DEUTSCHES ELEKTRONEN-SYNCHROTRON
Ein Forschungszentrum der Helmholtz-Gemeinschaft

DESY 20-112
KEK Preprint 2020-8
IFIC/20-34
LCTP-20-14
SLAC-PUB-17543
arXiv:2007.03650
July 2020

ILC Study Questions for Snowmass 2021

LCC Physics Working Group

ISSN 0418-9833

NOTKESTRASSE 85 - 22607 HAMBURG

DESY Zentralbibliothek Notkestraße 85 22607 Hamburg Germany	DESY Bibliothek Platanenallee 6 15738 Zeuthen Germany

DESY 20-112,
KEK Preprint 2020-8,
IFIC/20-34, LCTP-20-14
SLAC-PUB-17543
July, 2020

ILC Study Questions for Snowmass 2021

LCC Physics Working Group

Keisuke Fujii[1], Christophe Grojean[2,3], Michael E. Peskin[4]
(Conveners); Tim Barklow[4], Yuanning Gao[5], Shinya Kanemura[6],
Jenny List[2], Mihoko Nojiri[1,7], Maxim Perelstein[8], Roman Pöschl[9],
Jürgen Reuter[2], Frank Simon[10], Tomohiko Tanabe[1],
James D. Wells[11] (Physics WG); Mikael Berggren[2],
Esteban Fullana[12], Juan Fuster[12], Frank Gaede[2], Stefania Gori[13],
Daniel Jeans[1], Adrián Irles[9], Sunghoon Jung[14], Shin-Ichi Kawada[2],
Shigeki Matsumoto[7], Chris Potter[15], Jan Strube[15,16]
Taikan Suehara[17], Junping Tian[18], Marcel Vos[12],
Graham Wilson[19], Hitoshi Yamamoto[20], Ryo Yonamine[20],
Aleksander Filip Żarnecki[21] (Contributors);
James Brau[15], Hitoshi Murayama[7,22,23] (ex officio)

ABSTRACT

To aid contributions to the Snowmass 2021 US Community Study on physics at the International Linear Collider and other proposed e^+e^- colliders, we present a list of study questions that could be the basis of useful Snowmass projects. We accompany this with links to references and resources on e^+e^- physics, and a description of a new software framework that we are preparing for e^+e^- studies at Snowmass.

[1] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[2] *DESY, Notkestrasse 85, 22607 Hamburg, GERMANY*
[3] *Institut für Physik, Humboldt-Universität zu Berlin, 12489 Berlin, GERMANY*
[4] *SLAC, Stanford University, Menlo Park, CA 94025, USA*
[5] *Department of Physics, Peking University, Beijing 100871, CHINA*
[6] *Department of Physics, Osaka University, Machikaneyama, Toyonaka, Osaka 560-0043, JAPAN*
[7] *Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 277-8583, JAPAN*
[8] *Laboratory for Elementary Particle Physics, Cornell University, Ithaca, NY 14853, USA*
[9] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, FRANCE*
[10] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, GERMANY*
[11] *Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109, USA*
[12] *IFIC (University of Valencia/CSIC), Valencia, SPAIN*
[13] *Department of Physics, University of California, Santa Cruz, CA 95064 USA*
[14] *Dept. of Physics and Astronomy, Seoul National Univ., Seoul 08826, KOREA*
[15] *Department of Physics, University of Oregon, Eugene, Oregon 97403-1274, USA*
[16] *Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[16] *Department of Physics, Kyushu University, Fukuoka, JAPAN*
[18] *ICEPP, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, JAPAN*
[19] *Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA*
[20] *Department of Physics, Tohoku University, Aoba-ku, Sendai 980-8578, JAPAN*
[21] *Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, POLAND*
[22] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[23] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Contents

1 Introduction

Perhaps the most important question to be addressed in the 2021 Snowmass study is that of whether the US should take a major role in an electron-positron collider as the next global project in high-energy physics. A primary element of the physics motivation is the opportunity that such a facility offers to explore the properties of the Higgs particle with high precision. Electron-positron collisions also offer access to other important physics topics, including the study of top quark and fundamental tests of the electroweak and strong interactions.

In order for members of the US high energy physics community to grapple with this question, it is crucial for them to explore in some depth how a next-generation e^+e^- collider can advance the physics studies that they consider most important. Over many years, reports and reviews have been written about the prospects for measurements at next-generation e^+e^- colliders. But there is no substitute for actually working oneself on a physics analysis, confronting the capabilities of an e^+e^- collider with a particular issue in particle physics and exploring what can be learned beyond the reach of the LHC and other current facilities. The purpose of this document is to make such studies accessible to as many members of the community as possible. We expect that such studies will improve our current understanding of the best-studied measurements and also reveal new directions that can be explored with e^+e^- colliders.

The possible physics measurements of next-generation e^+e^- colliders have been studied for the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) under the auspices of the Linear Collider Collaboration. These measurements have also been studied by the Circular Electron-Positron Collider (CEPC) and the Future Circular Collider (FCC-ee) groups. There is a related program of detector R&D in the linear collider community that is now quite advanced. This program is focused on detector elements needed for e^+e^- physics: high-precision calorimetry, extremely low-mass tracking systems, vertex detectors positioned close to the interaction point. These research programs have spun off technologies already applied in the LHC detector upgrades. This report gives extensive references to these existing studies as a starting point for future developments.

At this moment, we see an opportunity for the ILC to actually be constructed for operation in the 2030's. This makes it especially important today to understand and evaluate the ILC capabilities.

Someone who is new to e^+e^- physics can join in studies for next-generation e^+e^- colliders at several levels. First, one can study the physics analysis of e^+e^- reactions and the use of measurements of these processes to improve our understanding of particle physics. Second, one can study in more detail the reconstruction of particle signals in the e^+e^- environment and the translation of the physics requirements into detailed detector designs. Third, one can study the current state of the art in detector components needed for high-precision measurements at e^+e^- colliders and new technologies that could play an important role.

For most people, we expect, the easiest route into e^+e^- physics will be to explore specific physics questions using a fast simulation framework or full-simulation data in a simplified high-level format. The main purpose of this document is to assist members of our community in joining the study at this level. We will describe simulation tools and simulation data sets that we will provide for the Snowmass study. We then present a list of possible study questions that deserve attention and that can provide a basis for thinking more deeply about the problems of experimentation at e^+e^- colliders. We recommend these questions as a way to provide useful contributions to the physics discussions at Snowmass 2021 and the physics issues of next-generation e^+e^- colliders more generally. In many cases, the full answer can only be determined with a fully realized detector model. However, we expect that fast-simulation or simplified full-simulation studies can give insights to estimate and minimize specific contributions to the final error budget.

We also provide here resources for those who would like to study detailed detector-related questions and questions about the underlying technologies. For the study of detectors, we feel it is important make use of the knowledge and resources of the current ILC detector collaborations. All of the major reactions at next-generation e^+e^- colliders have been studied using full-simulation tools developed by the International Large Detector (ILD) and Silicon Detector (SiD) collaborations. We recommend working with one of those collaborations and taking up an open project within their framework as a first step to developing new ideas about the design and optimization of e^+e^- detectors. This document includes a section with the relevant contact information for both detector groups.

Those people interested in the sensors and detector elements that underlie the detector designs should recognize that these elements are being developed by R&D collaborations that generally involve members of all of the next-generation e^+e^- collider proposals. The current status of the R&D projects has recently been summarized in an extensive report [1]. We recommend that people interested in technology development should read carefully the relevant sections of this report and reach out to the groups pursuing R&D along the lines of interest to them. This document includes a section that expands the description of e^+e^- R&D activities and provides contact information for the major collaborations.

We hope that you will find this document a useful resource in entering the community interested in research in e^+e^- collider physics.

The structure of this document is the following: In Section 2, we give general references on e^+e^- physics. In Section 3, we describe the fast- and full-simulation frameworks that we are offering to perform physics studies during Snowmass. In Section 4, we note some aspects of e^+e^- linear collider collisions that may be unfamiliar to people who have worked only on hadron collider physics. In Sections 5-15, we list possible study questions related to different aspects of e^+e^- physics. In Section 16, we give contact information for the ILC detector concept groups. In Section 17, we give contact information for R&D studies related to e^+e^- physics.

2 General references on ILC physics

There are many references to get started with Linear Collider physics. Here we highlight a few that we think are particularly useful:

- "Primer on ILC Physics and SiD Software Tools," by Chris Potter [2]
- lectures from the Linear Collider Schools (`https://lcschool.desy.de/`), in particular, the lectures at the most recent schools in 2014 [3], 2016 [4], and 2018 [5].

A comprehensive overview of the ILC physics issues and the design of the proposed detectors is given in the ILC Technical Design report, in particular, in the executive summary [6] and the volumes devoted to Physics [7] and Detectors [8].

The most up-to-date detailed references on ILC physics are the papers prepared for the European Strategy for Particle Physics study [9, 10]. Note that the projections from the TDR are updated, in some cases substantially, in these documents. The ILD detector concept group has also produced an updated Interim Design Report [11].

General references on the physics opportunities of other e^+e^- proposals can be found in [12, 13] for CEPC, in [14], for FCC-ee, and in [15, 16, 17], for CLIC. Other important recent references are the report of the ECFA panel on precision Higgs boson physics commissioned as input to the European Strategy for Particle Physics study [18], and the Briefing Book that summarizes the results of that study [19].

For help with ILC physics questions and the associated simulation tools described below, please feel free to contact:

- LCC Physics Working Group conveners:
  - Keisuke Fujii (keisuke.fujii@kek.jp), Christophe Grojean (christophe.grojean@desy.de), Michael Peskin (mpeskin@ slac.stanford.edu)
- ILC detector concept group physics coordinators:
  - SiD: Tim Barkow (timb@slac.stanford.edu)

  - ILD: Keisuke Fujii (keisuke.fujii@kek.jp), Jenny List (jenny.list@desy.de)

- ILC contacts for the various Energy Frontier working groups
  - EF01: Shin-ichi Kawada (shin-ichi.kawada@desy.de)
  - EF02: Maxim Perelstein (m.perelstein@cornell.edu)
  - EF03: Roman Poeschl (poeschl@lal.in2p3.fr)
  - EF04: Sunghoon Jung (sunghoonj@snu.ac.kr)
  - EF05: Juergen Reuter (juergen.reuter@desy.de)
  - EF08: Mikael Berggren (mikael.berggren@desy.de)
  - EF09: Taikan Suehara (suehara@phys.kyushu-u.ac.jp)
  - EF10: Aleksander Filip Żarnecki (filip.zarnecki@fuw.edu.pl)
  - TF07: Mihoko Nojiri (nojiri@post.kek.jp)
- Technical support: ilc-snowmass@slac.stanford.edu; ilc-snowmass on Slack
- ILC simulation resources for Snowmass: `http://ilcsnowmass.org` .

3 Simulation Tools and Data Sets

Over many years, the ILC community has developed a set of simulation tools appropriate for full-simulation studies of e^+e^- collider processes using detailed detector designs. These are included in the `iLCSoft` package [20]. Its output is based on the persistency framework and event data model `LCIO` [21]. Any `LCIO` file can be read and analyzed in Root after loading the corresponding shared library. Examples are given in the tutorials listed below.

Recently, we defined a new type of `LCIO` file, the so-called "miniDST". As described below, the "mini-DST" contains high-level reconstruction objects like jets, isolated leptons etc, but also ParticleFlow objects and MC truth information. It can be filled from three different simulation programs offering different levels of detail, as illustrated in Fig. 1.

For the Snowmass study, we have developed a description of a generic ILC detector in `Delphes` [22]. With the help of the Snowmass MC Task Force, we organized a series of tutorials giving a general introduction to ILC simulation with these tools. The topics include: first plots from miniDST data in Root and in a Jupyter notebook, the usage of the event generator `Whizard` for e^+e^-, and an analysis walk-through of a search for an exotic Higgs decay mode. We are also making available large sets of Standard Model events. In this section, we describe these data sets and analysis tools.

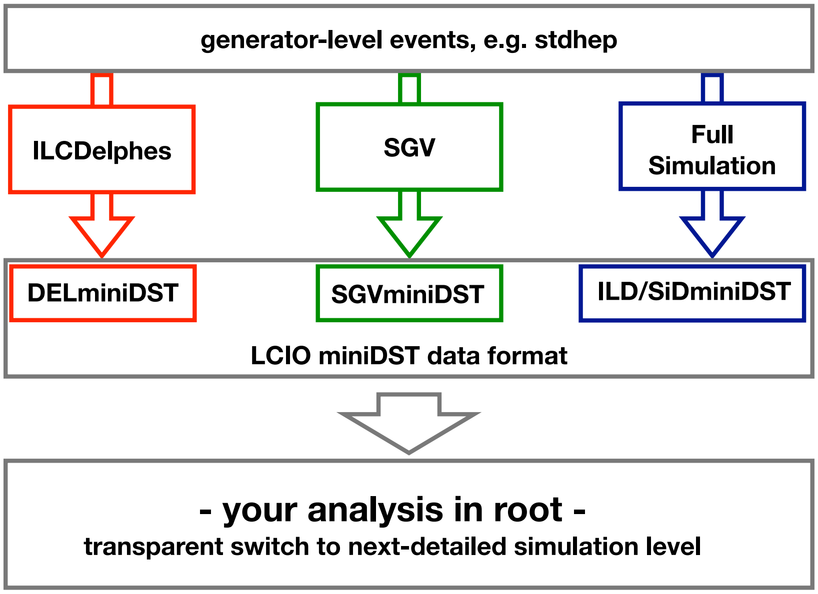

Figure 1: The miniDST format can be filled via Delphes, SGV or full simulation. Analyses developed against the miniDST format can easily switch between data from the different simulation tools.

