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Heavy-Ions at the High-Luminosity LHC

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The heavy-ion programme at the LHC after the Long Shutdown 2 (LS2) will profit from a significant increase in the total integrated luminosity in Pb–Pb collisions, with more than 10 nb^{-1} having been requested by the experiments, compared to ~ 0.1 nb^{-1} collected in Run-1 and the expected ~ 1 nb^{-1} of Run-2. The four major LHC experiments (ALICE, ATLAS, CMS and LHCb) are developing specific upgrade strategies, aiming to exploit the full potential of the LHC heavy-ion programme after LS2. The most relevant aspects of these upgrade programmes are revised in this contribution, together with some selected items from the foreseen physics programme.

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1. Introduction

Ultra-relativistic heavy-ion collisions are the most effective tool for studying the behaviour of hadronic matter under extreme conditions in laboratory. This allows one to test Quantum Chromo-Dynamics (QCD) across its phase diagram defined by the baryonic chemical potential μ_B and the temperature T. In particular, the high-energy Pb–Pb collisions provided by the Large Hadron Collider (LHC) at CERN are suited to reproduce the conditions of high temperature and low-μ_B present in the early Universe, with the hadronic matter deconfined in a Quark-Gluon Plasma (QGP) state. When colliding Pb nuclei at its top energy, the LHC behaves as a QGP factory producing the largest, the hottest and the longest-lived volumes of QGP available today in laboratory, allowing for a detailed study of this phase of the QCD matter.

The heavy-ion programme at the LHC after the Long Shutdown 2 (LS2) will profit from a significant increase in the total integrated luminosity in Pb–Pb collisions, with more than 10 nb^{-1} having been requested by the experiments, compared to $\sim$ 0.1 nb^{-1} collected in Run-1 and the expected $\sim$ 1 nb^{-1} of Run-2. Such an integrated luminosity should be collected during the two presently foreseen data taking periods, Run-3 and Run-4, the second one representing the first period of operation of the High-Luminosity LHC. During these data-taking periods the LHC will operate at the nominal 14 TeV and 5.5 TeV centre-of-mass energy for pp and Pb–Pb collisions, respectively. Reference samples with pp collisions at 5.5 TeV will also be collected, as well as a sample with p–Pb collisions at 8.8 TeV. The possibility of extending the programme to collisions of nuclei lighter than Pb (e.g. Ar–Ar or O–O) is being discussed.

The heavy-ion programme will continue to be the main focus of the ALICE scientific activity after LS2, motivating and imposing the constraints to the approved upgrades. The other three major LHC experiments, ATLAS, CMS and LHCb, will also participate in the entire heavy-ion programme after LS2, taking advantage of the upgrades foreseen in view of the High-Luminosity LHC machine startup in Run-4

2. Detector Upgrade Plans

The four major LHC experiments, ALICE, ATLAS, CMS and LHCb, will participate in the LHC heavy-ion programme after LS2 with upgraded detectors with respect to Run-1 and Run-2. The most relevant aspects of these detector upgrade programmes [1] are summarised in the following, separately for each experiment.

2.1 ALICE

Being the LHC experiment specifically designed for the QGP physics, ALICE upgrade plans have been driven and constrained by the specificities of the heavy-ion data taking. One of the main requirements of the upgrade plan is the improvement of the track reconstruction performance, in terms of spatial precision and efficiency, in particular for low-momentum particles, in order to select more effectively the decay vertices of heavy-flavour mesons and baryons. The particle identification capabilities of the apparatus will be consolidated: they represent a key specificity of the ALICE detector with respect to the other LHC experiments, and a crucial tool for the selection of heavy-flavour, quarkonium and dilepton signals at low momentum. The upgrade of the ALICE apparatus will also allow the event readout rate to be increased up to 50 kHz for minimum-bias triggered Pb–Pb collisions, in order to improve the efficiency for low-momentum processes. This increase will enable recording during Run-3 and Run-4 of a sample of minimum-bias collisions two orders of magnitude larger than during Run-2.

