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

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Abstract

The recent discovery of a Higgs-like state at the LHC with a mass near 125 GeV has opened a new era of particle physics. It will be of utmost importance to precisely determine the properties of this new state, with the aim to identify the mechanism of electroweak symmetry breaking (EWSB). This will require a comprehensive programme of high-precision measurements. Further measurements are also important in this context, in particular searches for manifestations of extended Higgs sectors, searches for new particles, and an improvement of electroweak precision measurements such as the mass of the top quark and the W boson as well as the effective weak leptonic mixing angle and triple gauge couplings. Finally the study of longitudinal vector boson scattering up to the highest energy scales is one of the key methods to discriminate between models and to reveal the nature of the symmetry breaking. The current experimental status of exploring the physics of electroweak symmetry breaking is briefly summarised, based on the results achieved at the LHC and elsewhere. The implications of the present and possible future results from the LHC for the physics programme of proposed future colliders are discussed.

1 Introduction

On July 4 2012, 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 the expectations for the Higgs boson of the SM. Less significant but nevertheless supporting evidence was also found by the TeVatron experiments. Despite the clear evidence of the production of a new particle fully consistent with a SM-like Higgs boson, its nature still needs to be firmly elucidated and its role in the mechanism of electroweak symmetry breaking (EWSB) needs to be explored. Although these recent results are a milestone, identifying in detail the complete nature of EWSB is a much broader and more challenging experimental endeavour. In order to identify the recently discovered particle as a Higgs boson, it is necessary to establish that it is the excitation of a field whose vacuum expectation value breaks the electroweak symmetry and determine its role in the unitarisation of $W_L W_L$ scattering. Furthermore it will be crucial to determine whether the EWSB sector is complete with the state discovered near 125 GeV or whether there are further states related to EWSB, such as additional states of an extended Higgs sector.

In order to identify the underlying physics associated with the new state a complete experimental profile of the newly discovered particle with high precision is needed:

- The spin of the particle must be zero or else the field cannot have a vacuum expectation value.
- The determination of its $\mathcal{CP}$ properties is a crucial part of the experimental programme that could reveal possible deviations from SM-like behaviour. $\mathcal{CP}$ violation in the Higgs sector could be important in the context of the asymmetry between matter and anti-matter.

- The mass, which within the SM is a free parameter that is indirectly constrained by electroweak precision data. In theories beyond the SM the mass of the corresponding Higgs boson is often directly predicted in terms of the other model parameters, so that the measurement of the mass enables a non-trivial test of relations of the model.
- The couplings to vector bosons are crucial to validate the mechanism of EWSB and to restore the $W_L W_L$ scattering unitarity at high energy. These features are important for distinguishing between different possible EWSB mechanisms.
- The couplings to fermions are crucial to test whether the mass generation of the fermions happens via Yukawa couplings. Together with the couplings to the gauge bosons the couplings to fermions test the fundamental prediction of the Higgs mechanism that the Higgs boson couplings to all other particles should be proportional to their masses.
- Structure of the EWSB sector — is the observed state compatible with the interpretation of a single doublet of complex scalar fields or are there indications for further states related to EWSB, for instance additional particles of an extended Higgs sector? Clearly, searches for additional Higgs bosons, which may be heavier but also lighter than the observed state at about $125\ \mathrm{GeV}$, are crucial in this context.
- The trilinear self interaction of the observed state is indispensable to gain experimental access to the Higgs potential.
- Elementary or composite? Information on this question can be obtained both from high-precision measurements of the Higgs couplings and from investigating the $W_L W_L$ scattering cross section where a new kind of strong interaction giving rise to a composite nature of the observed state at about $125\ \mathrm{GeV}$ could result in a rising cross-section and possible new resonances.

A broader question about the recently discovered state is related to its naturalness. The mass of a scalar particle is unprotected against quadratic divergencies, so that the observation of a fundamental scalar with a mass of about $125\ \mathrm{GeV}$ would either require additional new physics, such as supersymmetric partners to the SM fields, or an enormous level of fine-tuning. The precise measurements of the properties of the observed narrow resonance could shed light on this fundamental issue, which is at the heart of fundamental physics since several decades.

In the following, the present experimental status and the capabilities of the LHC (with its projected performance and possible extensions) and of future colliders to determine the properties of the new particle discovered [1], and to fully unravel the mechanism responsible for electroweak symmetry breaking, are discussed.

2 Discovery of a New Particle in the Search for the SM Higgs Boson at the LHC

2.1 Current results from the LHC

In 2011, the LHC delivered an integrated luminosity of slightly less than 6 fb^{-1} of proton-proton (pp) collisions at a centre-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 centre-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 20 on average. However, the increase in centre-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 results discussed herein are based on data collected at the LHC until June 2012. This dataset amounts to approximately $10 - 11$ fb^{-1} of pp collision data taken at two centre-of-mass energie ($7 -$

[1] For the sake of coherence, the observed new particle will often be referred to as a Higgs boson, not necessarily of the SM.

8 TeV). The LHC 2012 *pp* run will continue taking data until the end of December hopefully allowing the collection of 30 fb^{-1} per experiment. In March 2013 LHC 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 2021, hopefully accumulating approximately 300 fb^{-1}, before entering a second long stop which could lead to a high luminosity era with the upgrade of the injector, which would make it possible to reach integrated luminosities close to 3000 fb^{-1}. The latter part of the programme is not yet approved. A more complete description of the provisional timeline is given in Sec. 4.1. The very high pile-up conditions in the 2012 LHC run are an invaluable benchmark to study the performance of the analyses after LS1. Based on this, the ATLAS and CMS collaborations have prepared physics performance projections [1–3] in the context of the LHC future running scenarii.

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

A SM-like 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 $\tau^+\tau^-$ channels. Various combinations of W and Z-bosons subsequent decay modes are considered, with at least one decay involving a charged lepton. The mass range within which each channel is effective, the luminosity analysed up to ICHEP 2012, and the production processes for which exclusive searches have been developed are indicated in Table 1. A detailed description of the Higgs search analyses can be found in references [4, 5].

Table 1: Summary of the individual Higgs boson search channels in the ATLAS and CMS experiments. The Higgs boson hypothesis mass range and the integrated luminosities of the datasets analyzed are indicated. The $\surd$ symbol is used to indicate for each individual channel if an explicit exclusive search for the associated (with a vector boson or a top quar pair) or VBF production processes is done.

