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The ALICE experiment at LHC: physics prospects and detector design

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ABSTRACT

ALICE (A Large Ion Collider Experiment) is a dedicated detector designed to exploit the unique physics opportunities which will be offered by nucleus–nucleus collisions at the LHC. At the LHC, it will be possible to explore a radically new regime of matter, stepping up by a large factor in both volume and energy density from the nuclear interactions studied at the SpS and at RHIC. Thanks to the huge number of secondaries produced, it will be possible to measure most of the relevant variables on an event–by–event basis. The LHC energy and luminosity will allow the full spectroscopy of the Y family and of D and B mesons.

ALICE is conceived as a general–purpose detector, in which most of the hadrons, leptons and photons produced in the interaction can be measured and identified. The baseline design consists of a central ($|\eta| \leq 0.9$) detector covering the full azimuth and a forward ($2.4 \leq \eta \leq 4$) muon arm, complemented by a forward magnetic spectrometer to study vector meson production, a multiplicity detector covering the forward rapidity region (up to $|\eta|$=4.5) and a zero degree calorimeter. The central detector will be embedded in large magnet with a weak field of 0.2T, and will consist of a high–resolution inner tracking system, a cylindrical time projection chamber, particle identification arrays (time of flight and ring imaging cerenkov detectors), a transition radiation detector for electron identification and a single–arm electromagnetic calorimeter.

1 From fixed target to the LHC

The study of ultrarelativistic heavy–ion collisions is a fairly young field, since accelerators have been able to provide relativistic nuclear beams only since the early eighties, starting at the Bevalac. Since then, many experiments have been pursued both at the CERN SpS and at the BNL AGS. This vigorous program has first of all established the feasibility of experiments which analyze extremely complex events, with hundreds of secondaries produced in a small solid angle. These experiments have demonstrated that very high energy densities can indeed be reached in heavy–ion collisions, and provided evidence of the creation of a new state of matter, in which hadrons are melted together in a Plasma of Quarks and Gluons. A comprehensive overview of the results of the SpS program can be found in the proceedings of the latest Quark Matter Conference [1]. From these experiments, one can state that relativistic heavy–ion collisions are the best means to create a strongly interacting system which can be studied in thermodynamical terms, suggesting that heavy–ion collisions at the LHC will provide an ideal tool for the study of nuclear matter in a regime of thermodynamic behaviour, and will provide a perfect ground to study quark deconfinement.
The adventure of Ultrarelativistic Nuclear Physics now enters in a new era: the one of the colliders. At this very moment, the first collisions are recorded in the experiments at the Relativistic Heavy Ion Collider, a dedicated nuclear beam accelerator built at the Brookhaven National Laboratory. The RHIC experiments, with a center of mass energy of 200 GeV, will certainly open new ground in the study of Quark Gluon Plasma formation, and provide the indispensable intermediate point between the SpS and the LHC, which are almost three orders of magnitude away in $\sqrt{s}$.

The LHC, at a center-of-mass energy of 5.5 TeV/nucleon, will bring us into the true high-energy heavy-ion regime, reaching and even extending the energy range probed by cosmic ray nucleus–nucleus collisions. All parameters relevant to QGP formation will be more favourable: energy density, size and lifetime of the system, and relaxation times are all expected to improve by a large factor, typically by an order of magnitude, compared to Pb-Pb collisions at the SpS. In addition, the comparison with QCD predictions will be far more realistic, since lattice QCD is calculated only at zero baryon number density μ_B, and, unlike at lower energies, the central rapidity region will have $\mu_B \approx 0$. The state studied at the LHC will therefore have characteristics closer to the ones of the early universe. While at the AGS and SpS particle production is essentially a soft, non–perturbative process, at the LHC (and at RHIC) it will be dominated by minijet production, i.e. by semi–hard processes which are described by perturbative QCD. Indeed, the different process of energy loss by the fast (leading) partons of minijets (“jet quenching”) is one of the most promising signals of a phase trasition from a dense hadron gas to a plasma [2].