The technical details of the ALICE upgrade programme are described in several documents [2, 3, 4, 5, 6, 7, 8, 9]. In summary, it entails the following changes to the apparatus:

- a new Inner Tracking System (ITS) with seven layers equipped with Monolithic Active Pixel Sensors (MAPS) [5]; the innermost layer will have a radius of 23 mm, to be compared with 39 mm of the present ITS; the hit resolution of the detector will be of about 5 μm and the material budget of the three innermost layers will be reduced from the present 1.1 % to 0.3 % of the radiation length; these features provide an improvement by a factor about three for the track impact parameter resolution in the transverse plane (see Figure 1-left);

- a new Muon Forward Tracker (MFT) made of five disks of the same MAPS used in the upgraded ITS, which will provide precise tracking and secondary vertex reconstruction for muon tracks in $2.5 < \eta < 3.5$ [4] (see Figure 1-right);

- new readout chambers for the Time Projection Chamber (TPC), based on the Gas Electron Multiplier (GEM) technology, in order to reduce the ion backflow in the drift volume and enable continuous readout of Pb–Pb events for an interaction rate up to 50 kHz [6];

- a new Fast Interaction Trigger detector (FIT) based on Cherenkov radiators and scintillator tiles at forward rapidity around the beam pipe [7];

- an upgrade of the readout electronics of the TOF, MUON and ZDC detectors that enables recording Pb–Pb interactions at a rate of up to 50 kHz [7];

- a new integrated Online/Offline system for data readout, compression and processing (O^2) to reduce the volume of data by more than one order of magnitude before shipping them to permanent storage [2].

The installation of the new detectors and the commissioning for the upgraded ALICE experiment are scheduled for the LHC LS2 (2019–2020), with data taking starting in 2021.

2.2 ATLAS and CMS

Both the ATLAS and CMS detectors will undergo some specific upgrade during the LHC LS2 and then a major upgrade during LS3 in view of the High-Luminosity LHC machine startup in Run-4 [10, 11, 12]. In particular, the muon systems will be upgraded during LS2 and new higher-precision inner trackers will be installed during LS3, which will strongly improve heavy-flavour hadron and jet measurements in Pb–Pb collisions.

The data taking strategy of the ATLAS and CMS experiments after LS2 will be based mainly on highly-selective triggers on muons, jets and displaced high-p_{T} tracks, focusing on the higher p_{T} region and high signal-to-background observables. The Pb–Pb hadronic interaction rate of 50 kHz will be reduced by the trigger to the rate of a few kHz, which will be the input to the High Level Trigger, and then to $\sim$ 100 Hz, the expected rate of event recording to storage. This strategy is

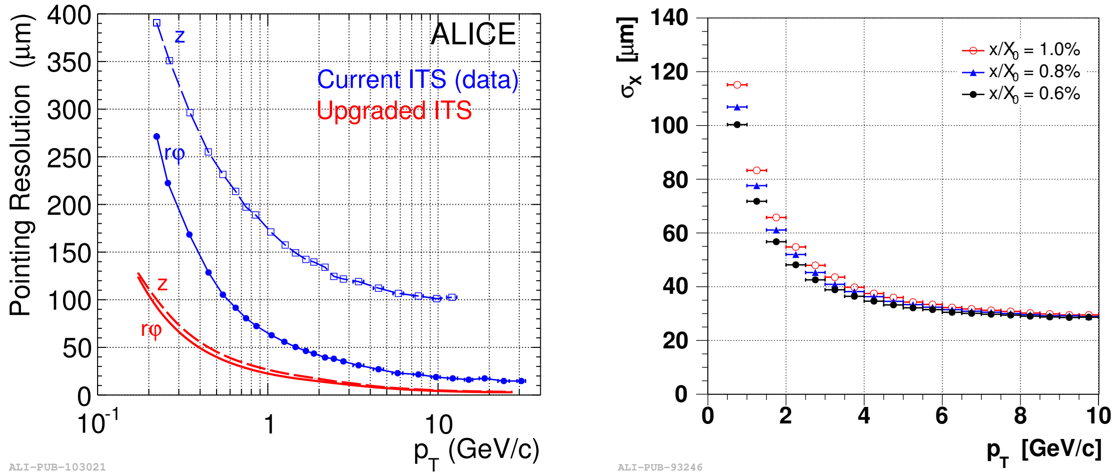

Figure 1: Left panel: offset resolution at the primary vertex for primary charged pions as a function of the transverse momentum for the present ITS (blue) and the upgraded ITS (red) in the transverse plane (solid lines) and in the longitudinal direction (dashed lines). Right panel: offset resolution at the primary vertex for prompt muons, under three different scenarios for the material budget of the single MFT disks.

