

THÈSE DE DOCTORAT DE

L'ÉCOLE NATIONALE SUPÉRIEURE MINES-TÉLÉCOM ATLANTIQUE
BRETAGNE PAYS DE LA LOIRE - IMT ATLANTIQUE

ÉCOLE DOCTORALE N° 596

Matière, Molécules, Matériaux

Spécialité : Physique Subatomique et Instrumentation Nucléaire

Par

Rita SADEK FINOT

Mise en service du MFT et préparation d'analyses de données Run 3 dans l'expérience ALICE (LHC, CERN)

Thèse présentée et soutenue à Nantes, le 28/10/2022

Unité de recherche : Laboratoire SUBATECH, UMR 6457

Thèse N° : 2022IMTA0308

Rapporteurs avant soutenance :

Andrea DAINESE Directeur de recherche INFN, section de Padoue
Cynthia HADJIDAKIS Chargée de recherche CNRS, IJCLab Orsay

Composition du Jury :

Président :	Luciano MUSA	Directeur de recherche, CERN
Examineurs :	Andrea DAINESE	Directeur de recherche INFN, section de Padoue
	Cynthia HADJIDAKIS	Chargée de recherche CNRS, IJCLab Orsay
	Pol-Bernard GOSSIAUX	Professeur IMT Atlantique, Subatech
	Thea Klæboe ÅRRESTAD	Chargée de recherche, ETH Zürich
Directeur de thèse :	Ginés MARTINEZ	Directeur de recherche CNRS, Subatech
Co-encadrants de thèse :	Guillaume BATIGNE	Maître-assistant IMT Atlantique, Subatech
	Maxime GUILBAUD	Maître-assistant IMT Atlantique, Subatech

Acknowledgements

I am both very happy and saddened to finally be able to write this part of my thesis! Firstly, I want to express how rich and beautiful this period has been for me. I would like to thank everyone who has been a part of my journey over the past three years. I apologize as I may forget or not be able to recall each and every name. These years have been a time of immense learning, and I have been fortunate to encounter so many people who have inspired and guided me along the way.

To begin with, I would like to thank my thesis supervisors, Ginés, Guillaume, and Maxime. It was a great pleasure to have the opportunity to work with you! I am very grateful to Ginés for his constant support throughout this journey. He has always been ready to offer various ideas and advice, and he always managed to find time for our discussions, even with his demanding role as Subatech director. Thank you for your helpfulness and generosity in sharing your insights and knowledge! I would like to express my sincerest gratitude to Guillaume, who has supported me throughout these years, always equipped with the right advice to give! Guillaume's dedication and availability (even on evenings and weekends), has been invaluable to me. Our exchanges have been incredibly enriching and have allowed me to broaden my knowledge and understanding of our field. Thank you so much for this, for your continuous good mood and for your kindness! Last but not least, Maxime, I am very thankful for all the **very** long exchanges we had, and for always addressing all my questions and uncertainties. Indeed, very often my "do you have 5 minutes" exchanges would last for entire afternoons! These were essential in helping me navigate some of the challenging aspects of my research. Thank you for all the time and effort you have devoted, for all the doubts you helped me clarify, and for all the laughs we shared, I am deeply appreciative!

I want to thank immensely my thesis jury and reviewers for taking the time to read my manuscript and for all the insightful questions and constructive feedback. I am honored to have had the opportunity to present my work to such a distinguished panel of experts in our field.

I am very grateful for the whole PLASMA team, with whom I was always able to discuss, and would always have advice to share with me! Their collaboration, expertise, and enthusiasm were

critical to me! Thank you, Marie, Philippe, Diego, Rafael, Barbara, Emine, Laurent, Gilles and Alexandre for all the rich discussions we have shared, and for all the help you never hesitated to provide me with, I feel very lucky to have been a part of this team!

I would also like to thank all of my colleagues in the ALICE collaboration, for always providing me with a stimulating and supportive work environment! Stefano, I want to express my gratitude for all the various ideas you always brought to my work. Your insight and creativity challenged me to always think from different angles, thank you! I would also like to thank Sarah for always following my work and for all the valuable advice she gave me! For all the people that I met at CERN and had so many interesting conversations with, Andry, and our passion for python, Charlotte, for your continuous encouragement whether at point 2 or on Duolingo. Thanks to everyone I have interacted and collaborated with in ALICE, and especially within the MFT team, it was a true pleasure!

Of course, I want to extend my appreciation to my office colleague, Ophélie, who has always been there whether to share joy or to hear me complain, and with whom I always had rich and very passionate discussions. Thank you for making the office a warm space! I would also like to thank my fellow doctoral students/post-docs, Nicolas, Victor, Momo and Kunal, for the great atmosphere we have shared within the group! Bon courage for your journey!

I want to also share my appreciation to all the colleagues with whom I interacted, worked, and discussed at Subatech, and with whom the CERN missions were always fun! Especially, thank you Stéphane, Stéphane, Christophe, Patrick, Patrice, Didier, Amanda, Farah, Meriadeg, Sophie, Véronique, Sara, and to everyone I came in contact with within these years in the Subatech halls!

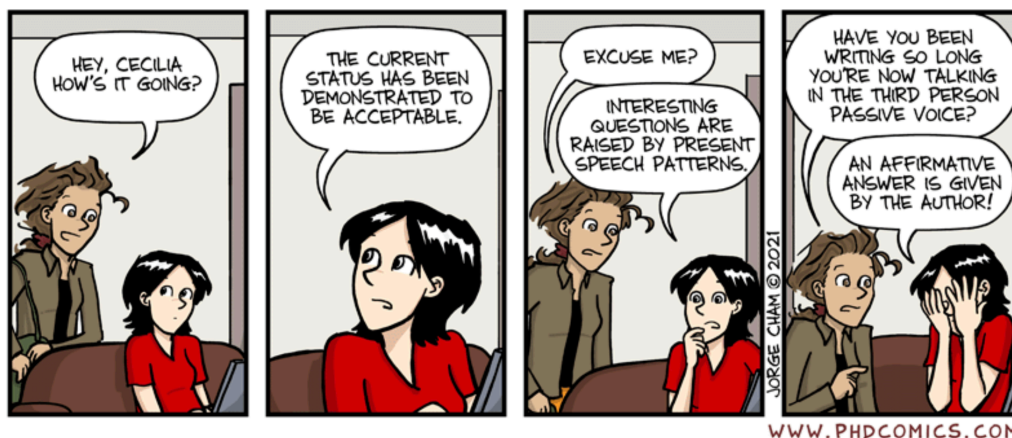
I want to give a special shoutout to all my fellow Subatech doctoral students and postdocs who have been my companions on this journey. Thank you, Stéphane, for the engaging conversations we've had over the years. It all began during my M1 internship at Grenoble, and I am very grateful for the opportunities we've had to discuss a wide, **very wide**, range of topics! Thank you, Quentin, for your constant optimism which was always uplifting, and for not giving up on encouraging me to do sports! Many thanks to Vincent, Grégoire, Arthur, Claudia, Johannes, Léonard, Johan, Mahbobeh, Maxime, Victor, Nadège, Tobie, Alexander, Eamonn, Etienne, Michael, Keerthana, and Yajing! We've shared countless conversations, coffee breaks, and laughs that have added enjoyment to the hours spent in the lab! I am very grateful for the friendships that we've formed and the support that we've given each other.

I would like to take a moment to express my deepest appreciation to all of my friends who have been there, always, whether it was in person or virtually. You all have been a great source of motivation and optimism throughout this journey!

I am deeply thankful to all of my family, in Lebanon and in France, for their love and support throughout the whole academic journey. Their non-stop encouragement and understanding

during some of the challenging moments of this journey were invaluable. Thank you from the bottom of my heart for making this possible, and thank you for always believing in me.

Lastly, Sylvain, your constant support and presence throughout these past years have been critical to me. I can't express enough my gratitude for the peaceful and loving environment that you have always provided. Thank you for being a part of my life and for your endless support.



["Piled Higher and Deeper" by Jorge Cham www.phdcomics.com]

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Acronyms

ALF ALice Frontend.

ALICE A Large Ion Collider Experiment.

ALPIDE ALice PIXel DETector.

AOD Analysis Object Data.

CEM Colour Evaporation Model.

CNM Cold Nuclear Matter.

COM Colour Octet Model.

CRU Common Readout Unit.

CSM Colour Singlet Model.

DCS Detector Control System.

FF Fragmentation Function.

FONLL Fixed Order Next-to-Leading-
Logarithm.

FRED FRont-End Device.

GBT-SCA Giga-Bit Transceiver - Slow Con-
trol Adapter.

GUI Graphical User Interface.

IP Interaction Point.

LHC Large Hadron Collider.

IQCD Lattice QCD.

MCH Muon CHambers.

MFT Muon Forward Tracker.

MID Muon IDentification.

ML Machine Learning.

NLO Next to Leading Order.

NN Neural Network.

NRQCD Non-Relativistic QCD.

PCA Point of Closest Approach.

PDF Parton Distribution Function.

pQCD Perturbative QCD.

PSU Power Supply Unit.

QFT Quantum Field Theory.

QGP Quark-Gluon Plasma.

RP Reaction Plane.

SC Synchrocyclotron.

SM Standard Model.

SQL Structured Query Language.

SV Secondary Vertex.

Introduction

Subatomic physics aims at describing matter and its behaviour at infinitesimal scales. The Standard Model defines the theoretical framework that describes the elementary particles and three out of the four fundamental forces. Elementary particles are divided into fermions, the constituents of matter, and bosons, the carriers of interactions. The fermions are divided into quarks and leptons. Quantum chromodynamics is the quantum field theory that describes the strong interaction, responsible for the strong nuclear force that is at the basis of nuclear structure. Gluons are the carriers of the strong interaction and quarks are the elementary particles forming all nuclear matter. In normal conditions, quarks and gluons are confined into nuclear matter; they cannot propagate freely like electrons or photons. Nevertheless, at high temperature and high energy density, there is a crossover to a new state of nuclear matter: the Quark-Gluon Plasma (QGP). This is a dense medium composed of strongly interacting matter within which quarks and gluons are free to move. Properties of the QGP can be studied with ultra-relativistic heavy-ion collisions by reproducing the necessary conditions in particle colliders such as the Large Hadron Collider (LHC).

The ALICE detector is located around one of the LHC collision points and specifically designed to study heavy-ion collisions. The measurement of inclusive quarkonium, an important probe of the QGP, is possible with ALICE down to $p_T = 0$ GeV/c in two rapidity regions: midrapidity, through their dielectron decay channel using central detectors, and forward rapidity, through their dimuon decay channel with the muon spectrometer. The front absorber of the muon spectrometer has been designed to filter particles and let only muons pass through. The counterpart is that the multiple scattering within it prevents to have a good spatial resolution at the level of the interaction point. Hence, only inclusive measurements were possible during the first two data taking periods of LHC (Run 1 and Run 2). In order to overcome this limitation and to extend the ALICE physics program at forward rapidities, a new high-resolution tracking detector, the Muon Forward Tracker (MFT), has been designed starting in 2011 and was installed late 2020.

The MFT constitutes the context of this thesis during which the LHC was in a period

known as the second long shutdown. During this period, the LHC was upgraded to increase its luminosity. A drastic change of the general readout system and online/offline software of ALICE had to be made to cope with this increase. The work of this thesis is divided into two parts. The first one is hardware oriented. It concerns the validation of the board controlling and monitoring the powering of the MFT and the creation of software tools to communicate with it. The second part concerned the preparation of data analysis. First, new methods based on Machine Learning for the matching between tracks from the MFT and the muon spectrometer have been developed. Once the track matching is done, the pairing of muon tracks to extract J/ψ has been improved. And finally the separation between prompt and non-prompt J/ψ could be studied.

This document is divided into two parts, the first consists of an introductory part (from chapter 1 to 4), and the second is devoted to the work of this thesis and the obtained results (from chapter 5 to 8). Chapter 1 tackles a brief theoretical background, consisting of tools that allow the understanding of heavy-ion collisions. The J/ψ probe is then introduced in chapter 2, notably the mechanisms responsible for its production are discussed, and its expected evolution in different collision systems. The ALICE apparatus for Run 3 is presented in detail in chapter 3, followed by a description of the MFT detector in chapter 4, both hardware- and software-wise. The power control of the MFT is presented in chapter 5, focusing on the software developments specific to the MFT commissioning and its adaptation to the framework of the MFT Detector Control System, which is the official Run 3 software that handles the full detector control. In chapter 6, machine learning techniques are applied to the track matching between the muon spectrometer and the MFT tracks. The purpose of this work is to improve the performances of the track matching. Muon tracks are then extracted after matching application. Information on the point of closest approach between the muon tracks is required for the separation of prompt and non-prompt J/ψ contributions. Thus, chapter 7 describes the vertex reconstruction algorithm and its first assessments. Finally, quality evaluations with official Run 3 simulations are presented in chapter 8, with the goal of preparing the upcoming data taking and analysis. New measurements, which are now accessible with the MFT and as a result of developments introduced in previous chapters, are also presented.

Chapter 1

Physics of heavy-ion collisions

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Ultra-relativistic heavy-ion collisions constitute an essential tool for studying the properties of nuclear matter. The first chapter focuses on the physics of these collisions, where essential theoretical notions are addressed. The Standard Model (SM), the model that governs all physics and, in particular, in the microscopic and macroscopic worlds (the two infinities), is introduced first. It helps to understand our environment in-depth by describing how elementary particles and three forces are related to each other, omitting gravity¹. Then Quantum ChromoDynamics

¹Quantum gravitation is still not known to this day, and thus not included in the SM.

(QCD) is introduced, which is the quantum field theory describing the strong interaction, one of the three forces of the SM responsible for the nuclear structure. At very high temperature or pressure, QCD predicts that the nuclear medium becomes a Quark-Gluon Plasma (QGP). The thermodynamic conditions of the Universe until $1 \mu\text{s}$ after the Big Bang correspond to those allowing the existence of a QGP. After this section, the most important aspects of collisions are presented, starting with the different collision systems, their space-time evolution, and their geometry. Finally, different experimental signatures of the QGP are discussed.

1.1 The Standard Model

The SM of particle physics describes the electromagnetic, weak, and strong interactions along with the particles that make up matter [1, 2]. According to this model, elementary particles are divided into three groups (Figure 1.1):

Fermions: particles with a spin of $1/2$ from which matter is built. They are divided into two categories: quarks and leptons, each of which consists of six particles and their respective six anti-particles, and are classified based on how they interact, as the interactions are exerted between charges (electric, weak, and colour charges for the electromagnetic, weak and strong interactions respectively). The lightest and most stable particles form the first generation, while second and third generation particles decay rapidly due to the weak interaction. The three generations of quarks are the (**u**,**d**) quarks as the first generation, the (**c**,**s**) as the second generation, and the third generation is formed by the (**t**,**b**) quarks. Quarks have an electric charge of $(+2/3 e)$ for (u, c, t), and of $(-1/3 e)$ for (d, s, b); as for the anti-quarks, they possess the opposite electric charge. Quarks are the only fermions with a colour charge and thus are sensitive to the strong interaction. Additionally, they mix into colourless composite particles, known as hadrons, divided into baryons (composed of three quarks) and mesons (composed of a quark and an anti-quark). As for the three generations of leptons, the first is composed of the (e^-, ν_e) , followed by (μ^-, ν_μ) , and lastly the (τ^-, ν_τ) . e^- , μ^- and τ^- leptons have negative electric charge, while anti-leptons have a positive electric charge. As for the ν_e , ν_μ and ν_τ neutrinos (and their corresponding anti-neutrinos), they have a null electric charge.

Gauge bosons: particles with spin of 1. They are the carriers of interactions and are composed of the following elementary particles:

- Photons, carriers of electromagnetic interactions, can be exchanged between fundamental particles that have an electric charge. There is no direct interaction taking place between photons, since they are electrically neutral.

- W and Z bosons, carriers of the weak interaction, can be exchanged between fermions. They allow a change of the particle flavour, in the doublets of each generation as well as in-between generations.
- Gluons, carriers of the strong interaction, can be exchanged between elementary particles having a colour charge. They carry themselves a net colour charge, and are therefore also sensitive to the strong interaction. The context of this thesis is the study of strong interaction. More details will be given later on.

Higgs boson: a massive scalar particle, with spin of 0, no electric and no colour charge. The masses of all elementary particles are related to their coupling constants with the Higgs field; the higher, the heavier.

mass	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
					SCALAR BOSON
	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
QUARKS	d down	s strange	b bottom	γ photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z^0 boson Z^0	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	± 1	
	1/2	1/2	1/2	1	
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$W^\pm$ boson $W^\pm$	
					GAUGE BOSONS

FIGURE 1.1: Standard Model elementary particles, values extracted from the PDG [1].

The absence of gravitation in the SM is not problematic, as it can be totally neglected on the particle physics scale. An estimation of the gravitational force magnitude with respect to the electromagnetic force is done with the classical approach between two electrons of mass $m_e = 511 \text{ KeV}/c^2$ and charge $q_e = -1.6 \times 10^{19} \text{ C}$:

$$\frac{F_g}{F_e} = \frac{\frac{Gm_e^2}{r^2}}{\frac{q_e^2}{4\pi\epsilon_0 r^2}} = Gm_e^2 \frac{4\pi\epsilon_0}{q_e^2} = \frac{G}{\hbar c} m_e^2 \frac{1}{\alpha} \simeq 2.4 \times 10^{-43} \quad (1.1)$$

with Newton's gravitational constant $G = 6.70861 \times 10^{-39} \hbar c \text{ (GeV/c}^2\text{)}^{-2}$ and with the fine-structure constant $\alpha = \frac{1}{4\pi\epsilon_0} \times \frac{q^2}{\hbar c} = \frac{1}{137}$ [3]. As one can observe, the intensity of the electromagnetic force is 43 orders of magnitude stronger than that of gravitation, making the gravitational effects completely negligible at the subatomic scale.

The SM is constructed with Quantum Field Theory (QFT) [4], based on symmetry principles, such as gauge invariance [5], Lorentz invariance, and wave equations (Dirac, Maxwell, Yang-Mills, Klein-Gordon) [2]. Gauge symmetries describe the interactions mentioned above. The gauge group of the SM is composed of $SU(3)_c \times SU(2)_L \times U(1)_Y$, and can be classified as follows:

- $SU(3)_c$, a unitary group at the basis of the quantum field theory of strong interactions known as the QCD [6], which will be described in the next section.
- $SU(2)_L \times U(1)_Y$, describes the electro-weak interaction, the unification of both electromagnetism and weak interaction. The Higgs mechanism was introduced to explain the unification between these two interactions [7] and the masses of the W and Z bosons (not yet measured at that time).

1.2 Quantum ChromoDynamics

The strong interaction taking place between partons, elementary particles carrying a colour charge, is described with quantum chromodynamics [8]. It is a non-abelian (non-commuting) quantum field theory, invariant under $SU(3)$ Lie's group. The colour charge, forming the fundamental representation of a $SU(3)$ symmetry group, are referenced after the three primary colours: red, green, and blue (R, G, B), and their respective anticolours: cyan, magenta, and yellow ($\bar{R}, \bar{G}, \bar{B}$). This quantum variable is deemed necessary after the formation of the quark model in order to respect Pauli's exclusion principle, which would have been violated while implementing the quark scheme for the Δ^{++} baryon ($J=3/2$): $\Delta^{++} = uuu$, with each u quark having the same spin of $J=1/2$. Thus the colour charge allows to re-write its wavefunction as $u_R u_G u_B$, preventing the violation of Pauli's exclusion principle. The interaction between colour charges is mediated by eight bicoloured gluons [2], forming a $SU(3)$ octet, as follows:

$$R\bar{G}, R\bar{B}, G\bar{R}, G\bar{B}, B\bar{R}, B\bar{G}, \frac{1}{\sqrt{2}}(R\bar{R} - G\bar{G}), \frac{1}{\sqrt{6}}(R\bar{R} + G\bar{G} - 2B\bar{B}) \quad (1.2)$$

Gluons, being coloured, can interact with each other. The $R\bar{R} + G\bar{G} + B\bar{B}$ state, being colourless (or white), has no interaction and thus has no existence. In the following, the Lagrangian of the QCD will be presented. It describes mathematically the strong interaction taking place between quarks and gluons.

1.2.1 Lagrangian QCD

Feynman diagrams (Figure 1.2) are tools that describe the mathematical expressions characterizing the subatomic particles behaviour. The diagrams are drawn according to the Feynman rules. They depend on the Lagrangian of the interaction and can be derived from the QCD action, which is renormalizable and invariant under Poincaré and local gauge transformations.

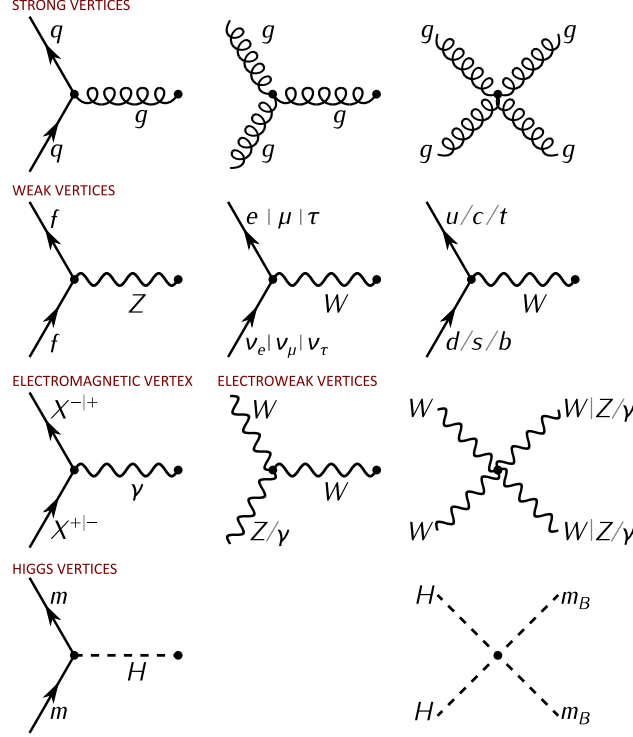


FIGURE 1.2: All Feynman diagram vertices of the Standard Model [9].

The quark field dynamics are described by the QCD lagrangian density, with the action principle:

$$\delta S = 0 \quad \text{for all } \delta q \quad (1.3)$$

where the action S is given by:

$$S = i \int d^4x \mathcal{L}_q \quad (1.4)$$

with the Lagrangian of a single flavour non-interacting quark given by:

$$\mathcal{L}_q = \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu - m_{q_f}) q_f \quad (1.5)$$

where q_f are quark-field spinors with the index f running over different flavours of quarks ($f = u, d, s, c, b, t$) with mass m_{q_f} and γ^μ represents Dirac γ -matrices.

The free Lagrangian is invariant under $SU(3)_c$ transformations as follows:

$$q_f^\alpha \rightarrow (q_f^\alpha)' = U_\beta^\alpha q_f^\beta \quad (1.6)$$

where $UU^\dagger = U^\dagger U = 1$, $\det(U) = 1$ with $U = e^{-ig_s T^a \theta_a}$, and $g_s^2 = 4\pi\alpha_s$ the QCD coupling constant. θ_a is an arbitrary parameter and $T_a = \lambda_a/2$ constitute traceless Hermitian generators, where λ_a ($a \in \llbracket 1; 8 \rrbracket$) are the Gell-Mann matrices. The Lie algebra is defined by the commutation relations: $[T^a, T^b] = if^{abc}T^c$, where f^{abc} are the structure constants.

The gluonic part is described by the lagrangian $\mathcal{L}_G$, where gluon fields are denoted by $G_\mu^a(x)$ (a going from 1 to 8), it is given by the following equation:

$$\mathcal{L}_G = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.7)$$

with the non-Abelian field strength tensor $G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f_{abc} G_b^\mu G_c^\nu$, where the last term represents the interaction between gluons.

The interaction lagrangian, $\mathcal{L}_{interaction}$, is described with the following term:

$$\mathcal{L}_{interaction} = -\sum_f g_s (\bar{q}_f \gamma^\mu T_a q_f) G_\mu^a \quad (1.8)$$

Thus, we can re-write the complete QCD lagrangian as follows:

$$\mathcal{L}_{QCD} = \mathcal{L}_q + \mathcal{L}_G + \mathcal{L}_{interaction} \quad (1.9)$$

$$= \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu - m_{q_f}) q_f - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} - \sum_f g_s (\bar{q}_f \gamma^\mu T_a q_f) G_\mu^a \quad (1.10)$$

$$= \sum_f \bar{q}_f (i\gamma^\mu D_\mu - m_{q_f}) q_f - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.11)$$

with the $SU(3)_c$ covariant derivative $D_\mu = \partial_\mu + ig_s G_\mu^a T_a$.

1.2.2 Renormalization and the running coupling constant $\alpha_s(Q^2)$

The scattering cross-section σ of a process can be calculated based on Richard Feynman's diagrams (Figure 1.2), following the Feynman rules. Nevertheless, vacuum fluctuations introduce fermions-antifermions and gluonic loop processes, leading to a divergence into the calculations. Thus, in QCD, the interactions must be renormalized by these fluctuations, giving rise to a running coupling constant $\alpha_s(Q^2)$, which describes the strength of the strong interaction depending on the energy scale given by Q^2 ². The evolution of this running constant is given

² $Q^2 = -q^2$ with q the transferred energy-momentum 4-vector between two particles (Q^2 being defined positive).

by:

$$Q^2 \frac{\partial \alpha_s(Q^2)}{\partial Q^2} = \beta(\alpha_s(Q^2)) \quad (1.12)$$

where $\beta(\alpha_s(Q^2)) = -\beta_0 \alpha_s^2(Q^2) + o(\alpha_s^2(Q^2))$ with $\beta_0 = \frac{11N_c - 2N_f}{12\pi}$. N_c is the number of colour charges, and N_f the number of quark flavours.

The first order solution to this equation gives the following form for the coupling constant:

$$\alpha_s(Q^2) = \frac{g_s^2}{4\pi} = \frac{1}{\beta_0 \log\left(\frac{Q^2}{\Lambda_{QCD}^2}\right)} = \frac{12\pi}{(11N_c - 2N_f) \log\left(\frac{Q^2}{\Lambda_{QCD}^2}\right)} \quad (1.13)$$

where Λ_{QCD} is the non-perturbative QCD scale parameter determined experimentally (around 200 MeV [3]).

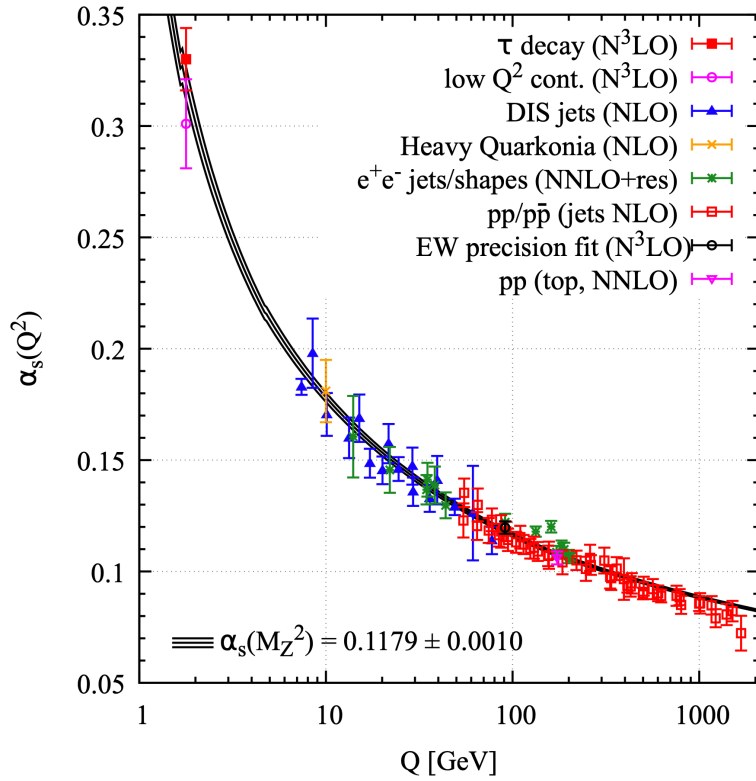


FIGURE 1.3: The coupling constant as a function of the momentum transfer [3].

Two regions can be deduced by studying the evolution of the coupling constant α_s as a function of the transferred momentum Q (Figure 1.3):

Confinement: at low momentum transfer, typically less than 1 GeV, or at poor spatial resolution as $Q \propto \frac{1}{\Delta r}$, where the coupling constant is large, the strong interaction strength between quarks and gluons implies the confined state of quarks within hadrons. In this region, α_s being close to one makes series expansion not applicable. Thus QCD calcu-

lations can only be performed by numerical methods such as lattice QCD (see section 1.3.2), explaining why the structure of hadrons is still not accurate.

Asymptotic freedom: at high momentum transfer, or at high spatial resolution, the coupling constant is small, implying the weakening of interactions between quarks and gluons. Perturbative QCD (pQCD) can then be used to calculate different QCD observables.

1.3 Quark-Gluon Plasma

1.3.1 Phase diagram

A consequence of the asymptotic freedom is the existence of a QGP state of matter. The QGP, in a few illustrative words, is a hot and dense medium made of strongly interacting quarks and gluons evolving in a deconfined state. The transition to this state from ordinary nuclear matter, prevailing at the low-temperature phase with the net baryon density equals unity, occurs around a critical temperature T_c at $\mu_B = 0$ (Figure 1.4). Around T_c the strong interaction intensity decreases significantly (section 1.5.6). Lattice QCD (lQCD) calculations, discussed in the next section, predict that the critical temperature for this phase transition is around 155 to 160 MeV at $\mu_B = 0$ [10–14].

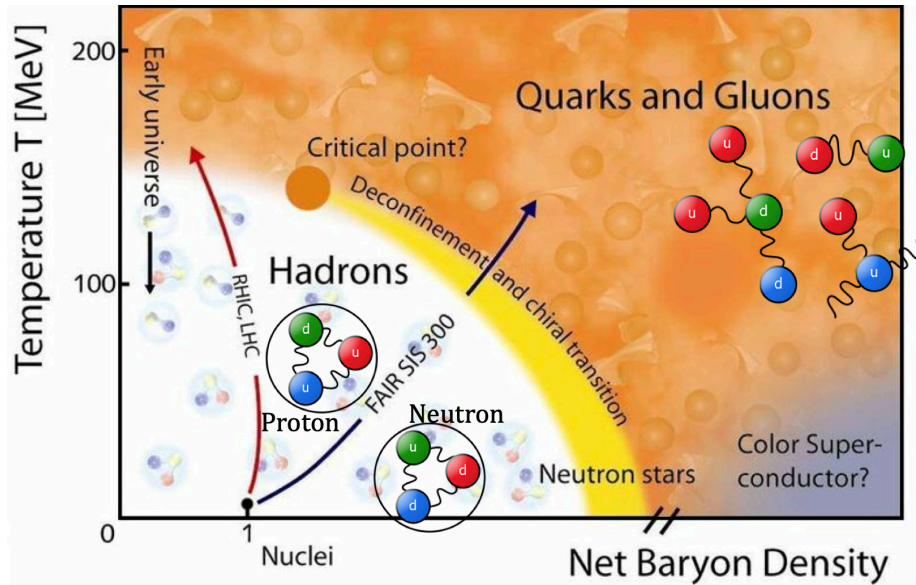


FIGURE 1.4: The phase diagram for nuclear matter, in terms of temperature and of the net baryon density. Figure adapted from [15].

1.3.2 Lattice QCD

As mentioned previously, lQCD is used to estimate the critical temperature required for the transition to the QGP state. Lattice QCD [16] is a non-perturbative implementation of QFT based on a discrete space-time (see Figure 1.5 - left), in which rotational and translational Lorentz symmetries are broken, and gauge symmetry is preserved. The space consists of sites corresponding to quark fields $\psi(x)$, and links corresponding to gluonic field G_a^μ parallel transporter $U(x) \sim e^{i \int_{x_j}^{x_i} G_a^\mu(y) dx_\mu}$.

The canonical partition function in the Euclidean space-time describes a system of particles in spatial volume V , in thermal contact with a heat bath at a temperature T , as it is the sum of all the possible states achievable by the system. Associated with the particles is a set of conserved charges N_i . It is defined as follows:

$$Z = \int DG_a^\mu D\psi(x) D\bar{\psi}(x) e^{-S} = \text{Tr}[e^{-(H - \mu_i N_i)/T}] \quad (1.14)$$

where S is the action and H is the hamiltonian.

Therefore, essential thermodynamical quantities can be obtained from the partition function as pressure p , entropy S , free energy density f , entropy density s and energy density ϵ :

$$f = \frac{-T}{V} \ln(Z) \quad (1.15)$$

$$p = -f = \frac{\partial(T \ln Z)}{\partial V} \quad (1.16)$$

$$S = \frac{\partial(T \ln Z)}{\partial T} \quad (1.17)$$

$$\epsilon = \frac{E}{V} = \frac{T^2}{V} \frac{\partial \ln Z}{\partial T} \quad (1.18)$$

$$s = \frac{S}{V} = \frac{\epsilon + p}{T} \quad (1.19)$$

$$\frac{\epsilon - 3p}{T^4} = T \frac{\partial}{\partial T} \frac{p(T)}{T^4} \quad (1.20)$$

These variables are the essential constituents for the lQCD analyses.

Figure 1.5 - right, shows the pressure, energy and entropy densities as a function of temperature computed by lattice QCD with 2 light (u,d) and 1 heavier (s) quark flavours [14]. A clear increase of the thermodynamical variables is observed around $T_c = 154 \pm 9$ MeV, at $\mu_B = 0$. One can also observe that the energy density limit for an ideal gas is not reached. Thus, even in a deconfined states, the interactions between partons are still prevalent. To attain this state of matter, impossible to observe in nature, ultra-relativistic heavy-ions collisions are used to reproduce the necessary conditions, as will be detailed in the next section.

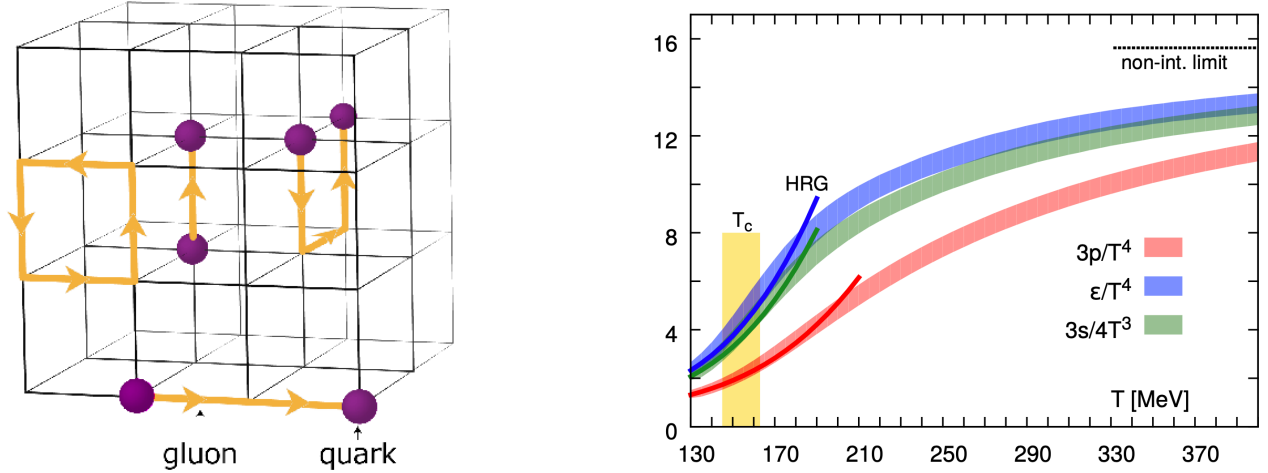


FIGURE 1.5: (left) Lattice QCD discrete space sketch [17]. (right) Normalized pressure, energy and entropy density as a function of temperature, with the calculated prediction with a hadronic thermodynamical model HRG (Hadron Resonance Gas). The black horizontal line represents the energy density limit for an ideal gas, and the yellow band corresponds to the crossover region. [14].

1.4 Different aspects of collisions

1.4.1 Collisions systems

Finite volumes of matter can be brought to large energy densities by colliding ultra-relativistic heavy-ions. Thus, if the transition temperature is achieved, a QGP droplet can be created.

In order to study the QGP, several collision systems are required (Figure 1.6):

AA collisions: heavy-ion collisions result in a large number of created particles. The system can thermalize and create a new medium, potentially the QGP. Properties such as the thermalization process, hydrodynamic expansion, transport coefficients, and hadronization can be studied in order to characterize the medium.

pp collisions: small system collisions allow to study QCD properties in vacuum. Measurements in proton-proton (pp) collisions are considered as a reference for pA and AA collisions.

pA collisions: collision systems composed of a proton and a heavy-ion (pA) allow to disentangle QGP effects from the so-called Cold Nuclear Matter (CNM) effects. Indeed, the initial states of p and A are different. Because of nuclear interactions in nuclei, parton distribution functions differ between the proton and nuclei; they are referred to as PDF and nPDFs respectively. Moreover, the created particles can interact with the nuclei,

inducing modifications in their production rates and distributions. In addition, coherent energy loss effects between the initial and final state may arise.

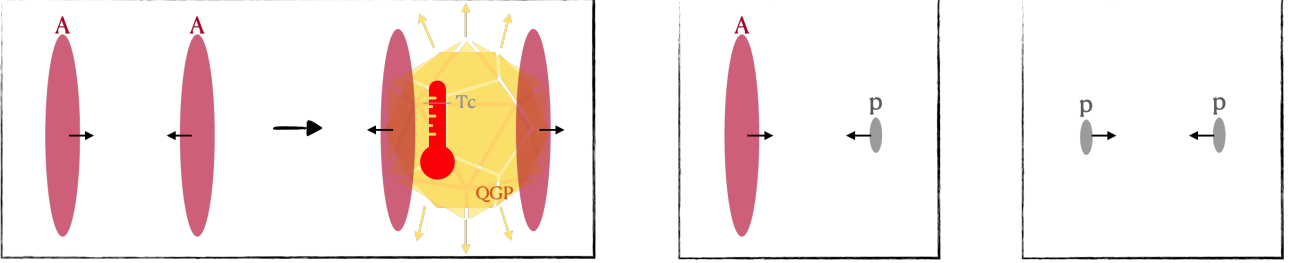


FIGURE 1.6: Sketch of three collision systems.

1.4.2 Space-time evolution

The evolution of heavy-ion collisions can be summarized, within the Bjorken model [18], illustrated in Figure 1.7 at LHC energies, with the following successive stages:

Pre-equilibrium phase: during the initial stage, parton-parton hard scatterings at high energy occur in the overlap region of the two colliding nuclei inducing hard processes (heavy quark production, high momentum particles, etc...).

Quark-Gluon Plasma: when the energy density is large enough, thermal equilibration occurs between created partons, leading to the QGP phase. It rapidly expands in the surrounding vacuum, decreasing its temperature and energy density.

Mixed state: as the medium is cooling down, partons start to hadronize, leading to a mixed-phase of QGP and hadronic gas.

Hadronic gas: as the system keeps expanding and cooling down, this stage occurs when all partons hadronize, and thus the medium is composed of only hadronic gas, where inelastic and elastic interactions take place.

Freeze-out: a chemical freeze-out occurs when all inelastic interactions cease. After which, when the energy density is low enough, the elastic collisions stop as well, leading to a kinetic freeze-out, after which hadrons freely stream out to the detectors. Thus, experimental measurements are pictures of this last stage.

For small systems, the formation of a QGP is not supposed to be achieved due to the small number of produced particles and low colour charge density. Thus, for this scenario, after the collision happens, a pre-hadronic phase occurs, followed by hadron formation, after which the freeze-out phase takes place.

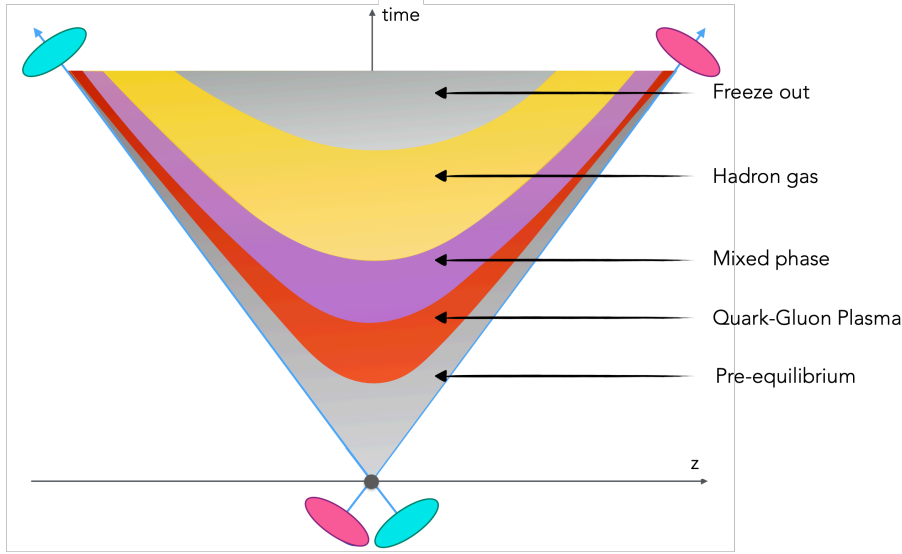


FIGURE 1.7: Sketch of the space-time evolution of heavy-ion collisions at LHC energies.

1.4.3 Key variables used in heavy-ion collisions

In heavy-ion collisions, the distributions of momentum, energy and nature of particles is essential to characterize the medium created during the collision. In addition, the way ions are colliding (head to head or from the edges) has to be known to determine the density and volume of the medium. This section introduces relevant kinematic variables and the impact parameter.

1.4.3.1 Kinematics

The geometry describing collisions is detailed within this section in the laboratory frame (Figure 1.8). The incident beam direction axis is known as the longitudinal axis (the z -axis by convention). The plane perpendicular to the longitudinal axis, the (x, y) plane, forms the transverse plane in which is defined the transverse momentum of particles with:

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (1.21)$$

The p_T is invariant under Lorentz boost along the beam axis. The transverse energy of a particle is thus calculated with:

$$E_T = \sqrt{p_T^2 c^2 + (mc^2)^2} \quad (1.22)$$

Where m refers to the particle's mass, and c is the speed of light in vacuum. The azimuthal angle ϕ and the polar angle θ give the direction of a particle's propagation. The total energy of the collision in the center of mass is given by the Mandelstam variable $\sqrt{s}$. This energy is easily evaluated from the four-momenta of the colliding particles: $s = (p_1 + p_2)^2$. As any Mandelstam variables, s is invariant under any Lorentz transformation. The rapidity y of a particle, which

describes its propagation direction along the beam axis, is defined by:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (1.23)$$

where the particle's energy E and its longitudinal momentum $p_z = p \cos(\theta)$ are components of the four-momenta vector $p = (E, p_x, p_y, p_z)$. The main property of rapidity is that, under a Lorentz boost, along z -axis ($\Lambda(\beta_z)$) rapidities are shifted by the same amount: $y \rightarrow y' + \Delta y$, with $\Delta y = \frac{1}{2} \ln \left(\frac{1 + \beta_z}{1 - \beta_z} \right)$. Thus, experimental rapidity distributions can be easily compared when they are measured in fixed target and collisional modes. Another fundamental variable is the pseudorapidity, which is purely geometrical with the purpose of describing the angle of the particle's trajectory with respect to the beam. It is defined as:

$$\eta = -\frac{1}{2} \ln \left(\frac{|p| + p_z}{|p| - p_z} \right) = -\ln \left(\tan \frac{\theta}{2} \right) \quad (1.24)$$

At relativistic energy scale ($p \gg m$), $\eta \simeq y$. If $\theta = \frac{\pi}{2}$, $\eta = 0$, and if $\theta = 0$, $\eta \rightarrow \infty$. Thus, η is a straightforward variable that allows a first order estimation of the acceptance of detectors.

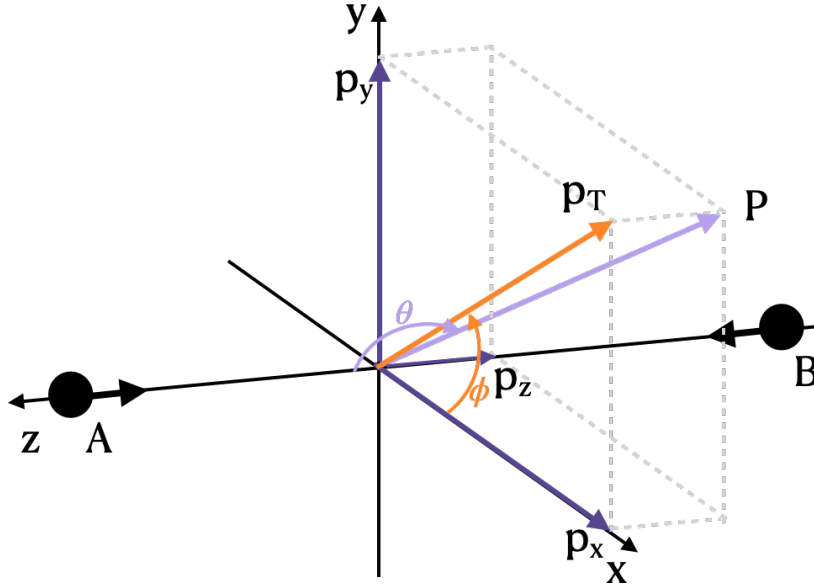


FIGURE 1.8: Coordinate system describing a collision between A and B nuclei.

1.4.3.2 Impact parameter

Other fundamental parameters of heavy-ion collisions are the impact parameter b , the number of nucleons participating in the collision N_{part} and the number of binary nucleon-nucleon collisions

N_{coll} . The impact parameter is the distance between the centers of the two colliding nuclei. Central collisions, at small b , yield large interaction regions with large numbers of participants N_{part} , while peripheral collisions, characterized by large values of b , yield smaller interaction regions with large numbers of spectator nucleons N_{spect} . Experimental data is used to allow the estimation of these quantities by theoretical methods, such as the Glauber model [19]. This model considers the independent distribution of nucleons inside a nucleus A , with the probability density distribution $\rho_A(x, y, z)$. In this model, a heavy-ion collision between target nucleus A and projectile B , with an impact parameter $\vec{b}$, collide on the incident beam direction z -axis. The calculations will focus around two flux tubes (Figure 1.9), located at a distance $\vec{s}$ with respect to the center of the target nucleus A . The probability of a nucleon to be located in this flux tube per unit of transverse area for the target particle A is:

$$\hat{T}_A(\vec{s}) = \int \rho_A(\vec{s}, z) dz \quad (1.25)$$

With a similar expression for the projectile nucleus B . One can define the probability of nucleons to overlap within the flux tubes for an impact parameter $\vec{b}$ with the integrated product of the probabilities, such as:

$$\hat{T}_{AB}(\vec{b}) = \int \hat{T}_A(\vec{s}) \hat{T}_B(\vec{s} - \vec{b}) d^2\vec{s} \quad (1.26)$$

This formula can be interpreted as an effective overlap area, for which a nucleon in A and in B can interact together. The probability of interaction is then given by $\hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}$, with σ_{inel}^{NN} is the inelastic cross section. Thus, the probability of having n interactions between nucleus A and B (with respectively A_A and A_B nucleons), supposing that one nucleon in A can only interact with one nucleon in B , as $\rho_B\sigma_{inel}^{NN}dz \ll 1$, is given with the following binomial distribution:

$$P(n, \vec{b}) = \binom{A_A A_B}{n} [\hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}]^n [1 - \hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}]^{A_A A_B - n} \quad (1.27)$$

with the first term representing the combinations possible for n collisions for a total number of possible interactions $A_A A_B$, followed by the probability term of having n collisions, and the last term represents the probability of having $A_A A_B - n$ misses. Thus, the number of nucleon-nucleon collisions possible between A and B is:

$$N_{coll}(\vec{b}) = \sum_{n=1}^{A_A A_B} n P(n, \vec{b}) = A_A A_B \hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN} \quad (1.28)$$

The number of participants is given with the following equation:

$$N_{part}(\vec{b}) = A_A \int \hat{T}_A(\vec{s}) \left\{ 1 - [1 - \hat{T}_B(\vec{s} - \vec{b}) \sigma_{inel}^{NN}]^{A_B} \right\} d^2 \vec{s} \quad (1.29)$$

$$+ A_B \int \hat{T}_B(\vec{s} - \vec{b}) \left\{ 1 - [1 - \hat{T}_A(\vec{s}) \sigma_{inel}^{NN}]^{A_A} \right\} d^2 \vec{s} \quad (1.30)$$

Additional to this numerical approach, a Glauber Monte Carlo approach is possible, where nucleons are located at specific spatial coordinates and can be modeled as disks in the most straightforward scenarios.

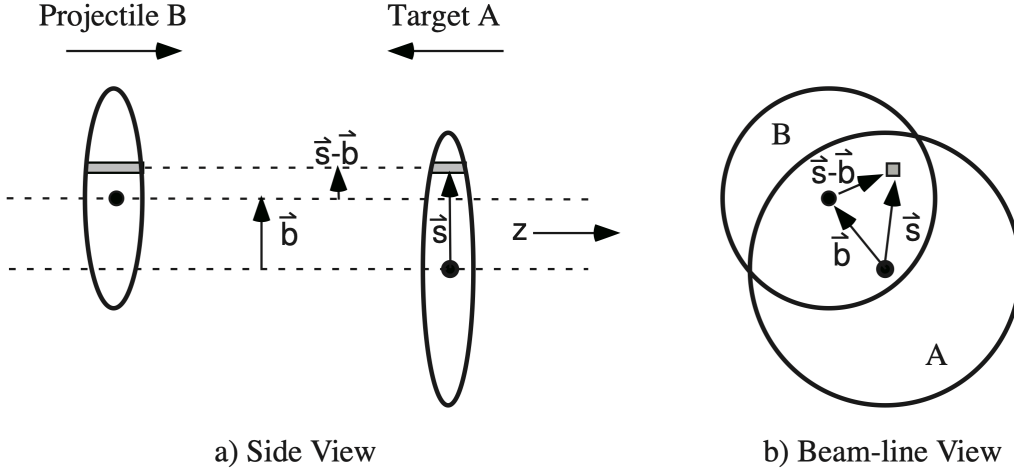


FIGURE 1.9: Sketch of Glauber model geometry, (a) longitudinal and (b) transversal view [19].

1.5 QGP experimental evidence

Properties of the medium can be extracted through the following listed probes, thus deepening our understanding of this medium and the behaviour of particles within. They can be categorized into soft probes for $Q \gtrsim \Lambda_{QCD}$ (particle yields, strangeness enhancement, elliptic flow) and hard probes for $Q \gg \Lambda_{QCD}$ (direct photons and thermal dileptons, jet quenching, heavy-flavour production, and quarkonium suppression). The first gives access to initial conditions, collective effects, and thermalization. The latter to partonic energy loss, medium temperature, and the hadronization of heavy quarks in a QGP.

1.5.1 Strangeness enhancement

In small colliding systems, the production of strange particles, hadrons containing s quarks, is less important with respect to the production of particles containing u and d quarks, due to the higher mass of s quarks [20]. The responsible processes for the $s\bar{s}$ production within

a QGP medium are the following: $gg \rightarrow s\bar{s}$, $u\bar{u} \rightarrow s\bar{s}$, $d\bar{d} \rightarrow s\bar{s}$. The dominance of gluonic production channel (Figure 1.10 - left) with the high gluon density within the QGP leads to the enhancement of strange hadron productions. This enhancement was first seen with the SPS experiments, then at RHIC and LHC. Different measurements for the yield of strange baryons (hyperons) and mesons as a function of N_{part} (different collision systems) show the enhancement of strangeness for high N_{part} , thus as expected from the QGP formation in heavy-ion collisions. In Figure 1.10 - right, measurements show the production ratio of strange hadrons to pions as a function of the charged particle multiplicity, for different collision systems with different energy scales. The multiplicity being the number of particles observed in a selected detector, a clear increase of the ratio can be seen with the increasing system multiplicity. Thus, displaying a strangeness enhancement with the increasing multiplicity.

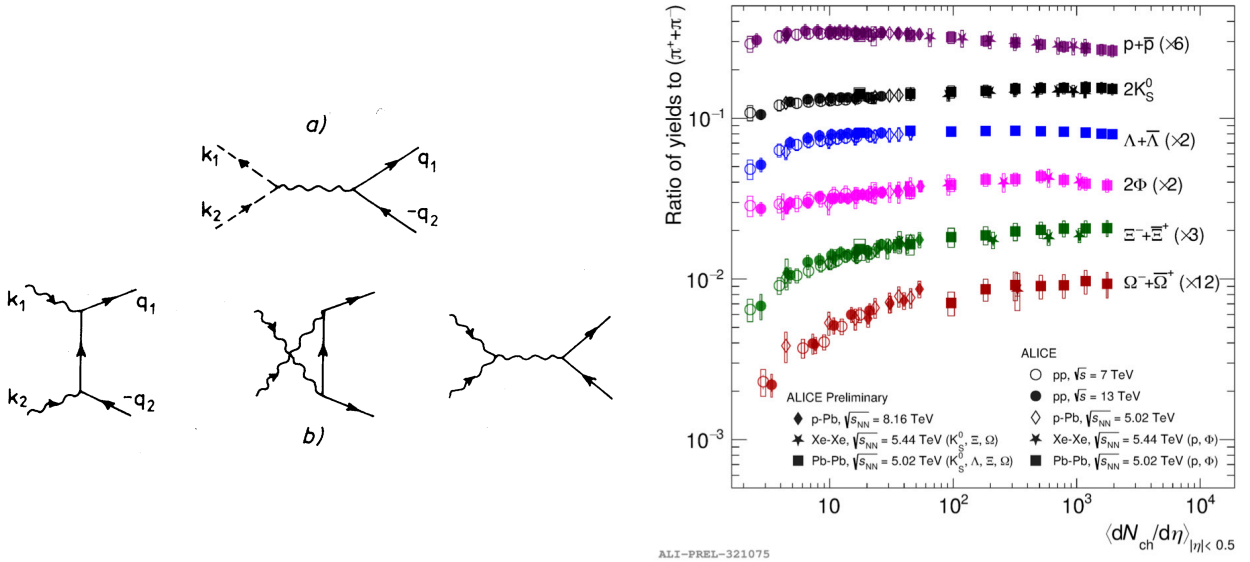


FIGURE 1.10: (left) First order QCD diagrams for $s\bar{s}$ production [21]. (right) Strange hadrons to pions production ratio as a function of charged particle multiplicity at midrapidity for pp collisions at $\sqrt{s} = 7$ TeV, $\sqrt{s} = 13$ TeV, p-Pb and Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, and Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV [22].

1.5.2 Elliptic flow

The elliptic flow is a fundamental QGP signature, as it allows the study of hydrodynamical properties of the medium's expansion (temperature and viscosity). This measurement studies the distribution of particles according to the azimuthal angle ϕ . It can describe the initial state of collisions as partons are highly sensitive to the medium, thus reflecting the formation (or absence) of the QGP. For non-central heavy-ion collisions, the distribution of matter is asymmetrical, thus creating a pressure gradient leading to an anisotropic momentum distribution

of particles. In order to characterize this anisotropy, one can use Fourier's expansion of the invariant distribution of outgoing particles:

$$E \frac{d^3N}{d^3\vec{p}} = \frac{d^2N}{2\pi p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{RP})] \right) \quad (1.31)$$

where ϕ is the azimuthal angle and Ψ_{RP} is the Reaction Plane (RP) angle. The RP is defined by the plane containing the impact parameter, and the beam direction.

The elliptic flow, v_2 , is the second term of Fourier's expansion and is given by the following equation:

$$v_2(p_T, y) = \langle \cos(2(\phi - \Psi_{RP})) \rangle \quad (1.32)$$

with $\langle \rangle$ indicating an average over all particles in all collisions. The v_2 is sensitive to the early medium, as it represents the system response to the initial conditions. In Figure 1.11 - right, the first ALICE measurement of the integrated elliptic flow v_2 of charged particles in Pb-Pb collisions at 2.76 TeV is displayed for a centrality of 20-30% [23]. It is presented as a function of center-of-mass energy, and compared to other results at lower energies with similar centralities. The non-zero v_2 indicates a collective behaviour. An increase of the v_2 is observed with the increasing energies.

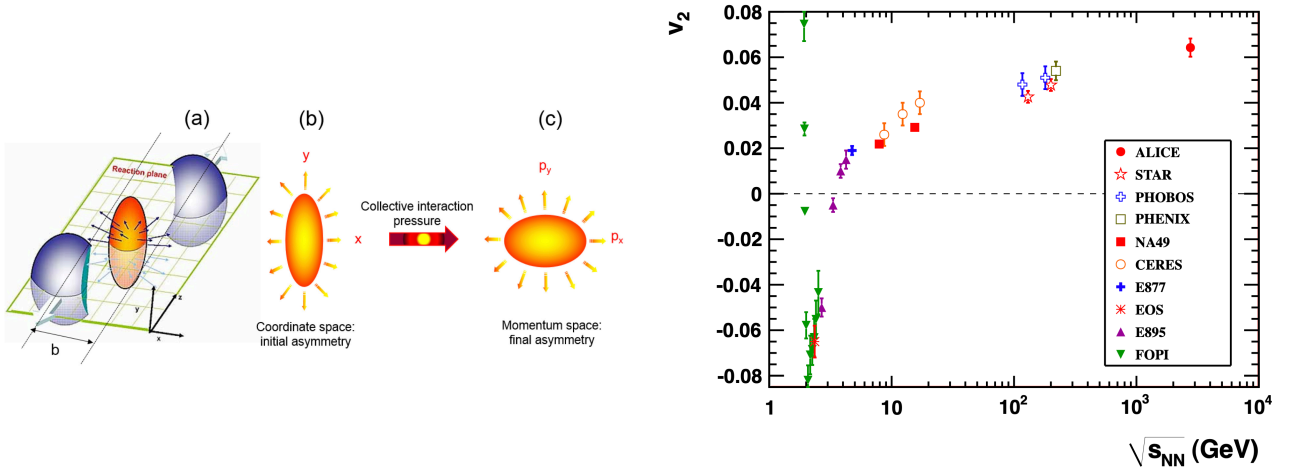


FIGURE 1.11: (left) Panel (a) presents schematically the collision zone between two incoming nuclei for non central collisions. Panel (b) illustrates initial-state anisotropy in the collision zone converting into final-state elliptic flow, and panel (c) measured as anisotropy in particle momentum [24]. (right) The integrated elliptic flow v_2 of the charged particles as a function of center-of-mass energies [23].

1.5.3 Direct photons and thermal dileptons production

Other essential probes allowing the study of QGP are photon and dilepton signals, as they only interact weakly and electromagnetically with the medium, reflecting on initial temperatures and the space-time evolution of the QGP. Direct photons (not produced from hadronic decays) are mainly produced following the Compton scattering and annihilation processes in a QGP at high p_T . The dileptons are produced by the annihilation of $q\bar{q}$ pairs through virtual photon intermediate states. These direct photons shed light on PDFs and nPDFs, and allow access to parton energy loss in the medium. At low p_T , thermal photon yields coming from QGP and hadron gas are expected to dominate the direct photon yield. ALICE collaboration published direct photon yields in Pb–Pb collisions, at $\sqrt{s_{NN}} = 2.76$ TeV for different centralities. The produced yield increases with the increasing centrality. The measurement is also compared to both Next to Leading Order (NLO) pQCD models in pp collisions (Figure 1.12 - left), and with models with pQCD photons with QGP formation (Figure 1.12 - right). In both figures, models are in agreement with experimental data within uncertainties at high p_T . However, in Figure 1.12 - left, an excess is observed at low p_T , increasing with the collisions centrality, with respect to the pQCD model, which can be due to thermal photon production contribution. In Figure 1.12 - right, models including pQCD photons contribution and thermal photons from QGP formation and hadron gas describe well the data in the full p_T range.

