IL NUOVO CIMENTO Vol. 37 C, N. 2 Marzo-Aprile 2014
DOI 10.1393/ncc/i2014-11730-6

Colloquia: LC13

First look at the physics case of TLEP

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ricevuto il 4 Febbraio 2014

Summary. — The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model at the TeV scale, has triggered interest in ideas for future Higgs factories. A new circular e^+e^- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics.

PACS 13.66.-a – Lepton-lepton interactions.

1. – Introduction

The Higgs boson with mass around 125 GeV recently discovered by the ATLAS and CMS experiments [1, 2] at the LHC is found to have properties compatible with the Standard Model predictions [3-5]. Coupled with the absence of any other indication so far for new physics at the LHC this fundamental observation seems to push the energy scale of any physics beyond the Standard Model above several hundred GeV. The higher-energy LHC run, which is expected to start in 2015 at $\sqrt{s} \sim 13$–14 TeV, will extend the sensitivity by a factor two, in many cases well above 1 TeV. Fundamental discoveries may therefore be made in this energy range by 2017–2018. Independently of the outcome of this higher-energy run, however, there must be new phenomena, albeit at unknown energy scales, as shown by the evidence for non-baryonic dark matter, the cosmological baryon-antibaryon asymmetry and non-zero neutrino masses, which are all evidence for physics beyond the Standard Model. In addition to the high-luminosity upgrade of the LHC, new particle accelerators will be instrumental to understand the physics underlying these observations.

The path towards the choice of the most appropriate machine(s) to analyse these new phenomena may be guided by historical precedents, which reveal the important rôles played by lower-energy precision measurements when establishing roadmaps for future discoveries with higher-energy machines. The details of the optimal strategy for the next large facility after the LHC can only be finalized once the results of the LHC run at 13–14 TeV are known. Depending on these results, a first step in the strategy to look beyond the LHC findings could require a facility that would measure the Z, W, top-quark and Higgs-boson properties with sufficient accuracy to provide sensitivity to new physics at a much higher energy scale.

For example, new physics at an energy scale of 1 TeV would translate typically into deviations δg_{HXX} of the Higgs boson couplings to gauge bosons and fermions, g_{HXX}, of up to 5% with respect to the Standard Model predictions [6, 7], with a dependence that is inversely proportional to the square of the new energy scale Λ:

$$\frac{\delta g_{\mathrm{HXX}}}{g_{\mathrm{HXX}}^{\mathrm{SM}}} \leq 5\% \times \left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)^2 . \tag{1}$$

Therefore the Higgs boson couplings need to be measured with a per-cent accuracy or better to be sensitive to 1 TeV new physics, and with a per-mil accuracy to be sensitive to multi-TeV new physics. Similarly, Electroweak precision measurements made at LEP with 10^7 Z decays, together with accurate W and top-quark mass measurements from the Tevatron, are sensitive to weakly-coupled new physics at a scale up to 3 TeV. To increase this sensitivity up to 30 TeV, an improvement in precision by two orders of magnitude, *i.e.*, an increase in statistics by four orders of magnitude to at least 10^{11} Z decays, would be needed. At the same time, the current precision of the W and top-quark mass measurements needs to be improved by at least one order of magnitude, *i.e.*, to better than 1 MeV and 50 MeV respectively, in order to match the increased Z-pole measurement sensitivity. These experimental endeavours will also require significant theoretical effort in a new generation of theoretical calculations in order to reap the full benefits from their interpretation.

The proposed TLEP e^+e^- collider [8,9], which could be hosted in a new 80 to 100 km tunnel [10] in the Geneva area, would be able to produce collisions at centre-of-mass energies from 90 to 350 GeV and beyond, at several interaction points, and make precision measurements at the Z pole, at the WW threshold, at the HZ cross section maximum, and at the $t\bar{t}$ threshold, with an unequalled accuracy. The same tunnel will be designed to host a hadron collider (called the VHE-LHC), at a centre-of-mass energy of up to 100 TeV, which would give direct access to new physics up to scales of 30 TeV. This global vision for an ambitious post-LHC collider program [11, 12] is now being implemented at CERN under the "Future Circular Colliders" (FCC) international design study. For more details on the project and its physics case please refer to ref. [9].