Access to the available samples, tutorials and in-depth documentation is available via http://ilcsnowmass.org/.

We hope that most members of the collider physics community can use these miniDST data sets, regardless whether based on `Delphes`, SGV, or full simulation, without any further introduction, based on the provided examples. Many open questions can be explored adequately with these formats. Their quality and limitations are discussed below. On the other hand, we will also support people who wish to dive into questions more intimately related to the detector and the reconstruction algorithms, which requires full-simulation data with more details than stored on the miniDST. Again, details are given below.

3.1 Overview on data samples and tools to be provided

We are making available data samples of Standard Model events and additional signal processes, corresponding to a significant fraction of the expected ILC integrated luminosity. The data will be provided in the following formats:

1. at generator-level, in stdhep format. These samples can be used for generator level studies, as input to `Delphes` using the card describing a "generic ILC

detector", or as input to the fast detector simulation tool `SGV` [23]. The `Delphes` and `SGV` tools are both described below.

2. in miniDST format. This format, described below, contains a condensate of the high-level reconstruction output, readable in Root. We currently provide two flavors of minDST: Delphes-miniDST, produced with `Delphes`, and ILD-miniDST, produced with the ILD full simulation and reconstruction chain. SGV-miniDST is in preparation.

Links to our software tools and data are given at [24]. The stdhep files are available on the grid vo "ilc" and physically reside at DESY and KEK storage elements. The stdhep and Delphes-miniDST files are available from a repository at SLAC, for easy access by the US community. If you would like to request access to a specific data set listed below, please send your request to the ILC contact persons listed in the previous section.

Here is a summary of the data sets and tools that we make available:

- available already:

DATA generator-level event samples, stdhep format, for $\sqrt{s} = 250\,\text{GeV}, 350\,\text{GeV}, 500\,\text{GeV}, 1\,\text{TeV}$

DATA Delphes-miniDSTs for the above generator-level samples

TOOL `SGV` fast simulation

TOOL `Delphes` card for a "generic ILC detector"

TOOL `delphes2lcio` to run `Delphes` with output in miniDST format.

- in preparation:

DATA SGV-miniDST for the above generator-level samples

- available on request and with ILD guest membership (see below):

DATA ILD-miniDST of new 250 GeV samples, other energies from previous MC production

We request that people who use the stdhep events, the `Delphes` card, the `Delphes` files or SGV-miniDST files, or the tool `SGV` cite this document along with the specific references for individual tools. Support for the use of these tools can be obtained from the authors and the contact persons in each working group.

Studies that require detailed modelling of the detector and its response should use full-simulation data. The full simulations of the SiD and ILD detector concepts and the corresponding reconstruction are contained in the `iLCSoft` package [20]. Both SiD and ILD welcome new collaborators and will support studies in the Snowmass context. Both ILD and SiD offer a "guest membership" for institutions and individuals. This has no cost but only requires that one follow the publication rules of the concept group. Contact information for SiD and ILD can be found in Section 16 of this report.

3.2 Generator-level events

The existing generator-level event samples have been produced based on a dedicated ILC tune of the event generator `Whizard 1.95` [25, 26]. They are available in stdhep format for center-of-mass energies of $\sqrt{s} = 250\,\mathrm{GeV}$, $350\,\mathrm{GeV}$, $500\,\mathrm{GeV}$, $1\,\mathrm{TeV}$. At each energy, the full Standard Model plus selected signal processes have been generated. The luminosity of a linear collider is expected to increase proportional to $\sqrt{s}$, so we have produced event samples corresponding to integrated luminosities increasing in the same way, roughly $250\,\mathrm{fb}^{-1}$ for $250\,\mathrm{GeV}$, up to $1000\ \mathrm{fb}^{-1}$ for $1\,\mathrm{TeV}$. A list of all generated processes, along with cross sections, numbers of events, *etc.*, can be browsed at `https://ilcsoft.desy.de/dbd/generated/`. The standard assumptions of the ILC run plan for total integrated luminosity at each energy can be found in [27], with an update for $\sqrt{s} = 250\,\mathrm{GeV}$ in [10, 28].

The new event generation at $250\,\mathrm{GeV}$ mentioned above will produce a $10\ \mathrm{ab}^{-1}$ SM data sample using `Whizard 2.8.3`. This sample incorporates a number of evolutionary improvements in `Whizard` and also includes a slightly harder spectrum of beamstrahlung radiation, as called for in the latest ILC 250 designs.

The ILC-tuned `Whizard` generator includes a model of the energy distribution of the incoming beams, giving the luminosity spectrum, for each of the projected energies. This was created by the beam-beam simulation code `GuineaPig` [29]. `Whizard` includes a full treatment of spin information from the inital helicity of the incoming electrons and positrons to the decay products of τ-leptons. Hadronization is performed by `Pythia6` [30] tuned to LEP data [31].

To study additional signal processes, for example, new particle pair production, one can generate events using `Whizard` to include a realistic luminosity spectrum. On the other hand, it is usually a reasonable first approximation to generate events at the nominal center of mass energy. In either case, it is important to use the SM backgrounds that we provide rather than generating a new set of backgrounds. We would be happy to help in the generation of new signal reactions, and in the production of miniDSTs for these samples.

The data sets have been generated for pure initial state helicities in all four possible combinations ($e^-_L e^+_R$, $e^-_R e^+_L$, $e^-_L e^+_L$, $e^-_R e^+_R$). A sample with any polarization (P_{e^-}, P_{e^+}) can be created by drawing events from these samples with appropriate weights. This allows one to study the effect of varying beam polarization and to compare to the situation of perfectly polarized beams. The ILC baseline is $P_{e^-} = \pm 80\%$ and $P_{e^+} = \pm 30\%$. We also consider an upgrade to $P_{e^+} = \pm 60\%$. The weights to create these polarization samples are given in Table 1 in Appendix A.

3.3 Delphes

We have developed a `Delphes` card for the Snowmass process describing a "generic ILC detector". We hope that this will provide an immediately accessible tool that mimics the response of the ILD and SiD detectors as closely as possible within the `Delphes` parametrized framework. This new description is based on, and improves upon, earlier `Delphes` cards for e^+e^- collider physics [33, 34, 35]. It offers information important for e^+e^- analyses that have not previously been available in `Delphes`, including charm tagging and the geometry of the very forward BeamCal and LumiCal detectors. It includes event interpretation with a fixed total number of jets, a standard method in e^+e^- physics that is included in the CLIC `Delphes` distribution [35], and also widely used in ILC analyses.

We have also developed a tool called `delphes2lcio` [36], which runs `Delphes` and provides output in the miniDST format. The advantage of using this output is that it will be easier to transform an analysis based on `Delphes` to one based on a more precise description of the ILC detectors. The new `Delphes` still omits some more detailed aspects of the ILC detector description, including the presence of a beam crossing angle and the proper correlations among flavor tags for each jet. These effects are included in the SGV-miniDST and ILD-miniDST files described below. Any analysis code developed against the `Delphes` miniDST format will be easily transferrable to run on SGV-miniDST or ILD-miniDST files, should the need for a more precise modeling of the detector response arise during the course of the study.

3.4 SGV (Simulation à Grande Vitesse)

The standard fast simulation tool used by the ILD concept group is `SGV` [23]. `SGV` is a fast-simulation program, in the sense that the calorimeter response is parametrized, but its description of tracking is derived from the specified geometry and point resolutions via a covariance engine approach. In practice, this means that `SGV` models the track and vertex reconstruction performance, and thereby also the flavour tag performance of the full simulation and reconstruction chain, almost perfectly. The calorimeter parametrization is more detailed than that of `Delphes` and is adapted to the strategy of highly granular calorimetry and particle flow that is used in ILC analyses. At the same time, `SGV` is as fast as `Delphes` in terms of CPU time/event [37].

`SGV` is available for download and usage from the DESY svn-server [38]. It can read externally stored events in various formats, including generator-level events in stdhep and in LCIO. It can also generate events on-the-fly, by calling `Whizard 1.95` or `Pythia6` internally.

3.5 miniDST

The miniDST is a high-level data format which contains the Monte-Carlo truth information, the reconstructed particle flow objects and the links between truth and reconstruction level, event shape variables, isolated electrons, muons, taus and photons, as well as the rest of the event clustered into 2, 3, 4, 5, and 6 jets, along with b- and c-tagging information. For the 500 GeV and 1 TeV samples the clustering extends from 2 to 8 jets. By loading the LCIO shared library and including the LCIO header file into your Root macro (or compiled program), the miniDST can be read directly in Root. Examples of how to access the different types of information are provided here [39] and in the Snowmass tutorial [40]. Thanks to the LCIO compression, the miniDST format requires about the same or even slightly less space per event than the stdhep format, despite the additional reconstruction-level information.

The miniDSTs can in principle be filled from a number of sources. In Sec. 3.1, we referred to ILD-miniDSTs and SGV-miniDSTs. For ILD-miniDSTs, the various objects are created from the full simulation and reconstruction chain of ILD. For SGV-miniDSTs, the miniDSTs are filled after simulating the detector response with `SGV`. As we have explained above, this gives a highly accurate representation of the full simulation, sufficient for most studies which can be done on the miniDST format. Delphes-miniDSTs are created via `delphes2lcio` [36].

As the new, `Whizard 2.8.3`-based $\sqrt{s} = 250$ GeV events are being processed through the ILD full simulation, ILD produces ILD-miniDSTs from the full simulation and reconstruction chain, depending on the demand. The existing ILD and SiD full simulation samples for the higher energies could also be produced in a miniDST version, provided demand and resources. To use the full simulation miniDSTs, however, one should get in contact with the relevant concept group ILD or SiD.

3.6 Matching Tools and Topics

For each of the topics listed in the following sections, we recommend a *minimal* level of detail to go beyond the current state of the art. The following labels are used:

TH	questions of phenomenology that do not require MC simulations
GEN	questions that can be studied from generator-level events

DEL	questions that can be addressed, to first order, using `Delphes`
miniDST	questions that can be studied with miniDSTs from `SGV` or full simulation
FULL	questions that require at least the full DST from full simulation and reconstruction, or detailed simulation of different detector variants, or development of high-level reconstruction tools.
SPEC	questions that require special tools, *e.g.*, to simulate the ILC beams or to incorporate higher-order theory calculations. Please consult with the experts listed above.

4 Notable features of e^+e^- collisions

We should note two important aspects of e^+e^- physics that might be unfamiliar to people who have worked only at hadron colliders. The first is that linear e^+e^- colliders will provide longitudinally polarized electron and positron beams. Control of the beam polarization can then be used as a powerful tool for e^+e^- physics. Beam polarization has an order-1 effect on ILC cross sections, since the e^-_L and e^-_R have different $SU(2) \times U(1)$ quantum numbers. The ILC expects to provide 80% polarization in the electron beam and 30% polarization in the positron beam, with the possibility in both cases of rapidly switching the polarization orientation. This effectively quadruples the number of observables. Some of the polarization asymmetries provide new physics information; others allow cross-checks for the estimation of systematic errors [10, 41].

The second is that the nominal center of mass energy of e^+e^- collisions is affected both by initial-state radiation and by radiation from the beam-beam interaction ("beamstrahlung"). Beamstrahlung and ISR have three important effects. First, they broaden the e^+e^- center of mass energy distribution. This broadening is a few percent at energies up to 500 GeV. This effect is included in all of the samples that we provide; see Sec. 3.2. More importantly, ISR and beamstrahlung produce photons that induce hard $\gamma\gamma$ and $e\gamma$ reactions. Those processes are often the major source of background events, in particular for many types of searches. They are included in the full SM event samples we provide, and they should be included by default, along with e^+e^--induced backgrounds, in all physics analyses. Finally, ISR and beamstrahlung radiation contribute an additional "overlay" background due to independent low-$\sqrt{s}$ electron-photon and photon-photon reactions, similar to pileup at hadron colliders. The rate of these events is energy dependent. At a center-of-mass energy of 500 GeV, for instance, they lead to, on average, 1.1 events of overlay background. This background source—mainly, very soft hadrons and leptons—has been shown to be well-manageable even at a center-of-mass energy of 1 TeV [8], and plays hardly any role at 250 GeV. Its residual effect will be included in the ILD-miniDSTs.

Finally, we emphasize the interest in considering all of the topics below within the context of the energy evolution of ILC. The initial stage of ILC will be at a CM energy of 250 GeV. Once the ILC infrastructure is in place and significant physics results have been obtained, it will be almost imperative to upgrade the machine to a CM energy of 500 or 550 GeV, opening up the precision study of the top quark, measurement of the top quark Yukawa coupling, measurement of the Higgs boson self-coupling, and an increased search region for new particles. Official ILC parameter sets have been presented for CM energies of 91 GeV, 250 GeV, 350 GeV, 500 GeV, and 1 TeV [10]. Especially at the lowest and highest of these energies, there are many issues that are still unexplored.