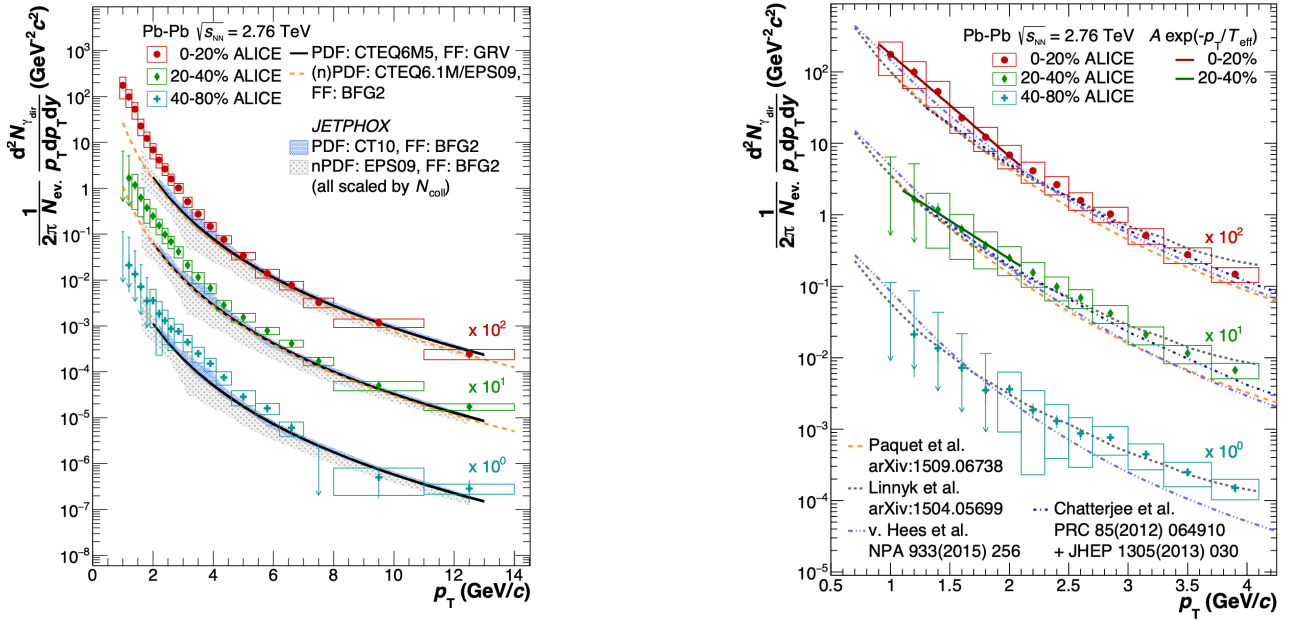


FIGURE 1.12: (left) Comparison of direct photons from model NLO pQCD predictions in pp scaled to Pb–Pb collisions with data in Pb–Pb collisions at 2.76 TeV. (right) Comparison of models with pQCD photons with QGP formation with data in Pb–Pb collisions at 2.76 TeV. Both figures are extracted from [25].

1.5.4 Jet quenching

Jets are collimated bunches of hadrons originating from partons after fragmentation and hadronization. Their production is a direct consequence of QCD confinement, as after high momentum transfer between partons, the hadronization process gives rise to a collimated spray of hadrons. Jet quenching is defined by the mechanism of energy loss of partons that occurs during their propagation in a QGP. Hard partons are mainly produced back-to-back during hard processes. In pp collisions one could observe this while looking at the azimuthal distribution in respect of a particle-tagged jet. Jet quenching mechanism can be shown in [Figure 1.13](#), where in pp and pA collisions, the back-to-back production is visible (with $\Delta\phi = \pi$), while for AA collisions, the peak at $\Delta\phi = \pi$ disappears.

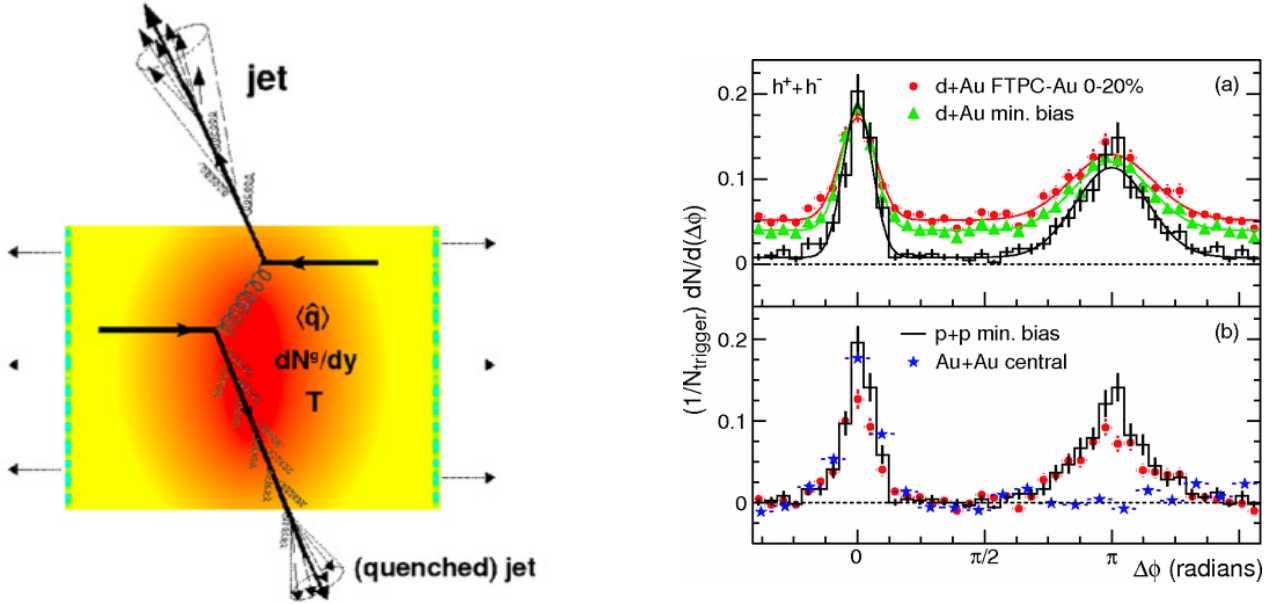


FIGURE 1.13: (left) A sketch illustrating the jet quenching [26]. (right) Azimuthal distribution in different collision systems with STAR [27].

1.5.5 Heavy-flavour production

Heavy-flavour measurements in heavy-ion collisions offer a unique way to probe the strongly-interacting matter created in such collisions, as heavy-flavour quarks (charm and bottom) are produced in hard-scattering mechanisms at the early stages of the collisions, and interact with the QGP medium and its constituents through elastic and inelastic processes. For a given hadron h , the cross-section is calculated with the perturbative expansion of QCD. Using the

QCD factorization theorem [28], the cross-section is given as:

$$d\sigma^{A+B \rightarrow h+X} = f_a(x_1, Q^2) \otimes f_b(x_2, Q^2) \otimes d\sigma^{ab \rightarrow c+X}(x_1, x_2) \otimes D_{c \rightarrow h}(z, Q^2) \quad (1.33)$$

The term $d\sigma^{ab \rightarrow c+X}(x_1, x_2)$ is the cross section for the production of parton c from the scattering of partons a and b which is calculated using pQCD at a given order in α_s . The other terms are non-perturbative:

- The Parton Distribution Function (PDF) $f_a(x_1, Q^2)$ represents the probability of finding a parton of flavour a inside the hadron A with a momentum fraction $x_1 = p_a/p_p$. The PDF appears twice in the equation: for parton a coming from hadron A and for parton b coming from hadron B . The final cross section must be summed over all possible combinations of a , b and c .
- The Fragmentation Function (FF) $D_{c \rightarrow h}(z, Q^2)$ describes the probability that the parton c fragments into a final state hadron h with a momentum fraction $z = p_h/p_c$.

PDF and FF rely on experimental measurements: PDFs are determined in Deep Inelastic Scattering (DIS) of electrons off protons or nuclei, while FFs come from jet measurements in high-energy e^+e^- collisions and electron-hadron collisions, where the clean environment allows for the determination of the state of the quark before hadronization.

1.5.6 Quarkonium suppression

One of the first probes proposed to study the QGP properties consists of measurements of quarkonium production (bound states of charmonium $c\bar{c}$ and bottomonium $b\bar{b}$). Their constituents, are produced at the early stages of collisions, thus experimenting the full system evolution. At LHC energies, their main production process is through gluon fusion. Matsui and Satz proposed in 1986 that the suppression of quarkonium production implies the presence of QGP [29]. In order to illustrate the suppression, one should look at the non-relativistic potential of interaction in a vacuum, between a quark and its anti-quark as a function of their distance r , known as the Cornell potential [30]:

$$V(r) = -\frac{\alpha}{r} + \sigma r \quad (1.34)$$

with the constants σ describing the confinement string tension, and α a coefficient determined by lQCD. The first term represents the Coulombian-like contribution of the interaction potential due to gluon exchange between the quark and its anti-quark, and the second term describes the confinement behaviour, prevailing at significant distances. At high energy densities, or high temperatures (Equation 1.18), the density of coloured partons increases. As the partons are

surrounding the quark and its anti-quark, a screening effect (known as the Debye screening) takes place, as described in Figure 1.14 - left, reducing thus the interaction potential between them, preventing the formation of bound states, leading to the suppression of quarkonium states. In a QGP, the interaction potential is described with the following equation:

$$V(r) = -\frac{\alpha}{r}e^{-r/\lambda_D(T)} + \sigma r \left(\frac{1 - e^{-r/\lambda_D(T)}}{r/\lambda_D(T)} \right) \quad (1.35)$$

with the screening radius $\lambda_D(T) \propto \frac{1}{T}$ (maximum distance allowing the formation of bound $q\bar{q}$ state, inversely proportional to the colour charges density), which thus decreases with an increase of the temperature. Due to different binding energy of each quarkonium state, each particle dissociates at different temperatures, revealing direct information about medium temperature (Table 2.2), as detailed in section 2.3.1. In Figure 1.14 - right, the interaction potential is displayed for different temperatures. It is observed to decrease with the increasing temperatures, thus displaying the screening effect for the increasing coloured partons densities.

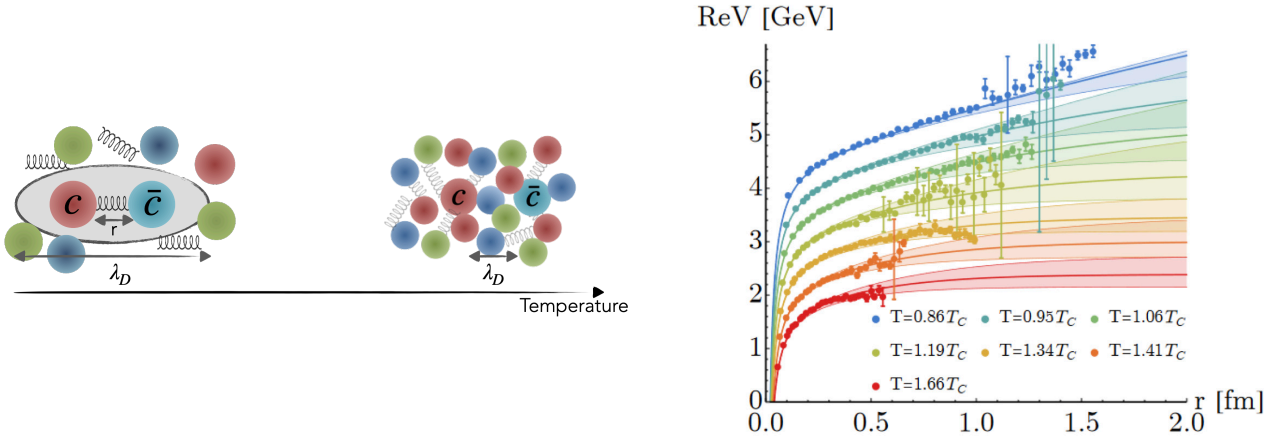


FIGURE 1.14: (left) Charmonia state in vacuum vs in QGP, where Debye screening takes place preventing the formation of bound state. (right) The interaction potential between $q\bar{q}$ as a function of their distance for different temperatures [31].

In addition, quarkonium production is affected by other mechanisms with different energy dependence, such as CNM effects, regeneration, feed down from excited states, secondary production. Therefore, measurements are done in varying collision systems with various energies to understand these different processes further. These effects will be further detailed in the next chapter.

1.6 Conclusion

The Standard Model, describing visible matter and its fundamental interactions, is presented in this chapter. The strong interaction is described using the QCD formalism. In particular, the QCD phase diagram was presented, which predicts two essential behaviours of matter. First, the confined matter which exists at the low-temperature phase with a unitary baryon density. Then, at very high temperatures, there is a crossover to the QGP, made of strongly interacting partons floating in a deconfined free state. This state is hardly observable in nature. Therefore, to reach these temperature scales, ultra-relativistic heavy-ion collisions take place in particle accelerators. Following these collisions, several stages of matter are described by the Bjorken model. If the medium is dense enough and the energies reached are sufficient, the QGP is produced in one of these stages. In order to investigate the QGP state and its properties, it is necessary to study various probes at different energies. Thus, the probes are categorized into soft and hard probes. One of the studied hard probes is the charmonium, which is created at the beginning of the collision. More precisely, the suppression of the latter is observed when a QGP is created. The next chapter will focus on the production of one of the most stable states studied of charmonium, the J/ψ particle.

Chapter 2

The J/ψ properties and production

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As discussed in the first chapter, ultra-relativistic heavy-ion collisions are the only experimental tool allowing the study of the QGP state by bringing finite volumes into high energy densities, thus bringing the nuclear matter to asymptotic freedom regime. The J/ψ , belonging to the charmonium family, is an essential QGP hard probe since the presence of a deconfined phase influences its production rate. The J/ψ particle was first detected in 1974 by two independent groups at Brookhaven National Laboratory and the Stanford Linear Accelerator Center, confirming the quark model proposed by Gell-Man [32] and Zweig [33]. The resonance discovered was around the mass of $3.1 \text{ GeV}/c^2$, in p-Be [34] and e^-e^+ [35] collisions. This chapter will focus mainly on the J/ψ , starting with an introduction of the charmonium state, followed by the production mechanisms of the J/ψ and its production in ultra-relativistic heavy-ion collisions. Finally, important experimental results will be discussed.

2.1 Charmonium states

Charmonium, as introduced in the first chapter, are bound states composed of a charm and anti-charm quarks ($c\bar{c}$). Each charmonium state can be described with the notation of $n^{2S+1}L_J$, with n the principal quantum number, S the spin, L the orbital momentum, and J the angular momentum, as presented in Figure 2.1. The J/ψ particle corresponds to the 1^3L_1 state with a mass of $3.1 \text{ GeV}/c^2$. J/ψ production can be either prompt, due to their direct production from hard processes or due to the feed-down of excited states, or non-prompt essentially due to the weak-decays of B hadrons. Their production mechanism will be discussed in the next section. As a reminder, the non-relativistic interaction potential in vacuum between a quark and its anti-quark is described in the first chapter (Equation 1.34). This potential can be used to model the charmonium potential. Solving the Schrödinger equation using this potential leads to the charmonium bound states. Masses and binding energies of the main charmonium resonances are presented in Table 2.1. With the increasing mass, the binding energy decreases, and the charmonium particle can be found in a weaker bound state.

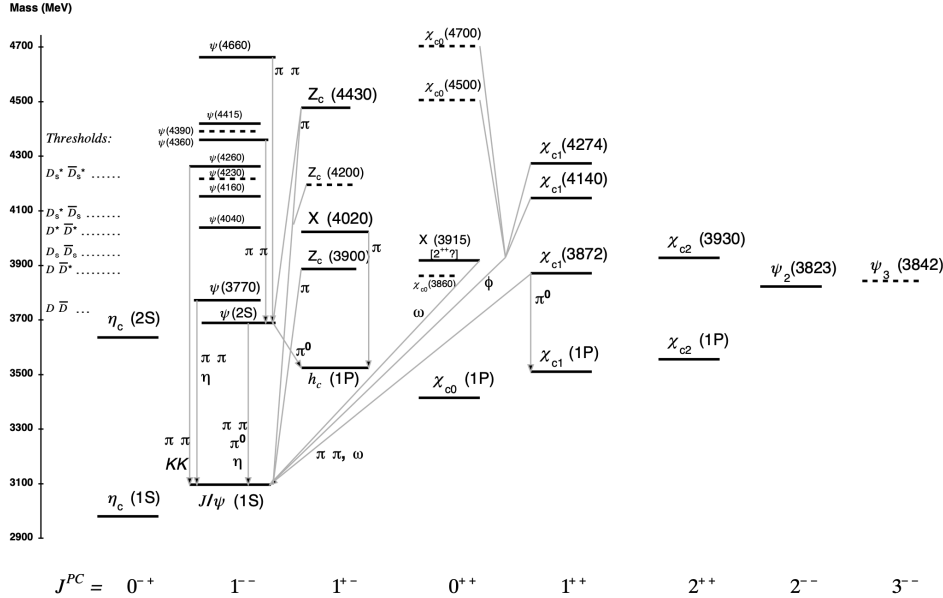


FIGURE 2.1: Level scheme of charmonium resonances [36].

Charmonium state	η_c	J/ψ	$\psi(2S)$
Mass (GeV/c^2)	2.98	3.10	3.69
ΔE (GeV)	0.75	0.64	0.05

TABLE 2.1: Table of the mass and binding energy for different charmonium states [37].

2.2 J/ψ production mechanisms

One of the main reasons leading to the study of J/ψ as a QGP probe lies in its formation time τ_f , which is proportional to the inverse of the mass of its constituents, such as $\tau_f \propto \frac{1}{2m_c}$ where m_c is the mass of charm quark. Thus, $\tau_f \simeq 0.1$ fm/c is smaller than the QGP formation time $\tau_{QGP} \simeq 1$ fm/c [38]. Therefore, the $c\bar{c}$ pair will experience the full evolution of the collision. As a condition for the J/ψ formation, the energy transfer (Q) of the parton system that initiates the process must be greater than the J/ψ 's mass: $Q > 2m_c$. This corresponds to the energy region where the pQCD approach is valid since $2m_c \gg \Lambda_{QCD}$. The main processes responsible for the formation of the $c\bar{c}$ pair, at leading order contribution, are shown in Figure 2.2. The first three processes consist of gluonic fusion and the last of quarks annihilation. The resulting $c\bar{c}$ pair can be either in a colour-singlet state (colourless), or in a colour-octet state (Equation 1.2). Charmonium particles can only exist in a colour-singlet state. In particular, as mentioned in the last section, the J/ψ particle can be categorized into prompt (due to the hadronization process or the feed-down), and non-prompt (essentially from B hadron decays) contributions. In the following, different models will be presented in order to describe both prompt and non-prompt production mechanisms.

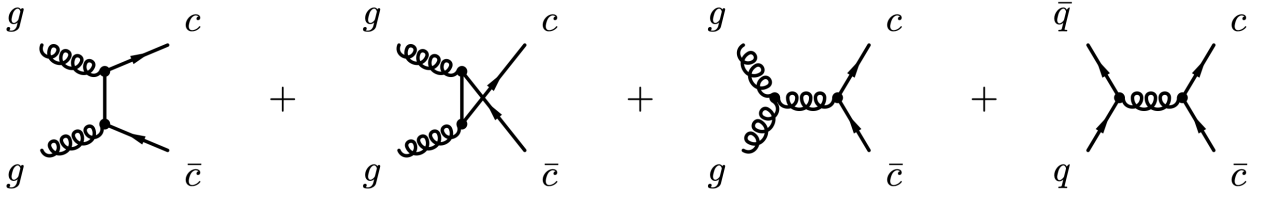


FIGURE 2.2: The production processes of $c\bar{c}$ with Feynman diagrams.

2.2.1 Prompt J/ψ production

The cross-section of prompt J/ψ is factorized into the c quark production process, which is perturbative, and the non-perturbative process of the c quark hadronization into the J/ψ meson. The main contrast between the different models is the hadronization process. Three historical models, the Colour Singlet Model (CSM), the Colour Evaporation Model (CEM), and the Colour Octet Model (COM) are presented.

The Colour Singlet Model

The first model introduced after the J/ψ discovery is the CSM [39, 40]. In this model, the $c\bar{c}$ pair produced, coming from a hard process, has a fixed quantum state that remains unchanged between the production and the hadronization. Thus, for the J/ψ production to occur, the

$c\bar{c}$ pair should be produced in a specific colour-singlet state. This model is based on the factorization for the cross-section calculation of the charmonium production, which separates the perturbative (cross-section for the $c\bar{c}$ production) and the non-perturbative contributions (the probability that the $c\bar{c}$ pair generates a J/ψ particle), suggesting that the perturbative and non-perturbative processes are correlated. The production cross-section of a charmonium state following the interaction between 2 partons, p_1 and p_2 , is factorized as:

$$d\sigma_{\text{charmonium}+X} = \sum_{p_1, p_2} f_{p_1, p_2} \otimes d\sigma_{p_1 + p_2 \rightarrow Q\bar{Q}+X} \otimes |\Psi_{\text{charmonium}}(0)|^2 \quad (2.1)$$

with the parton distribution functions f , and $|\Psi_{\text{charmonium}}(0)|^2$ the probability amplitude of hadronization into a charmonium state. The production cross-section of a charmonium state can be obtained experimentally or with IQCD. This model faces limitations reproducing the charmonium behaviour as it provides good estimation for data only at low energies [41, 42].

The Colour Evaporation Model

The CEM [43–45] was proposed by Fritzsche, describing quarkonium production following a statistical approach. The probability of a charmonium state formation is independent of the colour of the $c\bar{c}$ pair; thus, the main difference with the previous model is the non-fixed quantum state during its evolution. In this model, the perturbative and the non-perturbative processes are considered uncorrelated. The exchange of soft-gluons with the colour field destroys all previous information containing the quantum state of the $c\bar{c}$ pair, creating a probability for it to evolve to any given charmonium state. The production cross-section of a charmonium state is given by the following equation:

$$\sigma_{\text{charmonium}} = F_{\text{charmonium}} \int_{2m_Q}^{2m_H} dm_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}}{dm_{Q\bar{Q}}} \quad (2.2)$$

with the quarks mass m_Q and the open heavy flavour hadrons mass m_H (composed of one heavy quark). $F_{\text{charmonium}}$ is the hadronization probability to a charmonium state, obtained experimentally. A conclusion drawn from the CEM model is the independence of the ratio of two charmonium states to the kinematics. However, experimental data shows some dependencies [46]. Thus, while this model describes quarkonium production well, it still has its limitations.

Non-Relativistic QCD and the Colour Octet Model

The COM [47] mainly differs from the latter in that it additionally takes into account the contributions from the colour-octet states. The Non-Relativistic QCD (NRQCD) formalism is used, with the transitions into the colour-singlet state treated non-perturbatively. The production

cross-section of charmonium can be described with:

$$d\sigma_{\text{charmonium}+X} = \sum_{p_1, p_2} f_{p_1, p_2} \otimes d\sigma_{p_1 + p_2 \rightarrow Q\bar{Q}+X} \otimes \langle O^{\text{charmonium}}[n] \rangle \quad (2.3)$$

with $\langle O^{\text{charmonium}}[n] \rangle$ the probability amplitude of hadronization to a charmonium state described by the long-range matrix elements, determined experimentally. This model describes well the quarkonium production, with consistent predictions on cross-section and transverse polarization measurements at low p_T . However, difficulties are encountered to describe the polarization in the high p_T regions [48].

2.2.2 Non-prompt J/ψ production

The main process responsible for quarkonium production is the gluonic fusion (Figure 2.2). For the b quark, the process can be described with $gg \rightarrow b + \bar{b} + X$. This process is then followed by the formation of B -hadrons. The non-prompt J/ψ are mainly produced from the decays of the B -hadrons, as presented in Figure 2.3. The cross-section of the charmonium is factorized into the following:

$$d\sigma_{\text{charmonium}} = d\sigma_b \otimes D_{b \rightarrow B} \otimes g_{B \rightarrow \text{charmonium}} \quad (2.4)$$

the $d\sigma_b$ is the b quark cross production, which is a perturbative process evaluated by the Fixed Order Next-to-Leading-Logarithm (FONLL) [49] calculations, $D_{b \rightarrow B}$ the b fragmentation into the B -hadron process, which is non-perturbative and extracted from e^-e^+ experimental data, and $g_{B \rightarrow \text{charmonium}}$ is the weak decay function from B -hadron to charmonium state.

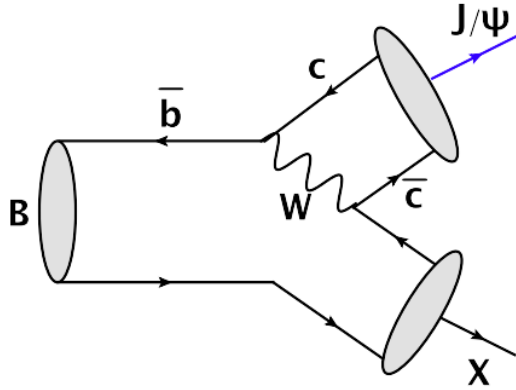


FIGURE 2.3: Feynman diagram of the weak-decay of B -hadron to J/ψ with leading order contribution [50].

2.3 J/ψ production in heavy-ion collisions

Another essential reason that makes the J/ψ a very interesting QGP probe is that its production rate is affected by the medium. In this section, the different processes and effects on the production of the J/ψ in ultra-relativistic heavy-ion collisions are discussed, and illustrated by experimental results. They are divided into two categories: hot nuclear effects induced by the QGP phase and cold nuclear effects induced by hadronic phase.

2.3.1 Hot nuclear effects

Sequential suppression

As discussed in chapter 1 (Equation 1.35), the increase of colour density induces a decrease in the range of the strong interaction (Debye screening effect). If this range, called Debye radius, is smaller than the radius of a bound state, the latter cannot be produced [51]. The reduction of the interaction potential between c and $\bar{c}$ quarks in the QGP can lead to the sequential suppression. In particular, this reduction can prevent the formation of bound states and leads to their suppression, depending on the temperature of the medium. This results in a dissociation temperature T_D , characterizing each bound state, above which it melts completely. Thus, a precise determination of different dissociation temperatures are required in order to estimate the QGP temperature. Various approaches can be used, such as LQCD temperature calculations and different potential models [52, 53]. The different values of the ratio of the dissociation to critical temperatures for different main charmonium resonances are presented in Table 2.2, obtained with a potential model [37]. The T_D is observed to increase with the increase of the binding energy.

Charmonium state	J/ψ	χ_c	$\psi(2S)$
T_D/T_c	2.10	1.16	1.12

TABLE 2.2: T_D/T_c for the main charmonium states [37].

Recombination

The production cross-section of the c and $\bar{c}$ quarks is proportional to the center of mass-energy; thus, the higher the energy, the higher the production of charm quarks. This can lead to a phenomenon known as recombination [54, 55], which was first described in 1980, before Matsui and Satz article. This process occurs at high energy, where charm quarks density is so important that it allows the recombination of these quarks into a charmonium state. At higher energies,

the recombination mechanism is stronger and can thus counterbalance the suppression. This process can occur during the evolution of the medium or during the hadronization phase [56].

Interaction with comovers

The comovers particles are final state constituents that can interact with charmonium states. This results in the suppression of charmonium due to these interactions, in particular through inelastic collisions. After such interactions, open charm can be created with the following process: $c\bar{c} + h \rightarrow D + \bar{D} + X$, where h refers to the comoving hadron. As can be observed in Figure 2.4, with the increasing energy density, the number of comovers particles increases and thus the suppression due to the comovers becomes significant.

The interplay between the explained mechanisms on the J/ψ production probability is sketched in Figure 2.4. The suppression steps trend indicate first the dissociation of the J/ψ coming from $\psi(2S)$, followed by the dissociation of the contribution from χ_c .

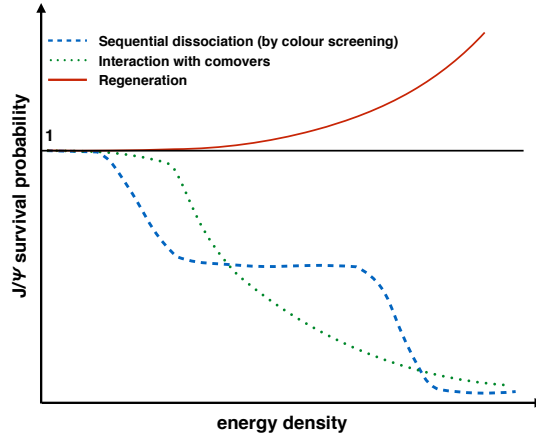


FIGURE 2.4: The J/ψ production probability vs the energy density (Equation 1.18) [50].

2.3.2 Cold Nuclear Matter effects

Shadowing and anti-shadowing effects

As heavy-quark production occurs at the earliest moments of collision, the initial state has great influence on the production of quarkonium, in particular PDFs. PDFs are described in the chapter 1, with their contribution to the cross-section calculation presented in Equation 1.33. Their determination relies on experimental measurements. However, there is a difference between the PDF in a free nucleon from the one inside a nucleus (nPDF). It was first discovered in 1983 by the European Muon Collaboration (EMC) by looking at the parton momentum distribution in Iron and in Deuterium, where a difference was observed [57]. The nPDF of a parton flavour i

at a given energy scale with a fraction x of longitudinal momentum can be expressed with the following equation:

$$f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i(x, Q^2) \quad (2.5)$$

with $f_i(x, Q^2)$ the PDF of the free nucleon, and $R_i^A(x, Q^2)$ the nuclear modification factor. The $R_i^A(x, Q^2)$ is presented in [Figure 2.5](#). Different regions of the modification factor can be observed, indicating different regimes [\[58\]](#). For $R_i^A(x, Q^2) < 1$ with a small fraction $x \leq 0.1$, heavy quark production is decreased. This is called the shadowing effect. It is explained by the multiple scattering taking place between the partons. Anti-shadowing occurs for the region $R_i^A(x, Q^2) > 1$ with $0.1 \leq x \leq 0.3$, with an increase of heavy quark production, explained by the constructive interference of amplitudes due to the multiple scattering.

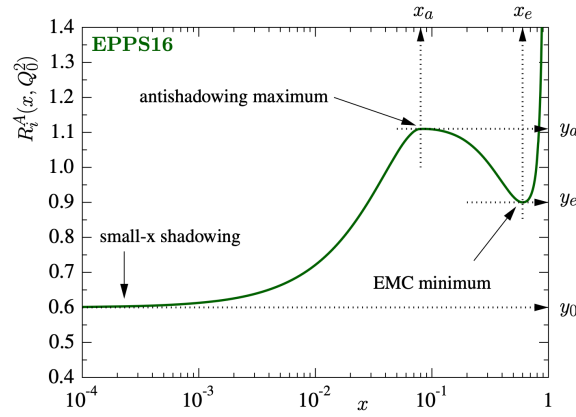


FIGURE 2.5: Illustration of $R_i^A(x, Q^2)$ as a function of x [\[59\]](#).

Thus, charmonium production can vary according to the energy and rapidity of collisions. In [Figure 2.6](#), theoretical models predictions of nuclear modification factor are presented as a function of rapidities and p_T for J/ψ in Pb–Pb collisions. A decrease of the suppression is observed with the increasing p_T , and at forward and backward rapidity regions.

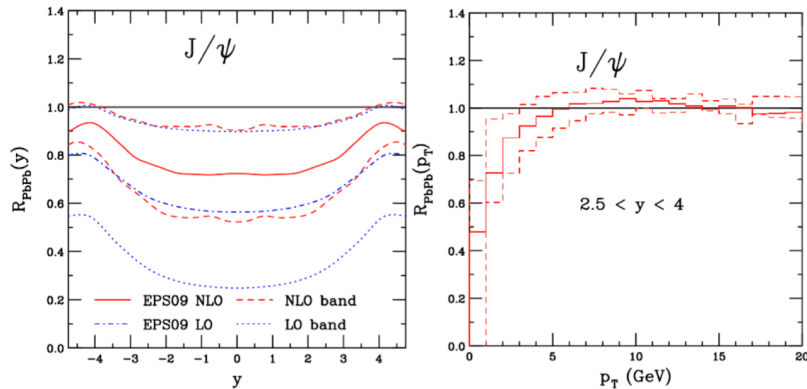


FIGURE 2.6: The J/ψ nuclear modification calculated with EPS09 nPDFs as a function of rapidities and p_T in Pb–Pb collisions [\[60\]](#).

Cronin effect

During the initial stages of the collision, partons undergo elastic scattering multiple times on colliding nuclei, acquiring transverse momentum at each collision. Therefore, the partons acquire a transverse momentum, shifted toward higher momenta value. This effect, known as the Cronin effect [61, 62], was first observed in pA collisions. Thus, this effect leads to the hardening of the transverse momentum distribution for the J/ψ production in AA and pA collisions with respect to pp collisions.

Nuclear absorption

The nuclear absorption corresponds to the dissociation of the charmonium states, caused by successive scatterings with spectator nucleons. The survival probability, S_{abs} , of a bound state can be determined with:

$$S_{abs} = e^{-\rho_A \sigma_{abs} L} \quad (2.6)$$

where ρ_A is the nuclear density, L is the mean propagation length, and σ_{abs} is the effective cross-section for quarkonium breaking. With the Glauber model, explained in the chapter 1, the cross-section is extracted from pA collisions data and extrapolated to the AA collisions.

2.4 Experimental results

As discussed in the first chapter, the properties of the QGP can be studied with heavy-ion collisions (AA) at relativistic energies, compared along with different collision systems (pp and pA). Lead nuclei are accelerated, to speeds close to the speed of light, enough to create, while colliding, a QGP droplet that can be studied with particle detectors. In this section, a review of experimental results will be presented, along with discussions on their physical implications.

2.4.1 Quarkonium: regeneration vs suppression

The hot nuclear matter effects can be investigated through measurements of the elliptic flow v_2 (presented in Equation 1.32) and the nuclear modification factor R_{AA} . The R_{AA} factor is a scaled ratio that compares the yields of particles in AA collisions with respect to pp collisions. It can be expressed by the following equation:

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \quad (2.7)$$

where $\langle N_{coll} \rangle$ is the average number of nucleon-nucleon collisions, $N_{AA,pp}$ correspond to the particle invariant yields in AA and pp collisions respectively.

2.4.1.1 Charmonium

In Figure 2.7 - left, the measurement of the nuclear modification factor of the inclusive J/ψ is presented in Pb–Pb collisions at ALICE, with a center of mass energy of $\sqrt{s_{NN}} = 2.76$ TeV and at $\sqrt{s_{NN}} = 5.02$ TeV, at forward rapidity. With this measurement, one can deduce that the J/ψ is highly suppressed due to the colour screening mechanism. Data is compared with a transport model [63, 64]. It is based on several effects, such as the suppression, recombination, shadowing, Cronin effect, as well as the feed-down from excited states production. The model is in good agreement with data.

In Figure 2.7 - right, the J/ψ elliptic flow measurement is displayed at forward rapidities in Pb–Pb collisions, with the centrality region [20% - 40%], at $\sqrt{s_{NN}} = 5.02$ TeV. A direct effect of the recombination mechanism at low p_T can be seen with the elliptic flow increase with increasing p_T , which is a consequence of the thermalization of $c\bar{c}$ pairs. A decrease is then observed, for $p_T > 6$ GeV/c. The TAMU model, a transport model, is in accordance with data for $p_T \leq 4$ GeV/c, but underestimates data afterwards, suggesting that a mechanism is missing from the model.

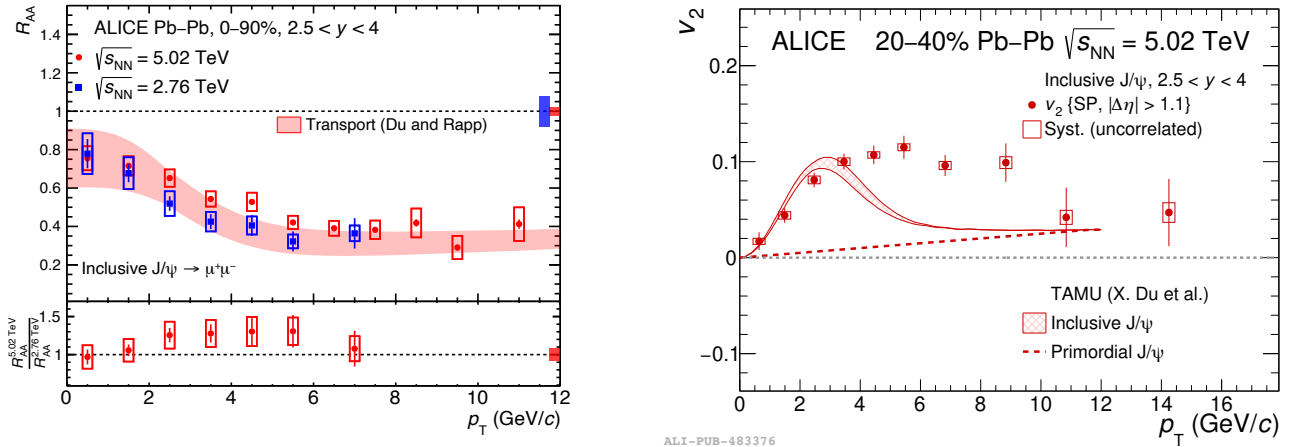


FIGURE 2.7: (left) The nuclear modification factor of J/ψ in Pb–Pb collisions [65]. (right) The elliptic flow v_2 of J/ψ in Pb–Pb collisions [66].

2.4.1.2 Bottomonium

The $\Upsilon(1S)$ particle is the bottomonium bound state that is commonly studied, as it is the less suppressed state in this family. This quarkonium state is out of the scope of this chapter, nonetheless presented to compare the different dominating effects between charmonium and bottomonium production.

In Figure 2.8 - left, the $\Upsilon(1S)$ nuclear modification factor is presented in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward rapidity. This measurement shows a high suppression of $\Upsilon(1S)$.

Unlike the J/ψ particle, there is no observable effect of regeneration. It is compared with two transport models, with and without the regeneration mechanism. The model predicts data well, and the regeneration effect is negligible within the measurement precision. This is in agreement with the expectations, as the b quark, being heavier than the c quark, has a lower production rate, thus the regeneration mechanism is supposed to be less important or even non-existent for the Υ mesons.

In Figure 2.8 - right, the elliptic flow of $\Upsilon(1S)$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward rapidity is presented. The absence of regeneration can be confirmed, as data fluctuates around zero. It is also compared to transport models, which predict well the data.

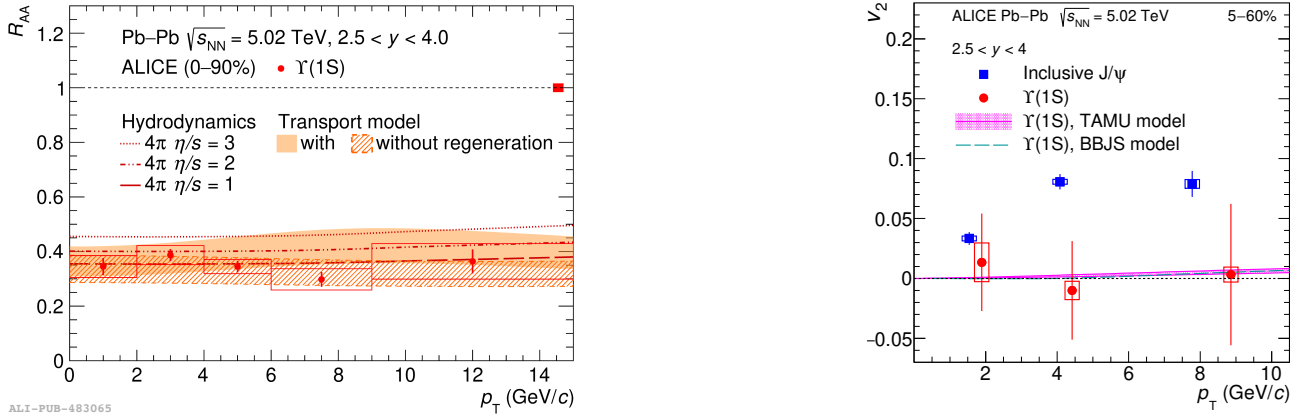


FIGURE 2.8: (left) The nuclear modification factor of Υ in Pb–Pb collisions [67]. (right) The elliptic flow v_2 of Υ in Pb–Pb collisions [68].

2.4.2 Cold Nuclear Matter effects

In order to fully understand Pb–Pb collisions, as previously discussed, hot nuclear matter effects need to be disentangled from the CNM effects. Thus, measurements in p–Pb collision systems are presented in the following, where CNM mechanisms can be disentangled.

In Figure 2.9 - left, the nuclear modification factor of the J/ψ is presented at $\sqrt{s_{NN}} = 5.02$ TeV at forward rapidity. In Figure 2.9 - right, the $\Upsilon(1S)$ is presented at $\sqrt{s_{NN}} = 8.16$. For both particles, the trend is similar, as suppression increases with the decreasing p_T . The different theoretical models, within their bandwidth, are in accordance with the data. Models with only suppression due to a shadowing contribution present a flat trend, which is not reflected by data. The nCTEQ15 model [69], describing well data, includes the interactions with comoving particles, in addition to the shadowing effects. Models based on the Colour Glass Condensate (CGC) [70] also reproduce well data. CGC is based on a non-linear evolution equation, and takes into account parton saturation for low- x partons.

Finally, in Figure 2.10 is presented the elliptic flow in p–Pb collisions, for the J/ψ particle,

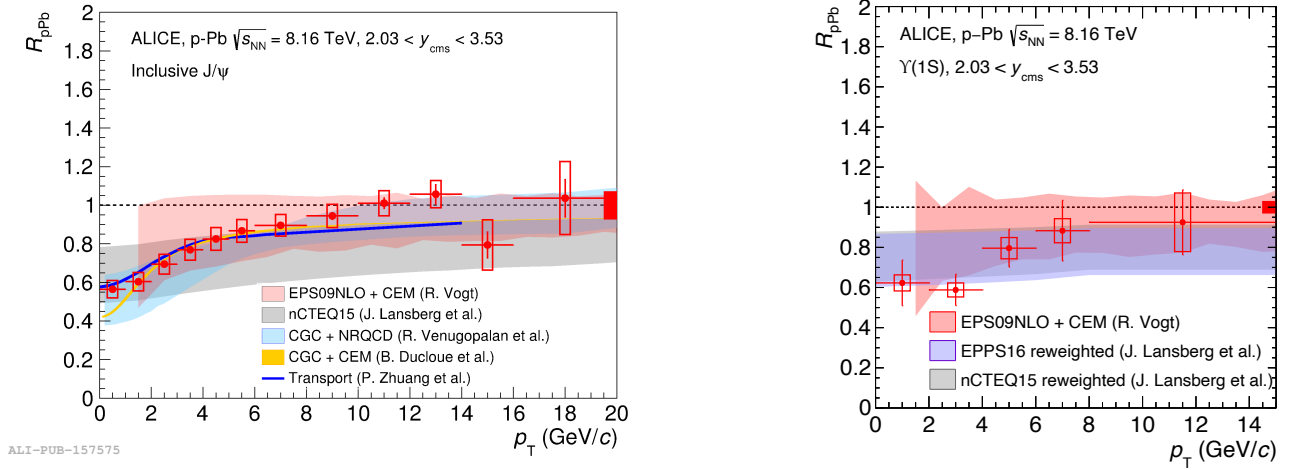


FIGURE 2.9: (left) The nuclear modification factor of J/ψ in p-Pb collisions [71]. (right) The nuclear modification factor of Υ in p-Pb collisions [72].

at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 8.16$ TeV, in the forward and backward rapidity regions. One would expect no recombination mechanisms to occur within these collisions, thus an elliptic flow fluctuating around zero. However, this is only the case for data with $p_T < 3$ GeV/c. As data with higher transverse momentum, $3 < p_T < 6$ GeV/c, a positive contribution for the elliptic flow is observed, comparable to the elliptic flow measurement in Pb-Pb collisions (within uncertainties). Thus, the transport model fails to reproduce the data, as the responsible underlying mechanism is not understood. One of the explanations for this positive elliptic flow is the recombination mechanism occurring due to canonical enhancement effects in p-Pb collisions.

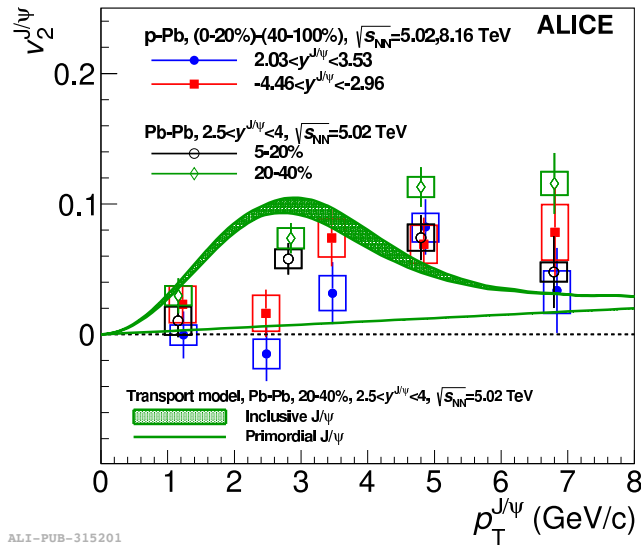


FIGURE 2.10: The J/ψ v_2 , in p-Pb at forward and backward rapidities and Pb-Pb at forward rapidity [73].

2.4.3 Charmonium production in pp collisions

In order to constrain the theoretical models discussed in this chapter, charmonium measurements in pp collision system are required, which are also considered as a reference for the measurements done in Pb–Pb and p–Pb systems.

First, inclusive J/ψ (Figure 2.11 - left) and $\psi(2S)$ (Figure 2.11 - right) cross-section measurements are presented at forward rapidity region ($2.5 < y < 4$) in different collision energies $\sqrt{s} = 5.02, 7, 8$, and 13 TeV, via the muonic decay down to $p_T = 0$ GeV/c. In addition, the ratio between cross-sections at different collision energies is done to reduce the energy-related uncertainties. An increase of the cross-section is observed with the increasing energy. A strong hardening of the J/ψ cross-section spectra at 13 TeV is noticed with respect to other energy scales. It can be explained by a predicted increase of prompt J/ψ mean p_T with energy, and an increase of the non-prompt contribution at high p_T (by FONLL). For both charmonium states, the NRQCD model describes the prompt contribution, and FONLL describes the non-prompt contributions. The models are in good agreement with the cross-section data. The same is also observed for the different ratios for both charmonium states within uncertainties, except for the 7-to-13 TeV J/ψ ratio. As can be seen, the latter is slightly overestimated by the models, as it's expected to be closer to the 8-to-13 TeV ratio.

In order to separate the different contributions, measurements for J/ψ prompt and non-prompt are presented at midrapidity region ($|y| < 0.9$) at $\sqrt{s} = 13$ TeV (Figure 2.12) and 5.02 TeV (Figure 2.13). For both prompt J/ψ measurements in the different collision energies, there is an agreement observed between the data and the Improved CEM model (ICEM) [75] and NRQCD based models, except for the NRQCD Lipatov calculations [76]. A slight overestimation of the data at low p_T is observed for the latter. The Lipatov factorization approach is based on p_T dependent gluon distribution functions, and takes into account the J/ψ contributions from the excited charmonium states. As for the non-prompt J/ψ , an agreement is observed between the FONLL model and the data. An indication of the decrease of the non-prompt fraction at lower collision energy is observed, as the fraction of non-prompt production is extracted for each energy scale, with the following results:

$$f_B^{visible, \sqrt{s}=13 \text{ TeV}}(p_T > 1 \text{ GeV}/c, |y| < 0.9) = 0.185 \pm 0.015(\text{stat.}) \pm 0.014(\text{syst.})$$

$$f_B^{visible, \sqrt{s}=5.02 \text{ TeV}}(p_T > 2 \text{ GeV}/c, |y| < 0.9) = 0.157 \pm 0.023(\text{stat.}) \pm 0.016(\text{syst.})$$

Additionally, data are compared for the $\sqrt{s} = 5.02$ TeV cross-section measurements (Figure 2.13) between ALICE, CMS and ATLAS; results are consistent in the common p_T region. These measurements show that the charmonium production in pp collisions is globally well described by models as ICEM, NRQCD, and FONLL within uncertainties.

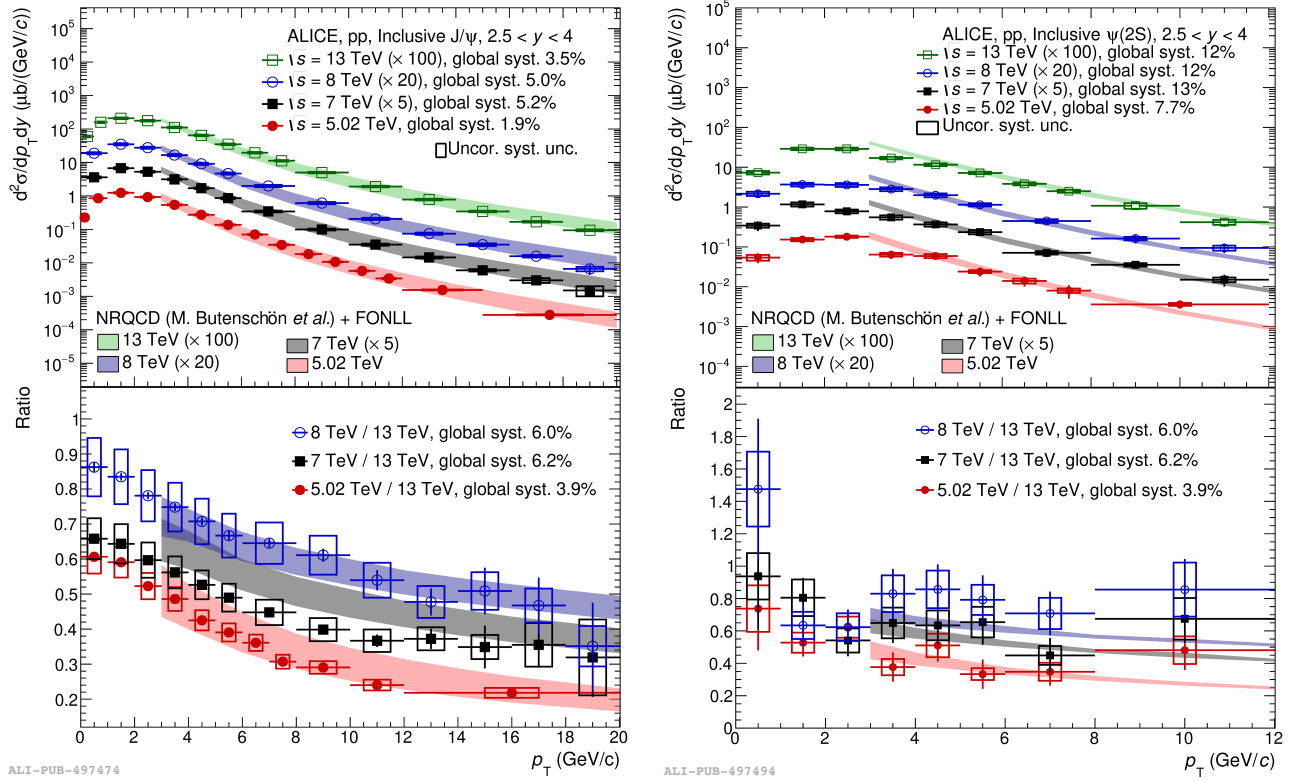


FIGURE 2.11: The inclusive (left) J/ψ and (right) $\psi(2S)$ cross-section measurements as a function of the transverse momentum p_T at forward rapidity pp collisions at $\sqrt{s} = 5.02, 7, 8$, and 13 TeV at the top, and the ratio of the 5.02, 7, and 8 TeV to 13 TeV measurements at the bottom. Both figures are extracted from [74].

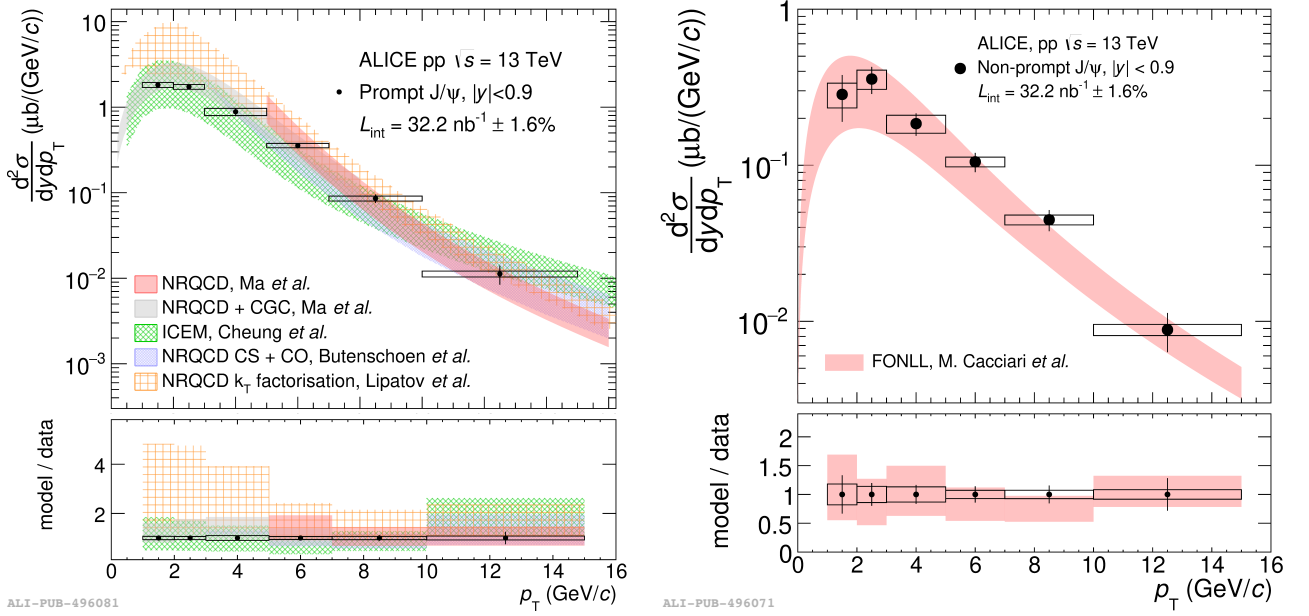


FIGURE 2.12: The (left) prompt and (right) non-prompt J/ψ cross-section measurements as a function of the transverse momentum p_T in midrapidity pp collisions at $\sqrt{s} = 13$ TeV. Both figures are extracted from [77].

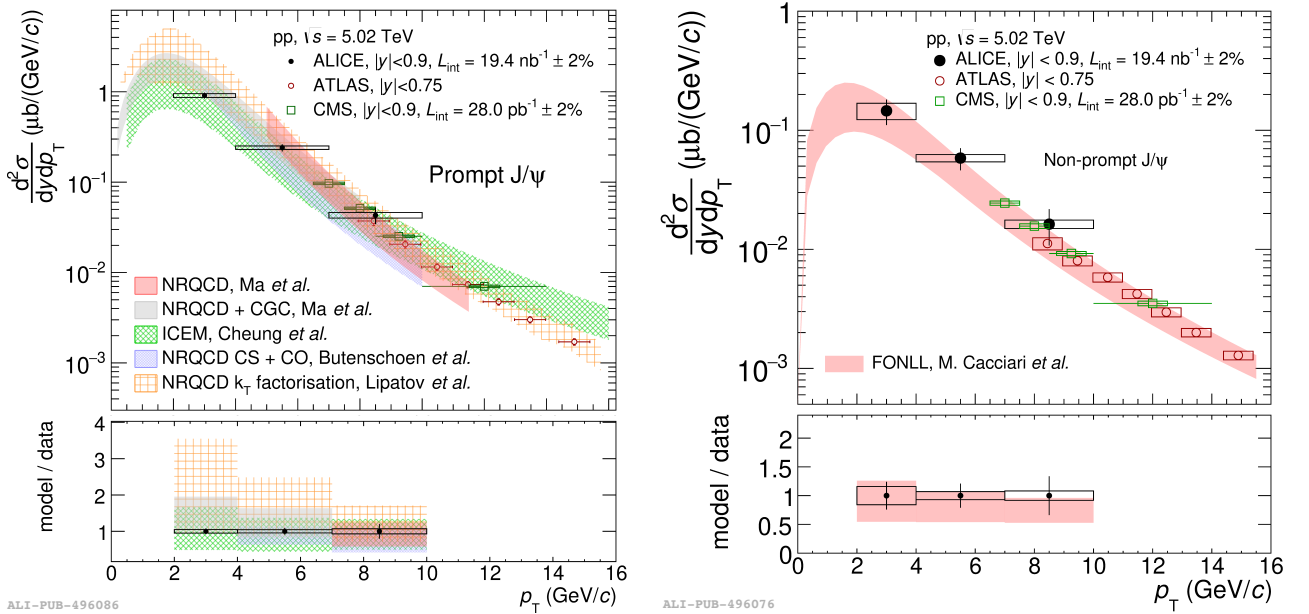


FIGURE 2.13: The (left) prompt and (right) non-prompt J/ψ cross-section measurements as a function of the transverse momentum p_T in midrapidity pp collisions at $\sqrt{s} = 5.02$ TeV compared between ALICE, CMS, and ATLAS measurements. Both figures are extracted from [77].

2.5 Conclusion

The J/ψ particle, consisting of an important QGP probe, is described in this chapter. It is a charmonium state that can be categorised into two groups. The prompt J/ψ , produced directly as a result of hard processes or following the feed-down of excited states. The non-prompt J/ψ , which are produced as a result of the weak-decays of B hadrons. Their production mechanisms are described by several theoretical models. The J/ψ production is very sensitive to the medium, making it a valuable probe. In particular, the different effects on the production of the J/ψ in hot nuclear matter following heavy-ion collisions essentially involve an interplay between charmonium suppression and recombination mechanisms. CNM effects are also studied in order to disentangle the effects of QGP from the nuclear effects induced by the presence of heavy nuclei. Thus, to visualise the mentioned hot nuclear matter effects and CNM effects, the J/ψ and Υ is studied in Pb–Pb and p–Pb collisions respectively. An indication of the regeneration and thermalization mechanisms of $c\bar{c}$ pairs is observed, which is not the case for the $b\bar{b}$ pairs. Finally, to constrain the theoretical models, the production of J/ψ is studied in pp collisions. The measurements presented in this chapter are performed in ALICE, a detector at the LHC accelerator, where only inclusive quarkonium measurements can be performed at forward rapidities, due to design limitations. The methods envisaged and implemented to overcome these limitations will be the subject of the following chapters.

Chapter 3

The Large Hadron Collider and ALICE

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As discussed in the first chapter, heavy-ion collisions at ultra-relativistic energies are the only experimental tool allowing the study of the Quark-Gluon Plasma. Within this chapter, the colossal machinery behind these tools is detailed. Starting with the presentation of the Large Hadron Collider (LHC), the world's most powerful particle accelerator, permitting the creation of conditions that are similar to those of the very early Universe. Inside the accelerator, two high-energy particle beams guided by a strong magnetic field travel in opposite directions close to the speed of light before colliding. Around one of the collision points is located A Large Ion Collider Experiment (ALICE), designed for the study of heavy-ion collisions. A description of the ALICE detector will be also provided in this chapter.

