NEAR- AND MID-TERM FUTURE OF THE LHC EXPERIMENTS*

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This contribution discusses the perspectives for heavy-ion physics with the experiments at the LHC. After reviewing the perspectives of LHC for the upcoming runs, the installed and planned upgrades of the four large experiments are presented. For the topics of major interest of heavy-ion physics, the experimental requirements and the physics prospects are discussed.

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1. LHC programme

The Large Hadron Collider (LHC) provides a unique potential to study phenomena of heavy-ion physics since it allows the production of nuclear matter at very high temperatures and at vanishing baryo-chemical potential in combination with large yields of heavy-flavour probes. During Long Shutdown 2 (LS2, 2019–2021), the accelerator and the experiments have undergone significant upgrades in preparation of Run 3, see Fig. 1 for the schedule. The LHC upgrades allow for an increase of the Pb–Pb collision to ~ 50 kHz [1]. In addition, preparatory measures have been taken for the HL-LHC upgrade to push the instantaneous pp luminosity to 4×10^{34} cm^{-2} s^{-1} in Run 4. Preliminary studies for a further increase of the ion luminosities have been performed [2], and Fig. 1 shows the projected evolution of the integrated nucleon–nucleon luminosities for both pp and ion operation of the LHC.

2. Upgrades of experiments

Given the different priorities, the upgrade plans of the LHC Collaborations align differently with the LHC schedule, see Fig. 1. In preparation of Run 3, ALICE and the LHCb have installed major upgrades during LS2 to

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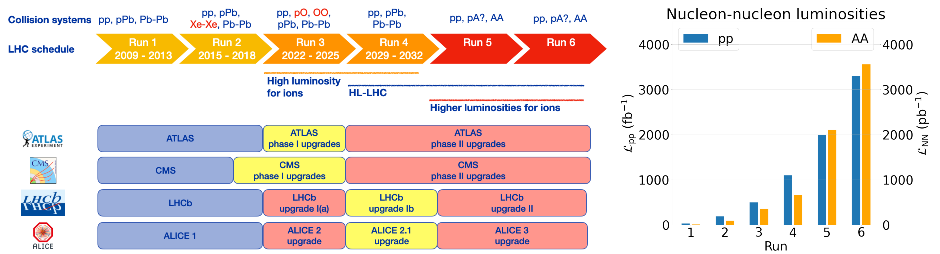

Fig. 1. LHC run schedule and upgrade phases of the large experiments (left) and projection of the accumulated nucleon–nucleon luminosity for *pp* and *AA* collisions in the LHC (right).

extend their physics reach by increasing the acceptable rates and improving the detector capabilities. In anticipation of the major (phase II) upgrades for the operation with high *pp* luminosities with the HL-LHC in Run 4, ATLAS and CMS have used the LS2 for preparatory installations but also for the upgrade of several systems. Most upgrades will then be installed during Long Shutdown 3, for which ALICE and the LHCb foresee intermediate upgrades. The latter foresees a second major upgrade phase in Long Shutdown 4 to further push their physics capabilities with LHC Runs 5 and 6.

2.1. ATLAS

During LS2, the ATLAS experiment has seen a significant upgrade of the trigger and data acquisition system that will allow the recording of larger data samples [3]. In addition, the zero-degree calorimeter was upgraded to make use of fused silica rods for improved radiation tolerance. Besides featuring on-detector processing, it provides improved performance and also serves as a reaction plane detector. The installation of the new small wheels (sTGC+MicroMegas) marks an important milestone for the muon system. The upgrade of the liquid argon calorimeter with segmented super cells now supports shower-shape discrimination at the trigger level. These upgrades will help the heavy-ion programme with larger data samples and the improved performance of the zero-degree calorimeter.