Channel	$m_{\rm H}$ range (GeV)	L$_{2011}$ (fb^{-1})		L$_{2012}$ (fb^{-1})		ggH		VBF		VH		ttH	
		A	C	A	C	A	C	A	C	A	C	A	C
$H \to \gamma\gamma$	110-150	4.8	5.1	5.9	5.3	$\surd$	$\surd$	$\surd$	$\surd$	-	-	-	-
$H \to \tau^+\tau^-$	110-140	4.7	5.1	-	5.0	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	-
$H \to b\bar{b}$	110-130	4.6	5.1	-	5.0	-	-	-	-	$\surd$	$\surd$	-	$\surd$
$H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$	110-600	4.8	5.1	5.8	5.3	$\surd$	$\surd$	-	-	-	-	-	-
$H \to WW^{(*)} \to \ell^+\nu\ell^-\bar{\nu}$	110-600	4.7	4.7	5.8	5.3	$\surd$	$\surd$	$\surd$	$\surd$	-	$\surd$	-	-
$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$	200-600	4.8	4.7	-	-	$\surd$	$\surd$	$\surd$	$\surd$	-	-	-	-
$H \to ZZ \to \ell^+\ell^- q\bar{q}$	130-600	4.8	4.7	-	-	$\surd$	$\surd$	$\surd$	$\surd$	-	-	-	-
$H \to WW \to \ell\nu q\bar{q}'$	300-600	4.8	4.7	-	-	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	-	-	-

Both the ATLAS and CMS experiments observe an excess of events for Higgs boson mass hypotheses near $\sim$125 GeV. The observed combined significances are 5.9σ for ATLAS [6] and 5.0σ for CMS [7] compatible with their respective sensitivities. Both observations are primarily done in the $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channels. For the $H \to \gamma\gamma$ channel 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. For the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ 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 expected 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 statistical analysis in both experiments use as parameter of interest the signal strength, μ, which acts as a scale factor to the total rate of signal events. The signal strength is defined as the ratio of the overall signal cross section in each channel to its SM expectation; the combination of channels employs a common strength parameter. The best fit values of the μ measured in both experiments are $\hat{\mu} = 1.4 \pm 0.3$ for ATLAS at a Higgs boson mass hypothesis of 126 GeV and $\hat{\mu} = 0.87 \pm 0.23$ for CMS for a Higgs boson mass of 125 GeV. The observed $\hat{\mu}$ in the combination and in the different final states are in agreement with the SM Higgs boson expectation. [4, 5].

The ATLAS and CMS experiments have also reported compatible measurements of the mass of the observed narrow resonance yielding:

$$126.0 \pm 0.4 \text{ (stat.) } \pm 0.4 \text{ (syst.) GeV (ATLAS).}$$
$$125.3 \pm 0.3 \text{ (stat.) } \pm 0.4 \text{ (syst.) GeV (CMS).}$$

2.3 Supporting Evidence from TeVatron Experiments

The CDF and D0 experiments at the TeVatron proton anti-proton collider have analysed the full statistics of about 10 fb^{-1} [8]. The main production mode is the associated production of a Higgs with a vector boson $q\overline{q} \to VH$, 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 bosons which then decay leptonically ($H \to WW \to l\nu l\nu$).

The Tevatron experiments have recently reported an excess of events in the mass region 115-140 GeV with a local significance of approximately 3.0 σ [8]. This excess was seen mostly in the $H \to b\bar{b}$ channel.

2.4 Exclusion Limits and Searches for Additional States

At the LHC, as shown in Table 1, the SM Higgs boson has been searched for in various channels to efficiently cover all Higgs boson mass hypotheses between 110 GeV and 600 GeV. This result completes a long history of searches for the Higgs boson which have covered all Higgs boson mass hypotheses up to 114 GeV. The latter is the stringent limit set by the experiments at LEP [9], which ran up to the year 2000 reaching a centre-of-mass energy of up to ~ 209 GeV.

At LEP, the Tevatron and at the LHC an extensive program of additional analyses searching for non standard Higgs boson decays has been developped. For instance in the context of the MSSM and NMSSM, searches for a pseudo-scalar Higgs bosons, using tau-leptons, muons and b-quarks in the final state have been performed; charged MSSM Higgs, for a low mass Higgs produced in top quark decays. Fermiophobic models and the SM with a fourth fermion generation have also been investigated; more exotic signatures have also being searched for, including doubly charged Higgs, Higgs decaying to long lived particles and Higgs decaying to light pseudo-scalar particles. An exhaustive review of exotic Higgs boson searches is beyond the scope of this report, however it should be noted that most possible production and decays modes have been investigated, so far only the searches for the Standard Model Higgs boson have succesfully observed a clear signal.

2.5 Constraints from electroweak precision data

Precision measurement in general, and the electroweak precision data in particular, allow to explore new physics at higher scales then the natural scale of the experiment through loop corrections. Observables measured at LEP, the SLC, the TeVatron and at lower energy experiments together with accurate theory predictions enable stringent tests of the electroweak sector. In particular a global fit within the SM, where the Higgs-boson mass is a free parameter, gives as preferred value of m_H=94 GeV, with an experimental uncertainty of +29 and -24 GeV (at 68%CL) [10]. The (one-sided) 95% CL upper limit is about 152 GeV. Thus, the observation of a Higgs-like state with a mass of about 125 GeV is well compatible with this indirect prediction within the SM.

2.6 Spin and Charge Parity ($\mathcal{CP}$)

A definite conclusion cannot be drawn on the fundamental quantum numbers of the observed narrow resonance for the time being, some 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 $\mathcal{CP}$ even scalar boson ($J^{PC} = 0^{++}$). The observation in this channel is 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 current dataset is not large enough to draw definite conclusions, but the observed distribution of the candidate events hints at compatibility with $J^{PC} = 0^{++}$.

A complete analysis will be necessary to conclude, but preliminary studies show that with the amount of data that will be accumulated at 8 TeV it will be possibile to separate a scalar from a spin 2 state at the 4σ level. The situation is much more difficult concerning the $\mathcal{CP}$-properties of the observed state. Firstly, the new state can a priori consist of any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components. Secondly, the observables considered at the LHC, namely Higgs boson decays into ZZ^* and WW^* as well as Higgs boson production in weak boson fusion all involve the Higgs boson coupling to two gauge bosons. For a wide class of models beyond the SM, including for instance extended Higgs sectors based on the most general Two-Higgs-Doublet models with $\mathcal{CP}$-violation, a tree-level coupling of a $\mathcal{CP}$-odd state to two gauge bosons is forbidden. In these classes of models a deviation from the behaviour expected for a $\mathcal{CP}$-even state could only occur as a loop-suppressed effect, which in general is expected to give rise only to small modifications of the angular dependence. The sensitivity of the considered observables for resolving effects of a $\mathcal{CP}$-odd behaviour are therefore rather limited, even in a situation where the newly discovered state would in fact contain a large admixture of a $\mathcal{CP}$-odd component. If one restricts to a test of only the two distinct hypotheses of a pure $\mathcal{CP}$-even or a pure $\mathcal{CP}$-odd state (the fact that the observed state has been detected via its decay into ZZ^* already rules out the possibility of a pure $\mathcal{CP}$-odd state in many scenarios of BSM physics, conversely a reduced WW and ZZ couplings would also be a sign of a $\mathcal{CP}$ odd component), by the end of the 8 TeV run a 3.5σ separation between the hypotheses of a pure $\mathcal{CP}$-even and a pure $\mathcal{CP}$-odd state could be reached.

