Remarks on Higgs boson production

A. Dobrovolskaya, V. Novikov
ITEP 117218 Moscow, Russia

Abstract

We demonstrate that Higgs boson production in fusion processes is accompanied by large azimuthal asymmetry. This asymmetry can be used to facilitate detection of Higgs boson events. We also demonstrate that the double Higgs boson production at threshold is a very appropriate process to test the existence of new physics at higher energy.
1 Introduction.

In the modern theory of electroweak interaction Higgs boson plays the very important role at high energies. Without Higgs bosons the scattering amplitudes of massive $W$ and $Z$ bosons grow with energy and violate unitarity. Diagrams with Higgs bosons exchange improve drastically this high-energy behaviour and protect amplitudes from violation of unitarity \cite{1}.

In contrast to the high-energy phenomena the contribution of Higgs bosons into low-energy processes is very small according to the Veltman’s screening theorem \cite{2}. As a result a little is known about Higgs boson properties from the current experiments. From all electroweak measurements at LEP1, SLC and LEP2 it follows that \cite{3}

$$70 \text{ GeV} < m_h < 465 \text{ GeV} \quad 95\% \text{c.l.}$$

and that is it.

The main mission of the future experiments is to discover Higgs boson and to study its interactions.

There are two different classes of such interactions. The first one is the class of Higgs couplings with quarks, leptons, $W$ and $Z$ bosons. These couplings are fixed by renormalizability of the theory. Any change in Yukawa interaction of Higgs boson with top quark or with $W$ and $Z$ bosons would immediately destroy the agreement of the loop calculation with precision electroweak data even if one introduce some reasonable effective cut-off. Any new physics can’t produce sizable change of these effective couplings from canonical ones.

The second class includes higgs self-interactions. In the Standard Model $3H$ and $4H$ vertices are determined by the value of higgs condensate and by the value of higgs mass. Though renormalizability works in this case as well, the new interactions can change $3$- and $4$-effective coupling constants from the canonical values and this change will produce only tiny effect for low energy physics. So phenomenologically Higgs self-interaction coupling constants are independent parameters. Experimental study of these parameters would provide information about new physics at higher scales.

In this talk I would like to present a few remarks concerning Higgs boson production and the ways to study effective Higgs boson self-interaction.
2 One Higgs boson production.

For the moderate value of Higgs mass \((m_h < 200 \, \text{Gev})\) the main mechanism for Higgs boson production in colliders is Higgs-strahlung process \(e^+e^- \rightarrow (Z^*) \rightarrow ZH\). The corresponding cross-sections drops as \(1/s\), where \(s\) is the c.m. energy of beams.

For higher higgs mass the main mechanism for \(H\)-production is the fusion mechanism. In this case at first stage the effective \(W\), \(Z\) (or gluon) beams are produced by colliding particles and then at the second stage Higgs bosons are produced in the collisions of \(WW\), \(ZZ\) or gluon-gluon effective beams. The corresponding cross sections have very weak dependence on energy

\[
\sigma \sim \text{const} \cdot \log(s/m_h^2) .
\]

For example in \(e^+e^-\) collision the \(WW\)-fusion cross section of \(H\)-production varies from 10 to 100 fb for all realistic values of \(s/m_h^2\). This cross section is two or three order of magnitude smaller than \(e^+e^-\) annihilation cross section into hadrons. So it is rather difficult problem to extract the events with Higgs boson production from the vast background events.

Our first remark is that the best way to look for higgs events is not to measure the total cross section but the special \(\phi\) dependent terms in the differential cross sections. Here \(\phi\) is the azimuthal angle between scattering planes of initial scattered fermions.

Indeed in the case of fusion production of Higgs bosons the cross section has a very strong azimuthal asymmetry \[4\]

\[
\sigma_H = \sigma_1(1 + A_1 \cos \phi + A_2 \cos 2\phi) \tag{1}
\]

It is important that numerically the factor \(A_1\) is very large in the whole region of expected Higgs mass and beam energies \(s\) \[4, 5\]

\[
A_1 \sim 0.5 - 0.7 .
\]

(factor \(A_2\) is much smaller; \(A_2 \sim 10^{-2}\)).

