Will ALICE run in the HL-LHC era?

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Abstract

We will present the perspectives for ion running in the HL-LHC era. In particular, ALICE is preparing a significant upgrade of its rate capabilities and is further extending its particle identification potential. This paves the way for heavy ion physics at unprecedented luminosities, which are expected in the HL-LHC era with the heaviest ions. Here, we outline a scenario, in which ALICE will be taking data at a luminosity of $\mathcal{L} > 6 \times 10^{27}$ cm^{-2}s^{-1} for Pb–Pb with the aim to collect of the order of at least 10 nb^{-1}. The potential interest of data-taking during high luminosity proton runs for ATLAS and CMS will also be commented.

CONSIDERATIONS FOR A HIGH RATE UPGRADE OF ALICE

The ALICE Experiment has been specifically conceived to study the properties of the Quark-Gluon-Plasma (QGP), the state of deconfined matter which prevailed in the universe following the electroweak phase transition until microseconds after the Big Bang. A precise determination of its properties like the critical temperature, the relevant degrees of freedom, the speed of sound, and, in general, transport coefficients of the various partons would be a major achievement towards a better understanding of QCD as a genuine multi-particle theory. With the established long lifetime and large system size in heavy ion collisions at the LHC [2] precision measurements linked to such complex issues as deconfinement and chiral symmetry restoration become feasible. The guiding principles for the upgrade plans have been spelled out in [1] and will in part be repeated here.

Future detailed studies of the QGP comprise:

- thermalization of partons in the QGP, with a focus on the massive charm and beauty quarks. Heavy-quark elliptic flow is especially sensitive to the partonic equation of state. Ultimately, heavy quarks might fully equilibrate and become part of the strongly-coupled medium.

- low-momentum quarkonium dissociation and, possibly, regeneration pattern, as a probe of deconfinement and of the medium temperature.

- production of thermal photons and low-mass dileptons emitted by the QGP to assess the initial temperature and degrees of freedom of the system, as well as to shed light on the chiral nature of the phase transition.

- in-medium parton energy loss mechanism, that provides both a testing ground for the multi-particle aspects of QCD and a probe of the QGP density. The relevant observables are: jet structure, jet–jet and photon–jet correlations, jets and correlations with high-momentum identified hadrons and heavy-flavor particle production. In particular, it is crucial to characterize the dependence of energy loss on the parton species, mass, and energy.

- systematic studies of very rare particle production such as anti-nuclei, the lightest multi-Λ hyper-nuclei such as ${}^{5}_{\Lambda\Lambda}$H [3] and objects like the bound states of $(\Lambda\Lambda)$ or the predicted H di-baryon, a possible (Λn) bound state as well as bound states involving multi-strange baryons.

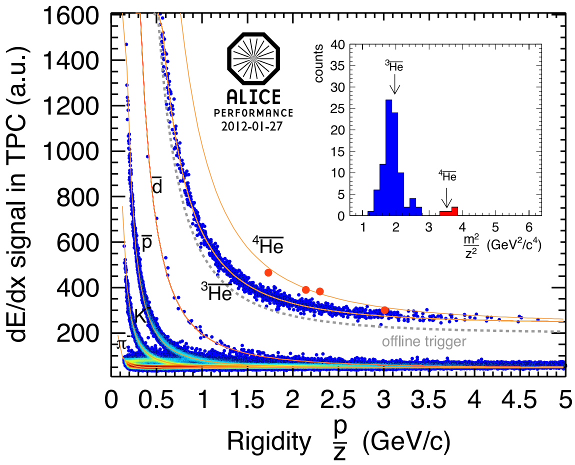

Figure 1: Particle identification for negatively charged particles. Shown in red are, in particular, Anti-^{4}He candidates identified via TPC dE/dx measurements in the full 2010 Pb–Pb statistics. The mass distribution of the candidates shown in the insert has been independently determined using the Time-of-Flight system.

For many of the above topics very high statistics is needed to achieve any level of precision. This is driven by the fact that progress is made, when the observables can be studied in an as differential as possible manner. This entails the selection of parameters such as collision centrality, transverse momentum $p_{\rm T}$, event-plane orientation, flavor dependence, or local particle density. When it comes to low-mass di-lepton pairs or low $p_{\rm T}$ phenomena in the charm and beauty sector, unfortunately triggers are of limited use and one is thus left with the necessity to inspect every single collision.This implies shipping all

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data to the online systems either continuously or upon a minimum-bias trigger. Full online calibration, event reconstruction and event data reduction will allow writing to tape a large fraction of the events, which will be selected on the basis of topological and PID criteria, one of the unique strengths of ALICE. The upgrade will allow operating the central barrel and the muon arm at 50 kHz in Pb-Pb collisions. It has been assumed that, with the HL-LHC upgrade it will be possible to achieve luminosities of the order of at least $\mathcal{L} = 6 \times 10^{27}$ cm^{-2}s^{-1} with Pb–beams. Under those conditions the target will be to collect of the order of 10 nb^{-1}. Along with the upgrade for higher rate capability also the particle identification capabilities, exemplarily shown in Figure 1, shall be further extended, both in the central barrel and for selected physics topics at large rapidity.

