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REPORT

Scientific Council of IN2P3

Session of February 13-14, 2025

IN2P3
Institut national de physique nucléaire
et de physique des particules

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1 Framework

The meeting of the Scientific Council was held on 13 and 14 February 2025 at CNRS headquarters in Paris. The first day was dedicated to the presentation of the projects in an open session. The second day consisted of a closed session of the Scientific Council, including discussions with the project PIs, the invited external experts and the IN2P3 management.

The charge of the Scientific Council was to review the contribution of IN2P3 to the Upgrade II of the LHCb experiment, planned to operate the experiment during Run 5 of the LHC High Luminosity phase.

The ultimate scientific motivation of these instrumental developments is to improve the sensitivity of LHCb to new physics beyond the standard model of particle physics. The LHCb experiment is optimised to achieve excellent precision of measurements in beauty and charm physics. It also has good potential in heavy ion physics to complement ALICE, with in particular good capabilities for the reconstruction and identification of heavy hadrons, a good forward acceptance to study the most central collisions, and the possibility of operating in fixed target mode. The physics programme of LHCb is therefore fully in line with the recommendations of the update of the European strategy in 2020, as well as with the IN2P3 Strategic Plan for French Nuclear, Particle and Astroparticle physics in the 2030 Horizon, mainly the following Science Drivers (SD):

- SD #2: Study matter-antimatter asymmetry and flavor transitions
- SD #3: Pursue searches for unknown particles and interactions
- SD #4: Understand the structure and the origin of the properties of hadrons
- SD #5: Pursue the exploration of the nuclear matter phase diagram

Many of LHCb's flagship measurements are still largely limited by the statistics of the collisions analysed, which justifies the need for a significant increase in luminosity. The Run 3 of the LHC is currently underway from 2022 to 2026, with an LHCb detector that underwent a first upgrade, to which IN2P3 has made a major contribution. It is planned to increase the accumulated statistics by a factor of 6, from 50 fb^{-1} at the end of the Run 4 in 2033 to at least 300 fb^{-1} with the Run 5 (2036-2041). To achieve this large statistics, the instantaneous luminosity in LHCb will be increased by almost an order of magnitude to reach 1.5 $\times 10^{34}$ cm^{-2} s^{-1}. The detector will need a major upgrade to adapt to the increased pile-up rate and radiation. The installation of this Upgrade II will take place mainly during the Long Shutdown 4 (LS4, 2034-2035) of the LHC, with however a little part installed already during the Long Shutdown 3 (LS3, 2026-2029) prior to the start of the Run 4.

The IN2P3 laboratories currently involved in the preparation of the Upgrade II of LHCb are CPPM, IJCLab, LAPP, LLR, LPCA and LPNHE, whose researchers are already members of the LHCb collaboration, as well as IP2I, LPCC and SUBATECH as technical collaborators. SUBATECH plans to leave ALICE and join officially the LHCb Run 5 heavy ion programme.

The IN2P3 teams are already working on three projects for LHCb Upgrade II, namely the PicoCal calorimeter, the data acquisition system and the real time event processing system (called RTA). An additional new contribution to the future Upstream Pixel tracker (UP), equipped with CMOS sensors, is also being considered by some teams, in particular because of its importance for the heavy ion programme. Due to the lower maturity of the UP proposal at IN2P3 compared to the other three proposed contributions mentioned above, this project

is not included in the assessment made here by the Scientific Council.

A first review of the contributions of the IN2P3 teams to LHCb Upgrade II has already been carried out by the Scientific Council of IN2P3 in February 2023. The recommendations made are available here. The Council noted the excellent visibility of the teams and the high quality of their work, and recommended that their progress be monitored, particularly in view of the large scope of proposed contributions and their tight schedule.

Agenda of the session and material

Description of the projects under review, agenda, support files and videos of the oral presentations, report issued by the Scientific Council including recommendations, are archived publicly on the web site of the Scientific Council of IN2P3.

Indico time-table of the open session: see https://indico.in2p3.fr/event/34399/.

2 General comments on the proposed contribution to the Upgrade II of LHCb

First, some general considerations about the overall IN2P3 contribution proposal are discussed here, before providing comments and recommendations for each project in the following sections.

Scientific motivation

By the end of the High-Luminosity LHC era (HL-LHC), LHCb will achieve the best precision in a broad panorama of measurements related to flavour physics, while presenting an excellent complementarity with the Belle II e^+e^- B-Factory in terms of the channels studied. It will be a unique laboratory in the quark sector for indirectly exploring new physics mass scales above $\mathcal{O}(10)$ TeV and largely beyond the reach of direct searches. The proposed Upgrade II will allow to exploit the full potential of LHCb. It will also allow to make an important and complementary contribution to ALICE in heavy ion physics, thanks to the incomparable forward acceptance and the possibility to have fixed target collisions. This is a very attractive activity within IN2P3, and several physicists and engineers are indeed planning to join in the coming years. All these topics covered by LHCb are fully in line with the science drivers of IN2P3.

