THE PHYSICS CASE OF THE INTERNATIONAL LINEAR COLLIDER*

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This article summarises the physics case of the International Linear Collider, ILC. It will cover all centre-of-mass energies needed to study the currently known Standard Model particles and the relevant interactions between them with high precision. Its discovery potential with respect to supersymmetric particles and dark matter complements that of the LHC. For the first time, it will be possible to study top-quark pair production through electroweak processes. This offers exciting possibilities to measure the mass of the top quark with highest precision and the electroweak couplings of the top quark in an unambiguous way.

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1. Introduction

With the discovery of the Higgs boson with a mass of $m_h \approx 125$ GeV by the LHC, the Standard Model of particle physics is complete. The Standard Model is a quantum field theory featuring $\mathrm{SU}(2)_\mathrm{L}\times\mathrm{U}(1)_Y$ symmetry. Here, L indicates that the symmetry is exact for fermions with left-handed chirality and the hypercharge Y. This symmetry is spontaneously broken at the electroweak scale leading to non-zero masses of the gauge bosons and the fermions. The breaking of the symmetry is associated to a scalar field that develops a non-zero vacuum expectation value. The Higgs boson is the quantum of this field and its discovery gives evidence that the concept of the spontaneously broken symmetry is indeed correct. Today, it is however unknown what is at the origin of the symmetry breaking and what generates the detailed shape of the Higgs potential. It is thus intuitive to assume that the Standard Model, as known today, is the low energy approximation of

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a theory that is valid at higher energies. The Standard Model, despite all its successes, presents no candidate for dark matter particles. Dark matter is, however, a decisive element to cosmological models. The universe is obviously asymmetric in its matter–antimatter content. A source for this asymmetry is CP violation. However, the CP violation that is generated by Standard Model processes is not sufficient to account for the observed matter–antimatter asymmetry. New physics is thus needed as a source for CP violation. A special role in the search for physics beyond the Standard Model will be played by the top quark or t quark. With a mass of about $m_t \approx 173$ GeV [1], it is the heaviest known particle today. Its mass is about 40 times heavier than that of the second heaviest fermion, the b quark.

A big hope to discover the onset of new physics is to put in the next run of the LHC providing pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. Complementary results to the LHC can be expected from measurements at lepton colliders. The QCD background is small and relevant processes are produced at comparable rates. The well known initial state of point-like leptons is an ideal premise for high precision measurements. New physics could be discovered either through direct observation of particles that escape the detection at the LHC or by deviations from Standard Model predictions at the level of quantum fluctuations. A viable experimental strategy must allow for the production of $t\bar{t}h$ final states and polarised beams since the Standard Model is a chiral theory and the manifestation of new physics may depend on the polarisation of initial and final state particles. Both requirements are met by the ILC. The ILC is a linear electron–positron collider, based on superconductive RF technology, designed for a centre-of-mass energy of $\sqrt{s} = 500$ GeV. Figure 1 illustrates the physics programme of the ILC at the example of a few typical processes and mass scales. A typical feature of linear colliders is that the luminosity increases with increasing energy, an attractive asset to compensate of the decreasing e^+e^- cross section. The

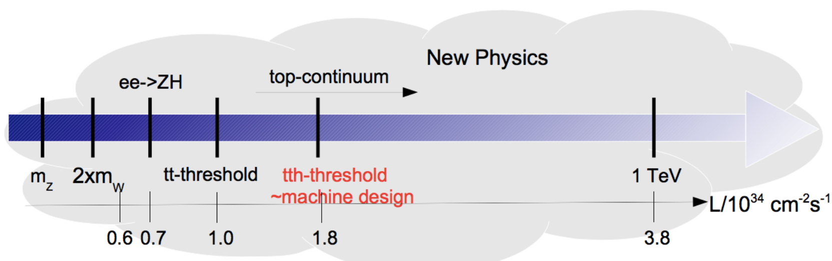

Fig. 1. A schematic overview of the ILC physics program at the example of typical processes and mass scales. The arrow in the bottom indicates the increasing instantaneous luminosity as the centre-of-mass energy increases.

