Implications of LHC results for TeV-scale physics: signals of electroweak symmetry breaking

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Abstract

The current status of Higgs/EWSB searches at the LHC and elsewhere are briefly summarized. The implications for future colliders such as the HL-LHC, the ILC, and CLIC are discussed. ls

1 Introduction

On July 4 2012, prior to the ICHEP conference to be held in melbourne, the discovery of a narrow resonance, with a mass near 125 GeV, in the search for the Standard Model (SM) Higgs boson at the LHC by both the ATLAS and CMS experiments was annouced at CERN. This narrow resonance is consistent with a SM Higgs boson. less significant but nevertheless supporting evidence was also found by the TeVatron experiments. Despite the clear evidence of the production of a new particle, and its consistency with the SM Higgs boson, its nature still needs to be elucidated and its role in the mechanism of electroweak symmetry breaking (EWSB), which is one of the main goals of the LHC, still needs to be established.

To further determine the role of this new particle in EWSB the main focus of experiments will be the precise measurement of fundamental properties such as its quantum numbers (J^{PC}) and its couplings with all other particles and with itself. The precise measurement of its mass is also important insofar as it will allow a more precise prediction of its couplings, but will not play a significant role in the global electroweak fit.

This new state at the multi-GeV scale, possibly the Higgs particle, could also restore the unitarity spoiled by the scattering of the $W_{\rm L}W_{\rm L}$ and $Z_{\rm L}Z_{\rm L}$. The role of this new resonance on this prediction should also be fully elucidated, and a direct measurement of the $W_{\rm L}W_{\rm L}$ scattering may allow to determine whether this new state is composite or elementary.

Finally a broader question about this recently discovered state, in particular if it is a Higgs boson, is its naturalness. This question, posed by the quadratic divergence of the Higgs boson mass has been at the heart of the fundamental physics for the past four decades. Since the seminal works of Refs. [**?**], countless EWSB scenarios addressing this issue have been investigated, among which the most popular is the Minimal Supersymmetric Standard Model (MSSM). The implications of this question is either the existence of new physics at the TeV-scale or a certain level of fine tuning. The precise measurement of the properties of the observed narrow resonance could shed light on this fundamental question.

Secondly, as the main part of this section, we summarize the capabilities of future colliders to further unravel the mechanism responsible for electroweak symmetry breaking and to confirm that a Higgs boson has indeed been observed. To do so we have to also considered that LHC will have by that time collected a given amount of luminosity at 13 – 14 TeV.

2 Experimental status

2.1 The LHC first years of running

In 2011, the LHC delivered an integrated luminosity of slightly less than 6 fb^{-1} of proton-proton (pp) collisions at a center-of-mass energy of 7 TeV to the ATLAS and CMS experiments.

By July 2012, the LHC delivered more than 6 fb^{-1} of pp collisions at a center-of-mass energy of 8 TeV to both the ATLAS and CMS experiments. For this dataset, the instantaneous luminosity reached record levels of approximately $7 \cdot 10^{33}$ cm^{-2}s^{-1}, almost double the peak luminosity of 2011 with the same 50 ns bunch spacing. The increased luminosity thus came at the expense of an unprecedented number of pp collisions per bunch crossing (pile-up), where the peak number of collisions corresponded to about 30 on average. However, the increase in center-of-mass energy, with respect to the 7 TeV data taken in 2011, increases the signal production cross sections more than those of the backgrounds in all channels. The resulting increase in sensitivity of the analyses due to the increase in energy is equivalent to an increase in integrated luminosity of approximately 15–20%.

The data collected at the LHC until June 2012, which amounts to approximately 10 fb^{-1} taken at two centre-of-mass energies, is the dataset upon which all the experimental results discussed herein are based.

The LHC 2012 run will continue taking data until the end of December hopefully allowing to collect about 30 fb^{-1} per experiment. It will then enter a Long Stop period (LS1) extending approximately two years to consolidate the machine and allow for the high energy run to take place. The LHC will then ramp up its luminosity to the nominal 10^{34} cm^{-2}s^{-1}. It will take data until 2018, hopefully accumulating approximately 300 fb^{-1}, before entering a second long stop and hopefully a high luminosity era with the upgrade of the injector that will allow to reach integrated luminosities close to 3000 fb^{-1}. The latter part of the program is not yet approved.

