HIGGS PRODUCTION WITH POLARIZED e^+e^- BEAMS

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Generalizing our previous work, we calculate the helicity amplitudes for the reactions $e^+e^- \to H\gamma$ and $e^+e^- \to H\mu^+\mu^-$ and using Kleiss' formalism of spinor products, we give the expressions for the cross sections, including beam polarization effects, in a form well suited for an event simulation programme.

Despite the enormous successes of the standard Glashow–Weinberg–Salam model [1], one of its basic ingredients – the Higgs sector [2] – remains untested. However, from a theoretical point of view, the existence of this sector is crucial for the renormalizability of the theory. Hence, searches for Higgs bosons will be one of the most important items of the experimental programmes to be carried out in the future e^+e^- colliders (see ref. [3] for a recent review).

It is generally known that a light Higgs, i.e., with a mass m_H, smaller than the Z boson mass if it exists, will be most likely seen in the reactions $e^+e^- \to H\mu^+\mu^-$ and $e^+e^- \to H\gamma$. Recently, we have published [4,5] a complete one-loop calculation of the unpolarized cross section for the $H\gamma$ channel. In ref. [4], we show the total cross section, σ, for several values of m_H and we also compare our results with the ones corresponding to the $\mu^+\mu^-H$ channel. In this letter our previous work is generalized to include the effect of the polarization of the colliding beams. The reason for doing this is two-fold. On the one hand, in the collider the beams will be almost transversally polarized, and, on the other hand, the expected number of events is so small that the analysis of the experiments requires the simulation of each event. In other words, transverse polarization effects are present in the differential cross section although they disappear from the integrated cross section. As we shall see, this remarkable fact is in agreement with a general result obtained by Hikasa [6].

Let us consider transversally polarized beams and let P denote the degree of polarization of the electrons (which we take equal and opposite to the polarization of the positron beam). Then, the $e^+e^- \to H\gamma$ differential cross section in the centre-of-mass (CM) frame is

$$\frac{d\sigma}{d\Omega}(e^+e^- \to H\gamma) = \frac{1}{64\pi^2 s}\left(1-\frac{M_H^2}{s}\right)\Sigma_{\text{pol}}(\theta,\phi), \tag{1}$$

where [7]

$$\Sigma_{\text{pol}}(\theta,\phi) = \tfrac{1}{4}\big(|M(+,-,+)|^2 + |M(+,-,-)|^2 + |M(-,+,+)|^2 + |M(-,+,-)|^2$$
$$+2P^2\,\mathrm{Re}\{\Phi_+(p_+,s_+)\Phi_-^*(p_-,s_-)\cdot[M(+,-,+)M^*(-,+,+)+M(+,-,-)M^*(-,+,-)]\}\big) \tag{2}$$

is a sum over helicity amplitudes[‡1], $M(\sigma_-,\sigma_+,\lambda)$, and $\Phi_-(\Phi_+)$ is the electron (positron) complex phase factor introduced by Kleiss [8] and given by

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[‡1] + means right-handed.

$$\Phi(p,s)=s^2-\mathrm{i}s^3-(s^0-s^1)(p^2-\mathrm{i}p^3)/(p^0-p^1)\,, \tag{3}$$

where p^μ and s^μ are the four-momentum and the spin polarization vector of the particle, respectively. At high energy, it is a very good approximation to neglect the electron mass. Hence, the helicity amplitudes are more easily derived using the spinor product formalism [7,9]. For massless fermions with momenta p_1 and p_2, there are only two nonzero spinor products, namely,

$$s(p_1,p_2)=\bar{u}_+(p_1)u_-(p_2)=-s(p_2,p_1),\quad t(p_1,p_2)=\bar{u}_-(p_1)u_+(p_2)=s^*(p_2,p_1), \tag{3a,b}$$

where $u_\sigma(p)$ are helicity spinors satisfying the equation

$$u_\pm(p)\bar{u}_\pm(p)=\gamma_\pm \not{p} \tag{4}$$

with

$$\gamma_\pm=(1\pm\gamma_5)/2. \tag{5}$$

The invariant amplitude, T, corresponding to the Feynman diagrams evaluated in ref. [4] can be written in the form

$$T=\bar{v}(p_+,s_+)[\mathcal{Q}_+(R_+\gamma_+ +L_+\gamma_-)+\mathcal{Q}_-(R_-\gamma_+ +L_-\gamma_-)]u(p_-,s_-) \tag{6}$$

with

$$\mathcal{Q}_\pm=k\cdot p_\pm \not{\epsilon}(k,\lambda)-p_\pm\cdot\epsilon(k,\lambda)\not{k} \tag{7}$$

and

$$R_\pm=\frac{eg^3}{16\pi^2M_W^2}\sum_i(a_i-b_i)G_i^\pm,\quad L_\pm=\frac{eg^3}{16\pi^2M_W^2}\sum_i(a_i+b_i)G_i^\pm. \tag{8a,b}$$