orthogonal to the ALICE approach, based on the maximisation of the recording rate up to 50 kHz for minimum-bias Pb–Pb collisions (with a strong online-offline reduction of the data volume for the recorded events), optimised for low- and intermediate-p_{T} measurements with unique access to untriggerable low signal-to-background probes.

2.3 LHCb

LHCb is the only LHC experiment which did not participate in the Pb–Pb data taking in Run-1. However, with the participation in the 2013 p–Pb run and the 2015 Pb–Pb, LHCb recently started to develop its own heavy-ion programme, with a number of important measurements based on the p–Pb data sample already reported, in particular in the sector of quarkonium production. While the performance of the LHCb detector in the conditions of high occupancy of central Pb–Pb events is still to be demonstrated, the experiment has very strong potential for the measurements of heavy-flavour production at low p_{T} and forward rapidity, and the Collaboration has expressed interest in continuing the heavy-ion programme in the LHC Run-3 and Run-4, exploiting also the major detector upgrade planned for LS2 [13]. The upgrade includes a complete replacement of the vertex detector and a faster readout system.

A unique feature of the LHCb apparatus, especially interesting in the context of heavy-ion physics, is the possibility to operate in a fixed-target mode in the frame of the LHCb-SMOG project with the gaseous target injected inside the beam pipe around the nominal interaction point. Center-of-mass energies of up to $\sim$ 100 GeV per nucleon pair can be achieved in a fixed-target data taking mode, complementing the physics programme at the top LHC energy in a region of the QCD phase diagram at finite baryonic density.

3. Physics Programme

In Run-3 and Run-4, the LHC heavy-ion programme will push forward the investigation of the QGP phase properties, taking up the challenge to make a quantitative leap in the precision of the experimental observations by exploiting the expected large integrated luminosity provided by the LHC. In the following, the main items of the foreseen physics programme are shortly revised.

3.1 Jets

The study of jet production in Pb–Pb collisions allows for a detailed characterisation of the 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 the jet structure and the di-jet imbalance at TeV energies, the b-tagged jets, the jet correlations with high-p_T photons and Z^0 bosons (produced in the primordial stages of the heavy-ion collisions, and unaffected by the presence of a QCD medium, see Figure 2).

A precise and extensive characterisation of these observables is crucial to address the flavour and the path-length dependence of the parton energy loss and will be the main focus of ATLAS and CMS, thanks to their favourable acceptance for high-p_T observables, and the triggering capabilities specifically designed for rare probes. ALICE will complement these observations in the low-momentum region, and carry out measurements of the flavour dependence of medium-modified fragmentation functions using light flavour, strange and charm hadrons reconstructed within jets, thanks to its excellent particle identification capabilities and the possibility to record minimum-bias Pb–Pb events at the unprecedented rate of 50 kHz.

3.2 Heavy Flavours

Heavy flavour measurements in Pb–Pb collisions allows for a large variety of studies, ranging from the precise characterisation of the quark mass dependence of the in-medium parton energy loss, to the study of the transport and possible thermalisation of heavy quarks in the medium, to the study of heavy quark hadronisation mechanisms in a partonic environment. These investigations require the measurement of the production rate and the azimuthal anisotropy of several charm and beauty hadron species, over a broad momentum range, including b-tagged jets. ALICE will focus mainly on the low-momentum region, down to zero p_T, and on the reconstruction of several heavy-flavour hadron species (including baryons) thanks to the possibility to precisely measure their decay topology in the new ITS, see Figure 3. For the first time, ALICE will also be able to separate charm and beauty contributions in the heavy-flavour muons at forward rapidity, thanks to the new MFT, including the statistical identification of the J/ψ contribution from beauty decays down to zero p_T, see Figure 4.