2. – The experimental environment

The TLEP collider complex consists of an accelerator ring and a storage ring [13], the former delivering continuous top-up injection to the latter, so that a constant level of luminosity is provided in collisions. The current TLEP working points can be found in ref. [8], for the four centre-of-mass energies of interest: the Z pole ($\sqrt{s} \sim 91$ GeV); the WW threshold ($\sqrt{s} \sim 161$ GeV); the HZ cross-section maximum ($\sqrt{s} \sim 240$ GeV);

TABLE I. – *Preliminary values of the luminosity for TLEP in each of the four planned configurations* [8]. *Other parameters relevant for the physics potential of TLEP* (*beam size, RF cavity gradient, number of bunches, total power consumption and integrated luminosity per year at each IP*) *are also listed.*

	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
$\sqrt{s}$ (GeV)	90	160	240	350
L ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$/IP)	56	16	5	1.3
# bunches	4400	600	80	12
RF Gradient (MV/m)	3	3	10	20
Vertical beam size (nm)	270	140	140	100
Total AC Power (MW)	250	250	260	284
L_{int} (ab^{-1}/year/IP)	5.6	1.6	0.5	0.13

and the top-pair threshold ($\sqrt{s} \sim 350\,\mathrm{GeV}$). The 12 GV RF system is designed to compensate for the energy loss by synchrotron radiation at $\sqrt{s} = 350\,\mathrm{GeV}$, at which a luminosity of $1.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ can be delivered at each interaction point (IP), in a configuration with four IPs. At lower centre-of-mass energies, the energy losses decrease steeply like E^4_{beam}, and the RF power can be used to accelerate a much larger number of $\mathrm{e}^{\pm}$ bunches, from 12 bunches at 350 GeV all the way to 4400 bunches at the Z pole. As a result, the luminosity increases approximately like $1/E^3_{\mathrm{beam}}$ when the centre-of-mass energy decreases. The preliminary values of the luminosities expected at each energy are displayed in table I, together with other important parameters of the machine (beam size, RF cavity gradient, number of bunches, and total power consumption), taken from ref. [8]. The last row gives the integrated luminosity expected at each interaction for one year of data taking (1 year = 10^7 seconds).

3. – Precise measurements of the Higgs boson properties

The primary goal of a Higgs factory is to measure the Higgs boson properties with the best possible precision as to be sensitive to physics beyond the Standard Model at the highest possible scale. Tree-level couplings of the Higgs boson to fermions and gauge bosons are expected to be modified with respect to the standard-model prediction, with a magnitude rapidly decreasing with the new physics scale Λ, typically like $1/\Lambda^2$. For $\Lambda = 1\,\mathrm{TeV}$, departures up to 5% are expected [6, 7]. To discover new physics through its effects on the Higgs boson couplings with a significance of 5σ, it is therefore necessary to measure these couplings to fermions and gauge bosons with a precision of at least 1%, and at the per-mil level to reach sensitivity to Λ larger than 1 TeV, as suggested by the negative results of the searches at the LHC.

The number of Higgs bosons expected to be produced, hence the integrated luminosity delivered by the collider, are therefore key elements in the choice of the right Higgs factory for the future of high-energy physics: a per-mil accuracy cannot be reached with less than a million Higgs bosons.

TABLE II. – *Relative statistical uncertainty on the Higgs boson couplings, as expected from the physics programme at* $\sqrt{s} = 240$ *and* 350 GeV *at TLEP.* (*The first column indicates the expected precision at TLEP when the sole* 240 GeV *data are considered. The substantial improvement with the inclusion of the* 350 GeV *data — in the second column — mostly stems from the precise total Higgs boson width measurement, which constrains all couplings simultaneously.*) *The numbers between brackets indicates the uncertainties expected with two detectors instead of four. For illustration, the uncertainties expected from the ILC baseline programme at* 250 *and* 350 GeV *are also given. The first three columns give the results of a truly model-independent fit, while the last two include the two assumptions made in ref.* [14] *on the W/Z couplings and on the exotic decays, for completeness and easier comparison. The last line gives the absolute uncertainty on the Higgs boson branching fraction to exotic particles* (*invisible or not*).

	Model-independent fit				Constrained fit		
Coupling	TLEP-240	TLEP		ILC	TLEP		ILC
g_{HZZ}	0.16%	**0.15%**	(0.18%)	0.9%	0.05%	(0.06%)	0.31%
g_{HWW}	0.85%	**0.19%**	(0.23%)	0.5%	0.09%	(0.11%)	0.25%
g_{Hbb}	0.88%	**0.42%**	(0.52%)	2.4%	0.19%	(0.23%)	0.85%
g_{Hcc}	1.0%	**0.71%**	(0.87%)	3.8%	0.68%	(0.84%)	3.5%
g_{Hgg}	1.1%	**0.80%**	(0.98%)	4.4%	0.79%	(0.97%)	4.4%
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%**	(0.66%)	2.9%	0.49%	(0.60%)	2.6%
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%**	(7.6%)	45%	6.2%	(7.6%)	45%
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%**	(1.8%)	14.5%	1.4%	(1.7%)	14.5%
$\mathrm{BR}_{\mathrm{exo}}$	0.48%	**0.45%**	(0.55%)	2.9%	0.16%	(0.20%)	0.9%

The accuracies on the Higgs boson couplings are obtained here from a fit to all observables reported in tables 4 and 6 in ref. [9] for TLEP at $\sqrt{s} = 240$ and 350 GeV. The fit closely follows the logic presented in ref. [14], and indeed reproduces the results presented therein for the combination of the ILC and LHC projections. Here, the results of standalone fits, *i.e.*, without combination with LHC sensitivities, are given in table II so as to compare the ILC and TLEP relative performance in terms of Higgs boson coupling and width measurements.

