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

Volker Drollinger, André Sopczak[a]
University of Karlsruhe

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 is 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.

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. First, results from an LHC study are given for the gluon fusion process where the Higgs boson mass is reconstructed by calculating the invariant mass of the four-muon final state. The simulation is based on the CMS detector response parametrization CMSJET [1]. The selection is outlined in Refs. [2,3] and it suppresses effectively the background.

The invariant four-muon mass distribution is shown in Fig. 1 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. The number of background events is fairly 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. 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. An example is shown in Fig. 2 and all results are given in Table 1. A description of the Higgs mass determination of the other LHC experiment, ATLAS, can be found in Ref. [4].

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 1: Simulated and reconstructed masses for a Gaussian (G) and Breit-Wigner (BW) fit and their statistical 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.

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 Higgsstrahlung production $\mathrm{e^+e^-} \to \mathrm{ZH}$, where the Z decays either to $\mathrm{e^+e^-}$ 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 $\mathrm{ZH} \to \mathrm{b\bar{b}q\bar{q}}$ channel was investigated [6]. In this channel the Higgs boson mass was calculated from the invariant mass of the $\mathrm{b\bar{b}}$ system. Beamstrahlung is included in all LC simulations and has only a small effect on the reconstructed mass distributions. Details of the extrapolations are given in Table 2. Figure 3 compares these LC studies with the Higgs boson mass determination for the LHC.

[a] speaker

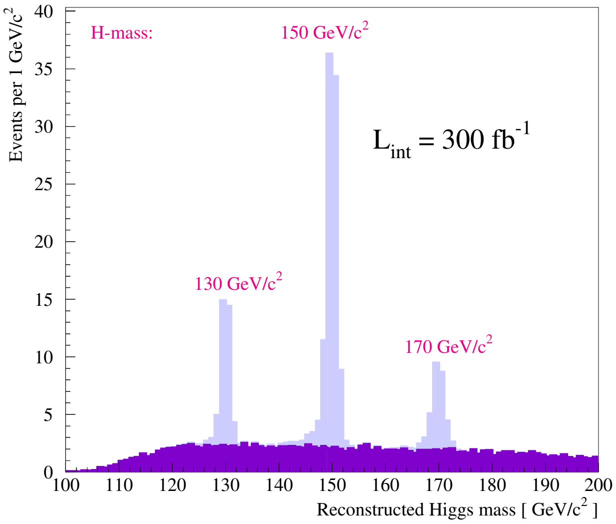

Figure 1: Expected signal and background in the CMS experiment for Higgs boson masses of 130, 150 and 170 GeV/c^2 in the $\mu^+\mu^-\mu^+\mu^-$ channel for an integrated luminosity of 300 fb^{-1}.

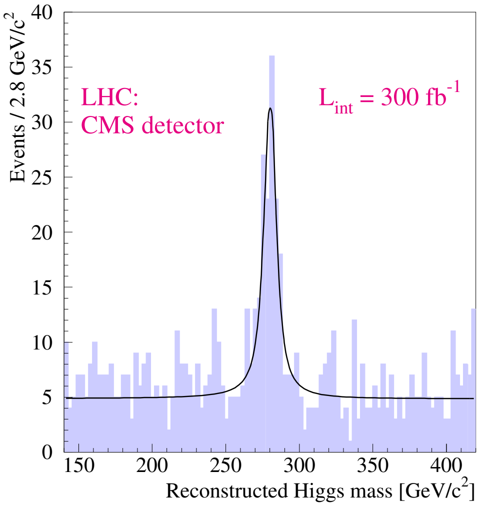

Figure 2: Reconstructed Higgs boson mass in the $\mu^+\mu^-\mu^+\mu^-$ channel as obtained from a CMS simulation (out of 100). For a simulated mass of 280 GeV/c^2, $m_{\rm H}^{\rm rec}$ = 280.2 $\pm$ 0.6 GeV/c^2 is reconstructed.

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: $\Delta m_H = \sqrt{\sigma_0/\sigma_{\rm H}} \times \Delta m_0$ for $\sqrt{s} = 350$ and 500 GeV
LC: b$\bar{\rm b}$q$\bar{\rm q}$	S: 120 GeV/c^2 at $\sqrt{s} = 500$ GeV [6]
	E: $\Delta m_{\rm H} = \sqrt{{\rm BR}_0({\rm H}\to{\rm b\bar{b}})/{\rm BR}_{\rm H}({\rm H}\to{\rm b\bar{b}})} \times \Delta m_0$

Table 2: 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.

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 before.

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 and results are given in Table 3. Figure 4 shows the expected accuracy, defined as the error on the fit normalized to the natural width of the SM Higgs boson (curve 1, CMS detector). For a SM Higgs boson mass below about 180 GeV/c^2, the predicted width [7] 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.

