction vertex, and smooths out any differences between signal and background.

To avoid this problem, a new observable can be taken into account, the Transverse Distance at Vertex (TDV). The TDV is the distance between the extrapolated muon track and the interaction vertex, measured in the plane orthogonal to the beam line and containing the vertex itself (see Figure 4.10). The extrapolation is performed starting from the parameters measured at the first tracking chamber and takes into account the magnetic field, but the corrections forcing the track to point to the vertex are removed.

The distributions of muons from the different sources as a function of the TDV was studied with full simulations of Pb-Pb collisions. Heavy flavors are generated with PYTHIA, tuned to reproduce the NLO pQCD calculation implemented in the program by M. Mangano, P. Nason and G. Ridolfi (HVQMNR) [9]. Disregarding the nuclear effects, the cross sections in Pb-Pb collisions can be obtained from p-p collisions, assuming a simple binary scaling with the number of elementary collisions among the ion nucleons. The parton distribution functions were modified for nuclear shadowing using the EKS [10] parameterization (see [3] for further details). The hadronic background is obtained from parameterizations of p_t and η distributions extracted from central Pb-Pb events generated with HIJING [4]. In this case, the transport in the detector of the particles with the high mul-

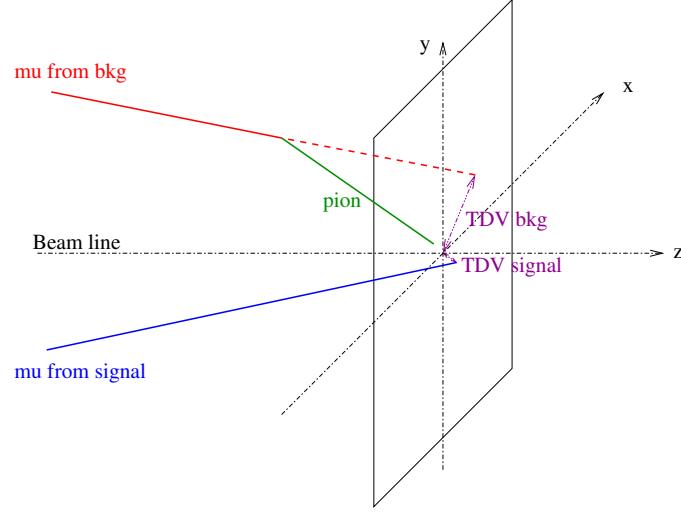


Figure 4.10: Construction of the Transverse Distance at Vertex (TDV). Corrections due to multiple scattering in the absorber, performed by considering the vertex itself as a point of the track, are not taken into account during the extrapolation.

tiplicity expected in Pb-Pb collisions at the LHC requires a big amount of computing time, hence a limited statistics could be produced. The collected statistics is high enough to provide general statements on the validity of the method, but for more detailed studies the Grid resources should probably be adopted in the future.

Figures 4.11(a)–(d) show the bi-dimensional distribution $d^2N/dp_t dTDV$ of the reconstructed muons from charm, beauty, primary and secondary π/K , respectively. The results are obtained by requiring the matching between the tracks in the tracker and in the trigger, the latter being produced only for particles with a transverse momentum $p_t \gtrsim 0.5$ GeV/c. As expected, the TDV distribution is broader for muons produced in the absorber than for other sources.

A cut on such variable can therefore be used to reduce the accepted secondary background while keeping at low level the signal rejection. The effects of a TDV cut of 21 cm on the acceptance of muons with $p_t > 0.5$ GeV/c are shown in Table 4.2: the number of secondary muons is reduced of almost 35%, with a loss in the charm production lower than 6%. The cut has a limited effect on muons from the decay in flight of pions and kaons, but their contribution can be subtracted with the method described in Section 4.1.1.

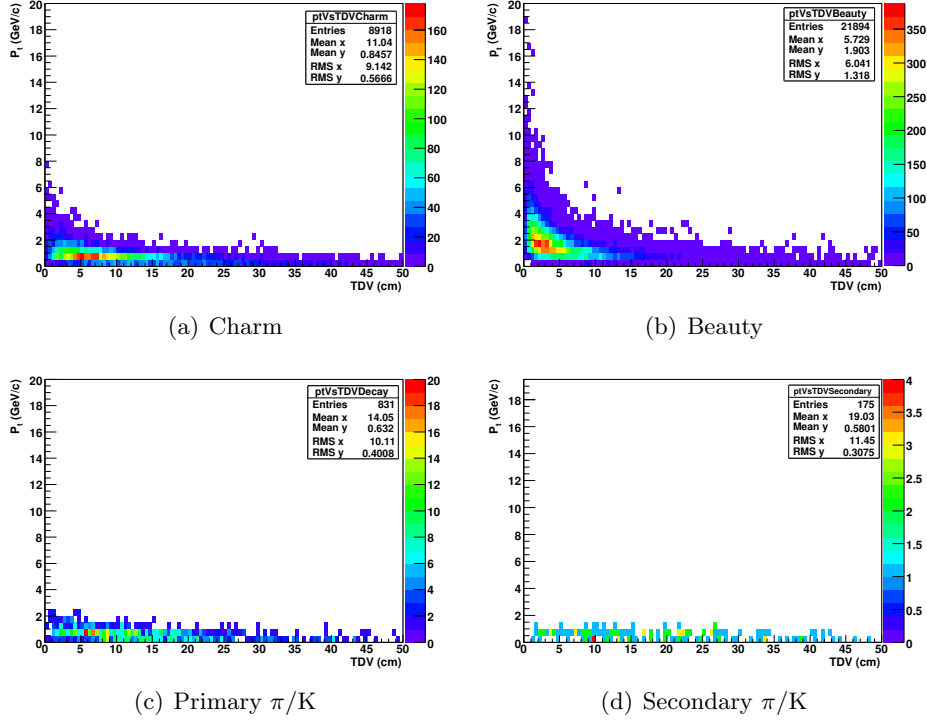


Figure 4.11: Bi-dimensional distribution in p_t and transverse distance at vertex for muons from different sources.

Source	Rejected
Open charm	5.9%
Open beauty	1.9%
Primary π/K	9.4%
Secondary π/K	35.4%

Table 4.2: Effects of a TDV cut of 21 cm in the rejection of muons with $p_t > 0.5$ GeV/c for signal and background sources.

It is worth noting that the cut on the Transverse Distance at Vertex can be applied track-by-track and that the same considerations done for Pb-Pb collisions hold in p-p.

Matching with the FMD

The Muon Spectrometer resolution on track extrapolation is dominated by the uncertainties related with the multiple scattering of particles in the

absorber. The situation can be considerably improved by measuring the tracks before the front absorber, as done in other heavy-ion experiments [11].

ALICE is equipped with one detector placed in front of the absorber with a good segmentation along the polar angle: the Forward Multiplicity Detector. The FMD consists of 51200 silicon strip channels distributed over five ring counters of two types, inner and outer with 20 or 40 sectors in the azimuthal angle, respectively. Three of the rings are placed in the opposite side of the Muon Spectrometer, while the remaining two are located on the same side, about 70 cm away from the interaction point, and cover a pseudorapidity range of $-3.4 < \eta < -2.01$ and $-2.29 < \eta < -1.7$ respectively (see Figure 4.12). The inner ring of the FMD3 partially covers the Muon

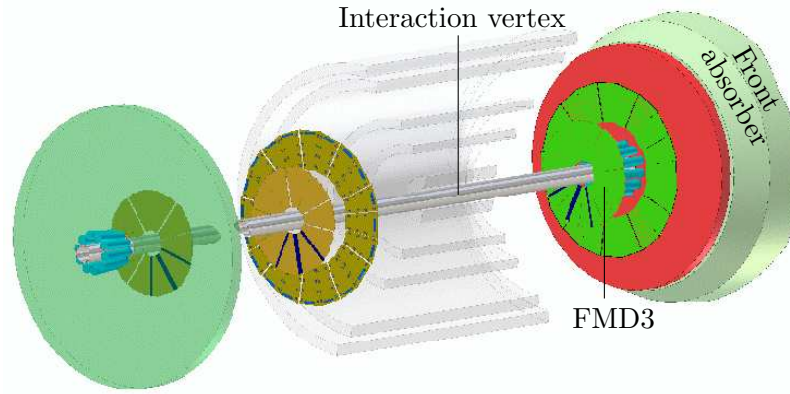


Figure 4.12: The ALICE Forward Multiplicity Detector.

Spectrometer acceptance in the common region $-3.4 < \eta < -2.5$. Such ring is made of 20 sectors of 512 strips each, with a pitch of $250 \mu\text{m}$ (see Figure 4.13). Although it is not a tracker but a multiplicity detector, the fine radial segmentation of the FMD can provide useful information on the muon track before the absorber, when the charged particle multiplicity (and consequently the detector occupancy) is limited.

The muons reconstructed in the Spectrometer are extrapolated back to the vertex, taking into account the effects of energy loss in the absorber. As already stated, this describes in a reasonable way the true momentum of heavy flavor muons, but provides a fake track for secondary muons, which are produced in the absorber. This implies that a search for fired strips around the track impact point on the FMD results in a positive match for

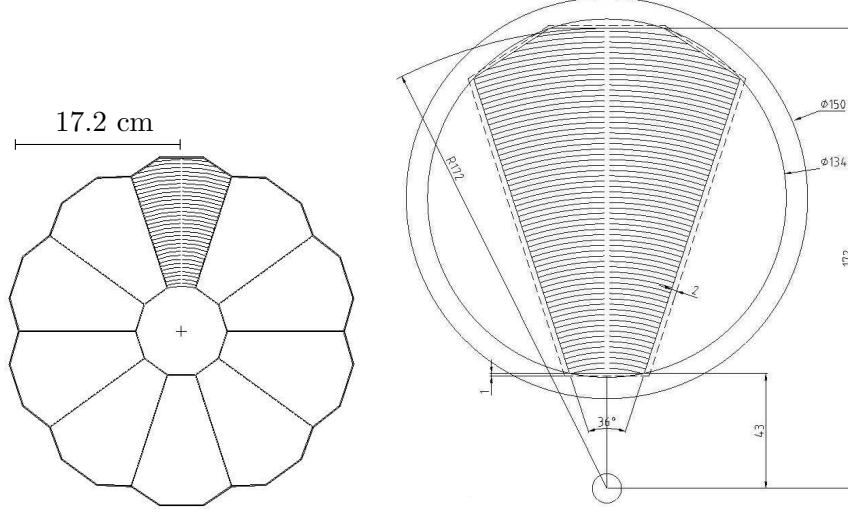


Figure 4.13: FMD3 inner sector layout.

the former and a negative match for the latter: the secondary muons can therefore be rejected.

The rejection is effective for low values of the FMD occupancy. In case of a huge production of charged particles, the probability of a random match between the virtual secondary muon track and a fired strip increases, thus leading to a considerable bias. For this reason the method cannot be applied to Pb-Pb collisions, where the expected multiplicity is of the order of few thousands of charged particles per unit of rapidity.