ILC has published a Technical Design Report in 2013 [2] that documents the maturity of the project. In the following, the physics case of the ILC will be highlighted. Most of the presented results are based on detailed simulation studies of the detector concepts ILD and SiD [3]. The text in the following is at many places inspired by the recent publication of the ILC Physics Working Group [4].

2. Higgs physics at the ILC

The Standard Model predicts an exact correlation between the Yukawa couplings of the Standard Model particles to the Higgs boson. Any tiny deviation from this correlation is an indisputable sign of new physics. The Higgs production cross section is shown in Fig. 2. The two major processes for Higgs production are the Higgs-strahlungs process $e^+e^- \to Z^0h$ and the W boson fusion process. The ILC will allow for measuring the couplings to all Standard Model particles that are heavier than light quarks or the electron in a model independent way.

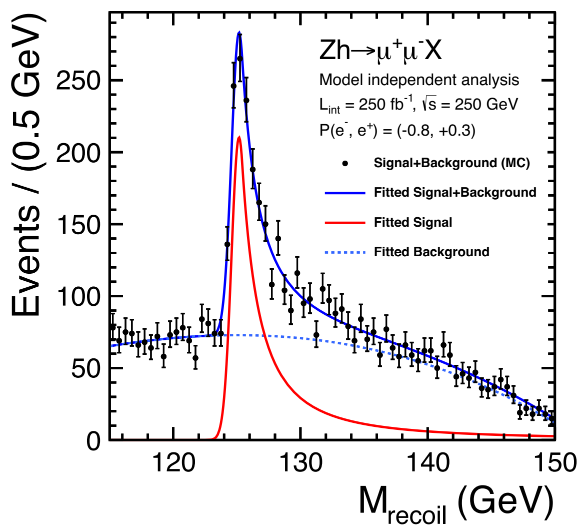

Fig. 2. Recoil mass distribution in the process $e^+e^- \to Z^0h$ followed by the decay $Z^0 \to \mu^+\mu^-$ at $\sqrt{s} = 250$ GeV. Figure is taken from [4].

A special advantage of the Higgs-strahlungs process is that by identifying the Z^0 boson, Higgs events can be identified without actually looking at the Higgs boson itself, being therefore sensitive to *invisible* decays of the Higgs boson. More general, the clean reconstruction of the Z^0 *decays* into electron and muon pairs allows for a precision measurement of the Higgs mass to an accuracy of about 30 MeV [5]. The clean signal peak is shown in Fig 2.

The Higgs-strahlungs process is also the key input to the determination of the total width Γ_h of the Higgs boson, a measurement that is impossible at a hadron collider. More precisely, the total width is obtained via the equation

$$\Gamma_h \sim \frac{\left(\sigma_{\nu\bar{\nu}b\bar{b}}/\sigma_{Zb\bar{b}}\right)^2}{\left(\sigma_{\nu\bar{\nu}WW}/\sigma_{Zh}\right)} \times \sigma_{Zh} \tag{1}$$

through a combination of various measurements at centre-of-mass energies of $\sqrt{s} = 250$ GeV and $\sqrt{s} = 500$ GeV. The proportionality factors can be precisely calculated for electroweak processes. Table I (see Appendix A) lists the expected precisions for Higgs couplings at the ILC for a so-called initial phase and those expected at the end of the ILC data taking. These precisions are illustrated in Fig. 3.