5 Questions about general e^+e^- event analysis

1. QCD generators. So far, most LC studies have been performed with signal and backgrounds generated by leading-order parton-level generators (especially, Whizard), followed by parton showering and hadronization in Pythia6 tuned to LEP data. Details of the tune used in studies for ILD are described in [31]. Is this approach adequate for the high-precision jet measurements needed for ILC physics studies and, if not, what should replace it? What additional experimental measurements would be helpful as inputs to the tuning? [GEN]

2. Jet reconstruction. In the past few years, there have been significant improvements in the theory of jet reconstruction, and current ILC studies do not yet take advantage of these. Jet reconstruction in e^+e^- collisions is different from that at hadron colliders. At e^+e^-, we have good knowledge of the CM energy and forward-backward momentum balance, so typically we analyze jets with full 3-dimensional information and assign the whole energy-momentum measured by the detector to jets. This affects both the distance criteria and the clustering schemes themselves. On the other hand, current jet reconstruction algorithms used in e^+e^- studies [42] are still similar to those from the LEP era. At the same time, calorimetry is expected to be much improved at future e^+e^- colliders, so that the 2-jet invariant mass resolution will be dominated not by detector resolution but rather by mis-clustering [43, 44]. Can we use our new understanding of jet structure in QCD to develop new clustering algorithms with higher fidelity? [GEN]

3. Tau identification and reconstruction. Taus can be reconstructed at e^+e^- colliders by identifying their individual decay products without relying on a jet algorithm. Still, high fidelity is needed, so it is important to consider how to

optimize the reconstruction of tau events, both to maximize efficiency and to minimize systematic errors. Current reconstruction algorithms are described in [45, 46]. The second of these extracts the tau neutrino momentum using kinematic constraints enabled by excellent resolution on impact parameters. [miniDST]

4. Tau polarization. How accurately can one measure tau polarization, both in Higgs decay ($p_{lab} \sim 50$ GeV) and at 500 GeV ($p_{lab} \sim 250$ GeV)? What are the dominant systematic errors? How can these be minimized? Current studies can be found in [47], for Higgs decays, and in [48], for $e^+e^- \to \tau^+\tau^-$ at 500 GeV. [FULL]

5. Lepton reconstruction. What detector specifications are needed to capture and recombine final-state radiation from leptons (including taus), and what are the resulting systematic errors on the lepton energy? An algorithm for recovery of bremsstrahlung and final state radiation in $Z \to e^+e^-$ and $\mu^+\mu^-$ events is included in the ILD reconstruction [49]. [FULL]

6. Luminosity measurement from Bhabha scattering. At the ILC, it is necessary to measure with high precision both the luminosity and the luminosity spectrum, which is a function of the actual $\sqrt{s}$ of the e^+e^- annihilation. It is envisioned that this will be done primarily by measuring small-angle Bhabha scattering. Current studies project uncertainties of a few per mille on the luminosity measurement at 500 GeV and at 1 TeV, where the leading contribution originates from the modeling of the electromagnetic deflection of the Bhabhas in the electric field of the outgoing bunch [50]. The systematic uncertainty on the shape of the luminosity spectrum has been studied for CLIC in [51] and for ILC in [52]. What uncertainty should be expected at 250 GeV and 350 GeV, in the absolute luminosity and the shape? Can the measurement strategy be improved? [SPEC]

7. Luminosity measurement from other processes. The reaction $e^+e^- \to \gamma\gamma$ is also sensitive to the luminosity spectrum and could also contribute to that spectrum measurement. What improvements are achievable from the use of this reaction? Are there other reactions that could contribute significantly? [GEN]

8. Implications of luminosity spectrum uncertainty. In questions below, we ask about the effect of the luminosity spectrum on measurements of the Higgs boson mass and the top quark mass. Are there other measurements that are affected in an important way by the uncertainty in the luminosity spectrum? What uncertainties on the luminosity spectrum are required to bring these sources of error under control? [GEN]

9. Precision calorimetry. Early studies of the physics case for e^+e^- colliders emphasized precision hadron calorimetry ($\sim 25\%/\sqrt{E}$) to be able to separate W

and Z bosons in their hadronic decay modes. This is an important motivation at 500 GeV and above, but less so for the initial 250 GeV program focusing on $e^+e^- \to Zh$. What performance is required for hadron calorimetry at to meet the needs of the physis at 250 GeV? A recent discussion of this issue is found in [53]. [Delphes]

10. Photon energy resolution. The SiD and ILD detector designs achieve excellent jet energy resolution by using highly granular electromagnetic sampling calorimeters. This comes at the expense of intrinsic photon energy resolution. Is there a better optimum with improved photon energy resolution or photon-finding efficiency? What are the advantages and disadvantages? [FULL]

11. Heavy Flavor tagging and vertex charge measurement. The SiD and ILD detectors are designed to have excellent efficiency for secondary vertices. The currently expected heavy flavor-tagging performance is described in [42]. It is also expected that these detectors can reconstruct the vertex charge, to discriminate heavy quarks from antiquarks [54, 55]. Can the performance on these quantities be improved by further detector optimization or more advanced machine learning techniques? [FULL]

12. Particle ID. The SiD and ILD detectors do not have dedicated subdetectors for particle ID; however, they can identify kaons by dE/dx measurement or by track timing. Identification of kaons is important for many aspects of e^+e^- physics, including the vertex charge measurement described in the previous question and the reconstruction of τ leptons from their final states. It is then interesting to consider how kaon identification could be improved, for example, using the new timing detector technologies being developed for HL-LHC, and the implications for e^+e^- physics measurements. [miniDST].

13. Strange quark tagging. It would be useful to be able to tag strange quark jets in e^+e^- processes. Studies of $Z \to s\bar{s}$ from the LEP/SLC era can be found in in [56, 57]; these use dedicated RICH/CRID particle ID detectors. More recent proposals for strange taggers, for general purpose detectors, are given in [58, 59, 60]. These strategies can surely be improved. [miniDST]

14. Tracking detector momentum scale. How well can a modern detector such as SiD and ILD be designed so as to control the momentum scale at levels which are interesting for a precision center-of-mass energy determination? This involves issues of magnetic field-mapping, alignment and tracker design. Can one approach the limitation set by the knowledge of the J/ψ at 2 ppm? Are there other particles that can be used as additional momentum standards? Some motivations for this study are described in [10]. [miniDST]

6 Questions about Higgs boson physics: $e^+e^- \to Zh$

1. Total cross section. The total cross section for $e^+e^- \to Zh$ can be measured cleanly using leptonic Z decays, but with much higher statistics using hadronic Z decays. For the ILC at 250 GeV, this cross section is expected to be measured to 0.8%. It is a key input to all Higgs coupling measurements. How can the Higgs events best be separated from $e^+e^- \to ZZ$ and other backgrounds? Current studies can be found in [61] for the leptonic recoil channel, and in [62, 63, 64], for the hadronic recoil channel. [miniDST]

2. Model-independence of the total cross section measurement. It is important that the total cross section measurement be independent of the Higgs decay final state to the greatest extent possible. This issue is studied for SM Higgs decays in [61, 64]. Can this model-independence be extended to the various possible types of exotic Higgs decays? [DEL]

3. Higgs boson mass – leading channel. It is important to measure the Higgs boson mass with as high a precision as possible. For ILC at 250 GeV, the expected statistical uncertainty is 14 MeV, using the recoil Z decay $Z \to \mu^+\mu^-$ [61]. List and estimate the sources of systematic error in this measurement. Sources to consider include the luminosity spectrum uncertainty, the tracker momentum scale, and the subtraction of $e^+e^- \to ZZ$ and other backgrounds. Is there a method for in-situ energy calibration? Our current estimate of the systematic error is 20-30 MeV, from the comparison to the kinematics of $e^+e^- \to ZZ$. Is there a complementary way to obtain this information? [miniDST]

4. Higgs boson mass – other channels. Is it possible to make competitive measurements of the Higgs boson mass using other Z decay channels? In particular, improvements in electron reconstruction might make $Z \to e^+e^-$ more competitive. For the current status, see [61]. [FULL]

5. Higgs boson mass – continuum. Is it possible to make a competitive measurement of the Higgs boson mass by reconstruction of the decay products in modes such as $h \to b\bar{b}$? This question could be investigated both for $e^+e^- \to Zh$, calibrated by $e^+e^- \to ZZ$, or for $e^+e^- \to \nu\bar{\nu}h$, calibrated by single Z and W production. A current study using $h \to b\bar{b}$ is given in [65]. [miniDST]

6. Invisible width. To maximize the event sample, invisible decays of the Higgs should be measured with the recoil Z decaying hadronically. How can one best suppress the backgrounds? What systematic errors result? Current studies are given in [66, 67]. [miniDST]

7. Higgs decays to 2 jets. At e^+e^- colliders, Higgs decays to all hadronic modes can be observed directly. Current studies of $h \to b\bar{b}, gg, c\bar{c}$ (*e.g.*, [68]) date from

the era before deep learning, and before the understanding of q/g jet separation gained from LHC. What, now, is the optimum method for separating these three decay modes. What systematic errors can be achieved? [miniDST]

8. Higgs decays to light quarks. One can add to the previous question the possibility of Higgs decay to $s\bar{s}$, $d\bar{d}$, $u\bar{u}$. What limits on these modes can be achieved? Can $h \to s\bar{s}$, with $BR = 10^{-4}$ in the SM, be observed? A theoretical study on the discrimination of light quark and gluon initiated jets can be found in [69]. The possibility of observing $h \to s\bar{s}$ is discussed in [59] and in question #12 of Sec. 5. [miniDST]
9. Higgs decay to WW^*. In the SM, $h \to WW^*$ proceeds through the vertex $hW_\mu W^\mu$, but in BSM models, the alternative structures involving the W field strength $hW_{\mu\nu}W^{\mu\nu}$ and $h\epsilon_{\mu\nu\lambda\sigma}W^{\mu\nu}W^{\lambda\sigma}$ can also appear. What is the optimal strategy for measuring separately the strength of these three operators? Which is most useful, the purely leptonic, semi-leptonic, or fully hadronic W decay modes? This question and the following one have recently been studied in the Ph.D. thesis [70]. [DEL]
10. Higgs coupling to ZZ^*. The hZZ coupling can have three components similar to those just described for the hWW coupling. These can be measured from the reaction $e^+e^- \to hZ$, including forward-backward and polarization asymmetries. How can the full information be combined optimally? [DEL]
11. Higgs decay to $\tau^+\tau^-$. How accurately can one measure the polarization correlation in $h \to \tau^+\tau^-$ decay? Studies of the sensitivity to CP-violating $h \to \tau^+\tau^-$ decays and be found in [47, 71, 72]. Can the results be improved by making use of better modelling of τ decays, using the large samples from Belle II and from ILC itself? [miniDST]
12. Higgs coupling to $Z\gamma$. The measurement of the $hZ\gamma$ coupling is useful to remove correlations in a global effective field theory fit to Higgs boson parameters. HL-LHC will give us a measurement of the $h \to Z\gamma$ signal strength, but another source of information might be the cross section for $e^+e^- \to \gamma h$. Is it possible to observe this process at the ILC at 250 GeV? What measurement accuracies or limits might be expected? Current studies are given in [73, 74]. [DEL]
13. Flavor-violating Higgs decays. What limits can be placed on $h \to \tau\mu$, $h \to bs$, and other flavor-violating fermion combinations? [miniDST]
14. Exotic Higgs decays. A general study of the visibility of possible exotic Higgs decays at e^+e^- colliders given in [75] surveyed possible exotic Higgs decays and estimated the limits that can be achieved at e^+e^- Higgs factories. Do a deep dive into one of the modes considered (*e.g.*, $h \to b\bar{b}$ + invisible light scalar). What are the non-Higgs backgrounds? To what extent is this mode separable

from the related SM model (*e.g.*, $h \to b\bar{b}$)? Would this mode be discovered as an enhancement of that mode or as a distinctly different final state? What limit, and what discovery BR, might be expected? [DEL]

15. Higgs decays to long-lived particles. A type of exotic Higgs decay that deserves special attention is the possiblity of decay to long-lived particles. A survey of the possibilities and discussion of searches for displaced-vertex signatures can be found in [76]. Further studies that are more specific about detector requirements and elimination of machine-related backgrounds would be very useful. [FULL]

7 Questions about Higgs boson physics: WW fusion and higher energy reactions

1. Total cross section. How can one best measure the total cross section for the WW fusion reaction $e^+e^- \to \nu\bar{\nu}h$, making use of branching ratios from ILC data at 250 GeV? If one observes only the Higgs decay products, what is the appropriate fiducial region to give the best cross section estimate? A current study can be found in [77]. [miniDST]

2. Higgs coupling to WW^*. Can one measure the separate components of the hWW coupling using WW fusion? What are the sources of systematic error? Are there specific tests for the presence of the CP-violating structure? This question is related to question #9 of the previous section and is also studied in [70]. [DEL]

3. ZZ fusion. The reaction $e^+e^- \to e^+e^-h$ (ZZ fusion) has a much smaller cross section than WW fusion. However, this process may be independently interesting as a probe of the hZZ coupling, as described in [78]. What analysis strategy allows us to make the best use of it? This process can also give insight into the structure of the hZZ coupling. In that aspect, it is related to question #10 of the previous section and is studied in [70]. [DEL]

4. Higgs self-coupling at 500 GeV. At 500 GeV, the Higgs self-coupling can be extracted from double Higgsstrahlung, $e^+e^- \to Zhh$. This determination would be model-independent, as discussed in [79]. The current ILC projection for the expected 4 ab^{-1} sample is a 27% measurement of the self-coupling, limited by the efficiency of the selection of signal from background. The most complete current analysis, described in the Ph.D. thesis [80], identified many parts of the event reconstruction and selection where significant improvements are possible. These include the flavour tag, the jet clustering, the identification and correction for semi-leptonic decays in b jets, the use of squared matrix elements as selection variables, and the inclusion of $h/Z \to \tau^+\tau^-$ channels. Many of these elements

could benefit from the use of advanced machine-learning techniques. How much improvement is possible? [miniDST]

5. Higgs self-coupling at higher energies. The same questions can be asked about the process $e^+e^- \to \nu\bar{\nu}hh$, which turns on at higher energy. This is projected to yield a 10% measurement of the Higgs self-coupling with the expected 8 ab^{-1} event sample for ILC at 1 TeV [81]. Studies for CLIC project a 9% accuracy from measurements at 1.5 TeV and 3 TeV [82]. Again, the limiting factor is signal/background discrimination. How can this be improved with more sophisticated tools? What is the lowest CM energy at which such a precise measurement can be achieved? [miniDST]

6. Off-shell Higgs couplings. Most ILC reactions involve the Higgs boson on mass shell. Are there reactions that can test the Higgs boson couplings at off-shell momenta, which can give additional information to test some BSM models? [GEN]

8 Questions about top quark physics

A recent overview of top quark physics at e^+e^- colliders can be found in [83].

