Higgs Studies at the LHC and a Linear e^+e^-Collider

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These lectures review the physics potential of the next colliders at the high energy frontier, for the discovery of the Higgs particle and the measurements of its properties.

1. INTRODUCTION

The Large Hadron Collider (LHC) is presently under construction at CERN, Geneva, Switzerland. The LHC will produce pp collisions with a center of mass system (CMS) energy of 14 TeV. The first collisions at the LHC are expected in 2007.

The e^+e^-Linear Collider (LC) is proposed to be the next facility at the high energy frontier, following the LHC, and is presently intensively studied. A project called the ILC (International Linear Collider), based on superconducting RF cavities, is now being worked out within a worldwide effort, aiming to produce a Conceptual Design Report in 2005. The ILC will have a maximum CMS energy of 1 TeV and could be ready for starting its construction by 2009, if the necessary budget will be assured. Another line of LC developments is the so called two-beam acceleration, as studied in the CLIC project. This potentially allows to reach very large accelerating gradients and thus large center of mass energies for the collisions: 3 to 5 TeV. The CLIC technology is of order of 5 years behind the ILC development.

The prime tasks for these new facilities will be to

- unravel the mystery of the Electroweak Symmetry Breaking (EWSB) mechanism in Nature. In short, it will answer the question: what gives mass to the elementary particles and why e.g. is the photon massless and the Z boson is as heavy as 91 GeV/c^2?
- search for new physics beyond the Standard Model (SM)

Both accelerators have complementary virtues for these studies. The hadron collider has the highest energy and thus mass reach for producing heavy new particles. The protons are however composite particles, and hence the relevant CMS energy is the one of the parton-parton scattering, which varies from collision to collision. The collisions which can convert most of the pp energy into new massive particles are rare and depend on the structure function of the protons. Furthermore, since the initial particles carry colour there will be a background of QCD processes which have generally large cross sections. The e^+e^-collider will be a machine for precision measurements. The incoming particles are elementary – as far as we know today– and the full CMS energy of the collider is used in the hard scattering process. The LC also allows for polarized beams, and the backgrounds are generally much smaller than at a pp collider.

The problem of EWSB was introduced in the lectures by M. Peskin[1] at this school. One of the most popular options for EWSB is the Higgs mechanism[2]. In these lectures we will discuss the potential for the discovery and measurement of Higgs particles at the LHC and e^+e^-linear collider. The discovery reach for new physics at these colliders is discussed in [3].

These lectures give only a quick tour of the subject. More detailed information can be found in e.g.[4–7].

2. THE HIGGS ROADMAP

Adding the Higgs fields to the SM Lagrangian leads us to expect at least one new scalar particle to exist: the scalar Higgs particle. Within the SM we know much of the properties of the Higgs boson but we do not know its mass. The LEP e^+e^-circular collider – which used the same tunnel now foreseen for the LHC – excludes by direct (non)observation a SM Higgs boson with mass below 114.4 GeV/c^2. Theory tells us that its mass should be below about 1 TeV/C^2 if it is to regularize the WW and ZZ cross sections, which would otherwise start to become divergent. Fits to precision measurements from all experiments at presently operating colliders give an indirect limit for the SM Higgs to be less than 251 GeV/c^{2}at 95% CL. A popular extension of the SM is supersymmetry. In the minimal supersymmetric model five Higgs particles are expected, the lightest one having a mass less than about 135 GeV/c^2, i.e. not far away from the present search limit.

Unless the Tevatron, presently operating at FNAL, Chicago, is lucky and discovers it first, we expect that the LHC will discover the SM Higgs – or exclude that it exists. The LHC will measure the mass of the Higgs particle and (mostly) ratios of couplings and in favourable situations it can also determine the spin. The LC will determine precisely the absolute couplings and measure all quantum numbers of the particle.

Hence the roadmap towards discovery of the Higgs(es) and measurements its properties are as follows

- Discover the Higgs
- Determine the mass
- Determine the spin and parity quantum numbers
- Determine the decays
  - Measure the Yukawa like patterns
  - Measure the relation between fermions and gauge boson couplings
  - Observe rare decay modes
  - Search for/observe unexpected decay modes (e.g. into new particles)
  - Measure the total width of the Higgs
- Reconstruct the Higgs potential by determination of the Higgs self coupling
- Determine the nature of the Higgs particle (SM, SUSY, composite)

Both the LHC and LC will be crucial in establishing the Higgs dynamics.

3. HIGGS AT THE LHC

The Higgs production mechanisms and cross sections at the LHC are well understood. Fig. 1 shows the main production mechanisms, namely gluon-gluon fusion, WW and ZZ fusion, associated W, Z production and $t\bar{t}$ fusion. All these mechanisms, except for the first one, have apart from the Higgs extra activity in the hard scattering process: two extra jets, a W or Z boson or two top (anti)quark jets, respectively.

The cross section as function of the SM Higgs mass is given in Fig. 2(left). The total cross section amounts to a few 10's of picobarns (pb) for low Higgs masses, but becomes less than a pb for the highest masses. During the first years we expect the LHC to deliver up to about 10 fb^{-1} per year, which leads to several 10K SM Higgses produced per year. Later we expected the luminosity of the LHC, and correspondingly the Higgs production rate, to increase by a factor of 10.

