The International Linear Collider
A Global Project*

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Input from the International Linear Collider community for the European Strategy Update: supplementary material

I. INTRODUCTION

5 pages Brau + Peskin

II. ILC MACHINE DESIGN

15 pages B. List + Michizono

III. ILC RUNNING SCENARIOS

5 pages J. List

Amoung the advantages of e^+e^- colliders is the ability to collect datasets with different center-of-mass energies and beam polarisation settings, according to the neeeds of the various physics measurements. While each measurement has its prefered data-taking mode, the combination with datasets collected other beam energies and/or beam polarisations provide important robustness against systematic uncertainties.

Any physics projection will depend on the exact assumptions on the assumed running scenario, i.e. the integrated luminosity collected at each considered center-of-mass energy with each polarisation setting.

The interplay of different datasets has been studied in detail in [?], with a special focus on optimising the Higgs precision measurements.

HERE: Tables with integrated luminsoities and polarisation mit from [?]

Time dependence: explain why need longer when starting at 250 GeV

explain new beam parameters, cite machine staging report

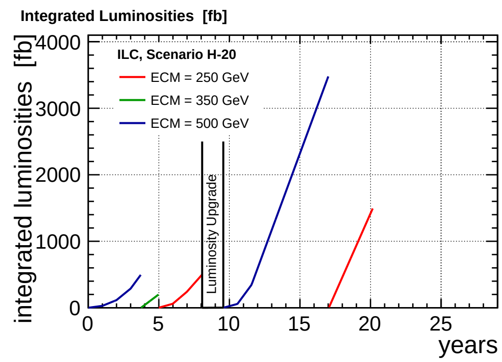

FIG. 1. The nominal 20-year running program for the 500-GeV-ILC [?].

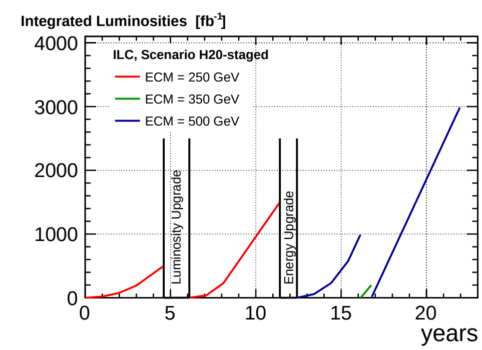

FIG. 2. The nominal 22-year running program for the staged ILC, starting operation at 250 GeV [?]. The integrated luminosities are the same of for the original H20 scenario.

IV. PHYSICS CASE (250 GEV)

10 pages Peskin

V. DETECTORS

10 pages Behnke + White

VI. SOFTWARE

10 pages Gaede + Miyamoto

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VII. PHYSICS SIMULATIONS: HIGGS

20 pages Tian + J. List

VIII. PHYSICS SIMULATIONS: SEARCHES

5 pages Berggren

IX. PROGRAM OF THE ILC BEYOND 250 GEV

10 pages Peskin, Fujii and Vos

Abstract: A key advantage of linear colliders is the possibility to upgrade the center-of-mass energy. After finalizing the programme discussed in Sections IV, VII and VIII the ILC can be expanded to explore energies well beyond 250 GeV. In this section, the potential of higher-energy operation is reviewed.

Intro and scope: While the energy reach of circular electron-positron colliders of a given circumference is limited by synchrotron radiation, linear colliders can be upgraded to reach higher center-of-mass energy. It is therefore natural to envisage a program beyond the baseline program at $\sqrt{s} = 250$ GeV discussed in Sections IV, VII and VIII. The energy extendability of linear colliders provides great flexibility to respond to new discoveries, at the ILC or elsewhere, by adapting the collider design. The exact outline of the high-energy program will likely change with the developing insight in the physics of the Standard Model, and what lies beyond it. The high-energy program is moreover affected by new developments in accelerator technology. This section presents a brief status for the most relevant accelerator R&D lines and a brief review of studies of the physics potential at center-of-mass energies greater than 250 GeV.

There exists an extensive literature on the subject. We refer in particular many detailed studies performed for the ILC [**?** **?**] and CLIC design reports [**?**].

Upgradability and technology: In major particle physics laboratories, the lifetime of collider elements and infrastructure is rarely limited to the scope of the project they were designed and built for. A famous example is the Proton Synchrotron at CERN. Initially commissioned in 1959, it is still in operation as part of the accelerator complex that prepares protons for injection in the Large Hadron Collider. Also the results of expensive civil engineering efforts are reused, so that their cost is effectively shared. The tunnel that was constructed for LEP now hosts the Large Hadron Collider and its luminosity upgrade. In very much the same way, one could envisage that the ILC forms the seed for a facility that contributes to the cutting edge of particle physics for decades.