The very large number of secondaries produced in nuclear collisions at the

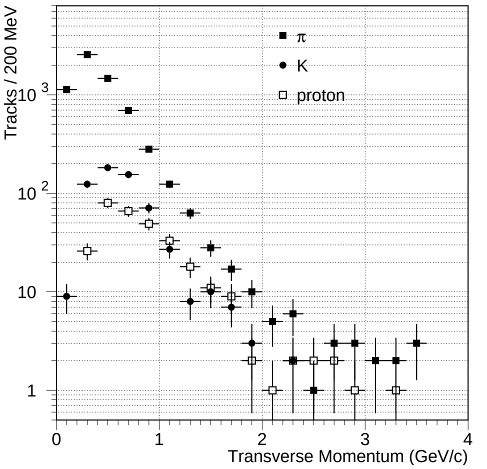

Figure 1: Transverse momentum distribution of pions, kaons and protons for a single event generated with the SHAKER generator, after tracking and PID reconstruction.

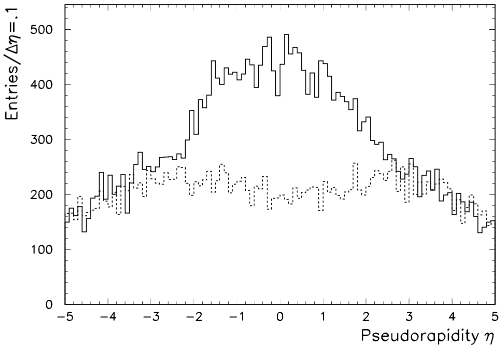

Figure 2: Rapidity distribution of charged particles for two central Pb–Pb collisions as generated by the HIJING generator, with (full line) and without (dashed line) the effect of "jet quenching" in the medium.

LHC (up to 8000 per unit of rapidity) will provide both a formidable experimental challenge and a unique opportunity. It will be possible to measure a large number of observables on an *event-by-event* basis: impact parameter, $\mathrm{d}N/\mathrm{dy}$, particle ratios and p_t spectra ($\pi, \gamma, \mathrm{K}, \mathrm{p}$) and size and lifetime from interferometry. It will be thus possible to study each event as a thermodynamical system, and to access correlations and non-statistical fluctuations which would be washed out when averaging over many events. Variables such as flow and "chemical" composition of the final state will be measured with unprecedented precision. As an example of these possibilities, in fig. 2 is shown the rapidity distribution for a single event in two different scenarios, as it would be measured by ALICE. Even more striking is the transverse momentum spectrum of a single event of the maximum foreseen multiplicity, shown in fig. 1. Including acceptance, tracking efficiency and decays, $\approx$ 6500 pions, $\approx$ 500 kaons and $\approx$ 300 protons are reconstructed, sufficient to measure the momentum spectra with high precision.

One of the most striking signatures for the QGP is an anomalously small cross section for the production of heavy vector mesons [3]. At the LHC one should be able to perform a complete quarkonium spectroscopy ($J/\Psi, \Psi', \Upsilon, \Upsilon', \Upsilon''$), measuring the sequential melting of resonances of progressively smaller radius as a function of energy density. B and D mesons will be copiously produced, and their identification will provide both a natural normalization for the measurement of quarkonium and an excellent tool to substract from the measured yield of J/Ψ's those coming from B-meson decay.

2 The ALICE experiment

The Large Hadron Collider (LHC) at CERN will accelerate both proton and heavy–ion beams up to energies of several TeV per nucleon. It will operate with heavy-ion beams approximately 10% of the running time and one large detector will be dedicated to heavy ions. The collaborations which are constructing dedicated pp detectors at the LHC, in particular CMS, have also expressed interest in the study of nuclear collisions. Since these detectors are optimized for physics differing from heavy-ion physics by several orders of magnitude in event rate, multiplicity, and p_{t}, they are limited to a small subset of high-mass, high-p_{t} heavy-ion phenomena, in particular high-mass dimuons. The ALICE Collaboration has designed [4, 5, 6] a dedicated, general-purpose detector, which will address most sensitive observables, detecting hadrons, di-leptons, and photons. In addition to the running with Pb ions, we foresee collisions of ions of lower mass to vary the energy density, while running with proton beams will provide reference data. The possibility of proton-Nucleus collisions is also considered.

