Polarization asymmetry and the Higgs boson production mechanisms

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Abstract

We calculate the cross section of Higgs boson production in the reaction $e^+e^- \rightarrow \nu\bar{\nu}bb$ for the case of left and right longitudinally polarized electron beam. Complete set of signal and irreducible background diagrams is considered.

We propose a new critical test to identify the Higgs boson provided by the ratio of cross sections with left and right beam polarization. This quantity is sensitive to the ratio of Higgs-$W$ and Higgs-$Z$ couplings, since it exhibits the interplay of bremsstrahlung and fusion mechanisms of Higgs boson production inherent to the Standard Model scheme.
1 Introduction

Direct experimental observation of the Higgs boson would be one of the most important evidences in favour of the Standard Model (SM) scheme. For this reason much experimental and theoretical effort has been applied to the problems of Higgs boson signal observation and the calculation of corresponding particle distributions.

The absence of Higgs signal in the $Z$ boson decays at LEP I sets the lower limit of the Higgs boson mass around 60 GeV. In the nearest future the possibilities to observe the Higgs particle will be given by the experiments at LEP II and Tevatron colliders. At LEP II it is expected to observe the light Higgs boson ($M_H < 120$ GeV) signal in the four fermion semi-leptonic final states containing $b$-quark pair $\ell \bar{b} \bar{b}$. Search for the signal in the four fermion states could be performed in the following at next colliders. Such states can be separated from the large hadronic backgrounds by the efficient $b$-tagging procedure.

Complete sets of tree level diagrams for the reactions $e^+e^- \to \nu \bar{\nu}b\bar{b}, e^+e^-b\bar{b}$ contain two "signal" diagrams with intermediate Higgs boson line (see the first row of diagrams in Fig.1) which are usually named as bremsstrahlung and fusion mechanisms of Higgs production. Besides signal graphs the complete tree level $2 \to 4$ body $\ell \bar{b} \bar{b}$ amplitude contains many other irreducible background diagrams (24, 21 and 48 for $l = \mu, \nu_e$ and $e$, correspondingly). Irreducible background contribution is not small and in order to understand completely the problem of signal separation from the bias it is not sufficient to calculate only signal mechanisms. It is highly desirable to consider bremsstrahlung and fusion mechanisms as the interfering parts of the same amplitude summing all diagrams coherently. Such calculations have been performed in $\mu^+\mu^-b\bar{b}$ channel, $\nu\bar{\nu}b\bar{b}$ channel and $e^+e^-b\bar{b}$ channel by means of eight-dimensional phase space Monte Carlo integration of the complete tree level amplitude. Semi-analytical results for the $\mu^+\mu^-b\bar{b}$ channel were obtained in $\nu\bar{\nu}b\bar{b}$ by means of symbolical integration over six angular variables and numerical integration over the remaining two invariant masses.

The calculations for $\nu\bar{\nu}b\bar{b}$ channel showed that it has the largest cross section for the signal and a very interesting interplay between the bremsstrahlung and fusion mechanisms. At the energies of LEP II ($175-205$ GeV) and $\sqrt{s} \sim M_H + M_Z$ (threshold region) the contributions of two mechanisms to
the cross section are of the same order additionally enhanced by the positive
interference between them. At larger energy Higgs bremsstrahlung is the
main one up to the energy of several hundred GeV, when fusion begins to
dominate. In the case of $e^+e^-b\bar{b}$ channel (when also two signal mechanisms
contribute) the picture is less interesting. First, the background from ladder
diagrams (multiperipheral mechanisms) is 100 times greater than the signal
and we need a special procedure of signal separation. Second, the
interference term between two mechanisms is negative compensating fusion
contribution in the threshold region.

2 Higgs boson identification and polarization asymmetry

In the situation of limited experimental statistics and many additional fac-
tors affecting the separation and reconstruction of the signal (initial state
radiation, beamstrahlung, final state radiation, efficiency of $b$-tagging, simu-
lation of jet fragmentation, simulation of detector) it is necessary to calculate
several experimental observables giving the possibility of unambiguous iden-
tification of the underlying mechanisms. If some new resonance appears in
the two $b$-jet invariant mass distribution at Next Linear Collider, additional
identification tests will be necessary to recognize the SM Higgs particle in
it. If the signal from a new scalar particle with the main decay channel to
$bb$ pair shows up in the future experiments, it will be not sufficient for iden-
tification of that particle as the Higgs boson. At the first stage comparison
of the measured and calculated total production rates of the scalar particle
can be used for identification. However, total rate has systematic errors from
luminosity measurement, $b$-tagging efficiency and other sources. Moreover,
in the nonminimal schemes it depends on the number of Higgs doublets and
the mixing angles of Higgs mass eigenstates.

