The ALICE TPC: Status and Perspectives

Hans Rudolf Schmidt, for the ALICE Experiment

GSI Helmholtz Centre for Heavy Ion Research GmbH, Darmstadt

h.r.schmidt@gsi.de

Abstract. The ALICE TPC is the largest Time Projection Chamber ever built. Given the performance requirements it is also, and justifiably so, dubbed the most challenging one. In this paper we browse through the often contradictory optimization strategies and outline the solutions taken to meet the specifications. Mainly on the basis of the commissioning data taken in 2008 and 2009 we will examine to which extend the ALICE TPC came up to its performance expectations, which were outlined elsewhere [1, 14]. First results on the performance of the TPC with proton-proton collisions in December 2009 are presented.

1. Introduction

The physics of hot and dense matter has been investigated over the last two decades at the AGS [2], the SPS [3] and at RHIC [4, 5, 6, 7]. The results obtained in recent years at RHIC have confirmed the previous SPS findings and, beyond that, given exciting new insights into the physics of strongly interacting matter. ALICE (A Large Ion Collider Experiment) is designed to study the physics of hot and dense matter and the transition to a quark-gluon plasma at the CERN Large Hadron Collider (LHC). The ALICE detector is optimized to cope with the highest particle multiplicities anticipated for PbPb collisions (dN_{ch}=dy up to 5000). In addition to heavy systems, the ALICE Collaboration will study collisions of lower-mass ions, which are a means of varying the energy density, and protons (both pp and pA), which primarily provide reference data for the nucleus-nucleus collisions. The pp data will in addition allow for a number of genuine pp physics studies.

2. The ALICE Experiment

The detector (cf. Figure 1) consists of a central part, which measures event-by-event hadrons, electrons and photons, and of a forward spectrometer to measure muons. The central part, which covers polar angles from 45° to 135° ($|\eta| < 0.9$) over the full azimuth, is embedded in the large L3 solenoidal magnet. The central barrel consists of: an Inner Tracking System (ITS) of high-resolution silicon detectors; a cylindrical Time-Projection Chamber (TPC), a Transition Radiation Detector (TRD) and a Time-Of-Flight (TOF) detector. A large lead-scintillator Electromagnetic Calorimeter covering $\Delta\phi = 110°$ and $|\eta| < 0.9$ complements the central barrel of ALICE. The single-arm detectors PHOS, a lead-tungsten crystal electromagnetic calorimeter and HMPID, a ring imaging Cherenkov hodoscope add to the central detectors.
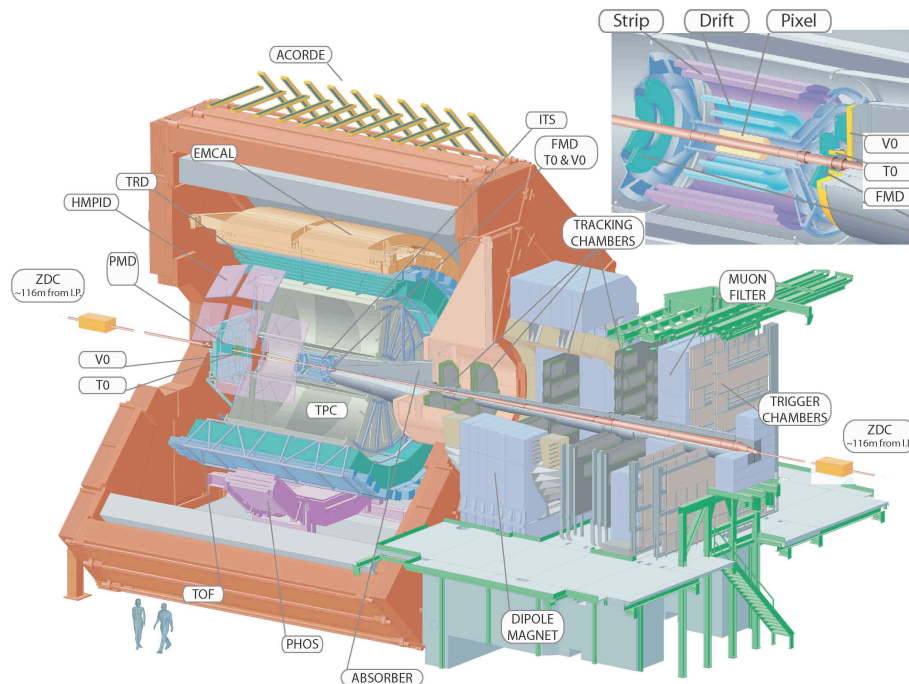
Figure 1. Sketch of the ALICE detector. The insert shows an expanded view of the inner tracking system (ITS).

