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Statement from the Americas Linear Collider Committee to the P5 subpanel

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Abstract

This statement from the Americas Linear Collider Committee to the P5 subpanel has three purposes. It presents a brief summary of the case for an e^+e^- Higgs factory that has emerged from Snowmass 2021. It highlights the special virtues of the ILC that are shared with other linear colliders but not with circular colliders. Finally, it calls attention to the resources available in an ILC White Paper submitted for for Snowmass 2021. The ALCC urges P5 to move the Higgs factory forward as a global project by assigning the idea of an e^+e^- Higgs factory high priority, initiating a global discussion of the technology choice and cost sharing, and offering the option of siting the Higgs factory in the U.S.

We are writing to convey the input of the Americas Linear Collider Committee (ALCC) to the P5 deliberations. The ALCC provides the interface between the international organization of the International Linear Collider (ILC) and laboratories, universities, and governmental agencies in the U.S. and elsewhere in the Americas. The members of the ALCC have devoted considerable time and effort over many years to the realization of the ILC because we feel that this project is essential to the progress of particle physics.

The Snowmass 2021 process has led to a great deal of information-gathering and community discussion on the future of the Energy Frontier in general and on e^+e^- Higgs boson factories in particular. This has led to a refined understanding of the case for an e^+e^- collider as the next global project in particle physics. This letter then has three purposes. First, we present a summary of the case for a Higgs factory that has emerged from Snowmass 2021. Second, we highlight the special virtues of the ILC that are shared with other linear colliders, but not with circular collider Higgs factory proposals. Finally, we call your attention to the resources that we have made available to you in the ILC White Paper for

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Snowmass (arXiv:2203.07622), which our committee has put together in collaboration with the ILC International Development Team established by ICFA and with the ILC community. That report provides a detailed justification for all aspects of the summary statement that we provide here. We will separately provide additional brief notes on budget and schedule of accelerator and experiment R&D and engineering design.

The case for a Higgs factory

Why is it so important to study the Higgs boson? It is well understood that the Higgs boson has a central role in the Standard Model. But what must be emphasized even more is that the Higgs boson is centrally responsible for the *mysteries* of the Standard Model. The framework of the Standard Model is provided by its particle content and gauge symmetry, but the physics of the model is controlled by numerous parameters whose origin we do not understand. The key to the weak interactions is the spontaneous breaking of the gauge symmetry (the Higgs mechanism). But whether or not this occurs depends on the Higgs mass parameter and self-coupling. The masses of the W and Z bosons, which set the scale of weak interactions, also depend on these values. Physics models that seek to explain these values invoke new particles, from additional bosons of a larger Higgs sector to concepts such as supersymmetry and Higgs field compositeness. The very existence of electroweak symmetry breaking suggests that there are new interactions at short distances waiting to be discovered.

Our lack of understanding of the Higgs boson is actually a crucial issue for all of the frontiers of particle physics. Flavor physicists seek to explain the masses and mixings of quarks and leptons. But in the Standard Model, these arise from the fermion-Higgs Yukawa couplings. CP violation also appears uniquely in the Yukawa couplings. Models of flavor are built using the ingredients of the Higgs sector models discussed in the previous paragraph. If we have the wrong picture there, we cannot build a correct model of flavor. Similarly, neutrino masses and mixings require electroweak symmetry breaking and so must also rely on our understanding of the Higgs field. In the cosmic frontier, it is possible to build models of dark matter that are independent of any other particle sector. But the most studied models of dark matter either use the new interactions responsible for electroweak symmetry breaking (as with supersymmetric dark matter candidates) or describe the dark matter particle itself as a Higgs-like particle (as with the axion). For all of these questions, there is no full understanding until we understand the Higgs field.

Since the values of the Standard Model parameters are now well known, we can make precise predictions within this model and search for anomalies that would signal new physics. We are now carrying out such searches at low energies with precision measurements, in rare weak interaction particle decays, and in particle searches at the high energies offered by the LHC. Oddly, the one place where we are not yet placing significant constraints on new physics is in the study of the Higgs boson itself. Explicit models of new physics predict deviations in the Higgs boson properties at the 10% level and below. Currently, the LHC measurements of Higgs boson processes, however technically impressive, are not yet in the game of searching for new physics. By the end of the HL-LHC, the ATLAS and CMS experiments expect to constrain Higgs boson couplings at the few-percent level. This may be sufficient to observe deviations from the Standard Model, but it is likely not sufficient to prove that the observed deviations are real. For this, we will need a different collider that is better adapted to achieving high precision while controlling systematic errors.

