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Production of pseudoscalar Higgs-bosons in $e\gamma$ collisions

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ABSTRACT

We investigate the production of a pseudoscalar Higgs-boson A^0 using the reaction $e\gamma \to e A^0$ at an $e\bar{e}$ collider with center of mass energy of 500 GeV. Supersymmetric contributions are included and provide a substantial enhancement to the cross section for most values of the symmetry breaking parameters. We find that, despite the penalty incurred in converting one of the beams into a source of backscattered photons, the $e\gamma$ process is a promising channel for the detection of the A^0.

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INTRODUCTION

The Higgs sector in supersymmetric extensions of the standard model contains charged Higgs-bosons as well as additional neutral Higgs-bosons [1]. Among the latter is a pseudoscalar particle usually denoted A^0. In this letter, we calculate the production cross section for the A^0 in the process $e\,\gamma \to e\,A^0$. Contributions to this process arise from triangle and box diagrams. The triangle contributions consist of diagrams in which the A^0 and photon are on-shell external particles and the remaining particle is a virtual photon or Z^0 in the t-channel. Since $t=0$ is in the physical region, the photon pole contribution dominates the Z^0 pole contribution in this set of diagrams. Moreover, because of the off-diagonal structure of the A^0 couplings to other bosons, the particles in the loop are either quarks, leptons or charginos. Here, we present the top quark, bottom quark, tau lepton and the two chargino contributions to the photon pole amplitude.

The box diagrams have a more complex particle structure, with leptons, charginos, neutralinos and scalar leptons in the loops. Like the Z^0 pole, these diagrams are non-singular at $t=0$, and should not contribute a sizable correction to the photon pole terms. They are not included in the present calculation.

THE $e\,\gamma \to e\,A^0$ CROSS SECTION.

The amplitude for the production of an A^0 of momentum k' and an e of momentum p' in the collision of an e of momentum p and a γ of momentum k and polarization $\varepsilon_\lambda(k)$ by the exchange of a γ in the t-channel is

$$\mathcal{M} = \frac{4i\alpha^2}{\sin\theta_W m_W}\bar{u}(p')\gamma_\mu u(p)\,\frac{\mathcal{A}_\gamma(t)}{t}\,\varepsilon_{\mu\nu\alpha\beta}\varepsilon_\nu(k)(p-p')_\alpha k_\beta\ , \tag{1}$$

where $t=-(p-p')^2$, and

$$\begin{aligned}\mathcal{A}_\gamma(t) \ =\ & \Big[-3\left(\frac{2}{3}\right)^2 m_t^2\cot\beta\, C_0(t,m_A^2,m_t^2) - 3\left(-\frac{1}{3}\right)^2 m_b^2\tan\beta\, C_0(t,m_A^2,m_b^2) \\ & -(-1)^2 m_\tau^2\tan\beta\, C_0(t,m_A^2,m_\tau^2) + 2m_W m_1 g_{11} C_0(t,m_A^2,m_1^2) \\ & + 2m_W m_2 g_{22} C_0(t,m_A^2,m_2^2)\Big]\ ,\end{aligned} \tag{2}$$

Here, m_t and m_b are the top and bottom quark masses, m_τ is the tau lepton mass, m_1 and m_2 are the chargino masses, m_W is the W mass and $\tan\beta$ is a ratio of vacuum expectation values [1]. The chargino coupling constants g_{11} and g_{22} depend on the elements of two 2×2 unitary matrices U and V which diagonalize the chargino mass matrix X, where [2]

$$X = \begin{pmatrix} M & \sqrt{2}m_W\sin\beta \\ \sqrt{2}m_W\cos\beta & \mu \end{pmatrix}\ , \tag{3}$$

and are chosen to ensure that m_1 and m_2 are positive. For illustrative purposes, we assume that the symmetry breaking parameters M and μ are real and consider two cases: $M\mu > m_W^2 \sin 2\beta$ and $M\mu < m_W^2 \sin 2\beta$. The couplings in these cases are

$$g_{11} = \frac{m_W}{m_1^2 - m_2^2}(m_2 + m_1 \sin 2\beta)\,, \quad g_{22} = -\frac{m_W}{m_1^2 - m_2^2}(m_1 + m_2 \sin 2\beta)\,, \tag{4}$$

