Physics opportunities at a future linear e^+e^- collider

Contribution du Comité Collisionneur Linéaire

à l'atelier GT01 des prospectives IN2P3

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Abstract

This document recalls briefly the motivation and the physics program at a future linear electron-positron collider with polarised beams. The linear technology is the only option known today that enables precision measurements between the Z pole and 1 TeV and more, crossing thereby important thresholds given by Standard Model particles including the threshold for the measurement of the Higgs self-coupling. In a second part the plans of IN2P3 groups that are members of the Comité du Collisionneur Linéaire for the next years together with an estimation of the needed resources are outlined.

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1. Introduction

The ongoing analysis of the data recorded at the LHC shows that the scalar particle discovered in 2012 agrees with predictions of the Standard Model of particle physics for the Higgs boson. This Higgs boson has a mass of $125.16 \pm 0.16\,\mathrm{GeV}$ [1]. Meanwhile the decay of this Higgs boson into pairs of bottom quarks [2, 3] and τ leptons [4, 5] have been observed as well as recently the radiation off a top quark in $\mathrm{t\bar{t}H}$ production at the LHC [6, 7]. The small mass of the discovered Higgs boson and sizeable corrections to the mass when taking into account higher orders in perturbation theory require, within the Standard Model, an unsatisfactory fine tuning between the bare and the renormalised mass. Further, the Standard Model cannot explain dark matter or energy whereas the existence of both, dark matter andi dark energy is suggested by cosmological observations. Theories to remedy these shortcomings at least partially as Supersymmetry fail to be discovered at the LHC. The exclusion limits for coloured supersymmetric particles is currently of the order of 1 TeV. Alternatives to Supersymmetry are composite models that are dual to models with extra-dimensions, which allow for perturbative calculations. Today's understanding is that the direct observation of the particle content of these models may be beyond the reach of the LHC or that the precision that can be achieved at the LHC is not sufficient for indirect discovery. There are in general two approaches to make progress:

- Operation at higher centre-of-mass energies to access first mass states of new physics.
- Increase the achievable precision of the measurements of the discovered Higgs boson and of particles that carry the *imprint of the Higgs particle* such as W and Z bosons or the top quark;

The impressive establishment of the electroweak theory as being correct up to the so far accessible energies is based on a tight interplay between hadron accelerators on one hand ($\mathrm{Sp\bar{p}S}$, Tevatron) and electron-positron colliders on the other hand (PETRA, TRISTAN, LEP, SLC). The precision of hadron machines is limited by the complicated structure of the initial state hadrons and the huge background from QCD induced reactions. Deep understanding of the physics beyond the Standard Model requires thus the parallel running of a precision machine.

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This is even more true after the discovery of a Higgs boson in 2012. In order to cover the full Standard Model phenomenology, centre-of-mass energies between the Z Pole and about 1 TeV are necessary. As already proven by SLC, polarised beams are an essential asset for precision tests of a chiral theory such as the Standard Model. Circular colliders are heavily limited by the energy loss by synchrotron radiation. The energy loss per turn of a particle with mass m and an energy E can be expressed as:

$$\frac{\Delta E}{\mathrm{Turn}} \sim \frac{\gamma^4}{r} \quad \mathrm{with}\, \gamma = \frac{E}{m} \tag{1}$$

and r being the radius of the circular accelerator or storage ring. This energy loss severely limits energy expandability to below $\sim$400 GeV.

Therefore the R&D in the last around 20 years has been concentrated on the development of linear accelerators. At least one of these projects, the ILC, has reached the necessary level of maturity to be considered as the next major project of particle physics. The bid to host the project is currently discussed at governmental level in Japan and it is expected that France will play a major role in the project on both, accelerator and experimental aspects. The data taking could start in the early 2030's. This document will therefore focus on the ILC. It is however acknowledged that a similar program can be conducted with CLIC as an alternative to the ILC that is also debated in the European Strategy discussion.

2. Physics studies - State of the art

This section presents selected projections of the physics potential of the linear colliders. For a complete overview see e.g. [8]. All projections are supported by intensive detector R&D and its embedding into detector models in collaboration with engineers, see for example the contributions to the GT08 Working Group[9, 10, 11, 12]. The tight connection between physics studies and detector (and accelerator) oriented studies lead to a high degree of realism of the presented results.

2.1. Results by IN2P3 Groups

Groups of IN2P3 play a leading role in the elaboration of the physics program of the ILC. The IN2P3 is present in the Lineal Collider Collaboration physics working group and IN2P3 Members serve as conveners of the physics working groups of the ILD Collaboration. In the following contributions by IN2P3 Groups are outlined.

