Diffractive Physics with ALICE at the LHC: 
the control of quantum collisions

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Abstract. We report on the status of the construction and installation of a new detector in the forward region of the ALICE experiment at the LHC. This detector will allow the study of processes with gaps at larger rapidity than those presently covered. A setup of two stations called AD (stands for ALICE Diffractive) on the right and on the left of the interaction point enhances significantly the efficiency to study diffractive physics and photon induced processes.

1. Introduction: The Large Hadron Collider
The Large Hadron Collider (LHC) [1] accelerates protons as well as heavy ions in a 27 km long ring located in the European Center for Nuclear Research (CERN) at Geneva, Switzerland. The production and acceleration of protons and ions starts in LINAC 2 and LINAC 3, respectively. The protons accelerated in LINAC 2 are injected with an energy of 50 MeV into a Proton Synchrotron Booster where they reach an energy of 1.4 GeV. The last step for the beam before LHC is the Super Proton Synchrotron (SPS) that was modified to deliver a high brightness proton beam. It takes 26 GeV protons from the PS and brings them to an energy of 450 GeV before they are transferred to the LHC. The accelerators complex at CERN is shown in Fig. 1.

The LINAC 3 produces 4.2 MeV/u lead ions. It uses the Low Energy Injector Ring (LEIR) as a storage and cooler unit which in turn, provides the ions to the Proton Synchrotron with an energy of 72 MeV/nucleon. Ions are further accelerated by the Proton Synchrotron and the Super Proton Synchrotron before they are injected into the LHC where they reach an energy of 2.76 TeV/nucleon.

The total cross section of proton-proton interaction at 7 TeV could be inferred from hadronic cross section measurements at lower energies [2]. It would be around 110 mb and it corresponds to about 60 mb of inelastic scattering processes. The LHC reaches a luminosity of $10^{32}$ sec$^{-1}$cm$^{-2}$, which means that the inelastic interaction rate is

$$\text{rate} = 10^{34} \times 60 \times 10^{-3} \text{ barn} \times 10^{-24} \frac{\text{cm}^2}{\text{barn}} \frac{\text{collisions}}{\text{s}}.$$ 

Out of these events, approximately $150 \times 10^6$ are diffractive processes. It is therefore natural that the ALICE collaboration becomes interested in collecting most of the hundredths of millions of diffractive collisions per second that carry important information about non perturbative QCD phenomena.
During the fall 2009 bunches of protons were injected into the LHC ring. During the start-up phase, first collisions with protons at 900 GeV were observed. In 2010 the beam was ramped to 3.5 TeV, it remained at this energy in 2011 while the number of bunches and their intensity was increased. By the middle of 2011 the maximum number of bunches, i.e. 1380, was achieved for a spacing of 50 ns between bunches. The performance of the LHC was then increased by reducing the emittances of the beams that were delivered by the injectors. In 2012 the beam energy was increased to 4 TeV and the bunch spacing was made to stay at 50 ns. A remarkable fact of the LHC performance during 2011 and 2012 was the high bunch intensity and lower than nominal emittance. The bunch intensity obtained was 150% of nominal. In 2012 the protons per bunch
reached $1.7 \times 10^{11}$ while the nominal design value is $1.15 \times 10^{11}$. The normalized emittance in the collision was 67% of the nominal values, which represents a significant improvement too. The LHC proved to be able to handle these brighter beams in terms of beam-beam effects. For the experiments this meant higher pile-up, an issue that imposes a challenge for the readout, analysis and storage speeds. The nominal mean number of events per bunch crossing at design values is 19 but, in 2012, with the parameters above, this number became 37. All of these was successfully managed by the experiments that announced the Higgs discovery in July 2012.

ALICE recorded data on proton-proton interactions during 2012 at a luminosity of $5 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$ with collisions between enhanced satellites bunches and the main bunches. Since the beginning of the LHC operation there have been two runs of heavy ion beams, one in 2010 for commissioning and analysis and the second one in 2011 with an instant luminosity above the nominal. These two heavy ion runs provided an integrated luminosity of 9.7 µb$^{-1}$ (2010) and 166 µb$^{-1}$ (2011) with a centre-of-mass energy of $\sqrt{S_{NN}} = 2.76 \text{TeV}$. In addition, in 2013 a proton-lead run at $\sqrt{S_{NN}} = 5.02 \text{TeV}$, provided a 30 nb$^{-1}$ integrated luminosity. The data collected in all these runs is being analyzed and has already produced very interesting physics results. In 2015 the LHC will operate at a higher energy. The goal is to run the physics programme at 13 TeV in the centre of mass. The accelerator recommissioning will start in March 2015 with a 50 ns bunch spacing to reduce it to 25 ns later on during the year. In November 2015 a 4 week long heavy ions run is foreseen. ALICE will be collecting the data of lead-lead interactions at the highest energy ever seen.

