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Comparison of Higgs Boson Mass and Width Determination of the LHC and a Linear Collider

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Abstract

Two important properties of a Higgs boson are its mass and width. They may distinguish the Standard Model (SM) Higgs boson from Higgs bosons of extended models. We show results from a direct mass and width reconstruction for a Higgs boson mass range from 120 to 340 GeV/c^2. The mass and width have been reconstructed from the $\mathrm{H} \to \mathrm{ZZ}^\star \to \mu^+\mu^-\mu^+\mu^-$ reaction in an LHC simulation of the CMS detector. The determined mass accuracy has been compared with that obtained from studies for a linear collider (LC). The mass precision from the latter studies are derived by scaling previous LC simulation results according to the expected event rates. For the Higgs boson width we compare a direct determination with indirect methods and find good complementarity.

1 Introduction

The search for Higgs bosons is one of the main goals of future colliders. After a discovery it will be very important to establish the properties of the Higgs boson. In order to constrain the Higgs sector in the Standard Model or its extensions, the mass and width of the Higgs boson have to be measured with as high a precision as possible. The statistical error will obviously depend on the expected signal event rate. The rate is mainly determined by the Higgs boson production cross section times the branching fraction of the Higgs boson decaying into a final state which is used for the reconstruction, and the integrated luminosity.

The main Higgs boson production mechanism at the LHC is typically gluon fusion, shown in Fig. 1a. The gluons couple to the Higgs boson via a quark loop. The main contribution to the total cross section of this process is the graph which involves a top quark loop.

At an LC the Higgs boson is mainly produced in association with a Z boson (Higgsstrahlung). The e$^\pm$ pair produces an off-shell Z boson which radiates the Higgs boson if the latter is not heavier than about $0.9(\sqrt{s}/c^2 - m_\mathrm{Z})$. Figure 1b shows the corresponding process. For large Higgs boson masses the W-fusion process dominates.

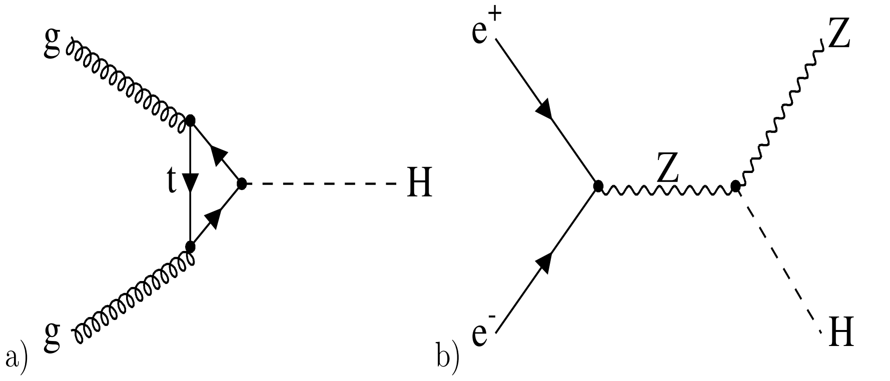

Figure 1: Dominant Higgs boson production channel at a) the LHC: gluon fusion, and b) an LC: Z Higgsstrahlung.

Figure 2 summarizes the branching fractions of the most important decay channels [1] for the SM Higgs boson. An indirect reconstruction using the recoil Z decay products does not depend on the specific Higgs boson decay mode; this has been investigated in an LC study. At the LHC the event rate in the $\mathrm{H} \to \mu^+\mu^-\mu^+\mu^-$ channel is very sensitive to the branching fraction of $\mathrm{H} \to \mathrm{ZZ}^\star$. In the mass range from about 120 to 200 GeV/c^2 this branching fraction varies rapidly with the Higgs boson mass, but at higher masses the branching to ZZ remains largely constant at about 30%.