It is well known that polarized electron beams allow us to reach higher
precision in the measurement of SM parameters otherwise unreachable
and impose stronger limits on the deviations from the SM scheme given by
new physical phenomena. Extremely interesting physical observable is the
polarization asymmetry.
\[ A_{LR} = \frac{\sigma(e^- e^+) - \sigma(e_R e^+)}{\sigma(e_L e^+) + \sigma(e_R e^+)} \]  

where \( e_R \) (\( e_L \)) denote right(left) longitudinal polarization of the electron beam. This quantity is much less affected by initial and final state radiative corrections than the total cross section and has no uncertainties appearing from the hadronization of final quarks. These corrections are cancelled in the ratio.

In the case of reaction \( e^+ e^- \to \nu_e \bar{\nu}_e b \bar{b} \) left and right polarized electron beams distinguish the bremsstrahlung and fusion mechanisms of Higgs boson production. In so far as the weak charged current includes only left spinors the right polarization of initial electron beam switches off the fusion mechanism. If we denote the coupling constants of the Higgs boson to gauge bosons by \( G_{WWH} \) and \( G_{ZZH} \) and factor them out, we can write for two signal diagrams

\[ \sigma(e^- e^+) = G_{WWH}^2 F_W^L + G_{WWH} G_{ZZH} F_W^L F_Z^L + G_{ZZH}^2 F_Z^L, \]  
\[ \sigma(e_R e^+) = G_{ZZH}^2 F_Z^R. \]  

Fusion diagram has additional electroweak coupling \( g \) in comparison with bremsstrahlung absorbed into \( F \). Defining \( A_{LR}' \) as the ratio of the right to the left cross section we get

\[ A_{LR}' = \frac{\sigma(e_R e^+)}{\sigma(e_L e^+)} = \left( R^2 \frac{F_W^L}{F_Z^L} + R \frac{F_W^L F_Z^L}{F_Z^L} + \frac{F_L^L}{F_Z^L} \right)^{-1}, \]

where

\[ R = \frac{G_{WWH}}{G_{ZZH}}. \]  

The interference term is negligible under some conditions we shall discuss later. One can expect very precise measurement of \( A_{LR}' \) at the energies of Next Linear Colliders. Cancellation of systematical errors from luminosity measurement and the effects of beamstrahlung in this quantity seems especially attractive. On the other hand, \( F_{L,R} \) can be accurately calculated and thus we can precisely define the factor \( R \) which in the SM is equal to

\[ R = \cos^2 \theta_W. \]
This relation is essential for the Higgs boson identification. In the SM (7) is a property of couplings of the Higgs-gauge field interaction lagrangian with spontaneously broken symmetry. In the case of polarized beams, a measurement of $A'_{LR}$ directly implies the verification of (7) on a better level of precision than by using total production rate, where the systematics and beam effects are not cancelled.

Since the relation (7) is independent of the number of Higgs doublets, it is satisfied also for CP-even Higgs bosons $h$ and $H$ of the MSSM. Additional factors in the $WWh(H)$ and $ZZh(H)$ vertices (mixing of Higgs mass eigenstates) are cancelled in the asymmetry for $h(H)$ boson production case and in this sense the dependence of $A'_{LR}$ is universal for the interplay of two mechanisms. The possibility to distinguish SM from MSSM using the polarised asymmetry measurement does not appear.

3 Cross sections in the case of polarized beams and the polarization asymmetry

Calculation of the amplitude has been performed simultaneously by means of two computer packages - GRACE [15] and CompHEP [16]. GRACE uses massive helicity amplitude method for numerical calculation of 23 diagrams (Fig.1), while CompHEP uses projection operators for energy and helicity states to calculate symbolic expressions for $23 \times (23+1)/2 = 276$ squared diagrams and interferences between them. Eight dimensional integration over the four particle phase space has been done with the help of adaptive Monte-Carlo integration package BASES [17]. More details about both packages can be found in [3].