Among the major upgrades during the next Long Shutdown 3 [4] will be the installation of the completely new Inner Tracker (ITk), based on hybrid silicon pixel and strip sensors, which extends the pseudo-rapidity coverage to $|\eta| < 4$. It will be complemented by a high-granularity timing detector in the forward direction ($2.5 < |\eta| < 4$) to cope with the large in-bunch pile-up with *pp* collisions and also to provide particle identification capabilities. The upgrade of the endcap calorimeters will provide higher granularity. A new HL-ZDC will be constructed in collaboration with CMS and provide the measurement of the reaction plane while tolerating higher levels of irradiation. Further upgrades are planned for the muon system, the luminosity detectors, the trigger and data acquisition, as well as for the most of the electronics. The heavy-ion programme will particularly benefit from the increased coverage of the tracking, the particle identification (in the forward direction), and the increased granularity in the endcap calorimetry.

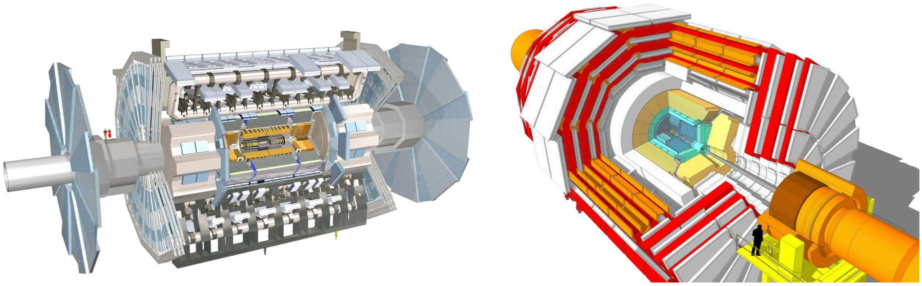

Fig. 2. Experimental setup of ATLAS (left) and CMS (right).

2.2. CMS

The CMS detector has undergone several upgrades during LS2 [5]. The new pixel tracker reduces the distance from the beam and features an additional layer both in the barrel and forward regions. The trigger system has been upgraded to use FPGAs at level-1 and to include the CSC and GEMs in the level-1 tracking, whereas the high-level trigger now makes use of GPUs. Additionally, the readout of the hadronic calorimeter and GEM chambers were upgraded as well as new frontend electronics were installed for the forward muon system. These upgrades result in an increased bandwidth and will allow the accumulation of a larger minimum bias data sample in heavy-ion collisions.

With the phase-II upgrades during Long Shutdown 3 [6], a completely new tracker based on hybrid silicon pixel and strip detectors will be installed. It will be complemented by the MIP timing detector with a time resolution of ~ 30 ps to cope with the increased in-bunch pile-up in pp collisions and will also provide particle identification both for the barrel and forward acceptance. The endcaps will be equipped with highly granular electromagnetic and hadronic calorimeters allowing the 4d reconstruction of showers. In the joint project with ATLAS (see above), the HL-ZDC will be installed. Additionally, there will be upgrades on the level-1 trigger, the high-level trigger, data acquisition, the forward muon system, the luminosity detectors, and the muon readout. The heavy-ion programme will particularly benefit from the extended acceptance with tracking up $|\eta| < 4$, muon identification and time-of-flight measurements up to $|\eta| < 3$, as well as the improved vertexing and the large coverage of the calorimetry.

2.3. LHCb

As shown in Fig. 3, the LHCb has seen a major upgrade for the start of Run 3 [7]. The tracking profits from the new Vertex Locator based on the VeloPix sensor and the improved performance with a thinner RF foil and the reduction of the distance from the beam axis to ~ 5 mm. The upstream tracker was upgraded to use silicon micro-strip detectors, and the new scintillating-fibre tracker with SiPM readout was installed. Further, the RICH systems were renewed and the new SMOG 2 system was installed for improved and more flexible fixed-target operation. In addition to the readout upgrade of the detectors, the data processing chain was extended to use GPUs and allow software triggers with a readout rate of 40 MHz. Together with the improved vertexing and the higher luminosity of the fixed target operation, these changes will significantly extend the capabilities for heavy-ion operation, in particular by allowing the analysis of Pb–Pb collisions down to 30% centrality.

