Particle identification in ALICE: an extra boost in QGP studies

Christian Lippmann

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Under extreme conditions of temperature and/or density, hadronic matter "melts" into a plasma of free quarks and gluons, the so-called QGP. To create these conditions in the laboratory, heavy ions (e.g. Pb nuclei) can be accelerated and collided, as it has been done at the CERN Large Hadron Collider (LHC) for two dedicated periods in the years 2010 and 2011. A key design consideration of the ALICE experiment at the LHC is the ability to study QCD and quark (de)confinement under these extreme conditions. This is done by using as probes those particles that are created inside the hot volume as it expands and cools down. What is measured in the ALICE detector are those particles that live long enough to reach the sensitive detector layers which are situated at some distance around the interaction region. The physics program of ALICE relies on being able to identify all of them, i.e. to determine if they are electrons, photons, pions, etc. and to determine their charge. For this purpose one tries to take maximum advantage of the (sometimes slightly) different ways particles interact with matter. This article is giving an overview of the methods used for particle identification (PID). All existing methods are actually used in ALICE, where they are implemented employing partly new technologies that push the state of the art. These implementations are also described, however without intent to be exhaustive.

Penetrating muons

Muons may be identified by the fact that they are the only charged particles able to cross almost undisturbed any material. This behaviour is connected to the fact that muons with momenta below a few hundred GeV/c do not suffer from radiative energy losses and thus do not produce electromagnetic showers. And because they are leptons, they are not subject to strong interactions with the nuclei of the material they pass through. This behavior is in general explored in any muon spectrometer installed in high energy physics experiments by installing muon detectors behind the calorimeter systems or thick absorber materials. All particles but muons are completely stopped, which produces electromagnetic (and hadronic) showers. The muon spectrometer in the forward region of ALICE features a very thick and complex front absorber and an additional muon filter (a 1.2 m thick iron wall). Muon candidates selected from tracks penetrating these absorbers are then measured precisely in a dedicated set of tracking detectors.

Pairs of muons are used to collect the spectrum of heavy quark vector meson resonances ($J/\Psi, \ldots$) from which they originate. The production rates can be analysed as a function of transverse momentum and collision centrality in order to investigate dissociation due to colour screening. In addition, muons from the semi-leptonic decay of open charm and open beauty can also be studied with the muon spectrometer.

Weighing particles

Hadron identification can be crucial for heavy-ion physics. Example are open charm and open beauty, which allow to investigate the mechanisms for the production, propagation and hadronization of heavy quarks in the hot and dense medium produced in the heavy-ion collisions. The most promising channel is the process $D^0 \rightarrow K^-\pi^+$, which requires a very efficient hadron identification due to its small signal-to-background ratio.

Charged hadrons (actually all stable charged particles) are unambiguously identified if their mass and charge are determined. The mass can be deduced from measurements of the momentum and of the velocity. Momentum as well as the charge sign are obtained by measuring the curvature of the particle's track in a magnetic field. To obtain the particle velocity there exist four methods: time-of-flight and ionization measurements, detection of transition radiation and Cherenkov radiation imaging. Each of these methods works well in different momentum ranges or for specific particle types. They are thus combined in ALICE in order to measure for example particle spectra. An example can be seen in Fig. 1, which shows the abundance of pions in Pb-Pb collisions as a function of transverse momentum and collision centrality.

Kicking electrons from atoms

The characteristics of the ionization process due to fast charged particles passing through a medium can be used for particle identification. The velocity dependence of the ionization strength is connected to the well-known *Bethe-Bloch* formula, which describes the average energy loss of charged particles due to inelastic Coulomb collisions with the atomic electrons of the medium. Multi Wire Proportional Counters (MWPCs) or solid state counters may be used. They provide signals with pulse height proportional to the ionization strength. Since energy loss fluctuations can be considerable, in general many pulse height measurements are performed along the particle track in order to optimize the resolution of the ionization measurement.