In order to study the QGP, a number of observables have to be analysed in a systematic and comprehensive way. The ALICE strategy is to study a number of *specific signals* in the same experiment together with *global information* about the events. The experiment will measure the flavour content and phase-space distribution event by event for a large number of particles whose momenta and masses are of the order of the typical energy scale involved (temperature $\approx \Lambda_{QCD} \approx 200$ MeV). The observables accessible to our detector include:

Global event features, which measure the geometry of nuclear reactions, i.e. impact parameter, overlap volume, and number of constituents participating in the interaction. In addition, they indirectly reflect some of the underlying dynamics in nuclear collisions (nuclear stopping, primary particle production mechanism, rescattering), and specify the initial energy density, thus constraining theoretical models.

The production cross section of J/Ψ *and* Y families of heavy quark resonances, coupled with the measurement of D and B mesons, which probes deconfinement.

Prompt photons and lepton pairs, can reveal the characteristic thermal radiation from the plasma, which could be observable in the medium-p_{t} range (around 1–3 GeV/c).

The cross-section of *high-*p_{t} *hadrons*, sensitive to the energy loss of the partons in the plasma.

Strangeness production, which is sensitive to the large s quark density expected from (partial) chiral symmetry restoration in the plasma, since the strange quark mass will be reduced from the constituent (≈ 500 MeV) to the current value (≈ 150 MeV); in particular, heavy multi-strange hyperons are potentially very good signatures [7] for the large strangeness density expected in the QGP. The ϕ meson is also extremely sensitive, since a shift of few MeV of the in-medium kaon mass would drastically alter the relative branching fractions of $\phi \rightarrow$ KK and $\phi \rightarrow$ ee.

Multiplicity fluctuations, which are a signature for the critical phenomena at the onset of a phase transition.

Particle interferometry, which measures the expansion time in the mixed phase, which is expected to be long in the case of a first-order phase transition.

Particle ratios, transverse–momentum distributions and *resonance line-shape parameters* are all sensitive to the dynamical evolution of the hadronic phase. We will measure simultaneously a large number of stable particles and resonances (π, η, ω, ϕ, p, K, Λ, Ξ, Ω) as a function of charged-particle density and p_{t}.

Some *particle ratios, measured on an event-by-event basis* allow to look for fluctuations and correlations with other observables.

Design Considerations The average event rate for Pb–Pb collisions at the LHC, given the maximum luminosity of 1.0 x 10^{27} $cm^{-2}s^{-1}$, a luminosity half–life of $\approx$ 5 hours and an inelastic cross– section of 8 b, will only be about 8000 minimum-bias collisions per second [8]. Of these events, approximately 2–3% correspond to the most central collisions [1]. This low interaction rate has a crucial role in the design of the experiment, since it allows the use of slow but high–granularity detectors, like the time projection chamber (TPC) and the silicon drift detectors (SDD's). We expect to collect a few 10^7 central events/year. To increment the statistical significance of the quarkonium measurement, dedicated trigger systems will select candidate events in the muon spectrometer and in the TRD. A partial readout of the relevant detectors will be performed following these triggers. The experiment is designed to cope with the highest anticipated multiplicities, which for central Pb–Pb collisions are 8000 charged particles per unit of rapidity. The rapidity acceptance has to be large enough to allow the study of particle ratios, p_{t} spectra and HBT (Hanbury-Brown-Twiss [7]) radii on an event-by-event basis, meaning several thousand reconstructed particles per event. Detecting the decay of particles at $p_{\mathrm{t}} < m$ requires about 2 units in rapidity (for masses above 1–2 GeV) and corresponding coverage in azimuth. In particular, efficient rejection of low-mass Dalitz decays, which is needed for the lepton-pair measurements, can only be approached with full azimuthal coverage. The rapidity coverage of our central detector ($|\eta| < 0.9$) has been chosen as a compromise between acceptance and cost. To be sensitive to the global event structure, $\mathrm{d}N_{ch}/\mathrm{d}\eta$ will be measured with multiplicity detectors in a large rapidity window ($|\eta| < 4.5$).