The forward muon arm (covering polar angles ϑ from 171° to 178°) consists of a complex arrangement of absorbers, a large dipole magnet, and 14 planes of tracking and triggering chambers. Several smaller detectors (PMD, ZDC, FMD, T0, V0) for global event characterization and triggering are located at forward angles. An array of scintillators (ACORDE) on top of the L3 magnet will be used to trigger on cosmic rays. The central detectors ITS, TPC and TOF are completely installed and commissioned. The TRD has 7 out of 18 super-modules installed and will be completed in 2011. Furthermore, the forward muon spectrometer, the central HMPID single-arm spectrometer and the Photon Multiplicity Detector PMD are installed and ready. Both the scintillator-lead calorimeter and the high resolution PHOS photon spectrometer are at present partially installed and are schedule to be completed in 2010/11. The ZDC (Zero Degree Calorimeter) as well as the other trigger detectors are ready as well. A High Level Trigger System (HLT) is fully operational for pp-collisions. Thus, at the restart of the LHC in fall 2009 the ALICE detector had full hadron and muon and partial electron and photon capability.

3. The ALICE Time Projection Chamber

3.1. Design

A comprehensive overview of the TPC design and some results on the performance with cosmic rays during commissioning are contained in [8]. The TPC is cylindrical in shape with an active radial range from about 85 to 250 cm, and an overall length along the beam direction of 500 cm, divided by the central HV electrode into two drift regions of 250 cm length (cf. Figure 2). Multi-wire proportional chambers are mounted into 18 trapezoidal sectors in each end-plate. The field cage is based on a design with a central high-voltage electrode and two opposite axial resistive potential dividers which create a highly uniform electrostatic field in the common gas volume. The central electrode is an aluminized, stretched Mylar foil. The potential of the drift region is defined by Mylar strips wound around 18 inner and outer support rods which contain the resistor chains, gas in- and outlet and a

system for distribution of laser rays. Because of the drift gas used in the TPC, the field cage has to be operated at a rather high gradient of 400 V/cm. The high at the central electrode is voltage 100 kV which results in a maximum drift time of about 100 µs. The field cage is surrounded by double-shelled containment vessels with CO_2 as insulator. Composite materials were chosen for high mechanical stability at a low material budget (only 3.5% of a radiation length for tracks with normal incidence). The readout chambers instrument the two end plates of the TPC cylinder with an overall active area of 32.5 m^2 with 18 sectors on either side. The chambers are multi-wire proportional chambers with cathode pad readout. The sectors are segmented radially into two chambers with varying pad sizes, optimized for the radial dependence of the track density. There are 557568 pads, radially pointing, with 3 sizes: 4 × 7.5 for the inner chambers, 6 × 10 and 6 × 15 mm^2 (r × φ) for the outer chambers.
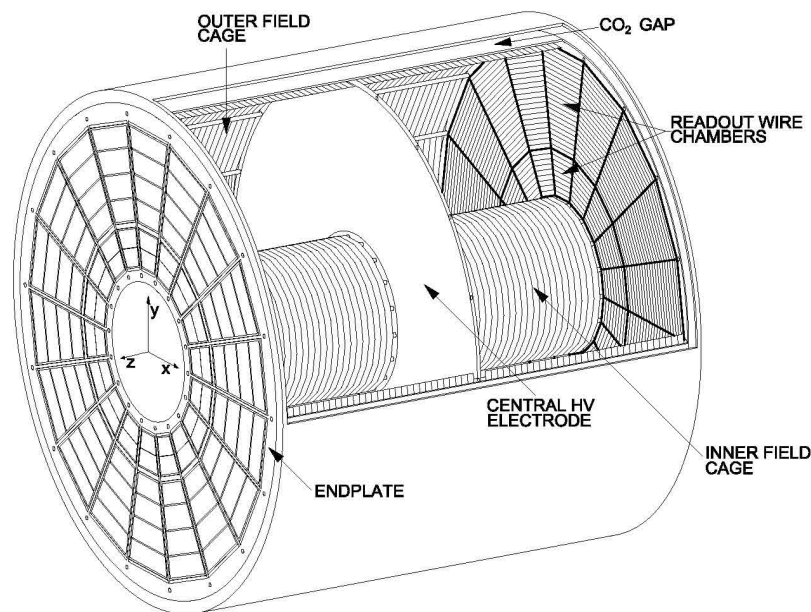

Figure 2. 3D view of the TPC field cage. The high voltage electrode is located at the center of the drift volume. The endplates with 18 sectors and 36 readout chambers on each end are shown.