In addition to the direct determination, results from indirect determinations for an LC (curve 2) and for the LHC (curve 3) are shown in Fig. 4. The indirect methods are based on the W-fusion production $\rm W^+W^- \to H$. In the LC case[8], and in contrast to the indirect LHC study, only the decay $\rm H \to b\bar{b}$ is considered (curve 2). The analysis of Ref. [9] (curve 3) makes use of several Higgs boson production processes. In the mass region below 150 GeV/c^2, where the $\rm H \to W^+W^-$ branching fraction falls off rapidly, the LC has a much higher sensitivity than the LHC. The current direct and indirect studies for the LHC and an LC are complementary.

In future studies, the relative errors should improve further when, for the LHC and LC, additional channels which use other decay modes are investigated.

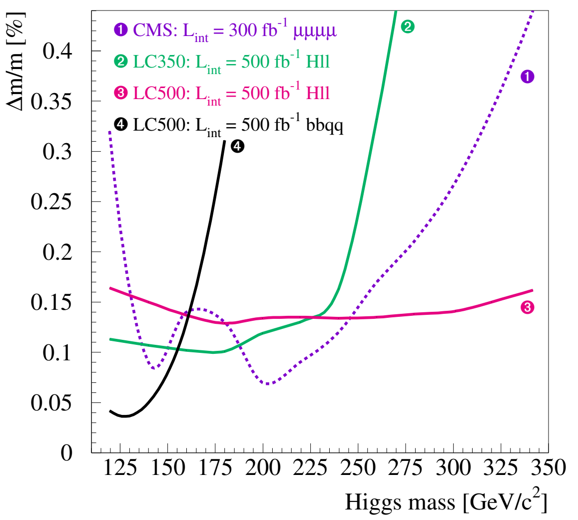

Figure 3: Relative error on the measurement of the SM Higgs mass versus mass for the LHC (CMS simulation) and an LC.

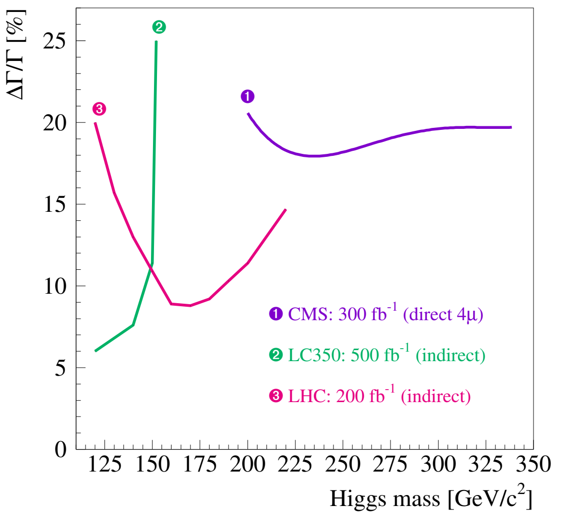

Figure 4: Relative error on the measurement of the SM Higgs width versus mass for the LHC (CMS simulation and indirect determination) and an LC.

Mass	120	140	160	180	200	220	240	260	280	300	320	340
Γ_H^{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 3: Simulated and reconstructed widths and their statistical 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.

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 $b\bar{b}$ for the $H \to ZZ^\star \to \mu^+\mu^-\mu^+\mu^-$ (LHC) and the $e^+e^- \to HZ \to b\bar{b}q\bar{q}$ (LC) channels, respectively. In contrast, determinations through the LC $H\ell\ell$ 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.

References

1. S. Abdullin, A. Khanov, N. Stepanov, CMSJET version of September 15, 1998, CMS TN/94-180.
2. V. Drollinger, A. Sopczak, LC-PHSM-2000-037, IEKP-KA/2000-15, in press EPJ.
3. I. Iashvili, R. Kinnunen, A. Nikitenko, D. Denegri, Study of the $\mathrm{H} \rightarrow \mathrm{ZZ}^{\star} \rightarrow 4\ell^{\pm}$ Channel in CMS, CMS TN/95-059;
   V. Drollinger, Studies of Higgs Boson Searches for the CMS Experiment, IEKP-KA/97-11, Diploma Thesis.
4. ATLAS Collaboration, Detector and Physics performance Technical Design Report, CERN/LHCC/99-15, vol. 2, Chapter 19.
5. P. Garcia-Abia and W. Lohmann, Measurement of the Higgs Cross Section and Mass with Linear Colliders, hep-ex/9908065.
6. A. Juste, M_{H} Determination from Direct Reconstruction of ZH ($\mathrm{Z} \rightarrow \mathrm{q\bar{q}}$), hep-ph/9912041.
7. A. Djouadi, J. Kalinowski and M. Spira, HDECAY: a Program for Higgs Boson Decays in the Standard Model and its Supersymmetric Extension, hep-ph/9704448.
8. K. Desch, N. Meyer, presentations at the LC Workshop, Obernai, France, Oct. 1999 and the LC Workshop, Padova, Italy, May 2000.
9. D. Zeppenfeld, et al., Measuring the Higgs boson coupling at the LHC, Phys. Rev. D62 (2000) 13009.