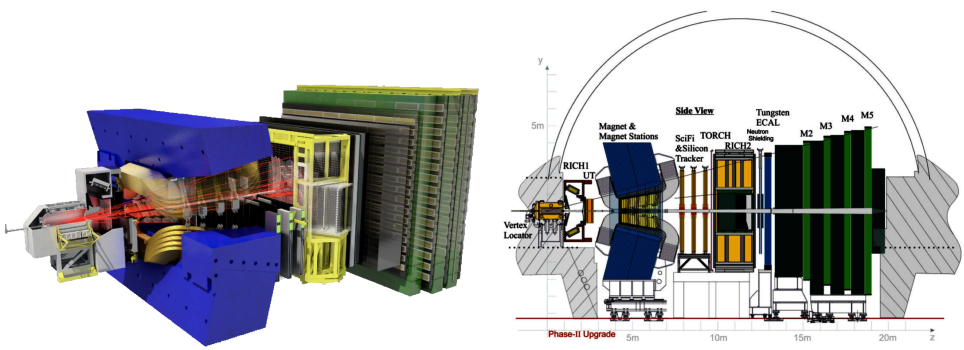

Fig. 3. Experimental setup of LHCb for Run 3 (left) and for Run 5 (right).

A further major upgrade leading to an essentially new experimental setup is planned for Long Shutdown 4 [8]. Some parts of the upgrade can be considered for installation during Long Shutdown 3. A further upgrade of the vertex locator will add precision timing to the vertexing. The combination of a new upstream tracker (incl. timing), the mighty tracker (scintilalating fibres+silicon), and new magnet stations will allow the tracking in high-multiplicity events and the extension of the p_{T} reach to below 5 GeV/c. The hadronic calorimeter in front of the muon stations will be replaced by passive shielding, resulting in improved muon performance. The particle identification capabilities will be extended by a Cherenkov-based time-of-flight wall (TORCH) and two ring-imaging Cherenkov detectors with precision timing. In addition, a new electromagnetic calorimeter based on SpaCal or Shashlik technology will be installed. Also, a fixed target installation with a polarised gas target or a solid target is discussed. These upgrades will alleviate the centrality limitation for AA collision and also provide excellent vertexing capabilities in the forward direction.

2.4. ALICE

Figure 4 shows the detector configuration of ALICE 2 and ALICE 3. As part of the LS2 upgrades [9], the Inner Tracking System has been replaced by a completely new detector based on monolithic active pixel sensors with improved pointing resolution while also supporting the planned Pb–Pb interaction rates of 50 kHz. It is extended by the Muon Forward Tracker that allows the precise propagation of tracks from the muon arm towards the interaction region and, thus, the cleaner assignment of tracks to the primary vertex. The Time Projection Chamber as the main tracking detector has been upgraded to also support the full Pb–Pb interaction rates without gating by installing GEM-based readout chambers (previously MWPC-based). A completely new Fast Interaction Trigger provides the minimum bias trigger as well as the luminosity measurements. In addition to the consolidation and readout upgrade of all detectors, an integrated online–offline system has been developed and deployed. It supports the full reconstruction synchronuously to the data taking by making use of 2000 GPUs in a computing farm of 250 nodes. In the Long Shutdown 3, the three innermost layers of the inner tracking system shall be replaced by truly cylindrical wafer-scale sensors, realised by stitching and thinning CMOS pixel sensors. In addition, a forward calorimeter is planned to allow for the measurement of isolated photons in the forward direction and to contribute to constraining the gluon PDFs.

