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POSGRADO EN FÍSICA APLICADA

Detection and discrimination of diffractive events with ALICE-LHC at CERN

PhD THESIS

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ABSTRACT

The objective of this thesis is the search and study of diffractive events within the ALICE (A Large Ion Collider Experiment) detector at the CERN Large Hadron Collider (LHC). The LHC is designed to collide proton on proton (pp) at a center of mass energy $\sqrt{s} = 13$ TeV, and lead on lead (Pb-Pb) at the center of mass energy per nucleon pair $\sqrt{S_{NN}} = 5.5$ TeV, at very high luminosities. Even though ALICE was designed for the study and characterization of the quark gluon plasma, which is generated at heavy nuclei accelerators (like LHC), ALICE also takes data during pp collisions in LHC, the data taken during this period serves like a reference for the heavy ion phase, but also is used to perform analysis where ALICE is competitive with other LHC experiments.

The cross sections of inelastic and diffractive processes in pp collisions are among the basic observables used to characterize the properties of interactions, for such reason, ALICE has a dedicated program to the study of diffractive events. During run 1 of LHC, ALICE presented a measurement of single and double diffractive cross sections, the results were consistent with all the comparisons made between other LHC experiments.

During the Long Shut Down 2 of LHC, the ALICE collaboration installed a forward detector known as ALICE Diffractive Detector, AD for short. This detector increased ALICE capabilities in the selection of diffractive processes in pp collision events, also optimized the trigger efficiencies at minimum bias level.

In the first two chapters of this thesis there is a brief introduction to the standard model of particle physics and a short description of the ALICE experiment together with the main LHC experiments. Since I found myself highly involved in the incorporation, maintenance and commissioning of ALICE Diffractive detector, in the third chapter I give a detailed description of this detector, along with some performance results during beam test at CERN facilities, and later on during pp collisions. As an extra, during my stay at CERN, I joined the effort for the measurement of the diffractive cross section at $\sqrt{s} = 13$ TeV, in the fourth chapter I present the results obtained in this analysis with 2015 pp data in ALICE. In the final section, there are some conclusions about the work done accompanied by a list of the publications obtained during the realization of this thesis.

DEDICATORIA

A mis padres y hermanos por su apoyo incondicional.

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INTRODUCTION

This chapter will give a briefly introduction to the fundamental particles and their interactions within the Standard Model of Physics. High energy physics is dedicated to the study and description of the elementary components of matter and of the interactions that rule them, physicist have developed and validated a theory of elementary particles and their interactions, called Standard Model (SM). Nevertheless, further investigation is necessary to answer unresolved questions, such like the nature of dark matter and dark energy or the origin of the matter-antimatter asymmetry in the universe.

All matter surrounding us consists of atoms build from electrons and nuclei which are composed of protons and neutrons. Protons and neutrons are bound states of quarks and gluons. The fundamental theory describing the dynamics of quarks and gluons is called Quantum Chromodynamics (QCD). Quarks and gluons do not exist as free particles, but only in bound states called hadrons.

If condensed matter is heated it will experiment a phase transition to the gas phase, and, if heated further, will become an electric plasma with free electrons and ions. Similarly, nuclear matter will experiment a phase transition to a medium of deconfined quarks and gluons if it is heated or compressed. The deconfined medium is called the Quark-Gluon Plasma (QGP).

As we know, the universe is expanding, assuming a constant expansion and extrapolating this expansion backwards in time, the universe was once much smaller, but much denser and hotter. During this time (a few microseconds after the Big Bang) the universe consisted of a QGP until the temperature dropped. The conditions that have existed during this early phase of the universe can be created in ultrarelativistic heavy-ion collisions. Heavy nuclei are collided to create a very dense medium with high temperature.

The medium created in relativistic heavy-ion collisions is present only for a short time before

the temperature drops and quarks and gluons form hadrons again. The properties of such medium can be studied only via the final state of these hadrons. In the four largest LHC experiments there is a dedicated program to study heavy-ion collisions. Also, in these experiments, there are studies with smaller collision systems, in particular proton-proton or proton-nucleus collisions, and they can use this data as a reference for the measurements in heavy-ion collisions.

1.1 The Standard Model

The Standard Model provides a classification of all the subatomic particles known in terms of elementary matter constituents. This theory has been validated with the experimental confirmation of the existence of quarks. Since then, it was completed with the discoveries of the $W^\pm$ and Z^0 bosons (1983), the top quark (1995), the tau neutrino (2000), and the Higgs boson (2012) [32], see fig 1.1.

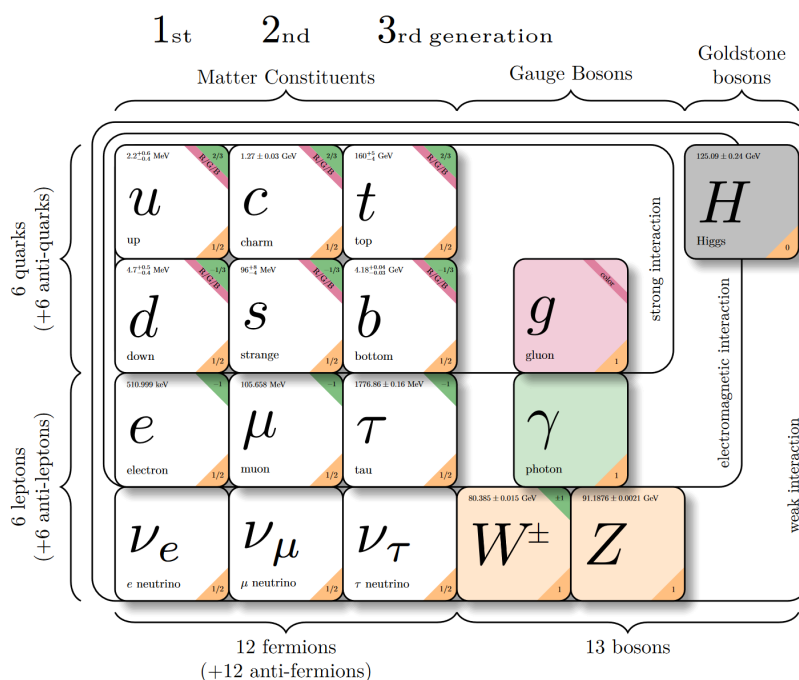


FIGURE 1.1. Basic constituents of the Standard Model of Physics.

Fundamental particles can be divided in two groups: fermions (six quarks and six leptons) with a half-integer spin and bosons with integer spin. The Standard Model describes the interactions between particles via the fundamental forces, the electromagnetic, the weak and the strong force. Gravity does not enter in the standard model and all the efforts to include it have been unsuccessful so far.

- The weak interaction has a small range, of the order of 10^{-18}m , and is mediated by the Z^0 ,

W^+ and W^- bosons. This interaction affects all known elementary fermions.

- The electromagnetic interactions is characterized by an infinite range and affects any particle having a non-zero electric charge. The associated boson is the photon.
- The strong interaction acts only at small distances, with a range of the order of 10^{-15}m . Within this range the strong interaction dominates over the other forces. The strong interaction is mediated by the exchange of massless gauge bosons called gluons which interact with quarks and anti-quarks via a charge called color charge.

The fermions interact via the exchange of gauge boson. The gluon is the gauge boson of the strong interaction, this strong force increases with distance separation. As this separation increases, the potential energy exceeds the pair-production energy and a quark-antiquark pair can be produced. Due to their production, we are never able to observe an isolated quark by itself. This property is called confinement.

1.2 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the theory that describes the strong interactions between quarks and gluons (which build up the hadrons). The dynamic of the interactions described by QCD presents several analogies with the Quantum Electrodynamics (QED) theory which explains the interactions between electrically charged particles in term of exchange of massless bosons called photons. The QCD charge responsible for the strong interaction is the so-called color charge.

Each quark can exist in one of three different color states, designed as red, blue and green. Gluons, which also carry a color charge, act as the exchange particles for the strong force (called also colored force) between quarks.

Properties of QCD include confinement and asymptotic freedom. Asymptotic freedom refers to the effect of the strong force between quarks becoming weaker at smaller distances, allowing them to act like independent particles. QCD predicts that at relatively high density and temperature it is possible to have free quarks and gluons, and their collective behavior exhibits fluid like properties. This state is called the Quark Gluon Plasma (QGP) [24].

1.3 Quark-Gluon Plasma

Since the strong interaction increases with the distance, it becomes impossible to isolate a quark by trying to separate it from its partner, however for systems with sufficiently high energy densities, the hadrons overlap and are compressed so much that their constituents can freely move inside the system without being confined inside hadrons. If the energy density becomes

very large, the interactions strength between quarks and gluons becomes weak and form the new state of matter called Quark-Gluon Plasma.

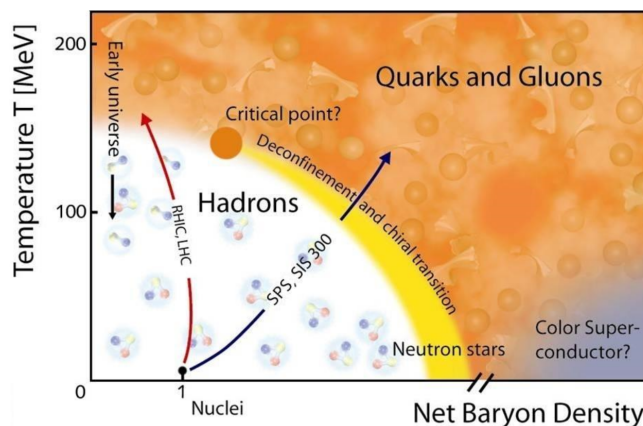


FIGURE 1.2. Schematic QCD phase diagram as a function of temperature and net baryon density.

The schematic in fig 1.2 [41] shows the QCD phase diagram, two main regions can be identified. The first region is at the low temperature and density where quarks and gluons are confined inside hadrons. The second region is characterized by large values of temperature and/or large values of net bayrion density, the regions where Quark Gluon Plasma is generated. These two regions are separated by a phase transition, which frontier is smooth from 0 to an hypothetical critical point as the value of net baryonic density increases. On the contrary, at a low temperature and extreme values of the net baryonic density, other hadron phases phases of the hadronic matter can be possible, and the phase transition changes.

The only way to get experimental access to the QCD phase diagram in the region of deconfinement, under controlled conditions, through performing ultra-relativistic heavy-ion collisions. Different regions of the phase diagram can be covered by changing the center-of-mass energy of the collision: as the energy increases, the initial temperature of the system increases and its net baryonic density decreases. At the high-energy frontier, the experiments carried at the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy-Ion Collider (RHIC) at the BNL are suited to reproduce the conditions of high temperature and low-net baryonic density present in the early Universe.

Despite the QCD has successfully explain a lot of questions in the strong interaction field, there are other questions that remains in without answer, a challenging problem is to understand the high energy behavior of hadronic scattering processes.

1.4 Diffraction

The inelastic processes are usually categorized into diffractive and non-diffractive contributions. The experimental signature of diffractive processes are regions in rapidity empty of particle production called rapidity gaps. In experimental particle physics, pseudo-rapidity (η) is a commonly used coordinate system, describing the angle of the particles relative to the beam axis. It is defined as

$$(1.1) \quad \eta = -\ln \left[\tan \frac{\theta}{2} \right]$$

where θ is the angle between the particle three-momentum $\mathbf{p}$ and the positive direction of the beam axis. Equation 1.1 can be rewritten as a function of $\mathbf{p}$ as:

$$(1.2) \quad \eta = \frac{1}{2} \ln \frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}$$

where p_L is the component of the momentum along the beam axis (sometimes denoted as p_z), for high relativistic particles ($m \ll |p| \Rightarrow E \approx |\mathbf{p}|$), the pseudo-rapidity converges to the definition of rapidity normally used in experimental particle physics:

$$(1.3) \quad y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$

The rapidity y is a useful variable because the rapidity difference between any pair of particles remains unchanged if we go from the centre of mass frame to any other frame reached from it by a longitudinal boost. The rapidity gaps and the elastic scattering are explained in theory as an exchange of a colorless object between the diffracted particles. The dynamics of such object exchanged is poorly understood. This object is a colour singlet object with the quantum numbers of the vacuum (Pomeron).

The Feynman diagrams corresponding to Pomeron exchange in elastic, single, double and central processes are shown in figure 1.3. These processes can be considered as binary collisions, in which one or both incoming protons may become an excited system, which decays into stable final-state particles.

Single Diffraction is similar to elastic scattering except that one of the protons breaks up, producing particles in a limited rapidity region, in these processes there is a rapidity gap between the outgoing protons and the other particles produced in the fragmentation of the diffractive system. In double Diffraction, both protons break up, but there is a rapidity gap between the two diffractive systems.

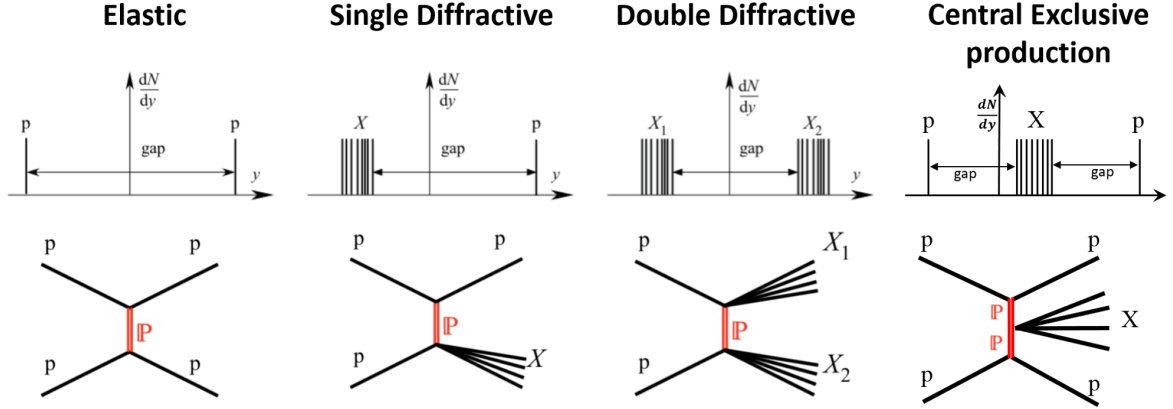


FIGURE 1.3. Top: Schematic rapidity (y) distribution of outgoing particles in elastic, single, double and central diffractive processes. Bottom: Feynman diagrams for diffractive processes with low Pomeron exchange order. $\mathbb{P}$ stands for Pomeron, p for proton, and X (X_1, X_2) for the diffractive system.

Experimentally, there is no possibility to distinguish large rapidity gaps caused by a Pomeron exchange from those caused by other colour-neutral exchanges, the separation is model dependent. In practice, a number of approximations are required for defining and measuring the rapidity gaps. In the fourth chapter of this thesis we present a different approach to the measurements of diffractive processes using the forward detectors in the ALICE experiment at LHC.

THE LHC AND THE ALICE EXPERIMENT

CERN (Conseil Européen pour la Recherche Nucléaire) is one of the biggest and respectful investigation centers in the world. The main topic of investigation is particle physics, and the fundamental constituents of matter. In 1957 CERN started the first experiments in particle and nuclear physics with the Synchrocyclotron (SC), since then CERN has been always going one step ahead in accelerator technologies, in 1959 the Proton Synchrotron (PS) started its operations, reaching energies up to 25 GeVs, and by 1976 it would have become the particle supplier for the new machine, the Super Proton Synchrotron (SPS). The SPS is at the moment the second-largest machine in CERN, it measures nearly 7 kilometers in circumference, and can operate up to 450 GeV. The Super Proton Synchrotron takes particles from the PS and accelerates them in order to provide beam for different experiments in CERN, such as NA61 [27], NA62 [12], ISOLDE [21] and the LHC.

NA61 is a fix target experiment that studies the properties of hadron production in collisions of beam particles and different fixed nuclear targets, while NA62 studies the rare kaon decays firing the beam coming from the SPS into a stationary beryllium target. Furthermore ISOLDE, dedicates its facilities to the production of radioactive ion beams which are used in different experiments in materials and life sciences.

2.1 The Large Hadron Collider

The Large Hadron Collider is the world's largest particle collider build in CERN, it is located in the border between France and Switzerland, in consists of approximately 27 km of superconducting electromagnets situated 100 m underground. Two beam particles formed of protons or ion nuclei travel inside this accelerator reaching almost the speed of light, they travel in different directions in two parallel beamlines.



FIGURE 2.1. A view into the tunnel of the LHC.

Each of the beams in LHC are made of bunches of protons spaced 7 meters (25 nanoseconds), being 2556 the maximum number of bunches, and each of the bunches containing roughly 100 billion protons. These bunches are squeezed when they approach the experiments along the LHC, in these experiments the circulating beams are made to collide. Not all the protons in each beam collide during this process, the remaining protons are focused again and they continue their path to the next experiment in LHC.

LHC started its operations in 2009 (Run 1, 2009-2013) exploring several energies and three collision systems (pp, p-Pb, Pb-Pb). Different center-of-mass energies were considered, going from 0.9 to 8 TeV in pp collisions, and for the case of p-Pb (Pb-Pb) 5.02 TeV (2.76 TeV).

Run 1 of LHC was followed by the first Long Shutdown (LS1), a period dedicated to the upgrade of the systems in the different experiments and the machine itself, the major upgrade in LHC gave as result an increase in the collision energy, moving from 7 TeV to 13 TeV in proton-proton collision (from 2.76 to 5.02 TeV in Pb-Pb). LHC started its operations after the LS1 in June 2015, running continuously (with small pauses every end of year) until December 2018.

In high energy physics the luminosity is an essential concept, basically express the interaction rate normalized to the intensity of the interacting fluxes of particles. During Run 2 of LHC there was an increment of the luminosity delivered to the different experiments, this luminosity is defined in equation 2.1, where N_b is the number of particles per bunch, n_b is the number of bunches per beam, f_{rev} the revolution frequency, γ is the relativistic factor, ϵ_n the transverse beam emittance, β^* the beta function at the interaction point and F is a correction factor due to the crossing angle at the interaction point.

$$(2.1) \quad \mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F$$

2.1.1 The LHC Experiments

The LHC accelerator complex currently has 4 cross or colliding points, in which 4 big experiments are located, ATLAS, ALICE, CMS and LHCb located at point 1, 2, 5 and 8 respectively.

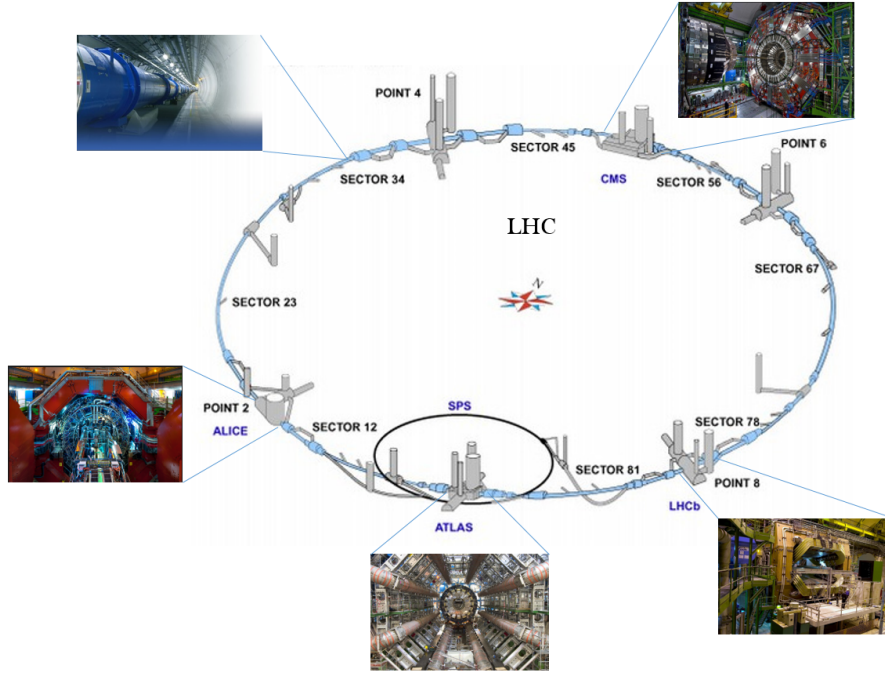


FIGURE 2.2. Schematic of LHC experiments.

Each of these experiments are formed by an independent collaboration, and even though they use the same machine, LHC, they have different topics of investigation. During most of the year LHC carries out its proton-proton program, and at the end of each year the Heavy-Ion program starts.

The goal of the LHC heavy-ion program is to produce the largest volumes of Quark Gluon Plasma in laboratory, in order to provide a precise characterization of this new state of matter. For this reason, during the end of each year of data taking LHC provides nucleus-nucleus (and proton-nucleus) collisions. In addition to LHC, there are other Heavy-Ion colliders such as RHIC (Relativistic Heavy Ion Collider) located at BNL (Brookhaven National Laboratory) in the US, or NICA (Nuclotron-based Ion Collider fAcility) that is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, to study properties of dense baryonic matter.

In the LHC complex, ALICE is an experiment optimized for the study of QGP state, having detectors that focus on the characterization of strongly interacting matter at extremely high energy density.

2.2 The ALICE Experiment

ALICE (A Large Ion Collider Experiment) was design as a heavy-ion detector in LHC. It exploits the physics potential of nucleus-nucleus interactions at LHC energies. It has an excellent particle identification (PID) capabilities in a wide transverse momentum range ($0.15 \leq P_T \leq 20$ GeV/c).

THE ALICE DETECTOR

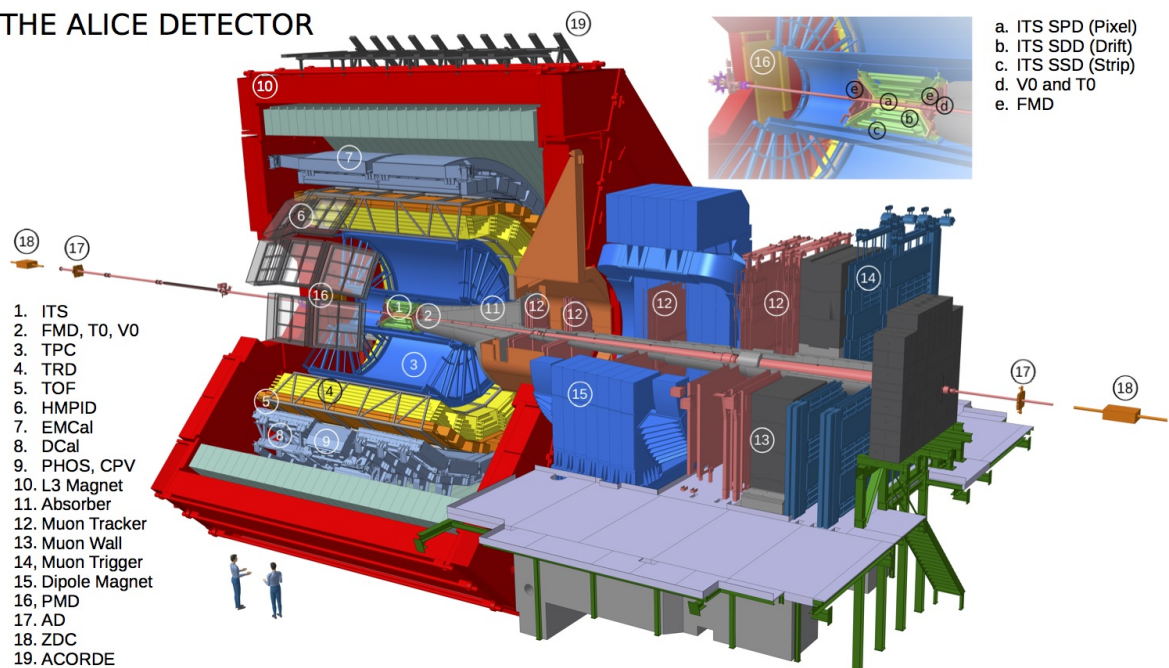


FIGURE 2.3. Schematic of the ALICE experiment.

ALICE was designed to operate at a very high multiplicity environment, which is presented in LHC Pb-Pb collisions. The main purpose of the experiment is to study the quark-gluon plasma, which is expected to be created at extreme energy densities of strongly interactive matter.

The ALICE project involves an international collaboration of more than 1500 physicists, engineers and technicians, from more than 150 physics institutes in 37 countries across the world. It is located at Pint 2 of LHC, roughly 50 m underground, its overall dimensions are $16 \times 16 \times 26 \text{ m}^3$ with a total weight of approximately 10,000 tons. A layout of the ALICE experiment is presented in fig 2.3, it could be divided in three main parts, the central barrel, the muon arm and the forward detectors.

The (0,0,0) of the coordinate system in ALICE (x, y, z) is located at the center of the central barrel, the z -axis points along the beam line away from the muon arm, the x -axis points toward the center of LHC ring, and the y -axis point upwards, orthogonal to the xz plane.

2.2.1 The central barrel

It is situated inside the solenoid magnet (L3), which has a magnetic field parallel to the the beam axis in the central region with an intensity of $B = 0.5 \text{ T}$. The L3 magnet has two main functions in ALICE: it bends the trajectory of the charged particles in the transverse plane so that ALICE can perform a nice PID estimating the momentum, and the second function of L3, it suppresses the diffusion of secondary electrons in the time-projection chamber (TPC).

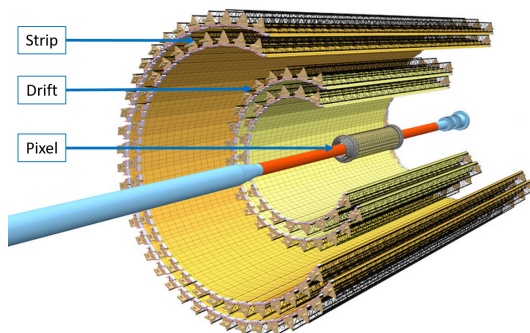


FIGURE 2.4. Schematic of the Inner Tracking Detector.

The detectors that make up the central barrel are used for triggering, but mainly for particle tracking and identification, the detectors in the central barrel have a full azimuthal coverage in the pseudo-rapidity region $|\eta| < 0.9$, and consists of 9 subsystems:

- The Inner Tracking System (ITS), which can be considered as 3 subsystems:
 - The Silicon Pixel Detector (SPD)
 - The Silicon Drift Detector (SDD)
 - The Silicon Strip Detector (SSD)
- The Time-Projection Chamber (TPC)
- The Transition Radiation Detector (TRD)
- The Time of Flight detector (TOF)
- The High-Momentum Particle Identification Detector (HMPID)
- The Photon Spectrometer (PHOS)
- The Electromagnetic Calorimeter (EMCAL).