A schematic layout of the front-end electronics readout chain is shown in Figure 3. The pad signals are treated in a charge-sensitive amplifier and shaper in 0.35 µm CMOS technology with 16 channels per chip. One 10-bit ADC per channel samples the analog signal at a rate of 5 or 10 MHz (500 or 1000 samples). The following pipelined digital processor performs pedestal subtraction, tail cancellation, zero-suppression, baseline restoration, formatting and buffering. The ADC's and digital circuits of 16 channels are implemented in one chip (ALTRO) in a 0.25 µm CMOS process. The digital signal processing is essential for the performance at high occupancy and rate. An important feature is that processing parameters and algorithms can be reconfigured. The overall system noise value is about 600e rms for the typical pad capacitance of 12 pF. The front-end electronics chain consists of a 128 channel front-end card (FEC) with only 40 mW/channel, a frontend bus for rows of up to 25 FEC's linked to one readout control unit (RCU), with 6 RCUs for each of the 36 readout sectors. Connection to the data acquisition system is via optical links (one per RCU).
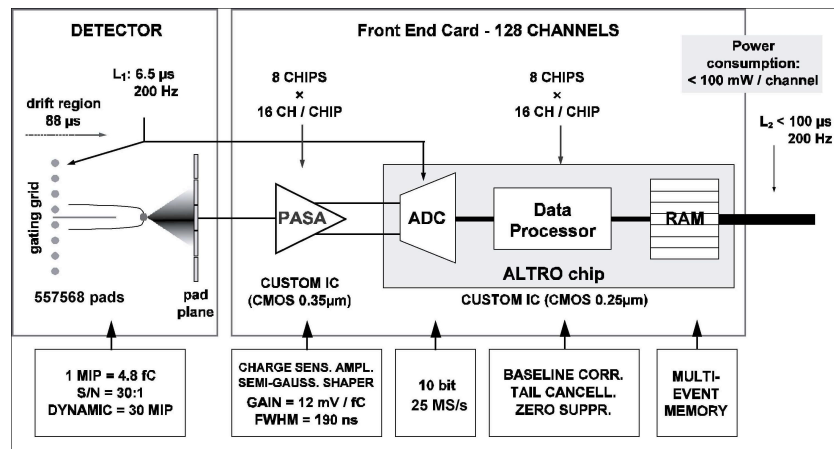
Figure 3. An overview of the ALICE TPC front-end electronics.

The design of the TPC is thus 'conventional' in overall structure but innovative in many details. This is necessitated by the extreme environment expected for Pb-Pb collisions at center-of-mass energy of 1144 TeV. In the following section we will outline in detail the specific challenges imposed by this environment and the attempts of technical solutions.

3.2. Challenges

The ALICE Time-Projection Chamber is designed for operation in the extreme environment of heavy ion collisions up to Pb–Pb at LHC. The TPC has been designed for a maximum multiplicity $dN_{ch}/dy=8000$, resulting in 20000 charged primary and secondary tracks in the acceptance, an unprecedented track density for a TPC. Although this multiplicity is by now likely be higher by a factor of 4 than the extrapolation from RHIC data, this upper limit has been kept for the design and simulations. At the Pb–Pb design luminosity, a minimum bias interaction rate of 8 kHz is expected of which about 10% are to be considered as central collisions. Extreme multiplicities and high rates set new demands on the design of a TPC.

The obvious answer to high multiplicity events is to adapt the granularity of the readout chambers, i.e., the pad sizes and time bins, to the expected spatial and temporal track density. This approach has, however, the following caveats:

- due to diffusion of the electron clouds while drifting towards the anode grid, the granularity is limited by the transverse diffusion. The width of the charge cloud after 250 cm of drift is of the order of mm depending on the choice of the drift gas and voltage, i.e., any reduction of the pad beyond a certain size results in an oversampling of the track without any gain of information;
- small pad sizes imply a small (primary) signal, hence the pad size a limited by achievable signal-to-noise ratio. Moreover, a sufficient number of pads per charge cluster in terms of position resolution is 2-3. Thus an increase in the number of pads is sensible only if the induced charge from the (point-like) avalanche spreads over no more the 2-3 pads. This can be achieved by reducing the distance between anode wire and pad plane. However, at a certain point the distance HV-GND gets critical;
- similarly, one could think of increasing the frequency of the time sampling. However, as diffusion occurs also in longitudinal direction this would result as well in an oversampling of the pulse. The choice of a shorter shaping time is limited by the fact that below 150-200 ns shaping time the signal/noise ratio becomes critical.