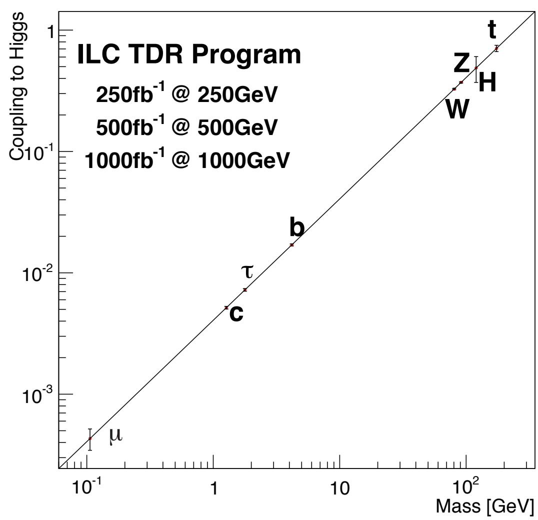

Fig. 3. Precision on couplings to Standard Model particles to the Higgs boson as expected at the end of the ILC Physics program. The straight line illustrates the Standard Model prediction that these couplings are exactly proportional to the particles mass. Figure is taken from [6].

The results prove that precisions at the percent level can be expected. This precision is to be confronted with deviations predicted by models of new physics. These deviations are of the order of 5%. The ILC will thus be able to validate or falsify new physics models at the level of several standard deviations.

2.1. Top Yukawa coupling

It is easy to understand that the study of the interaction between the Higgs boson and the heaviest particle of the Standard Model, the t quark, bears a big potential to unravel the nature of new physics. Through QCD bound state effects of the $t\bar{t}$ pair, this process opens up at $\sqrt{s} = 500$ GeV. At this centre-of-mass energy, the top Yukawa coupling can be measured to a precision of about 6% with an integrated luminosity of 3500 fb^{-1}. Due to the strong increase of the $t\bar{t}h$ production cross section, a 10% increase of the centre-of-mass energy would result in a precision that will be about a factor of two better for the same integrated luminosity. As will be shown later, the mass of the t quark can be extremely well measured. This reduces considerably the systematic uncertainty to be taken into account for the top Yukawa coupling.

2.2. Higgs self-coupling

The exact shape of the Higgs potential can be determined by measuring the self-coupling of the Higgs boson. The actual value of the self-coupling may reveal the nature of the phase transition the universe went through when changing from a symmetric state to a state with broken symmetry as manifested by the existence of the Higgs boson. In a first order phase transition, the universe would have been out of thermal equilibrium. Possible CP violation through interactions in Higgs sector may produce enough matter–antimatter asymmetry to explain the current observed dominance of matter in the universe. From studies of the Higgs decays into W boson pairs and b quarks at $\sqrt{s} = 500$ GeV, a 3σ evidence for Higgs self-coupling after an integrated luminosity of 4000 fb^{-1} is reported within the Standard Model that implies a continuous phase transition. A first order phase transition would modify the Higgs self-coupling by about a factor of 2, thus, turning the 3σ evidence nearly into a 5σ observation. By an energy upgrade of the ILC to $\sqrt{s} = 1$ TeV, the precision within the Standard Model can be improved to about 10% and correspondingly better in the case of a first order phase transition.

3. The top quark

The ILC would be the first machine at which the t quark is studied using a precisely defined leptonic initial state. Therefore, individual events can be analysed in more detail. It also changes the production mechanism for t quark pairs from the strong to the electroweak interactions, which are a step closer to the phenomena of electroweak symmetry breaking that we aim to explore. Finally, this change brings into play new experimental observables, weak interaction polarisation and parity asymmetries that are very sensitive to the coupling of the t quark to possible new interactions. It is very possible that, while the t quark might respect Standard Model expectations at the LHC, it will break those expectations when studied at the ILC.