2. The ALICE experiment
ALICE is a multipurpose detector that exploits the unique potential of lead-lead collisions at the LHC energies [3]. ALICE also studies proton-proton interactions in research topics where it is competitive with other LHC experiments. Most of all, the study of proton-proton reactions gives the possibility to compare a number of phenomena that occur in lead-lead interactions. The ALICE detector provides identification of hadrons, electrons, muons and photons produced in the collisions. It measures also their trajectories, momentum and energy in specific regions covered by various sub detectors (Fig. 2).

One of the main differences of ALICE with the other experiments at the LHC is particle identification. ALICE uses all known techniques for particle identification:

- The Inner Tracking System is formed by six cylindrical layers of silicon detectors (Silicon Pixel, Silicon Strip and Silicon Drift) that provides not only a precise determination of the main and secondary vertices of unstable particles but also energy loss measurements that separates particle species in the central pseudo-rapidity region.

- The Time Projection Chamber is used as the main tracking detector for charged particles. It is the biggest Time Projection Chamber ever built and consists of 88 m$^3$ cylinder filled with gas and divided in two drift regions by a central electrode. The gas ionization of charged particles traversing the volume provides energy loss measurements for particle identification.

- The Time-Of-Flight system combines time measurement with the momentum and track length measured in the tracking detectors to identify particles. It separates pions and kaons with momenta lower than 2 GeV/c and protons with momenta lower than 4 GeV/c. It consists of a multigap resistive plate chamber with a double stack of 0.5 mm glass.

- The Transition Radiation Detector is the main electron detector. It identifies electrons of high momenta ($p_t > 1 \text{GeV/c}$). The detector consists of several modules, with radiator and a drift chamber which is operated with a mixture of Xe and CO$_2$, that are surrounding the interaction point in the barrel region.

- The High Momentum Particle Identification detectors is a ring imaging Cerenkov detector. It consists of seven modules $1.5 \times 1.5$ meter each mounted in an independent support cradle.
It provides particle identification in the 1 to 5 GeV/c momentum range complementing the barrel detectors.

In the forward direction on one side of the interaction point, a set of tracking chambers inside a dipole magnet measures muons. An absorber stops all the products of the interaction except for the muons which travel across and reach the tracking chambers. The whole structure is called muon arm. The barrel region of ALICE is located inside a big solenoid that provides a magnetic field of 0.5 T. The central tracking and particle identification systems cover $-0.9 < \eta < 0.9$. Electrons and photons are measured in the central part: photons are measured in PHOS which is a high resolution calorimeter located 4.4 meters below the interaction point. PHOS is made of lead-tungstate (PWO) crystals which have a high light output. It covers $-0.12 < \eta < 0.12$ in pseudo-rapidity and 100 degrees in azimuth for a total area of 8 m². An Electromagnetic Calorimeter covers the central barrel. EMCAL is made of plastic scintillators and lead plates in a sandwich array which is read out with wavelength-shifting optical fibers. Avalanche photodiode sensors are used to convert light into an electric signal. A Forward Multiplicity Detector (FMD) consists of several stations of silicon strip detectors on both sides of the interaction point. A Zero Degree Calorimeter (ZDC) covers the very forward region providing information on the charge multiplicity and energy flow. It is a spaghetti calorimeter made of a stack of heavy metal plates with grooves that host quartz fibers. A honeycomb proportional counter for photon multiplicity measurements (PMD Photon Multiplicity Detector) is located in the forward direction on one side of the ALICE detector. The trigger system is complemented by a high level trigger (HLT) system which makes use of a computer farm to select events after read-out. In addition, the HLT system provides a data quality monitoring.

A Mexican group from CINVESTAV and the National Autonomous University of Mexico designed and built the V0A detector which is one of the two detectors that form the V0 system. The V0 system is used as the main interaction trigger.