Another serious difficulty imposed by high multiplicity events (at high rate) is the accumulated space charge in the drift volume. Owing to the much smaller mobility of the ions as compared to the electrons a quasi-stationary positive charge will distort the drift field significantly.

3.3. Solutions

From the above constraints it is obvious that the gas choice is a critical issue. The requirements to the gas are low diffusion (a "cold" gas) and low space charge. A straightforward choice, also taken previously by the NA49 experiment [9] for their vertex TPC, is $NeCO_2$ as drift gas, which fulfils the above two requirements. However, this selection is not without severe drawbacks:

- as a low Z gas the number a primary electrons is scarce (about $20e^-$/cm track length). This aggravates the above mentioned already small signal/pad due to the pad size itself. A possible solution is an increase in amplification, i.e., gas gain. This, however, is by itself again not with out problems since CO_2 is not a very good quencher. CH_4 would, in this respect be much better, but its diffusion properties and the increased ageing due to its organic nature are not acceptable;

- the drift velocity in $NeCO_2$ is, differently from the $ArCH_4$ mixture used in STAR, not saturated, which means that it depends sensitively on the gas temperature. The change in drift velocity is about 0.35%/K at 400 V/cm. This means that a temperature difference larger than 0.1 K over the full drift length of 250 cm results in longitudinal position variations Δz of the order of 1 mm at v_{Drift}= 2.64 ms/cm. This exceeds the internal resolution of the readout chambers. Therefore the detector cooling and temperature stabilization systems are involved [10];

- the drift velocity is comparatively small. This limits the internal rate capability of the TPC. While STAR achieved v_{Drift}= 5.5 cm/µs at 150 V/m drift field, the field inside the ALICE TPC has to be raised to 400 V/cm to reach a drift velocity v_{Drift} of 2.64 cm/µs. This, of course, requires sophisticated insulation of the field cage vessel, e.g., the double walled field cage vessels are flushed with CO_2 as an insulation gas.
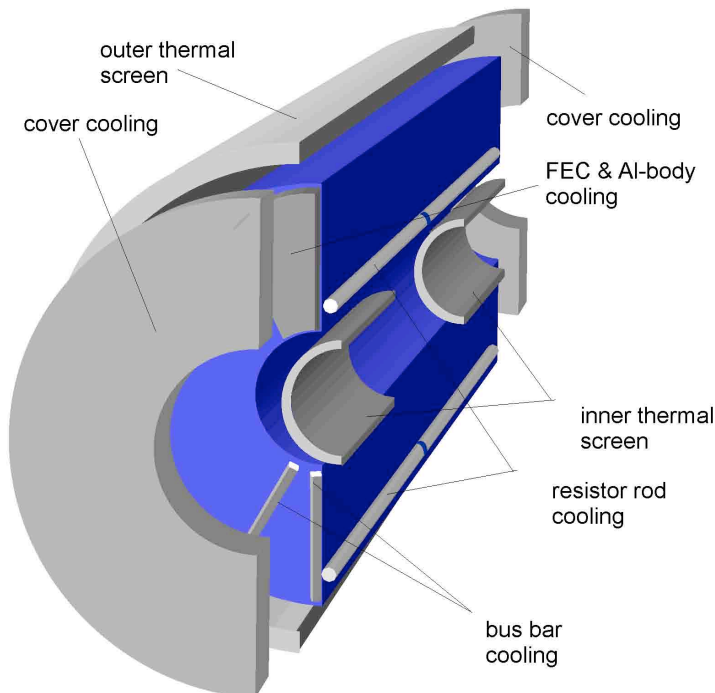

Figure 4. Schematic view of the various TPC cooling elements.

4. Commissioning and Calibration of the Time Projection Chamber

First particles from the LHC were seen on June 15th, when the ALICE Silicon Pixel Detector received a significant load of muons after the injection of particles from the SPS into the LHC. During LHC tune-up until October 2008, and thereafter from July 2009 until the end of November 2009 the detectors were mostly operated under "realistic" conditions, i.e., continuous 24 hours data taking in global mode (all detectors participating in the data stream). The data taken were comics, laser, source or pulser data and were used to calibrated and align the detector. Altogether, more then 5×10^8 event have been recorded.