3.1. $e^+e^- \to t\bar{t}$ at threshold

One of the unique capabilities of an e^+e^- linear collider is the ability to carry out cross section measurements at particle production thresholds. The accurately known and readily variable beam energy of the ILC makes it possible to measure the shape of the cross section at any pair-production threshold within its range. Because of the leptonic initial state, it is also possible to tune the initial spin state, giving additional options for precision threshold measurements. The $t\bar{t}$ pair production threshold at a centre-of-mass energy $\sqrt{s} \approx 2m_t$ allows for precise measurements of the t quark mass m_t as well as the t quark total width Γ_t and the QCD coupling α_s. Because the top is a spin-$\frac{1}{2}$ fermion, the $t\bar{t}$ pair is produced in an angular S-wave state. This leads to a clearly visible rise of the cross section even when folded with the ILC luminosity spectrum as shown in Fig. 4.

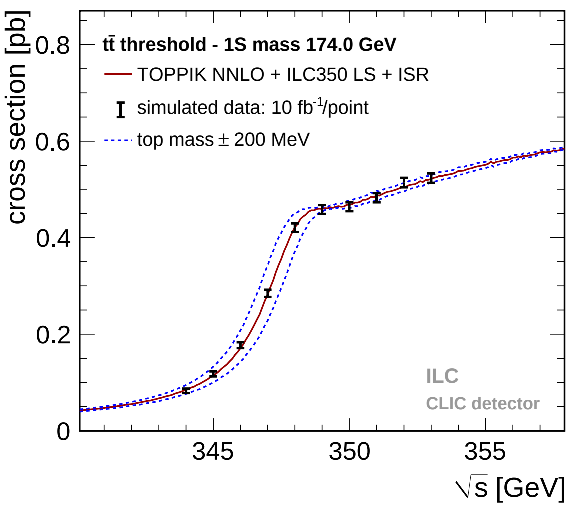

Fig. 4. Result of a simulation study of a top threshold scan that includes the luminosity spectrum of the ILC beams. The figure is taken from [7].

A simultaneous fit may allow to extract simultaneously the t quark mass, its width Γ_t and the top Yukawa coupling y_t. In this case, the expected statistical accuracies for 200 fb^{-1} of integrated luminosity are: $\delta m_t \approx 17$ MeV, $\delta\Gamma_t \approx 26$ MeV and $\delta y_t = 4.2\%$. The measurement of the latter becomes possible since the virtual exchange of the Standard Model Higgs boson enhances the cross section at threshold by about 9%. The dependence of the

t quark cross section shape on the t quark mass and interactions is computable to high precision with full control over the renormalisation scheme dependence of the top-mass parameter. A recent publication [8] shows that the $1S$ mass as resulting from the described analysis can be translated to *e.g.* the $\overline{\mathrm{MS}}$ mass, typically used in theoretical calculations to a precision of about 10 MeV.

3.2. Open top production

References [9, 10] report on the determination of CP conserving form factors, and couplings as introduced above have been derived by means of a full simulation study of the reaction $e^+e^- \to t\bar{t}$ at a centre-of-mass energy of $\sqrt{s} = 500$ GeV with 80% polarised electron beams and 30% polarised positron beams. The unique feature of the ILC to provide polarised beams allows for a largely unbiased disentangling of the individual couplings of the t quark to the Z^0 boson and the photon. These couplings can be measured at the sub-percent level at the ILC, see also Table I in Appendix A. This is, when referring to the results in [11, 12], considerably better than it will be possible at the LHC even with an integrated luminosity of $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$. The improving analyses of the LHC experiments will, however, be observed with great interest.

Beam polarisation is a critical asset for the high precision measurements of the electroweak t quark couplings. Experimental and theoretical effects manifest themselves differently for different beam polarisations. It seems that the configuration of positive-electron beam polarisation is more benign in both, experimental aspects due to the suppression of migrations in the polar angle spectrum of the final state t quark, see *e.g.* [9, 10] and theoretical aspects due to the somewhat simpler structure of higher order electroweak corrections [13]. It is intuitively clear that the described facts would greatly support the discovery of effects due to new physics. The precision, as expected for the ILC, would allow for the verification of a great number of models for physics beyond the Standard Model, see Fig. 5. Examples for these models are extra dimensions and compositeness. The current results constitute, therefore, a perfect basis for discussions with theoretical groups. Note at this point that the community currently discusses running scenarios for the ILC that would yield up to 10 times more luminosity. Moreover, it can be expected that the event reconstruction will be improved by *e.g.* the measurement of the b quark charge. A study of systematic errors will become very important. Already from the achieved precision, it is mandatory that systematics are controlled to the 1% level or better, in particular, for the measurement of the cross section. This issue is addressed in ongoing studies.