2.2.1.1 The Inner Tracking System

The ITS is the nearest detector to the interaction point, roughly 4 cm for the innermost layer, and 43 cm for the outermost. It consists of three subsystems, each one with different technology: the SPD, SDD and SSD (see fig 2.4). Each subsystem contains 2 layers of concentric silicon detectors. The pseudo-rapidity coverage of the ITS is $|\eta| \leq 0.9$. The main purposes of ITS are triggering, tracking, primary and secondary vertex finder and particle identification at low P_T .

The first two layers of the ITS form the **SPD** [40], it consists of ~ 9.8 million cells that are read out by 1200 chips, it is able to operate at a very dense charged-particle environment and can reconstruct secondary vertices.

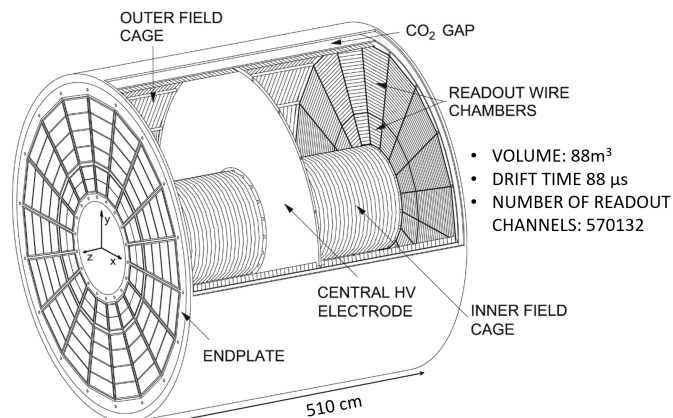


FIGURE 2.5. Schematic of the Time Projection Chamber.

The **SDD** [8, 28] consist of the two middle layers of ITS, it is form by two dimensional sensors providing high resolution coordinates. The inner (outter) layer of the SDD is conformed by 14 (22) ladders, each one of them supporting six (eight) sensors with $\sim 7.02 \times 7.53 \text{ cm}^2$ of active area.

The **SSD** [28, 37] occupies the two outermost layers of the ITS, its main role is the matching of the tracks between the TPC (Time Projection Chamber) and the ITS.

2.2.1.2 The Time Projection Chamber

The time-projection chamber (fig: 2.5) is the main detector of ALICE, used fro tracking and particle identification [10]. It surrounds the ITS, and it is composed of a 5.1 m long cylindrical drift volume of 88 m^3 . The end plates are equipped with multiwire proportional chambers. It covers the same pseudo-rapidity as the ITS ($|\eta| \leq 0.9$). The TPC performs charge-particle identification by measuring the specific ionization energy loss dE/dx . The momentum resolution of the tracks is better than 2.5% for tracks with a momentum below 4 GeV/c. The TPC allows up to 8,000 tracks per unit of rapidity in one collision event to be reconstructed and identified.

2.2.1.3 The Transition Radiation Detector (TRD)

he Transition Radiation Detector (TRD) [16] is the main electron detector in ALICE. In conjunction with the TPC and the ITS, it provides the necessary electron identification capability to study production of light and heavy vector mesons as well as the continuum in the di-electron channel, semi-leptonic decays of hadrons with open charm and open beauty via the single-electron channel using the displaced vertex information provided by the ITS, jets with high transverse energy by requiring several high pt tracks in one single TRD module.

2.2.1.4 The Time of Flight detector (TOF)

The TOF [17] covers pseudo-rapidity range $|\eta| < 0.9$, it has a length of 7.5 m, an inner radius of 3.7 m and outer radius 3.9 m. It is designed to identify particles. It has a modular structure organized into eighteen sectors in azimuth and five modules along the beam axis (see fig: 2.6). The main task of TOF is to improve particle identification in ALICE. Using the time of flight of particles to distinguish between protons, kaons, and pions. The TOF has an intrinsic time resolution of about 50 ps thanks to the technology of Multi-Resistive Plate Chambers (MRPC).

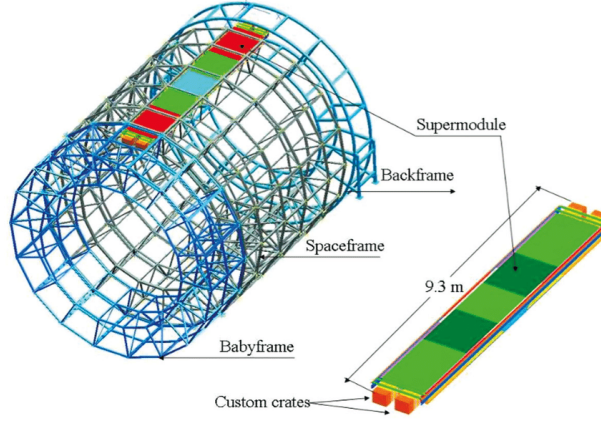


FIGURE 2.6. Schematic of the Time Of Flight Detector.

2.2.1.5 The High-Momentum Particle Identification Detector (HMPID)

The High Momentum Particle IDentification (HMPID) [38] system enhance the PID capability of ALICE beyond the momentum range allowed by the energy loss measurements (ITS and TPC) and by the TOF. The pseudo-rapidity acceptance is $|\eta| < 0.6$ and an azimuthal coverage between 1 and 59°, corresponding to 5% of the central barrel acceptance. The HMPID allows one to extend the particle identification for π and K up to $p_T \approx 3$ GeV/c and $p_T \approx 5$ GeV/c for protons.

2.2.1.6 The PHOton Spectrometer (PHOS)

The PHOton Spectrometer (PHOS) [31] is a high resolution electromagnetic spectrometer, covering the pseudo-rapidity range $|\eta| < 0.13$ and the azimuth between 220 to 320°, it is installed at a radial distance of 460 cm. The detector technology is based on lead-tungstate (PbWO₄) crystals. The PHOS is used to detect photons in the transverse momentum range between 0.5 to 10 GeV/c.

2.2.1.7 The Electromagnetic Calorimeter (EMCAL)

The ElectroMagnetic Calorimeter (EMCal) [14] and its extension the Di-jet Calorimeter (DCal) are sampling electromagnetic calorimeters with the pseudo-rapidity coverage $|\eta| < 0.7$ and

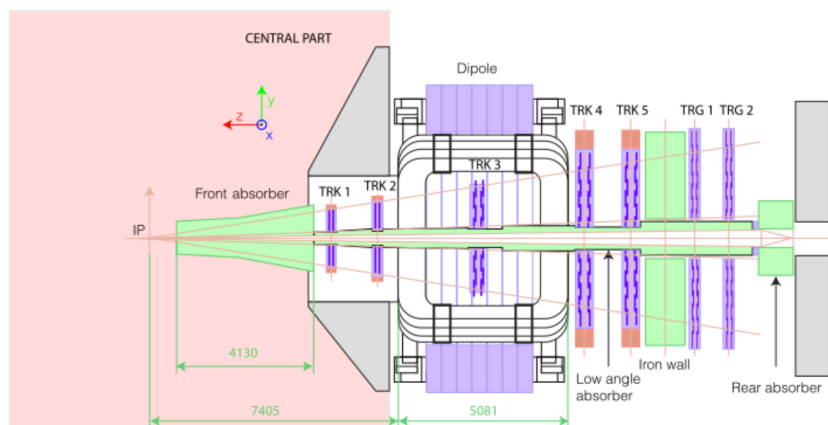


FIGURE 2.7. Schematic of the ALICE muon spectrometer.

azimuth coverage from 80 to 187° (for the ECal) and 260 to 327° (for the DCal). The combined information of the ECal and the DCal allows to study jets and di-jets, providing trigger signals for hard jets, photons and electrons.

2.2.2 The Muon Spectrometer

The muon spectrometer [2] consists of a front absorber, five tracking stations (the third one inside a warm dipole) and iron wall and finally two triggering chambers (figure 2.7), each chamber with pads in both sides of the gas gap in order to get correlated x-y measurement in each chamber. The pseudo-rapidity covered is $-4.0 < \eta < -2.5$. It was design to study quarkonia (J/ψ and γ families) and production of light vector mesons through their muon decays.

The **absorber** is located just after the V0-C, at 90 cm from the interaction point, it suppresses all the particles except muons coming from the interaction, it is made with carbon and concrete. The **dipole magnet** is design to produce a horizontal magnetic field perpendicular to the beam axis, it is at 9.9 m from the interaction point, and it can delivers a maximum magnetic field of 0.7 T.

The **tracking chambers** are composed of five stations, with different designs according to their dimensions. The chambers are based on a Multiwire Proportional Chamber technology with pad-segmented cathodes. The full tracking system was design to achieve the spatial resolution of $100 \mu\text{m}$. The **iron wall** is used to complement the hadron absorber. It is 1.2 m thick, located at 15 m from the interaction point, it suppresses the hadrons emerging from the front absorber.

At the end of the ALICE muon spectrometer there are two trigger stations, based on Resistive Plate Chamber (RPC) technology. These stations are in charge of the selection of events of interest for the muon physics, the trigger logic can be defined in terms of two different p_T thresholds.

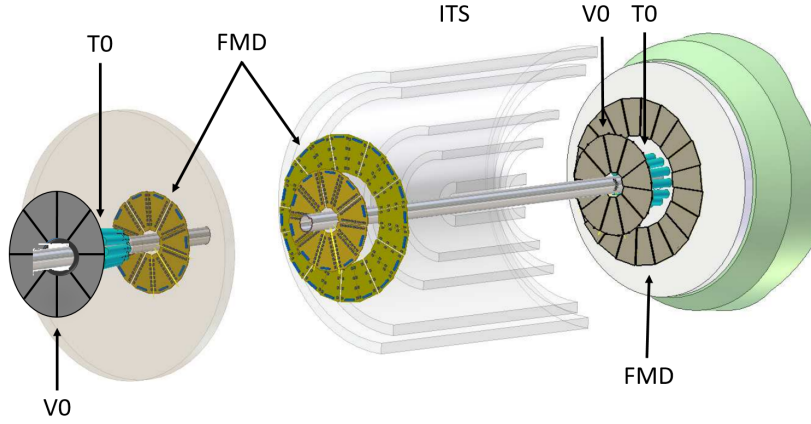


FIGURE 2.8. Schematic of the ALICE Forward Detectors (V0, T0 and FMD).

2.2.3 The Forward Detectors

ALICE has several detectors covering the forward/backward acceptance regions, these detectors are used to measure global observables like centrality, event plane, and as an extra, ALICE has a program dedicated to the study of diffractive events. Thanks to the forward detectors, ALICE has a pseudo-rapidity coverage $-7.0 < \eta < 6.3$ with a gap uncovered (geometrically) from $-4.9 < \eta < -3.7$. The forward region in ALICE is covered by 6 subsystems:

- The Forward Multiplicity Detector (FMD)
- The "Time 0" detector (T0)
- The "Vertex 0" detector (V0)
- The Photon Multiplicity Detector (PMD)
- The ALICE Diffractive Detector (AD)
- The Zero Degree Calorimeter (ZDC)

2.2.3.1 Forward Multiplicity Detector (FMD)

The Forward Multiplicity Detector (FMD) [13, 15] is based on the silicon strip technology. It is divided into seven disks perpendicular to the beam pipe located at distances between 42 and 225 cm from the interaction point. The goal of this sub-detector is to study the charged particle multiplicity in the pseudo-rapidity ranges $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.1$.

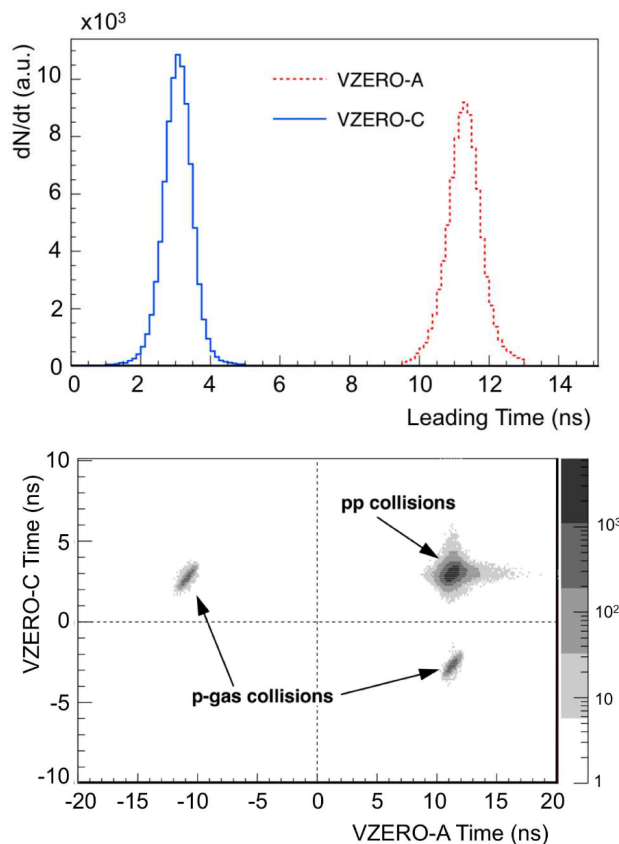


FIGURE 2.9. Top: VZERO-A (red-dashed line) and VZERO-C (blue-solid line) time of flight distributions for beam-beam collisions, with 0.45 and 0.35 ns r.m.s. respectively. Bottom: time of flight of the particles detected in VZERO-C versus VZERO-A.

2.2.3.2 The T0 detector

The T0 [15] detector consists of two arrays of PMTs equipped with Cherenkov radiators, these arrays are on opposite sides of the interaction point, at 70 cm for the C-side and 3.6 m for the A-side. The main task of T0 is to supply fast timing signals (L0) to the central trigger processor, it also gives a wake-up signal for the TRD and acts as a reference from collision time to the Time of Flight detector.

2.2.3.3 The V0 detector

The V0 [15] detector consists of two arrays of plastic scintillator installed on both sides of the interaction point at 329 cm (90 cm) for the case of V0-A (V0-C). The main function of V0 detector is to measure charge particle multiplicity, it provides physics measurements of luminosity, it gives a minimum-bias trigger for the central barrel detectors, and also works as a beam-induced background rejection thanks to the time-of-flight measurements (see fig 2.9).

The signal produced by the scintillator tiles of the VZERO is related by a monotonic function

to the number of particles traversing the detector. The detector can therefore be used to estimate the centrality of a Pb–Pb collision since the number of produced particles is strongly correlated with the impact parameter of the collision.

2.2.3.4 Photon Multiplicity Detector (PMD)

The PMD [3] consists of two identical planes of detectors that use gas as a sensitive medium. It is located at 360 cm from the interaction point in the A-Side (positive η). The PMD covers the pseudo-rapidity region $2.3 < \eta < 3.7$. By measuring the multiplicity and spatial distribution of photons on an event-by-event basis, the PMD is able to study event shapes and fluctuations in the forward region where large particle densities impose very severe constraints on the design of the detectors.

2.2.3.5 Zero Degree Calorimeter (ZDC)

The Zero Degree Calorimeter (ZDC) [20] is composed of two neutron and two proton calorimeters located symmetrically on both sides of the interaction point at 115 m (fig 2.10). It is used for the measurement of the spectator nucleons and serves mainly for the triggering. The ZDC is made of a stack of heavy metal plates grooved to allocate a matrix of quartz fibres. High energy protons and neutrons hitting the passive material in the detector creates a cascade of particle, called “shower”. When one of these shower particles crosses a fiber (if its speed is high enough) it can produce light (Cherenkov effect). This light propagates in the fibre by total reflection up to its end, where a photomultiplier converts the light into an electric signal.

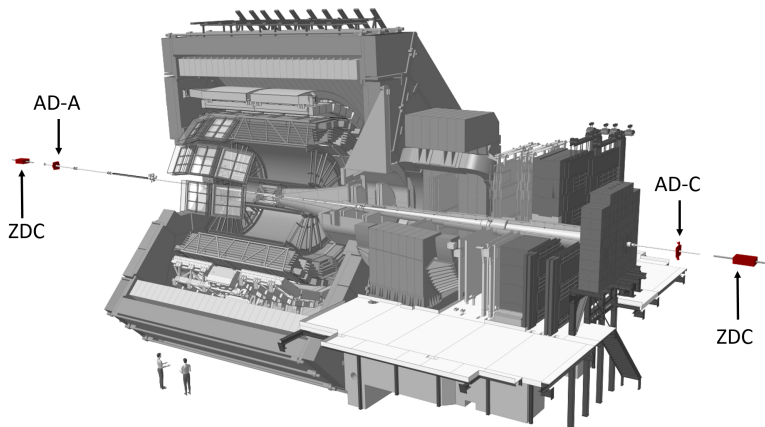


FIGURE 2.10. Schematic of the ALICE experiment showing the position of AD and ZDC detectors.

2.2.3.6 ALICE Diffractive Detector (AD)

The ALICE diffractive detector (AD) is a sub-detector installed in ALICE during the LHC Long Shutdown 1 [22], the goal of this detector is to increase the pseudo-rapidity coverage of ALICE experiment. It also improves the minimum bias trigger to lower diffractive masses. The next chapter in this thesis is dedicated to a full explanation of this detector.

2.3 Diffractive Cross Section in ALICE at $\sqrt{7}$ TeVs

The cross sections of inelastic and diffractive processes in proton–proton (pp) collisions are among the basic observables used to characterize the global properties of interactions, and thus are always a subject of interest at a new centre-of-mass energy. At a center-of-mass energy $\sqrt{s} = 1.8$ TeV, at the Tevatron, the diffractive processes represent about 25 % of inelastic collisions. At the energies reached by LHC, the fraction of diffractive events its expected to be larger.

At LHC energies, the diffractive events can dominate the overall systematic error, therefore ALICE together with the rest of LHC’s experiments performed a measurement of diffractive processes with Run 1 data. ALICE presented its results in [18].

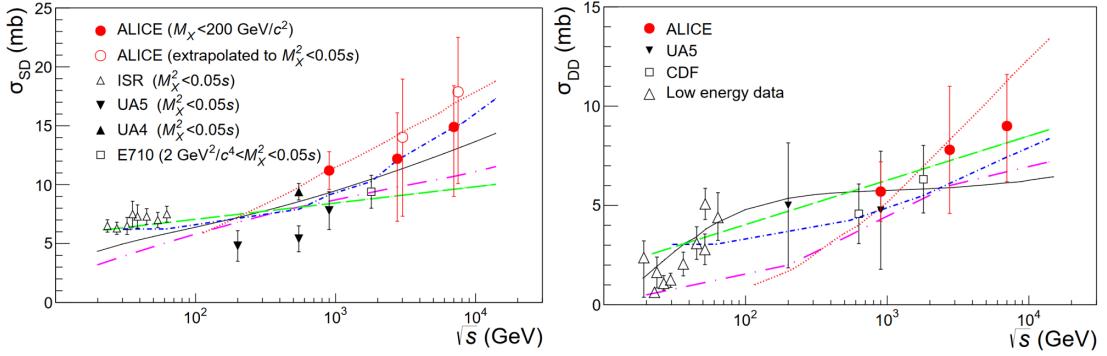


FIGURE 2.11. Left: Single-diffractive cross section as a center-of-mass energy. Comparison between ALICE and other experiments, including an extrapolation to $M_X^2 < 0.05s$. Right: Double diffractive cross section as a function of center-of-mass energy, including a comparison with the theoretical model and the results from other experiments.

The cross sections for single and double diffractive processes were obtained in ALICE combining the measured inelastic cross sections with diffractive relative rates. The results were compared to other measurements at LHC, and the results seems to be consistent with all the comparisons within certain uncertainties.

THE ALICE DIFFRACTIVE DETECTOR

In order to optimize the trigger efficiencies and purities in selecting diffractive events, the ALICE collaboration installed a very forward detector during the LHC Long Shut-Down 1, called AD or ALICE Diffractive detector. The forward physics capabilities of ALICE were substantially upgraded by the installation of AD detector systems [4, 7]. Since I found myself involved in AD detector from the construction, the calibration, installation and then the commissioning during LHC run 2, I will dedicate a chapter to the description of this detector.

3.1 Geometry and Composition

The AD detector consists of two stations (ADA and ADC), installed on each side of the interaction regions at $Z_{ADA} = +16.96$ m and at $Z_{ADC} = -19.54$ m, each station is made of two layers of BC404 plastic scintillator, and each layer consists of four scintillator pads (8 pads in total per station) 3.1. The two stations are installed around the beam pipe, ADA is located after the compensator magnet on the ALICE A-Side (see fig 3.3), and ADC is located inside the LHC tunnel (ALICE C-Side).

Each AD cell is coupled to a 1.5 inches PMT (Hamamatsu H6153-70) through an array of approximately 200 clear optic fibers and two wavelength-shifting bars, one on each side of every pad (see fig 3.2), between the pads and each wavelength-shifting bar there is a 0.4 mm air gap, to ensure the maximum light transmission. The length of the fibers differs in each side, in the case of ADC, the fibers are 2.5 m long, and for ADA it is split in "top" and "bottom", for the top modules the length is 1.0 m, and for the bottom modules 0.57 m (this is due to space limitations). In order to place the AD stations as close as possible to the beam pipe, there is a hole near the corner of the modules, leaving a gap of the order of 5 mm between the beam pipe and AD modules.

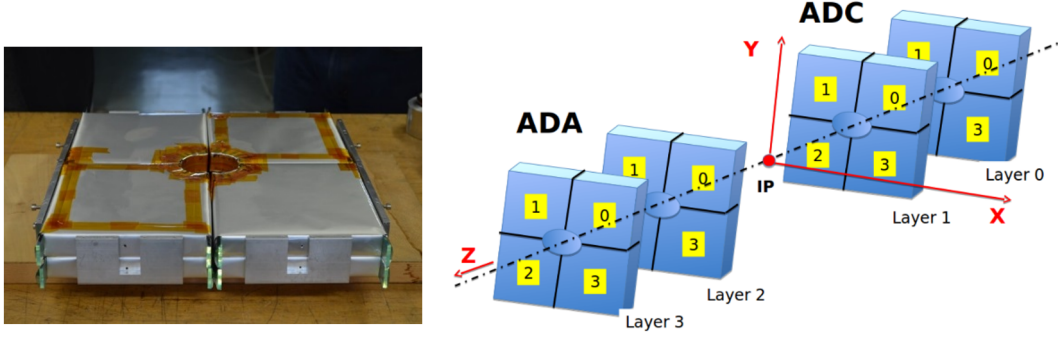


FIGURE 3.1. (Left) Real picture of one station of the ALICE Diffractive detector. (Right) Schematic of the two stations that make up the detector with indication of the numbering scheme. The ALICE coordinate system is shown in red

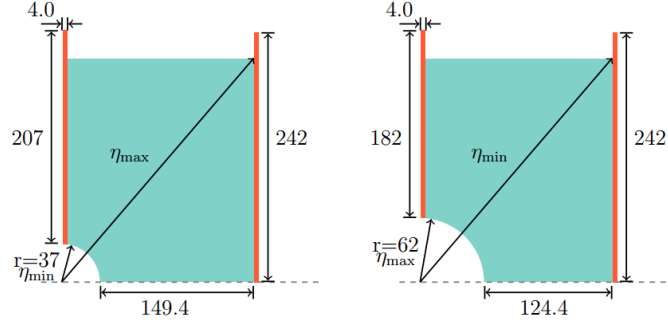


FIGURE 3.2. Layout of ADC (left) and ADA (Right) modules, showing the geometry of the scintillator pads (green) and the wavelength-shifting bars (red). All dimensions are in millimeters.

3.2 Simulation and Pseudo-rapidity coverage

Due to the special beam optics conditions at the ALICE interaction point (IP2), the experiment has ideal running conditions for diffractive physics. ALICE collects pp collision data with minimal pile-up, in well understood background conditions during the nominal low-x runs designed for the ATLAS and CMS searches of rare phenomena at large transverse momentum processes.

The AD detector increases substantially the acceptance and the trigger efficiency for low diffractive masses, close to threshold ($m_p + m_\pi$), and also improves the trigger efficiency for Minimum Bias Events (see fig 3.5). Because of its geometrical size and position, this detector increases significantly the pseudo-rapidity coverage of the ALICE experiment, with ranges $-7.0 < \eta < -4.9$ for ADC, and $4.8 < \eta < 6.3$ for ADA, so it can be used for extend the pseudo-rapidity gap trigger, used for the study of central exclusive production.

With the inclusion of AD, ALICE finds itself in a better position in geometrical pseudo-rapidity range, from -7.0 to $+6.3$, with a gap of $\Delta\eta = 1.2$ between -4.9 and -3.7 (see fig 3.4), even more,

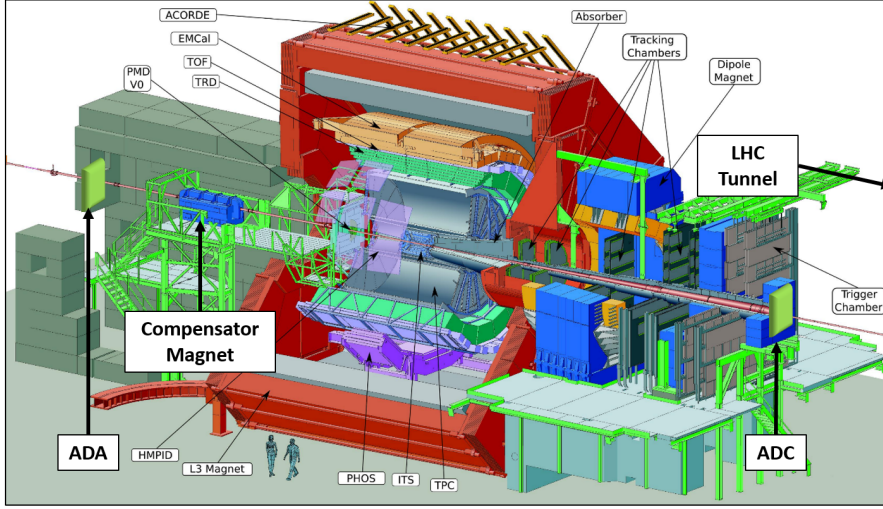


FIGURE 3.3. Schematic of ALICE experiment showing the position of ADA (after the compensator magnet) and ADC (in the LHC tunnel).