The ALCC and its international partners have given considerable thought to the issue of observing beyond-Standard-Model effects in the Higgs boson properties. We believe that experiments with e^+e^- colliders are necessary. At hadron colliders, even the simple observation of Higgs boson processes is complex and requires a sophisticated analysis. In e^+e^-, this starting point is straightforward to achieve. From this point, one can go forward with increasing sophistication to measure the rates and distributions for Higgs boson processes with detectors of higher capability than those possible at the LHC, and with more independent observables to provide cross-checks on the level of systematic uncertainties. We anticipate measuring all of the leading Higgs boson couplings to better than 1% precision and the couplings to W and Z to parts-per-mil precision. These coupling determinations will be highly robust, in particular, constraining the Higgs boson width in a model-independent way, even in the presence of exotic decay modes. Thus, we expect to measure the full pattern of Higgs boson decays, exposing deviations from the Standard Model predictions with high significance. This pattern in turn will give clues to the ultimate origin of electroweak symmetry breaking and the principles underlying the Higgs field.

At the same time, we will systematically improve our knowledge of precision electroweak observables. Higgs factories will dramatically improve our knowledge of the nonlinear couplings of the W and Z bosons. And, Higgs factories will be able, for the first time, to carry out precision measurements of the electroweak couplings of the top quark. Many models of new physics that attempt to explain the origin and importance of the large size of the top quark mass predict deviations from the Standard Model in these couplings and in the coupling of the top quark to the Higgs field.

A worldwide consensus has developed that these measurements are centrally important for particle physics, and that the next global accelerator should be an e^+e^- Higgs factory. This conclusion is front and center in the report from the most recent update of the European Strategy for Particle Physics and in the Snowmass 2021 Energy Frontier report. Such a collider is not inexpensive, but its cost is well within the resources of the global particle physics community.

There is also a cost to not building a Higgs factory. Today, the technologies for e^+e^- Higgs factories are the only accelerator technologies that are fully mature, allowing a new collider to be built and operating before 2040. Without a Higgs factory on this time scale, we risk a long period with no operating collider in the world, and perhaps the end of collider physics altogether.

But, we are not making progress toward this goal. The most mature proposal, the International Linear Collider in Japan, appears to be stalled at the level of Japanese government. CERN has proposed the circular collider FCC-ee but by itself does not appear to have the resources to realize this project until the end of the 2040's. FCC-ee is necessarily entangled with the prospects for FCC-hh, which, however attractive, still lacks a demonstration of its technical feasibility and a sharp scientific justification for its large cost. Proposals for a U.S.-sited Higgs factory have been discussed at Snowmass, including ILC in the U.S. and other options. However, we should not restrict ourselves to a strictly regional approach. The world needs a coherent plan, involving all of the regions active in particle physics, to carry out this important physics program on a time scale relevant to the students and postdocs now beginning their careers at the LHC. P5 must help break the impasse by assigning the idea of an e^+e^- Higgs factory high priority, initiating a global discussion of the technology choice and cost sharing, and offering the option of siting the Higgs factory in the U.S.

Linear vs. circular

Proposed Higgs factories come in two types—linear and circular. Both types of accelerator can meet the basic demands of the Higgs factory physics case that we have presented here. However, we feel that the proposed linear colliders—in particular, the ILC—have significant advantages over the proposed circular colliders. It is true that circular e^+e^- collider designs can claim higher instantaneous luminosity than established linear collider designs, at least for center of mass energies up to 250 GeV. However, the ILC offers important compensatory advantages:

1. **Beam polarization:** e^+e^- colliders primarily enable studies of the electroweak interactions, which have order-1 parity violation. In the Standard Model, the left- and right-handed chiral components of fermions have different quantum numbers, signalling a different fundamental origin. With e^+ and e^- longitudinal beam polarization, we can selectively study the properties of these states. This can compensate for smaller luminosity (by a factor of 2.5 in the Higgs boson studies), but more importantly it allows us to study more specific observables.

2. **Design for precision:** Observation of a deviation from the Standard Model will require precise measurements with excellent control of systematic experimental uncertainties. Linear colliders offer a larger suite of tools for this purpose. Examples include the use of power-pulsing of the detector electronics between bunch trains to reduce cooling requirements, allowing a much reduced material budget in the tracker. The experiments can use larger magnetic fields without perturbing the beams, allowing high-resolution, compact detectors. The greater distance between beamline components at the interaction point allows detector coverage to much smaller angles. For control of systematics, electron and positron polarization can be used to produce relatively background-free and background-dominated data sets.

3. **Higher energy:** Though the luminosity of circular e^+e^- colliders is high at low energy, it plummets at center of mass energies above 350 GeV. The luminosity of a linear collider increases roughly linearly with energy, enabling energy upgrades to 500 GeV and beyond. This is part of the ILC plan. It allows us to measure the full suite of top quark electroweak form factors, the top quark-Higgs Yukawa coupling, and the cross section for double Higgs production, sensitive to the Higgs self-coupling. These elements are essential parts of a complete precision measurement program for the Standard Model.

