LATEST RESULTS FROM ALICE

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Abstract

In this paper selected results obtained by the ALICE experiment at the LHC will be presented. Data collected during the pp runs taken at $\sqrt{s}=0.9$, 2.76 and 7 TeV and Pb-Pb runs at $\sqrt{s_{NN}}=2.76$ TeV allowed interesting studies on the properties of the hadronic and nuclear matter: proton runs gave us the possibility to explore the ordinary matter at very high energy and up to very low $p_t$, while Pb-Pb runs provided spectacular events where several thousands of particles produced in the interaction revealed how a very dense medium behaves, providing a deeper picture on the quark gluon plasma (QGP) chemical composition and dynamics.

1. Detector description

The most important requirements for a general purpose heavy ion experiment at the LHC are a powerful particle identification over a wide momentum interval, a robust tracking capability in a very high multiplicity environment and a very low cut in transverse momentum $p_t$. The ALICE detector matches these needs using several detectors, and implementing almost all the known particle identification (PID) techniques. A robust tracking and the vertex finding are provided by the Internal Tracking System (ITS), made by three different silicon based detectors, followed by a large volume TPC [1]. As fas as the PID is concerned, each detector covers a different range of momentum: $dE/dx$ vs $p_t$ is provided by ITS and by TPC, particle masses difference, reflecting in a different time of flight and Cherenkov angle, is measured by the Time Of Flight (TOF) and by the High Momentum Particle Identification System (HMPID). Electrons are tagged by the Transition Radiation Detector (TRD), $\gamma$-rays by the Photon...
Spectrometer (PHOS), electromagnetic shower by the EMCAL, while muons from the forward muon arm. The barrel, immersed in a 0.5 T solenoidal magnetic field, is made of several detectors: the Silicon Pixel Detector (SPD), the closest to the interaction point (IP), is followed by the Silicon Drift Detector (SDD) and by the Silicon Strip Detector (SSD). These dominate the vertex resolution, ranging from 250 $\mu$m ($p_t = 0.2$ GeV/c) to 20 $\mu$m ($p_t = 10$ GeV/c). Placed at a radius ranging from 0.85 to 2.5 m, the large TPC, consists of two 2.5 m long drift volume ($\simeq 88 m^3$), separated by a central cathode. The large number of samples allows the TPC to measure the track $dE/dx$ with a 5% error. The TOF is a high segmentation MRPC detector ($\simeq 150,000$ channels) with an excellent time resolution, better than 100 ps, placed over the full azimuthal angle and $|\eta|<0.9$. It provides a $3\sigma$ discrimination for $\pi/K$ and $K/p$ up to 2.5 GeV/c and 4 GeV/c respectively. The goal of the TRD detector, made of a radiator and a drift chamber operated with Xe/CO$_2$ mixture (85%/15%), is the tagging of the electrons. The PHOS, the EMCAL and the HMPID are additional detectors with partial coverage of the central barrel. The largest detector in the forward region is the “muon arm”, consisting of an hadron absorber, MWPC chambers, a 0.7 T dipole followed by RPCs to tag muons and to and measure their $p_t$. Several small and important detectors run in the forward and backward region and close to the beam pipe: T0, V0, Photon Multiplicity Detector (PMD).
and the Forward Multiplicity Detector (FMD). Spectator protons and neutrons are detected by the Zero Degree Calorimeters (ZDC), consisting of two sets of calorimeters placed at ± ±116 m from the IP. More information on detector design and performance can be found in [1].

2. Results from Proton-Proton collisions

One of the initial ALICE goals in the pp run is the fine tuning of the detector Monte Carlo simulation. Although a first successful commissioning was performed with cosmic ray data, hadronic collisions offered the possibility to make a step forward in the detector understanding and Monte Carlo modelling. As an example photon tagging allowed a measurement of the material budget radial distribution. This gave the possibility to improve the detector knowledge and to obtain a much better detector simulation, where the $\gamma$ yield as a function of the distance from the IP nicely agree in the data and in the MC. Proton runs are a rich source of physics, where ALICE exploits its peculiarity, making use of the low momentum cut.