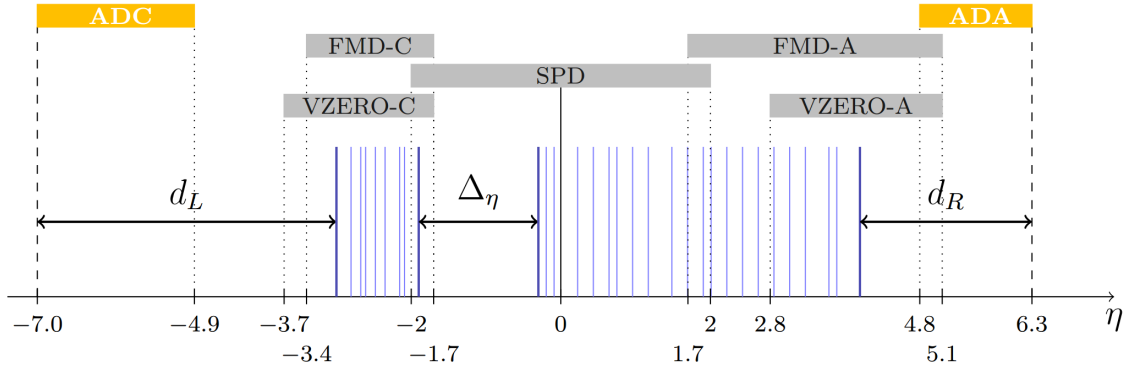


FIGURE 3.4. Geometrical η coverage of the ALICE experiment after the inclusion of AD detector.

AD has the capability of generate a trigger on the charge deposited in the modules, function that can be used for centrality trigger during both Pb-Pb and pPb collisions.

Due to the large material budget found between the interaction point and the two stations of AD, there is a large amount of secondary particles reaching the scintillators, this has a double effect in AD, increasing the efficiency and η coverage, while at the same time making it more uncertain.

3.3 Readout System and Detector Control System

The ALICE Data-Acquisition system (DAQ) handles the data coming from the 20 sub-detectors. Each of these detectors is able to send event fragments to DAQ system in parallel through the

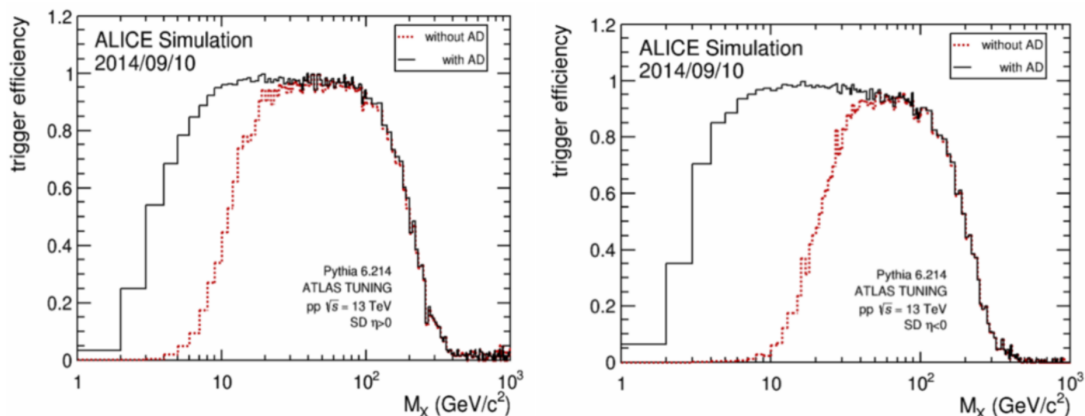


FIGURE 3.5. Trigger Efficiency for single diffractive events before and after the inclusion of AD. For $\eta < 0$ (left) and $\eta > 0$ (right).

ALICE Detector Data Link (DDL). Every sub-detector has a Front-End Electronics (FEE) able to handle the information coming from the detector itself and with the capability of generate or build the sub-event that will be stored by the DAQ system.

3.3.1 AD Front-End Electronics

In the case of AD, the readout and data acquisition is design to be compatible with different running modes in ALICE. The system is able to generate 5 trigger signals, which are sent to the Central Trigger Processor (CTP). As explained in section 3.1, AD consist of two stations (ADA & ADC), each station with two layers of scintillators, in order to generate a Minimum Bias trigger signal in AD, 2 adjacent pads need to have one event detected.

The signals generated by each AD cell pass through a pre-amplifier, which delivers two signals for different purposes: one amplified by a factor 10, that will be used for trigger generation and time measurement, and the second one with a factor 1 (buffer) which will be used for charge measurement. All the signals are connected to the main electronics, located at a 9U VME crate, used for mechanical support and voltage supply.

All the data taking for AD detector is synchronize with LHC clock (40 MHz). In order to read the integrated charge with this clock period, there is an array of two integrators working alternately for the buffered signal. These integrators have a programmable gate width (from 5 ns to 30 ns in steps of 5 ns) and the recovery time will be null due to this alternate phase (see fig 3.6). In other words, one integrator will operate during odd BC (Bunch Crossing) periods and the other one in even BC periods. The reset/width of the integrator is controlled by an FPGA (Cyclone IV family).

All the Front-End Electronics system of AD is based in the V0 detector [42], this system consist mainly of three elements:

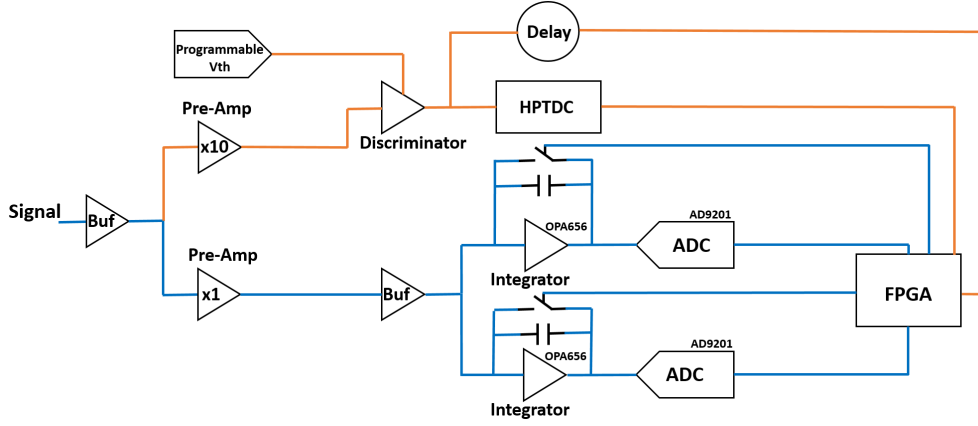


FIGURE 3.6. Dual high speed integrator block diagram. Two outputs coming from pre-amplifier, one for trigger and time measurement with programmable threshold, the second one for charge integration with dual scheme.

Timing, trigger and Control Interface Unit (TTCIU), this board is the interface between the Timing and Trigger Control (TTC) distribution system and the main board of the FEE.

The TTCIU also handles the clock and trigger distribution along the FEE through the VME back panel. The main component of this board is the TTCrx, which acts as an interface between the TTC system for LHC clock and trigger messages and the receiving users (in this case, AD FEE).

The second element is the **Channel Interface Unit (CIU)**, this unit is the first receiver and processor of the signals coming from the detector after the pre-amplification stage. Here the charge is measured with a dual high speed integrator (see fig 3.6) based on a dual channel, 20 MHz 10 bit resolution ADC (AD9201). The CIU also handles the digitization of the time for all the hits detected, for this, it uses an ASIC for time measurement, the High Performance Time to Digital Converter (HPTDC) [13], capable of performing precise time measurement for multiple channels, in the order of 16 ps RMS (Root Mean Square). Finally in the CIU a pre-processing of the different triggers generated is done, as well as data storage during L0 and L1 trigger.

The final element of the Front-End would be the **Channel Concentrator Interface Unit (CCIU)** which collects and organize the data from all the CIU boards connected, it makes the final processing of the trigger signals, and works as an interface between the general ALICE systems (DAQ, CTP & DCS)

3.3.2 AD Detector Control System (DCS)

All the operation and control of the experiments is done through the ALICE control system, which is centrally managed by the ALICE control coordination group. Every detector in the experiments has to develop its own control system under some standards that allows the integration with the

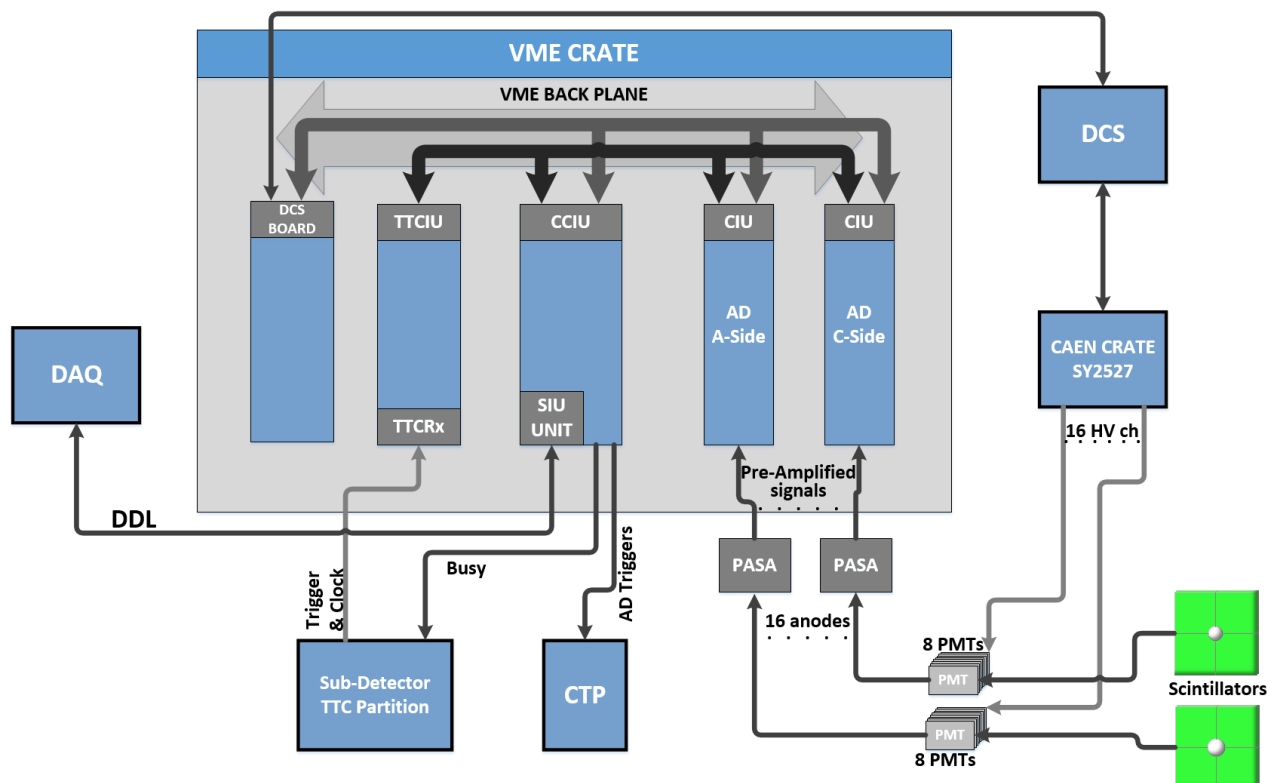


FIGURE 3.7. AD Data acquisition Scheme, including slow control (DCS), trigger and DAQ links.

ALICE control system. The DCS for AD is used for monitoring, configuration and control of the detector from a user interface (fig 3.8).

The user interface has access to all the configurations possible in the FEE, from this interface the detector expert can change different parameters such as time windows, logic for triggering, delay of signals, discrimination voltage and more. In the same interface one can find the control for the different detector configurations at a top level, represented as finite state machines, from here the user can move the detector from a state "OFF" to a state "Ready" passing through several states. Basically what this means is that the user can turn on the high & low voltage, can configure the FEE, and can set the detector ready for ALICE data taking.

In addition, the DCS archives the detector configuration during each run, this information may be useful for future physics analysis. One important function of the DCS is the automation of all these tasks, in order to reduce the risk of human errors as well as creating the possibility to control ALICE by a reduced team of people (shifters).

The devices monitored can be identified as the high and low voltage power supply, the preamplifier shoe box, the VME crate with the FEE boards and the temperature sensors close

3.3. READOUT SYSTEM AND DETECTOR CONTROL SYSTEM

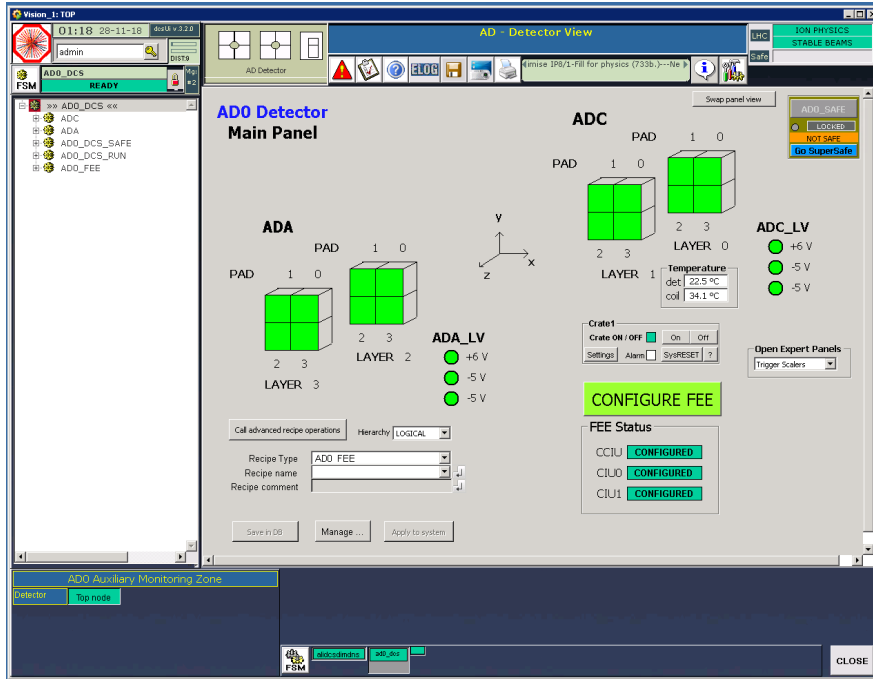


FIGURE 3.8. User interface of AD Detector Control System.

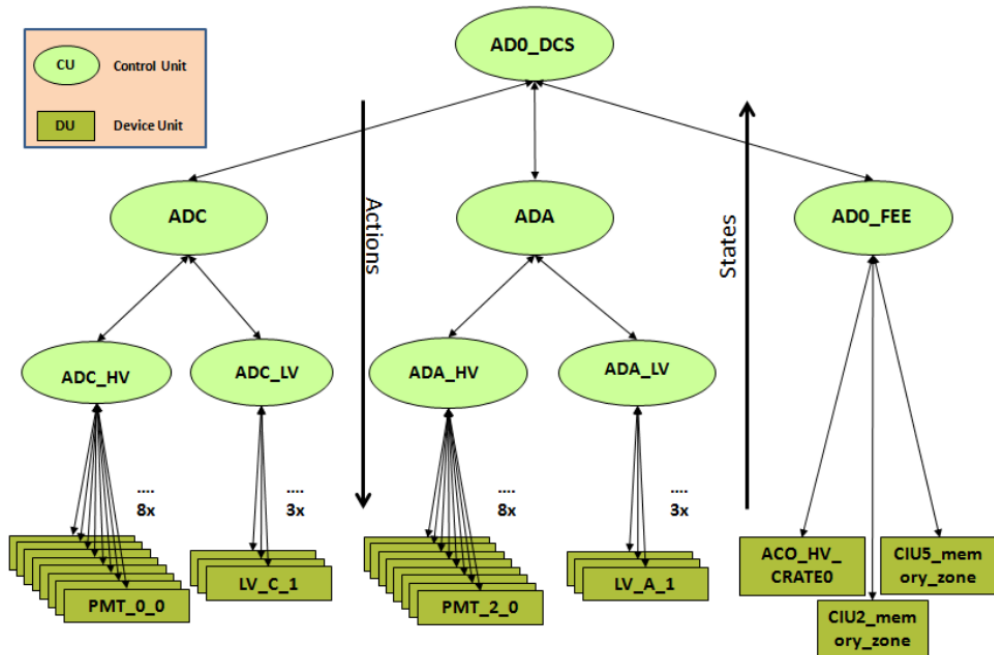


FIGURE 3.9. Hierarchical software architecture of the AD DCS.

to the magnet in ADC. The figure 3.9 shows a logical representation of the AD detector that is implemented in the DCS software, the control and device units are programmed as finite state

machines, the state of a device unit depends on the real status of the hardware it models, while the state of a given control unit depends on the states of the units just below it.

This hierarchical architecture allows the detectors to present a much simpler human interface, where the shifter can easily monitor the status of the detector, as well as moving it to a status "ready" for data taking, or a status "safe" when the LHC beams are not stable.

3.4 Calibration

In order to start ALICE data taking with a good calibration and understanding of the different parts conforming AD, we performed a calibration for each of the 16 sensors of the detector. Two scintillator pads were placed to arrange a cosmic trigger (fig:3.10), and in the middle of these pads an AD module with the sensor under test. For every step of 50 volts we obtained the efficiency and the value of the integrated charge.

The efficiency is the fraction of events according to equation (3.1):

$$(3.1) \quad Efficiency = \frac{N}{N_{Trigger}} = \frac{N_{Trigger} \wedge N_{Module}}{N_{Trigger}}$$

where N is the number of events that fulfill the 3-fold coincidence condition, defined by the logical AND ($\wedge$) between the trigger modules and the module under test, similarly $N_{Trigger}$ is given by the 2-fold coincidence between the trigger modules.

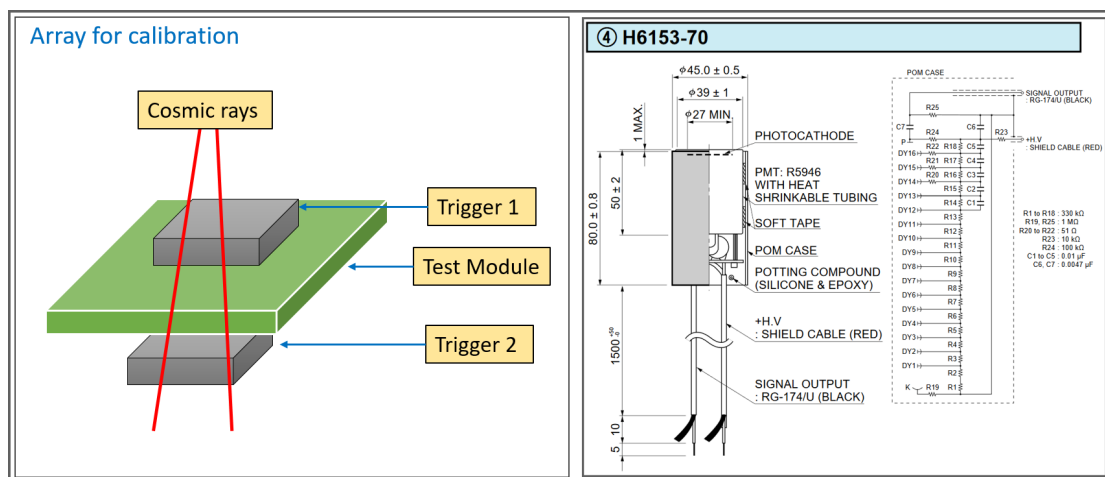


FIGURE 3.10. Left: Array for PMT calibration using cosmic muons and two modules as a trigger. Right: PMT electrical schematic, 16 dynode stages.

AD electronics continuously records the integrated charge every 25 ns, and it has the capability to deliver the recorded charge for 21 BCs (525 ns), this is done when a trigger is detected, in the case for calibration, we use as trigger condition the logical AND between the two hodoscopes.

With an analysis off-line, we are able to know when we had a triple coincidence, at the same time we can measure the integrated charge for the module under test. Using this information we can decide the optimal operating voltage for each of the sensors (see fig 3.11).

Once we found the operating voltage range for each sensor, we defined an optimal point according to the gain given by the PMT. For each of the sensors we defined a gain such that our detector is sensitive to low charges (which implies a high gain), without going into a saturation state in the charge integrators.

During a normal year of data taking in LHC, there are two periods of collisions, the largest period is for proton-proton collision, and at the end of the year there is a period of heavy ions collisions. During these two periods it is necessary to change the gain of the PMTs in AD, always with the compromise of remaining as sensitive as possible avoiding saturation.

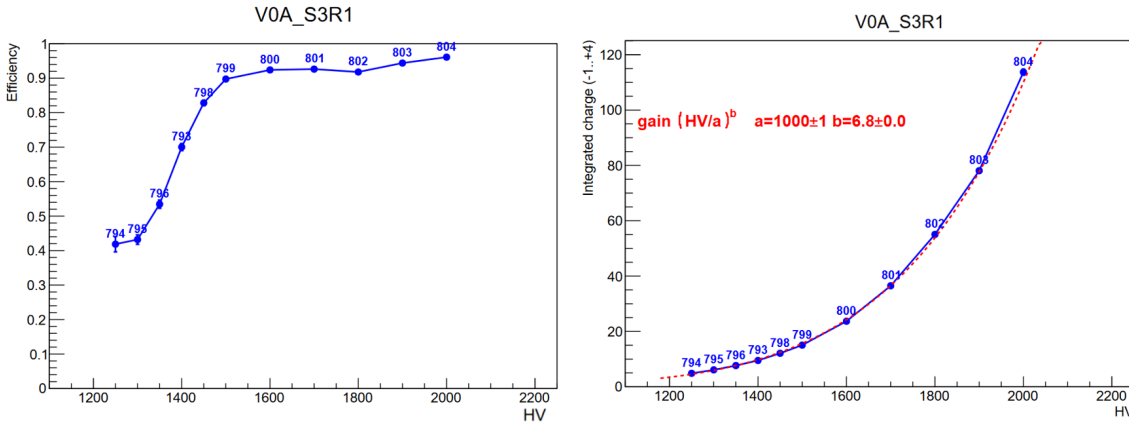


FIGURE 3.11. Standard plots obtained for PMT calibration. Left: Efficiency curve, number of events seen with respect to the trigger defined. Right: Gain curve, integrated charge in 6 bunch crossings (150 ns).

3.5 Beam Test

Two AD modules identical to those installed in the experiment (one for A-Side, one for C-Side) were studied in the T10 beam line facilities in the PS (Proton Synchrotron) at CERN. The main proposes of this beam test were:

- To study the uniformity of the detector response along the entire area of the modules to determine the limit acceptance near the edges.
- To compare the response of the detector to pions, protons and muons, to expand the calibration for Minimum Ionizing Particles (MIP).
- Obtain the time and charge distribution, to study the trigger capabilities in ALICE data taking.

- To study the different stages of the data taking chain (FEE), which is the same as in the experiment.
- To study the procedures for data analysis, such as time slewing correction.

3.5.1 Experimental Setup

The schematic distribution of the detectors as placed in the beam line is shown in figure 3.12. The arrangement was labeled in the beam direction (indicated by the red arrow), and corresponds to two scintillator hodoscopes, named as black-start and Black-end, separated from each other by 1221 cm. Also along the beam line we placed two round shape Cherenkov radiators (provided by T0 detector group) labeled as T0-start and T0-end, with 50 cm between them. And finally the two modules under test, labeled as AD1 and AD2, were placed between the first hodoscope and the first cherenkov detector.



FIGURE 3.12. Beam test setup scheme at T10 beam line. Distances are marked in centimeters, and the red arrow show the direction of the beam.

The T0 cherenkov detectors were placed with a small overlap (highlighted in red in fig 3.13), this area help us to define a smaller triggered area.

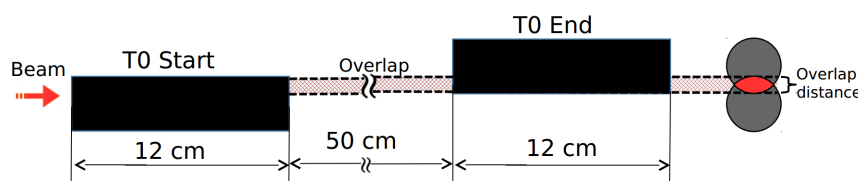


FIGURE 3.13. Area defined by the overlap of T0 cherenkov detectors use for fine triggering.

3.5.2 Data samples

The AD modules were placed on top of a movable table, which can be moved in a perpendicular plane to the beam line. In this way it is possible to select the position where the beam hits the detector. The figure 3.14 shows the reference coordinate system together with the different components where the beam was directed.

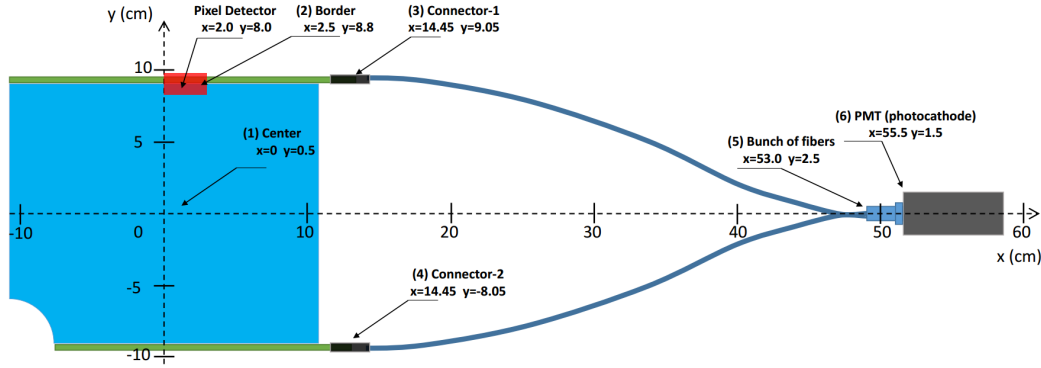


FIGURE 3.14. Scheme of the different positions scanned with respect to the center of the plastic scintillator.