The V0A is installed at a distance of 3.3 meters from the interaction point. It is an array of 32 cells of plastic scintillators, distributed in 4 rings forming a disc with 8 sectors. A detailed description of the V0 system can be found in [4]. The V0 system is part of the baseline of ALICE. It provides level 0 trigger signals, beam gas suppression, a default centrality measurement, and the event reaction plane in the ion-ion collisions as well as the on-line luminosity measurement.

A second group of researchers from CINVESTAV, the University of Puebla, the National Autonomous University of Mexico and University of Sinaloa designed and built the Cosmic Ray Detector (ACORDE). It is an array of 60 scintillator counters located in the upper part of the ALICE magnet [5]. The Cosmic Ray Detector generates a single muon trigger to calibrate the Time Projection Chamber and other components of ALICE. It also generates a multi-muon trigger to study cosmic rays with the help of tracking systems like the ITS and the TPC.

After several months shutdown in 2013 and 2014, the ALICE experiment will take data with both protons and lead ions in 2015. Thereafter, in 2016-17, the experiment will collect more data on Pb-Pb interactions at $\sqrt{s_{NN}} = 5.5$ TeV, just before the long break in 2018.

ALICE would complete the initial program on Pb-Pb before the shutdown in year 2022. After year 2022 an upgraded detector will be able to take data at a minimum bias rate of 50 kHz for Pb Pb collisions. The upgraded detector will have a better determination of the main vertex and a tracking system for low transverse momentum. The upgraded ALICE experiment will preserve the particle identification capabilities.

The upgrade of ALICE includes a smaller radius beam pipe, a new inner tracking system as well as a high rate read-out for the Time Projection Chamber, Transition Radiation Detector, Time-of-Flight, Electromagnetic Calorimeter, Muon Arm and Trigger Detectors. The V0 detector will be replaced with a new design to collect more light in order to define more precisely the nominal region of interaction and to achieve a time resolution of the order of 100-200 picoseconds. The new detector is planned to be installed in 2018 during the long shutdown.
In order to collect 10 nb$^{-1}$, several years of data taking after 2022 are needed.

In addition to the research on heavy ion interactions and proton-proton collisions, ALICE pursues a diffraction physics program by extending the detector efficiency to smaller diffractive masses for single and double diffraction events. A new detector system increases the detection of gaps in the pseudo-rapidity distribution of particles produced in the collision. This improves the capabilities of ALICE to study central diffractive processes.

3. Diffractive Physics

Quantum Chromo-Dynamics is the theory of strong interactions. Though it has been successful to describe many processes the strong coupling constant limits the success of the theory for nonperturbative scattering. In the strong interaction gluons carry the colour charge. However, gluons may group in a way that their colour charges add up to neutralize. A neutral object like this would behave in a different way than single gluons with colour charge. The dynamics of such colourless object is at present poorly understood.

Diffractive reactions are driven by the strong force. The high energy proton collisions of this kind are characterized by the exchange of a neutral state of gluons, called pomeron. It leaves a gap in the rapidity distribution of the particles produced. The interaction has the quantum numbers of the vacuum. In such reactions, the colliding protons deflect only a little and continue their trajectory very close to the original direction.

![Figure 2. The ALICE detector systems and the new AD device, © CERN-ALICE.](image)

The total cross section for proton-proton collisions is the sum of elastic, non-diffractive and diffractive interactions (Fig. 3). The cross section at the energy in the centre of mass at which the LHC will run in 2015 is unknown. The scaling with the energy of the cross sections for the different processes is model dependent.

ALICE has a forward muon spectrometer at a rapidity region $-4.0 < \eta < -2.5$ which is not covered by the experiments CMS or ATLAS. The muon arm of ALICE may give us the possibility to study $J/\psi$ production in single diffractive events. A measurement of $J/\psi$ production in ultra-peripheral Pb Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV center-of-mass energy has been published [6]. A measurement of inelastic, single- and double-diffraction cross section in p-p [7], has been reported too. The experiments ATLAS and CMS at the LHC have also made proposals for installing forward detectors for diffractive studies [8]. These experiments, however, are not suited to access a very low transverse momentum of centrally produced tracks. ALICE
has excellent particle identification capabilities and can resolve low transverse momentum tracks, i.e., ALICE is in a unique position to study soft and hard diffractive events at the LHC. We have already installed two additional detectors around the interaction point in order to improve the efficiency to tag diffractive events [9]. The detector system could be easily extended to four stations of scintillation counters. In order to cover the spectra of small diffractive masses, as well as to enhance the sensitivity of the detector to tag diffractive events, a pseudo-rapidity coverage beyond 5 units is needed.

