LHCb France input to the IN2P3 national prospects 2020-2030

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The Standard Model of Particle Physics includes a set of particles which have now all been discovered. The complete set of measurements performed over decades are in agreement with its predictions. In spite of those successes, there are solid reasons to believe that the Standard Model is an incomplete theory, but the new physics is yet to be discovered.
Indeed, beyond these extraordinary successes, fundamental questions remain. The Cabibbo-Kobayashi-Maskawa matrix, which parametrises the mixing of quark flavors, displays a clear hierarchical structure that the Standard Model does not explain. New particles are also expected to help understanding for example, Dark Matter, but none

have been discovered so far at the LHC. In addition, although many extensions to the Standard Model have been developed, they do not all clearly point to a single mass scale at which new physics is expected to be found. Eventually, we do not know whether the Standard Model may be valid up to the Planck mass and why.

In this context, very high precision measurements in the flavour sectors can play a leading role since flavour changing neutral currents are sensitive to new particles with a mass scale far beyond the one available at the LHC. In addition, understanding pattern of deviations in a large set of measurements is a meaningful strategy to understand the nature of new objects. Therefore, precision measurements from indirect search coupled to the direct ones are the best tools to progress in that field. In the coming decade, the experimental program will be dominated by LHCb and Belle II in the flavour sector and by the general purpose experiments ATLAS and CMS.

The Belle II experiment will mainly study the B^+, B^0 mesons at the e^+e^- machine at KEK, although it is also expected to make important contributions to the study of charmed mesons. The data taking is foreseen to last until 2027, aiming to collect $50\,\mathrm{ab}^{-1}$. This experiment is very complementary to LHCb namely for its capability to detect neutral particles and reconstruct final states with neutrinos. It will provide similar sensitivity for observables which can be measured by LHCb with the integrated luminosity collected up to Run 3, helping to confirm critical discoveries and to understand the nature of any discovered new physics.

LHCb is a general purpose forward detector at the LHC, optimized to allow a precise characterization of quark mixing and to search for new physics in rare or forbidden decays of beauty and charm hadrons. The current LHCb detector has proven enormously successful, running at twice the design luminosity during Runs 1 and 2 at the LHC and demonstrating the ability to make precise measurements of matter-antimatter asymmetries, discovering CP violation in charm and in B_s^0 mesons, discovering new exotic hadrons, and studying electroweak and heavy-ion phenomena in the forward direction. It has also made crucial measurements of rare decays as well as tree- and loop-level semileptonic decays of beauty hadrons, finding several deviations from the Standard Model. While not yet conclusive, these measurements are presently the single, coherent array of deviations in collider physics, and they continue attracting substantial theoretical activity.

LHCb is upgraded during the ongoing long shutdown LS2 (2019-2020) in order to run at a luminosity 5 times higher, $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, than the current one, with a full rebuild of the tracking system and the removal of the hardware first level trigger in favour of a fully flexible real-time data processing based on commodity computing hardware. This new detector has been funded and approved to take data until 2029.

Motivated by its success and the lack of evident systematics limitations to its key measurements, the LHCb collaboration prepared an expression of Interest [1] and a physics case [2] for further upgrades of the detector during LS3 (2024-2026) and LS4 (2030), eventually culminating in the ability to run above an instantaneous luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and aiming to collect at least $300\ \mathrm{fb}^{-1}$ of integrated luminosity during the High Luminosity HL-LHC period. These documents were very well received by the LHCC and the collaboration will deliver a Framework TDR by the summer 2021. The European Strategy for Particle Physics noted that "The LHCb Upgrade II (...) will enable a wide range of flavour observables to be determined at HL- LHC with unprecedented precision, complementing and extending the reach of Belle II, and of the high transverse-momentum physics programme" [3].

The French community has played a major role in LHCb since its beginning. Our first priority in the next ten years will be to continue the exploitation of LHCb data and ensure the success of the LHCb upgrade. We are convinced that the proposed future upgrades of LHCb are crucial for the field. In particular, we are motivated to build such an ultimate LHCb detector to:

1. Test the Standard Model picture of quark mixing at the per mil level;
2. Search for the presence of new physics in rare decays, in tree- and loop-level semileptonic modes, and, if successful, use this unprecedented statistical precision to characterize its properties;
3. Search for new long-lived particles beyond the Standard Model;
4. Characterize forward particle and heavy flavour production in Ion and fixed-target collisions with ultimate precision.

There is therefore a growing activity in France dedicated to these upgrades. In particular, we are participating in R&D for future upgrades of the tracking system, the readout boards, the software trigger, and the calorimeter. We also proposed additional instrumentation to greatly enhance LHCb's ability to directly search for new long-lived particles. These areas of R&D are closely connected to the above physics interests:

- At a luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ bunch crossings at LHCb will be saturated by the signal. For example, every bunch crossing will produce a charm hadron in the detector acceptance. It is therefore of prime importance to develop reconstruction strategies based on modern highly parallel computing architectures which can enable an affordable but fully flexible real-time reconstruction and analysis of LHCb's data in this environment.
- Greatly reducing the vertex detector material budget and augmenting its pixels with $O(100)$ ps timing capability will be crucial in enabling the real-time reconstruction of collisions at a luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, accurately associating particle decays to pp collisions for pileup suppression, reducing systematic uncertainties linked to reconstruction efficiencies, and improving the detector resolution for processes with missing energy such as the crucial tree-level semileptonic beauty hadron decays.
- Greatly improving the spatial granularity of the tracker in the region close to the beamline, for example using CMOS sensors, will be crucial for enabling an accurate and affordable real-time reconstruction.
- Improving the energy and position resolutions of the Electromagnetic Calorimeter and adding timing capability to its readout will be crucial in allowing neutral particles to be associated to pp collisions. Such an upgrade will maintain LHCb's ability to study modes with electrons, photons, and other neutral particles, ensuring the breadth of the physics program and allowing complementary ways to characterize any discovered new physics.
- The DELPHI cavern, situated next to the LHCb experimental area and partially shielded by a concrete wall, is an ideal location to place a detector for very long-lived particles which would otherwise be hard to detect or distinguish from backgrounds inside the LHCb acceptance. As the LHCb trigger farm is moving

to the surface, a space of 1000 cubic metres will become available, and French LHCb members proposed to inexpensively instrument this space with RPCs and potentially calorimetry. This proposal, called CODEX-b, would be sensitive to a wide range of New Physics models, with sensitivity which is both competitive with and complementary to similar proposals (MATHUSLA, FASER, SHIP,...) and at a much lower price than most of them. Furthermore, because of LHCb's triggerless readout, events of interest in CODEX-b can be naturally linked to activity in LHCb, allowing any signals to not only be observed but also characterised. It is proposed to install an 8 cubic metre demonstrator for CODEX-b already in Run 3, in order to prove the detector concept and understand any issues before proceeding to the full detector in Upgrade 2 of LHCb.

French LHCb groups intend to leverage their existing and longstanding expertise in these areas to make important contributions to the design and construction of future LHCb upgrades, and to play a major role in the full exploitation of the collected data.

References

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