\textbf{ττ Fusion to SUSY Higgs Bosons at a Photon Collider:}

\textbf{Measuring tan β}

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\textbf{ττ fusion to light $h$ and heavy $H,A$ Higgs bosons is investigated in the Minimal Supersymmetric Standard Model (MSSM) at a photon collider as a promising channel for measuring large values of tan β. For standard design parameters of a photon collider an error $\Delta \tan \beta \sim 1$, uniform for $\tan \beta > 10$, may be expected, improving on complementary measurements at LHC and $e^+e^-$ linear colliders.}

1.) The measurement of the mixing parameter $\tan \beta$, one of the fundamental parameters in the Higgs sector of the Minimal Supersymmetric Standard Model [MSSM] and other supersymmetry scenarios, is a difficult task. Many of the observables, in the chargino/neutralino sector for instance, involve only $\cos 2\beta$ and thus are quite insensitive to the parameter $\tan \beta$ for large values. Remarkably different however are the heavy $H/A$ Higgs couplings to down-type fermions which, for values of the pseudoscalar Higgs boson mass at the electroweak scale and beyond, both are directly proportional to $\tan \beta$ if this parameter becomes large, see \textit{e.g.} Ref.\textsuperscript{1}, so that they are highly sensitive to its value. Also the down-type couplings of the light $h$ Higgs boson in the MSSM are close to $\tan \beta$ if the pseudoscalar mass is moderately small.

In this note we point out that $\tau\tau$ fusion to Higgs bosons at a photon collider\textsuperscript{2} can provide a valuable method for measuring $\tan \beta$, after searching for and exploring Higgs bosons in $\gamma\gamma$ fusion\textsuperscript{3,4}. The entire Higgs mass range up to the kinematical limit can be covered for large $\tan \beta$ by this method.

2.) The formation of the light and heavy $\Phi = h/H/A$ Higgs bosons in $\tau\tau$ fusion at a photon collider proceeds as shown in Fig.1. For the large-$\tan \beta$ case
studied here, all the Higgs bosons $\Phi$ decay almost exclusively [80 to 90\%] to a pair of $b$ quarks. Therefore the final state consists of a pair of $\tau$'s and a pair of resonant $b$ quark jets.

$$\gamma \rightarrow \tau^+\tau^- \rightarrow h/H/A$$

**Figure 1:** The process of $\tau\tau$ fusion to Higgs bosons in $\gamma\gamma$ collisions.

In the equivalent-particle approximation the process can be decomposed into two consecutive steps: photon splittings to tau pairs, $\gamma \rightarrow \tau^+\tau^-$, followed by the fusion process of two (almost on-shell) taus to the Higgs bosons, $\tau^+\tau^- \rightarrow \Phi$. The cross section is given by the convolution of the fusion cross section with the $\tau\tau$ luminosity in the colliding photon beams:

$$\sigma[\gamma\gamma \rightarrow \tau^+\tau^-\Phi] = \frac{\pi m_\tau^2}{2\sqrt{s}} g_{\Phi\tau\tau}^2 \times 2 \int_\tau^1 \frac{dz}{z} D_\gamma^\tau(z)D_\gamma^\tau(\tau/z)$$

$v$ is the Higgs vacuum expectation value, $v \simeq 246$ GeV; $\sqrt{s} = E_{\gamma\gamma}$ is the c.m. energy of the photons, and $\tau = M_\Phi^2/s$. The couplings $g_{\Phi\tau\tau}$ are normalized to the Standard Model Higgs coupling to a tau pair, $m_\tau/v$. For large $\tan \beta$, the couplings are given by

$$
\begin{align*}
g_{\Phi\tau\tau} &= \tan \beta \quad \text{for } \Phi = A \\
g_{\Phi\tau\tau} &\simeq \tan \beta \quad \text{for } \Phi = h, H
\end{align*}
$$

if the pseudoscalar mass parameter $M_A$ is sufficiently light in the case of $h$, and sufficiently heavy in the case of $H$, cf. Ref.\(^1\) for details. From the $\gamma \rightarrow \tau$ splitting function\(^5\) $D_\gamma^\tau(z)$ the $\tau\tau$ luminosity

$$F_{LL}(\tau) = \left(\frac{\alpha}{2\pi}\right)^2 \log^2 \frac{M_\Phi^2}{m_\tau^2} \times [2(1 + 2\tau)^2 \log^{-1} - 4(1 - \tau)(1 + 3\tau)]$$

in the second part of Eq.(1) can easily be derived.
A rough estimate, based on the equivalent-particle approximation introduced in Eq. (1), shows the size of the fusion cross section to be \( \sim 8 \text{ fb} \) for the \( \gamma\gamma \) c.m. energy \( E_{\gamma\gamma} = 600 \gev \) and the Higgs parameters \( M_{H/A} = 400 \gev \) and \( \tan \beta = 30 \). For an integrated luminosity of 200 \( \text{fb}^{-1} \), about 3,000 events can be expected in both \( H \) and \( A \) decay channels. As a result, a statistical error of order 1\% can be predicted that compares favorably well with other methods\(^6\text{,}^7\). On the other hand, the light Higgs boson \( h \) and, for moderate mass values, the heavy Higgs bosons \( H, A \) can also be produced at lower energies, e.g. \( E_{\gamma\gamma} = 400 \gev \).

