

ASPECTS OF SCALAR PRODUCTION ($m_h \leq 300$ GeV) in the e^-e^- COLLIDER OPERATING MODE *

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ABSTRACT

Production of the standard Higgs-scalar in the reaction $e^-e^- \rightarrow e^-e^-h$ is discussed requiring equal sensitivity within a wide band of mass : $m_h \leq 300$ GeV.

I. THE Z-Z FUSION PROCESS

$$e^-e^- \rightarrow e^-e^-h$$

We consider the production of a standard scalar or for the case of several doublets of all scalars suitably projected on the Goldstone mode in the reaction

$$e^-e^- \rightarrow e^-e^-h \quad (h_\alpha) \quad (1)$$

through Z-Z fusion according to the Feynman diagrams in Fig.1

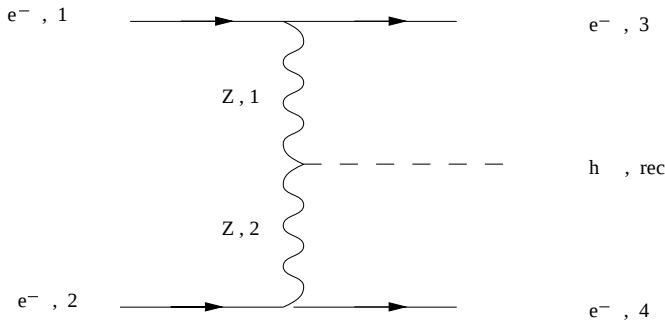


Figure 1:

Feynman diagrams for central scalar production in the reaction $e^-e^- \rightarrow e^-e^-h$.

The kinematic variables associated with the diagrams in figure1 are

$$e^-, 1, 2 : p_{1,2}, \sigma_{1,2} \quad ; \quad e^-, 3, 4 : p_{3,4}, \sigma_{3,4}$$

$$Z, 1 : q_1 = p_1 - p_{3(4)} \quad ; \quad h : p_{rec} = p_1 + p_2 - p_3 - p_4$$

$$Z, 2 : q_2 = p_2 - p_{4(3)} \quad (2)$$

In eq. (2) $\sigma_\alpha = L, R$; $\alpha = 1, \dots, 4$ denotes the helicity of respective electrons. Virtual momenta associated with the fusing Z bosons and corresponding to the crossed diagram are indicated in round brackets.

In the tree approximation adopted here for the reaction in eq. (1) [1] , [2] - [4] , the mass of the produced scalar is given by the recoil momentum p_{rec} reconstructed from the (four)momenta of the four electrons, which we assume to be primary *measured quantities*.

$$M_{rec}^2 = (p_{rec})^2 \quad (3)$$

This entails that the two outgoing electrons are tagged and thus we demand an angular cut away from the forward and backward direction. To be specific this angular cut is set to 5 degrees in the following.

The cross section shows three main features as a function of c.m. energy :

- The total cross section saturates for energies beyond the threshold region. It becomes proportional to m_Z^{-2} and independent of the scalar mass for $m_h = M_{rec} \ll \sqrt{s}$.
- The cross section with the angular cut imposed is geometric beyond the threshold region. It becomes proportional to s^{-1} and independent of the scalar mass for $m_h \ll \sqrt{s}$.
- The production cross section shows little dependence on the polarization of the incoming electrons and also remains almost the same in crossing from the e^-e^- to e^+e^- lepton channel. Respective coupling strengths become exactly equal when the effective weak mixing angle $s_w = \sin^2 \vartheta_W^{eff} = 1/2$.

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The above features are shown in figure 2 for lefthanded incoming electrons with and without the angular cut described above.