The Higgs particles will be observed in detectors at the LHC. Two so-called general purpose detectors, optimized for the discovery of new physics and the Higgs particle, ATLAS[9] and CMS[10], are under construction. From the point of view of the these detectors the Higgs will decay instantaneously after its production. The SM Higgs decays into two fermions or bosons according to well calculable rates (branching ratios), which depend only on the Higgs mass. The result is shown in Fig. 2(right).

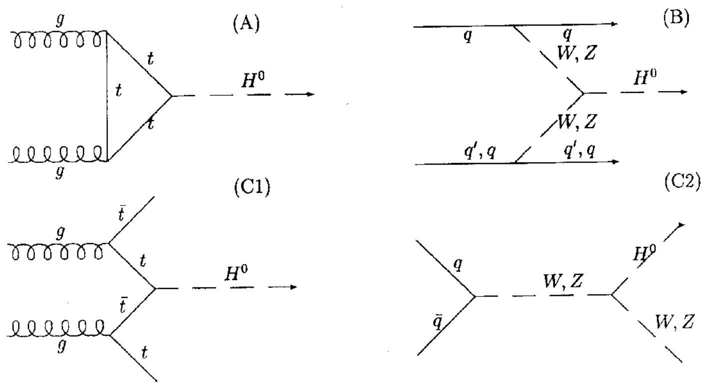


Figure 1: Higgs production processes in pp collisions: a) gluon gluon fusion; b) WW or ZZ fusion; c) $t\bar{t}$ fusion; d) associated W, Z production.

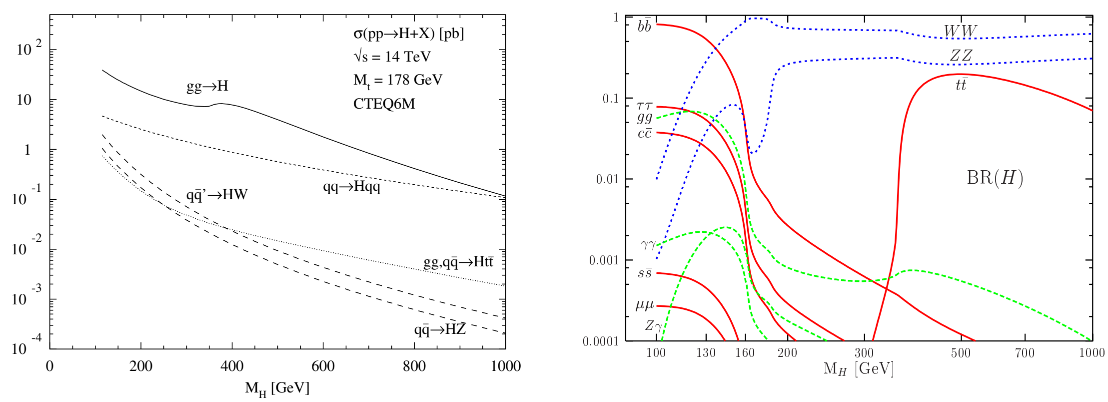


Figure 2: (left) NLO cross sections for SM Higgs production[8]; (right) Branching ratios of the SM Higgs.

We generally separate two regions of interest for the search of the Higgs boson, namely the regions $m_H < 2M_Z$ and $m_H > 2M_Z$. In the first region the decay $H \to b\bar{b}$ is dominant. However this channel cannot be used in a pure inclusive mode, e.g. $gg \to H \to b\bar{b}$, due to the large QCD background of $b\bar{b}$ production: the total $b\bar{b}$ cross section is several hundred μb! Also the mass resolution of this decay is O(10-15%) ie. rather broad and hence it would be difficult to detect the signal on top of a large background. The $b\bar{b}$ channel can be used however e.g. in the W, Z associated production process or top fusion process, shown in Fig. 1

After detailed detector studies with the CMS and ATLAS detectors the following channels are presently considered for SM Higgs studies [4, 5]:

- $H \to \gamma\gamma$, inclusive, in ttH and WH processes

- $H \rightarrow ZZ^* \rightarrow 4$ leptons
- $H \rightarrow WW^* \rightarrow l\nu l\nu$
- $H \rightarrow b\bar{b}$ in ttH and WH
- $qqH, H \rightarrow WW^* \rightarrow l\nu l\nu$
- $qqH, H \rightarrow \tau\tau \rightarrow l + \tau_{jet}, ll$

In case $m_H > 2m_Z$ the golden channel for the Higgs discovery and its measurements is the decay channel $H \rightarrow ZZ \rightarrow$4 leptons (electrons and muons). Both ATLAS and CMS are tailored for precise high p_T lepton measurements, and thus this channel will allow for a precise determination of the Higgs parameters, such as the mass. The channels for this region are:

- $H \rightarrow ZZ \rightarrow 4$ leptons
- $H \rightarrow WW \rightarrow l\nu jj$
- $H \rightarrow ZZ \rightarrow ll\nu\nu$
- $H \rightarrow ZZ \rightarrow lljj$

The latter channels become particularly important at the highest Higgs masses: the Z branching ratio in to leptons is only about 3% per lepton species. Hence since the cross sections decrease with increasing Higgs mass, the statistics for the 4 lepton channel gets too low, and additional channels with larger branching ratios have to be included as well.

Next we give a few examples of Higgs searches.