The very high pile-up conditions in the 2012 LHC run are an invaluable benchmark to study the performance of the analyses after LS1. The ATLAS and CMS experiments are preparing an input to the Krakow meeting based on this knowledge to estimate the physics reach of the 2015-2018 run.

2.2 Discovery of a Narrow Resonance in the Search for the SM Higgs boson at the LHC

The SM Higgs boson is searched for at the LHC mainly in four exclusive production processes: the predominant gluon fusion $gg \to H$, the vector boson fusion $q\bar{q} \to Hq\bar{q}$, the associated production with a vector boson $q\bar{q} \to VH$ and the associated production with a top-quark pair $gg \to t\bar{t}H$. The main search channels are determined by five decay modes of the Higgs boson. The $\gamma\gamma$, $ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$. Various combination of W and Z-bosons subsequent decay modes are considered, with at least one decay to charged leptons or neutrinos.

Table 1: Summary of the individual Higgs boson search channels in the ATLAS and CMS experiments.

Channel	m_{H} range	L$_{2011}$ (fb^{-1})		L$_{2012}$ (fb^{-1})		ggH		VBF		VH		ttH	
		A	C	A	C	A	C	A	C	A	C	A	C
$H \to \gamma\gamma$	low	4.8	5.1	5.8	5.3	√	√	√	√	-	-	-	-
$H \to \tau^+\tau^-$	low	4.8	5.1	-	5.0	√	√	√	√	-	-	-	-
$H \to b\bar{b}$	low	4.8	5.1	-	5.0	√	√	√	√	-	-	-	√
$H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$	full	4.8	5.1	5.8	5.3	√	√	√	√	-	-	-	-
$H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$	full	4.8	4.7	-	5.3	√	√	√	√	-	-	-	-
$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$	high	4.8	4.7	-	-	√	√	√	√	-	-	-	-
$H \to ZZ \to \ell^+\ell^-q\bar{q}$	high	4.8	4.7	-	-	√	√	√	√	-	-	-	-
$H \to WW \to \ell\nu q\bar{q}'$	high	4.8	4.7	-	-	√	√	√	√	-	-	-	-

Both the ATLAS and CMS experiments observe an excess of events for a Higgs boson mass hypotheses near ∼125 GeV. The observed combined significances are around 5.0σ for both ATLAS and CMS, while the expected significances for a SM Higgs boson are 4.6σ and 5.9σ for ATLAS and CMS respectively. The lower sensitivity of the ATLAS searches is in part due to the smaller number of channels updated with the 2012 dataset, in particular the single most sensitive channel $H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$ and to a different analysis strategy in the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channel where the angular distribution of the leptons is not used by the ATLAS experiment.

Both observations are primarily done in the $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channels, where excesses of 4.5σ and 4.1σ are observed at Higgs boson mass hypotheses of 126.5 GeV and 125 GeV, in agreement with the expected sensitivities of around 2.5σ, in the ATLAS and CMS experiments respectively. In the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ channel, the significances of the excesses are 3.4σ and 3.2σ at Higgs boson mass hypotheses of 125 GeV and 125.5 GeV in the ATLAS and CMS experimentes respectively. The sensitivities at those masses are 2.6σ in ATLAS and 3.8σ in CMS respectively.

The other channels do not contribute significantly to the excess, but are nevertheless individually compatible with the presence of a signal.

The CMS experiment has produced a measurement of the mass of the narrow resonance yielding 125.3±0.3 (stat.) ±0.4 (syst.) GeV.

The mass range within which each channel is effective, the luminosity analysed in the ICHEP 2012 run, the production processes for which exclusive searches have been developped, are indicated in Table 1.

A detailed description of the Higgs search analyses can be found in references [**?**, **?**].

2.3 Supporting Evidence from TeVatron Experiments

The CDF and D0 experiments at Tevatron proton anti-proton collider have analysed the full statistics of about 10 fb^{-1} [**?**]. The main production mode is the associated production of a Higgs with a vector boson $q\overline{q} \rightarrow VH$, with the subsequent decay of the Higgs into a $b\bar{b}$ pair, and the gg-fusion production with the subsequent decay into two W boson than then decay leptonically ($H \rightarrow WW \rightarrow l\nu l\nu$). They exclude at 95% C.L. a SM Higgs boson with mass m_H between 147 and 180 GeV, and between 100 and 103 GeV. An excess with a local significance of 2.5σ is seen that might be interpreted as coming from a Higgs boson with a mass in the region of 115 to 135 GeV. An excess with a local significance of 2.9σ is seen in the combination of CDF and D's $H \rightarrow bb$ channels.