4.1. Temperature Stabilization

The strong dependence of the drift velocity on the temperature for the gas mixture used in the TPC requires to stabilize the temperature to better than 0.1 K over the full drift volume of 88 m^3. This is achieved by very efficient heat removal from the front-end electronics and by well-defined iso-thermal surfaces around the TPC barrel via thermal screens. In addition, the Al-bodies of the readout chambers and the resistive voltage divider chain of the field cage ("resistor rod"), which face or are inside of the gas volume, respectively, are set to precisely defined temperatures. The cooling system (cf. Figure 4) consists of 60 individual sub-atmospheric cooling circuits, which can be regulated in flow and temperature. The histogram of the skirt temperature sensor distribution is shown in Fig. 5. The so-called skirt sensors are arrays of Pt1000 sensors, which are installed within the gas volume of the TPC close to the outer circumference of the readout-plane. The temperatures were sampled over a period of 24 hrs with stable environmental conditions. The RMS value of the histogram is below 50 mK showing that the desired temperature homogenization of the TPC gas volume below 0.1 K is within reach.

4.2. Noise Performance

In Fig. 6 the histogrammed noise distributions obtained during the final stage of commissioning are shown for all pads and for the different pad sizes separately. Only 1.7 (0.14)% of the channels show noise values above 1(1.5) ADC channels. The largest pads with 5.7 (0.4)% contribute most to this value. The mean ENC in the TPC is about 730 e. A systematic variation in the noise level is observed increasing from the center of each readout partition towards its edges. This variation is directly related to the variation in length of the traces on the pad-plane PCB board, which connects the pads with the connectors on its back side. With the trace length the capacitance at the input of the charge-sensitive preamplifier/shaping chips (PASAs) rises and hence the noise level rises. A detailed description of the noise performance is contained in [11].
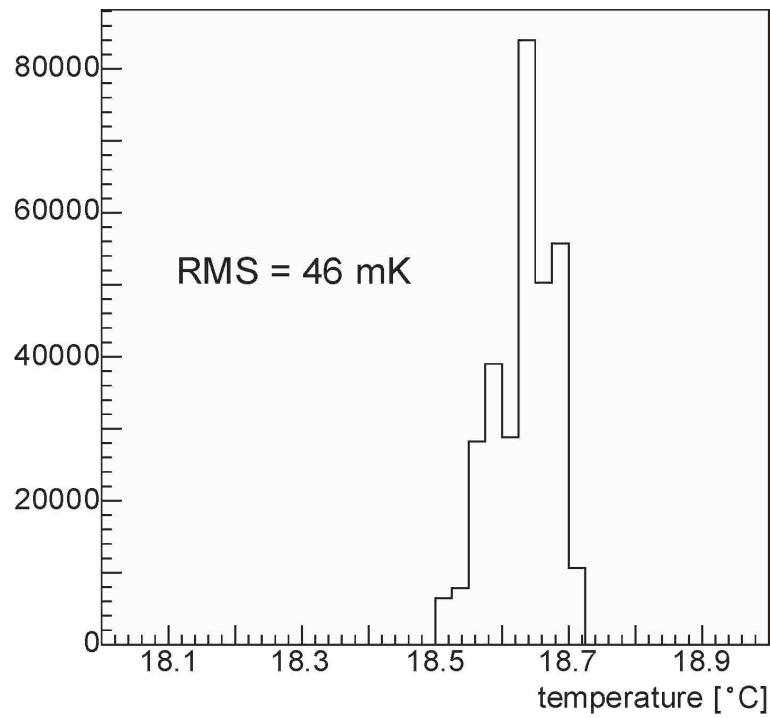
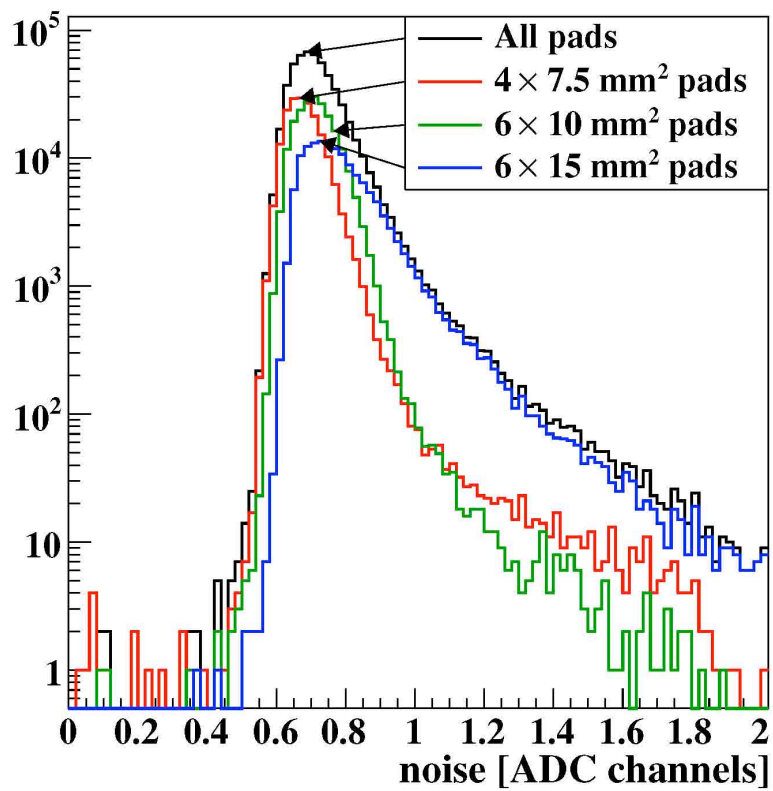**Figure 5.** Temperatures distribution measured with the skirt PT1000 sensors.