1. Top quark threshold. The top quark pair-production threshold is a sudden jump in the e^+e^- cross section over an interval of a few GeV. Its detailed shape depends on m_t, Γ_t, α_s, and the top quark Yukawa coupling y_t. It is washed out, to a certain extent, by initial-state radiation, beamstrahlung, and machine energy spread. Because the threshold is sharp, we expect a measurement of the top quark mass with a statistical uncertainty better than 20 MeV. The dominant error comes from the theory of the threshold shape. The extraction of the physics parameters and the optimal scanning strategy has been studied for some time; see [84, 85, 86, 87] and references therein. Some issues that still need further study are: Can the precision in these parameters be improved by using the dependence of the cross section on beam polarization? Can the precision be improved using properties of the observed final state $b\bar{b}W^+W^-$? [GEN]

2. Top quark threshold – unfolding: Effects of initial state- and beamstrahlung radiation and machine energy spread on the top quark threshold shape deserve further study. To what extent can one use measurements of these effects to better unfold the underlying threshold shape? [SPEC]

3. Top quark mass from pair production. It is also possible to obtain a precise top quark mass from measurements of the kinematics of top quark pair-production.

There is an interesting theoretical literature on this question [88, 89], which explains that a short-distance top quark mass such as the $\overline{MS}$ mass can be obtained from measurements well above threshold. However, little attention has been given to the experimental aspects of this program. A method for determining the top quark mass from $e^+e^- \to t\bar{t}\gamma$ events has been studied in [90]. What is the best strategy to extract a short-distance top quark mass with high precision from pair-production events? [miniDST]

4. Top quark spin. The spin of the top is transferred to its decay products before hadronization and can thus be measured from the final state of top decay. How well can one measure the top quark spin and the $t\bar{t}$ spin correlation, for example, as a function of the production angle? How does the accuracy of this measurement compare to that at hadron colliders? [miniDST]

5. Top quark form factors. There are 4 possible form factors for the top quark coupling to each of γ and Z, with one, in each case, CP-violating. How can one best make use of beam polarization, the choice(s) of the center of mass energy, and the measurement of t and $\bar{t}$ spins to determine these form factors independently? What is the most powerful signal of top quark-associated CP violation at the ILC? Current studies of these questions are given in [91, 92, 93]. A more expansive version of this question, in the context of SM Effective Field Theory, is given in question #6 of Sec. 15. [GEN]

6. Form factors near threshold. At threshold, the combinations of top quark form factors that appear in the spin-1 S-wave are dominant, while orthogonal combinations are suppressed. To what extent can the separate form factors be measured? How can beam polarization assist in measuring these form factors? How can the CM energy-dependence, as one moves through the threshold, be used? [TH]

7. Top quark width. How well can the top quark width be measured directly at the ILC? How would we best combine the determinations from the threshold region and from higher energies? [GEN]

8. Higgs coupling to $t\bar{t}$. The top quark Yukawa coupling is very important to measure precisely. The measurement of this quantity at 500 GeV is limited by the fact that this energy is very close to the threshold for the reaction $e^+e^- \to t\bar{t}h$. The precision is expected to improve to about 2% at 550–600 GeV, from simple cross section scaling [27]. Can this be confirmed by a full study? [DEL]

9 Questions about $e^+e^- \to f\overline{f}$

1. New vector resonances. There is an extensive literature on searching for signals of new s-channel resonances through deviations of the $e^+e^- \to f\overline{f}$ cross sections from the SM expectations [94]. However, the theoretical landscape changes with time, and much phase space available to earlier studies has now been excluded by measurements at the LHC. What is the current situation? [TH]

2. New observed vector resonances. There is substantial phase space for the discovery of a BSM resonance in Drell-Yan production at the HL-LHC. Imagine the discovery of a resonance at a mass of 4 TeV. What new information would the measurement of $e^+e^- \to f\overline{f}$ at the various ILC stages bring? How close can we come to completely characterizing this resonance using all available information from HL-LHC and ILC? [TH]

3. $e^+e^- \to b\bar{b}$. In BSM models in which the top quark plays a role in the dynamics of a composite Higgs boson, there must also be BSM effects on the b quark, and these might be visible in $e^+e^- \to b\bar{b}$ at high energy. A current study at 250 GeV can be found in [54]. A related study of $e^+e^- \to c\bar{c}$ is given in [96]. What information can we obtain from this reaction that would complement the ILC studies of the top quark? [TH]

4. $e^+e^- \to \tau^+\tau^-$. Just as for the top quark, the polarization of τ leptons in $e^+e^- \to \tau^+\tau^-$ can be measured from the τ decay final states. A current study at 500 GeV can be found in [48]. How can we best use this additional handle to constrain or discover BSM models? [TH]

10 Questions about W boson physics

1. W boson mass. It is possible to improve the precision of the W boson mass by studies of W^+W^- and single W production at 250 GeV. Some strategies are explored in [10]. How can we further improve the systematic uncertainties from these and other possible techniques? [miniDST]

2. Complete event reconstruction and analysis for $e^+e^- \to W^+W^-$. There are 3 possible form factors for the W coupling to each of γ and Z, with 1, in each case, CP-violating [97]. An $e^+e^- \to W^+W^-$ event can be completely reconstructed, with all 5 decay angles determined in each event (up to a front-back ambiguity in the case of hadronic decays). In the older literature, it is shown that even a set of 14 complex form factors can be disentangled using optimal observables [98]. However, current full-simulation studies [99, 100, 101] use only 3 angles. It

would be interesting to revisit this question and understand how much detailed information is available in practical measurements. [DEL]

3. Beam polarization and $e^+e^- \to W^+W^-$. The SM cross sections for $e^+e^- \to W^+W^-$ using e^-_L and e^-_R beams have a completely different form both in the production angle and the final W polarizations. This implies that there must be a strong advantage to using polarized beams for measurements of the the W form factors. Can you quantify this? Are there measurements that require beam polarization? [GEN]
4. CP violation in $e^+e^- \to W^+W^-$. What are the strongest signatures of CP violation in the W system? What are the key observables linear in CP-violating parameters? [TH]
5. W polarization from hadronic decays. There is an ambiguity in the determination of the W decay angle between the quark and antiquark directions when a W decays to light quarks. However, when a W^+ decays to $c\bar{s}$, the quark direction can be determined by charm tagging. Even for $W^+ \to u\bar{d}$, measurement of the final jets distinguishes transverse from longitudinal W bosons. What is the quantitative effect of the use of the quark directions on the measurement of W form factors? How can this capability be used in other aspects of W physics? [TH]
6. Interaction of W couplings and precision electroweak. Almost all current studies of W form factors — both for e^+e^- and pp colliders – assume that the couplings of SM gauge bosons to fermions take their SM values. However, this approximation might not be warranted as the precision on the W form factors improves. Deviations of the $e\nu W$ and eeZ couplings can lead to effects on the $e^+e^- \to W^+W^-$ cross section that grow as s/m_W^2. How well do we need to know these electroweak couplings to meet the goals of future W boson measurements? [TH]
7. LHC constraints. Non-standard couplings of the W are already significantly constrained by measurements at the LHC. How should these constraints be compared to the ILC capabilities? What model-dependence present in the LHC limits can be removed by ILC measurements using events with fully reconstructed kinematics? How does beam polarization enter this comparison? [TH]

11 Questions about precision electroweak measurements

Precision electroweak observables can be addressed at the ILC both through measurements at high energies and through a dedicated run at the Z resonance. For details, see [10].

1. Radiative return. Even before the ILC carries out a dedicated program of measurements at the Z resonance, it can improve the current determination of $\sin^2\theta_w$ by measuring the polarization asymmetry of the radiative return reaction $e^+e^- \to Z\gamma$. The expected statistical precision on $\sin^2\theta_w$ is of the order of 10^{-4} [10, 102]. What are the sources of systematic error? Estimate these, taking into account that most events are measured by the detectors in the forward region. [miniDST]

2. ILC "Giga-Z" program. The ILC could carry out a program of measurements on the Z resonance, collecting 5×10^9 polarized Z bosons [10]. This sample would be 200× larger than that from LEP and $10,000$ times larger than that from the polarized Z program at SLC. It is interesting to assess this program in relation to the program proposed for circular e^+e^- colliders, with a much larger event sample but no beam polarization. In particular, how close do the measurements in each program come to the expected level of systematic errors? [DEL]

3. Forward-backward asymmetries. In the ILC program on the Z resonance, it is possible to obtain powerful constraints on the $Zq\bar{q}$ couplings by measuring forward-backward asymmetries with polarized beams. The quark and antiquark directions would be determined by jet charge, or, for heavy quarks, vertex charge (see question #10 of Section 5). However, one must assume that the jet directions measured in 2-jet events (in an appropriate fiducial region) are aligned with the initial quark directions, which ceases to be true at higher orders in QCD. What is the systematic error on the measurement of forward-backward asymmetries due to QCD uncertainties in jet formation and hadronization? [GEN]

4. Tau polarization. The determination of $\sin^2\theta_w$ from tau polarization depends on unambiguously identifying the tau decay mode, since each mode has its own characteristic dependence on polarization [103]. In a detector of the quality of foreseen ILC detectors, how well can the various tau decay modes be separated? A current study is given in [48]. What is the implication for the systematic error on the $\sin^2\theta_w$ measurement obtained from $Z \to \tau^+\tau^-$? [miniDST]

5. Flavor at the Z pole. The dedicated ILC run at the Z resonance is expected to produce 5×10^9 polarized Z bosons. This must offer unique opportunities for heavy flavor physics, but there have been few studies of these possibilities. The physics opportunities of the sample of 10^8 polarized Λ_b baryons are explored in [104]. [TH]

12 Questions about QCD and jets

1. Jet shapes and jet substructure. There is now an extensive literature on the shapes and substructure of QCD jets motivated by studies of jets at the LHC [105, 106]. This theory can be tested much more stringently at ILC, using the known CM energy, the absence of underlying events and pile-up, and the higher precision calorimetry. What level of precision is possible here? What level of precision can be achieved in the measurement of α_s? Can we study effects of the b and c masses? Are there interesting BSM models that can become visible through these measurements? [GEN]

2. Hadronization. The large sample of 2-jet events that the ILC will make available offers the opportunity to test and improve models of hadronization. What can be learned beyond the knowledge that we gained from LEP? Specific physics topics that need new data are: flavor production in jets, and characterization of s- and g-initiated jets; baryon production; polarization of vector mesons (especially, D^*) and baryons in jets. To what extent can this improved information feed back into improvements in LHC event analysis? [TH]

3. Tests of parton showers. Simulations of parton showers now aim for NLO and even NNLO accuracy (*e.g.*, [107, 108, 109]). How well can we test the accuracy of parton shower generators at e^+e^- colliders, both for their general accuracy in reproducing event shapes and for specific modelling of features of QCD that appear at high order? [GEN]

4. Structure of gluon jets. The Higgs production processes in e^+e^- with the decay $h \to gg$ gives a clean, low-background sample of gluon-initiated jets. A study of the QCD structure of this final state can be found in [110]. How can we use this sample to improve our knowledge of gluon jet substructure and nonperturbative gluon fragmentation? [GEN]

5. Structure of top quark final states. The reaction $e^+e^- \to t\bar{t}$ gives a well-characterized and almost background-free sample of top quark events. How can this be used to improve our knowledge of QCD jet structure? [GEN]

13 Questions about searches for new particles

1. Light Higgsino. In the MSSM, the Higgsino can be light compared to the other superpartners, and the splitting between Higgsino mass eigenstates is then naturally less than 5 GeV. In this parameter region, it is very difficult to discover the Higgsino at the LHC, while the ILC can be a Higgsino factory. Some studies of Higgsinos at the ILC can be found in [111, 112, 113, 114]. The

signatures change rapidly as a function of the $\widetilde{h}^+$-$\widetilde{h}^0$ mass splitting, so it is interesting to extend these studies and explore the full range of this parameter. [miniDST]

2. Light or compressed SUSY scenarios: More generally, once the masses of colored superpartners are taken to be above the reach of the LHC, the signatures of color-neutral superpartners and the corresponding search strategies depend on the fine details of the SUSY parameter set. Models with large mass gaps between the wino ($\widetilde{w}$) and bino ($\widetilde{b}$) and models with sleptons below the wino mass are relatively accessible at the LHC, but, other choices are more difficult. This issue has been analyzed in [115]. Pick up one of the scenarios discussed in this paper (for example, models with a small lepton-neutralino mass difference), and make a detailed comparison of the HL-LHC and ILC prospects. [DEL]

3. R-parity violating SUSY. R-parity violation in the leptonic sector can lead to new resonant reactions such as $e^+e^- \to \widetilde{\nu}$ and to new leptonic and hadronic decays of neutralinos. Extensive searches were made for lepton R-parity violation at LEP (for example, [116, 117, 118]), but there has been little work on the prospects for future e^+e^- colliders, even though existing LHC searches leave many possibilities open. A current study can be found in [119]. A useful theory reference is [120]. [DEL]

4. New Higgs scalars – pair production. Models of new physics often contain new scalar bosons, perhaps from an extended Higgs sector. At an e^+e^- collider, the cross sections for pair-production of new scalar bosons are unambiguously predicted, depending only on the masses and quantum numbers. The situation is complementary to that of hadron colliders, where both production and decay rates depend on the detailed parameter choices. To what extent can ILC fill in the gaps and exceptions in the search for new scalars left by the LHC? Some studies of scalar pair production at e^+e^- colliders, for LEP, ILC, and higher-energy colliders, are given in [121, 122, 123, 124]. [DEL]

5. New Higgs scalars – Z recoil. Just as the Higgs boson appears as a resonance in the missing mass in $e^+e^- \to Z^0 + X$, a new scalar can also appear as such a resonance, discoverable with couplings very small compared to the hZZ coupling. A current study, based on the use of $Z \to \mu^+\mu^-$ decays, is given in [125]. Can the use of hadronic decays of the Z provide stronger constraints or sensitivity? [DEL]

6. New particles addressing the hierarchy problem. The above questions relate to specific models that solve the gauge hierarchy problem. But, in general, any solution to this problem requires some set of new particles that appear in loop diagrams and cancel the ultraviolet divergences of the SM. These particles can be of many types, bosonic or fermionic (or both), colored or color-singlet.

