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500 GeV ILC Operating Scenarios

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The ILC Technical Design Report documents the design of a 500 GeV linear collider, but does not specify the centre-of-mass energy steps of operation for the collider. The ILC Parameters Joint Working Group has studied possible running scenarios and the evolution of physics outcomes based on a realistic estimate of the real time accumulation of integrated luminosity, including initial operations ramp-up and upgrades, constrained by a realistic power budget. These physics goals include Higgs precision measurements, top quark measurements and searches for new physics. We present this "optimized" operating scenario and the anticipated evolution of the precision of the ILC measurements.

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1. Introduction

The ILC Technical Design Report (TDR) [1] provides a blueprint based on many years of a globally coordinated R&D program. This realistic technical design and implementation plan has been optimized for performance, cost and risk. The R&D program included: construction and commissioning of superconducting RF test facilities for accelerators all over the world; improvement in accelerating cavities production processes; and plans for mass production of 16,000 superconducting cavities needed to drive the ILC's particle beams. The TDR includes details for two state-of-the-art detectors (SiD and ILD) operating in a push-pull configuration, as well as an extensive outline of the geological and civil engineering studies for ILC siting.

The physics program envisioned for the 500 GeV ILC is rich (Figure 1), with the collider operating at different center-of-mass energy points to optimize physics outcomes. Operations will start at the full center-of-mass energy of 500 GeV, followed by 250 and 350 GeV running, for an initial total of eight to ten years. The collider luminosity will then be upgraded for intense running for about another ten years.

ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• **g**HWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak couplings of the top quark	✔		
• precision **W** couplings	✔	✔	
• precision search for **Z′**	✔		
• search for supersymmetry	✔		
• search for Dark Matter	✔		
• top quark mass from threshold scan		✔	
• precision Higgs mass			✔

Figure 1: ILC Physics Goals.

2. Running Scenarios

While the TDR specifies the upper energy of 500 GeV for the initial phase of the ILC, there is flexibility in choosing the operating energy; this is one of the strengths of the ILC. Various running scenarios for a 500 GeV ILC have been compared, taking into consideration machine and physics issues. The actual running scenario will depend on many future factors, including physics results of the LHC and the ILC.

The basis for the scenarios considered was the TDR baseline, emphasizing the upper energy reach with maximum discovery potential, and assuming 20 years of operation. Many scenarios were compared and contrasted. This full study is presented elsewhere in more detail [2].

The detailed assumptions for this study were:

- Each year operates 8 months at a 75% efficiency (as the RDR [3]), corresponding to 1.6×10^7 seconds of integrated running, higher than a Snowmass year of 10^7 seconds.
- When operating the accelerator at 250 or 350 GeV, the spare electrical power allows the repetition rate of collisions to be increased from 5-Hz to 10 or 7-Hz.
- A ramp-up of luminosity performance is assumed where expected.
  - For the initial physics run after construction and year 0 commissioning, the RDR ramp of 10%, 30%, 60% and 100% is assumed over the first four years.

  - The ramp after the shutdowns for installation of the luminosity upgrade is assumed to be slightly shorter (10%, 50%, 100%) with no year 0.
  - Going down in center-of-mass energy from 500 GeV to 350 GeV or 250 GeV is assumed to have no ramp, since there is no machine modification.
  - Going to 10-Hz operation at 50% gradient does assume a ramp (25%, 75%, 100%), since 10-Hz affects the entire machine.
- A major 18-month shutdown is assumed for the luminosity upgrade.

The physics reach of the ILC program depends on the total integrated luminosities collected at various center-of-mass energies, as well as the various beam polarization combinations collected at each of those energies. The highest achievable degree of polarization is desirable, and the TDR presents the assumed polarizations of P(e^-) = 80% and P(e^+) = 30% (higher values are possible for both species). The choice of combinations results from the dependence of processes on the polarization and are described in [2].

Figure 2 presents the assumed progression of integrated luminosities for two contrasting scenarios (G-20 and H-20). In both cases, a luminosity upgrade is planned after eight to ten years.