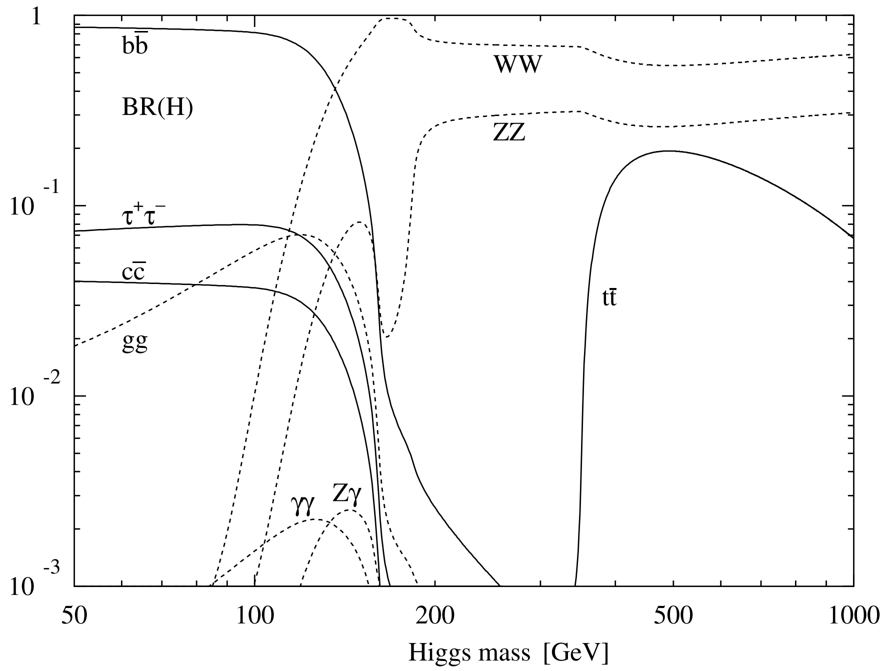

Figure 2: SM Higgs boson decay branching fractions.

Type	Cuts
Isolated $\mu^\pm$	$\vert\eta\vert < 2.4$; $\epsilon_{\mathrm{rec}} = 90\%$; $p_{\mathrm{T}} > 20, 10, 7, 7$ GeV/c; $\sigma(d_0) < 3.0$
On-shell Z	$85 < m_{\mathrm{inv}} < 97$ GeV/c^2
Off-shell Z	$12 < m_{\mathrm{inv}} < 76$ GeV/c^2 for $m_{\mathrm{H}} < 160$ GeV/c^2
	$32 < m_{\mathrm{inv}} < 96$ GeV/c^2 for $160 \leq m_{\mathrm{H}} < 200$ GeV/c^2
	$85 < m_{\mathrm{inv}} < 97$ GeV/c^2 for $m_{\mathrm{H}} \geq 200$ GeV/c^2

Table 1: Selection cuts in the $\mu^+\mu^-\mu^+\mu^-$ channel. The cut parameter η is the pseudorapidity and $\sigma(d_0)$ the significance of the transverse impact parameter.

2 Higgs Boson Mass Reconstruction at the LHC

For the process shown in Fig. 3 the Higgs boson mass is reconstructed by calculating the invariant mass of the four final state muons. The simulation is based on the CMS detector response parametrization CMSJET [2] where the CMS tracker and muon system response is modeled as a function of η and p_{T}. The selection steps outlined in Table 1 are used in order to suppress the background [3]. The cut on the reconstructed off-shell Z mass is varied for the different Higgs boson mass regions as indicated.

The invariant four-muon mass distribution is shown in Fig. 4 for three different Higgs boson masses. The resulting peaks are clearly visible over the expected background which consists of ZZ, $\mathrm{t\bar{t}}$ and $\mathrm{Zb\bar{b}}$ events. Details are given in Ref. [3]. The number of background events is rather constant and only about two events per 1 GeV/c^2 for an integrated luminosity of 300 fb^{-1}. The signal and background simulation is repeated 100 times for each investigated mass, where the background distribution is generated randomly according to the expected rate per mass bin. The results of the 100 fits are averaged in order to obtain the most likely outcome of the future experimental analysis. Note that the 150 GeV/c^2 signal is larger than that of 130 GeV/c^2 because of the larger ZZ branching fraction (Fig. 2). The 170 GeV/c^2 peak is lower owing to the drop of the $\mathrm{H} \rightarrow \mathrm{ZZ}^\star$ branching ratio at the opening of the $\mathrm{H} \rightarrow \mathrm{W^+W^-}$ decay with two on-shell W's, as visible from Fig. 2.

