HEAVY ION COLLISIONS AT THE LHC:
THE ALICE EXPERIMENT

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Abstract
ALICE (A Large Ion Collider Experiment) is a detector designed to exploit the physics potential of nucleus–nucleus interactions at the LHC. Being a general purpose experiment, it will allow a comprehensive study of hadrons, electrons, muons and photons, produced in the collision of heavy nuclei, up to the highest particle multiplicities anticipated ($dN_{ca}/dy = 8000$). In addition to heavy systems (Pb–Pb), we will study collisions at smaller energy densities by using lower-mass ions (e.g. $A \sim 40$). Reference data will be obtained from pp and p–nucleus collisions.

The central part of ALICE covers $\pm 45^\circ$ ($|\eta| < 0.9$), and consists of an inner tracker (ITS), a TPC and a particle identification array (PID), all embedded in a large magnet with a weak solenoidal field. The experiment is completed by two small area spectrometers in the barrel region (an electromagnetic calorimeter, PHOS, and a high momentum PID detector, HMPID), a forward muon spectrometer ($2^\circ$ to $9.5^\circ$) and a ZDC.
1 Introduction

The aim of high-energy heavy-ion physics is the study of strongly interacting matter at extreme energy densities. Statistical QCD predicts that, at sufficiently high energy densities, hadronic matter melts into a plasma of deconfined quarks and gluons — a transition which took place, in the inverse direction, some $10^{-5}$ s after the Big Bang and which might still play a role in the core of collapsing neutron stars.

Using methods and concepts from both nuclear and high-energy physics, the study of the phase diagram of QCD matter and of quarks and gluons in a deconfined medium, constitutes a new and interdisciplinary approach in investigating the small scale structure of matter and its interactions. It explores and tests QCD on its natural scale ($\Lambda_{\text{QCD}}$) and addresses the understanding of confinement and chiral-symmetry breaking.

The current heavy ion program, in particular the new results obtained with Pb beams at the SPS, gives clear indications that very dense matter is produced in these reactions, the high energy densities leading to new phenomena, beyond expectations from p–A physics.

At the LHC, besides the pp program, nucleus–nucleus collisions at a centre-of-mass energy of about 6 TeV/nucleon are foreseen as a prominent part of the initial experimental program. Heavy-ion collisions at the LHC will certainly provide a suitable environment for the study of strongly interacting matter. Extrapolating from present results, the parameters relevant to the formation of the Quark–Gluon Plasma (energy density, size and lifetime of the system, etc.) will all be more favourable. The average energy densities should be well above the deconfinement threshold, and the QGP is expected to be probed in its asymptotically free ‘ideal gas’ form. Unlike at lower energies, the central rapidity region will have nearly vanishing baryon number density, similar to the state of the early universe.

ALICE groups together people and experience from the community presently engaged in the SPS heavy-ion program, joined by new groups coming from both nuclear and high-energy physics. It currently includes around 600 physicists, from 65 institutions. The ALICE technical proposal [1] was submitted in December of 1995, providing a detailed description of the central detector. As was already the case for the Letter of Intent [2,3], the forward muon spectrometer will be described in a specific additional document, currently under preparation and due by October of 1996.

ALICE is designed as a general-purpose heavy ion detector, sensitive to the majority of known observables (including spectra of hadrons, electrons, muons and photons) and will be operational at the LHC start-up. In addition to the heavier systems (Pb–Pb), ALICE will study collisions of lower-mass ions (e.g. $A \sim 40$), in order to vary the energy density. Reference data will be obtained from pp and (when available) p–nucleus collisions.

2 The ALICE detector

The overall detector layout of the ALICE experiment is shown in figure [1]. The central part, covering ± 45° ($|\eta| < 0.9$) over the full azimuth, is embedded in a large magnet with a weak solenoidal field (about 0.2 T) — a compromise between momentum resolution, low momentum acceptance and tracking efficiency — aiming at full tracking and particle identification. It consists of three cylindrical sub-detector layers: the inner tracker (ITS) with six layers of high-resolution silicon tracking detectors, the TPC and the particle identification array of TOF counters (PID). Still in the barrel region, there are two single-arm detectors: an electromagnetic calorimeter (PHOS) and an array of counters optimized for high-momentum inclusive particle identification (HMPID), made up either of RICH or of TOF counters. The forward muon
spectrometer covers the angular acceptance between $9.5^\circ$ and $2^\circ$ ($\eta = 2.5 - 4.0$). A zero-degree calorimeter, located some 92 m away from the intersection point, will measure the energy of the spectator nucleons and, therefore, access the collision geometry. Finally, a forward multiplicity detector (FMD) will extend the central rapidity coverage into $|\eta| < 4$.

Figure 1: Longitudinal view of the ALICE detector.