In ALICE this technique is used for particle identification in the large Time Projection Chamber (TPC), but also in four layers of the silicon Inner Tracking System (ITS). A TPC is a large volume filled with a gas as detection medium. Almost all of this volume is sensitive to the traversing charged particles, but it features a minimum material budget. The straightforward pattern recognition (continuous tracks) make TPCs the perfect choice for high multiplicity environments like heavy-ion collisions, where thousands of particles have to be tracked simultaneously. Inside the ALICE TPC, the ionization strength of all tracks is sampled up to 159 times, which results in a resolution of the measurement as good as 5%. In Fig. 2 the TPC ionization signal is shown as a function of the particle rigidity (momentum divided by charge) for negative particles. It shows the different characteristic bands for various particles. A particle can be identified when the corresponding point in the diagram can be associated with only one such band within the measurement errors. The method works very well, in particular for low momenta up to several hundred MeV/c.

Using a stop watch

Time-of-flight (TOF) measurements yield the velocity of a charged particle by measuring the flight time over a given distance along the track trajectory. Provided that also the momentum is known, one can derive the mass of the particle from these measurements. The ALICE TOF detector is a large area detector based on Multi-gap Resistive Plate Chambers (MRPCs), covering a cylindrical surface of 141 m^2 with an inner radius of 3.7 m. MRPCs are parallel plate detectors built of thin sheets of standard window glass creating thin gas gaps with high electric fields. The plates are separated using fishing lines to create the desired spacing; ten gas gaps per MRPC are needed to arrive at a detection efficiency close to 100 %. The simplicity of the construction permits to build a large system with an overall TOF resolution of 80 ps at a relatively low cost. This performance allows the separation of kaons, pions and protons up to momenta of a few GeV/c. Combining such a measurement with the PID information from the ALICE TPC has shown to be very useful to improve the separation between the different particle types. This is shown exemplary in Fig. 3 for a given momentum range.

Detecting additional photons

The identification of electrons and positrons in ALICE is achieved using a Transition Radiation Detector (TRD). In a similar manner as the muon spectrometer this system enables detailed studies of the production of vector-meson resonances, but with extended coverage down to the light vector meson ρ and in a different rapidity region. Below 1 GeV/c electrons can be identified via a combination of PID measurements in the ALICE TPC and TOF. Above 1 GeV/c the fact that electrons may create transition radiation (TR) when passing a dedicated radiator can be exploited. Inside the radiator fast charged particles may emit Transition Radiation (TR) photons when crossing boundaries between materials with different dielectric constants. In the momentum range from 1 to 10 GeV/c only electrons reach the necessary velocities. The effect is tiny, and the radiator has to provide many hundred material boundaries in order to achieve a sufficient probability to produce at least one photon. TR photons have energies in the X-ray range and are detected in MWPCs filled with a Xenon-based gas mixture and placed just behind the radiator. The TR photons deposit their energy on top of the ionization signals from the charged particle track.

The ALICE TRD was designed to derive a fast trigger for charged particles with high momentum and can significantly enhance the recorded vector meson yields. For this purpose $1/4$ million CPUs are installed right on the detector in order to identify high momentum track candidates and analyse the energy deposition associated with them as fast as possible (while the signals are still being created in the detector). This information is sent to a Global Tracking Unit, which combines all information to search for electron-positron track pairs within only 6 μs.

Measuring an angle

Cherenkov radiation is a shock wave resulting from charged particles moving through a material faster than the velocity of light in that material. The Cherenkov radiation propagates with a characteristic angle with respect to the particle track, which depends on the particle velocity. Cherenkov detectors make use of this effect and in general consist of two main elements: a radiator in which Cherenkov radiation is produced and a photon detector. *Ring Imaging Cherenkov* (RICH) detectors resolve the ring shaped image of the focused Cherenkov radiation which enables a measurement of the Cherenkov angle and thus the particle velocity. This in turn is enough to determine the mass of the charged particle.