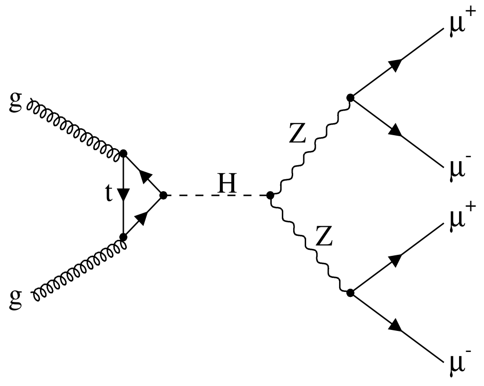

Figure 3: Higgs boson production in the $\mu^+\mu^-\mu^+\mu^-$ channel.

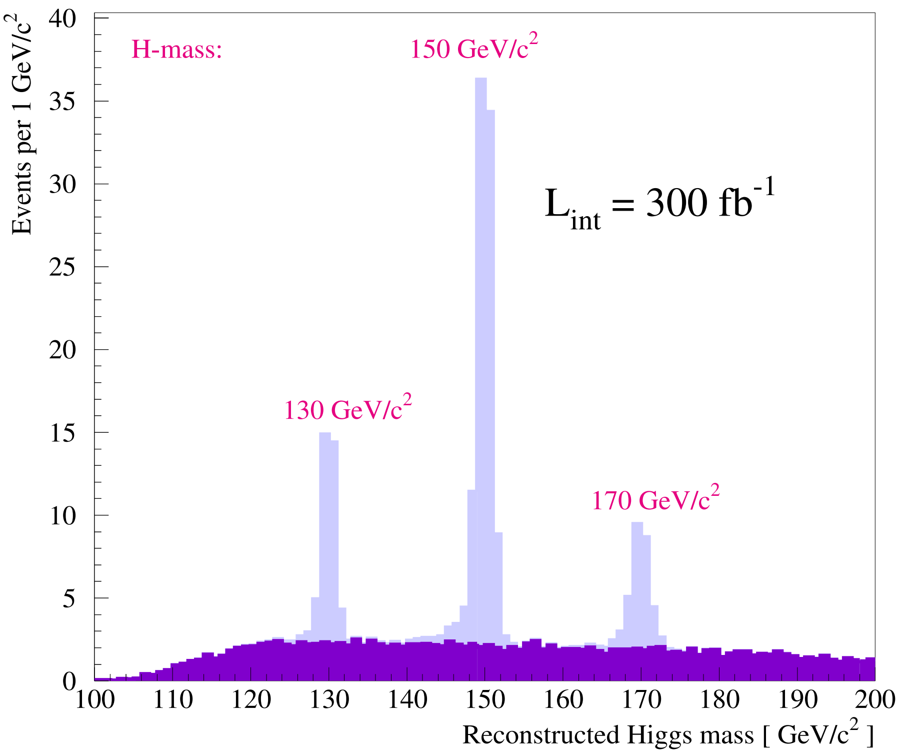

Figure 4: Expected signal and background in the CMS experiment for Higgs boson masses of 130, 150 and 170 GeV/c^2 in the $\mu^+\mu^-\mu^+\mu^-$ channel for an integrated luminosity of 300 fb^{-1}.