How general is the ability of e^+e^- colliders to discover or exclude the various possibilities? To what extent can e^+e^- measurements test the "naturalness sum rules" [126, 127] on masses and couplings that must be satisfied to cancel the ultraviolet divergences of the SM? [TH]

7. ILC response to LHC discovery. For all of the models discussed above, there is still ample phase space for the discovery of new particles at the HL-LHC. Pick a particular example of a new particle that can be discovered, and discuss the additional information on the underlying model that can be obtained from e^+e^- experiments. What e^+e^- center of mass energies are relevant? (Remember that new physics models typically have implications for modifications to Higgs boson couplings.) A worked example can be found in [128]. [TH]

8. Relaxion. The relaxion is a field postulated to solve the hierarchy problem by relaxing in the early universe to a ground state that picks out the 100 GeV mass scale [129]. It is possible for the relaxion to have a mass in the range of tens of GeV and to be observable through relaxion-Higgs mixing [130]. In this case, a measurement of the coupling of that particle to the Higgs boson can test the relaxion mechanism. To what extent can an e^+e^- collider confirm or refute this idea? [TH]

9. Dark matter candidates – effective Lagrangian approach. In the same way that dark matter production at the LHC can be parametrized by an effective Lagrangian with $q\bar{q}\chi\chi$ 4-fermion operators, dark matter production at the ILC can be parametrized by an effective Lagrangian with $e\bar{e}\chi\chi$ operators. At the ILC, dark matter production is observed using initial-state photon emission. For the various possible Lorentz structures, how close can we explore up to the limit $m_\chi = \frac{1}{2}\sqrt{s}$? Two useful current references are [131, 132]. [DEL]

10. Dark matter candidates – photon-induced reactions. A possible effective Lagrangian term that gives a portal to dark matter is the coupling to photons: $F_{\mu\nu}F^{\mu\nu}\chi\chi$. What limits can be obtained from photon-photon collisions at e^+e^- colliders? [GEN]

11. Dark matter candidates – light mediators. There are many scenarios in which the mediator that links the SM and dark matter sectors is light – 10s of GeV and below – so that the effective Lagrangian description in which the mediator is integrated out is not valid. It would be interesting to study the sensitivity in e^+e^- to a particular model, perhaps one considered in the LHC studies [133], as the mediator mass varies from the 10 GeV to the 100 GeV region. [DEL]

12. Dark matter candidates – Higgs sector. It is possible that extensions of the Higgs sector contain symmetries that would stabilize a heavy neutral bosonic dark matter candidate. Searches at e^+e^- colliders for new particles in a model of

this type have been studied in [134, 135]. It is interesting, then, to think about dark matter scenarios with extended-Higgs-type signatures, and to compare the capabilities of ILC and LHC to discover these models. [DEL]

13. Dark matter candidates – top quark sector. It is possible that the most important process for dark matter production at high energies involves the radiation of the mediator from a top quark, producing, for example, the final state $t\bar{t}$ + (missing). What constraints can one put on this dark matter production mechanism at e^+e^- colliders? [DEL]

14. Dark photons. In the study of models with "dark sectors", there are benchmark "visible" and "invisible" A' models, defined, for example, in [136, 137]. The A' is produced at an e^+e^- collider in $e^+e^- \to A' + \gamma, Z$. What is the sensitivity of the ILC to these models at the various ILC energy stages? For the visible A' models, compare the sensitivities from the various A' decay channels. [DEL]

15. Axion-like particles (ALPs). ALPs can be produced at e^+e^- colliders in $e^+e^- \to$ ALP $+ \gamma, Z, h$ and in Z decays to ALP $+ \gamma$, with ALP decay to $\gamma\gamma$. In some parameter regions, the ALP decay can be displaced. A review of ALP searches at a variety of colliders can be found in [138]. What is the sensitivity of ILC at its various energy stages? [DEL]

16. Long-lived particles. New weakly coupled and long-lived particles could be pair-produced in e^+e^- collisions. Scenarios with long-lived neutral particles are more difficult to constrain at the LHC and provide an opportunity for discovery at the ILC. It is interesting to analyze the separation of these signal events from physics and machine-induced backgrounds. Some results for scenarios in which the new particles arise from Higgs decays can be found in [76]. Other sources, including photon-photon collisions and WW fusion, may be more difficult to analyze. The ILC machine and detectors have a characteristic time structure with 5 or 10 bunch trains per second, each of total duration about 1 msec. Between trains, the ILC detectors will be powered down to avoid the need for active cooling, an important element in the design of a precision detector with minimal material. Does this affect the ability to discover long-lived particles? [FULL]

14 Questions about ILC fixed-target capabilities

1. Beam-dump experiments. ILC will produce intense, high-energy electron and positron beams that will eventually pass through the ILC interaction region and be brought to beam dumps. This would give a new opportunity to search for exotic dark-sector particles such as dark photons, millicharged particles and

ALPs. What is the reach of these experiments? A general orientation to fixed-target dark sector experiments can be found in [139]. Experiments proposed for the near term are reviewed in the reports [140, 141]. By how much does ILC extend their capabilities? Some studies of this questions can be found in [142, 143]. [GEN]

2. Positron beams. The availability of high-energy positron beams offers a novel type of fixed-target process, with positron annihilation on atomic electrons. This process has been studied at low energy in [144]. What capability is available with the ILC beams? [GEN]

15 Questions about the theory of Higgs boson couplings

1. Higgs inverse problem. Though predictions for deviations of Higgs couplings from the SM expectations have been computed in many models, there is still a poor understanding of the inverse problem: To what extent does the observation of a specific set of Higgs coupling deviations point to a specific class of BSM models. How well can this relation be characterized? Within the set of SUSY models, some of this relation is captured by general SUSY parameter fitting programs such as Fittino [145], SFitter [146], and MasterCode [147]. [TH]

2. Higgs couplings from heavy SUSY. There is a significant parameter space in which SUSY models with very heavy superpartners (with squark masses at, say, 5 TeV) can give rise to order 5% deviations from the SM in the hbb and $h\tau\tau$ couplings. Examples of such models are given in [124, 148, 149]. It would be interesting to explore more systematically the predictions for Higgs couplings in SUSY models with masses too heavy to be discovered at the HL-LHC. What distinct mechanisms can promote large deviations in the Higgs deviations, and what regions of SUSY parameter space are made accessible in this way? [TH]

3. Higgs couplings to WW. Although the SM Effective Field Theory allows couplings of the form $hW_{\mu\nu}W^{\mu\nu}$ in the leading order in BSM effects, such couplings are highly suppressed in BSM models with a weak-coupling description, including not only SUSY but also Randall-Sundrum and other extra-dimensional models. Can these couplings arise in other types of composite Higgs models? What would be the implications of the discovery of a coupling with this structure? [TH]

16 Questions about SM Effective Field Theory interpretation of e^+e^- measurements

1. Combination of ILC measurements. The ILC physics program gains much of its power from the ability to combine measurements of Higgs processes with those of $e^+e^- \to W^+W^-$ and precision electroweak observables in the context of SM Effective Field Theory (SMEFT) [150, 151]. From this point of view, what are the weak links that require improved measurements or special attention? [TH]

2. Combination of ILC and LHC. Comparing the SMEFT analyses in [9] and [18], the former group includes only a few of the simplest LHC measurements while the latter group proposes a more general fit using the whole corpus of LHC Higgs data. In some sense, this is a trade-off between including more available information and reducing the number of model assumptions. Is there a more optimal way to combine ILC and LHC information? [TH]

3. Adequacy of SMEFT as a description of electroweak symmetry breaking. It is possible that the 125 GeV Higgs boson is not the only source of $SU(2) \times U(1)$ symmetry breaking. Additional sources of symmetry breaking may come from additional heavy Higgs multiplets or from the $SU(2) \times U(1)$-violating masses of heavy particles. Integrating out these heavy particles yields an effective Lagrangian more general than SMEFT, called Higgs-Electroweak Effective Field Theory or HEFT [152, 153]. This Lagrangian is non-analytic in the SM Higgs doublet Φ or, equivalently, treats the Higgs scalar field and its associated Goldstone boson fields separately using an nonlinear realization of the symmetry [154, 155]. To what extent can we test using e^+e^- colliders whether SMEFT is an adequate description or whether the additional freedom in HEFT is required? [TH]

4. Limitations of the SMEFT. In the SMEFT description of BSM models, the approximation of considering only dimension-6 operators breaks down when the BSM particles, assumed to be integrated out in SMEFT, have masses close to the Higgs boson and top quark masses or the process CM energy. Are there concrete models for which the use of the approximation of keeping dimension-6 terms only leads to an incorrect or misleading interpretation of the data? [TH]

5. Higgs couplings in the presence of exotic decays. Is there a formally correct way to include the possibility of both high-mass effects parametrized by SMEFT and of light particles giving new exotic Higgs decays in the same analysis of ILC data? [TH]

6. Top quark in SMEFT. The top quark appears in a large number of dimension-6 SMEFT operators. There are 10 operators that modify top quark-vector boson

form factors and another 10 operators that give 4-fermion contact interactions contributing to ILC observables. At a fixed energy, these two classes of operators affect observables in similar ways, so it is difficult to distinguish them. The analysis [157] demonstrates that it is possible to determine these operator coefficients independently using ILC measurements at 500 GeV and 1 TeV. This point merits further analysis. What is the best way to obtain independent determinations of these operator coefficients? [TH]

7. Loop effects in SMEFT. Almost all current e^+e^- SMEFT analyses treat SMEFT effects only at the leading order in perturbation theory. Some exceptions are studies of loop effects of the top Yukawa coupling [158, 159, 160] and the Higgs self-coupling [161], in which only these specific couplings are considered at 1-loop order. Are there other important SMEFT loop effects that need to be taken into account in ILC analyses? [TH]
8. Global SMEFT analysis. Most SMEFT analyses in the literature discuss a specific subset of higher-dimension operators in isolation from the rest. Separate analyses are done for precision electroweak interactions, W trilinear couplings, Higgs couplings, top quark couplings, 4-fermion interactions, and the Higgs self-coupling. Studies that combine constraints from different sectors (*e.g.*, [150, 161, 162, 151]) find interesting synergies and increased power. At e^+e^- colliders, it is surely easier than at hadron colliders to achieve a full global analysis that constrains or, hopefully, overconstrains all possible SMEFT contributions. What is needed to achieve this goal? [TH]

17 Contact information for the SiD and ILD detector groups

For the most part, the questions listed above can be investigated using the simplified simulation tools described in Sec. 3 above. But some people would like to carry out deeper-level analyses, investigating issues associated with detailed reconstruction algorithms, detector optimization, and alternatives for detector design. For work at this level, there is a dedicated software framework called ILCSoft [20]. Both SiD and ILD have constructed detailed detector models based on this framework and have used it to carry out full-simulation analyses. The analysis frameworks being used for CEPC and CLIC analyses are also based on ILCSoft. To learn this framework, we strongly encourage you to join one of these existing collaborations. Each has a long list of low-level reconstruction projects that would be suitable for contributions to Snowmass and would provide an accessible starting point for developing your own ideas.

Both SiD and ILD are offering free guest memberships for participants in the Snowmass study. These will give access to the group resources and technical support with the ILCSoft analysis packages. To join ILD in this way, please see [163]. To join SiD, please contact the spokespersons.

At this moment, participants in the four e^+e^- collider proposals are collaborating in developing a common and more modern software package using the CERN ACTS framework [164]. But it is unlikely that this package will be ready in time for Snowmass 2021 projects.