for $M\mu > m_W^2 \sin 2\beta$, and

$$g_{11} = \frac{m_W}{m_1^2 - m_2^2}(-m_2 + m_1 \sin 2\beta)\,, \quad g_{22} = -\frac{m_W}{m_1^2 - m_2^2}(-m_1 + m_2 \sin 2\beta)\,, \tag{5}$$

for $M\mu < m_W^2 \sin 2\beta$. Notice that, these couplings are symmetric in m_1, m_2 and, unlike the A^0-top coupling, there is no enhancement factor of $m_{1,2}/m_W$ [3]. Due to the reality of M and μ, m_1 and m_2 in Eqs. (4,5) are subject to certain constraints discussed below [4]. The scalar function $C_0(t, m_A^2, m^2)$ is [5]

$$C_0(t, m_A^2, m^2) = \frac{1}{i\pi^2} \int d^4q \frac{1}{(q^2 + m^2)\left((q + p - p')^2 + m^2\right)\left((q + p - p' + k)^2 + m^2\right)}\,. \tag{6}$$

Since one of the external particles is a photon, this function can be expressed in terms of inverse trignometric or hyperbolic functions [1, 6] as

$$C_0(t, m_A^2, m^2) = \frac{1}{(t - m_A^2)}\Big(C(\frac{m_A^2}{m^2}) - C(\frac{t}{m^2})\Big)\,, \tag{7}$$

where

$$C(\beta) = \int_0^1 \frac{dx}{x} \ln\Big(1 - \beta x(1-x) - i\varepsilon\Big) \tag{8}$$

$$= \begin{cases} 2\left(\sinh^{-1}(\sqrt{-\frac{\beta}{4}})\right)^2 & \beta \leq 0 \\ -2\left(\sin^{-1}(\sqrt{\frac{\beta}{4}})\right)^2 & 0 \leq \beta \leq 4 \\ 2\left(\cosh^{-1}(\sqrt{\frac{\beta}{4}})\right)^2 - \frac{\pi^2}{2} - 2i\pi \cosh^{-1}(\sqrt{\frac{\beta}{4}}) & \beta \geq 4 \end{cases}\,. \tag{9}$$

The cross section is given by

$$\frac{d\sigma(e\gamma \to eA_0)}{d(-t)} = \frac{1}{64\pi s^2} \sum_{\text{spin}} |\mathcal{M}|^2\,, \tag{10}$$

and we have

$$\sum_{\text{spin}} |\mathcal{M}|^2 = \frac{\alpha^4}{\sin^2\theta_W m_W^2}(s^2 + u^2)\frac{|\mathcal{A}_\gamma(t)|^2}{(-t)}\,, \tag{11}$$

where $s = -(p+k)^2$ and $u = -(p'-k)^2$. The presence of the $1/t$ in Eq. (11) means it is necessary to introduce a cutoff in the calculation of the total cross section. One approach to obtaining a finite cross section is use the effective photon or Weizsäcker-Williams approximation for the exchanged photon [7]. Here, we integrate the exact amplitude and impose an angular cutoff. The expression for the total cross section is

$$\sigma_{e\gamma\to eA^0}(s) = \frac{\alpha^4}{64\pi \sin^2\theta_W m_W^2} \int_{\eta(s-m_A^2)}^{(s-m_A^2)} \frac{dy}{y}\left(2 - 2\frac{(m_A^2+y)}{s} + \frac{(m_A^2+y)^2}{s^2}\right)|\mathcal{A}_\gamma(-y)|^2 , \quad (12)$$

where η is an angular cutoff. We investigated the effect of varying $\eta = \sin^2(\theta_{\min}/2)$ by comparing the standard model cross section with and without the Z^0 exchange. For $\theta_{\min}$ as large as $\pi/6$, the Z^0 contribution is only 3%-4% of the total. The result scales approximately as the logarithm of η, and we use $\eta = 10^{-5}$ in the figures.