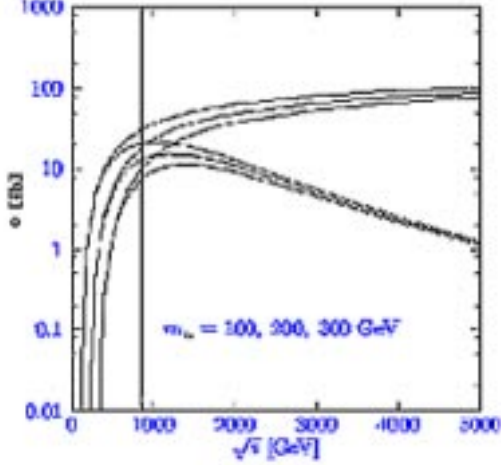


Figure 2:

Cross sections for production of a standard scalar as function of c.m. energy with and without angular cut. The incoming electrons are purely lefthanded. The onset of saturation corresponding to $\sqrt{s} = 850$ GeV is also shown.

Assuming an integrated luminosity $\mathcal{L} = 40 \text{ s} [\text{TeV}^2] / \text{fb}$ the cross section with angular cut yields the event rates shown in figure 3 [5].

The squared moduli of the four polarization dependent amplitudes $\mathcal{A}_{LL}$, $\mathcal{A}_{RR}$, $\mathcal{A}_{LR}$, $\mathcal{A}_{RL}$ are in the limit of vanishing electron mass

$$\begin{aligned} |\mathcal{A}_{LL}|^2 \\ |\mathcal{A}_{RR}|^2 \\ |\mathcal{A}_{LR}|^2 \\ |\mathcal{A}_{RL}|^2 \end{aligned} = \frac{1}{8} \left(\frac{g}{c_w} \right)^6 \begin{cases} (1 - 2s_w^2)^4 B_{LL} \\ 16s_w^8 B_{RR} \\ 2s_w^2 (1 - 2s_w^2)^2 B_{LR} \\ 2s_w^2 (1 - 2s_w^2)^2 B_{RL} \end{cases}$$

$$B_{LL} = B_{RR} = K_{12} K_{34} \left(\frac{1}{P_{13} P_{24}} + \frac{1}{P_{14} P_{23}} \right)^2$$

$$B_{LR} = B_{RL} = \frac{K_{14} K_{23}}{(P_{13} P_{24})^2} + \frac{K_{13} K_{24}}{(P_{14} P_{23})^2}$$

$$K_{ij} = (p_i + p_j)^2 \quad ; \quad P_{ij} = m_Z^2 + K_{ij}$$

(4)

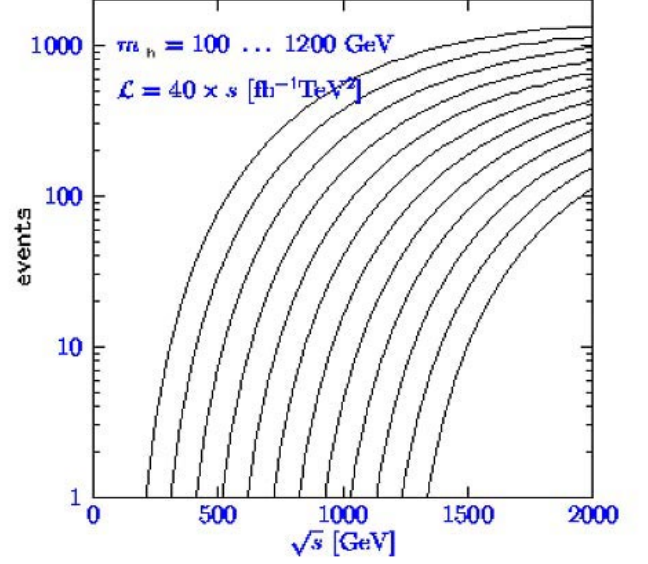


Figure 3:

Event rates for production of a standard scalar as function of c.m. energy.

For definiteness we set $s_w^2 = 0.2315$.