Figure 6. Noise distribution; for all chambers and separately for the different pad sizes.

4.3. Gain Calibration and dE/dx calibration

The gain of 557568 individual readout pads located at the two TPC end-planes was calibrated injecting radioactive ^{83}Rb into the TPC gas. ^{83}Rb ($\tau_{1/2}$=86.2 d) decays to ^{83m}Kr via electron capture. The decay of the isomeric Krypton state ($\tau_{1/2}$=1.83 hrs) produces via IC with a large probability an electron cluster of 41 keV, which is used to equalize the gains. This calibration procedure reveals an average pad-to-pad gain variation of 15%, which is well within the range expected from the production tolerances.

Having the gain equalized, the response of the pads to the differential energy loss dE/dx of charged tracks in the gas is calibrated as a function of γ to match the Bethe-Bloch curves. The resolution in dE/dx is close to the design value of 5.5%. This allows to separate particles (protons, kaons, pions and electrons) on a statistical basis in the region of the relativistic rise, i.e., at momenta above 1-2 GeV/c.

4.4. Space Point and Momentum Resolution

Both the space point and the momentum resolution of individual tracks are determined from cosmic rays showers measured in the TPC. The space point resolution is determined from cosmic rays. It is, both in rϕ- and z –direction, in agreement with simulations. It is limited by diffusion. The resolution relevant for high p_t tracks (large drift and diffusion) is of the order 300-800 μm.
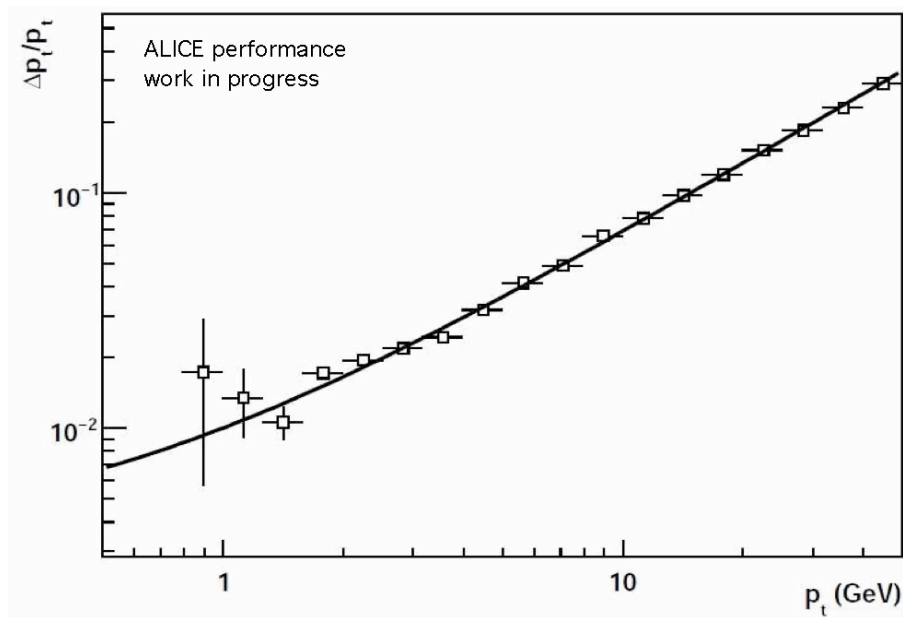

Figure 7. Transverse momentum resolution obtained from cosmics tracks.