Various Higgs boson event samples in the mass range from 120 to 340 GeV/c^2 are simulated with the CMS detector assuming a total integrated luminosity of $\mathcal{L}_{\rm int}$ = 300 fb^{-1}. This luminosity corresponds to about three years of data-taking at high luminosity. The number of events can be increased by approximately a factor of four if the $\rm Z \rightarrow e^+e^-$ decay channel is also taken into account as discussed in Ref. [3]. Although resolutions and radiative tails are different for electron and muon final states, the dominant statistical error is cut approximately in half. Two examples are shown in the Figs. 5 and 6. Each invariant mass distribution is fitted with a Gaussian below a Higgs boson mass of 200 GeV/c^2 and a Breit-Wigner distribution otherwise. The results are given in Table 2. The absolute energy scale determination will be an important systematic uncertainty which can be deduced by normalizing the energy scale to the precisely known Z mass. In the investigated $\rm H \rightarrow ZZ^\star \rightarrow \mu^+\mu^-\mu^+\mu^-$ reaction, the muon pair from each Z decay can be conveniently used for normalization. A description of the Higgs mass determination of the other LHC experiment, ATLAS, can be found in [4].

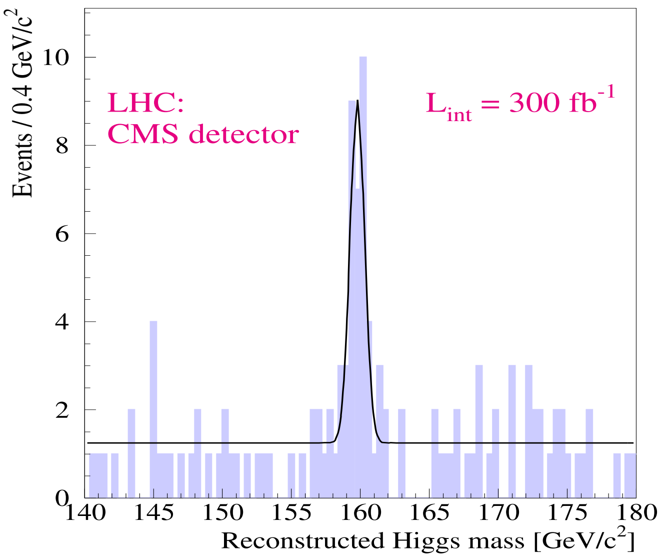

Figure 5: Reconstructed Higgs boson mass in the $\mu^+\mu^-\mu^+\mu^-$ channel as obtained from a CMS simulation. For a simulated mass of 160 GeV/c^2 $m_{\mathrm{H}}^{\mathrm{rec}} = 159.8 \pm 0.1$ GeV/c^2 is reconstructed. This is one example out of 100 simulated test experiments.

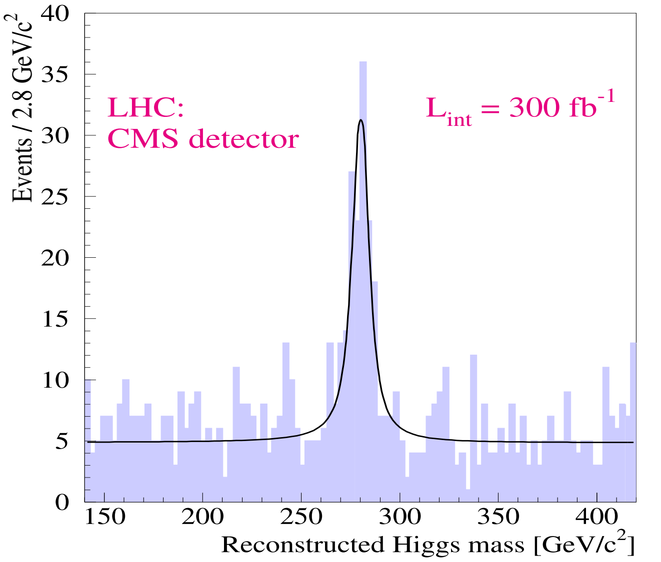

Figure 6: Reconstructed Higgs boson mass in the $\mu^+\mu^-\mu^+\mu^-$ channel as obtained from a CMS simulation: For a simulated mass of 280 GeV/c^2 $m_{\mathrm{H}}^{\mathrm{rec}} = 280.2 \pm 0.6$ GeV/c^2 is reconstruected. This is one example out of 100 simulated test experiments.