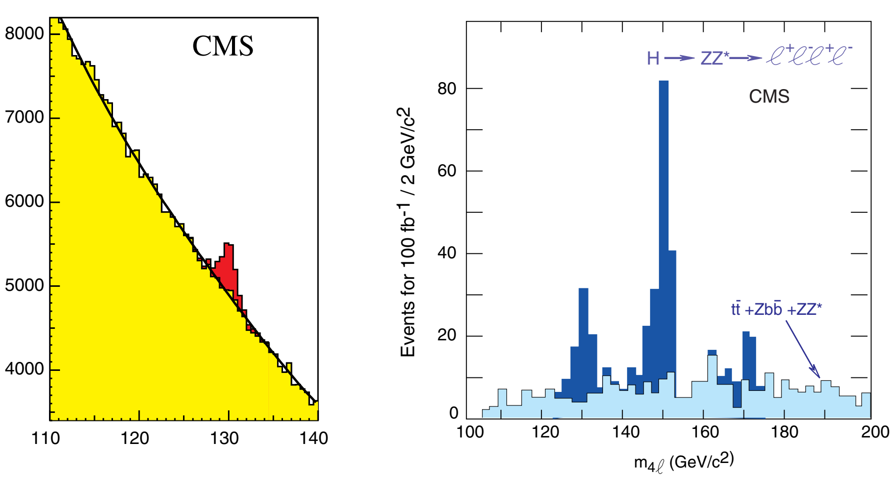


Figure 3: (left) Reconstructed di-photon invariant mass distribution of the $H \rightarrow \gamma\gamma$ signal (dark) and the background (light) with $M_H = 130$ GeV/c^2 for 100 fb^{-1} with K factors for both signal and background. (right) Reconstructed four-lepton invariant mass distribution of the $H \rightarrow ZZ^* \rightarrow 4l$ signal (dark) and the background (light) with $M_H = 130, 150$ and 170 GeV/c^2 for 100 fb^{-1} with LO cross sections.

Remarkably, at first sight, one of the favourable channels at the LHC turns out to be the Higgs$\rightarrow \gamma\gamma$ channel. The branching ratio for this channel is only a few times 10^{-3} but the final state has less background than the $b\bar{b}$ channel, and it can be detected owing to the good energy resolution of the electromagnetic (EM) calorimeters of ATLAS and CMS. For example the energy resolution of the EM-calorimeter in CMS is $\Delta E/E = 3\%/\sqrt{E} + 0.5\%$. The mass resolution with which one can reconstruct the Higgs is better than 1 GeV/c^2($M_H \sim 100$ GeV/c^2) and the signal to background ratio is approximately 1/20, as shown in Fig. 3(left).

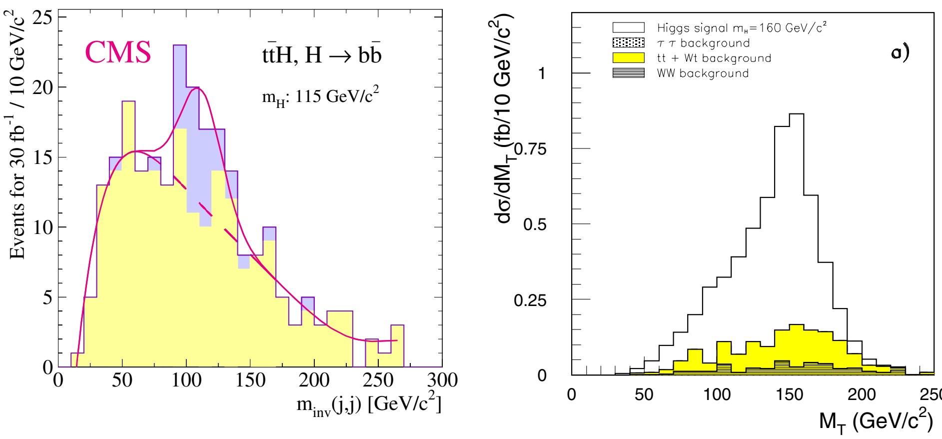


Figure 4: (left) Reconstructed Higgs mass for $t\bar{t}H, H \to b\bar{b}$ superimposed on the total background for $m_H = 115$ GeV/c^{2}with 30 fb^{-1}. (right) Distribution of the accepted cross section of the transverse mass M_T for the channel $qqH \to qqWW^* \to qql\nu l\nu$ for a Higgs mass of 160 GeV/c^2[11].