The performance of this method for background subtraction was tested on p-p collisions. Heavy flavor contribution is generated through parameterization of NLO pQCD results obtained with the HVQMNR program [9]. The hadronic background is produced using PYTHIA, with the settings for minimum bias interactions and switching off the production of heavy quarks to avoid double counting. Figures 4.14(a)–(d) show the number of matching strips in the inner ring of FMD3 for muon tracks with $p_t > 0.5$ GeV/c: the maximum distance between the fired strip and the track extrapolation is set to be $\Delta r < 4.5$ mm. The number of secondary muons is reduced of almost 70%, with a loss in the charm production lower than 5%. The muon rejection with a cut in the transverse distance at vertex, the matching with the FMD in a road of $\Delta r < 4.5$ mm and the combination of the two methods is shown in Table 4.3. The use of the information provided by the

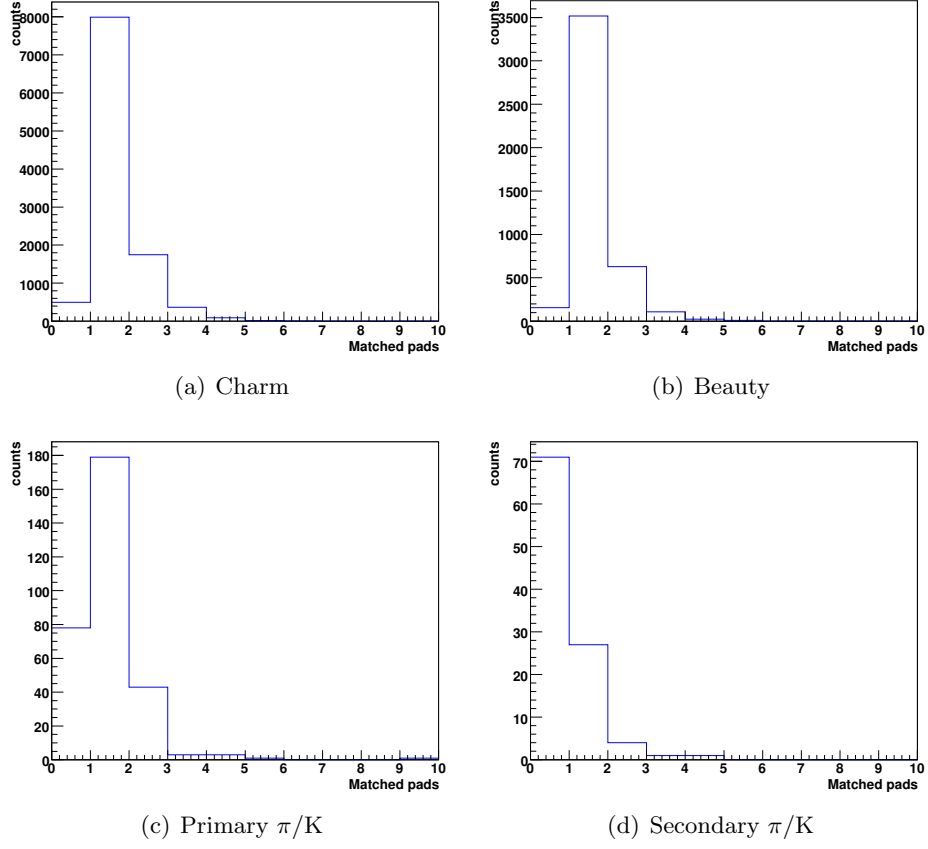


Figure 4.14: Number of matching strips in the inner ring of FMD3 for muon tracks with $p_t > 0.5$ GeV/c: the maximum distance between the fired strip and the track extrapolation is set to be $\Delta r < 4.5$ mm.

Source	Rejected (%)		
	TDV	FMD	Combined
Open charm	3.6	4.5	7.5
Open beauty	1.7	3.5	4.8
Primary π/K	6.5	25.1	29.0
Secondary π/K	31.7	68.3	76.9

Table 4.3: Rejection of muons with $p_t > 0.5$ GeV/c for signal and background sources with a TDV cut of 20 cm (second column), the matching with the FMD in a road of $\Delta r < 4.5$ mm (third column) and the combination of the two (fourth column).

FMD can consistently improve the secondary background rejection in the pseudorapidity region of $-3.4 < \eta < -2.5$.

It is worth noting, however, that the simulations performed assume a perfect efficiency of the FMD detector. Any possible bias arising from a realistic value of the efficiency should be studied in detail in the future.

4.1.3 Extensive tests on the Grid

A detailed study of the performance of the described methods for the heavy flavor measurements in the forward Muon Spectrometer requires the simulation of minimum bias events with high statistics ($\sim 10^8$ events). This was achieved through a large production on the Grid, called PDC08.

In preparation of the first circulating beams at the LHC, the methods were tested on p-p collisions at 14 TeV, rather than on Pb-Pb collisions. The production, performed between March 17 and May 12 2008, consists of 195×10^6 events, with the only request that at least one charged particle (not necessarily a muon) is in the spectrometer acceptance. The generation of hadronic background is performed through PYTHIA, with the heavy flavor production switched off. The latter were sampled from a fast generator of $c\bar{c}$ and $b\bar{b}$, based on PYTHIA parameterizations. The generator cocktail is completed by quarkonia production from parameterizations, but this contribution to the single muon spectrum is negligible.

The whole simulation chain for Muon Spectrometer, Silicon Pixel Detector (SPD), V0 and FMD was performed, from generation to reconstruction and, eventually, ESD creation.

For the production, the trigger Look-Up Tables were modified in such a way that the Low- p_t (High- p_t) cut selects muons with roughly $p_t \gtrsim 0.5$ GeV/c ($p_t \gtrsim 1$ GeV/c). We recall that the trigger cut is not sharp (see Section 2.2.4), hence the detection of particles below such values is reduced but not forbidden.

About 77 millions events were analyzed by exploiting the grid resources. The reconstructed tracks are identified as muons if they pass the Low- p_t trigger cut ($\sim 5 \times 10^5$ events). For each muon track, the longitudinal position of the primary vertex is provided by the SPD: it is therefore possible to build the $p_t - z_v$ histogram which will be fitted to subtract the decay muon contribution. The fitting procedure is slightly different from the one depicted in Section 4.1.1: the intermediate step of dividing the distribution by the vertex smearing $\rho(z_v)$ and fitting the result with a line was suppressed, and the slice of the bi-dimensional distribution at a given p_t bin is interpolated

with the function:

$$f(z_v; p_t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(z_v - \mu)^2}{2\sigma^2}} [\alpha(p_t) |z_{\text{abs}} + \Delta z_I - z_v| + \beta(p_t)] \quad (4.4)$$

which is the Gaussian distribution of the vertex position multiplied by the linear dependence on the distance between the vertex and the absorber. The function has four free parameters: the mean value μ and standard deviation σ of the Gaussian and the slope α and intercept β of the straight line. From the comparison with Eq. 4.2, it is possible to notice that the intercept of the line, $\beta(p_t)$, corresponds to the yield of heavy flavor muons, though biased by the secondary background contribution.

The parameter $\beta(p_t)$ was calculated for different p_t bins, and the result is plotted in Figure 4.15. As expected, the method can subtract the contribution of muons from the decay of π/K produced in the interaction point, reproducing the yield of heavy flavor muons plus secondaries.

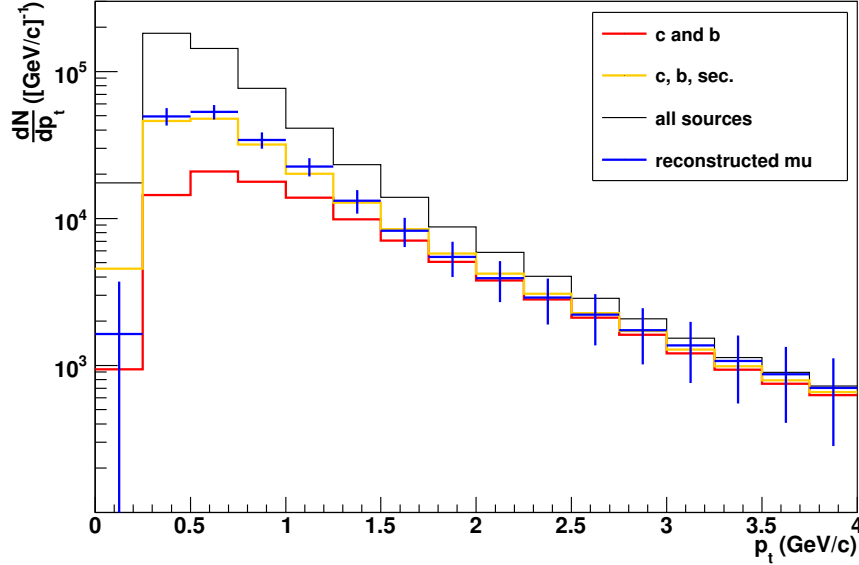


Figure 4.15: Transverse momentum of muons reconstructed in the ALICE Muon Spectrometer and passing a p_t trigger cut of about 0.5 GeV/c. The contribution of heavy flavor muons (red line) and heavy flavor plus secondary muons (yellow line) is shown. The muon yields extracted with the method described in Section 4.1.1 (blue line) reproduce the sum of signal and secondary background, as expected from Eq. 4.2: the decay muon contribution is subtracted.

Despite the longitudinal position of the vertex is centered at zero, the key parameter of the study is the free path travelled by particles, which is centered at $d = |z_{\text{abs}} + \Delta z_I| \simeq 130$ cm. The determination of the intercept is therefore affected by the wide extrapolation interval between $d \simeq 130$ cm and $d = 0$. In particular, the error on the parameter $\beta(p_t)$ is correlated with the (statistical) error on the slope $\alpha(p_t)$. At high p_t , where the contribution of the background is low, the distribution is rather flat in d , and the slope parameter is determined with large statistical errors, which is reflected in the error of the intercept. Further improvements of the fitting procedure could be performed in the future in order to provide better error estimation at large transverse momenta.

TDV cut performance

The high statistics of the PDC08 production allows to study the performance of the cut in the Transverse Distance at Vertex for the secondary background rejection in bins of p_t .

As already pointed out, in the ideal case of perfect determination of the initial particle momenta, the extrapolation of the muon tracks from the decay of heavy flavors is expected to point approximately to the interaction vertex, while large distances are expected for the extrapolated secondary muon tracks. In the reality, beyond the experimental resolution of the track reconstruction, the extrapolation is affected by the multiple scattering in the absorber which is important for low-momentum particles. The effect on the TDV is a resolution which improves with the muon p_t , allowing to better separate the different muon sources. This is shown in Figure 4.16: at low p_t the multiple scattering results in a broadening of the TDV for all sources; at high p_t , on the contrary, the mean TDV for muons produced before the absorber is shifted to lower values, while the same quantity calculated for secondary muons remains almost constant.