To join the SiD group, please contact

- Spokespersons: Andrew White (awhite@uta.edu), Marcel Stanitzki (marcel.stanitzki@desy.de)
- Physics Coodinator: Tim Barklow (timb@slac.stanford.edu)

To join the ILD group, please contact

- Spokesperson: Ties Behnke (ties.behnke@desy.de)
- Physics Coodinators: Keisuke Fujii (keisuke.fujii@kek.jp), Jenny List (jenny.list@desy.de)
- Executive Team member from the US: Graham Wilson (gwwilson@ku.edu)

18 R&D collaborations, and contact information for joining them

Over the past few decades, a large number of groups have pursued extensive generic detector R&D studies, applicable to any Linear Collider (LC) detector concept. This reseach has been carried out both within the detector concept groups SiD, ILD, and CLICdp and within collaborations such as CALICE, LCTPC, and FCAL. The directions being pursued and an update of the most recent R&D results are summarized in the "Linear Collider Collaboration Detector R&D Report" [1]. This document provides a "snapshot" entry point for new groups, to help them to learn about the current landscape of the LC R&D efforts and the areas where they might be interested to contribute. The latest update, dated December 2018, was submitted as supplemental LCC input to the European Strategy Update. The next version will be released in July 2020. Please contact the editors Jan Strube (jstrube@uoregon.edu) and Maxim Titov (maxim.titov@cea.fr) for any questions about this document or for further information about the LC R&D program.

There are a number of "transversal" R&D collaborations dedicated to streamline effort and resources, handle new technologies, and match common components to on-going engineering developments or production. Here is a list of the largest collaborations, with contact information and a summary of the questions that they address:

- CALICE — highly granular electromagnetic and hadron calorimetry
  - `https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome`
  - Spokesperson: Roman Poeschl (poeschl@lal.in2p3.fr)
  - development of sensor technologies and electronics, mass production strategies and system aspects
  - analysis of test beam data for detector performance, reconstruction algorithm;
  - development and the study of hadronic shower physics
- FCAL — Highly compact and precise electromagnetic calorimeters for forward region of e^+e^- detectors
  - `https://fcal.desy.de`
  - Spokesperson: Wolfgang Lohmann (wolfgang.lohmann@desy.de)
  - development of ultrathin detector planes and dedicated electronics;
  - construction of prototypes;
  - performance studies using test-beam data;
  - study of the radiation tolerance of sensors
- LCTPC — Time Projection Chamber for a Linear Colider
  - `https://www.lctpc.org`
  - Spokesperson: Jochen Kaminski (kaminski@physik.uni-bonn.de)
  - Regional coordinator for the Americas: Alain Bellerive (alainb@physics.carleton.ca)
  - construction/test-beams of TPC endplates with GEM, Micromegas, In-Grid readout;
  - development/engineering challenges for ion blocking techniques ("gating");
  - development of readout electronics, DAQ, cooling
- SiDR&D — silicon tracking and EM calorimetry for the SiD detector concept
  - Spokesperson: Marty Breidenbach (mib@slac.stanford.edu)
  - ultra-low-mass silicon sensors

- high granularity electromagnetic calorimetry with small Molière radius

In addition, several groups world-wide are developing technologies for precision vertex detectors, such as CMOS MAPS, DEPFET, FPCCD, and SOI. Details on these studies can be found in the R&D report.

ACKNOWLEDGEMENTS

We are grateful to the members of the LCC Physics and Detectors Executive Board and the Americas Linear Collider Committee and to Zhen Liu and Lian-Tao Wang for contributions to this document. The work of the DESY group is supported by the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy, EXC 2121 "Quantum Universe", grant 390833306. The work of the KEK group is supported in part by the Japan Society for the Promotion of Science under the Grants-in-Aid for Science Research 16H02173, and 16H02176. The work of Graham Wilson is supported by the US National Science Foundation under award PHY-1913886. The work of James Wells is supported in part by the the US Department of Energy, contract DE-SC0007859. The work of Sunghoon Jung is supported by the National Research Foundation of Korea under grant NRF-2017R1D1A1B03030820. The work of the SLAC group is supported by the US Department of Energy, contract DE–AC02–76SF00515. The work of Junping Tian is supported in part by the Japan Society for the Promotion of Science under the Grant-in-Aid for Science Research 15H02083.

A Event weight factors for various choices of electron and positron polarization

	$e^-_L e^+_R$	$e^-_R e^+_L$	$e^-_L e^+_L$	$e^-_R e^+_R$
(P_{e^-}, P_{e^+})	$\frac{(1-P_{e^-})(1+P_{e^+})}{4}$	$\frac{(1+P_{e^-})(1-P_{e^+})}{4}$	$\frac{(1-P_{e^-})(1-P_{e^+})}{4}$	$\frac{(1+P_{e^-})(1+P_{e^+})}{4}$
$(-80\%, +30\%)$	0.585	0.035	0.315	0.065
$(+80\%, -30\%)$	0.035	0.585	0.065	0.315
$(-80\%, -30\%)$	0.315	0.065	0.585	0.035
$(+80\%, +30\%)$	0.065	0.315	0.035	0.585
$(-80\%, +60\%)$	0.72	0.02	0.18	0.08
$(+80\%, -60\%)$	0.02	0.72	0.08	0.18
$(-80\%, -60\%)$	0.18	0.08	0.72	0.02
$(+80\%, +60\%)$	0.08	0.18	0.02	0.72

Table 1: Weight factors to reweight events with a given initial-state helicity for any general polarization, and specifically for the ILC baseline and possible upgrade values.

References

[1] "Linear Collider Collaboration Detector R&D Report" `http://linearcollider.org/physics-detectors/working-group-detector-rd-liaison` .

[2] C. Potter, "Primer on ILC Physics and SiD Software Tools," Eur. Phys. J. Plus **135**, 525 (2020), [arXiv:2002.02399 [hep-ph]].

[3] Proceedings of the Linear Collider School 2014, `https://indico.desy.de/indico/event/9329` .

[4] Proceedings of the Linear Collider School 2016, `https://indico.desy.de/indico/event/11046` .

[5] Proceedings of the Linear Collider School 2018, `https://indico.desy.de/indico/event/19355` .

[6] T. Behnke, J. E. Brau, B. Foster, J. Fuster, M. Harrison, J. M. Paterson, M. E. Peskin, M. Stanitzki, N. Walker and H. Yamamoto, "The International Linear Collider Technical Design Report - Volume 1: Executive Summary," [arXiv:1306.6327 [physics.acc-ph]] .

[7] H. Baer, *et al.*, "The International Linear Collider Technical Design Report - Volume 2: Physics," [arXiv:1306.6352 [hep-ph]] .

[8] T. Behnke, *et al.*"The International Linear Collider Technical Design Report - Volume 4: Detectors," [arXiv:1306.6329 [physics.ins-det]] .

[9] P. Bambade, *et al.*, "The International Linear Collider: A Global Project," [arXiv:1903.01629 [hep-ex]] .

[10] K. Fujii *et al.* [LCC Physics Working Group], "Tests of the Standard Model at the International Linear Collider," [arXiv:1908.11299 [hep-ex]] .

[11] H. Abramowicz *et al.* [ILD Concept Group], "International Large Detector: Interim Design Report," [arXiv:2003.01116 [physics.ins-det]] .

[12] CEPC Study Group, "CEPC Conceptual Design Report: Volume 1 - Accelerator," [arXiv:1809.00285 [physics.acc-ph]] .

[13] J. B. Guimarães da Costa, *et al.* [CEPC Study Group], "CEPC Conceptual Design Report: Volume 2 - Physics & Detector," [arXiv:1811.10545 [hep-ex]] .

[14] A. Abada, *et al.* [FCC], "FCC-ee: The Lepton Collider," Eur. Phys. J. ST **228**, 261 (2019), `http://fcc-cdr.web.cern.ch/` .

[15] M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte and N. Toge, "A Multi-TeV Linear Collider Based on CLIC Technology," CERN Yellow Report 2012-007 (2012), `https://cds.cern.ch/record/1500095?ln=en` .

[16] P. Burrows, *et al.* [CLICdp and CLIC], "The Compact Linear Collider (CLIC) - 2018 Summary Report," CERN Yellow Report 2018-002 [arXiv:1812.06018 [physics.acc-ph]] .

[17] J. de Blas, *et al.*, "The CLIC Potential for New Physics," [arXiv:1812.02093 [hep-ph]] .

[18] J. de Blas, M. Cepeda, J. D'Hondt, R. Ellis, C. Grojean, B. Heinemann, F. Maltoni, A. Nisati, E. Petit, R. Rattazzi and W. Verkerke, "Higgs Boson Studies at Future Particle Colliders," [arXiv:1905.03764 [hep-ph]] .

[19] R. K. Ellis, *et al.*, "Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020," [arXiv:1910.11775 [hep-ex]] .

[20] LCC Working Group on Software and Computing, `https://github.com/iLCSoft/` and `https://ilcsoft.desy.de/portal`.

[21] F. Gaede, T. Behnke, N. Graf and T. Johnson, "LCIO: A Persistency framework for linear collider simulation studies," eConf **C0303241**, TUKT001 (2003) [arXiv:physics/0306114 [physics]] .

[22] J. de Favereau *et al.* [DELPHES 3], "DELPHES 3, A modular framework for fast simulation of a generic collider experiment," JHEP **02**, 057 (2014) [arXiv:1307.6346 [hep-ex]]] .

[23] M. Berggren, "SGV 3.0 - a fast detector simulation," [arXiv:1203.0217 [physics.ins-det]] .

[24] `http://ilcsnowmass.org` .

[25] W. Kilian, T. Ohl and J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC," Eur. Phys. J. C **71**, 1742 (2011) [arXiv:0708.4233 [hep-ph]] .

[26] J. Reuter, S. Braß, P. Bredt, W. Kilian, T. Ohl, V. Rothe and P. Stienemeier, "Status of the WHIZARD generator for linear collider," [arXiv:2002.06122 [hep-ph]] .

[27] T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker and K. Yokoya, "ILC Operating Scenarios," [arXiv:1506.07830 [hep-ex]] .

[28] K. Fujii, *et al.*, “Physics Case for the 250 GeV Stage of the International Linear Collider,” [arXiv:1710.07621 [hep-ex]] .

[29] D. Schulte, “Beam-beam simulations with GUINEA-PIG,” CERN-PS-99-014-LP.

[30] T. Sjostrand, S. Mrenna and P. Z. Skands, “PYTHIA 6.4 Physics and Manual,” JHEP **05**, 026 (2006) [arXiv:hep-ph/0603175 [hep-ph]] .

[31] M. Berggren, lecture available at `https://agenda.linearcollider.org/event/4917/`.

[32] `https://github.com/ILCSoft/ILCDelphes` .

[33] C. Potter, “DSiD: a Delphes Detector for ILC Physics Studies,” presentation at LCWS2015, [arXiv:1602.07748 [hep-ph]]; `https://dsid.hepforge.org/`.

[34] C. Chen, X. Mo, M. Selvaggi, Q. Li, G. Li, M. Ruan and X. Lou, “Fast simulation of the CEPC detector with Delphes,” [arXiv:1712.09517 [hep-ex]] .

[35] E. Leogrande, P. Roloff, U. Schnoor and M. Weber, “A DELPHES card for the CLIC detector,” [arXiv:1909.12728 [hep-ex]] .

[36] `https://github.com/iLCSoft/LCIO/tree/master/examples/cpp/delphes2lcio`

[37] M. Berggren, lecture available at `https://agenda.linearcollider.org/event/8525/` .

[38] `svn export https://svnsrv.desy.de/public/sgv/tags/SGV-3.0rc1/SGV-3.0rc1/` `bash install` .

[39] `https://github.com/ILDAnaSoft/miniDST`

[40] `https://indico.fnal.gov/event/45031/`

[41] K. Fujii, *et al.*, “The role of positron polarization for the initial 250 GeV stage of the International Linear Collider,” [arXiv:1801.02840 [hep-ph]] .

[42] T. Suehara and T. Tanabe, “LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies,” Nucl. Instrum. Meth. A **808**, 109 (2016) [arXiv:1506.08371 [physics.ins-det]] .

[43] M. Boronat, J. Fuster, I. Garcia, P. Roloff, R. Simoniello and M. Vos, “Jet reconstruction at high-energy electron–positron colliders,” Eur. Phys. J. C **78**, 144 (2018) [arXiv:1607.05039 [hep-ex]] .

[44] J. Tian, "Study of Jet Clustering at e^+e^-", presentation at the 2018 ILD Meeting 2018, Ichinoseki, `https://agenda.linearcollider.org/event/7760/timetable/` .

[45] S. Kawada, K. Fujii, T. Suehara, T. Takahashi and T. Tanabe, "A study of the measurement precision of the Higgs boson decaying into tau pairs at the ILC," Eur. Phys. J. C **75**, 617 (2015) [arXiv:1509.01885 [hep-ex]] .

[46] D. Jeans, "Tau lepton reconstruction at collider experiments using impact parameters," Nucl. Instrum. Meth. A **810**, 51 (2016) [arXiv:1507.01700 [hep-ex]].

[47] D. Jeans and G. Wilson, "Measuring the CP state of tau lepton pairs from Higgs decay at the ILC," Phys. Rev. D **98**, 013007 (2018) [arXiv:1804.01241 [hep-ex]].

[48] D. Jeans and K. Yumino, "ILD benchmark: a study of $e^-e^+ \to \tau^-\tau^+$ at 500 GeV," [arXiv:1912.08403 [hep-ex]] .

