PROCEEDINGS OF SCIENCE

Prospects for measurements of the Higgs boson couplings at TLEP

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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 up to scales of several hundred GeV, 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 Higgs boson studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. 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. This paper describes the expected precision on the measurement of the Higgs boson couplings with a TLEP run between 250 and 350 GeV.

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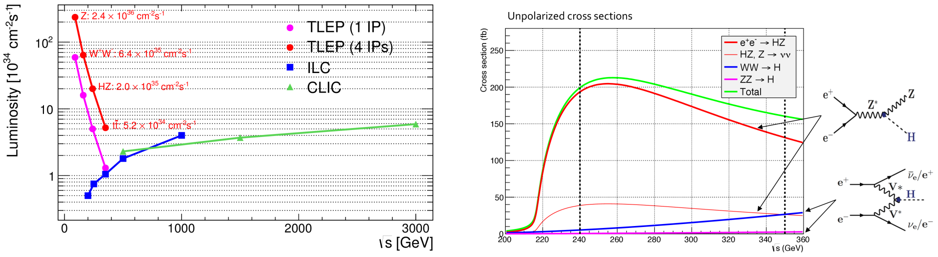


(a) (b)

Figure 1: a. Expected instantaneous luminosity as a function of $\sqrt{s}$ for TLEP (1-4 IPs) ILC and CLIC. b.Higgs production cross section for different processes in unpolarized e$^+$e$^-$ collisions, as predicted by the `HZHA` program [10].

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, 4]. 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, creating the need to study the new particle with ultimate precision. Such precision requires huge integrated luminosities that can be achieved only through circular colliders. The proposed TLEP e$^+$e$^-$ collider [5], which could be hosted in a new 80 to 100 km tunnel [6] in the Geneva area, would be able to produce collisions at centre-of-mass energies from 90 to 350 GeV and beyond and make precision measurements with an unequalled accuracy. The same tunnel also provides a path to 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 10 TeV or more.

2. Higgs boson production in e^+e^- collisions

The number of Higgs bosons expected to be produced, hence the integrated luminosity delivered by the collider, are key elements in the choice of the right Higgs factory for the future of high-energy physics. The huge gain of a circular e^+e^- collider is the amount of luminosity that it can deliver. With a maximum centre of mass energy of 350 GeV, the RF power can be used to accommodate more bunches in lower energies increasing dramatically the luminosity at the ZH, WW and Z threshold. Figure 2.a shows the luminosity as a function of centre of mass energy for TLEP (1 or 4 interaction points) and the two linear collider projects, ILC [7, 8] and CLIC [9].

The Higgs production cross section (obtained with the `HZHA` generator [10]), through the Higgs-strahlung process e$^+$e$^-$ → HZ and the WW or ZZ fusion processes, are displayed in Fig. 2 b. The cross section is maximal around 255 GeV however given the luminbosity profile of TLEP , the maximal number of Higgs bosons is produced at $\sqrt{s} = 240$ GeV.

Table 1: Integrated luminosity and number of Higgs bosons produced with TLEP at $\sqrt{s} = 240/350$ GeV (summed over four IPs), for the Higgs-strahlung process and the WW fusion. For illustration, the corresponding numbers are also shown for the baseline ILC programme [11] at $\sqrt{s} = 250/350$ GeV.

	TLEP 240	ILC 250	TLEP 350	ILC 350
Total Integrated Luminosity (ab^{-1})	**10**	0.25	**2.6**	0.35
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**	70,000	**340,000**	65,000
Number of Higgs bosons from boson fusion	**50,000**	3,000	**70,000**	22,000

3. Measurements at $\sqrt{s} = 240$ and $\sqrt{s} = 350$ GeV

At $\sqrt{s} = 240$ GeV, the TLEP luminosity is expected to be $5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at each interaction point, in a configuration with four IPs. The total integrated luminosity accumulated in five years, assuming running for 10^7 seconds per year, is shown in Table 1, together with the corresponding numbers of Higgs bosons produced demonstrating that TLEP is in a position to produce enough Higgs bosons in a reasonable amount of time to aim at the desired sub-per-cent precision for Higgs boson coupling measurements.