The effects of a TDV cut in different transverse momentum ranges were analyzed. Figure 4.17 shows the fraction of rejected muons with respect to the total for each source. As an example, the TDV cut values which limit the signal rejection to at most $\sim 5\%$ and $\sim 8\%$ in different p_t ranges are shown in Table 4.4. The ratio of signal (muons from charm plus muon from beauty) and secondary background after the cut, S/B , is also shown, thus

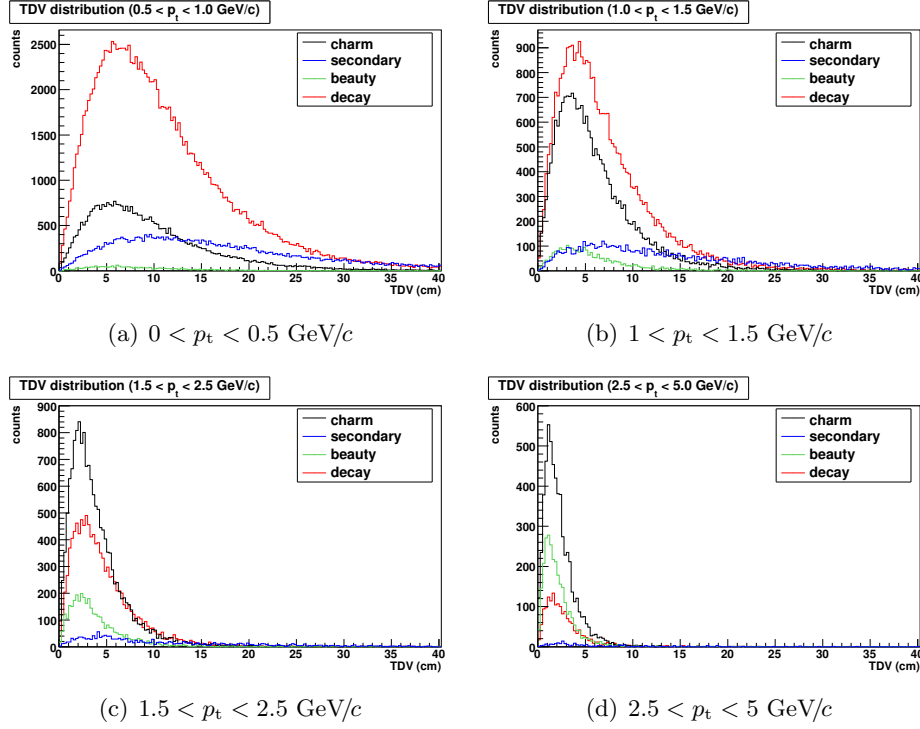


Figure 4.16: Distribution of the TDV variable for the various muon sources in different p_t ranges.

providing an information on the accuracy with which it is possible to extract the heavy flavor contribution.

The distribution of the sub-sample of muons passing the set of TDV cuts keeping the signal rejection below 5% in each p_t bin was fitted with the method for decay background subtraction: the results are shown in Figure 4.18. A comparison with Figure 4.15 shows that the yields of signal are almost unaffected, while the contribution of secondary background is reduced.

FMD cut performance

The secondary background in the acceptance region common to the Muon Spectrometer and the Forward Multiplicity Detector ($-3.4 < \eta < -2.5$) can be further reduced by exploiting the information of the latter detector. The effect of a cut in the distance between the extrapolated muon track to the FMD plane and the closest fired pad (Δr) was analyzed. Figure 4.19

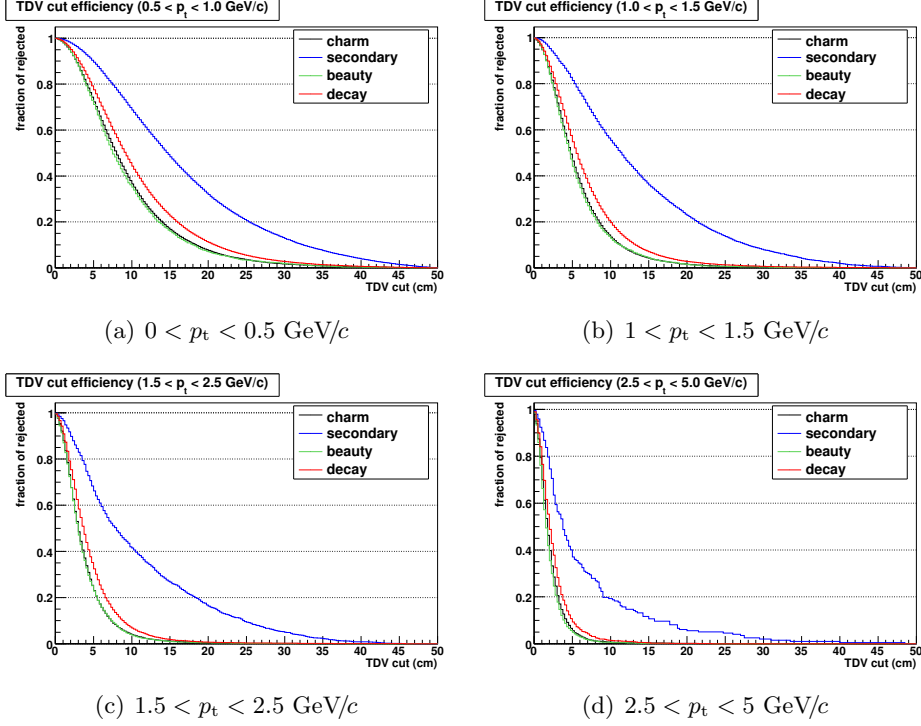


Figure 4.17: Fraction of rejected muons as a function of the TDV cut, for different p_t ranges.

shows the fraction of rejected muons for each source as a function of $\Delta r/\sigma_r$, where σ_r is the error on the track extrapolation. It is worth noting that the value of the rejected fraction at a given $\Delta r/\sigma_r$ does not vary significantly in different p_t bins for heavy flavor muons, while it shows consistent changes for secondary muons. This is an effect related with the multiple scattering: at low- p_t the error on the track extrapolation increases, thus making more difficult to separate the signal from the background. This can be seen by comparing Figure 4.19 with Figure 4.20, showing the effect of the cut as a function to the absolute distance Δr : the value of Δr at which the fraction of rejected muons is the same obtained with a fixed cut in $\Delta r/\sigma_r$ changes with p_t .

The performance of the TDV cut, the FMD matching, and the combination of the two for muons in the pseudo-rapidity interval $-3.4 < \eta < -2.5$ is summarized in Table 4.5: in each p_t bin, the cuts were chosen in such a way that the maximum signal rejection for the combination of the two methods is below $\sim 8\%$ (10% in the lowest bin). The sub-sample of muons

p_t bin (GeV/c)	TDV cut (cm)	S/B	Rejected muons (%) from			
			Open charm	Open beauty	Primary π/K	Secondary π/K
0.5–1.0	23.5	1.43	4.9	4.7	7.5	26.3
1.0–1.5	14.5	5	5	5.1	8.2	38.9
1.5–2.5	9.5	17.18	5.1	4.7	8.5	44.5
2.5–5.0	5.5	65.36	4.8	4.3	8.5	36
0.5–1.0	20	1.56	8.2	7.5	12	34.8
1.0–1.5	12.5	5.5	7.7	7.9	12.3	46.2
1.5–2.5	8.2	18.27	7.7	8	12.8	49.3
2.5–5.0	4.8	69.09	7.6	6.3	11.9	41.1

Table 4.4: TDV cut performance for different p_t bins: the cuts are selected in such a way to reject at most the $\sim 5\%$ (upper part) and $\sim 8\%$ (lower part) of signal. The ratio of accepted heavy flavor muons (charm plus beauty) and accepted secondary muons, S/B , is also shown.

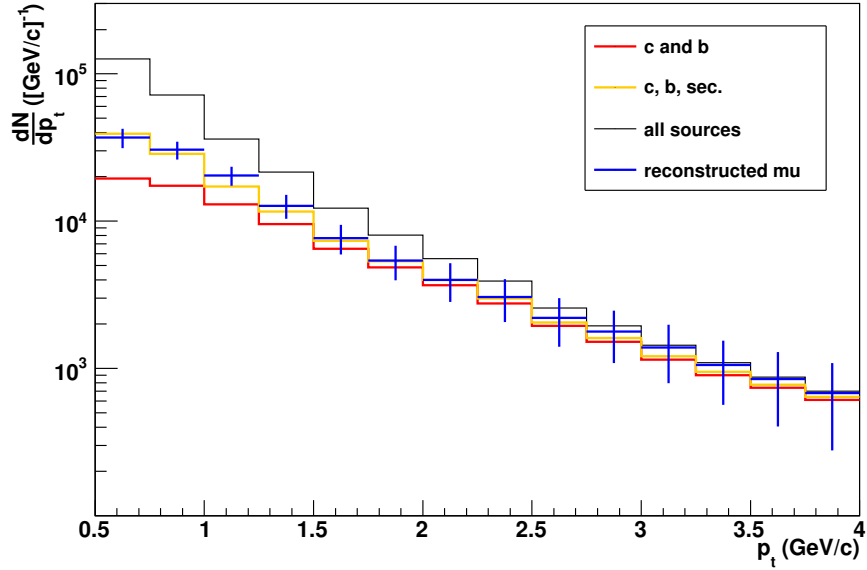


Figure 4.18: Same as Figure 4.15 with the additional condition that muons have to pass the set of TDV cuts keeping the signal rejection below 5% (see Table 4.4).

obtained after applying the described cuts was then fitted with the method for decay background subtraction: the result is shown in Figure 4.21. The picture shows that the combination of cuts allows to determine the heavy flavor muon yield down to $p_t \gtrsim 1.5$ GeV/c.

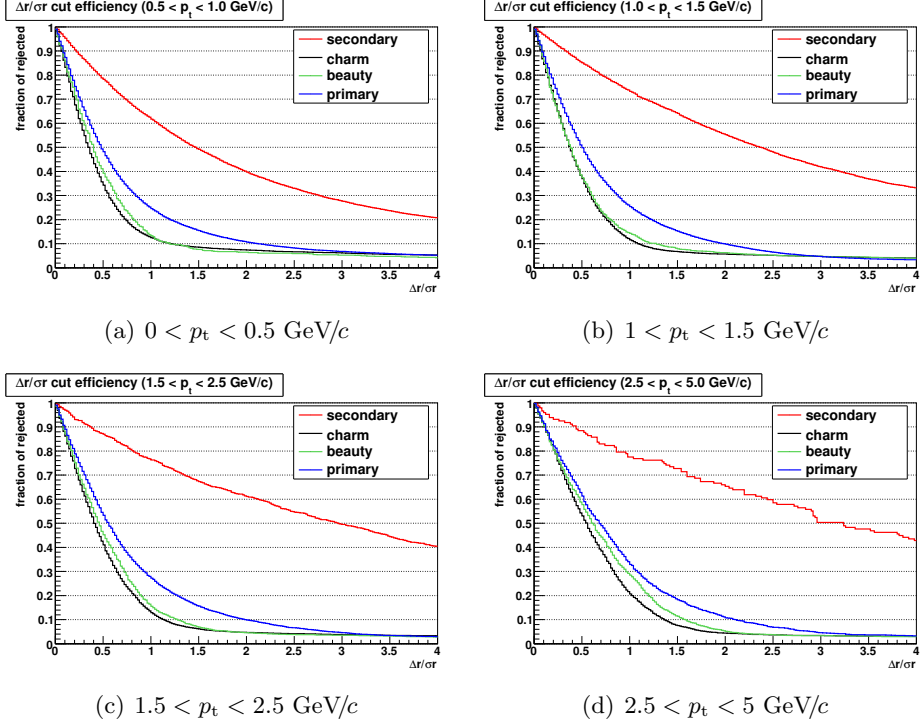


Figure 4.19: Fraction of rejected muons as a function of the distance between the position of the track extrapolated at the FMD and the closest fired strip, normalized to the extrapolation error ($\Delta r/\sigma_r$) for different p_t ranges.