- Multiplicity studies

Multiplicity studies provide informations on the energy density of the interaction and is one of the primary information needed to test Monte Carlo simulation. Moreover this is a basic variable, so that a quick comparison between the four LHC experiment is made available. ALICE measured the charged particle multiplicity per pseudorapidity interval $dN/d\eta_{ch}$ at $\sqrt{s}=0.9$, 2.36 and 7 TeV, with the average charged particle multiplicity per unit of rapidity ranging from $(3.81 \pm 0.01 \text{ (stat)} \pm 0.07 \text{ (sys)})$ to $(6.01 \pm 0.01 \text{ (stat)} + 0.20,-0.12 \text{ (sys)})$. While data agree nicely with the other LHC detectors, none of the investigated models (Pythia, Phojet) and their tunes describe the average multiplicity and the multiplicity distribution well. At $\sqrt{s}=0.9$ and 2.36 TeV, the Pythia tunes Perugia-0 and D6T fail in reproducing the average multiplicity, while Phojet does not reproduce data at $\sqrt{s}=7$ TeV and is far away from describing the increase in multiplicity from $\sqrt{s}=0.9$ TeV to $\sqrt{s}=2.36$ TeV and from $\sqrt{s}=2.36$ TeV to $\sqrt{s}=7$ TeV. At 0.9 TeV, the high-multiplicity tail of the distributions is best described by the Phojet model, while at 2.36 TeV,
Pythia tune ATLAS-CSC is the closest to the data.

The situation does not improve when considering the particle $p_t$ prediction: the transverse momentum distribution at 900 GeV and the dependence of average $p_t$ on $N_{ch}$ is not reproduced by the ATLAS-CSC Pythia tune \[10\]. At present we do not have an event generator/tune that can reproduce the LHC data in a satisfactory way.

- **Strange baryons**
  
  The yields and $p_t$ spectra of identified charged particle ($\pi$, K, p) and neutral strange particles ($K^0$, $\Phi$, $\Lambda$, $\Xi$) have been measured at $\sqrt{s}=0.9$ and 7 TeV. While the $\phi$ is properly reproduced by Pythia (especially by the D6T tune), the $K^0$ transverse momentum spectrum is overestimated by the Pythia tune ATLAS-CSC and Phojet below 0.75 GeV/$c$ but is lower by a factor of $\approx 2$ in the $p_t$ range 1-3 GeV/$c$. As far as strange baryons is concerned, Phojet and Pythia tunes are well below the data by a factor ranging from 3 to 10, depending on the baryon and on the particle $p_t$. Moreover data taken at $\sqrt{s}=7$ TeV shows the ratio $\Omega/\Xi$ is underestimated by Pythia of a factor up to 6. From an experimental point of view it’s worth noting the ratio of $\Lambda/K^0$ agrees very well with the STAR data taken at $\sqrt{s}=200$ GeV and the ratio $\Xi/\Lambda$ is within the error.

- **$J/\psi$ study**
  
  $J/\psi$ study has been one of the most compelling evidence for quark gluon plasma formation more than two decades ago. The study of this vector meson suppression at higher energy allows a big step in the understanding of the color field mechanisms at work in this new state of the matter. Proton-proton runs offer the possibility to test the detector performance in $J/\psi$ detection and a reference data for Pb-Pb analysis. ALICE can detect the $J/\psi \rightarrow \mu^+\mu^-$ channel taking advantage of the forward muon arm detector ($2.5 < y < 4$) and the $J/\psi \rightarrow e^+e^-$ channel by using the barrel detectors ($|\eta| < 0.9$). ALICE measurement at central rapidity reaches $p_t = 0$ and is therefore complementary to the CMS data, available at $|y| < 1.2$ for $p_t > 6.5$ GeV/$c$, and ATLAS, which covers the region $|y|<0.75$ and $p_t > 7$ GeV/$c$. At $\sqrt{s}=7$ TeV the ALICE measured cross section is \[2\]:

$$\sigma_{J/\psi}(|y| < 0.9) = 10.7 \pm 1.2(\text{sta.}) \pm 1.7(\text{sys.}) + 1.6(\lambda = 1) - 2.3(\lambda = -1) \mu b \quad (1)$$
\[ \sigma_{J/\psi}(2.5 < y < 4) = 6.31 \pm 0.25(\text{sta.}) \pm 0.80(\text{sys.}) + 
+ 0.95(\lambda = 1) - 1.96(\lambda = -1) \mu b, \] (2)

where \( \lambda = 1 \) is for fully transverse and \( \lambda = -1 \) for longitudinal polarization. The \( J/\psi \) decaying into muons are compared to those detected by LHCb at \( 2.5 < y < 4 \), finding a good agreement. In the barrel region the CMS data (\( |y| < 2 \)) and ATLAS (\( |y| < 0.9 \)) can be compared with those detected by ALICE only for \( p_t > 7 \) GeV. It is worth noting these results refer to inclusive production, therefore the measured yield is a superposition of a direct component and of \( J/\psi \) coming from the radiative decay of higher-mass charmonium states.

3. Results from Pb-Pb collisions

Data collected during the 2010 gave a first look at the hot and dense medium formed at \( \sqrt{s_{NN}} = 2.76 \) TeV when Pb-Pb ions collide.

- Energy density

The energy density available in the Pb-Pb interactions is much larger with respect to the p-p one, resulting in a very high number of particle produced. At \( \sqrt{s_{NN}} = 2.76 \) TeV and for central collisions, ALICE measured an average density of primary charged particles at midrapidity \(<N_{ch}> = (1584 \pm 4(\text{stat}) \pm 76(\text{sys}))\). Normalizing per participant pair, we obtain \( dN_{ch}/d\eta/(0.5N_{\text{part}}) = (8.3 \pm 0.4(\text{sys})) \), about a factor 2 higher with respect to RHIC. This is larger than most of the predictions and about 50% more than expected from simple phenomenological extrapolations from RHIC energy: the logarithmic law that described the multiplicity dependence with energy, does not hold anymore. Following the Bjorken approach the average energy density has been derived. The average amount of transverse energy produced per unit of pseudorapidity per participant pair in central collisions is about 9 GeV, a factor \( \approx 3 \) larger than at RHIC (the larger multiplicity at LHC being accompanied by an increase in the average transverse momentum of the produced particles), corresponding to an energy density of about 15 GeV/fm\(^3\). The centrality dependence of the charged particle multiplicity is rather mild, favouring models incorporating some mechanism (such as parton saturation) moderating the increase with centrality of the average multiplicity per participant pair.
The partons generated by a ion-ion collision at high energy, experience high energy loss collisions in the hot dense medium, showing a high opacity to their traveling inside. The depletion in the hadron yield is a powerful probe to investigate this effect. The nuclear modification factor $R_{AA}$ is defined as the ratio of the charged particle yield in Pb-Pb to that in pp, scaled by the number of binary nucleon-nucleon collisions $N_{coll}$. ALICE measured the nuclear modification factor $R_{AA}$ of inclusive charged particle momentum distributions out to $p_t=20$ GeV/c, where the spectra are dominated by leading jet fragments. ALICE performed a first analysis where the prediction at $\sqrt{s}=2.76$ TeV was extrapolated from the data collected at $\sqrt{s}=0.9$ and 7 TeV. The analysis was improved after data at $\sqrt{s}=2.76$ TeV where taken. The two analysis agree quite well within the systematic error and show the $R_{AA}$ ratio has a minimum at around 6 GeV, where the suppression is stronger than at RHIC ($\sqrt{s_{NN}}=0.2$ TeV), and then rises smoothly towards higher momentum. This latter feature is not evident has not been seen in the published RHIC data. However, initial state effects (shadowing/saturation), which presumably are very strong at LHC and which might depend on both impact parameter and momentum transfer, can complicate a straight forward interpretation of the data and the comparison between different beam energies. The powerful ALICE PID allows the study of $R_{AA}$ for different hadrons separately. $R_{AA}$ looks almost universal for $p_t>6$ GeV/c; at low $p_t$ the $\Lambda$ baryon don’t show any nuclear modification factor ($R_{AA} \approx 1$ ) while K behaves like all the other hadrons. It is worth noting D mesons are expected to show a smaller nuclear modification factor, since the main source of energy loss (gluon radiation) is depleted by the Casimir effect for heavy quark. This is found, although with a still high statistical error, in the data where a larger $R_{AA}$ is found for $D^0, D^+$ in the interval $4$ GeV/c$\leq p_t \leq 5$ GeV/c.

