Fermi National Accelerator Laboratory

FERMILAB-Conf-87/138-T
September 1987

# HIGGS SEARCH AT FUTURE COLLIDERS

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## 1. INTRODUCTION

In the the last year more than 250 papers have been published which had in their title the keyword 'Higgs'. This remarkable activity is, of course, well motivated. The Higgs boson is the main missing ingredient of the standard model. Its discovery would give important experimental information on the nature of the electroweak symmetry breaking mechanism. Alternatively the absence of the Higgs below 1 $TeV$ will give experimental evidence for the existence of deeper structure of elementary particles [1].

At present there is no direct and/or indirect experimental evidence for the existence of the Higgs particle. The theory is unable to predict its mass. Low energy experiments like studies of nuclear reactions ($0^+ - 0^+$ transitions, angular correlations, neutron scattering), $\pi^+ \rightarrow e^+\nu\phi$ , $K^+ \rightarrow \pi^+\phi$ and $\eta\prime \rightarrow \eta\phi$ decay properties could exclude the mass range $0 - 400\ MeV$. Recent analyses of the $\Upsilon \rightarrow H\ \gamma$ decay have concluded that the Higgs mass cannot be in the mass range $0.5 - 3.5\ GeV$ . The only region not covered is a small mass interval around the kaon mass. At LEP-I, a mass limit $\approx 60\ GeV$ will be attained while at LEP-II the mass limit of $\approx 85\ GeV$ can be established [2]. Additional information we have on the Higgs sector is the measured value of the rho parameter $\rho = m_W^2/m_Z^2/cos^2\theta_W$. It is equal to 1 within the 5 percent experimental error ( $\rho \approx 1.03 \pm 0.05$), the value predicted by the standard model with one or more doublets . The data support the minimal Higgs structure. It is likely that Nature does not prefer the proliferation of Higgs bosons .

Some attempts have been made recently to understand certain features of the scalar sector without using perturbation theory. The $\phi^4$ field theory is a free-field theory. Perturbative renormalization group analysis indiates that presumably it remains free even in the presence of weakly coupled gauge fields. However, it can be considered as an effective field theory with a cut-off. In this case the renormalized perturbation theory of low energy processes is valid up to $O(E^2/\Lambda^2)$ corrections where $E$ is the value of the typical energy scale of the process and $\Lambda$ is the cut-off in momentum space related to the Higgs mass. With the measurement of the value of the Higgs mass, we can obtain the value of the cut-off providing us with the limit of the validity of the theory. In a recent paper, Lüscher and Weisz [3] studied $\phi^4$ field theory in the symmetric phase and they have found that the value of the cut-off becomes equal to the value of the Higgs mass close to the region where perturbative unitarity is violated. This numerical agreement is not apriori necessary and might give further support to the validity of the arguments based on perturbative unitarity.

## 2. HIGGS SEARCH AT SSC, LHC AND CLIC

It is an exciting prospect that the next generation of proton-proton colliders the LHC ($\sqrt{s} = 16.5\ TeV$) and the SSC ($\sqrt{s} = 40\ TeV$) and perhaps the 'post LEP' $e^+e^-$ colliders like CLIC ($\sqrt{s} = 2\ TeV$), will reach the necessary energies where decisive experimental information can be gained on the existence of the Higgs boson. The Higgs mass range can be explored up to $O(1\ TeV)$, a value close to the unitarity limit. Furthermore, direct experimental information can be obtained on the scattering of longitudinal weak vector bosons. This is the key process in the study of the electroweak symmetry breaking mechanism. This is the reaction where the effects which motivated the introduction of the Higgs



*To appear in the Proceedings of the "International Europhysics Conference on High Energy Physics", Uppsala, Sweden, June 25–July 1, 1987.

boson will show up in leading order: without the contribution of the Higgs boson, the cross-section of this process will grow and violate the unitarity limit. The Higgs boson appears as an $s$-channel resonance and its coupling strength to longitudinal gauge bosons grows like $O(m_H{}^2/m_W{}^2)$. At LHC, SSC and CLIC, the effective luminosity of the longitudinal $W$ bosons is high enough to give measurable rates with the designed luminosity of $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$. One of the main goal of recent workshop studies for LHC, SSC and CLIC was to establish the feasibility of a Higgs search up to the 1 $TeV$ regime.

Let us summarize the most significant new results of these studies (see the recent reports by G. Altarelli, by D. Froideveux [4] at the La Thuile Workshop (1987, LHC, CLIC) and by J. Gunion et al. [5] at the Madison Worshop (1987,SSC)). One can naturally devide the discussions of the Higgs search (after LEP-II) into three mass regions

Intermediate mass region $m_W < m_H < 2m_W$
Heavy Higgs mass region $2m_W < m_H < 0.8\ TeV$
Strong interaction region $m_H > 0.8\ TeV$.

This classification is useful for both $pp$ and $e^+e^-$ machines. There are four main production mechanisms for hadron colliders : gluon-gluon fusion, associated production with heavy quarks, associated production with weak gauge bosons and $WW/ZZ$ fusion. For $e^+e^-$ colliders only the last mechanism is relevant.

At $e^+e^-$ colliders, jet spectroscopy appears to be the best method for the Higgs search [3]. At hadron colliders, however, in all the three mass regions it is almost impossible to find the Higgs in its hadronic decay into heavy quarks. The QCD production of heavy quark pairs is overwhelming [6].