2.4 Brief Summary of LEP results

LEP run up to the year 2000, and during the last year at a center-of-mass energy of up to $\sim$ 209 GeV. The main results for SM searches were published in [**?**], and a SM-like Higgs boson was excluded up to 114.4 GeV at the 95% C.L. Less model dependent searches were published in [**?**], setting limits, for instance, on the relation of Higgs boson mass and the Higgs boson coupling to Z bosons. Especially, Higgs bosons with a substantially reduced coupling to Z bosons are allowed below the SM-limit of 114.4 GeV.

During the 11 years of running, the 4 experiments measured with high precisions the Z and W boson characteristics. Combining these results with the ones from SLD, CDF, and D0 experiments and assuming the Standard Model to be the correct theory of nature, the $\Delta\chi^2$ curve of the fit to the high-Q^2 precision electroweak measurements as a function of the Higgs-boson mass, gives as preferred value for the Higgs boson mass m_H=94 GeV, with an experimental uncertainty of +29 and -24 GeV (at 68%CL).

While this is not a proof that the Standard-Model Higgs boson actually exists, it does serve as a guideline in what mass range to look for it. The precision electroweak measurements tell us that the mass of the Standard-Model Higgs boson is lower than about 152 GeV (one-sided 95%CL). This limit increases to 171 GeV when including the LEP-2 direct search limit of 114.4 GeV.

2.5 Summary of the results

check numbers! The search results for a SM-like Higgs boson, obtained at LEP and the Tevatron are now complemented and superseeded by the Higgs boson searches at the LHC. A SM-like Higgs particle is excluded from $\sim$ 100 GeV (lower values were not considered so far) to 123 GeV, as well as from 127 GeV to about 600 GeV by ATLAS and CMS individually. In the remaining range both experiments show a clear excess of events that is roughly compatible with the expectations from a SM-like Higgs boson (a more detailed analysis can be found below). Consequently, for the further discussion on Higgs boson properties we assume

$$M_H = 125.0 \pm 1.0 \text{ GeV} , \tag{1}$$

Both experiments individually see an effect around 5σ. A combined analysis is so far not available.

Assuming that the $\sim 5\,\sigma$ excesses correspond to a new state the characteristics of this new particle have been analyses. The ATLAS and CMS data yields a signal cross section in agreement with the SM expectation:
$-\ \hat{\mu} = 1.2 \pm 0.2$ for ATLAS and $\hat{\mu} = 0.8 \pm 0.22$ for CMS The different final state are in agreement with the SM expectation within the limited statistics (**??**).

2.6 Spin and Charge Parity

A definite conclusion cannot be given on the fundamental quantum numbers of the observed narrow resonance. A few qualitative remarks can nevertheless be made.

1.- The observation is made mainly in the diphoton channel. Assuming that the observation is indeed made on a resonance of two photons (and not for instance two photons superposed as in the decay of a light scalar particle), the observed particle should be a boson and according to the Landau-Yang theorem its spin should be either 0 or 2.

2.- The high sensitivity of the $H \to WW^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$ analysis is based on the assumption that the Higgs boson is a CP even scalar boson ($J^{PC} = 0^{++}$). The observation in this channel is a little low, but consistent with the production of a Standard Model Higgs boson with a mass near 125 GeV.

3.- The CMS experiment has used in its $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ analysis a matrix element based variable assuming $J^{PC} = 0^{++}$, combining the information of the angular distribution of the four leptons. The statistics in the excess region is still too low to conclude but the observed distribution of the candidate events hints at a compatibility with $J^{PC} = 0^{++}$.

A complete analysis will be necessary to conclude.

2.7 Couplings

At this early stage of the observation of a new state, a precise analaysis of its couplings is impossible in particular since it has been observed predominantly in two channels (hgg and $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$) which are mostly driven by the gluon fusion production mode. It should however be noted that no significant deviation from the standard model couplings has been observed.