Mass	120	140	160	180	200	220	240	260	280	300	320	340
m_{G}	120.0	139.9	160.0	179.9	—	—	—	—	—	—	—	—
Δm_{G}	0.38	0.13	0.23	0.24	—	—	—	—	—	—	—	—
m_{BW}	—	—	—	—	199.9	219.9	239.8	259.9	279.9	299.8	320.1	340.3
Δm_{BW}	—	—	—	—	0.14	0.20	0.28	0.44	0.58	0.81	1.1	1.5

Table 2: Simulated masses, reconstructed masses for a Gaussian (G) and Breit-Wigner (BW) fit and their errors for the LHC study in the $\mu^+\mu^-\mu^+\mu^-$ channel. All values are given in GeV/c^2. The masses and their statistical errors are the averages from 100 simulated test experiments.

3 Comparison with LC Mass Reconstruction

This LHC study has been compared with two LC studies which have been extrapolated to the mass range investigated here. The first study has exploited the production channel $e^+e^- \to ZH$, where the Z decays either to e^+e^- or $\mu^+\mu^-$. The reconstruction of the recoiling mass to the $\ell^+\ell^-$ pair from the Z decay is used for the Higgs boson mass reconstruction. The two leptons from the Z boson decay can be reconstructed with a high precision [5]. In a second study the $ZH \to b\bar{b}q\bar{q}$ channel was investigated [6]. In this channel the Higgs boson mass was calculated from the invariant mass of the $b\bar{b}$ system. At the LC, the effective center-of-mass energy varies slightly due to beamstrahlung. The beamstrahlung is included in all LC simulations and has only a small effect on the reconstructed mass distributions.

LHC: $\mu\mu\mu\mu$	S: 120 - 340 GeV/c^2 (CMS detector response)
LC: H$\ell\ell$	S: 120 - 160 GeV/c^2 $\sqrt{s} = 350$ GeV [5]
	E: $\Delta m_H = \sqrt{\sigma_0/\sigma_{\mathrm{H}}} \times \Delta m_0$ for $\sqrt{s} = 350$ and 500 GeV
LC: $b\bar{b}q\bar{q}$	S: 120 GeV/c^2 at $\sqrt{s} = 500$ GeV [6]
	E: $\Delta m_{\mathrm{H}} = \sqrt{\mathrm{BR}_0(\mathrm{H} \to b\bar{b})/\mathrm{BR}_{\mathrm{H}}(\mathrm{H} \to b\bar{b})} \times \Delta m_0$

Table 3: Summary of simulations S and extrapolations E. The variables with index zero are the values at the simulated Higgs boson mass of 120 GeV/c^2, and those with index H the values at higher Higgs boson masses used for the extrapolation.

Figure 7 compares these LC studies with the Higgs boson mass determination for the LHC. The notations LC350 and LC500 are used for an LC running at a center-of-mass energies $\sqrt{s} = 350$ and 500 GeV, respectively. Curve 1 is determined from the simulation described in Sec. 2. The worse precision around 170 GeV/c^2 is due to the suppressed $H \to ZZ^\star$ branching fraction. The increasing uncertainty at higher masses is due to the smaller production cross section, i.e. event rate, which can be approximated by the simple relation: the statistical error on the mass determination is roughly equal to the mass resolution (instrumental and natural width) divided by $\sqrt{N_{\mathrm{expected}}}$, where N_{expected} is the expected number of events. Curves 2 and 3 are extrapolations from simulations around $m_{\mathrm{H}} = 120$ GeV/c^2 for the recoiling mass from the lepton pair [5]. Curve 4 is based on the direct $\mathrm{H} \to \mathrm{b\bar{b}}$ mass reconstruction [6]. The different studies are summarized in Table 3.