The design of our tracking system has primarily been driven by the requirement for safe and robust track finding. It uses mostly three-dimensional hit information and dense tracking with many points in a weak magnetic field. The

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[1] for definitions of this and other terms used here, which are common in heavy ion physics, please see [9]

field strength, ≈ 0.2 T, is a compromise between momentum resolution, low momentum acceptance, and tracking efficiency. The momentum cut-off should be as low as possible (< 100 MeV/c), in order to study collective effects associated with large length scales. A low-p_{t} cut-off is also mandatory to reject the soft conversion and Dalitz background in the lepton-pair spectrum. The most stringent requirement on momentum resolution in the low-p_{t} region is posed by identical particle interferometry, owing to the large source radii and the correspondingly narrow momentum correlation enhancement. In the intermediate energy regime, the mass resolution should be of the order of the natural width of the ω and ϕ in order to maximize the signal-to-background ratio and, more importantly, to study mass and width of these mesons in the dense medium. At high momenta, the resolution has to be sufficient to measure the spectrum of jets via leading particles. The detection of hyperons, and even more of D and B mesons, requires in addition a high–resolution vertex detector close to the beam pipe.

The momentum range for particle identification can be restricted for the bulk of the hadronic signals to a few times the average p_{t} (>97% of all charged particles are below $p_{\mathrm{t}} = 2$ GeV/c). Good π/K/p separation (better than 3–4σ) is needed on a track-by-track basis for the abundant soft hadrons in order to study HBT with identified particles, decays (hyperons, $\phi \rightarrow$K K and charmed mesons), and event-by-event particle ratios. A statistical analysis (separation better than 2–3σ) will be sufficient to measure inclusive particle ratios and p_{t} spectra in the mini-jet region. The e/π rejection has to be sufficient to reduce the additional combinatorial background due to misidentification to below the level remaining from unrejected Dalitz pairs, and extend to sufficiently high p_T to measure the decay of the Υ family in di-electrons.

The accuracy of the single inclusive photon spectra will be determined by systematic errors on photon-reconstruction efficiency and the knowledge of the decay background. An acceptable systematic error can be obtained only at low channel occupancy and therefore requires a calorimeter with small Molière radius at a large distance (≈ 5 m) from the vertex.

3 Detector layout and performance

A longitudinal view of the ALICE experiment is shown in Fig. 3. The central part, which covers $\pm$ 45° ($|\eta| < 0.9$) over the full azimuth, is embedded in a large magnet with a weak solenoidal field. It consists of the Inner Tracking System with six layers of high-resolution silicon detectors, the cylindrical Time Projection Chamber, a barrel particle identification array (Time of Flight - TOF), a transition radiation detector for electron identification, a small–area detector at large distance for the identification of high momentum particles (Ring Imaging Cherenkov - RICH - detectors), and a single-arm electromagnetic calorimeter of high density crystals. A muon detector covers the very forward region ($2.4 \leq$

$\eta \leq 4$), constructed of a low-Z absorber very close to the vertex followed by a spectrometer with a dipole magnet and, finally, an iron wall to select the muons. Not visible are the array of Multiplicity Counters, located near the beam pipe, and the Zero–Degree Calorimeters (ZDC), which are located ≈ 90 m downstream. The open geometry of the detector mantains the possibility of future modifications or upgrades.