For electron-positron collisions, any facility at energies much higher than those already realized must be a linear collider in a long, straight tunnel. The ILC infrastructure will provide a basis for collisions at 500 GeVand also, with new generations of technology, a setting for electron-positron collisions at still higher energies. It will allow Japan to host a laboratory in Asia of comparable importance to CERN on the world scene in particle physics, one that will be the global host for experiments with electron and positron beams into the longer-term future.

The most obvious energy upgrade path is an extension of the linear accelerator (LINAC) sections of the colliders, which provides an increase in center-of-mass energy that is proportional to the length of the LINACs. The design of the ILC presented in the Technical Design Report [**?** **?** **?**] envisaged a center-of-mass energy of 500 GeV in a facility with a total length of 31 km. The reference staging scenario (H20-staged [**?**]) consists of operation at three energy stages: 250, 350, and 500 GeV. The ILC TDR also documents a possible extension to 1 TeV based on current superconducting RF technology.

An even larger increase in center-of-mass energy may be achieved by exploiting advances in accelerator technology. The development of cavities with higher accelerating gradient can drive a significant increase in the energy while maintaining a compact infrastructure. Superconducting RF technology is rapidly evolving and important progress has been made in developing cavities with a gradient well beyond the 35 MV/m required for the ILC [**?** **?**]. and even beyond the 45 MV/m envisaged for the 1 TeV ILC. In the longer term, alternate-shape or thin-film-coated Nb_3Sn cavities or multi-layer coated cavities offer the potential of significantly increased cavity performance [**?**]. Novel acceleration schemes may achieve even higher gradient. The CLIC drive beam concept has achieved accelerating gradients of up to 100 MV/m [**?**]. Finally, the advent of novel acceleration schemes based on plasma wakefield acceleration may open up the energy regime up to 30 TeV. A report of the status of accelerator R&D and remaining challenges is found in Refs. [**?** **?**], with further details and a brief description of the potential of such a machine in the addendum [**?**].

The case for high-energy operation

Higher energy can enhance the scientific return of the installation in several ways. It naturally increases the direct discovery reach of the collider. Experience at previous e^+e^- colliders suggests that for most scenarios it is straightforward to discover or exclude pair-production of new particles with masses almost up to the kinematic limit of half the center-of-mass energy [**?**]. Additional Higgs bosons of an extended Higgs sector can be discovered as long as the sum of the masses is less than the center-of-mass energy. The potential of the 500 GeV (and 1 TeV) ILC has been demonstrated in detailed simulations for many important benchmark scenarios [**?** **?**], including scenarios with WIMP dark matter [**?**] and SUSY scenarios with a light electroweak sparticle spectrum[**?**].

An e^+e^- collider with a center-of-mass energy beyond 250 GeV can also probe several new Standard Model processes. Top quark physics starts at the top quark pair production threshold at $\sqrt{s} \sim 2m_t$. A Linear Collider with a center-of-mass energy above this threshold can provide a precise scrutiny of top quark properties and its (electroweak) interactions. Two further thresholds are found around 500 GeV, where Higgs boson pair production and associated production of a Higgs boson with top quarks open up. The analysis of these processes allow for a much more model-independent extraction of the Higgs trilinear self-coupling (in Zhh and $\nu\bar{\nu}hh$ production [**?**]) and the top quark Yukawa coupling (in $t\bar{t}h$ production [**?**]). Furthermore, many t-channel processes become accessible or even dominant at higher energy. Therefore, the relevance of vector-boson fusion Higgs production and di-boson production, to name but two examples, grow strongly enhanced at higher energy.

Finally, the added value of higher energy can be understood in an EFT analysis. The precision measurements at a linear e^+e^- form an ideal set of constraints on the Wilson coefficients of the dimension-six operators in the SM EFT. Ultimately, the ILC data may allow to constrain a global fit of all (59) dimension-six operator coefficients. In the EFT the impact of certain operators [**?** **?**] grows strongly with center-of-mass energy. Precision measurements in high-energy operation therefore provide tight constraints on the SM EFT and may reveal hints of new physics that go unobserved in the same process at lower energy. The combination of the data taken at $\sqrt{s} = 250$ GeV with those of a second, higher-energy run thus forms a very powerful constraint on the SM EFT.

Higgs physics

Higher-energy operation extends the Higgs physics programme in several ways. The rate for vector-boson fusion production of the Higgs boson increases with center-of-mass energy. Even more importantly, data taken at 500 GeV or higher energy opens two new channels that provide direct access to key couplings, the Higgs self-coupling [**?**] and the top quark Yukawa coupling [**?**].