During the test, the AD modules were hit in different parts such as the wave length shifting bars, the optical fibers and the PMTs. In table 3.1 are listed the different positions, and the number of entries for the runs used in this analysis, the momentum of the beam for all of these test was set to 1 GeV/c.

Additionally, two different scans along the x & y axis starting from the center of the module took place. These scans were made to study the uniformity of the PMT signals and the efficiency all along the scintillator pad. When the beam is near the edge of AD, some particles do not hit the scintillator but they manage to trigger the cherenkov detectors, for this reason the efficiency decreases.

The efficiency was calculated in the same way as in equation 3.1, but in this case our trigger was given by the logical AND of the cherenkov detectors.

No.	Section	x position (cm)	y position (cm)	Entries
1	Center	0	0.5	18561
2	Border	2.5	8.8	250159
3	Connector 1	14.45	9.05	1071
4	Connector 2	14.45	-8.05	1020
5	Fibers	53.0	-1.5	47117
6	PMT	55.5	-0.5	2357
7	WLS	2.0	8.0	32640

TABLE 3.1. Different positions where AD was hit during Beam Test. The beam momentum was set to 1 GeV/c.

3.5.3 Charge and Time measurements

Using all the setup described, time and charge for the different points in the test modules were measured. The high voltage of AD1 and AD2 was fixed at 1650 V and 1500 V respectively. A typical

charge distribution is shown in figure 3.15, the histograms were fitted to a Gaussian-Landau functions. The Most Probable Value (MPV) was taken as the position of the MIP.

The dark gray histogram corresponds to the 2-fold coincidences, and the light gray distribution corresponds to the 3-fold coincidence (when we include the module under test).

The results of the different scans are summarized in the plots of the figures 3.16, 3.17 and 3.18. The information shown in each of this plots corresponds to:

- The efficiency of AD1 and AD2, represented by the green and orange triangles respectively.
- The MPV of the charge, represented by the blue circles for AD1 and red squares for AD2, with an extra shading for reference.
- The position of the beam with respect to the center of the module, represented in the horizontal axis.
- The efficiency (left scale) and charge (right) scale are represented in the vertical axis.

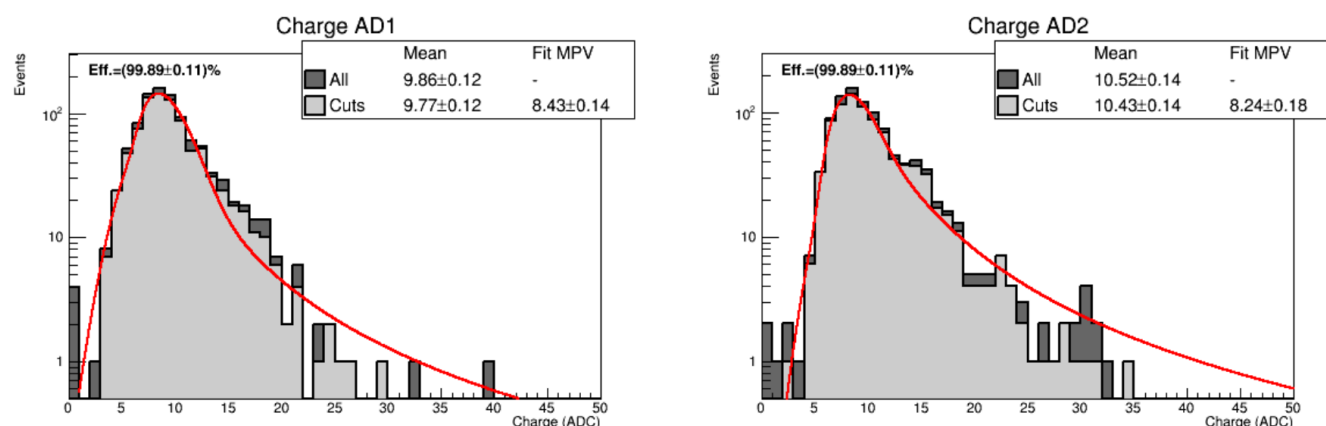


FIGURE 3.15. Charge distribution of AD modules. Dark gray distributions are all the events recorded, and light gray the events selected by the 3 fold coincidence.

The two scans for the scintillators were made along the center of the pads, the efficiency for both scans is uniform as shown in figure 3.16. In the y-axis scan there are some missing points, but even so we can assume that the efficiency is uniform.

At the edges of the scintillator, the efficiency decreases, but the integrated charge remains constant. Using this information, and the capabilities of the FEE, we could define a "Charge Trigger" for ALICE data taking.

When the beam hits the optical connectors the efficiency of the detector decreases (see fig 3.17), although when we take a look at the charge, it continues with a very similar value as if hitting the scintillator. A similar behaviour is observed when hitting the different parts of the

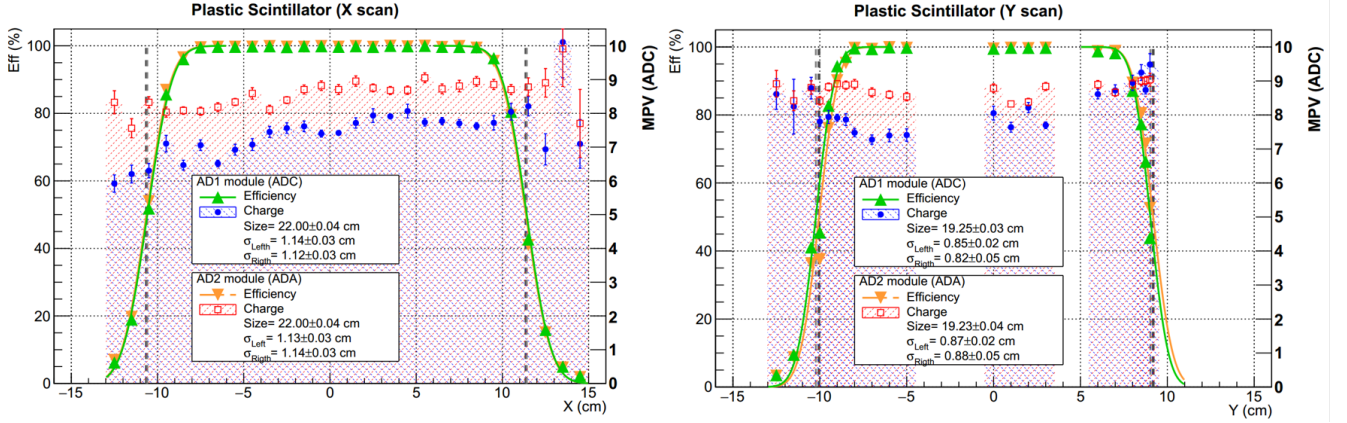


FIGURE 3.16. Charge and efficiency obtained along X-axis (left) and y-axis (right) scans for AD1 and AD2.

PMT, the charge can reach high values, the efficiency in this case reduces as the beam hits farther from the photocatode. This kind of events could be mistaken during ALICE data taking as "good events".

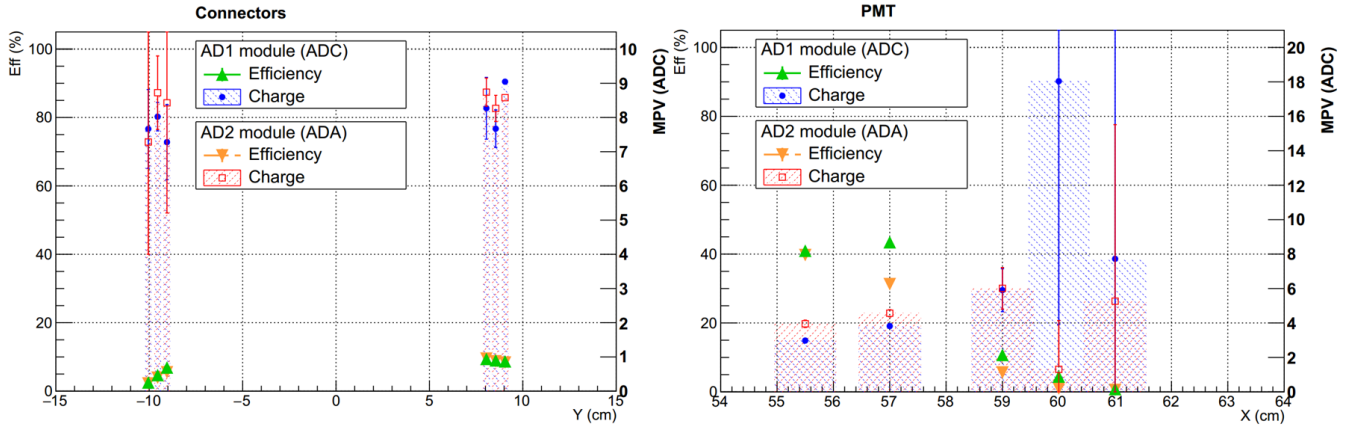


FIGURE 3.17. Charge and efficiency obtained when the beam hits the optical connectors (left) and the PMT structure (right) for AD1 and AD2.

To distinguish events that do not hit the scintillator, but even so generate a high integrated charge the time information is used, AD FEE has the capability to discriminate events according to the leading time.

Something similar is observed when the beam hits the optical fibers, the efficiency drops but we still have charge measurements (see fig 3.18).

A detailed analysis on the time response was done during the beam test, for this it was necessary to use all the detectors placed in the beam line, since the particles coming from the PS

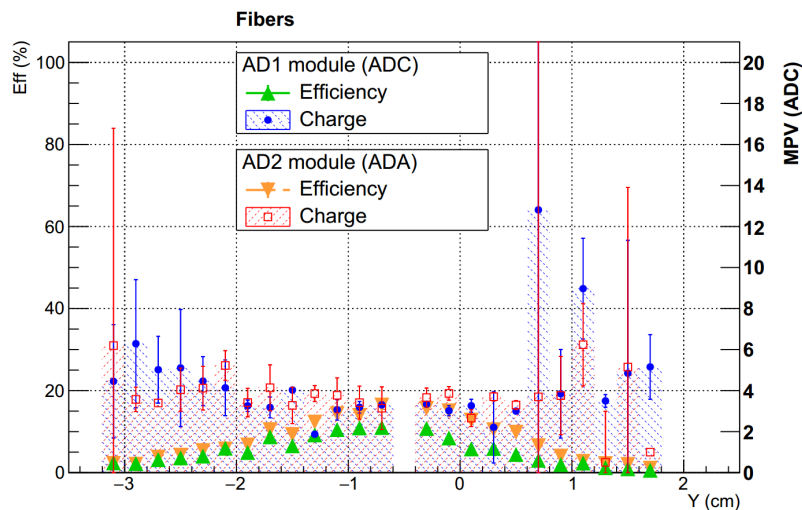


FIGURE 3.18. Charge and efficiency when the beam hits the optical fibers.

arrived at a random time. The T0 cherenkov detector were chosen as primary reference because of their good time resolution (~ 50 ps).

The two dimension histograms in figure 3.19 (top row) show that the time measurement is affected by an slewing effect depending on the charge, an can be corrected applying a simple technique. In the figure 3.19 we can see the profile of the time with respect to the charge (black dots), this behavior can be parametrized according to the function 3.2.

$$(3.2) \quad t(Q) = p_0 + p_1 \cdot Q^{p_2}$$

where p_0 , p_1 and p_2 are constant parameters that we can obtain from the histogram fit. Finally the time corrected for each individual event just by subtracting this $t(Q)$ from the time measured was computed.

After the time slewing correction, the time resolution with respect to the beam energy was estimated.. The resolution will be obtained from the time distributions after the time slewing correction, finally obtaining the results in table 3.2.

3.6 Performance of AD at $\sqrt{13}$ TeV in proton-ptoron collisions

LHC run 2 started officially on June 3 2015, since the beginning of data taking ALICE Diffractive detector has been participating actively. In the beginning AD was proposed as a detector to expand the pseudo-rapidity coverage of ALICE, improving the capabilities for the study of diffractive events. As an extra, AD is used as a minimum bias trigger, as well as a monitor for LHC beam conditions.

3.6. PERFORMANCE OF AD AT $\sqrt{13}$ TEV IN PROTON-PTORON COLLISIONS

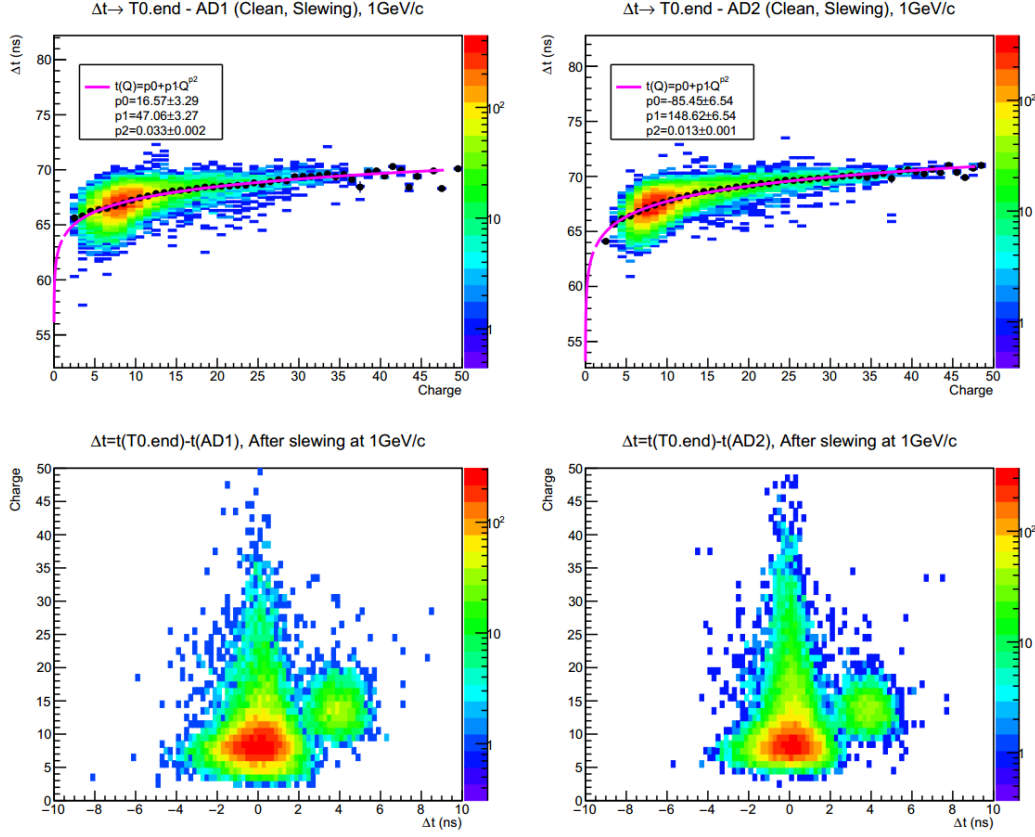


FIGURE 3.19. Time slewing correction calculated using the pions distributions of AD1 and AD2 (top plots).

Momentum (GeV/c)	AD1		AD2	
	σ (ns)	Slewing corrected σ (ns)	σ (ns)	Slewing corrected σ (ns)
1.0	0.87+/-0.05	0.76+/-0.04	0.78+/-0.05	0.74+/-0.04
1.5	1.43+/-0.06	1.48+/-0.07	1.64+/-0.07	1.54+/-0.06
2.0	1.82+/-0.03	1.70+/-0.03	1.84+/-0.03	1.60+/-0.02
6.0	1.20+/-0.03	1.12+/-0.03	1.27+/-0.03	1.18+/-0.02

TABLE 3.2. Time resolutions of AD1 and AD2 at different momentum of protons during the beam test in T10, with and without time slewing correction.

Due to its excellent time and charge resolution, AD trigger signal was used by ALICE central trigger processor to reject beam-gas events (see fig 3.20), it played an important role in ALICE, used as a Level 0 trigger used for centrality measurements in both pp and Pb-Pb collisions.

Each ring of the LHC is divided into 35640 buckets, most of these do not contain a bunch of particles, it is well known that these empty buckets can contain a small population of particles,

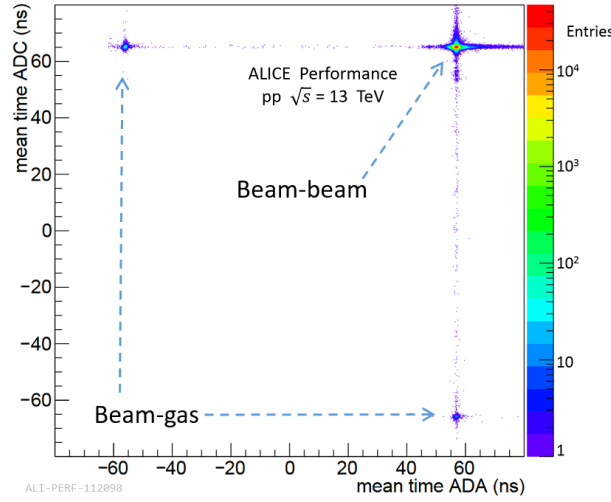


FIGURE 3.20. ALICE data taking at $\sqrt{13}$ TeVs. Mean Time measurement of ADA versus mean time ADC. Due to the good time resolution of AD Beam-Gas background can be identified clearly

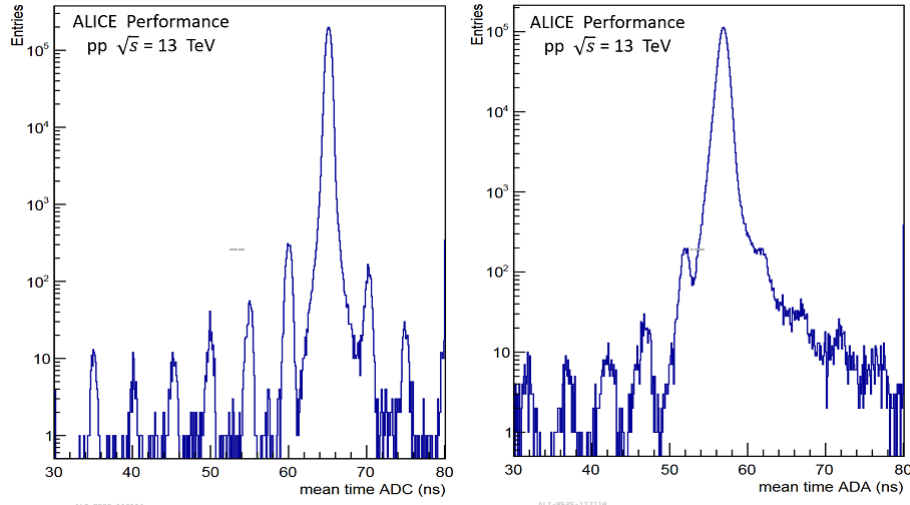


FIGURE 3.21. Time distribution for ADC (left) and ADA (right) for proton-proton collisions at 13 TeV, every 5 ns is possible to observe the satellite bunches generated in LHC.

these intruders are known as satellite bunches in LHC [29]. By looking into the time information of AD, we noticed that AD is sensitive to these satellites, normally presented as an structure every 5 ns (See fig 3.21). This extra information is used as a background rejection strategy in data analysis that include AD.

Since the beginning of LHC run 2 AD has been exposed to the radiation produced by LHC, including the beam-induced background contribution. This accumulated radiation had an effect

AD participation during LHC Run 2			
Number of Runs with Beam	Hours	Number of Cosmic Runs	Hours
4067	6082	913	1483

TABLE 3.3. AD was part of ALICE data taking since the beginning of LHC run 2, participating in most of the runs (collisions and cosmic data). [1]

on the amplitude of the signals from the PMTs. Thanks to the gain scans done for each individual channel it was possible to counteract this ageing effect.

3.6.1 AD in the ALICE trigger system

Once LHC has circulating beams, the first step towards collisions is a transversal scan of one of the beams through the other to minimize unwanted effects during injection and ramp, and to optimize the luminosity during data taking. This transversal scan known as Van Der Meer Scan [39] is also use as a reference for trigger rate and luminosity calculation in physical analysis.

AD is part of level 0 trigger detectors in ALICE, and it is used as a minimum bias trigger, so it took part in the different Van Der Meer scans performed during LHC Run 2, in figure 3.22 we can see the results from the calibration performed in IP2 (Interaction Point 2 of LHC) taken with AD.

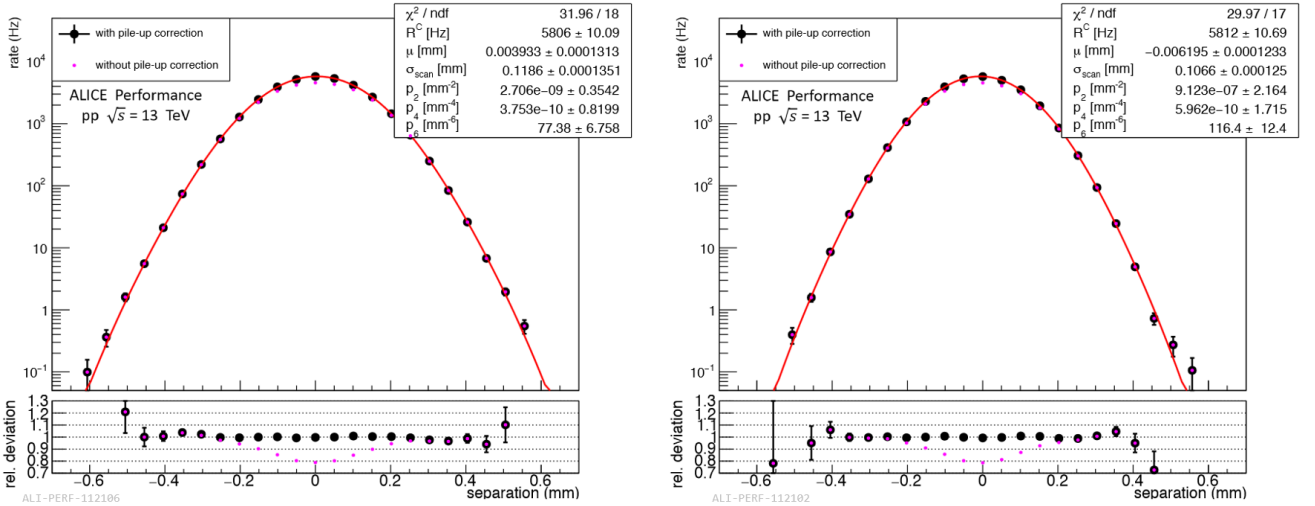


FIGURE 3.22. Horizontal and vertical scan in IP2 using AD. Both in logarithmic scale with a Gaussian fit.

Now that LHC Run 2 has finished, we can conclude that AD had a nice performance during the 4 years of data taking. During all this time there were necessary several interventions both in hardware and in software to improve the operation of AD. Taking into account all the runs

where AD participated (collision and cosmic runs), AD took more than 7500 continuous hours of data, the equivalent to 315 days of non-stop operations (see table 3.3).

3.7 Diffraction in ALICE run 2

The inelastic cross section and characterization of diffractive processes in proton-proton collisions are among the basic observables used to characterize the global properties of interactions, with the start of run 2 at a new center of mass energy it becomes a subject of interest. ALICE has measured inelastic, single and double diffractive cross sections at $\sqrt{7}$ TeVs, now, with the inclusion of AD, ALICE finds itself in a better position compare to the conditions in run 1 (see table 3.4).

The ALICE Diffractive detector substantially increases the acceptance for diffractive physics. The range in pseudo-rapidity was extended from 8.8 to 12.1 units in η , which translates into an increased sensitivity for lower diffractive masses.

During Run-2, ALICE has collected a large sample of inclusive diffractive events and gap-gap triggers, with all this information there are ongoing detailed studies on central production and diffractive cross sections.

Pseudo-rapidity coverage during LHC run 2		
ALICE	$-7.0 < \eta < -4.9, -3.7 < \eta < -1.7, \eta < 2, 1.7 < \eta < 6.3$	$M_x > 4.0 \text{ GeV}$
ATLAS	$ \eta < 3.8, 5.6 < \eta < 5.9$	$M_x > 13 \text{ GeV}$
CMS	$ \eta < 2.5, 3.0 < \eta < 5.2, -6.6 < \eta < -5.2$	$M_x > 29 \text{ GeV}$
TOTEM	$3.1 < \eta < 4.7, 5.3 < \eta < 6.5$	$M_x > 3.3 \text{ GeV}$

TABLE 3.4. Comparison of ALICE pseudo-rapidity coverage after the inclusion of AD with respect to other experiments in LHC.

DIFFRACTIVE CROSS SECTION AT $\sqrt{13}$ EVs

Some 20% to 30% of the high energy proton proton interactions are considered to be diffractive [18], hence the reason for having a dedicated program to study these events in LHC. Besides the fundamental physics interest by itself, diffractive scattering, and the underlying soft processes are an integral part of the experimental analyses of hard scattering processes, to be investigated in detail.

Due to the special beam optics conditions at the ALICE interaction point (IP2), the experiment has ideal running conditions for diffractive physics. ALICE collects pp collision data with low pile-up, in well understood background conditions during the nominal low-x runs design for ATLAS and CMS searches of rare phenomena at large transverse momentum processes.

The ALICE experiment was conceived for precision studies of heavy ion collisions, and its design features are precise in diffractive scattering studies. Access to low transverse momentum particles (pT , $min \approx 50 MeV/c$) in high multiplicity of particles environments, particle identification capabilities (PID), efficient beam-gas rejection techniques and redundant forward detector coverage allows detailed analysis of diffractive event samples of high purity.

During my PhD studies I joined the effort for the measurement of the diffractive cross section at $\sqrt{13}$ TeVs, in this chapter I present the results and progress of this measurement.

4.1 ALICE Forward experimental lay-out

By combining the central barrel and forward detectors, ALICE has a continuous acceptance over an interval of 12 units in pseudo-rapidity. These geometric acceptances are extended by the secondary particles and the particles bent into AD fiducial volume by the ALICE muon spectrometer magnet and the compensating dipole. Taking advantage of this, and the access to very low transverse momenta, ALICE carries out a dedicated study of proton-proton diffractive

processes. An over-all description of ALICE experiment is given in [5]; only brief accounts on the sub-detectors used for the present cross section analysis are included here.