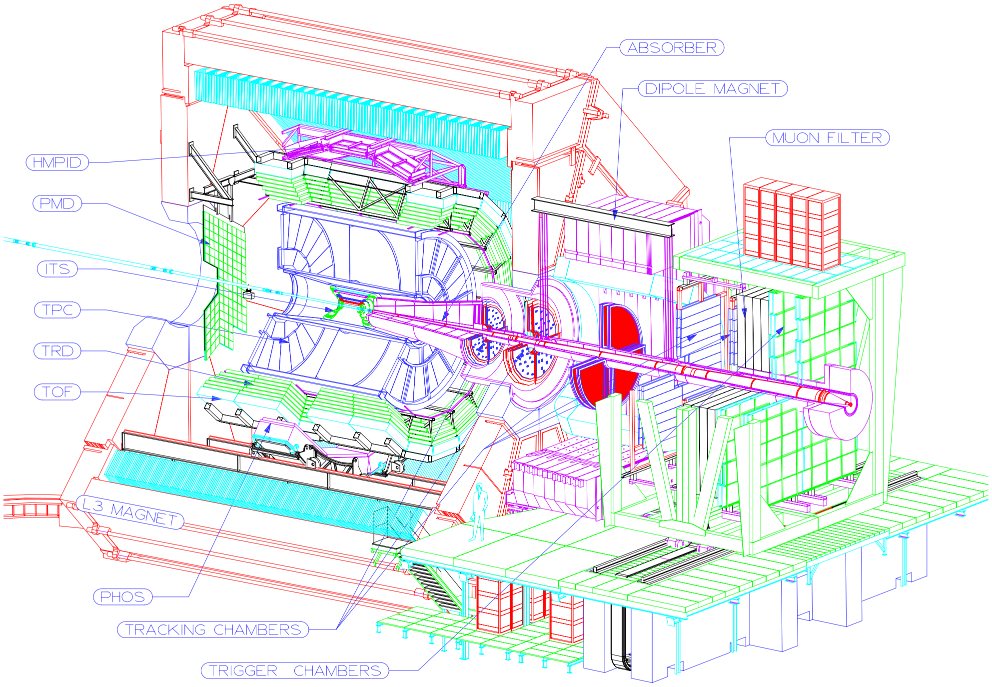

Figure 3: Longitudinal view of the ALICE detector.

Inner Tracking System The inner tracker provides secondary vertex reconstruction for hyperon and charmed meson decays, tracking and identification by species of low-p_{t} particles, and improved momentum resolution for the higher-p_{t} particles which also traverse the time projection chamber. The six cylindrical layers are located at r=4, 7, 15, 24, 39 and 44 cm. Four layers will have analog readout to provide particle identification via $\mathrm{d}E/\mathrm{d}x$ in the $1/\beta^2$ region, which will give the ITS a stand-alone capability as low-p_{t} particle spectrometer. Because of the particle density and for good impact parameter resolution below 100 μm, pixel detectors have been chosen for the innermost two layers, and silicon drift detectors for the following two. Double-sided silicon micro-strip detectors will equip the two outer layers. Minimization of the material thickness is an absolute priority, and the average thickness, all included, is kept below 1% of X_0 per layer.

Time Projection Chamber The TPC has an inner radius of 90 cm, given by the maximum acceptable hit density (0.1 cm^{-2}), and an outer radius of 250 cm, given by the length required for a $\mathrm{d}E/\mathrm{d}x$ resolution of $< 10\%$, necessary for

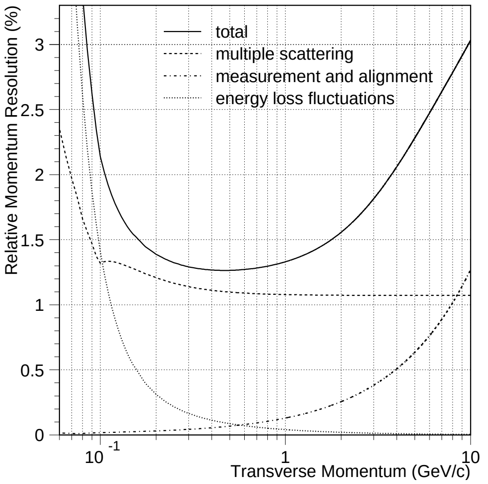

Figure 4: Momentum resolution for pions as a function of transverse momentum, showing separately its main components.

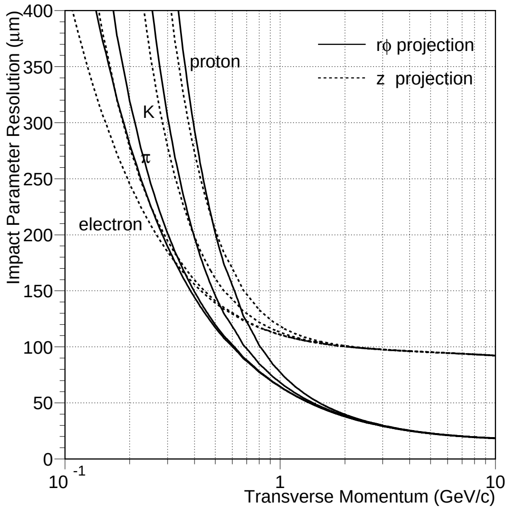

Figure 5: Impact parameter resolution for electrons, pions, kaons and protons as a function of transverse momentum

electron identification. The design is optimized for good double-track resolution; in particular, the use of Ne/CO_2 (90/10) minimises electron diffusion and reduces the space charge.