If a dense medium (large refractive index) is used, only a thin radiator layer of the order of a few centimeters is required to emit a sufficient number of Cherenkov photons. The photon detector is then located at some distance (usually about 10 cm) behind the radiator, allowing the light cone to expand and form the characteristic ring-shaped image. Such a *proximity-focusing* RICH is installed in the ALICE experiment. The High-Momentum Particle IDentificaton (HMPID) is a single-arm array that has a reduced geometrical acceptance. Similar to the ALICE TOF it is able to identify the individual charged hadrons up to momenta of a few GeV/c, but with slightly higher precision.

Other pieces to the puzzle

The ALICE detector contains more components which can be used to identify particles. A high-resolution electromagnetic calorimeter (PHOS) covering a limited acceptance domain at central rapidity provides data to test the thermal and dynamical properties of the initial phase of the collision by measuring direct photons emerging from the collision. Finally, a pre-shower detector (PMD) studies the multiplicity and spatial distribution of such photons in the forward pseudo-rapidity region. Each of the described methods provides a different piece of information. However, only by combining them in the analysis of the data produced by ALICE, the particles produced in the collisions can be measured in the most complete way possible.

Further reading

The ALICE Collaboration, *The ALICE experiment at the CERN LHC*, JINST 3, S08002 (2008).

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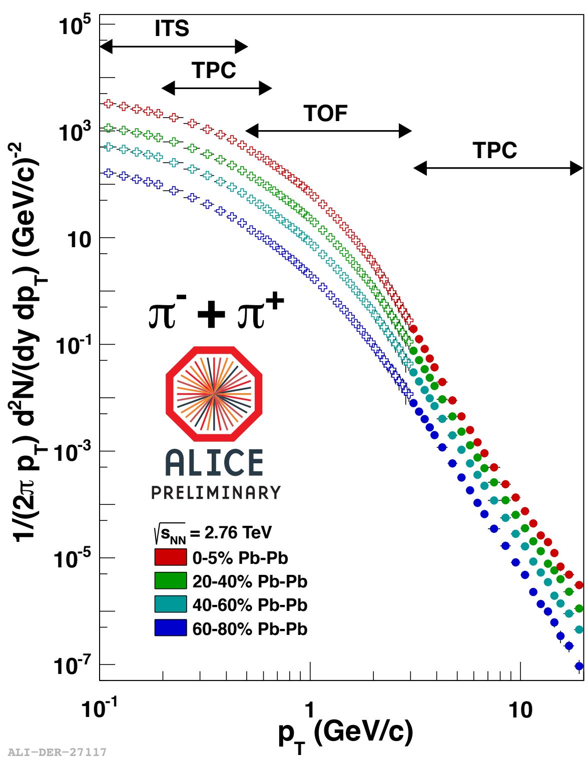

Figure 1: Pion yield from Pb-Pb collisions at center of mass energy $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ for different collision centralities (0-5% corresponds to the most central) measured in ALICE. To cover the whole momentum range the data from different ALICE subdetectors are combined, in this plot ionization measurements (ITS and TPC) and time-of flight measurements (TOF). The collaboration is currently working on including also data from the ALICE RICH detector (HMPID) for this years Quark Matter conference.