[49] O. Wendt, F. Gaede and T. Kramer, "Event Reconstruction with MarlinReco at the ILC," in Proceedings of LCWS06, Pramana **69**, 1109 (2007) [arXiv:physics/0702171 [physics]] .

[50] I. Božović Jelisavčić, S. Lukić, G. Milutinović Dumbelović, M. Pandurović and I. Smiljanić, "Luminosity measurement at ILC," JINST **8**, P08012 (2013) [arXiv:1304.4082 [physics.acc-ph]] .

[51] S. Poss and A. Sailer, "Luminosity Spectrum Reconstruction at Linear Colliders," Eur. Phys. J. C **74**, 2833 (2014) [arXiv:1309.0372 [physics.ins-det]] .

[52] A. P. Sailer, "Studies of the measurement of differential luminosity using Bhabha events at the International Linear Collider," Humboldt University Diploma thesis, `http://www-library.desy.de/preparch/desy/thesis/desy-thesis-09-011.pdf` .

[53] M. Ruan, *et al.*, "Performance requirement from the hadronic event/jet", talk presented at LCWS 2019, `https://agenda.linearcollider.org/event/8217/contributions/44771/attachments/34967/54047/Jet_Requirement-LCWS.pdf` .

[54] S. Bilokin, R. Pöschl and F. Richard, "Measurement of b quark EW couplings at ILC," [arXiv:1709.04289 [hep-ex]] .

[55] S. Bilokin, A. Irles, R. Pöschl, and F. Richard, "Methods for b quark EW couplings measurements at ILC250 with 2000 fb^{-1}". (To appear soon; please contact the authors.)

[56] H. Stängle, "Measurement of the $Z \to s\bar{s}$ Coupling at the SLD", Colorado State University Ph.D. thesis, SLAC-R-549 (1999); `https://www-public.slac.stanford.edu/scidoc/docMeta.aspx?slacPubNumber=slac-R-549` .

[57] P. Abreu *et al.* [DELPHI], "Measurement of the strange quark forward backward asymmetry around the Z0 peak," Eur. Phys. J. C **14**, 613 (2000)

[58] Y. Kats, "Measuring polarizations of bottom, charm, strange, up and down quarks in top decays," in Proceedings of TOP2015, PoS **TOP2015**, 028 (2015) [arXiv:1601.07462 [hep-ph]] .

[59] J. Duarte-Campderros, G. Perez, M. Schlaffer and A. Soffer, "Probing the Higgs-strange-quark coupling at e^+e^- colliders using light-jet flavor tagging," Phys. Rev. D **101**, 115005 (2020) [arXiv:1811.09636 [hep-ph]] .

[60] Y. Nakai, D. Shih and S. Thomas, "Strange Jet Tagging," [arXiv:2003.09517 [hep-ph]].

[61] J. Yan, S. Watanuki, K. Fujii, A. Ishikawa, D. Jeans, J. Strube, J. Tian and H. Yamamoto, "Measurement of the Higgs boson mass and $e^+e^- \to ZH$ cross section using $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ at the ILC," Phys. Rev. D **94**, 113002 (2016) [arXiv:1604.07524 [hep-ex]] .

[62] A. Miyamoto, "A measurement of the total cross section of σ_{Zh} at a future e^+e^- collider using the hadronic decay mode of Z," [arXiv:1311.2248 [hep-ex]] .

[63] T. Tomita, "Hadronic Higgs Recoil Mass Study with ILD at 250GeV", presentation at the 2015 Asian Linear Collider Workshop, `https://agenda.linearcollider.org/event/6557/contributions/31831/` .

[64] M. Thomson, "Model-independent measurement of the e$^+$ e$^-$ $\to$ HZ cross section at a future e$^+$ e$^-$ linear collider using hadronic Z decays," Eur. Phys. J. C **76**, 72 (2016) [arXiv:1509.02853 [hep-ex]] .

[65] J. Tian, "A new method for measuring the Higgs mass at the ILC", ILD-PHYS-PUB-2019-001 (2020), available at `https://confluence.desy.de/download/attachments/42357928/ILD-PHYS-PUB-2019-001.pdf`

[66] A. Ishikawa, "Search for invisible Higgs decays at the ILC", presentation at LCWS2014, `http://agenda.linearcollider.org/event/6389/session/0/contribution/140` .

[67] Y. Kato, "Probing the dark sector via searches for invisible decays of the Higgs boson at the ILC," presentation at the 2019 EPS-HEP conference, [arXiv:2002.12048 [hep-ex]] .

[68] H. Ono and A. Miyamoto, "A study of measurement precision of the Higgs boson branching ratios at the International Linear Collider," Eur. Phys. J. C **73**, 2343 (2013) [arXiv:1207.0300 [hep-ex]] .

[69] J. Gao, "Probing light-quark Yukawa couplings via hadronic event shapes at lepton colliders," JHEP **01**, 038 (2018) [arXiv:1608.01746 [hep-ph]] .

[70] T. Ogawa, "Sensitivity to anomalous VVH couplings induced by dimension-6 operators at the ILC", KEK Sokendai Ph.D. thesis, `https://ir.soken.ac.jp/?action=pages_view_main&active_action=repository_view_main_item_detail&item_id=5889&item_no=1&page_id=29&block_id=155` . [Look for the "Thesis" link at the bottom of the page. The thesis itself is in English.]

[71] R. Harnik, A. Martin, T. Okui, R. Primulando and F. Yu, "Measuring CP Violation in $h \to \tau^+\tau^-$ at Colliders," Phys. Rev. D **88**, 076009 (2013) [arXiv:1308.1094 [hep-ph]] .

[72] S. Berge, W. Bernreuther and H. Spiesberger, "Higgs CP properties using the τ decay modes at the ILC," Phys. Lett. B **727**, 488-495 (2013) doi:10.1016/j.physletb.2013.11.006 [arXiv:1308.2674 [hep-ph]] .

[73] Y. Aoki, K. Fujii, S. Jung, J. Lee, J. Tian and H. Yokoya, "Study of the $h\gamma Z$ coupling using $e^+e^- \to h\gamma$ at the ILC," presentation at the LCWS2018 workshop [arXiv:1902.06029 [hep-ex]] .

[74] Y. Aoki, K. Fujii, S. Jung, J. Lee, J. Tian and H. Yokoya, "Study of the $h\gamma Z$ coupling at the ILC," presentation at the LCWS2019 workshop [arXiv:2002.07164 [hep-ex]] .

[75] Z. Liu, L. Wang and H. Zhang, "Exotic decays of the 125 GeV Higgs boson at future e^+e^- lepton colliders," Chin. Phys. C **41**, 063102 (2017) [arXiv:1612.09284 [hep-ph]] .

[76] S. Alipour-Fard, N. Craig, M. Jiang and S. Koren, "Long Live the Higgs Factory: Higgs Decays to Long-Lived Particles at Future Lepton Colliders," Chin. Phys. C **43**, 053101 (2019) [arXiv:1812.05588 [hep-ph]] .

[77] C. Dürig, K. Fujii, J. List and J. Tian, "Model Independent Determination of HWW coupling and Higgs total width at ILC," [arXiv:1403.7734 [hep-ex]] .

[78] T. Han, Z. Liu and J. Sayre, "Potential Precision on Higgs Couplings and Total Width at the ILC," Phys. Rev. D **89**, 113006 (2014) [arXiv:1311.7155 [hep-ph]].

[79] T. Barklow, K. Fujii, S. Jung, M. E. Peskin and J. Tian, "Model-Independent Determination of the Triple Higgs Coupling at e+e- Colliders," Phys. Rev. D **97**, no.5, 053004 (2018) [arXiv:1708.09079 [hep-ph]] .

[80] C. F. Dürig, "Measuring the Higgs Self-coupling at the International Linear Collider", DESY Ph.D. thesis, `inspirehep.net/record/1493742`.

[81] J. Tian, "Study of Higgs self-coupling at the ILC based on the full detector simulation at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV," in proceedings of the 3rd Linear Collider Forum, DESY, `https://inspirehep.net/conferences/1186663` .

[82] P. Roloff, U. Schnoor, R. Simoniello, and B. Xu [CLICdp], "Double Higgs boson production and Higgs self-coupling extraction at CLIC," [arXiv:1901.05897 [hep-ex]] .

[83] M. Vos, *et al.*, "Top physics at high-energy lepton colliders," [arXiv:1604.08122 [hep-ex]] .

[84] P. Comas, M. Martinez, R. Miquel, S. Orteu and M. Schmitt, "Recent studies on top quark physics at NLC," in the proceedings of LCWS 1995, IFAE-UAB-95-05.

[85] F. Simon, "Impact of Theory Uncertainties on the Precision of the Top Quark Mass in a Threshold Scan at Future e+e- Colliders," PoS **ICHEP2016**, 872 (2017) [arXiv:1611.03399 [hep-ex]] .

[86] F. Simon, "Scanning Strategies at the Top Threshold at ILC," [arXiv:1902.07246 [hep-ex]] .

[87] K. Nowak and A. F. Żarnecki, "Extracting the top-quark mass and Yukawa coupling from the threshold scan at CLIC," Proc. SPIE Int. Soc. Opt. Eng. **11176**, 1117648 (2019).

[88] A. H. Hoang, S. Mantry, A. Pathak and I. W. Stewart, "Extracting a Short Distance Top Mass with Light Grooming," Phys. Rev. D **100**, 074021 (2019) [arXiv:1708.02586 [hep-ph]] .

[89] B. Dehnadi, A. H. Hoang, V. Mateu, M. Preisser and I. W. Stewart, "Monte Carlo Top Quark Mass Calibration," PoS **RADCOR2017**, 062 (2018) [arXiv:1803.02321 [hep-ph]] .

[90] M. Boronat, E. Fullana, J. Fuster, P. Gomis, A. Hoang, V. Mateu, M. Vos and A. Widl, "Top quark mass measurement in radiative events at electron-positron colliders," Phys. Lett. B **804**, 135353 (2020) [arXiv:1912.01275 [hep-ph]] .

[91] M. Amjad, *et al.*, "A precise characterisation of the top quark electro-weak vertices at the ILC," Eur. Phys. J. C **75**, 512 (2015) [arXiv:1505.06020 [hep-ex]].

[92] P. Khiem, E. Kou, Y. Kurihara and F. Le Diberder, "Probing New Physics using top quark polarization in the $e^+e^- \to t\bar{t}$ process at future Linear Colliders," [arXiv:1503.04247 [hep-ph]] .

[93] W. Bernreuther, L. Chen, I. García, M. Perelló, R. Pöschl, F. Richard, E. Ros and M. Vos, "CP-violating top quark couplings at future linear e^+e^- colliders," Eur. Phys. J. C **78**, 155 (2018) [arXiv:1710.06737 [hep-ex]] .

[94] Recent surveys include Section 8 of [10], Chapter 3 of [7], and [95].

[95] T. Han, P. Langacker, Z. Liu and L. T. Wang, "Diagnosis of a New Neutral Gauge Boson at the LHC and ILC for Snowmass 2013," [arXiv:1308.2738 [hep-ph]] .

[96] A. Irles, *et al.* [ILD], "Production and measurement of $e^+e^- \to c\bar{c}$ signatures at the 250 GeV ILC," [arXiv:2002.05805 [hep-ex]] .

[97] K. Hagiwara, R. Peccei, D. Zeppenfeld and K. Hikasa, "Probing the Weak Boson Sector in $e^+e^- \to W^+W^-$," Nucl. Phys. B **282**, 253 (1987).

[98] M. Diehl, O. Nachtmann and F. Nagel, "Triple gauge couplings in polarized $e^+e^- \to W^+W^-$ and their measurement using optimal observables," Eur. Phys. J. C **27**, 375 (2003) [arXiv:hep-ph/0209229 [hep-ph]] .

[99] T. L. Barklow, "WW physics at future e^+e^- linear colliders," [arXiv:hep-ph/0106046 [hep-ph]] .

[100] I. Marchesini, "Triple gauge couplings and polarization at the ILC and leakage in a highly granular calorimeter," DESY-THESIS-2011-044, `http://www-library.desy.de/cgi-bin/showprep.pl?thesis11-044`.

[101] A. Rosca, "Measurement of the charged triple gauge boson couplings at the ILC," presentation at ICHEP 2014. Nucl. Part. Phys. Proc. **273-275**, 2226 (2016).

[102] T. Ueno, "A simulation study on measurement of the polarization asymmetry A_{LR} using the initial state radiation at the ILC with center-of-mass energy of 250 GeV", Tohoku University Master's thesis, `http://lambda.phys.tohoku.ac.jp/gppu/news/20190208QE1/students/ueno2019/thesis_ueno.pdf` .

[103] S. Schael, *et al.* [ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group and SLD Heavy Flavour Group], "Precision electroweak measurements on the Z resonance," Phys. Rept. **427**, 257-454 (2006) [arXiv:hep-ex/0509008 [hep-ex]] .

[104] G. Hiller and A. Kagan, "Probing for new physics in polarized Λ_b decays at the Z," Phys. Rev. D **65**, 074038 (2002) [arXiv:hep-ph/0108074 [hep-ph]] .

[105] A. J. Larkoski, I. Moult and B. Nachman, "Jet Substructure at the Large Hadron Collider: A Review of Recent Advances in Theory and Machine Learning," Phys. Rept. **841**, 1 (2020) [arXiv:1709.04464 [hep-ph]] .

[106] R. Kogler, *et al.*, “Jet Substructure at the Large Hadron Collider: Experimental Review,” Rev. Mod. Phys. **91**, 045003 (2019) [arXiv:1803.06991 [hep-ex]] .

