Expert contribution to the public debate on FCC

What if we focus on a Higgs Factory?

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Abstract

In the recommendations presented in December 2025 the European Strategy Group (ESG) clearly identified Future Circular electron-positron Collider (FCC-ee) as a preferred option for the future collider at CERN with no alternative. However, it is important to understand that this conclusion resulted from the assumed physics goals. FCC-ee offers the broadest possible research programme covering almost all branches of collider physics. However, it is the construction of an electron-positron Higgs Factory that has been considered as the highest priority in the field for the last twenty years. When we just focus on this goal, a linear collider option has to be considered as an attractive alternative, if the full FCC-ee project can not be realised.

August 2026

Simple example

Particle Physics, operation of giant particle colliders and experiments can be difficult to understand. That is why I tried to find a simple example from everyday life, which could help me visualize the problem.

Consider the situation of a professional birdwatcher who wants to buy the right lens for his camera. A long focal length is needed for this task and dedicated lens with 250-550 mm focal length offer the best picture quality. However, it is also clear that one will not be able shoot nice landscape photos or portraits with such lenses. If the same lens is to be used in different situations, universal zoom lens 90-365 mm would probably be a better choice. It is likely to be more expensive and the quality of bird pictures will not be the same, but it can be used for taking photos in a variety of situations. So the choice of the lens type clearly depends on how we set the priorities.

Priorities in Particle Physics

Higgs boson can be considered a corner stone of the Standard Model (SM), the theory which was developed to describe fundamental particles and their interactions. Even before the Large Hadron Collider (LHC) at CERN was completed and the Higgs boson was discovered by ATLAS and CMS experiments in 2012, it was clear that the next energy frontier collider has to be an electron-positron machine. It was also reflected in the European Strategy for Particle Physics (ESPP) approved by the CERN Council in 2006: "*It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier;*" [1].

The Higgs boson was discovered in 2012 and turned out to be relatively light. The first update of the ESPP concluded in 2013 clearly indicated the need for constructing the Higgs factory: "*There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded*" [2].

Also the 2020 Update of the European Strategy [3] stated that "*An electron-positron Higgs factory is the highest-priority next collider.*" This was clearly driven by the science case: "*Given the unique nature of the Higgs boson, there are compelling scientific arguments for a new electron-positron collider operating as a "Higgs factory". Such a collider would produce copious Higgs bosons in a very clean environment, would make dramatic progress in mapping the diverse interactions of the Higgs boson with other particles and* *would form an essential part of a research programme that includes exploration of the flavour puzzle and the neutrino sector."*

In response to the ESPP recommendations, European Committee for Future Accelerators (ECFA) launched a series of workshops to further explore challenges of the Higgs factory project. One of the goals of the study was to extend our understanding of the physics potential of the considered machines. The facility was described as "Higgs / Top / Electroweak factory", pointing to two other areas or research (top-quark physics and studies of electroweak interactions) where precision measurements at energy frontier were crucial.

After extended discussions within the Physics Potential working group of the study, a list of so called focus topics was defined [4]. These were high priority targets, where further studies were needed for full understanding of the physics potential of the future collider. With clear focus on Higgs, top and electroweak physics, they also included a wide range of other measurements, from precision determination of the actual collider "brightness" (so called luminosity) to direct searches for "new physics" phenomena (effects not described by the SM, but expected in other theories). It is important to note that running of the collider at energies of at least 500 GeV was relevant for 13 out of 14 topics (see Table A.1 in the Appendix). The report concluding the study [5] was submitted as an input to the 2026 Update of the ESPP.