CURRENT LIMITATIONS OF THE ALICE EXPERIMENT

ALICE data taking is currently limited by the fixed deadtime of 1 ms of the Si-Drift detectors. The readout bandwidth of the front-end electronics is limited to 520 Hz in minimum bias collisions. Furthermore, the gating grid of the TPC cannot be opened at rates exceeding 3.5 kHz, while the detector itself can cope with the expected interaction rate of 10 kHz in Pb-Pb collisions at full LHC energy. This is in line with the ALICE program, which is detailed below. For the coming five years it is based on the expectation that, after the first two Pb–Pb runs of 2010 and 2011, with integrated luminosities of $\approx 10\ \mu$b^{-1} and $\approx 100\ \mu$b^{-1}, respectively. Following LS 1 there will be several Pb–Pb runs at full energy, where a few hundred μb^{-1} each will be collected.

This will ensure that, by 2017 ALICE will have data at a level of ≈ 1 nb^{-1}, which is the target integrated luminosity for which ALICE has been approved.

UPGRADE CONCEPT FOR ALICE AT HIGH RATE

In order to enhance the particle identification techniques and to render ALICE fit for the anticipated interaction rates the collaboration has endorsed the plan to replace a) the beam pipe by one with a smaller radius (r=19.8 mm), b) to rebuild the Inner Tracking System both to enhance the scope for particle identification and cope with the much higher rates, c) to upgrade the central barrel and muon arm detector electronics to cope with the rate and to look into operating the TPC in a continuous readout mode. This goes in hand with a major overhaul of the DAQ and Trigger System. Furthermore, three new detectors are under consideration to address specific physics issues: a) a Very High Momentum Particle Identification RICH detector (VHMPID) providing Kaon-proton separation out to 20 GeV/c, a Muon Forward Tracker (MFT) to facilitate b-tagging and low-mass di-muon measurements, and a Forward Calorimeter (FoCal) for small-x physics with identified γ and π^0.

HEAVY QUARK MEASUREMENTS

For the sake of this paper, we limit ourselves to the anticipated improvement for one of the many observables listed above: heavy quark production.

Given the smaller color coupling of quarks with respect to gluons, their energy loss is expected to be smaller than that of gluons. In addition, the *dead-cone effect* should reduce small-angle gluon radiation for heavy quarks with moderate energy-over-mass values. Given the properties of parton-energy loss, in the range $p_{\mathrm{t}} < 10$ GeV/c where heavy-quark masses are not negligible with respect to their momenta, an increase of the R_{AA} value (i.e. a smaller suppression) is expected when going from the mostly gluon-originated light-flavor hadrons (e.g. pions) to D and B mesons. Precision measurements and comparison of these different medium probes would provide a unique test of the color-charge and mass dependence of parton energy loss.

Using the vertexing of the current ALICE ITS system as well as the measurements from TPC and TOF, we have reconstructed for the first time D-mesons in central Pb–Pb collisions down to transverse momentum as low as 2 GeV/c. The corresponding nuclear modification factor is shown in Fig. 2. The results are remarkable: the nuclear modification factor for D-mesons is close to that measured for unidentified hadrons. This clearly implies significant energy loss of charm quarks in the dense medium of the fireball. Note also the low-p_{t} coverage of ALICE compared to what is measured by CMS. For a quantitative understanding shadowing effects need also to be taken into account. First results on this front are expected from a p–Pb run in 2012 at the LHC.