Electroweak symmetry breaking via the Higgs mechanism sets a well-defined ratio for the couplings of the Higgs boson to the W and Z bosons, g_{HWW}/g_{HZZ}, protected by the custodial symmetry. Under this assumption two free parameters c_V and c_F can be introduced and fitted. The first, c_V, scales the standard model Higgs boson couplings to the W and Z bosons, while preserving their ratio. The other, c_F, scales all couplings to fermions by one constant factor. At LO, all partial widths, except for $\Gamma_{\gamma\gamma}$, scale either as c_V^2 or c_F^2. The partial width $\Gamma_{\gamma\gamma}$ is induced via loop diagrams, with the W boson and top quark being the dominant contributors; hence, it scales as $|\alpha\, c_V + \beta\, c_F|^2$, where factors $\alpha(m_H)$ and $\beta(m_H)$ are taken from predictions for the SM Higgs boson [**?**]. Then, the event yield in any production×decay mode can be easily rescaled for any $c_V \neq 1$ and/or $c_F \neq 1$, starting from the following equation:

$$N(xx \to H \to yy) \sim \frac{\Gamma_{xx}\,\Gamma_{yy}}{\Gamma_{\text{tot}}}. \tag{2}$$

In this equation Γ_{tot} is also a function of c_V and c_F; it is calculated as the sum of the rescaled partial widths. The c_V and c_F re-scaling factors do not represent any particular physics model and serve the sole purpose of testing the compatibility of the observation with the standard model Higgs boson hypothesis. The 2D likelihood scan and the 68% and 95% confidence regions for c_V and c_F are shown in [**?**]. In this scan, c_V and c_F are constrained to be positive. The reached precision with 5 fb^{-1} at 7 TeV and 5 fb^{-1} at 8 TeV are 20-30%. More statistics is needed to add more coupling modifiers (as an example splitting the fermions in up and down type, and then adding the specific flavour and eventually a coupling to invisible particles),

3 Interpretation of the Higgs boson search results

After the observation of a new resonance at the LHC the next goal is to measure its characteristics (mass, width, branching ratios, couplings, …). Only if the profile agrees completely (within sufficiently small experimental errors) with that predicted for a SM Higgs boson, one could be convinced that the SM Higgs mechanism is realized in nature.

We assume here the mass measurement as given in Eq. (1).

3.1 Effective theory approach

A convenient way to test the compatibility with the SM and possible new physics scenarios is making use of an effective theory. It allows us to capture the most general interaction of the Higgs with matter fields and gauge bosons in a systematic way. A convenient framework is to use the a chiral EW Lagrangian of the Goldstone bosons $\Sigma(x) = e^{i\sigma_a \pi^a/v}$ and the a scalar field h (see e.g. Giudice:2007fh ...)

$$\begin{aligned}\mathcal{L}_{eff} &= \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left[1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots\right], \\ &\quad -\frac{v}{\sqrt{2}}\,(\bar{u}^i_L \bar{d}^i_L)\,\Sigma\left[1 + c_j\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y^u_{ij}\,u^j_R \\ y^d_{ij}\,d^j_R \end{pmatrix} + h.c.\cdots, \qquad (3)\end{aligned}$$

with $V(h) = \frac{1}{2}\,m_h^2\,h^2 + \frac{d_3}{6}\,(\frac{3\,m_h^2}{v})\,h^3 + \frac{d_4}{24}(\frac{3m_h^2}{v^2})h^4 + \cdots$. The leading contribution of new heavy states with masses above a scale Λ can be included by adding the higher dimensional operators

$$\mathcal{L}_{HD} = -\frac{c_g\,g_3^2}{2\,\Lambda}\,h\,G^A_{\mu\nu}G^{A\,\mu\nu} - \frac{c_\gamma\,(2\,\pi\,\alpha)}{\Lambda}\,h\,F_{\mu\nu}F^{\mu\nu}, \qquad (4)$$

- discuss current status (CV vs. CF plot of CMS?). Compatibility with SM
- add disclaimer : custodial symmetry, positive-parity assumed, invisible width
- limit on composite Higgs, extended Higgs sectors, light Higgs, dilaton, pure femiophobic Higgs
- Higgs imposters

3.2 Interpretation as a non-SM Higgs boson

Despite the fact that the results shown in Sect. **??** are compatible with a SM-like Higgs boson, the results can also be interpreted in other models. Many models with an extended Higgs sector possess one Higgs boson that is SM-like, i.e. it fits the results in Tabs. **??**, **??** as well as the SM Higgs boson.