Focusing on Higgs

In many presentation I saw about the FCC-ee, the main focus was put on the Z-pole running with extreme intensity (at energy of 91 GeV) and not on the Higgs physics (Higgs factory running at 240 GeV and above) or top-quark physics (at 350 GeV and above). This change of priorities was also adopted for the 2026 Update of the ESPP and resulted in the recommendation of the FCC- ee as the preferred (and also as an alternative) option for the next flagship collider at CERN [6]. The deliberation document [7] clearly confirms that "*In comparison with the FCC-ee, CLIC1500 and LCF550 would provide a stronger physics programme in top-quark physics and a comparable programme in Higgs physics, although with a better Higgs self-coupling measurement. On the other hand, both colliders would remain significantly less powerful than an FCC-ee-like facility in terms of EWPOs, flavour physics, and precision QCD, which constitute core elements of the full physics programme for the exploration of the Standard Model.*"

In fact, these are flavour physics[1] and QCD studies which result in FCC-ee clearly outperforming other future collider options in overall physics

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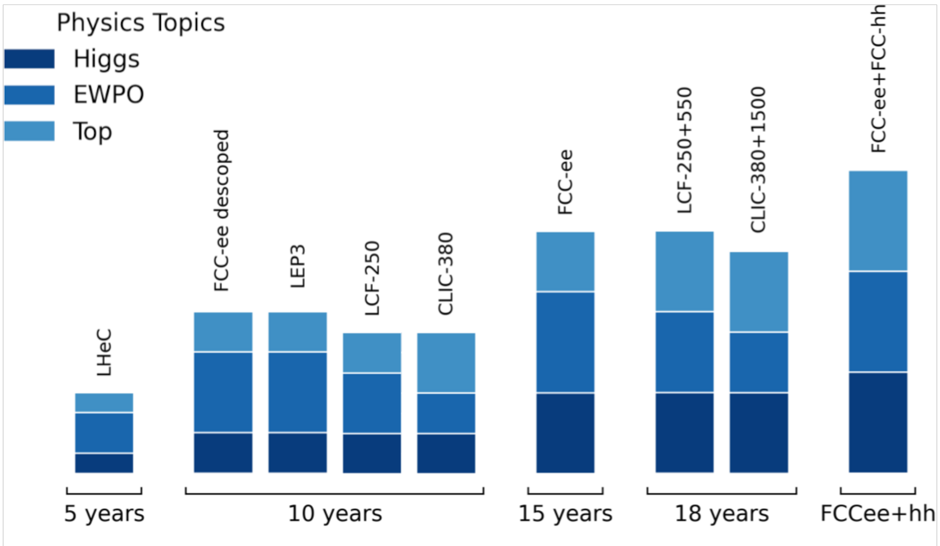
1 Branch of particle physics studying properties of different types (so called "flavours") of fundamental particles, b and c quarks, and tau leptons in particular.

Figure 1: Overall physics assessment of different future collider options if only Higgs, top and electroweak precision measurements are taken into account. Figure adapted from [8], see Appendix for original figure (Figure A.1).



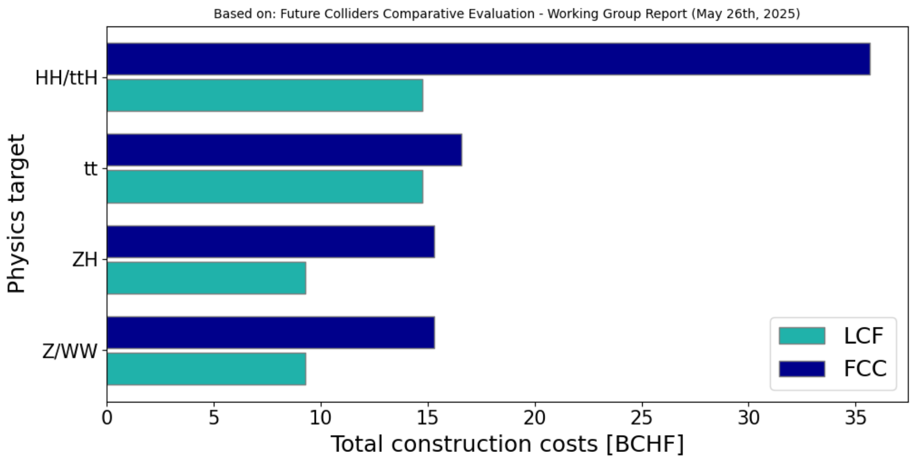
assessment made by the Strategy Group. If only Higgs, top and electroweak precision measurements are taken into account, see Figure 1, linear collider options match the expected performance of FCC-ee. What is still not taken into account in this comparison is that linear colliders, when running at energies of 500 GeV or above (Linear Collider Facility (LCF) at 550 GeV or Compact Linear Collider (CLIC) at 1500 GeV), can also directly measure two extremely important SM parameters: Higgs boson self-coupling and top-quark Yukawa coupling. These two parameters are not directly accessible at FCC-ee (can only be constrained indirectly, which is always based on some additional assumptions) because the collision energy is just too small.