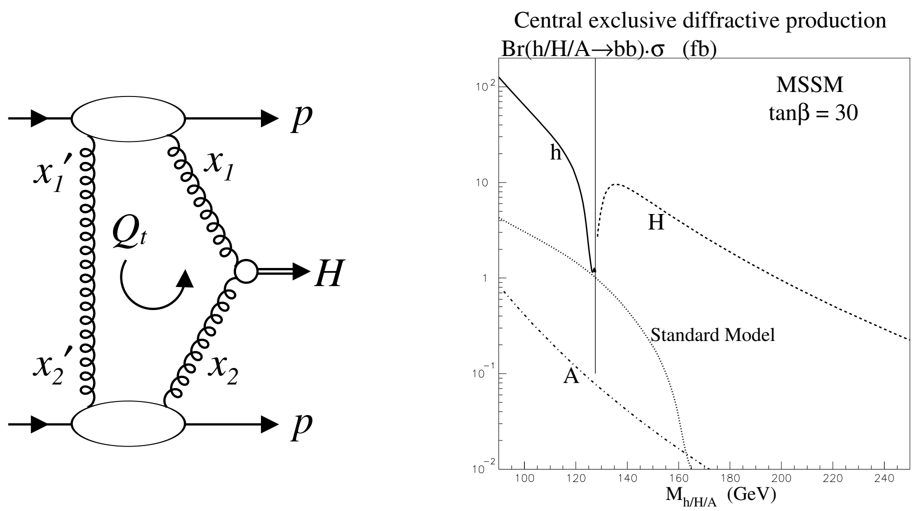


Figure 5: (left) Schematic diagram of the central exclusive diffractive production of the Higgs; (right) The cross section times the $b\bar{b}$ branching ratio predicted for central exclusive diffractive production, for the SM and MSSM with $\tan\beta = 30$.

The channel $H \to$ four leptons is very clean and useful over a large mass range, basically from $130 < M_H < 500$ GeV/c^2. A typical signal is shown in Fig. 3(right). The mass resolution is better than 1 GeV/c^{2}in the low mass region.

Two further examples are shown in Fig. 4: $ttH \to ttbb$ and $qqH \to qqWW^* \to qql\nu l\nu$. Recently important progress was made studying the latter boson fusion diagram. This channel, together with the $H \to \tau\tau$ decay mode, will allow that each experiment by itself can discover the Higgs with a 5σ significance with 30 fb^{-1} of data.

A novel channel, not yet completely explored at the detector level, is the central exclusive diffractive production channel $pp \to p + H + p$. The diagram of this process is shown in Fig. 5 (left). The two protons leave the interaction intact, with some energy loss which is transformed to create the central Higgs. [12]. If these protons can be detected, eg. by means of so called Roman Pot detectors [13] then one could measure the Higgs mass without explicitly using the Higgs decay products. Indeed for exclusive processes the Higgs mass can be calculated from the missing mass of the system: $M_H^2 = (p_1 + p_2 - p_1' - p_2')^2$ with p_i (p_i') the four-momenta of the incoming (outgoing) protons. In this process also the $b\bar{b}$ decay mode becomes accessible because the QCD background process at LO is strongly

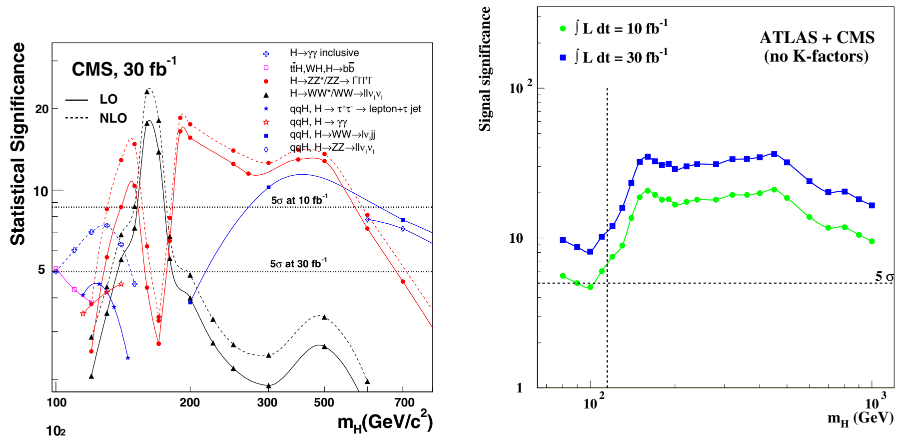


Figure 6: (left) Expected statistical significance for the SM Higgs as a function of m_H for 30 fb^{-1} with the CMS detector. (right) Expected statistical significance for the combined ATLAS and CMS detector for 10 and 30 fb^{-1}.

suppressed. Apart from the challenges for the trigger and forward proton detectors the drawback of this process is the small cross section. The cross section for $H \to b\bar{b}$ as function of the mass m_H is shown in Fig. 5 (right). The cross section values are in the range of a few fb only. The figure shows also the cross section for a MSSM Higgs for high $\tan\beta$ value: in this case the cross section could be a factor 20 larger.

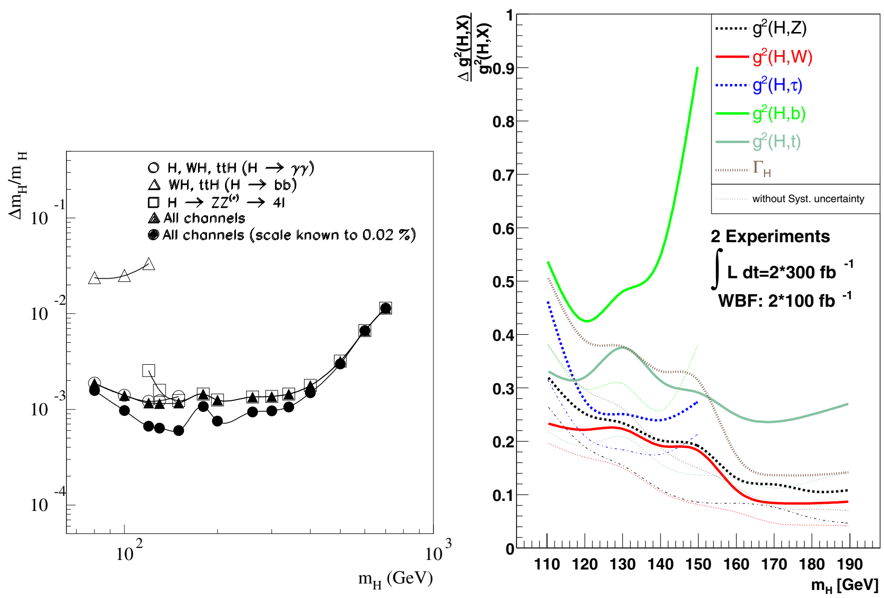
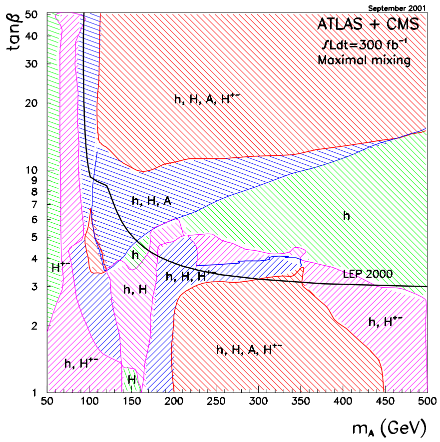