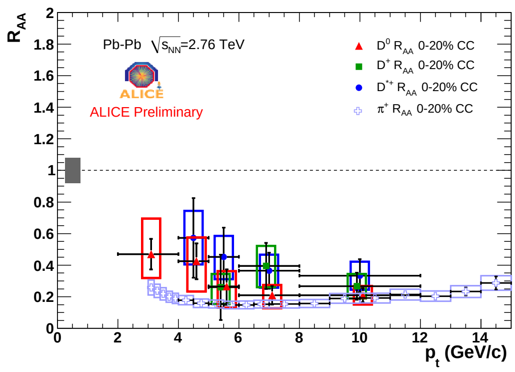

Figure 2: Comparison of the suppression of high transverse momentum D mesons and pions in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$TeV

Since charm quarks do not disappear from the fireball (annihilation is expected to be very small [4]), this implies that the majority of charm quarks will be shifted to very low transverse momenta, where the corresponding R_{AA} (in the absence of strong shadowing) should reach or exceed unity. Those charm quarks will then carry momenta in the thermal region and will provide stringent tests of models of the bulk medium, as their large mass and small cross sections make them more sensitive to details of equilibration. Much better low-transverse-momentum coverage and much improved statistics is evidently needed to make these measurements precise enough for quantitative comparisons to predictions from theoretical models, in particular for the rarely produced charmed baryons. A detailed discussion of the integrated luminosity needed can be found in the following paragraph. Effects of the QGP on charm and beauty quarks will manifest themselves if one can simultaneously cover both low and intermediate transverse momenta in the charm and beauty sector.

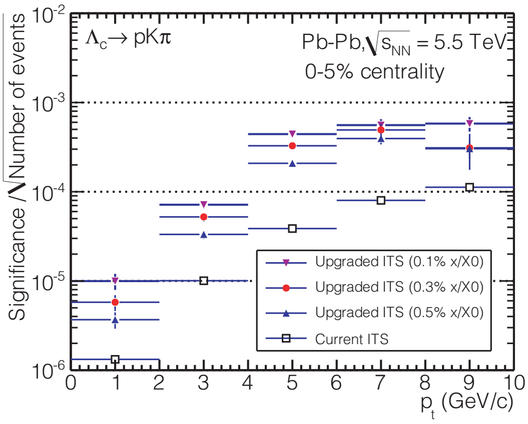

Figure 4: $\Lambda_c \rightarrow pK^-\pi^+$ in central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV: significance per event for the current and upgraded ITS. For the upgrade, three different scenarios are considered: the baseline configuration is labeled "0.3%"; the cases labeled "0.1%" and "0.5%" represent variations of the layer thickness only (with respect to the baseline configuration), for the innermost two layers to 0.1% of radiation length and for all layers to 0.5% of radiation length, respectively.

It is still an open question to what extent heavy quarks participate in the collective expansion of the medium. Heavy-quark elliptic flow (v_2) is especially sensitive to the partonic equation of state, since the experimentally observed hadron mass dependence of elliptic flow parameters gets more pronounced with increasing mass. In particular, the measurement of charm-quark triangular flow (v_3) is of utmost interest due to its sensitivity to the viscosity-to-entropy-density ratio [5]. Ultimately, heavy quarks might fully (kinetically) equilibrate and become part of the strongly coupled medium. Precision measurements of flow parameters for mesons and baryons containing heavy quarks will need much improved tracking efficiency at low transverse momenta and a Pb–Pb integrated luminosity of several nb^{-1}. As an example we expect, for 1 nb^{-1} integrated luminosity to measure Λ_c baryons with a significance of about 3 in the $p_{\rm t}$ range $2 < p_{\rm t} < 4$ GeV/c as shown in Figure 4. These estimates are based on the analysis performed in [6]. For a detailed flow analysis this has to be divided into typically six bins in azimuth, implying that 1 nb^{-1} as might be available after three Pb–Pb runs at full energy in 2015–2017 is statistically insufficient and an order of magnitude more data, as planned with the upgrade, are needed.

Performance of the upgraded Inner Tracking System

To facilitate a measurement like the production of Λ_c as outlined above the current Inner Tracking System (ITS) will be replaced. The overriding design criteria for the new ITS have been detailed in [6]. For the purpose of this article, again exemplarily, we show in Figure 3 the crucial performance improvement with respect to the pointing resolution in r$\cdot\varphi$- and z-direction, which is key to the separation of displaced vertices as well as the improvement in the stand-alone momentum resolution, which is key to deriving kinematic triggers at Level 2. In both plots two different upgrade scenarios, which are described in detail in [6], are compared to the current ITS: black lines denote the current ITS performance, green lines refer to an ITS consisting of pixel and strip layers, and red lines refer to an all pixel solution. As a result of, a) the addition of another layer closer to the beampipe at a radius of 22 mm, b) smaller pixels and c) a much reduced material budget per layer ($X/X_0 \approx 1.14\%$ for the current ITS and $X/X_0 \approx 0.3$-0.5% for the upgraded ITS), the improvement for both, the pointing resolution and the stand-alone momentum resolution are of the order of a factor of three. At the same time the tracking efficiency is improved to momenta significantly below 100 MeV/c.