Performance of the Tracking System For the highest particle multiplicity considered we find a reconstruction efficiency in the TPC better than 90%, practically independent of $p_{\rm t}$ down to 100 MeV/c and with a negligible number of ghosts. The efficiency of connecting tracks from the TPC to the ITS is also better than 90%, resulting in an overall tracking efficiency for the TPC and the ITS combined of almost 90% for transverse momenta above 100 MeV/c (for pions). Low $p_{\rm t}$ electrons (and pions) are reconstructed in the ITS used as a stand-alone tracker after the hits of the higher–momentum tracks are removed. The momentum resolution $\Delta p/p$ is shown for pions in fig 4. It is generally better than 1.5 % for the relevant momentum range.

The impact parameter resolution, shown in fig. 5, is better than 100 μm for $p_{\rm t}$ larger than 600 MeV (for kaons). The effective mass resolution of a particle decaying into an e^+e^- pair is $\Delta m/m \approx 1\%$, i.e. 8 MeV/c^2 for ρ and ω, 10 MeV/c^2 for ϕ, and 30 MeV/c^2 in the J/ψ region. Particle interferometry depends on two–track resolution, momentum resolution and acceptance; in ALICE, single–event pion interferometry should be feasible with a relative error of $\approx$ 20% up to effective sizes of 15 fm. For the hyperons, after reconstruction and identification, we can accept 50 $\pm$ 10% of the Λ's with $p_{\rm t} > 600$ MeV/c, with very negligible background.

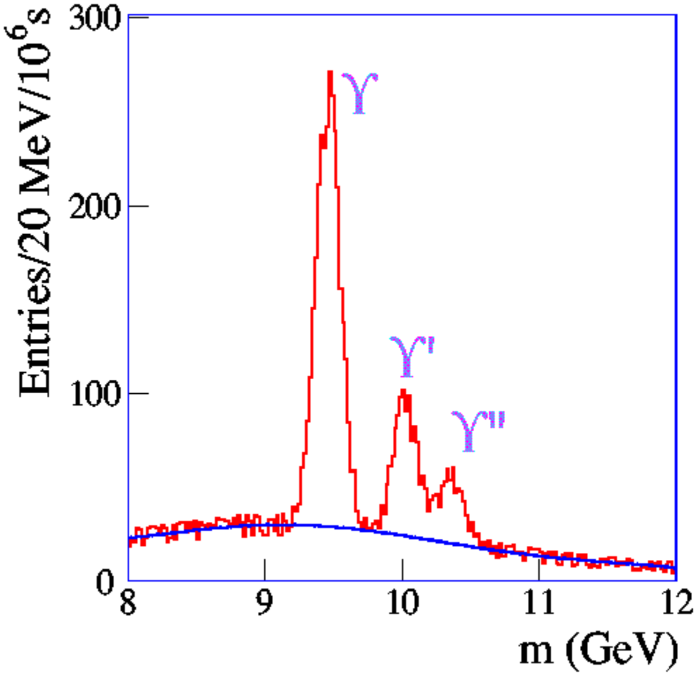

Figure 6: Expected dimuon spectrum after a running time of 10^6 s.

Particle Identification System Two separate systems will provide hadron identification. The barrel TOF at r=3.7 m will provide the identification of the bulk of the particles for event-by-event analysis and contribute to the e/π rejection. The small-area RICH will provide the particle identification needed to measure inclusive particle ratios up to higher momenta.

For the TOF, multigap resistive plate chambers (MRPC) have been chosen, since they couple a good intrinsic time resolution with a rather simple construction techniques. The RPC is a gaseous detector with resistive electrodes, which quench the streamers so that they do not initiate a spark breakdown. Thus the RPC can be operated at much higher gains in avalanche mode. The multigap RPC is made of a series of gas gaps with a single set of read-out strips reading out all gas gaps in parallel. The intermediate plates take correct voltage due to electrostatics and are kept at correct voltage with flow of positive ions and electrons generated by the avalanche. The intermediate planes are “transparent” for avalanche signals, thus the induced signal on the external electrodes is the “analog sum” of the avalanches in all the gaps. Including the sources of timing errors, a resolution of $\sim$ 150 ps is expected for the TOF. This resolution would guarantee a 3σ K/π separation up to $p_{3\sigma}$=1.7 GeV/c.