- To which models does it fit?
  → many contributors … (MSSM, NMSSM, exotics?)
- Heavier SUSY Higgs bosons?
  (This seems trivial and c/should be included above?)
- Impact on other models?
  General coupling fits?
- …

3.3 Compatibility with non-SM-like Higgs bosons at other mass scales

The error bars in Tabs. **??**, **??** are still very large and leave room for a Higgs particle whos couplings deviate substantially from a SM Higgs boson.

- Light SUSY Higgs bosons?
  Interpretation of the 124.5 GeV excess as "another" SUSY Higgs!
  → many contributors . . . (MSSM, NMSSM, exotics?)
- A very heavy SM-like Higgs?
  → Giampiero et al.?
- . . .

4 From the LHC to terascale physics

The LHC running at high(er) luminosity (subsequently called $\text{LHC}_{300/\text{fb}}$, assuming the collection of $\sim$ 300 fb^{-1} per detector at 13 – 14 TeV) will follow within the next years, expanding the knowledge about the Higgs sector. In this section we will analyze what can be gained from future colliders in the various scenarios beyond what is anticipated from the $\text{LHC}_{300/\text{fb}}$. As future colliders, we discuss in some detail HL-LHC [**?**], the ILC [**?**] and CLIC [**?**] as well as an e^+e^- circular collider with an energy of up to about $\sqrt{s} \sim 240$ GeV (LEP3).

Other options could be an LHC running at 33 TeV (HE-LHC), see Ref. [**?**] and references therein, and a VLHC (Very Large Hadron Collider), with an energy of $\sqrt{s} = 40 - 200$ TeV [**?**, **?**]. More information can also be found in Refs. [**?**, **?**]. At the moment it seems unclear which energy reach would be required for auch a machine. The physics case for exploring the multi-TeV range in this way could emerge from discoveries at the $\text{LHC}_{300/\text{fb}}$ and a future linear collider. In view of the discovery of a new state at $\sim$ 125 GeV the measurement of its tri-linear coupling could be of interest. Similarly, the HE-LHC could also be useful for probing the mechanism unitarizing the WW scattering cross section. → check existing studies

Another option for future accelerators could be a $\mu^+\mu^-$ collider [**?**, **?**], with an energy of $\sqrt{s} \sim M_H$. At a $\mu^+\mu^-$ collider, with an integrated luminosity of $\mathcal{L}^{\text{int}} \lesssim 10\,\text{pb}^{-1}$ an ultra-precise measurement of a Higgs boson mass and width would be possible [**?**] and coupling measurements up to the same level as at the ILC could be performed. The $\mu^+\mu^-$ collider could thus help to determine the Higgs profile. In the following, however, we will not discuss the physics capabilities of a HE-LHC, VLHC or a $\mu^+\mu^-$ collider, as the technical feasibility studies are in very preliminary stages. Those kind of studies are further advanced for an electron proton collider using the LHC proton beam (LHCeC). The physics potential of this machine for exploring electroweak symmetry breaking are, however, restricted to a possible investigation of Higgs production in weak boson fusion, i.e. competing with the physics potential of the $\text{LHC}_{300/\text{fb}}$.

In the following we discuss the physics potential of the $\text{LHC}_{300/\text{fb}}$, HL-LHC, ILC, CLIC and LEP3 in view of the experimental situation outlined in Sect. **??**, in particular in view of the recent discovery of a new particle at $\sim$ 125 GeV compatible with a SM-like Higgs boson.

$\underline{\text{LHC}_{300/\text{fb}}\text{:}}$
Going to the $\text{LHC}_{300/\text{fb}}$ will allow the observation of a Higgs boson candidate in more production and decay modes compared to the LHC. This will yield a better determination of ratios of partial widths as well as absolute couplings.

If we assume that the total uncertainty for each analyzed channel will scale with the luminosity, we can get an estimate of the precision with which we can measure the different cross section times branching ratios as in table **??**. After 300 fb^{-1} at 13 TeV, we precision for ggF and subsequente H decay to fermions will be of the order of 10%, and 5% for the decay into bosons. The VBF Higgs production and subsequent decay to boson will be of 10% precisions and 15% for fermionic decays. Combining all these measurements into a C_V and C_F fit, the two coupling modifiers can be estimated at the 1-2% level. This could mean that each individual coupling can be estimated at a 2-3% precision.