Figure 7: (left) Relative precision $\Delta M_H/M_H$ on the measurement of the Higgs mass as a function of M_H, assuming 300 fb^{-1}; (right) Relative precision of the fitted Higgs couplings squared as function of the Higgs boson mass for 2×300 fb^{-1} (and three times less for VBF measurements), from[14].

The LHC reach for a SM Higgs discovery is shown in Fig. 6(left) for different channels for CMS and in Fig. 6(right) for ATLAS and CMS together. It shows that with a luminosity of 10 fb^{-1} the LHC will discover the SM Higgs boson in the entire range of interest. A luminosity of 10 fb^{-1} could be collected after one good year (but probably not the first one) of data collection at the LHC.

The LHC will determine the mass of the Higgs, typically with a precision of 0.1-1% depending on the mass, see



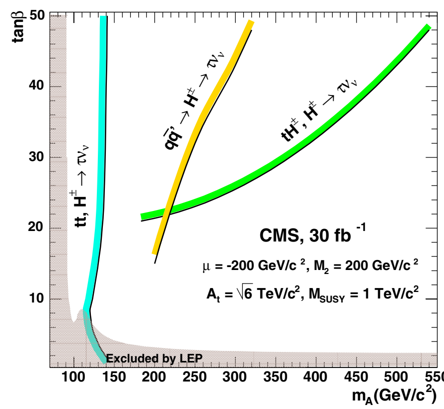


Figure 8: (left) Expected 5 σ discovery range for the MSSM Higgs bosons with maximal stop mixing in the ATLAS and CMS detectors for 300 fb^{-1}. (right) The 5 σ discovery potential for charged Higgs bosons for 30 fb^{-1}.

Fig. 7(left), after a collection of 300 fb^{-1} of data. The width of the Higgs can be determined directly to better than 10% for $m_H > 250$ GeV/c^{2}with 300 fb^{-1}. Indirect, model dependent, methods have been proposed to measure the total width for the lower mass region, giving a precision of $\sim 20\%$.

The LHC cannot determine the absolute couplings of the Higgs to fermions or bosons without additional theoretical assumptions. The precision with which the ratios of couplings can be measured is typically of the order of 10-20% for the full statistics. Some mild theoretical assumptions (basically assuming $g(H,Z) < g(H,Z)_{SM}$)[14] allow to get absolute couplings with precisions in the range of 10-40%, and also allow for a measurement of the total width, see Fig. 7(right)

Apart from the mass, width and (relative) couplings, the LHC may address the question of the spin of the Higgs particle, in case the decay mode $H \rightarrow ZZ \rightarrow$ four leptons is available [15]. It turns out that for $m_H > 250$ GeV/c^{2}this will allow to distinguish between $S = 0, 1$ and CP even or odd, while for $m_H < 250$ GeV/c^{2}one cannot distinguish the spin 0 and 1, but only the CP state.

While most of the discussion on the Higgs searches so far was on the SM Higgs, many studies have been performed for Higgs particles in models beyond the SM. The most detailed studies have been performed for the MSSM model, and a detailed summary can be found in[7]. Fig. 8 shows an overview of the reach at the LHC for the $h, A, H, H^{\pm}$ Higgses, as function of the mass of the CP odd Higgs A and the value of $\tan\beta$. The figure shows the typical wedge at medium $\tan\beta$ values, and $M_A > 200$ GeV/c^2, ie. a region where only the lightest Higgs h will be detectable at the LHC.

4. HIGGS AT THE LC

The LC offers a much cleaner environment compared to the LHC for precision studies. The Higgs production diagrams are shown in Fig. 9: Higgs-strahlung from a Z and WW fusion. The cross sections are shown in Fig. 10, and are typically of the order of 100 fb in the low Higgs mass region. The luminosities of a TeV class LC allow to collect data samples of the order of 500 fb^{-1} at a CMS energy of 500 GeV and 1 ab^{-1} for a 1 TeV collider. The cross section/event rate is optimal at a CMS energy of 350 GeV for a 120 GeV Higgs. For 500 fb^{-1} about 90 K Higgs events will be produced at a LC with a CMS energy of 350 GeV.