Parametrically \(A_1\) and \(A_2\) depend on \(m_h\) and energy \(s\) : \(A = A(m_h, s)\). For heavy higgs and large energy \(s \gg m_h^2\) one can find \[4\]

\[
A_1 = \pi^2(m_W^2/m_H^2) ,
\]

\[
A_2 \sim (m_W^2/m_H^2)^2 .
\]
So in the case of $H$-production the first and the second terms (harmonics) in eq.(1) are of the same order of magnitude.

For the background events the cross section is also a sum of three harmonics

$$\sigma_{Bkgd} = \sigma_2(1 + B_1 \cos \phi + B_2 \cos 2\phi)$$

(2)

but the value of the coefficients in eq.(2) is quite different. The first term in eq. (2) - the total cross section $\sigma_2$ - is two or three order of magnitude larger than $\sigma_1$ in eq.(1). The third term is also large; as a rule $B_2 \sim 1$. As for the second term in eq.(2) it is extremely small. Parametrically factor $B_1$ is of the order of

$$B_1 \sim <q^2>/ <s> ,$$

where $<s>$ is the mean value of energy of the effective $W$ beams and $<q^2>$ is the mean value of virtual momenta of $W$. Thus for production of light hadron

$$B_1 \sim \Lambda_{QCD}^2 / <s> \leq 10^{-4} ,$$

i.e. it is small correction to the corresponding $\phi$-dependent term in $H$-production cross section. For lepton $L$ and heavy quark $Q$ production

$$B_1 \sim m_{L,Q}^2 / <s>$$

and also is a small correction to the $H$-production for all cases with one exception - top-quark production has to be considered separately.

So our statement is that the best way to look for $H$-production events is to measure the first harmonic, i.e. $\cos \phi$ term in the differential cross section but not the total cross section. It seems that experimentally it is quite possible to separate one harmonics from another one.

The physical reason for such behaviour is rather simple. The $\phi$-dependent terms in eqs.(1)-(2) originate from the interference of the amplitudes with different helicities of $W(Z)$ bosons. The considered $\cos \phi$ term corresponds to spin-flip interference from helicity 1 to helicity 0 states. The polarization vector $\varepsilon_{\mu}(0)$ of $W$, $Z$ or gluon corresponding to the state with helicity 0 is proportional to the momenta $q$

$$\varepsilon_\mu(0) = q_\mu / \sqrt{-q^2} + O(\sqrt{-q^2} / s)$$

(3)

Vector bosons interact with conserved or partially conserved currents of fermions, as a result the large component $\sim q_\mu$ in eq.(3) is washed out from
the amplitudes of quarks and leptons production. As for the $HWW$ or $HZZ$ vertices they are not transversal and large components $\sim q_\mu$ gives 100% contribution into $H$-production.

We repeat in conclusion that if one can separate experimentally three harmonics from each other he will find that the first harmonic is enriched enormously by Higgs boson events.

3 Experimental study of Higgs selfinteraction.

Self-interaction coupling constants can be measured only in the multy Higgs bosons processes. The first nontrivial sample is double Higgs boson production.

Corresponding cross section is very small in SM

$\sigma(2H) \sim 1\text{fb}$ for $\sqrt{s} \sim 1\text{ TeV}$, $m_H \sim 100\text{ GeV}$.

Nevertheless sooner or later we have to start to study such processes.

Our second remark is that ”new physics” beyond the SM can enhance enormously the double Higgs boson production at threshold.

Indeed in the SM we have a very special choice of parameters. Potential for Higgs boson doublet $\phi$ depends only on two parameters

$V_{SM} = \frac{\lambda}{4}(|\phi\phi^+|^2 - \eta^2)^2$ \hspace{1cm} (4)

On the other hand $V$ describes four physical quantities:

- higgs condensate: $\eta$;
- higgs mass: $m_H = \lambda\eta$;
- 3H vertex: $\lambda_3\left(\frac{m_H^2}{2\eta}\right)H^3$; \hspace{1cm} (5)
- 4H vertex: $\lambda_4\left(\frac{m_H^2}{8\eta^2}\right)H^4$.