4.1.4 Discussion

A study for the heavy flavor measurement in the low- p_t region with the ALICE Muon Spectrometer was presented. The contribution of muons from the decay of π/K produced in the interaction vertex can be subtracted with a method exploiting the different dependence shown by the muon sources on the longitudinal position of the vertex. It was proved that the decay muon subtraction is effective both in Pb-Pb and p-p collisions. However, the result of the method is the sum of the yields of muons from the semi-leptonic decay of charm and beauty and of muons produced in the interaction with the front absorber, the latter being non-negligible for $p_t \lesssim 2.5 \text{ GeV}/c$.

The extraction of signal for lower transverse momenta, in the region where the heavy flavor contribution is dominated by charm, requires the subtraction of the secondary background through other methods. This can be partially reduced with a cut on the Transverse Distance at Vertex, al-

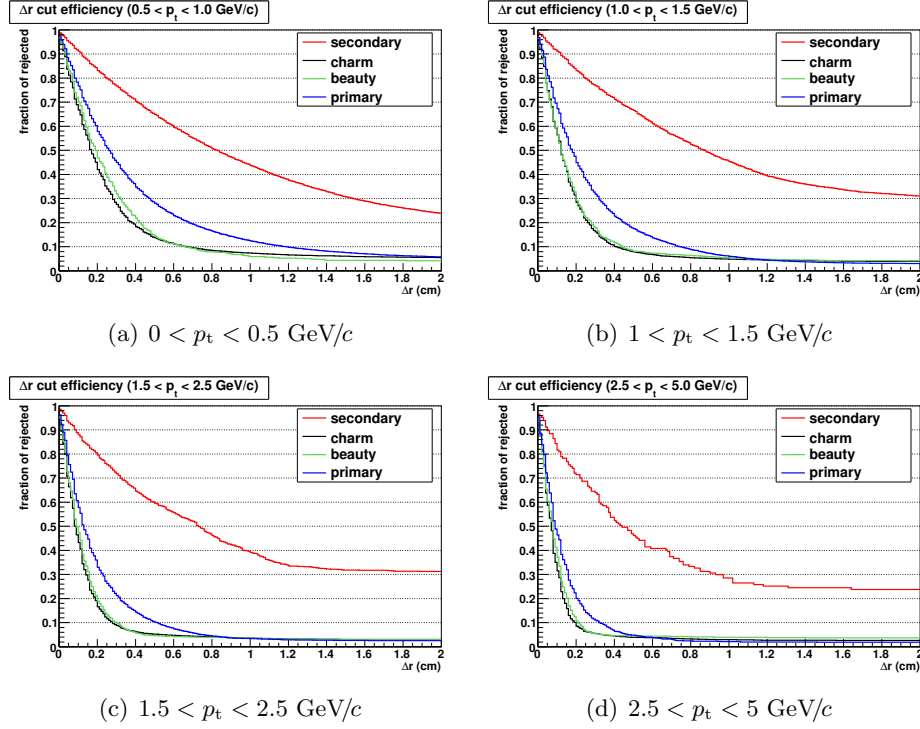


Figure 4.20: Fraction of rejected muons as a function of the absolute distance between the position of the track extrapolated at the FMD and the closest fired strip (Δr) for different p_t ranges.

lowing to push measurements down to $p_t \gtrsim 2 \text{ GeV}/c$. The advantages of the method are that it can be performed track-by-track and is effective in both Pb-Pb and p-p collisions.

Finally, in p-p collisions, where the charged particle multiplicity is limited, the information provided by the Forward Multiplicity Detector, placed between the interaction point and the muon absorber, can be exploited to further reduce the secondary background contribution. In the limited region of intersection between the spectrometer and FMD acceptances ($-3.4 < \eta < -2.5$) the heavy flavor yield can be extracted down to $p_t \gtrsim 1.5 \text{ GeV}/c$. The results are obtained by assuming a perfect efficiency of the FMD detector: further studies are needed to account for any bias in the background rejection due to an efficiency lower than 1.

The measurement of muons from charm and beauty with $p_t \geq 0$ will probably require the use of Monte Carlo simulations. In the following we will discuss a possible technique, which should have a limited model dependency.

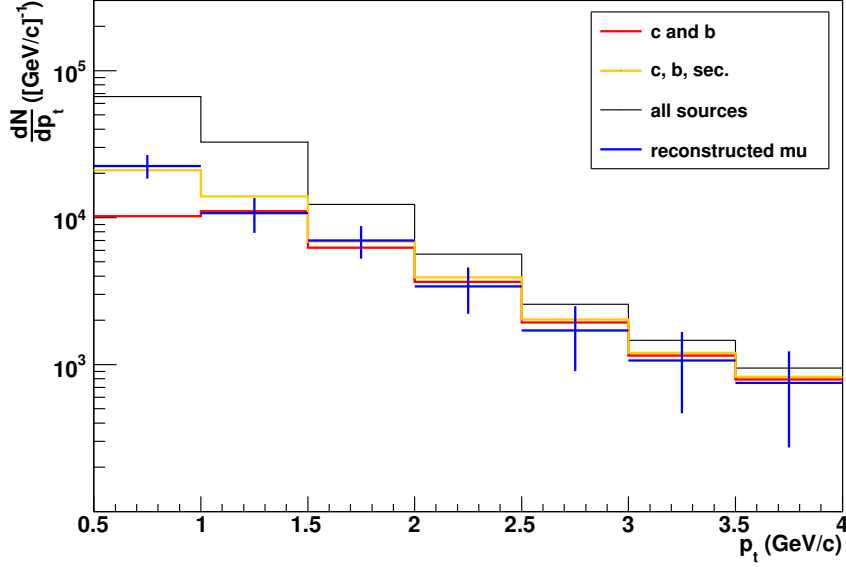


Figure 4.21: Transverse momentum of muons reconstructed in the ALICE Muon Spectrometer and entering the FMD acceptance ($3.4 < \eta < -2.5$). The muons have to pass a p_t trigger cut of about 0.5 GeV/c, the TDV set of cuts in Table 4.5 and to match a fired strip in the FMD at a distance not larger than 2.5 times the extrapolation error ($\Delta r/\sigma_r < 2.5$).

The method exploiting the information of the longitudinal position of the vertex is based on a fit, with the function of Eq. 4.4, to the bi-dimensional $p_t - z_v$ muon distribution of Eq. 4.2. The method returns two parameters related with the three muon sources (the terms $B_{\text{sec}}(p_t)$ and $A_{\text{sec}}(p_t)$ are not independent):

$$\begin{cases} \alpha(p_t) = A_{\pi/K}(p_t) - A_{\text{sec}}(p_t) \\ \beta(p_t) = B_{c/b}(p_t) + B_{\text{sec}}(p_t) \end{cases} \quad (4.5)$$

An additional relation between any of the sources would allow to close the equation system and measure each contribution.

It is worth noting that there is a strict correlation between the number of muons from the decay of π/K produced in the interaction point and the ones produced in the absorber: given an initial π/K distribution, the decay and secondary muons yields depend only on the interaction with the absorber, which can be safely described with Monte Carlo simulations. The result could probably be affected by the uncertainties in the knowledge of the initial

π/K distribution, but this can be reduced with an iterative comparison with data.

The knowledge of the ratio of secondary over decay muons per p_t bin, together with the determination of the $\alpha(p_t)$ and $\beta(p_t)$ parameters of the equation system 4.5 would therefore be enough to separate the muon sources contribution at all p_t .

(a) $0.5 < p_t < 1$ TDV < 28 cm

Source	TDV	Rejected (%)	
		FMD	Combined
Open charm	3.5	6.7	9.9
Open beauty	5.3	5.9	10.8
Primary π/K	5.7	8.3	13.4
Secondary π/K	24	33	49
S/B	0.78	0.86	1.09

(b) $1 < p_t < 1.5$ TDV < 19 cm

Source	TDV	Rejected (%)	
		FMD	Combined
Open charm	3.2	5.3	8.2
Open beauty	3.4	5.5	8.4
Primary π/K	4.5	6.6	10.6
Secondary π/K	31.8	48.3	63.4
S/B	3.07	3.96	5.42

(c) $1.5 < p_t < 2.5$ TDV < 12 cm

Source	TDV	Rejected (%)	
		FMD	Combined
Open charm	3.6	4.6	7.8
Open beauty	3.5	4.4	7.6
Primary π/K	5.2	6.8	11.7
Secondary π/K	42.8	55.2	69.6
S/B	12.4	15.63	22.3

(d) $2.5 < p_t < 5$ TDV < 6 cm

Source	TDV	Rejected (%)	
		FMD	Combined
Open charm	3.1	4.7	7.5
Open beauty	2.7	5.2	7.6
Primary π/K	6	7.2	12.9
Secondary π/K	36.7	58.5	70.1
S/B	53.6	80.18	108.05

Table 4.5: TDV and FMD cuts performance for different p_t bins. Results refer to a FMD cut of $\Delta r/\sigma_r < 2.5$. The TDV cut is selected in such a way that the fraction of rejected signal with both cuts applied is below $\sim 8\%$ (below 10% in the lowest p_t bin). The ratio of accepted heavy flavor muons (charm plus beauty) and accepted secondary muons, S/B , is also shown.

4.2 Effects of heavy-quark energy loss in the dimuon continuum

One of the most remarkable results obtained at the Relativistic Heavy Ion Collider (RHIC) is the high-momentum leading-particle suppression in nucleus-nucleus with respect to proton-proton collisions [12, 13]. The effect can be explained in terms of the attenuation of energetic partons produced in the initial hard scattering process, as a consequence of the interaction with the dense QCD medium, which is expected to be formed in heavy-ion collisions. The high- p_t region of the hadron spectra is thus depleted in favor of the low- p_t one. Several theoretical works on this subject identify the main mechanism of partonic energy loss with the medium-induced gluon radiation [14, 15]. The interaction between the hard parton and the high-density medium results in an increased emission of gluons with a consequent softening of the parton spectrum.