The basic input parameters used in calculations are

\[
\begin{align*}
M_W & = 80.20 \text{ GeV}, \\
M_Z & = 91.16 \text{ GeV}, \\
\Gamma_Z & = 2.53 \text{ GeV}, \\
m_b & = 5 \text{ GeV}, \\
\cos^2 \vartheta_W & = \frac{M_W^2}{M_Z^2}.
\end{align*}
\]

The results are presented for three different Higgs boson masses with the
corresponding tree-level widths

\[
M_H = 110, 130, 150 \text{ GeV},
\]

\[
\Gamma_H = 6.12, 7.26, 8.40 \text{ MeV}.
\]

We used the "fixed width" (or "naive") prescription for the insertion of exact (Breit-Wigner form) propagators in the complete tree level amplitude. Generally speaking, the result can be strongly dependent on the prescription \cite{12}, especially in the threshold energy region. Latest discussion of the subject can be found in \cite{18}. Fixed width method seems to be more adequate to the situation than other methods.

First we calculate the cross sections for two signal diagrams only (first row in Fig.1). Total cross sections for the individual signal diagrams in the processes \( e_L^+e^- \rightarrow \nu\bar{\nu}b\bar{b} \) and \( e_R^+e^- \rightarrow \nu\bar{\nu}b\bar{b} \) are shown in Fig.2. Here three neutrino species \((\nu = \nu_e, \nu_\mu, \nu_\tau)\) are summed up. The fusion mechanism (dotted lines in Fig.2a) is switched off in the \( \nu_e\bar{\nu}_e b\bar{b} \) channel by right polarization of the electron beam. For muon and tau neutrino channels only the Higgs bremsstrahlung exists.

However, this picture is unphysical because we have not taken into account the interference between signal mechanisms and neglected the irreducible background diagrams. Main background comes from \( e^+e^- \rightarrow Z^*Z^* \), \( Z^*\gamma \) mechanisms. In order to suppress their contribution we introduced the \( M(b\bar{b}) \) invariant mass cut of \( \pm 1 \) GeV around the Higgs resonance. The result of complete tree level calculation is shown in Fig.3. Even at the threshold region, \( \sigma(e_L^+e^-) \) is about twice larger than the \( \sigma(e_R^+e^-) \). Left polarisation of electron beam enhances the total rate.

For the \( e_L^+e^- \rightarrow \nu_\mu\bar{\nu}_e b\bar{b} \) case at \( M_H = 110 \) GeV the contributions from bremsstrahlung, fusion, and interference terms separately are shown in Fig.4. We can see that even with the strong cut the signal interference and bias graphs cannot be completely neglected. For instance, in the left polarized beam case at \( \sqrt{s} = 220 \) GeV and \( M_H = 110 \) GeV the bremsstrahlung gives 71 fb, fusion diagram squared gives 12 fb and about 3 fb comes from signal interference and the irreducible background. At \( \sqrt{s} = 340 \) GeV destructive interference reduces the "pure signal" cross section by \(-3.3 \) fb.

It is interesting to notice that in the case of polarized beams the signal interference term \( F_{WZ} \) in (5) changes sign and at some energy rather far from the threshold \( M_H + M_Z \) it is equal to zero. If the contribution of
irreducible background diagrams is small, the experimental measurement of $A'_{LR}$ is directly related to the Higgs-gauge boson coupling ratio (6).

We show the correction to polarization asymmetry $A'_{LR}$ originating from the signal interference and irreducible background diagrams in Fig.5. At the energies near the threshold $M_H + M_Z$ the correction exceeds 40%. However, near the zero point of signal-signal interference it is almost negligible indeed.

Polarization asymmetry $A'_{LR}(s)$ calculated with initial state radiative corrections (ISR) is shown in Fig.6. We are using the structure function approach in this calculation [13]. The normalization and shape of $A'_{LR}$ energy dependence are affected around 10% by ISR. Fortunately there is a flat region of a CM energy dependence of the cross section as shown in Fig.3. In these regions the effect of the ISR is very small. Moreover these regions coincide with zero-interference regions.

We have chosen a benchmark point at $M_H$=110 GeV and the CM energy of 230 GeV and estimated an expected accuracy of the $A'_{LR}$ measurement. At this point an effect of the interference term and initial state radiation is very small. We assume that 0.1% accuracy can be obtained in the calculation of functions $F$ in equation (5) by using our event generators and the detailed detector simulation and 0.2% accuracy can be reached for $\cos^2 \vartheta_W$ measurement. A main source of the systematic error of the measurement may come from uncertainty of the polarization measurement. 1% accuracy was achieved in SLAC experiment at SLC [13]. The expected accuracy of the $A'_{LR}$ measurement with 1.0, 0.5, and 0.1% errors of the polarization measurement are shown in Fig.7 as a function of the integrated luminosity after the detector acceptance correction. The same values of the integrated luminosity for the left and right polarized beams are assumed. One can expect approximately 2% accuracy of the polarized asymmetry measurement.