In the same way the size of the cross section for the main background channel can be estimated: \( \tau^+\tau^- \) annihilation into a pair of \( b \)-quarks, via \( s \)-channel \( \gamma/Z \) exchanges. As this mechanism is of higher order in the electroweak interactions, it is naturally small and strongly suppressed away from the \( Z \) resonance region. [The reverse process, annihilation of \( b \)'s to \( \tau \)'s, is very small due to the fractional \( b \) electric charge.] A second background channel is associated with diffractive \( \gamma\gamma \rightarrow (\tau^+\tau^-)(b\bar{b}) \) events, the pairs scattering off each other by Rutherford photon exchange. This diffractive background can be suppressed strongly by choosing proper cuts: the paired fermions in diffractive events travel preferentially parallel to the \( \gamma \) axes and they carry small invariant mass, a topology quite different from the signal events.

3.) For an \( e^+e^- \) collider c.m. energy of 800 \gev, the maximum of the \( \gamma\gamma \) energy spectrum is close to 600 \gev. Adopting the detailed TESLA parameters, an integrated \( \gamma\gamma \) luminosity of about 200 \( \text{fb}^{-1} \) per annum can be expected in the margin 20\% below the maximum \( e^+e^- \) energy\(^8\). Similarly, about 100 \( \text{fb}^{-1} \) may be accumulated for a \( \gamma\gamma \) energy of 400 \gev at a 500 \gev \( e^+e^- \) collider.

In the numerical analysis the full set of diagrams for the signal processes \( \gamma\gamma \rightarrow \tau^+\tau^- + \Phi \rightarrow b\bar{b} \) and all diagrams for the background processes \( \gamma\gamma \rightarrow \tau^+\tau^- b\bar{b} \), generated by means of \texttt{CompHEP}\(^9\), are taken into account. This set includes for the signal in particular the bremsstrahlung of the Higgs bosons off the external \( \tau \) legs.

The exact cross sections for the signals of \( H \) and \( A \) Higgs-boson production in the \( \tau\tau \) fusion process, together with all the background processes, are presented in the top panel of Fig. 2. The cuts on the final states have been chosen such that the diffractive \( \gamma \)-exchange mechanism is suppressed sufficiently well: the invariant \( b\bar{b} \) mass has been constrained to the bracket \( \Delta = 0.05M_{\Phi} \), the taus are assumed visible and traveling in opposite directions to the beam axis with tau energies in excess of 5 \gev, and polar angles beyond 130 mrad to account for the shielding. From the complementary bottom panel of Figure 2
Figure 2: The cross sections for the production of the $H/A$ (top) and $h$ (bottom) Higgs bosons in the $\tau\tau$ fusion process at a $\gamma\gamma$ collider for $\tan\beta = 30$. Also shown is the background cross section for experimental cuts as specified in the text. $\sqrt{s}$ denotes the $\gamma\gamma$ collider c.m. energy, corresponding to approximately 80% of the $e^+e^-$ linear collider energy.
it is clear that $\tau\tau$ fusion to the light Higgs boson $h$ can also be exploited to measure $\tan\beta$ for large values if the pseudoscalar mass is moderately small.

| $M_{\text{Higgs}}$ [GeV] | $E_{\gamma\gamma} = 400$ GeV | $E_{\gamma\gamma} = 600$ GeV |
|----------------------|-----------------|-----------------|
| 100                  | $A \oplus h$    | $A \oplus h$    |
| 200                  | $A \oplus H$    | $A \oplus H$    |
| 300                  |                 |                 |
| $\tan\beta$          | $\text{I, II}$ | $\text{IV, V}$  |
| 10                   | 8.4%            | 8.0%            |
| 30                   | 2.6%            | 2.4%            |
| 50                   | 1.5%            | 1.5%            |

Table 1: Relative errors $\Delta \tan\beta / \tan\beta$ on $\tan\beta$ in measurements for $\tan\beta = 10$, 30 and 50, based on: combined $A \oplus h$ [I, IV] and $A \oplus H$ [II, III, V–VIII] production, assuming $[E_{\gamma\gamma} = 400$ GeV, $L = 100$ fb$^{-1}$] and $[E_{\gamma\gamma} = 600$ GeV, $L = 200$ fb$^{-1}$]. Cuts and efficiencies are applied on the final–state $\tau$'s and $b$ jets as specified in the text.