The momentum resolution has been estimated from the correlation of semi-tracks, i.e., cosmic tracks crossing the TPC through the center have been split into to half tracks. Those are reconstructed in two parts due to the optimization of the reconstruction code for the collider geometry. The extracted momentum resolution is shown in Figure 7 and is 6.5% for 10 GeV/c tracks and 1 % for 1 GeV/c tracks. This is, with the present set of corrections, somewhat worse than the design resolution (4.5% at 10 GeV/c).

5. Proton-Proton Collisions

First proton-proton collisions were recorded in the ALICE experiment on Nov. 23rd 2009. For the initial data taking period the TPC had been switched off as a precaution. The data published in [12] refer to those first 285 events taken.

On Dec. 6th 2009 the TPC saw its first tracks from collisions at √s=900 GeV/c. The TPC trigger rate from the collisions of 4 on 4 counter-rotating proton bunches was up to 10 Hz. Each of the bunches containing initially up to 10^{11} protons. The trigger included both empty events and beam-gas interaction. The events size was in average of the order of 170 kB owing to the excellent low noise behaviour of the TPC readout chain. The magnetic field was set to ±0.5 T and, for alignment purposes, to B=0 T. An online monitor plot of tracks of a central collision is shown in Fig. 8.
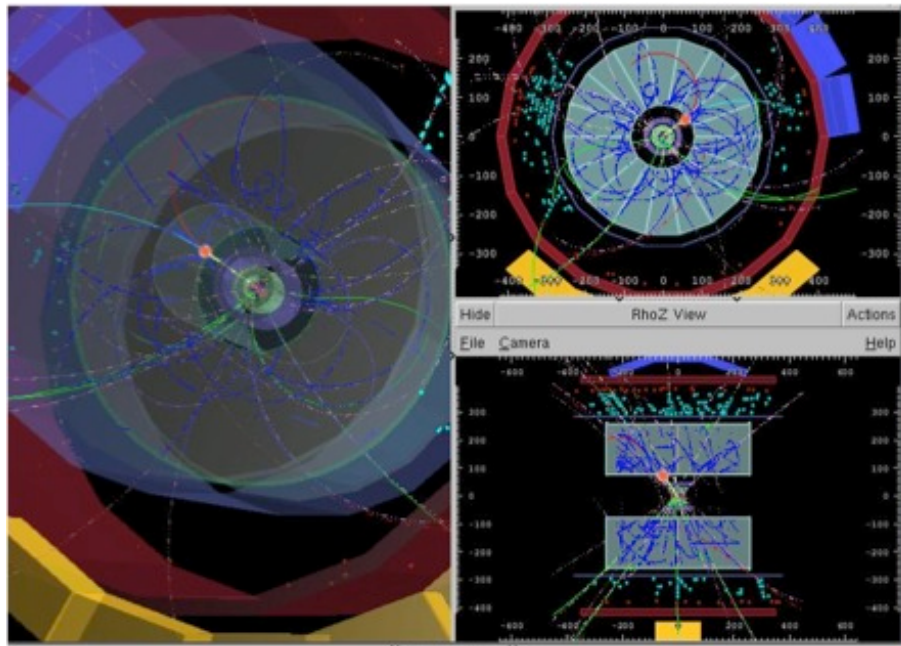

Figure 8. Online monitor picture of a central collision.

To ensure immediate feedback on the data quality and to optimize the calibration of the detector, the raw data of all events was immediately transferred to GSI. The events were directly reconstructed and analyzed using the entire GSI Tier 2 batch farm and High Performance Cluster where 2000 cores and 1 PB of storage on Lustre were available. Results on the detector performance were available within a few hours after the data had been recorded.

In parallel, calibration parameters were extracted. Several reconstruction passes with iteratively improved values were performed yielding continuously better results. All steps were automated as much as possible and all results were constantly communicated to the CERN detector control room. Thanks to the outstanding performance of the GSI computing infrastructure, the whole chain was running uninterrupted during the complete 2009 data taking period.