3.1 The Large Hadron Collider

3.1.1 A brief history of the Large Hadron Collider

After the end of World War II, European researchers were faced with several difficulties, including the threat of destruction of culture, migration of researchers, and insufficient means devoted to research in each country, as scientific research was becoming increasingly expensive. Thus, a solution was proposed with the creation of a European atomic physics laboratory, allowing the share of the financial costs between the different member countries of this organization. At the European conference of culture in 1949, Louis de Broglie made a first official proposal for the creation of the latter [78]. Afterwards, at the UNESCO meeting in Paris in 1951, the European Council for Nuclear Research, with the acronym CERN, was born. The first CERN accelerator, the Synchrocyclotron (SC), was built in 1957. The SC was capable of accelerating protons up to 600 MeV. It was followed by the Proton Synchrotron (PS) [79] and the Super Proton Synchrotron (SPS) [80] accelerators. The story of the LHC [81] starts around 1977, with the former directors of CERN, John Adams and Leon van Hove. They pioneered the project of the largest hadron accelerator, with the prospect of achieving collisions at center-of-mass energies in the TeV scale. Around 1997, it was officially approved, then put in operation around 2008. The first collisions took place around November 23rd 2009, marking the official start of the first LHC data taking period, also known as Run 1. At the 30th of November, a world record was set with a beam energy reaching 1.18 TeV. A second world record was set just after, around the 16th of December, with collisions at center-of-mass energy of 2.36 TeV. During the first Run, different collision systems were used: pp collisions with a center-of-mass energy peak at 8 TeV, p–Pb collisions reaching 5.02 TeV, and Pb–Pb collisions with a peak at 2.76 TeV. This Run lasted until February 2013, after which the first long shutdown (LS1) took place for two years, allowing detector upgrades to take place to prepare for the next Run, with increased collision energy scale. The second operational Run took place from 2015 to 2018. During this period, a top collision energy of 13 TeV, 8.16 TeV and 5.02 TeV was reached in pp, p–Pb and Pb–Pb collisions, respectively. In addition, a new Xe–Xe collision system at 5.44 TeV was delivered. After Run 2, and during the timeline of this thesis, the LHC was in the second long shutdown (LS2) period. Preparations were ongoing for the next data taking period, with increased luminosity and a wider physics program resulting from detectors upgrades. Run 3 has officially started with pp collisions on the 5th of July 2022.

3.1.2 Structure

The LHC is located in a tunnel with a circumference of 27 km, between 50 and 175 m beneath the France-Switzerland borders. Inside the accelerator, two beams of particles are guided in

separate vacuum pipes, in opposite directions, by a strong magnetic field provided by superconducting electromagnets, hence, the magnets are kept at very low temperatures of -271.3°C with liquid helium. Before particles start circulating inside the LHC, they pass through a chain of several accelerators (Figure 3.1), gaining more energy in each step until reaching a center-of-mass energy at the TeV scales. These particles, grouped into bunches, consist of protons (extracted from hydrogen gas), lead, or xenon ions. The beam size and trajectory are controlled with quadrupole and dipole magnets, respectively. The two beams, accelerated at very high speeds, will cross at four different points, around which are located the different CERN experiments: ATLAS, LHCb, CMS, and ALICE.

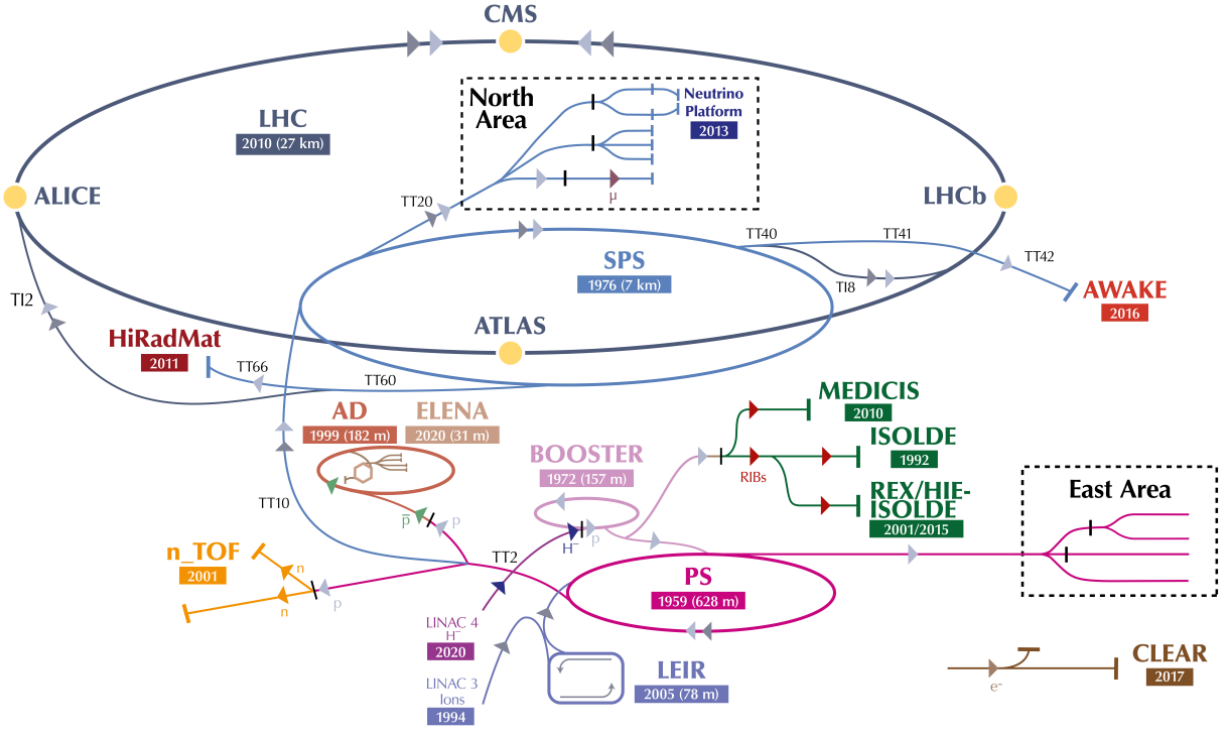


FIGURE 3.1: The CERN detailed accelerator structure [82].

Proton beams First, protons are extracted from a hydrogen gas inserted in a metal cylinder, a duoplasmatron, where the H_2 gas is surrounded by an electrical field, breaking it into protons and electrons. Protons are then accelerated to an energy of 50 MeV and split into bunches using radiofrequency cavities within the Linac2 [83] (linear accelerator) [83]. Following this step, proton bunches are sent into a Proton Synchrotron Booster (PSB) [84], gaining energy up to 1.4 GeV. The next accelerator in the chain consists of the PS, where bunches are separated periodically, with a time step of 25 ns between each bunch, and accelerated to reach the energy of 25 GeV. Then, proton bunches are sent to the SPS, where they reach the energy of 450 GeV. Finally, the bunches are separated and sent in opposite directions into the LHC accelerator,

where proton beams can reach a maximum energy of 6.8 TeV.

Lead beams A pure Pb source is heated to around 800°C, resulting in a partial extraction of Pb atoms. The Pb atoms are then passed to the Electron Cyclotron Resonance [85], where electrons are stripped from Pb atoms. Following this, Pb^{27+} ions are then accelerated with Linac3 up to 4.2 MeV per nucleon, losing more electrons in the process. Then, accelerated up to 72 MeV per nucleon and separated into bunches in the Low Energy Ion Ring (LEIR) [86]. Following this step, the chain is the same as for the protons. First, the Pb ions are accelerated in the PS up to 5.9 GeV per nucleon, where all the remaining electrons are stripped (Pb^{82+}). Then, they are injected into the SPS, where they reach an energy of 177 GeV per nucleon. Finally, they are separated into 2 opposite directions into the LHC accelerator, where the maximum energy reached per nucleon is of 2.51 TeV in Run 2.

3.1.3 Luminosity

In order to characterize a collision between two bunches, luminosity measurements, an essential parameter, is required. The instantaneous luminosity $\mathcal{L}$ indicates the rate of inelastic collisions that can be produced, in units of $\text{cm}^{-2}\text{s}^{-1}$. It can be calculated theoretically with the following equation:

$$\mathcal{L} = \frac{1}{\sigma_p} \times \frac{dR}{dt} \quad (3.1)$$

where σ_p is the production cross-section of a determined processes and $\frac{dR}{dt}$ is the number of such processes per unit of time. In the case of the LHC, a circular accelerator, the luminosity can be calculated with:

$$\mathcal{L} = \sum_{i,j} \frac{N_i N_j f_{rev}}{I_{overlap}} \quad (3.2)$$

with f_{rev} is the revolution frequency, equal to the collisions frequency, $N_{i/j}$ the number of colliding particles, with i, j the index of bunches per beam, and $I_{overlap}$ is the integral of the overlap area between the two bunches. The integrated luminosity $\mathcal{L}_{int}$ is obtained by the integration of $\mathcal{L}$ over time.

3.1.4 The four giants

The four largest experiments surrounding the collision points of the LHC accelerator as displayed in Figure 3.1 are the following:

A Toroidal LHC ApparatuS (ATLAS) [87]: ATLAS is a general-purpose detector designed to study the standard model of physics and beyond with Higgs boson, supersymmetric particles, and other physics beyond SM, as well as contributing to the QGP study. It is located

100 m under ground, weighs 7,000 tonnes, with the dimensions of a cylinder, measuring 46 m long and 25 m in diameter, making it the largest detector of the LHC. It comprises six subsystems around the interaction point, necessary for the measurements of trajectory, momentum, and energy. For precise momentum measurements, a large magnet system bends the path of the charged particles passing through, with a magnetic field of 2 T. The acceptance pseudorapidity of this detector is $|\eta| < 2.5$, with p_T acceptance for muon measurements down to 3 GeV/c. The ATLAS detector is displayed on [Figure 3.2](#).

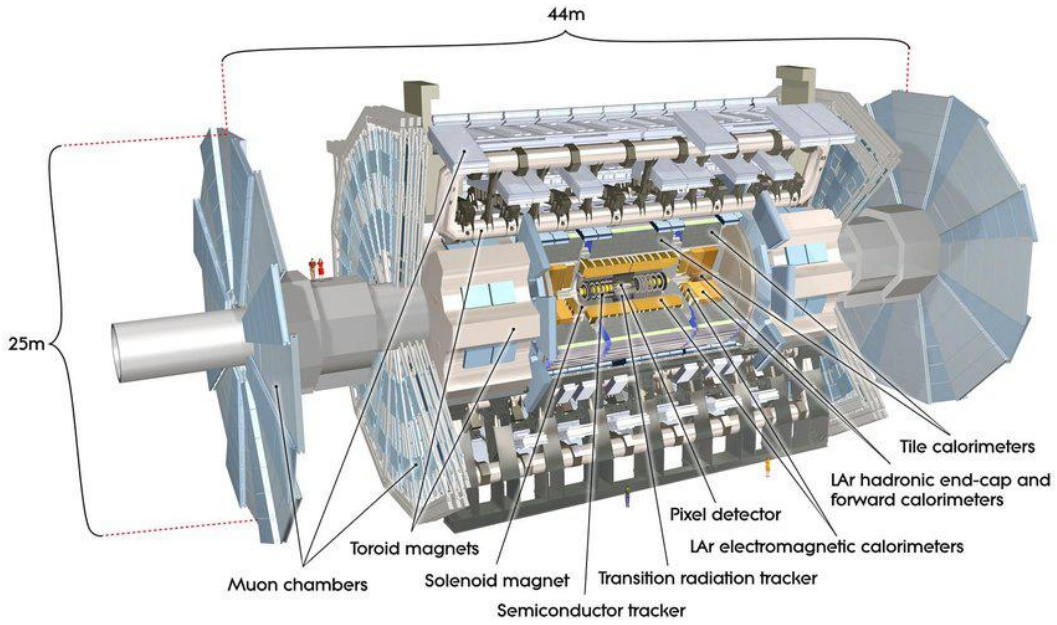


FIGURE 3.2: The ATLAS detector structure [\[88\]](#).

Compact Muon Solenoid (CMS) [\[89\]](#): The CMS, as the ATLAS detector, is also a general-purpose detector with the same physics objectives. It is the heaviest detector of the LHC, weighing 14,000 tonnes, with dimensions of 21 m long and 15 m in diameter. The detector is constructed around a large solenoid magnet, taking the form of a cylindrical coil of superconducting cable, creating a magnetic field of 4 T, around 100,000 times stronger than that of the earth. The pseudorapidity region of this detector is $|\eta| < 2.5$, with the minimum transverse momentum for muon measurements going from 1.2 to 3.5 GeV/c. The CMS detector structure is displayed in [Figure 3.3](#).

LHC beauty (LHCb) [\[91\]](#): The LHCb's main goal is the study of heavy-flavour physics, notably the B -mesons decays, in order to shed light on the CP (charge-parity) symmetry violation. The detector weighs 5,600 tonnes and is 21 m long, 10 m high, and 13 m wide. It is a single-arm forward spectrometer, constructed initially to study pp collisions. It is the only

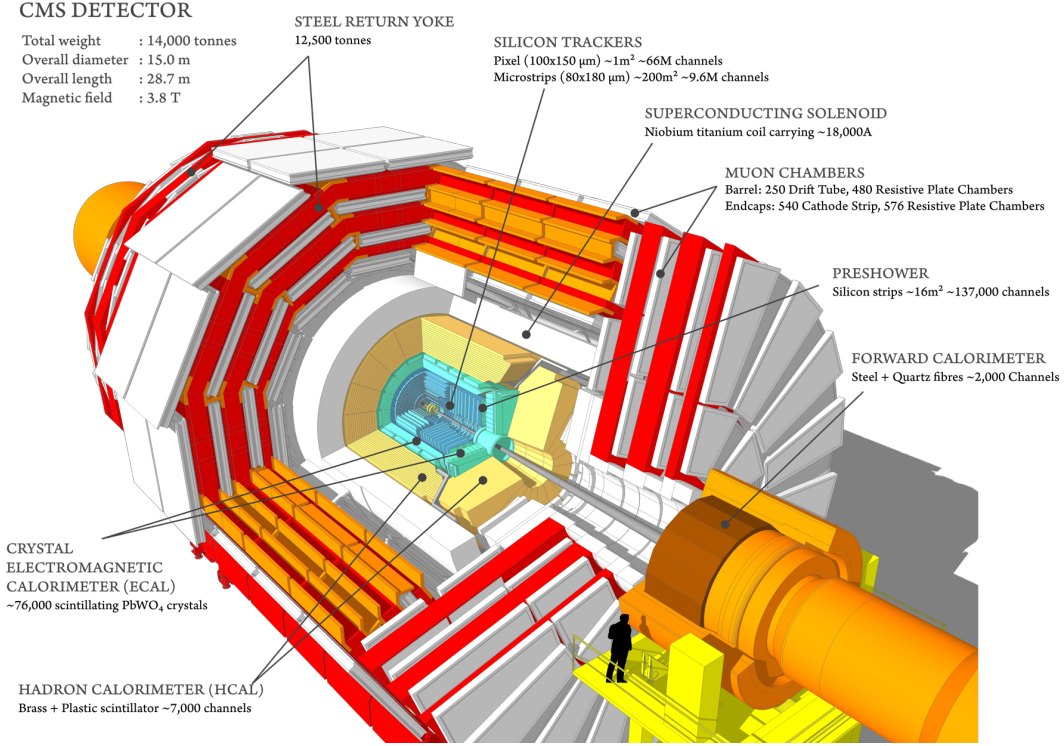


FIGURE 3.3: The CMS detector structure [90].

LHC experiment with fixed-target mode nuclear gas injection (He, Ne, Ar), with its injection system SMOG [92]. In 2013 and 2016, the collaboration participated in data taking for p–Pb collisions, and in 2015, for Pb–Pb collisions, with luminosity leveling, allowing thus the widening of their physics reach, with heavy-flavor hadrons and Z-bosons analyses studied in these collision systems. The pseudorapidity acceptance is of the range $2 < \eta < 5$, optimised for the study of B –mesons decays, with measurements done down to $p_{\text{T}} = 1 \text{ GeV}/c$. The LHCb detector layout is displayed in Figure 3.4.

A Large Ion Collider Experiment (ALICE) [94]: The ALICE detector is the only detector designed to study the QGP with heavy-ion collisions. ALICE is located 56 m underground, measuring 26 m long, 16 m high, 16 m wide, and weighting 10,000 tonnes. It consists of 18 subdetectors, grouped within the following categories: the global detectors, the central barrel detectors, and the muon spectrometer. Quarkonium measurements can be performed down to $p_{\text{T}} = 0 \text{ GeV}/c$ in the electronic decay channel in the midrapidity region of $|\eta| < 0.9$ and in the muonic decay channel at forward rapidity $-4 < \eta < -2.5$. The ALICE detector, presented in detail with Figure 3.5, will be described in the next section.

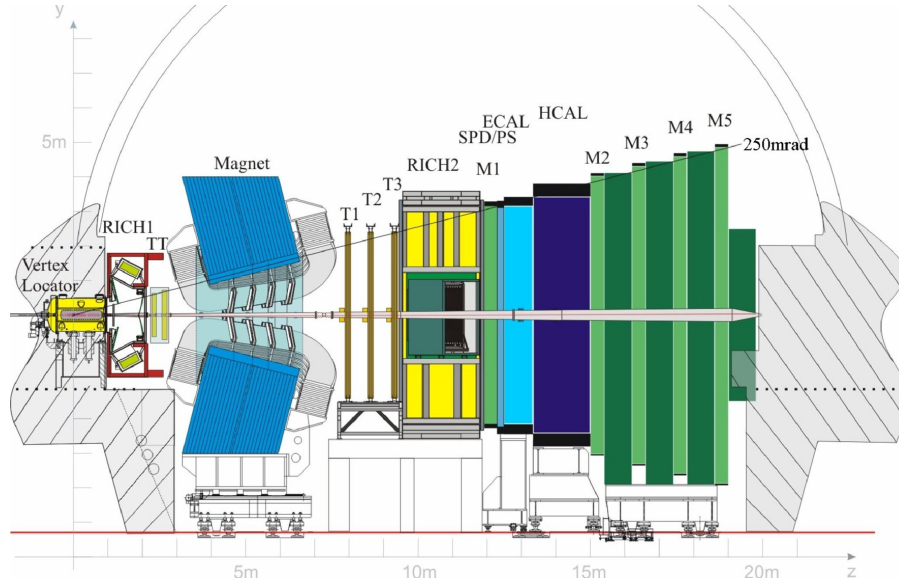


FIGURE 3.4: The LHCb detector structure [93].

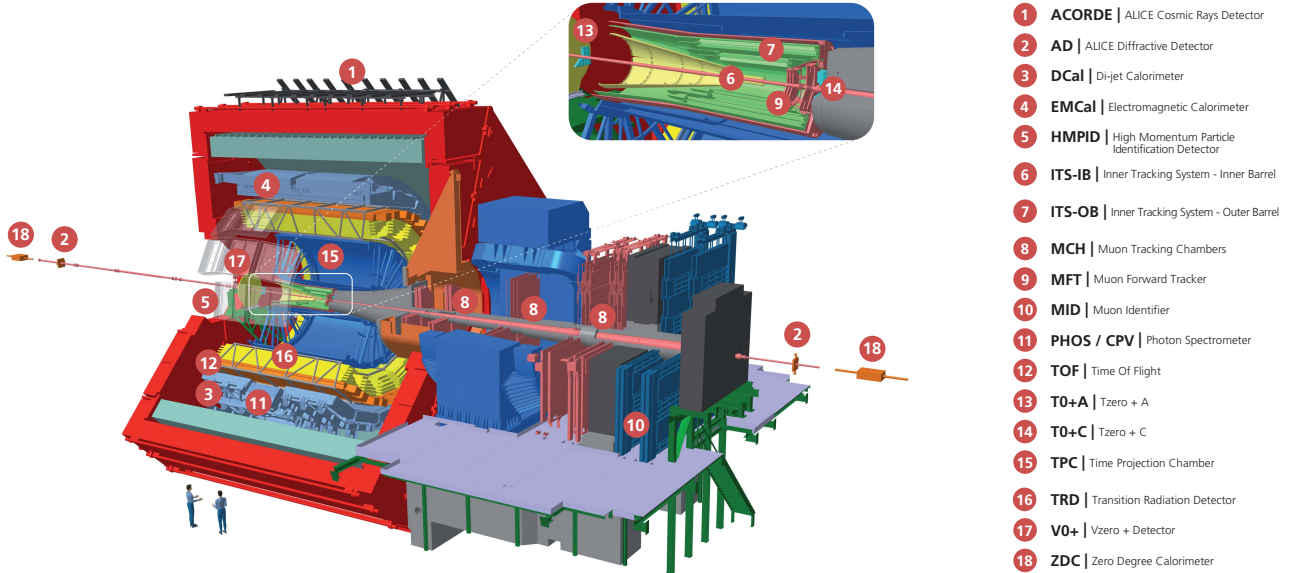


FIGURE 3.5: The Run 3 ALICE detector structure [95].

3.2 A Large Ion Collider Experiment

As discussed previously, ALICE is the only LHC experiment dedicated to the QGP study with heavy-ion collisions, particularly with unique low p_T measurements. The several independent detectors, operated synchronously, can be grouped within the following three categories. First, the global detectors, located around the interaction point (IP). They provide general quantities measurements, such as the collision centrality, collision time, and particle multiplicity. Then, the central barrel detectors are necessary for the identification and tractography of charged particles and photons. Lastly, the muon spectrometer, placed in the forward rapidity region $-4.0 < \eta < -2.5$, intended for the measurement of muons. The axis parallel to the beam pipe of the ALICE detector, z -axis, is oriented to the IP of ATLAS, known as A-side. The C-side concerns the opposite direction, pointing toward the CMS detector. The x -axis is oriented toward the center of the LHC, and the y -axis points upwards. First, a description of the ALICE apparatus after LS2 upgrades is presented (Figure 3.5), with a detailed description provided for two detectors relevant for this thesis: the Inner Tracking System (ITS) and the muon spectrometer. The ALICE objective for Run 3 is to study rare events at low p_T , such as open heavy-flavours for which the definition of a trigger is a challenge. For this goal, the detector electronics is improved [96] in order to allow for continuous readout. This results in no dead time for the data acquisition, leading to an increase of statistics and performance of the rare events. In addition, an increase of the data rate is expected, up to 50 kHz for Pb–Pb collisions (few kHz in Run 2). The final increase of statistics is expected to be around 100 times more data than Run 1 (depending on the physics channel). In addition, the track reconstruction resolution and measurements at low p_T for certain detectors are improved.

3.2.1 Global detectors

The Zero Degree Calorimeter (ZDC): The ZDC [97] detector comprises two hadronic calorimeters and two electromagnetic calorimeters placed around the IP. The hadronic calorimeters, farthest detectors located on opposite sides of the IP with $z = \pm 112.5$ m, measure the energy deposited by the spectator particles. As for the electromagnetic calorimeters, placed in the forward region of the detector at 7 m from the IP, they detect the energy deposited by photons at forward rapidity. The ZDCs, based on the Cherenkov light detection, are composed of quartz fibers, read out by photomultiplier tubes (PMTs). The Cherenkov light, produced by the charged particles passing through the quartz material at a speed higher than the speed of light within this material, is collected and transformed into an amplified signal with the PMTs. Thus, properties such as the centrality of collisions and their reaction plane can be estimated by these calorimeters.

The Fast Interaction Trigger detector (FIT): Fit [98] is composed of the following three detectors, ranging from -19.5 m to 17 m from the IP:

The FT-zero (FT0) detector: The FT0 consists of two detectors, FT0+A and FT0+C, located on opposite sides of the IP, each composed of 12 Cherenkov counters. These counters are made of quartz fibers, connected to PMTs, with the same detection method using Cherenkov light, as explained for the ZDC. This detector provides a precise collision time with 25 ps resolution, and determines a vertex position for the collisions.

The FV-zero+ (FV0+) detector: The FV0+ is composed of two scintillator counter arrays placed on opposite sides of the IP. Both of these arrays are divided into 32 counters, as each is segmented into four rings in the radial direction, with each of these rings divided into eight sections in the azimuthal direction. When a particle hits a counter, the light produced is transmitted to PMTs through optical fibers. This detector discriminates the beam-beam interaction from the beam-gas background interactions, thus providing a minimum bias trigger. Additionally, it provides the beam luminosity, charged particles multiplicity, and azimuthal distributions.

The Forward Diffractive Detector (FDD): The FDD is composed of two sub-detectors placed on opposite sides of the IP. Each array consists of eight rectangular scintillator pads. When a particle hits a counter, as the V0+, it emits light that is carried by optical fibers to the PMTs. This detector provides measurements of diffractive cross-sections and centrality, selections of ultra-peripheral collisions, and monitoring of the beam quality.

3.2.2 Central barrel detectors

The ALICE Cosmic Ray Detector (ACORDE): The ACORDE [99] detector is placed on the upper surface of the L3 magnet. It is composed of scintillator modules, providing the detection of cosmic rays. In addition, this detector is a cosmic ray trigger for ALICE, used for calibration and detection of atmospheric muon events.

The ElectroMagnetic Calorimeter - Di-jet Calorimeter (EMCal - DCal): EMCal [100] is located at 4.28 m from the IP, with the azimuthal coverage of $\Delta\phi = 110^\circ$ and the pseudorapidity region $|\eta| < 0.7$. It is a layered Pb-scintillator sampling calorimeter. The DCal [101] was installed to widen the physics reach of EMCal, allowing the study of back-to-back correlations, covering the azimuthal angle of $\Delta\phi = 70^\circ$, with the same pseudorapidity region. These electromagnetic calorimeters allow the identification of particles as photons and neutral mesons via their photonic decay channel.

The PHOton Spectrometer (PHOS): PHOS [102], located at 4.6 m from the interaction point with an azimuthal coverage of $\Delta\phi = 70^\circ$, in the pseudorapidity region $|\eta| < 0.12$,

consists of an electromagnetic calorimeter. PHOS is made of dense scintillating crystals, and its detection channels are based on lead-tungstate crystals. Additionally, in front of the calorimeter is located a Multi-Wire Proportional Chamber (MWPC), used as a Charged Particle Veto (CPV). PHOS measures photons and neutral mesons via their photonic decay channel, allowing the study of jet quenching for measurements at high p_T .

The High Momentum Particle Identification Detector (HMPID): The HMPID [103], located at 4.9 m from the IP with an azimuthal coverage of $\Delta\phi = 58^\circ$ within the pseudorapidity rapidity region $|\eta| \leq 0.6$, is based on the Ring Imaging CHerenkov (RICH) technology. It is composed of 7 modules for the measurement of the cone angle of the Cherenkov radiation, allowing for particle identification. The HMPID extends other central barrel detectors (such as the ITS, TPC, and TOF) information, allowing for kaons and pions separation up to 3 GeV/c, and kaons and protons separation up to 5 GeV/c.

The Time Of Flight detector (TOF): The TOF detector [104], located radially at 3.7 m from the IP, is composed of a cylindrical array with an active area of 141 m^2 , arranged in 18 sectors based on Multigap Resistive Plate Chambers (MRPC), covering the full azimuthal angle in the central pseudorapidity region of $|\eta| \leq 0.9$. TOF measures the time at which the particle crossed the detector with a resolution better than 50 ps. The difference of this time and the collision time, provided by FT0, allows to determine the particle velocity. The detector identifies protons with $p_T < 4\text{ GeV}/c$, pions and kaons with $p_T < 2.5\text{ GeV}/c$.

The Transition Radiation Detector (TRD): The TRD [105] consists of a cylinder with a diameter of 7 m and 7 m long; it covers the full azimuthal angle and is located in the pseudorapidity region of $|\eta| \leq 0.84$, radially situated from 2.9 m to 3.68 cm from the IP, around the TPC. Each TRD readout chamber consists of MWPC with an amplification and a drift region, filled with $XeCO_2$ gas mixture, and a radiator, where energetic electrons passing through produce transition radiation. Thus, this detector distinguishes between electron-pion particles with $p_T \geq 1\text{ GeV}/c$, and provides tracking information to complete other central barrel detectors.

The Time Projection Chamber (TPC): The TPC [106], a 90 m^3 cylinder filled with $Ne - CO_2 - N_2$ gas, covers the full azimuthal angle, with the middle pseudorapidity region coverage of $|\eta| \leq 0.9$. Charged particles passing through will ionize the gas, thus producing electron-ion pairs. With the electric field, the liberated electrons will drift towards the TPC endplates, based on Gas Electron Multipliers (GEM), thus collecting track information for particle identification task, tracking and momentum measurements for charged particles.

The Inner Tracking System 2 (ITS2)

The ITS is the most central detector of ALICE. It allows determination of primary vertex position of collisions and the secondary vertices of heavy hadrons decays. It also provides tracking down to low p_T and improves the momentum and angular resolution for the TPC. During Run 1 and Run 2, the ITS [107] was composed of six cylindrical layers. The two most internal layers compose the Silicon Pixel Detector (SPD), the following two layers consist of the Silicon Drift Detector (SDD), and the farthest layers consist of the Silicon Strip Detector (SSD). During the LS2, the ITS detector [108] (Figure 3.6) has been fully upgraded for Run 3. ITS2 comprises seven silicon layers, covering the full azimuthal distribution, from 2.2 cm to 40 cm radially around the IP, with the pseudorapidity region $|\eta| \leq 1.3$. It is based on ALPIDE chips [109], a Monolithic Active Pixel Sensors (MAPS) technology, which will be discussed in detail in the next chapter. The detector's active silicon area is around 10 m^2 , segmented into 12.5 billion pixels. The resolution of the impact parameter is improved by a factor of around 3 in the $r\phi$ coordinate and around 5 in the z -coordinate at $p_T = 0.5 \text{ GeV}/c$. This improvement is mainly due to the location of the ITS2, closer to the IP from 39 mm for the ITS to 21 mm, a reduced pixel size and a reduced material budget for the inner barrel (from 1.14% X_0 to 0.35% X_0). Additionally, a better tracking efficiency is expected due to the increased granularity. Finally, the readout rate is improved to cope with 50 kHz in Pb–Pb collisions and 500 kHz in pp collisions.

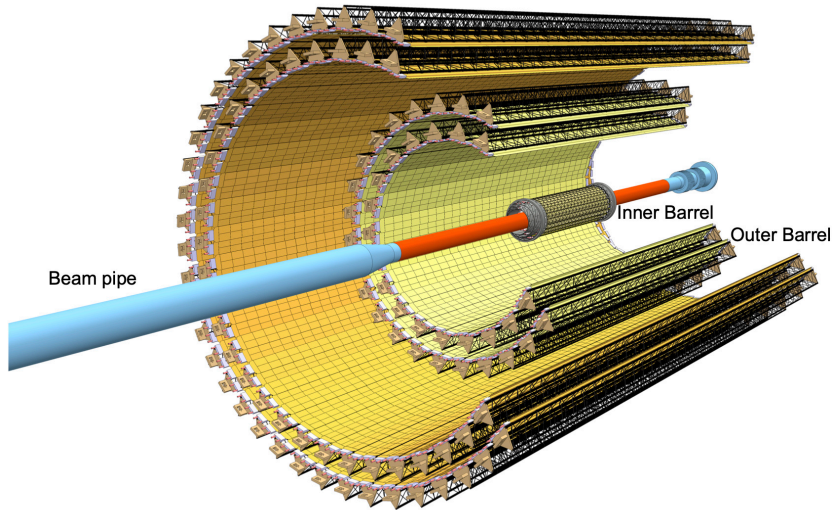


FIGURE 3.6: The ITS2 scheme [108].

3.2.3 The muon spectrometer

The muon spectrometer [110] was added to the design of the ALICE experiment around 1995. Its purpose is the study of quarkonia ($J/\psi, \psi(2S), \Upsilon, \Upsilon', \Upsilon''$), as well as the low mass vector mesons (ρ, ω, ϕ), open heavy flavor (D and B mesons), and gauge bosons ($Z^0, W^\pm$) at forward pseudorapidities ($-4 < \eta < -2.5$) via their muonic decay channel, in pp, p-Pb, and Pb-Pb collisions. The spectrometer covers the full azimuthal angle. A schematic view of the muon spectrometer is presented in Figure 3.7. It's composed of a dipole magnet, tracking and trigger stations, and absorbers. Nevertheless, due to the location of the frontal absorber between the spectrometer and the interaction point, tracks extrapolated to the IP undergo multiple scattering resulting notably in resolution degradation. Thus, limitations are imposed on the exploitable physics program, in particular the inability to separate open charm and beauty contributions. To overcome these limitations for Run 3, the Muon Forward Tracker (MFT) [111] is added to the muon spectrometer, between the interaction point and the frontal absorber. The next chapter will be dedicated to a detailed description of this detector.

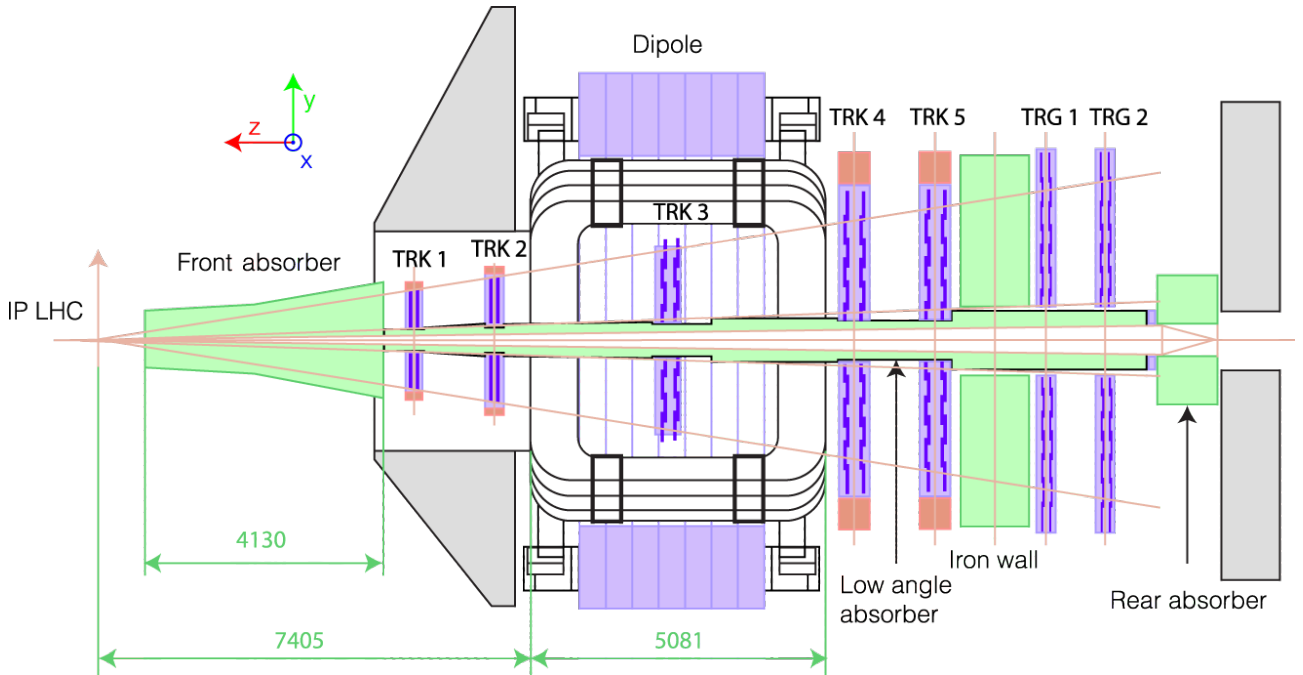


FIGURE 3.7: A schematic view of the ALICE muon spectrometer in the (z, y) plane [112].

3.2.3.1 Detector layout

The absorbers: The **front absorber** (displayed in Figure 3.8) is the first absorber. It is designed to reduce the contamination of hadrons and of low momentum muons, mainly coming from pion and kaon decays. It is 4.13 m long and located inside the solenoid magnet and at 90 cm from the IP. This absorber is optimized to limit multiple scattering that affects the

momentum and invariant mass resolution. Thus, to reduce the multiple scatterings, the closest region to the IP is made of low-Z material, carbon, followed by concrete. Furthermore, materials with high-Z are used on the absorber's end side, such as Pb and Tungsten. The goal is to stop photons at low energies, along with the secondaries created in the absorber. Additionally, in order to protect the spectrometer from beam-gas interactions and secondaries produced at high rapidities, the **low angle absorber** is located around the beam pipe and is made of dense material such as Pb, Tungsten, and steel. Furthermore, an **iron wall**, measuring 1.2 m long, is present between the tracking and trigger chambers, with the objective of filtering muons, thus stopping the energetic hadronic background. The minimum momentum for a muon passing through is 4 GeV/c. Lastly, a **rear absorber**, measuring 1.1 m, is present in the back of the trigger chambers, intending to limit the contamination from beam-gas interactions from attaining the back of trigger chambers.

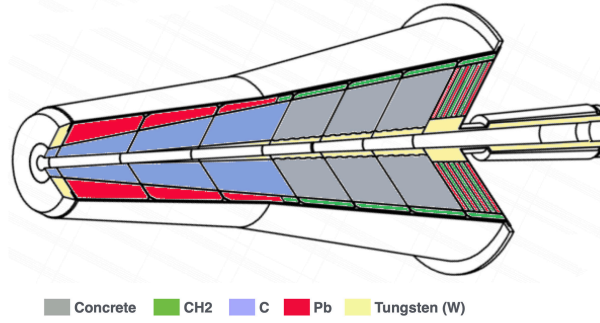


FIGURE 3.8: A schematic view of the front absorber with its composition [50].

The dipole magnet: The dipole magnet, measuring 5 m in length, 6.6 m wide, and 8.6 m in height, is situated at 7 m from the IP. It creates an integral magnetic field of 3 T.m perpendicular to the beam-axis. The plane perpendicular to the magnetic field is known as the bending plane. The magnet provides the needed energy to bend energetic particles passing through, allowing the measurements of its curvature ρ . Thus, it is possible to determine the momentum of particles p and their electric charge (supposing that they are muons).

The tracking chambers: The trajectory reconstruction is provided from the information collected by the tracking chambers, or the Muon CHambers (MCH), which will be discussed in this section. The tracking system consists of 5 stations, each composed of 2 chambers, located between 5.2 m and 14.4 m from the IP. These chambers are optimized in order to minimize the scattering that can take place by the muons going through; thus, they are composed of low-Z materials, such as carbon fibers. They consist of high granularity MWPC, each composed of a central anode wires situated between two cathode planes. The chambers are filled with a gas mixture of Argon (80%), and CO₂ (20%). Thus, a particle passing through will ionize the

volume, liberating electrons that will drift to a close cathode, generating a signal. A scheme of a chamber with a muon passing through in the bending plane (perpendicular to the magnetic field) is presented in Figure 3.9.

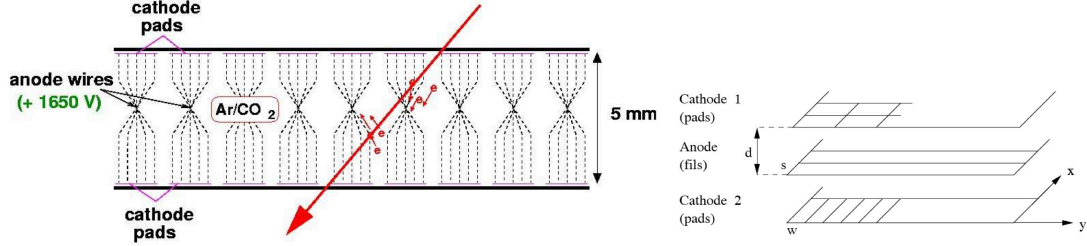


FIGURE 3.9: A schematic view of the ALICE muon chambers.

The Muon IDentification (MID): The MID detector is located 16 m away from the IP, downhill the muon filter. It is composed of 2 stations, each made of two planes of Resistive Plate Chambers (RPCs) covering each station, as can be visualized in Figure 3.10. The RPCs are composed of highly resistive Bakelite electrodes, separated by a gap of 2 mm filled with gas. Thus, the crossing of charged particles induces an avalanche of secondary electrons. The time of response when a muon passes through these chambers is around 2 ns, allowing fast signal processing. It is smaller than both the bunch time spacing for pp and for Pb–Pb collisions, thus allowing a precise track association to the corresponding collision.

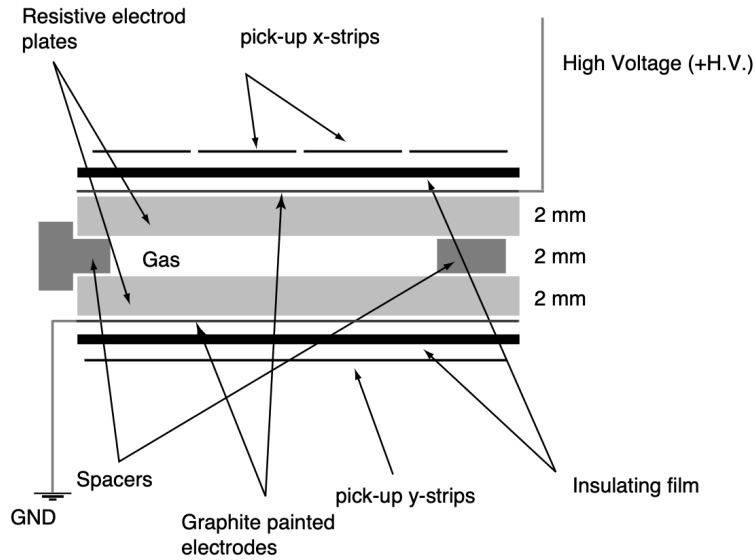


FIGURE 3.10: A schematic view of the RPC structure in the muon identification chambers [94].

3.2.4 Online-Offline control system

In order to accommodate the requirements necessary for Run 3 and Run 4, an essential LS2 upgrade is required: a new computing system O² (Online-Offline) [113]. A general workflow pipeline is presented in Figure 3.11. It includes the data processing that takes place from raw data, to the Analysis Object Data (AOD). AODs are then used for physics analysis purposes. This upgrade is critical, to accommodate with the continuous readout and with the increased

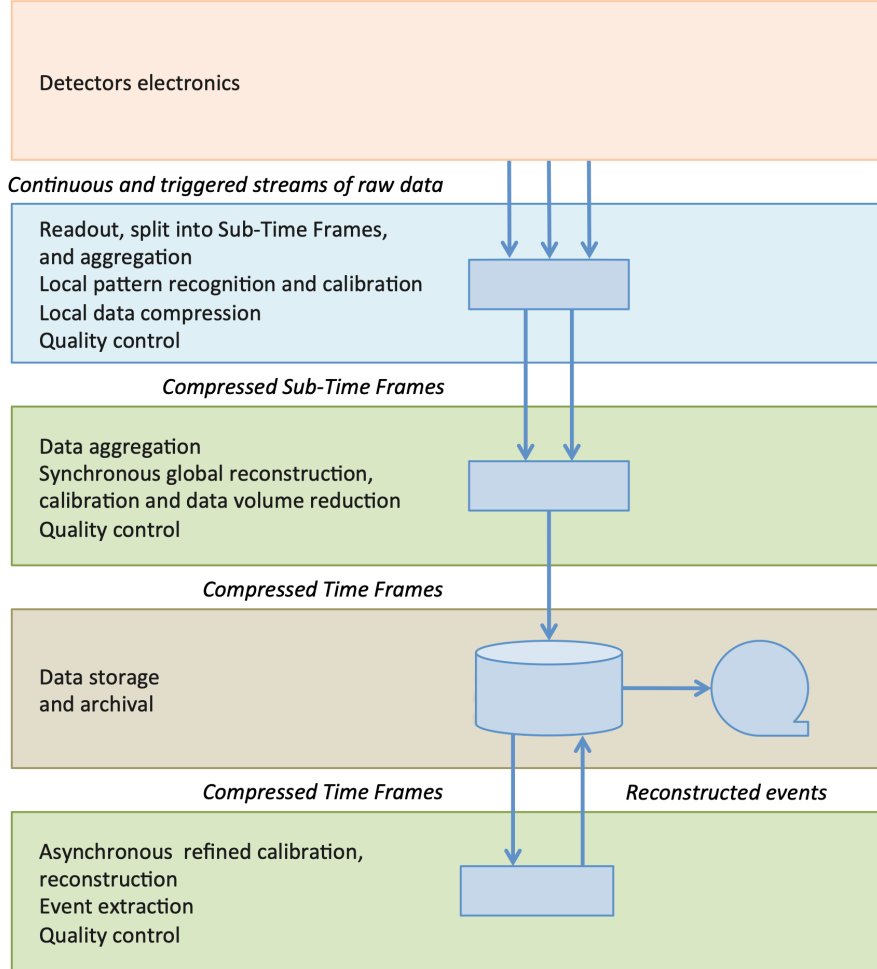


FIGURE 3.11: A full scheme of the online-offline computing system [113].

luminosity. The computing system will be composed of around 100,000 processes distributed over around 1000 nodes, operating on two data-driven workflows under synchronous and asynchronous operations. The synchronous workflow consists of continuous raw data arriving from the detector to the First Level Processor (FLP) nodes, where first data compression is done in Common Readout Units (CRUs), an FPGA based on readout cards, or C-RORC (Common Readout Receiver Card), depending on the detectors, allowing a two way communication between the detectors front-end electronics and the O² farm. Next, data is divided into Sub-Time

Frames (STFs), with each STF around 11.4 ms long. Following this step, data arrives from the FLPs to the Event Processing Nodes (EPNs), where the Sub-Time Frames are merged within complete TFs, and where calibration and further data compression is done for a total factor of compression of around 35. The compressed TFs are then stored on a 60 PB disk buffer. These synchronous operations will be followed by the asynchronous process, where data reconstruction and final calibrations from the Condition and Calibration Data Base (CCDB) are done on EPNs and on the Worldwide LHC Computing Grid-like environments, to be finally stored permanently under Compressed Time Frames (CTFs) and AODs. Following this, analysis of the AODs can be performed within the O^2 analysis framework, discussed in the following, for physics measurements and analysis purposes.

3.2.5 Online-Offline analysis framework

The results of the asynchronous operations are the AOD files, which are stored in ROOT trees, allowing bulk reading and writing. With the continuous data flow expected for Run 3, collision vertices are associated to tracks with an index, and collisions and tracks related parameters are presented in separate tables, mapping a data format based on structure-of-arrays, which is proven efficient in leveraging modern hardware capabilities. Thus, the data model for Run 3 is a collection of flat tables, arranged in a database-like relational database structure, based on the index connections. A scheme of the workflow is displayed in [Figure 3.12](#). Many operations between the separate tables are available, similar to database operations, such as join, group, filter, and combine the different flat tables. Data analysis within O^2 is structured around analysis workflows, consisting of modular and flexible collections of interconnected Data Processing Layers (DPLs) data processors, known as tasks. For each user, specific tasks, in C++ language, are created with specific data tables as inputs. The outputs vary depending on user needs, from data tables intended for further processing to the ones intended for storage. With the sequential manner of input data processing through pipelines, common tasks can be shared among different analyses, such as table reader, writer, calibrations, and quality filtering tasks.

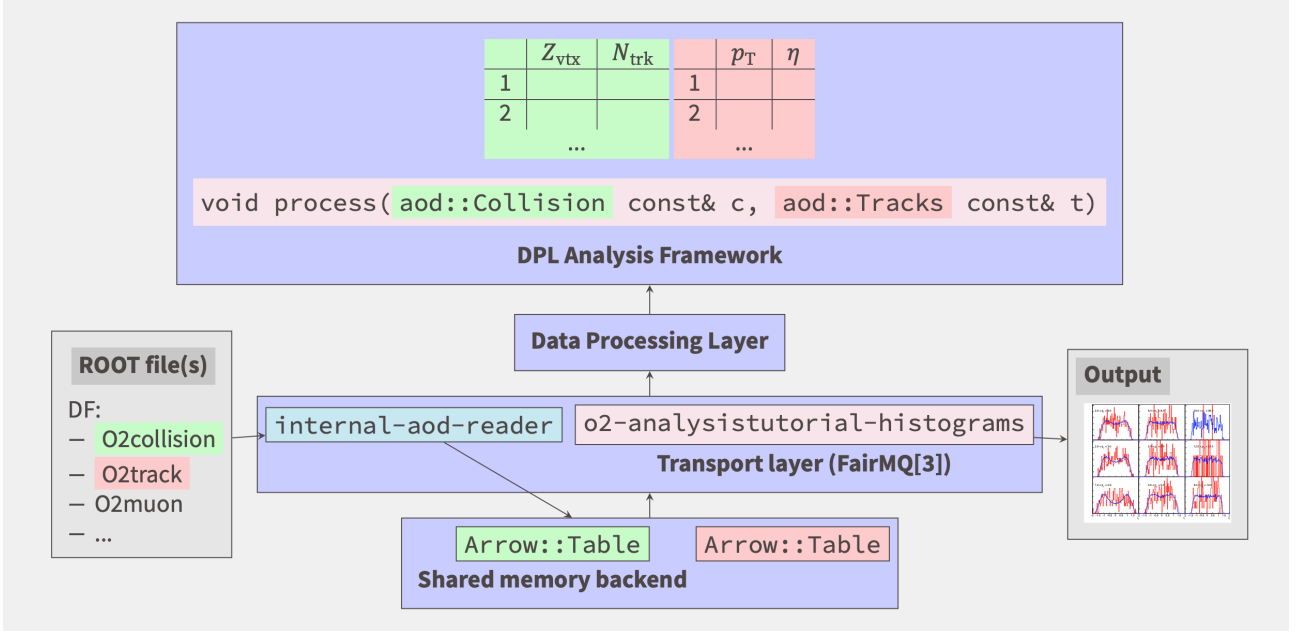


FIGURE 3.12: The different aspects of the online-offline computing system [114].

3.2.6 Monte Carlo simulations

In order to assess the collected data, one should understand the uncertainties, resolutions, and thus different detector effects that affect the data. Therefore, it is essential to reproduce the expected experimental data with Monte Carlo (MC) simulations in order to understand the detector effects and performances. The simulations are based on the following steps:

Generation: Event generators, or particle generators based directly on their kinematics distribution, generate primary particles based on theoretical models, along with their decays to a specific final state. To generate pp and Pb–Pb collisions, PYTHIA [115] and HIJING [116] generators are commonly used. For the tasks of generating muons and pions particles in this thesis, MuBoxGen and PiParam generators will also be used for specific analysis purposes. They consist of generators where muons or pions are generated with flat distributions in p , η , and ϕ .

Propagation: After particle generation, their propagation taking into account the different detectors' effects is done through transport codes. It simulates the passage of particles through the different detectors, absorbers and support materials, taking into account their precise geometry and characteristics. GEANT4 [117] and GEANT3 [118] are commonly used propagator.

In this thesis, embedded simulations will be used based on a background of Minimum-Bias (MB) pp or Pb–Pb events (with PYTHIA8), with additional signal embedded per event, for statistics purposes, as J/ψ prompt and non-prompt.

3.3 Conclusion

The LHC, the most powerful particle collider in the world, is presented in this chapter. The LHC was in a long shutdown period during which detectors were upgraded in order to prepare for the next data taking period, Run 3, which officially started on the 5th of July 2022. The ALICE detector is then detailed after the LS2 upgrades. With the upgrades carried out for Run 3, the physics program of ALICE is extended. In particular, due to the higher interaction rate expected and to the improved electronics, increased statistics can be achieved. Also, an improved spatial resolution at midrapidity will be accomplished with the upgraded ITS. Finally, at forward rapidity, a better signal extraction is expected and a separation of the prompt and non-prompt J/ψ contributions will be attainable with a new detector, the MFT, added to the muon spectrometer. The MFT, constituting the subject of this thesis, will be fully described in the next chapter.

Chapter 4

The Muon Forward Tracker

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As discussed in chapter 3, the muon spectrometer has been designed to study essentially open heavy-flavours, quarkonia states, and the low mass vector mesons, via their muonic decay channel at forward pseudorapidities. Nevertheless, the front absorber, located between the spectrometer and the interaction point, is limiting the physics program. In order to overcome these limitations, a new detector, the Muon Forward Tracker (MFT), has been installed between the interaction point and the front absorber during the LS2, covering the pseudorapidity region of $-3.6 < \eta < -2.45$. In this chapter, the MFT detector will be described, hardware and software-wise.

4.1 Physics motivation

The muon spectrometer allows to access a whole range of physics via the measurement of muons at forward rapidity. First, the study of the open heavy-flavours is performed [119], shedding light notably on the normalization of the quarkonium yield, in-medium heavy quarks energy loss, and other effects as shadowing. Additionally, on the quarkonium side [120], the evaluation of $q\bar{q}$ production, dissociation, and recombination to the production of charmonium and bottomonium states is performed, as discussed in chapter 2. Finally, for the measurements of low mass vector mesons [121], studies concerning the modification of their spectral function and the dilepton thermal radiation due to the cooling of the QGP have been performed. However, due to the multiple scattering in the front absorber, the origin of muons is impossible to determine with sufficient precision. Therefore, muons produced from heavy quarks decays cannot be distinguished from those produced by pion and kaon decays, thus introducing a high background. In addition, only inclusive measurements are possible, due to the missing information on secondary vertices. Thus, prompt and non-prompt J/ψ measurements as well as the muons produced from charm and beauty decays can not be disentangled. Furthermore, the multiple scatterings lead to a reduced angular resolution, thus the resonances have a limited mass resolution (Equation 4.1), in particular at the low masses (ω and ϕ mesons).

Observable	MUON only		MUON + MFT	
	$p_T^{\min}$ (GeV/c)	uncertainty	$p_T^{\min}$ (GeV/c)	uncertainty
Inclusive J/ψ R_{AA}	0	5% at 1 GeV/c	0	5% at 1 GeV/c
ψ' R_{AA}	0	30% at 1 GeV/c	0	5% at 1 GeV/c
Prompt J/ψ R_{AA}		not accessible	0	10% at 1 GeV/c
J/ψ from b -hadrons		not accessible	0	10% at 1 GeV/c
Open charm in single μ			1	7% at 1 GeV/c
Open beauty in single μ			2	10% at 2 GeV/c
Open HF in single μ	4	30% at 4 GeV/c		
no c/b separation				
Low mass spectral func. and QGP radiation		not accessible	1 – 2	20% at 1 GeV/c

TABLE 4.1: Table describing the extended physics program with the MFT [111].

To address these limitations, the MFT upgrade [111, 122] has been proposed. The MFT is located 40 cm from the interaction point and in front of the front absorber. The first goal of this detector is to improve the muon pointing resolution. A precise determination of the muon production vertices can be provided with the extrapolation of muon tracks to the IP. By overcoming the limitations due to the design of the muon spectrometer, the MFT extends

the physics program within the forward rapidity region (Table 4.1). In particular, some of the essential physics topics, where critical improvements are expected, are listed below:

Heavy-flavour: Better access to the open charm will be available with the MFT upgrade due to the rejection of the muonic background originating from pions and kaons decays. As a consequence, measurements of charm hadrons will be accessible down to $p_T = 1$ GeV/c, allowing the total open charm cross section measurement by extrapolating to $p_T = 0$ GeV/c. As for the open beauty, the channel $B \rightarrow J/\psi + X$ can be investigated.

Quarkonium: The disentanglement between prompt and non-prompt charmonia will be possible with the MFT, widening the physics reach at forward rapidities. As for the charmonium excited state $\psi(2S)$, with the higher signal-to-background ratio expected in the most central Pb–Pb collisions due to the background suppression, a better extraction is expected (Figure 4.1). For the bottomonium side, the Υ will be studied more precisely by the muon spectrometer in Run 3 and Run 4, along with the open beauty measurements providing essential insight into beauty physics.

Low-mass dimuons: The invariant mass can be expressed as a function of the opening angle θ between the momentum of the two muons with:

$$M_{\mu^-\mu^+} = \sqrt{2p_{\mu^-} \cdot p_{\mu^+}(1 - \cos\theta)} \approx \sqrt{p_{\mu^-} \cdot p_{\mu^+}}\theta \quad (4.1)$$

This approximation can be applied for $\theta \rightarrow 0$. Thus, with the improved resolution on the dimuon opening angle and the background reduction, an enhanced mass resolution is expected.

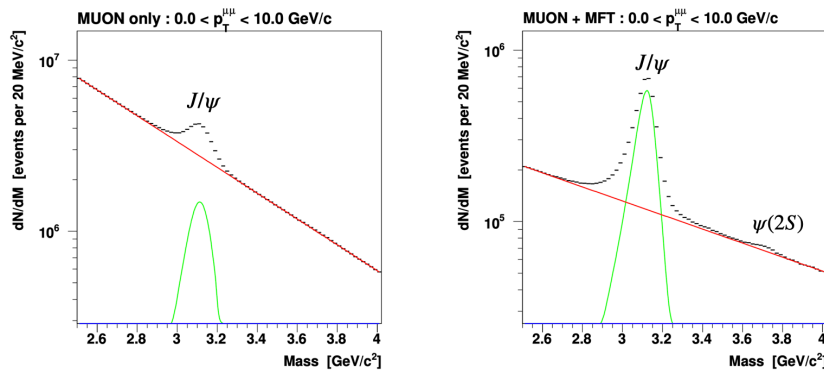


FIGURE 4.1: Dimuon mass distribution for Pb–Pb collisions simulated with HIJING at 0–10 % centrality at $\sqrt{s_{NN}} = 5.5$ TeV without the MFT (left) and with the MFT (right) [111].

4.2 Layout of the MFT

The MFT detector is composed of 5 double-sided disks coaxial around the LHC beam pipe (Figure 4.2), on which are positioned silicon pixel sensors. A high-resolution tracker in a radioactive and high-multiplicity environment is subject to several requirements and constraints, as detailed in the following section. Then, a complete description of MFT apparatus is presented.

4.2.1 Requirements and constraints

For high multiplicity environments, the sensors must have a very small spatial resolution (about $5\ \mu\text{m}$) to ensure track separation. Therefore, the MFT must have a high granularity. Then, to prevent multiple scattering and resolution degradation, the material budget must be as low as possible. A radiation-tolerant material is also essential for the radioactive environment in which the MFT is located (designed to withstand $400\ \text{kRad}$ and $5.10^{12}\ 1\text{MeV}\ n_{eq}/\text{cm}^2$ with a ten-fold security factor). In addition, the readout of the MFT must be able to withstand Run 3 collisions rate of $50\ \text{kHz}$ in Pb–Pb and $500\ \text{kHz}$ in pp collisions. The integration of all services (power, readout, cooling) is challenging given the limited volume: $35\ \text{cm}$ for the diameter of the first disk, $46\ \text{cm}$ for the last disk, with $36\ \text{cm}$ of total length. In addition, one of the beam pipe supports is crossing the volume allocated to the MFT. The power consumption of sensors have to be as low as possible to limit cooling power (the higher, the more material it would require). Furthermore, because of the frontal absorber, the MFT can only be extracted through the A-side, implying the removal of ITS and TPC first. As these complex operations require a lot of time (disconnection, extraction, repositioning, reconnection), they cannot be done during a winter shutdown. Hence, the MFT cannot be accessed during a whole LHC Run (3-4 years), but only during long shutdowns. Thus, the MFT must have high reliability.