4.1.1 Tracking and trigger detectors

As mentioned in the previous chapter, the ALICE collaboration installed a very forward detector, called AD or ALICE diffractive detector. The forward physics capabilities of ALICE were substantially upgraded by the installation of AD [7, 22, 26]. The diffractive mass (M_{AD}) coverage of the AD detector extends down to $M_{AD} \approx 1.2$ GeV, and at $\varepsilon_{AD} = 50\%$ efficiency, the AD detector sees diffractive systems down to masses of $M_{AD} \approx 3.0$ GeV (see fig 3.5). For neutral pions, the acceptance in P_T extends to the MeV range due to the gamma conversions and subsequent (indirect) detection by the AD detectors.

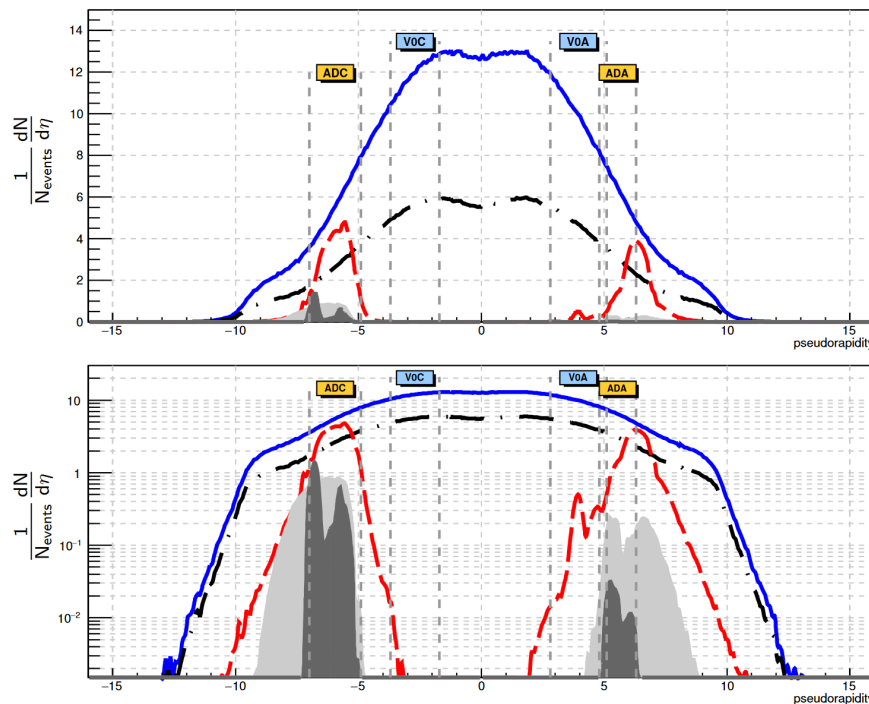


FIGURE 4.1. Upper panel: AD detector acceptances as a function of pseudo-rapidity, η , for all primary particles in Pythia6 simulated at 13 TeV proton-proton minimum bias events (blue solid line). The charged primary particles (black dash-dotted line) and the primary particles inducing secondaries into AD fiducial volume (red dashed line) are shown separately. The light gray regions indicate those charged primary particles which reach the AD detectors directly, and the dark gray regions the electrically neutral primaries arriving into AD detector. The vertical dashed lines mark the geometrical η -coverage of AD and V0. Lower panel: same plot in logarithmic scale. The plots are normalized to the total number of generated events. [22]

The V0 detector [6] consists of two scintillator hodoscopes, placed on each side of the interaction region, at $z = 3.3$ m and at $z = -0.9$ m (z is the coordinate along the beam line, with its origin at the centre of the ALICE barrel detectors), oriented in the direction opposite to the muon spectrometer [5], covering the pseudo-rapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively (see fig 3.4). The time resolution of each hodoscope is better than 0.5 ns. The V0 detectors register diffractive systems (at $\epsilon_{V0} \geq 50\%$) having an invariant mass above $M_{V0A} > 20$ GeV (A-side) or $M_{V0C} > 10$ GeV (C-side).

The Inner Tracking System (ITS) consists of six layers of high resolution silicon tracking detectors, arranged in six cylindrical layers at radial distances to the beam from 3.9 to 43 cm. The two layers closest to the beryllium beam vacuum chamber, the Silicon Pixel Detectors (SPD) [40], cover the pseudo-rapidity ranges of $|\eta| < 2$ and $|\eta| < 1.4$, and used for primary vertex definition and for constraining track reconstruction. The SPD is surrounded by two Silicon Drift Detector layers (SDD) [8], followed by two layers of double-sided Silicon Strip Detectors (SSD) [28, 37]. The SDD and SSD detectors contribute in tracking, and in particle identification (PID) for low p_T ($p_T < 0.7$ GeV) particles. At very low p_T , the ITS is used for stand-alone tracking.

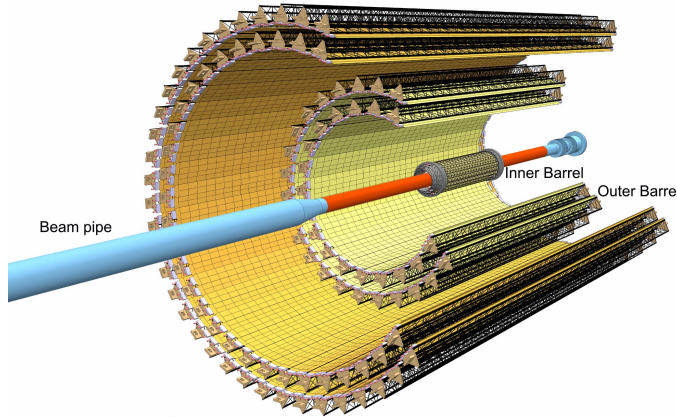


FIGURE 4.2. Schematic of the Inner Tracking System, formed by 6 different layers (SPD, SSD, SDD).

The V0 and AD scintillator hodoscopes together with the two inner layers of ITS (SPD) provide the minimum bias trigger, MB_{or} , during the data taking.

The T0 detector [5] consists of two arrays of Cherenkov counters, 12 counters per array. Each Cherenkov counter is based on a fine-mesh photomultiplier tube optically coupled to a quartz radiator. The pseudo-rapidity range of T0-C is $-3.28 < \eta < -2.97$. On the opposite side of the Interaction Point (IP), the T0-A is grouped together with the other forward detectors and covers the pseudo-rapidity range of $+4.61 < \eta < 4.92$. In the radial (transverse) direction both T0 arrays are placed as close to the beam pipe as possible to maximize triggering efficiency.

The TPC [11] is a large cylindrical drift detector with a central high voltage membrane at $z = 0$, maintained at + 100kV and two read-out planes at the end-caps. The material budget

between the interaction point and the active volume of the TPC corresponds to 11% of a radiation length when averaged over $|\eta| < 0.9$.

The neutron ZDC detector is described in detail in [19] and it includes neutron and proton calorimeters based on tungsten absorber and optical fiber read-out systems at $z = \pm 116$ m from IP2. Together with the zero degree calorimeters, ZDNA/ZDNC, the forward diffractive states are covered down to their lowest masses. Each neutron ZDC detector is composed of 44 grooved W-alloy slabs and the sensitive material is formed by 1,936 quartz fibers. The front face is a square of 7.2 cm^2 , and it has a depth of 100 cm corresponding to 8.5 interaction lengths. The read-out has five PMT channels.

The transverse momentum and pseudo-rapidity space covered by the ALICE ZDC, AD, V0 and SPD detectors are depicted in figure 4.1.

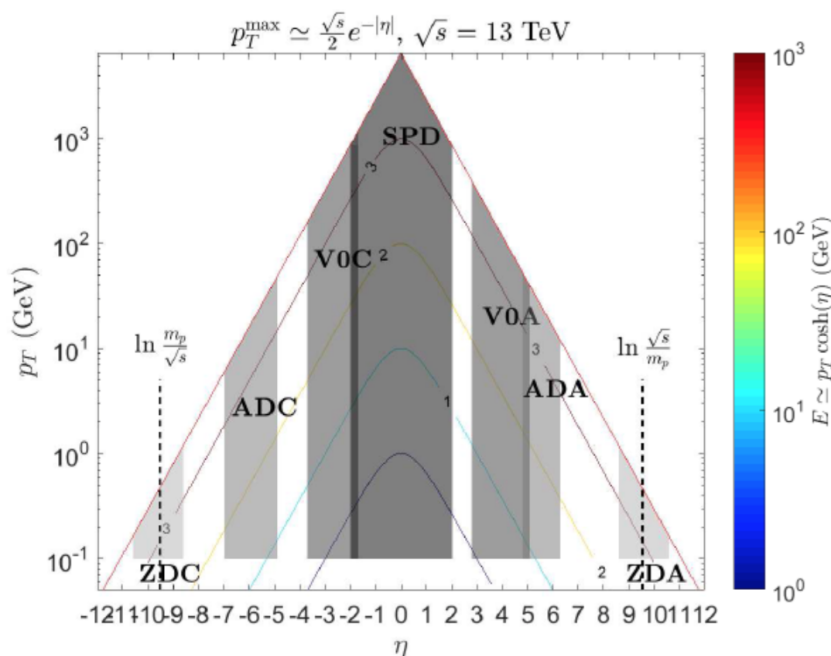


FIGURE 4.3. The transverse momenta and pseudo-rapidity covered by the ALICE forward detectors [33].

The main functionality of the Forward Multiplicity Detector (FMD) [5] is to provide charged-particle multiplicity information in the pseudo-rapidity range $-3.4 < \eta < -1.7$ and $+1.7 < \eta < +5.0$. An overlap between the FMD silicon rings and the ITS inner pixel layer provides redundancy and cross-checks of measurements between sub-detectors and ensures that continuous coverage for a distribution of vertices along the z -axis. Additionally, high radial detector segmentation allows for the study of multiplicity fluctuations on an event-by-event basis while azimuthal segmentation allows for the determination of the reaction plane for each event and the analysis of flow within the FMDs pseudo-rapidity coverage.

In the present analysis, highly efficient scintillation counters are used to veto and to detect particles emitted with small scattering angles. Subsamples of events are extracted where combinations of additional small angle detectors Forward Multiplicity Detectors (FMDs), T0 and the Zero Degree Calorimeters (ZDCs) are used for assessing the backgrounds and diffractive interactions with the leading neutrons.

4.2 Experimental conditions, data and trigger description

4.2.1 Beam optics conditions

In this analysis a measurement of the diffractive proton-proton cross sections are presented using data registered by the ALICE experiment at the LHC at $\sqrt{s} = 13$ TeV. The data was collected during the first runs in 2015 after the LHC long shut down. During the first data taking stage of LHC run 2 there were special runs dedicated for diffraction studies. The main characteristics of these runs, are the low number of interacting bunches, reflected as a low mean number of inelastic interactions per crossing μ (μ is the average number of visible interactions per bunch crossing), which varied between 0.01 and 0.05 in these fills.

4.3 Trigger Strategy

A diffractive process can be represented by the following reaction (CEP case):

$$(4.1) \quad p + p \rightarrow p(*) + X + p(*),$$

where $p(*)$ can be a proton or an excited state of it, and X is the diffractive produced system. Since we are not able to identify the outgoing protons, we need to find an alternative way to select this process. Using ALICE Trigger capabilities we are able to slice the pseudo-rapidity space into N intervals, where we can identify and categorize the X system produced from our diffractive reaction.

With the use of $GlobalMB_{OR}$ (ADA $\parallel$ V0A $\parallel$ SPD $\parallel$ V0C $\parallel$ ADC), we can slice most of ALICE η coverage. To be more precise, this $GlobalMB_{OR}$ is the logical OR between the corresponding trigger classes for each of the detectors involve (see fig:4.4, table:4.1).

For our analysis we defined a topological ID (IDentifier) for the different trigger combinations. We used a binary selection for all the detectors involved (ADC, V0C, SPD, V0A, ADA), where "1" means that there is a hit or trigger generated in the detector, and "0" means the opposite, or a veto with the same. Using these 5 detectors, we obtain 32 mutually exclusive combinations in which we can slice the pseudo-rapidity coverage of ALICE.

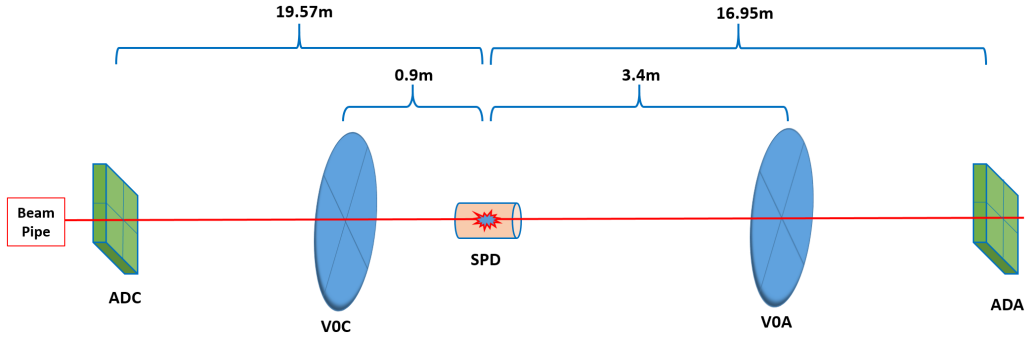


FIGURE 4.4. Distance to IP2 of the main detectors used in this analysis.

Trigger Class	Detector
C0UBC-B	ADC
C0UBA-B	ADA
C0VBC-B	V0C
C0VBA-B	V0A
C0SMB-B	SPD

Table 4.1: Trigger Classes and its detector correspondence.

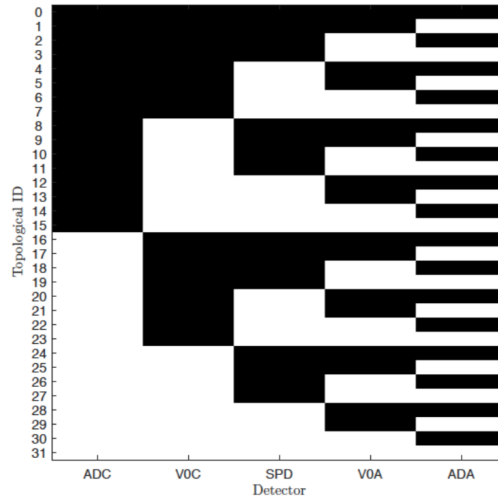


FIGURE 4.5. ALICE forward detector combinations (topological ID) presented in terms of the binary code "white=0, black=1" for each of the detectors: ADC, V0C, SPD, V0A, ADA.

4.3.1 Event Selection Criteria

Since this analysis is based on a trigger selection, it is necessary to understand how these triggers were generated.

The Silicon Pixel Detector (SPD) (the two innermost layers of ALICE Inner Tracking System) is composed by 120 basic modules (half-staves), 40 in the inner layer and 80 in the outer layer. On each of these half-staves an array of silicon sensors are bonded to 10 read-out chips, for a total of 1200 chips in the entire SPD.

Whenever one or more SPD pixel cells (in the half-staves) records a hit, an output signal is generated, this output signal is known as Fast-OR. The Pixel Trigger system has to extract and process all the 1200 Fast-ORs to deliver an input signal for the Level 0 trigger in ALICE. In particular the trigger class C0SMB-B is generated when one of these Fast-ORs delivers a signal.

The V0 detector consists of two hodoscopes placed on each side of the interaction point, and the generation of the minimum bias trigger is effective as soon as there is one hit detected by V0A (C0VBA-B), or V0C (C0VBC-B), for that is necessary to verify on each hodoscope the event occurrence at the expected time, 11 ns after the collision on V0A and 3 ns after the collision on V0C (fig:4.6).

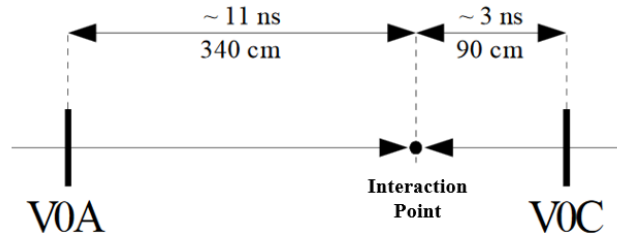


FIGURE 4.6. Time alignment condition on V0A and V0C.

Similar to V0, the ALICE Diffractive Detector (AD) is formed by 2 main stations (see fig:3.1). Each station consists of 2 layers with 4 plastic scintillator pads each (8 pads per side), in order to generate a trigger signal (C0UBA-B/C0UBC-B) a hit in two adjacent pads is required in either side.

4.4 Data Selection

In order to select good quality runs we started by simple filters applied in ALICE Electronic Logbook (see table 4.2), from these filters we obtained a total of 6 runs from period LHC15f, and 8 runs from LHC15h (see table 4.3) corresponding to 4 different fills in LHC.

4.4.1 Runs Characteristics

From the filtered runs, there was a so-called golden run for diffraction studies, the run 226062. The first studies for this analysis in the data and background were made using data from this run.

Logbook filters applied	
Beam Mode	STABLE BEAMS
Beta Star	Between 18 and 19
Duration	15 minutes or more
# of Detectors	10 or more
Detectors as Trigger	At least AD, V0 and SPD
Detectors as Readout	At least AD, V0 and SPD
Data Taking Quality Flag	Good Run
AD Quality Flag	Good Run
V0 Quality Flag	Good Run
SPD Quality Flag	Good Run
T0 Quality Flag	Good Run
ZDC Quality Flag	Good Run

Table 4.2: Filters applied for Run selection.

Period	Run Numbers
LHC15f	226500, 226495, 226483, 226225, 226220, 226062
LHC15h	233978, 233977, 233976, 233975, 233974, 233973, 233972, 233971,

Table 4.3: List of possible runs for this analysis.

- 226062 (golden run for diffraction studies):
 - Duration: 01:38:49
 - Period: LHC15f
 - sample used for analysis: pass2
 - participant detectors: ACORDE, AD, CPV, FMD, HMPID, MUONTRG, MUONTRK, PHOS, PMD, SDD, SPD, SSD, T0, TOF, TPC, TRD, TRIGGER, V0 and ZDC
 - trigger detectors: AD, MUONTRG, SPD, T0, V0 and ZDC
 - L3 magnet current: -30 kA
 - Dipole Magnet current: -6 kA
 - Fill number: 3846
 - Beam energy: 6500 GeV
 - Beta star = 18.85 m
 - # interacting bunches: 15
 - # Non-Interacting Bunches Beam 1: 24
 - # Non-Interacting Bunches Beam 2: 24

- Total Events: 3,274,636
- Event Rate: 542.97 Hz
- Total Physics Events: 3,191,343

In ALICE there were two minimum-bias trigger definitions (MB_{OR} and MB_{AND}), after the inclusion of AD detector, there is a new defined ($GlobalMB_{OR}$) as following:

- MB_{OR} : V0A $\parallel$ SPD $\parallel$ V0C
- MB_{AND} : V0A $\&\&$ SPD $\&\&$ V0C
- $GlobalMB_{OR}$: ADA $\parallel$ V0A $\parallel$ SPD $\parallel$ V0C $\parallel$ ADC

where $\parallel$ is the logical function OR, $\&\&$ is the logical function AND, and the detector name corresponds to hits in the given detector. After the run selection, our data sample is given by this $GlobalMB_{OR}$ trigger. In table (4.4) a summary of the numbers for the golden run used for this analysis is given.

	Numbers
Total number of events	2,995,914
Total number of $GlobalMB_{OR}$ Events	1,508,819
Number of AD_{OR} events	1,208,312
Number of $V0_{OR}$ events	1,168,717
Number of SPD events	1,348,154

Table 4.4: Statistics of analyzed data with run 226062.

4.5 Event purity selection

To be sure about the quality of the data taken into account for the analysis, we observed the information of each detector individually. The AD trigger algorithm is based on the time measurement of the signals generated by the detector, so, in this case, to clean up the trigger sample of AD, we defined a time window in such a way that the events inside that window will be taken as real hits, and the events outside were considered as Beam-Induced background interactions.

For AD C-Side the defined windows was 7.5ns width ($61.5ns < time < 69ns$). We looked at different trigger conditions, and different channels, and this window proved to be consistent. See figures 4.7 , 4.8 and 4.9.

Something that we were able to notice, is that AD is sensitive to "satellites" in the LHC, these satellites are small populations of particles contained in what should be empty buckets in the

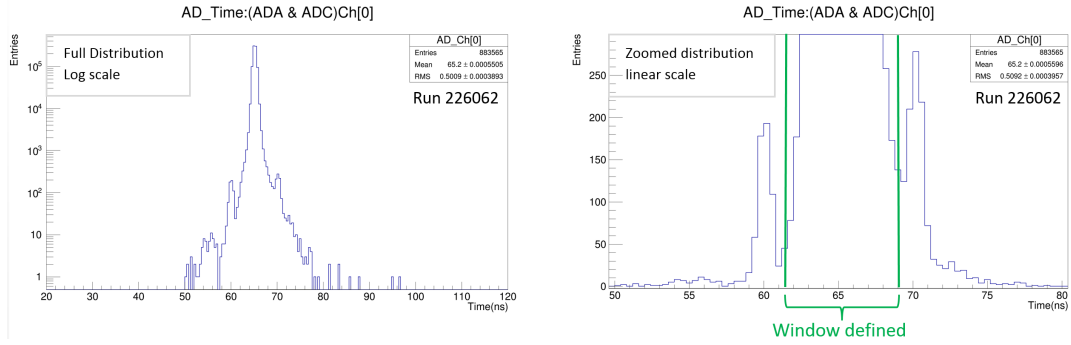


FIGURE 4.7. Time distribution for AD C-side offline channel 0, run 226062, at least one hit in ADA **and** ADC. Left: Full distribution in logarithmic scale, Right: Zoom in linear scale to the same distribution with the time window defined in green.

LHC. We can see from AD information (see fig 4.8) that they form structures every 5 ns distance. With the time window defined for our selection we remove the contribution from these "fake" events, and we only keep the data from the main collision.

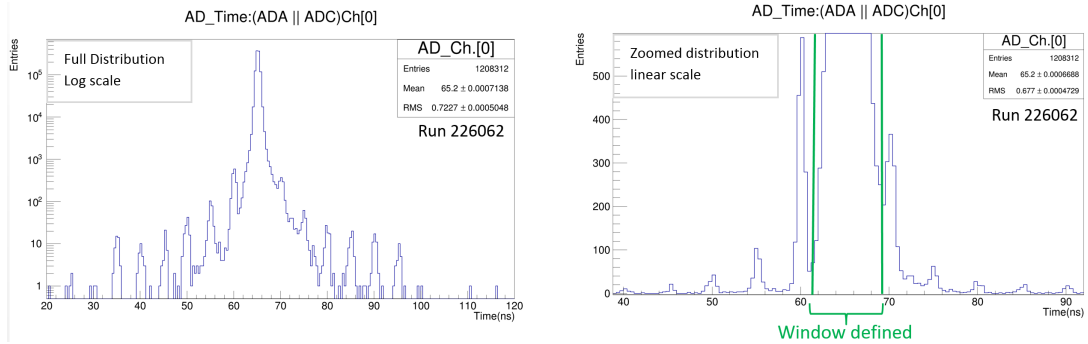


FIGURE 4.8. Time distribution of AD C-side offline channel 0, run 226062, at least one hit in ADA **or** ADC. Left: Full distribution in logarithmic scale, events from satellites are visible. Right: Zoom in linear scale to the same distribution with the time window defined in green.

For AD A-Side, it was observed that the time distributions are contaminated with some early hits, this is due to the fact that the PMTs in this side are closer to the beam pipe (AD beam-test proved this effect). In this case, a time window was defined in such a way that we can eliminate Beam-Gas events as well as the satellites also visible in this side, but not all the early hits.

To start, we defined a time window of 40ns width ($40ns < time < 80ns$). (See figures 4.10, 4.11 and 4.12.) Although this window may seem to be extremely wide, we will see in the systematic study the effect of reducing its size considerably.

Since the V0 detector started its activities since Run 1 of LHC, it is expected that the standard offline cuts are in a good shape, so, the sample was cleaned applying the offline Beam-

4.5. EVENT PURITY SELECTION

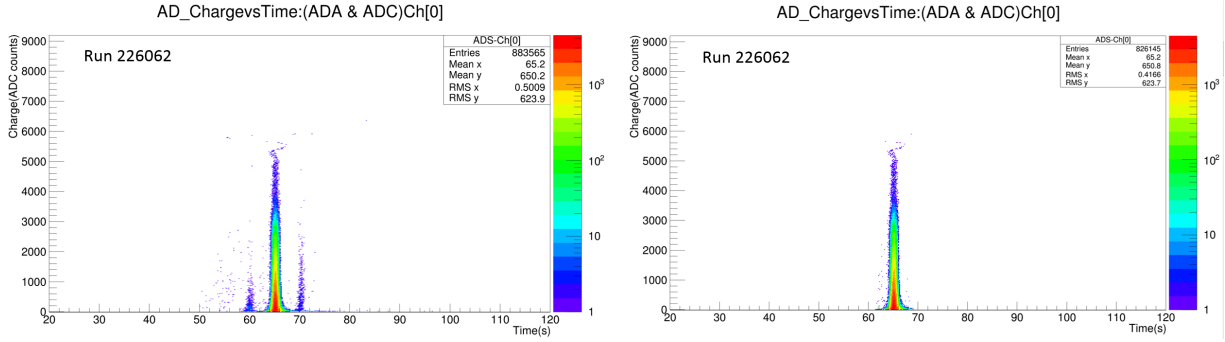


FIGURE 4.9. Charge vs Time distribution for AD C-side offline channel 0, run 226062, at least one hit in ADA **and** ADC. Left: Full distribution before the cut. Right: Same distribution after the cut applied.

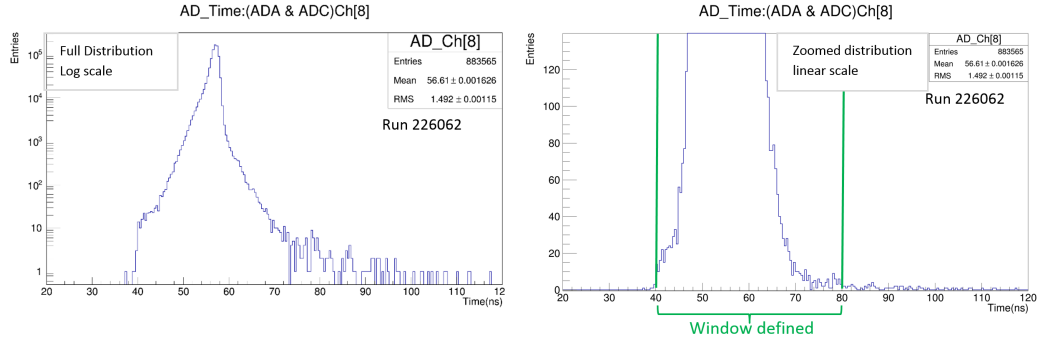


FIGURE 4.10. Time distribution for AD A-side offline channel 8, run 226062, at least one hit in ADA **and** ADC. Left: Full distribution in logarithmic scale, Right: Zoom in linear scale to the same distribution with the time window defined in green.