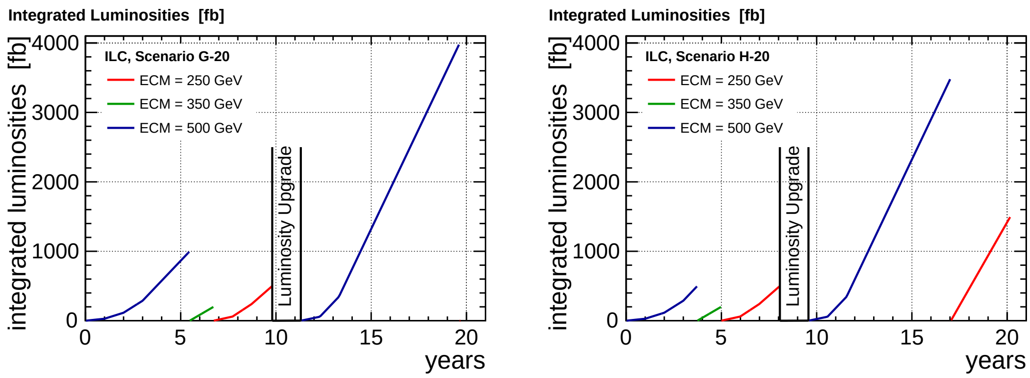

Figure 2: Integrated luminosities for the G-20 and H-20 scenarios.

3. Higgs boson

The evolution of the Higgs coupling precisions for HZZ, HWW, Hbb and Htt were compared for various scenarios, leading to the choice of H-20 for its slightly better precision and longer 250 GeV operation, which may be needed for the best Higgs mass measurement as well as the optimal CP analysis [4]. Figure 3 shows the full set of couplings measured in scenario H-20. It must be emphasized that these precisions are model-independent. The H-20 scenario has been approved by the Linear Collider Board (LCB) as the official scenario to use in ILC physics projections. Table 1 summarizes the total integrated luminosities for this LCB-approved scenario.

The Higgs boson mass is a fundamental parameter of the Standard Model and impacts the Higgs decay rates, for example WW and ZZ, through its couplings as well as the size of phase space. Uncertainty on the Higgs mass leads to uncertainty in the determination of couplings from measurements of decay rates. The LHC precision of about $\delta M_H = 200\,\mathrm{MeV}$ [5] causes uncertainties of 2.2% and 2.5% on the partial widths of $H \to WW$ and $HH \to ZZ$, respectively [4], while an uncertainty of $\delta M_H = 20\,\mathrm{MeV}$ is required to reach coupling uncertainties of $\sim 0.2\%$. Currently the only way demonstrated with full detector simulation to reach this level of precision is the Higgs recoil mass measurement with $Z \to \mu\mu$ at $\sqrt{s} = 250\,\mathrm{GeV}$. With a momentum scale calibration from $Z \to \mu\mu$ at the Z pole and an in-situ beam energy calibration from $\mu\mu\gamma$ events, systematic uncertainties should be controlled at the $1\,\mathrm{MeV}$ level [6]. Figure 4 shows the luminosity scaling of the Higgs recoil mass uncertainty. With $500\,\mathrm{fb}^{-1}$ of data collected at $\sqrt{s} = 250\,\mathrm{GeV}$, $\delta M_H = 25\,\mathrm{MeV}$ is reached.

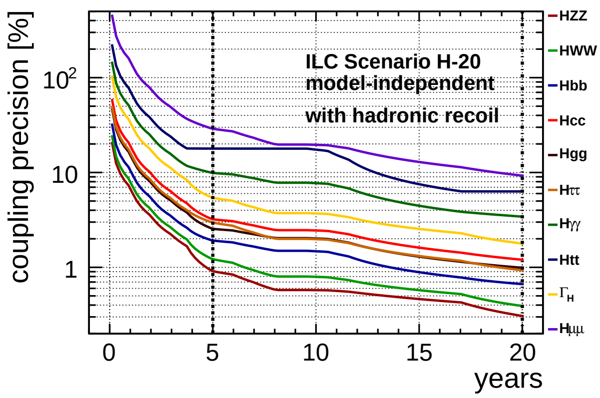

Figure 3: Higgs coupling precision for H-20.