2.7 Couplings

At this early stage of the observation of a new state, a precise analysis of its couplings is impossible in particular since it has been observed predominantly in two channels ($H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$) which are mostly driven by the gluon fusion production mode. No significant deviation from the SM couplings has been observed up to now.

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 custodial symmetry. Under this assumption the Higgs boson couplings to WW and ZZ can be expressed in terms of a common free parameter, c_V. If also the couplings to all fermions are assumed to be scaled with a common factor c_F, all tree-level Higgs boson couplings to fermions and gauge bosons can be expressed in terms of these two parameters ($c_V = c_F = 1$ corresponds to the SM case). Making the additional non-trivial assumptions that the loop-induced couplings Hgg and $H\gamma\gamma$ receive no additional contributions besides the ones from SM particles and that the Higgs boson does not decay into invisible (such as particles not interacting or interact only very weakly in the detector) or indiscernible (such as colored particles which cannot be distinguished in the overwhelming background) decay modes, all partial widths, except for $\Gamma_{\gamma\gamma}$, scale either as c_V^2 or c_F^2 at LO. The partial width $\Gamma_{\gamma\gamma}$ receives dominant contributions at LO from a W-boson loop and a top-quark loop, and hence scales as $|\alpha\, c_V + \beta\, c_F|^2$. The factors $\alpha(m_H)$ and $\beta(m_H)$ are taken from predictions for the SM Higgs boson [11]. Under these assumptions, using the narrow width approximation, the event yield in any production$\times$decay mode as compared to the SM case can be expressed in terms of the two parameters c_V and c_F, starting from the following expression:

$$N(ii \to H \to ff) \sim \frac{\Gamma_{ii}\,\Gamma_{ff}}{\Gamma_{\rm tot}}. \tag{1}$$

Here $\Gamma_{\rm tot}$ is also a function of c_V and c_F and $ii \in \{gg, W^+W^-, ZZ, t\bar{t}\}$ and $ff \in \{\gamma\gamma, b\bar{b}, \tau^+\tau^-, W^+W^-, ZZ\}$; it is calculated as the sum of the rescaled partial widths of the Higgs boson decays into SM particles. 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 SM Higgs boson hypothesis. 7 TeV and 5 fb^{-1} at 8 TeV on c_V and c_F is 20-30%. More data is needed for obtaining sensitivity to parametrisations with more coupling modifiers (*e.g.* splitting the fermions into up and down type, and then adding the specific flavour and eventually additional contributions to the loop-induced couplings and a coupling to indiscernible particles).

3 Phenomenological Framework of EWSB and Interpretation of the Recent LHC Data

The SM of electroweak and strong interactions describes (nearly) all experimental data with high precision. A cornerstone of the SM is the Higgs mechanism to give masses to the $W^\pm$ and Z bosons as well as to the fermions. Furthermore, a Higgs boson is needed for a perturbative unitarization of the $W_L W_L$ scattering amplitude at high energies. As outlined in Sect. 2.4 the SM is consistent with a low mass Higgs. Within the SM the cross sections and branching ratios can be calculated (as a function of M_H) with high precision, and the predictions have to be confronted with experimental data to test the Higgs mechanism.

Within the SM the Higgs boson mass, M_H, is not stable under radiative corrections, the "hierarchy problem", hinting towards new physics stabilizing the EW scale. Furthermore, a value of $M_H \lesssim 130$ GeV tends to lead to an unstable minimum in the Higgs potential, and new physics is expected to extend the model to higher energy scales.

In this section we will investigate the compatibility of the SM with the currently available experimental information on the recently discovered state and discuss possible alternatives to the SM in view of the current experimental situation. It should be kept in mind in this context that it is still a logical possibility that the state at ~ 125 GeV is not connected to EWSB. This fact underlines the utmost importance of measuring all its characteristics with high precision, where then differences to a (SM-like) Higgs boson should be revealed.

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 one to parametrise the most general interaction of the Higgs boson with matter fields and gauge bosons in a systematic way. A convenient framework is to use the chiral EW Lagrangian of the Goldstone bosons $\Sigma(x) = e^{i\sigma_a\,\pi^a/v}$ and a scalar field h (see e.g. [12])

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

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

$$\mathcal{L}_{HD} \;=\; -\frac{c_g\,g_3^2}{2\,\Lambda}\,h\,G^A_{\mu\nu}G^{A\,\mu\nu} - \frac{c_\gamma\,(2\,\pi\,\alpha)}{\Lambda}\,h\,F_{\mu\nu}F^{\mu\nu}, \tag{3}$$

which allows to have additional new physics contributing to $\Gamma(h \to gg)$ and $\Gamma(h \to \gamma\gamma)$, respectively. The EFT can be mapped to the SM for a particular set of coefficients ($a = b = c_i = d_3 = d_4 = 1$

and $b_3 = c_2 = c_g = c_\gamma = 0$). Any new physics alleviating the UV sensitivity of the Higgs mass will generically have sizable couplings to the Higgs boson and will therefore impact these values compared to the SM. A precise determination of these coefficients allows to indirectly constrain many new physics models at the TeV scale, like supersymmetry and other models with an extended Higgs sector, composite Higgs, little Higgs, dilaton, and more. The EFT can be straightforwardly adjusted to depart from the assumptions of custodial symmetry and positive-parity and one can additionally include an invisible width.

A crucial question therefore for the next years will be a precise determination of these coefficients. This is complementary to direct searches for new physics. As mentioned in Sect. 2.1, CMS has provided a first fit to a and c, denoted by c_V and c_F, respectively, where all other parameters have been set to their SM values; see Sect. 2.1 for a more detailed account of the involved assumptions. Independently, several fits have been carried out in the literature using the publicly available results. Even though there is some tension in the two-parameter fit based on c_V and c_F (the fit improves with an enhanced rate in the diphoton channel), this is not yet statistically significant. It should be noted that since the LHC can only measure certain products of cross sections and branching ratios it is not possible to determine the total width of the discovered particle without further assumptions. A sizable partial width into invisible or undetectable final states is therefore a possibility that needs to be taken into account in present and future analyses.

If the enhancement in the di-photon rate as compared to the SM expectation were to become more robust with increasing luminosity, this could be an indication of a non-SM naure of the observed state. An enhanced di-photon rate could be caused by the enhancement of the partial width of the new state into two photons, which could point to the presence of relatively light new charged particles. An enhanced di-photon rate for a light Higgs could however also be a consequence of a suppression of the decay into $b\bar{b}$, which within the SM is the dominant decay mode for a light Higgs boson.