The basic functions of the inner tracker — secondary vertex reconstruction of charm and hyperon decays, particle identification and tracking of low-momentum particles, improvement of the momentum resolution — are achieved with six barrels of high-resolution silicon detectors. The number of layers and their radial position has been optimized for efficient pattern recognition and impact parameter resolution. Because of the high particle density, the four innermost layers will be silicon pixel and silicon drift detectors. The two outer layers will be equipped with silicon micro-strip detectors. With the exception of the two innermost pixel planes, all layers will have analog readout for independent particle identification via $dE/dx$ in the non-relativistic region, allowing track finding of low-$p_t$ charged particles, down to a $p_t$ of $\sim 20$ MeV$/c$ for electrons.

The need for efficient and robust tracking has led to the choice of a TPC as the main tracking system. In spite of its drawbacks concerning speed and data volume, we have concluded that only a conventional device and redundant tracking can guarantee reliable performance at up to 8000 charged particles per unit of rapidity. The inner radius of the TPC ($r \approx 90$ cm) is given by the maximum acceptable hit density (0.1 cm$^{-2}$), while the outer radius (250 cm) is determined by the length required for a $dE/dx$ resolution better than 7%. With such a resolution, the TPC can also be used to identify electrons of momenta up to $\sim 2.5$ GeV$/c$. The track finding in the TPC achieves an efficiency of close to 97% for $p_t$ as low as 100 MeV$/c$.

Particle identification over a large part of the phase space and for many different particles is an important design feature of ALICE. It is of crucial importance for a number of signals
(e.g. flavour composition and chemical equilibrium, lepton pairs, strangelets) and very useful for others (e.g. momentum spectra, HBT, charm, jet quenching). We have two detector systems dedicated exclusively to PID, a TOF array optimized for large acceptance and average momenta and a small system specialized on higher momenta. Two TOF technologies, Pestov spark counters and parallel plate chambers (PPC), are being studied for the large area PID barrel, located at a radius of about 3.5 m. A timing resolution of less than 50 ps (r.m.s.) has already been achieved with first prototypes of Pestov counters. For the PPCs, corresponding values of $\lesssim 200$ ps have been obtained. A second PID system, of smaller acceptance and at larger radii, will extend the accessible momentum range for inclusive particle spectra into the semi-hard region. The current technological choice is a proximity-focusing RICH detector with liquid freon radiator, solid photocathode and pad readout.

Prompt photons, $\pi^0$'s and $\eta$'s will be measured in a single-arm high-resolution electromagnetic calorimeter. It is located 5 m from the vertex and will be built from PbWO$_4$ scintillating crystals, a material with small Molière radius (2 cm), in order to keep a reduced occupancy. Since we are interested in accessing relatively small energies ($\lesssim 15$ GeV) the crystals will be cooled to $-25^\circ$C, to increase the light output (the magnetic field imposes silicon photodiodes readout).

One of the most promising signatures for the existence of deconfined matter is the suppression of heavy quarkonia resonances. The forward muon arm will measure the dimuon decay of heavy quarkonia ($J/\psi$, $\psi'$, $\Upsilon$, $\Upsilon'$ and $\Upsilon''$) with a mass resolution sufficient to separate all resonances.

During the heavy-ion run, two different types of events will be collected. In the first type, all detectors are read out, leading to a huge volume of data (up to 40 MByte per event, at a rate of 50 Hz). In the second type, specific for the physics of high-mass muon pairs, only the muon arm and the pixel planes (for vertex finding) are read out. These triggers, interposed with the previous ones, have a much higher rate (up to 1 kHz) but the event size is much smaller, the data throughput being only 20% of the total. The very large data volume, imposed by up to 12 000 charged tracks going through the TPC, leads to $\sim 1000$ TByte written during one month of heavy-ion running (the pp LHC experiments reach a similar data volume after one year).

3 Physics with the ALICE detector

In order to establish and analyse the existence of QCD bulk matter and the QGP, a number of observables have to be studied with ALICE in a systematic and comprehensive way. Some observables are needed to characterize the global event features of the state created in the nucleus–nucleus collision, to access the number of colliding nucleons and the energy density reached. This information is necessary to interpret a specific signal as an indication of new physics. We will study several of these specific signals together with global information about the events, in the same experiment.

The signals accessible to ALICE are described in detail in Chapter 11 of Ref. 1. They are summarized below according to the aspect of the collision on which they have a bearing (see, for example, Ref. 4 for original references).

The thermal radiation from both the QGP and the mixed phase will be observable with the photon spectrometer in the medium-$p_t$ range (around 1–3 GeV/c) if its rate is more than 5% of the (abundant) photons from hadronic decays. At higher momenta, prompt photons from the pre-equilibrium phase (3–6 GeV/c) contain information on the parton dynamics at very early stages, on the equilibration times and on the transition from perturbative to non-perturbative phenomena.
The light vector mesons, with lifetimes of the order of the expansion time scale, will partially decay during the evolution of the system. Their properties (mass, width, branching ratios), observable in the leptonic decay, should change in dense matter owing, for example, to ‘collision broadening’, ‘induced radiation’ and other in-medium effects. In the vicinity of the phase transition, partial restoration of chiral symmetry will lead to additional shifts of the mass. The excellent mass resolution of ALICE for electron pairs ($\Delta m/m \approx 1\%$) will allow to observe significant changes for both the $\omega$ and $\phi$ mesons.