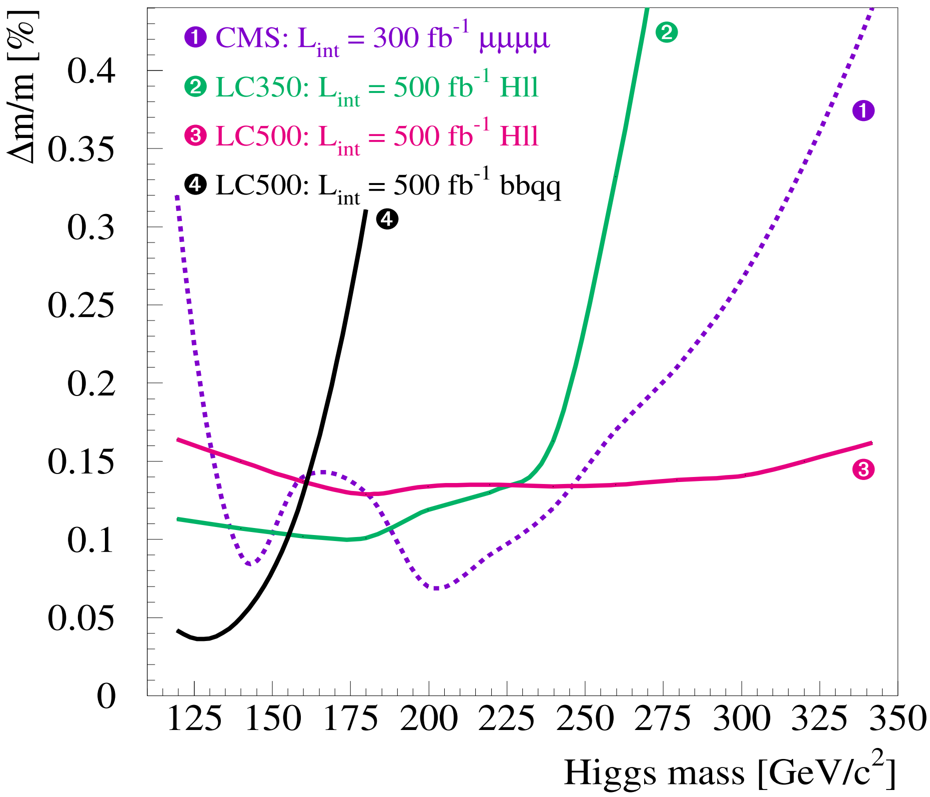

Figure 7: Relative statistical error on the measurement of the SM Higgs mass versus mass for the LHC (CMS detector) and an LC.

Figure 7 shows a strong dependence of the Higgs boson mass precision on $\mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}^\star)$ at the LHC. For masses larger than 200 GeV/c^2 the natural Higgs width increases quickly. The inclusion of the electron final states and in particular other Higgs boson decay modes, as shown in Fig. 2 would improve the precision. the dominant statistical error is cut approximately in half. The reconstruction of the recoiling mass at an LC is different for the two center-of-mass energies. For low Higgs boson masses the precision of LC350 is higher due to the larger expected event rate, but cannot cover the whole mass range considered. The precision is nearly constant at an LC500. For Higgs boson masses below 160 GeV/c^2 the decay channel $\mathrm{H} \to \mathrm{b\bar{b}}$ is an alternative for the LC Higgs boson mass determination.

4 Higgs Boson Width Determination

In addition to the Higgs boson mass determination, the determination of the Higgs boson width may allow a Higgs boson of an extended model to be distinguished from a SM Higgs boson. For the direct width determination at the LHC in the four-muon channel, the detector response simulation and event selection is applied as described in Sec. 2. The reconstructed four-muon mass distribution is then fitted, as shown in Figs. 5 and 6 for two Higgs boson mass values, and all results are given in Table 4. First, the detector resolution is determined by fitting the Higgs boson width in a simulation where its intrinsic width is set to zero. Second, this detector resolution can be experimentally determined directly from a reconstruction of the width of the Z bosons coming from the Higgs boson decay in the four-muon channel. The advantage is that the same muons are used for the determination of the detector resolution and the Higgs boson width. For an example of a 200 GeV/c^2 Higgs boson the detector resolution (Table 4) is confirmed independently by reconstruction of the Z mass in the Higgs boson simulation.