Vector-boson fusion production of the Higgs boson

The WW-fusion Higgs-production process, $e^+e^- \to \nu\bar{\nu}h$, opens up at 500 GeV, which provides another powerful channel to study Higgs boson couplings. The addition of this second production channel provides complementary constraints in a global fit of the Higgs boson couplings. Global fits of the ILC H20 scenario find that addition of the data set at $\sqrt{s} = 500$ GeV improves the precision on most of couplings by approximately a factor two [**?**]. CLIC studies arrive at the same conclusion after an analysis of the potential of the runs at 1.5 TeV and 3 TeV [**?**].

Higgs-boson pair production and measurement of the trilinear self-coupling

The value of the trilinear Higgs coupling gives evidence on the nature of the phase transition in the early universe from the symmetric state of the weak interaction theory to the state of broken symmetry with a nonzero value of the Higgs field. The Standard Model predicts a continuous transition. Models with a first-order phase transition, which may provide an explanation for the baryon asymmetry of the universe, can predict large (order 100%) deviations from the SM prediction for the Higgs self coupling.

A high-energy e^+e^- collider can probe the trilinear Higgs self coupling directly in Higgs pair production. Detailed simulation studies at a center-of-mass energy of 500 GeV show that a discovery of the double Higgs-strahlung process is possible with less than 4 ab^{-1}. A combination of several decay channels could yield a precision of 27% on the trilinear Higgs self coupling [**?**]. At still higher energy vector boson fusion becomes the dominant production channel.

The trilinear Higgs self coupling can also be extracted indirectly from a very precise measurement of the $e^+e^- \to Zh$ cross section [**?**]. Barklow et al. [**?**] and Grojean et al. [**?**] revisit this claim with a realistic fit of all relevant EFT parameters, finding that with 5 ab^{-1}at 240 GeVthe global constraint is very poor, of order (few), while the determination in Higgs boson pair production is robust.

Measurement of the top quark Yukawa coupling coupling in associated production of a Higgs boson and a top quark pair

The top quark Yukawa coupling is one of the key parameters of the Standard Model. It can be inferred, indirectly through loop contributions, from the $e^+e^- \to Zh$ cross section at $\sqrt{s} = 250$ GeV and the $h \to gg$, $h \to \gamma\gamma$ and $h \to \gamma Z$ partial widths. Especially $h \to gg$ is very promising, with potentially better than 1% precision [**?**]. This precision exceeds the HL-LHC expectation by an order of magnitude. In a realistic multi-parameter fit, the $h \to \gamma\gamma$, $h \to \gamma Z$ and $h \to gg$ partial widths constrain combinations of the top quark Yukawa and other Higgs [**?**] and top quark operators [**?**]. The potential of the 250 GeV data to isolate the Yukawa coupling in a global analysis remains to be performed.

The top-quark Yukawa coupling can furthermore be extracted from the $t\bar{t}$ cross section very close to the $t\bar{t}$ production threshold. A 4 % precision can be achieved [**?**] if the theory prediction can be made more precise (propagation of the scale uncertainty of the current NNNLO calculation yields an uncertainty of approximately 20 % [**?**] on y_t).

A direct determination of the top-quark Yukawa coupling can be performed in $e^+e^- \to t\bar{t}h$ production. In this channel the impact of the top-quark Yukawa coupling is accessible in a model-independent fashion. If the measurements at $\sqrt{s} = 250$ GeV yield evidence of a deviation from the SM, the direct measurement provides an essential confirmation of the result, and valuable additional information to fingerprint the new physics that is responsible for the effect. The cross section for $t\bar{t}h$ production increases rapidly above $\sqrt{s} \sim 500$ GeV, reaching several fb for $\sqrt{s} = 550$ GeV. Detailed studies of selection and reconstruction of these complex multi-jet events have been performed by the ILC at 500 GeV [**?**] and 1 TeV [**?**] and by CLIC at 1.5 TeV [**?**]. The direct measurement of the top quark Yukawa coupling at the ILC can reach 3% precision [?], with 4 ab^{-1}at 550 GeV.

Top physics

Among the Standard Model fermions, he top quark stands out for a number of reasons. First, the Higgs boson and the top quark are the only two Standard Model particles to escape scrutiny at the previous generation of e^+e^- colliders. Top quark couplings, especially those to the electroweak gauge bosons, are therefore relatively unconstrained by experiment. Second, in many extensions of the Standard Model, including supersymmetric scenarios and composite Higgs models, the top sector plays a crucial role in the dynamics of electroweak symmetry breaking. Top quark precision measurements may therefore provide the first direct signs of new physics. And, third, the fact that the top quark decays (to a W-boson and a b-quark) gives access to important information. Top quark pair production, with a six-fermion final state, is readily distinguished from other Standard Model processses. Top quarks and anti-quarks can be distinguished efficiently and the top quark polarization and $t\bar{t}$ spin correlations are acccessible.