4.2.2 Global structure

For insertion reasons, the structure of the MFT is divided into two halves, labeled H0 (bottom half) and H1 (top half). A total of 936 ALPIDE sensors [109], representing an area of $0.5\ \text{m}^2$, are distributed over 280 ladders, which consist of Flexible Printed Circuits (FPCs) connected to between 2 and 5 sensors. Each face of half-disk contains between 24 and 34 ladders, and is divided into four zones (composed of 3 to 5 ladders). The number of zones per disk is a trade-off between high segmentation and the number of control lines and components. The disks are labeled from 0 to 4 (Table 4.2) with a diameter increasing with the distance from the IP to the front absorber. In order to power the ALPIDE sensors, three different voltage supplies are requested: digital, analog and back-bias (see section 4.2.3). The low voltage power supply modules (CAEN LV) are located 40 meters away from the MFT, outside the ALICE

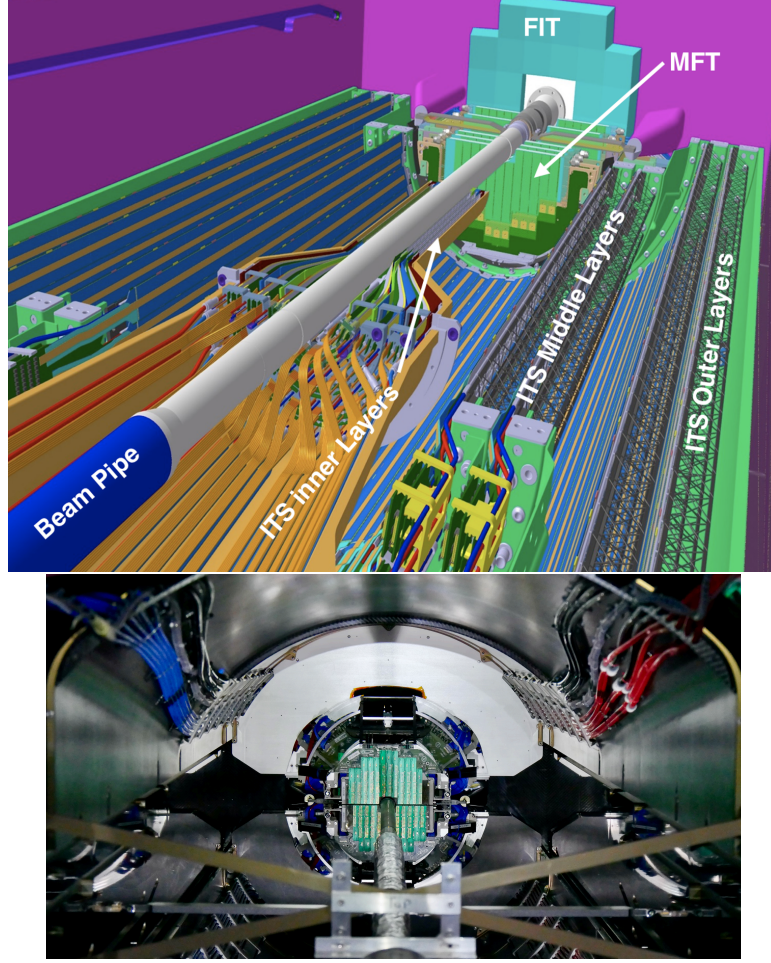


FIGURE 4.2: (up) A Schematic view of the location of the MFT inside the ALICE central barrel [111]. (bottom) The MFT fully installed in its final position around the beam pipe.

solenoid. The powering and monitoring of all the half-disks of the detector are managed by a specific kind of board, called Power Supply Unit (PSU), located between the 4th and the 5th disks. Its location and design are intended to minimise the voltage drop from the CAEN LV modules to the sensors. The PSU and the powering of the MFT are further described in chapter 5. The MFT detector, composed of 80 zones, is managed and controlled by a total of 4 PSUs for the powering and 80 Readout Units (RUs) for the readout. The half-disks and PSUs are positioned and fixed on supports called half-cones (see Figure 4.3), themselves fixed on half-barrels, composite structures designed to hold and position the MFT. Powering and cooling services are running along the half-barrels (see Figure 4.2) whereas the readout cables are guided along the front absorber to be connected to the RUs located at the end of this absorber.

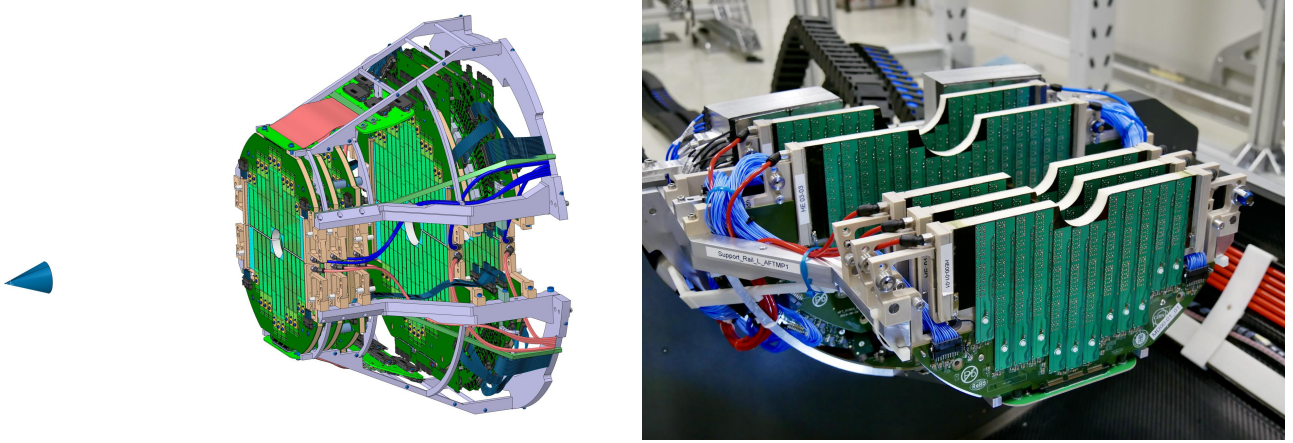


FIGURE 4.3: (left) A Schematic view of the full MFT detector [111]. (right) An assembled half-cone view of the MFT detector.

4.2.3 The ALPIDE chip

In order to fulfill a part of the mentioned requirements, mainly in terms of readout rate, spacial and momentum resolutions, the ALice Pixel DEtector (ALPIDE) chip [109] was designed to equip both the ITS and the MFT. It consists of a $0.18\ \mu\text{m}$ Complementary Metal Oxide Semiconductor (CMOS) Imaging Sensor process of TowerJazz [123], based on Monolithic Active Pixel Sensors (MAPS) technology [124]. Each chip measures $15\ \text{mm} \times 30\ \text{mm}$, composed of a $512\ \text{rows} \times 1024\ \text{columns}$ pixels matrix, and $50\ \mu\text{m}$ thick. The detection principle of the ALPIDE chip is presented in Figure 4.4. When a charged particle crosses the p-type epitaxial silicon layer, it will create electron-hole pairs in the material. The electrons, confined by the potential barriers, will drift thermally, reaching the depletion volume (corresponding to the white zone on Figure 4.4), then focused on the diode and generating a signal at the input of the pixel front-end electronics, where signal amplification and digitization is performed. A reverse back-bias voltage is applied on the substrate to increase the depletion volume, thus compensating the efficiency decrease due to irradiation. To ensure proper conditions, a separate analog and digital power supply are provided to the ALPIDE chips, at $1.8\ \text{V}$ each with a 10% tolerance, as well as a back-bias negative voltage, ranging from 0 to $-3\ \text{V}$. The digital voltage is intended for the readout, as the analog is intended for the pixel circuitry. The power consumption of the chips is estimated to be around $24\ \text{mW}$ for the analog power supply, and $187\ \text{mW}$ for the digital power supply. As for the back-bias consumption, it is estimated to be very low, around $9\ \text{mW}$.

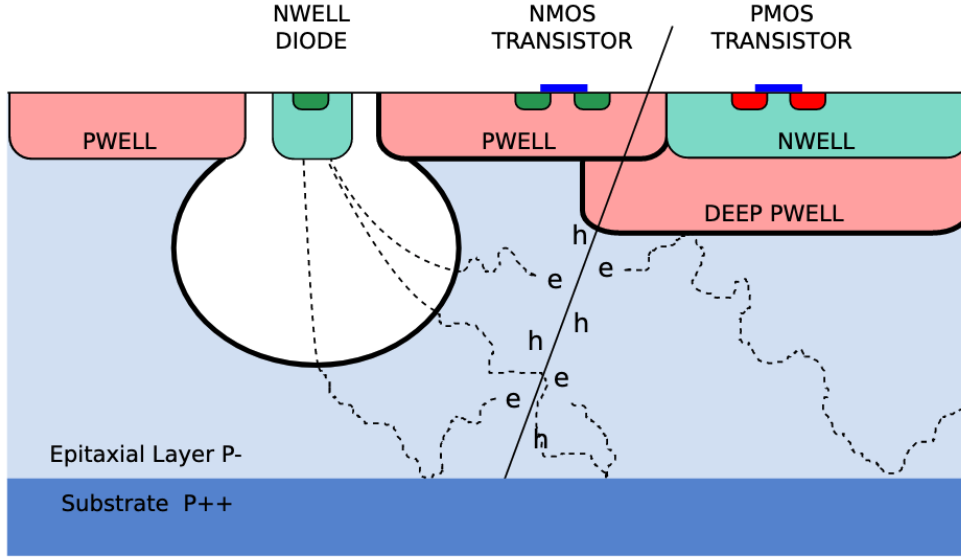


FIGURE 4.4: Schematic view of the cross-section of a CMOS pixel [108].

4.2.4 Ladders

The conductive lines of FPCs are made out of aluminum (to reduce material budget), and are used for powering, readout and slow control. The sensors and FPCs are interconnected by wire bonding (3 wires per pad for redundancy reasons). Each ladder, constituted of between 2 and 5 sensors, is connected to a Printed Circuit Board (PCB) located outside the acceptance of the detector. A total of 500 ladders have been produced to cover three half-MFT plus 20% of spares. A three-axis placement machine has been used for the ladder assembly.

4.2.5 Half-disks

As discussed previously, the MFT is composed of ten double-sided half-disks. In total, there are four different types of half-disks, as the first two disks are identical (Table 4.2). The expected maximum hit densities and radiation levels for each disk are presented in Table 4.3. In addition, contributions from e^-e^+ pairs generated by the electromagnetic interactions of the crossing beams are also presented as QED electrons. Each face of a half-disk is composed of a support in PEEK (PolyEtherEtherKetone plastic), a PCB, and a heat exchanger, on which the ladders are glued, and both screwed to the support and connected to the PCB. The PCB ensures the readout and control of sensors and distributes the analog, digital, and back-bias voltages to the ladders. Additionally, each PCB is equipped with decoupling capacitors, resistors and a temperature sensor (PT100), allowing the measurement of temperature at the level of disk faces. It provides as well a reference for the ALPIDE chips temperature measurements. This information is sent to the PSU with a dedicated line of power cables.

Half-Disk	0	1	2	3	4	Full MFT
Inner radius (mm)	25.0	25.0	25.0	38.2	39.2	—
Outer radius ^a (mm)	92.6	98.0	104.3	130.1	143.5	—
z-position (mm)	−460	−493	−531	−687	−768	—
No. sensors	64	64	76	112	132	896
No. ladders with:						
1 sensor	2	2	2	2	0	16
2 sensors	4	4	4	2	4	36
3 sensors	18	18	14	6	4	120
4 sensors	0	0	6	22	18	92
5 sensors	0	0	0	0	8	16
No. ladders	24	24	26	32	34	280

^a Radius to reach $\eta = 2.5$ with a vertex position at $z = 100$ mm from the nominal IP position.

TABLE 4.2: Detailed description table for the disks structure geometry [111].

Disk	Radius (mm)	Particles ^a (cm ^{−2})	QED electrons ^b (cm ^{−2})	NIEL ^c (1MeVn _{eq} /cm ²)	TID ^d (krad)
0	25.0	12.7	8.9	5.7×10^{12}	350
	92.6	1.9	6.9×10^{-2}	1.1×10^{12}	52
1	25.0	12.9	8.6	5.9×10^{12}	380
	98.0	1.7	6.0×10^{-2}	1.1×10^{12}	50
2	25.0	12.6	8.6	5.7×10^{12}	347
	104.3	1.6	4.8×10^{-2}	1.1×10^{12}	44
3	38.2	11.9	3.4	3.5×10^{12}	317
	130.1	1.1	2.7×10^{-2}	1.1×10^{12}	34
4	39.2	12.9	3.1	3.8×10^{12}	350
	143.5	0.9	2.2×10^{-2}	1.3×10^{12}	29

^a Average hit densities in central Pb – Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV (including secondaries produced in material).

^b Integration time of 4μ s, and interaction rate of 100kHz.

^c Non-Ionizing Energy Loss. Including a safety factor 10.

^d Total Ionizing Dose. Including a safety factor 10.

TABLE 4.3: The maximum hit densities and radiation levels obtained for 5.5 TeV Pb–Pb collisions simulations with PYTHIA generator and with FLUKA and GEANT transport models [111].

4.2.6 Water-cooling system

The ALPIDE chips must be maintained below 30°C in order to limit aging. The cooling is mainly ensured by leak-less water system; the circulating water is under pressure to avoid any water leakage outside the circuitry. The main object to cool the sensors is the heat exchanger, displayed in light blue in Figure 4.5 - left. The heat (about 300 W in total) is extracted by cold plates on both sides, each consisting of three layers of carbon fiber with resin with a $300\text{ }\mu\text{m}$ thickness, equipped with 1 mm diameter kapton water pipes. The two cold plates are separated by Rohacell foam of 14mm thickness. With this design, the total material budget of a half-disk is $0.7\%X_0$. The water flow is distributed to pipes by a manifold on each side. Quality assessment of heat exchangers is performed first with X-ray tomography, to check glue distribution and eventually broken pipe, and second by measuring the water flow of each pipe in order to check flow uniformity indicating that no pipe is pinched. In addition to the water cooling, small air flow is blown in the cone volume to homogenize the temperature inside.

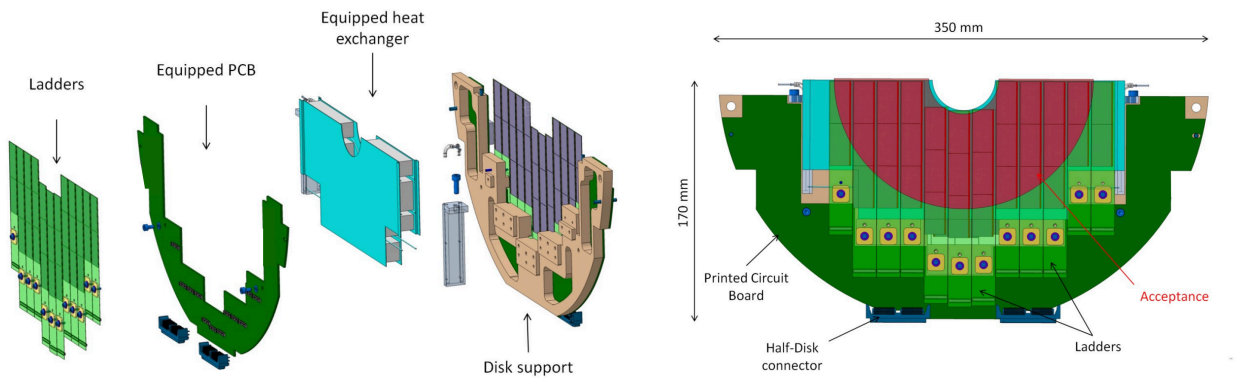


FIGURE 4.5: (left) A detailed view of a half disk's face components. (right) A schematic view of the half-disk 0.

4.2.7 Cone and barrel

Each 5 half-disks and PSUs are positioned and fixed in a half-cone, mechanical structure made in aluminum, on which are placed 3 motherboards for the readout, along with the services (power, cooling and readout). The half-cone structure has been studied to limit the sagging to $100\text{ }\mu\text{m}$. Each half-cone is then fixed on its back on a patch-panel in aluminum whose function is to guide all cables and pipes into the half-cone but also to hold the FT0+C detector. The patch-panels are then fixed on half-barrels, a 4m long composite structure designed for the services distribution, support of half-MFT and for insertion purposes.



FIGURE 4.6: (left) A detailed view of the patch-panel, the FT0+C and readout cables. (right) A view of the barrel and the readout cables (bottom of the picture and on the right, folded for transport), with power cables, water pipes and air ducts.

4.2.8 Geometrical survey

In order to ensure an efficient track reconstruction and a good pointing resolution, the positions of pixels must be known with accuracy (at the level of micrometer). To this aim, positioning crosses on the four corners of the sensors were added in the process of lithography. Holes in the FPCs allow to see them. After gluing ladders on half-disk, the position of each sensor in respect to reference point on disk support is measured. Then the position of half-disks in respect of the half-cone are measured by photogrammetry. After installation in the experiment, the position of half-cones are measured also by photogrammetry. All this information allows to build the initial misalignment data. The final measurement of the position of pixels will be performed by using straight line tracks from data taken without magnetic field.

4.3 Tracking and matching

The quality of reconstructed tracks and of the track matching is of great importance for the physics performances, as it consists of the essential basis needed for physics analysis. In [Figure 4.7](#) - left, the acceptance of the MFT can be visualized with tracks extracted from the commissioning data in pp collisions at 900 GeV. In [Figure 4.7](#) - right, the last disk occupancy is displayed with the position on the (x,y) plane for the MFT clusters¹.

Two steps are needed to achieve the forward track reconstruction within the MFT.

¹The term cluster refers to a reconstructed object for a deposited hit.

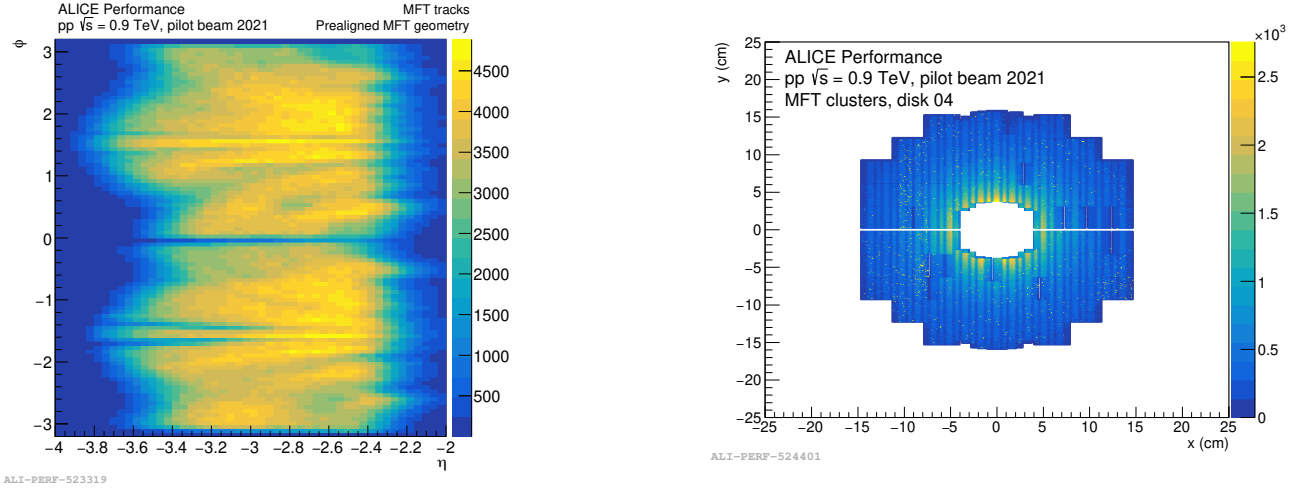


FIGURE 4.7: (left) A mapping of the η and ϕ for the MFT tracks. (right) The position x and y for the MFT clusters in the last disk.

Track finding:

Two methods are deployed for this task, the **Cellular Automaton** [125] and the **Linear Track Finding**. The Cellular Automaton is deployed for low momentum tracks, sensitive to the Coulomb scattering in the front absorber. The Cellular Automaton algorithm consists of reconstructing a track following a chain of neighboring cell segments. The first segment is composed of 2 clusters on the first and the second disk, respectively, following the propagation direction of the particles, with the condition of pointing to the interaction point (within a certain angular limit). This segment is then propagated from disk to disk by applying the same method. Thus, a track candidate is found when it is composed of 4 segments. Tracks are then selected following cuts on the limit of the angle for each segment. An example of the Cellular Automaton algorithm functioning is illustrated in Figure 4.8.

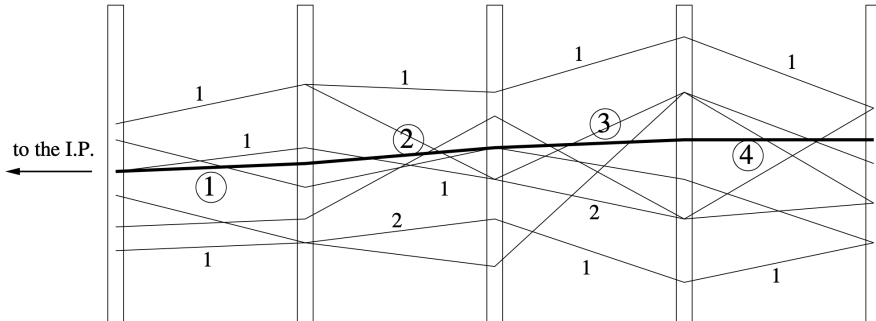


FIGURE 4.8: A sketch describing the functioning of the track finding with Cellular Automaton in the MFT [111].

As for the Linear Track Finding, the MFT can benefit from linear track approximation since the magnetic field is weak in the MFT volume. It consists of finding the track where the distance between the clusters is minimised to a straight line within a search radius.

Track fitting:

When a track is found, the fitting is performed using a **Kalman filter** [126, 127] in order to extract track kinematic parameters. The Kalman filter updates the track parameters following each measurement on each disk, defining and improving the evolution of the state vector, constituted of the estimated position and velocity.

A global representation of the described steps for global muon tracks finding are displayed in [Figure 4.9](#). After the track reconstruction is done, track matching is then required in order to extract global muon tracks, which are the tracks matched between MFT, MCH, and MID detectors.

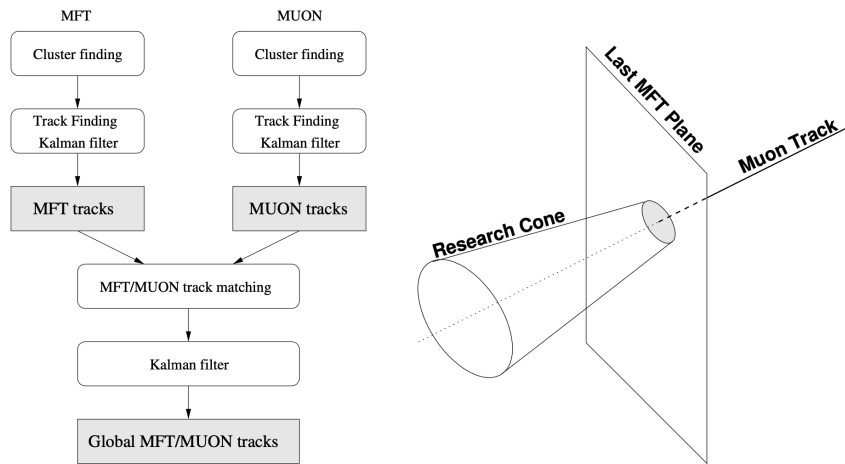


FIGURE 4.9: (left) Map for obtaining global muon tracks. (right) Example of the matching [111].

Thus, different track types are present in the spectrometer ([Figure 4.10](#)):

MFT standalone tracks: can be used for multiplicity analyses and underlying event characterization.

MCH standalone tracks: can be used to study soft muons or muons with $\eta > 3.6$.

Muon standalone tracks: consist of the MCH + MID matched tracks, corresponding to the Run 1 and 2 tracks.

Global forward tracks: consist of MFT + MCH matched tracks.

Global muon tracks: consist of MFT + MCH + MID matched tracks, will be used for physics analysis using muons.

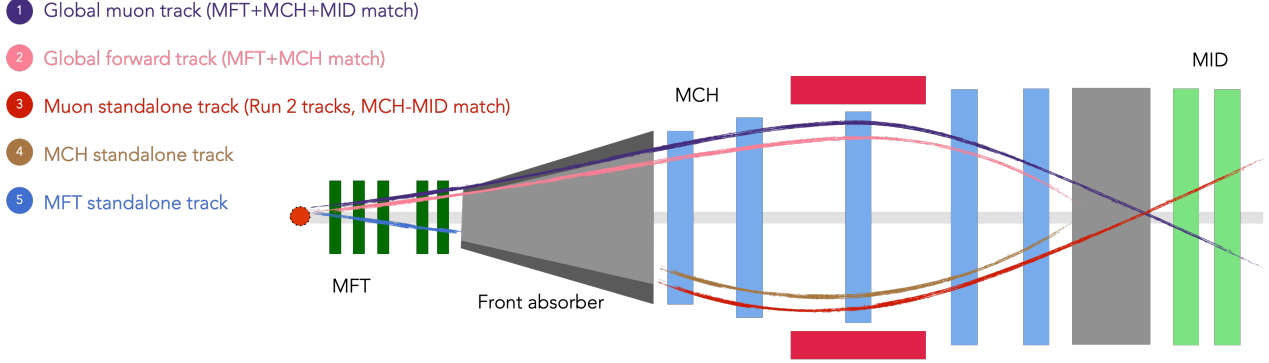


FIGURE 4.10: The different track types present in the muon spectrometer for Run 3.

Matching:

The matching task takes place after the tracking process. The reconstructed MCH standalone tracks are extrapolated through the absorber, with multiple scattering and energy loss corrections, to a selected matching plane. The selected plane in chapter 6 corresponds to the 5th disk of the MFT. The MCH track is then compared to the MFT tracks, within a search area, in order to find the best match following a defined matching method. The matched MCH-MFT track constitutes then the global forward track. Finally, with the MID identification response added, a global muon track is reconstructed with the Kalman filter.

A (x, y) display of the 5th disk, at $z = -77.5$ cm, is shown in Figure 4.11. All the **standalone MFT tracks** are presented with the extrapolated **MCH track**. Around the latter are defined the **MFT candidate tracks**, in a selected search area, on which the track matching code runs in order to find the **correct MFT match**.

The standard method used for the matching task is the following. First, the coordinates system used for this task corresponds to the MFT coordinates selected as follows in order to best describe the path of a helical track (due to the magnetic field along the beam axis):

$$\vec{s} = (x, y, \phi, \tan\lambda, \frac{q}{p_T}) \quad (4.2)$$

where ϕ the azimuthal angle, indicating the p_T direction, q the particle charge and λ the complementary polar angle, such as $\lambda = \frac{\pi}{2} - \theta$ (Figure 4.12). The helical track model describes well the path of particles in the MFT with low momentum.

The matching is performed on MFT track candidates within a given search area. The search

area is defined using the covariance matrix elements for the MCH track after extrapolation as follows:

$$\sqrt{(x_{MFT} - x_{MCH})^2 + (y_{MFT} - y_{MCH})^2} < 3 \times \sqrt{\sigma_{XX,MCH}^2 + \sigma_{YY,MCH}^2} \quad (4.3)$$

$$\phi_{MFT} - \phi_{MCH} < 3 \times \sigma_{\phi\phi,MCH} \quad (4.4)$$

$$\tan\lambda_{MFT} - \tan\lambda_{MCH} < 3 \times \sigma_{\tan\lambda\tan\lambda,MCH} \quad (4.5)$$

A χ^2 score is then calculated between the MCH and the MFT candidate tracks. The MCH-MFT pair with the minimum χ^2 score is selected as a match. The χ^2 is presented with the following equation:

$$\chi^2 = P^T \times C^{-1} \times P \quad (4.6)$$

with the residuals of parameters P given with the 5×1 vector as:

$$P = \begin{pmatrix} x_{MFT} - x_{MCH} \\ y_{MFT} - y_{MCH} \\ \phi_{MFT} - \phi_{MCH} \\ \tan\lambda_{MFT} - \tan\lambda_{MCH} \\ \left(\frac{q}{p_T}\right)_{MFT} - \left(\frac{q}{p_T}\right)_{MCH} \end{pmatrix}$$

and the covariance residuals C described by a diagonal 5×5 matrix with the diagonal elements $\Delta\sigma^2$ between the MFT and MCH diagonal covariance elements of the 5 coordinates ([Equation 4.2](#)).

Nonetheless, in high multiplicity environments, the χ^2 method encounters some limitations, affecting the performance of the matching. Matching with machine learning is presented in chapter 6.

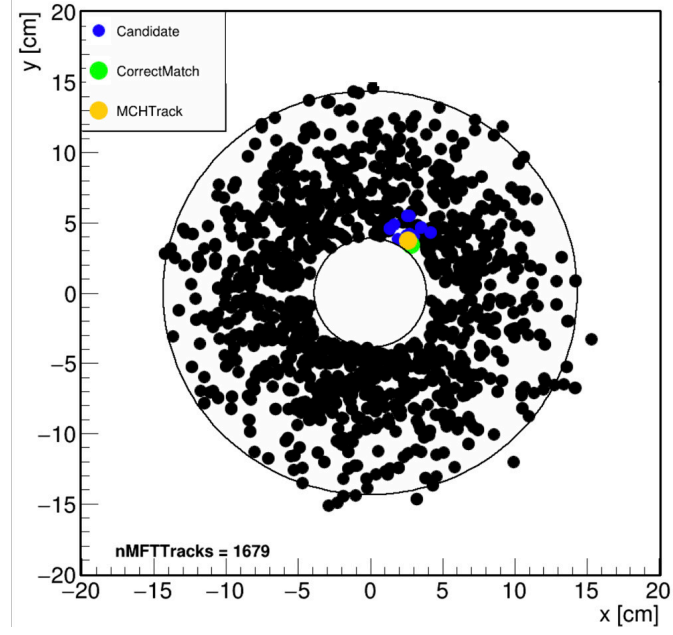


FIGURE 4.11: Display of the matching plane during the task of MCH-MFT track matching.

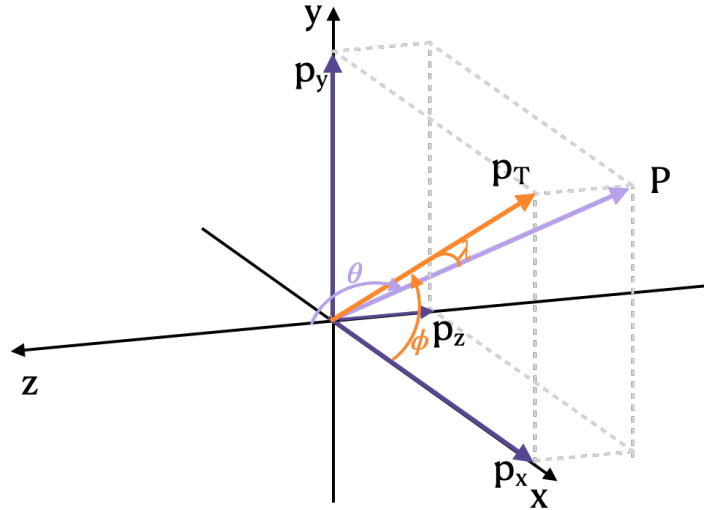


FIGURE 4.12: The coordinate system used in the muon spectrometer.

4.4 Conclusion

In order to extend the ALICE physics program at forward rapidity, the MFT detector was designed, built and installed. The MFT project took 9 years from design to installation. This chapter was dedicated to the MFT description, a detector based on silicon pixel sensors (with high spatial resolution and resistance to radiation). It is composed of 5 double-sided disks segmented into 4 zones for the readout and power management. The powering and monitoring of the MFT with the PSU will be the subject of the next chapter, which consists of the first part of work for this thesis. Finally, the algorithms for track reconstruction and matching are presented. The introduced track parameters consist of input data that will be used for matching with machine learning, that will be detailed in chapter 6.

Chapter 5

Power control of the MFT

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This chapter describes the first part of the work carried out in this thesis, consisting of software developments with the goal of fully powering and controlling the MFT detector. First, the PSU is presented, which is responsible for the hardware powering and safety of the detector. Then, the first software designed to control the entire detector is detailed. It allowed detector commissioning, firmware developments and detector calibrations, as the official ALICE framework was still under development. A full description is also provided for the latter in the following. It consists of the official software for Run 3 developed for the MFT, thus running 24h/24h in the ALICE site, allowing complete control and monitoring of the MFT detector.

5.1 The Power Supply Unit

As discussed in chapter 4, three voltage supplies are required for the proper functioning of the sensors: the analog voltage to power pixel circuits, the digital voltage to power the readout and the slow control, and the back-bias voltage to increase the depletion zone. In order to decrease the voltage drop between the low voltage power supply and the sensors, the PSU is installed between the 4th and the 5th disks (Disk03 and Disk04), as illustrated in [Figure 5.1](#). The power management in the MFT detector is divided as the detector is composed of a total of 80 zones. It is divided first by half-MFT (bottom or top), then by face (front or back), by half-disk (0 to 4), and finally by zone (0 to 3). Some constraints were imposed on the PSU design, as it can not overlap with the acceptance of the detector, and it must be equipped with radiation-tolerant components (up to 75 krad). In addition, considerations such as trade-off between the granularity and the number of control lines constrained by available volume are taken into account to optimize the reliability of the MFT power supply system. Hence, the MFT is composed of four main PSU boards controlled through a dedicated CRU. More precisely, on each PSU main board, composed of around 3300 components, is attached a PSU mezzanine, composed of around 600 components ([Figure 5.1](#)), on which 5 Giga-Bit Transceiver - Slow Control Adapters (GBT-SCAs) [128] are located. The GBT-SCA is a radiation tolerant ASIC for detector control, with the purpose of managing slow control information (as will be detailed in section 5.2.1). In particular, each GBT-SCA is intended to establish communication with a corresponding face of half-disk ([Figure 5.2](#), [Figure 5.4](#)). The cruciality of this aspect will be displayed in the following, on which the simultaneous communication with the detector is based. On the other side, the PSU is connected via long SamTech cables to the PSU interface board, equipped with a GBTx and a GBT-SCA. They are located in the same racks as the RUs, on the sides of the end of the front absorber. They are used to convert the optical signal coming from the CRU to an electrical signal, sent to the PSU mezzanine in the detector, and the other way around. Thus, each PSU interface is responsible for the communication with five half-disk faces, along with the transfer of information of the corresponding face of the half-PSU. Therefore, in order to control the complete detector, composed of twenty half-disk faces, the total number of PSU interface boards required is four.

[Figure 5.1](#) shows the full PSU mapping within the MFT detectors. The PSUs are supplied with low voltage by two types of low voltage power supply units. The A3009 CAEN modules, with outputs of 8 V, powering the analog and digital parts of the sensors. The A3006 CAEN modules, with an input of ± 8 V, powering the back-bias part of the sensors and the amplifiers of the PSU.

The main features of the PSU can be summarized as follows:

- **Voltage conversion**, from the input received from CAEN modules at 8 V, to the different

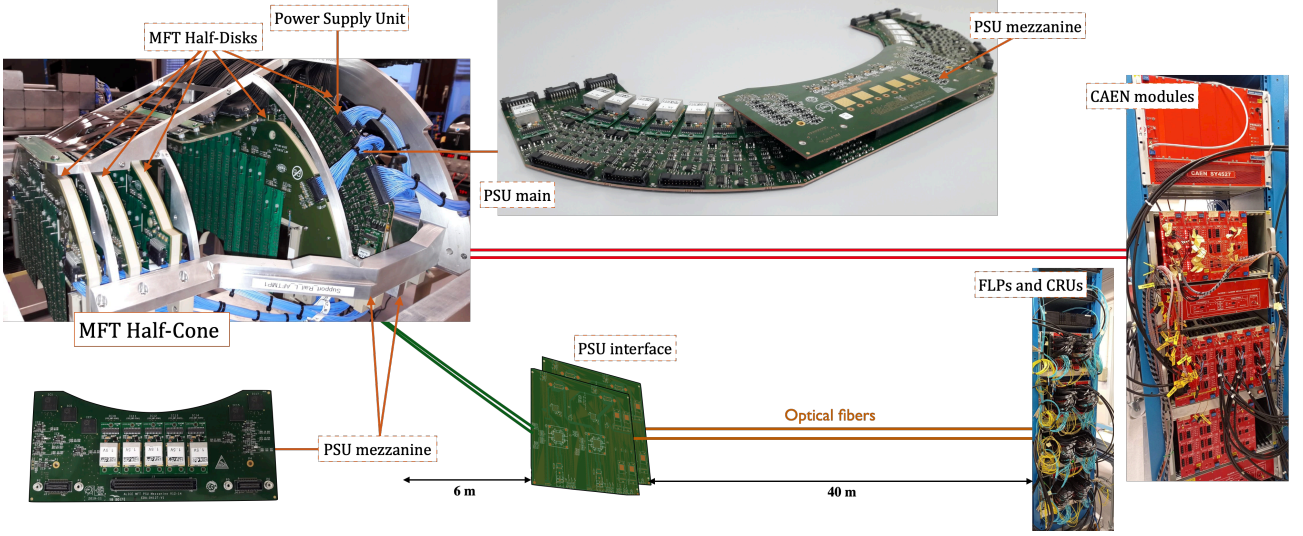


FIGURE 5.1: MFT map with the different elements of the PSUs and the connections linking them.

output channels required for the sensors through DC-DC converters [129]. The DC-DC converters are modules developed by CERN, as radiation-tolerant ASIC with the purpose of providing HEP experiments with converter modules. The voltage drop from the PSU to the sensors is taken into consideration and the DC-DC converters output voltage is adjusted accordingly. For the analog voltage, each DC-DC is used to enable voltage for two zones on the same face of a half-disk, as for the digital voltage except for the last two disks, disks 3 and 4, where each DC-DC converter provides power per zone (since each zone is composed of more sensors and the output current is limited at 4 A). Additionally, due to the limited space, a multiplexer is implemented allowing the generation of 4 different voltages (back-bias voltage and threshold voltages, the necessity of which is detailed in the next paragraph) per zone on 1 line.

- As the MFT is located in a very radioactive environment, particles passing through might ionize the sensors and disrupt its configuration, resulting in a current over consumption. Thus, when the current consumption (analog, digital, or back-bias) of a zone is greater than the threshold set, all voltages in the concerned zone will be switched off; this is known as a **latch-up** state, one of the features of the PSU.
- **Continuous communication** done simultaneously with the entire MFT detector, 80 zones, ensured by the GBT-SCAs. In addition to powering the 20 half-disk faces, the PSU continuously measures the state of each by providing the measurements of voltages, currents, temperatures (face of half-disks, cooling input/output of PSUs, and ambient temperatures), and the humidity. Besides these measurements, the PSU provides different features such as resetting zones, adjusting the back-bias voltage and all thresholds on

current consumption, and providing the latch-up information and the status of each zone.

- o In case of a communication loss during a time period greater than 6 s, a **fail-safe** procedure was implemented, resulting in shutting down the full detector, thus avoiding losing control on the powering of sensors.

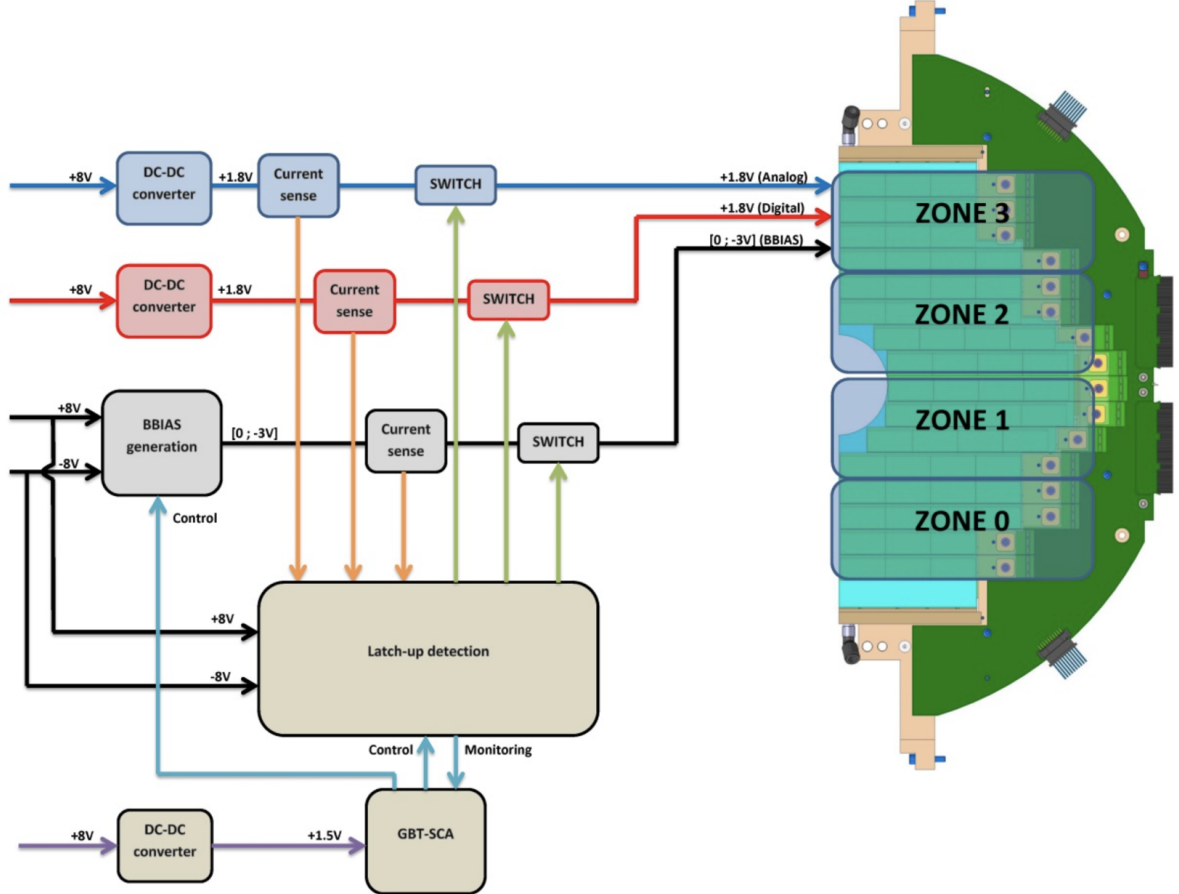


FIGURE 5.2: The Power Supply Unit features scheme for one disk.

5.2 Detector commissioning

5.2.1 The Giga-Bit Transceiver

The GBT-chipset [128] is employed to establish communication with each corresponding face of a half-disk, with the goal of providing a simultaneous transfer of data, timing, and trigger information, as well as detector slow control and monitoring signals to the front-end electronics embedded in the detectors. The GBT-SCA ASIC consists of an integrated circuit built-in radiation-tolerant 130 nm CMOS technology. Its structure is composed of two e-ports connecting it to the slow control port of the GBTx, and a network controller that transmits information.

The GBTx ASIC is a 3.2-4.48 Gb/s transceiver that manages the communication between the counting room and the front-end modules. The GBTx-SCA communication is transparent to the slow control protocol, as the GBTx encodes slow control packets and sends them as SCA packets to the requested GBT-SCA. Thus, the operation of sending commands and receiving answers from the GBT-SCA by the detector is managed by a GBTx. The two e-ports allowing the GBTx and GBT-SCA communication correspond to primary and auxiliary port. They consist of two functionally identical e-ports, ensuring redundancy in case of failures on optical links.

Essentially, the main user interface ports composing the GBT-SCA consist of the following:

I2C channels, implements 7-bit and 10-bit addressing transactions with a configurable transfer rate.

JTAG channel, allows programming, configuring and serial communication with devices by performing bus transactions of up to 128-bit length.

SPI channel, implements a synchronous serial bus master with a transaction length up to 128 bits and a configurable transfer rate.

GPIO channel, provides 32 configurable input-output lines latched with external clock signal or internal clock.

DAC channel, implements 4 independent digital-to-analog converter outputs with 8-bit resolution, generating voltage between 0 V to 1 V.

ADC channel, implements a 12-bit resolution analog-to-digital converter, with 32 multiplexed analog inputs, with automatic offset calibrations and gain error corrections. One of the 32 analog inputs is connected to the temperature sensor. Additionally, the inputs have a switchable 100 μA current source compatible for the use of resistance temperature sensors.

Clock and reset logic allows activating or deactivating a core in the SCA chip.

In total, the MFT detector consists of 8 GBTx (including both primary and auxiliary access, for redundancy purpose), present on the 4 PSU interface boards. They are connected to a total of 24 GBT-SCAs: 20 SCAs are present on the 4 PSU mezzanine boards, each connected to a specific face of a half-disk. The remaining 4 SCAs are present on the 4 PSU interface cards for the slow control of this board. The GBTx and GBT-SCA allows the implementation of the main features of the PSU mentioned in section 5.1. In particular, the features consist of switching on and off each zone independently, monitoring the voltages, currents, temperatures, and humidity, controlling the back-bias voltage, setting the latch-up current thresholds, monitoring the 80

zones status individually, as well as applying security locks on each. It will be further detailed later in this chapter (section 5.2.3).

5.2.2 Test-bench

The first version of the test-bench (Figure 5.3 - left), located at Subatech, consisted of a generic development VLDB card, on which is located a GBTx, replacing the PSU interface board which was in production, and a GBT-SCA (version 1, [128]), replacing the PSU mezzanine board. In particular, there is a difference between the VLDB card and the PSU, concerning the version of the GBT-SCA, which is of version 2 on the PSU. The VLDB is connected via e-links to a CRU board, installed in a First Level Processor (FLP) machine. Thus, this primary bench was used to reproduce the functionalities of the communication board between a CRU, the PSU, and the disks using a disk simulation board prototype. Then, gradually, the VLDB was replaced with the PSU boards. The commissioning and official software were designed and validated using the test-bench in order to address the discussed features of the PSU, and adapted as a function of the production status. After validation, the commissioning and official softwares were then deployed at CERN.

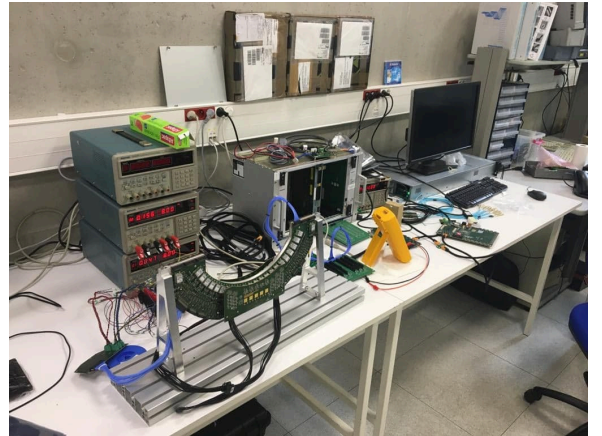
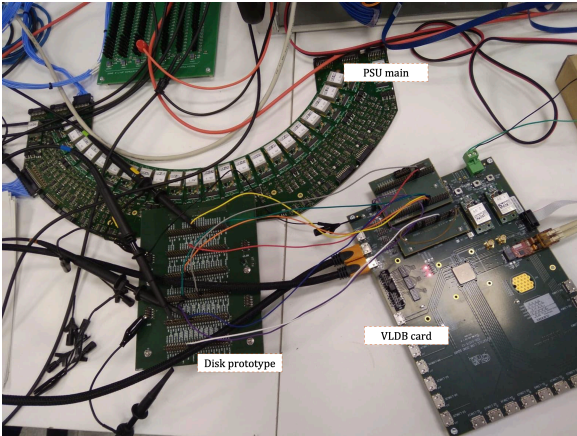


FIGURE 5.3: (left) A detailed view of the first test-bench. (right) A photo of the full test-bench view.

5.2.3 The commissioning software

Global structure

The first step to achieve the slow control of the detector is the configuration of the 4 GBTx, corresponding to a specific communication port (primary or auxiliary). Each GBTx is configured by enabling the communication with all the 6 GBT-SCAs connected: 1 on the PSU interface, and the remaining 5 are present on the PSU mezzanine and are connected to the GBTx via

special e-links on the PSU interface allowing data transfer. This particular configuration, illustrated in Figure 5.6, required a specific firmware of the CRU (developed by ALICE DAQ team). After this initial configuration, the GBTx and the GBT-SCAs share the same frequency, thus allowing a flow of information. The GBT-SCAs are then in a state ready to receive command sequences and return responses.

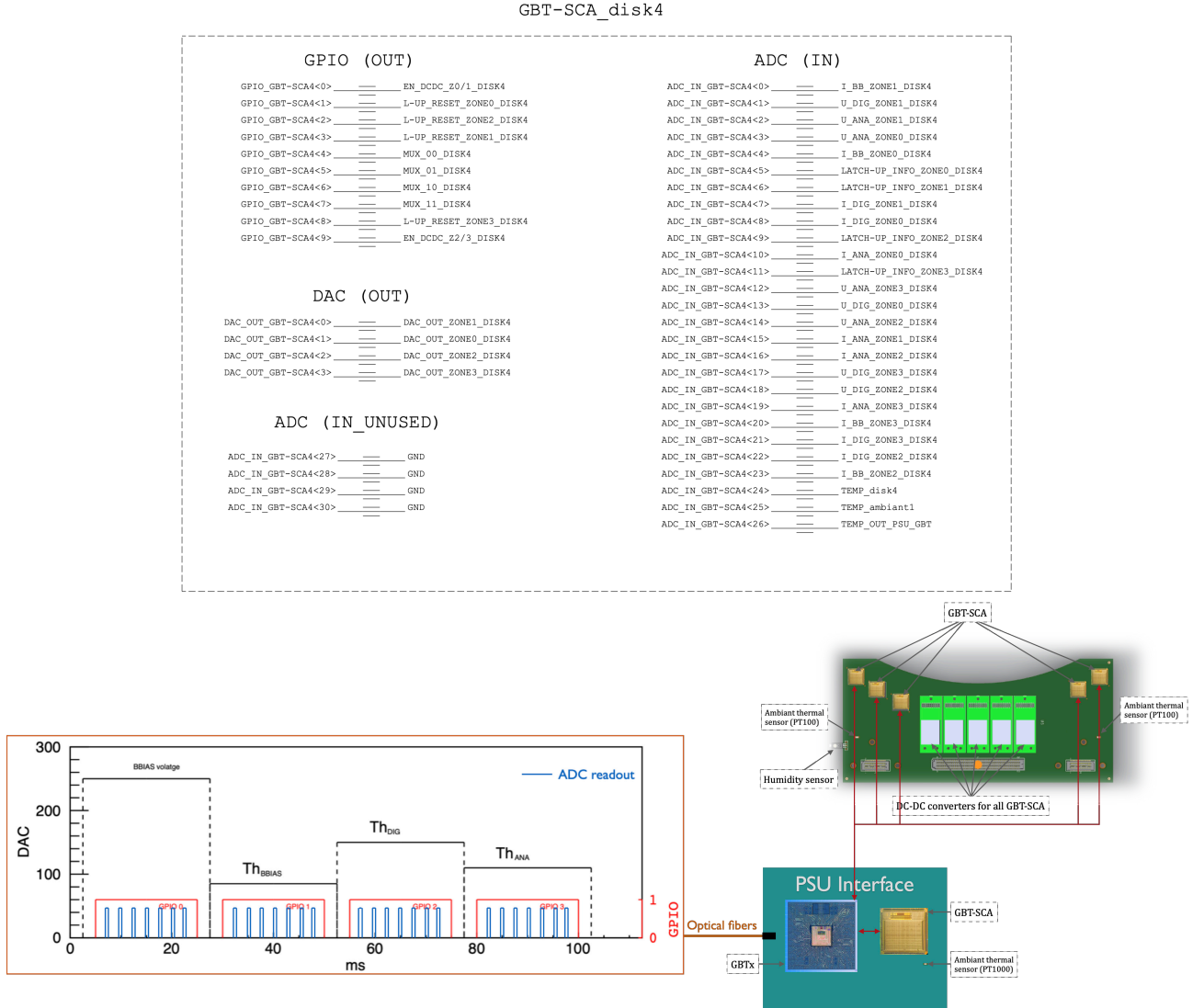


FIGURE 5.4: (up) A detailed view of the GBT-SCA registers for the face of half-disk 4. (bottom) A schematic representation of the monitoring sequence sent to the PSU interface.

The sequences sent to each GBT-SCA consist of two parts: the first one is for configuration, and the second one consists of the monitoring/control sequence specific to the registers of each GBT-SCA (Figure 5.4 features an example of registers for the face of half-disk 4). The role of each core is resumed as follows:

The configuration sequence: Two types of configuration sequences are sent, depending on

whether the GBT-SCA is connected to a disk or to a PSU interface. For all the SCAs connected to the disks, the configuration sequence consists of enabling all GPIOs, ADC, DAC and disabling I2C, SPI and JTAG. Concerning the configuration for the SCAs connected on the PSU interface, the configuration is more or less the same, with a difference of DAC disabling and an additional command to enable current on a specific ADC pin out, consisting of the PT100 and PT1000 temperature sensors.

The monitoring sequence: Six types of monitoring sequences are sent, each depending on the object that is being monitored and controlled. This is necessary because each face of a half-disk has a specific architecture (an example of Disk04 architecture is displayed in [Figure 5.4](#)). The ADC, DAC, and GPIOs addresses change from one half-disk face to the other. The condition of continuity of the monitoring sequences sent in parallel to 24 GBT-SCAs in a loop is mandatory for the detector operation. Each monitoring sequence has a duration of approximately $\tau = 100$ ms, which can be modified but should nonetheless respect the condition of $\tau < 6$ s. If this condition is not respected or if the communication to the detector is lost, the fail-safe feature is triggered. Thus, if the monitoring sequence stops running for more than 6 seconds, the detector is switched off in response. This duration can not be modified, as the PSU was constructed with components¹ that definitely set this duration. A temporization was introduced to the list of commands sent in the monitoring sequence, allowing a custom temporization of each sequence. The GBT-SCA monitoring sequence per face of a half-disk is responsible essentially for the following:

- ADC: The measurements of voltages and currents (analog, digital, and back-bias), temperature sensors, humidity sensors, and the latch-up information.
- DAC: Setting the back-bias voltage and latch-up thresholds for each of the four zones.
- GPIO: Control of the multiplexer to set back-bias voltage and latch-up thresholds on specific zones, enabling or disabling the DC-DC converters, and resetting zones after a latch-up state is triggered.

For the PSU interface, the monitoring consists of ADC and GPIO control, allowing to monitor the temperature sensors on the board, and to reset communication between the GBTx and GBT-SCA in case of failure.

Requirements

For the functioning of the software, the following specific python packages are required:

¹The components consist of RC filters.

Multiprocessing, to enable a continuous parallel communication on all 24 GBT-SCAs.

Shared Memory, to store in a common memory and share the sequences between the different scripts running. This allows to modify the sequences on the flight following operations done by a user and sent to the detector, and return the different responses of the corresponding GBT-SCAs.

Tkinter, to develop a Graphical User Interface (GUI), which allows the users to monitor and control of the detector.

In order to use these packages, python with a minimum version of 3.8 is required on the FLP. Thus, they ensure the functioning of the different aspects of the code by allowing parallelism between the 24 GBT-SCAs, a shared memory between the SCA objects and the graphical interface (Figure 5.5), and finally by providing the possibility of a live-display on a GUI for a user-friendly monitoring and control of the MFT.

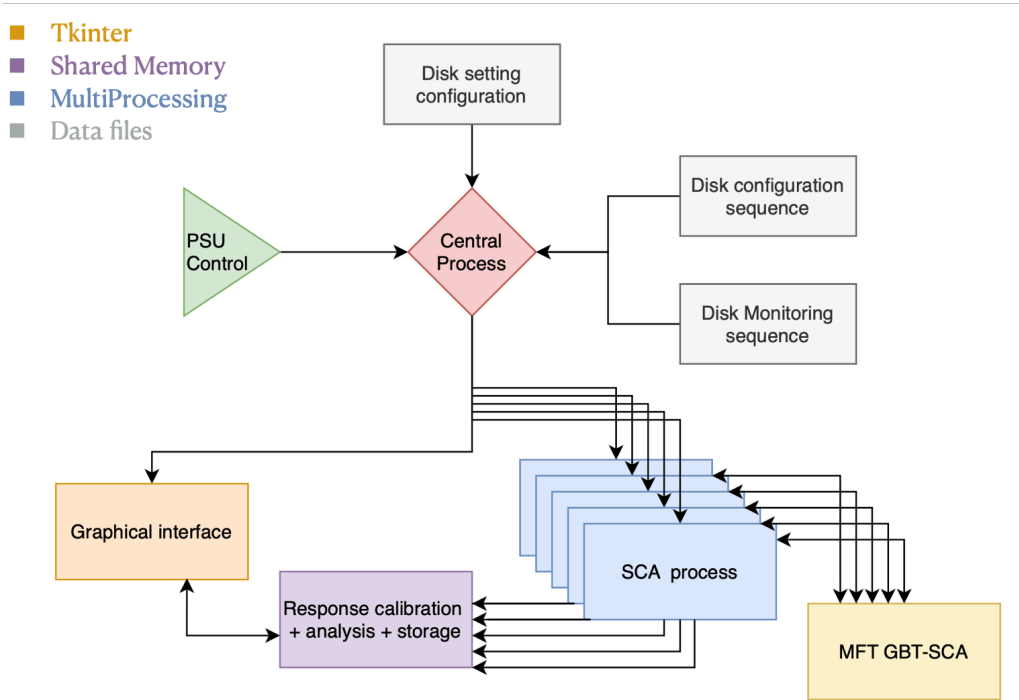


FIGURE 5.5: A schematic algorithmic map of the commissioning software.

Operational overview

With all the essential tools introduced, the operational side of the algorithm is presented briefly in the following, where a description of the control process concerning a face of a half-disk is detailed (Figure 5.5). As mentioned above, each control process operates the communication

with one GBT-SCA, thus is responsible for the control of one face of a half-disk. A total of 20 processes is required for the MFT disks control, as well as 4 processes for the PSU interface boards control. Each process is composed of a configuration sequence, sent once per GBT-SCA at the beginning, followed by the monitoring sequences sent in loop with a period of 4s, each consisting of 4 sub-cycles. Each sub-cycle is delimited by the GPIO multiplexer actions, which are defined by a binary command to enable or to disable a specific GPIO address. Thus, the sub-cycle will start with setting the back-bias voltage, or setting a specific analog, digital, or back-bias threshold, on 4 corresponding DACs, each corresponding to one zone, then enabling the specific GPIO address for 25 ms, during which ADC commands are sent to read different registers. The sub-cycle ends by disabling the corresponding GPIO. In addition to these SCA operations, enabling and disabling the DC-DC converters for 2 specific zones by the face of half-disk, as well as resetting a specific zone after a latch-up notification or a specific warning flag, is possible by adding the address registers on the GPIO actions throughout the cycles. The chronology of the sub-cycles is displayed in [Figure 5.4](#), where the monitoring sequence is displayed for one zone. This process is a hexadecimal command-response exchange on the lowest GBT-SCA level, which is then treated by a central process. The central process retrieves the data sets containing configuration/monitoring sequences specific for each GBT-SCA. Then, it launches the GUI interface process, followed by the creation of different shared memory containers by GBT-SCA in order to link the information received on the GUI (user operation), allowing to modify the SCA commands accordingly. The shared memory contains essentially the commands to send to the GBT-SCA, data retrieved from the GBT-SCA, and configuration settings (start/stop communication with each GBT-SCA, activation/deactivation of DC-DC converters, latch-up reset, ...). Numerous multi-processes are created per GBT-SCA, allowing a parallelism of the communication with the whole MFT detector. Calibrations are then required, as will be discussed in the next section. This software allowed CRU firmware commissioning and developments, as the goal is to provide a correct routing to the register addresses of the different GBT-SCAs, so that the information reaches the corresponding disks with both primary and auxiliary ports ([Figure 5.6](#)).

Calibrations

The measured quantities (currents, voltages, temperatures, humidity) and those to be set (U_{BB} , thresholds) are digitized via ADCs and DACs respectively. Different factors, such as conversion factor, gain and offset, can vary from one component to another. Therefore, calibration is required to convert physical quantities into digitized values and vice versa. In particular, few subtleties have to be considered, as the difference in resolution between DACs (8-bit resolution) and ADCs (12-bit resolution). Thus, with each cycle, the responses are converted, analyzed (in order to check the good functioning and potentially create warnings or errors), and stored. This

work was also done at Subatech, for the 4 half-PSU faces, that were shipped later to CERN and installed for the commissioning to resume.

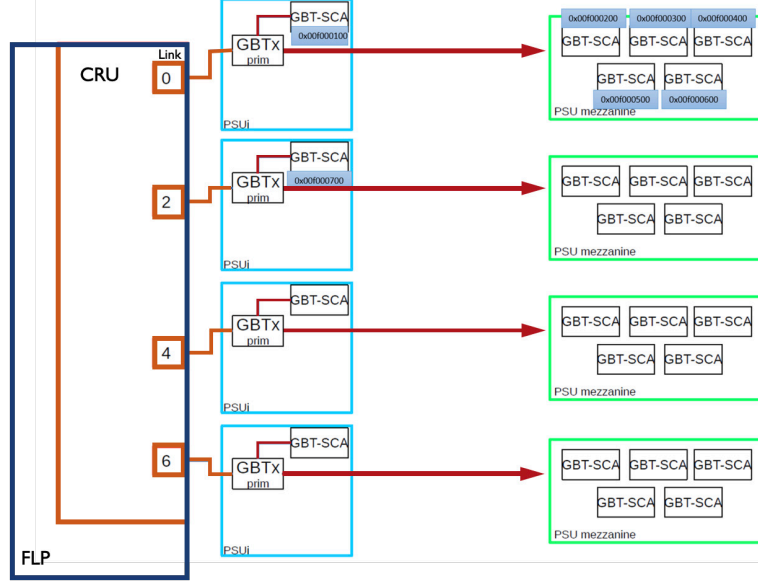


FIGURE 5.6: A schematic overview for the official firmware used for the MFT.