Table 2: Examples of the precision of SM-like Higgs observables at the LHC at $\sqrt{s} = 14 TeV$ assuming a Higgs mass of 125 GeV. For the direct measurements, an integrated luminosity of $\mathcal{L}^{\rm int} = 300$ fb^{-1} is assumed.

Decay	Prod	$60 fb^{-1}$ at 8 TeV	$300\ fb^{-1}$ at 14 TeV
$H \to bb$	VH	30%	10 %
$H \to bb$	ttH	60%	10 %
$H \to \tau\tau$	ggH	40%	10 %
$H \to \tau\tau$	qqH	40%	10 %
$H \to \gamma\gamma$	ggH	20%	6 %
$H \to \gamma\gamma$	qqH	40%	10 %
$H \to WW$	ggH	16%	5 %
$H \to WW$	qqH	60%	16 %
$H \to ZZ$	ggH	16%	5 %

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Several studies for the measurement of the tri-linear Higgs coupling, g_{HHH}, have been performed, assuming $M_H \gtrsim 140$ GeV with $H \to WW^{(*)}$ as the dominant decay mode [**?**, **?**, **?**]. The studies conclude that at the LHC$_{300/\rm fb}$ a determination of g_{HHH} will not be possible.

With a larger data sample the spin and $\mathcal{CP}$ quantum numbers can be inferred from the angular distributions of the leptons in the $H \to ZZ \to 4\ell$ decay mode and in the $WW \to l\nu l\nu$ mode and in the $\gamma\gamma$ final state ...

HL-LHC:

The HL-LHC is a luminosity upgrade of the LHC which aims for an ultimate luminosity of 1000 fb^{-1}/year sometime after 2018. Assuming that the detector capabilities remain roughly the same as those anticipated for the LHC, the HL-LHC [**?**] will increase the discovery potential for high mass objects by $25 - 40\%$.

By the time the HL-LHC is realized, the Higgs discovery phase at the LHC will be largely completed. For processes which are limited by statistics at the LHC, the HL-LHC may be useful. The increased luminosity of the HL-LHC could enable the observation of rare Higgs decays. The HL-LHC could also potentially increase the accuracy of the measurements of Higgs couplings. There might be some sensitivity on the tri-linear Higgs self-coupling [**?**]; however, some background contributions might have been underestimated. Further studies to clarify these issues are currently in progress, see Ref. [**?**] for a discussion. A key concern is maintaining detector performance, since the increased luminosity will result in significantly more pileup per beam crossing, increasing occupancy rates in the tracking systems.

ILC:

The following details are based on DBD, hep-ph/1207.2516 (Peskin) and Le Diberder panel. The initial stage of the ILC is expected to have an energy of up to $\sqrt{s} = 500$ GeV with a luminosity of 2×10^{34}/cm^2/s, along with 90% polarization of the e^- beam and $30 - 45\%$ polarization of the e^+ beam. A future upgrade up to $\sqrt{s} = 1$ TeV or $\sqrt{s} = 1.5$ TeV (with an even higher luminosity) is envisioned. An advantage of the machine is that it is designed to have low beamstrahlung and a precise knowledge of the luminosity ($\delta\mathcal{L}/\mathcal{L} < 10^{-3}$) and energy ($(\delta\sqrt{s})/\sqrt{s} < 200$ ppm), along with excellent detector resolution. The tunable energy scale allows for a scan of particle thresholds.

The ILC offers a clean environment for the precision measurement of all quantum numbers, $\mathcal{CP}$-properties and couplings of the Higgs boson, in addition to precision measurements of its mass and width. The Higgs-strahlung process provides the opportunity to study the couplings of the new state in a *model independent* way. From the Higgs-strahlung process near threshold an absolute measurement of

Table 3: Examples of the precision of SM-like Higgs observables at a $\sqrt{s} = 500$ GeV ILC assuming a Higgs mass of 120 GeV. Very similar results are expected for a Higgs mass of ~ 125 GeV. For the direct measurements, an integrated luminosity of $\mathcal{L}^{\rm int} = 500\ {\rm fb}^{-1}$ is assumed (except for the $t\bar{t}$ channel, which assume $\sim 1\ {\rm ab}^{-1}$ at $\sqrt{s} = 800$ GeV). For the indirect measurements at GigaZ, a running time of approximately one year is assumed, corresponding to $\mathcal{L} = \mathcal{O}(10\ {\rm fb}^{-1})$. Will be updated with latest numbers from DBD, hep-ph/1207.2516 (Peskin) and Le Diberder panel.