The amount of energy loss depends on the nature of the partons. In the vacuum the radiation is depleted for angles $\Theta < m/E$ (dead cone effect), where m is the mass of the parton and E its energy. Generically, medium-induced gluon radiation is found to fill the dead cone, but it is reduced at large gluon energies compared to the radiation off light quarks [16]. The interplay between the two effects results in a smaller energy loss for massive quarks than for massless ones. However, recent data from RHIC [17, 18], showing a suppression of the non-photonic electrons (expected to be produced in the semi-leptonic decay of charm and beauty hadrons) in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV with respect to proton-proton, indicate a substantial energy loss of heavy quarks as well.

The study of medium-induced heavy quark energy loss will be one of the most captivating topics at the LHC, where the high energy per nucleon-nucleon collisions in Pb-Pb, about 30 times larger than at RHIC, will open up a new energy domain for the exploration. Thanks to its unique particle identification abilities, the ALICE experiment will be able to carry out a direct comparison of the attenuation of light-flavor hadrons, D mesons and B mesons, allowing a better understanding of the mass dependence of the phenomenon [19]. An important contribution to the study in the forward rapidity region can be provided by the ALICE Muon Spectrometer. At the LHC energies, indeed, high- p_t muons are predominantly produced in

semi-leptonic decays of heavy flavored hadrons (mostly B mesons for $p_t^\mu \gtrsim 4 \text{ GeV}/c$). Hence the muon p_t distribution is sensitive to b-quark energy loss effects [20].

The modification of heavy flavored hadrons and their decay muon spectra in heavy-ion collisions should be carefully taken into account in the analysis of quarkonia resonances as well, since it affects the shape of the dimuon continuum. Heavy quarkonia appears as peaks in the invariant mass distribution of opposite sign muon pairs. The main sources contributing to the dimuon continuum can be divided in two categories:

- **combinatorial**, consisting in opposite sign muons from the decay of pions and kaons as well as uncorrelated decay of charm and beauty hadrons.
- **correlated**, consisting in opposite sign muons from the chain decay of one $c\bar{c}$ or $b\bar{b}$ pair.

The former source can be subtracted with event mixing techniques, based on the principle that the combinatorial background can be well reproduced by combination of muons from different events, which are uncorrelated by definition. The latter, on the contrary, can be described only with a good knowledge of the physics that lies behind.

The goal of the following study is to provide a qualitative description of the expected correlated background variation due to the medium-induced energy loss of the heavy flavors in the medium.

4.2.1 Quenching weights

The modelling of heavy flavor energy loss via medium-induced gluon radiation used in the following study is based on the quenching weights in the multiple soft scattering approximation [21], which are derived in the framework of the Baier-Dokshitzer-Mueller-Peigné-Schiff (BDMPS) formalism [14, 15]. The calculation of mass dependent quenching weights is implemented in a publicly available CPU-inexpensive FORTRAN routine accompanying the paper of Ref. [22].

In a simplified picture, an energetic parton produced in a hard collision undergoes, along its path in the dense medium, multiple scatterings in a

Brownian-like motion with mean free path λ , which decreases as the medium density increases. In this process, the gluons in the parton wave function pick up a transverse momentum k_t with respect to its direction, and they may eventually decohere and be radiated. The characteristic energy of the radiated gluon,

$$\omega_c = \frac{1}{2}\hat{q}L^2 \quad (4.6)$$

is proportional to the square of the in-medium path length L of the parton and to the transport coefficient $\hat{q}$. The latter is defined as the average medium-induced transverse momentum squared transferred to the parton per unit path length,

$$\hat{q} = \frac{\langle k_t^2 \rangle_{\text{med}}}{\lambda} \quad (4.7)$$

and it is expected to be proportional to the medium density.

In absence of the medium, the heavy flavored hadron cross section can be expressed with the collinearly factorized expression:

$$\begin{aligned} \frac{d^2\sigma_{vacuum}^{AB \rightarrow h}}{dp_t dy} &= \sum_{i,j} \int dx_{i/A} dx_{j/B} dz f_{i/A}(x_{i/A}) f_{j/B}(x_{j/B}) \times \\ &\times \frac{d^2\sigma^{ij \rightarrow Q}}{dp_{t,Q} dy_Q} \times \frac{D_{Q \rightarrow h}(z)}{z^2} \end{aligned} \quad (4.8)$$

where $f_{i/A}(x_{i/A})$ ($f_{j/B}(x_{j/B})$) is the parton distribution function for parton i (j) carrying the fraction x_i (x_j) of the nucleon A (B) momentum; $\sigma^{ij \rightarrow Q}$ is the hard partonic scattering cross section for the heavy quark Q production and $D_{Q \rightarrow h}(z)$ is the fragmentation function of the quark into the hadron h , carrying a fraction z of the parent parton momentum.

The energy loss induced by a dense medium can be obtained by modifying Eq. 4.8 into:

$$\begin{aligned} \frac{d^2\sigma_{medium}^{AB \rightarrow h}}{dp_t dy} &= \sum_{i,j} \int dx_{i/A} dx_{j/B} dz d\Delta E f_{i/A}(x_{i/A}) f_{j/B}(x_{j/B}) \times \\ &\times \frac{d^2\sigma^{ij \rightarrow Q}}{dp_{t,Q} dy_Q}(p_{t,Q} + \Delta E/c) \times P\left(\frac{\Delta E}{E}, L, \hat{q}, \frac{m_Q}{E}\right) \times \frac{D_{Q \rightarrow h}(z)}{z^2} \end{aligned} \quad (4.9)$$

where the quenching weight $P(\Delta E/E, L, \hat{q}, m_Q/E)$ is the probability that

the hard parton Q of mass m_Q and energy E , radiates the energy ΔE due to the scattering in the spatially extended QCD matter.

The feature of the medium enter the quenching weights via the path length L and the transport coefficient $\hat{q}$. The former can be calculated in the framework of the Glauber model for the collision geometry [23], with the assumption that the distribution of the parton production points in the transverse plane and the transverse density of the medium, $\rho_{\text{coll}}(x, y; b)$, are both proportional to the impact parameter (b) dependent product of the thickness functions of the two nuclei. In the following the nuclear thickness function is defined as the z -integrated Wood-Saxon density profile. For a parton with production point (x_0, y_0) and azimuthal direction $\vec{u} = (u_x, u_y)$, the path length is defined as [24]:

$$L = \frac{\int_0^\infty d\xi \xi \rho_{\text{coll}}(x_0 + \xi u_x, y_0 + \xi u_y; b)}{0.5 \int_0^\infty d\xi \rho_{\text{coll}}(x_0 + \xi u_x, y_0 + \xi u_y; b)} \quad (4.10)$$

Concerning the transport coefficient, its profile at central rapidity is assumed to be proportional to the particle multiplicity, which is correlated with the entropy density. The total multiplicity is the sum of both soft and hard contributions which scale with the number of participants and with the density of binary collisions, respectively. For this study, the limit case of a transport coefficient proportional to the latter density is considered. However it is worth noting that, due to the onset of saturation effects, the differences arising by assuming a proportionality to the number of participants rather than to binary collisions are limited. In addition, in order to account for the reduced medium density in the forward direction, a dependence on the pseudo-rapidity was introduced: $\hat{q}$ is assumed to scale with the gluon pseudo-rapidity density of the medium, dN_g/dV , which scales in η as $dN_g/d\eta$. Finally, assuming the pseudo-rapidity density of charged particles and of gluons to have the same dependence on η , the transport coefficient can be written as [20]:

$$\hat{q}(x, y, \eta) = k \rho_{\text{coll}}(x, y) \left[\frac{dN_{ch}}{d\eta}(\eta) \bigg/ \frac{dN_{ch}}{d\eta}(0) \right] \quad (4.11)$$

where k is a constant that sets the scale of $\hat{q}$.

Such scale can be constrained by comparisons with recent RHIC data [12]. Figure 4.22 shows the π^0 nuclear suppression factor as a function

of the transverse momentum for 0-5% Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The data are compared to the calculations based on quenching weights for massless partons [25], assuming average transport coefficient values ranging from 0.3 GeV²/fm to 101.4 GeV²/fm. The comparison are shown only for $p_t > 5$ GeV/c as that is where the calculations are considered applicable. The best fit is obtained with $\langle \hat{q} \rangle = 13.2^{+1.8}_{-4.2}$ GeV²/fm. In a conservative ap-

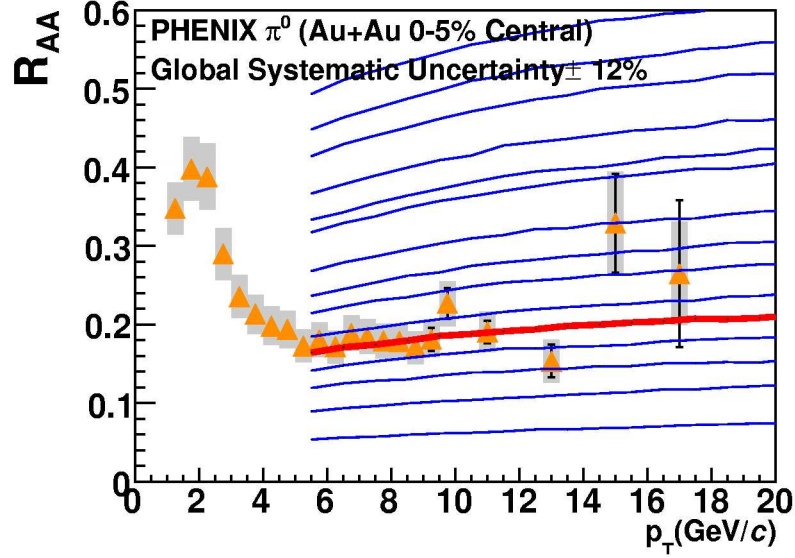


Figure 4.22: π^0 nuclear suppression factor as a function of the transverse momentum for 0-5% Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, measured by the PHENIX experiment [12]. The prediction for the Parton Quenching Model (PQM) [25] with $\langle \hat{q} \rangle$ values ranging from 0.3 GeV²/fm to 101.4 GeV²/fm are also shown (blue lines). The red line indicates the best fit case of $\langle \hat{q} \rangle = 13.2$ GeV²/fm.

proach, the analogous quantity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at the LHC, is expected to be in between 25 GeV²/fm and 100 GeV²/fm [25].

4.2.2 Simulations

The simulation of heavy quark energy loss in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV is based on the Monte Carlo approach introduced in Ref. [25], with the necessary adaptations to cope with correlated quark pairs instead of single quarks.