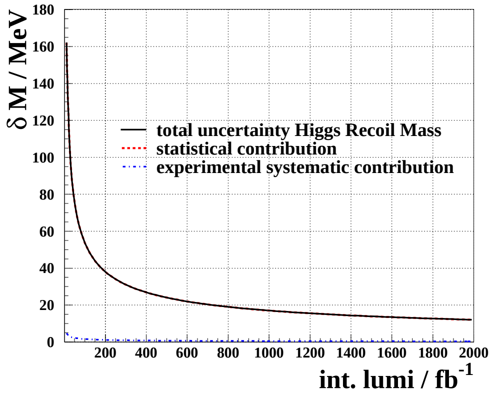

Figure 4: Higgs mass precision versus integrated luminosity at $\sqrt{s} = 250$ GeV.

	first phase	after lumi upgrade	total
250 GeV	500 fb^{-1}	1500 fb^{-1}	2 ab^{-1}
350 GeV	200 fb^{-1}		0.2 ab^{-1}
500 GeV	500 fb^{-1}	3500 fb^{-1}	4 ab^{-1}
time	8.1 years	10.6 years	20.2 years*

Table 1: LCB-approved integrated luminosities for the ILC. (*includes 1.5 years for luminosity upgrade.)

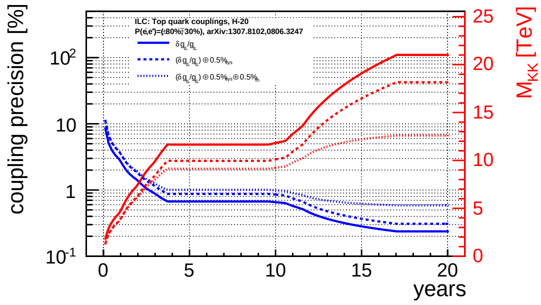

Table 2: Top electroweak left-handed couplings and the derived mass scale sensitivity for Kaluza-Klein excitations in an extra-dimensions model for scenario H-20.

4. Top electroweak couplings

The precision measurement of the electroweak couplings of the top quark is a key goal of the ILC physics program. It requires beam polarization to disentangle the couplings to the Z boson and the photon, which have different chiral properties. Besides being an important test of the Standard Model, the top quark couplings are a prime indicator for physics beyond the Standard Model. Due to the top quark's uniquely large mass, and thus its particularly strong coupling to the Higgs boson, new phenomena could become visible first in the top sector.

Figure 2 shows the time evolution expected for the left-handed top coupling [7], and the sensitivity to the mass scale of new physics in an Extra-Dimension model derived by excluding deviations of the left-handed top coupling from its Standard Model prediction [8]. In this model, indirect sensitivity for new physics can extend easily into the 10-15 TeV regime.

5. Higgs self-coupling

An unambigous tree-level probe of the Higgs self-coupling requires a measurement of the double Higgs production cross section. At the ILC, double Higgs production can be observed for $\sqrt{s} \geq 450$ GeV; this measurement is challenging and requires a large integrated luminosity. A study based on full simulation of the ILD detector concept at $\sqrt{s} = 500$ GeV [9][10] using combined $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}WW^*$ channels has shown a precision of 30% assuming an integrated luminosity of 4 ab^{-1}, shared equally between $P(e^-e^+) = (\pm 80\%, \mp 30\%)$. Recently, improvements in the sensitivity of the analyses have been identified. Figure 5 shows the time evolution of the precision on the Higgs self-coupling for a few scenarios, including H-20. Before the luminosity

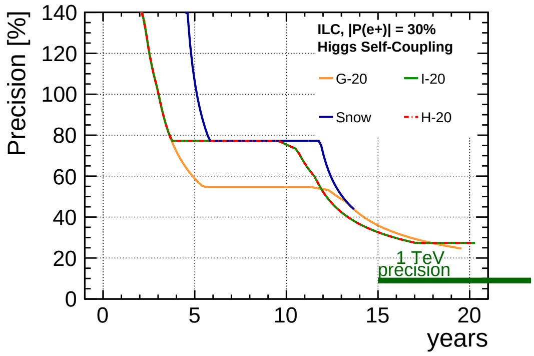

Figure 5: Higgs self coupling. The ultimate precision for the 1 TeV ILC is shown on the right.

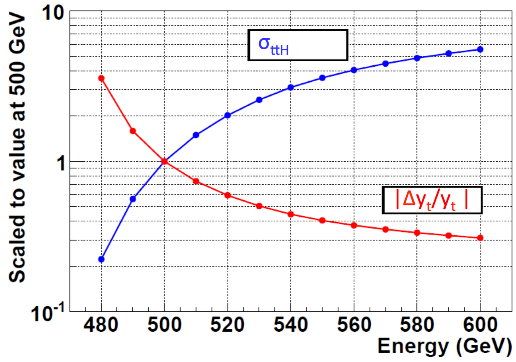

Figure 6: tth cross section and top Yukawa coupling versus center-of-mass energy.

upgrade, the precision is modest, but the full H-20 program reaches 27% [11]. This would clearly demonstrate the existence of the Higgs self-coupling. The green line indicates the precision that would be reached with the 1 TeV ILC upgrade, where 10% or better can be achieved.