As is clearly visible from table II, a model-independent precision better than 1% for all couplings (and at times approaching the per-mil level), required for these measurements to become sensitive to (multi-)TeV new physics, can be obtained with the TLEP high-statistics data samples.

It is also important to compare the projections of TLEP to those from the HL-LHC, as to evaluate the added value of a circular e^+e^- Higgs factory after $3\,\mathrm{ab}^{-1}$ of proton-proton collision data. Given that a truly model-independent fit cannot be performed from proton-proton collision, constraints similar to those used in ref. [15] are applied here: it is assumed that no Higgs boson exotic decays take place, and that deviations of the charm and top couplings are correlated.

The CMS report [16] submitted to the recent Snowmass process contains estimates of the CMS projected performance with $3\,\mathrm{ab}^{-1}$, with similar hypotheses, in two scenarios:

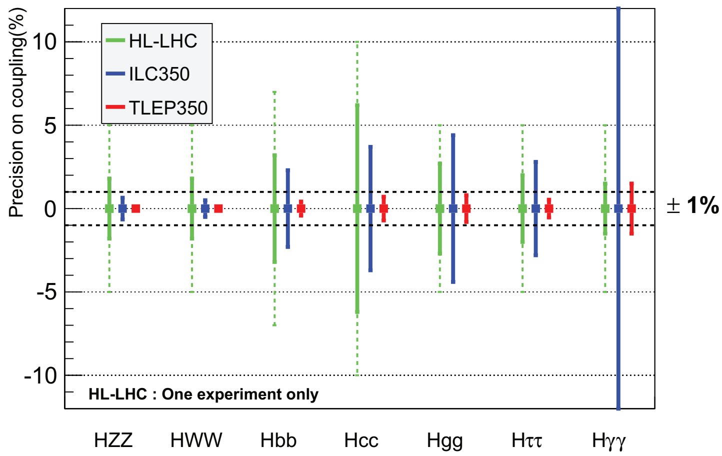

Fig. 1. – Comparison between the projections of the HL-LHC (green) and of e^+e^- Higgs factories (blue: ILC, red: TLEP) for the Higgs boson coupling relative uncertainties. For the HL-LHC projections, the dashed bars represent CMS Scenario 1 and the solid bars represent CMS Scenario 2, for one experiment only [16]. For the Higgs factories, the data up to $\sqrt{s} = 350\,\text{GeV}$ are combined. The dashed horizontal lines show the $\pm 1\%$ band, relevant for sensitivity to multi-TeV new physics.

Scenario 1 with all systematic uncertainties unchanged, and Scenario 2, with experimental systematic uncertainties scaling like $1/\sqrt{L}$ and theoretical errors halved. These estimates are displayed in fig. 1 and compared to a fit of the TLEP projections extracted with the same assumptions about the theoretical uncertainties in Higgs boson decays.

4. – Measurements with MegaTop

With an integrated luminosity of the order of $130\,\text{fb}^{-1}$ per year and per experiment, TLEP will be a top factory as well, with over one million $t\bar{t}$ pairs produced in five years (hence the "MegaTop" appellation) at $\sqrt{s} \sim 345\,\text{GeV}$. The precise measurement of the cross section at the $t\bar{t}$ production threshold is sensitive to the top-quark pole mass, m_{top}, the total top-quark decay width, Γ_{top}, as well as to the Yukawa coupling of the top quark to the Higgs boson, λ_{top}, through the virtual exchange of a Higgs boson between the two top quarks.

The expected TLEP statistical uncertainties are summarized in table III. In addition to the ten-fold increase in the number of $t\bar{t}$ events at TLEP, which reduces the statistical uncertainties by a factor of three, the much better knowledge of the beam-energy spectrum, and the precise measurement of the strong coupling constant with TeraZ and OkuW are bound to reduce the main experimental systematic uncertainties by one order of magnitude, hence below the statistical uncertainties.

An overall experimental uncertainty of 10 to 20 MeV is therefore considered to be a reasonable target for the top-quark mass measurement at TLEP.