Charm and beauty heavy quark pairs were produced with the PYTHIA

event generator [5] (version 6.214), tuned to reproduce the NLO pQCD calculations performed by Mangano-Nason-Ridolfi (MNR) [9], as described in Ref. [26]. The CTEQ 4L parton distribution functions [27] are used as inputs with EKS98 nuclear corrections [10]. In order to achieve a high statistics in the whole phase space, the generation was performed in different bins of the hard partons transverse momentum, starting from a minimum of $p_{t,\text{hard}}^{\min} = 2.1$ GeV/ c and $p_{t,\text{hard}}^{\min} = 2.75$ GeV/ c for charm and beauty production, respectively. A high-statistics five dimensional distribution with $p_{t,1}$, $p_{t,2}$, y_1 , y_2 , $\Delta\phi$, of the heavy quark pairs was then created.

The energy loss is then applied as follows:

1. generation of the quark pair sampled from the obtained 5-dimensional distribution.
2. determination of the two input parameters L and $\hat{q}$: the parton production point is sampled in the transverse plane (x, y) according to the Glauber model density of binary collision, $\rho_{\text{coll}}(x, y; b)$. The azimuthal propagation direction for the first quark of the pair is then sampled with a uniform distribution ($0^\circ < \phi < 360^\circ$); the corresponding direction of the anti-quark is automatically determined by the $\Delta\phi$ angle. The path length of each quark is finally calculated, together with the transport coefficient, which is an average of the local $\hat{q}(x, y)$ along the path of the partons.
3. sampling of an energy loss ΔE value, according to the quenching weight $P(\Delta E/E, L, \hat{q}, m_Q/E)$. The quark kinematic is changed to $p'_t = p_t - \Delta E/c$. Since the partons co-move with the longitudinally expanding medium it is expected that the variation of the kinematic parameters along the direction of the expansion is reduced. This is parametrized by stating that either the rapidity or the longitudinal momentum remain constant. Simulations in the two different cases $y' = y$ and $p'_z = p_z$ are therefore performed.
4. fragmentation of the heavy quarks into hadrons using the Peterson fragmentation functions [28].
5. hadron decay into muons according to the spectator model [29], which assumes that the heavy quark in a meson is independent of the light quark and is decayed as a free particle. The momentum of the hadron

is assumed to be entirely carried by the constituent heavy quark and the three-body decay $c \rightarrow s\mu\nu$ and $b \rightarrow c\mu\nu$ are performed. In a following step, the c quark from the decay of b is decayed as well. The obtained muons are weighted with the corresponding charm (beauty) semi-muonic branching ratio of 7.7% (10.5%).

Quenched and unquenched distributions are obtained including or excluding the third step.

For the determination of the correlated background, a realistic number of $c\bar{c}$ and $b\bar{b}$ pairs is generated per each event by sampling from a Poisson's distribution with the mean value equal to 102 and 4.06, respectively, corresponding to the average number of $Q\bar{Q}$ pairs expected in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV in a 10% centrality class. The values are summarized in Table 4.6.

	Charm	Beauty
$N_{Q\bar{Q}}$	102	4.06
C_{shad}	0.65	0.84
$\text{BR}_{Q \rightarrow \mu}$	7.7%	10.5%

Table 4.6: Main parameters for heavy quark production and their semi-leptonic decay in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

The invariant mass of the opposite sign muon pairs from the chain decay of one $Q\bar{Q}$ is then built. Each muon is weighted with the detection probability, defined as the product of the acceptance, tracking efficiency and trigger efficiency, provided by the fast simulation of the spectrometer response. Figure 4.23 shows the invariant mass distribution of opposite sign muon pairs from the semi-leptonic decay of a $c\bar{c}$ (left panel) and $b\bar{b}$ (right panel) pair (correlated background) in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, for an average transport coefficient of $\langle\hat{q}\rangle = 0$ (no energy loss), 25 and 100 GeV²/fm. In the simulation the rapidity of the parton is assumed not to be modified by quenching. The assumption that the longitudinal momentum does not undergo variation is investigated in Figure 4.24: the two cases do not show significant variations.

As expected, the softening of the hadron spectra due to heavy quark energy loss results in a softening of the invariant mass distribution, with a consequent depletion of the background under the Υ and J/ψ peak.

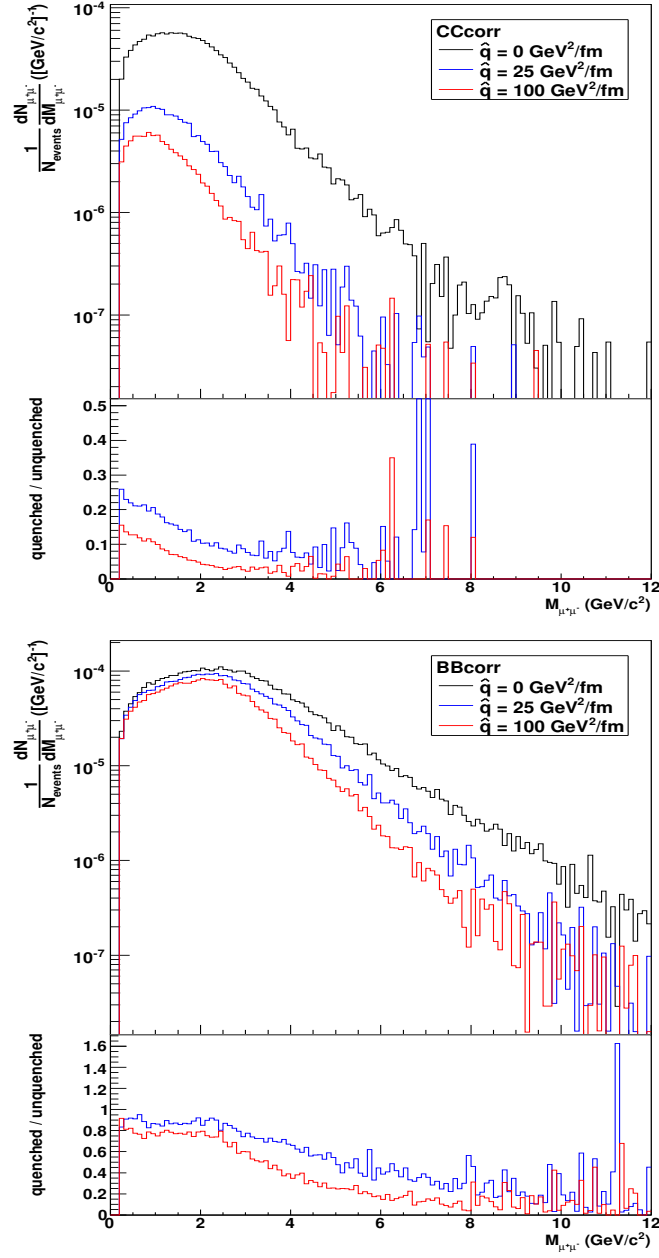


Figure 4.23: Invariant mass distribution of opposite sign muon pairs from the semi-leptonic decay of a $c\bar{c}$ (left panel) and $b\bar{b}$ (right panel) pair (correlated background) in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Muons are weighted with the detection probability, with a p_t trigger cut of about 1 GeV/c. In simulations, the rapidity of the parton is assumed to be unchanged by the quenching. The ratio between the quenched and unquenched case is also shown.

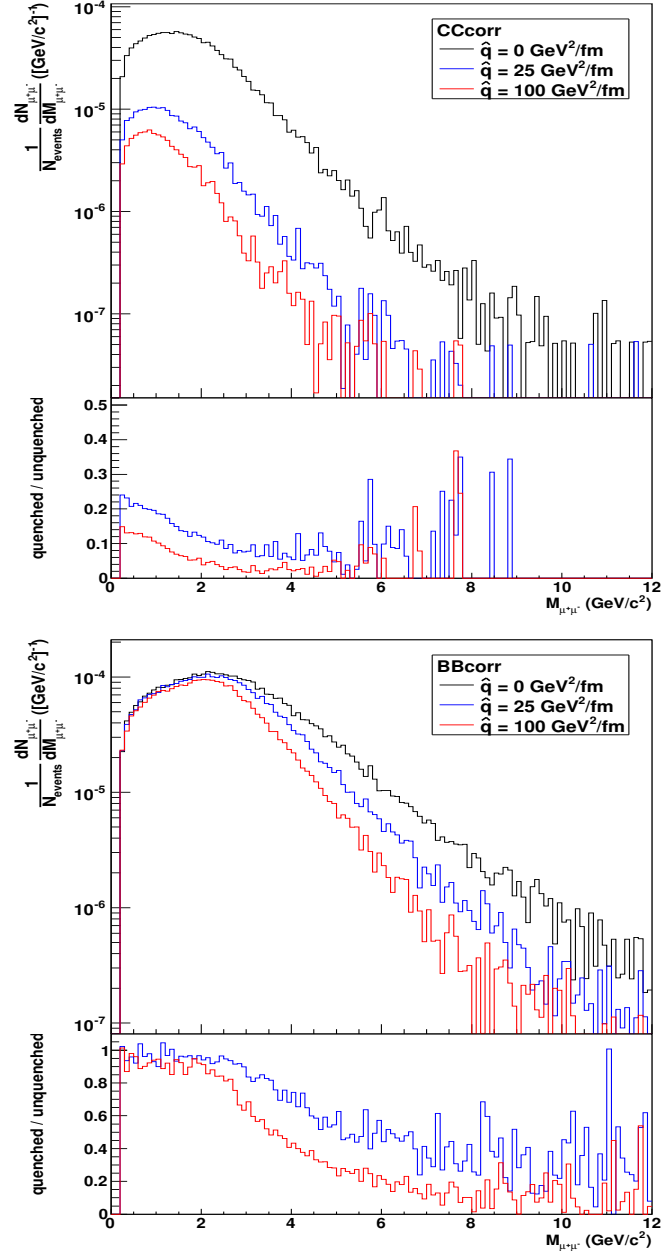


Figure 4.24: Same as Figure 4.23, but in simulations, the longitudinal momentum p_z of the parton is assumed to be unchanged by the quenching, while the parton rapidity changes with its energy.

It is worth noting that, due to the trigger cuts on the muon transverse momentum applied by the spectrometer, the energy loss results in a global reduction of the detected pairs. The effect is more pronounced for muons coming from the decay of charmed particles, whose lower mass gives rise to a softer muon spectrum.

The total correlated background, sum of the correlated $B\bar{B}$ and $D\bar{D}$ contribution is shown in Figure 4.25 and Figure 4.26 for the two different assumptions of unmodified rapidity or longitudinal momentum, respectively.