Observable	Expected precision	Reference
SM-like Higgs with $M_H \approx 125$ GeV		
M_H [GeV]	0.04 %	[?]
Γ_H [GeV]	0.056 %	[?]
g_{HWW}	1.2 %	[?]
g_{HZZ}	1.2 %	[?]
g_{Htt}	3.0 %	[?]
g_{Hbb}	2.2 %	[?]
g_{Hcc}	3.7 %	[?]
$g_{H\tau\tau}$	3.3 %	[?]
g_{Htt}	7 %	[?]
g_{HHH}	22 %	[?]
BR($H \to \gamma\gamma$)	23 %	[?]
$\mathcal{CP}_H$	4.7σ diff. between even and odd	[?]
GigaZ Indirect M_H [GeV]	7 %	[?]
Additional Measurements for Non-SM Higgs with $M_H \approx 120$ GeV		
BR($H \to$ invisible)	< 20 % for BR> 0.05	[?]

the cross section can be perfromed from the recoil of the Higgs against the Z boson (using $Z \to \mu^+\mu^-$ or $Z \to e^+e^-$) without having to consider the actual pattern of the Higgs decay. At higher center-of-mass energies the weak boson fusion process dominates over the Higgs-strahlung channel, providing a high statistics and accordingly high precisions. A summary of the anticipated accuracies for Higgs boson couplings for $M_H \sim 125$ GeV is given in Tab. **??**

The per-cent level accuracies reachable at the ILC for the couplings to gauge boson and light fermions are expected to be crucial for identifying the underlying physics of electroweak symmetry breaking, as typical deviations from a SM-like behavior are expected to manifest themselves at this level. Give example? The accuracy reachable at the LHC, which is typically an order of magnitude lower, on the other hand, provides only a limited sensitivity. Center-of-mass energies of 500 GeV or above will be essential to measure the top Yukawa coupling, which has a high sensistivity to potential effects of new physics. Similarly, the measuremet of the trilinear Higgs self-coupling, which will be a crucial ingredient in establishing the Higgs mechanism, becomes feasible at $\sqrt{s} = 500$ GeV and above.

One particular strength of the ILC is that the total width can be measured in a model independent way (i.e. without additional theoretical assumptions, which are necessary for a determination of the total width at the LHC). The measurements at the ILC will allow in particular a high precision determination of invisible decay modes of a Higgs boson (and also of decay modes that are undetectable at the LHC). The investigation of invisible Higgs decay modes could offer the exciting opportunity of Dark Matter production in Higgs decays.

The ILC also has unique capabilities for determining the $\mathcal{CP}$ properties of the observed state. Since the new state can a priori be an arbitrary admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components, the determination of the $\mathcal{CP}$-properties is experimentally much more challenging than the measurement of the spin, which essentially only needs to discriminate between the spin 0 and spin 2 hypotheses. The observables relate to Higgs decays into ZZ^* and WW^* at the LHC as well as to Higgs production in weak boson fusion at the LHC project out the $\mathcal{CP}$-even components of the Higgs. They are therefore insensitive to discriminating a pure $\mathcal{CP}$-even state from an admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components. At the ILC the $\mathcal{CP}$-properties of the new state can be determined with high precision and in an unambigous way from the top Yukawa coupling, in particular via the threshold behavior of $e^+e^- \to t\bar{t}H$. This provides the potential for a precision measurement of $\mathcal{CP}$-mixing even if it is small. The spin of the new state can be determined unambigously from measuring the threshold behavior of the Higgs-strahlung cross section as well as from angular distributions of $H \to ZZ^*$.

The observation of a Higgs-like state at ~ 125 GeV provides a strong motivation for searching for additional non-SM-like Higgs bosons, which would be an unambigous proof of an extended Higgs sector. Additional Higgs bosons of such extended Higgs sectors can either be heavier than the state observed at 125 GeV, but there exists also the possibility that the state at 125 GeV is in fact the second lightest Higgs in the spectrum. The latter possibility would imply the exisitence of a lighter Higgs state, possibly below the LEP limit for a SM-like Higgs with reduced couplings to gauge bosons in accordance with the search limits from LEP, the Tevatron and the LHC. The ILC offers excellent prospects for the discovery of such additional states, where for the low-mass region a substantial improvement with respect to LEP is expected. For the high-mass region, on the other hand, Higgs states can be pair-produced up to half the ILC center-of-mass energy. A larger reach woud be achieved in the s-channel production of such a heavy Higgs at the $\gamma\gamma$ option of the ILC, where $\sim 0.8\sqrt{s}$ can be reached. Combining ILC and $\gamma\gamma$ measurements, the $H\gamma\gamma$ coupling could be determined at the level of $\sim 3\%$.