The double Higgs production mechanisms at the two center-of-mass energies (500 GeV and 1 TeV) are different. The sign of the interference term is different for double Higgsstrahlung and double Higgs production in WW-fusion. This means that a deviation of λ from its Standard Model value will lead to a larger cross section for one process and a smaller cross section for the other. Thus the two measurements are complementary in their sensitivity to new physics.

6. Top Yukawa coupling

The top Yukawa coupling is measured at the ILC from the process $e^+e^- \to t\bar{t}h$, which opens kinematically at around $\sqrt{s} = 475\,\text{GeV}$. Full detector simulation studies showed that at $\sqrt{s} = 500\,\text{GeV}$, the top Yukawa coupling can be determined with a precision of 9.9% based on an integrated luminosity of $1\,\text{ab}^{-1}$ with $P(e^-,e^+) = (-80\%,+30\%)$ [12]. This translates into final precision for H-20 of about 6%.

Figure 6 presents the relative cross section for $t\bar{t}h$ production as a function of $\sqrt{s}$; it is still steeply rising at $\sqrt{s} = 500\,\text{GeV}$, increasing nearly four-fold by $\sqrt{s} = 550\,\text{GeV}$. Since the main backgrounds (non-resonant tbW and $t\bar{t}b\bar{b}$ production) decrease, the precision on the top Yukawa coupling improves by better than a factor of two w.r.t. $\sqrt{s} = 500\,\text{GeV}$ for the same integrated luminosity. This significant improvement in precision motivates serious consideration of extending the upper center-of-mass reach of the nominally 500 GeV ILC to about 550 GeV.

7. Natural supersymmetry, light Higgsinos, and WIMP dark matter

The motivations for physics beyond the Standard Model include the hierarchy problem and dark matter. A possible solution to these mysteries is provided by natural supersymmetry, including the possibility of light Higgsinos and WIMP dark matter candidates. Should they exist, the ILC offers valuable discovery potential. The highest available center-of-mass energy as well as the possibility for threshold scans at lower energy are critical to this potential. The possibility to operate with all four helicity configurations strengthens the role of the ILC in interpreting new particles. Refer to the full report for details [2].

8. Other operational details

A number of additional operational issues have been considered. If new phenomena appear at the LHC or the ILC the choice of running scenarios will be modified. One strength of the ILC is the ability to perform follow-up threshold scans for any such discovery. Choices of beam helicity operations provide additional insight into the nature of new physics. The possibility of operating at WW-threshold or at the Z-pole may prove to be important capabilities. Each of these issues is discussed in [2].

9. Conclusions

Based on studies of possible operating scenarios for the 500 GeV ILC and current knowledge a preferred scenario, H-20, has been identified. Table 1 presents the assumed integrated luminosity for the 20-year program. After starting operation at the full center-of-mass energy of 500 GeV, running is planned at 250 and 350 GeV before the collider luminosity is upgraded for intense running at 500 GeV and at 250 GeV. Scenario H-20 optimizes the possibility of discoveries of new physics while making the earliest measurements of the important Higgs properties. It includes a sizeable amount of data taken at $\sqrt{s} = 250$ GeV.

The physics impact of the ILC is significantly improved if the maximum energy of the ~ 500 GeV ILC is stretched to ~ 550 GeV where the top Yukawa precision is more than a factor of two times better than at 500 GeV.

The choice of scenario H-20 is based on the physics that is absolutely certain to be done with the ILC. This physics includes precision measurements of the Higgs boson and the top quark, and possibly measurements of the W and Z gauge bosons. While this certain program provides a compelling and impactful scientific outcome, discoveries by the LHC or the early running of the ILC could expand the scientific impact of the ILC. There exist scientific motivations to anticipate such possibilities. Such discoveries could alter the run plan from that described by H-20, as operations at or near the threshold of a pair-produced new particle, for example, would be added, a capability that is one of the particular operational strengths of the ILC.

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