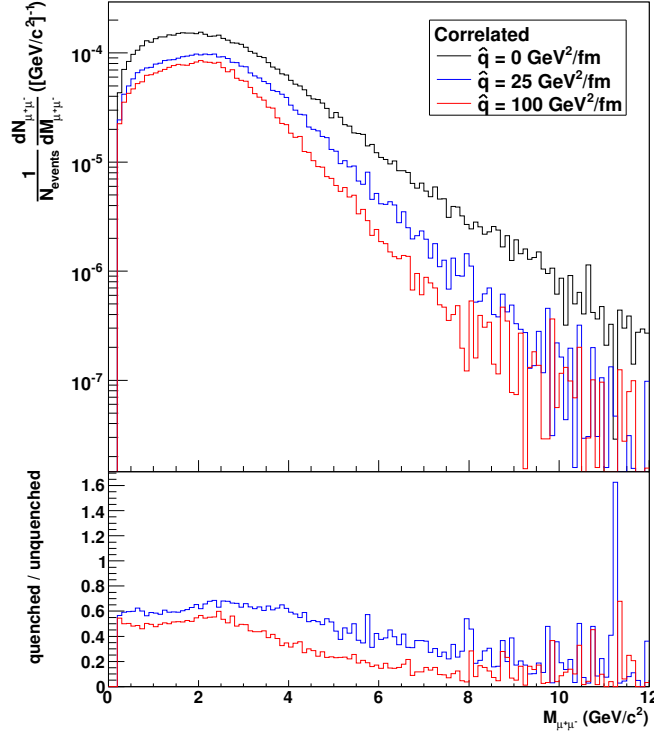


Figure 4.25: Invariant mass distribution of the correlated background, obtained as the sum of the $B\bar{B}$ and $D\bar{D}$ contributions of Figure 4.23.

4.2.3 Discussion

The calculation of heavy flavor energy loss is based on quantities, such as the in-medium path length L and the transport coefficient $\hat{q}$, which depend on the modelization of the medium features. In the current study, the medium geometry is described in the framework of the Glauber model, with a Wood-

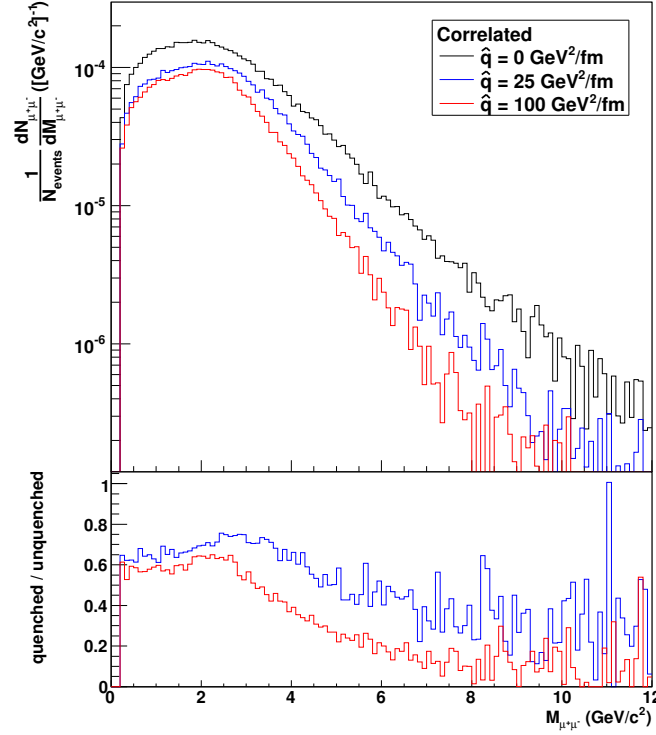


Figure 4.26: Invariant mass distribution of the correlated background, obtained as the sum of the $B\bar{B}$ and $D\bar{D}$ contributions of Figure 4.24.

Saxon density profile for nuclei. The expected reduction of the medium-induced energy density in the forward direction is taken into account by assuming the transport coefficient to scale with the pseudo-rapidity density of charged particles. The model, however, assumes that the entire energy of the collision is released at $z = 0$ along the beam line: only the transverse dimension is taken into account. The configuration is a good approximation in the description of the parton dynamics at central rapidities, but some modification could occur at forward rapidities. From geometrical considerations, it turns out that, at $y = 0$, the amount of crossed matter depends only on the azimuthal direction (ϕ) in the transverse plane, orthogonal to the beam line. At forward rapidities, on the contrary, the dependence on ϕ is attenuated (and vanishes in the limiting case of $y \rightarrow \infty$). This should introduce a correlation between the energy loss of the quark and the anti-quark emitted back-to-back in the center of mass system, which can in principle enhance the effects of the loss. Further studies with a better modelization

of the medium evolution at forward rapidities could be therefore carried out for a better quantitative understanding of the phenomenon.

Chapter 5

Conclusions

ALICE Muon Spectrometer trigger system

In view of the short-coming data taking, the whole ALICE collaboration spent lots of efforts in order to improve the understanding of the detector performances: in this thesis some of the progresses done by the Muon Spectrometer trigger system are described.

The effects of a non-perfect alignment of the trigger chambers on the dimuon trigger efficiency were studied in details. The simulation results show that the measured efficiency depends on the relative position of the misaligned plane in the trigger system and the direction along which the chamber is moved with respect to the others. Due to the trigger algorithm design, the effects of a misalignment in the vertical direction (y), orthogonal to the magnetic field, are negligible up to few millimeters. On the contrary, a shift of the chambers in the horizontal direction (x) is a more delicate issue, which puts some constraints on the alignment precision which is required during installation. In particular, it is found that the chamber positioning should be done with an accuracy not worse than about 2 mm.

The trigger system alignment was recently performed through theodolite and photogrammetry measurements. The results show an accuracy of about 1 mm along y and of about 1.4 mm along x at one sigma level. Preliminary simulations were performed by introducing a chamber misalignment sampled from the measured distributions: the resulting reduction of the trigger efficiency with respect to the perfect alignment case was found to be lower than 1% for J/ψ and of 2% for Υ .

Another important variable affecting the trigger efficiency for muons is the intrinsic efficiency of the Resistive Plate Chambers. Although the efficiency of each chamber was measured during the validation tests after production (before the final installation in the ALICE cavern), and proved to be of the order of 95% or higher, the possibility to monitor any global or local variation of such value for each RPC is fundamental for a large area detector designed to collect data over a long time period.

In this thesis, a method for measuring the efficiency of each chamber from data was developed. The method is based on the trigger response and estimates the efficiency of the smallest unit of the detector entering the trigger algorithm, the local trigger board, thus providing an efficiency map for each RPC. The granularity of the maps changes with the segmentation from a minimum of 7 to a maximum of 18 efficiency points for the chambers furthest and closest to the beam pipe, respectively.

Few minutes of data taking will allow to collect enough statistics for the determination of the efficiency with a statistical accuracy better than 1%. The systematics of the method depend on the number of hits in the trigger chambers and are therefore larger in Pb-Pb than in p-p collisions. However, in both cases, they should be lower than 1%, for a chamber efficiency of 95% or higher.

Heavy flavor physics

The heavy flavor measurement in both p-p and Pb-Pb collisions is a central issue in the ALICE physics programme and will be carried out in the whole experiment acceptance, from mid to forward rapidities. In the latter case, difficulties arise from the impossibility to measure the secondary vertex through the silicon tracker at $|y| > 1.98$. The contribution of muons from the semi-leptonic decay of beauty hadrons is expected to dominate the high- p_t (high invariant mass) region of the single-muon (dimuon) distribution, and can then be extracted through fitting procedures. The determination of the charm yields, on the contrary, is a more challenging task, since it requires the subtraction of background muons from the decay of pions and kaons at low- p_t .

In this thesis, three methods were developed for background subtraction in the single-muon p_t spectrum down to low- p_t . The first method taken into account exploits the muon yield dependence on the distance between the

hadron-hadron interaction point along the beam line and the front absorber, which is expected to be flat for the signal and, in part, for the background produced in the absorber, and linearly growing for muons from the decay in flight of primary π/K . The simulation results show that the latter contribution can be totally subtracted at all transverse momenta, both in Pb-Pb and p-p collisions.

The remaining background source, consisting of muons produced in the front absorber, can be partially eliminated with other two methods. The first is based on the distance between the extrapolation of the reconstructed track in the spectrometer to the longitudinal position of the interaction vertex and the vertex itself. It is proved that a cut on this variable allow to measure heavy flavor muons down to $p_t \gtrsim 2$ GeV/ c in p-p collisions. The method is effective also in Pb-Pb collisions.

Finally it is shown that in p-p collisions, where the charged particle multiplicity is limited, the information of the Forward Multiplicity Detector can be used to further improve the background rejection down to $p_t \gtrsim 1.5$ GeV/ c in the acceptance region common to the Muon Spectrometer and the FMD.

The last topic discussed in this thesis is related with the heavy flavor energy loss in the hot and dense medium formed in Pb-Pb collisions. The energy loss results in a softening of the charm and beauty hadrons transverse momentum spectra, which is reflected in the muon p_t distribution measured by the ALICE Muon Spectrometer. The consequent effects on the dimuon spectrum at forward rapidities have been studied in this thesis, with the aim of understanding the behavior of the correlated muon pair invariant mass under the mass region of quarkonia.

The heavy flavor energy loss was simulated through the quenching weights developed in the BDMPS formalism, accounting for the finite mass of the quarks. The detection probability for muons coming from charm and beauty decay was obtained with a fast simulation. The final results show a significant softening of the invariant mass of muon pairs from the correlated decay of $c\bar{c}$ quarks as well as an overall reduction of the dimuon yields from this source. The latter phenomenon is related with the trigger cut applied by the spectrometer and is a direct consequence of the shift of the single muon p_t spectrum towards low- p_t . These effects are proved to be limited for

dimuons from the correlated decay of $b\bar{b}$ pairs due to the higher mass of the beauty hadrons which limits the medium-induced gluon radiation. Nevertheless, the overall effect is a reduction of the correlated dimuon continuum under the J/ψ and Υ mass regions.