In addition, the high flux of photons associated with electromagnetic fields of lead ions will produce high luminosity photon-photon collisions. The physics of photon interactions spans a big variety of QED and QCD processes like lepton pair and jet production. ALICE would be able to undertake a review of resonance production in Central Diffractive events. In previous experiments [10], unexpected structures appeared but they were not fully understood. The absence of the $\rho^0$ resonance may be taken as indication of double Pomeron exchange. It would be very interesting to further study production mechanisms in this channel. By analysing vector meson production, Odderon signatures can be studied [11], since they might be the result of Photon-Odderon and/or Pomeron-Odderon exchange. Some theoretical developments based on exclusive production, predict new physics [12]. ALICE is well suited to explore these predictions.

The experimental study of diffractive interactions is very challenging since most of the time the protons remain in the beam pipe after a soft collision. The very low transverse momentum of the products of such collisions gives rise to technical difficulties to measure and to characterize the reaction. The incorporation of new detectors placed far from the interaction point will enhance significantly the efficiency to tag diffractive and low transverse momentum events.

4. ALICE Forward Hodoscopes - AD

During Run 1 in 2012 a couple of pad stations on both sides of the interaction point were installed. They were successfully used as a beam radiation monitor. The system was capable of detecting minimum ionizing particles. It measured background and provided an online determination of luminosity. The asynchronous read out of charge deposited in the detector worked rather well. For Run 2 we decided to integrate the detectors to the read-out of ALICE. The array was completely redesigned and the final position changed. One of the old stations will remain in the previous position at a distance of 8 meters from the interaction point on the A side. It will continue working as part of the beam diagnostic system.

For the data taking in Run 2 of the LHC, the ALICE collaboration installed, in the forward region, two small detectors made of scintillation plastic. One of the two stations is located on the C side, at 20 meters from the interaction point. This station is inside the LHC tunnel. The second station is on the opposite side (A side), at 18 meters from the interaction point.

The AD device on the A side covers a pseudo rapidity interval: $4.8 < \eta < 6.3$ while the C-side
detector covers: $-7.0 < \eta < -4.9$. With this new system, the ALICE sensitivity to diffractive masses will be close to the diffraction threshold of 1.08 GeV/$c^2$ which corresponds to the sum of proton and pion masses.

Figure 4. Design of the ALICE Diffractive Detector (AD). The WLS bars transfer the light to transparent optical fibers connected to photo-multiplication tubes, © CERN.

Figure 5. Proto 0 of the ALICE Diffractive Detector: AD. The prototype was tested in a pion beam of 7 GeV provided by Proton Synchrotron of CERN in October 2014.
Each AD detector consists of 8 cells of scintillation plastic of about $22 \times 22$ cm and 2.5 cm thick each, arranged around the beam pipe in two layers (Fig. 4). The light produced by BC404 plastic is collected by Wave Length Shifting bars attached, but not glued, on two sides of each cell. The WLS bars transfer the collected light to a bunch of 96 transparent optical fibres per bar, that route the light to the PMTs (outside the tunnel for the C-side). The light is converted into an electric pulse by a fine mesh PMT from Hamamatsu R5946 (hybrid assembly H6153-70). The final prototype of the detector can be seen in Fig. 5. The signal from the PMT is sent to an electronic card which delivers two signals: one, amplified by a factor of 10 and clamped at about 300 mV which is used for timing measurement, the second, direct signal, is used for charge integration. The shoe box with this electronics are several meters away from the detector close to the Front End Readout electronics. The Front End Electronics provides signals for the level 0 trigger of ALICE. The readout electronics is the one presently used in the V0 detector [4]. The trigger signals of the AD counters will expand the pseudo-rapidity coverage of the present Minimum Bias trigger which is used in multiplicity studies. Moreover it will be possible to trigger on charge deposition in the two AD detectors providing an extended centrality trigger in both Pb-Pb and proton-Pb collision studies.

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