The decay into a heavy quark pair is the dominant mode in the intermediate mass region. Therefore, the tentative conclusion has been drawn in earlier studies that the observation of the 'intermediate' Higgs boson at hadron colliders may not be feasible. However, the prospects for observing the intermediate Higgs boson improve significantly in the heavy top quark case of favoured by recent Argus data on $B^0 - \bar{B}^0$ mixing and UA1 data on isolated lepton production. If $m_t < m_H/2$, then the dominant decay mode is the decay into $b\bar{b}$. This is itself an advantage since the mass resolution and tagging efficiency is better for $b$-quarks than for $t$-quarks. Moreover, the branching ratio into $\tau^+\tau^-$ and $\gamma\gamma$ increases to $\approx 4 \times 10^{-1}$ and $\approx (1-5) \times 10^{-4}$, respectively, giving promising rates and good signatures for detection. In a recent paper by R.K. Ellis et al. [7] it has been shown that the prodution mechanism with $gg \to Hg$ with subsequent decay of the Higgs boson into $\tau^+\tau^-$ gives measurable rate and good signal to background ratio assuming $\approx 10\%$ mass resolution in the measurement of the invariant mass of the $\tau$ pairs. The main observation of the paper is that mass resolution improves significantly by considering Higgs production with large transverse momentum. A detailed study for the three most important decay modes ($b\bar{b}, \tau^+\tau^-$ and $\gamma\gamma$) has revealed that they tend to give observable signatures in complementary mass interval[8].

At CLIC, the observation of an 'intermediate' Higgs boson is rather easy in heavy quark jet final states [4].

In the heavy Higgs region the decay $H \to ZZ$ with both Z's decaying to $e$'s or $\mu$'s gives an unmistakable signature of Higgs production. The crucial issue here is to establish the value of the discovery limit in the Higgs mass. An upper limit of $m_H \approx 0.6\ TeV$ has been obtained at LHC [4] while it is $m_H \approx 0.8\ TeV$ at SSC [5]. Studies are in progress at CERN and at SSC workshops to consider a higher luminosity option, $O(10^5 pb^{-1})$, with special high resolution lepton detectors. The aim is to push the discovery limit to larger Higgs mass values. The decay mode $H \to WW$ with one $W$ decaying into leptons and with the other decaying into jets is overwhelmed with huge QCD background of $W + jets$ production. When the Higgs boson is produced by $WW$ fusion mechanism it is produced in association with forward-backward jets at small angles and transverse momentum of the $O(m_W/2)$. It has been argued that the background can be suppressed by tagging these forward jets. Whether this is a realistic idea requires further study. This is an important question since this decay mode has a larger branching ratio, therefore, the discovery limit could be extended up to 0.8 $TeV$ at the LHC and $1.0 - 1.2\ TeV$ at the SSC. The third useful decay mode of the heavy Higgs boson is provided by the decay $H \to ZZ$ with one $Z$ decaying into $\nu\bar{\nu}$ and with the other $Z$ decaying into $e$ or $\mu$ pairs. The branching ratio of this channel is also relatively large. However, it has a large background from three different sources . There is $q\bar{q} \to ZZ$ continuum production of $Z$ pairs as well as continuum production of $WZ$ pairs when the charged lepton of the $W \to l\nu$ decay remains undetected. The most difficult background however comes from the contribution of $Z + 2jets$ when one of the jets remains undetected giving large unbalanced transverse momentum. Detection of this signal requires central production of the lepton pairs and crack-free detectors. While this is an exacting demand, estimates indicate that the observation of the Higgs particle in this channel should be feasible. It is unlikely that this decay mode could be used to extend the discovery limit to higher values than the value obtained in the case when both $Z$ bosons decay to charged lepton pairs.

At CLIC, heavy Higgs production can be best observed in four jets final states. The background processes $\gamma\gamma \to W^+W^-, \gamma W \to WZ, \gamma\gamma \to$ four QCD jets etc. have been calculated [4]. They are significant, but their suppression does not cause any special problem. At CLIC, the discovery limit (assuming luminosity of $\mathcal{L} \approx 10^{32} cm^{-2} s^{-1}$) is about $m_H < 0.8\ TeV$

Of course, it would be very interesting to be able to 'peek' into the regime of the strongly interacting $W_L W_L$ sector which is expected to emerge for $m_H > 0.8\ TeV$. The theoretical analysis of this regime requires at least a partial understanding of two questions. First, we have to analyze whether the effective $W$-approximation, which gives the theoretical framework to relate the machine luminosity to the longitudinal gauge boson luminosity remains valid in the case of strongly interacting gauge bosons. The question has been positively answered recently [9]. To formulate the effective $W$ approximation in the axial gauge proved to be very powerful. The next important question concerns whether we can estimate reliably the cross-sections of $WW$ scattering at $\sqrt{s} > 0.8\ TeV$. With some assumptions concerning s-channel resonances, the answer is affirmative also to this question. The key observation is that the longitudinal gauge bosons are the Goldstone bosons of the Higgs sector, therefore, the soft boson theorems ( similar to soft pion theorems) determine the magnitude of the cross-section in the region around 1 $TeV$ centre of mass energy [10].

From the discussion of the heavy Higgs region, it is clear that with the present design parameters of LHC ( even of SSC) we can obtain only indicative experimental information on this region. A detailed exploration requires even higher energy.

Acknowledgements. I would like to thank G. Altarelli, R. K. Ellis, G. Kane, R. Peccei, M. Soldate and W.J. Stirling for discussions. I also thank the Central Research Intitute of Physics, Budapest, for extended leave of absence.

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