FUTURE HEAVY ION PROGRAM

In Table 1 we summarize the anticipated program for heavy ion operation, which would allow to collect the approved integrated luminosity of 1 nb^{-1} in Pb-Pb collisions, possibly extend the p-nucleus collisions to the highest possible energy and collect some data with lighter ions. For the HL-LHC era, we anticipate to collect at least 10 nb^{-1} as outlined above. It needs to be noted that, since no p-nucleus data has been collected thus far, details of the running schedule may be subject to change depending on the success and physics outcome of these runs.

While, ATLAS and CMS have clearly stated that the pp program at high luminosity remains their highest priority, both have also stated their interest to extend the heavy ion program into the HL-LHC era. This statement has been made under the provision that ion operation does not impede the HL-LHC pp upgrade and that the overall running with ions remains limited to about 10% of the time.

Ion species

Initially it was thought that deuteron beams would be useful in order to mitigate the rapidity shift incurred, when

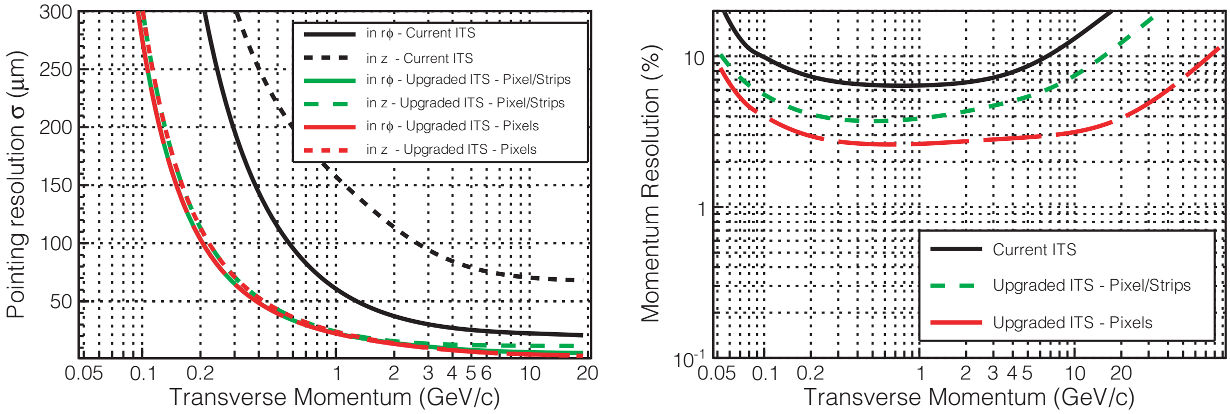

Figure 3: ITS stand-alone tracking performance: left) pointing resolution in r$\cdot\varphi$- and z-direction; right - momentum resolution (black lines - current ITS performance, green lines - upgraded ITS consisting of pixel and strip layers, red lines - upgraded all pixel ITS).

Table 1: Anticipated future ion schedule. (Adapted from J.M. Jowett, these proceedings.)

Year	**Beams**	**Program**
2013 2014	none	Long Shutdown 1
2015 2016	Pb-Pb Pb-Pb	Design luminosity ($\approx$250 μb^{-1}) Design luminosity ($\approx$250 μb^{-1})
2017	Pb-Pb p-Pb	If int. lumi. still insufficient, else at highest possible energy
2018	none	Long Shutdown 2, ALICE upgrade installation, DS collimators to protect magnets
2019	Pb-Pb	Operation beyond design luminosity
2020-21	p-Pb Ar-Ar	If still priority, else intensity to be seen from injector commissioning for SPS fixed target
2022	none	Long Shutdown 3, stochastic cooling?
$>$2022	ions	Lumi. production, other ions (U?)

colliding protons with nuclei. Given the possibility to reverse the circulating beams within one run, this is no longer a strong argument. Also, possible isospin dependences are considered to be negligible at these energies.

Owing to the large shape deformation of Uranium nuclei (aspect ratio of the ellipsoid $\approx$1.5), there is the potential to further increase the maximum energy density reached in ion collisions at the LHC by another 50%, albeit with small cross sections. Experiments at RHIC are scheduled to explore this option this year. Pending the findings, there may be interest to study U-U collisions inthe far future.

SUMMARY

ALICE has conceived an upgrade program, which would well exploit the physics potential provided by 10 nb^{-1} Pb-Pb collisions, which come into reach, when the machine can be operated at $\mathcal{L} > 6 \times 10^{27}$ cm^{-2}s^{-1} for Pb–Pb in the HL-LHC era. Installation of the upgrade is currently foreseen for LS2. The physics program addresses fundamental questions of QCD as a true multi-particle theory.

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