4 Conclusion

If some new signal similar to that expected from the Higgs boson will be observed at Next Linear Collider, it would need to be studied in more details. At LEP II energies the only observables of detailed study that were discussed [3] are the angular distribution of the Higgs boson from bremsstrahlung, which is expected to be rather flat, and similar to this the angular distribution of Higgs decay products (reconstructed in the Higgs decay frame).
Electron beam polarization provides us a very useful tool to study the mechanisms of Higgs boson production. The measurement of left-right asymmetry (4) for the semi-leptonic four fermion channels $\nu \bar{\nu} b \bar{b}$ in the $e_{L,R} e^+$ collisions could give important information about the interplay of bremsstrahlung and fusion Higgs boson diagrams in the complete tree level amplitude and could be employed as an essential Higgs identification test.

In the case of many irreducible background diagrams contributing to the observables (total cross sections and distributions of the $b$-quarks) it is important to separate reliably the signal and exclude the situation when bias contribution could be misidentified as anomalous signal. In the case under consideration the irreducible background can be removed by the $M(b\bar{b})$ cut around the Higgs peak. We observe an interesting feature of bremsstrahlung-signal interference, which changes sign as the energy increases and at some energy above the $M_Z + M_H$ threshold has “interference zero”. At this point the experimentally measurable value of polarized asymmetry is defined only by individual contributions of two Higgs boson ‘signal’ diagrams and is directly related to the ratio of $ZZH$ and $WWH$ couplings. One can expect about 2% accuracy of the measurement for the polarization asymmetry at future linear colliders with reasonable integrated luminosity.

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1 ISR spectrum given by formula (11.221) of this Ref. has a misprint. Last two terms
in the square bracket $-6 + x$ should be replaced by $-2x$. 
Figure 1: Complete set of tree diagrams for the process $e^+e^- \rightarrow \nu_e \bar{\nu}_e b \bar{b}$.  

11
(a) Total cross sections calculated separately for the bremsstrahlung (solid lines) and fusion (dotted lines) mechanisms of Higgs boson production in the process $e^- L e^+ \to \nu \bar{\nu} b \bar{b}$, $\nu = \nu_e, \nu_\mu, \nu_\tau$. Masses of the Higgs boson $M_H = 110, 120$ and $130$ GeV, $m_b = 5$ GeV, $M_Z = 91.16$ GeV, $\Gamma_Z = 2.53$ GeV, $\alpha = 1/128$.

(b) Total cross sections for the bremsstrahlung mechanism at the same parameter values for the process $e^- R e^+ \to \nu \bar{\nu} b \bar{b}$.

Figure 2:
Figure 3: Complete tree level cross sections vs energy for the processes $e_L e^+ \rightarrow \nu \bar{b} b$ (solid lines) and $e_R e^+ \rightarrow \nu \bar{b} b$ (dashed lines) for the masses of Higgs boson $M_H = 110, 120$ and $130$ GeV. $M(b\bar{b})$ cut of $\pm 1$ GeV around $M(b\bar{b}) = M_H$ is imposed.
Figure 4: The contributions of bremsstrahlung, fusion and bremsstrahlung-fusion interference to the signal cross section for $M_H = 110$ GeV, $\Gamma_H = 6.12$ MeV are shown by dotted lines. The results of complete tree level calculation (CTL) and two signal diagrams squared sum are also shown by solid and dashed lines, respectively. The (signal) interference term changes sign and is practically negligible around $\sqrt{s} \sim 235$ GeV. For $M_H = 130$ GeV, $\Gamma_H = 7.26$ MeV the 'interference zero' takes place at $\sqrt{s} \sim 250$ GeV.
Figure 5: The polarization asymmetry (upper plot, see formula (5)) for monochromatic beams, $M_H = 110, 120$ and 130 GeV. $A'_{LR}$ calculated using signal diagrams only (no signal interference) is shown by a dotted line. The ratio of non-interfering signal diagrams to complete tree level cross section is shown in the lower plot.
Figure 6: The polarization asymmetry (see formula (5)) calculated with initial state radiative corrections, $M_H = 110, 120$ and $130$ GeV.
Figure 7: The expected accuracy of the $A'_{LR}$ measurement at CM energy of 230 GeV and $M_H=110$ GeV. We assume 0.1% accuracy for the calculation of functions $F$ in equation (5) and 0.2% accuracy for $\cos^2 \vartheta_W$ measurement. Three different values of the polarization measurement accuracy were used in the simulation.