In the case of Standard Model

$\lambda_3 = \lambda_4 \equiv 1$

For general effective potential $V_{eff}(\phi)$ these four parameters are independent and factors $\lambda_3$ and $\lambda_4$ are out of tune

$\lambda_3 \neq \lambda_4 \neq 1$. \hspace{1cm} (6)
So one can expect some special relations for Higgs boson amplitudes that take place in SM and that are invalid beyond the SM. Indeed this is the case. The simplest example is double Higgs boson production in the beams of longitudinal $W$ bosons. Corresponding amplitude vanishes at threshold in the SM in tree approximation \([4]\). Moreover the amplitude with $n$ Higgs boson in final state goes to zero at threshold as well \([3]\).

This fine-tuning cancellation of different diagrams at threshold takes place only if $\lambda_3 = \lambda_4 = 1$. If new physics at scale $\Lambda \gg m_h$ modifies Higgs boson effective potential at low energy the exact cancellation will be destroyed. So, in general, any new physics works only in favorable direction – it enhances cross section for Higgs production at threshold.

Of course, it is possible that ”new physics” is screened at low energy by small factor $(m_h^2/\Lambda^2)$ \([4]\). In this case the influence of ”point-like” ”new physics” at threshold effects is small and we have no chance to learn a lot from the experiments at threshold.

It is also possible that large scale $\Lambda$ has ”soft”, infrared origin \([8]\). In this case if new interaction can be treated perturbatively the effective low-energy potential for Higgs field $H(x)$ has a form

$$\delta V_{\text{eff}} = \frac{1}{4} \gamma H^4(x) \ln \frac{H^2(x)}{\Lambda^2}$$

(7)

It is a general form for any perturbative one-loop effective potential, where factor $\gamma$ is connected with $\beta$-function of new coupling constants and $\Lambda$ determines the scale of new interaction. For this potential the effective 3 and 4-vertex factors $\lambda_{3,4}$ are rather arbitrary, but not absolutely arbitrary.

Stability of the Standard Model vacuum that corresponds to

$$\langle H \rangle = 246 \text{ GeV}$$

takes place only if effective 3-vertex $\lambda_3$ varies in the region

$$1 < \lambda_3 < 7/3$$

For any value $\lambda_3 \neq 1$ the $2H$ boson amplitude does not vanish at threshold. Since the energy of effective $W$ bosons is not fixed but it has some distribution we can’t see this infinite threshold enhancement. It is replaced by finite, but large factor. For $\lambda_3 = 7/3$ the estimates show that this factor is of the order of 5 to 10 \([8]\).
4 Conclusion.

We have analyzed the $\phi$ dependence of single Higgs boson production cross section and demonstrated that the first harmonic proportional to $\cos \phi$ is enriched by Higgs boson events.

We also demonstrated that the double Higgs boson production at threshold is the very appropriate process to test the existence of new non-standard physics at higher scales.

5 Acknowledgments.

This work is partially supported by INTAS-RFBR grant 95-0567.

References

[1] B.Lee, C.Quigg and H.Thacker, Phys. Rev. D16, 1514 (1977).
[2] M.Veltman, Nucl. Phys. B213, 89 (1977).
[3] A.Böhm, Result from the Measurements of Electroweak Processes at LEP1, talk at XXIInd Rencontre de Moriond, Les Arcs 1, Savoie, France, March 15-22, 1997.
[4] A.Dobrovolskaya, V.Novikov, Z.Phys. C52, 427 (1991).
[5] P.Bambade, A.Dobrovolskaya, V.Novikov, Phys. Lett. B319, 348 (1993).
[6] M.Voloshin, Phys. Rev. D47, 2357 (1993); D47, 2573 (1993).
[7] A. De Rujula et al., Nucl. Phys. B384, 3 (1992).
[8] A.Dobrovolskaya, V.Novikov, Z. Phys. Z57, 865 (1993).