Couplings of the Higgs boson: The scalar particle discovered at LHC will naturally play also a central role in the physics program of linear colliders. The ILC will most likely start data taking at a centre-of-mass energy of 250 GeV, which is close to the threshold of the Higgs-strahlung process $e^+e^- \to HZ$. The Higgs boson is measured by its recoil to the Z boson. This model independent measurement will allow for an absolute determination of the Higgs couplings. A summary of full simulation studies for ILC and CLIC on the couplings of the Higgs boson can be found in Refs. [8, 13]. The expected precision on Higgs-couplings for linear and circular e^+e^- colliders under the assumption that the data will be taken after the completion of the HL-LHC [14]. The results show that already at 250 GeV a linear collider will lead to precisions comparable to that of circular machines. An upgrade to 500 GeV where the WW fusion process is the dominant source of Higgs production, is beneficial to the measurement of the coupling of the Higgs boson to the W boson and for the determination of the total width. Analyses carried out in the frame of the Standard Model Effective Field theory (SMEFT) come to similar conclusions [15, 8]. In this basis the influence of electroweak precision observables is emphasised due to $SU(2) \times U(1)$ symmetry induced relations between the corresponding Wilson coefficients.

At IN2P3 Higgs production cross section in the $e^+e^- \to Z(q\bar{q})H$ has recently been studied [16]. This channel in which Z decays hadronically completes the study of the Higgs production through the so-called golden channels in which the Z decays in pairs of electrons or muons. Although the hadronic channel does not have the same purity the leptonic channel provides due to the difficulty to associate the jets belonging to the Z in presence of the Higgs decay (if visible), It presents larger statistics that allow confirming the results obtained with the leptonic Z decays.

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Electroweak couplings of light fermions: Linear colliders will be electroweak precision machine that bear a large discovery potential in two fermion processes. New physics may manifest itself as a function of the chirality of the incoming and outgoing fermions. The differential cross section for relativistic two fermion production reads

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2 \tag{2}$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RL}(1+\cos\theta)^2 + \Sigma_{RR}(1-\cos\theta)^2, \tag{3}$$

where Σ_{IJ} are helicity amplitudes that contain electroweak couplings g_L, g_R (or equivalently g_V, g_A). All four helicity amplitudes for all fermions are only accessible with polarised beams as they are available at linear colliders. HL-LHC cannot do these kind of measurements. The electroweak couplings of quarks and leptons are modified in many theoretical models as for example Randall-Sundrum models with warped extra dimensions. A particular class of these models is Grand Higgs Unification [17, 18] which proposes elegant solutions for the introduction of the Higgs potential so far introduced ad-hoc to the Standard Model.

In recent years the process $e^+e^- \to b\bar{b}$ at $\sqrt{s} = 250$ GeV has been studied in great detail [19, 20] . The proper measurement of the polar spectrum requires to determine the b quark charge on an event-by-event basis. The b quark charge is measured using double tagged events with an efficiency of about 30% by using tracks pointing to a secondary vertex or by identifying Kaons in the TPC of ILD. The double tagging allows for correcting migration effects from the data alone and therefore for reducing drastically systematic errors in asymmetry measurements compared to corresponding measurements at LEP and SLC. The resulting precisions for all helicity amplitudes are of the order of 0.1% taking into account statistical and systematic errors.

Note at this point that at the LCWS2019 a study on $e^+e^- \to c\bar{c}$ at $\sqrt{s} = 250\,\mathrm{GeV}$ has been presented for the first time [21]. The final efficiency for double tagged events is of the order of 5%. The purity for the charge measurement in case of single tagged events is however more than 90% (compared with 75% - 80% for the b quark charge) such that it can be envisaged to use single tag events for the final results. The efficiency in this case would be around 25% leading to a corresponding reduction of the statistical error. The scrutinisation of these results is work in progress and will be available for the GT01-Meeting in March. It is however justified to expect that the precisions on the electroweak couplings of the c quark will be similar to those of the b quark.

The interpretation of results will depend decisively on input from the GigaZ running as the LEP results are by far not accurate enough in this context. Therefore, the capabilities of the ILC (and also CLIC) to run on the Z pole have been revised in 2019 [22, 23]. About $5 \cdot 10^9$ Z bosons can be collected in about 2-3 three years of running. For relevant electroweak precision observables the expected precision at a linear collider is comparable to the precision of circular machines. As a reminiscent of LEP/SLC it has to be noted that beam polarisation compensates for about a factor of 30 in luminosity. For the measurement of a central parameter as the weak mixing angle $\sin^2\theta^{\ell}_{\mathrm{eff.}}$ a linear collider will be able to make use of the hadronic Z decays. As pointed out in Ref. [22] the complementarity between the GigaZ and running at higher energies yield sensitivities to masses of new Z' bosons as they appear in models with Grand Higgs Unification of the order of at least 10 TeV.