For full exploration of Higgs and top-quark sectors FCC-ee has to be complemented by FCC-hh running at much higher energies, which is clearly considered as a second stage of the project, but usually not included when presenting its cost or the schedule. When just looking at the costs summarized in [9] one can realize that the full exploration of the Higgs, electroweak and top-quark physics at the FCC (FCC-ee followed by FCC-hh) will be much more expensive than at the LCF550 option, see Figure 2.

About precision

When considering the physics goals of the future Higgs factory one should still take two additional factor into account. First, there are other facilities in the world, already running or in the construction phase, where precision

Figure 2: Total construction cost to address different precision measurements of Higgs boson, top quark and electroweak phenomena. Figure prepared by the author based on the data from [9].

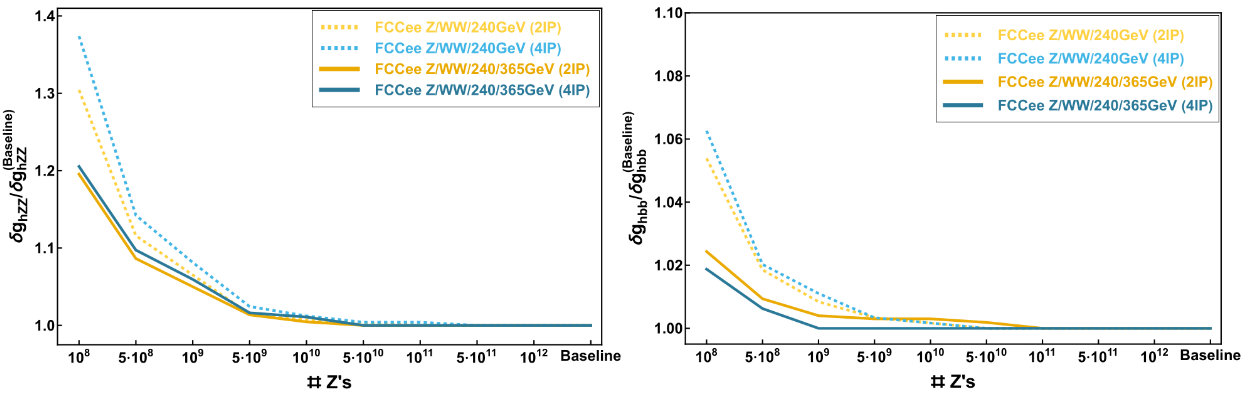


measurements in flavour physics and QCD can be made. Just to mention the Belle II Experiment at SuperKEKB electron-positron collider in Japan expected to run for another 20 years (also including its upgrade) and to improve precision of many flavour measurements by an order of magnitude, and the Electron Ion Collider (EIC) under construction in the US with a wide range of precision QCD studies planned. Also at CERN, the LHC experiment dedicated to b-quark physics, LHCb, will greatly improve precision of flavour measurements in the High Luminosity LHC phase (HL-LHC), collecting two orders of magnitude more heavy quark events than it is possible at the FCC-ee. Enormous progress in these research domains in the next decades is already guaranteed.