In the last two equations the sum over i is a sum over the diagrams, the a_i, b_i and $G_i^\pm$ are given in table 3 of ref. [4], and $\lambda=\pm$ are the polarizations of the photon with momentum $k\equiv(\omega,\bar{k})$. Following Kleiss [9], we write the photon polarization four-vector $\epsilon^\mu(k,\lambda)$ in terms of spinors, i.e.,

$$\epsilon^\mu(k,\lambda)=[4k\cdot p]^{-1}\bar{u}_\lambda(k)\gamma^\mu u_\lambda(p), \tag{9}$$

where p is *any* light-like four-vector *not* proportional to k. Once this is done, it is fairly easy to obtain from eq. (6) the helicity amplitudes. Our results are

$$M(+,-,+)=Ns(p_+,k)[s^*(p_-,p)\,|s(p_+,k)|^2-s^*(p_-,k)s(p_+,k)s^*(p_+,p)]R_+,$$

$$M(+,-,-)=Ns^*(p_-,k)[s(p_+,p)\,|s(p_-,k)|^2-s(p_+,k)s^*(p_-,k)s(p_-,p)]R_-,$$

$$M(-,+,+)=Ns(p_-,k)[s^*(p_+,p)\,|s(p_-,k)|^2-s^*(p_+,k)s(p_-,k)s^*(p_-,p)]L_-,$$

$$M(-,+,-)=Ns^*(p_+,k)[s(p_-,p)\,|s(p_+,k)|^2-s(p_-,k)s^*(p_+,k)s(p_+,p)]L_+, \tag{10}$$

with

$$N=[4k\cdot p]^{-1}.$$

For the sake of completeness we also give the value of the spinor product $s(p_1,p_2)$ in terms of the kinematical variables, i.e. [7],

$$s(p_1,p_2)=(p_1^2+\mathrm{i}p_1^3)[(p_2^0-p_2^1)/(p_1^0-p_1^1)]^{1/2}-(p_2^2+\mathrm{i}p_2^3)[(p_1^0-p_1^1)/(p_2^0-p_2^1)]^{1/2}. \tag{11}$$

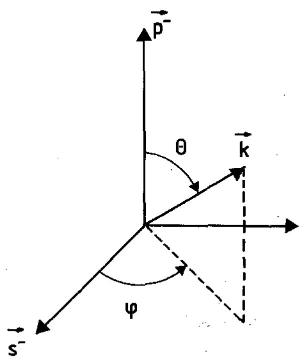

Fig. 1. Definition of the polar angles used in eq. (13).

As was pointed out before [9], using a different vector p in eq. (9) corresponds to a different choice of gauge. T is obviously gauge invariant [4,5] and so, one can use this gauge freedom to simplify the results. With $p=p_+$, eqs. (10) give

$$M(+,-,+)=Ns(p_+,k)s^*(p_-,p_+)|s(p_+,k)|^2R_+,$$

$$M(+,-,-)=Ns(p_+,k)[s^*(p_-,k)]^2s(p_+,p_-)R_-,$$

$$M(-,+,+)=Ns^*(p_+,k)[s(p_-,k)]^2s^*(p_+,p_-)L_-,$$

$$M(-,+,-)=Ns^*(p_+,k)s(p_-,p_+)|s(p_+,k)|^2L_+. \tag{12}$$

Before we consider the other reaction, it is interesting to show that any polarization effect disappears from the total cross section. In fact, defining the angles θ and ϕ as shown in fig. 1, it is trivial to rewrite eq. (2) in the form

$$\Sigma_{\mathrm{pol}}=\Sigma_{\mathrm{unp}}-2P^2\omega^2s^2\sin^2\theta\,\{\cos 2\phi\,\mathrm{Re}(R_+L_-^*+R_-L_+^*)-\sin 2\phi\,\mathrm{Im}(R_+L_-^*+R_-L_+^*)\}, \tag{13}$$

where Σ_{unp} is the sum of the first four terms in eq. (2). It is now clear that

$$\frac{1}{2\pi}\int_0^{2\pi}\mathrm{d}\phi\,\Sigma_{\mathrm{pol}}=\Sigma_{\mathrm{unp}}, \tag{14}$$

in agreement with the general theorem derived by Hikasa [6].

Polarization effects for the reaction $e^+e^-\to H\mu^+\mu^-$ were studied before [10]. However, we think that it is useful to give the helicity amplitudes since the present formalism is well suited for numerical computation. The differential cross section, $\mathrm{d}\sigma$, is

$$\mathrm{d}\sigma=\frac{Q}{64(2\pi)^5s\sqrt{s}}\Sigma_{\mathrm{pol}}\,\mathrm{d}\Omega\,\mathrm{d}\Omega^*\,\mathrm{d}m_{\mathrm{L}}^2, \tag{15}$$

where $m_{\mathrm{L}}^2=(q_-+q_+)^2$ is the square of the invariant mass of the final fermions ($f\bar{f}$), $\mathrm{d}\Omega$ is the solid angle for the difermion production in the e^+e^- CM, $\mathrm{d}\Omega^*$ is the solid angle in the CM of the $f\bar{f}$ system,

$$Q=\{[s-(m_{\mathrm{L}}+M_{\mathrm{H}})^2][s-(m_{\mathrm{L}}-M_{\mathrm{H}})^2]/(4s)\}^{1/2}, \tag{16}$$

and

$$\Sigma_{\mathrm{pol}}=\tfrac{1}{4}(|M(+-;+-)|^2+|M(+-;-+)|^2+|M(-+;+-)|^2+|M(-+;-+)|^2$$
$$+2P^2\,\mathrm{Re}\{\Phi_+(p_+,s_+)\Phi_-^*(p_-,s_-)[M(+-;+-)M^*(-+;+-)+M(+-;-+)M^*(-+;-+)]\}).$$