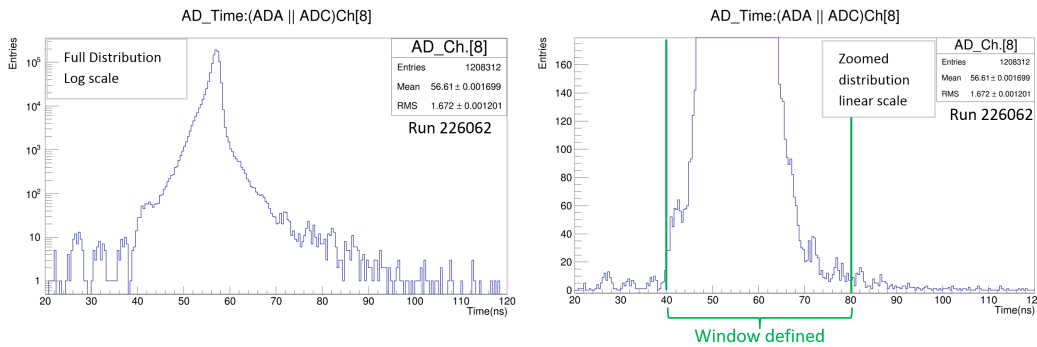


FIGURE 4.11. Time distribution of AD A-side offline channel 8, run 226062, at least one hit in ADA **or** ADC. Left: Full distribution in logarithmic scale, satellites are visible. Right: Zoom in linear scale to the same distribution with the time window defined in green.

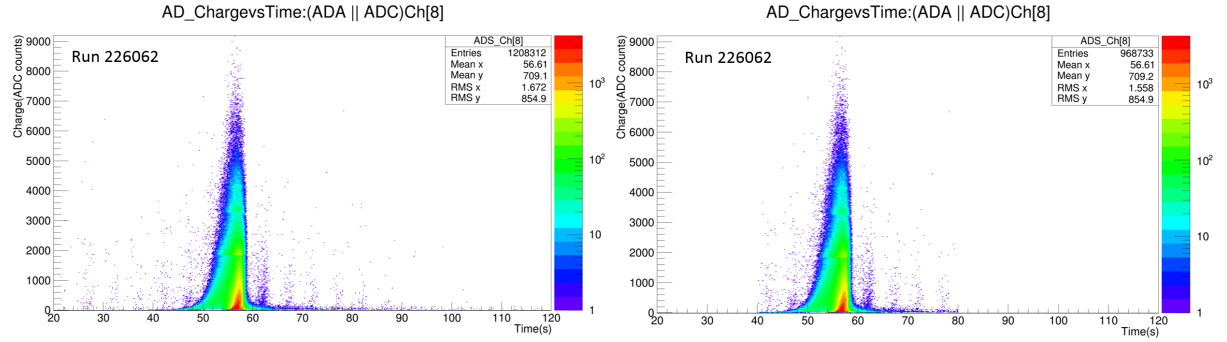


FIGURE 4.12. Charge vs Time distribution for AD A-side offline channel 8, run 226062, at least one hit in ADA **or** ADC. Left: Full distribution before the cut. Right: Same distribution after the cut applied.

Gas rejection, based on the V0-Decision, and also in the trigger generated by the same detector. See figure 4.13. The V0-Decision uses the time information in a very similar way as we defined the cuts for AD.

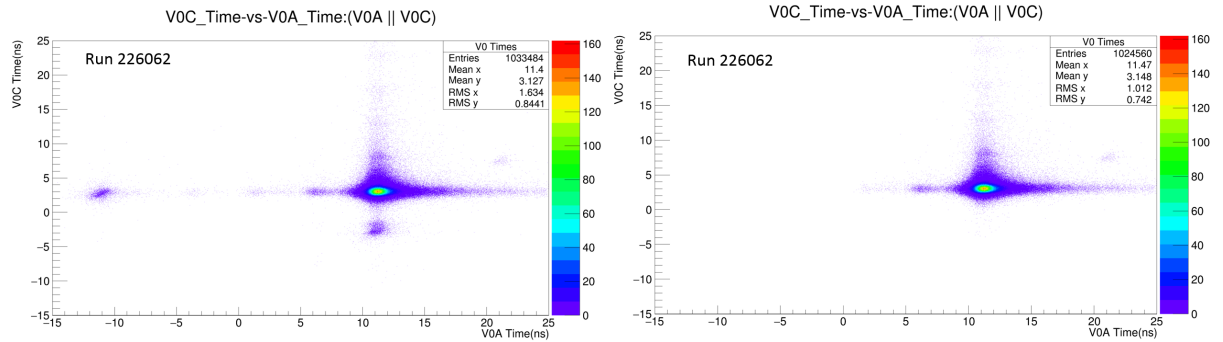


FIGURE 4.13. V0-C-Side vs V0-A-Side, run 226062, at least one hit in V0C **or** V0A). Left: Full distribution before applying V0-Decision. Right: Same distribution after V0-Decision is applied.

We can see the effect of the V0-Decision for one individual channels in fig 4.14. Basically the V0-Decision takes the time information (time of flight) from the hits detected by each pad, and decides if its coming from a Beam-Beam interaction or Bram-Induced background.

In the case of SPD, after selecting the events with the trigger class (C0SMB-B), we applied a standard cut in the events, this cut is done taking into account the number of tracklets versus the number of clusters fired, we can see in fig 4.15 an example for this cut, represented with a black line, all those events above this line of slope 45 and offset 55 are considered pile-up events, and are rejected from our selection.

After this selection in SPD, we notice that there were some noisy chips in SPD (see fig 4.16),

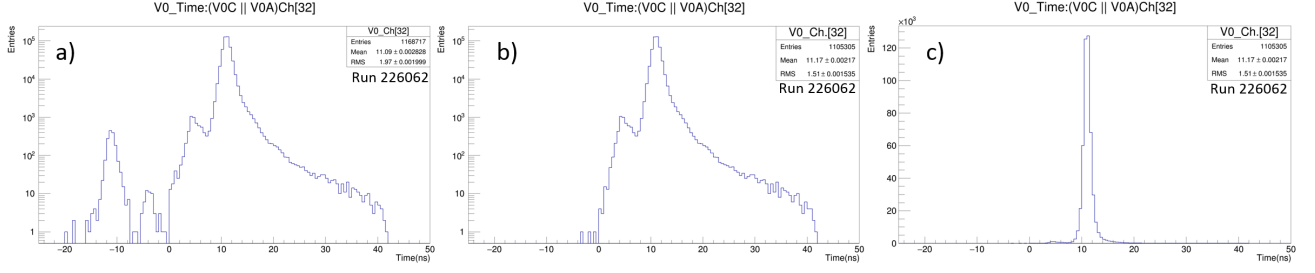


FIGURE 4.14. Effect of the V0 decision in channel 32, trigger condition V0or a)Time distribution in log scale, only applying trigger selection, b)Time distribution in log scale, after applying V0-Decision c)Time distribution in linear scale after applying V0-Decision.

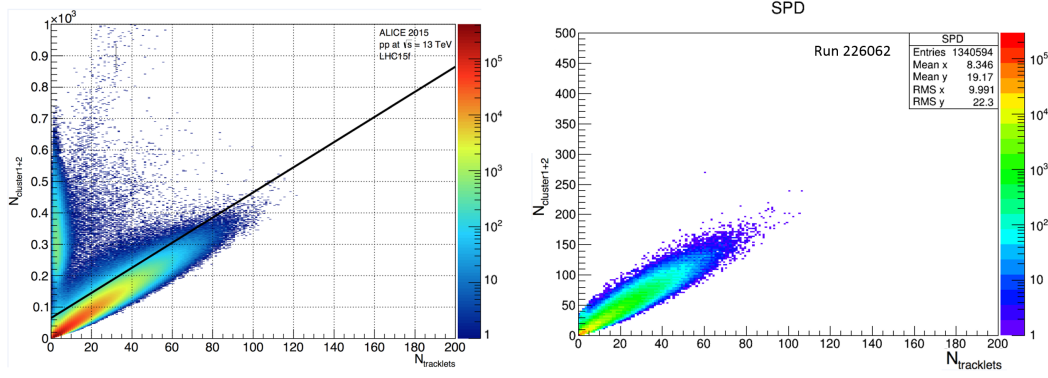


FIGURE 4.15. SPD Number of Clusters vs Tracklets. Left: full distribution for LHC15-period, the black line shows the standard cut applied. Right: Same plot only for run 226062 (Golden Run) after applying the pile-up rejection method.

and as we mentioned, these noisy chips can generate a Fast-OR event, and in consequence, a level 0 trigger. For such reason we remove from our selection the noisy chips, by applying an extra condition in the events in SPD. The condition implemented was to have at least 2 Fast-OR fired chips, one in the inner layer and one in the outer layer of SPD. As an extra in the systematic studies we saw the effect of applying different conditions to these fired chips.

4.5.1 Average Number of Events for Golden Run

The effect of applying our selection criteria for each detector is shown in table 4.5. The evolution in the number of events for our analysis with this event selection is listed.

Once the selection is defined by each one of the detectors used, we obtained 32 mutually exclusive combinations that we can generate with these detectors (ADC, V0C, SPD, V0A, ADA) occupying both, the trigger fired classes masks and the cuts mentioned before.

In order to have a better reference, we assign an "ID" to each trigger combination. This ID

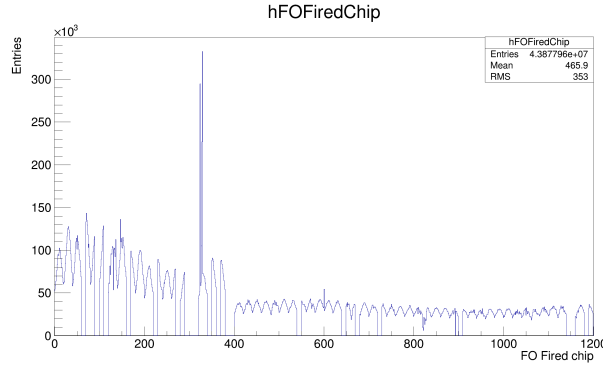


FIGURE 4.16. SPD Fired Chip Map, we can see the exrange behavior present in three channels from the inner layer (324, 328 and 329).

Selection of events	Number of events
Total number of events	2,995,914
GLOBAL MB_{OR} events C0SMB C0VBC C0VBA C0UBC C0UBA	1,508,819
SPD events C0SMB-B-NOPF-ALLNOTRD	1,348,154
SPD events after pile up rejection	1,337,396
SPD events after pile up and noisy events rejection	1,030,672
V0 events C0VBC C0VBA	1,168,717
V0 events C0VBC C0VBA after V0-Decision	1,159,969
AD events C0UBC C0UBA	1,208,312
AD events C0UBC C0UBA after time cuts defined	1,201,298
Global MB_{OR} after cleaning all the sample (mixing all the cuts)	1,190,370

Table 4.5: Number of events per criteria.

represents the detectors used for the analysis arranged from negative to positive in pseudo-rapidity units (ADC, V0C, SPD, V0A, ADA). The ID is meant to be interpreted as a binary selection, where "0" means "no hit" or veto, and "1" means "a hit" in the given detector (see table 4.6).

4.5.2 Consistency checks with T0

As mentioned before, ALICE has more detectors in the forward region, in this case, we took T0 for consistency tests, since it has some redundancy in pseudo-rapidity coverage with V0 detector, we made a comparison for some trigger combinations that make sense (see fig 4.17). We noticed that our selection is indeed consistent when we include T0 in the combination.

ID	Trigger combination	# events	ratio w.r.t. MBOR
00000	!ADC!/V0C!/SPD!/V0A!/ADA	0	0.00000
00001	!ADC!/V0C!/SPD!/V0A/ADA	24892	0.01650
00010	!ADC!/V0C!/SPD/V0A!/ADA	10590	0.00702
00011	!ADC!/V0C!/SPD/V0A/ADA	21812	0.01446
00100	!ADC!/V0C/SPD!/V0A!/ADA	1667	0.00110
00101	!ADC!/V0C/SPD!/V0A/ADA	433	0.00029
00110	!ADC!/V0C/SPD/V0A!/ADA	3408	0.00226
00111	!ADC!/V0C/SPD/V0A/ADA	11086	0.00735
01000	!ADC/V0C!/SPD!/V0A!/ADA	5346	0.00354
01001	!ADC/V0C!/SPD!/V0A/ADA	582	0.00039
01010	!ADC/V0C!/SPD/V0A!/ADA	463	0.00031
01011	!ADC/V0C!/SPD/V0A/ADA	1427	0.00095
01100	!ADC/V0C/SPD!/V0A!/ADA	3068	0.00203
01101	!ADC/V0C/SPD!/V0A/ADA	882	0.00058
01110	!ADC/V0C/SPD/V0A!/ADA	8988	0.00596
01111	!ADC/V0C/SPD/V0A/ADA	43649	0.02893
10000	ADC!/V0C!/SPD!/V0A!/ADA	45014	0.02983
10001	ADC!/V0C!/SPD!/V0A/ADA	5592	0.00371
10010	ADC!/V0C!/SPD/V0A!/ADA	2423	0.00161
10011	ADC!/V0C!/SPD/V0A/ADA	7551	0.00500
10100	ADC!/V0C/SPD!/V0A!/ADA	824	0.00055
10101	ADC!/V0C/SPD!/V0A/ADA	323	0.00021
10110	ADC!/V0C/SPD/V0A!/ADA	2455	0.00163
10111	ADC!/V0C/SPD/V0A/ADA	9894	0.00656
11000	ADC/V0C!/SPD!/V0A!/ADA	18396	0.01219
11001	ADC/V0C!/SPD!/V0A/ADA	3602	0.00239
11010	ADC/V0C!/SPD/V0A!/ADA	2820	0.00187
11011	ADC/V0C!/SPD/V0A/ADA	9188	0.00609
11100	ADC/V0C/SPD!/V0A!/ADA	17484	0.01159
11101	ADC/V0C/SPD!/V0A/ADA	7851	0.00520
11110	ADC/V0C/SPD/V0A!/ADA	105772	0.07010
11111	ADC/V0C/SPD/V0A/ADA	812888	0.53876
Total:		1,190,370	0.78894

Table 4.6: Mutual exclusive trigger combination for diffractive event selection

ID	Trigger Combination	# of Events	Ratio wrt MBor	ID	Trigger Combination	# of Events	Ratio wrt MBor
00100	!ADC/!V0C/SPD/!V0A/!ADA	259151	0.17175	0001000	!ADC/!T0C/!V0C/SPD/!V0A/!T0A/!ADA	259133	0.17175
00001	!ADC/!V0C/!SPD/!V0A/ADA	24892	0.01650	0000001	!ADC/!T0C/!V0C/!SPD/!V0A/!T0A/ADA	24892	0.01650
00101	!ADC/!V0C/SPD/!V0A/ADA	697	0.00046	0001001	!ADC/!T0C/!V0C/SPD/!V0A/!T0A/ADA	697	0.00046
10000	ADC/!V0C/!SPD/!V0A/!ADA	45014	0.02983	1000000	ADC/!T0C/!V0C/!SPD/!V0A/!T0A/!ADA	44968	0.02980
10100	ADC/!V0C/SPD/!V0A/!ADA	1290	0.00085	1001000	ADC/!T0C/!V0C/SPD/!V0A/!T0A/!ADA	1279	0.00085
10101	ADC/!V0C/SPD/!V0A/ADA	489	0.00032	1001001	ADC/!T0C/!V0C/SPD/!V0A/!T0A/ADA	486	0.00032



FIGURE 4.17. Comparison between 6 trigger combinations including T0 detector for redundancy.

4.6 Background and systematic studies

4.6.1 Systematic studies

To verify that our event selection is done correctly, we made similar selections applying different parameters in the cuts defined. Even so, we did not try removing filters like the V0-Decision or the pile-up rejection in SPD, since this will not make sense. The main variations were done in the SPD event selection, in the clusters versus tracklets correlation (fig 4.15), where we apply a linear cut with an offset of 55 with slope 4. Three variations were done in the offset (35, 45, 65) and four variations in the slope (3, 3.5, 4.5, 5). For the selection of AD, we tried reducing 20 ns the time window for ADA (from 40-80 ns to 50-70 ns), we also saw the effect of including AD offline decision. Putting all this together, we have a total of eleven comparisons, we can see an example of these variations with respect to our original selection in fig 4.18.

For all of these comparisons we request for the trigger mask for each detector (MB_{OR}), and we also require the condition in SPD to have at least 2 Fast-Or fired chips, one in the inner layer and one in the outer layer.

To summarize all the effects on all the 32 trigger combinations we have table 4.7

4.6.2 Beam-Induced background analysis

For background subtraction, the following calculation was carried out [9]:

$$(4.2) \quad BG = A \cdot f_A + C \cdot f_C - E \cdot f_E$$

where,

- BG : Total number of background events.

4.6. BACKGROUND AND SYSTEMATIC STUDIES

ID	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11
00000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
00001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.987	0.987
00010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
00011	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.989	0.989
00100	1.000	1.002	1.005	1.005	1.000	1.000	0.998	1.000	1.000	1.000	1.000
00101	1.000	1.005	1.012	1.014	1.000	1.000	0.998	1.005	1.000	0.979	0.979
00110	1.000	1.004	1.006	1.008	1.000	0.999	0.996	1.001	1.000	1.000	1.000
00111	1.000	1.001	1.003	1.004	1.000	1.000	0.999	1.000	1.000	0.991	0.991
01000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
01001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.993	0.993
01010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
01011	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.978	0.978
01100	1.000	1.009	1.014	1.019	0.999	0.997	0.992	1.002	1.000	1.000	1.000
01101	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.981	0.981
01110	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
01111	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.992	0.992
10000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.996	0.996
10001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.982	0.982
10010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.997
10011	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.984	0.984
10100	1.000	1.016	1.023	1.036	0.999	0.996	0.986	1.002	1.000	1.000	1.000
10101	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.963	0.963
10110	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.997
10111	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.990	0.990
11000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999
11001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.980	0.980
11010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999
11011	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.986	0.986
11100	1.000	1.004	1.006	1.008	1.000	0.999	0.997	1.001	1.000	0.999	0.999
11101	1.000	1.000	1.000	1.001	1.000	1.000	1.000	1.000	0.999	0.977	0.977
11110	1.000	1.001	1.001	1.001	1.000	1.000	1.000	1.000	1.000	0.999	0.999
11111	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.993	0.993

Table 4.7: Systematic comparisons with different criteria for selection of diffractive processes.

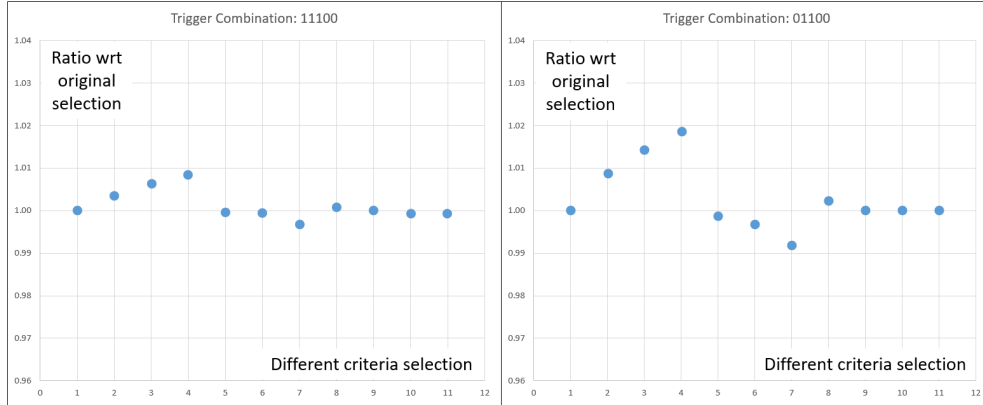


FIGURE 4.18. Example of systematic studies, on the vertical axis the ratio with respect to our selection defined in the previous section, on the horizontal axis the each point indicates a different criteria, such like time window defined for AD, or number of fired chips for SPD. Left: the effect in combination "11100", right: the effect in "01100".

- A : Events induced by Beam - Empty (no beam) background, meaning beam from A side and no beam in C side.
- C : Events induced by Empty (no beam) - Beam background.
- E : Events induced by Empty - Empty background
- f_A, f_C : scaling factors for accounting the beam intensity in A and C.
- f_E : scaling factor for the number of E (empty) bunches in the filling scheme.

The scaling factors, f_A and f_C , are obtained by dividing the number of interacting bunches w.r.t. the number of non-interactive bunches. For the golden run 226062, with the values from table 4.8, we have

$$f_A = \frac{IntBunchBeam1}{NonIntBunchBeam1} = \frac{1.16E + 11}{1.78E + 11} = 0.651,$$

$$(4.3) \quad f_C = \frac{IntBunchBeam2}{NonIntBunchBeam2} = \frac{1.21E + 11}{1.97E + 11} = 0.614,$$

$$f_E = \frac{InteractingBunches}{EmptyBunches} = \frac{15}{2} = 7.5$$

To obtain the number of events given by A , C and E , we computed the 32 mutual exclusive trigger combinations as before, but changing the trigger mask for the minimum bias in order to obtain the contribution of each of the cases.

	SOR	EOR	Avg.
Interacting Bunches Beam 1	1.16E+11	1.16E+11	1.16E+11
Non Interacting Bunches Beam 1	1.78E+11	1.78E+11	1.78E+11
Interacting Bunches Beam 2	1.21E+11	1.20E+11	1.20E+11
Non Interacting Bunches Beam 2	1.97E+11	1.97E+11	1.97E+11

Table 4.8: Beam intensity for Run 226062. The Beam 1 is the clockwise LHC Beam (For ALICE, Beam from A-side), Beam 2 is anti-clockwise LHC Beam (For ALICE, Beam from C-side)

- For **A**: $MB_{OR} - A$ (C0SMB-A-NOPF-ALLNOTRD || CINT10-A-NOPF-ALLNOTRD)
- For **C**: $MB_{OR} - C$ (C0SMB-C-NOPF-ALLNOTRD || CINT10-C-NOPF-ALLNOTRD)
- For **E**: $MB_{OR} - E$ (C0SMB-E-NOPF-ALLNOTRD || CINT10-E-NOPF-ALLNOTRD)

Using the information of the table 4.9 and the correction factors f_A , f_B and f_C , we can correct the values from table 4.6 obtaining table 4.10. As an example lets take combination "11101": the scaling factors (f_A , f_B and f_C) are the same for all the different combinations, and the values for A, C and E from equation 4.2 are given in table 4.9, so we obtained:

$$(4.4) \quad BG = (40)(0.651) + (211)(0.614) - (7)(7.5) = 103.094$$

we use this result to correct the value from table 4.6 (for "11101") obtaining:

$$(4.5) \quad N_{11101} = 7851 - 103.094 = 7747.904$$

The result from equation 4.5 is the number presented in table 4.10. A similar treatment is done for all the 32 combinations.

4.6.3 Total Number of Events

With all our data selection and after the background correction, only 78% of the total *Global* MB_{OR} (see table 4.4) events remains. However this sample is the set of data of our interest, therefore we normalize to "1" the ratio with respect to minimum bias events (same factor as normalizing the number of events to the total number of *Global* MB_{OR} events), obtaining table 4.11.

4.6.4 Expanding the Systematic Studies

In order to crosscheck our data selection, we decided to compare our results with different runs (see table 4.3), for this case we took 4 runs.

ID	#events $MB_{OR} - A$	#events $MB_{OR} - C$	#events $MB_{OR} - E$
00000	4	0	0
00001	0	0	0
00010	2	0	0
00011	22	0	0
00100	28	3	0
00101	4	0	0
00110	10	0	0
00111	92	0	0
01000	0	0	0
01001	0	0	0
01010	0	0	0
01011	1	0	0
01100	1	0	0
01101	0	0	0
01110	0	0	0
01111	47	0	0
10000	0	0	0
10001	0	0	0
10010	0	0	0
10011	7	0	0
10100	0	6	0
10101	2	1	0
10110	2	0	0
10111	150	7	2
11000	0	34	0
11001	0	38	0
11010	0	0	0
11011	0	0	0
11100	0	47	0
11101	40	211	7
11110	0	35	0
11111	14	45	0
Total:	426	427	9

Table 4.9: The 32 combinations, with the number of events for each of the cases (-A, -C -E). The correction factor applied in each case was taken from expression 4.3

ID	Trigger combination	# events	ratio w.r.t. MBOR
00000	!ADC!/V0C!/SPD!/V0A!/ADA	0.0	0.00000
00001	!ADC!/V0C!/SPD!/V0A/ADA	24892.0	0.01650
00010	!ADC!/V0C!/SPD/V0A!/ADA	10588.7	0.00702
00011	!ADC!/V0C!/SPD/V0A/ADA	21797.7	0.01445
00100	!ADC!/V0C/SPD!/V0A!/ADA	1646.9	0.00109
00101	!ADC!/V0C/SPD!/V0A/ADA	430.4	0.00029
00110	!ADC!/V0C/SPD/V0A!/ADA	3401.5	0.00225
00111	!ADC!/V0C/SPD/V0A/ADA	11026.1	0.00731
01000	!ADC/V0C!/SPD!/V0A!/ADA	5346.0	0.00354
01001	!ADC/V0C!/SPD!/V0A/ADA	582.0	0.00039
01010	!ADC/V0C!/SPD/V0A!/ADA	463.0	0.00031
01011	!ADC/V0C!/SPD/V0A/ADA	1426.3	0.00095
01100	!ADC/V0C/SPD!/V0A!/ADA	3067.3	0.00203
01101	!ADC/V0C/SPD!/V0A/ADA	882.0	0.00058
01110	!ADC/V0C/SPD/V0A!/ADA	8988.0	0.00596
01111	!ADC/V0C/SPD/V0A/ADA	43618.4	0.02891
10000	ADC!/V0C!/SPD!/V0A!/ADA	45014.0	0.02983
10001	ADC!/V0C!/SPD!/V0A/ADA	5592.0	0.00371
10010	ADC!/V0C!/SPD/V0A!/ADA	2423.0	0.00161
10011	ADC!/V0C!/SPD/V0A/ADA	7546.4	0.00500
10100	ADC!/V0C/SPD!/V0A!/ADA	820.3	0.00054
10101	ADC!/V0C/SPD!/V0A/ADA	321.1	0.00021
10110	ADC!/V0C/SPD/V0A!/ADA	2453.7	0.00163
10111	ADC!/V0C/SPD/V0A/ADA	9807.1	0.00650
11000	ADC/V0C!/SPD!/V0A!/ADA	18375.1	0.01218
11001	ADC/V0C!/SPD!/V0A/ADA	3578.7	0.00237
11010	ADC/V0C!/SPD/V0A!/ADA	2820.0	0.00187
11011	ADC/V0C!/SPD/V0A/ADA	9188.0	0.00609
11100	ADC/V0C/SPD!/V0A!/ADA	17455.1	0.01157
11101	ADC/V0C/SPD!/V0A/ADA	7747.9	0.00514
11110	ADC/V0C/SPD/V0A!/ADA	105750.5	0.07009
11111	ADC/V0C/SPD/V0A/ADA	812851.3	0.53873
Total:		1,189,900	0.78863

Table 4.10: Corrected mutual exclusive trigger combination for diffractive event selection.