The suppression of heavy quarkonia resonances via Debye screening is an important tool to diagnose deconfinement and the early stages of the QGP. The muon spectrometer will measure the production (and suppression) rates for the complete spectrum of heavy quarkonia. Open charm production will probe the parton kinematics in the very early stage. The cross-section of high-$p_t$ hadrons is sensitive to the energy loss of the partons in the plasma.

Strangeness production is sensitive to the large s-quark density expected from (partial) chiral-symmetry restoration in the plasma. Multiplicity fluctuations are a sign of critical phenomena at the onset of a phase transition. The expansion time in the mixed phase, expected to be long in the case of a first-order phase transition, can be measured by particle interferometry. High statistics data will be available at the LHC to make a differential space-time analysis as a function of $dN/dy$ and $p_t$.

A large number of hadrons ($\pi, \eta, \omega, \phi, p, K, \Lambda, \Xi, \Omega$) will be measured as a function of charged-particle density and $p_t$. This will test thermalization (equilibrium of particle ratios and momentum distribution) and dynamical evolution scenarios in the hadronic phase. Enhanced production of strangeness from the QGP phase might still be visible in the hadronic matter and can be searched for with a few percent accuracy event-by-event. The shape of the $p_t$ distribution and the average $p_t$ will be measured for the many pions, kaons and even protons on an event-by–event basis. Therefore individual events can be assigned a ‘temperature’ per particle type which can be correlated with other observables. Inclusive high-statistics measurements of hadrons will allow the investigation of expansion dynamics and collective flow phenomena.

The freeze-out radius of the hadronic fireball can be measured by interferometry on an event by event basis up to 15 fm, and inclusively up to 30–40 fm. The large radii and the long lifetimes expected at LHC pose severe requirements on the detector in terms of momentum and two-track resolution.

Among the most challenging measurements ALICE will perform are di-electrons and open charm, both very demanding in terms of statistics, in view of the small signal to background ratio.

The di-electron measurement requires very high efficiency to track and identify electrons in order to recognize and eliminate the background from Dalitz decays and conversions. The design of the ITS has been optimized in this respect, in particular for low-$p_t$ electrons (20 to 100 MeV/c), for which the outer detectors are less useful.

The photon conversion background is greatly reduced by requiring a hit in the first pixel layer, which is expected to have an efficiency $\geq 98\%$. About $80\%$ of the conversions which still occur, in the beam pipe ($0.17\% X_0$) and in the first pixel layer itself ($0.15\% X_0$), can be recognized by reconstructing the secondary vertex (conversion point). The remaining conversions are well below the level of electrons from Dalitz decays, which will also be reduced, essentially by rejecting very low mass pairs ($m_{ee} \lesssim 100$ MeV). Semileptonic charm decays are suppressed by checking if the electron track points to the main vertex. The $\omega/\phi$ region of the expected invariant mass distribution of pairs passing the selection cuts is shown in figure 2, where we can see the effect of having an excellent mass resolution ($\sim 1\%$).
Figure 2: Left: Low mass di-electron spectrum, after cuts, for $5 \times 10^7$ central events, including tracking efficiency and momentum resolution. Right: $K^-\pi^+ (+\text{c.c.})$ invariant mass distribution before and after (inset) background subtraction.

Figure 2 also shows the invariant mass spectra of $K^-\pi^+$ (and $K^+\pi^-$), where the clearly visible signal of $D^0$ production ($S/\sqrt{B} = 32$) corresponds to a sample of $10^7$ events (about five days of running at 50% data taking efficiency), after quite stringent event selection cuts to improve the signal to background ratio. This measurement relies on a very good impact parameter resolution, expected to be better than 100 $\mu$m, in the bending direction, for $\pi$ and $K$ mesons of $p_t \geq 600$ MeV/c. A very large gain in $S/B$ is also obtained by requiring the momentum vector of the $D^0$ candidate to be aligned with the line connecting the primary vertex to the candidate decay vertex.

4 Conclusion

Heavy ion collisions at the LHC will open a new regime of very high energy density but low baryon density. With Pb–Pb collisions at a $\sqrt{s}$ of more than 1200 TeV, we expect extreme particle densities (several thousand per unit rapidity), systems approaching 100 000 fm$^3$ and initial energy densities 50 to 100 times larger than present in normal nuclear matter. ALICE will be well prepared to explore this ‘little Big Bang’ and enter the wonderland of QCD thermodynamics.

References

1. ALICE Collaboration, Technical Proposal, CERN/LHCC 93-16.
2. ALICE Collaboration, Letter of Intent, CERN/LHCC 93-16.
3. ALICE Collaboration, addendum to the LoI, CERN/LHCC 95-24.
4. H.R. Schmidt and J. Schukraft, J. Phys. G19 (1993) 1705.