Electroweak couplings of the top quark: Above the $t\bar{t}$-threshold eletroweak couplings of the top-quark can be extracted. The clean environment of e^+e^- collisions and energies well above the $t\bar{t}$ threshold are particularly suited for this measurement. This has been demonstrated in Ref. [24] which presents a full simulation study with the ILD Detector of the $e^+e^- \to t\bar{t}$ process at at $\sqrt{s} = 500\,\mathrm{GeV}$. Using the cross section and forward backward asymmetry, the precisions on electroweak couplings are of the order of 1.5% - 2.0% for an integrated luminosity of $500\,\mathrm{fb}^{-1}$, which reduces to about 0.5% for an integrated luminosity of $2000\,\mathrm{fb}^{-1}$. The update will be published in the IDR of ILD and, as before, has been obtained in a full simulation study. An e^+e^- machine running at 500 GeV is superior to LHC and also to circular colliders. The main reasons are the possibility to disentangle the individual form factors thanks to beam polarisation but in particular the higher centre-of-mass energy that increases the sensitivity to e.g. axial couplings.

An alternative for the extraction of the form factors is the matrix element method that analyses the final state polarisation of the top quarks. The method has been presented in Ref. [25] and has been subject to a master thesis of the University of Tohoku that has been supervised by an IN2P3 member.

All results have been obtained in leading order electroweak theory. For a consistent interpretation of the results theoretical calculations at (at least) next-to-leading order electroweak theory are needed. Motivated by the experimental studies introduced above these calculations are addressed by theory groups of IN2P3. A summary of first results can be found in Ref. [26] and a journal publication is under preparation.

2.2. Further relevant results

With today's technology linear colliders can be operated at energies well above the $t\bar{t}$ threshold. At around 500 GeV the double Higgs production and associated $t\bar{t}H$ production channels open giving direct access to the triple Higgs coupling λ and the top-Yukawa coupling y_t. For both measurements detailed simulation studies are available for ILC and for CLIC [27, 23, 13, 28, 29, 30].

The explanation of the Baryon asymmetry in the universe by electroweak baryogenesis requires a first order phase transition of the Higgs potential from the unbroken to the broken phase. Such a phase transition implies $\lambda \neq \lambda_{SM}$. Depending on the actual value, the precision on the self-coupling constant at the ILC will be between 5% and 15% using a combination of the $e^+e^- \to ZHH$ and $e^+e^- \to \nu\bar{\nu}HH$ processes. The results for the ILC assume integrated luminosities of $4\,\mathrm{ab}^{-1}$ and $8\,\mathrm{ab}^{-1}$ at 500 GeV and

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1 TeV, respectively. The threshold for $t\bar{t}H$ production is at around 480 GeV. The cross section rises quickly and, assuming an integrated luminosity of 4 ab^{-1}, the precision of y_t develops from 6.3% at 500 GeV to 2.0% at 600 GeV centre-of-mass energy. Reference [31] shows that such a precision gives sensitivity to masses of Kaluza-Klein excitations of Standard Model bosons between 5 and 10 TeV. The $t\bar{t}H$ production is also considered to be a sensitive probe of the CP properties of the Higgs boson [32].

3. Plans for Physics Studies by IN2P3 Groups

In the past years the IN2P3 Groups have developed world wide recognised competences in the study of the physics potential of $e^+e^- \to q\bar{q}$. Where $q\bar{q}$ is any of $t\bar{t}$, $b\bar{b}$ and $c\bar{c}$. New physics may manifest itself only in the electroweak couplings of the heavy quark doublet (t, b) or in a pattern visible in the electroweak couplings of all quark flavours. For $e^+e^- \to t\bar{t}$ and $e^+e^- \to b\bar{b}$ we have shown that electroweak couplings can be determined to about 0.5% for top and around 0.1% in case of the bottom quark. Results for $e^+e^- \to c\bar{c}$ will be available as well soon. LHC can measure the electroweak couplings of the top quark, albeit with 10-100 times less precision, but is incapable to measure electroweak couplings to the Z boson of lighter quarks. The projected precisions using leading order electroweak processes as input are impressive. However, our analyses also show a drop in acceptance at polar angles larger than about 0.75-0.8. In order to distinguish signals of new physics from e.g. higher order electroweak corrections a larger coverage in polar angle is necessary. This requires a revision of the inner part of the ILD Detector. Two aspects will be investigated: a) Reducing the distance of the first layer of the micro vertex detector to the beam axis and b) Improving the acceptance of the inner and forward tracking system of ILD by a revision of layout of these systems that currently foresees a Faraday cage (or a cryostat). The IN2P3 Groups have all necessary competences for these kind of studies.