3.2 Interpretation in specific BSM models

We now turn from the description in terms of an effective Lagrangian to the discussion of specific models. Many models with an extended Higgs sector possess a parameter region where one Higgs boson is SM-like (often referred to as the "decoupling limit"). This Higgs boson is then naturally in agreement with the characteristics as outlined in Sect. 2 equally well as the SM Higgs boson. Furthermore, the still very large uncertainties in the property determination (and the observed slight deviations from the SM predictions) leave substantial room for non-SM-like behaviour. Consequently, it is not necessary that a model is fully in the decouping limit and thus the couplings can still deviate substantially from a SM Higgs boson without being in disagreement with the experimental results. Fotheremore, if the Higgs sector is extended other Higgs states than the one around ~ 125 GeV could be in the reach of the LHC or other future facilities.

The LHC searches have already ruled out many possible manifestations of BSM scenarios. Models that have come under significant pressure are in particular technicolor, the SM4 or the fermiophobic Higgs. We discuss in the following the compatibility of commonly studied models beyond the SM with the results reviewed in Sect. 2

3.2.1 The Two Higgs Doublet Models (THDM)

The THDM is a simple extension of the SM with one additional SU(2) doublet of scalar fields, where each doublet has its own vacuum expectation value, v_1 and v_2, respectively. The simplest version of THDM (corresponding to the Z_2 symmetric potential) with CP conservation and possible non-decoupling phenomena, may lead to various SM-like or non-SM-like scenarios. The former includes the possibility of the existence of the neutral, CP-even Higgs boson with mass around 125 GeV and with tree-level decay rates to fermions and gauge bosons WW/ZZ as in SM, in agreement with recent ATLAS and CMS measurements. Such a Higgs boson in the THDM, however, may have loop-induced couplings different from the SM predictions due to the additional contribution due to the charged scalar H^+ ($\gamma\gamma$, $Z\gamma$) and/or different sign of the top coupling (gg and $\gamma\gamma$, $Z\gamma$). These effects can lead to an enhanced $\gamma\gamma$ rate (for the charged Higgs contributions the constraints from flavour physics, in particular from BR($b \to s\gamma$), need to be taken into acoount).

3.2.2 The Minimal Supersymmetric Standard Model (MSSM)

The MSSM is one of the most studied models beyond the SM. In the MSSM Higgs sector higher-order contributions are known to give numerically large effects. Including higher-order corrections a firm upper limit for the light Higgs boson mass of 135 GeV has been established (for SUSY mass scales in the TeV range). For $M_A \gtrsim 2M_Z$ the light MSSM Higgs boson enters the decoupling region and becomes SM-like. The discovery of the new state near ~ 125 GeV, is naturally compatible with the light Higgs boson in or close to the decoupling regime. On the other hand, for lower values of M_A the heavy $\mathcal{CP}$-even Higgs can have a mass around ~ 125 GeV with SM-like properties. An enhancement of the $\gamma\gamma$ rate at the LHC is possible in both cases, as a consequence of an enhanced $\gamma\gamma$ partial width and / or a suppression of the decay into $b\bar{b}$ (and also $\tau^+\tau^-$). The case where the state at ~ 125 GeV corresponds to the heavier $\mathcal{CP}$-even Higgs of the MSSM would imply the existence of a lighter Higgs state with a mass possibly below 100 GeV and suppressed couplings to gauge bosons, in agreement with the limits from the LEP Higgs searches.

In order to test the MSSM (or the NMSSM as detailed below), it will be vital to: (a) measure the couplings (signal rates in various channels) of the 125 GeV state as precisely as possible, since (N)MSSM effects could manifest themselves as small deviations from the SM predictions; and, (b), search for additional Higgs states (notably with reduced signal rates) in all possible channels, with masses both below (possibly far below) and above 125 GeV.

The above discussion is valid for the general MSSM without any further theoretical restrictions. However, many models have been proposed in which the MSSM is embedded in a Grand Unified Theory (GUT) and various mass scales unify at the scale $M_{\rm GUT}$ [13], where the CMSSM is the most prominent example. Most of these GUT-based realizations of the MSSM are in agreement with current experimental data and can, though with relatively high mass scales, possess a SM-like Higgs boson around ~ 125 GeV. (More information can be found in the report of the LHC2TSP Working Group 2.)

3.2.3 The Next to Minimal Supersymmetric Standard Model (NMSSM)

A simple extensions of the Minimal Supersymmetric Model (MSSM) is the Next-to-Minimal Supersymmetric Model (NMSSM) in which a single additional singlet Higgs superfield $\hat{S}$ (containing a complex scalar component, S) is added to the two Higgs-doublet superfields of the MSSM. The NMSSM solves the so-called μ problem, can naturally have low fine-tuning and has only dimensionless couplings in the superpotential. The additional complex singlet field, S, leads to one additional CP-even and one additional CP-odd Higgs boson beyond the h, H and A of the MSSM, resulting in three CP-even Higgses $h_{1,2,3}$ and two CP-odd states $a_{1,2}$.

The presence of the coupling λ between $\hat{S}$ and the Higgs doublet superfields implies that the mostly SM-like Higgs boson, h (which can be either the first or second lightest state) can easily acquire mass of order 125 GeV without large radiative corrections requiring heavy stop masses and mixings, especially if λ is not too small and if $\tan\beta$ is not large. Enhanced rates for $gg \to h \to \gamma\gamma$ can occur in the NMSSM in the same way as in the MSSM, and in addition due to the property of the state near 125 GeV being a mixed doublet-singlet state. It is possible for h_1 and h_2 to be close in mass leading to a very rich Higgs phenomenology, but also for the lighter state to have a mass below the LEP bound for a SM-like Higgs boson, with reduced couplings to the Z boson. The relevant searches are similar to those described above for the MSSM.

3.2.4 A strongly interacting light Higgs

The SM is very economical in its formulation of EWSB, only one degree of freedom remains: the Higgs boson. It leaves unexplained, however, the dynamical reason of the symmetry breaking, nor does it give an explanation why the Higgs should be light. An increasingly studied paradigm, which is actually quite old, is that the Higgs is a bound state of new strong dynamics close to the weak scale. The fact that it is composite solves the hierarchy problem, as the quantum fluctuations of its mass are saturated at the compositeness scale. Recent progress on the theoretical construction of the theories has come from the AdS/CFT duality and realistic models have been proposed which avoid the severe shortcomings of the original models. The Higgs boson can be treated as an effective field arising from new dynamics which is expected to become strong at a scale not much larger than the EW scale. Various attempts share the feature that the composite Higgs is lighter than the rest of the strong states due to it being a Goldstone boson, as in the holographic Higgs and little Higgs models. The ideal experimental signature would be the production of new states, but as a first sign, one expects deviations from SM properties in Higgs and longitudinal gauge boson processes. These effects can be described by the model-independent Lagrangian of Sec. 3.1.