To conclude, the final version of this software allows the full control and the simultaneous monitoring of the MFT detector. After the assembly of both half-MFT cones at CERN, the commissioning software was deployed. An example of the GUI is shown in [Figure 5.7](#). The commissioning software was approved and used by the MFT Collaboration throughout the on-surface commissioning period. The commissioning phase was successfully finished in mid-November 2020. In January, the MFT detector was fully installed in ALICE cavern, and on-site commissioning phase started. The MFT commissioning software allowed mainly detector commissioning, detector calibrations, firmware tests and developments. Finally, it set the way for the official framework creation, which will be discussed in the next section.



FIGURE 5.7: The commissioning software, display of one of the last official GUI panel for 5 face of disks. 4 of these panels are required for the full MFT control.

5.3 Detector Control System

In this section, the creation of the MFT part of the ALICE Detector Control System (DCS) framework is detailed [130], consisting of the official tool deployed and used at the ALICE experimental site (point 2) throughout Run 3. The DCS is upgraded for the upcoming run, following the O² environment upgrades. The global DCS structure is described in the [Figure 5.8](#). The software structure is based on several modules over the network, communicating via DIM protocol (Distributed Information Management system) [131]. The ALice Frontend (ALF) module is located on the lowest level (FLP). It can establish communication with the CRUs, thus sending and receiving data directly from the detectors with the GBT-chipset protocol. The data is then transferred to the middle-level module, the FFront-End Device (FRED) software [132]. FRED sends commands to the detector through ALF module via DIM protocol and receives the detector response. The response is then treated, converted, and published via DIM services to a supervisory control process, known as the detector node, based on WinCC Open Architecture (WinCC OA). Thus, the FRED Server is the logical section within the DCS, producing and interpreting physical data from the raw hardware responses provided by ALF.

FRED allows a parallel handling of multiple ALF servers, it is customizable following detectors requirements and is responsible for the configuration and monitoring sequences, which supports input messages to accommodate user operations. Additionally, FRED allows an error-handling protocol, introduced by dedicated DIM services. Finally, it provides a Message Application Programming Interface (MAPI) for advanced customization. MAPI is mainly defined by ProcessInputMessage (PIM) and ProcessOutputMessage (POM). The PIM operates through message identification protocol and treats the input requests from WinCC OA, transforming them into specific sequence of commands to send to ALF. As for the POM, it consists of treating the responses received by ALF and transmitting analyzed and calibrated information through specific ANS or ERR channels, which are used for the panel display. For the PSU Control purpose, a specific MAPI running indefinitely in loop has been designed in FRED, allowing to reproduce the commissioning tool features. This MAPI tool allows an execution process to run in a loop, thus maintaining the communication with the PSU and avoiding the fail-safe scenario. Finally, FRED is also connected to a configuration database within the DCS network, which will be discussed in the next section.

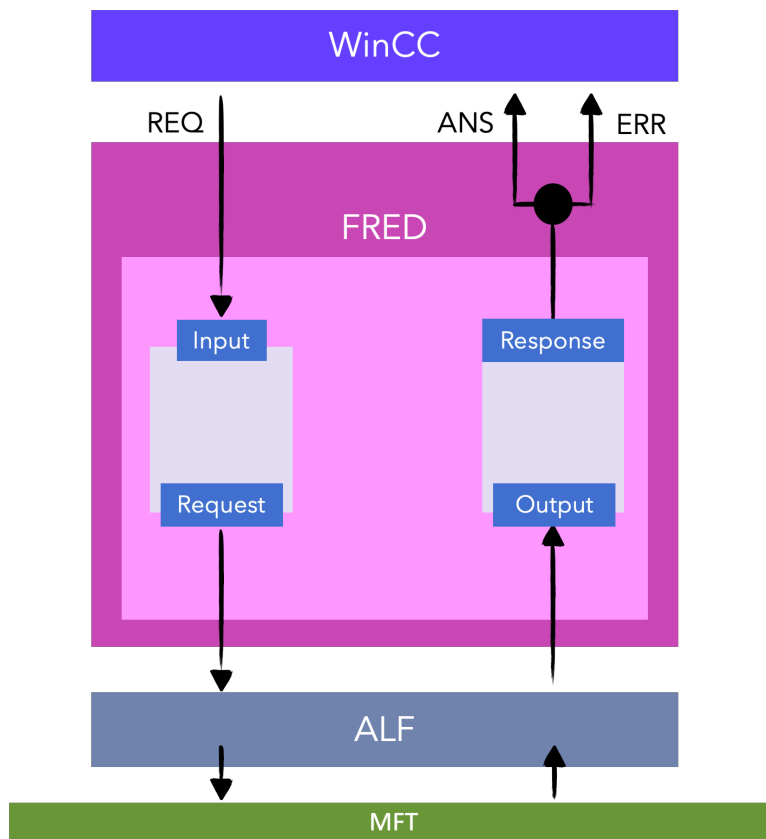


FIGURE 5.8: The ALFRED scheme, with the display of relational links between the different levels, done with DIM protocol (adapted from [132]).

5.3.1 DCS database

The Configuration DataBase (ConfDB) consists of organized storage of structured data, accessible via FRED, in order to retrieve detector information, calibrations, thresholds, and configuration parameters. The data is organized under relational models with the ConfDB management system based on ORACLE. ORACLE is a cross-platform system with a logical data structure partitioned, allowing a division of a large amount of data into different structures, which are then stored within data dictionaries. Data manipulation is done with Structured Query Language (SQL), which is the software language used for complete relational database management. In particular, the information stored in the configuration files for the commissioning tool have been structured and filled in the ConfDB, allowing versioning management. The relational database diagram infrastructure is displayed in [Figure 5.9](#).

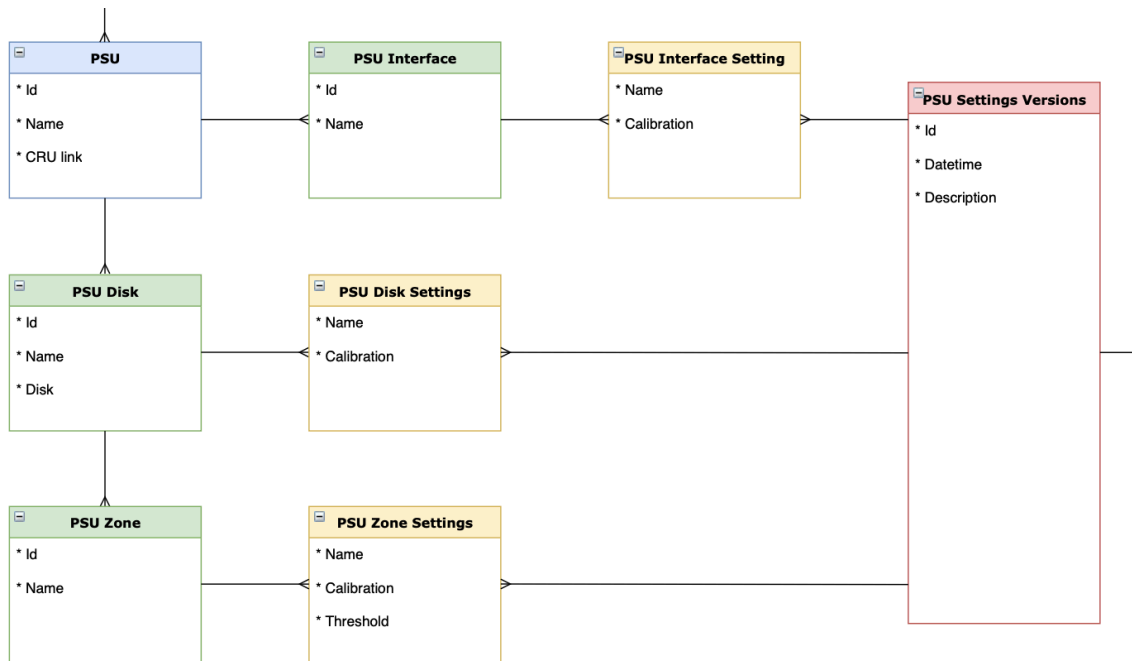


FIGURE 5.9: The PSU relational database diagram.

5.3.2 The FRont-End Device software

After presenting the essential tools, the logical part responsible for the MFT detector's full control, the FRED Server, will be described in this section. It is deployed on dedicated Linux machines. In particular, FRED sends commands interpretable by ALF via DIM (SCA protocol). In order to control all the 20 faces of half-disks and the 4 PSU interface boards, 24 services are created. Each service corresponds to one GBT-SCA, allowing parallel monitoring, and thus maintaining communication with the full detector. The full structure of the FRED Server is

described in Figure 5.10. When the FRED Server is launched, all the services are created first, then a connection is done to ConfDB, and a standby mode is triggered for a list of designed commands sent from WinCC OA after user operation, as discussed in the next section. The commands are configured in order to allow the same detector control provided by the commissioning software. The requests are received, decoded, interpreted, and assigned to the specific SCA in ProcessExecution (see Figure 5.10), then redirected to the PIM, where the commands are treated, with information loaded from ConfDB, in order to have raw data sequences sent to the detector. In return, ALF sends back the response of the SCA following the same raw data format. The response received is then treated, converted and analyzed in the POM and then published on the corresponding channels to WinCC OA. The response analysis essentially consists of checking the physical state of the detector, and triggering protective interlocks if a problem occurs. As for the operational side, the process execution runs in loop mode, to avoid the fail-safe scenario, sending a configuration sequence first to each service after receiving the start signal, and then by the monitoring sequence sent every 4 seconds. Furthermore, the described operation treats any additional user-sent commands, thus modifying the SCA sequence sent to the detector. An example of FRED operations is presented in Figure 5.11. It features the FRED Server level of different commands sent before response treatment, where only raw data from GBT-SCA is displayed. When treated and analyzed, this raw data is published to corresponding WinCC OA supervisory process.

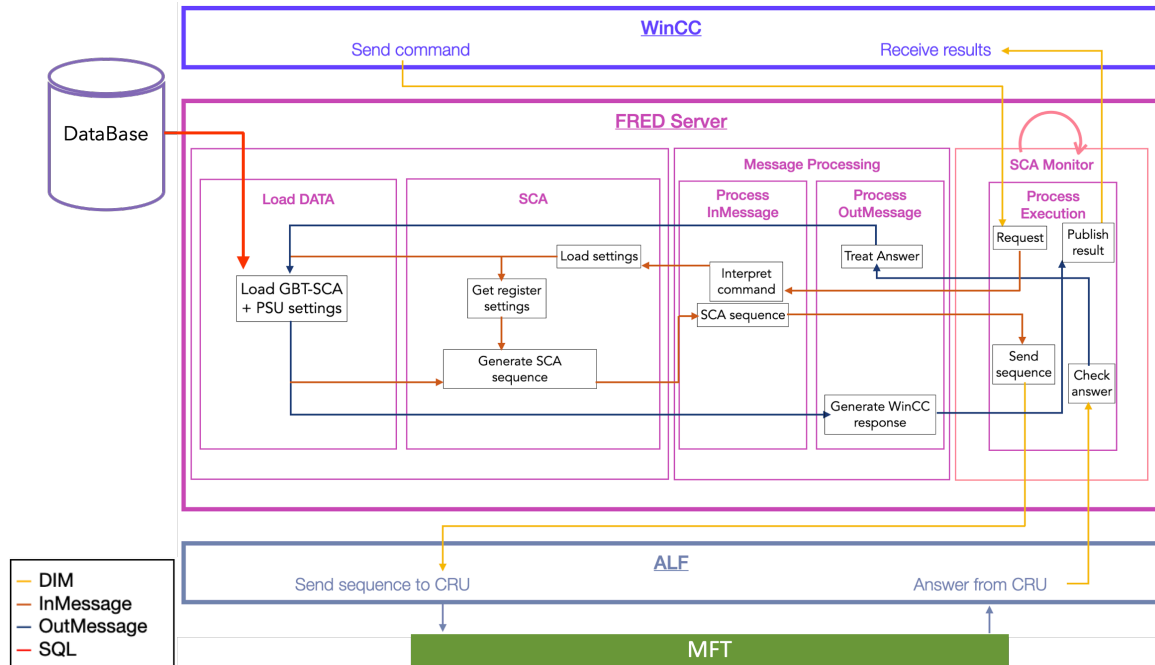


FIGURE 5.10: The full DCS structure for the MFT control: ALF on the lowest module, FRED middle module detailed within the different processes, and WinCC OA the supervisory process.



FIGURE 5.11: An example of the display for ALFRED communication on low level, before publishing the response to winCC.

5.3.3 Supervisory control process

As previously mentioned, the supervisory control process is responsible for user operations. Depending on the operation, commands are sent to the FRED Server via DIM, and the treated responses are then received, from which datapoints are updated and displayed on specified panels. The supervisory process used is based on WinCC OA, which is deployed on dedicated windows machines. The different developed scripts consist essentially of the 3 following phases:

- Creation of datapoint types and datapoints for three distinct analyzed objects: PSUDisk, PSUZone, and PSUInterface. The datapoint structure is displayed in the [Figure 5.12](#).
- Establishes DIM connections between FRED services and the WinCC OA.
- The published SCA response scripts are accorded to every element received from FRED by distributing the data to the corresponding datapoints element. Thus, WinCC OA scripts analyze the published response and place every specific value on the corresponding output panel, allowing the user to access all monitoring and control information.

These datapoints are linked directly to the panels, allowing user operations and a live display of the MFT. To resume, the final results of the full MFT-PSU DCS framework are displayed

in the following figures (from Figure 5.13 to Figure 5.18), featuring a set of panels running officially at point 2 for Run 3, allowing the full detector control and monitoring.

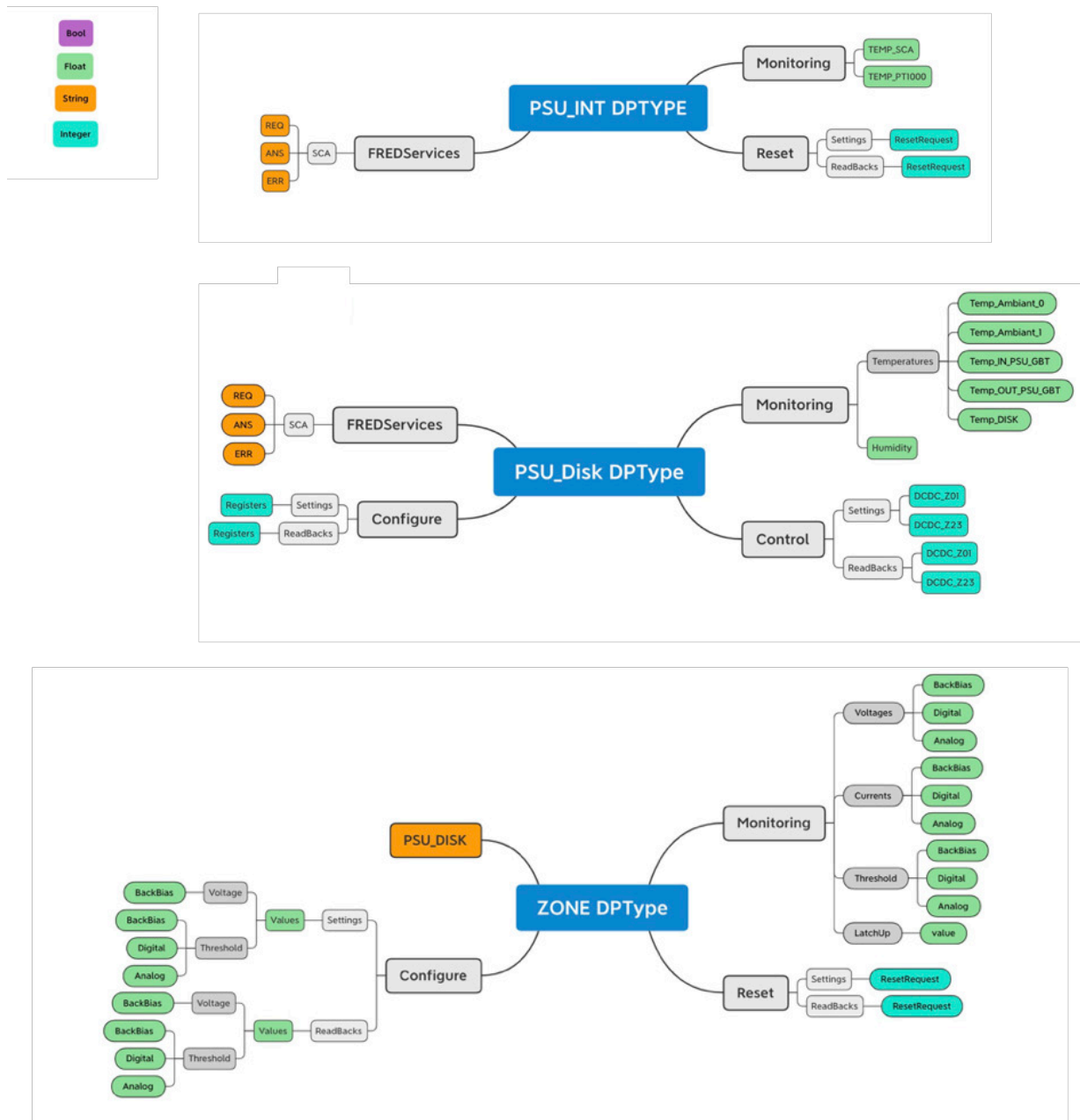


FIGURE 5.12: The organization of datapoints, responsible for the information displayed on the panels.

Chapter 5. Power control of the MFT



FIGURE 5.13: Expert view of the status of the MFT.

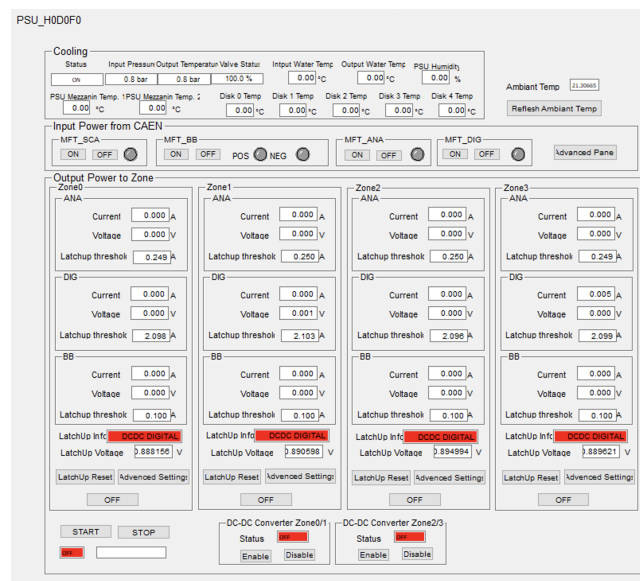


FIGURE 5.14: Expert view of a face of a half-disk.

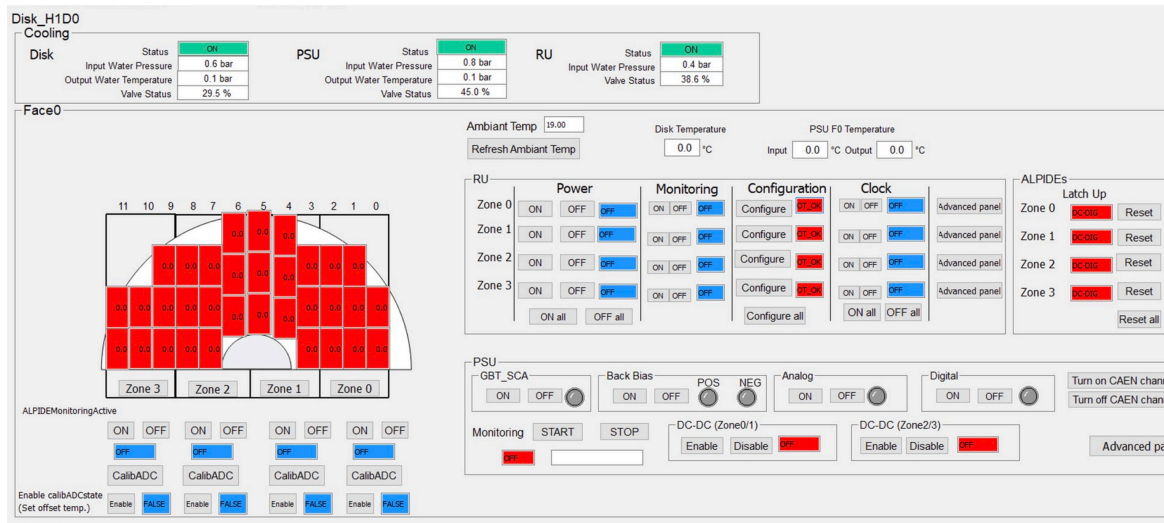


FIGURE 5.15: Control of a face of a half-disk (cooling,PSU,Readout Unit).

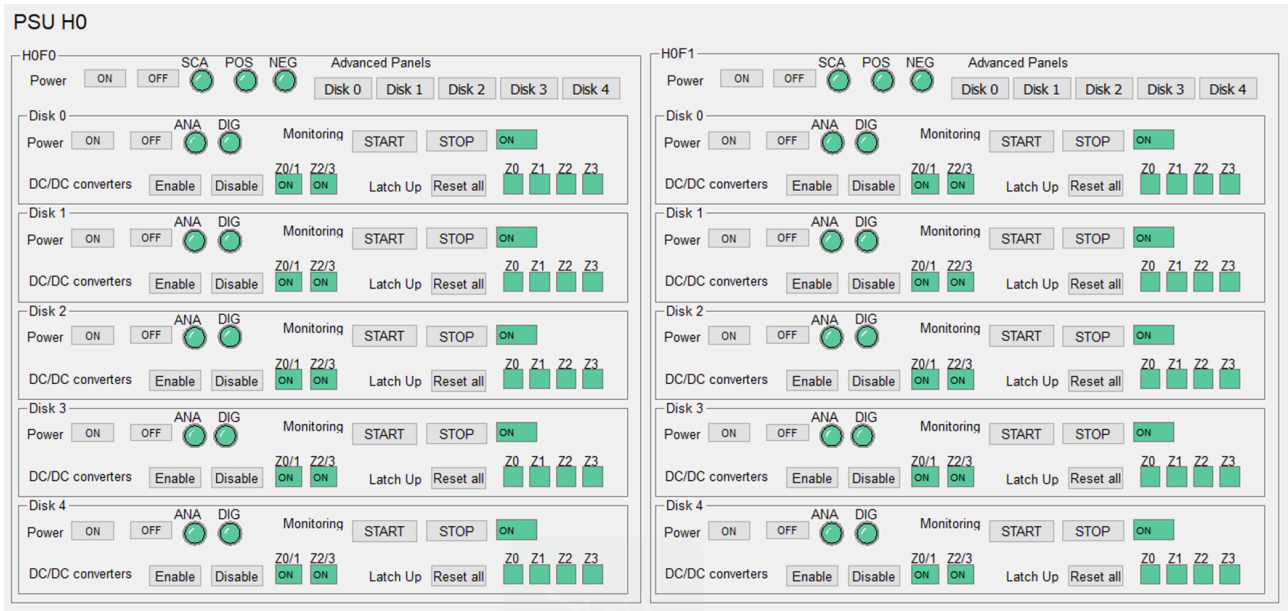


FIGURE 5.16: Control of the PSU of a half-cone.

Chapter 5. Power control of the MFT



FIGURE 5.17: History preview, monitoring of different measures trends.

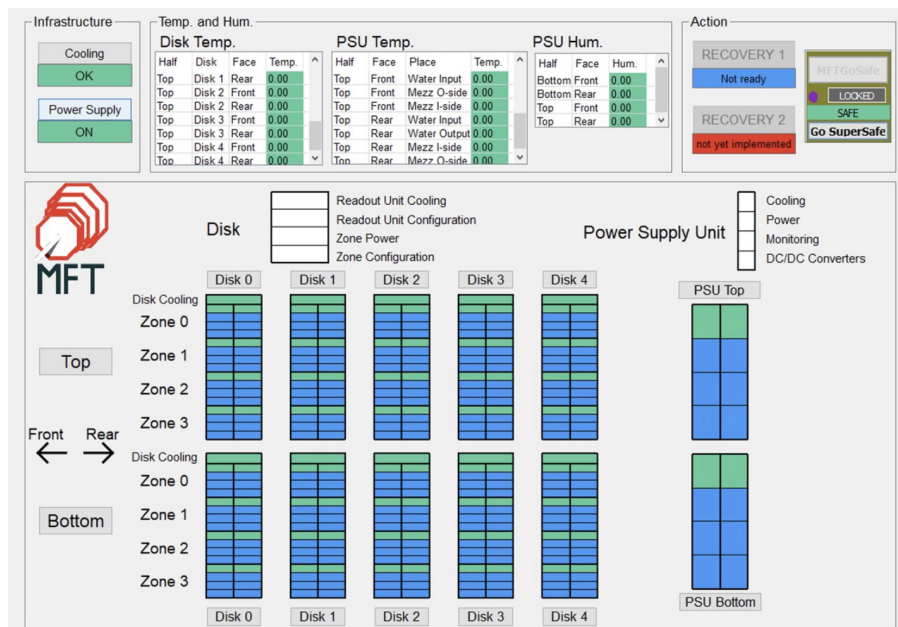


FIGURE 5.18: General overview of the full MFT status.

5.4 Conclusion

The powering of the MFT is managed by the PSU, located between the two farthest disks from the IP. The control is ensured by GBT-SCAs components. The first part of this thesis work is described in this chapter, with the goal of fully piloting the MFT detector. At the start, when the official framework was under development, the MFT control was required to perform on-surface commissioning. Thus, a commissioning software was fully developed allowing the control of the MFT detector through a user interface. It was approved by the MFT Collaboration and used during the whole commissioning period. It allowed detector commissioning, firmware developments and tests, detector calibrations and set the way for the official framework creation. For the official software in the DCS framework, the developments of the dedicated software (FRED Server), the building of the database (ConfDB) for storing detector's data, and the creation of the scripts for datapoints links with the panels (WinCC OA) are explained in this chapter. It allows the full control of the MFT during Run 3 operations. This framework is running 24h/24h in the ALICE cavern, allowing the entire detector's powering, monitoring, and control. Once the detector is operational, the aim is then to be able to derive physics performance and prepare the Run 3 analysis.

Chapter 6

Matching with Machine Learning

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As discussed in chapter 4, the MFT will allow access to a broad physics program by overcoming limitations imposed by the front absorber. In particular, access to the vertex of global muon tracks will be possible, allowing the separation of prompt and non-prompt J/ψ contributions at forward rapidity. For this purpose, efficient matching between MCH and MFT tracks from pp to Pb–Pb collisions down to low p_T is crucial to correctly identify global muon tracks. In particular, high multiplicity is expected in the MFT in Pb–Pb collisions, resulting in a significant background and thus leading to a considerable amount of fake matches. Therefore, powerful tool is requested in order to overcome and manage this background to maintain high performance. In this chapter, developments based on machine learning methods are presented for the matching to face these challenges.

6.1 Machine Learning

Artificial Intelligence (AI) is a science specialized in emulating human behaviour and abilities with algorithmic means. Its goal is to enable computers to analyse, learn and act like humans. The mathematician Alan Turing is considered the founding father of AI. In 1950, he was the first to address this notion, notably in a publication which tackled the question "Can machines think? " [133]. He therefore conducted various experiments to determine whether a machine could be deemed conscious.

Machine Learning (ML) [134] consists of an application of AI that refers to the algorithmic process of training machines to find an efficient way to solve a particular problem. More specifically, it is a science that trains machines to recognize patterns in a database and perform predictions accordingly. The first machine learning algorithms date back to the 1950s [135]. The domain of ML is vast, as it can be used to various ends, such as filtering spam e-mails, autonomous driving, handwriting recognition, economic predictions, and direct applications in physics field. For the latter, ML applications began in the 1990s and are widely expanding, especially with the high complexity faced within high energy physics. Depending on the task to be accomplished, different ML approaches may be considered (as presented in Figure 6.1), in particular:

Supervised learning: this approach is used when labeled data is provided. Thus, the training is done on these datasets with the goal of predicting an output following the trend learned on the training dataset.

Unsupervised learning: it mainly consists of cluster analysis, thus pattern identification within unlabeled datasets.

Supervised learning will be used to solve the task of matching classification, as will be discussed in the following.

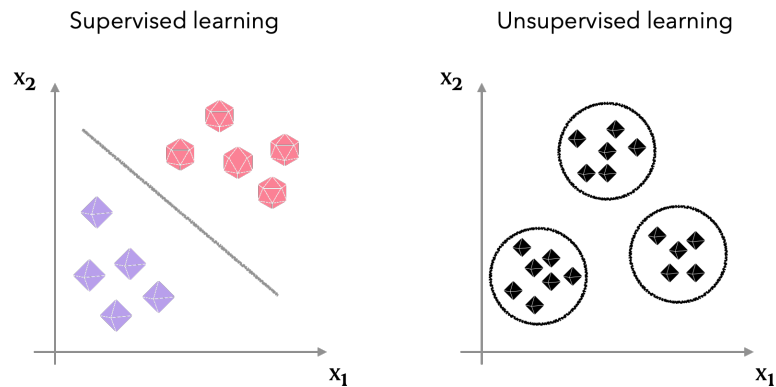


FIGURE 6.1: An example of supervised vs unsupervised learning.

6.1.1 Artificial neural network

The human brain consists of a neuron chain. Each neuron (Figure 6.2 - left) is composed of dendrites (input), capable of collecting signal, that is processed and transmitted to the axon (output). The signal is then split into several branches and carried to the synapse, which passes the electrical impulse to another neuron of the chain. This is the basis of the concept of artificial Neural Network (NN), where the training methods mimic the brain. A neural network is composed of an **input layer**, a vector of selected variables, an **output layer**, giving the result computed by the NN, and an intermediate level, composed of a configurable network of **hidden layers**, each of them composed of a selected number of neurons. An example of a NN is displayed in Figure 6.2 - right.

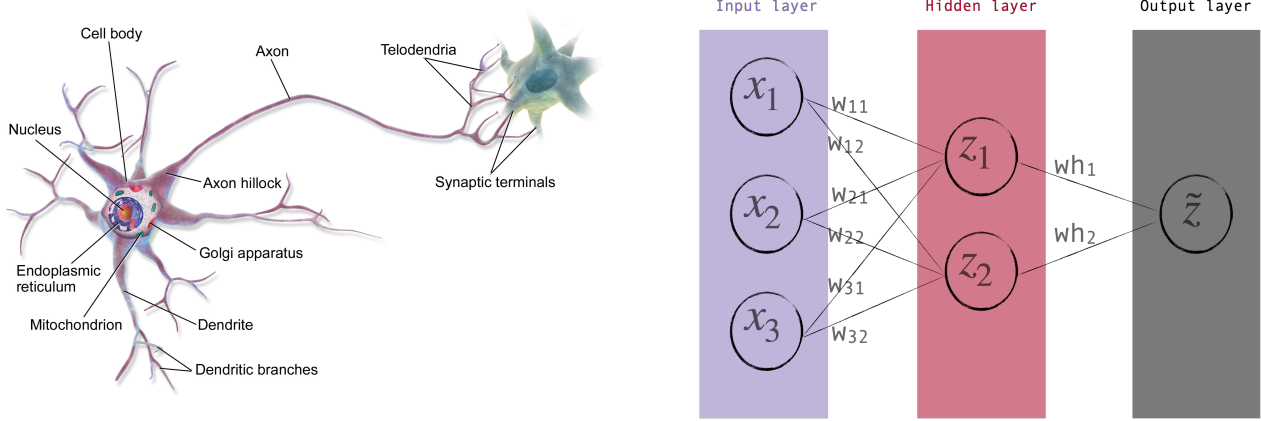


FIGURE 6.2: (left) A scheme of a neuron [136]. (right) A neural network structure.

In the following, various notions will be introduced in order to detail the propagation of information flow and to present the essential components constituting a feed-forward NN. Figure 6.2 - right is presented to visualize the different notations used. For the sake of simplicity, the propagation will be explained between the first two layers (input and first hidden layer). Nevertheless, the same logic is applied throughout all the different layers in the NN model. First, the input layer consists of a vector composed of n dimensions, such as:

$$X = \{x_1, \dots, x_i, \dots, x_n\} \quad (6.1)$$

It is connected to a first hidden layer, with m dimensions. In the case of Figure 6.2 - right, $n = 3$, $m = 2$ and the structure is composed of only 1 hidden layer. The links between neurons from two consecutive layers are characterised by a weight matrix $\mathbf{W}$. It is composed of the elements w_{ij} , where i corresponds to the index of the neuron of the input layer (from 1 to n), and j to the first hidden layer (from 1 to m).

A linear **summation function** is then defined as follows:

$$y_j = \sum_{i=1}^n w_{ij}x_i + b \quad (6.2)$$

where b is a constant **bias neuron**. It can be added to a layer to enhance the model flexibility.

An **activation function** is then applied on the summation function, with its output constituting the value of neuron j of the next hidden layer. Different activation functions can be deployed for the propagation, such as the **sigmoid function** with output values ranging from 0 to 1, the **hyperbolic tangent function** (tanh), with values ranging from -1 to 1, and the **rectified linear activation function** (ReLU), outputs 0 when the input ≤ 0 , or outputs the input value if it's positive. For the matching purpose, as a result of the tests that were conducted, the sigmoid function is selected. Thus, the neuron j of the hidden layer is given by:

$$z_j = \frac{1}{1 + e^{-y_j}} \quad (6.3)$$

The propagation between all the neurons for all the layers in the neural network follows the same logic. It is known as the forward propagation. The final value computed by the model, $\tilde{z}$, corresponds to a probability score, thus $\tilde{z} \in [0, 1]$ (the output layer in [Figure 6.2](#) - right). A threshold value C is then selected for the classification purpose. As a result, the output predicts 1 if $\tilde{z} > C$. The threshold can be tuned to obtain the best performance.

To quantify the performance of a NN model, the **loss function** is introduced. It represents the difference between the true result and the NN calculated prediction. Thus, the smaller the outputs of the loss function the better the performance. For the classification process, the loss function is a negative log-likelihood, given by:

$$L = -z_{MC} \times \log(\tilde{z}) - (1 - z_{MC}) \times \log(1 - \tilde{z}) \quad (6.4)$$

where z_{MC} is the matching truth (1 or 0), provided by MC for each MCH-MFT tracks associated in the input of the network. For the classification task, the negative log-likelihood is used in order to strongly penalize the learning algorithm, if the prediction and truth are not in accordance. As if the $z_{MC} = 1$ and $\tilde{z} \simeq 0$ (or vice versa), $L \rightarrow \infty$, while if $z_{MC} \simeq \tilde{z}$, then $L \rightarrow 0$.

In order to reduce the error on the predicted output, the weight parameters are adjusted to minimise the loss function outputs. This is known as the backward propagation process in a NN, and is introduced with specific optimizers. The knowledge is updated and propagated through the NN, changing thus the weights of neurons accordingly and minimising the loss

function after each iteration. For this purpose, the weights are updated as following:

$$w_{ij}^{(t+1)} = w_{ij}^{(t)} - \alpha \frac{\partial L}{\partial w_{ij}} \quad (6.5)$$

where t indicates the iteration step and α is a **learning rate**. The learning rate defines the size of each step updating the weights at each iteration. If α is too high, there is a high probability that the learning will diverge, and thus no minimization is possible for the loss function. In the opposite, if α is too small, the number of iterations needed to reach the minimum and thus to train the NN model is higher and might be time-consuming. The different scenarios are presented in Figure 6.3. As for the term $\frac{\partial L}{\partial w_{ij}}$, it is calculated with the chain rule as follows:

$$\frac{\partial L}{\partial w_{ij}} = \frac{\partial L}{\partial \tilde{z}} \frac{\partial \tilde{z}}{\partial y_j} \frac{\partial y_j}{\partial w_{ij}} = (\tilde{z} - z_{MC})x_i \quad (6.6)$$

This iterative optimization with the goal of finding the global minimum of the Loss function is known as the gradient descent. As will be discussed latter, the **optimizer** choice might introduce other internal parameters to tune the weights. Additionally, a dynamic learning rate can be used, thus the user can define an initial value of α , which will be tuned and adapted with the iterations.

Each **iteration** consists of one forward and one backward propagation for a selected number of training samples. This number is defined as the **batch size**, the higher it is the more memory-consuming the process is. Finally, an **epoch** is defined as one forward and one backward propagation for all the training data samples.

The dataset is thus divided into the training and testing samples. The training sample is used to fit and build the model. The testing sample is used to evaluate the performance of the model, allowing an error estimation on a new set of data on which the model was not trained. A **split ratio** is thus applied on the main dataset, dividing it into these two sub-categories.

In order to favor the equitable distribution of information within each link, a **drop-out rate** could be added. It indicates a proportion of links that will be removed between the selected layers. This is not used in the context of matching, as the selected model structures are relatively small.

Therefore, in order to improve the learning process, a search and selection of the mentioned **parameters** must be done in order to find the best performing model. This procedure is referred to as the **hyperparameter** tuning.

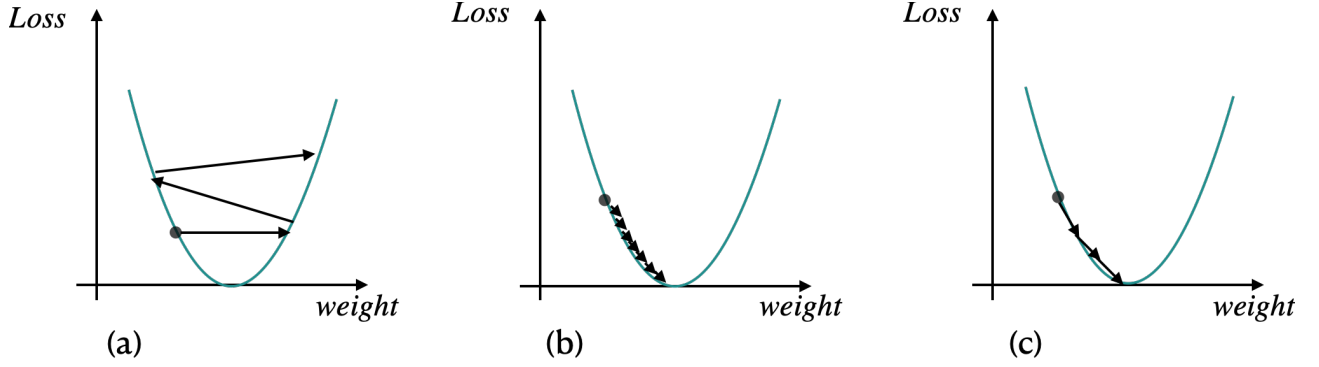


FIGURE 6.3: The loss function minimization (2D visualization) with different learning rates α scenario. (a) Consists of a large α , resulting in deviation, (b) of very small α , slow convergence to the minima, and (c) consists of a coherent rate behaviour.

6.2 Matching application

6.2.1 Motivations

As detailed in section 4.3, the standard method used to find the global muon tracks consists of selecting the MCH-MFT track with the minimum χ^2 score. In high multiplicity environments, a high density of MFT tracks in the search area is present on the matching plane (an example of display is presented in Figure 4.11). The extrapolation of the MCH track through the front absorber is described by a gaussian function, as there is uncertainty due to the multiple scatterings occurring within the absorber. Thus, this uncertainty can induce an association with a wrong MFT track, implying a change of the χ^2 score ranks for the true track (expected to have the smallest χ^2) due to the high density of tracks. As a result, incorrect matching is expected, resulting in fake global muon tracks. The matching performance is also deteriorated for low p tracks, as they are more sensitive to multiple scatterings in the absorber.

To illustrate the limitations of the standard χ^2 method, 300 events of 1000 π and 10 μ each have been generated, to obtain a high multiplicity environment. Then, correct MC matches (i.e. the true global muon tracks) are extracted, with their corresponding χ^2 rank. Each MC global muon track is classified according to its χ^2 score rank with respect to all the MCH-MFT candidates present in a selected search area. As presented in Figure 6.4 - left, the χ^2 method would have predicted correctly only the first bin of the histogram since they contain the first ranked correct MCH-MFT tracks. More precisely, only 60% of the tracks are correctly associated following the χ^2 score method, as the other 40% correct tracks do not have the minimum MCH-MFT χ^2 score.

In Figure 6.4 - right, the χ^2 score is displayed for all the MCH-MFT associated tracks. There is a distinction between the **signal**, corresponding to the MC correct MCH-MFT match,

and the **background** corresponding to the incorrect MCH-MFT match as a function of χ^2 . A loose cut for the maximum accepted χ^2 score is applied on the associated tracks. Thus, it can be noted that a rigid cut is insufficient to disentangle efficiently the signal from the background.

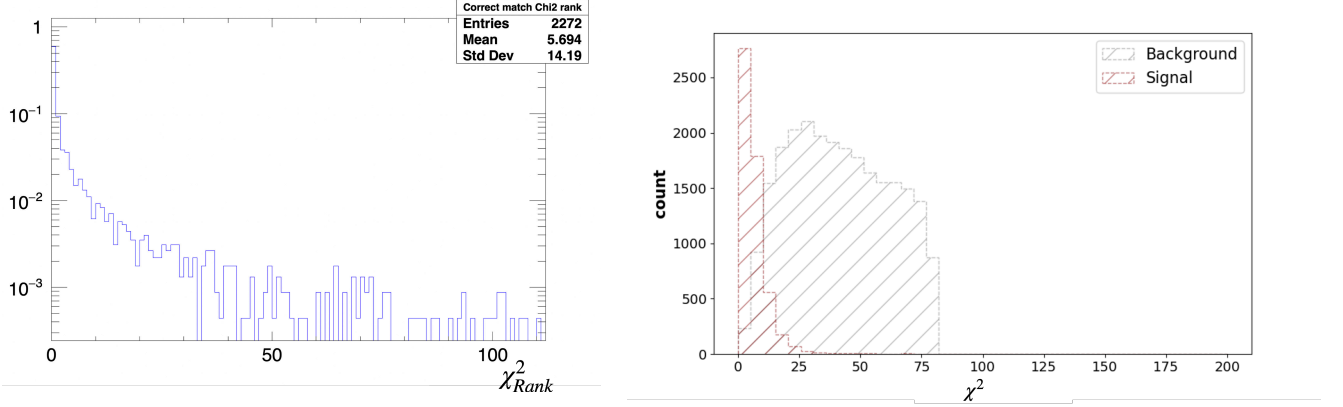


FIGURE 6.4: (left) Correct matches as a function of the chi2 rank. (right) the χ^2 score for signal and background with a cut applied on the maximum admitted score.

Furthermore, Figure 6.5 shows the ϕ_{MCH} as a function of the x_{MFT} (Figure 4.12), with a zoom on the figure to show the signal-background interplay. Refined tools are needed in order to establish non-linear functions with the goal of extracting the signal by finding the correct MCH-MFT matching pairs. For this task, machine learning tools are developed and implemented in order to calculate a matching probability score between MCH and MFT tracks to improve the track matching.

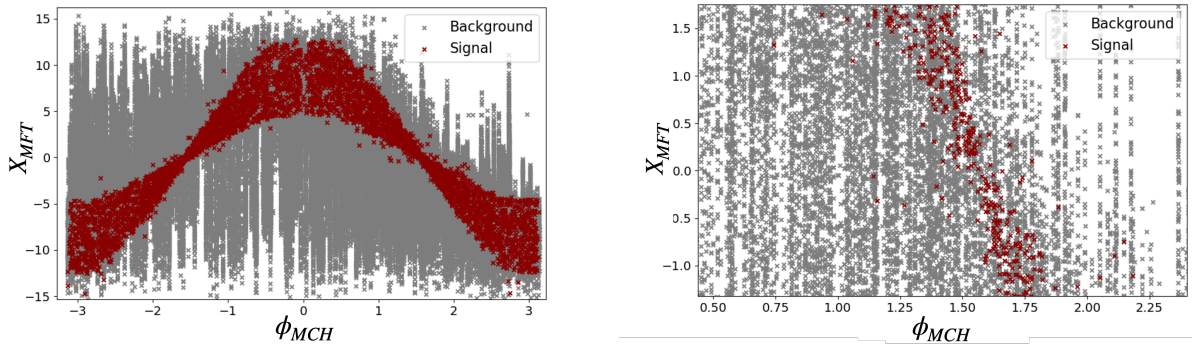


FIGURE 6.5: (left) The distribution of the x_{MFT} as a function of ϕ_{MCH} for true and fake matched tracks. (right) Zoomed-in figure on the x_{MFT} as a function of ϕ_{MCH} .

6.2.2 Data production and structure

The generators used throughout this chapter are PiParam and MuBoxGun. PiParam generates a number of pions, representing the background on the MFT side. MuBoxGun generates the muons that hit the MFT disks and pass through the absorber to the MCH. The detector effects and propagation are taken into account with GEANT3 [118]. As the generated MFT tracks are numerous, one should expect unbalanced datasets due to the high expected pion background. Thus, pre-processing is required to optimize the learning process with NNs, as will be discussed in section 6.4.2.

For the matching task, the input layer consists of a vector composed of the MCH and MFT track coordinates, expressed in the MFT coordinate system (as discussed in chapter 4, with Equation 4.2). The selected input layer corresponds to the following vector:

$$X = \left\{ x_{MCH}, y_{MCH}, \phi_{MCH}, \tan\lambda_{MCH}, \left(\frac{q}{p_T} \right)_{MCH}, x_{MFT}, y_{MFT}, \phi_{MFT}, \tan\lambda_{MFT}, \left(\frac{q}{p_T} \right)_{MFT}, \chi^2 \right\}$$

All of the values are evaluated at the 5th disk matching plane, thus for $z = 77.5$ cm. For each MCH track, a subset of MFT tracks are selected based on a search area, which corresponds to the same 3σ cut around the MCH track as in Equation 4.5. The output layer consists of one dimension, providing a matching probability score calculated by the NN. It is then transformed to a binary output of 0 or 1, through a threshold value. It indicates a mismatch or a correct match respectively between the associated tracks. The threshold defines the minimum probability accepted for correct track matching identification. If 1 is predicted, the MCH-MFT track is considered as a forward muon track. The output thus classifies each MCH-MFT track as a match (**signal**) or not (**background**). Two different NN approaches were tested in order to find the most convenient one for this challenge.

6.3 Performance evaluation criteria

An assessment workflow is used to evaluate the training process of the NN. Various steps of this workflow and useful definitions are presented in this section. It allows the determination of the training quality, as well as the matching performance.

6.3.1 Training evaluation

The loss function (Equation 6.4) is crucial for evaluating the training process, as it is applied on both training and testing datasets and can reflect if the NN model is able to learn patterns, or if there is an issue of overfitting or underfitting. Overfitting occurs when the model memorizes the training data pattern with the statistical fluctuations, thus performs poorly on testing data.

Underfitting occurs when the model is unable to identify any pattern, thus predicts poorly on both training and testing datasets.

Another useful metric is the accuracy. It is a percentage calculating the correct predictions done by the model for both training and testing data, with the following formula:

$$\text{accuracy} = \frac{\text{correct predictions}}{\text{all predictions}} \quad (6.7)$$

Thus, the higher the accuracy the better the model is learning.

In order to reflect the efficiency and the purity of the training, the F_{score} is essential. In order to understand this metric, the extraction of the matrix following Table 6.1 will be required.

	ML = 0	ML = 1
MC = 0	TN	FP
MC = 1	FN	TP

TABLE 6.1: Table describing the variables TN, FN, TP and TN.

True Negative (TN) occurs when the MC truth and the ML model does not predict a match, with $MC = ML = 0$. The Fake Positive (FP) indicates when the ML predicts an incorrect match, the Fake Negative (FN) is when the ML mis-predicts a true match, and the True Positive (TP) means there is a correct match and both $MC = ML = 1$. Thus, in order to calculate the purity of the predictions, the proportion of positive identifications that are actually correct, the precision variable is needed:

$$\text{Precision} = \frac{TP}{TP + FP} \quad (6.8)$$

As for the efficiency of the predictions, the recall is calculated. It represents the proportion of positive results on real tracks:

$$\text{Recall} = \frac{TP}{TP + FN} \quad (6.9)$$

The combination of both precision and recall will result in the F_{β} measurement, which reflects the network's accuracy by combining both the purity and the efficiency of the predictions:

$$F_{\beta} = (1 + \beta^2) \times \frac{\text{precision} \times \text{recall}}{\beta^2 \times \text{precision} + \text{recall}} = (1 + \beta^2) \frac{TP}{(1 + \beta^2)TP + \beta^2 FN + FP} \quad (6.10)$$

For the matching, the weight is equally partitioned on both aspects ($\beta = 1$). Thus, in this study, the F_{score} is defined as F_1 :

$$F_{\text{score}} = 2 \times \frac{\text{precision} \times \text{recall}}{\text{precision} + \text{recall}} = \frac{TP}{TP + 0.5 \times (FP + FN)} \quad (6.11)$$

Finally, once the training is satisfactory and the models are selected, an evaluation is done to

compare the different selected models in order to deduce the optimal model. This evaluation is performed with the Receiver Operating Characteristic (ROC) curve, which is represented by a graph showing the performance of each classification model parameterised by the classification threshold (PS cut), going from 0 to 1. The ROC curve plots the True Positive Rate (the recall) as a function of the False Positive Rate ($FPR = \frac{FP}{TN + FP}$). The ROC curve is explained in Figure 6.6, where 3 different scenarios are presented, ranging from the best-case to the worst-case scenario. Thus, the model with the better performance will correspond to the model with the largest area below the curve.

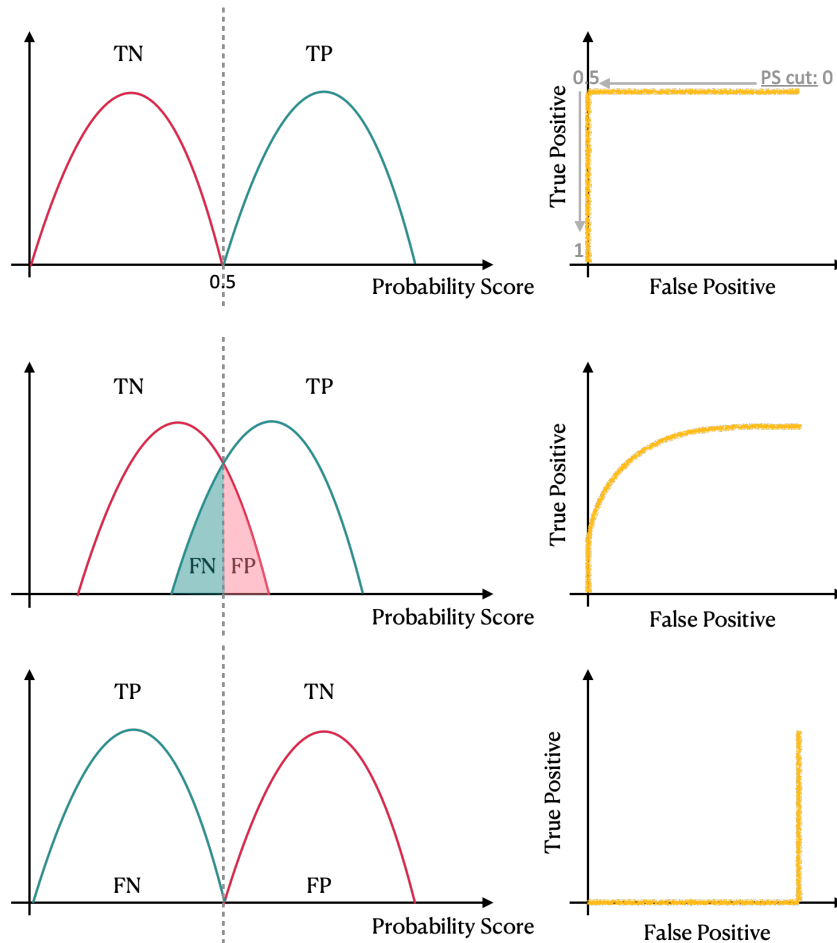


FIGURE 6.6: A range of different performance scenarios (left) with their corresponding ROC curves (right).

6.3.2 Matching performance

After the model selection based on the training performance, a different dataset is used to perform and assess the matching performance with ML. The model provides a probability (the output of the NN) for each MCH track with the corresponding MFT track candidates. The

matched MCH-MFT tracks correspond to the one with the highest probability score. Tools to evaluate the matching performance are then required to perform a comparison between the different methods and models in order to assess the optimal one. First, for this purpose, the pairing purity is calculated in order to visualize the correct sample in the predicted signal:

$$P_{pairing}^{GM} = \frac{N_{true}^{GM}}{N_{Rec}^{GM}} \quad (6.12)$$

where N_{true}^{GM} is the number of Global Muon (GM) tracks with correct MCH-MFT matching, and N_{Rec}^{GM} is the total number of all reconstructed global muon tracks (including the correct and the fake matches). Additional to the sample purity, the pairing efficiency should be accounted for in order to visualize how much of the signal is conserved for the pairing efficiency:

$$\epsilon_{pairing}^{GM} = \epsilon_{true}^{GM} + \epsilon_{fake}^{GM} = \frac{N_{Rec}^{GM}}{N_{Pairable}^{GM}} \quad (6.13)$$

where the $N_{Pairable}^{GM}$ is the number of pairable global muon tracks, which are the tracks that have been correctly reconstructed by both MFT and MCH and comes from the same generated particle. The pairing efficiency is thus the sum of both true and fake efficiencies, which are presented as below:

$$\epsilon_{true}^{GM} = \frac{N_{true}^{GM}}{N_{Pairable}^{GM}} \quad (6.14)$$

$$\epsilon_{fake}^{GM} = \frac{N_{fake}^{GM}}{N_{Pairable}^{GM}} \quad (6.15)$$

with N_{fake}^{GM} the number of fake matched Global Muon (GM) tracks. All concepts and key quantities to optimize and to assess the performances of model have been introduced. The next section is dedicated to their applications on MCH-MFT track matching.

6.4 Model selection

The first designed machine learning tool was developed with the MultiLayer Perceptron (MLP), which is a Neural Network toolkit available in the ROOT framework. A preliminary study was concluded with MLP, which is presented below. Due to optimizations for time-consumption reduction, another ML algorithm has been also developed, consisting of the NN method with TensorFlow (TF) python package, reducing the time-consumption considerably. Thus, the algorithmic development and the full analysis will be presented with the TF package in the following. The datasets used for both ML methods consist of the following: for the training

purpose, a dataset composed of 1000 events, each consisting of 800 π and 80 μ has been produced. As for the testing and evaluation purposes, a dataset of 500 events, each composed of 800 π and 10 μ is used.

6.4.1 Preliminary study

The MLP consists of a feed-forward neural network with a configurable structure, as described in section 6.1.1. The input vector is normalized, and the information is propagated between the layers with sigmoid activation functions. As for the used optimization method, it is known as the Robbins-Monro stochastic approximation [137], where the values of the weights are updated after each iteration in order to minimize the total errors. The evolution of the weights for a $t + 1$ iteration is described with the following:

$$w_{ij}^{(t+1)} = w_{ij}^{(t)} + \Delta w_{ij}^{(t)} \quad (6.16)$$

$$\Delta w_{ij}^{(t)} = -\eta(de_p/dw_{ij} + \delta) + \epsilon\Delta w_{ij}^{(t-1)} \quad (6.17)$$

where the η is the learning rate, δ and ϵ are parameters. They are initialized and then adjusted after each step, in order to minimize the error referred to as e_p between the output predictions ($\tilde{z}_p$) and the MC response ($z_{MC,p}$): $e_p = \tilde{z}_p - z_{MC,p}$.

A series of tests have been done on the network structure in order to choose the optimal model. First, the choice of input parameters is studied, in order to assess and choose for the best performing structure. Thus, Table 6.2 presents these tests, with the corresponding training F_{score} as an evaluation method of comparison between the different structures. The column of 11 parameters consists of the vector described in section 6.2.2, at the matching plane. The column of 21 input parameters contains additionally the diagonal covariance elements for each track. The F_{score} presented consists of an average score calculated following a given number of

Hidden layers	21 input parameters	11 input parameters
$20 \times 20 \times 20$	0.54	0.67
$30 \times 30 \times 30$	0.5	0.62
$20 \times 20 \times 20 \times 20$	0.66	0.76
$30 \times 30 \times 30 \times 30$	0.71	0.74
$20 \times 20 \times 20 \times 20 \times 20$	0.51	0.55
$30 \times 30 \times 30 \times 30 \times 30$	0.4	0.46

TABLE 6.2: The F_{score} for different structures of hidden layers with different input layer vectors.

tests. The score is extracted after 100 epochs for each selected structure. Tests on the network structure were also done, with additional input neurons containing different combinations of the main parameters, but the training process did not benefit from this additional combined

information, as no improvement in the F_{score} was observed. Thus, following these tests, the 11 input parameters with a $20 \times 20 \times 20 \times 20$ structure is selected (as displayed in Figure 6.7).

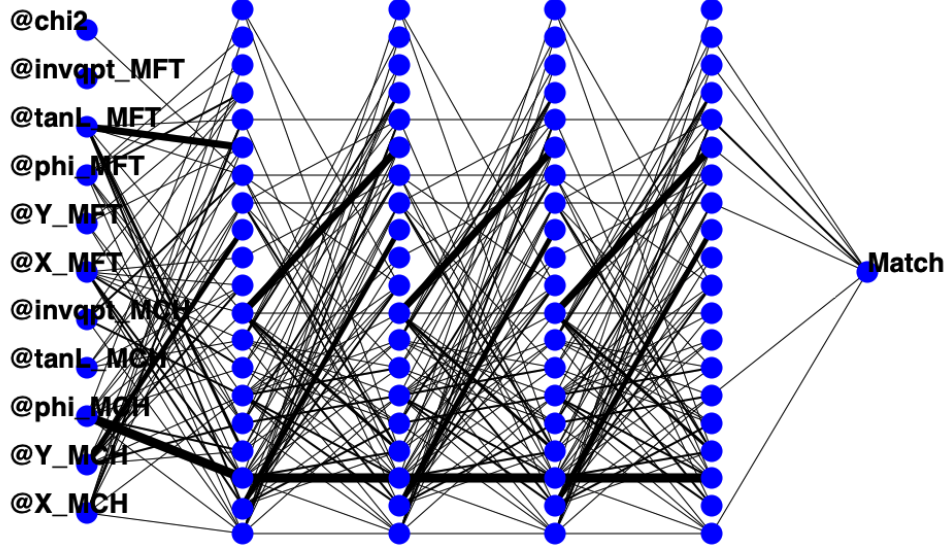


FIGURE 6.7: The Neural Network structure for the best performing model.

The number of epochs for the learning process is crucial, as it should be enough to allow the weight optimizations to take place and thus find the minimum of the loss function, while avoiding any overfitting on the data. A visualization of the importance of this parameter is shown in Figure 6.8, showing the learning process with the MC truth vs. the ML predictions (i.e. $\hat{z}$), where the left corresponds to the network state after 10 epochs, and the right corresponds to the network state after 1600 epochs. Additionally, time consumption should be taken into account, so that when the network stabilizes, the number of epochs can be selected. Thus, Table 6.3 presents the F_{score} for different epochs.

Number of epochs	50	100	200	600	1000	1600
F_{score}	0.01	0.7	0.67	0.79	0.81	0.81

TABLE 6.3: The resulting F_{score} for training with different number of epochs.

As can be observed, around 1000 epochs are needed to reach a stable point in the learning process for this NN structure.

To further visualize this learning steps, Figure 6.9 - up shows the MC signal for the ϕ_{MCH} as a function of x_{MFT} . The signal consists of the correct MCH-MFT matches. In Figure 6.9 - bottom, the MCH-MFT matching signal is reconstructed by using the developed ML method, with a $20 \times 20 \times 20 \times 20$ structure, after 10 epochs (left) and after 1600 epochs (right). This performance check is done after the model is selected and saved, then it is applied on simulations,

by associating the tracks with the highest probability score between each associated MCH-MFT track.