For massless fermions the helicity amplitudes $M(\sigma_-\sigma_+;\lambda_-\lambda_+)$ are

$$M(+-;+-)=C(g_V^e-g_A^e)(g_V^f-g_A^f)s(p_+,q_-)s^*(p_-,q_+),$$

$$M(+-;-+)=C(g_V^e-g_A^e)(g_V^f+g_A^f)s(p_+,q_+)s^*(p_-,q_-),$$

$$M(-+;+-)=C(g_V^e+g_A^e)(g_V^f-g_A^f)s(p_-,q_-)s^*(p_+,q_+),$$

$$M(-+;-+)=C(g_V^e+g_A^e)(g_V^f+g_A^f)s(p_-,q_+)s^*(p_+,q_-), \tag{18}$$

where $\sigma_-\sigma_+$, λ_- and λ_+ denote the electron, positron, f and $\bar{\text{f}}$ helicities respectively,

$g_V^f=\frac{1}{2}T_3^f-Q^f\sin^2\theta_w,\quad g_A^f=\frac{1}{2}T_3^f,\quad C=(g/\cos\theta_w)^3 2M_Z/D(s)D(m_L^2),$

with

$D(x)=x-M_Z^2+iM_Z\Gamma_Z.$

If the polarization of the final particles is not measured, the integration over $d\Omega^*$ gives [11]:

$$\frac{d\sigma(e^-e^+\to Hf\bar{f})}{d\Omega\, dm_L^2}=\frac{m_L\Gamma(m_L)}{\pi|D(m_L^2)|^2}\frac{d\sigma(e^-e^+\to HZ^*)}{d\Omega}, \tag{19}$$

where $\Gamma(m_L)$ is the width for a virtual Z* with mass m_L to decay into $f\bar{f}$ and

$$\frac{d\sigma(e^-e^+\to HZ^*)}{d\Omega}=\frac{1}{32\pi^2 s}\frac{Q}{\sqrt{s}}\Sigma'_{pol} \tag{20}$$

with

$$\Sigma'_{pol}=\frac{3}{8\pi m_L^2}\int d\Omega^*\,\tfrac{1}{4}\{|M(+-)|^2+|M(-+)|^2+2P^2\,\mathrm{Re}[\Phi_+(p_+,s_+)\Phi_-^*(p_-,s_-)M(+-)M^*(-+)]\}. \tag{21}$$

Now, the polarization of the beam appears in the effective amplitudes $M(\sigma_-\sigma_+)$ which are

$$M(+-)=(g/\cos\theta_w)^2[2M_Z/D(s)](g_V^e-g_A^e)s(p_+,r_2)s^*(p_-,r_1),$$

$$M(-+)=(g/\cos\theta_w)^2[2M_Z/D(s)](g_V^e+g_A^e)s(p_-,r_2)s^*(p_+,r_1). \tag{22}$$

The four vectors r_i $(i=1,2)$ were introduced in ref. [9] to express the polarization vector for a spin-one massive particle in terms of massless spinoirs. They must satisfy the requirements

$r_1^2=r_2^2=0,\quad r_1+r_2=q_++q_-,$

and so a convenient choice is $r_1=q_+$ and $r_2=q_-$ or vice versa. In eq. (21) the integration is over the solid angle of r_1 (or r_2) *in the rest frame of Z** and the factor $3/(8\pi m_L^2)$ is the normalization necessary for the Ω^* integration to correspond to the sum over the Z* polarizations [9].

In conclusion, we can say that, given any set of kinematical variables obtained by a Monte Carlo event generator for instance, our expressions above lead immediately to the differential cross sections for the reactions $e^+e^-\to H\gamma$ and $e^+e^-\to H\mu^+\mu^-$ with polarized beams. From the four momenta, one evaluates the appropriate spinor products [eq. (11)] and after that it is straightforward to compute the helicity amplitudes [eqs. (12) and (18) or (22)]. Once this is done, eqs. (1) and (15) enable us to compute the cross sections in terms of a weighted sum of helicity amplitudes denoted by Σ_{pol}. These are given by eqs. (2) and (17) for transversally polarized beams but in the general case the corresponding expressions can be found in ref. [8].

Bearing in mind the importance of the Higgs searches at LEP, we think that it is important to include the effects of the beam polarizations. This is even more so when minimal supersymmetric extensions of the standard model predict [12] that the lightest neutral Higgs should have a mass smaller than M_Z. Therefore, even a lower bound on M_H will be very interesting.

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