The Lagrangian density which exclusively represents contributions from Z-Z fusion—assuming no or negligible CP violation in the scalar selfinteraction—is given by

$$\begin{aligned} \mathcal{L}_{sc-ZZ} = & \frac{g^2}{4c_w^2} Z^\mu Z_\mu \left[v h(x) + \sum_{\alpha=1}^n (h_\alpha^2 + a_\alpha^2)(x) \right] \\ h = \sum o_\alpha h_\alpha \quad ; \quad \sum o_\alpha^2 = 1 \quad ; \quad v = (\sqrt{2} G_F)^{-1/2} \end{aligned} \quad (5)$$

In eq. (5) the fields h_α , $\alpha = 1, \dots, n$ denote the CP even scalar fields in the mass eigenstate basis for n scalar doublets. In the MSSM (minimal supersymmetric standard model) they are conventionally denoted by $h_1 = h$, $h_2 = H$.

a_1 denotes the (unphysical) Goldstone mode, whereas a_α , $\alpha = 2, \dots, n$ —for $n > 1$ —correspond to physical CP odd scalars. In the MSSM the conventional notation is $a_2 = A$.

Finally the real parameters o_α denote the mixing of CP even scalars with respect to the Goldstone doublet. In the MSSM we have

$$(o_1, o_2) = (\sin(\alpha - \beta), \cos(\alpha - \beta)) \quad (6)$$

For comparable mixing strengths $|o_\alpha|^2$ all CP even scalars can be observed within a given sensitivity range in mass. At the same time Z-Z fusion also produces pairs of scalars :

$$hh, hH, HH, AA$$

The associated cross section for production of a standard model pair hh proves to be quite small compared to the main irreducible background from the process $e^- e^- \rightarrow e^- e^- W^+ W^-$. Hence we concentrate on single scalar production.

II. OBSERVABILITY OF SCALARS IN THE $e^- e^-$ MODE AT C.M. ENERGY 850 GeV

Demanding a range of equal sensitivity of scalar masses up to 300 GeV, we can read off the required minimal c.m. energy from figure 2. The onset of saturation for the case of 300 GeV scalar mass with the angular cut of 5 degrees imposed amounts to a c.m. energy of at least 850 GeV. This is a high quality demand and signals beyond the envisaged mass range can be observed at $\sqrt{s} = 850$ GeV as well as signals within this range at lower c.m. energies.

Backgrounds

In the given c.m. energy region the leading two processes are single W^- , Z gauge boson production, with total cross sections approximately 10 pb :

$$\begin{aligned} e^- e^- &\rightarrow e^- \nu_e W^- \rightarrow e^- \nu_e e^- \bar{\nu}_e \quad (I) \\ e^- e^- &\rightarrow e^- e^- Z \quad (II) \end{aligned} \quad (7)$$

We classify both background reactions as reducible : (I) can be reduced by choosing righthandedly polarized electrons in conjunction with the angular cut on outgoing electrons. The branching fraction of 10% of $W^- \rightarrow e^- \bar{\nu}_e$ also helps. In the second reaction the recoiling mass is the Z mass, abstracting from distortions due to mainly initial state radiation. The case of a scalar, degenerate in mass with the Z boson, has to be studied at much lower c.m. energy, preferentially in the reactions $e^+ e^- \rightarrow hZ$; ZZ [6].

Irreducible background is the central production of heavy $q\bar{q}$ and $W^+ W^-$ pairs

$$\begin{aligned} e^- e^- &\rightarrow e^- e^- b \bar{b} (t \bar{t}) \quad (III) \\ e^- e^- &\rightarrow e^- e^- W^+ W^- \quad (IV) \end{aligned} \quad (8)$$

Reaction (III) dominates for the recoiling mass below 2 W threshold and (IV) above.