The Higgs-strahlung $e^+e^- \rightarrow HZ$ process is of particular interest. It allows to detect the Higgs via the recoil to the measured Z boson. An example of a recoil mass measurement is shown in Fig. 11 (left). A clear mass peak of the Higgs is seen, which allows a Higgs mass measurement to a precision of about 100 MeV/c^2. The observation of the Higgs particle with this method is independent of the decay mode, which means that it also may contain e.g.

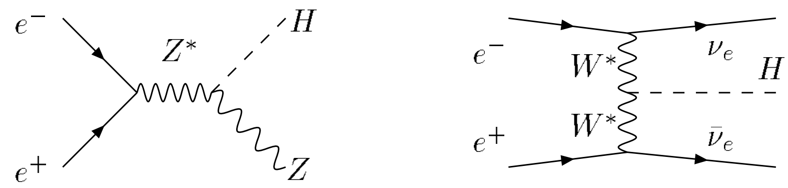


Figure 9: Higgs production processes in e^+e^-interactions: left Higgs-strahlung, right WW fusion.

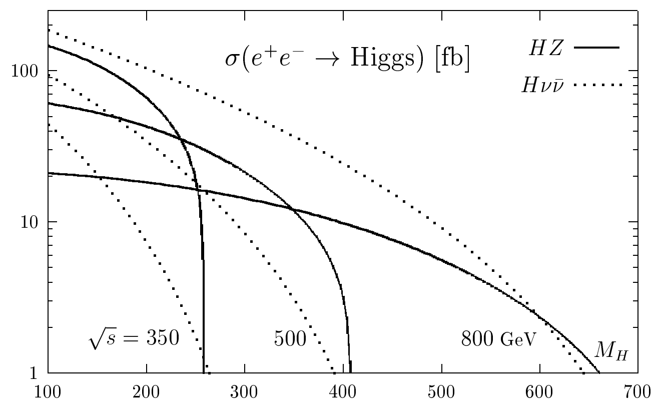


Figure 10: The Higgs production cross section at a LC for different CMS energies and for both production processes separately.

invisible decay modes to for example supersymmetrical particles, as discussed below.

Apart from the recoil mass measurement, several other methods can be used to determine the mass, such as measurements of Higgs mass spectra in the processes/decays $ZH \to llWW, ZH \to qqbb$, and $ZH \to llqq$, where the use of the channel depends on the mass of the m_H. Combining all channels leads to expect a precision of about 40 MeV/c^2 on the Higgs mass measurement.

Branching ratios can be determined in a model independent way at a LC. A collection of measurement precisions is shown in Fig. 11(right) for different decays. A summary of the results is given in Table 1 [16]. The Higgs couplings can then be determined from the measured branching ratios. A global fit to all observables is made and correlations are taken into account. The precise determination of the effective couplings opens a window on the sensitivity to the nature of the Higgs boson, as demonstrated in Fig. 12(left).

Table I: Comparison of the relative errors obtained with a new analysis shown at the LCWS04 and previous analyses from the TESLA TDR and the Snowmass 2001 workshop[16].

selection	LCWS 2004	TESLA TDR (2001)	Snowmass 2001
$\Delta(\sigma \times BR(H \to b\bar{b}))/(\sigma \times BR(bb))_{SM}$	1.0%	0.9%	1.6%
$\Delta(\sigma \times BR(H \to c\bar{c}))/(\sigma \times BR(cc))_{SM}$	12.0%	8.0%	19.0%
$\Delta(\sigma \times BR(H \to gg))/(\sigma \times BR(gg))_{SM}$	8.2%	5.1%	10.4%

Spin and quantum numbers can be determined rather easily at a LC. At threshold the spin can be determined form the β dependence of the onset of the cross section as shown in Fig. 12(right). In the continuum angular distributions can be used.

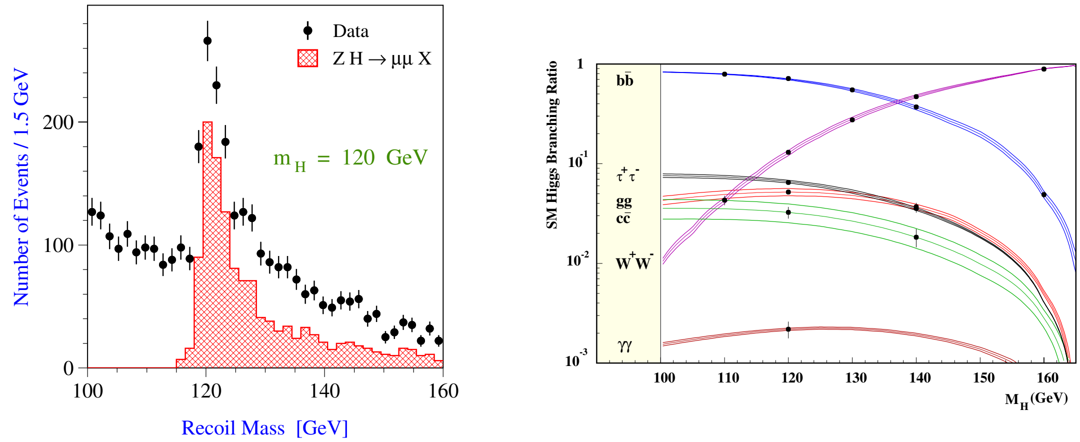


Figure 11: (left) Di-lepton recoil mass in the Higgs-strahlung process $e^+e^- \to HZ \to Xl^+l^-$. (right) SM predictions for the Higgs boson decay branching ratios as a function of M_H. Points with error bars show the expected experimental accuracy while lines show the estimated uncertainties on the SM predictions due to the value of the fermion masses and α_s.