**Elliptic flow**

The elliptic flow represents a powerful test to investigate the hydrodynamical properties of the quark gluon plasma. A perfect fluid shows a very small viscosity: this can be studied by looking at the efficiency in transferring the geometrical collision system anisotropy into momentum anisotropy. The distribution of the azimuthal angle, measured with respect to the reaction plane, is expanded into Fourier terms,
where the second coefficient is the so called “elliptic flow”, $v_2$. The large elliptic flow observed at RHIC, is described reasonably well by theoretical models based on relativistic hydrodynamics with a QGP equation of state and a ratio of the shear viscosity to the entropy density within a factor of $\simeq 5$ by the supposed universal lower bound of $1/4 \pi$. This indicates the QGP expands as a nearly perfect fluid. The first ALICE results [4] shows the elliptic flow at $\sqrt{s_{NN}} = 2.76$ TeV is $\simeq 30\%$ larger with respect to RHIC. Nevertheless the $v_2$ as a function of $p_t$ is close to the RHIC measurement, showing the system hydrodynamic properties at RHIC and LHC are similar. The increase of the elliptic flow observed at LHC therefore comes from the increase of the average $p_t$. An important difference with respect to RHIC results is the elliptic flow study for different hadrons separately. While at RHIC the $v_2/n_q$, where $n_q$ is the number of hadron valence quark, is similar for pion, kaons and protons, at LHC just pion and kaons $v_2/n_q$ is compatible; protons have a lower $v_2/n_q$, showing the quark scaling does not hold for $p_t < 0.5$ GeV/$c$.

- **J/$\psi$ suppression**

$J/\psi$ measurement is one of the key measurement for a high energy heavy ion experiment. For $p_t>0$ and $2.5<y<4$, ALICE tags the $J/\psi$ through the $J/\psi \to \mu^+ \mu^-$ channel. A rather small $J/\psi$ suppression
of about 0.5 was observed, practically independent of centrality: this is a smaller suppression than that observed at RHIC. An interesting result is the comparison with ATLAS, where data are taken only at $p_t > 6.5 \text{ GeV}/c$, shows a much stronger centrality dependence and suppression, hinting for a $p_t$ dependence of the $J/\psi$ suppression. The measurement of the $J/\psi$ in the $J/\psi \rightarrow e^+e^-$ channel is challenging with the present statistics and large hadronic background. However the signal has been extracted in the centrality class 0-40% and the central to peripheral (40-80%) ratio ($R_{CP}$) has been evaluated. Within the large systematic uncertainties, the dielectron $R_{CP}$ is compatible with ATLAS and ALICE di-muon $R_{CP}$ measurements.

The above results hint at $J/\psi$ regeneration in hot matter at LHC energies, but it is worth noting the $J/\psi$ production can be modified by the initial state effect which could modify the medium: ALICE needs a p-Pb run as reference to disentangle the contributions from cold nuclear matter.

References

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