The statistical accuracy with which large $\tan\beta$ values can be measured in $\tau\tau$ fusion to Higgs bosons can be estimated from the predicted cross sections and the assumed integrated luminosities. Efficiencies for $b\bar{b}$ tagging, $\epsilon_{b\bar{b}}$, and $\tau\tau$ tagging, $\epsilon_{\tau\tau}$, reduce the accuracy. For $\epsilon_{b\bar{b}} \sim 0.7$ and $\epsilon_{\tau\tau} \sim 0.5$, for example, the errors grow by a factor $1/\sqrt{\epsilon_{b\bar{b}} \epsilon_{\tau\tau}} \sim 1.7$. The expected errors for $h/H/A$ production are exemplified for three $\tan\beta$ values, $\tan\beta = 10$, 30 and 50, in Table 1. The integrated luminosities are chosen to be 200 fb$^{-1}$ for the high energy option and 100 fb$^{-1}$ for the low energy option. For $h$ production, the mass parameters are set to $M_A \sim 100$ GeV and $M_h = 100$ GeV; for the production of the heavy pseudoscalar $A$ the mass is varied between 100 and 500 GeV. Results for scalar $H$ production are identical to pseudoscalar $A$ in the mass range above 120 GeV. The two channels $h$ and $A$, and $H$ and $A$ are combined in the overlapping mass ranges in which the respective two states cannot be discriminated. In Table 1 we have presented the relative errors $\Delta \tan\beta / \tan\beta$. Since in the region of interest the $\tau\tau$ fusion cross sections are proportional to $\tan^2\beta$ and the background is small, the absolute errors $\Delta \tan\beta$ are nearly independent of $\tan\beta$, varying between

$$\Delta \tan\beta \simeq 0.9 \quad \text{and} \quad 1.3$$

for Higgs mass values away from the kinematical limits.

It should be noted that away from the kinematical limits, the Higgs fusion cross sections vary little with the $\gamma\gamma$ energy since the suppression of the
parton subprocess with rising energy is almost compensated by the luminosity function. As a result, the smearing of the $\gamma\gamma$ energy has a mild effect on the analysis presented here. Moreover, since the $\gamma\gamma$ machine-luminosity rises with the collider energy, the errors on $\tan\beta$ decrease correspondingly.

4.) $\tau\tau$ fusion to the heavy Higgs bosons $H/A$ of the MSSM at a photon collider is a promising channel for measuring the Higgs mixing parameter $\tan\beta$ at large values. Complemented by $\tau\tau$ fusion to the light Higgs boson $h$ for moderately small values of the pseudoscalar Higgs boson mass $M_A$, the MSSM parameter range can nicely be covered in all scenarios. This analysis compares favorably well with the corresponding $b$-quark fusion process at the LHC\textsuperscript{7}. Moreover, the method can be applied readily for a large range of Higgs mass values and thus is competitive with complementary methods in the $e^+e^-$ mode of a linear collider\textsuperscript{6}.

References

1. M. Spira and P. M. Zerwas, Lectures at the Schladming Winter School 1997 [arXiv:hep-ph/9803257]; E. Boos, A. Djouadi, M. Mühlleitner and A. Vologdin, Phys. Rev. D \textbf{66} (2002) 055004 [arXiv:hep-ph/0205160].
2. S.Y. Choi, J. Kalinowski, J.S. Lee, M.M. Mühlleitner, M. Spira and P.M. Zerwas, arXiv:hep-ph/0404119 [to be published in Phys. Lett. B].
3. M. Mühlleitner, M. Krämer, M. Spira and P. M. Zerwas, Phys. Lett. B \textbf{508} (2001) 311 [arXiv:hep-ph/0101083]; M. M. Velasco \textit{et al.}, in \textit{Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)}, [arXiv:hep-ex/0111055]; D. M. Asner, J. B. Gronberg and J. F. Gunion, Phys. Rev. D \textbf{67} (2003) 035009.
4. P. Nieżurawski, A. F. Zarnecki and M. Krawczyk, arXiv:hep-ph/0307180, hep-ph/0307183, and hep-ph/0403138.
5. M. S. Chen and P. M. Zerwas, Phys. Rev. D \textbf{12} (1975) 187.
6. J. F. Gunion, \textit{et al.}, in “LHC/LC Physics Document”, 2004.
7. R. Kinnunen, S. Lehti, F. Moortgat, S. Nikitenko and M. Spira, CMS–Note CMS AN 2003/014.
8. B. Badelek \textit{et al.} [ECFA/DESY Photon Collider Group], TESLA-TDR, Part VI, DESY 02-011 [arXiv:hep-ex/0108012]; E. Boos \textit{et al.}, Nucl. Instrum. Methods A \textbf{472} (2001) 100 [arXiv:hep-ph/0103090].
9. A. Pukhov \textit{et al.}, CompHEP Collaboration, arXiv:hep-ph/9908288.
10. K. Desch, \textit{private communication}. 

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