

# Contributions of the CMS group of Institut Pluridisciplinaire Hubert Curien (IPHC) to the French ESPPU consultation

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## Abstract

This contribution is the outcome of two brainstorming sessions with the permanent and post-doctoral researchers of the CMS-IPHC group. We are convinced that it is of the most importance to have the next collider at CERN both for scientific reasons as well as to keep expertise for the construction of the next generation of detectors and accelerators. We prioritize FCC-ee for its precision in Standard Model studies not restricted to the Higgs sector, and future upgrade potential to a hadron collider (FCC-hh), which provides a long-term, sustainable infrastructure. The group highlights also the importance of continuing detector and accelerator R&D, beyond FCC-ee, and of minimizing the ecological footprint.

## 1 Scientific motivations for a new collider

First, it is worth remembering that the primary scientific questions for the next collider include understanding the stability of the electroweak vacuum and the shape of the Higgs potential, verifying if the Standard Model (SM) accurately describes particles and their interactions at higher energy scales, and exploring the origin of matter-antimatter asymmetry. Additionally, physicists seek to determine the origin of neutrino masses, dark matter, and dark energy, as well as to resolve the strong CP problem and the hierarchy problem that challenge current theoretical models. Naturally, the physics program of any new collider should focus on addressing these questions, which will advance our understanding of fundamental physics beyond the SM.

### 1.1 General considerations

The group acknowledges that a future collider must balance precision studies (such as Higgs physics) and the exploration of new physics beyond the SM. In particular, our group highlights the need for a collider that can address both, direct searches for new particles and indirect searches using Effective Field Theory (EFT) methods.

The group emphasizes the importance of building the next collider at CERN not only for advancing scientific knowledge but also for maintaining Europe's leadership in the field of high-energy physics (HEP) and ensuring continued expertise in building the next-generation detectors and accelerators. Therefore our primary focus is on collider options at CERN, comparing the FCC-ee (Future Circular Collider for electron-positron collisions), ILC (International Linear Collider), and CLIC (Compact Linear Collider). Each collider offers unique strengths:

- **FCC-ee:** High luminosity and flexibility with up to four experimental sites make FCC-ee particularly suitable for precision measurements of the SM parameters and indirect searches for Beyond Standard Model (BSM) physics. Although FCC-ee's centre-of-mass energy is limited to 365 GeV, which limits some direct BSM searches, its infrastructure could later support a high-energy hadron collider, FCC-hh, enhancing its long-term value.

- **ILC and CLIC:** Both would allow for beam polarization and would achieve higher centre-of-mass energies (500 GeV and beyond), which would allow for the production of processes like ZHH and ttH, facilitating Higgs self-coupling studies.

Precise measurements of the top mass and the Higgs mass will give us a point in the  $m_t$  vs  $m_H$  plane. The best top mass measurement would be achieved at FCC-ee, due to its narrow beam energy spread. The high luminosity of FCC-ee will allow us to characterize with ultimate precision the SM particles (W, Z, top and Higgs) and the electroweak symmetry breaking mechanism. Also, the “Tera Z” allows for high precision measurements of SM parameters such as  $\alpha$ ,  $\alpha_s$ ,  $\theta_W$ . The measurements at the Z peak will be very important in order to reduce systematic uncertainties at other energies.

## 1.2 Importance of Higgs physics

With the next collider, we clearly want to learn more about the Higgs boson (its total width, invisible and rare decays, the couplings to SM particles, and the self coupling). It is not necessarily clear for us which project among FCC-ee, ILC or CLIC, would provide the best scientific results on this question. FCC-ee will deliver the largest luminosity for ZH production, while ILC and CLIC would take advantage of a polarized beam. Even if the self-coupling could be studied at FCC in ZH production, we see as a drawback for FCC-ee that it does not reach a 500 GeV centre-of-mass energy which would kinematically allow the ZHH and ttH production, while ILC or CLIC could. We probably need either an about 10 TeV ee machine, a FCC-hh or a muon collider to study the self-coupling with an improved precision compared to the HL-LHC.

## 1.3 Continuing the search for new physics

Pending questions that cannot be solved within the SM need to be addressed by a dedicated scientific program. Electron-positron colliders could explore the direct BSM phase space at low masses and/or low couplings, and indirectly probe very high masses (up to tens of TeV) through EFT fits. FCC-ee will benefit from high statistics at the Z pole, while CLIC (and to a lesser extent, ILC) would enable probing higher masses directly due to their larger centre-of-mass energies. However, only the FCC-hh, in the more distant future, would extend this range beyond the HL-LHC capabilities.

Therefore, the ability to reuse the FCC-ee tunnel for the FCC-hh is seen as a long-term advantage. The group also stresses the importance of completing the HL-LHC (High-Luminosity LHC) program up to 2-3 at-1, as it will provide the only means of directly searching for heavy resonances over the next few decades.

# 2 Considerations on technology and future R&D, international and political context, and environmental aspects

## 2.1 Technology and Future R&D Directions

The FCC-ee feasibility study is ongoing and should be able to conclude about the technological capacity to construct such a collider. The situation regarding the maturity of technologies does not seem clear for CLIC, and hosting the ILC project at CERN seems under consideration. In a somewhat similar situation, the possibility of a Muon Collider seems particularly appealing, but is expected to be mature only in a far future. Therefore, considering the various options of a next  $e^+e^-$  collider at CERN, we think it is important for the future of the field that the next collider comes within a reasonable time scale. This aspect should also be considered.

The group emphasizes the importance of pursuing research and development (R&D), primarily for detector concepts for future  $e^+e^-$  collider at CERN. The fact that up to 4 experiments could be installed at FCC-ee is clearly an important advantage too, and requires significant involvement of the community to develop complementary and innovative detector concepts. But also beyond the next  $e^+e^-$  collider, R&D for next-to-next collider at CERN should continue. In particular, this concerns magnet R&D for the FCC-hh and Muon Collider R&D.

## 2.2 International Context

The international landscape regarding collider projects, particularly in relation to potential competition from the CEPC (Circular Electron Positron Collider) in China, has to be thought of. There is concern that China’s rapid positioning for the CEPC could undermine European efforts, with the risk of Europe losing its leadership in collider research.

Concerns are also raised about the implications of pursuing an CEPC in China, particularly for researchers who do not want to engage in projects outside of Europe due to environmental and logistical issues (such as the carbon footprint of international travel), or even for political reasons. A new collider will in any case make people travel as it will be an international project, but the concern is raised that European people may disengage from collider physics to choose other physics topics.

The group concludes that CERN should continue to lead the next collider project, independently of CEPC’s decision in China. CERN has already the infrastructure, knowledge and know how to do it.

## 2.3 Environmental Considerations

A crucial point raised throughout the discussion is the importance of environmental responsibility. The next collider project at CERN must incorporate green technologies and minimize the ecological footprint. It is noted that the project must minimize energy and resource consumption for construction, operation and computing, and strive for a “green” collider to align with modern environmental priorities. It is of utmost importance that the community spends a significant effort in reducing the environmental impact, by all means possible, which would also favour widespread support within the scientific community and beyond.

## 3 Conclusion

In summary, the CMS-IPHC group favours FCC-ee as the next collider project, recognizing it as a necessary step for both scientific discovery and sustaining CERN’s technical leadership. The FCC-ee’s precision physics program and potential for expansion into FCC-hh make it an attractive option that aligns with CERN’s long-term vision. This decision, however, should imply continued R&D and commitment to ecological responsibility. Other, non collider programs have to continue, in particular the search for dark matter and neutrino experiments, which address open physics question beyond the Standard Model.