The Higgs phenomenology is determined by the ratio $\xi = v^2/f^2$ where v is the EW vev and f is the scale of spontaneous symmetry breaking in the strong sector. In concrete models, the deviations of the Higgs couplings from the SM are correlated and functions of ξ, e.g. in the $SO(5)/SO(4)$ minimal composite Higgs, the coupling to gauges fields is $g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$. Constraints from electro-weak precision observables put a bound on $\xi \lesssim 1/3$. The fermion couplings are more model dependent: they depend on the $SO(5)$ embedding and whether the fermions couple bilinearly to the Higgs or couple linearly to fermionic operators of the strong sector (partial compositeness). A precise determination of the properties of the recently discovered state will be crucial for enabling a distinction between a weakly coupled Higgs boson or an effective particle emerging from a strongly-interacting sector. Furthermore, a composite Higgs only partially unitarizes $W_L W_L$ scattering and an investigation of the $W_L W_L$ cross-section therefore could reveal signatures of strong coupling at higher energy.

3.2.5 The SM with additional fermions

A model with a sequential fourth generation family of chiral quarks gives a Higgs signal far too strong compared to the observed one. However, models with additional vector-like singlets or doublets (which can be realized in a variety of BSM scenarios) can contain a SM-like particle around ~ 125 GeV and can thus be compatible with the recent discovery.

4 From the LHC to Terascale Physics

The full experimental exploration of the EWSB mechanism will require three main lines of approach:

1.- High-precision measurements of the main properties of the newly discovered state, including spin, $\mathcal{CP}$ properties, gauge quantum numbers, and its mass, couplings to other particles, its total width, and self couplings.

2.- The direct search for additional physical states pertaining to the EWSB sector or to any other sector having implications for it.

3.- The unitarization of high-energy vector boson scattering, which together with the precision measurements of its couplings might shed light on whether the new state is elementary or composite. It is important to note that if the observed state partially, but not completely, protects WW scattering from violating unitarity, then any problematic behaviour of WW scattering can be deferred to energies well above a TeV.

In this section the capabilities of proposed future facilities for exploring the EWSB mechanism will be discussed in view of the present experimental situation, taking into account the prospects for the LHC running at a centre-of-mass energy of 13–14 TeV and accumulating ~ 300 fb^{-1} of data per detector, subsequently called LHC$_{300/\mathrm{fb}}$.

The discussion of proposed future facilities herein focusses on the one hand on extensions of the LHC project, namely a luminosity upgrade, HL-LHC [14], and a higher-energy proton-proton collider in the LHC tunnel running at 33 TeV, HE-LHC, see Ref. [15] and references therein. On the other hand, an e^+e^- Linear Collider (ILC [16, 17] or CLIC [18, 19]) is discussed as well as the recent proposal of a e^+e^- circular collider in the LHC tunnel with an energy of up to about $\sqrt{s} \sim 240$ GeV [20, 21]. Since ILC and CLIC have many similarities, the two projects will be discussed together; the results for $\sqrt{s} \leq 1000$ GeV are mainly based on ILC studies, while the results for higher energies are based on CLIC studies.

More remote projects such as a Very Large Hadron Collider (VLHC) [15, 22] with a centre-of-mass energy of $\sqrt{s} = 40$–200 TeV and a muon collider [23, 24], which could potentially produce a 125 GeV Higgs boson in the s-channel, yielding a very precise determination of the mass and the total width [25], are not detailed in this document. The feasibility studies for those projects are still in rather early stages. Another project that will not be discussed in detail is an ep collider using the LHC proton beam (LHeC). The physics potential of this machine for exploring EWSB is restricted to the investigation of Higgs production in weak boson fusion.

Only prosepects in the framework of EWSB are discussed in this report. Neither the full physics case for the proposed facilities, which is in general wider than the sole EWSB issues, nor the technical aspects of these projects are discussed herein.

4.1 LHC$_{300/\mathrm{fb}}$ and HL-LHC

The case for running the ATLAS and CMS experiments at a high luminosity LHC is discussed in detail in Refs. [1, 3] for both the 300 fb^{-1} (LHC$_{300/\mathrm{fb}}$) and 3 ab^{-1} (HL-LHC) cases. The main conclusions of these studies are reported here. The aforementionned luminosities correspond to two distinct running phases of the LHC. The first is scheduled to start in 2015, after the two years long shutdown dedicated to the consolidation of the dipole interconnections, which will allow the LHC to run at the close-to nominal centre-of-mass energy of 13–14 TeV, with a nominal instantaneous luminosity of around $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This running phase of the LHC will be interrupted in preparation for the luminosity upgrade around 2018, and will restart at higher instantaneous luminosity to reach in 2021 an integrated luminosity of 300 fb^{-1} (LHC$_{300/\mathrm{fb}}$). This part of the programme is fully approved. The second part, aiming at reaching 3 ab^{-1} (HL-LHC), is not completely approved. It will require improvements of the injection system, installation of crab cavities and installation of new quadrupoles. The foreseen instantaneous luminosity is of the order of $\mathcal{L} = 5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with relatively reasonable levels for the average number of pileup events.

Assuming that the detector capabilities remain roughly the same as those anticipated for the LHC, the HL-LHC [14] 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. The physics potential of the HL-LHC will be of particular interest for processes that are limited by statistics at the LHC, e.g. rare Higgs decay channels that are not observable at the LHC$_{300/\mathrm{fb}}$. Particular examples would be clean measurements related to the top- and μ-Yukawa couplings in the $t\bar{t}H(H \to \gamma\gamma)$ and $H \to \mu^+\mu^-$ channels, which are expected to show very significant signals above an otherwise flat background. Also other channels, and especially those where a narrow resonant peak can be reconstructed, would profit from the increased luminosity which makes possible the reduction of both statistical and systematical uncertainties.

4.1.1 Mass, Spin and CP properties

The foreseen precision on the measurement of the mass in the 2011–2012 LHC datset is already dominated by systematic uncertainties and should reach at this run the order of the permil level. This measurement can of course be improved at higher luminosity, but these improvements are not discussed herein.

As explained above, the observables at the LHC involving the coupling of the new state to two gauge bosons, i.e. $H \to ZZ^*, WW^*$ and production in weak boson fusion, have limited sensitivity for distinguishing a pure CP-even state from an admixture of CP-even and CP-odd components. Concerning testing hypotheses of pure CP-even and pure CP-odd states, a study of the separation of spin/CP states (0+, 0-, 1+, 1-, 2+, and 2-) already yields a separation of the order of three standard deviations for any combination of possible states using the $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channel alone. Both the $H \to WW^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$ and $H \to \gamma\gamma$ channels can provide supporting evidence of the spin and CP properties. In the $H \to WW^{(*)} \to \ell^+\nu\ell^-\overline{\nu}$ channel a different analysis strategy must be used as the spin correlation is one of the essential ingredients of the search. A quantitative assessment of the separation with these channels is not yet available. However a conclusive answer regarding the distinction of a pure CP-even from a pure CP-odd state should be reached at the $\text{LHC}_{300/\text{fb}}$ in each channel individually. The decay $H \to \tau^+\tau^-$ or the process $ZH, H \to b\bar{b}$ could provide additional sensitivity at $\text{LHC}_{300/\text{fb}}$.