The potential of linear e^+e^- colliders for top quark physics is discussed in detail in the ILC design reports [] and in Refs. [? ? ?].

Measurement of the top-quark mass:

The top quark mass is a fundamental parameter of the Standard Model, that has to be determined experimentally. Precise measurements are essential for precise tests of the internal consistency of the Standard Model, through the electro-weak fit [?] or and extrapolation of the Higgs potential to very high scale [?].

The top quark pair production threshold was identified long ago [?] as an ideal laboratory to measure the top quark mass, and other properties such as the top quark width and the Yukawa coupling and the strong coupling constant [?]. The large natural width of the top quark acts as an infrared cut-off, rendering the threshold cross section insensitive to the non-perturbative confining part of the QCD potential and allowing reliable cross section calculation with perturbative QCD to the NNNLO [?] and NNLL resummation [?]. Fully differential results are available in WHIZARD [?].

The threshold scan involves measurements of the $t\bar{t}$ cross section at ten e^+e^- center-of-mass energy points around the threshold region. A fit of the line shape allows for a precise extraction of the top quark mass [? ? ?]. The statistical uncertainty on the threshold mass is reduced to below 20 MeVwith a scan of ten times 20 fb^{-1}. The total uncertainty on the $\bar{M}S$ mass can be controlled to the level of 50 MeV. The extraction from the threshold scan is not affected by the ambiguities in the interpretation that plague direct mass measurements at hadron colliders. The systematic uncertainties include a rigorous evaluation of theory uncertainties in the threshold calculation and in the conversion to the $\bar{M}S$ scheme [?]. A linear e^+e^-collider can achieve a precision that goes well beyond even the most optimistic scenarios for the evolution of the measurements at the LHC.

Top-quark electro-weak couplings

In composite Higgs models and models with extra dimensions, large corrections to the top quark couplings to neutral electroweak gauge bosons are naturally predicted [? ? ?]. The study of top quark pair production at an e^+e therefore form a stringent test of such extensions of the SM.

The potential of the 500 GeV ILC for the measurement of the cross section and forward-backward asymmetry in $t\bar{t}$ is characterized in detail in Ref. [?]. With two configurations of the beam polarization the contributions of the photon and Z-boson are disentangled and very precise constraints on anomalous top quark couplings are achieved. Especially designed CP-odd observables provide precise constraints on CP-violation in the top quark sector [?]. Finally, the authors of Ref. [?] perform an EFT fit with twelve degrees of freedom. A combination of the 500 GeVrun, with excellent sensitivity to two-fermion operators, with 1 TeV data, with increased sensitivity to four-fermion operators, is found to yield tight constraints on the coefficients of all operator coefficients[1]. This study demonstrates the feasibility of a global EFT analysis of the top sector at the ILC and shows that the expected sensitivity of the ILC exceeds that of the HL-LHC programme by one to two orders of magnitude. Translated into discovery potential for concrete BSM scenarios, a linear collider operated above the top quark pair production threshold can probe very high scales, up to 10 TeVand beyond [?].

gauge boson pair production

Measurements of the γW^+W^- and ZW^+W^- triple gauge boson couplings (TGC) test the $SU(2) \times U(1)$ gauge boson self-coupling structure of the SM and probe BSM physics. A simultaneous fit of three independent couplings and the polarization on the 250 GeV data is expected to offer a substantial improvement beyond the results of LEP 2 and the LHC [?]. At higher energy the sensitivity grows and constraints are even tighter. A factor of two in precision[?] with respect to the 250 GeV programme can be achieved with an integrated luminosity of 4 ab^{-1}at $\sqrt{s} = 500$ GeV. Further improvements are possible at $\sqrt{s} = 1$ TeV [?].

Direct searches for new particles

In this section, we summarize the potential of high-energy stages of the ILC for directly producing new particles. In particular, we highlight cases where the discovery potential of the ILC is strongly enhanced and is complementary to that of the LHC. A summary of the most important studies is found in Ref.[?]. A comparison to other future collider projects was included in the Snowmass white paper [?].

Dark matter

General WIMP with mono-photon analysis. SUSY dark matter.

Extended Higgs sector

2HDM. The ILC probes Higgs boson masses up to $\sqrt{s}/2$. It also probes low-mass Higgs bosons.

X. CONCLUSION

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[1] The energy dependence of four-fermion operators is also present in other two-fermion productions processes, such as $e^+e^- \to b\bar{b}$ production [**?**]. It is therefore expected that also the global constraints in the bottom, charm and light-fermion sectors improve with the addition of higher-energy data.