The tagging capabilities of the ILD Detector allow for extending the existing results to the light quark flavours uds. One can expect to improve results obtained by DELPHI (LEP) by about one order of magnitude. Experimental requirements are a clean anti-veto of heavy quarks by the vertex detectors and a deep understanding of particle identification, i.e. $\pi/K/p$ separation, with the TPC of ILD. In a first step the analysis will be carried with fully simulated samples at a centre-of-mass energy of 250 GeV that will become available during 2020. GigaZ running adds decisively to the physics potential of the ILC. We propose thus to extend the results for b, c and light quarks using full simulation at the Z Pole and to apply/adapt the methods developed at 250 GeV. The on-average smaller energy of the final state particles may also benefit from a shorter distance of the first layer of the micro vertex detector to the beam axis.

We have embarked on a study to improve the precisions for Higgs couplings beyond the state of the art. The idea is to extract e.g. the Higgs coupling to the Z boson from a simple counting experiment instead of relying on the momentum resolution of the tracking chambers. The efficiency is extracted from a 'Reference Sample' created by $e^+e^- \to HZ$ recoil events in which the Z decays into a muon pair. From this the efficiency for the reconstruction of Higgs signals is extracted and applied to channels in which the Z boson decays to particles other than a muon pair. An important ingredient to the analysis is the number of final state hadrons. A preliminary study at parton level shows that with about 2.5% the expected precision on g_{HZZ} is similar to that obtained with the standard method. In the coming years the results will be scrutinised with a full detector simulation study.

The analyses of hadronic final states of the process $e^+e^- \to HZ$ by IN2P3 groups is supported by the intense development of a new generation of highly granular calorimeters (SiW ECAL and SDHCAL) and the realisation of the first technological prototypes within the CALICE collaboration. It also benefits from the development by the IN2P3 groups of a new PFA algorithm called (APRIL) that intends to exploit the high granularity of the new calorimeters to achieve the best possible jet energy resolution.

We will of course closely follow the results delivered by the LHC. This implies the evaluation of the adaptation of the physics program of a linear e^+e^- collider in case of discoveries or the manifestation of anomalies at the LHC.

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3.1. Resources and deliverables:

All proposed studies will be carried out in detailed simulation of detector proposals such as ILD. Emphasis will be put on the estimation of the systematic error and the consequences for the detector layout. This is important since, in case the ILC is going to be approved in the coming five years, the final design of most of the detector components has to be available by then. Each of the proposed studies requires a sustained support in terms of manpower, which translates into the attribution of at least one researcher at postdoctoral level per subject. Ideally, these postdoctoral researchers collaborate with PhD students. The expected deliverables in the next 3-5 years are:

- A full characterisation of the physics potential of $e^+e^- \to q\bar{q}$ processes at linear colliders including an estimation of systematic errors and the interpretation in terms of models of new physics.
- A significant contribution to the precision of Higgs couplings at both, experimental and phenomenological level.
- Significant contributions to the final design of a detector for a linear collider. The optimisation extends to the accelerator in order to make sure that the precision is not compromised by accelerator related effects such as beamstrahlung.

Depending on the evolution of the ILC, the proposed studies may at some point generate an IN2P3 Master project with corresponding sustained resources in which experimentalists and theorists are federated and the link to the accelerator community is ensured.

4. Conclusion

This document outlines the outstanding physics potential of a linear e^+e^- collider. It summarises the contributions made by IN2P3 groups in recent years. It has been shown that electroweak couplings of fermions can be fully determined at the 0.5% to 0.1% level. GigaZ is an indispensable component of the running program of a linear collider. In terms of Higgs couplings a linear collider running at $\sqrt{s} = 250\,\mathrm{GeV}$ is on equal footing with other proposals at the $e^+e^- \to HZ$ threshold and gets superior by its capability to make measurements well above the $t\bar{t}$ threshold. The plans for the next about five years will lead to a scrutinisation of existing studies but beyond that it is planned to extend the results on $e^+e^- \to q\bar{q}$ to the full set of quarks. New approaches to determine the Higgs couplings will be studied and evaluated in great detail. The detector design will depend decisively on the conclusions of the studies in terms of for example the final layout of the vertex detectors and the calorimeters. In summary this document proposes a rich program of simulation studies that will contribute to detector and accelerator design and yield into the ILC construction expected to start around the Year 2025.

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