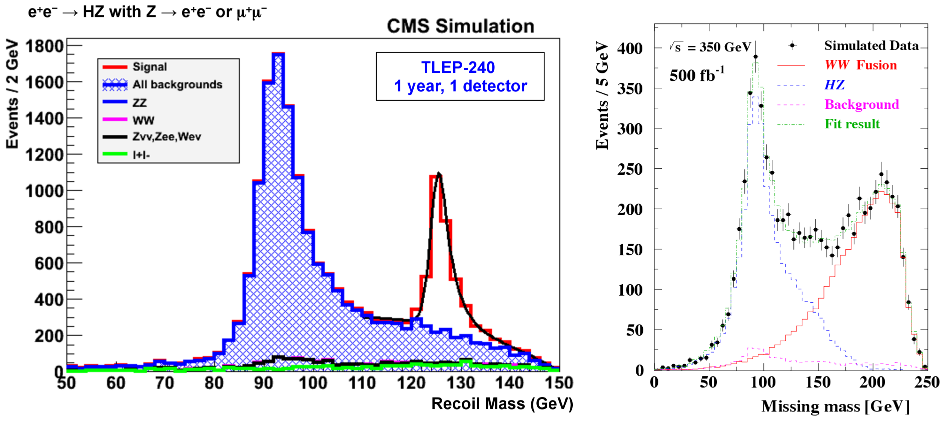
Simple analyses using detailed full simulation of the CMS detector have been carried out in Ref. [12] to demonstrate the methoidology of achieving the claimed precision.

For example, the distribution of the mass recoiling against the lepton pair in the e^+e^-H and $\mu^+\mu^-H$ final states, independently of the Higgs boson decay, is shown in Fig. 2 a, taken from Ref. [12], for one year of data taking in the CMS detector. The number of Higgs boson events obtained from a fit to this distribution of the signal and background contributions allows the total $e^+e^- \to HZ$ cross section to be measured with a precision of 0.4% at TLEP.

One other example is the measurement of the Higgs boson width. In e^+e^- collisions, it is not possible to directly observe the width of the Higgs boson if it is as small as the Standard Model prediction of 4 MeV. However, the total width of the Higgs boson is given by $\Gamma_{\mathrm{tot}} = \Gamma(H \to ZZ)/\mathrm{BR}(H \to ZZ)$. The partial decay width $\Gamma(H \to ZZ)$ is directly proportional to the inclusive cross section σ_{HZ}, measured with a precision of 0.4% from the "recoil mass" distribution of Fig. 2 a. The Higgs boson branching ratio to ZZ, $\mathrm{BR}(H \to ZZ)$, is in turn obtained from the number of ZZZ events, itself proportional to $\sigma_{HZ} \times \mathrm{BR}(H \to ZZ)$, measured with a 3.1% relative precision. Therefore, with the sole 240 GeV data, TLEP is able to determine the Higgs boson decay width with a precision of the order of 3% from this channel.

A summary of the statistical precision of the measurements presented in Ref. [12] for $\sqrt{s} = 240$ GeV – extrapolated to the TLEP luminosity and to four detectors – is given in Table 2. For illustration, the baseline ILC figures at $\sqrt{s} = 250$ GeV, taken from Ref. [14], are also given.

At $\sqrt{s} = 350$ GeV, the TLEP luminosity is expected to amount to $1.3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at each IP. The total integrated luminosity accumulated in five years is also shown in Table 1, together with the corresponding numbers of Higgs bosons produced. The additional events from the Higgs-strahlung process at 350 GeV allow the statistical precision for all the aforementioned measurements to be improved by typically 5% for TLEP with respect to the sole 240 GeV data. In addition, the large number of Higgs bosons produced in boson fusion can improve the total width



(a) (b)

Figure 2: a.Distribution of the mass recoiling against the lepton pair in the $e^+e^- \rightarrow HZ$ channel, in the $Z \rightarrow \ell^+\ell^-$ final state ($\ell = e, \mu$), taken from Ref. [12], for an integrated luminosity equivalent to one year of data taking with one TLEP detector (assumed to be the CMS detector). b. Distribution of the mass recoiling against the $b\bar{b}$ system in the $b\bar{b}\nu\bar{\nu}$ final state, from Higgs-strahlung (blue) and WW-fusion (red) production for 500 fb^{-1} at $\sqrt{s} = 350$ GeV, taken from Ref. [13].

Table 2: Statistical precision for Higgs measurements obtained from the proposed TLEP and ILC programme at $\sqrt{s} = 240$ and $\sqrt{s} = 250$ GeV respectively .