4.1.2 Coupling Measurements

The $\text{LHC}_{300/\text{fb}}$ will allow the observation of a Higgs boson in more exclusive modes compared to the present analyses and allow for a more precise determination of ratios of partial widths as well as absolute couplings under a certain set of theory assumptions about the underlying model.

The analysis sensitivity projections presented in this section, for channels already published in the current LHC data, are done extrapolating existing results assuming that the statistical uncertainty for each analyzed channel scales with the luminosity and the systematic uncertainty is constant. The latter assumption is in most cases conservative as more data also contributes to reducing the systematic uncertainties, however the increase in number of pileup events can also increase them. An estimate of the precision with which the different cross section times branching ratios can be measured after 300 fb^{-1} at 14 TeV are given in Tab. 2. The statistical precision for cross section times branching ratio for the gluon fusion process and subsequent 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 WW^* or ZZ^* will reach a statistical precision of 10%.

The two coupling modifiers discussed in Sect. 2.7 can be estimated using the assumptions made therein at the 2–5% precision. At higher luminosity the number of coupling modifiers to fit could be increased to five, c_γ, c_{gluon}, c_V, c_l and c_q, representing the assumed overall scaling factors for the couplings to photons, gluons, W and Z, leptons and quarks. As before, the restriction to those five coupling modifiers involves an assumption about the total width of the new state, which cannot be measured directly. Furthermore, this parametrisation assumes that the couplings of up-type and down-type quarks are modified in the same way. The projected uncertainties for these coupling modifiers range between 5% (for gluon, vector boson, and photons), to 10% for quarks and leptons. These numbers are very basic projections for one experiment only which do not include a robust treatment of the reduction of systematic uncertainties with more data, and the potential inclusion of additional final states.

For the processes $\sigma(gg \to H) \times \text{BR}(H \to \mu^+\mu^-)$, and ttH production with $H \to \gamma\gamma$ subsequent decay, it was estimated that a precision of respectively 10% and 15% can be reached after 3 ab^{-1} at the HL-LHC.

4.1.3 The Invisible Width

One stringent assumption in the coupling measurements is that of the absence of decays of the Higgs boson to invisible (such as particles not interacting or very weakly in the detector) or undetectable decay products (such as coloured particles which cannot be distinguished from the overwhelming background). The final states that have been investigated are the VBF and the associated production modes with a W or a Z, and with a pair of top quarks. Preliminary studies have shown that with 30 fb^{-1} at 7 TeV and 8 TeV, a Higgs boson decaying invisibly with 100% branching ratio can be excluded at the 95% CL [26]. Other production modes yielding different invisible Higgs boson final states should in principle have some sensitivity but have not been yet fully investigated. These analyses are also of interest in the framework of Dark Matter searches.

Table 2: Examples of the precision of SM-like Higgs production times branching ratio for one experiment only at the LHC at $\sqrt{s} = 8$ and 14 TeV assuming a Higgs boson mass of 125 GeV. For the direct measurements of $\sigma \times$ BR an integrated luminosity of $\mathcal{L}^{\rm int} = 10, 60$ and 300 fb^{-1} is assumed. It is furthermore assumed that the statistical error will scale with the luminosity, while the systematic and theoretical error will stay the same. This is a very conservative assumption.

Decay	Prod	10 fb^{-1} 7 - 8 TeV	60 fb^{-1} 8 TeV	300 fb^{-1} 14 TeV
$H \to b\bar{b}$	VH	70%	30%	10 %
$H \to b\bar{b}$	$t\bar{t}H$	-	60%	10 %
$H \to \tau\tau$	ggH	64%	40%	10 %
$H \to \tau\tau$	qqH		40%	10 %
$H \to \gamma\gamma$	ggH	38%	20%	6 %
$H \to \gamma\gamma$	qqH		40%	10 %
$H \to WW^*$	ggH	42%	16%	5 %
$H \to WW^*$	qqH	-	60%	16 %
$H \to ZZ^*$	ggH	40%	16%	5 %
c_V	-	10%	-	2%
c_F	-	25%	-	5%

4.1.4 The Higgs Boson Self Couplings

The measurement of the structure of the Higgs potential is essential to fully reveal the nature of the mechanism responsible for EWSB. To do so there are two main components that need to be assessed: the Higgs trilnear coupling λ_{HHH} and the Higgs quartic coupling λ_{HHHH}. Measurements of these couplings require resonant production channels of two or three Higgs bosons.

Several studies for the measurement of the tri-linear Higgs coupling, λ_{HHH}, have been performed, assuming $M_H \gtrsim 140$ GeV with $H \to WW^{(*)}$ as the dominant decay mode [14, 27]. The studies conclude that at the LHC$_{300/\text{fb}}$ a determination of g_{HHH} will not be possible. The situation is even less encouraging for $M_H \sim 125$ GeV, where the BR$(H \to WW^*)$ is even lower.

The prospects for the measurement of λ_{HHH} have also been investigated for the $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}W^+W^-$ channels. The former has the advantage of allowing for a full reconstruction of the two Higgs bosons which results in a considerable gain in sensitivity. The latter will be very challenging.

Studies in the context of the HL-LHC indicate that there might be some sensitivity on the tri-linear Higgs self-coupling; however, this will require a careful estimate of background contributions. Further studies to clarify these issues are currently in progress, see Ref. [28] for a discussion.

The prospects for the measurement of λ_{HHHH} is of course even more difficult, but an essential component of the full understanding of the Higgs potential. This coupling could in principle be accessed by searches of a resonance in the three Higgs bosons final state. Feasibility studies were made but have shown that *a priori* such measurement is neither possible at the LHC nor at the ILC or CLIC. It was shown to be challenging even at the VLHC.

4.1.5 The W_LW_L, W_LZ_L and Z_LZ_L Scattering

Fully exploring the mechanism that regularizes the weak boson scattering cross section is a fundamental test of the EWSB mechanism. In particular it can potentially discriminate between a fundamental and a composite scalar.