IN2P3 contribution

The French contribution comprises three main projects: the development of the new calorimeter PicoCal, the Data Aquisition system and the Real Time Analysis. IN2P3 physicists and engineers have key positions and a very high visibility globally, as well in the collaboration as in these three projects. These efforts rely heavily on French expertise, which IN2P3 should maintain for the future.

Planning and human resources

Overall, the Upgrade II planning is realistic and includes safety margins that significantly reduce the risks associated with any delay. Nevertheless, it is crucial to ensure stable human resources for a period beyond 2028-2029. In particular, it is very important that the institutes involved in Upgrade II guarantee the necessary IT contribution to the PicoCal and the DAQ projects.

In addition to the physics case discussed in this document, the Scientific Council considers that the participation in the LHCb Upgrade II is an excellent opportunity to attract young scientists to a collider experiment in operation, and to provide them with the best possible training using real data. The Council notes that it is also very important to ensure a high impact and visibility of IN2P3 in the next generation of collider experiments. In this respect, the strong support expressed by the French flavour physics community for the FCC-ee project during the ESPPU process is noteworthy, and the LHCb teams are encouraged to ensure that the expertise gained at the HL-LHC is preserved while laying the foundations for the next era of high energy physics research. Regarding the requested resources, the Scientific Council does not see a critical conflict between LHCb Upgrade II and the preparation of the future e^+e^- collider detector beyond 2030. However, this statement must be tempered by the fact that the Council has not yet evaluated the proposed IN2P3 contributions to FCC-ee, and therefore the laboratories involved in both projects will need to keep this point under review.

Computing aspects

The increase in luminosity associated with the triggerless mode of the LHCb data acquisition will increase the number of events to be recorded by a factor of about 10. Although efforts are being made to reduce the event size, the LHCb data storage will need to be increased for Run 5. In addition, the need to simulate large data samples for analysis and for training AI methods (in particular for RTA), will require more computing resources. The Scientific Council recommends that IN2P3, in coordination with the LHC Computing Grid and the CC-IN2P3 computing centre, reviews the CPU and storage requirements to validate whether a contribution at the level of the LHCb fair share is compatible with the expected increase in IN2P3 resources for Run 5.

3 The PicoCal project

3.1 Introduction and highlights

The PicoCal project of LHCb is essential in order to maintain the current performance of the electromagnetic calorimeter while operating in a much more demanding environment characterised by high radiation levels and occupancy. It addresses these challenges through several key design features: higher granularity, longitudinal segmentation, excellent timing resolution and high radiation tolerance. A major part of the upgrade will be the readout electronics, which will have to ensure performance in terms of energy and time resolution at a collision rate of 40 MHz. This will be achieved through the development of two separate ASICs: SPIDER, designed for precise timing measurements and ICECAL65, designed for energy measurements. The front-end boards (FEBs) that will house the ASICs, will also include radiation-hard FPGAs from the MicroSemi PolarFire family. These FPGAs will perform the digital processing of the signals coming from the ASICs and format the information for transmission through low power GigaBit Transceiver (lpGBT) components via optical fibre to the back-end electronics. The upgrade of the electromagnetic calorimeter will take place in two phases: during LS3, the central modules will be replaced, while the electronics will remain essentially the same. Then, during LS4, the new electronics will be introduced with the new front-end boards. Depending on the scenario chosen, it will be necessary to produce either 4,000 ASICs and 500 FEBs, or 2,600 ASICs and 350 FEBs.

3.2 Comments

The PicoCal development is a historical activity and responsibility of IN2P3, with a very high visibility, through which the institute remains a key actor in the LHCb collaboration. This project consists on the one hand of the improvement of the mechanical structure and the services that will be installed during the LS3, and on the other hand of the development and production of the SPIDER ASIC and the front-end boards. The SPIDER ASIC targets a resolution of 15 ps, which is challenging but should be achievable. The development of such an ASIC will benefit the entire IN2P3 community beyond its use in LHCb. The above activities remain critical for LHCb Upgrade II under all scenarios considered, and there is little room to reduce the PicoCal financial contribution for IN2P3. In particular, removing the longitudinal segmentation as proposed in the low scenario, could be detrimental to the particle identification capability in LHCb and to physics. The schedule is realistic for all three activities related to the PicoCal. The design of the mechanical structure and services is at a late stage. The SPIDER and FEB plannings include well defined safety margins.