FCC-ee could most likely further improve precision of many QCD and flavour measurements, and electroweak precision observables. However, the question remains, if this increase is crucial. Will the higher precision of the measurements considered have an actual impact on our understanding of the Universe?! For each measurement, there is a precision threshold beyond which our understanding of the Universe is hardly affected. With six trillion ($6x10^{12}$) Z bosons produced, FCC-ee should be able to measure Z boson mass (91.2 GeV) with statistical precision of 4 keV. But this is like measuring the distance from Orleans to Paris (111 km) with 5 mm precision. This can be done (with proper choice of reference points in the two cities), but is clearly not relevant for most applications.

We come back to the question of priorities. As shown in the FCC-ee Midterm Report [10], see Figure 3, from the perspective of the Higgs couplings analysis, it is sufficient to collect few billions (10^9) of Z events to approximately saturate the expected precision of the physics programme. This is also the reason why

Figure 3: Estimated decrease in the precision of the HZZ (left) and Hbb (right) couplings as a result of a reduction in the number of collected Z events. Figure from FCC Midterm Report [10].



the baseline running schedule for LCF at CERN assumes collecting only 5 billion of events at the Z pole. When focusing on the Higgs physics, this is all we need.

Conclusions

The broadest possible research programme offered by the FCC-ee resulted in the recommendation of the facility as the preferred option for the next flagship collider at CERN. Still, I do think that recommendation of an alternative option should not be based on the same selection of research goals. If we can not secure resources required for the FCC project, we should rather consider redefining our priorities, narrowing the list of our objectives. Future electron-positron collider is the only option for most precise measurements of the Higgs boson and this should be adopted as a primary goal for any alternative collider option.

If we just focus on the Higgs physics, but also when we include top-quark and electroweak research programme, the linear collider option has to be considered as an attractive alternative to FCC-ee. The project is mature and technically feasible, and offers physics programme comparable to that of FCC- ee, at significantly lower initial cost and environmental footprint.

LCF option for CERN also allows for much greater flexibility. After the initial physics programme is completed, different upgrade options (both luminosity and energy upgrades) can be considered, depending on the technology developments but also physics results obtained until then (including final results from HL-LHC !). In 25 years we should be able to make a much more knowledge-based decision about the next collider and the future of our field.

About myself

I am a full professor at the Faculty of Physics, University of Warsaw, with 40 years of experience in experimental particle physics and phenomenology of fundamental interactions. My adventure with particle physics started in 1986 when I joined an international collaboration of the ZEUS experiment at DESY, Hamburg. I contributed to the prototype tests, detector construction and commissioning. After the experiment started to collect data, my activities focused mainly on searches for "new physics" phenomena (signatures of effects not described the SM). This remains one of my main topics of interest until today.

Over the years I contributed to multiple studies addressing the physics potential of different future collider projects including linear electron-positron colliders, electron-proton and photon-photon colliders. Since 2010 I have been involved in the activities of the International Large Detector (ILD) concept study group. ILD detector was initaily proposed for the International Linear Collider (ILC) in Japan, but is now considered also for FCC-ee and Linear Collider Facility at CERN. In 2015 I also became a member of the CLIC (Compact LInear Collider) detector and physics (CLICdp) collaboration at CERN. I was appointed a Coordinator of the Physics Working Group of the ILD and Convener of the Analysis Working Group of the CLICdp, which I also consider as a recognition of my contributions to both collaborations.

My contributions to the European Strategy

I have participated in the discussions on the European Strategy for Particle Physics (ESPP) since the "Open Symposium" held in Orsay in 2006. In 2009-2014 I was selected as a representative of the Polish High Energy Community in the Restricted ECFA (European Committee for Future Accelerators). Nominated by RECFA, I was involved in the first update of the ESPP in 2013 as a member of the so called Preparatory Group. I contributed to the organization of the second Open Symposium in Krakow in 2012, writing the Physics Briefing Book as an input for the Strategy Group to draft the update, and to the strategy drafting session in Erice, in January 2013. I was also involved in the preparation of the Polish community input submissions to the initial ESPP discussions and the following updates, including the last one [11].