Signal detection

a) $m_h \leq 2 m_W$

A characteristic case of $m_h = 120$ GeV and $\sqrt{s} = 500$ GeV has been studied by T. Han in [2]. While in this study only the

invariant mass of the produced $b\bar{b}$ pair is used with severe cuts on angle and transverse momenta of the two b jets, it illustrates clearly the observability of the standard scalar in the mass range below 2 W threshold. The imposed cuts reduce the scalar production cross section to 1.3 fb as compared to the recoil mass criterion alone of ~ 9 fb as deduced from figure 2 which applies to lefthanded incoming electrons.

b) $m_h > 2 m_W$

We propose to illustrate here the potential of the $e^- e^-$ mode for standard scalar production in the mass range above 2 W threshold within the selected mass range $m_h \leq 300$ GeV — $m_h = 240$ GeV to be specific. The two electron mode is distinguished in the present context only through absence of electron-positron annihilation backgrounds.

The following two step strategy is adopted

- i) The recoil mass, defined in eqs. (2) and (3), is selected with angular cuts on outgoing electrons of 5 degrees and the distribution with respect to m_{rec} determined both for background reaction (IV) (eq. (8)) and the signal in question.
- ii) If an enhancement indicating the possible mass region of a scalar is found, the structure of the final state forming the recoiling mass is analyzed, whereby the distortion of the recoil mass distribution is corrected. For $m_h = 240$ GeV the main decay modes are through $W^+ W^-$ and ZZ to four quark jets.

We concentrate on step i) here.

At $\sqrt{s} = 850$ GeV the total cross section for reaction (IV) amounts to ~ 840 fb. The distribution in the recoil mass of reaction (IV) (eq. (8)) is shown for unpolarized electrons and $\sqrt{s} = 500$ GeV in figure 4 with no angular cut together with the effect of 5 and 10 degree cuts [7]. The latter two distributions are shown rescaled in figure 5.

The standard scalar with a mass of 240 GeV decays mainly into two gauge bosons with respective widths

$$\Gamma_{h \rightarrow BB} = \begin{cases} 2.31 \text{ GeV} & W^+ W^- \\ 1.00 \text{ GeV} & Z Z \end{cases}; \Gamma_{h \text{ tot}} \sim 3.3 \text{ GeV} \quad (9)$$

The signal and irreducible background distributions (reaction (IV)) are superimposed for unpolarized incoming electrons and $\sqrt{s} = 850$ GeV, $\vartheta_{cut} = 5^\circ$ in figure 6 [2]. We note that there is constructive interference in the $W^+ W^-$ channel, unaccounted for here. The background reduction results in a signal to background ratio of approximately 5. The angular cut on outgoing electron directions could without significant loss of signal be relaxed to 7.5 or even 10 degrees, yet the choice made here proves quite optimal if ideal beam and detection dynamics is assumed.

The cross section under the scalar resonance is 7 fb (4.5 fb from $e_R e_R$). With the assumptions on integrated luminosity adopted this signal corresponds to ~ 200 events.

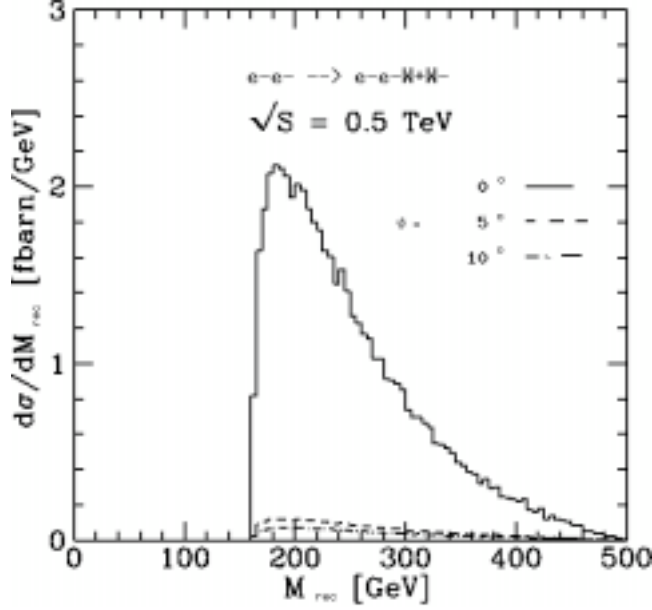


Figure 4:

Distribution in the recoiling mass of the background reaction $e^+e^- \rightarrow e^+e^- W + W^-$ with various angular cuts between incoming and outgoing electrons.