ATLAS and CMS will focus mainly on b-tagged jets and on D and B mesons at higher p_T. LHCb has a strong potential for all these measurements thanks to the excellent tracking capabilities in the vertex region, pending the detector performance in central Pb–Pb collisions.

3.3 Quarkonia

Measurements of charmonium and bottomonium states allows for the study of their dissociation and possible regeneration in the hot medium. In turn, these mechanisms can be used as probes

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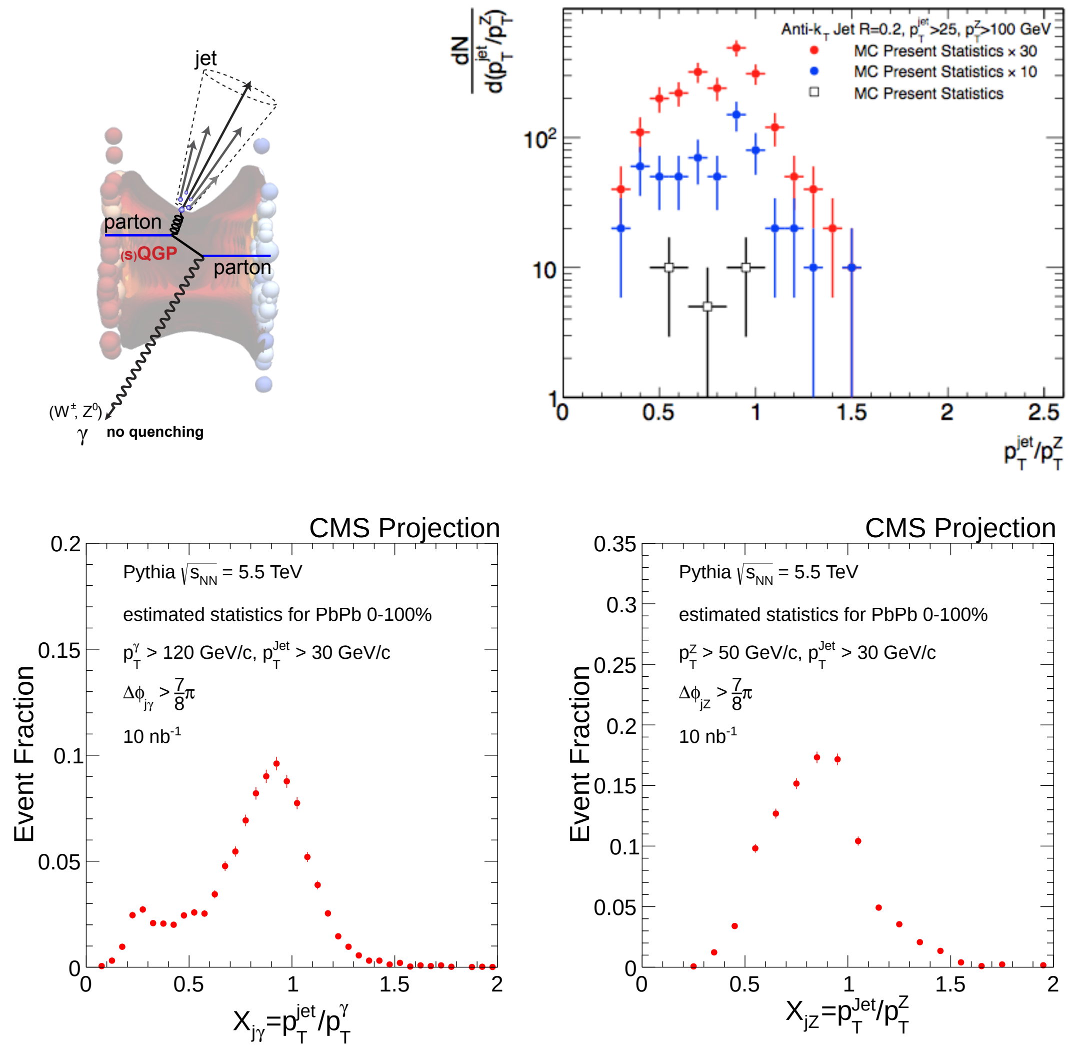