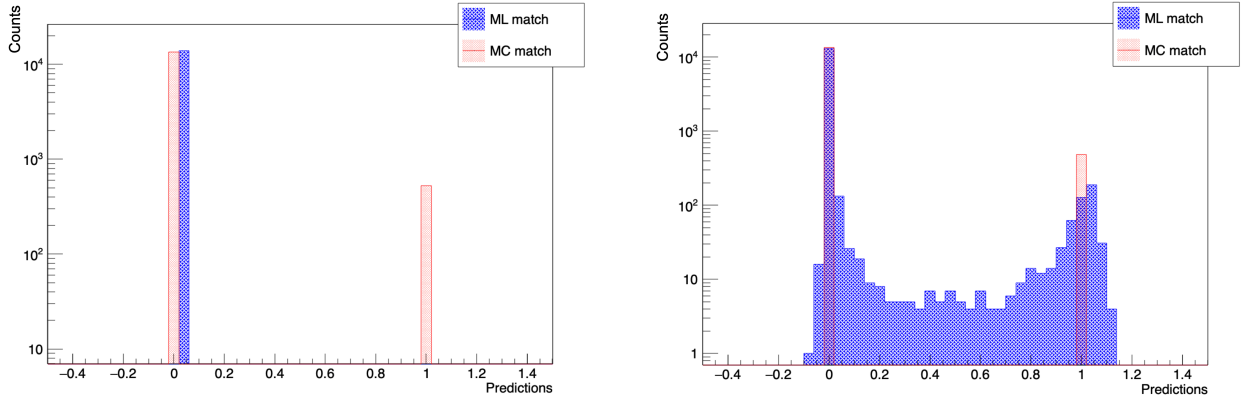


FIGURE 6.8: The learning process visualization as a function of different epochs, where the predictions ($\tilde{z}$) are displayed for both MC and ML (left) 10 epochs (right) 1600 epochs.

Finally, for the time-consumption estimations (2,7 GHz Intel Core i7 with 4 cores), 45 seconds are required for every 10 epochs with the training done on the 500 events dataset. This consumption can become demanding, as training on bigger datasets might be required, depending on the task. Thus, the reduction of this time-consumption is a crucial optimization. For the same structure and the same dataset, with a NN developed with the TensorFlow python package, 10 epochs require less than 3 seconds.

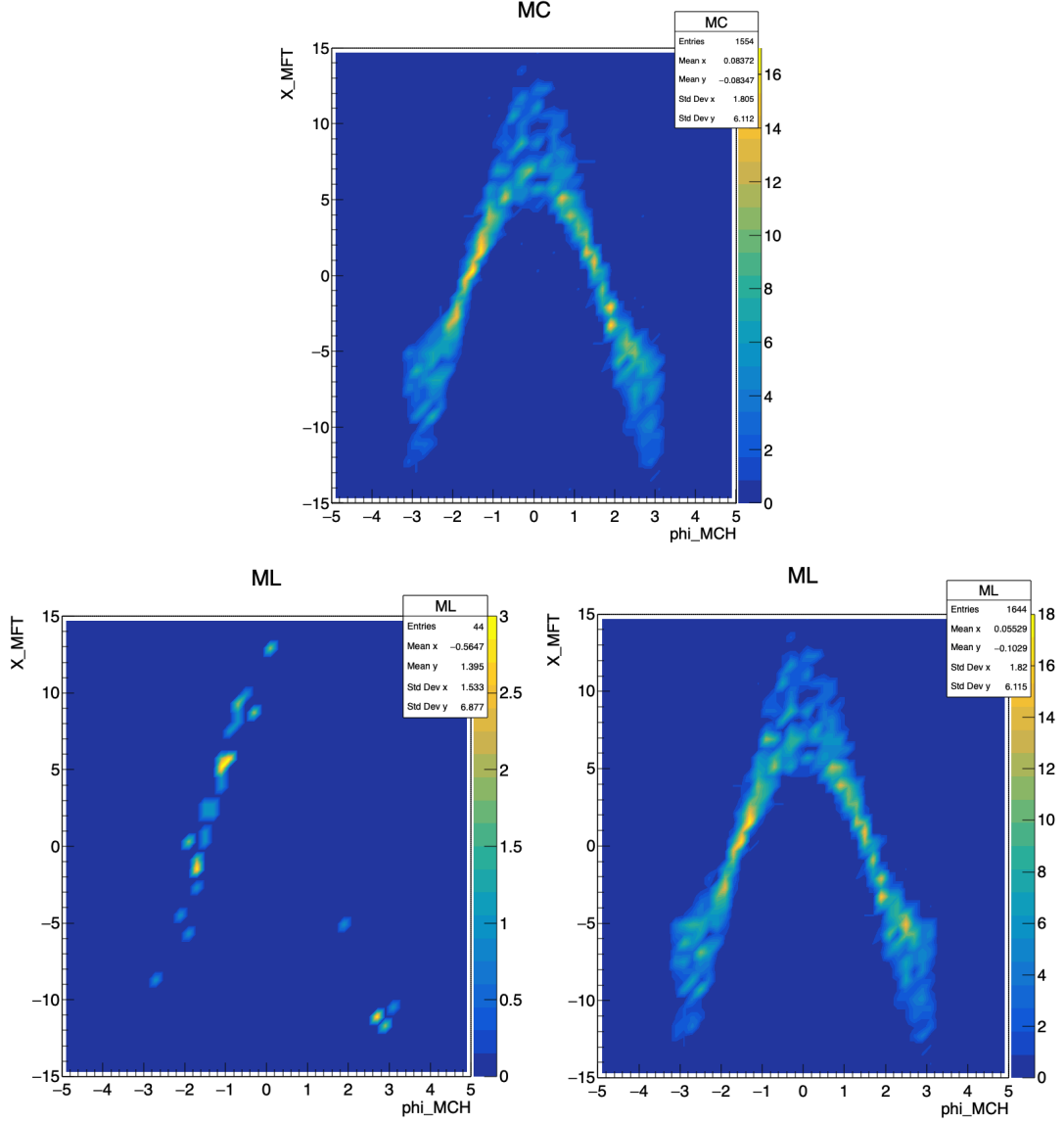


FIGURE 6.9: The MC distribution of true tracks in the (x_{MFT}, ϕ_{MCH}) plane (up). The ML distribution of the predicted global muon tracks (bottom) for ML poorly performing model (left) and for the ML best performing model (right).

6.4.2 Official framework

After the MultiLayer Perceptron preliminary tests, TensorFlow python package has been deployed for the matching classification task. First, the developed algorithm will be detailed in the following, describing the workflow of the matching with ML within the various phases. For this goal, the algorithm structure is detailed in [Figure 6.10](#). It is composed of the following workflow:

Pre-processing: The datasets are highly unbalanced, as will be further described in the following, making the learning process complicated since the signal is very small compared to the background. A data sampling method is proposed as a solution for this unbalance, where its importance and results are discussed in this section. This method consists of applying cuts mainly on the search area for MCH-MFT tracks scan, with the goal to reduce the background (fake associations) and keep the signal as intact as possible. Additionally, to further reduce the time-consumption, a dimensional reduction is proposed in order to project the data in a new reduced dimension while conserving its variance (described in section 6.6). Once these steps are done, the data is split into training and testing sub-datasets for the processing step.

Processing: The model architecture is set in YAML files. Different options are proposed to allow building model structures. After the model structure selection and **hyperparameter** tuning (detailed in section 6.1.1), the training is then performed on a dedicated training dataset. Next, a first evaluation based on the criteria explained in section 6.3.1 is done to assess the models. Then, depending on the output, an option to retrain the model is proposed. If the model has a good performance, it is extracted and saved for matching purposes. Following this, a selection of models, based on their performance, are loaded in order to be compared. Once the optimal models are identified, they are selected for the next stage, the post-processing.

Post-processing: A new dataset is used for this stage, along with the selected NN models. For each MCH-MFT pair, a matching probability score is calculated by each NN model. The highest probability score between the MCH track and the corresponding MFT candidate is extracted and considered as a match. Some additional cuts can be considered on the selection of the matches, thus after the extraction of all MCH-MFT tracks with the highest probability score. Then, to further improve the purity of the set, an additional threshold is applied on the probability, discarding all the MCH-MFT matches with a probability below the selected threshold. This threshold selection can affect both the purity and the efficiency. Following these steps, the matching performance is assessed by evaluating the different variables discussed in section 6.3.2, where the different models and methods are compared, in order to finally select the best model for the matching.

Each step of the described workflow will be detailed in the following in order to fully explain the full analysis pipeline. To start, data sampling is required to allow optimal learning. Thus, two types of data are distinguished: the non-treated and the treated data (Figure 6.11). Different methods of treating data can be applied to reduce the background and keep the signal. For this task, the treatment of data is divided into two steps. First, the tracks having

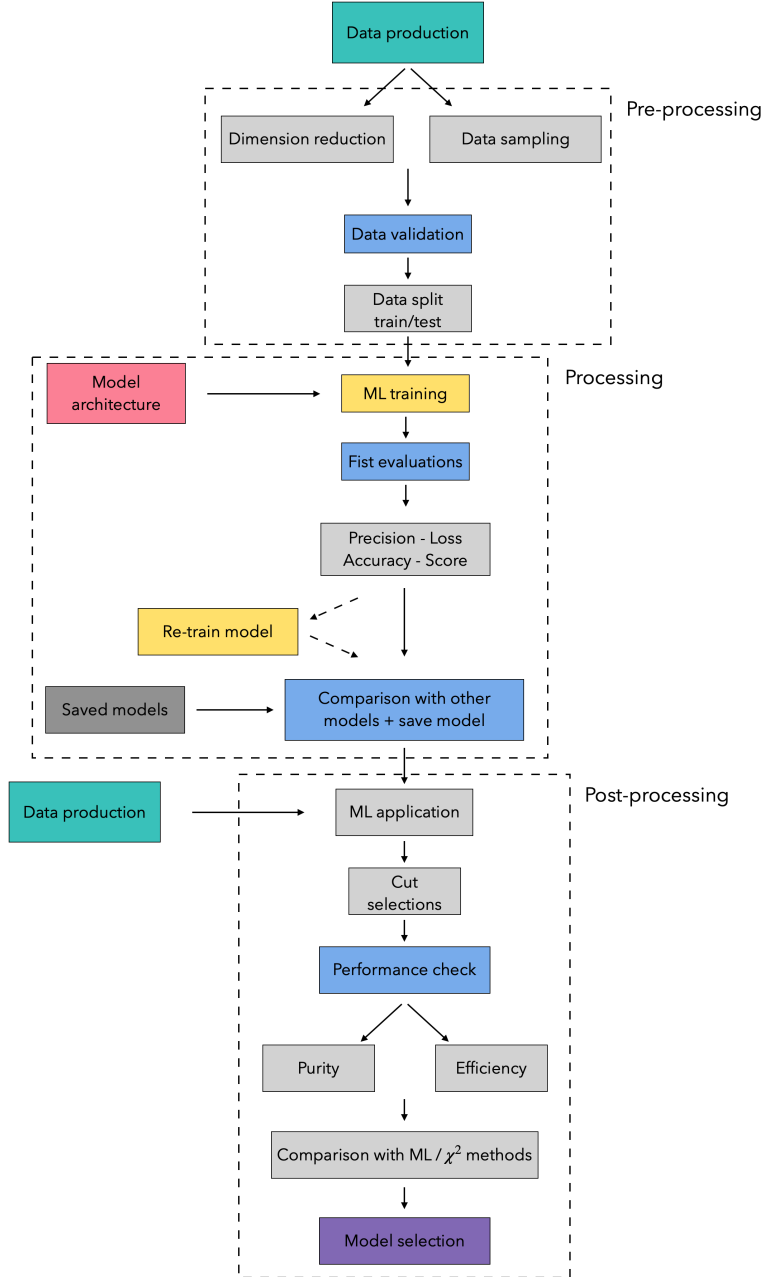


FIGURE 6.10: The matching with ML algorithm structure.

no possible association (referred to as dangling tracks) are removed. More precisely, if a MCH track (without MC match on the MFT side) is associated with a number of MFT tracks exceeding a selected threshold, the latter are removed. This type of tracks contribute to an

important contamination of the dataset without any gain for the ML training. Then, loose cuts on the χ^2 score are applied, keeping only the MCH-MFT tracks with $\chi^2 < 80$. Some margin is taken on the χ^2 to allow a training carried on the background. Following this sampling, $\frac{S}{S+B}$ goes from a value of 0.04 for the unbalanced data, to 0.18 for the treated data, losing only 1% of the signal within this process (Figure 6.11). As for the training, it's enhanced as tests were conducted for the same model structure with the 2 datasets, with and without pre-processing. At the end of this procedure, the F_{score} increases from 0.81 to 0.93, confirming the necessity of the data sampling process.

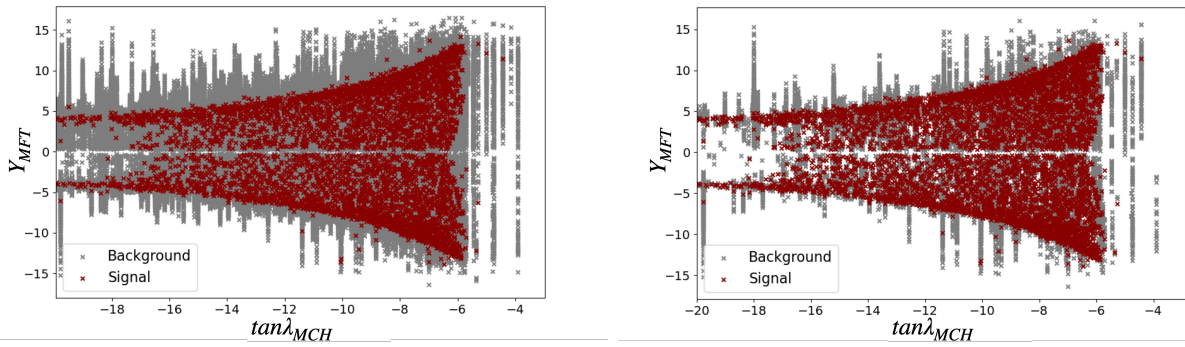


FIGURE 6.11: The distribution of the y_{MFT} as a function of $\tan \lambda_{MCH}$ for true and fake matched tracks for non-treated (left) and treated datasets (right) .

After the pre-processing, the network structure and the different hyperparameters should be selected. For this process, two different network architectures are developed: Early Fusion (EF) and Late Fusion (LF) (Figure 6.12). The first consists of the standard method used, as for the MLP, where the features are not separated and go through the same layers. The second method consists of separating features into 2 sub-model structures, then combining them on the forward level, with the goal of removing redundant information.

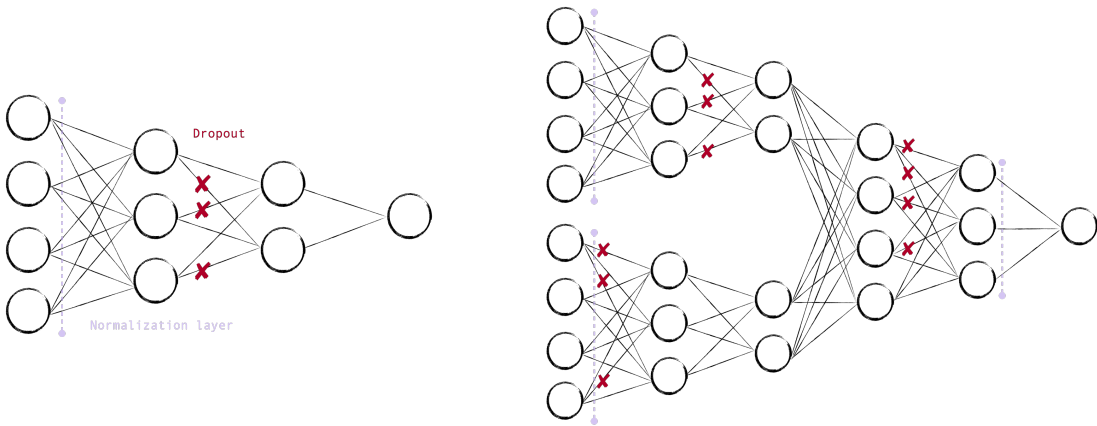


FIGURE 6.12: Early fusion vs late fusion.

For the classification task, the loss function L was calculated as described previously with the equation 6.4. The weights are updated with the Adams Optimiser [138], which consists of an adaptive learning rate method, with the following equations:

$$m^{(t)} = \beta_1 m^{(t-1)} + (1 - \beta_1) \nabla_w L^{(t)} \quad (6.18)$$

$$v^{(t)} = \beta_2 v^{(t-1)} + (1 - \beta_2) (\nabla_w L^{(t)})^2 \quad (6.19)$$

$$\hat{m}^{(t)} = \frac{m^{(t)}}{1 - \beta_1^t} \quad (6.20)$$

$$\hat{v}^{(t)} = \frac{v^{(t)}}{1 - \beta_2^t} \quad (6.21)$$

$$w^{(t+1)} = w^{(t)} - \eta \frac{\hat{m}^{(t)}}{\sqrt{\hat{v}^{(t)} + \epsilon}} \quad (6.22)$$

where η is the learning rate, t the iteration, β the exponential decay rates, and ϵ is a small number preventing any division by 0.

Different structures were tested for the assessment, with both the F_{score} on training and testing calculated to check if there's an overfitting issue. For the testing purpose, a learning rate of $\eta = 5 \times 10^{-4}$ is set, with the sigmoid activation function. The first test was concluded on the different network structures. Table 6.4 presents the F_{score} on training and testing datasets (not treated, like the MLP for comparison purpose), for the selected networks, after 100 epochs with the 11 dimension inputs (as section 6.4.1).

Hidden layers	$F_{\text{score}}^{\text{training}}$	$F_{\text{score}}^{\text{testing}}$
$30 \times 60 \times 30$	0.82	0.81
$20 \times 20 \times 20 \times 20$	0.82	0.82
$15_2 \times 60 \times 40$	0.92	0.9

TABLE 6.4: The training and testing F_{score} for different structures of hidden layers. First two lines consist of EF, and last line of LF.

The first 2 selected network structures consist of early fusion. The first is composed of 3 hidden layers, consisting of 30-60-30 neurons each. The second is composed of 4 hidden layers with 20 neurons each. The last structure is a late fusion network, where the input vector is separated into 2 sub-models, each composed of a hidden layer of 15 neurons, then combined in the same model composed of 2 hidden layers of 60 and 40 neurons. Every structure starts with an additional normalization layer, normalizing the input MCH-MFT coordinates vectors, to simplify the learning process.

As for the choice of the activation function, the sigmoid is selected following tests done with different functions, notably the tanh and the reLU functions. The tanh tests had poor performance, with F_{score} decreasing to around 0.6 when the function is integrated for both

training and testing data. The reLU activation function was also tested, as the main difference with the sigmoid function is the absence of the vanishing gradient. More precisely, the vanishing gradient occurs with the sigmoid activation function, where the learning process stagnates due to the weights update depending on the gradients of the loss function, thus the gradient of the activation functions (Equation 6.4). The derivative of the sigmoid function will saturate around 0 for large negative or positive values, thus inducing the vanishing gradient. The reLU activation function can be used to avoid this effect, which tunes the weights on each iteration with a different gradient. The loss trend of this test is presented in Figure 6.13, where clear overfitting can be observed. Additionally, the calculated F_{score} increases on the training data, but decreases greatly on the testing data. Therefore, as a conclusion, the sigmoid function allows the best training performance, and will be applied to the selected network structures.

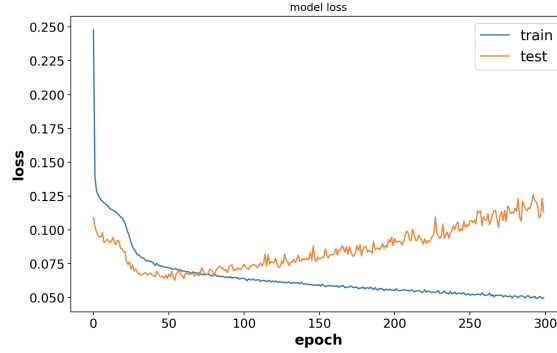


FIGURE 6.13: The loss trend following the reLU activation function.

Other hyperparameters were tuned in order to find the optimal performance, such as adding a bias neuron on selected layers. Following the same testing procedure, the performance of the selected networks was not improved with the added bias, thus no bias was added in the end. Furthermore, the batch size was set to 128 for time-consumption reduction, as the performance was not affected by this parameter. As for the learning rate, after tuning to avoid divergence and allow the optimal learning for the network with reasonable time limits $\eta = 5 \times 10^{-4}$ is selected. These effects are less severe with the used optimizer, as Adams Optimiser applies a dynamic learning rate that adapts along the training process. Finally, the number of epochs was selected following the loss and accuracy trends. Precisely, the selection is done when small fluctuations around constant loss and accuracy values is established, ensuring a stable state of the network. An example of the loss and accuracy measurements is presented in Figure 6.14 for the previously selected Late Fusion network, with 2000 epochs. The first few epochs reflect the unbalanced data, as there is a significant leap due to the huge background. Thus, the accuracy (Equation 6.7) is high even if all the correct matches are mis-predicted, since the NN will provide $\tilde{z} = 0$ (as observed in Figure 6.8 - left) before any pattern learning. The true signal extraction is learned afterwards, when the slope is smaller.

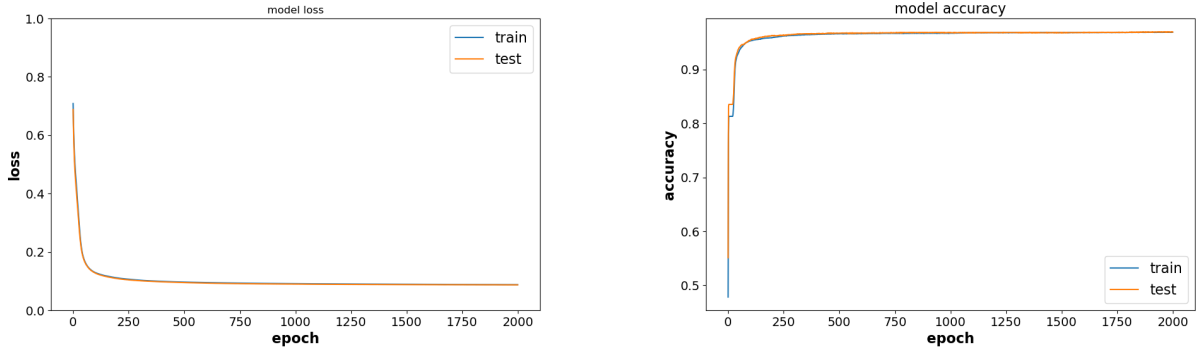


FIGURE 6.14: (left) Loss and (right) accuracy as a function of number of epochs.

Once the training process is finished for all the selected models discussed above, the first evaluations and comparisons are performed, as can be shown in Figure 6.15. The ROC curves are presented for the three models, along with the total number of incorrect and correct estimations, represented by 0 and 1, respectively. As a first conclusion, the early fusion models seem to be performing better. The complete details of the 3 selected models matching performance are presented in the next section and compared with the standard χ^2 method.

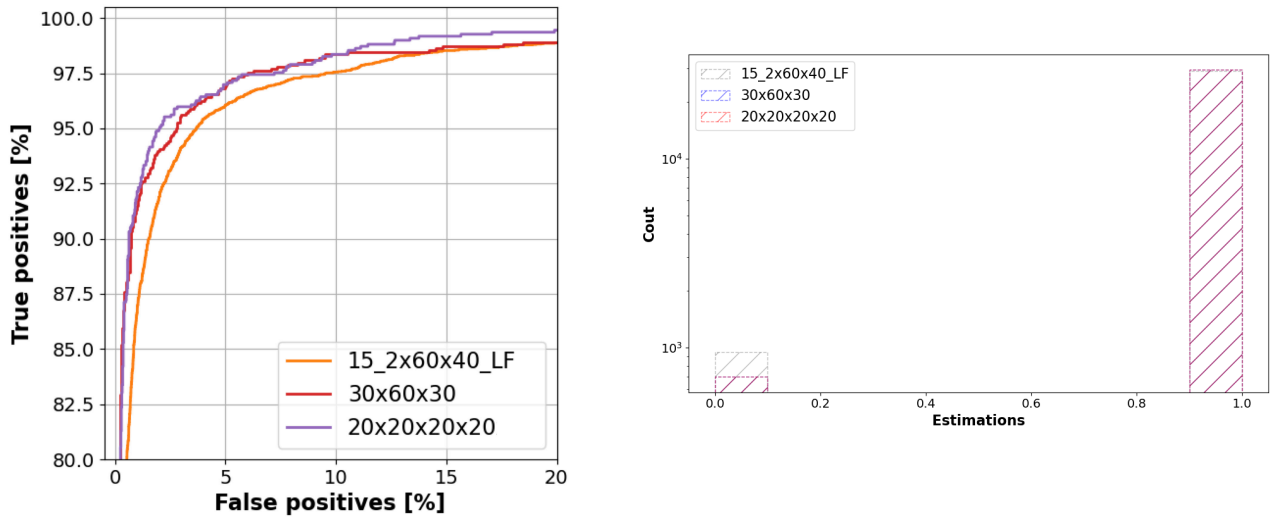


FIGURE 6.15: (left) True positive as a function of false positive percentage and (right) true and false estimations for the different selected models.

6.5 Results and performance

The purpose of this work on ML is to identify the global muon tracks, thus to extract the signal in highly unbalanced datasets, with the highest purity and efficiency possible. The pre-

processing and processing stages were discussed previously, with the models selection done in the previous section. Hence, this section is dedicated into the analysis of the matching performance for the different methods, more precisely for the 3 best NN models extracted after their first evaluations and the standard χ^2 method. First, the ratio $\frac{S}{S+B}$ is studied, as a first evaluation criteria, for the different matching methods. S is the signal (true match), and B the background (fake match). It indicates the purity of the extracted signal by directly looking at the contamination of the sample. The first column of Table 6.5 presents this ratio.

Matching method	$\frac{S}{S+B}$	$(\frac{S}{S+B})_{cut}$
χ^2	0.89	0.91
$30 \times 60 \times 30$	0.93	0.97
$20 \times 20 \times 20 \times 20$	0.95	0.97
$15_2 \times 60 \times 40$	0.90	0.96

TABLE 6.5: The $\frac{S}{S+B}$ ratio comparison for selected matching methods with and without additional applied cuts.

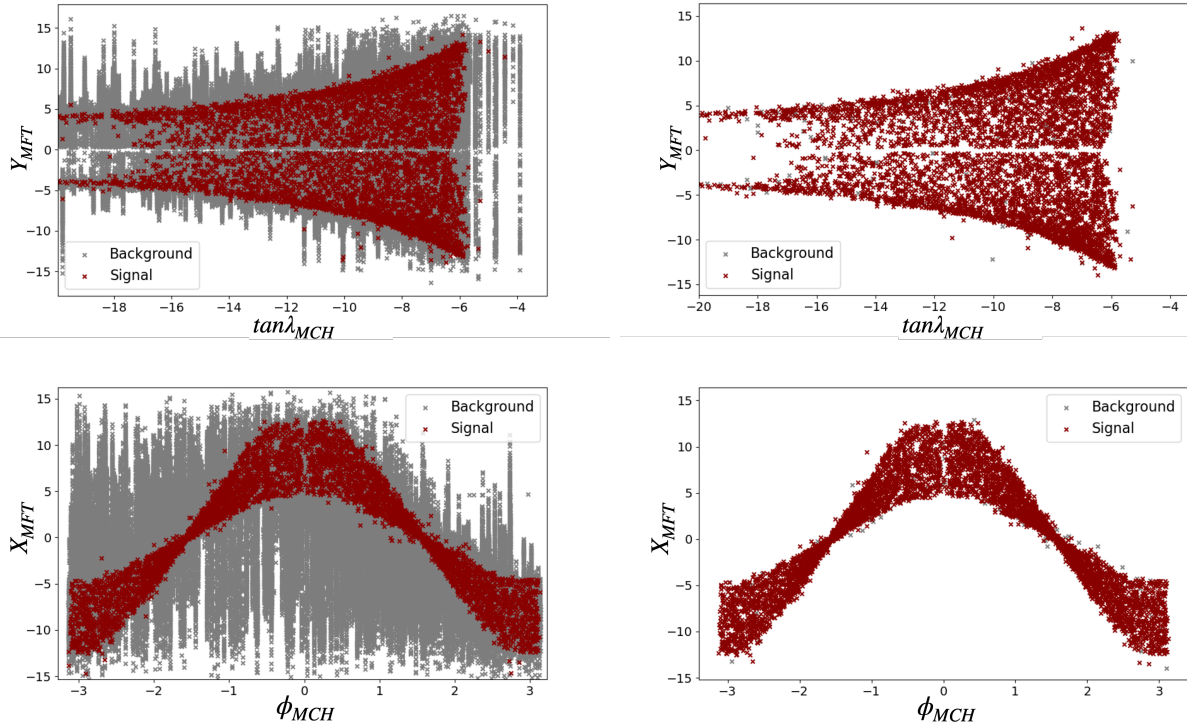


FIGURE 6.16: Different distributions for non-treated MC dataset (left) and extracted global muon tracks after ML application (model $20 \times 20 \times 20 \times 20$) (right).

In order to further enhance the matching performance, additional cuts are applied during the signal extraction process for the ML, where a threshold on the lowest accepted probability

to consider MCH-MFT tracks a match is applied. And a maximum threshold is also applied on the χ^2 in order to discard MCH-MFT tracks having a χ^2 score greater than the set threshold. With these cut applications (not too tight cuts, in order to keep a high efficiency), the ratios obtained $(\frac{S}{S+B})_{cut}$ are presented in the second column of Table 6.5.

Furthermore, Figure 6.16 illustrates the performance of ML method application on the extraction of muon tracks with the different distributions. A comparison of the signal and background is displayed for the non-treated data on the left, and on the right is presented the extraction of global muon tracks by the ML network $20 \times 20 \times 20 \times 20$, where the signal presents the correct matches predicted by the ML, and the background is the incorrect predicted matches. Thus, a high purity and efficiency of the ML method can be deduced, as the signal is conserved and the contamination of the sample is small. In the following, these variables will be further studied.

The performance of the best selected networks is compared with the χ^2 method as a function of p_T in Figure 6.17 - up. As previously explained, the matching task is expected to perform poorly at low p_T , affecting thus the low mass vector mesons measurements. This can be seen in the left panel in Figure 6.17 - up, at low p_T , where the purity is critically low, as the extracted signal is equivalent to the background. However, with the ML methods, the purity and efficiency improve greatly for low p_T measurements (the right panel of Figure 6.17 - up). Additionally, to

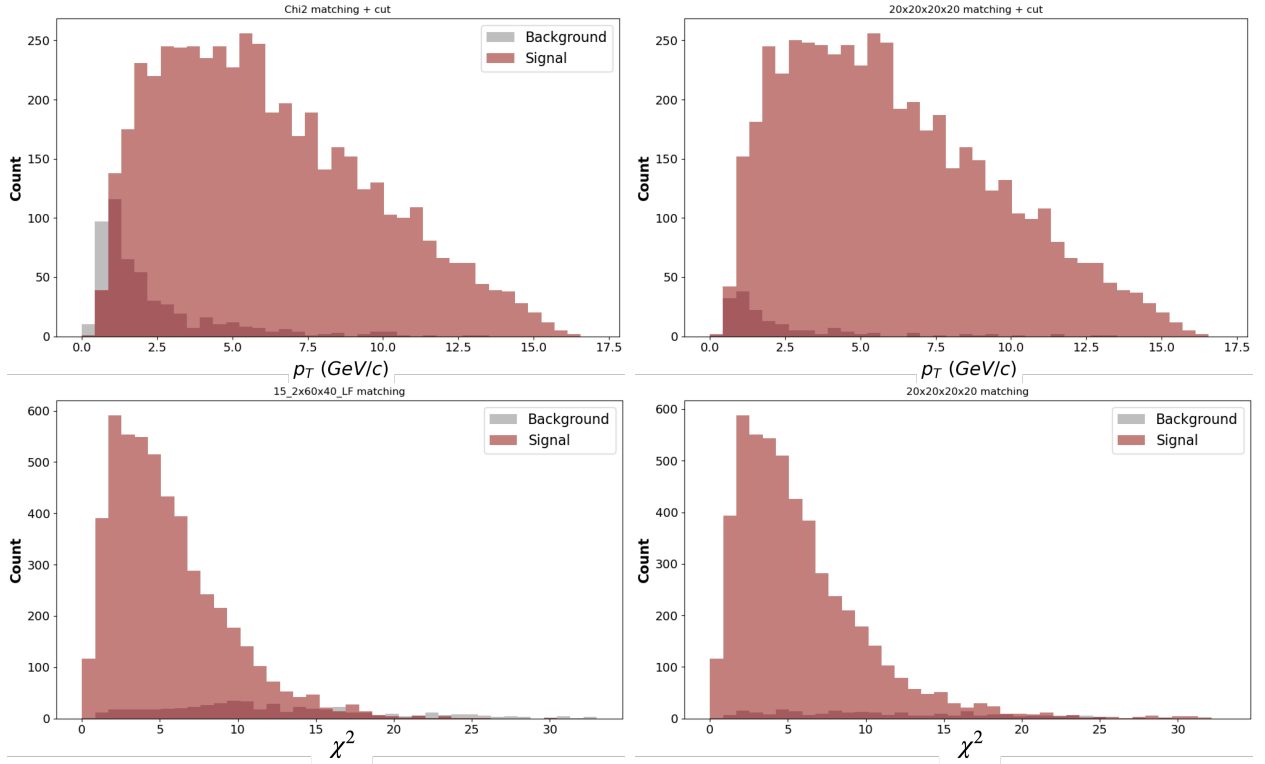


FIGURE 6.17: The extracted muon tracks with different methods as a function of p_T (up) and as a function of χ^2 (bottom).

further understand the difference within the best selected networks performance, they are also compared as a function of χ^2 in Figure 6.17 - bottom. The difference is mainly noticed on high χ^2 , where the selected model with the lowest performance (LF) predicts only the background. As opposed to the network with the optimal performance (EF) which predicts the signal at higher χ^2 . Thus, learning additional hidden links and establishing the main difference between the lowest and the best performing models.

As for the matching performance assessment, the previously discussed measurements (section 6.3.1) as the pairing efficiencies and purity, are done for the selected models and for the χ^2 method and displayed in Figure 6.18. Furthermore, their corresponding values are calculated and presented in Table 6.6 in order to fully assess the matching performance.

Matching method	$P_{pairing}^{GM}$	$\epsilon_{pairing}^{GM}$	TR	FR
χ^2	0.91	1.03	0.93	0.1
$30 \times 60 \times 30$	0.97	0.98	0.94	0.04
$20 \times 20 \times 20 \times 20$	0.97	0.97	0.94	0.03
$15_2 \times 60 \times 40$	0.96	0.98	0.94	0.04

TABLE 6.6: Purity and different efficiencies for the selected matching methods assessments.

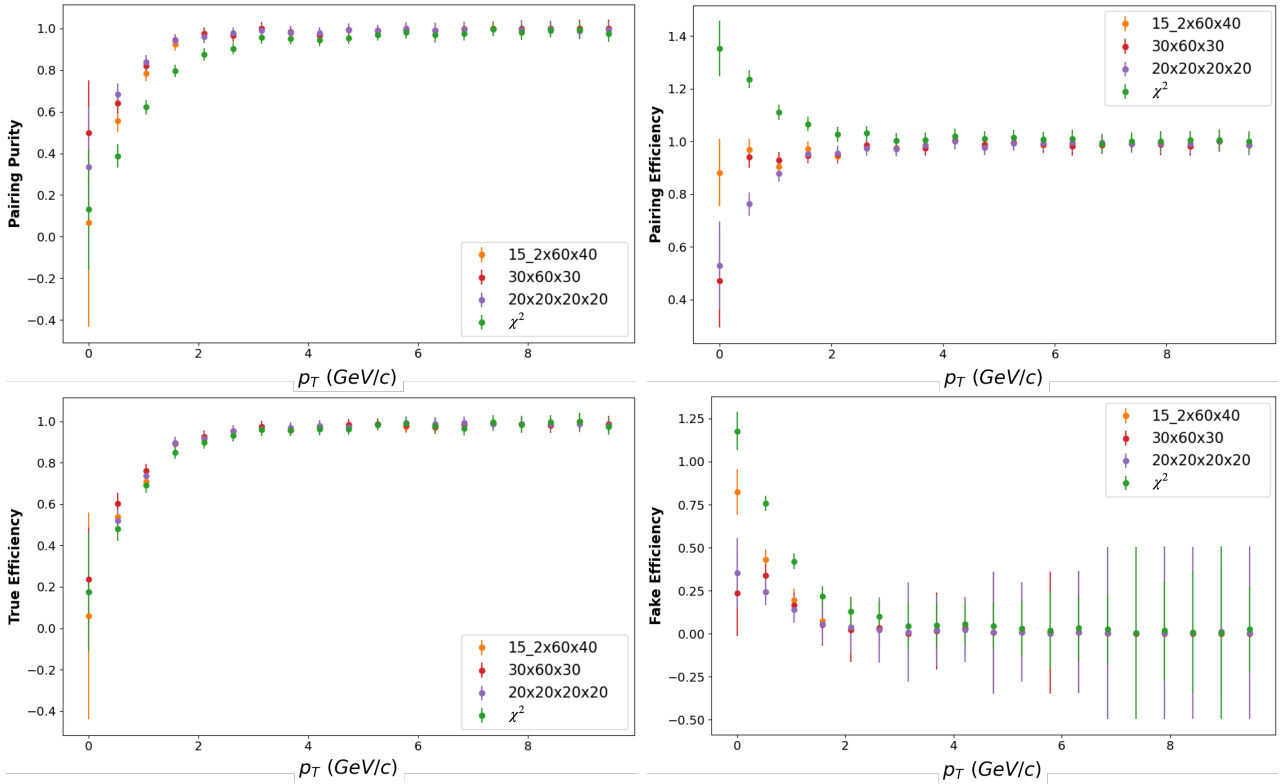


FIGURE 6.18: The performance assessment of different methods with pairing purity, pairing efficiency, true and fake efficiencies as a function of p_T .

To conclude, both selected EF models are high performing, with a very small difference for fake efficiency, lower by 0.01 for the $20 \times 20 \times 20 \times 20$.

Figure 6.19 shows the signal extraction difference between the non-treated data on the left, and the $20 \times 20 \times 20 \times 20$ model on the right, where the signal and background are presented, as a function of the χ^2 . It displays clearly the advantages of a non-rigid χ^2 cut, with disentangling of the signal from the background, while keeping a high purity of the signal and a high efficiency.

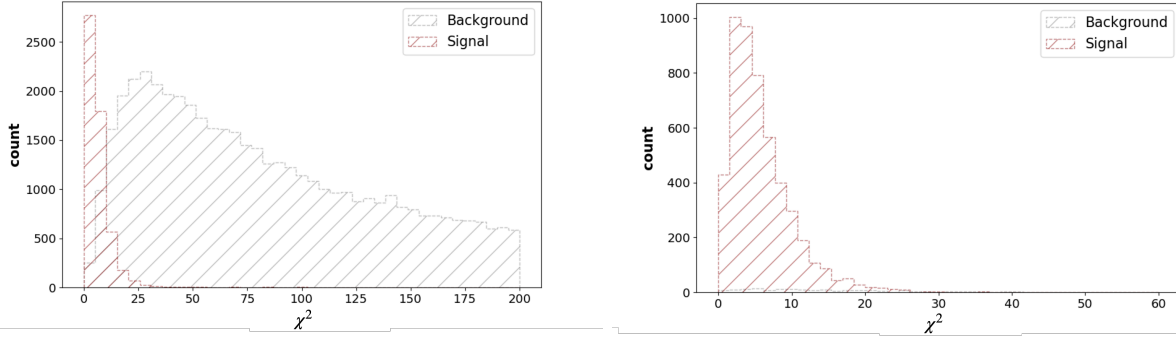


FIGURE 6.19: The distribution of predicted global muon tracks as a function of χ^2 (left) and best ML model method application (right).

6.6 Principal component analysis

As discussed in the previous section, time and resources reduction is essential, particularly when training is needed on large datasets. Thus, a possibility of dimensionality reduction is proposed with Principal Component Analysis (PCA), within the data pre-processing in the algorithm (Figure 6.10). This section is dedicated for the PCA method explanation and the demonstration of its utility. The method of dimensional reduction, such as $x \in \mathbb{R}^{n \times m} \rightarrow z \in \mathbb{R}^{k \times m}$ with $k < n$, consists of the following consecutive steps:

Input vector normalization: The input vector, $x \in \mathbb{R}^{n \times m}$, is normalized: $x_j^i \rightarrow \frac{x_j^i - \mu_j}{S_j}$, with the mean μ and the standard deviation S .

Covariance matrix calculation: The covariance matrix Σ is calculated: $\Sigma = \frac{1}{m} \sum_{i=1}^n x^i (x^i)^T$

Calculate corresponding eigenvalues and eigenvectors: Determination of the eigenvalues λ , of the covariance matrix, with $\det(\Sigma - \lambda I)$, and the eigenvectors U , as $\Sigma U_i = \lambda_i U_i$, with $U \in \mathbb{R}^{n \times n}$.

Conserving high variance: In order to reduce the dimensions, an essential variable, the variance, should be checked, in order to conserve the information, with $V = \frac{\sum_{i=1}^k \lambda_i}{\sum_{i=1}^n \lambda_i}$.

New dimension choice: For the corresponding k -dimensions choice, $U \in \mathbb{R}^{n \times k}$, with

$$U = \begin{pmatrix} \vdots & & \vdots \\ U^1 & \dots & U^k \\ \vdots & & \vdots \end{pmatrix}.$$

Projection in space with reduced dimensions: Project the x input vector, $x \in \mathbb{R}^{n \times m}$, in the space with chosen k -dimensions, such as $z = U^T x$, with $z \in \mathbb{R}^{k \times m}$.

Therefore, this PCA method can be applied on the selected dataset, in order to reduce considerably the input dimensions. For the testing purpose of this method, the MCH-MFT input tracks, with their diagonal covariance elements, composed of 21 dimensions $x \in \mathbb{R}^{21 \times m}$ (previously used with MLP, Table 6.2), is used. The dimensions of the input vector is thus reduced to 17 dimensions, $z \in \mathbb{R}^{17 \times m}$, conserving a variance of $V > 98\%$. As a result, following this PCA application, time-consumption for the training process has decreased considerably, by half to be precise. This dimensionality has been selected since it's the best balance between time reduction factor, accuracy and loss conservation (Figure 6.20), and high variance interval.

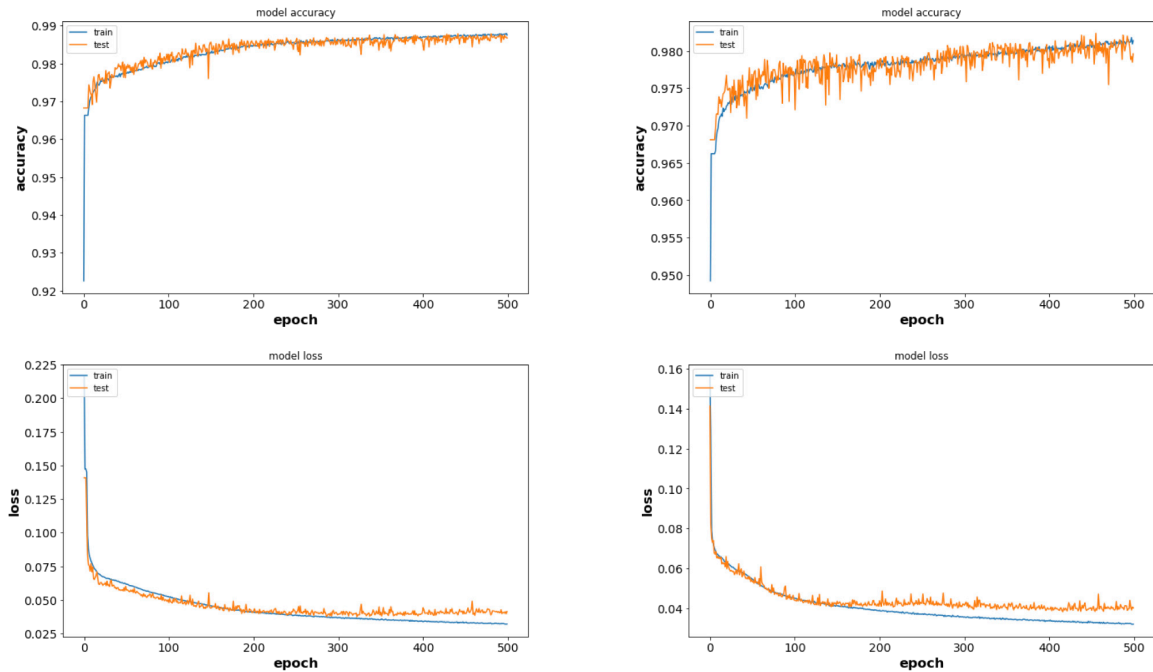


FIGURE 6.20: The trend for accuracy and loss as a function of iteration number for (left) $x \in \mathbb{R}^{21 \times m}$ and (right) $z \in \mathbb{R}^{17 \times m}$.

6.7 Machine Learning integration in O²

In order to include the matching with ML learning methods into O² environment, a specific pipeline should be integrated. The goal of this section is to provide the ability to exploit these methods fully for Run 3 data. This requires adjustments, allowing to benefit from the advantages of the different environments.

In order to integrate the ML on python to the O² C++ environment, ONNXRuntime [139] is used in order to convert a ML model from python format to ONNX format, thus allowing its deployment in a C++ environment. The full workflow architecture is described in the Figure 6.21, where the previous algorithm (Figure 6.10) is adapted and made more general, to allow other ML methods applications. It consists of the following 3 main categories:

Training data production: the production is done in O², where simulations are tuned depending on the matching requirements. Once the simulations are done, the MCH-MFT tracks combinations within a search area on a matching plane are extracted, for the next step process.

Training and model selection: in the python environment, the parameters are extracted, where preliminary checks are done in order to judge the necessity of data pre-processing, such as dimensional reduction and data sampling. Then, the ML training takes place, where different methods are proposed, leading to a model which is saved in a ONNX format, in order to be able to use it within O². Following this, still on python, first model evaluations take place, which were discussed previously.

Matching on runtime simulations: on the O² environment side, realistic MC production is launched. Then, when the matching is taking place to find the global muon tracks, the selected method is used to calculate the MCH-MFT track matching probability, thus, producing the global muon tracks. After this step, the final performance evaluations are done in order to assess the used methods and calculate the expected signal extraction, purity, efficiency, and different variables as discussed previously.

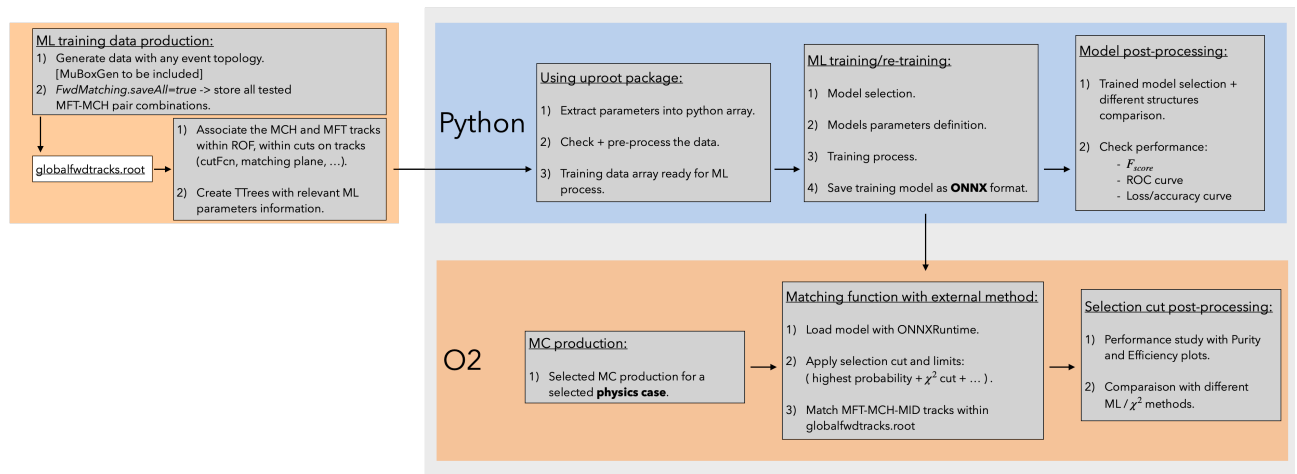


FIGURE 6.21: The workflow for matching with different methods in O².

6.8 Conclusion

High performance of the matching between MCH and MFT tracks is essential for Run 3 analysis, as it impacts the quality of global muon tracks that will be used. The standard algorithm deployed to find the global tracks is based on a χ^2 criteria between MCH and MFT tracks. In high multiplicity environments, a more refined tool is required for a high performance matching. Therefore, this chapter consists of the second part of this thesis, addressing the matching task with machine learning. A full workflow was then designed with TensorFlow, allowing to train, test and assess the matching performance. As a result, promising performance for matching with ML was observed. It allows to recover high matching efficiency and purity, in comparison to the standard χ^2 method, especially at low p_T , thus required for low-mass dimuons physics. Finally, to further improve the performances of the learning process, a Principal Component Analysis method was developed to reduce resource consumption while keeping the same matching performances. This work will improve the results of physics analysis and especially the study of prompt and non-prompt J/ψ .

Chapter 7

Vertex reconstruction

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As mentioned in chapter 4, prompt and non-prompt charmonia disentanglement was not possible before Run 3 at forward rapidities. As a matter of fact, the main reason is that the muon multiple scattering and energy loss in the front absorber lead to a worsening of the muon spectrometer resolution. One of the main goal of the MFT detector is to work around this issue. Indeed, as discussed in chapter 5, high quality global muon track are required, which means high matching performance between the reconstructed muon spectrometer and MFT tracks. For the separation of prompt and non-prompt contributions, in addition to the matching, vertexing is also required. It will be thoroughly discussed in this chapter, where the development of the algebra, algorithm and first preliminary tests are presented.

7.1 Physics case review

As discussed in chapter 2, the non-prompt J/ψ production is an essential measurement to study beauty physics. The open-beauty production can be studied with measurements of the non-prompt J/ψ cross-section [111]. The distance between the Primary Vertex (PV), corresponding to the Interaction Point (IP), and the Secondary Vertex (SV), corresponding to the decay point of the B-hadron, is measured to access the non-prompt J/ψ . This distance, illustrated in Figure 7.1, corresponds to the order $c\tau \approx 500 \mu\text{m}$, with τ the pseudo-proper time. The pseudo-proper time in the laboratory's reference system, taking into account the Lorentz boost corresponds to $\gamma\tau$, with the Lorentz factor $\gamma = \frac{E}{m}$. Therefore, the measured distance travelled before the decay of a particle corresponds to $\beta c\gamma\tau$, with $\beta = \frac{v}{c}$. As $\gamma = \frac{E}{m} = \frac{m_T}{m} \cosh(y) > \cosh(y)$, at forward rapidities (with $2.5 < |y| < 3.6$), the result is $\gamma > 6.1$ and $\gamma > 18.3$. In the studied ultra-relativistic collisions, as $\beta \approx 1$, the measured distance at $|y| > 2.5$ corresponds to $\beta c\gamma\tau > 3.05 \text{ mm}$.

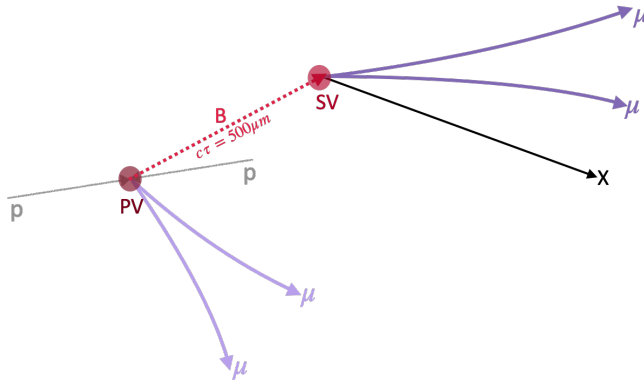


FIGURE 7.1: A schematic presentation for the prompt and non-prompt J/ψ production.

In order to separate the prompt and non-prompt J/ψ contributions, a statistical separation following the pseudo-proper time t distribution is essential, as explained in the following. The t equation is given by:

$$t = \frac{|\vec{L}| M_{J/\psi}}{p} = \frac{|\vec{L}|}{\beta\gamma c} \quad (7.1)$$

with p the momentum, $M_{J/\psi}$ the invariant mass, and $\vec{L}$ the longitudinal decay length, such as:

$$\vec{L} = \vec{r}_{PV} - \vec{r}_{SV} \quad (7.2)$$

A projection of the transverse or the longitudinal components of the pseudo-proper time is studied, for a better separation of prompt and non-prompt J/ψ . The longitudinal pseudo-

proper time is presented as:

$$t_z = \frac{L_z M_{J/\psi}}{p_z} = \frac{(z_{PV} - z_{SV}) M_{J/\psi}}{p_z} \quad (7.3)$$

As for the equation of the transverse pseudo-proper time:

$$t_{xy} = \frac{\sqrt{(x_{PV} - x_{SV})^2 + (y_{PV} - y_{SV})^2} M_{J/\psi}}{p_T} \quad (7.4)$$

At forward rapidities, the Lorentz boost effect acts mainly on the z-direction, thus the longitudinal pseudo-proper time t_z is the most discriminating variable to select non-prompt decays. The distribution of t_z displayed in Figure 7.2, is produced with HIJING [116] simulations. The figure is extracted from the MFT technical design report, published in 2015 [111]. The total t_z distribution is composed of three components: the prompt and non-prompt J/ ψ signal, and the background. The fit templates for the t_z distribution were estimated with MC simulations using a variable-width Gaussian parameterization. Since all muon pairs are considered, the background is essentially composed of the muons coming from pions and kaons decays. The normalization of the background was fixed following the fit done on the invariant mass spectrum. The distribution of the prompt J/ ψ , it is peaked around 0 with a width constrained by the experimental resolution. The non-prompt J/ ψ distribution corresponds to a positive tail since the decay happens at $L_z > 0$, displaying the b-hadron decay times. The asymmetry observed for the background distribution results from a fraction of the muons composing the combinatorial pairs produced at close distances from the IP.

The aim is to update these results with the latest developments on tracking and matching, with the final goal of preparing the tools for Run 3 data analysis.

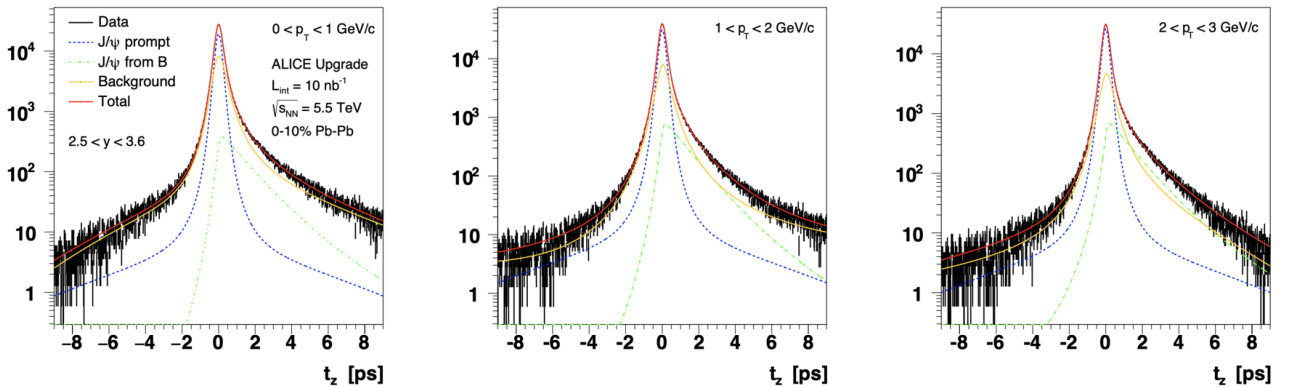


FIGURE 7.2: The t_z distribution for Pb-Pb collisions at 5.5 TeV with different prompt and non-prompt J/ ψ distributions [111].

7.2 Vertex reconstruction algorithm

The secondary vertex corresponds to the decay point of the B-hadron. As the time of flight of the J/ψ is negligible (with a lifetime of around 7.2×10^{-21} s), the secondary vertex is experimentally determined by the point of crossing of the two muons coming from the J/ψ decay. This is the purpose of the algorithm developed and described in this chapter. The point of crossing of the two muons, or the point where the distance between the two muons is minimal, is referred as by the Point of Closest Approach (PCA) (Figure 7.3). Given the resolution of the detectors, two muons that originate from the decay of the same J/ψ have a PCA compatible with zero.

In order to understand the vertexing algorithm and its functioning, its operational aspect is presented, and the corresponding algebra are established in the forward rapidity region. The goal is to find the PCA between a given number of muon tracks (μ_1 and μ_2 , as displayed in Figure 7.3). Thus, the coordinates of the secondary vertex corresponds to the displaced vertex $\vec{V} = \{V_x, V_y, V_z\}$ of the extrapolated global muon tracks with the minimum residual distance between the tracks. The PCA will be determined following a χ^2 minimization method, as will be detailed in the section 7.3.

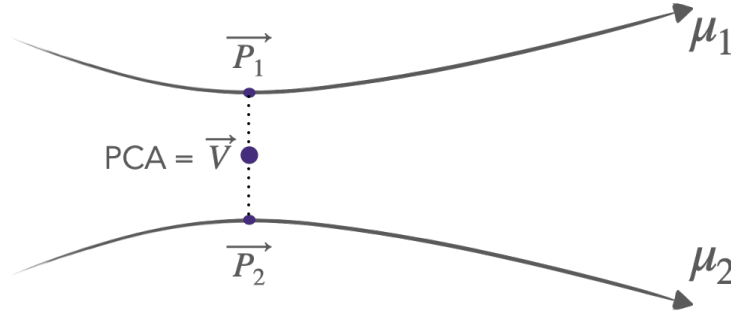


FIGURE 7.3: A schematic presentation of the point of closest approach between muon tracks.

7.2.1 Overview

In this section, the operational side of the PCA finding algorithm is described. A global overview is presented in Figure 7.4. First, the algorithm takes n tracks as input, each track having the same number of parameters (section 4.3). Then, a first check is performed based on analytical hypothesis, derived from central barrel tools (referred to as FwdTrackHelper¹ in the following), on the number of crossing points for the input tracks. If a crossing point is found on the plane (x,y), a check of the crossing is performed on the (y,z) plane. This procedure is named a condition check. If the conditions are not verified, the crossing point is discarded. A starting

¹An analytical tool designed to find a first estimation of the PCA based on the curvature of the tracks.

seed is then defined with a seed finder method. Its goal is to minimize the distance between the input tracks on the (x,y) plane. Then, using an iterative method, the best possible vertex position is determined by the mean of a 3D χ^2 minimization, by using the Newton-Raphson minimization. The convergence status is reached when the propagation on the z-axis becomes smaller than a determined value, or when the relative change between the last two calculated χ^2 score is smaller than a determined percentage. A maximum number of iterations is allowed to find this convergence status, to avoid infinite loops. Finally, the calculated χ^2 score is extracted for each crossing point. The higher the probability of these tracks crossing, the lower the χ^2 score. In the next section, this iterative χ^2 minimization method will be detailed.

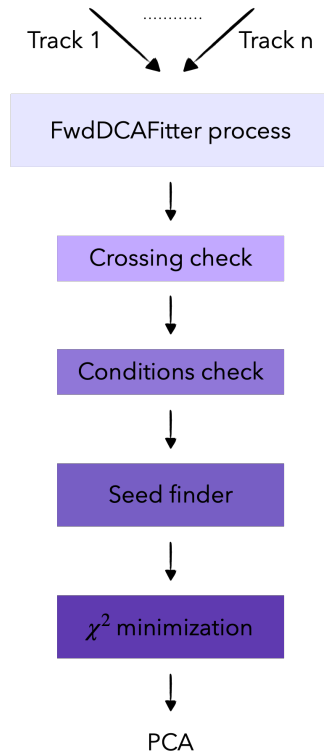


FIGURE 7.4: Algorithmic overview for the PCA finder in forward rapidities.