3.3 Recommendations

- It is crucial to ensure that there is sufficient personpower (both engineers and physicists) for the whole period, especially for the SPIDER characterisation.
- In order to complete the project on time, the Scientific Council recommends that the knowledge transfer to the newly recruited engineer, who will soon replace an experienced engineer at IJCLab, be monitored over the next few years.
- It would also be important to obtain a commitment from IP2I and LPCC that the engineers involved in the PicoCal project will be available beyond 2026 if needed.

In conclusion, the Scientific Council considers that the PicoCal Upgrade II project is a very important activity of the IN2P3 community, that the project is realistic and well consolidated, and that the physics potential is high.

4 The Real Time Analysis (RTA) project

4.1 Introduction and highlights

The triggerless data acquisition system in LHCb is already the biggest data challenge in High Energy Physics today. It relies on a real-time reconstruction, including alignment, calibration and online selection, based on two levels of High-Level Trigger (HLT1 and HLT2).
The French LHCb groups, having successfully secured European grants, have played a leading role in the implementation of the triggerless concept in the experiment, with a successful deployment in Run 3 (also under development for Run 4). The upcoming Run 5 requires a superior system that can handle the expected increase in data volume, from 4 TB/s to 25 TB/s. The IN2P3 groups are coordinating the LHCb RTA project, and are well positioned to lead the further development of this new heterogeneous computing framework.
The IN2P3 RTA project is organised in four work-packages: WP1 (Allen software framework), WP2 (Exploration of AI/ML methods), WP3 (Reconstruction algorithms within Allen, for sub-detectors with IN2P3 contributions), WP4 (Reconstruction for Heavy Ion collisions).

4.2 Comments

- The success of the RTA project is absolutely crucial for the achievement of the physics program of Run 5, as it conditions the full use of the delivered luminosity.

- The RTA project requires a high level of expertise in Artificial Intelligence and Machine Learning (AI/ML) methods. The know-how acquired during the project is clearly strategic for IN2P3 in the long term.
- The RTA project is mostly a software project with limited hardware investment, as the GPU farm will be provided by the collaboration. It should allow some flexibility in terms of human resource investment.
- Overall, the risks are well assessed. In particular, a data acquisition efficiency of 50% is assumed during the first year of Run 5 to cope with a probable commissioning period to optimise the algorithms with data. Moreover, the experience gained during Runs 3 and 4 will consolidate the project for Run 5.
- A well-structured plan for the required volume of Monte-Carlo (MC) samples is essential to prepare the RTA system for the Upgrade II. MC simulations are crucial for modelling physics processes in the high-luminosity collision environment. The upgraded detector requires detailed simulations to account for radiation effects, material interactions and reconstruction efficiencies. In addition, MC simulations are essential for training ML algorithms.

4.3 Recommendations

- The main part of the RTA project in France is the development of the Allen framework (WP1), for which the project will allow portability for external use. The Scientific Council recommends to maintain the same level of involvement, visibility and dynamism for the LHCb Upgrade II.
- Although undoubtedly promising, the use of specific machine learning techniques (such as Graph Neural Networks, Large Language Models, etc.) within the project is still preliminary and probably deserves further investigation before deciding to implement them in a production context. In particular, the question of error propagation control remains. This question is little studied and poorly understood in general and in the literature, leading to possible uncontrolled biases in data selection, or sub-optimal solutions.
- Regarding Monte-Carlo production, it is recommended that the CC-IN2P3 be consulted quickly on the hardware requirements and corresponding cost estimates to support such an unprecedented dataset footprint, and that the contribution expected from IN2P3 be made clear. This budget should be explicitly included in the funding request.
- Regarding human resources, the WP2 (AI/ML) relies mainly on PhD/post-docs to test new ML algorithms. It is recommended to reinforce this activity also with permanent positions and/or to look for new collaborators. One also recommends to secure the necessary human resources beyond 2027-28.
- Regarding hardware, the Scientific Council recommends to monitor the possible impact of export restrictions on the GPU technology and the risk of technology obsolescence.
- Concerning the WP4 (Heavy Ions), the Scientific Council recommends to study how the scientists coming from ALICE and planning to join LHCb could contribute to strengthening this activity.
- In the long term, the AI/ML field is strategic for IN2P3: the Scientific Counclil recommends to keep developing what will be a key skill for future projects in HEP and to propagate these skills to new generations of physicists and engineers.