III. CONCLUSIONS

We have shown that the central production of a standard model scalar — and any scalar from an electroweak doublet with comparable projection on the Goldstone one — through Z-Z fusion in the e^+e^- mode of a linear collider — offers unique sensitivity in its detection. This detection implies the measurement of the distribution with respect to recoil mass, reconstructed from the momenta and directions of all four electrons involved. The key quantity, which enforces high sensitivity uniform with respect to the scalar mass in a given range, is the c.m. energy. For the range $m_h \leq 300$ GeV chosen here the optimal c.m. energy is 850 GeV. The reactions studied can serve as guideline in choosing the design parameters of a future linear collider.

Acknowledgements

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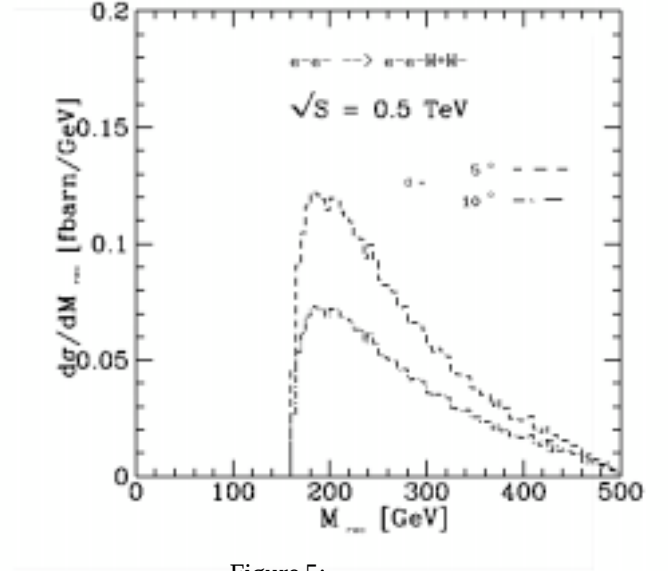


Figure 5:

Distribution in the recoiling mass of the background reaction $e^+e^- \rightarrow e^+e^- W + W^-$ with angular cuts between incoming and outgoing electrons.

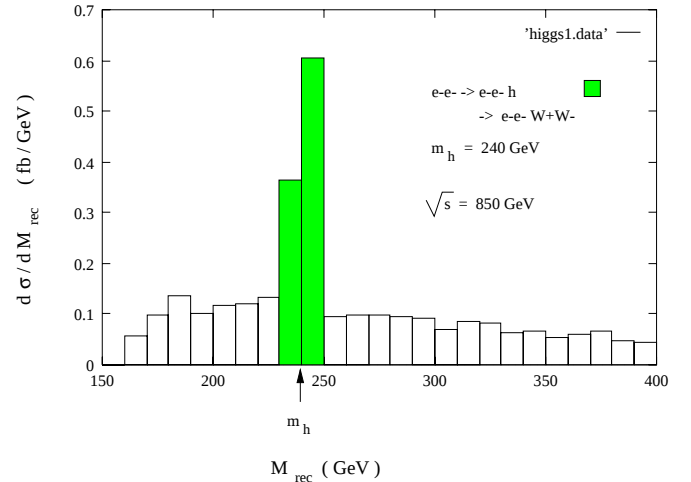


Figure 6:

Differential cross section of standard scalar production for $m_h = 240$ GeV — at c.m. energy $\sqrt{s} = 850$ GeV and the background reaction $e^+e^- \rightarrow e^+e^- W^+ W^-$ with respect to recoil mass. — An angular cut between incoming and outgoing electrons is essential to define the recoiling mass and to reduce background.

IV. REFERENCES

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