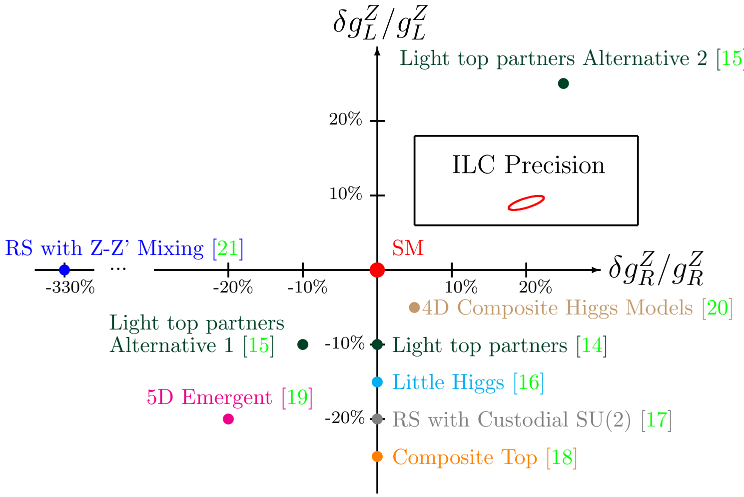

Fig. 5. Predictions of several models that incorporate Randall–Sundrum (RS) models and/or compositeness or Little Higgs models on the deviations of the left- and right-handed couplings of the t quark to the Z^0 boson. The ellipse in the frame in the upper right corner indicates the precision that can be expected for the ILC running at a centre-of-mass energy of $\sqrt{s} = 500$ GeV after having accumulated $\mathcal{L} = 500$ fb^{-1} of integrated luminosity shared equally between the beam polarisations $\mathcal{P}_{e^-}, \mathcal{P}_{e^+} = \pm 0.8, \mp 0.3$. The original version of this figure can be found in [22].

4. New particles

Many models on new physics predict the existence of several Higgs boson as compared to the Standard Model that comprises exactly one Higgs boson. The minimal extension of the Standard Model in the respect contains two vacuum expectation values v_1 and v_2 and five Higgs bosons. Of these, at least one is much heavier than the discovered scalar state at the LHC. Figure 6 shows the fraction of models excluded in the parameter space allowed in the so-called phenomenological Minimal Supersymmetric Model pMSSM in the plane defined by the mass of the heavy Higgs particle and $\tan\beta = v_1/v_2$ [23]. In this case, that is however representative, the large power of the ILC to probe supersymmetric models is clearly demonstrated.

In contrast to the indirect searches, as described previously, the LHC has a remarkable potential to discover heavy new particles. On the other hand, new light particles may escape the detection at the LHC. This is particular true if the lightest and next-to-lightest particles of the new physics are nearly degenerated in mass due to the appearance of soft particles in the corresponding decay chain. In well motivated models of supersymmetry, a neutral and a charged Higgsino, supersymmetric partners of the Higgs