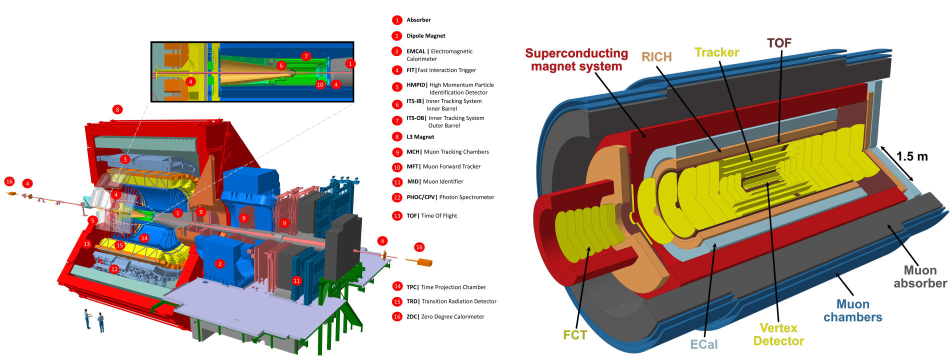

Fig. 4. Detector setup of ALICE 2 in Run 3 (left) and ALICE 3 in Run 5 (right).

A new detector concept, ALICE 3, is planned for installation in Long Shutdown 4 and operation in Run 5 [10]. It is built around an all-silicon tracker comprising barrel layers and forward discs in a super-conducting magnet system to cover a large pseudo-rapidity range. It is extended by a retractable vertex detector installed in a secondary vacuum within the beampipe to minimise the distance from the interaction point and optimise the pointing resolution. The tracker is surrounded by time-of-flight and ring-imaging Cherenkov detectors for particle identification over the full acceptance. An electromagnetic calorimeter contributes to electron identification and allows the measurement of photons. Outside of the main magnet, muons are detected in two layers behind an iron or steel hadron absorber. A dedicated forward conversion tracker shall allow the measurement of ultrasoft photons.

3. Physics perspectives

The prospects for heavy-ion physics with Runs 3 and 4 have been studied extensively in the report on the physics prospects at the HL-LHC [11] and the potential for Runs 5 and 6 has been presented in the letter of intent for ALICE 3 [10].

Better constraints of the gluon densities in nuclear PDFs down to low x depend on new measurements of gluon-probing processes in p–Pb and Pb–Pb collisions, which can be achieved by an increase in luminosity and new detectors. Run 3 will bring refined measurements, *e.g.* of the Drell–Yan process and the asymmetry of W production in p–Pb collisions as well as of the photoproduction of vector mesons in ultra-peripheral Pb–Pb collisions. New collision systems in the fixed target configuration will further add to the coverage. In Run 4, the ALICE FoCal will enable the measurement of isolated photons in the forward direction in p–Pb collisions to constrain the gluon PDFs down to $x \approx 10^{-5}$.

The understanding of the thermodynamic state in the early collision phases relies on measurements of direct photons and dileptons, which so far have been limited by statistics, the amount of detector material, and the heavy-flavour contamination. The LS2 upgrades will allow the extraction of an average plasma temperature at the LHC. More precise measurements will become available only with the upgraded experiments in Runs 5 and 6 and then also provide sensitivity to the time evolution and mechanisms of chiral symmetry restoration.

An important confrontation of experimental results with predictions from QCD calculations on the lattice is possible by thorough measurements of net-baryon fluctuations, often expressed in the form of the cumulants κ_n. They require excellent particle identification over a large acceptance. The improved statistics from Runs 3 and 4 will already help to get new results but a major step forward can be expected from the jump in statistics and acceptance with ALICE 3, *e.g.* sufficient for a precise extraction of the 6^{th}-order cumulants.

In the jet sector, the larger data samples from Runs 3 and 4 will allow us to look at tagged jets and the jet substructure up to transverse momenta in the range of TeV/c, including the precise measurement of the nuclear modification factor. In addition, new results are expected from the smaller collision systems, *e.g.* limits on the energy shift out of the jet cone. New ideas are being explored to probe the medium more differentially, *e.g.* by exploiting top decays to start the shower evolution only a certain time after the hard scattering. The full realisation of such measurements will require the data from Runs 5 and 6.