Figure 2: γ-jet and Z-jet correlations in heavy-ion collisions at the LHC energy: pictorial view (top left) and expected event rate for the ATLAS (top right) and CMS (bottom panels) upgrade programmes.

of the deconfinement properties of the QGP and as an indirect measurement of its temperature. After LS2, ALICE will improve the precision of the measurements already available from Run-1 and Run-2, especially through the measurement of the yields and the azimuthal anisotropy of J/ψ, ψ(2S) and Υ yields starting from zero p_{T}, at both central and forward rapidity. At forward rapidity, in particular, the new MFT will allow the prompt J/ψ component to be statistically seperated from the displaced production, and the ψ(2S) to be observed even in the most central Pb–Pb collisions thanks to a strong reduction of the non-prompt background.

ATLAS and CMS will focus on precise multi-differential measurements of the Υ states to map the dependencies of their suppression pattern. They will also complement to high momentum the charmonium measurements. Also in this case, LHCb has a strong potential, pending the detector performance in central Pb–Pb collisions.

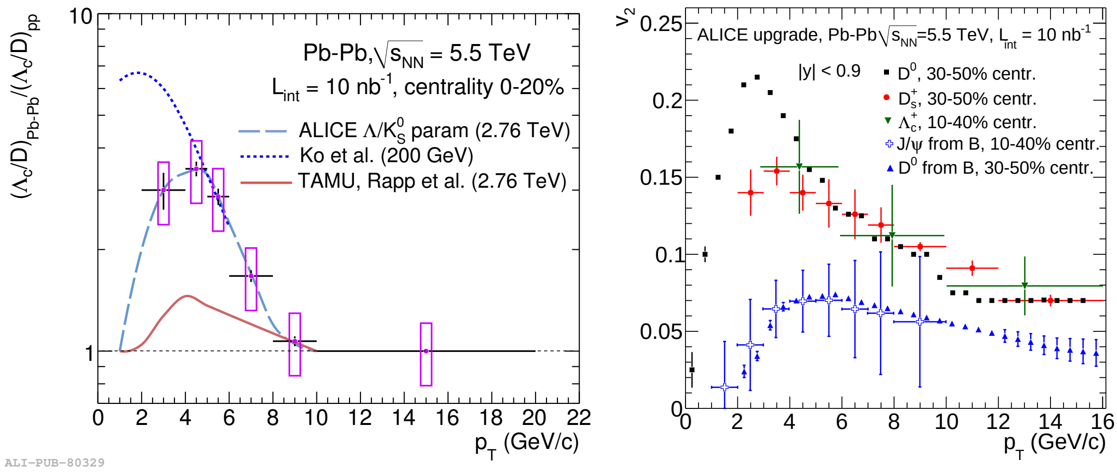

Figure 3: Performance for the measurement of the double ratio of Λ_c over prompt non-strange D-meson production in Pb–Pb and pp collisions (left panel) and for the measurement of v_2 for prompt non-strange D mesons, D_s^+, Λ_c, and D meson and J/ψ from B-meson decay (right panel), with the uncertainties expected after the ALICE upgrade [5].