TABLE III. – *Expected statistical uncertainties for m_{top}, Γ_{top} and λ_{top} for TLEP, obtained from a five-years scan of $\mathrm{t\bar{t}}$ threshold at $\sqrt{s} \sim 350\,\text{GeV}$. The dominant experimental systematic uncertainties on the top quark mass are expected to be of the order of or smaller than the statistical uncertainties for TLEP. Also indicated is the baseline ILC potential for these measurements.*

	m_{top}	Γ_{top}	λ_{top}
TLEP	**10 MeV**	**11 MeV**	**13%**
ILC	31 MeV	34 MeV	40%

5. – Global fit of the EWSB parameters

Once the Higgs boson mass is measured and the top quark mass determined with a precision of a few tens of MeV, the Standard Model prediction of a number of observables sensitive to Electroweak radiative corrections will become absolute with no remaining additional parameters. Any deviation will be a demonstration of the existence of new, weakly interacting particle(s). As it is described in detail in ref. [9], TLEP will offer the opportunity of measurements of such quantities with precisions between one and two orders of magnitude better than the present status of these measurements. The theoretical prediction of these quantities with a matching precision will be a real challenge but the ability of these tests of the completeness of the Standard Model to discover new weakly-interacting particles beyond those already known is real.

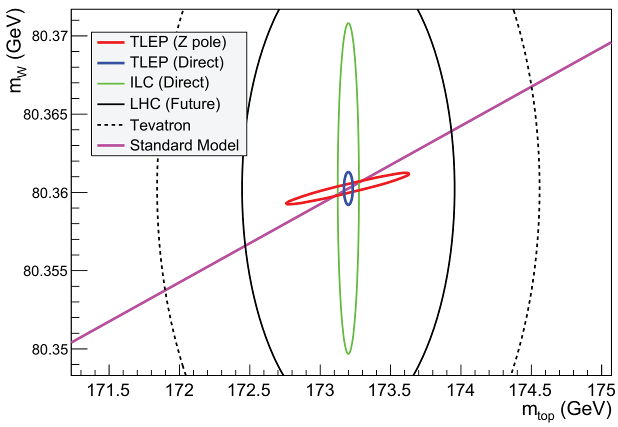

Fig. 2. – The 68% C.L. contour from the fit of all Electroweak precision measurements from TLEP-Z (red curve) in the $(m_{\text{top}}, m_{\text{W}})$ plane, should the relevant theory uncertainties be reduced to match the TLEP experimental uncertainties, compared to the direct W and top mass precisions (blue curve) expected at TLEP-W and TLEP-t. For illustration, the LHC (black curve) and ILC (green curve) projections for the direct m_{W} and m_{top} precisions are also indicated, as well as the current precision of the Tevatron measurements (dashed curve). The value of the Tevatron W mass was modified in this figure to match the SM prediction for $m_{\text{top}} = 173.2\,\text{GeV}$. The purple line shows the prediction from the Standard Model for $m_{\text{H}} = 125\,\text{GeV}$. (For the LHC or the ILC on their own, the thickness of this line would need to be increased by at least the error stemming from the Z mass measured at LEP, *i.e.*, about $\pm 2\,\text{MeV}$ on the W mass. This error disappears in the case of TLEP.) No theory error was included in this line.

As an illustration, the result of the fit of the Standard Model to all the Electroweak measurements foreseen with TLEP-Z, as obtained with the GFitter program [17] under the assumptions that all relevant theory uncertainties can be reduced to match the experimental uncertainties and that the error on $\alpha_{\mathrm{em}}(m_{\mathrm{Z}})$ can be reduced by a factor 5, is displayed in fig. 2 as 68% C.L. contours in the $(m_{\mathrm{top}}, m_{\mathrm{W}})$ plane. This fit is compared to the direct m_{W} and m_{top} measurements expected from TLEP-W and TLEP-t. For illustration, a comparison with the precisions obtained with the current Tevatron data, as well as from LHC and ILC projections, is also shown.

6. – Conclusion

The discovery at the LHC of a particle that resembles strongly the long-sought Higgs boson of the Standard Model has placed studies for the next large machine for high-energy physics in a new perspective. The prospects for the next decade already look quite promising: the HL-LHC is an impressive Higgs factory, with great potential for measuring many Higgs couplings with accuracies of a few per-cent. The LHC run at 13–14 TeV may well discover something else, and it would be premature to mortgage the future of high-energy physics before knowing what it reveals. In the meantime new ideas are emerging for possible future Higgs factories. In our view, TLEP, a large e^+e^- circular collider in a tunnel with 80 to 100 km circumference, would best complement the LHC, as it would provide i) per-mil precision in measurements of Higgs couplings, ii) unique precision in measurements of Electroweak Symmetry-Breaking parameters and the strong coupling constant, iii) a measurement of the Z invisible width equivalent to better than 0.001 of a conventional neutrino species, and iv) a unique search programme for rare Z, W, Higgs, and top decays. The design study of TLEP has now started, in close collaboration with the VHE-LHC design study, with worldwide collaboration from Asia, USA and Europe, and with full support from the CERN Council. Technically, and if given the necessary financial and political support, TLEP could be ready for physics in 2030.

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The author would like to thank the ECT* for the hospitality and the financial support.

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