Making use of the planned O–O run but also of high-multiplicity pp collisions, Runs 3 and 4 will enable systematic measurements of particle production and flow coefficients as a function of system size and, thus, bring new insights into the evolution from small to large systems.

Understanding the transport of heavy-flavour quarks in the QGP has been one of the topics motivating the LS2 upgrades, and significant progress is expected from precision measurements of R_{AA} and v_2 for both charm and beauty. These will become possible in Runs 3 and 4 with the larger data samples and considerably better vertexing performance. The interpretation also depends on the hadronisation of heavy-flavour quarks, which can be constrained by measurements of baryon-to-meson ratios and flow coefficients. The luminosity, vertexing, and particle identification performance will allow measurements in the charm sector with the Runs 3 and 4 data but conclusive measurements in the beauty sector only with Runs 5 and 6 data. Also, direct measurements of charm–anti-charm decorrelation patterns will become possible only with Runs 5 and 6.

Another goal in the heavy-quark sector is to understand the dynamics in the QGP through precision measurements of bound states such as bottomonium and P-wave charmonium states. This relies on the increase in luminosity and excellent particle identification capabilities. To understand the formation and behaviour of heavy quarks, measurements of hadron–hadron correlations have been proven a useful tool. To probe states like the T_{cc} will require the luminosity, acceptance, and particle identification of Runs 5 and 6, but other analyses, *e.g.* Ω–Ω interactions are expected for Runs 3 and 4 already.

An important prospect for the heavy-ion programme at the LHC is the systematic measurement of hadron yields up to masses of several GeV/c^2 and up to a charm quark number of 3. Single-charm states will become accessible with the Runs 3 and 4 data but double and triple-charm states will require Runs 5 and 6. These states are of particular interest to probe the formation of hadrons from the QGP as they require the combination of independently produced heavy quarks. With thermal models predicting enhancements by orders of magnitude with respect to pp collisions, these probes provide extraordinary sensitivity.

There are many more opportunities arising from the heavy-ion programme at the LHC, which should be thoroughly explored to fully exploit the LHC. This reaches from non-standard BSM searches in regimes out of reach for ATLAS and CMS over testing Low's theorem on the production of ultra-soft photons in association with charged final-state particles to yet unexplored areas.

4. Conclusions

The start of LHC Run 3 marks the beginning of the high-luminosity operation with ions. The combination of an increase in luminosity, the addition of new collision systems, and the improvement of the detectors leads to remarkable prospects for the coming years, also in view of the upgrades in the next long shutdown. Eventually, the plans for a heavy-ion programme in LHC Runs 5 and 6, with a next-generation dedicated heavy-ion experiment, provide a roadmap for an exciting and comprehensive heavy-ion programme with all large LHC experiments.

REFERENCES

[1] LHC Collaboration, «LS2 upgrades», to be published in *J. Instrum.*

[2] R. Bruce *et al.*, presentation at the 196th HiLumi WP2 Meeting, https://indico.cern.ch/event/1078695/contributions/4537274

[3] ATLAS Collaboration, «LS2 upgrades», to be published in *J. Instrum.*

[4] ATLAS Collaboration, «Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment», Technical report, CERN, Geneva, 2012.

[5] CMS Collaboration, «LS2 upgrades», to be published in *J. Instrum.*

[6] D. Contardo *et al.*, «Technical Proposal for the Phase-II Upgrade of the CMS Detector», Technical report, Geneva, 2015.

[7] LHCb Collaboration, «LS2 upgrades», to be published in *J. Instrum.*

[8] CERN (Meyrin) LHCb Collaboration, «Framework TDR for the LHCb Upgrade II — Opportunities in flavour physics, and beyond, in the HL-LHC era», Technical report, CERN, Geneva, 2021.

[9] ALICE Collaboration, «LS2 upgrades», to be published in *J. Instrum.*

[10] ALICE Collaboration, «Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC», Technical report, CERN, Geneva, March 2022.

[11] Z. Citron *et al.*, *CERN Yellow Rep. Monogr.* **7**, 1159 (2019).