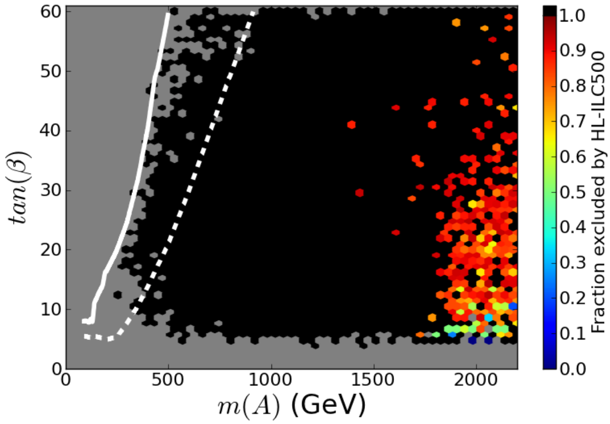

Fig. 6. Scan of the parameter space as allowed in the pMSSM model projected onto the plane defined by the mass $m(A)$ of the heavy Higgs particle and $\tan\beta = v_1/v_2$. The colour code indicates the fraction of pMSSM points that can be excluded for given $m(A)$ and $\tan\beta = v_1/v_2$. The exclusion of pMSSM points, as expected from the LHC, is given by the full white (for an integrated luminosity of 300 fb^{-1}) and dashed white (for an integrated luminosity of 3000 fb^{-1}) lines.

boson, form this set of close-to-degenerated particles. If they exist, it is also intuitive to assume that their mass is not too different from the mass of the scalar state observed at the LHC. The ILC offers a great discovery potential in the described likely scenario. A particular clean way goes through initial state radiation, ISR, events that, similar to Higgs-strahlungs events, measure the invariant mass of the system that recoils against the photon. In the recoil mass spectrum, as shown in Fig. 7, a clear signal peak is visible up to the centre-of mass energy of 500 GeV as used in the corresponding study [24]. The mass of the charged Higgsino can be determined by a fit to the onset of the recoil mass spectrum.

The soft particles that occur in these events can be very well detected in typical ILC detectors. From this measurement, the mass difference between the lightest and next-to-lightest particles can be determined for differences as small as about 1 GeV. In the described scenario, as well as in other comparable scenarios, the lightest particle is stable. It is thus a candidate for the particle composition of the relic dark matter that makes up about 25% of the universe. Illustrative examples for the discovery of dark matter particles are also discussed in *e.g.* [25]. One is given in Fig. 8 where a new Z' with a mass of $m_{Z'} = 550$ GeV recoils against the ISR photon. Independent of the details of the model, the example shows that beam polarisation helps considerably to reduce the Standard Model and supports thus the discovery potential.

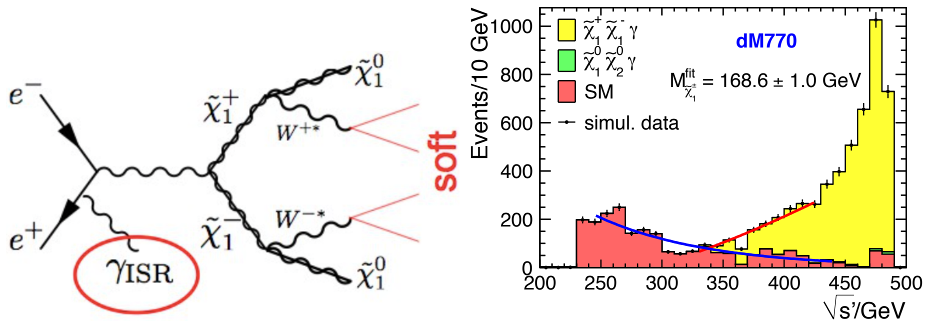

Fig. 7. Left: Feynman diagram for the production in radiative e^+e^- collisions of neutral Higgsinos from the decay of nearly mass generated charged Higgsinos giving rise to a radiative photon and a set of soft particles detectable is a typical ILC detector. Right: Spectrum of the mass of the system recoiling against the radiative photon. The chosen mass difference in this case is $dM = 770$ MeV.