Particle identification is achieved combining the information of the TOF with the dE/dx measurements in the TPC and in the ITS. The combined separation power, is more than 3σ for π and K identification up to 2 GeV/c and for protons up to 3 GeV/c. For the high-momentum particle identification a RICH detector of the proximity focusing type is used, placed at a distance of $\approx$ 4.5m from the beam axis. It will use a liquid C_6F_{14} radiator and a MWPC with pad readout as UV detector. The photocathode will be a thin layer of CsI evaporated onto the pad plane. The RICH will extend the 3 σ limit of π/K identification to $\approx$ 3.4 GeV/c. Thanks to the combination of particle identification and vertexing capabilities, it will be possible to measure in ALICE the production of neutral charmed mesons with a significance (signal over square root of the background) of about 30.

Electron Pairs The di-electron measurement is a formidable challenge at the LHC, since it requires the capability to recognize and remove from the sample the electrons from Dalitz decays, whose combinations form most of the background in the invariant mass spectrum and will be several per event, entering the plot in all possible combinations. Electron identification is achieved in ALICE by combining the particle identification capability of ITS, TPC and TOF and complementing it with a dedicated Transition Radiation Detector. The TRD will consist of six layers of radiator foil stacks followed by Time Expansion Chambers, providing an e/π rejection power of 100 in high multiplicity operation. The TRD fast tracking capability can also be used to trigger on high-p_t leptons, thus enriching their statistical sample.

Photon Spectrometer (PHOS) Prompt photons, π^0's and η's will be measured in a single-arm, high-resolution electromagnetic calorimeter. Prompt photons are a small fraction of the meson decay photons, which must be accurately known before the former can be determined. This requires high granularity, and good energy and spatial resolution. The cell size must not exceed one Molière radius R_{M} and the occupancy 3%. The gamma reconstruction efficiency should be measurable to an accuracy of $\approx$ 4%. The PHOS will be located 5 m vertically beneath the interaction region and will be built from $PbWO_4$, a material with small Molière radius and high light output.

Large Rapidity Detectors A multiplicity counter array close to the interaction region will measure the pseudorapidity distribution of charged particles over most of the phase space ($|\eta| < 4.5$). A set of small calorimeters will be used to measure and trigger on the impact parameter of the collisions. Owing to their different Z/A values, it is possible to separate in space the neutron and proton spectators and the beam particles (Z/A $\simeq$ 0.4) by means of the first LHC dipole. Therefore, we will detect the neutron and proton spectators in two distinct calorimeters, made respectively of tantalum and brass with embedded quartz fibres, located on both sides of the interaction region $\approx$ 90 m downstream in the machine tunnel.

The Forward Muon Spectrometer The forward muon spectrometer will allow the study of vector meson resonances like $J/\Psi, \psi', Y, Y'$ and Y'' via their $\mu^+\mu^-$ decay. The signals will appear on a continuum due to B and D meson decays and Drell-Yan processes. The spectrometer must have an efficiency for dimuons better than 90% and a mass resolution better than 100 MeV in the Y region and better than 70 MeV in the J/Ψ region. The momentum precision must be about 1%. The muon spectrometer consists of a composite absorber ($\approx 10\lambda_{INT}$) starting close to the interaction point(one meter) to reduce the μ background due to π and K decays. The absorber is carefully designed with layers of both high and low Z materials to reduce multiple scattering and particle leakage. It is followed by a dipole magnet with a nominal field of 0.7 T, giving a 3 Tm field integral. The dipole will accept μ at angles smaller than 9 degrees. A small angle absorber with a central hole will shield the angles from 0 to 2 degrees and allow the non interacting Pb ions to traverse the spectrometer. Ten planes of thin multiwire proportional chambers with cathode pad readout placed in front, inside and following the dipole will provide the tracking information for the muons. Finally the muons will be identified as the particles crossing a second absorber ($\approx 10\lambda_{INT}$ of iron) at the end of the spectrometer. Two resistive plate chamber planes will detect these particles and trigger the spectrometer. The dimuon spectrum in the Y region expected after one month of running is shown in Fig 6.

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