7.2.2 Vertex definition

Each global muon track is associated with a set of local points $\{\vec{P}_i\}$, such as $\vec{P}_i = (x_i, y_i, z_i)$. The corresponding covariance matrix is given by:

$$E_i = \begin{pmatrix} \text{cov}(x,x) & \text{cov}(x,y) & 0 \\ \text{cov}(x,y) & \text{cov}(y,y) & 0 \\ 0 & 0 & \text{cov}(z,z) \end{pmatrix} = \begin{pmatrix} \delta_{xx} & \delta_{xy} & 0 \\ \delta_{xy} & \delta_{yy} & 0 \\ 0 & 0 & \delta_{zz} \end{pmatrix}^{-1} \quad (7.5)$$

The inverse matrix is calculated to introduce the δ factors, as they are convenient for the following calculations.

A crucial difference between the mid and forward rapidity equations concerns the transformation from the local to the laboratory frame. At midrapidity, it consists of a rotation with the following transformation matrix:

$$M_i = \begin{pmatrix} \cos\alpha_i & -\sin\alpha_i & 0 \\ \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (7.6)$$

with α_i the rotation angle between the local track frame and the laboratory frame. As for the forward rapidity region, no transformation from local to laboratory frame is needed, as it consists of the same frame, $\alpha = 0$, thus the transformation matrix is unitary:

$$M_i = I = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (7.7)$$

The vertex of a set of muon tracks (illustrated in [Figure 7.3](#)), with corresponding local points $\{\vec{P}_i\}$, consists of a linear combination of $\vec{P}_i$ such as:

$$\vec{V} = \sum_i T_i \cdot \vec{P}_i, \quad \text{where } \vec{V} = \{V_x, V_y, V_z\} \text{ is in the laboratory frame} \quad (7.8)$$

With $\vec{\Delta}_i$ presenting the local residuals, defined as following:

$$\vec{\Delta}_i = \vec{P}_i - M_i^T \vec{V} = \vec{P}_i - \vec{V} \quad (7.9)$$

Thus, $\vec{V}$ is considered as the barycenter between the P_i , with their respective weights, calculated as:

$$\vec{V} = \sum_j (E_j)^{-1} \sum_i E_i \cdot \vec{P}_i = \sum_i T_i \cdot \vec{P}_i \quad (7.10)$$

Finally, T_i can be presented by:

$$T_i = \sum_j (E_j)^{-1} E_i \quad (7.11)$$

7.3 χ^2 minimization by Newton-Raphson

As mentioned above, the PCA corresponds to the point with the minimum χ^2 score. The χ^2 is given with the following equation:

$$\chi^2 = \frac{1}{2} \sum_i \vec{\Delta}_i^T \cdot E_i \cdot \vec{\Delta}_i \quad (7.12)$$

The iterative Newton-Raphson method for the χ^2 minimization is used in both mid and forward rapidity regions. At each iteration, tracks are propagated in the direction that minimizes the χ^2 . Thus, to reach the point where its first derivative is zero, and its second derivative is positive. The iterations of the tracks propagation function is based on a Taylor expansion, with the following correction $\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1}$ applied between each iteration. According to the Newton-Raphson minimization, the track point evolution follows:

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} x_1 - \frac{\partial x_1}{\partial z} \left(\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1} \right) - \frac{1}{2} \frac{\partial^2 x_1}{\partial z^2} \left(\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1} \right)^2 \\ y_1 - \frac{\partial y_1}{\partial z} \left(\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1} \right) - \frac{1}{2} \frac{\partial^2 y_1}{\partial z^2} \left(\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1} \right)^2 \\ z_1 - \frac{\partial z_1}{\partial z} \left(\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1} \right) - \frac{1}{2} \frac{\partial^2 z_1}{\partial z^2} \left(\frac{d\chi^2}{dz} \left(\frac{d^2\chi^2}{dz^2} \right)^{-1} \right)^2 \end{pmatrix} \quad (7.13)$$

More precisely, each iteration consists of the following calculations:

- the updated (x, y, z) coordinates for each track,
- the new coordinates of the PCA $\vec{V}$,
- the tracks residuals $\vec{\Delta}_i$,
- the updated χ^2 following these new coordinates with Newton-Raphson.

These iterations take place until the convergence of the χ^2 . The vertex for the tracks is found and extracted, as well as the χ^2 score. This score will consist also as an assessment metric for the PCA. As mentioned, the smaller the χ^2 value, the higher the probability of the presence of a crossing point between given tracks. Thus, cuts on this χ^2 score might be applied to consider or discard the PCA as a secondary vertex. This will be further detailed in the next chapter, where data quality assessment is done with cuts applied on χ_{PCA}^2 on official simulations.

As observed in the presented equations (Equation 7.13), the track derivatives are required

for the iterative minimization. Their first and second order derivatives are the following:

$$\frac{\partial(x, y, z)}{\partial z} = \left(\frac{\cos\phi}{\tan\lambda}, \frac{\sin\phi}{\tan\lambda}, 1 \right) \quad (7.14)$$

$$\frac{\partial^2(x, y, z)}{\partial z^2} = \left(\frac{\rho \cdot \sin\phi}{\tan^2\lambda}, -\frac{\rho \cdot \cos\phi}{\tan^2\lambda}, 0 \right) \quad (7.15)$$

with the track curvature² $\rho = \frac{1}{r} = \frac{0.3qB_z}{p_T}$, with B_z the magnetic field on the z-axis, q is the charge of the particle (in the unit of the elementary charge, e), and r is the radius (in meter).

In addition, the first and the second order z derivatives of χ^2 are also required for the minimization. Thus, the corresponding equations are the following:

$$\frac{\partial\chi^2}{\partial z} = \sum_i \vec{\Delta}_i^T \cdot E_i \cdot \frac{\partial\vec{\Delta}_i}{\partial z} \quad (7.16)$$

$$\frac{\partial^2\chi^2}{\partial z^2} = \sum_i \left(\frac{\partial\vec{\Delta}_i^T}{\partial z} \cdot E_i \cdot \frac{\partial\vec{\Delta}_i}{\partial z} + \vec{\Delta}_i^T \cdot E_i \cdot \frac{\partial^2\vec{\Delta}_i}{\partial z^2} \right) \quad (7.17)$$

$$\text{with } \frac{\partial\vec{\Delta}_i}{\partial z} = \sum_k (\delta_{ik} - T_k) \cdot \frac{\partial\vec{P}_k}{\partial z} \text{ and } \frac{\partial^2\vec{\Delta}_i}{\partial z^2} = \sum_k (\delta_{ik} - T_k) \cdot \frac{\partial^2\vec{P}_k}{\partial z^2} \quad (7.18)$$

where k refers to the total number of input tracks.

Particular case of PCA calculation

If no weights are taken into consideration for the tracks, the covariance matrix corresponds to a unitary matrix. In the following, the presented equations necessary for the PCA finding are adapted for this particular case, which is currently used in O² at both mid and forward rapidities. The $\vec{V}$ and the local residuals become:

$$\begin{aligned} \vec{V} &= \sum_i T_i \cdot \vec{P}_i = \frac{1}{N} \sum_i \vec{P}_i \quad \text{with } T_i = \frac{1}{N} I \\ \vec{\Delta}_i &= \sum_k (\delta_{ik} - R_{ik}) \vec{P}_k, \quad \text{with } R_{ik} = \frac{I_i^T I_k}{N} = \frac{1}{N} I \end{aligned} \quad (7.19)$$

Then, for the minimization of the χ^2 , the following equations can be obtained:

$$\begin{aligned} \frac{\partial\chi^2}{\partial z} &= \sum_i \vec{\Delta}_i^T \frac{\partial\vec{\Delta}_i}{\partial z} \\ \frac{\partial^2\chi^2}{\partial z^2} &= \sum_i \left(\frac{\partial\vec{\Delta}_i^T}{\partial z} \frac{\partial\vec{\Delta}_i}{\partial z} + \vec{\Delta}_i^T \frac{\partial^2\vec{\Delta}_i}{\partial z^2} \right) \end{aligned} \quad (7.20)$$

²In the curvature formula, p_T is expressed in GeV/c.

Where the derivatives of the residuals are expressed as follow:

$$\begin{aligned}\frac{\partial \vec{\Delta}_i}{\partial z} &= \sum_k (\delta_{ik} - R_{ik}) \frac{\partial \vec{P}_k}{\partial z} \\ \frac{\partial^2 \vec{\Delta}_i}{\partial z^2} &= \sum_k (\delta_{ik} - R_{ik}) \frac{\partial^2 \vec{P}_k}{\partial z^2}\end{aligned}\tag{7.21}$$

Finally, for $k = j$ with $R_{ij} = \frac{1}{N}I$, the residual derivatives can be calculated with the following terms:

$$R_{ij} \cdot \frac{\partial P_j}{\partial z} = \frac{1}{N} \begin{pmatrix} \frac{\partial x_j}{\partial z} \\ \frac{\partial y_j}{\partial z} \\ 1 \end{pmatrix}\tag{7.22}$$

$$R_{ij} \cdot \frac{\partial^2 P_j}{\partial z^2} = \frac{1}{N} \begin{pmatrix} \frac{\partial^2 x_j}{\partial z^2} \\ \frac{\partial^2 y_j}{\partial z^2} \\ 0 \end{pmatrix}\tag{7.23}$$

The 3D minimization method presented is the only method used at midrapidity for the PCA finding, where track types are described by helix models due to the magnetic field. However, muon tracks at forward rapidities are not as affected by the magnetic field as at midrapidity. Thus, the quadratic and linear track models allow an accurate description of their trajectories. If the Newton-Raphson method is applied to the tracks at a point far from the PCA, difficulties may be encountered that limit the performance of the method. In particular, depending on the nature of the tracks (helix vs linear), the minimization algorithm may face difficulties to convergence because of either a large number of iterations required to reach the PCA, or null first order derivatives of the tracks. This will be demonstrated in the next section. At forward rapidities, seed finder methods have been developed to constrain this decrease of performance by providing a starting seed close to the PCA during the 3D minimization. The way the seed is calculated is detailed in the following section.

7.4 Seed finder methods

The seed finder is essential for the PCA finding and for the reduction of time and computing resource consumption. It provides an initial seed close to the PCA for the iterative Newton-Raphson minimization process. Several methods are developed for this seed initialization.

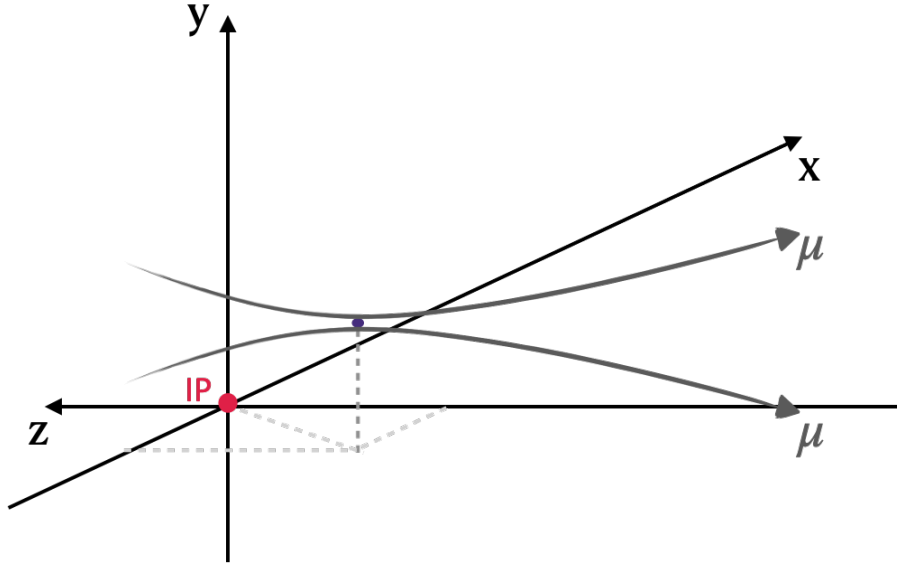


FIGURE 7.5: A 3D scheme of two crossing muon tracks.

Simple iterative method:

For the first developed method, the algorithm starts at the first MFT disk, with the global muon tracks propagated to this plane with $T_0(X_0, Y_0, Z_0 = -46.5)$ and $T_1(X_1, Y_1, Z_1 = -46.5)$. For both tracks, a first analytical estimation of x and y coordinates is provided by the FwdTrackHelper tool at the crossing point ($X_{0/1, PCA}$ and $Y_{0/1, PCA}$) is provided, such as $T_0(X_{0, PCA}, Y_{0, PCA}, Z_0)$ and $T_1(X_{1, PCA}, Y_{1, PCA}, Z_1)$. The goal is to find the corresponding $Z_{0/1}$. A defined step size is provided (by default around 0.001 cm). An iterative scan takes place afterwards, propagating the tracks quadratically from the first disk towards the estimated PCA. Each iteration on the z -axis corresponds to the size of the defined step, and the corresponding X and Y are retrieved from the global tracks fit. For each step, the distance between the new retrieved X, Y and the estimated X_{PCA}, Y_{PCA} is calculated for each track, with $d_{XY} = \Delta X^2 + \Delta Y^2$. The distance at the 3 last iterations is stored. When the following condition applies for the corresponding track: $d_{XY}[2] > d_{XY}[1]$ & $d_{XY}[1] < d_{XY}[0]$, the $Z_{0/1}$ coordinate of the $d_{XY}[1]$ is then extracted. Finally, when the Z coordinate is found for both tracks, the seed Z position can be calculated such as $Z = \frac{Z_0 + Z_1}{2}$.

Dichotomy:

This method deviates from the first by following a dichotomy approach. It consists firstly of setting 2 planes, for two different z -coordinates on each side of the estimated secondary vertex, then proceeds to calculate the distance between two global muon tracks T_0 and T_1 on (x, y) plane with $d_{XY} = \Delta X^2 + \Delta Y^2$ for the 2 selected positions following quadratic propagation

of tracks. The distance value is then compared, and the plane with the largest distance d_{XY} between the tracks will be translated to a plane with a new z -coordinate, corresponding to the middle distance between both planes, thus to $z_2 = \frac{z_0 + z_1}{2}$, where z_0 and z_1 correspond to the z -coordinate of the (x,y) planes before any operations. Therefore, with each iteration, the distance between the 2 planes Δz is reduced, converging to the z where the tracks have the smallest d_{XY} . The Δz is checked after each iteration, until the condition $\Delta z < \epsilon$ applies, with a predefined ϵ , and thus the seed is extracted with $Z = \frac{z_{i-1} + z_i}{2}$. This method is optimized on the time and computing resources consumption, as the number of iterations needed in comparison to the first method is smaller in average. An example of 3 consecutive steps for this dichotomy method are presented in Figure 7.6.

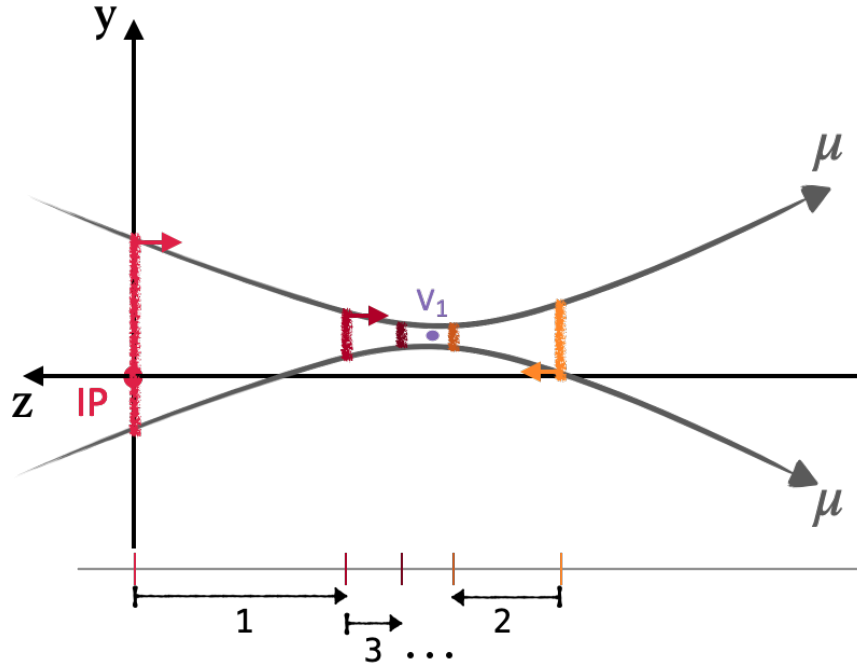


FIGURE 7.6: A schematic representation of the different consecutive steps of the dichotomy method.

Linear approximation:

A linear approximation for the tracks path is proposed as a seed finder method. This method is detailed in the following for tracks T_0 and T_1 . To find the z corresponding to their first seed, two steps are considered. First, the calculation of 2 z -coordinates is done, on (y,z) and the (x,z) planes respectively. The equation in the (y,z) plane for the T_0 and T_1 tracks correspond respectively to $y(T_0) = a_0 \times z(T_0) + b_0$ and $y(T_1) = a_1 \times z(T_1) + b_1$. In order to find the $a_{0,1}$, and $b_{0,1}$, each track is propagated on the z -axis to 2 different defined planes.

Then, the z -coordinate is calculated from the equations with $y(T_0) = y(T_1)$ and $z(T_0) = z(T_1)$ conditions. Thus this leads to the following equation: $Z = \frac{b_0 - b_1}{a_0 - a_1}$. The same steps are also done on the (x, z) plane. Finally, the average of these 2 calculated z -coordinates corresponds to the extracted seed z .

Analytical approach:

In order to be more accurate, the curvature of the tracks are taken into account with the following developed analytical method. The principle of this method consists of solving the track propagation equations analytically for each track in order to find the Z seed at the PCA ($z_{T_0} \approx z_{T_1}$). With the p_T at the order of 1 GeV/c and the magnetic field of 0.5 T, the curvature radius is at the order of 6 m. In the case of the MFT, $\frac{\Delta z}{r} \ll 1$. Hence, the track equation can be approximated by the following quadratic formula:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 + \Delta z \frac{\cos(\phi_0)}{\tan \lambda_0} + \frac{(q/p_{T0})H_z \Delta z^2 k \sin(\phi_0)}{2 \tan^2 \lambda_0} \\ y_0 + \Delta z \frac{\sin(\phi_0)}{\tan \lambda_0} + \frac{(q/p_{T0})H_z \Delta z^2 k \cos(\phi_0)}{2 \tan^2 \lambda_0} \\ \Delta z + z_0 \end{pmatrix} \quad (7.24)$$

with $k = 0.3|B_z|$ and $H_z = \frac{B_z}{|B_z|}$. In order to establish the equations at the crossing point, an estimation of x and y is provided by the FwdTrackHelper tool at the PCA. The goal is to find the z -coordinate at the PCA in the equation. For the initial points, the track is propagated to $z_0=0$, and the corresponding x_0 and y_0 are extracted. Additionally, the required values can be extracted, determining the variables as follows:

$$A_x = \frac{q/p_{T0} \times H_z \times k \times \sin(\phi_0)}{2 \times \tan^2 \lambda_0} \quad (7.25)$$

$$B_x = \frac{\cos \phi_0}{\tan \lambda_0} \quad (7.26)$$

$$C_x = x - x_0 \quad (7.27)$$

The same is done for A_y , B_y , and C_y . In order to find the z -coordinate, the following second degree equations are established:

$$A_x \Delta z^2 + B_x \Delta z + C_x = 0 \quad (7.28)$$

$$A_y \Delta z^2 + B_y \Delta z + C_y = 0 \quad (7.29)$$

Where the corresponding $\Delta z = z - z_0$ are calculated. This leads to finding the z -coordinate at PCA for the track, which is the average of the solutions for both [Equation 7.28](#) and [Equation 7.29](#). This analytical method is done for both tracks, with the final Z seed corresponding

to the average of their extracted z -coordinates.

Neglecting the curvature, the propagation of the tracks follows a linear equation:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 + \Delta z \frac{\cos(\phi_0)}{\tan \lambda_0} \\ y_0 + \Delta z \frac{\sin(\phi_0)}{\tan \lambda_0} \\ \Delta z + z_0 \end{pmatrix} \quad (7.30)$$

Therefore, the established equations to solve are:

$$B_x \Delta z + C_x = 0 \quad (7.31)$$

$$B_y \Delta z + C_y = 0 \quad (7.32)$$

The Z seed is thus extracted with the same resolution method as the analytical case.

The seed finder can optimize the timing and resource consumption for the vertexing algorithm, by providing an initial estimation of the seed for the iterative gradient descent with the Newton-Raphson minimization. In addition, the seed finder is essential to avoid possible divergence which can occur with the Newton Raphson minimization for the tracks with small curvature. This effect can be observed in [Figure 7.7](#), where the variable $\Delta_z = Z_{PV} - Z_{SV}$ is presented for both approaches.

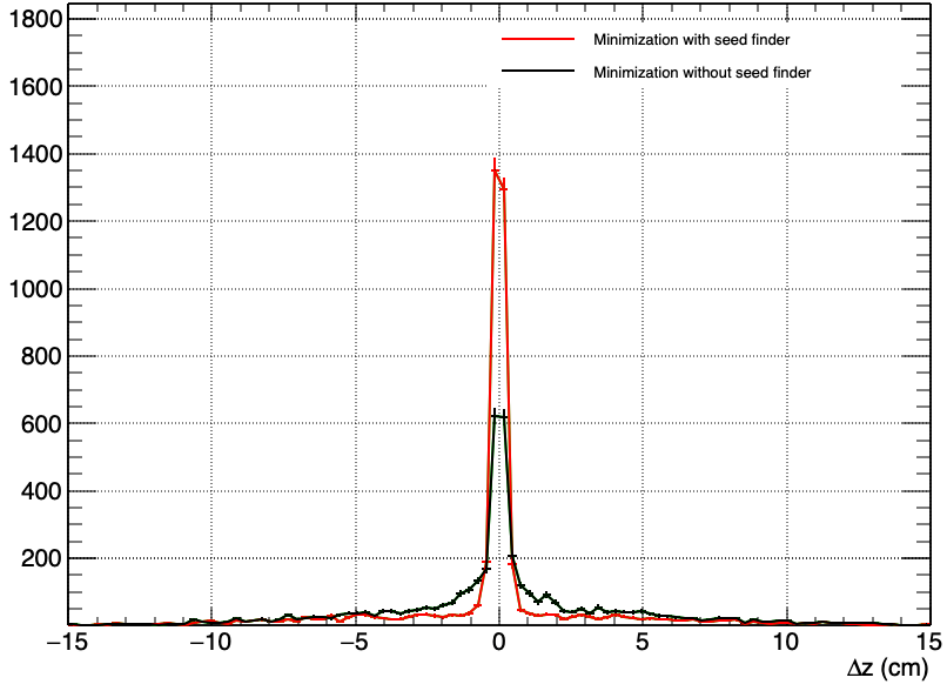


FIGURE 7.7: The Δ_z for PYTHIA8 simulation with embedded prompt J/ψ signal, with and without an initial seed provided by the seed finder (with dichotomy method).

Thus, for a precise determination of the seed, the selected method is the dichotomy. Since for the simple iterative method and the analytical approach method, a dependency is present on estimations from FwdTrackHelper on the initial positions of X and Y at the PCA. This can lead to uncertainties on the provided seed. As for the linear approximation, depending on the geometry of the reconstructed tracks, linear or quadratic, the seed finder can fail to find a seed, as displayed on [Figure 7.8](#).

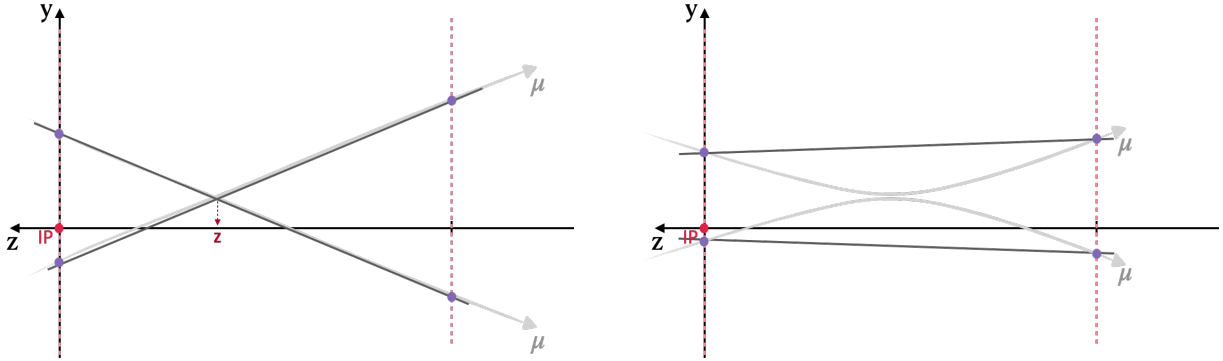


FIGURE 7.8: A schematic demonstration of the linear approximation method with (left) linear and (right) quadratic tracks.

7.5 First assessments and results

Preliminary tests are presented in this section, in order to validate the vertexing reconstruction algorithm. 10^3 events are generated, each containing 2-prong MC decays with generated vertices $\vec{V}$ at $z = 10$ cm. The tracks are then passed to the forward PCA algorithm for assessment.

After reconstructing the coordinates of the vertex, the PCA with $\vec{V} = V_x, V_y, V_z$ is extracted and compared with the MC-generated PCA, in order to check the validity of the algorithm and its resolutions. This allowed optimizations on parameters and the validation of the reconstruction algorithm. As presented in [Figure 7.9](#), the distance on (x,y) plane d_{XY} between both muon tracks is calculated as a function of z . The tracks cross at $z = 10$ cm, where the absolute generated minimum is located (in red), and the predicted minimum, following the PCA algorithm calculation, is presented with the green point. The goal being to reduce as much as possible the distance between the two points. The following two methods were proposed for the validation process:

Loop validation: the concept of « loop validation » is literal, serving as a proof of concept.

There are no uncertainties added on the spatial coordinates of the generated tracks. As a result, the algorithm should reconstruct the PCA with high precision.

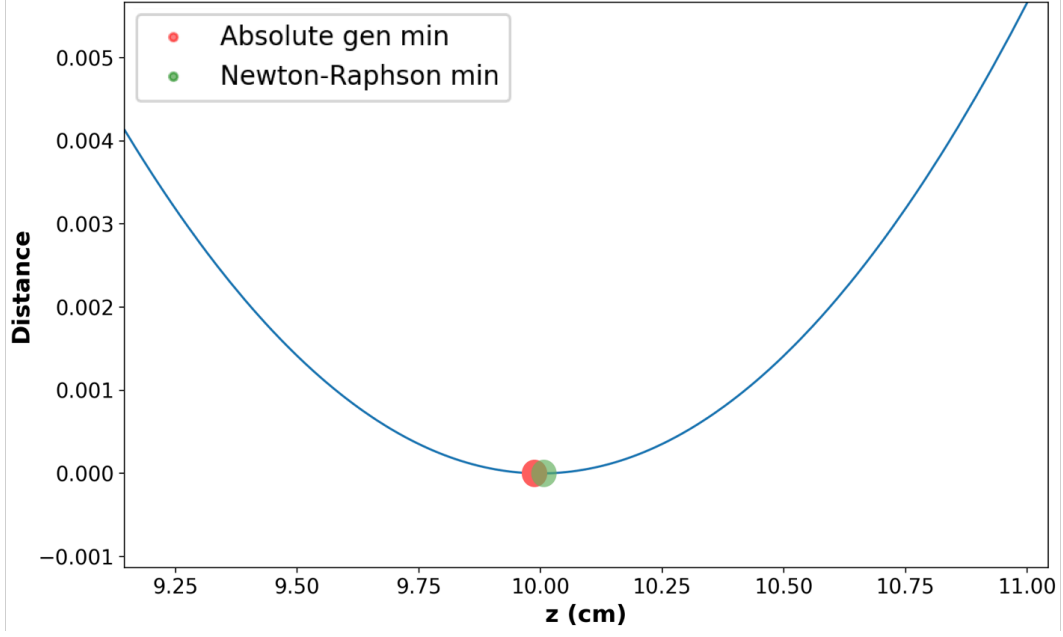


FIGURE 7.9: The distance XY of two tracks as a function of Z, where the generated minimum is presented in red and the reconstructed minimum in green.

Resolution validation: uncertainties are added on x and y parameters for each track, of an order of about 10^{-2} cm, implying a z uncertainty of the order of 10^{-1} cm. A random error is thus added within this order of magnitude while generating the particles, implying that after reconstruction and propagation, there will be a shift of the PCA between both tracks. The main purpose of this test is to determine how the error on the reconstruction of the tracks is translated on the vertexing reconstruction. An example of the difference between a **generated** and a **reconstructed** vertex for this resolution test is presented on Figure 7.9.

Additionally, two track types (helix and linear tracks) are generated in this MC simulation for the validation to study the DCA algorithm's performance on the different track models.

Firstly, the loop validation tests are carried out in order to ensure that the code works properly and check its performance. The errors between the reconstructed and the generated PCA as a function of the nature of the associated track models are presented on the left panels of Figure 7.10 and Figure 7.11. The calculated error on the z -axis, Δ_z , and the relative error on the 3 axes, Δ_{xyz} , are displayed respectively, such as $\Delta_z = z^{\text{rec}} - z^{\text{gen}}$ and $\Delta_{xyz} = \sqrt{\Delta_x^2 + \Delta_y^2 + \Delta_z^2}$. In Figure 7.12 - left, the error is presented for each coordinate separately ($\Delta_{x,y,z}$), where as expected, the z -coordinate resolution is lower than that of the x - and y -coordinates. The difference in the (x,y,z) coordinates for the reconstructed and the generated PCA are presented in Table 7.1.

	$\bar{\Delta}_x$ (cm)	$\bar{\Delta}_y$ (cm)	$\bar{\Delta}_z$ (cm)
helix-helix	1.26e-04	9.54e-05	1.78e-03
helix-line	5.09e-05	3.90e-05	6.86e-04
line-line	1.45e-06	1.27e-06	2.13e-05
all	5.95e-05	4.53e-05	8.29e-04

TABLE 7.1: The loop validation results for vertexing reconstruction with calculated $\bar{\Delta}_x$, $\bar{\Delta}_y$ and $\bar{\Delta}_z$ for different track models geometry helix and linear.

Finally, the relative error is calculated for all track models as follows:

$$\bar{\Delta}_{xyz} = \sqrt{\bar{\Delta}_x^2 + \bar{\Delta}_y^2 + \bar{\Delta}_z^2} = 0.00084cm \quad (7.33)$$

A high precision can be deduced for the first validation test, where the vertex reconstruction algorithm ensures a high accuracy between the reconstructed and generated PCA. Additionally, a better precision can be deduced for the linear muon tracks.

The resolution validation tests are presented on the right panels of [Figure 7.10](#), [Figure 7.11](#) and [Figure 7.12](#). The resulting values of $\bar{\Delta}_x$, $\bar{\Delta}_y$ and $\bar{\Delta}_z$ are shown in [Table 7.2](#).

	$\bar{\Delta}_x$ (cm)	$\bar{\Delta}_y$ (cm)	$\bar{\Delta}_z$ (cm)
helix-helix	0.0072	0.0074	0.09
helix-line	0.0079	0.0082	0.11
line-line	0.0079	0.0088	0.12
all	0.0077	0.0081	0.11

TABLE 7.2: The resolution validation results for vertexing reconstruction with calculated $\bar{\Delta}_x$, $\bar{\Delta}_y$ and $\bar{\Delta}_z$ for different track models geometry helix and linear.

The relative error is also calculated, with the following result:

$$\bar{\Delta}_{xyz} = \sqrt{\bar{\Delta}_x^2 + \bar{\Delta}_y^2 + \bar{\Delta}_z^2} = 0.11cm \quad (7.34)$$

As opposed to the validation loops, no important difference can be observed between the linear and helix associated track models. As for the different errors contributions in [Figure 7.12](#), the same trend can be noticed for x - and y -coordinates. As for the errors on the z -coordinate, the trend is wider and therefore reflecting the errors calculated in the table [Table 7.2](#). The calculated resolutions are within the expected and predicted interval, reflecting the errors implemented on the coordinates for the resolution validation.

Following these preliminary tests, the vertex reconstruction tool at forward rapidities has been officially integrated to O².

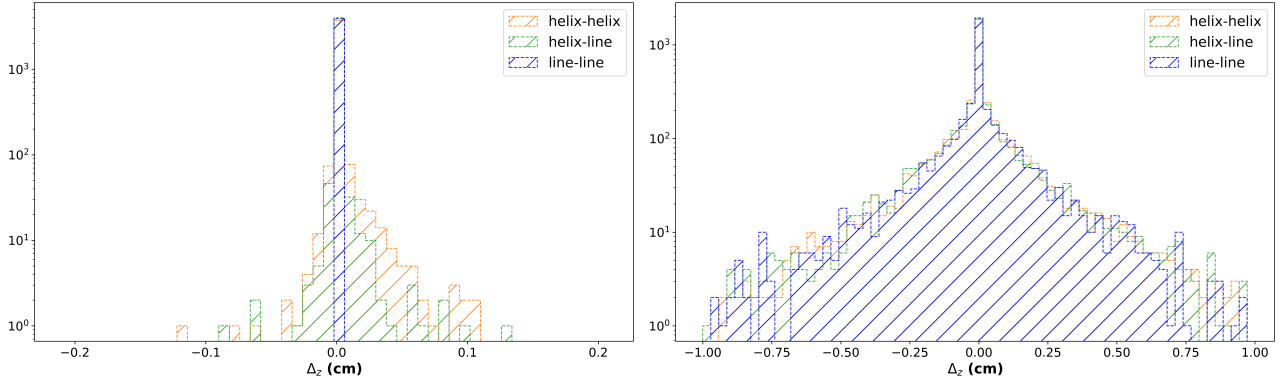


FIGURE 7.10: The calculated Δ_z for loop validation (left) and realistic (right) - with error propagation datasets as a function of track type.

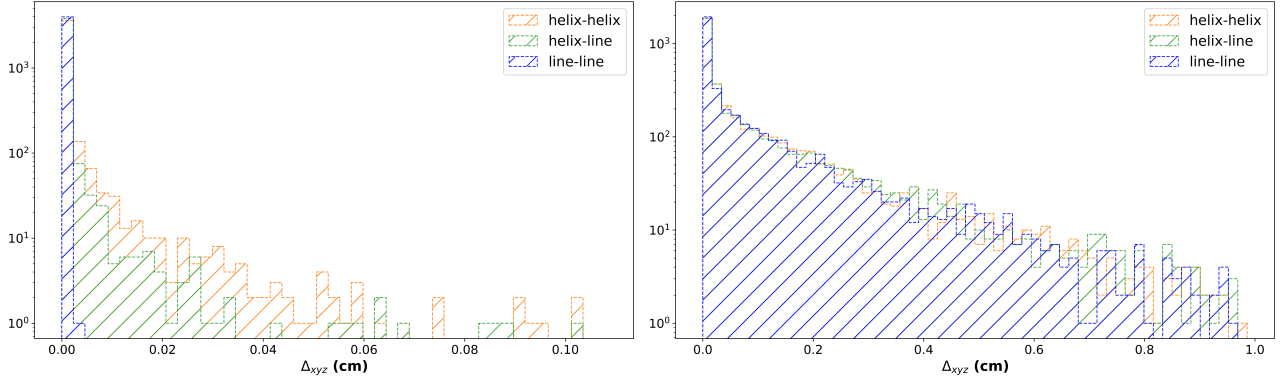


FIGURE 7.11: The Δ_{XYZ} for loop validation (left) and realistic - (right) with error propagation datasets as a function of track type.

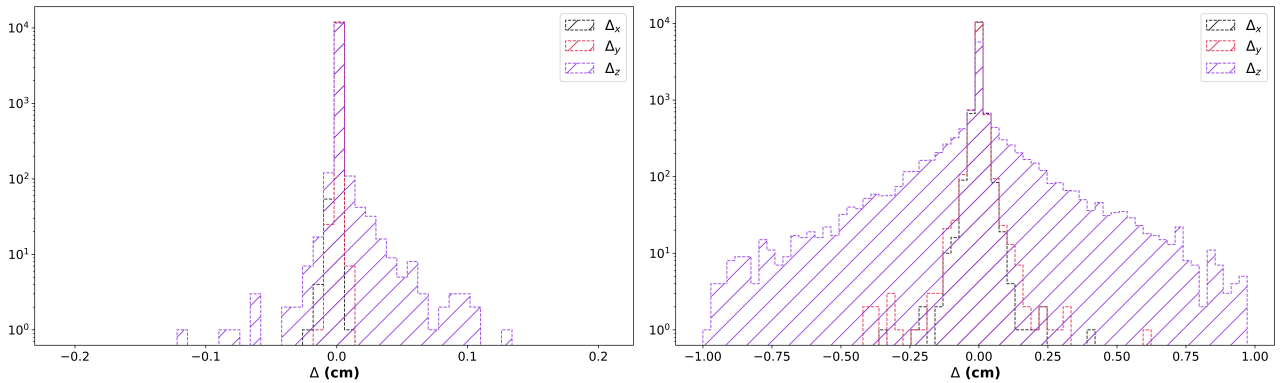


FIGURE 7.12: The calculated Δ per axis for loop validation (left) and realistic (right) - with error propagation datasets as a function of axis.

7.6 Conclusion

One of the main objectives of the MFT is to allow the separation of the prompt and non-prompt J/ψ contributions. This consists of the goal of the third part of this thesis, with an algorithmic approach developed and deployed in O^2 for finding the vertex of global muon tracks at forward rapidity. This algorithm aims at finding the point of closest approach variable for n tracks, and calculate a χ^2 score for the distance between the vertex and each of the tracks at a specific plane. The higher the probability of these n tracks to cross is, the lower the χ^2 is. The algorithm can be summarized as follows: first, a seed finder method is executed, in order to minimize approximately the distance between two tracks on (x,y) plane (dichotomy method is selected). After which, an iterative method takes place, the Newton-Raphson minimization, which is used to converge to a spatial point at a χ^2 minima, with high precision, thus following a 3D minimization. Following these developments, validation tests were carried out, ensuring that the algorithm works as intended and effectively. As a result to this algorithm, new measurements as the longitudinal decay length, the longitudinal and transverse pseudo-proper time can now be calculated at forward rapidities, as performed in the MFT TDR. Therefore, a separation between prompt and non-prompt J/ψ can be achieved. In the next chapter, official simulations are evaluated using the vertexing reconstruction algorithm.

Chapter 8

Separation of prompt and non-prompt J/ψ contributions

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The MFT was designed for the separation of the prompt and non-prompt J/ψ contributions at forward rapidity in Runs 3 and 4. It provides access to the required information for the muon tracks before the absorber, allowing a precise determination of their production vertices. In particular, after the extraction of global muon tracks, they are gathered in pairs and processed with the vertexing algorithm (as detailed in chapter 7). In order to further prepare for Run 3 analyses, this chapter will focus on investigating the separate prompt and non-prompt J/ψ contributions using first official MC productions of pp collisions. This consists of a very preliminary study, with the goal to further develop and prepare the analysis framework. In the following, the matching is based on the χ^2 method. Indeed, the χ^2 matching performance should be sufficient in pp collisions, as the effects discussed in section 6.2.1 are only significant in Pb–Pb collisions for J/ψ analyses. Moreover, the access to the ML libraries was not fully available in O² at the time of this work.

8.1 J/ψ pseudo-proper time distribution

8.1.1 Data production and structure

The data used in this section comes from an official MC production composed of pp collisions at 900 GeV, with signal embedded of prompt charmonia. More precisely, each event contains 4 J/ψ and 2 $\psi(2S)$, in order to enhance statistics. This embedded signal is produced using dedicated particle generators. The pp background is based on PYTHIA8 simulations. The propagation of particles through detectors is done with GEANT4.

Through this chapter, muon tracks are categorized as the following:

- **Track type 0:** global muon tracks, MFT-MCH-MID matched tracks.
- **Track type 2:** forward tracks, MCH-MFT matched tracks.
- **Track type 4:** MCH standalone tracks.

Track type 1 consists of MFT tracks and 3 of MCH-MID tracks. However, these track types won't be used in the following.

8.1.2 Signal $J/\psi \rightarrow \mu^+\mu^-$ extraction

In order to have an indication on the J/ψ mass resolution, the signal will be extracted with the evaluation of the invariant mass distribution:

$$m_{\mu^+\mu^-} = \sqrt{m_{\mu^+}^2 + m_{\mu^-}^2 + 2(E_{\mu^+}E_{\mu^-} - |\vec{p}_{\mu^+}||\vec{p}_{\mu^-}|\cos\theta_{\mu^+\mu^-})}, \quad (8.1)$$

with m_{μ^+/μ^-} , E_{μ^+/μ^-} and p_{μ^+/μ^-} being respectively the mass, energy, and momentum of muons, and $\theta_{\mu^+\mu^-}$ the opening angle between them. In addition, a cut of $p_T > 0.5$ GeV/c is applied on the selected muons. This cut removes part of the background coming from pion decays.

Different methods can be used to perform signal extraction. In this study, the opposite-charge dimuon distribution is fitted using empirical function. This fit contains both contributions from the signal (J/ψ) and background (mainly coming from pions and combinatorial background) to the mass spectrum. As this chapter is dedicated to the separation of the prompt and non-prompt J/ψ contributions, muons produced by $\psi(2S)$ are discarded.

Different functions were tested for the fitting procedure. The selected fit functions will be those that give the smallest χ^2 fitting score. The final selected functions are:

Signal function: an extended Crystal-Ball function is used. It consists of a gaussian function with additional tails on both sides to take into account the response of the detectors (energy loss and resolution).

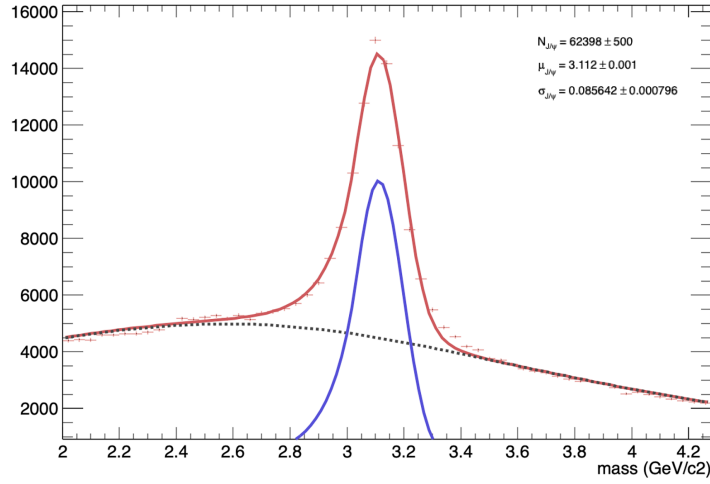


FIGURE 8.1: The invariant mass distribution of dimuons with the signal and background contributions.

Background function: the ratio of two polynomials is used to describe the background shape.

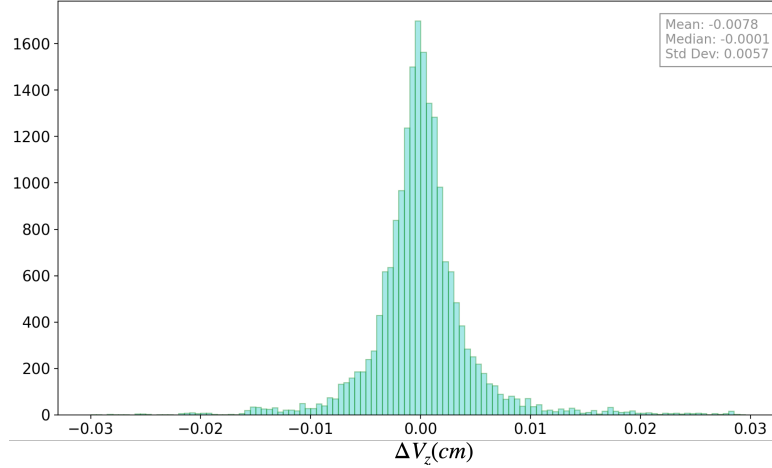
The numerator consists of a polynomial of the second order and the denominator one of the third order. Thus, this function is composed of 7 parameters in total.

The result is shown in Figure 8.1. The number of J/ψ extracted for this dataset consists of $N_{J/\psi} = 62398 \pm 500$, with a mass of $\mu_{J/\psi} = 3.112 \pm 0.001$ GeV/c^2 and a mass resolution around 86 MeV/c^2 .

8.1.3 Vertexing resolution

Firstly, the ability of the vertexing algorithm to reconstruct the vertices at the correct positions is tested in this simulation by looking at the difference between the reconstructed (V_z^{Rec}) and generated (V_z^{MC}) z-coordinates of the vertices. The distribution is extracted for opposite-charge dimuons, with a $p_T > 0.5$ GeV/c cut on the selected muons. Track type 4, equivalent to Run 2 muon tracks, is used for this study and thus, tracks are extrapolated to the primary vertex reconstructed by the ITS. Therefore, if the vertexing algorithm runs properly, the resolution width of the $\Delta V_z = V_z^{Rec} - V_z^{MC}$ distribution has to be compatible with the resolution of the ITS on the vertex reconstruction. This distribution is presented in Figure 8.2. The ΔV_z mean and width are -0.0078 cm and 0.0057 cm respectively. As expected, the latter is compatible with the ITS primary vertex resolutions.

Secondly, a similar test is conducted using track type 0 (global muon tracks) to get an estimation of the Run 3 resolutions. This study aims at understanding the resolution effects on the pseudo-proper time distribution. The difference between the Z position of the primary vertex Z_{IP} and a secondary vertex Z_{SV} is firstly studied. As this MC production contains only prompt decays, the charmonium decay vertices (denoted as secondary vertex: SV) are


 FIGURE 8.2: The $\Delta V_z = V_z^{Rec} - V_z^{MC}$ distribution for MCH standalone tracks.

supposed to be the same as the IP. The $\Delta V_z = Z_{IP} - Z_{SV}$ is presented in Figure 8.3. If no cut is applied, the distribution has a mean and a width of about 0.13 cm and 0.15 cm respectively. The obtained mean value is compatible with zero within one standard deviation. However, any potential mean shift, mainly due to the fake matching between MCH and MFT, is still thoroughly investigated in the following. In particular, no search area was applied on the matching process, resulting in a contamination of matched tracks with high χ^2 scores. Notably, this is due to the difference of acceptance between MCH and MFT detectors. Tracks in the border of MCH acceptance (with $|y| > 3.6$), without any MFT corresponding track, are still associated with a track in the MFT based on the minimum matching χ^2 , resulting in fake matches with large χ^2 scores. To remove the fake matched tracks in the reconstructed distribution, a cut on the $\chi_{MCH-MFT}^2 < 35$ (see Figure 6.19) is applied on the global muon tracks. As shown in Figure 8.3, the reconstructed distribution with this cut applied is consistent with the ΔV_z distribution coming from the MC truth. Finally, an additional cut on the PCA χ^2 (denoted by χ_{PCA}^2 , Equation 7.12) is attempted. No significant improvement is observed on the distribution.

To conclude, this study shows the necessity of applying a cut on the matching χ^2 in order to restore proper performances, eliminating a significant part of the background due to fake matching.

Finally, the next study focuses on the impact of the previously presented cuts on the $J/\psi \rightarrow \mu^+\mu^-$ signal only. Therefore, muon tracks coming from $\psi(2S)$ or background (as pions and kaons decays from PYTHIA) are filtered out. A 3D view is presented in Figure 8.4 - up, where a linear correlation is observed between the generated and the reconstructed vertex, as expected for the prompt quarkonium production. This allows a visualization of the performance of the vertexing algorithm, as the width of this correlation reflects the resolution of the vertexing. Furthermore, a 2D view is presented in Figure 8.4 - bottom, with $\chi_{PCA}^2 < 10^{-3}$ cut applied

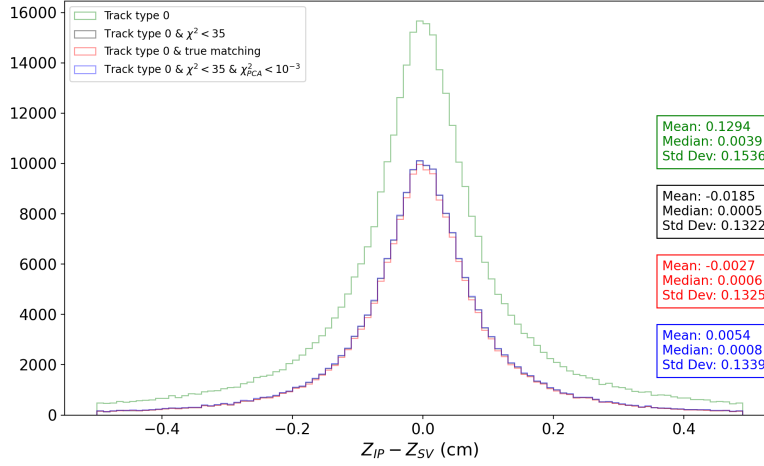


FIGURE 8.3: The $\Delta V_z = Z_{IP} - Z_{SV}$ distribution for global muon tracks with different cuts.

on both. On the right side, to observe a significant effect on the signal, a more stringent $\chi^2_{MCH-MFT} < 15$ cut is applied. With the 2 scenarios presented, the purity and efficiency (as defined in section 6.3.2) is calculated. There is a purity increase of 13% and an efficiency decrease of 2% when the $\chi^2_{MCH-MFT}$ is added. Therefore, by using a looser cut of $\chi^2_{MCH-MFT} < 35$, the efficiency can be maintained while the purity improves.

Finally, modifications on the vertexing algorithm hyperparameters (as discussed in section 7.2.1) are applied to study if the resolution can be further improved with more realistic simulations. The first hyperparameter modified is the convergence status, where the change between the last two PCA χ^2 scores calculated is reduced. Then, the number of iterations permitted to reach the convergence status is increased. The result of this study is presented in Figure 8.5. No significant change can be observed on the distributions with and without the modifications. Both distributions have a mean of around 0.001 cm with the same resolution of around 0.15 cm. This resolution is wider than the true muon tracks distribution resolution, which is expected as no cut on the $\chi^2_{MCH-MFT}$ matching is applied.

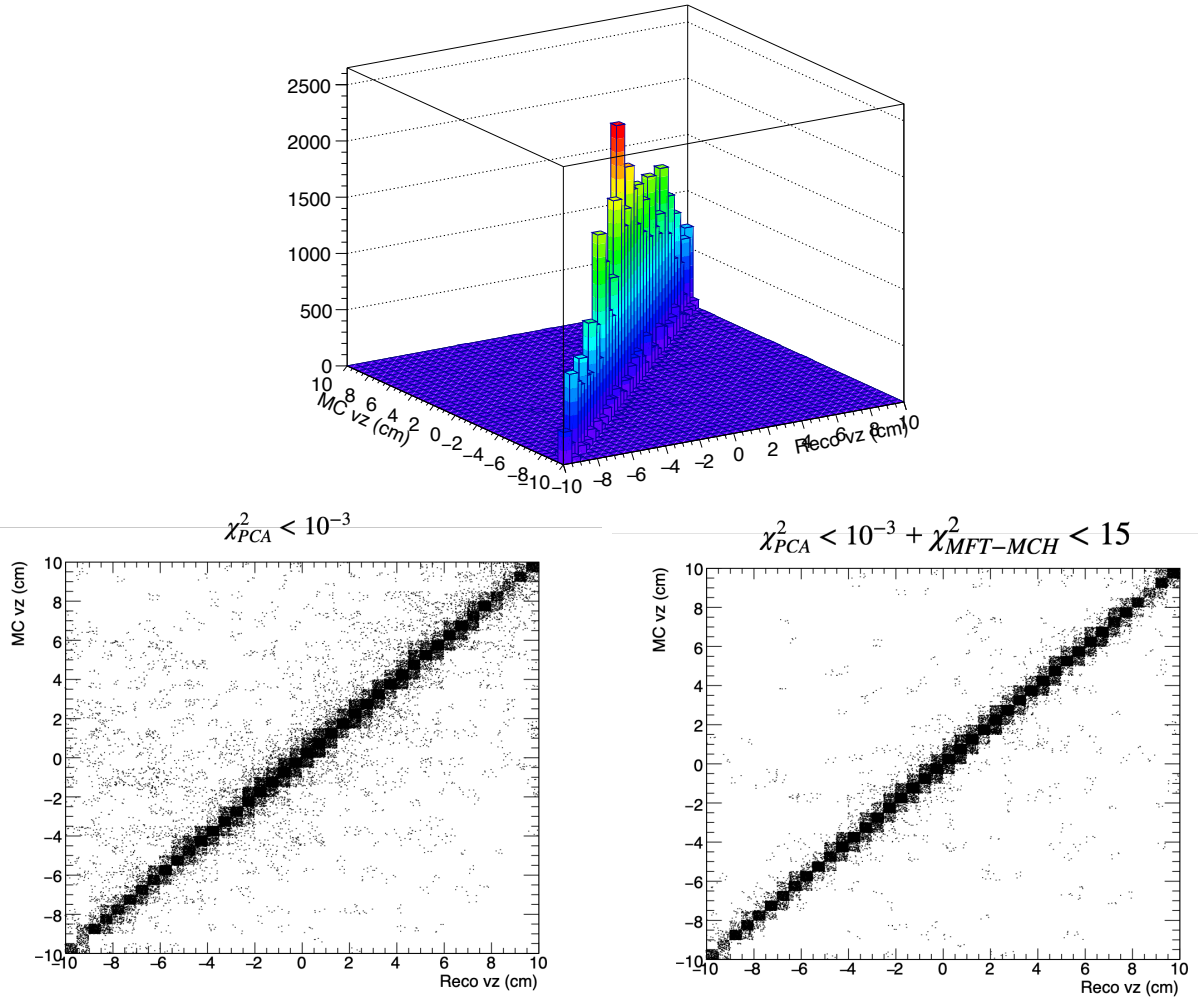


FIGURE 8.4: The MC IP vertex vs the reconstructed SV for $J/\psi \rightarrow \mu\mu$ signal for global muon tracks (up) without any cut (bottom left) with $\chi^2_{PCA} < 10^{-3}$ and (bottom right) with additional matching $\chi^2 < 15$ cut.

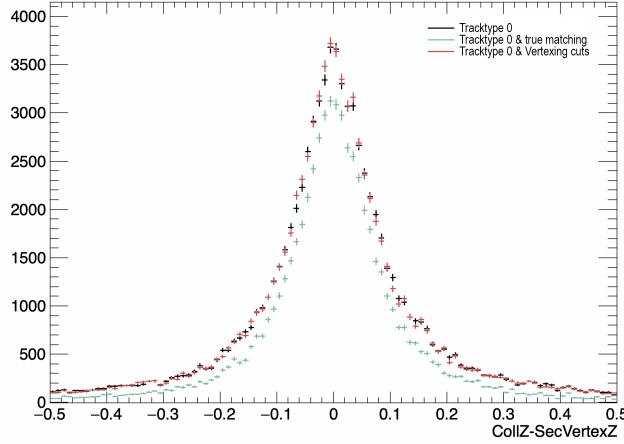


FIGURE 8.5: The distribution for true MC signal ($J/\psi \rightarrow \mu\mu$) of the distance between the collision vertex and the secondary vertex, expected to be around 0 cm for prompt quarkonia, with different cuts applied.

8.1.4 Pseudo-proper time distributions

The pseudo-proper time distribution t is a key ingredient allowing the prompt and non-prompt J/ψ contributions measurement. As the $J/\psi \rightarrow \mu\mu$ is measured at forward rapidity, due to the boost, the most discriminating component of the pseudo-proper time is the longitudinal one t_z . The t_z distribution for prompt J/ψ is expected to be a gaussian with a mean around zero, where the width depends on the detector and track reconstruction resolution. In Figure 8.6, t_z is presented using the opposite-charge dimuon spectra. A huge background is observed. Indeed, the main contribution to the combinatorial background come from the signal, as each event contains 4 J/ψ and 2 $\psi(2S)$. Each muon of a given charge is mixed with 5 others of the opposite charge. These mixed pairs will contribute to the combinatorial background. This contribution, at maximum, amounts to 30 inputs in the combinatorial background per event, for 6 signal inputs. The reconstructed signal per event will be less than 6, with a signal-like background of around 30 inputs. This contribution to the background, peaking at $t_z = 0$ s, is not realistic. Indeed, the combinatorial background should be dominated by muons from pion decays, and a lot less signal per event is expected. Furthermore, an unexpected asymmetry in the signal distribution is observed (see purple curve in Figure 8.6).

In Figure 8.7, an additional cut on $\chi^2_{MCH-MFT} < 35$ is applied. As seen in Figure 8.6, there is a large contribution to the combinatorial background, with $\frac{S}{B} = 0.09$ in the $[-0.002, 0.002]$ ns range. The asymmetry that was observed before decreases. This might be an indication that it is due to fake matching, which needs to be further investigated. On the right side, the χ^2_{PCA} distributions are presented for the signal and for the background separately. It can be observed that the signal is covered by the background, and there is no way to differentiate them.

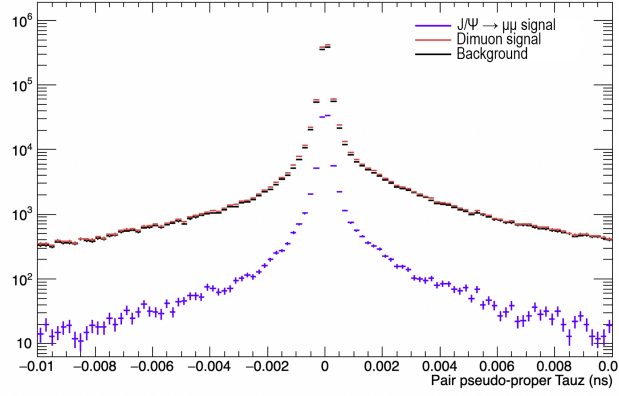


FIGURE 8.6: The pseudo-proper time t_z distribution for the dimuons with opposite-charge, without any cut applied.

In Figure 8.8, muons coming from a J/ψ or $\psi(2S)$ decays are discarded from the background distribution. After this removal, the $\frac{S}{B}$ ratio increases to 12.27. A coherent distribution can also be observed for the χ^2_{PCA} distribution, where at low values, the signal is larger than the background. This is the expected behavior, as muons coming from J/ψ decays are supposed to have a crossing point (small residuals between the tracks, thus small χ^2_{PCA}), as opposed to muons coming from the combinatorial background.

In Figure 8.8 - left, an asymmetry can be observed, even if it is less pronounced than the asymmetry in Figure 8.6, where no cut is applied. This can be attributed to resolution effects on the kinematic variables that compose the t_z . Various kinematic resolutions are studied in the following, to further understand this asymmetry. Moreover, more realistic simulations are explored to obtain distributions consistent with expectations, avoiding the effect of a large number of signals per event.

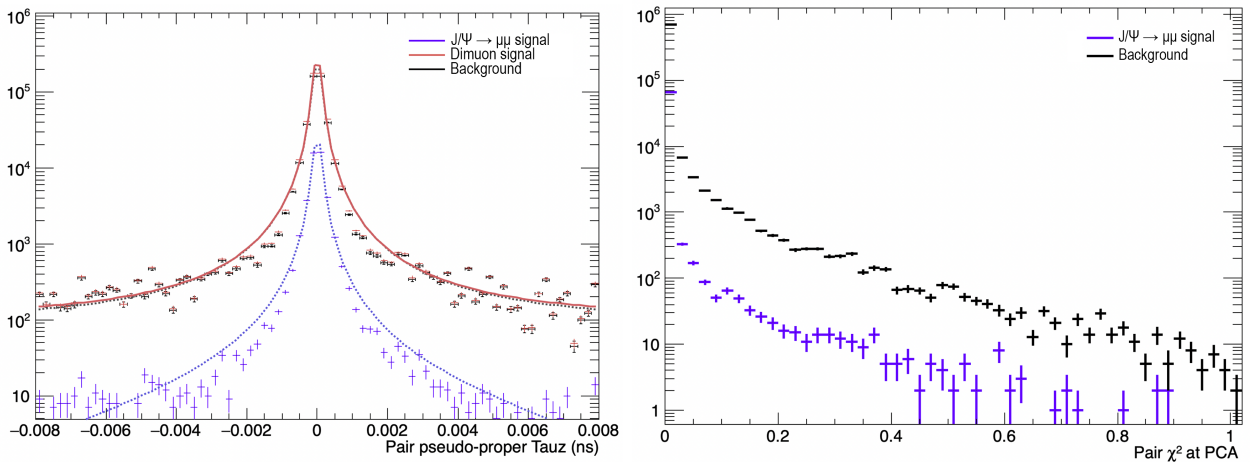


FIGURE 8.7: (left) The pseudo-proper time t_z and (right) χ^2_{PCA} distributions for the dimuons with different signal and background contributions with cuts on V_z , matching and PCA χ^2 .