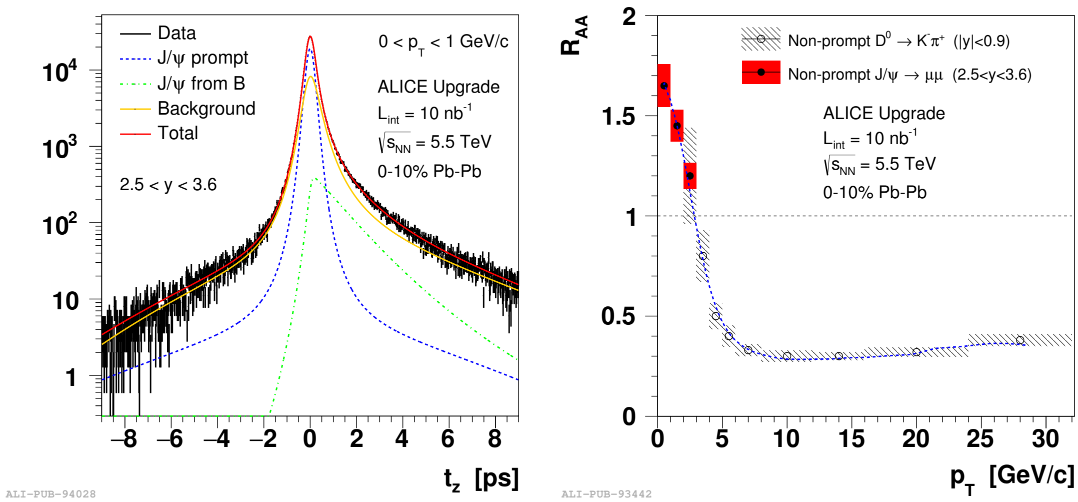

Figure 4: Example of combined fit on the J/ψ pseudo-proper decay time distribution at forward rapidity, for the statistical separation of the prompt and displaced contributions (left panel), and resulting performance for the measurement of the nuclear modification factor of the J/ψ and D^0 from beauty decays (right panel) with the upgraded ALICE detector [4].

3.4 Low-Mass and Thermal Dileptons

Low-mass and thermal dileptons are emitted through the whole evolution of the deconfined medium, being thus sensitive to its initial temperature and equation of state, as well as to the chiral nature of the phase transition. These measurements will be carried out by ALICE, which will strengthen its unique, very efficient dielectron and dimuon reconstruction capabilities down to almost zero p_{T} (see Figure 5), as well as the readout capabilities for recording a very high statistics minimum-bias sample needed for these untriggerable probes. Specific studies are also undergoing to assess the sensitivity of ALICE to the measurement of possible low-mass dark matter bosons decaying into electron or muon pairs, thanks to the improvement of the discrimination between prompt and non-prompt dileptons.

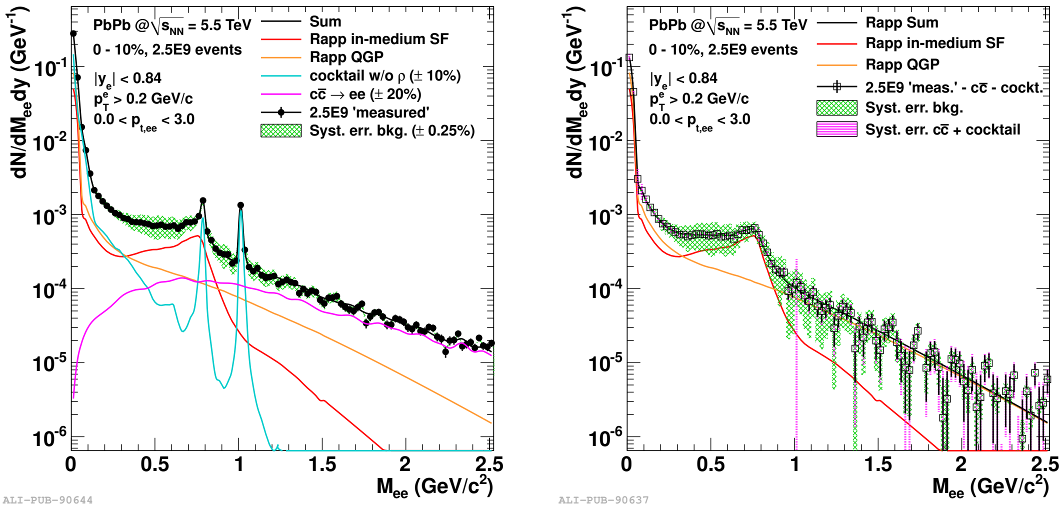

Figure 5: Expected performance for the measurement of the low-mass dielectron spectrum (left panel) and the isolation of the thermal continuum and the modified ρ line shape (right panel), with the upgraded ALICE detector [5].

4. Conclusions

The heavy-ion programme at the LHC will continue after the LS2, profiting from a significant increase in the total integrated luminosity with respect to Run-1 and Run-2. The four major LHC experiments (ALICE, ATLAS, CMS and LHCb) are developing specific upgrade strategies, aiming to exploit the unique scientific potential of the high-luminosity heavy-ion era of the LHC. The ambitious physics programme will be based on high-precision measurements of jets, heavy-flavours, quarkonia and low-mass dileptons observables, with the data taking foreseen to start in 2021.

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