ID	Trigger combination	# events	ratio w.r.t. MBOR
00000	!ADC/!V0C/!SPD/!V0A/!ADA	0.0	0.00000
00001	!ADC/!V0C/!SPD/!V0A/ADA	31563.6	0.02092
00010	!ADC/!V0C/!SPD/V0A/!ADA	13426.7	0.00890
00011	!ADC/!V0C/!SPD/V0A/ADA	27639.9	0.01832
00100	!ADC/!V0C/SPD/!V0A/!ADA	2088.3	0.00138
00101	!ADC/!V0C/SPD/!V0A/ADA	545.8	0.00036
00110	!ADC/!V0C/SPD/V0A/!ADA	4313.2	0.00286
00111	!ADC/!V0C/SPD/V0A/ADA	13981.3	0.00927
01000	!ADC/V0C/!SPD/!V0A/!ADA	6778.8	0.00449
01001	!ADC/V0C/!SPD/!V0A/ADA	738.0	0.00049
01010	!ADC/V0C/!SPD/V0A/!ADA	587.1	0.00039
01011	!ADC/V0C/!SPD/V0A/ADA	1808.6	0.00120
01100	!ADC/V0C/SPD/!V0A/!ADA	3889.5	0.00258
01101	!ADC/V0C/SPD/!V0A/ADA	1118.4	0.00074
01110	!ADC/V0C/SPD/V0A/!ADA	11397.0	0.00755
01111	!ADC/V0C/SPD/V0A/ADA	55309.1	0.03666
10000	ADC/!V0C/!SPD/!V0A/!ADA	57078.7	0.03783
10001	ADC/!V0C/!SPD/!V0A/ADA	7090.8	0.00470
10010	ADC/!V0C/!SPD/V0A/!ADA	3072.4	0.00204
10011	ADC/!V0C/!SPD/V0A/ADA	9569.0	0.00634
10100	ADC/!V0C/SPD/!V0A/!ADA	1040.2	0.00069
10101	ADC/!V0C/SPD/!V0A/ADA	407.1	0.00027
10110	ADC/!V0C/SPD/V0A/!ADA	3111.3	0.00206
10111	ADC/!V0C/SPD/V0A/ADA	12435.5	0.00824
11000	ADC/V0C/!SPD/!V0A/!ADA	23300.0	0.01544
11001	ADC/V0C/!SPD/!V0A/ADA	4537.8	0.00301
11010	ADC/V0C/!SPD/V0A/!ADA	3575.8	0.00237
11011	ADC/V0C/!SPD/V0A/ADA	11650.6	0.00772
11100	ADC/V0C/SPD/!V0A/!ADA	22133.5	0.01467
11101	ADC/V0C/SPD/!V0A/ADA	9824.5	0.00651
11110	ADC/V0C/SPD/V0A/!ADA	134093.9	0.08887
11111	ADC/V0C/SPD/V0A/ADA	1030712.5	0.68313
	Total:	1,508,819	1.000

Table 4.11: Corrected mutual exclusive trigger combination for diffractive event selection after normalization.

- 233971, 233972, 233976, 233978:
 - Duration: 01:12:15 - 01:06:10 - 01:08:23 - 01:52:13
 - Period: LHC15h
 - sample used for analysis: pass2
 - participant detectors: ACORDE, AD, CPV, FMD, HMPID, MUONTRG, MUONTRK,

PHOS, SDD, SPD, SSD, T0, TOF, TPC, TRD, TRIGGER, V0 and ZDC

- trigger detectors: AD, SPD, T0, TPC, V0 and ZDC
- L3 magnet current: -30 kA
- Dipole Magnet current: -6 kA
- Fill number: 4266
- Beam energy: 6500 GeV
- Beta star = 18.85 m
- # interacting bunches: 7
- # Non-Interacting Bunches Beam 1: 37
- # Non-Interacting Bunches Beam 2: 37
- Total Events: 3,146,346 - 2,914,672 - 3,230,164 - 5,154,053
- Event Rate: 706.57 - 717.02 - 766.17 - 755.17
- Total Physics Events: 3,087,616 - 2,859,478 - 3,173,604 - 5,060,774

Using the same criteria for event selection as for the so called golden run, we computed the 32 mutually exclusive combinations for these runs (LHC15h period), see table 4.12.

The average of the ratios for each single combination in table 4.12 was obtained, then a comparison between each different run was computed, the result for run 233971 is shown in figure 4.19. The results obtained are satisfactory for all the exclusive combinations, being the major variation in the order of 5%.

4.7 Statistical and systematic error

With all the information obtained we can give the final numbers including the statistical and systematic errors. We used the standard statistical error (4.6) together with the error propagation assuming independent variables from the different systematic studies.

$$(4.6) \quad \sigma_s = \frac{\sigma}{\sqrt{N}} \quad , \quad \sigma_{Sis} = \sqrt{(\sigma_1)^2 + (\sigma_2)^2 + (\sigma_3)^2}$$

Where σ_s is the statistical error, σ is the standard deviation, and N is the total number of events. On the other side σ_{Sis} is the total systematic error, $\sigma_{1,2,3}$ is the error from the different systematic studies done. Together all this information give us the table 4.13, which can summarize all the work so far.

ID	Run 233971	Run 233972	Run 233976	Run 233978
00000	0.00000	0.00000	0.00000	0.00000
00001	0.01716	0.01717	0.01707	0.01715
00010	0.01042	0.01040	0.01028	0.01035
00011	0.01551	0.01567	0.01536	0.01534
00100	0.00148	0.00148	0.00140	0.00143
00101	0.00029	0.00033	0.00030	0.00029
00110	0.00447	0.00447	0.00424	0.00431
00111	0.00822	0.00826	0.00824	0.00819
01000	0.00383	0.00385	0.00373	0.00376
01001	0.00040	0.00040	0.00040	0.00038
01010	0.00054	0.00054	0.00054	0.00055
01011	0.00101	0.00097	0.00102	0.00100
01100	0.00279	0.00287	0.00260	0.00262
01101	0.00069	0.00072	0.00066	0.00069
01110	0.01165	0.01149	0.01145	0.01169
01111	0.03347	0.03308	0.03353	0.03328
10000	0.03787	0.03800	0.03807	0.03796
10001	0.00396	0.00402	0.00397	0.00398
10010	0.00292	0.00290	0.00296	0.00296
10011	0.00548	0.00542	0.00544	0.00543
10100	0.00076	0.00074	0.00079	0.00076
10101	0.00023	0.00024	0.00024	0.00024
10110	0.00326	0.00323	0.00320	0.00330
10111	0.00782	0.00780	0.00773	0.00781
11000	0.01478	0.01493	0.01481	0.01482
11001	0.00239	0.00240	0.00234	0.00232
11010	0.00333	0.00338	0.00332	0.00332
11011	0.00623	0.00618	0.00618	0.00623
11100	0.01519	0.01526	0.01504	0.01516
11101	0.00543	0.00544	0.00539	0.00538
11110	0.14191	0.14199	0.14185	0.14256
11111	0.63650	0.63638	0.63785	0.63673

Table 4.12: Comparison between the ratios of the 32 mutually exclusive combinations for runs from period LHC15h, after the cuts defined and normalization.

4.8 Defining the observables

Soft diffraction bases theoretically on Pomeron exchange, the vacuum singularity of Regge theory. Experimentally, soft diffraction is traditionally characterized with registering of large rapidity gap events. In practice, a number of approximations are required for defining and measuring the rapidity gaps.

Usually the experimental definition when talking about soft diffraction goes through large

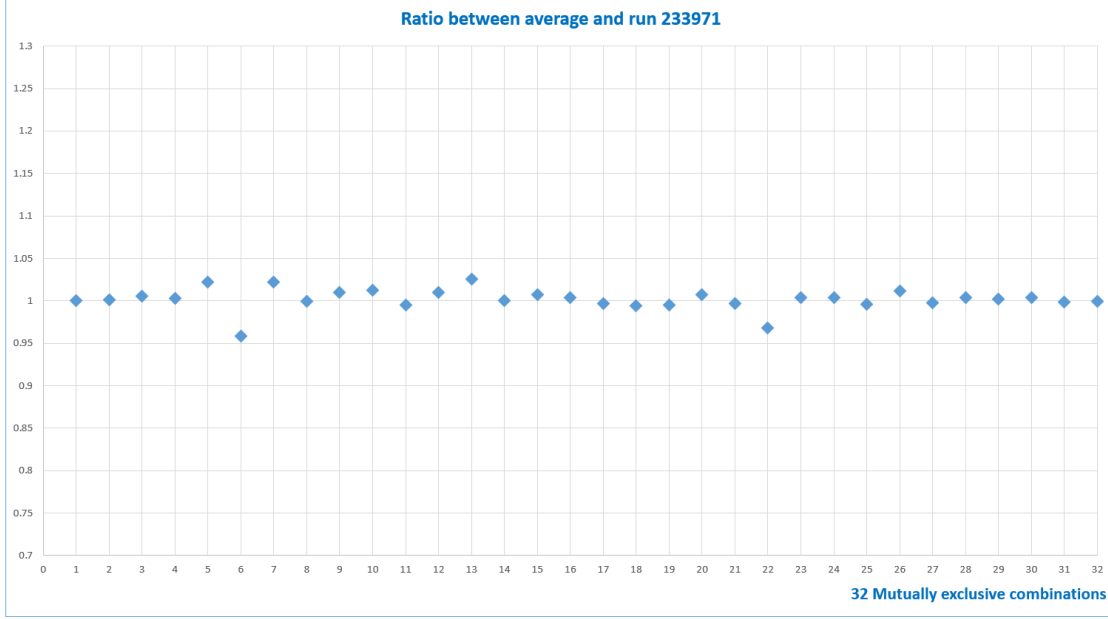


FIGURE 4.19. Comparison of run 233971 with respect to the average obtained from the runs of period LHC15h. The data selection was done as the one defined for run 226062.

rapidity gaps $\Delta_y \simeq 3$ and the total inelastic cross section is defined as [25]:

$$(4.7) \quad \sigma_{inel}^{pp} \equiv \sigma_{SDL} + \sigma_{SDR} + \sigma_{DD} + \sigma_{CD} + \sigma_{ND}$$

The decomposition above is experimentally well posed only in limited phase space. Now, instead of this natural decomposition, we defined $n = 2^N - 1$ partial cross sections, where N is the number of slices in pseudo-rapidity covered by the experiment [30] (5 in our case), which gave us:

$$(4.8) \quad \sigma_{inel}^{pp} \equiv \sigma_1 + \sigma_2 + \sigma_3 + \dots + \sigma_n$$

Where each σ_k corresponds to one particular final state topology class. These span $k = 1, 2, \dots, 2^{N-1}$ encodes whether at least one final state in the given rapidity slice (detector) is observed. The basic cross section calculation is given by:

$$(4.9) \quad \sigma_n = \frac{E(N_{data} - N_{bckg})}{\mathcal{L}}$$

Where:

- $\mathcal{L}$ is the integrated luminosity

ID	Num of Events	Ratio wrt. MBor	Statistical Error (+/-%)	Systematic Error (+%)	Systematic Error (-%)
00000	0	0	0	0	0
00001	31658.019	0.020982	0.033	0	1.346
00010	13451.962	0.008916	0.077	0	0
00011	27558.679	0.018265	0.037	0	1.086
00100	1864.862	0.001236	0.488	0.539	0
00101	517.578	0.000343	1.88	1.386	2.079
00110	4251.55	0.002818	0.239	0.763	0.059
00111	13337.626	0.00884	0.073	0.406	0.938
01000	6799.123	0.004506	0.152	0	0
01001	740.196	0.000491	1.399	0	0.687
01010	588.85	0.00039	1.758	0	0
01011	1806.6	0.001197	0.571	0	2.172
01100	3893.649	0.002581	0.265	1.858	0.326
01101	1121.741	0.000743	0.923	0	1.927
01110	11431.073	0.007576	0.091	0.011	0
01111	55124.316	0.036535	0.019	0.009	0.848
10000	57249.481	0.037943	0.018	0	0.446
10001	7111.989	0.004714	0.146	0	1.77
10010	3081.608	0.002042	0.336	0	0.33
10011	9545.518	0.006326	0.108	0	1.603
10100	1001.122	0.000664	0.988	3.641	0.364
10101	386.428	0.000256	2.52	0	3.716
10110	3105.747	0.002058	0.332	0	0.285
10111	11668.292	0.007733	0.082	0.01	0.98
11000	23130.805	0.01533	0.044	0	0.108
11001	4284.338	0.00284	0.226	0	1.971
11010	3586.518	0.002377	0.289	0	0.142
11011	11685.436	0.007745	0.089	0	1.361
11100	21869.393	0.014494	0.047	0.841	0.069
11101	9341.558	0.006191	0.104	0.051	2.254
11110	134249.103	0.088976	0.008	0.078	0.053
11111	1033375.838	0.684891	0.001	0.025	0.737

Table 4.13: Final numbers after correction of the number of triggered events, including the correction for beam-induced background, the calculation for statistical error and the systematic error from the different studies done with Run 226062 (golden run) and the runs from period LHC15h.

- $N_{data} - N_{bckg}$ is the total number of events minus the induced background events
- E is a experimental correction, given by the trigger efficiency obtained from Monte-Carlo

The basic idea behind the fiducial definition is to have a result of the measurement which

closely follows what the detector can really observe. Some of the problems that this definition has in the mismatch between geometric η boundaries and effective η boundaries, because of material secondaries. The more forward we go, the more blurred the definition becomes. Currently there is no reliable procedure to study this from data. This problem affects every analysis using forward detectors at fundamental level. It could be corrected if the forward detector would be a forward tracker. One could have the possibility to extrapolate the tracks to the interaction point.

However, based on ALICE geometry, we will obtain these visible or fiducial partial cross sections, even so we are missing the trigger efficiency obtained from Monte-Carlo simulation from the previous parameters (4.9).

4.9 Monte-Carlo comparison

To obtain the experimental correction (E), we analyze MC data anchored to the runs previously analyzed with collision data.

- Runs 226062, 233971, 233972 and 233978.
- PYTHIA 8, Monash - 2013.
- LHC15f and LHC15h anchored.
- ALIROOT - 6500.
- Monalisa label: LHC16b3d.

We used the same criteria for the selection in our 32 mutually exclusive combinations. As an extra, an advantage of Monte-Carlo data, is that we can know in advance which kind of process is generating our events. This means that we can separate them as:

- Non-Diffractive ($p + p \rightarrow p(*) + p(*)$).
- Single Diffractive Right ($p + p \rightarrow p(*) + X$).
- Single Diffractive Left ($p + p \rightarrow X + p(*)$).
- Double Diffractive ($p + p \rightarrow X + X$).
- Central Diffractive ($p + p \rightarrow p(*) + X + p(*)$).

We can see in fig 4.20 the consistency within Monte-Carlo data, the ratio of the different runs anchored compared looks very similar, except for two of our trigger combinations (00100 & 01010). The same selection was done with different sets of MC-data requiring the initial condition for the different kind of processes (non diffractive, single diffractive, etc.).

ID	Ratio wrt MBor Run 233971	Ratio wrt MBor Run 233972	Ratio wrt MBor Run 233978	Ratio wrt MBor Run 226062
00000	0.00000	0.00000	0.00000	0.00000
00001	0.01053	0.01047	0.01059	0.01084
00010	0.00282	0.00289	0.00289	0.00290
00011	0.01839	0.01852	0.01830	0.01894
00100	0.00017	0.00002	0.00003	0.00018
00101	0.00004	0.00005	0.00004	0.00004
00110	0.00211	0.00199	0.00206	0.00218
00111	0.01427	0.01422	0.01432	0.01470
01000	0.00044	0.00041	0.00043	0.00045
01001	0.00008	0.00009	0.00007	0.00009
01010	0.00007	0.00005	0.00029	0.00007
01011	0.00028	0.00028	0.00028	0.00029
01100	0.00064	0.00064	0.00063	0.00066
01101	0.00020	0.00018	0.00019	0.00020
01110	0.00679	0.00676	0.00678	0.00700
01111	0.04124	0.04130	0.04159	0.04248
10000	0.01888	0.01888	0.01878	0.01944
10001	0.00298	0.00303	0.00299	0.00307
10010	0.00095	0.00091	0.00093	0.00098
10011	0.00605	0.00602	0.00598	0.00623
10100	0.00009	0.00008	0.00008	0.00009
10101	0.00004	0.00004	0.00004	0.00004
10110	0.00093	0.00098	0.00093	0.00095
10111	0.00585	0.00593	0.00590	0.00603
11000	0.01431	0.01431	0.01446	0.01474
11001	0.00263	0.00268	0.00262	0.00271
11010	0.00130	0.00127	0.00130	0.00134
11011	0.00585	0.00587	0.00586	0.00602
11100	0.01930	0.01906	0.01917	0.01988
11101	0.00440	0.00445	0.00439	0.00453
11110	0.09559	0.09510	0.09481	0.09845
11111	0.72280	0.72352	0.72330	0.74448

Table 4.14: Event classification with Monte-Carlo sample for runs 233971, 233972, 233978 and 226062. For purity selection the same criteria as in collision data is applied.

In figure 4.21 we can see the distribution of non-diffractive events in our 32 combinations, as expected the mayor outcome is in ttrigger combination "11111", in figures 4.22, 4.23 and 4.24 we have the result for single and double diffractive events.

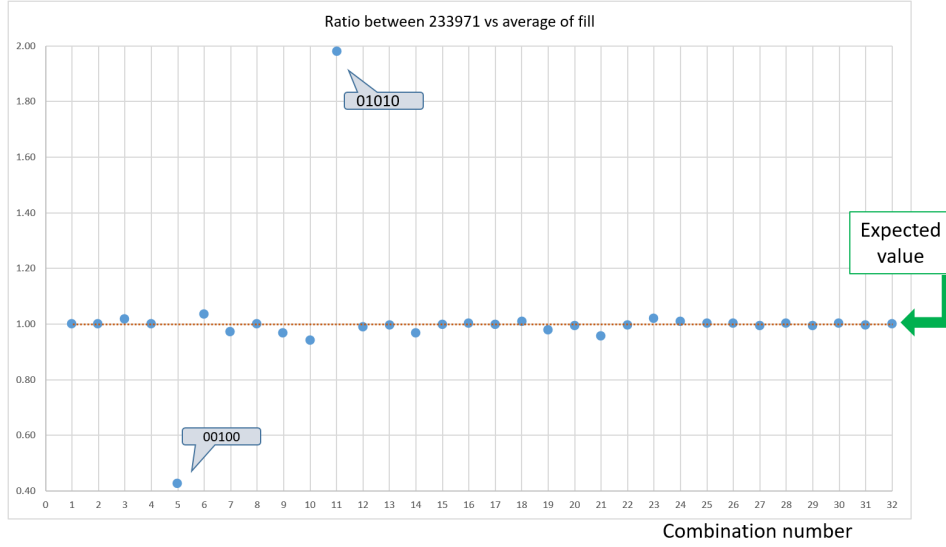


FIGURE 4.20. Comparison of run 233971 with respect to the average obtained from the runs of period LHC15h (Monte-Carlo). The data selection was done as the one defined for run 226062.

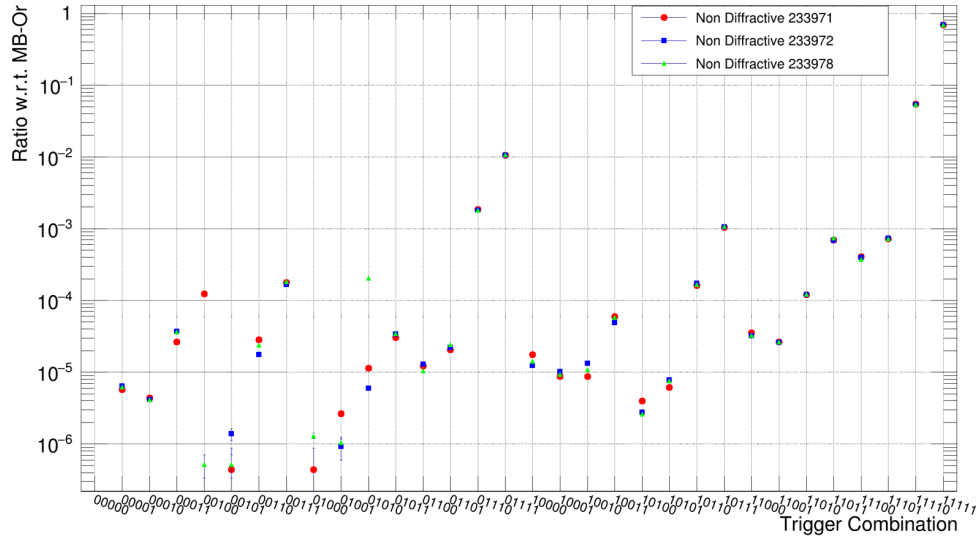


FIGURE 4.21. Comparison of MC-data for runs 233971, 233972 and 233978 for Non-Diffractive events (logarithmic scale) using our selection criteria. The mayor number of events is in combinations "11111", "11110" and "01111".

4.9.1 Monte-Carlo corrections

All the produced Monte-Carlo Samples are consistent for our trigger selection including the different process classification (4.21, 4.22, 4.22 and 4.24). The major problem came when comparing data from collision to MC. In figure 4.25 we can see the ratio between data generated from MC

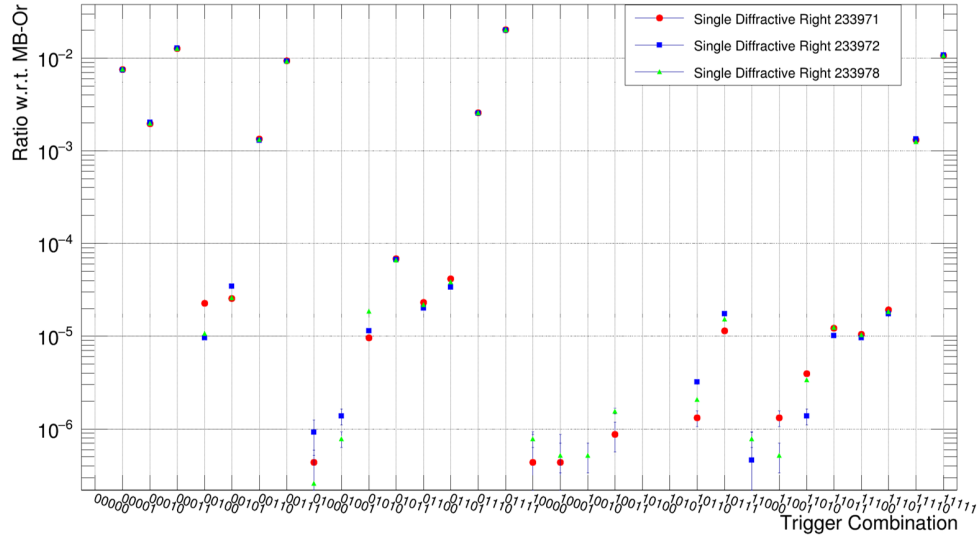


FIGURE 4.22. Comparison of MC-data for runs 233971, 233972 and 233978 for single diffractive right events(logarithmic scale) using our selection criteria. The mayor number of events is in combinations "11111", "01111", "00111" and "00011".

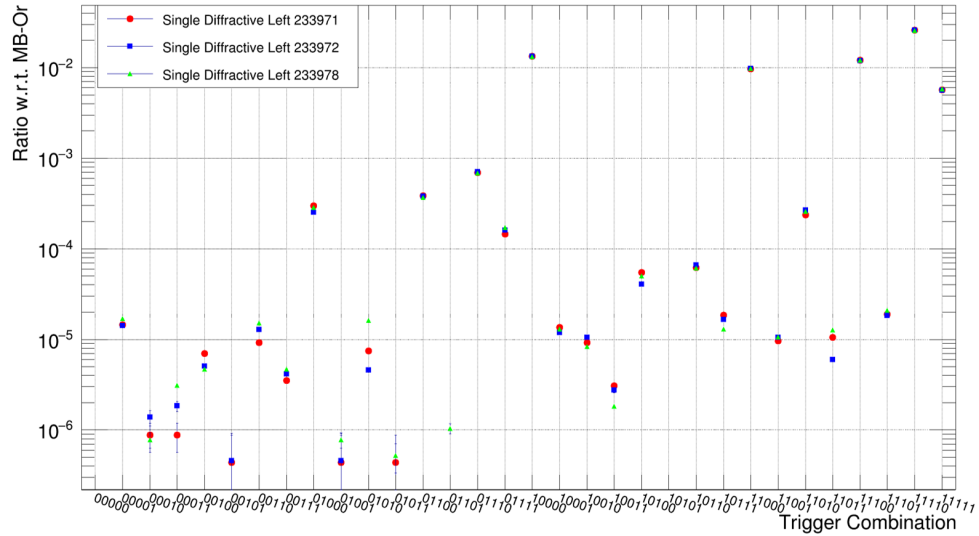


FIGURE 4.23. Comparison of MC-data for runs 233971, 233972 and 233978 for single diffractive left events(logarithmic scale) using our selection criteria. The mayor number of events is in combinations "11111", "11110", "11100", "11000" and "10000".

and data from collisions for run 233978.