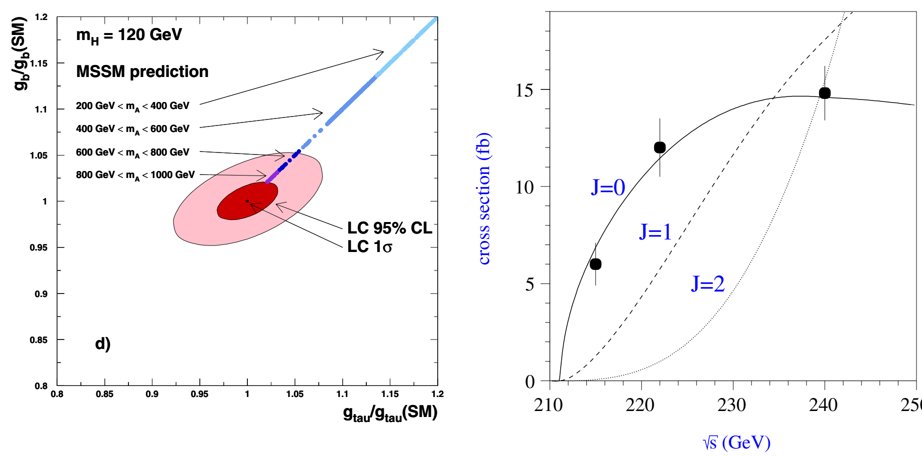


Figure 12: (left) Higgs Couplings determined at the LC. The plot shows the contours for g_{Hbb} versus $g_{H\tau\tau}$ couplings for a 120 GeV/c^{2}Higgs boson as measured with 500 fb^{-1} of data. (right) Simulated measurement of the $e^+e^- \to HZ$ cross section for m_H= 120 GeV/c^{2}with 20 fb^{-1} per point at three center of mass energies compared to the predictions of a spin-0 (full line), and examples of spin-1 (dashed line) and spin-2 (dotted line) particles.

Rare Higgs decays become observable with large luminosities and at high CMS energies. Examples include:

- $H \to b\bar{b}$ at large m_H masses
- $H \to \mu\mu$
- $H \to \gamma Z$

An example for $H \to \mu\mu$ is shown in Fig. 13(left). The precision on the $H \to b\bar{b}$ and $H \to \mu\mu$ is around 15% for 1 ab^{-1} of data.

In extended models the Higgs particle could decay 'invisibly' ie. in weakly interacting particles that do not interact in the detector and thus escape direct detection. A popular example is a Higgs decaying in two neutral gauginos that are the lightest sparticles in a SUSY model. There is some sensitivity at the LHC, but the LC can relatively easily detect these directly in ZH events, when tagging on the Z. One can observe a peak in the recoil mass of the ZH events. The "invisible branching ratios" can be determined with good precision: to better than 5% for large enough branching ratios, as shown in Fig. 13(right).

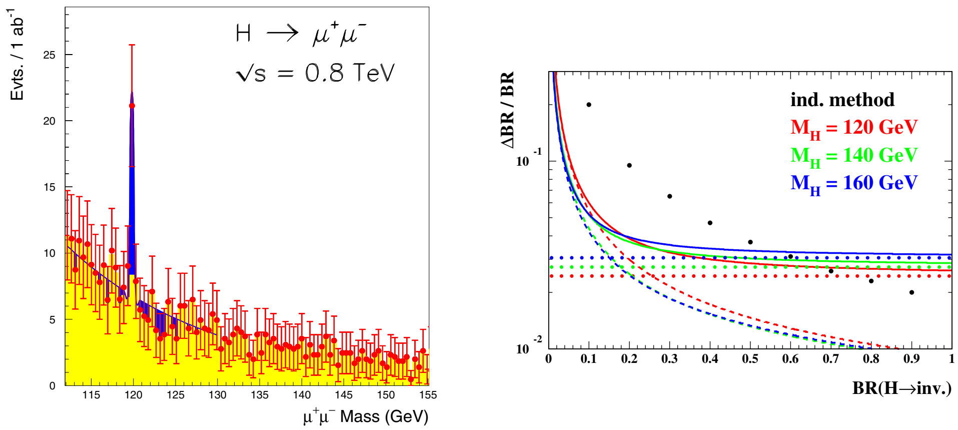


Figure 13: (left) Expected mass spectrum for the decay $H \rightarrow \mu\mu$ from a sample of 1 ab^{-1} at 800 GeV CMS energy, for m_H= 120 GeV/c^2. (right) Accuracy on the branching ratio $H \rightarrow$ invisible as a function of $BR(H \rightarrow \text{invisible})$ for three Higgs masses using 500 fb^{-1} at 350 GeV. The dashed and dotted lines indicate the contributions from the measurement of the invisible rate and from the total Higgs-strahlung cross section measurements respectively. The large dots are the result of the indirect method.