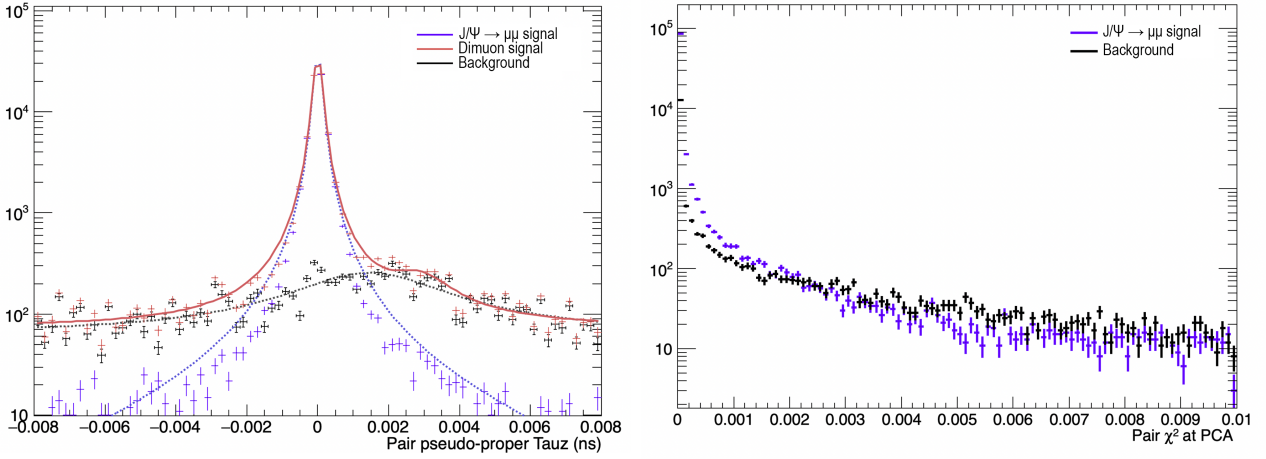


FIGURE 8.8: (left) The pseudo-proper time t_z and (right) χ^2_{PCA} distributions for the dimuons with cuts on V_z , matching+PCA χ^2 and a treated background (signal contribution removed).

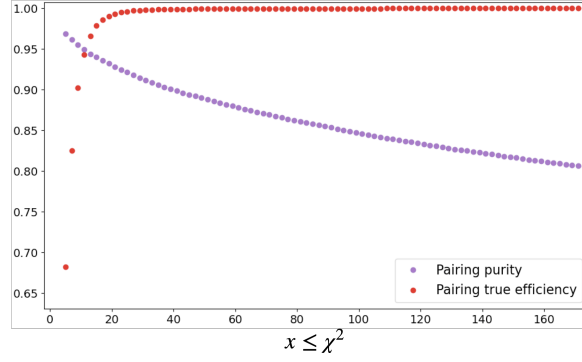
8.2 Towards more realistic simulations: study of MC pp collisions at 13 TeV

Two official MC productions (LHC21i3d2 and LHC21i3g2) are studied in the following, both consisting of pp collisions at 13 TeV. The embedded signal is different between the productions. In LHC21i3d2, the signal is composed of one prompt J/ψ per event. The LHC21i3g2 signal is composed of one $b\bar{b}$ pair per event, forced to decay into $J/\psi + X$ in the final state. This constitutes the non-prompt contribution. Another essential difference between the MC production used in the previous section and these production concerns a seed modification on the tracking reconstruction. In this section, resolution studies on different kinematic variables of muon tracks are performed. Then, various information for the prompt and non-prompt contributions are extracted separately.

8.2.1 Kinematics resolutions

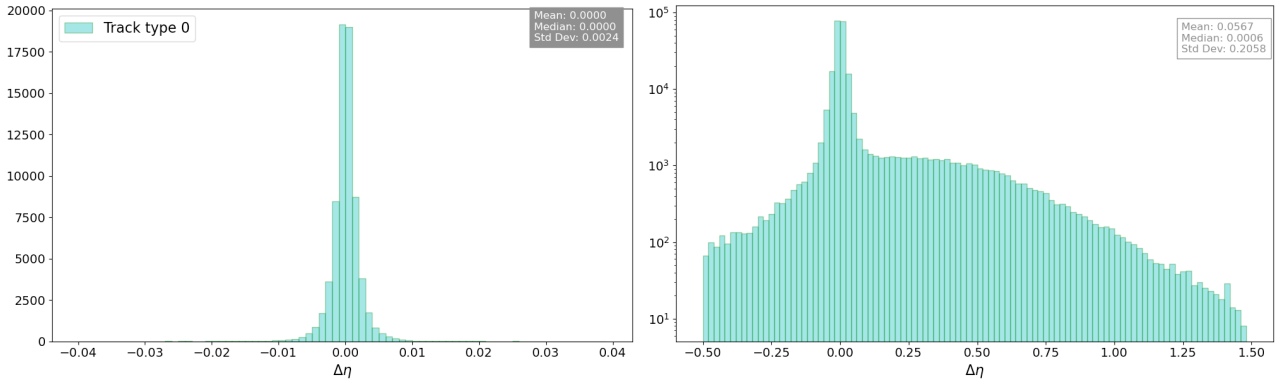
The $\chi^2_{MCH-MFT}$ cut effect on the pairing true efficiency and purity is firstly evaluated. The pairing purity and the true pairing efficiency are calculated for each $\chi^2_{MCH-MFT}$ cuts values and presented in Figure 8.9. As can be observed, the pairing purity distribution deteriorates as a function of the $\chi^2_{MCH-MFT}$ cuts. In comparison to the previous study, in which the cut was set at $\chi^2_{MCH-MFT} < 35$, the cut is updated to $\chi^2_{MCH-MFT} < 20$ in the following. This allows to maintain a good pairing purity while obtaining a sufficiently high true pairing efficiency.

In the following, the resolutions of different kinematic variables of single muons is investigated, starting with the pseudo-rapidity η , followed by the transverse momentum p_T , and


 FIGURE 8.9: The pairing purity and true efficiency presented as a function of different χ^2 cut.

finally, the momentum projected on the z-axis, p_z . The definitions of these variables have been outlined in section 1.4.3.1.

First, the $\Delta\eta = \eta^{Rec} - \eta^{MC}$ distribution is studied, where η^{Rec} is the reconstructed value of η for the reconstructed muon track, and η^{MC} is the corresponding MC truth value. In Figure 8.10 - left, true global muon tracks have been extracted to determine the expected distribution for this variable. The resolution of η is of around 0.0024 for a mean of 0. Then, true and fake reconstructed tracks are presented in Figure 8.10 - right, with all track types (0, 2 and 4) included. An asymmetry is observed for all the track types combined, with a mean of 0.057. In the following, the track type 0 is studied and is compared to the other track types for reference. In Figure 8.11 - left, the different track type distributions are presented separately.


 FIGURE 8.10: The $\Delta\eta = \eta^{Rec} - \eta^{MC}$ distribution for (left) true global muon tracks and (right) all track types without any applied cuts.

The distributions are normalized to compare the different contributions, each having different statistics. MCH standalone tracks have a symmetric distribution around the mean of 0.0028, with a resolution of 0.096. The forward tracks have a mean of 0.25 and a resolution of around 0.42, and the global muon tracks have a mean of around 0.11 and a resolution of 0.25. The latter resolution is affected by the fake matching present on the forward tracks, leading to the observed asymmetry. The reduction of fake track rate is essential for a better resolution, thus

8.2. Towards more realistic simulations: study of MC pp collisions at 13 TeV

the selected $\chi^2_{MCH-MFT} < 20$ cut is applied on global muon tracks in Figure 8.11 - right. Two different shapes of the distributions can then be distinguished. Reduction of the asymmetry is observed for the global muon η distribution with cut. Indeed, a better mean and resolution is observed with values of 0.0079 and 0.075 respectively.

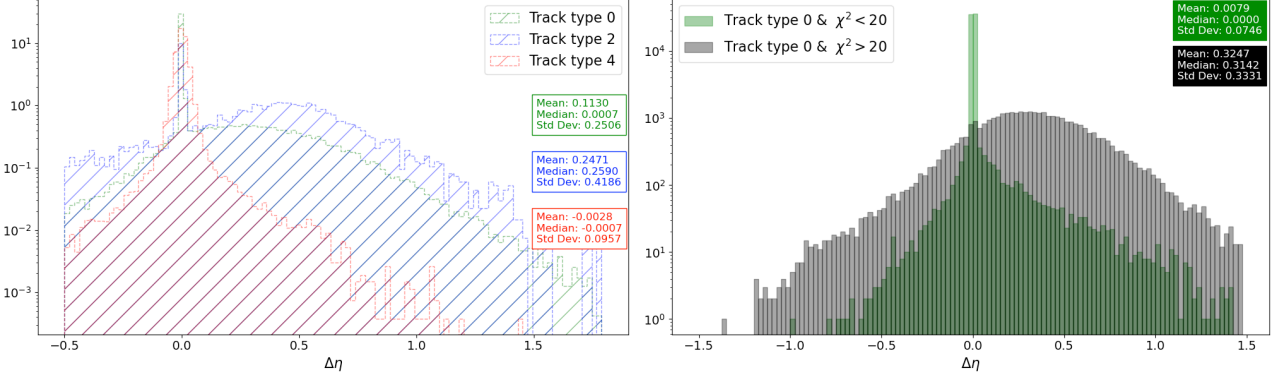


FIGURE 8.11: The $\Delta\eta = \eta^{Rec} - \eta^{MC}$ distribution for (left) separated track types and (right) global muon tracks with matching χ^2 cut application.

Then, the transverse momentum resolution is investigated with the same strategy explained above. The distribution of the $\Delta p_T = p_T^{Rec} - p_T^{MC}$ is presented for the global muon tracks in Figure 8.12 - left. The mean is 0.0032 GeV/c with a resolution of 0.16 GeV/c. All the muon track types without any cuts are presented in Figure 8.12 - right, with a mean of 0.0038 GeV/c and a resolution of 0.24 GeV/c. The different contributions are then extracted and presented in Figure 8.13 - left. The Δp_T distribution for the global muon tracks has a mean of 0.023 GeV/c and a resolution of 0.22 GeV/c. For the forward tracks, an asymmetry is also observed, with a mean of 0.099 GeV/c and a resolution of 0.92 GeV/c. This is not the case for the standalone muon tracks, having a mean of -0.018 GeV/c and a resolution of 0.15 GeV/c. Finally, the effect of the fake tracks is investigated with the $\chi^2_{MCH-MFT}$ cut on the global muon tracks in Figure 8.13 - right. This induces two different distributions, as observed for the $\Delta\eta$, with an enhanced transverse momentum resolution for the $\chi^2_{MCH-MFT} < 20$ distribution. In particular, its mean is reduced to 0.0053 GeV/c and an improved resolution of 0.17 GeV/c is observed. The conclusion that can be drawn from these results are thus consistent to the one concluded from the η distribution study.

Finally, the distribution of the momentum projected on the z-axis $\Delta p_z = p_z^{Rec} - p_z^{MC}$ is presented with the same strategy. The resolution of the Δp_z for the true global muon tracks is presented in Figure 8.14 - left. The mean of this distribution is around -0.037 GeV/c, with a resolution of 1.85 GeV/c. In Figure 8.14 - right, the distribution of Δp_z for all the tracks is presented. A large mean of 2.03 GeV/c is observed and a resolution of 8.05 GeV/c. The Δp_z distribution for all track types is presented in Figure 8.15 - left. The global muon tracks have a mean of 3.6 GeV/c and a resolution of 10.37 GeV/c. The forward tracks have a mean of around

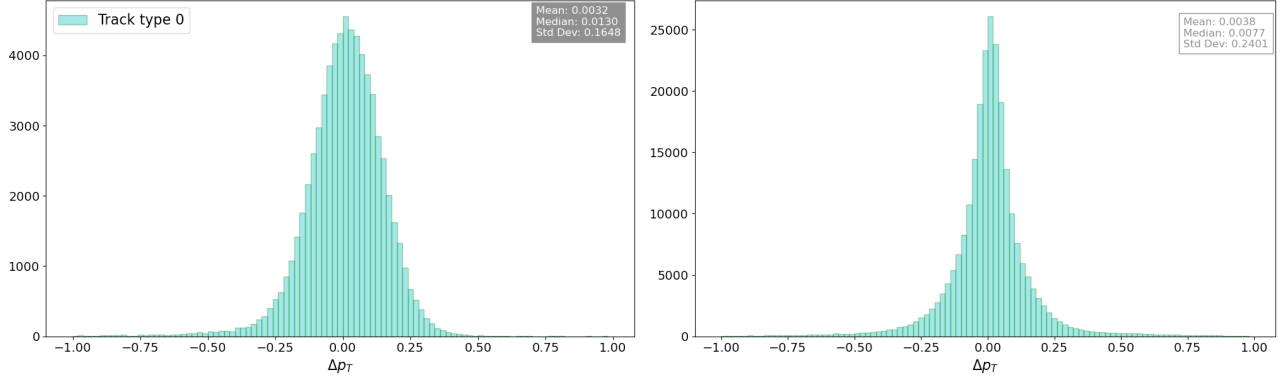


FIGURE 8.12: The $\Delta p_T = p_T^{Rec} - p_T^{MC}$ distribution for (left) true global muon tracks and (right) all track types without any applied cuts.

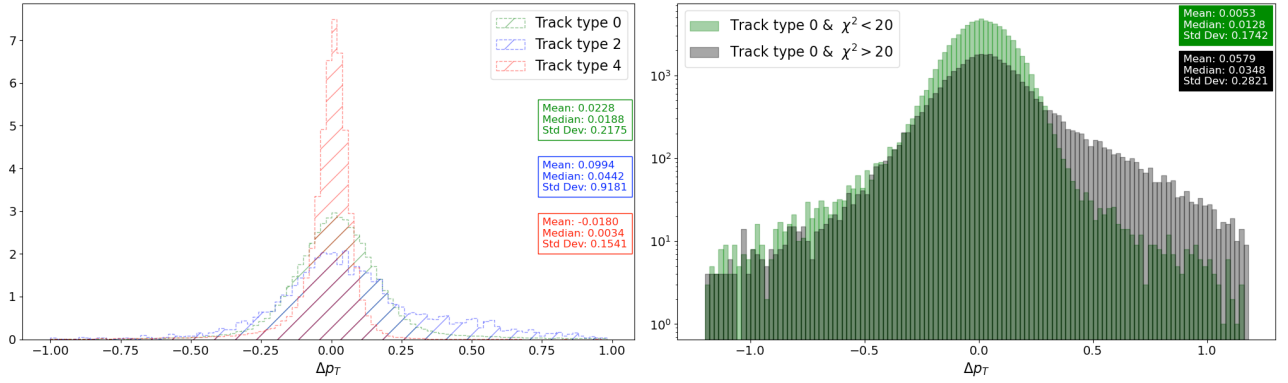


FIGURE 8.13: The $\Delta p_T = p_T^{Rec} - p_T^{MC}$ distribution for (left) separated track types and (right) global muon tracks with matching χ^2 cut application.

8.61 GeV/c and a resolution of 17.39 GeV/c, and the standalone muon tracks have a mean of 0.31 GeV/c and a resolution of 2.75 GeV/c. As discussed for the other distributions, the matching cut is thus essential in order to restore, as much as possible, the resolution observed for the true muon tracks. This is shown in Figure 8.15 - right, where the distribution with $\chi_{MCH-MFT}^2 < 20$ has a reduced mean of -0.016 GeV/c, and an improved resolution around 2.028 GeV/c.

To conclude, it can be noted that the asymmetry observed on global muon tracks kinematics is mainly due to the fake matching. Thus, the asymmetry observed on the t_z distributions consists of a consequence of the fake matching. Fine-tune cuts on the matching $\chi_{MCH-MFT}^2$ are crucial for the analysis.

8.2. Towards more realistic simulations: study of MC pp collisions at 13 TeV

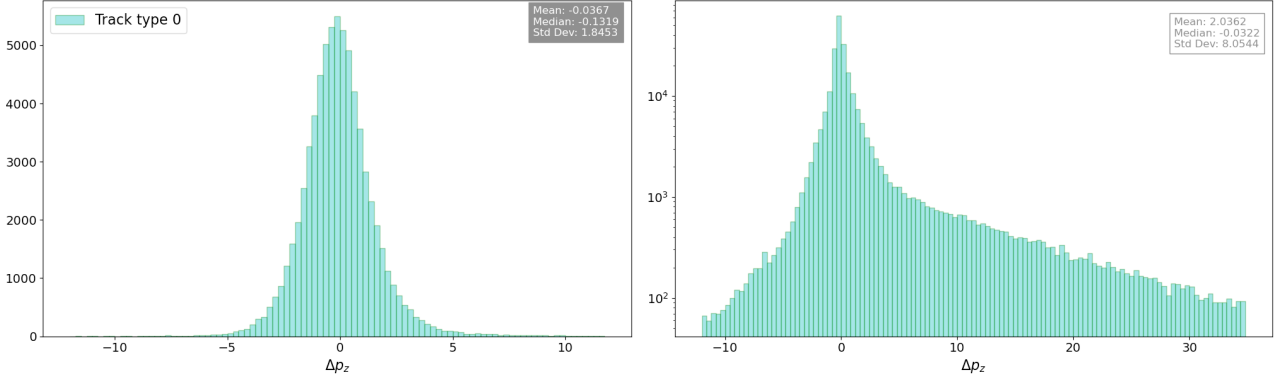


FIGURE 8.14: The $\Delta p_z = p_z^{Rec} - p_z^{MC}$ distribution for (left) true global muon tracks and (right) all track types without any applied cuts.

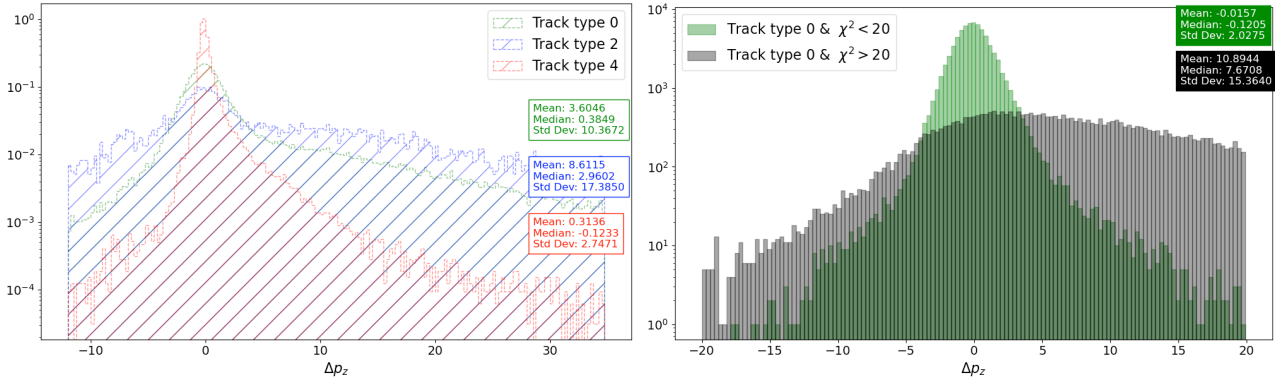


FIGURE 8.15: The $\Delta p_z = p_z^{Rec} - p_z^{MC}$ distribution for (left) separated track types and (right) global muon tracks with matching χ^2 cut application.

8.2.2 Prompt J/ψ signal characterization

In this section, the focus is brought on the prompt J/ψ contribution with a more realistic simulation compared to the 900 GeV production (higher center-of-mass energy of 13 TeV, different track reconstruction, less signal per event).

All of the following histograms are filled with global muon tracks, with muons coming only from J/ψ decay. The $\Delta_z = IP_z - SV_z$ distribution for MC truth muon tracks is presented in Figure 8.16 - left, with a mean at -0.00077 cm and a resolution of 0.21 cm. The resolution of the vertexing depends on the track reconstruction and the detector resolutions. A difference can be noticed between the prompt productions at 900 GeV and 13 TeV due to the track reconstruction modifications. Unfortunately, due to fake matching, muons coming from J/ψ can be well reconstructed in the muon spectrometer, but match with the wrong track in the MFT. To have some insight on the contribution coming from the fake matching, the distribution in Figure 8.16 - right is extracted. This distribution only contains contribution from pairs of muons with a good MCH track and the wrong MFT track. It is peaked around zero, have a

mean of -0.48 cm, and a standard deviation value of 5.72 cm.

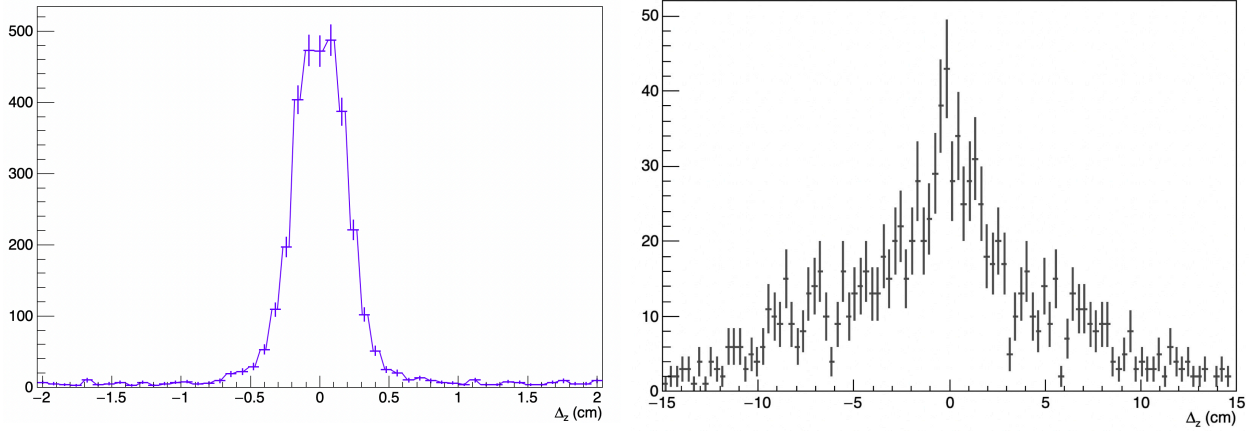


FIGURE 8.16: The distribution for (left) true and (right) fake global muons signal, $J/\psi \rightarrow \mu\mu$ of the distance between the collision vertex and the secondary vertex, expected to be around 0 cm for prompt quarkonia, with different cuts applied.

One of the first measurements that will be performed with data consists of the calculation of the J/ψ cross sections (prompt and non-prompt). However, a fraction of the muons coming from J/ψ can be well reconstructed in the MCH but matched with the wrong MFT track (fake matching on the real signal), which can modify the kinematics of these muons. This contribution will be called background-like distribution in the following. If a χ^2 cut is applied, the background-like signal will be partially removed, resulting in biased measurements. Thus, the fraction of the fake matching background should be properly estimated in the J/ψ cross section calculations. This study gives an estimation on how much signal is lost and considered background while applying the discussed χ^2 cuts. A sketch showing the expected shapes of the different contributions is provided in Figure 8.17 - left. These different shapes correspond to the distribution of the J/ψ signal without any cuts (in black), reconstructed by two true muon tracks (in purple), the background-like coming from the fake-fake associated tracks (in blue), and the combinatorial background containing all the other combinations, consisting of true muon tracks associated with fake tracks (in red). The two latest contributions will be treated as background-like in the following. Figure 8.17 - right presents both the complete signal composed of all muon tracks from J/ψ decays in black, and the true tracks coming from J/ψ in purple.

Different cuts are applied on both $\chi^2_{MCH-MFT}$ and χ^2_{PCA} scores in the following. The result is presented in Figure 8.18. The number of reconstructed J/ψ without any cut is $N_{J/\psi} = 4816 \pm 63$ (in black), while the number of reconstructed true J/ψ is $N_{J/\psi} = 3144 \pm 55$. Thus, the fraction of signal that can be lost in the background is of 0.35. A $\chi^2_{MCH-MFT} < 20$ cut is applied (brown distribution), and the extracted signal is of $N_{J/\psi} = 3340 \pm 55$, thus a fake tracks contamination

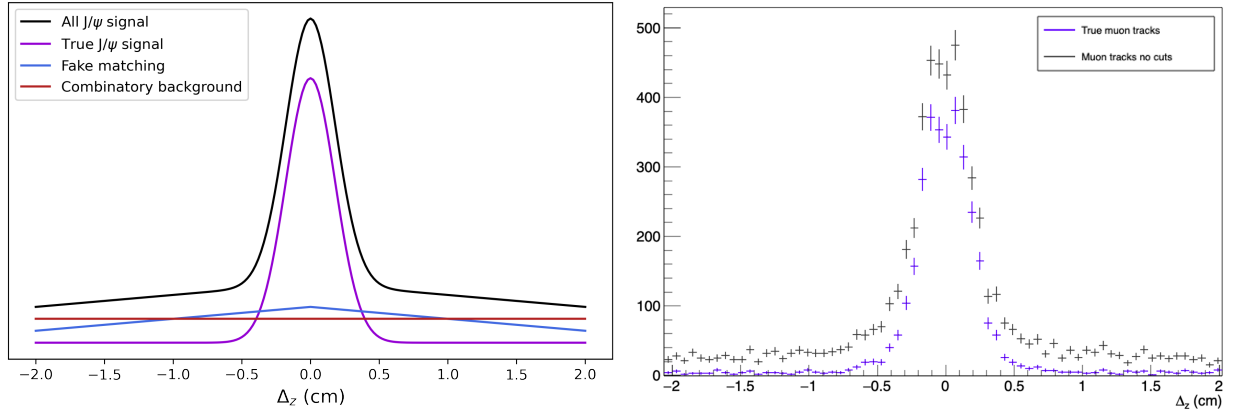


FIGURE 8.17: (left) A sketch for the different contributions composing the distribution of Δ_z for the dimuons coming from J/ψ particles. (right) The Δ_z distribution for all the muon tracks coming from J/ψ in black, and for only the true muon tracks from J/ψ .

of 0.056. Finally, an additional $\chi^2_{PCA} < 10^{-3}$ cut is applied. The resulting extracted number of J/ψ is of $N_{J/\psi} = 2520 \pm 49$. This results in a higher purity but poor efficiency, as a fraction of around 0.2 of the signal is lost. The change in the effectiveness of this cut, compared to the previous simulation, is mainly due to the change in the tracking reconstruction of the MFT.

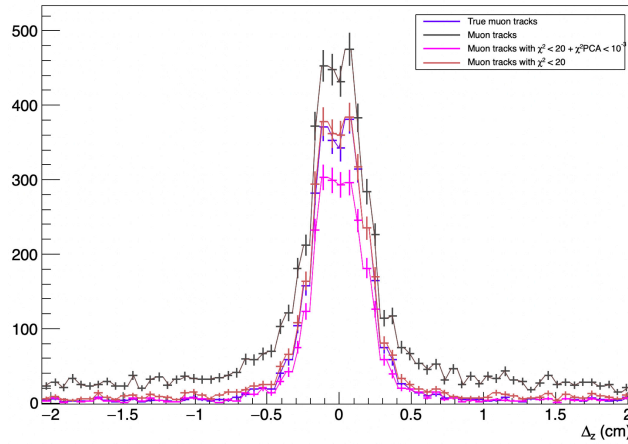


FIGURE 8.18: The distribution for the global muons signal, $J/\psi \rightarrow \mu\mu$ from prompt J/ψ , of the distance between the reconstructed IP and the SV, with different cuts applied.

The Figure 8.19 - left shows the invariant mass distribution for the various signal and background contributions. The $\chi^2_{MCH-MFT} < 20$ cut and a $p_T > 0.5$ GeV/c cut is applied on global muon tracks. The background that is presented in these distributions consists of both combinatorial background, and background-like due to fake matching. In the range $[2.5, 3.5]$ GeV/c, the total number of J/ψ is $N_{J/\psi} = 7389 \pm 68$, with a signal-to-background ratio of $\frac{S}{B} = 1.45$.

The pseudo-proper time t_z is presented in Figure 8.19 - right. An additional cut on the invariant mass of $2.5 \text{ GeV}/c^2 < m_{\mu\mu} < 3.5 \text{ GeV}/c^2$ is applied to minimize the background. In the range $[-0.002, 0.002] \text{ ns}$, the total extracted number of J/ψ is $N_{J/\psi} = 4475 \pm 54$ with a signal-to-background of $\frac{S}{B} = 2.25$.

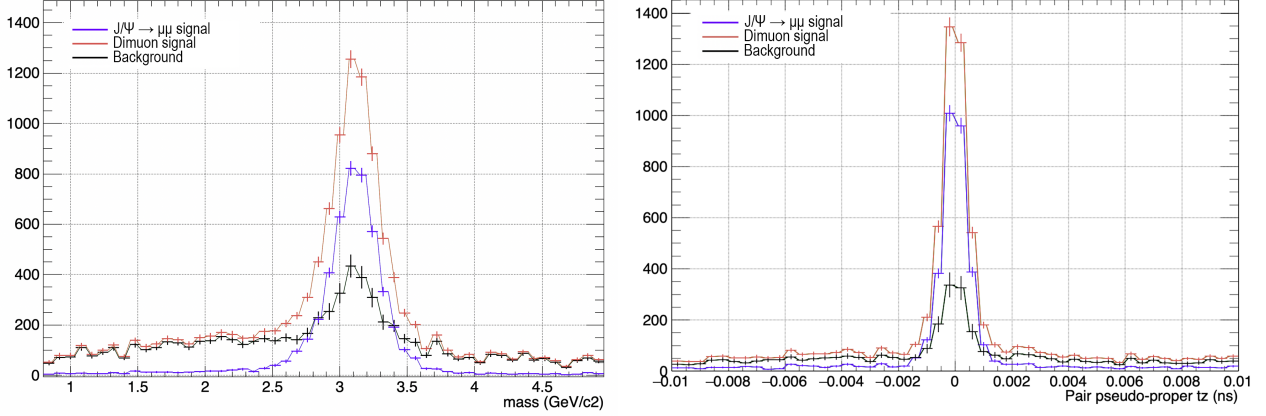


FIGURE 8.19: (left) The invariant mass and (right) the t_z distribution of dimuons.

8.2.3 Non-prompt J/ψ signal characterization

After examining the prompt J/ψ production, this section will focus on the non-prompt production with the goal of assessing its essential characteristics. First, the same strategy as in the previous section is followed with the study of $\Delta_z = IP_z - SV_z$ for the true reconstructed global muon tracks as presented in Figure 8.20 - left, and the fake reconstructed tracks as shown in Figure 8.20 - right. In this section, the J/ψ is produced from the b-hadron decays. The mean of true reconstructed muons coming from J/ψ mother particles is displaced around 0.56 cm, with a resolution of 1.18 cm. As for the trend of the fake reconstructed muons, with a noticeable peak around zero.

Different set of cuts are applied on the Δ_z distribution in Figure 8.21, to find the best one, in order to extract the signal with the less possible background-like distribution, as performed previously for prompt J/ψ . The number of reconstructed J/ψ without cuts is $N_{J/\psi} = 3172 \pm 33$ (in black), while the number of reconstructed true J/ψ is $N_{J/\psi} = 1968 \pm 30$. Therefore, the fraction to be re-integrated to the signal distribution for cross-section calculations is of 0.38. When a $\chi^2_{MCH-MFT} < 20$ cut is applied, the extracted number of J/ψ is $N_{J/\psi} = 2412 \pm 31$, with a fake tracks contamination of 0.18. Finally, the set of cuts with the lowest contamination consists of an additional $\chi^2_{PCA} < 1.5 \times 10^{-3}$ cut, resulting in a $N_{J/\psi} = 2017 \pm 30$, with a contamination of a fraction of 0.02.

In Figure 8.22 - left, the pseudo-proper time t_z of the opposite-charge dimuons is extracted, with the signal and background contributions. In addition to the $\chi^2_{MCH-MFT} < 20$ and $\chi^2_{PCA} <$

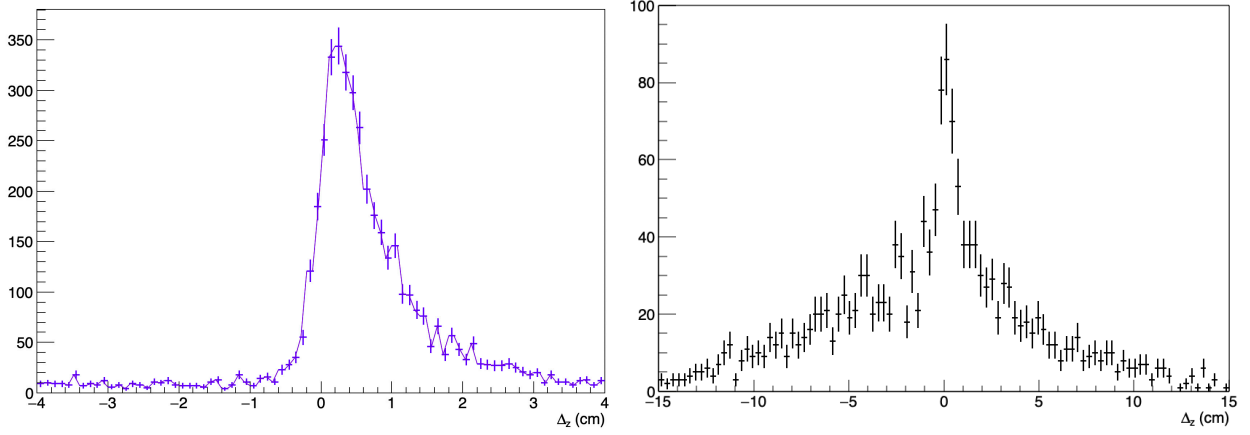


FIGURE 8.20: The distribution for (left) true and (right) fake global muons signal, $J/\psi \rightarrow \mu\mu$ coming from displaced J/ψ decay of the distance between the reconstructed IP and the SV.

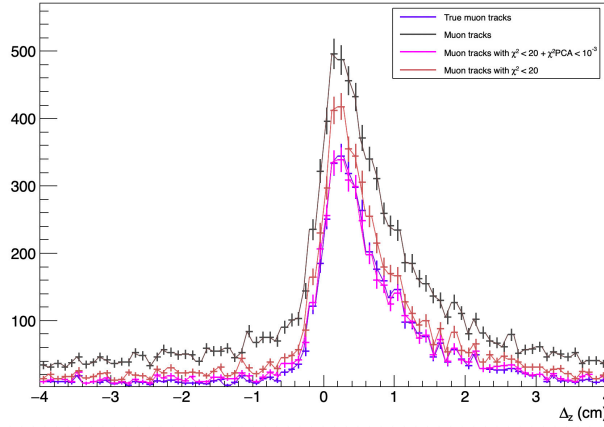


FIGURE 8.21: The distribution for the global muons signal, $J/\psi \rightarrow \mu\mu$ from the displaced J/ψ , of the distance between the reconstructed IP and the SV, with different cuts applied.

1.5×10^{-3} cuts, a $p_T > 0.5$ GeV/c cut is applied on the muons, and $2.5 \text{ GeV}/c^2 < m_{\mu\mu} < 3.5 \text{ GeV}/c^2$ is applied on the selected dimuons. Within the range of $[-0.1, 0.1]$ ns, the number of J/ψ extracted is $N_{J/\psi} = 1617 \pm 22$, with a signal-to-background ratio of $\frac{S}{B} = 3.9$.

Additionally, the decay length calculation is performed in order to check the physics consistency for the non-prompt production. For this purpose, the t_{xyz} is extracted for the true reconstructed dimuon tracks, as presented in Figure 8.22 - right. An exponential fit is done, such as $e^{-\frac{t}{\tau} + c}$, to find the τ corresponding to this distribution. Then, the decay length is calculated with $l = c\tau$, resulting in a value of $l = c\tau = 487.4 \pm 22.07 \mu\text{m}$. For the B-hadron decay length (section 7.1), the highest decay length contribution¹ comes from J/ψ , which is

¹In the B frame of reference, the highest B-hadron decay mode including the J/ψ state $B \rightarrow J/\psi + K$ results with $\left(\frac{1}{\beta\gamma c}\right)_{J/\psi} = 1.85$ and $\left(\frac{1}{\beta\gamma c}\right)_K = 0.29$.

thus compatible with τ discussed in chapter 7.

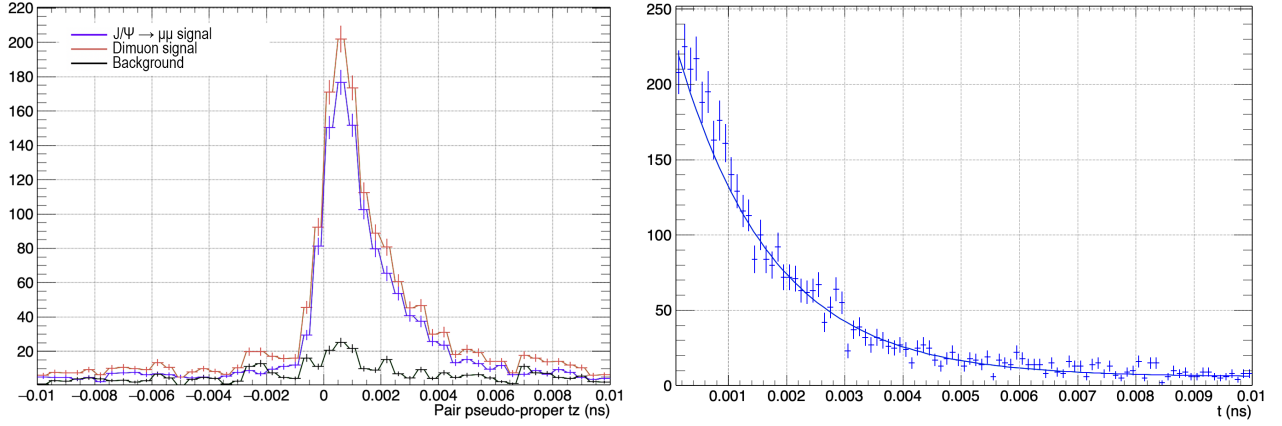


FIGURE 8.22: The pseudo-proper time (left) t_z and (right) t_{xyz} distributions for the dimuons coming from the non-prompt J/ψ decays.

8.3 First prompt and non-prompt J/ψ separation

The different contributions of the prompt and non-prompt J/ψ are merged in order to have a first look into the different distributions, with all detectors included for Run 3, corresponding to the centrally produced MC data of 13 TeV pp collisions at forward rapidity. For this purpose, the t_z distribution is presented for the opposite-charge dimuons, the prompt and non-prompt J/ψ contributions and the total background (the observed peak around zero comes from an identified simulation bug). This is the first separation performed after the simulations in the TDR presented in chapter 6 (Figure 7.2). The cuts applied for this study are the following: $p_T > 0.5$ GeV/c for the selected muon pairs, $2.5 \text{ GeV}/c^2 < m_{\mu\mu} < 3.5 \text{ GeV}/c^2$, the vertex position region within $|V_z| < 10$ cm, the matching $\chi^2_{MCH-MFT} < 20$ to eliminate the fake tracks, and an additional cut on the PCA applied for the non-prompt contribution allowing the best signal extraction, as described in the section 8.2.3, such as $\chi^2_{PCA} < 1.5 \times 10^{-3}$. In order to have a realistic distribution, the cross sections of the prompt and non-prompt J/ψ at forward rapidity in pp collisions at $\sqrt{s} = 13$ TeV has been integrated [140], and applied on this study with rescaling, following the cross-section values as:

$$\sigma(\text{prompt } J/\psi, p_T < 14 \text{ GeV}/c, 2 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94 \text{ } \mu\text{b} \quad (8.2)$$

$$\sigma(J/\psi\text{-from-b}, p_T < 14 \text{ GeV}/c, 2 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14 \text{ } \mu\text{b} \quad (8.3)$$

In addition, to guide the eye, linear interpolation is applied to each contribution. The result of this work is presented in Figure 8.23, in which a first look of the different prompt and non-prompt J/ψ contributions can be observed.

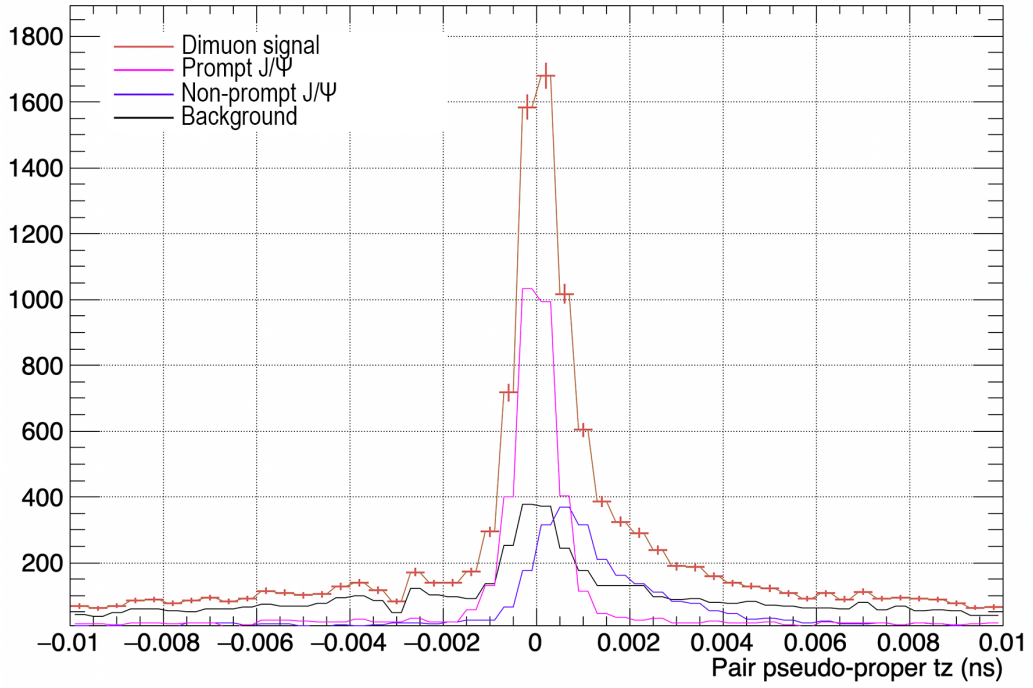


FIGURE 8.23: The pseudo-proper time t_z distributions for the dimuons with the different J/ψ prompt and non-prompt contributions.

8.4 Conclusion

The O^2 environment is in development for the framework preparation for Run 3 data analysis. On this topic, work is on-going to produce and assess the quality of simulations, constituting the last part of this thesis. The simulations will allow the understanding of the impact on our physics observables coming from the various efficiency and fake rate of the detector, as fake matching and resolution effects. First, assessment of the developed tool for the vertexing is done, where detector resolution effects are studied. Then, the first official simulations of pp collisions at $\sqrt{s} = 13$ TeV with embedded signal of prompt and non-prompt J/ψ are studied, with different kinematics resolutions presented where the fake matching effect was visualized. Then, the decay length was extracted for the non-prompt J/ψ . Finally, the distribution for the longitudinal pseudo-proper time with all the different prompt and non-prompt contributions was presented.

Conclusion

The work of this thesis was mainly devoted to the commissioning of the MFT and to the preparation of the Run 3 analyses, as it took place during the second long shutdown of the LHC. It is the period when all the detectors and upgrades were in preparation for the next data taking period, which officially started on the 5th July 2022.

The first part of this thesis was dedicated to the on-surface commissioning of the detector, and the preparation of the official framework enabling detector operations during Run 3. In particular, this work consisted of the creation of a specific software, from front-end to back-end, which allows communication, monitoring and the control of the MFT. It was approved by the collaboration, and extensively used for the whole period of the on-surface commissioning of the MFT and as a reference to validate the official control software. This work required the understanding of the functioning of complex electronics and its communication protocol, in order to integrate this into a more general and user-friendly framework, allowing complete operations of the MFT. This work consists of the control of 24 GBT-SCA in parallel, allowing a fluid control of the whole detector. In addition, the entire development of a graphical interface was necessary to achieve this. In parallel, the middleware software (FRED) was developed for the MFT within the DCS framework. This was successfully completed and is currently running 24 hours a day on the experiment during the last period of the on-site commissioning and the Run 3 operations. This work consisted of an essential brick for the MFT detector. The development of the MFT-FRED software was essential to allow constant communication with the detector through messages. This part is mainly in charge of sending periodically commands to the detector and decoding the detector's responses. It receives also commands from the operator to change some settings (calibration) or to execute some actions (reset, enabling/disabling some components, etc.). Thus, this middleware establishes the communication between the operator and the MFT. Database development was also necessary to store the different configurations. Finally, additional developments were required to collect and distribute the information to the panels of the graphical interface. Specifically, creating and structuring data points on WinCC

OA allowed their display in a proper way on the panels available to the operator.

The second part of the work in this thesis focused on the track matching between the muon spectrometer and the MFT. Tools based on ML have been designed and implemented in order to exploit neural networks to extract global tracks. This study proved the usefulness of ML for the matching task at high multiplicity environments, as the purity and efficiency results based on ML were significantly better than those based on a standard χ^2 method. The development of a full framework for data pre-processing, ML training, and performance evaluation has been developed in this thesis. With machine learning applied to small signal over background environments ($\frac{S}{B} = 0.22$), muon tracks could be unravelled with $\frac{S}{B} = 32$, compared to the χ^2 methods, where $\frac{S}{B} = 10$. In particular, with ML, the pairing purity increases (from 0.91 to 0.97) and the efficiency of the fake tracks is reduced considerably (from 0.1 to 0.03) compared to the χ^2 method. It is also important to note the dependence of these results on the training datasets. In the future, the training of these tools on data that describe collisions will be exploited. More specifically, official simulations based on PYTHIA8 will be studied, in order to prepare the NN for the Run 3 data. Another prospect for this work should focus on the evaluation of uncertainties due to the matching with ML.

The third part of this thesis focused on finding the vertices of muon tracks. The construction of the algorithm responsible for this task is an essential building block for Run 3. It will allow the separation of the different contributions of the production of J/ψ . The prompt (from collision point) and non-prompt (from B-decay) J/ψ could be extracted for the first time in ALICE at forward rapidities. For this task, the algorithm consists of two essential cores. The first is composed of a seed finder method, consisting of a 2D minimization of the distance between the tracks. It is then followed by a 3D minimization, with Newton-Raphson method for finding the vertex of the muon tracks. Initial evaluations have shown the efficiency of this algorithm, with a capacity of vertex reconstruction with an uncertainty of 8.4×10^{-4} cm. This vertexing algorithm was officially implemented in the O^2 environment.

The last part of this thesis consisted of first evaluations of pp collisions with official Run 3 MC simulations, using the new vertexing algorithm. As the preparation unfolds for Run 3, the O^2 environment is in continuous development for the analysis framework preparation. In this part, the resolution of vertexing was studied, and the importance of matching was highlighted. Notably, for the reduction of fake tracks, the importance of cuts application arises. Moreover, the fraction of signal that can be lost due to the cuts to reduce the fake matching was investigated. Finally, the first pseudo-proper time measurement with the different contributions of prompt and non-prompt J/ψ was presented.

When the data will arrive, many analyses prospects can be investigated for Run 3. Firstly, the cross section of the B-hadron can be measured, adding a complementary measurement to the one done by LHCb extended towards more central collisions. Additionally, the extraction of the beauty contributions can be performed with ML tools. A study should therefore be carried out to see whether beauty extraction with ML is more efficient than with standard methods. The separation of charm and beauty contributions can also be achieved down to low p_T .

Résumé en français

La ChromoDynamique Quantique (QCD) est la théorie quantique des champs qui décrit l'interaction forte, responsable de la force nucléaire forte qui est à la base de la structure nucléaire (proton, neutrons et plus généralement hadrons). Dans des conditions normales, les quarks et les gluons sont confinés dans la matière nucléaire. Néanmoins, à haute température et haute densité d'énergie, un nouvel état de la matière nucléaire existe connu sous le nom de Plasma de Quarks et de Gluons (PQG). Il s'agit d'un milieu dense composé de matière en forte interaction au sein duquel les quarks et les gluons sont déconfinés. Les propriétés du PQG peuvent être étudiées en reproduisant les conditions nécessaires par des collisions ultra-relativistes d'ions lourds dans des collisionneurs de particules tels que le Large Hadron Collider (LHC, CERN). Le détecteur ALICE, situé autour de l'un des points de collisions du LHC, est conçu pour étudier le PQG à travers les collisions d'ions lourds (majoritairement entre noyaux de Pb).

L'une des sondes historiques proposées pour étudier les propriétés du PQG est la mesure de la production de quarkonia, particules composées d'un quark lourd et de son anti-quark, plus précisément la suppression de l'une d'entre elles, le charmonium J/ψ . Cependant, un autre mécanisme affectant la production de ce dernier a également été observé : la recombinaison. Celle-ci se produit à très haute densité d'énergie, quand le nombre de quarks charmés est si important qu'il permet la recombinaison de ces quarks dans un état de charmonium J/ψ .

La mesure inclusive de quarkonia peut être effectuée dans ALICE jusqu'à une impulsion transverse p_T de 0 GeV/c dans deux régions de rapidité différentes. À mi-rapidité ($|y| < 0.9$), les mesures de quarkonia sont effectuées via leur canal de désintégration diélectronique et la séparation des contributions prompte et non-prompte est possible. À rapidité vers l'avant ($2.5 < y < 4$), seule la mesure inclusive de quarkonia peut être faite par leur canal de désintégration muonique dans le spectromètre à muons.

Le spectromètre à muons est composé de stations de trajectographie (Muon CHambers, MCH) et de déclenchement (Muon TRigger, MTR) et d'un absorbeur frontal situé après le point d'interaction (IP). Il a été conçu pour étudier d'importants sujets de physique liés à la mesure des saveurs lourdes ouvertes, de la production de quarkonia et de mésons vecteurs légers.

Cependant, en raison de la diffusion multiple qui se produit dans l'absorbeur frontal entraînent un manque de précision sur l'origine des muons, certaines des performances du spectromètre sont limitées. Les muons produits par les désintégrations de hadrons de saveurs lourdes ne peuvent pas être distingués de ceux produits par la désintégration de pions et de kaons, ce qui introduit un bruit de fond élevé. En outre, seules des mesures inclusives de $J\psi$ sont possibles en raison de l'absence d'information sur les vertex secondaires. Pour remédier à ces diverses limitations, le Muon Forward Tracker (MFT) a été proposé, construit et installé.

Pendant la période de ma thèse, le LHC était en période d'arrêt prolongé, au cours de laquelle des améliorations de détecteurs ont été effectuées afin de préparer la prochaine période de prise de données (Run 3).

Le MFT est situé à 40 cm du point d'interaction, devant l'absorbeur frontal. Le premier objectif de ce détecteur est d'améliorer la résolution de pointage des traces de muons. Cela peut être réalisé par l'extrapolation des traces de muons reconstruites par le spectromètre à muons et leurs association avec celles du MFT.

En surmontant les limites imposées par la conception du spectromètre à muons, le MFT étend le programme de physique dans la région de rapidité vers l'avant. Notamment, sur les saveurs lourdes, un meilleur accès au charme ouvert sera possible. Ainsi, les mesures à faible p_T seront possibles grâce à la réduction du bruit de fond. De plus, la séparation entre les J/ψ prompts et non-prompts sera possible, et une meilleure extraction du signal $\psi(2S)$ est attendue. En ce qui concerne les dimuons de faible masse, une meilleure résolution en masse est attendue.

Le MFT repose sur la technologie de capteurs monolithiques à pixels actifs (MAPS), permettant une reconstruction de trace avec une excellente résolution dans un environnement à haute multiplicité. Les capteurs sont assemblés dans des circuits intégrés hybrides qui équipent un système de 5 disques à double faces autour du faisceau du LHC. L'alimentation et le contrôle des disques du détecteur sont gérés par une carte spécifique, la Power Supply Unit (PSU), située entre les quatrième et cinquième disques. La communication avec le détecteur est assurée par la technologie GBT-SCAs (Giga-Bit Transceiver - Slow Control Adapter). Le détecteur exige une grande fiabilité car il n'est pas accessible pendant toute la durée de prise de données. En outre, les capteurs doivent être maintenus à une température inférieure à 30 °C. Enfin, tous les services doivent être intégrés dans un volume limité : 35 cm pour le diamètre du premier disque, 46 cm pour le dernier disque, avec 36 cm de distance totale entre ces 2 disques. Ces défis ont été relevés avec succès. Le MFT a achevé la phase de mise en service et a été l'un des premiers détecteurs à être installés dans ALICE en décembre 2020. Une autre étape essentielle a été franchie lorsque les premières données ont été enregistrées avec le faisceau pilote du LHC (collisions proton-proton à 900 GeV) en octobre 2021.

Pour la première partie de mon travail de thèse, j'ai travaillé sur le développement du système de contrôle du détecteur, comme détaillé dans le chapitre 5. Cela implique le développe-

ment de logiciels, du plus bas niveau (communication directe avec les registres des GBT-SCA) au plus haut niveau (interface graphique pour les opérateurs). La PSU est responsable de l'alimentation et de la surveillance de tous les capteurs du détecteur. Le détecteur comprend quatre cartes PSU principales et un total de 28 GBT-SCAs, assurant le transfert simultané des informations de contrôle et de surveillance du détecteur. Pour cette partie de ma thèse, j'ai développé le logiciel de commissioning pour le détecteur, connu sous le nom de PSU Control, responsable du contrôle complet du détecteur. Il a été approuvé et utilisé par la collaboration MFT pendant toute la période de commissioning, et a servi de référence pour le logiciel officiel de l'expérience ALICE pour le Run 3. J'ai ensuite développé ce dernier, le Detector Control System (DCS) du MFT, également détaillé dans le chapitre 4.

La deuxième partie de mon travail, présenté dans le chapitre 6, concerne un aspect très important de l'upgrade du MFT : l'association de traces entre le MCH et le MFT afin d'extraire les traces de muons à rapidité à l'avant. La méthode utilisée pour l'association consiste à extrapoler les traces MCH à un plan spécifique du MFT, et de sélectionner la trace MFT sur la base d'un critère de score χ^2 . Cependant, en raison de la diffusion multiple à l'intérieur de l'absorbeur entre le MFT et le MCH, une incertitude sur l'extrapolation des traces est introduite. Ainsi, la méthode peut perdre en efficacité et en pureté d'association lors du processus d'extraction des muons, notamment dans des environnements à forte multiplicité et pour des particules à faible p_T . Par conséquent, des outils plus raffinés sont nécessaires pour la tâche d'associations de traces. Pour cela, j'ai conçu et étudié des méthodes de machine learning afin de calculer la probabilité d'association entre les traces MFT et MCH. J'ai développé une procédure logicielle complète pour cela, du pré-traitement des données à l'évaluation des performances en passant par la phase d'apprentissage, afin de trouver la meilleure méthode d'association pour une extraction optimale des traces de muons. L'extraction de traces de muons en a été ainsi améliorée, avec le rapport signal (vraies traces de muons extraites) sur bruit (fausses traces extraites) passant de 10 à 32 avec le machine learning.

Le chapitre 7 est dédié à la troisième partie de mon travail, consacrée aux développements algorithmiques nécessaires à la séparation des J/ψ prompts et non-prompts. Plus précisément, cela porte sur le développement de l'algorithme de reconstruction des vertex des traces de muons à rapidité à l'avant. L'algorithme est composé de deux principales parties : tout d'abord, une minimisation 2D est effectuée sur la distance séparant les traces de muons afin d'obtenir une première estimation de la position du vertex, suivie ensuite d'une minimisation 3D avec la méthode de Newton-Raphson pour obtenir précisément la position du vertex des muons. J'ai également effectué des évaluations et des tests pour valider cet algorithme, qui promet une précision importante, avec une capacité de reconstruction avec une incertitude de $8,4 \times 10^{-4}$ cm.

La dernière partie de cette thèse, présentée dans le chapitre 8, a consisté en la première

évaluation des simulations Run 3 officielles des collisions proton-proton (pp) afin de préparer l'environnement et des outils d'analyse. Les travaux portent sur un large éventail de sujets, allant de l'évaluation de la qualité de ces simulations, à la compréhension de l'impact provenant de l'efficacité et de la pureté de l'association de traces sur les observables physiques, à la préparation de codes d'analyse pour mesurer différentes observables. Plus précisément, des simulations officielles de collisions pp à 13 TeV ont été produites en utilisant l'algorithme de reconstruction des vertex décrit dans le chapitre 7. Différentes résolutions ont été étudiées, notamment l'effet d'association incorrecte de traces a été souligné. Enfin, pour la première fois dans la région de la rapidité à l'avant, des mesures de temps propre ont été effectuées permettant des premières separation entre les contributions de J/ψ prompts et non-prompts.

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Titre : Mise en service du MFT et préparation d'analyses de données Run 3 dans l'expérience ALICE (LHC, CERN)

Mot clés : LHC, ALICE, MFT, charmonia, commissioning, apprentissage automatique

Résumé : Le détecteur ALICE est conçu pour étudier le Plasma de Quarks et de Gluons (PQG), un état dans lequel la matière hadronique se trouve déconfinée dans un milieu chaud et dense. La mesure de quarkonium, une sonde importante du PQG, est possible avec ALICE dans deux régions de rapidités : la rapidité centrale, par leurs désintégrations diélectroniques, et la rapidité en avant, par leurs désintégrations dimuons avec le spectromètre à muons. Afin d'élargir le programme de physique dans la région de rapidité vers l'avant, le Muon Forward Tracker (MFT) a été installé dans ALICE durant la période d'amélioration du LHC, précédant le Run 3 (période de prise de données actuelle). Le travail de cette thèse se concentre d'abord sur les développements

d'un outil de commissioning du MFT ainsi que le système de contrôle officiel du détecteur. Dans un deuxième temps, un algorithme reposant sur des techniques de machine learning a été développé pour l'association des traces entre spectromètre à muons et le MFT. Après l'associations de ces traces, et donc la possibilité d'extraction des traces globales de muons, le calcul du point de distance minimale entre ces dernières est requis afin de pouvoir séparer les contributions prompt et non-prompt de particules telles que le J/ψ . Donc, l'outil nécessaire a été également développé. Enfin, des évaluations de simulations Run 3 ont été menées afin de préparer la prise de données.

Title: MFT commissioning and preparation for Run 3 data analysis with ALICE (LHC, CERN)

Keywords: LHC, ALICE, MFT, charmonia, detector commissioning, machine learning

Abstract: The ALICE detector is designed to study the Quark-Gluon Plasma (QGP), a state in which strongly interacting partonic matter is deconfined in a hot and dense medium. The measurement of quarkonium, an important probe of QGP, is possible with ALICE in two regions: at midrapidity, through their dielectron decays, and at forward rapidity, through their dimuon decays with the muon spectrometer. In order to expand the physics program at the forward rapidity region, the Muon Forward Tracker (MFT) was installed in ALICE during the long shutdown, a period in which upgrades take place to prepare for the next

data taking period. The work of this thesis focuses first on software developments for MFT commissioning tool and the official detector control system. Then, algorithm development was done for the track matching between the muon spectrometer and the MFT based on machine learning. Once the matching is performed and global muon tracks are extracted, the calculation of the point of closest approach between the muon tracks was required for the separation of prompt and non-prompt J/ψ contributions. Thus, the secondary vertexing algorithm was also developed. Finally, quality assessments for Run 3 simulations were done to prepare for the upcoming data taking.