[107] S. Hoeche, Y. Li and S. Prestel, “Combining parton showers and NNLO matrix elements,” [arXiv:1507.05325 [hep-ph]] .

[108] S. Hoeche, F. Krauss and S. Prestel, “Implementing NLO DGLAP evolution in Parton Showers,” JHEP **10**, 093 (2017) [arXiv:1705.00982 [hep-ph]] .

[109] P. F. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, “MiNNLO$_{\mathrm{PS}}$: A new method to match NNLO QCD to parton showers,” [arXiv:1908.06987 [hep-ph]] .

[110] J. Gao, Y. Gong, W. L. Ju and L. L. Yang, “Thrust distribution in Higgs decays at the next-to-leading order and beyond,” JHEP **03**, 030 (2019) [arXiv:1901.02253 [hep-ph]] .

[111] M. Berggren, F. Brümmer, J. List, G. Moortgat-Pick, T. Robens, K. Rolbiecki and H. Sert, “Tackling light higgsinos at the ILC,” Eur. Phys. J. C **73**, 2660 (2013) [arXiv:1307.3566 [hep-ph]] .

[112] H. Baer, V. Barger, D. Mickelson, A. Mustafayev and X. Tata, “Physics at a Higgsino Factory,” JHEP **06**, 172 (2014) [arXiv:11404.7510 [hep-ph]] .

[113] H. Baer, M. Berggren, K. Fujii, J. List, S. L. Lehtinen, T. Tanabe and J. Yan, “The ILC as a natural SUSY discovery machine and precision microscope: from light higgsinos to tests of unification,” Phys. Rev. D **101**, 095026 (2020) [arXiv:1912.06643 [hep-ex]] .

[114] M. T. N. Pardo de Vera, M. Berggren and J. List, “Chargino production at the ILC,” [arXiv:2002.01239 [hep-ph]] . [arXiv:2002.01239 [hep-ph]].

[115] M. Berggren, “What pp SUSY limits mean for future $\mathrm{e}^+\mathrm{e}^-$ colliders,” [arXiv:2003.12391 [hep-ph]] .

[116] P. Achard *et al.* [L3], “Search for R parity violating decays of supersymmetric particles in e^+e^- collisions at LEP,” Phys. Lett. B **524**, 65 (2002) [arXiv:hep-ex/0110057 [hep-ex]] .

[117] G. Abbiendi *et al.* [OPAL], “Search for R parity violating decays of scalar fermions at LEP,” Eur. Phys. J. C **33**, 149 (2004) [arXiv:hep-ex/0310054 [hep-ex]] .

[118] J. Abdallah *et al.* [DELPHI], “Search for supersymmetric particles assuming R-parity nonconservation in e^+e^- collisions at $\sqrt{s} = 192$ GeV to 208 GeV,” Eur. Phys. J. C **36**, 1 (2004) [arXiv:hep-ex/0406009 [hep-ex]] .

[119] B. Vormwald and J. List, “Bilinear R parity violation at the ILC: neutrino physics at colliders,” Eur. Phys. J. C **74**, 2720 (2014) [arXiv:1307.4074 [hep-ex]].

[120] D. Aristizabal Sierra, M. Hirsch and W. Porod, “R-parity violating sneutrino decays,” JHEP **09**, 033 (2005) [arXiv:hep-ph/0409241 [hep-ph]] .

[121] M. Battaglia, N. Kelley and B. Hooberman, “A Study of $e^+e^- \to H^0A^0$ Production and the Constraint on Dark Matter Density,” Phys. Rev. D **78**, 015021 (2008) [arXiv:0805.1506 [hep-ex]] .

[122] M. Battaglia, F. Bogert, A. Ferrari, J. Relefors and S. Zalusky, “A Study of Heavy Higgs Properties at a Multi-TeV e^+e^- Collider,” [arXiv:1203.0668 [hep-ex]] .

[123] G. Abbiendi *et al.* [ALEPH, DELPHI, L3, OPAL and LEP], “Search for Charged Higgs bosons: Combined Results Using LEP Data,” Eur. Phys. J. C **73**, 2463 (2013) [arXiv:1301.6065 [hep-ex]] .

[124] H. Bahl, P. Bechtle, S. Heinemeyer, S. Liebler, T. Stefaniak and G. Weiglein, “HL-LHC and ILC sensitivities in the hunt for heavy Higgs bosons,” [arXiv:2005.14536 [hep-ph]] .

[125] Y. Wang, M. Berggren and J. List, “ILD Benchmark: Search for Extra Scalars Produced in Association with a Z boson at $\sqrt{s} = 500$ GeV,” [arXiv:2005.06265 [hep-ex]] .

[126] C. R. Chen, J. Hajer, T. Liu, I. Low and H. Zhang, JHEP **09**, 129 (2017) [arXiv:1705.07743 [hep-ph]] .

[127] C. Csáki, F. Ferreira De Freitas, L. Huang, T. Ma, M. Perelstein and J. Shu, “Naturalness Sum Rules and Their Collider Tests,” JHEP **05**, 132 (2019) [arXiv:1811.01961 [hep-ph]] .

[128] K. Fujii *et al.* [LCC Physics Working Group], “Implications of the 750 GeV gamma-gamma Resonance as a Case Study for the International Linear Collider,” [arXiv:1607.03829 [hep-ph]] .

[129] P. W. Graham, D. E. Kaplan and S. Rajendran, “Cosmological Relaxation of the Electroweak Scale,” Phys. Rev. Lett. **115**, 221801 (2015) [arXiv:1504.07551 [hep-ph]] .

[130] C. Frugiuele, E. Fuchs, G. Perez and M. Schlaffer, “Relaxion and light (pseudo)scalars at the HL-LHC and lepton colliders,” JHEP **10**, 151 (2018) [arXiv:1807.10842 [hep-ph]] .

[131] M. Habermehl, M. Berggren and J. List, "WIMP Dark Matter at the International Linear Collider," Phys. Rev. D **101**, 075053 (2020) [arXiv:2001.03011 [hep-ex]] .

[132] M. Habermehl, "Dark Matter at the International Linear Collider," DESY Ph.D. thesis, `http://bib-pubdb1.desy.de/record/417605` (2018).

[133] A. Boveia and C. Doglioni, "Dark Matter Searches at Colliders," Ann. Rev. Nucl. Part. Sci. **68**, 429-459 (2018) [arXiv:1810.12238 [hep-ex]] .

[134] J. Kalinowski, W. Kotlarski, T. Robens, D. Sokolowska and A. F. Żarnecki, "Benchmarking the Inert Doublet Model for e^+e^- colliders," JHEP **12**, 081 (2018) [arXiv:1809.07712 [hep-ph]] .

[135] A. F. Zarnecki, J. Kalinowski, J. Klamka, P. Sopicki, W. Kotlarski, T. Robens and D. Sokolowska, "Searching Inert Scalars at Future $\mathrm{e}^+\mathrm{e}^-$ Colliders," [arXiv:2002.11716 [hep-ph]] .

[136] J. D. Bjorken, R. Essig, P. Schuster and N. Toro, "New Fixed-Target Experiments to Search for Dark Gauge Forces," Phys. Rev. D **80**, 075018 (2009) [arXiv:0906.0580 [hep-ph]] .

[137] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster and N. Toro, "Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX," Phys. Rev. D **99**, 075001 (2019) [arXiv:1807.01730 [hep-ph]] .

[138] M. Bauer, M. Heiles, M. Neubert and A. Thamm, "Axion-Like Particles at Future Colliders," Eur. Phys. J. C **79**, 74 (2019) [arXiv:1808.10323 [hep-ph]] .

[139] E. Izaguirre, G. Krnjaic, P. Schuster and N. Toro, "New Electron Beam-Dump Experiments to Search for MeV to few-GeV Dark Matter," Phys. Rev. D **88**, 114015 (2013) [arXiv:1307.6554 [hep-ph]] .

[140] M. Battaglieri, *et al.*, "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report," [arXiv:1707.04591 [hep-ph]] .

[141] R. Alemany, *et al.*, "Summary Report of Physics Beyond Colliders at CERN," [arXiv:1902.00260 [hep-ex]] .

[142] S. Kanemura, T. Moroi and T. Tanabe, "Beam dump experiment at future electron–positron colliders," Phys. Lett. B **751**, 25 (2015) [arXiv:1507.02809 [hep-ph]] .

[143] Y. Sakaki and D. Ueda, "Search for new light particles at ILC main beam dump," [arXiv:2009.13790 [hep-ph]] .

[144] L. Marsicano, *et al.*, "Novel Way to Search for Light Dark Matter in Lepton Beam-Dump Experiments," Phys. Rev. Lett. **121**, 041802 (2018) [arXiv:1807.05884 [hep-ex]] .

[145] P. Bechtle, K. Desch and P. Wienemann, "Fittino, a program for determining MSSM parameters from collider observables using an iterative method," Comput. Phys. Commun. **174**, 47 (2006) [arXiv:hep-ph/0412012 [hep-ph]]; `https://flcwiki.desy.de/Fittino` .

[146] R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, "Measuring Supersymmetry," Eur. Phys. J. C **54**, 617 (2008) [arXiv:0709.3985 [hep-ph]]; `https://atlas.lal.in2p3.fr/physics/sfitter/` .

[147] O. Buchmueller, *et al.*, "Frequentist Analysis of the Parameter Space of Minimal Supergravity," Eur. Phys. J. C **71**, 1583 (2011) [arXiv:1011.6118 [hep-ph]] . [arXiv:1011.6118 [hep-ph]]; `https://mastercode.web.cern.ch/` .

[148] M. Cahill-Rowley, J. Hewett, A. Ismail and T. Rizzo, "Higgs boson coupling measurements and direct searches as complementary probes of the phenomenological MSSM," Phys. Rev. D **90**, 095017 (2014) [arXiv:1407.70213 [hep-ph]] .

[149] J. D. Wells and Z. Zhang, "Effective field theory approach to trans-TeV supersymmetry: covariant matching, Yukawa unification and Higgs couplings," JHEP **05**, 182 (2018) [arXiv:1711.04774 [hep-ph]] .

[150] T. Barklow, K. Fujii, S. Jung, R. Karl, J. List, T. Ogawa, M. E. Peskin and J. Tian, "Improved Formalism for Precision Higgs Coupling Fits," Phys. Rev. D **97**, 053003 (2018) [arXiv:1708.08912 [hep-ph]] .

[151] J. De Blas, G. Durieux, C. Grojean, J. Gu and A. Paul, "On the future of Higgs, electroweak and diboson measurements at lepton colliders," JHEP **12**, 117 (2019) [arXiv:1907.04311 [hep-ph]] .

[152] G. Buchalla, O. Catà and C. Krause, "Complete Electroweak Chiral Lagrangian with a Light Higgs at NLO," Nucl. Phys. B **880**, 552 (2014) [arXiv:1907.04311 [hep-ph]] .

[153] I. Brivio, T. Corbett, O. Éboli, M. Gavela, J. Gonzalez-Fraile, M. Gonzalez-Garcia, L. Merlo and S. Rigolin, "Disentangling a dynamical Higgs," JHEP **03**, 024 (2014) [arXiv:1311.1823 [hep-ph]].

[154] S. Chang and M. A. Luty, "The Higgs Trilinear Coupling and the Scale of New Physics," JHEP **20**, 140 (2020) [arXiv:1902.05556 [hep-ph]] .

[155] A. Falkowski and R. Rattazzi, "Which EFT," JHEP **10**, 255 (2019) [arXiv:1902.05936 [hep-ph]].

[156] G. Durieux, M. Perelló, M. Vos and C. Zhang, "Global and optimal probes for the top-quark effective field theory at future lepton colliders," JHEP **10**, 168 (2018) [arXiv:1807.02121 [hep-ph]] .

[157] G. Durieux, A. Irles, V. Miralles, A. Peñuelas, R. Pöschl, M. Perelló and M. Vos, "The electro-weak couplings of the top and bottom quarks – global fit and future prospects," JHEP **12**, 098 (2019) [arXiv:1907.10619 [hep-ph]] .

[158] E. Vryonidou and C. Zhang, "Dimension-six electroweak top-loop effects in Higgs production and decay," JHEP **08**, 036 (2018) [arXiv:1804.09766 [hep-ph]] .

[159] G. Durieux, J. Gu, E. Vryonidou and C. Zhang, "Probing top-quark couplings indirectly at Higgs factories," Chin. Phys. C **42**, no.12, 123107 (2018) [arXiv:1809.03520 [hep-ph]] .

[160] S. Jung, J. Lee, M. Perelló, J. Tian and M. Vos, "Higgs, top and electro-weak precision measurements at future e^+e^- colliders; a combined effective field theory analysis with renormalization mixing," [arXiv:2006.14631 [hep-ph]] .

[161] S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau and T. Vantalon, "A global view on the Higgs self-coupling at lepton colliders," JHEP **02**, 178 (2018) [arXiv:1711.03978 [hep-ph]] .

[162] A. Falkowski, M. Gonzalez-Alonso, A. Greljo, D. Marzocca and M. Son, "Anomalous Triple Gauge Couplings in the Effective Field Theory Approach at the LHC," JHEP **02**, 115 (2017) [arXiv:1609.06312 [hep-ph]] .

[163] `https://confluence.desy.de/display/ILD/ILD+by-laws` .

[164] X. Ai [ACTS Developers], "ACTS: A common tracking software," [arXiv:1910.03128 [physics.ins-det]] .