The two main channels for the direct measurement of longitudinal gauge boson scattering are the

Table 3: Examples of the precision of couplings, g_{Hxx}, and branching ratios, $\mathrm{BR}(H \to xx)$, for a SM-like Higgs at a $\sqrt{s} = 500$ GeV LC assuming a Higgs boson mass of 125 GeV. The branching ratio into invisible final states is denoted as "BR(invis.)". The results are based on the ILC set-up for an integrated luminosity of $\mathcal{L}^{\rm int} = 500\,\mathrm{fb}^{-1}$.

g / BR	g_{HWW}	g_{HZZ}	g_{Hbb}	g_{Hcc}	$g_{H\tau\tau}$	g_{Htt}	g_{HHH}	$\mathrm{BR}(\gamma\gamma)$	$\mathrm{BR}(gg)$	BR(invis.)
Precision	1.4 %	1.4 %	1.4 %	2.0 %	2.5 %	15 %	40 %	15 %	5 %	0.5 %

VBF production $q\bar{q} \to WW + 2j \to \ell\nu + 4j$ and $q\bar{q} \to WW + 2j \to e\nu\mu\nu + 2j$. The two leading jets are required to be observed at large pseudo rapidity separation, and stringent cuts must be applied to isolate the longitudinal boson contribution. Observing the differences between the SM weak coupling regime and strong scattering or the possible formation of new resonant states requires sufficiently high energy and high precision. A large integrated luminosity is therefore crucial for such measurement.

Concerning the above mentioned processes, the latter has little sensitivity, while the former can make use of the W-mass constraint and has a higher cross section, but it also has a much higher QCD background. They both have the sensitivity to make an observation at about three standard deviations level in most possible scenarii at $\mathrm{LHC}_{300/\mathrm{fb}}$, but the luminosity will not be sufficient to investigate all possible scenarii, *e.g.* theories in which the Higgs is a pseudo-goldstone boson (SILH). The HL-LHC will allow a clear observation in most possible benchmark cases [1, 3].

4.2 An e^+e^- Linear Collider: ILC and CLIC

We discuss the capabilities of the LC, where results for $\sqrt{s} \leq 1000$ GeV are mainly based on ILC studies, and results for larger centre-of-mass energy in particular apply to CLIC. The following details are based on [16, 17, 19]. The initial stage of the LC 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. Within the ILC design a future upgrade up to $\sqrt{s} = 1$ TeV (or $\sqrt{s} = 1.5$ TeV with an even higher luminosity) is envisioned. 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 up to $\mathcal{L} \sim 6 \times 10^{34}$/cm^2/s.

The LC offers a clean environment for the precision measurement of all quantum numbers, $\mathcal{CP}$-properties and a large number of couplings of the Higgs boson (rare decays such as $H \to \mu^+\mu^-$ become accessible for LC measurements at $\sqrt{s} \sim 1$ TeV and above because of the large statistics that can be accumulated in the WW fusion channel), 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. At $\sqrt{s} \approx 250$ GeV the LC is a Higgs factory with $\mathcal{O}(10^5)$ Higgs bosons expected for $\sim 250\,\mathrm{fb}^{-1}$. From the Higgs-strahlung process near threshold an absolute measurement of the cross section can be performed 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 centre-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, based on ILC studies [17], is given in Tab. 3. Besides the couplings to known particles shown in Tab. 3, the LC provides a unique sensitivity to invisible decay modes of the Higgs boson, extending down to a branching ratio into invisible states as low as about 0.5%. The level of precision reached on the measurement of the Higgs boson mass is 0.03%. In addition to the direct measurement of the Higgs boson mass, the high-precision measurements at the GigaZ option of the LC, i.e. a run at the Z peak with polarised e^- and e^+ beams collecting about 10^9 events, enable also a precise indirect determination of the Higgs boson mass. Within the SM, an indirect determination of the Higgs-boson mass with a precision of about 7 % [29] is possible in this way, providing a very stringent test of the electroweak theory.

The percent level accuracies reachable at the LC for the individual couplings to gauge boson and light fermions (and not only on the product of production cross section times branching ratio) are expected to be crucial for identifying the underlying physics of electroweak symmetry breaking, as typical deviations from a SM-like behaviour are expected to manifest themselves at this level. Centre-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 LC is that the total width can be measured in a model independent way. i.e. without additional theoretical assumptions. The measurements at the LC 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 $\mathrm{LHC}_{300/\mathrm{fb}}$). The investigation of invisible Higgs decay modes could offer the exciting opportunity of Dark Matter production in Higgs decays.

The LC 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. As explained above, the observables related 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 and therefore have limited sensitivity to discriminating a pure $\mathcal{CP}$-even state from an admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components. At the LC 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, as outlined in Sect. 3.2. 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 (see Sect. 3.2). The latter possibility would imply the existence 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 LC 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 LC centre-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 LC, where $\sim 0.8\sqrt{s}$ can be reached. Combining LC and $\gamma\gamma$ measurements, the $H\gamma\gamma$ coupling could be determined at the level of $\sim 3\%$.

The Higgs boson naturally possesses a large Yukawa coupling to the top quark. In models where the Higgs boson mass is not a free parameter, as it is the case in many models with extended Higgs sectors, a strong sensitivity of the Higgs boson mass prediction to the top quark mass is present, roughly limiting the accuracy of the Higgs boson mass prediction to the experimental uncertainty of the top mass. The precise determination of m_t via an $e^+e^- \to t\bar{t}$ threshold scan will improve the knowledge on m_t by one order of magnitude with respect to LHC measurements and thus enable high-precision predictions and tests via M_H.

Additional sensitivity to physics of electroweak symmetry breaking is provided by the high precision measurements at the GigaZ option at the LC (10^9 Z's at $\sqrt{s} \approx M_Z$) [29, 30], and by the WW threshold. These measurements allow precision tests of the SM with uncertainties reduced approximately by one order of magnitude compared to the present situation. 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. The high-precision measurements of the Higgs couplings to WW and ZZ at the LC are also crucial in this context. In case that the Higgs state at ~ 125 GeV is composite, these measurements could reveal effects of new strong resonances.

Going to higher center-of-mass energies as it is envisaged at CLIC, the discovery reach for additional heavy Higgs bosons is extended. The high statistics of the weak boson fusion production of a light Higgs at the high center-of-mass energies of the LC permit the measurement of rare decay modes such as $H \to \mu^+\mu^-$ or the triple Higgs coupling, as summarized in Tab. 4.

Table 4: Examples of the precision, $\delta g_{Hxx}/g_{Hxx}$, for measurements of Higgs couplings at an LC with $\sqrt{s} = 3$ TeV with 3 ab^{-1} [19]

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

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

4.3 LEP3

Measurements of the state observed at ~ 125 GeV that are possible at the ILC with a centre-of-mass energy below ~ 250 GeV could also be performed in a similar fashion at an electron-positron circular collider. The option of installing such a machine in the existing LHC tunnel, called LEP3, has recently been investigated in a preliminary study [20]. In its high centre-of-mass energy mode, LEP3 is foreseen to operate at $\sqrt{s} \sim 240$ GeV with an instantaneous luminosity of 10^{34} cm^{-2}s^{-1}. With an integrated luminosity of 100 fb^{-1} per year this would correspond to roughly 20000 Higgs boson events per year per experiment [20]. Up to four interaction points are discussed in Ref. [20], where the two existing omni-purpose experiments operating at the LHC, ATLAS and CMS, could be used as well at LEP3. The use of two additional detectors specifically developed for the LC is also discussed.