4. **Cost:** Proposed circular Higgs factories require tunnels of order 100 km in size. The estimated cost of the tunnel and civil engineering for the FCC is comparable to the full estimated cost of the 250-GeV ILC.

Resources for P5

Because the question of a global Higgs factory is central to the mission of P5, the ILC community has created a detailed reference work that covers all of the aspects of the ILC program and the program of Higgs factories more generally. This volume, the *"International Linear Collider Report to Snowmass 2021"* [1], is 350 pages long and contains almost 800 references; it represents the work and opinions of more than 500 authors. We do not expect all members of P5 to read the full report, but we expect that many will find this volume useful both as an introduction to Higgs factory physics and as a guide to the literature on this subject. In the next few paragraphs, we review its contents.

Chapters 1–3 provide a general introduction and a description of the ILC accelerator and physics organization.

Chapter 4 describes the ILC accelerator. We claimed above that the ILC is the most mature Higgs factory proposal. In this chapter, we defend that statement through a detailed review of the ILC design and the accelerator issues that it takes into account. This chapter also includes a discussion of the ILC cost, which has been thoroughly reviewed as a part of the evaluation in Japan. It also reviews strategies to make the ILC sustainable ("Green ILC").

Chapter 5 is an introduction to particle physics processes at Higgs factory energies. It gives perspective on the various Standard Model processes and background sources. It also introduces the physics of electron and positron beam polarization, a unique tool of linear e^+e^- colliders, covering both the precision measurement of beam polarization and the variety of its applications to the ILC experimental program.

Chapter 6 describes the detectors for ILC. Two complete designs, ILD and SiD, have been created and studied in detail at the full-simulation level. This discussion brings up to date our current understanding of what is possible for precision measurement in collider physics. Ideas to improve the performance of Higgs factory measurements even further are also discussed. Simulation studies require also a complete simulation framework, which is described in Chapter 7. Projections of physics capabilities quoted later in the book are obtained using full-simulation data and the described analysis toolkit, allowing us to account for all anticipated sources of physics and machine-induced backgrounds and systematic uncertainties.

Chapter 8 reviews in detail the physics simulation studies done for the ILC at a center of mass energy of 250 GeV. The experimental program here is already broad, covering not only Higgs boson measurements but also the highest-precision studies of the W boson couplings and of perturbative QCD. These, and the work described in Chapters 9 and 10, are the most complete studies done for any proposed Higgs factory. However, since the e^+e^- environment is relatively benign, their results can also be used to estimate the capabilities of alternate proposals.

Chapter 9 reviews the capability of the ILC for improved precision measurements of the electroweak interactions. The importance of beam polarization is especially striking in precision electroweak measurements. We show in Chapter 9 that the measurement of $\sin^2\theta_w$ using beam polarization can compensate a factor of 10^3 in luminosity, while at the same time offering better control of systematic errors.

Chapter 10 reviews the physics simulation studies at the top quark threshold and at 500 GeV, covering studies of the Higgs boson in WW fusion and the Higgs self-coupling measurement, measurements of W boson and top quark interactions, the study of fermion pair production, and the direct search for new elementary particles.

Chapter 11 describes the proposed fixed-target program of the ILC, accessing dark sector particles by the use of high energy electron and positron beams and exploring strong-field QED in extreme regimes relevant to active galaxies and cosmic ray production.

Chapter 12 describes the use of Standard Model Effective Field Theory to combine data from Higgs boson, W boson, and electroweak measurements. This method gives the most powerful constraints from experiment to compare to Standard Model predictions, including a model-independent determination of the Higgs boson total width. This chapter also provides a summary of our projections for the values of the uncertainties in the measurement of Higgs boson couplings expected at the ILC.

Chapters 13 and 14 discuss the theoretical interpretation of Higgs factory measurements. Chapter 13 describes how the Higgs factory program sheds light on the major large-scale questions of particle physics. Chapter 14 discusses the comparison of Higgs factory capabilities to the predictions of beyond-Standard-Model theories. This chapter also estimates the new particle mass scales that can be accessed by Higgs factory precision measurements.

Finally, Chapter 15 presents ideas for future colliders that could make use of the ILC Laboratory after the ILC program ends. With new acceleration technologies, the long, straight tunnel needed for a linear collider could be the basis for a program at much higher energy, reaching to 10 TeV and beyond.

We believe that anyone who studies this volume will be convinced that an e^+e^- Higgs factory, especially one based on a linear collider, provides a superb opportunity to advance our understanding of the most important issues in particle physics.

And we expect that, armed with this understanding, P5 will create a plan that will make this opportunity available to the current younger generation of particle physicists.

Acknowledgements

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References

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