To complete the calculation of the cross section for the $e\gamma$ process, it is necessary to fold the cross section, Eq. (12), with the distribution $F_\gamma(x)$ of backscattered photons having momentum fraction x [8] to obtain

$$\sigma_T = \frac{1}{s}\int_{m_A^2}^{0.83s} d\hat{s} F_\gamma(\frac{\hat{s}}{s})\sigma_{e\gamma\to eA^0}(\hat{s}) , \quad (13)$$

with $\hat{s} = xs$. Here, we have taken the usual upper limit on the allowed x value, $x = 0.83$.

This cross section is plotted in Fig. (1) for $M\mu > m_W^2 \sin 2\beta$ and in Fig. (2) for $M\mu < m_W^2 \sin 2\beta$. The dotted line in each panel is the contribution from the top and bottom quarks and the tau lepton. For large $\tan\beta$, the tau contribution is important. This is illustrated in the $\tan\beta = 20$ panel of Fig. (1), where the dot-dashed line is the contribution from the top and bottom quarks. The solid lines are the total contribution for $m_1 = 250$ GeV and $m_2 = 50$ GeV, which are within the range of values found in studies of minimal supersymmetric models [9]. In Fig. (1), the dashed lines are $m_1 = 250$ GeV and m_2 the largest value consistent with the constraint $(m_1 - m_2) \geq m_W\sqrt{2(1+\sin 2\beta)}$, which is needed to ensure that M and μ are real. Similarly, in Fig. (2), the dashed lines correspond to $m_1 = 250$ GeV and m_2 the largest value consistent with $(m_1 - m_2) \geq m_W\sqrt{2(1-\sin 2\beta)}$. Unlike the $M\mu > m_W^2 \sin 2\beta$ case, when $M\mu < m_W^2 \sin 2\beta$ it is possible for m_1 and m_2 to be equal for $\tan\beta = 1$ provided the $m_1, m_2 \geq m_W$.

In most cases, the inclusion of the chargino contribution leads to a significant increase in the cross section, especially for the larger values of $\tan\beta$.

Discussion

We would like to point out that the $e\gamma$ cross sections calculated here are very likely to be much larger than those of the related process $e\bar{e} \to \gamma A^0$ at 500 GeV. We have checked this for the production of the standard model Higgs-boson using the complete (standard model) calculation of $e\,\bar{e} \to \gamma H^0$ [6] and the photon pole contribution to $e\,\gamma \to e\,H^0$. At an $e\,\bar{e}$ center of mass energy of 500 GeV, we find the cross section $\sigma(e\,\bar{e} \to \gamma H^0)$ for the production of a 200 GeV H^0 is 0.08 fb, whereas $\sigma(e\,\gamma \to e\,H^0) = 5.9$ fb for the same Higgs-boson mass.

This enhancement is implicit in a previous calculation of scalar Higgs-boson production [7]. In Ref. [7], the Weizsäcker-Williams approximation is used for the t channel photon together with the on-shell $H \to \gamma\gamma$ amplitude. This is essentially equivalent to setting $y = 0$ in the parentheses of Eq. (12) and using m_e^2 as the cutoff in the remaining integral [10]. Our comparison of the approximate results of Ref. [7] with an exact calculation suggests that the Weizsäcker-Williams approach tends to overestimate the cross section. Apart from minor variations depending on how the calculation is performed, it is nevertheless true that the t channel cross section is substantially larger than its s channel counterpart.

To the extent that the photon pole contribution can be isolated, this method of searching for the A^0 has the advantage that the contributions from supersymmetry are significant and limited to one type supersymmetric particle. Should one observe a cross section larger than any standard model prediction, the case for the presence of chargino contributions is rather strong.

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References and Footnotes

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[10] To see this in detail, compare the simplified Eq. (12) with Eq. (1) of Ref. [7].