Fig. 9 shows a dE/dx vs. momentum spectrum from pp collision at 900 GeV/c employing the calibration data from the cosmic and krypton runs. As can be seen the excellent particle separation anticipated from the cosmic runs is also manifest in the collision data, e.g., by the π/μ-separation visible at low momentum.
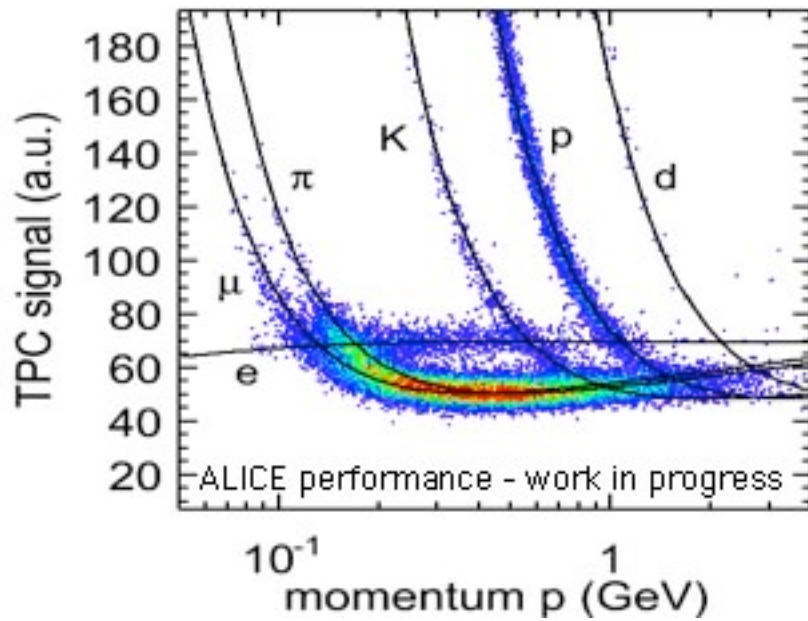
Figure 9. Particle identification the TPC.

This, together with precise tracking, readily allows reconstructing invariant mass spectra. As a further example of the TPC performance with data we show in Fig. 10 the K^0_s-invaiant mass plot from the $\pi^+\pi^-$ V0 decays vertices. The narrow width and the perfect agreement with the PDG mass should be taken as certification of the readiness of the TPC for the upcoming pp and PbPb runs in 2010.
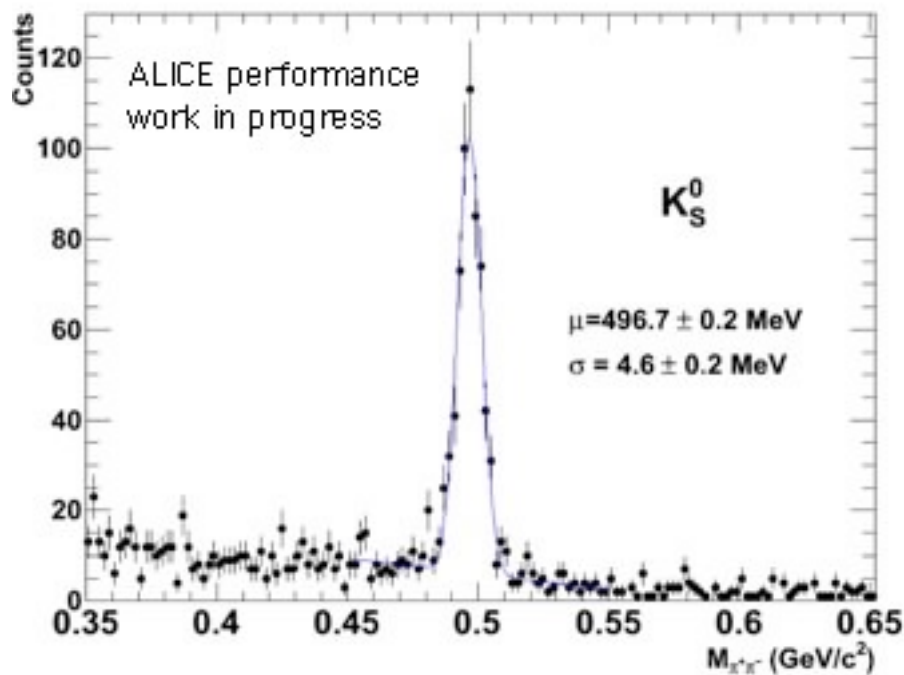

Figure 10. Reconstructed K^0_s from $\pi^+\pi^-$-V0 decays vertices.

6. Summary

From the very first ideas on an ALICE Time Projection Chamber as outlined in the Letter-of-Intent [13] in 1993 it took more then 15 years to develop, build, test and commission the detector. The very intense decade of R&D and testing of an exceptionally ambitious detector is now rewarded by the very successful operation both during the commissioning with cosmic rays as well as with the first pp collisions in Dec. 2009. The TPC fulfills the promised technical specifications and performance figures as outlined in the Technical Proposal [14] and the Physics Performance Reports [1].

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