For masses below 200 GeV/c^2 the detector resolution dominates and a Gaussian fit function is used, while for higher masses a Breit-Wigner distribution convoluted with the detector resolution is fitted. Figure 8 shows the expected statistical accuracy, defined as the error on the fit normalized to the natural width of the SM Higgs boson. The direct LHC determination (curve 1, CMS detector), the indirect determination for an LC (curve 2) and the LHC (curve 3) are shown.

Mass	120	140	160	180	200	220	240	260	280	300	320	340
$\Gamma_{\mathrm{H}}^{\mathrm{SM}}$	0.004	0.008	0.077	0.63	1.4	2.3	3.4	4.8	6.5	8.5	10.9	13.8
Det. resolution	0.35	0.63	0.63	0.76	0.96	1.1	1.4	1.6	1.8	2.0	2.3	2.4
σ	0.31	0.65	0.62	0.97	—	—	—	—	—	—	—	—
$\Delta\sigma$	0.27	0.12	0.22	0.24	—	—	—	—	—	—	—	—
Γ	—	—	—	—	1.6	2.7	4.1	4.8	7.5	9.5	12.8	15.5
$\Delta\Gamma$	—	—	—	—	0.29	0.41	0.64	0.85	1.3	1.6	2.2	2.7

Table 4: Simulated masses, reconstructed widths and their errors, and theoretical widths. The simulated values are the averages for 100 test experiments for the LHC study in the $\mu^+\mu^-\mu^+\mu^-$ channel. σ is the Gaussian fit result, while Γ is the fit result from a Breit-Wigner convoluted with the detector resolution. All values are given in GeV/c^2.

For a SM Higgs boson mass below about 180 GeV/c^2, the predicted width [1] becomes much smaller than the detector resolution. In this range a direct width reconstruction is not possible and only an upper limit can be derived.

The indirect methods are based on the W-fusion production $\mathrm{W^+W^-} \to \mathrm{H}$. The analysis of reference [7] (curve 3) makes use of several Higgs boson production processes. However some signal production channels and their background reactions were studied only at parton level in contrast to the detector simulations performed for the direct mass and width reconstruction. In this approach [7], the uncertainties of the coupling measurement are analyzed to obtain the uncertainty on the total width. Two assumptions are made, which are fulfilled in the SM, but require detailed investigation in extensions of the SM. Firstly, the couplings of the Higgs boson to b- and τ-pairs are assumed to be given by the mass ratios and secondly, the total width is assumed to be dominated by the $b\bar{b}$, $\tau^+\tau^-$, W^+W^-, ZZ, gg and $\gamma\gamma$ decay modes. The total width Γ is then extracted from the determination of the $q\bar{q} \to q\bar{q}H$ ($H \to W^+W^-$) cross section. The maximal sensitivity for indirect LHC study is obtained for a Higgs boson mass of 170 GeV/c^2 at the maximum $H \to W^+W^-$ branching fraction, as shown in Fig. 2.

In the LC case [8], and in contrast to the indirect LHC study, the decay $H \to b\bar{b}$ is considered (curve 2). Therefore, in the mass region below 150 GeV/c^2, where the $H \to W^+W^-$ branching fraction falls off rapidly, as seen from Fig. 8, the LC curve shows a much higher sensitivity compared to the LHC study. The current direct and indirect studies for the LHC and an LC are complementary. Figure 8 shows that for the whole mass range 120 to 340 GeV/c^2 the SM Higgs boson width can be measured with a relative error of about 10%.

In future studies, the relative errors should improve further, when for the LHC and LC additional channels, which use other decay modes, are investigated. For the current indirect LHC study a total luminosity of 200 fb $^{-1}$ is assumed and for a larger integrated luminosity the curve 3 would not change much for masses above 140 GeV/c^2, since the Higgs branching ratio into W^+W^- pairs is large and thus systematic errors dominate [9].