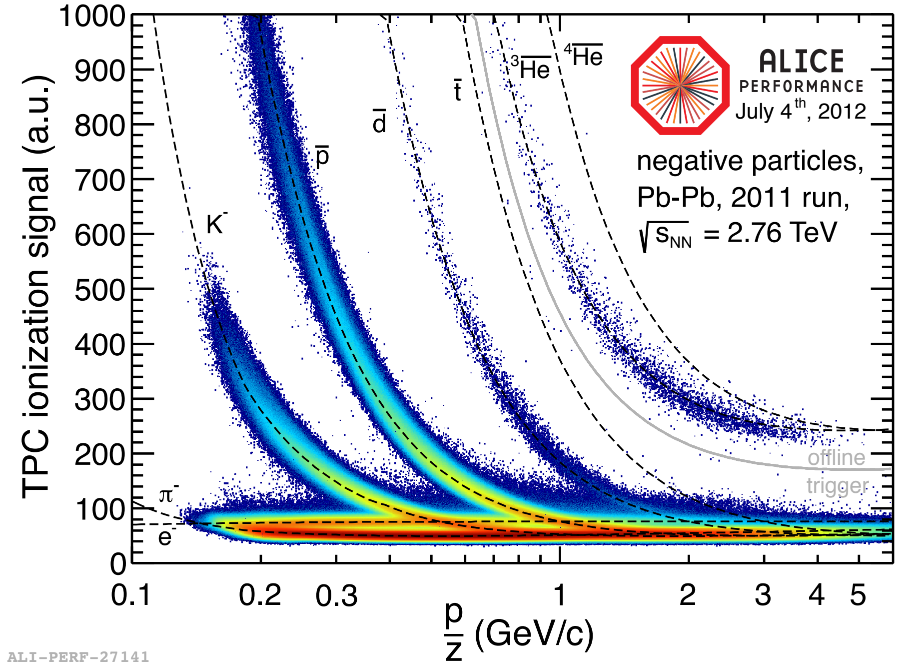

Figure 2: Measured ionization signals in the ALICE TPC as a function of the particle momentum for Pb-Pb collisions at center of mass energy $\sqrt{s_{NN}} = 2.76$ TeV. An offline trigger was applied in order to enhance track samples with charges $z < -1$. The charged (anti-)hadrons are well separated, in particular at low momentum. Electrons, anti-deuterons, anti-tritons and anti-^{3}He nuclei are visible as well. The dashed lines are parameterizations of the Bethe-Bloch curve.

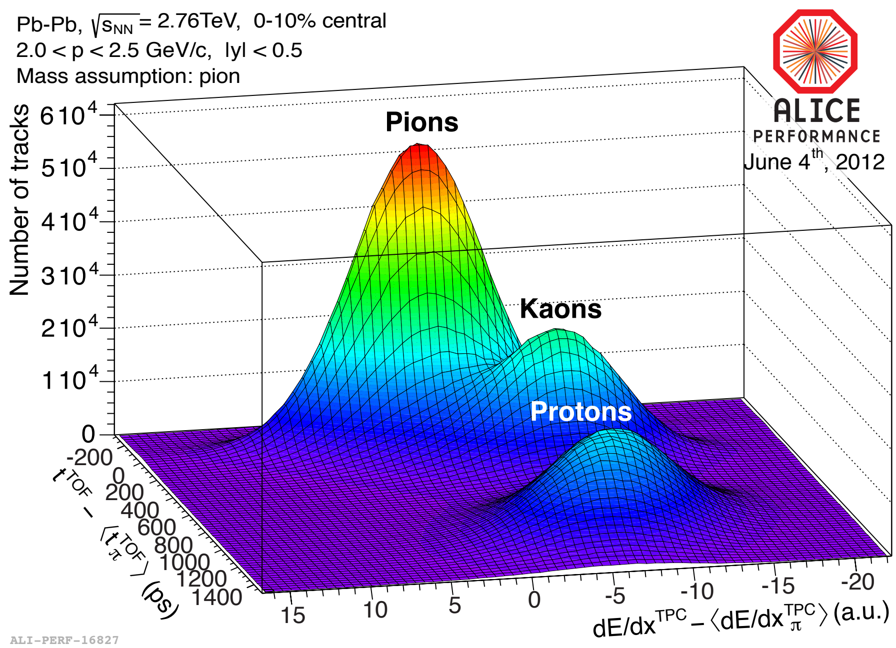

Figure 3: In ALICE different particle identification measurements may be combined in order to achieve better separation of the different particle species. The plot shows exemplary for a certain momentum window a combination of time-of-flight measurements in the ALICE TOF detector with ionization measurements ($\mathrm{d}E/\mathrm{d}x$) in the ALICE TPC.