Figures

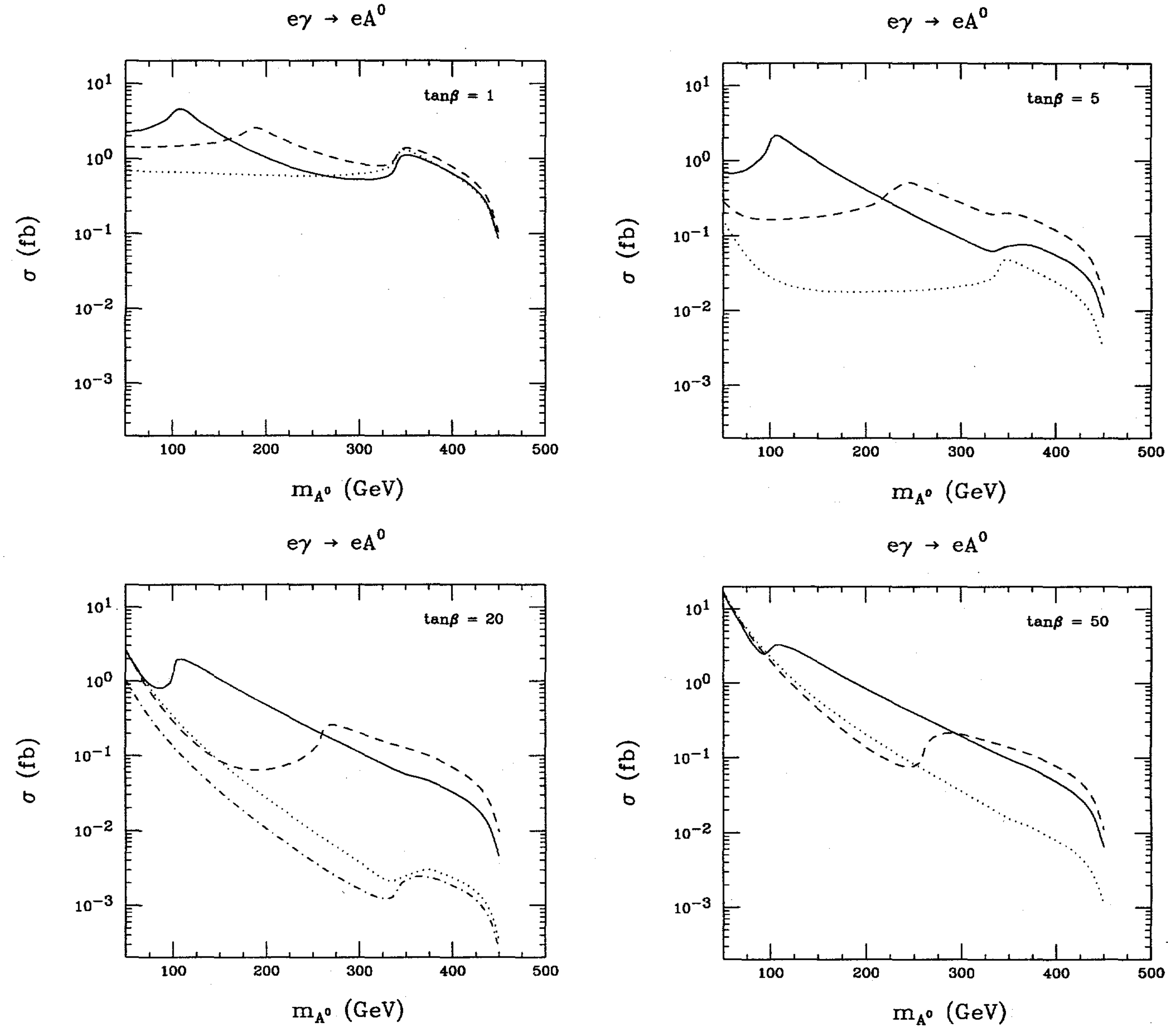

Figure 1: Cross sections for the production of A^0 are shown for various values of $\tan\beta$ and an $e\,\bar{e}$ center of mass energy of 500 GeV when $M\mu > m_W^2 \sin 2\beta$. In each case, the solid line corresponds to chargino masses $m_1 = 250$ GeV and $m_2 = 50$ GeV, and the dotted line is the standard two Higgs doublet model contribution without charginos. The dashed lines correspond to $m_1 = 250$ GeV and m_2 the largest value consistent with the restriction $(m_1 - m_2) \geq m_W\sqrt{2(1 + \sin 2\beta)}$. In these graphs, the angular cutoff η is taken to be 10^{-5}.