Fully simulated e^+e^- events in CMS have been used to study the achievable precision on the Higgs properties [21]. A subset of the possible channels has so far been considered for performance benchmarking. The total Higgs-strahlung cross section can be measured in a model independent way, similarly to the LC, with a precision of $\sim 4\%$ in each experiment. Table 5 summarizes the precision achievable on a few benchmark Higgs cross sections and couplings at LEP3 in the scenario with two detectors. As a further option, also the running at the Z pole with luminosities as high as 5×10^{35} cm^{-2}s^{-1} (corresponding to $\mathcal{O}(10^{11})$ Z decays per year) and just above the WW threshold has been investigated in Ref. [20].

The main limitation of a circular collider as LEP3 however remains the non-extensibility, therefore

Table 5: Estimated precisions for some benchmark Higgs cross sections and branching ratios at LEP3 with two detectors, based on studies using the CMS detector design [21], for an integrated luminosity of 500 fb^{-1} per experiment.

σ_{HZ}	$\sigma_{HZ}.BR_{H\to b\bar{b}}$	$\sigma_{HZ}.BR_{H\to\tau^+\tau^-}$	$\sigma_{HZ}BR_{H\to\text{invisible}}$	g_{HZZ}	g_{Hbb}	$g_{H\tau\tau}$
2.7%	1.2%	3.2%	1%	1.3%	1.5%	2.1%

higher energy processes as the top pair production to measure the top quark properties and the top Yukawa coupling, the trilinear Higgs self-coupling or the Higgs production by means of vector boson scattering cannot be directly probed.

In Ref. [20] the option of installing a circular e^+e^- collider in a new, longer tunnel is also discusssed. Using a tunnel circumference of 80 km, a machine operating up to the $t\bar{t}$ threshold could be conceived [20].

4.4 HE-LHC

A possible option for a hadron collider at the energy frontier is a proton-proton collider at $\sqrt{s} = 33$ TeV replacing the LHC, denoted as HE-LHC. It is expected to collect at least 300 fb^{-1}. Such a high centre-of-mass energy can only be achieved with challenging 20 T superconducting magnets. The physics case of such a machine is mostly aimed at exploring the energy frontier in search for new phenomena with a mass reach of up to approximately 20 TeV. However it can play an important role in the measurement of the trilinear Higgs self-coupling, as well as the W_LW_L, W_LZ_L and Z_LZ_L scattering.

In the measurement of the trilinear coupling through the two-Higgs bosons production, the increase of centre-of-mass energy does not change by large amounts the signal-to-background ratio, but increases the cross sections of the signal and the background by a factor of roughly three, which can be used as a rough estimate of the sensitivity reach of the HE-LHC. The extrapolation of the systematic uncertainties is not obvious, in particular for the pileup, which cannot trivially be extrapolated at higher energies.

Quantitative studies of the measurement of the quartic coupling at the HE-LHC are not available yet. The energy increase in this case might be favourable to the production of three higgs bosons in the final state. This question has been investigated for the VLHC project. Although a quantitative assessment of the HE-LHC reach still needs to be produced, the possibility of such a measurement is quite remote.

The increase of centre-of-mass energy will benefit more the measurement of weak boson scattering processes. The longitudinal vector boson scattering is substantially larger at higher energy. It is important to notice that both the increase in luminosity of HL-LHC and the increase in energy determine a higher effective luminosity for the measument of vector boson scattering for boson boson masses of at least a TeV. It turns out however that HE-LHC in this case has a higher physics potential, as the gain in discrimination power is about 1.5 times better at the HE-LHC, and higher energy scales of the order of 2-3 TeV can be examined in these processes.

5 Conclusions

The LHC is currently exploring the mechanism responsible for electroweak symmetry breaking. The two experiments, ATLAS and CMS, have independently discovered a new particle with a mass near 125 GeV. Within the current experimental uncertainties this new state is compatible with a SM-like Higgs boson.

Firmly identifying the underlying physics of this new state will be a prime goal of the future programme of High Energy Physics. This will require in particular a comprehensive set of high-precision measurements of the properties of the new state, i.e. its mass, its couplings to as many other particles as possible, its spin and $\mathcal{CP}$ properties, and its self-coupling, where for a Higgs boson the latter measurement is indispensable to gain access to the Higgs potential. Complementary information will be obtained from studying longitudinal gauge boson scattering, where unitarisation could arise from the exchange of an elementary scalar but where also resonances could occur as a result of a new kind of strong interaction. Furthermore a high sensitivity is necessary to possible effects of new physics, for instance additional states of an extended Higgs sector, which could occur with masses above but also below the new state at about 125 GeV.

The continued operation of the LHC, in particular the accumulation of about 300fb^{-1} of data at 14 TeV, will improve the experimental situation very significantly as compared to the present state. A further increase in the integrated luminosity by about one order of magnitude, as will be achievable at the luminosity upgrade of the LHC, HL-LHC, will allow measurements of the weak bosons scattering process, possibly have some sensitivity to the trilinear self-coupling, and improve the statistics-limited processes, such as rare Higgs decays. The HL-LHC will also increase the LHC discovery potential for high mass objects.

Because of its clean experimental environment, an e^+e^- Linear Collider in the energy range up to 350 GeV will be an ideal tool for studying with high precision the properties of the new state near 125 GeV. In particular, absolute and model-independent measurements of the production cross section and the couplings of the new state to various fermions and bosons will be possible. For a Linear Collider running at 500 GeV or above also the trilinear self-coupling and the top-Yukawa coupling will be accessible, where the latter studies will also provide crucial information on the $\mathcal{CP}$ properties of the new state. Running the Linear Collider at energies above a TeV will increase the statistics and therefore the achievable precision and extend the discovery potential for high mass objects.

Measurements of the observed state at $\sim$ 125 GeV that are possible at an e^+e^- Linear Collider with centre-of-mass energy below 250 GeV could also be carried out at a circular e^+e^- collider installed in the LEP tunnel currently hosting the LHC, LEP3. A circular machine operating up to the $t\bar{t}$ threshold could also be conceived using a new tunnel with a circumference of approximately 80 km.

The energy upgrade of the LHC, HE-LHC, could improve the precision on the trilinear self-coupling of the observed state at ~ 125 GeV and the sensitivity to longitudinal vector boson scattering processes. For the latter processes, the cross section at the HE-LHC would increase by about a factor 7 as compared to the cross section at the nominal LHC energy of about 14 TeV.

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