	TLEP 240	ILC 250
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \rightarrow b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \rightarrow c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \rightarrow gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \rightarrow WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \rightarrow \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \rightarrow ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \rightarrow \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \rightarrow \mu\mu)$	**13%**	100%

precision by exploiting the partial decay width $\Gamma(H \rightarrow WW)$ measured in ZH events combined with the $\sigma_{WW \rightarrow H} \times BR(H \rightarrow b\bar{b})$ measurement in a similar fashion as described in the case of σ_{HZ} and $\Gamma(H \rightarrow ZZ)$. At $\sqrt{s} = 350$ GeV, both the Higgs-strahlung process (when the Z decays to a neutrino pair) and the WW fusion contribute to this final state with a similar cross section (Fig. **??** b). The mass recoiling against the $b\bar{b}$ system (also called missing mass), however, peaks at m_Z for the Higgs-strahlung and clusters around $\sqrt{s} - m_H$ for the WW fusion. A fit of the HZ and WW fusion contributions to the distribution of this missing mass, shown in Fig. 2 from Ref. [13], allows $\sigma_{WW \rightarrow H} \times BR(H \rightarrow b\bar{b})$ to be obtained with a relative precision of 0.6% at TLEP. The statistical precision with which $\sigma_{WW \rightarrow H} \times BR(H \rightarrow b\bar{b})$ can be measured at both centre-of-mass energies is displayed in Table 3.

Table 3: Statistical precision of the TLEP measurement of $\sigma_{\mathrm{WW}\to\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}})$. For illustration, the ILC potential at the same centre-of-mass energies is also indicated.

$\sqrt{s}$ (GeV)	TLEP	ILC
240 - 250	**2.2%**	10.5%
350	**0.6%**	1.0%

Table 4: Statistical precision of the total Higgs boson width measurements with TLEP at $\sqrt{s} = 240$ and 350 GeV. For illustration, the ILC potential at the same centre-of-mass energies is also indicated.

Process and final state	TLEP	ILC
$\mathrm{e^+e^-} \to$ HZ with $\mathrm{H} \to$ ZZ	**3.1%**	20%
WW $\to$ H with $\mathrm{H} \to \mathrm{b\bar{b}}$ at 240 GeV	**2.4%**	12%
WW $\to$ H with $\mathrm{H} \to \mathrm{b\bar{b}}$ at 350 GeV	**1.2%**	7%
Combined	**1.0%**	6.0%

Combining the relevant measurements, TLEP is therefore able to determine the Higgs boson decay width with a precision of the order of 1.2% (2.4%) at $\sqrt{s} = 350(250)$ GeV with WW fusion. When combined with the ZZZ final state, the precision on the total Higgs boson width from TLEP is estimated to be 1.0%. These numbers are summarized in Table 4.

4. Global fit for Higgs boson couplings

The accuracies on the Higgs boson couplings are obtained here from a fit to all observables reported in Tables 2 and 3 for TLEP at $\sqrt{s} = 240$ and 350 GeV. The fit closely follows the logic presented in Ref. [15], 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 so as to compare the LHC, ILC and TLEP relative performance in terms of Higgs boson coupling and width measurements. The other two assumptions made in Ref. [15] consist in *(i)* bounding from above the couplings to the Z and the W to the Standard Model couplings; and *(ii)* saturating the exotic decay width by the sole invisible Higgs boson decays. These assumptions introduce some model dependency which are not called for when it comes to measure the Higgs boson properties in a truly model-independent manner. These two assumptions were therefore removed from the fit, the results of which are presented in the first three columns of Table 5. For completeness, and for direct comparison with Ref. [15], the results of the fit with these two assumptions are also given in the last two columns of the same table.

As is clearly visible from Table 5, a model-independent precision systematically better than 1% (and at times approaching the per-mil level), required for the coupling measurements to become sensitive to (multi-)TeV new physics, can be obtained with the TLEP high-statistics data samples. The luminosity expected to be produced at linear colliders is insufficient for this purpose.

Table 5: Relative statistical uncertainty on the Higgs boson couplings, as expected from the physics programme at $\sqrt{s} = 240$ and 350 GeV at TLEP. 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. [15] on the W/Z couplings and on the exotic decays, for completeness and easier comparison. The column labelled "TLEP-240" holds for the sole period at 240 GeV for TLEP. The last line gives the *absolute* uncertainty on the Higgs boson branching fraction to exotic particles (invisible or not).

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%

5. 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 LHC is currently the only Higgs factory being able with a luminosity upgrade to measure the Higgs couplings up to a precision of few percent and pursue new discoveries at higher energies . In the case of no new physics discoveries at the LHC, a new instrument will be needed to reveal the scale of new physics via sub-percent precision measurements of the Higgs couplings. The luminosity needed for such precision can only be achieved with a circular collider. TLEP, a circular e^+e^- collider hosted in a 80 km tunnel can satisfy the requirements for a high precision Higgs program and can be the first step towards a future hadron collider to purse new discoveries in energies up to 100 TeV.

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