To the final ECFA Higgs / Top / Electroweak factory study report [5] submitted as an input to the 2026 Update of the ESPP my group at the University of Warsaw contributed with results from seven different studies. I also contributed to the inputs submitted by the ILD study group [12] and the LC Vision collaboration [13-14]. I also submitted my individual contribution [15] summarizing my critical remarks to the way the strategy process was ongoing.

Glossary of acronyms

CLIC (Compact LInear Collider): concept of linear electron-positron collider developed at CERN, based on normal-conducting accelerating cavities. Three construction/energy stages were proposed for CLIC: 380 GeV (**CLIC380**), 1500 GeV (**CLIC1500**) and 3000 GeV (**CLIC3000**).

EWPOs (ElectroWeak Precision Observables): parameters describing electroweak interactions, which can be very precisely measured in an experiment and compared with very precise theory calculations to constrain Standard Model parameters or search for possible deviations from its predictions.

ECFA (European Committee for Future Accelerators): committee advisory to CERN Management, CERN Council and its Committees. Restricted ECFA (RECFA) is composed of one member per country from all CERN member states and acts mainly as the communication channel to each participating country.

ESPP (European Strategy for Particle Physics): first prepared in 2006 and then updated every 6-7 years, addresses the main lines of Particle Physics in Europe, accelerator-based and non-accelerator based, defines the medium-and long-term priorities of the field.

ESG (European Strategy Group): mandated by the CERN Council to establish a proposal for the ESPP (or its update), to be approved by the Council.

FCC (Future Circular Collider): proposed next circular collider at CERN. Two stages are considered for FCC: electron-positron collider (**FCC-ee**) with energy reach up to 365 GeV and proton-proton collider (**FCC-hh**) with energy up to 100 TeV.

ILC (International Linear Collider): concept of linear electron-positron collider based on superconducting accelerating cavities considered for construction in Japan. Two construction/energy stages were proposed for ILC: 250 GeV (ILC250) and 500 GeV (ILC500), with possible upgrade up to 1 TeV.

LHC (Large Hadron Collider): circular proton-proton collider at CERN, running since 2009, currently being upgrade to high luminosity phase (**HL-LHC**), expected to run until early 2040s.

LCF (Linear Collider Facility): concept of linear electron-positron collider for CERN, based on superconducting accelerating cavities considered previously for ILC. Two construction/energy stages were proposed for LCF@CERN: 250 GeV (**LCF250**) and 550 GeV (**LCF550**).

QCD (Quantum Chronodynamics): theory describing strong interactions. Strong interactions are responsible for binding quarks inside protons and neutrons (and many other particles called hadrons) and for binding protons and neutrons inside atomic nuclei.

SM (Standard Model): the theory combining description of electromagnetic, weak and strong interactions, summarizes our understanding of fundamental particles and the structure of matter.

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Appendix

Table A.1: Overview of ECFA study focus topics and relevant centre-of-mass energies. Energies applicable to the considered topic are indicated with '✓'. Table taken from [4].

	Topic	Lead group	Relevant $\sqrt{s}$ [GeV]				
			91	161	240–250	350–380	$\geq$ 500
1	HtoSS	HTE			✓	✓	✓
2	ZHang	HTE (GLOB)			✓	✓	✓
3	Hself	GLOB			✓	✓	✓
4	Wmass	PREC		✓	✓	✓	✓
5	WWdiff	GLOB			✓	✓	✓
6	TTthres	GLOB (HTE)				✓	✓
7	LUMI	PREC	✓	✓	✓	✓	✓
8	EXscalar	SRCH			✓	✓	✓
9	LLPs	SRCH	✓	✓	✓	✓	✓
10	EXtt	SRCH				✓	✓
11	CKMWW	FLAV		✓	✓	✓	✓
12	BKtautau	FLAV	✓				
13	TwoF	HTE (PREC)	✓	✓	✓	✓	✓
14	BCfrag and Gsplit	PREC (FLAV)	✓	✓	✓	✓	✓

Figure A.1: Overall physics assessment of different future collider options in terms of precision physics, as presented by Karl Jakobs at European Strategy Colloquium at CERN, February 2026 [8]. Also included in [7].