Additional sensitivity to physics of electroweak symmetry breaking is provided by the high precision measurements at the GigaZ option at the ILC (10^9 Z's at $\sqrt{s} \approx M_Z$) [**?**, **?**], and by the WW threshold [**?**]. These measurements allow precision tests of the SM with uncertainties reduced approximately by one order of magnitude from the predictions of current ILC studies. As an example, this would allow the mass of the SM Higgs boson to be constrained quite tightly by indirect methods, to be compared with the direct measurement of ~ 125 GeV.

High precision measurements at higher energies, in particular $e^+e^- \to W^+W^-$ and $e^+e^- \to \nu_e\bar{\nu}_e W^+W^-$ provide a high sensitivity to the mechanism that unitarizes these processes in this energy regime. In case that the Higgs state at ~ 125 GeV is composite, these measurements could reveal effects of new strong resonances.

CLIC:

→ to be extended

CLIC is proposed as a multi-TeV e^+e^- collider with an energy of up to $\sqrt{s} \sim 3$ TeV and a luminosity of $\mathcal{L} \sim 10^{34}$/cm^2/s. While the CLIC technology requires further R&D, the CLIC Conceptual Design Report, outlining the physics prospects, has just been released.

The physics capabilities of CLIC in the energy range of $0.5 - 1$ TeV are similar to those of the ILC, as described above. We will concentrate in the following on the additional information that can be obtained from $1 - 3$ TeV. With a higher center-of-mass energy of CLIC the discovery reach for additional heavy Higgs bosons is extended with respect to the ILC. The high statistics of the weak boson fusion production of a light Higgs at the high center-of-mass energies of CLIC permit the measurement of rare decay modes such as $H \to \mu^+\mu^-$ or the triple Higgs coupling, as summarized in Tab. **??**.

The higher center-of-mass energy also useful for testing the mechanism unitarizing the WW scattering cross section. As an example, at CLIC with 3 TeV and 1ab^{-1} a compositeness scale of up to 60 TeV can probed.

LEP3:

The measurements of the state observed at ~ 125 GeV that are possible at the ILC with a center-of-mass energy below ~ 250 GeV could also be performed in a similar fashion at LEP3, provided that the beam

Table 4: Examples of the precision, $\delta g_{Hxx}/g_{Hxx}$, for measurements of Higgs couplings at a $\sqrt{s} = 3$ TeV CLIC with 3 ab^{-1} [**?**, **?**]

coupling	g_{HWW}	g_{Hbb}	g_{Hcc}	$g_{H\mu\mu}$
precision	$\leq 2\%$	2%	2%	7.5%

energy spread can be kept at a similarly low level at the ILC and that similar luminosities can be reached. Since this machine is not extendable to higher energies measurements requiering higher center-of-mass energies, such as top Yukawa coupling or the trilinear Higgs self-coupling are not possible.

5 Conclusions

The LHC is currently exploring the mechanism responsible for electroweak symmetry breaking. Assuming that a new state as a possible candidate for a Higgs boson is being observed at the LHC, the full identification of the mechanism of electroweak symmetry breaking will require to measure all its characteristics. This comprises an accurate mass determination, a (model-independent) measurement of its individual couplings to other particles, a determination of the self-couplings to confirm the “shape” of the Higgs potential, as well as measurements of its spin and $\mathcal{CP}$-quantum numbers . At the LHC, even running at high luminosity, these measurements will only partially be possible.

We reviewed the current status of Higgs boson searches at the LHC (and other colliders). Based on the excess of Higgs-like events around 125.0 ± 1.0 GeV we investigated the capabilities of future colliders to further unravel the Higgs mechanism.

While the HL-LHC will be able to extend the reach and precision of the LHC$_{300/\mathrm{fb}}$ it seems clear that a full exploration of the Higgs sector will require either the ILC or CLIC.

6 References