List of Tables

1.1	Quarkonium dissociation temperatures in the screening theory framework.	24
2.1	Summary of the position and sizes of the FMD detector rings.	36
2.2	Examples of declustering for bit pattern with cluster size from N=1 to N=5.	50
2.3	Examples of conversion of the bit patterns into mini-road Singles and Doubles, and the subsequent DS reduction.	51
3.1	Example of strip pattern modification due to the misalignment of MT12 plane along x	62
3.2	Example of strip pattern modification due to the misalignment of one plane along y	64
3.3	Example of strip pattern modification due to the misalignment of one station along x	67
3.4	Multiplicity scenarios adopted in simulations.	86
3.5	Muon multiplicity per event in the trigger chambers.	86
3.6	Total number of hits (from muons and background) per event on trigger chambers.	88
3.7	Explanation of the 16 bits word associated to an ESD track with the results of the trigger chamber efficiency determination algorithm.	93
4.1	Muon sources decay lengths	99
4.2	Effects of a TDV cut of 21 cm in the rejection of muons with $p_t > 0.5$ GeV/ c for signal and background sources.	112

4.3	Rejection of muons with $p_t > 0.5$ GeV/ c for signal and background sources with a TDV cut of 20 cm (second column), the matching with the FMD in a road of $\Delta r < 4.5$ mm (third column) and the combination of the two (fourth column). . .	115
4.4	TDV cut performance for different p_t bins.	121
4.5	Combined TDV and FMD cuts performance for different p_t bins.	126
4.6	Main parameters for heavy quark production and their semi-leptonic decay in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.	133

List of Figures

1.1	D meson production measurements compared to FONLL calculations (left and middle panels) and beauty production measured in the $B \rightarrow J/\psi + X$ decay channel compared with FONLL and MC@NLO calculations (right panel) in p- $\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at Tevatron.	3
1.2	Color-singlet and color-octet contributions to direct J/ψ production in $p + \bar{p} \rightarrow J/\psi + X$ at the Tevatron ($\sqrt{s} = 1.8$ TeV, pseudorapidity cut $ \eta < 0.6$) compared to experimental data from CDF.	4
1.3	Comparison between the transverse momentum distributions of J/ψ (left panel) and Υ (right panel) calculated with the Color Evaporation Model and the CDF data at $\sqrt{s} = 1.8$ TeV. For the Υ case, the effect of an intrinsic transverse momentum of $\langle k_t \rangle = 0$ GeV/c (dashed), 1.25 GeV/c (dotted), 2.0 GeV/c (solid) and 2.5 GeV/c (dot-dashed), is also shown.	5
1.4	J/ψ (left panel) and Υ (right panel) polarization measured in p- $\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The comparison with the expected polarization from NRQCD calculations is shown. . .	6
1.5	Schematic representation of the universe evolution.	9
1.6	Schematic view of the QCD phase diagram.	12
1.7	Energy density and three times the pressure normalized to the fourth power of the temperature as a function of the temperature	13
1.8	Behavior of the chiral order parameter $\langle \bar{\psi}\psi \rangle$ in the $T - \mu_B$ plane.	14
1.9	Gluon distribution as extracted at HERA, as a function of x in three bins of Q^2	15

1.10	The γ^*p cross-section at HERA, plotted against the scaling variable $\tau = Q^2/Q_s^2(x)$	16
1.11	The configuration of two colliding nuclei before (left) and after (right) the collision.	18
1.12	Schematic representation of the QGP evolution in a nucleus-nucleus collision.	19
1.13	Nuclear modification factor R_{AA} for non-photonics electrons as a function of p_t in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the different centrality classes.	22
1.14	Heavy-to-light ratios for D meson (upper panels) and B mesons (lower panels) for the case of a realistic quark mass (right panels) and for a case study in which the quark-mass dependence of parton energy loss is neglected (left panels). . .	23
1.15	J/ψ and χ_c spectral functions at different temperatures. . . .	24
1.16	Ratio of the J/ψ to Drell-Yan cross sections as a function of the nuclear path length measured at the CERN SPS.	26
1.17	J/ψ nuclear modification factor as a function of the number of participants N_{part} measured in Au-Au collisions at RHIC, compared to cold nuclear matter extrapolations.	26
1.18	J/ψ nuclear modification factor as a function of the number of participants N_{part} measured in the hottest SPS (Pb-Pb) and RHIC (Au-Au) collisions.	27
2.1	The accelerator complex at CERN.	30
2.2	Layout of the ALICE experiment.	32
2.3	Particle identification with the ALICE experiment.	38
2.4	Layout of the ALICE Muon Spectrometer.	39
2.5	Layout of the front absorber.	41
2.6	Layout of the dipole magnet.	42
2.7	The cathode plane layout of Station 1.	43
2.8	Layout of the tracking system Station 2, installed in the ALICE cavern.	43
2.9	Scheme of a station with slat architecture.	44
2.10	Layout of the tracking Stations 4 and 5, installed in the ALICE cavern.	44
2.11	General view of the GMS setup	46

2.12	Layout of the trigger stations and the iron wall, installed in the ALICE cavern.	47
2.13	Resistive Plate Chamber scheme.	48
2.14	View of one of the trigger chambers showing the 18 RPCs and the 234 trigger boards.	49
2.15	The muon arm trigger principle	50
2.16	Schematic view of the AliRoot framework.	53
2.17	Data processing framework.	54
2.18	The Tiers structure.	56
3.1	Chamber plane MT12 moved along the non-bending direction x	60
3.2	Trigger efficiency as a function of the misalignment of chamber MT12 along the non-bending direction x	61
3.3	Chamber plane MT12 moved along the bending direction y	62
3.4	Trigger efficiency as a function of the misalignment of chamber MT12 along the bending direction y	63
3.5	Trigger efficiency as a function of the misalignment of chamber MT12 along y : no p_t cut is performed.	64
3.6	Ratio between trigger efficiency measured with MT12 shifted by 8 mm along y and the value measured without misalignment as a function of the muon p_t	65
3.7	Probability of correctly identifying the $\mu^+\mu^-$ as an unlike-sign muon pair, as a function of the misalignment of chamber MT12 along y	65
3.8	Station MT2 moved along x	66
3.9	Trigger efficiency as a function of the misalignment of station MT2 along x	66
3.10	Station MT2 moved along y	67
3.11	Trigger efficiency as a function of the misalignment of station MT2 along y	67
3.12	Combined shift of chamber plane MT12 and MT21.	68
3.13	Trigger efficiency for J/ψ and Υ as a function of the misalignment of chamber MT22 along y , with two different misalignments for MT12.	69

3.14	Trigger efficiency for J/ψ and Υ as a function of the misalignment of chamber MT22 along x , with three different misalignments for MT12.	70
3.15	Detail of the trigger chambers installation	71
3.16	Trigger efficiency as a function of the misalignment of chamber MT12 along z	72
3.17	Target equipment for photogrammetry (left) and theodolite (right) measurements.	73
3.18	Open position and Closed position of trigger chamber half-planes.	73
3.19	Distribution of the measured trigger chamber position with respect to the nominal one along x (left panel) and y (right panel).	74
3.20	Trigger efficiency for J/ψ and Υ with a realistic chamber misalignment from data	75
3.21	Reconstructed and input efficiencies per RPC in the bending plane.	80
3.22	Reconstructed and input efficiencies per RPC in the non-bending plane.	81
3.23	Difference between the reconstructed efficiency and input for all RPCs in bending and non-bending plane.	82
3.24	Reconstructed and input efficiencies per board in the bending plane.	83
3.25	Reconstructed and input efficiencies per board in the non-bending plane.	84
3.26	Difference between the reconstructed efficiency and input for all boards in bending and non-bending plane.	85
3.27	Difference between the reconstructed efficiency and input divided by the statistical error for all boards in bending and non-bending plane.	85
3.28	Systematics in trigger chamber efficiency evaluation as a function of multiplicity	87
3.29	Hit density on trigger chambers	88
3.30	Examples of conversion of histograms used in calculation, and the corresponding human-readable display.	92

3.31	Schematic view of the analysis task train. Trigger chamber efficiency is computed from the ESDs.	94
4.1	Schematic view of the production point of the three muon sources with respect to the Muon Spectrometer front absorber.	99
4.2	Definition of the π/K free path length.	101
4.3	Bi-dimensional distribution ($\frac{d^2 N^\mu}{dp_t dz_v}$) of reconstructed muons.	103
4.4	Vertex distribution ($\frac{dN^\mu}{dz_v}$) of reconstructed muons with $p_t > 1$ GeV/c.	104
4.5	Plots of $\frac{1}{\rho(z_v)} \frac{d^2 N^\mu}{dp_t dz_v}$, obtained at different values of p_t	105
4.6	Transverse momentum distributions of muons from all sources and contribution of muons from heavy flavors reconstructed with the method for decay background subtraction.	106
4.7	Reconstructed p_t distributions. The relative abundance of muons from π/K and heavy flavors is multiplied by a factor of 2 (a) and 0.5 (b)	107
4.8	Same as Figure 4.6 with the 10% (left panel) and 1% (right panel) of the statistics expected in one year of data taking at $5 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$	107
4.9	Efficiencies and acceptance dependence on vertex position.	109
4.10	Construction of the Transverse Distance at Vertex (TDV).	111
4.11	Bi-dimensional distribution in p_t and transverse distance at vertex for muons from different sources.	112
4.12	The ALICE Forward Multiplicity Detector.	113
4.13	FMD3 inner sector layout.	114
4.14	Number of matching strips in the inner ring of FMD3 for muon tracks with $p_t > 0.5$ GeV/c.	115
4.15	Transverse momentum of muons reconstructed in the ALICE Muon Spectrometer and passing a p_t trigger cut of about 0.5 GeV/c.	117
4.16	Distribution of the TDV variable for the various muon sources in different p_t ranges.	119
4.17	Fraction of rejected muons as a function of the TDV cut, for different p_t ranges.	120

4.18	Same as Figure 4.15 with the additional condition that muons have to pass the set of TDV cuts keeping the signal rejection below 5% (see Table 4.4).	121
4.19	Fraction of rejected muons as a function of the distance between the position of the track extrapolated at the FMD and the closest fired strip, normalized to the extrapolation error ($\Delta r/\sigma_r$) for different p_t ranges.	122
4.20	Fraction of rejected muons as a function of the absolute distance between the position of the track extrapolated at the FMD and the closest fired strip (Δr) for different p_t ranges. .	123
4.21	Transverse momentum of muons reconstructed in the ALICE Muon Spectrometer and entering the FMD acceptance ($3.4 < \eta < -2.5$). The muons have to pass a p_t trigger cut of about 0.5 GeV/c, the TDV set of cuts in Table 4.5 and to match a fired strip in the FMD at a distance not larger than 2.5 times the extrapolation error ($\Delta r/\sigma_r < 2.5$).	124
4.22	π^0 nuclear suppression factor as a function of the transverse momentum for 0-5% Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. .	131
4.23	Invariant mass distribution of opposite sign muon pairs from the semi-leptonic decay of a $c\bar{c}$ (top panel) and $b\bar{b}$ (bottom panel) pair (correlated background) in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.	134
4.24	Same as Figure 4.23, but in simulations, the longitudinal momentum p_z of the parton is assumed to be unchanged by the quenching, while the parton rapidity changes with its energy.	135
4.25	Invariant mass distribution of the correlated background, obtained as the sum of the $B\bar{B}$ and $D\bar{D}$ contributions of Figure 4.23.	136
4.26	Invariant mass distribution of the correlated background, obtained as the sum of the $B\bar{B}$ and $D\bar{D}$ contributions of Figure 4.24.	137

List of Acronyms

AliEn	ALice ENvironment
AOD	Analysis Object Data
BCAM	Boston CCD Angle Monitor
BDMPS	Baier-Dokshitzer-Mueller-Peigné-Schiff
CDF	Collider Detector at Fermilab
CGC	Color Glass Condensate
ESD	Event Summary Data
FMD	Forward Multiplicity Detector
GMS	Geometry Monitoring System
LUT	Look-Up Tables
MNR	Mangano-Nason-Ridolfi
OCDB	Offline Calibration DataBase
PDC	Physics Data Challenge
pQCD	Perturbative Quantum Chromo-Dynamics
PQM	Parton Quenching Model
QA	Quality Assurance
QGP	Quark-Gluon Plasma
RHIC	Relativistic Heavy Ion Collider

RPC	Resistive Plate Chamber
SPD	Silicon Pixel Detector
SPS	Super Proton Synchrotron
TDV	Transverse Distance at Vertex

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