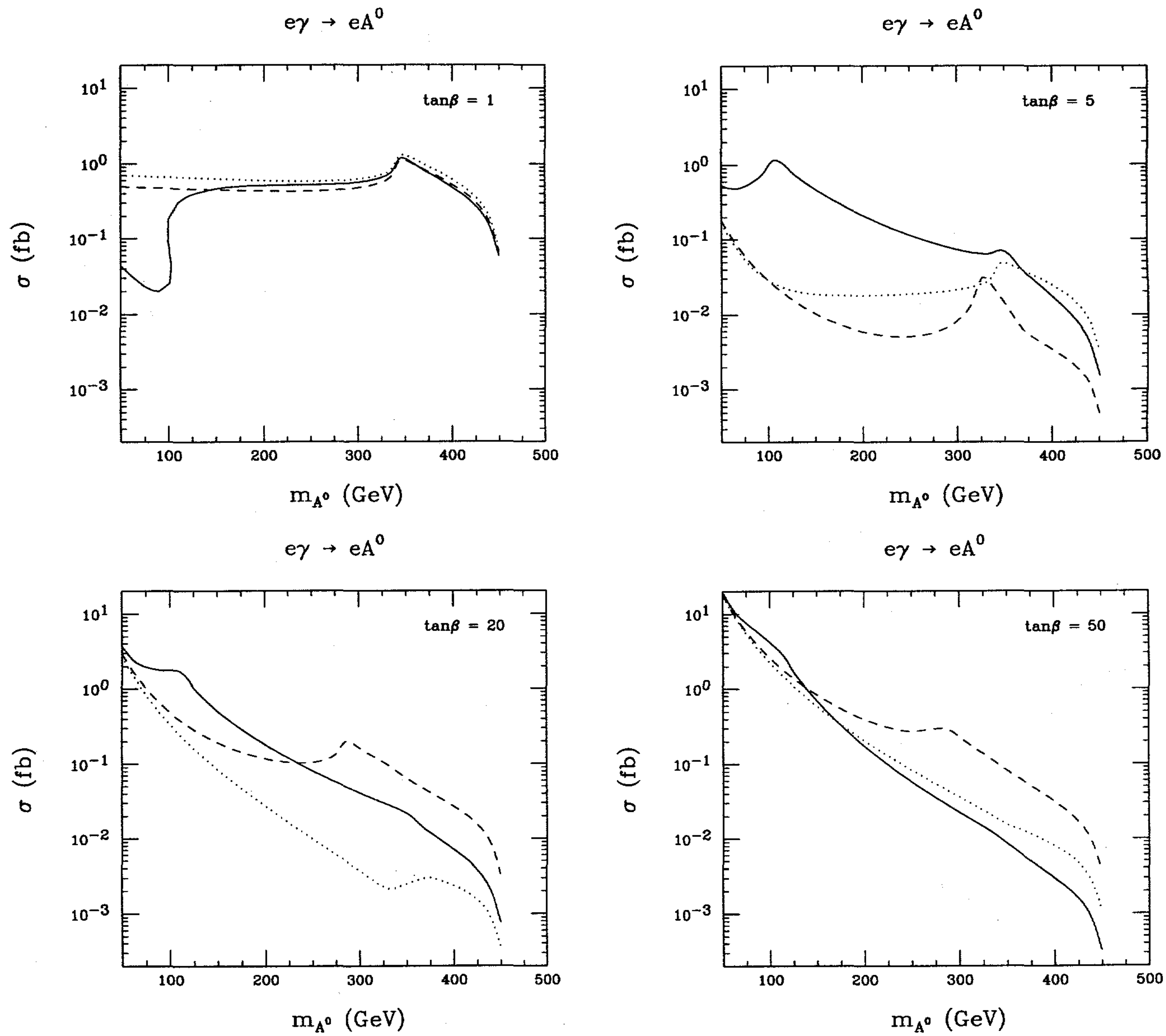

Figure 2: Same as Fig (1) for $M\mu < m_W^2 \sin 2\beta$. In this case, the constraint is $(m_1 - m_2) \geq m_W\sqrt{2(1-\sin 2\beta)}$.