The top-Higgs Yukawa couplings is very large ($g_{ttH} \sim 0.7$ compared to $g_{bbH} \sim 0.02$). To date we have no explanation for that, and therefore precise measurements of this quantity are very important since these could reveal the largest deviations to new physics in the Higgs sector. Again this measurement will need a collider of around 1 TeV CMS energy and large luminosity. If $m_H < 2m_t$ then one needs to measure the process $e^+e^- \rightarrow ttH$. If $m_H > 2m_t$ then one can get the information directly from the branching ratio $H \rightarrow t\bar{t}$. Precisions on the coupling in the range of 5-10% can be obtained for 1 ab^{-1} of data.

A last fundamental test of the Higgs sector with a light Higgs boson is the study of the Higgs self-couplings and the reconstruction of the Higgs potential. The symmetry breaking in the Standard Model is completely encoded in the scalar Higgs potential. In the SM the mass of the Higgs M_H and its self-couplings are fixed in terms of a single parameter, λ. Higher-order operators may change the relationship between the Higgs mass and its self-couplings, as well as the couplings to the Goldstone bosons. Probing the Higgs potential amounts to measuring the self-couplings of the Higgs, of which the most accessible is the trilinear coupling. The triple-Higgs coupling g_{HHH} can be accessed at a TeV-class LC in the double-Higgs production process $e^+e^- \rightarrow HHZ$ [17]. However, this measurement is made difficult by the tiny production cross section and by the dilution due to diagrams, leading to double Higgs production, that are not sensitive to the triple Higgs vertex. It has been concluded that a LC operating at $\sqrt{s}$ = 500 GeV can measure the HHZ production cross section to about 15% accuracy if the Higgs boson mass is 120 GeV/c^2, corresponding to a fractional accuracy of 23% in g_{HHH} [18].

This accuracy can be improved by performing the analysis at multi-TeV energies, as seen in Fig. 14, using the process $e^+e^- \rightarrow HH\nu\overline{\nu}$ and introducing observables sensitive to the presence of the triple-Higgs vertex. No polarization has been included in this study. However, the double Higgs production for polarized beams is four times larger, indicating a further potential improvement of the accuracy by a factor of 2. Assuming that only some fraction of the time favorable polarized beams will be used, the precision is on the triple-Higgs coupling will be in the range of 0.07 to 0.09.

A qualitative study of the channel $e^+e^- \rightarrow H\nu\nu$ was further made, taking into account both background and signal, for a wider range of Higgs masses (120 to 240 GeV/c^2) and several CMS energies (1.5 to 5 TeV). Figure 14 (right) shows the cross section of the processes, the sensitivity of the cross section to the triple Higgs coupling, and the expected precision with which the triple Higgs coupling can be determined. The calculations include the branching ratios into the relevant channels, and a reconstruction efficiency as determined for 3 TeV. The assumed integrated luminosity is 5 ab^{-1}.

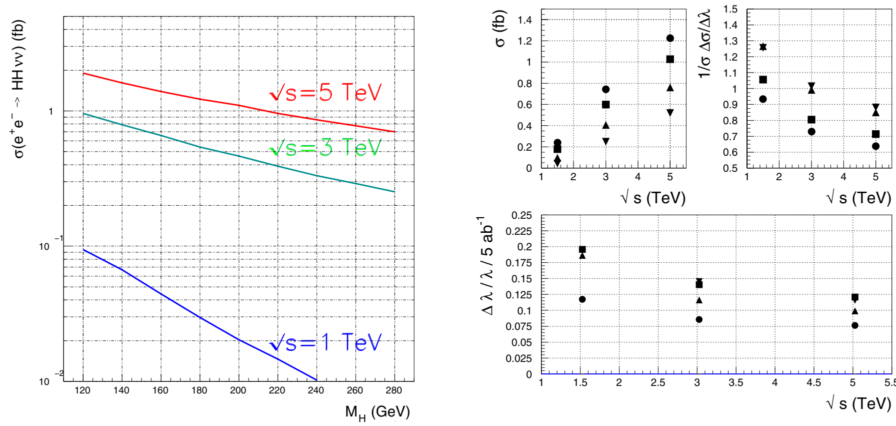


Figure 14: (left) Double Higgs production at CLIC: cross section for the $e^+e^- \to HH\nu\bar{\nu}$ process as a function of the Higgs boson mass for different centre-of-mass energies (left) and the $|\cos\theta^*|$ distributions for different values of the triple Higgs coupling. (right) The cross section of the processes $e^+e^- \to H\nu\nu$, the sensitivity of the cross section to the triple Higgs coupling, and the expected precision with which the triple Higgs coupling, for the masses 120 GeV/c^2(circle), 140 GeV/c^2(box), 180 GeV/c^2(triangle), and 240 GeV/c^2(inverse triangle), for 5 ab^{-1}.

5. CONCLUSIONS

THe LHC will be the next collider at the high energy frontier that will start operation in just a few years from now. The prospects to discover the SM Higgs and measure some of its properties were never looking so good: the LHC will cover the whole mass region of interest within roughly one good year of operation, for a discovery. In other words for the Standard Model Higgs the LHC will be the final word. One should keep in mind though that it will take some time to understand and calibrate the detectors. Once the Higgs is found its mass can be measured to a precision of about 0.1%, using the full statistics of 300 fb^{-1}, for masses up to about 500 GeV/c^2.

The LC will provide precision measurements on absolute couplings, quantum numbers, the Higgs potential etc., allowing tests at the quantum level.

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