An extensive study was done to understand this asymmetry between data and MC, we used different generators for MC, and different data runs. During this process we found a problem in the simulation of AD.

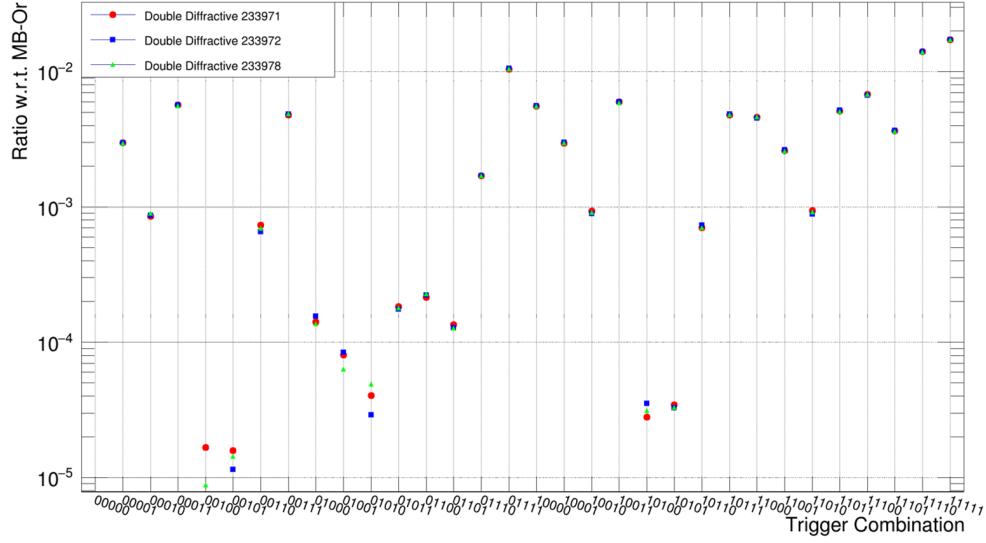


FIGURE 4.24. Comparison of MC-data for runs 233971, 233972 and 233978 for double diffractive events(logarithmic scale) using our selection criteria. The mayor number of events is in combinations "11111", "11110", "11100", "11000" and "10000".

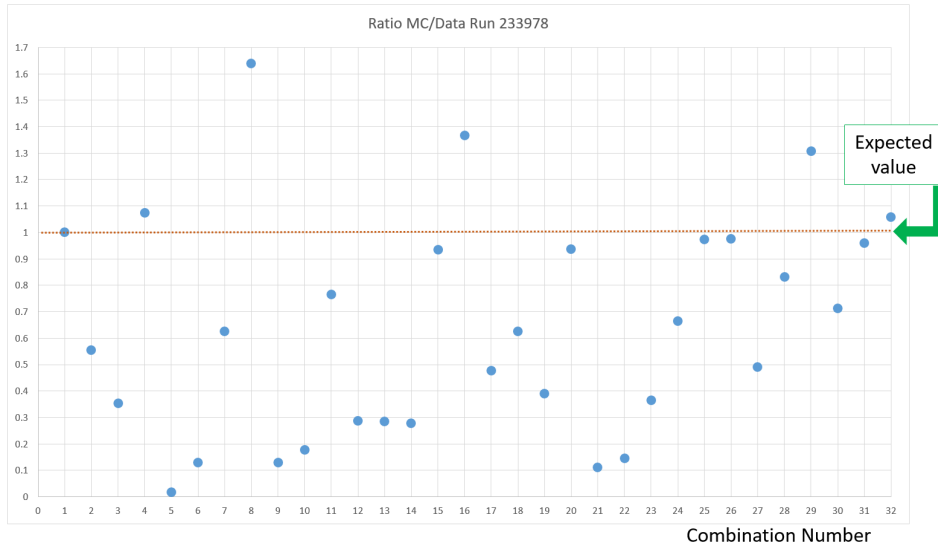


FIGURE 4.25. Comparison of Monte-Carlo generated data versus Collisions data for Run 233978. The red line indicates the expected value. We can observe a random behaviour.

Taking advantage of the two layers that conform AD, we can obtain a trigger efficiency coming from collision data, the way to do this is by taking a look at adjacent pads and the charge and time information registered by them, one would expect that if the front pad (closest to IP) detects a particle, this particle should be registered by the adjacent pad, as AD trigger is generated only when both adjacent pads have a time measurement (threshold level exceeded) we can obtain a

trigger efficiency with this information.

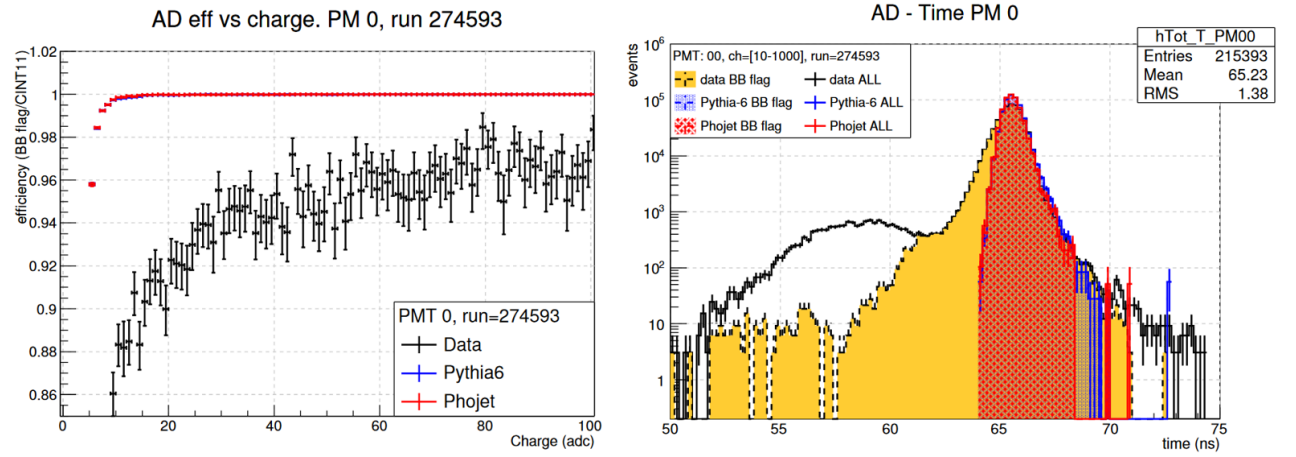


FIGURE 4.26. Left: Trigger efficiency comparison between Phojet, Pythia6 and collision data for AD. Right: Time information comparison.

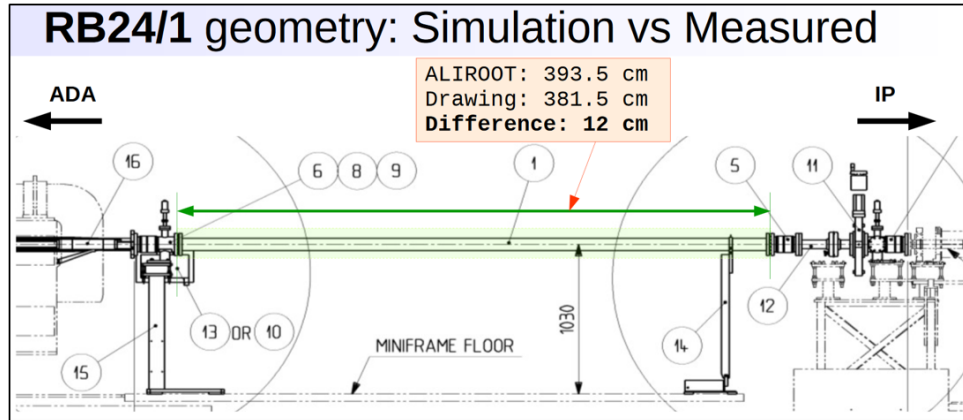


FIGURE 4.27. Official drawing in ALICE mini-frame, a correction was needed both in Monte-Carlo simulation and ALICE official drawings, different materials non existent in the drawings were found in ALICE cavern.

As time information is used for trigger, we also took a look at the time information according to different simulators and compare them to real collision data (4.26).

We took a look at the official drawing of ALICE experiment, and to those implemented in the simulation, we found a couple of differences between the official drawings, the drawings from the simulation and the real material budget placed in front of AD detector. A correction to the geometry was implemented in 2017, this new geometry is official in ALICE since the LHC17j period of data taking (July 2017), after the correction a new Monte Carlo sample was generated.

4.10 Measured Fiducial Rates

The basic idea behind the fiducial definition is to have a result of the measurement which closely follows what the detector can really observe, which are as model independent as possible. The single, double and non-diffractive cross sections are extracted using multidimensional fits [34]. In figure 4.28 we can see the results for the fiducial rates using ALICE collision data at 13 TeV and with different samples from Monte-Carlo with different generators .

For this result we split SPD into positive and negative η , which gave us a total of 64 different trigger combinations.

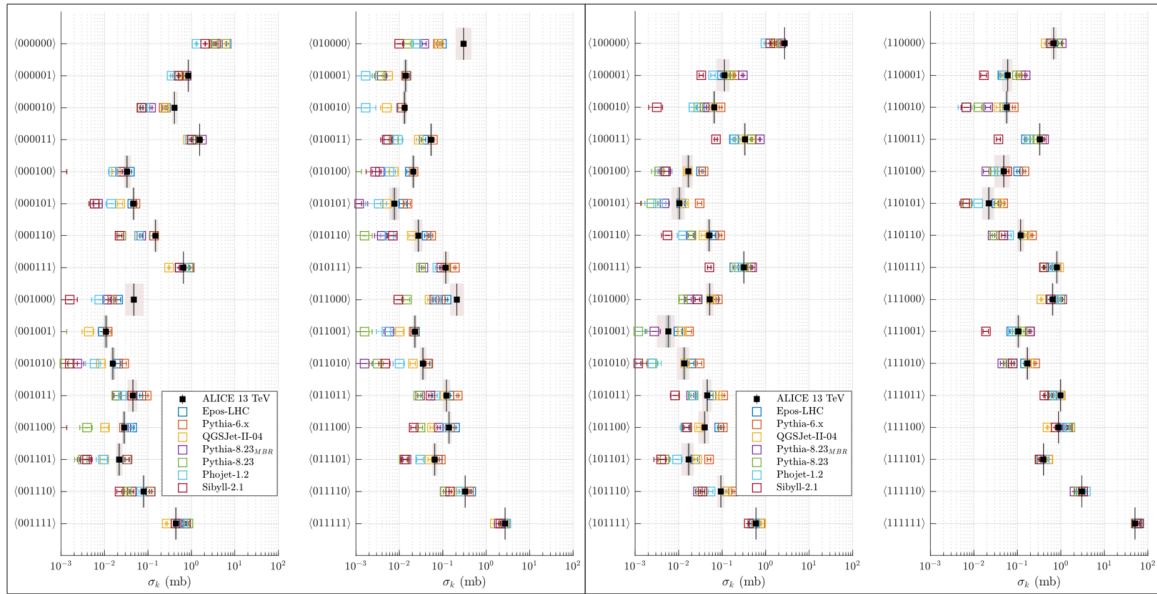


FIGURE 4.28. All the fiducial rates obtained with our measurement and different generators [35, 36]. For this case we split SPD coverage in two parts (positive and negative η).

The physics work group involved in the diffractive cross section measurement is almost ready to present a final result, we are missing the implementation of the last corrections for Monte-Carlo which will include the geometry correction, the trigger efficiency and the time measurement. We expect to conclude this work in the upcoming months.

SUMMARY AND OUTLOOK

During Run 2 the LHC provided an increase in collision energy with respect to Run 1 by a factor two, this combined with the good performance of the machine (high statistics) gave opportunity to new analysis in different areas of interest. Even though ALICE was design as a heavy ion experiment, it takes data during the full period of LHC, and due to its minimal pile up, access to low transverse momentum particles, it's efficient beam-gas rejection and redundant forward detector coverage, ALICE has a dedicated program to study diffractive events in proton-proton collisions.

With this in mind, during the Long Shut-down 1 (LS1) of LHC a new detector was proposed to the ALICE collaboration, a detector formed by two stations on each side of the interaction point (AD), this detector enhanced significantly the ALICE trigger efficiency to study diffractive physics.

In this thesis a detailed description of ALICE Diffractive detector (AD), which was incorporated to ALICE in the end of 2014 was presented. I had the opportunity to find myself involved since the beginning in the creation of this detector, the calibration of the different sensors that form it, as well as in the instrumentation necessary to adapt the signals to the FEE proposed, incorporate it to ALICE data taking system, and later on all the work included in the commissioning of the detector during LHC Run 2, meaning future calibrations, hardware interventions and monitoring of the good performance during the full period of data taking.

Also, I joined the effort for the measurement of the diffractive cross section at $\sqrt{13}$ TeVs, which was proposed as a new kind of measurement (fiducial rates), being this method less model dependent. With the inclusion of AD, ALICE has an advantage in the sensitivity to diffractive masses with an extra range in pseudo-rapidity coverage, using the forward capabilities together with the complex trigger system in ALICE we proposed this measurement, based on a binary,

which means a result closer to what the detector can really record. The single, double and non-diffractive cross sections are extracted using multidimensional fits.

Even though there is a progress in this measurement, we found different inconsistencies between data samples generated with Monte-Carlo and those from collisions. The method used has probe to be very sensitive to small changes either in the detector configurations as well as the parameters used for simulation. There is a progress correcting the small discrepancies, after this a MC sample has to be produced again and finally present the result. All the work done so far is well documented in ALICE twiki in the Diffraction work group page

5.1 Future work

The analysis dedicated to the measurement of the diffractive cross sections at $\sqrt{13}$ TeVs is not concluded, an update on monte-carlo simulation is needed to correct detector (in-)efficiency. With this correction, we could present both, the fiducial rates, and the extracted single and double cross sections.

ALICE has prepared a substantial upgrade for the upcoming Run 3 of LHC, there will be a mayor change in the Data Acquisition System and in the Central Trigger Processor. These changes must prepare ALICE for a continuous data taking up to the conditions required for the High-Lumi runs foreseen in LHC run 3. The AD group has presented to the ALICE collaboration (in the end of 2018) an upgrade for AD, named Forward Diffractive Detector (FDD).

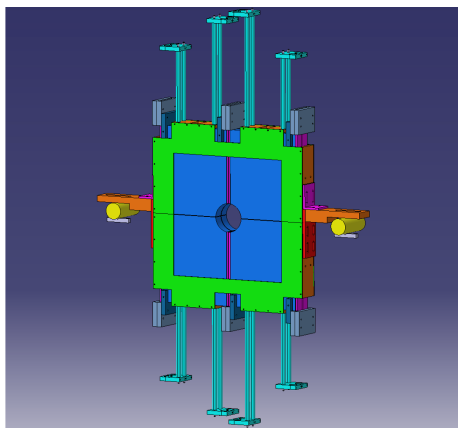


FIGURE 5.1. Prototype for the upgrade of ALICE Diffractive Detector [23].

This proposal for the upgrade of AD [23], describes the physics motivations, the design and construction plans. Based on the good performance presented by AD, the new goal is to improve the capabilities to the new running conditions of ALICE. The inclusion of a system in an experiment like ALICE involves a lot of work at all design levels (mechanical, hardware, software), the Mexican contribution in this detector is crucial, which implies a lot of work for the upcoming years.

5.2 Publications

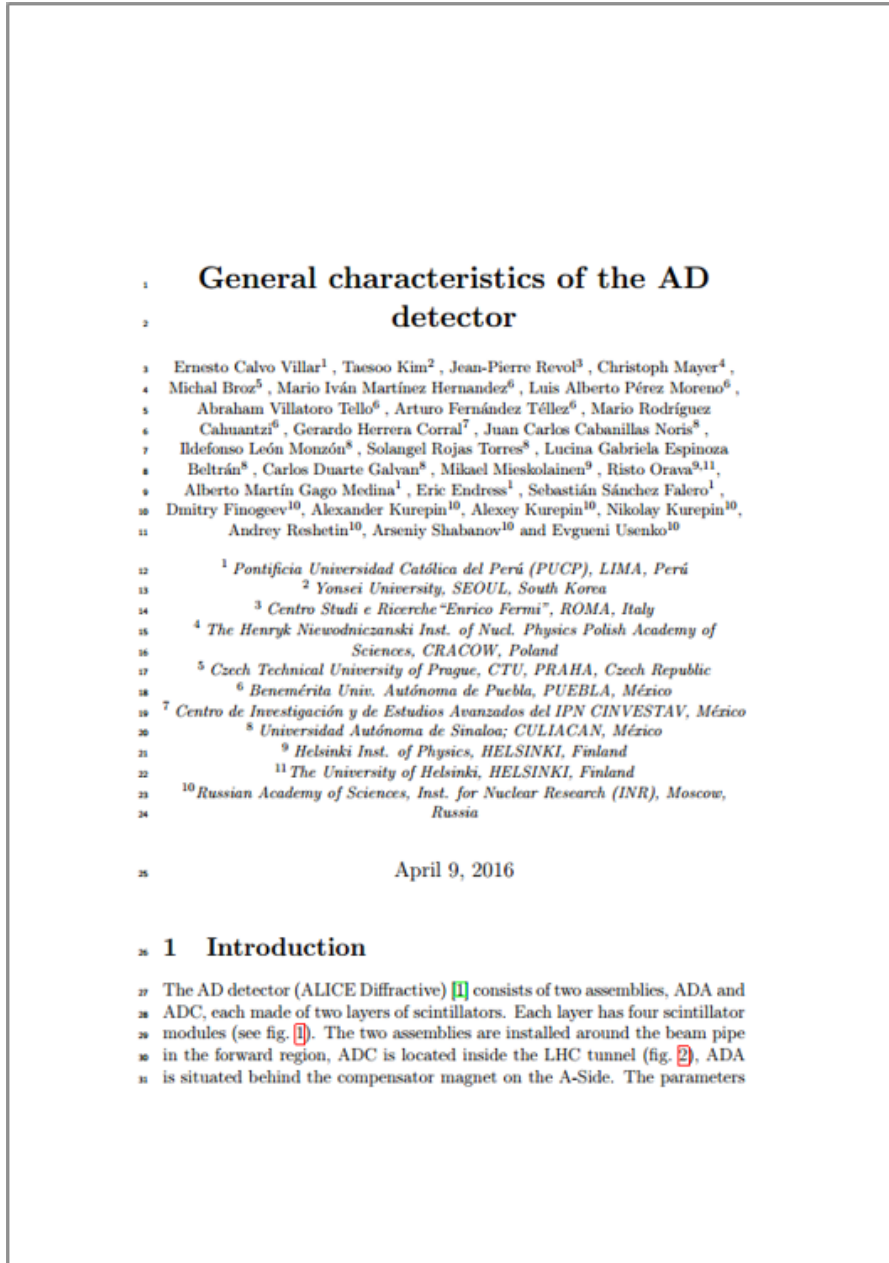


FIGURE 5.2. ALICE Technical Note, 2016, Ernesto Calvo Villar..., A Villatoro Tello, Arturo Fernández Téllez, Mario Rodríguez, et al. URL = https://alice-notes.web.cern.ch/system/files/notes/public/475/2016-Apr-20-public_note-AD.Note_.Final_Apr09_v2.pdf



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LHC Forward Physics

Editors: N. Cartiglia, C. Royon
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FIGURE 5.3. J.Phys. G43 (2016) 110201, LHC Forward Physics Working Group (K. Akiba, ..., M. Rodríguez, A. Villatoro Tello, et al)

AD, the ALICE Diffractive Detector.

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ABSTRACT. ALICE is one of the four large experiments at the CERN Large Hadron Collider (LHC). As a complement to its Heavy-Ion physics program, ALICE started during Run 1 of LHC an extensive program dedicated to the study of proton-proton diffractive processes. In order to optimize its trigger efficiencies and purities in selecting diffractive events, the ALICE Collaboration installed a very forward AD detector during the Long Shut Down 1 of LHC. This new forward detector system consists of two stations made of two layers of scintillator pads, one station on each side of the interaction point. With this upgrade, ALICE has substantially increased its forward physics coverage, including the double rapidity gap based selection of central production, as well as the measurements of inclusive diffractive cross sections.

INTRODUCTION

In diffractive scattering, no colour is exchanged between the particles interacting at high energies. Different components of the wave functions of the incoming particles are absorbed during the diffractive scattering process, leaving the outgoing states unchanged (elastic scattering) or excited into a diffractive system (single and double diffraction). In central production, a state with the vacuum quantum numbers is created together with a pair of leading protons, or their diffractively excited states (see Figure 1).

Diffractive processes have become a vast area of study in particle physics, at the LHC energies, the traditional signature of diffraction, Large Rapidity Gaps (LRGs) is all but lost since the LRGs tend to be filled up by so called rescattering corrections and incomplete transverse energy/momentum reach of the experiments. Experimentally there is no conclusive way to distinguish if the LRGs are caused by a Pomeron exchange, by other color-neutral exchanges, or by incomplete detector acceptance, so this separation is model dependent. ALICE, with its excellent coverage of low transverse momentum final state particles, is well placed in measuring soft diffractive scattering. During Run 1 of LHC, ALICE made first pivotal measurements of diffractive processes [3].

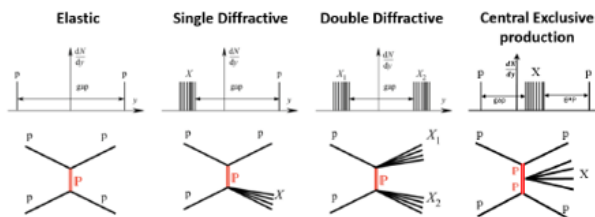


FIGURE 1. Usual decomposition of the total cross section of proton-proton collisions.

THE ALICE EXPERIMENT

Alice is one of the four large experiments in LHC, it was built as a dedicated heavy-ion detector. The main purpose of ALICE is the study and characterization of a new phase of matter, the quark-gluon plasma. Even so ALICE mainly studies the collision of heavy nuclei, it also takes data during proton-proton collisions, either for comparison with lead-lead or to carry on analysis where ALICE

FIGURE 5.4. Proceeding, A. Villatoro Tello, on behalf of the ALICE collaboration, AIP Conference Proceedings 1819, 040020 (2017); <https://doi.org/10.1063/1.4977150>

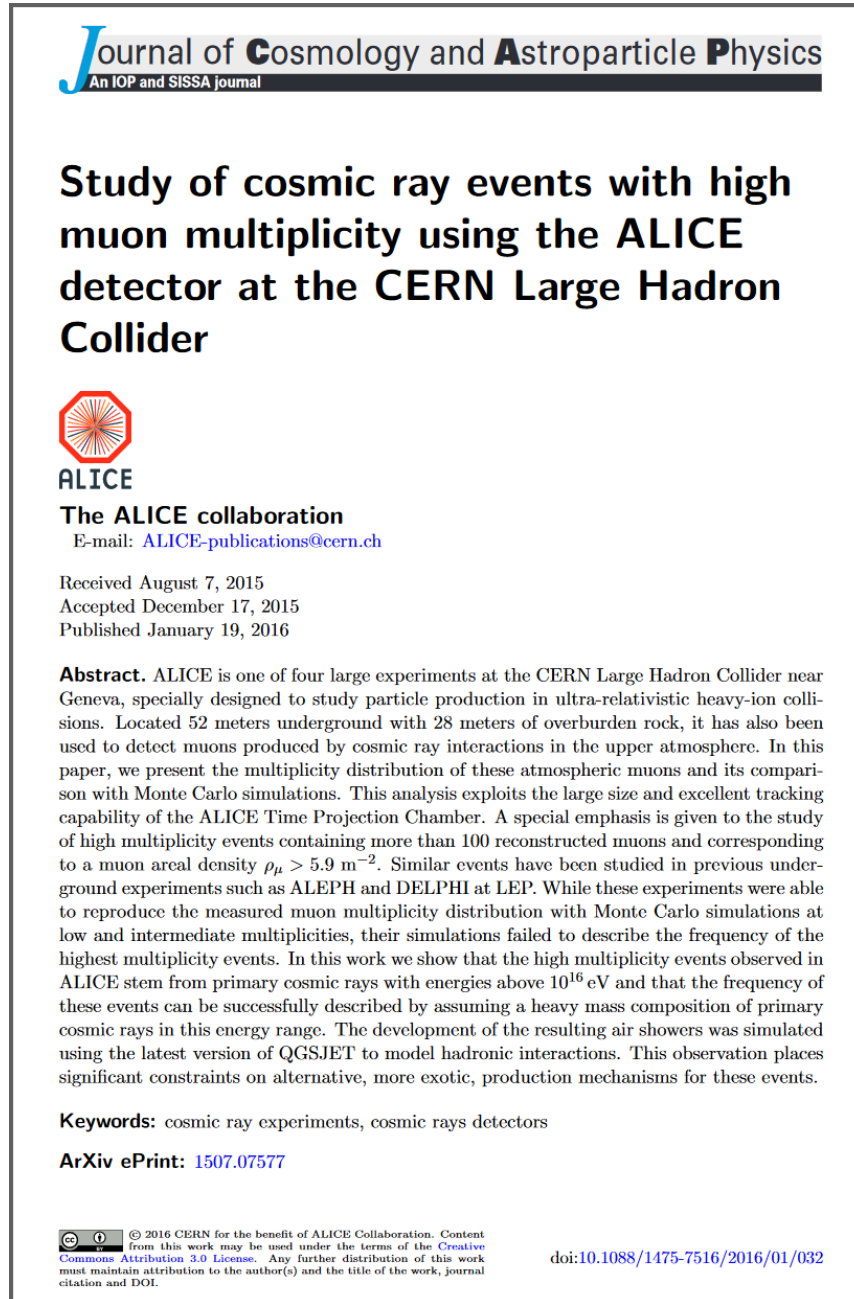


FIGURE 5.5. Journal of Cosmology and Astroparticle Physics, The ALICE Collaboration, JCAP 1601 (2016) no.01, 032.

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