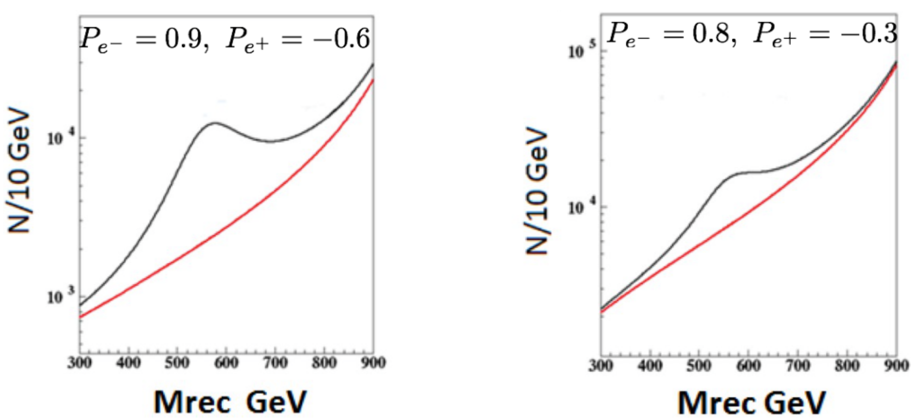

Fig. 8. Recoil mass spectrum of a invisible system recoiling against an ISR photon. In the model, a Z that couples to vector-like Dirac type dark matter and axial-vector-like to ordinary matter. The plots show the results for beam polarisation at a centre-of-mass energy of $\sqrt{s} = 1$ TeV.

Hence, the ILC is also suited to discover dark matter and/or to contribute significantly to the understanding of dark matter. As discussed in Ref. [6], a determination of the relic dark matter density at the precision of about 20% may require the full ILC centre-of-mass energy of 1 TeV or higher when future technological improvement will allow to reach these energies.

5. Concluding remarks on the ILC physics programme

The ILC physics programme is not restricted to the examples given above. It offers, for example, excellent opportunities for testing the CP quantum numbers of the Higgs boson by *e.g.* measuring angular correlations in the decay $h \to \tau\tau$. The CP mixing angle can be determined to the level of a few degrees [26]. When entering the TeV regime, new gauge bosons may appear. The search for these new boson will make use of the generic two fermion processes $e^+e^- \to f\bar{f}$. As the Standard Model makes predictions at the 0.1% level of the corresponding cross sections, the measurements will be sensitive even if these new resonances have masses well above the actual centre-of-mass energy. In the future, it will be very interesting to compare effects expected for leptons and light quarks with those expected for the heavy t quark. Although the ILC is oriented mainly towards higher centre-of-mass energies, there exists a strong motivation to maintain the capability to make measurements at energies smaller than 250 GeV, *i.e.* at the WW threshold and the Z^0 pole. This is important as the legacy of LEP and SLC left a discrepancy in the input to the determination of the effective weak mixing angle $\sin^2\theta^f_{\mathrm{eff}}$ [27] derived from the forward–backward asymmetry w.r.t. the polar angle in the process $e^+e^- \to b\bar{b}$ (LEP) and the asymmetry with respect to the cross section for different electron beam polarisations (SLC). The ILC will allow for the final word on this discrepancy and put it into the context of insights into physics beyond the Standard Model. Finally, the precise measurement of the mass of the W and Z^0 bosons at the few MeV level will greatly support consistency tests of the Standard Model and models of new physics.

6. Summary and outlook

The ILC is a versatile machine for precision physics in the mass range between the mass of the Z boson and about 1 TeV. Precision measurements of the Higgs boson and the top quark, both are considered to be messengers to new physics, constitute a guaranteed rich physics program. Both particles would be for the first time produced in the benign environment of an e^+e^- collider. It can probe scenarios for new physics that go well beyond the reach of the LHC. If the LHC will discover new particles in the forthcoming run at a centre-of-mass energy of 13 TeV, the ILC is still crucial to decipher the details of the new physics that is associated to the new particles. This observation together with the discovery potential at the ILC itself will make the ILC a facility of equal footing with the LHC in terms of the importance for the future of particle physics. Any future e^+e^- facility at the energy frontier will be a linear collider. Therefore, the ILC lays the foundation for precision physics at and beyond the TeV scale for the next century and can be used if new accelerator technologies will become available. Currently, Japan discusses carefully to place the bid to host the ILC. Political decisions are expected in the coming years. This decision making process will the accompanied by an continuous update of the ILC physics potential, particularly in view of the expected results from the LHC, and to bring detectors and accelerator in a state of being ready for construction at the end of this decade. This implies studies to identify, understand and remedy potential systematic errors on both experimental and theoretical side. These will also have an impact on the final machine design. New ideas to even increase the scientific potential of the ILC by outperforming the projections as they today are always highly welcome.

