Contribution ID: **89** Type: **not specified**

Future strategies for the discovery and the precise measurement of the Higgs self coupling

The European Strategy for Particle Physics (ESSP) submitted in 2013 a deliberation document to the CERN council explaining that a lepton collider with "energies of 500 GeV or higher could explore the Higgs properties further, for example the [Yukawa] coupling to the top quark, the [trilinear] self-coupling and the total width.".

In view of the forthcoming ESPP update in 2020, variations on this qualitative theme have been applied, inaccurately, to the case of the ILC, to argue that an upgrade to 500 GeV would allow the measurement of the Higgs potential and would increase the potential for new particle searches. As a consequence, the strategic question was raised again whether the FCC-ee design study ought to consider a 500 GeV energy upgrade. In this note, we revisit the ESSP 2013 statement quantitatively and find

- that the FCC-ee can measure the total width of the Higgs boson with a precision of 1.3% – the best precision on the market – with runs at $\sqrt{s} = 240$, 350, and 365 GeV, and without the need of an energy upgrade to 500 GeV;
- that the top Yukawa coupling will have been determined at HL-LHC at the $\pm 2.5\%$ level, albeit with some model dependence, without the need of 500 GeV e^+e^- collisions; and that the combination of this HL-LHC result with the FCC-ee absolute Higgs coupling and width measurements breaks the model dependence, without the need of an energy upgrade to 500 GeV;
- that, with the run plan presented for the ILC, the trilinear Higgs self-coupling can be inferred with a 3σ significance from the double-Higgs production cross-section measurement at the ILC500 after three decades of operation; but that the FCC-ee provides a similar sensitivity in 15 years, from the precise measurement of the single-Higgs production cross section as a function of $\sqrt{s}$, without the need of an energy upgrade to 500 GeV;
- that the same FCC-ee, with four experiments instead of two, might well achieve the first model-independent 5σ demonstration of the existence of the trilinear Higgs self-coupling, while a centre-of-mass energy of about 1 TeV or more is required for a linear collider to reach a similar sensitivity in a reasonable amount of time; and that a precise measurement of the trilinear Higgs self-coupling at the few per-cent precision level can realistically only be provided by the combination of FCC-ee and FCC-hh, being beyond reach of lepton colliders with a centre-of-mass energy up to at least 3 TeV.

On the new particle search front, the run plan of the FCC-ee includes an electroweak precision measurement program that is sensitive to new physics scales up to 70 TeV. The Z factory run of the FCC-ee with 5×10^{12} Z decays can discover particles (e.g., dark matter or heavy neutrinos) that couple with a strength down to as little as 10^{-11} of the weak coupling. Finally, the FCC-hh potential for new particle searches at high mass exceeds that of any proposed linear collider project.

We conclude that 500 GeV is not a particularly useful energy for the lepton colliders under consideration, especially for the FCC-ee. A 5σ demonstration of the existence of the Higgs self-coupling is within reach at the energies foreseen for the FCC-ee, with a moderate change of configuration, which certainly deserves consideration.

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Track Classification: Electroweak physics (physics of the W, Z, H bosons, of the top quark, and QED)