- The project PIs recognise the need to remain flexible with evolving hardware technology, market fluctuations, and possible monopoly situations. This flexibility helps to adopt new technologies and approaches. However, the Scientific Council encourages the project PIs to clearly assess milestones for the decision process in the future, to decide when to freeze the technology choices. Within the same budget envelope, it is also recommended to consider a wider range of accelerators (GPU, FPGA, etc.) to ensure optimal performance.

In conclusion, the Scientific Council strongly supports the RTA project, as it is considered to be of strategic importance for both the LHCb collaboration and IN2P3.

5 The Data Acquisition project

5.1 Introduction and highlights

Upgrading the DAQ system from the PCIe40 board to the PCIe400 board is required to increase bandwidth and accommodate the data throughput following Upgrade II. In addition, the implementation of new protocols and interfaces, such as the lpGBT protocol and Versatile Link+ (VTRx+) transceivers, is essential to support next-generation front-end ASICs in LHCb detectors and overcoming the limitations of previous technologies. An improved time distribution from white-rabbit to lpGBT is required to take advantage of the improved time resolution offered by the Upgrade II detectors. The development of the readout board for Upgrade II is planned in two phases: the first phase will be the development of the PCIe400 board (a prototype of which already exists), and the second phase will be the design of the board for Upgrade II. The PCIe400 board will be used already during Run 4 to instrument the readout of the RICH and the downstream tracker.

5.2 Comments

- The IN2P3 team is widely recognised for its expertise and leadership in both hardware development (since PCIe40) and low level interfaces, including common firmware and frameworks.
- The project is well organised and the key points are well identified.
- The architecture chosen for the PCIe400 board, directly inherited from PCIe40, is at the state of the art and a first prototype is already available.
- Good timing distribution was identified as being of paramount importance, and preliminary studies showed that this requirement should be met by the new system. However, further studies on a larger scale are required and are already being planned. A backup scenario has already been identified. It consists in using the PCIe40 for timing distribution in addition to dedicated PCIe400 DAQ boards.
- The FPGA is the main cost driver of the PCIe400 board. For the prototyping phase, the largest FPGA was chosen as there were no clear specifications from the LHCb Collaboration at this stage. Further optimisation should be possible in the near future. LHCb has already mandated a working group to optimise the entire readout chain, which will certainly provide valuable input. Another important input should come from porting the already existing algorithms implemented on the PCIe40 board to the PCIe400 board, taking into account the increased detector granularity.

- At this stage it is not clear to the Scientific Council whether a further upgrade (namely the Upgrade II) of the DAQ board will be required. In the absence of a clear development plan, the funding requested is on the high side (around 600 k€). It should be noted that the funding requested is three times higher than the funding requested for Long Shutdown 3.

- A concentrator board is already under discussion in the Collaboration to further optimise the use of the new DAQ system based on the PCIe400 board. If such a development is required, the present plan of the team is to develop it at CPPM. However, the necessary human resources have yet to be identified, either internally within IN2P3 or externally within the LHCb collaboration.

- The Scientific Council believes that the identified shortfall in human resources could jeopardise the timely and successful completion of the LS3 DAQ system.

5.3 Recommendations

- The Scientific Council recommends that the team develop a plan in a timely manner to mitigate the potential loss of leadership following the departure of the scientific coordinator.

- The already identified lack of resources in the development of timing distribution, should be addressed as soon as possible. This could be done either by identifying expertise within IN2P3 or externally in the LHCb Collaboration.

- The Work Package 2 gateware development focuses on the low level interface, in addition to the framework for versioning and for the continuous integration of gatewares specific to the sub-detectors. The integration tests with sub-detectors will require significant effort in terms of gateware development and technical support. The team needs to assess whether more effort can be allocated to ensure successful integration tests.

- The Scientific Council recommends that this IN2P3 flagship project at CERN should be strongly supported and that the team should actively seek to broaden the involvement of other IN2P3 laboratories and LHCb collaborators.

6 Conclusion

Regarding the choice of different scenarios, the middle scenario is expected to provide good physics performance while being less challenging in terms of detector development and less expensive. It seems to the Scientific Council to be a very good balance between cost and physics, although it could probably be further optimised. On the other hand, the trade-off seems less interesting for the low scenario case, which would be particularly detrimental, for example for charm physics which is one of the flagships of LHCb. The low scenario guarantees a lower cost but has a non-negligible impact on the overall expected sensitivity, as the more comfortable recording conditions cannot compensate for the drop in integrated luminosity.

The contribution to the LHCb Upgrade II project is a key activity for the future of IN2P3. The upgrade projects undertaken by IN2P3 are well balanced, the planning is realistic taken into account the expected human resources, and the technological challenges are both ambitious and achievable. The community is dynamic and will grow in the coming years providing timely support from IN2P3.