I would like to thank the EPIPHANY team for the organisation of the symposium and the opportunity to present and discuss the ILC Physics Case. I have enjoyed the hospitality during my stay at Kraków.

Appendix A

Projected ILC accuracies

Projected accuracies of measurements of Standard Model parameters at the two stages of the ILC program proposed in the report of the Joint Working Group on ILC Beam Parameters [33] are presented in Table I. This program has an initial phase with 500 fb^{-1} at 500 GeV, 200 fb^{-1} at 350 GeV, and 500 fb^{-1} at 250 GeV, and a luminosity-upgraded phase with an additional 3500 fb^{-1} at 500 GeV and 1500 fb^{-1} at 250 GeV. Initial state polarisations are taken according to the prescriptions of [33]. Uncertainties are listed as 1σ errors (except where indicated), computed cumulatively at each stage of the program. These estimated errors include both statistical uncertainties and theoretical and experimental systematic uncertainties. Except where indicated, errors in percent (%) are fractional uncertainties relative to the Standard Model values. More specific information for the sets of measurements is given in the text. For each measurement, a reference describing the technique is given. Table is taken from [4].

TABLE I

Projected accuracies of measurements of Standard Model parameters at the two stages of the ILC program. Table is taken from [4].

Topic	Parameter	Initial phase	Lumi-upgrade	Units	Ref.
Higgs	m_h	25	15	MeV	[5]
	$g(hZZ)$	0.58	0.31	%	[28]
	$g(hWW)$	0.81	0.42	%	[28]
	$g(hb\bar{b})$	1.5	0.7	%	[28]
	$g(hgg)$	2.3	1.0	%	[28]
	$g(h\gamma\gamma)$	7.8	3.4	%	[28]
		1.2	1.0	%, LHC incl.	[7]
	$g(h\tau\tau)$	1.9	0.9	%	[28]
	$g(hc\bar{c})$	2.7	1.2	%	[28]
	$g(ht\bar{t})$	18	6.3	%, direct	[28]
		20	20	%, $t\bar{t}$ threshold	[29]
	$g(h\mu\mu)$	20	9.2	%	[28]
	$g(hhh)$	77	27	%	[28]
	Γ_{tot}	3.8	1.8	%	[28]
	Γ_{invis}	0.54	0.29	%, 95% C.L.	[28]
Top	m_t	50	50	MeV (m_t(1S))	[7]
	Γ_t	60	60	MeV	[29]
	g_{L}^{γ}	0.8	0.6	%	[10]
	g_{R}^{γ}	0.8	0.6	%	[10]
	g_{L}^{Z}	1.0	0.6	%	[10]
	g_{R}^{Z}	2.5	1.0	%	[10]
	F_2^{γ}	0.001	0.001	absolute	[10]
	F_2^{Z}	0.002	0.002	absolute	[10]
W	m_W	2.8	2.4	MeV	[30]
	g_1^Z	8.5×10^{-4}	6×10^{-4}	absolute	[31]
	κ_γ	9.2×10^{-4}	7×10^{-4}	absolute	[31]
	λ_γ	7×10^{-4}	2.5×10^{-4}	absolute	[31]
Dark matter	EFT Λ: D5	2.3	3.0	TeV, 90% C.L.	[32]
	EFT Λ: D8	2.2	2.8	TeV, 90% C.L.	[32]

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