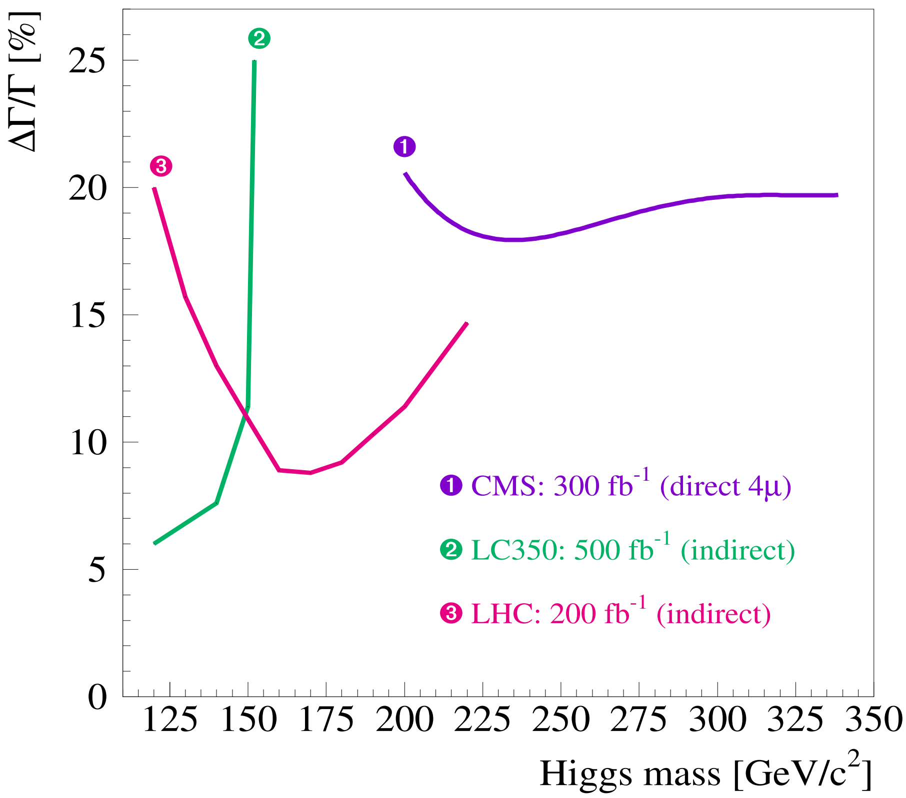

Figure 8: Relative error of the width versus mass of the Standard Model Higgs boson. Curve 1 shows the direct width determination and curves 2 and 3 are results from indirect width determinations.

5 Conclusions

We have investigated the accuracy with which the Higgs boson mass and width could be measured at the LHC in the four-muon channel. These are compared with the results from LC studies extrapolated into the range 120 - 340 GeV/c^2 in the case of the mass determination. The accuracy of the mass measurement is limited by $\sigma \times$ BR of the corresponding Higgs boson decay into ZZ and $\mathrm{b\bar{b}}$ for the $\mathrm{H \to ZZ^\star \to \mu^+\mu^-\mu^+\mu^-}$ (LHC) and the $\mathrm{e^+e^- \to HZ \to b\bar{b}q\bar{q}}$ (LC) channels, respectively. In contrast, determinations through the LC $\mathrm{H}\ell\ell$ channel are independent of the Higgs boson decay mode. In the latter case the event rate depends only on the cross section, which decreases slowly with the Higgs boson mass and falls off rapidly at the kinematic production limit. For a large mass range the mass precisions of the LHC and an LC are comparable in the considered channels, and amount to about 0.1%.

For the Higgs boson width determination we show that direct measurements and indirect methods cover the mass range 120 - 340 GeV/c^2 with a relative error of about 10%. The overall precision will be higher when all Higgs decay modes are investigated.

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