A selection of benchmark studies at FCC-ee

Contribution to Snowmass 2021

Abstract

The FCC-ee is a frontier Higgs, Electroweak, and Flavour factory, to be operated in a 100 km circular tunnel built in the CERN area. In addition to offering an outstanding and largely unique physics program, it serves as the first step of the FCC integrated programme towards 100 TeV proton-proton collisions in the same infrastructure. A selection of significant benchmark studies is proposed. The focus is on measurements that are either unique, or for which the high statistics of FCC-ee lead to the most demanding requirements on detector design or on theoretical calculations. The ultimate goal is that experimental or theory systematic errors match the statistical limit. The list presented in this document is not exhaustive, and will evolve in time.

Introduction

A brief presentation of the FCC project with a set of references and Snowmass contacts can be found here: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF-RF-TF-IF-CompF-TOPIC0-003.pdf. To keep informed on FCC-ee and have access to meetings, you can register to the design study by filling this form. Registration to the FCC-ee design study will not lead to signing anything that has not been agreed to, and commitment is limited to participation to the particular work. Participation to the studies is an opportunity for trail-blazing, original contributions, on the way to detector designs matching the FCC-ee challenges. Please feel free to propose your own.

A non-exhaustive list of studies is presented below. A more extensive document with short descriptions of each of them is available at https://www.overleaf.com/read/dyjpdszrqxhz; it will be regularly updated with more case studies and contacts. Meanwhile, Alain Blondel, Patrick Janot, and Markus Klute are the main entry points to these case studies.

Most studies address essential FCC-ee physics benchmark measurements, giving rise to requirements on detector performance or design, or on the precision of theoretical calculations and tools. These benchmark measurements are part of a largely unique scientific program [1, 2], made possible by the high luminosity, by the 1-4 ppm beam energy calibration at the Z, WW, ZH, and $\mathrm{t\bar{t}}$ energies, and, if possible, by monochromatisation at $\sqrt{s} = m_{\mathrm{H}}$.

- The Tera-Z factory with several trillions of Z produced, offers several orders of magnitude improvements for a variety of electroweak measurements, flavour (b, c, τ) physics, and searches for SM symmetry violations and feebly coupled particles.
- With 3×10^8 W pairs, one can contemplate a relative precision on the W mass of 7 ppm or better, and with over a million top pairs, a precision on the top quark mass to a few tens of MeV and per-cent level determination of its electroweak couplings.
- The Higgs factory, with over one million Higgs bosons produced at $\sqrt{s} \sim 240$ and 365 GeV, will allow model-independent extraction of many of the Higgs couplings (with a precision down to the per mil for the HZZ coupling) and of the total Higgs boson width (with a precision around the per cent). A first model-independent demonstration of the existence of the trilinear Higgs self-coupling can be achieved with a combination of the total cross-section measurements at these two energies. In combination with HL-LHC, a first absolute determination of the top Yukawa coupling can be obtained with a precision better than 3%.
- The possibility to observe the *s*-channel Higgs production, $\mathrm{e^+e^-} \to \mathrm{H}$, leads to a unique chance of measuring the Yukawa coupling of the electron.

This large leap in precision on a variety of electroweak observables, QCD, flavour physics, Higgs and top properties, might lead to the discovery of tiny deviations with respect to the standard model predictions, shedding light on new physics as required by today's mysteries. Moreover, these essential inputs used as "fixed candles" will enhance and maximise the physics reach of FCC-hh at the precision and the energy frontiers, thanks to the strong complementarities and synergies of FCC-ee and FCC-hh [3]. The high luminosity expected at all centre-of-mass energies also opens the possibility of direct discoveries, either with the observation of SM symmetry violations and other new phenomena; or with the direct search for, or observation of, feebly interacting new particles (such as sterile neutrinos, axion-like particles, dark photons, ...) over many order of magnitudes of coupling strengths down to 10^{-11} of the weak coupling.

A first list of benchmark studies

1. Towards an ultimate measurement of $R_\ell = \frac{\sigma(\mathrm{Z}\to\mathrm{hadrons})}{\sigma(\mathrm{Z}\to\mathrm{leptons})}$
2. Towards an ultimate measurement of the Z total width Γ_Z
3. Towards an ultimate measurement of the Z peak cross section
4. Direct determination of $\sin^2\theta^\ell_\mathrm{eff}$ and of $\alpha_\mathrm{QED}(m^2_\mathrm{Z})$ from muon pair asymmetries
5. Determination of the QCD coupling constant $\alpha_\mathrm{S}(m^2_\mathrm{Z})$
6. Tau Physics, Lepton Universality, and Lepton Flavour Violation
7. Tau exclusive branching ratios and polarization observables
8. Z-pole Electroweak observables with heavy quarks
9. Long lived particle searches
10. Measurement of the W mass
11. Measurement of the Higgs boson coupling to the c quark
12. Measurement of the ZH production cross section
13. Measurement of the Higgs boson mass - Part I
14. Measurement of the Higgs boson mass - Part II
15. Inferring the total Higgs boson decay width - Part I
16. Inferring the total Higgs boson decay width - Part II
17. Determination of the HZγ effective coupling
18. Electron Yukawa via s-channel $\mathrm{e^+e^-} \to \mathrm{H}$ production at the Higgs pole
19. Measurement of top properties at threshold and above
20. Search for FCNC in the top sector
21. Theory Needs for FCC-ee
22. Beyond MFV: constraints on RH charged currents and on dipole operators
23. Construction of CP-odd observables to probe CP-violating Higgs couplings
24. Combined fit of Higgs and top data

References

[1] FCC collaboration, A. Abada et al., *FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2*, *Eur. Phys. J. ST* **228** (2019) 261–623.

[2] N. Alipour Tehrani et al., *FCC-ee: Your Questions Answered*, in *CERN Council Open Symposium on the Update of European Strategy for Particle Physics* (A. Blondel and P. Janot, eds.), 6, 2019. 1906.02693.

[3] FCC collaboration, A. Abada et al., *FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1*, *Eur. Phys. J. C* **79** (2019) 474.