We review some recent developments in Higgs physics at a $\gamma\gamma$ collider. We begin with single Higgs boson production in $\gamma\gamma$ collisions proceeding via the hadronic content of the photon. For SM Higgs masses of current theoretical interest, the resolved photon contributions are non-negligible in precision cross section measurements. We found that production of the heavier Higgs bosons, $H^0$ and $A^0$, of the MSSM can probe regions of the SUSY parameter space that will complement other measurements. We showed that associated $tH^{\pm}$ production in $\gamma\gamma$ collisions can be used to make an accurate determination of $\tan\beta$ for low and high $\tan\beta$ by precision measurements of the $\gamma\gamma \rightarrow H^{\pm}t + X$ cross section. We then reviewed recent progress on Higgs physics in direct photon processes in which the Higgs bosons are produced via virtual loops. Precision measurements of the magnitude and phase of the $H\gamma\gamma$ coupling at a photon collider can be used to determine Higgs parameters related to physics beyond the SM.

1 Categories of Higgs physics at a $\gamma\gamma$ collider

The photon-photon “Compton Collider”, which utilizes laser light backscattered off of highly energetic and possibly polarized electron beams, has been advocated as a valuable part of the LC physics program. In this talk we review some recent progress on Higgs physics in: (1) resolved photon processes and (2) direct photon processes. Due to space limitations, some important issues cannot be included, for example, Higgs pair production which is crucial for the measurement of the triple Higgs coupling.

We begin by exploring various aspects of Higgs boson production in resolved photon processes, i.e. via the hadronic content of the photon, which we briefly describe. Details and complete references are given in Ref. 2 and 3. In the resolved photon approach the quark and gluon content of the photon are treated as partons described by partonic distributions, $f_{q/\gamma}(x,Q^2)$, in direct analogy to partons inside hadrons. The parton subprocess cross sections are convoluted with the parton distributions to obtain the final cross sections. These have to be further convoluted with the photon energy distributions obtained from either the backscattered laser or the Weizsäcker Williams distributions to obtain cross sections that can be compared to experiment.

We then review recent progress on Higgs physics in direct photon processes. It is well known that one of the strongest motivations for the Compton collider is to measure Higgs boson properties via single neutral Higgs production through loops. Measurement of the $\gamma\gamma \rightarrow H$ cross section is especially interesting as it proceeds via loop contributions and is therefore sensitive to new particles that cannot be produced directly. Based on the precise measurements of the magnitude and phase of $H\gamma\gamma$ at a photon collider, Higgs parameters for new physics beyond the SM can be precisely determined.

2 Resolved Photon processes

2.1 Single neutral Higgs production

Due to the importance of single neutral Higgs boson production via $\gamma\gamma \rightarrow H$, it is important that all SM contributions to this process be carefully considered. The resolved
photons contributions to Higgs production are shown in Fig. 1 for the backscattered laser case with $\sqrt{s_{ee}} = 500$ GeV. We also show the $\gamma\gamma \rightarrow H$ cross section which proceeds via loops and the contribution from gluon fusion, $\sigma(gg \rightarrow H)$, which arises from the gluon content of the photon. A final process is $\gamma\gamma \rightarrow HW^{+}W^{-}$ whose cross section is comparable to the resolved photon processes. Although the loop process dominates over the resolved photon processes for the full range of Higgs masses, the latter processes contribute at the percent level for $M_H \sim 150$ GeV and $\sqrt{s_{ee}} = 500$ GeV increasing to several percent for $\sqrt{s_{ee}} = 1.5$ TeV. Thus, Higgs production via the hadronic content of the photon may not be negligible for precision measurement of $\sigma(\gamma\gamma \rightarrow H)$ suggesting that these contributions deserve further study.

In the MSSM there exist a total of three neutral Higgs bosons which can be produced in $\gamma\gamma$ collisions: $\gamma\gamma \rightarrow h^0, H^0, A^0$. However, the resolved photon process has different dependence on $\tan\beta$ than that of the loop processes. If $H$ and $A$ were produced in sufficient quantity the cross section could be used to constrain $\tan\beta$. This can be seen most clearly in Fig. 2 which shows the regions of the $\tan\beta - M_A$ plot which can be explored via $A$ production for $\sqrt{s_{ee}} = 500$ GeV. The regions covered would complement measurements made in other processes.

### 2.2 Measurement of $\tan\beta$ in associated $tH^\pm$ production

The ratio of neutral Higgs field vacuum expectation values, $\tan\beta$, is a key parameter needed to be determined in type-II Two-Higgs Doublet Models and the MSSM. $\tan\beta$ can be measured in associated $tH^\pm$ production in $\gamma\gamma$ collisions. The subprocess $b\gamma \rightarrow H^-t$ utilizes the $b$-quark content of the photon. $\tan\beta$ enters through the $tbH^\pm$ vertex. In Fig. 3 we show the cross section as a function of $\tan\beta$ with the measurement precision superimposed. We found that $\gamma\gamma \rightarrow tH^\pm + X$ can be used to make a good determination of $\tan\beta$ for most of the parameter space with the exception of the region around $\tan\beta \simeq 7$.
where the cross section is at a point of inflection. This measurement provides an additional constraint on $\tan \beta$ which complements other processes.

### 2.3 Other resolved photon process

Choi et al.\(^{11}\) studied the related process of $\tau \tau \to H$ where the $\tau$'s come from the fermionic content of the photon. They show that $\Delta \tan \beta \sim 0.9$ to 1.3 is uniform in $\tan \beta$ for all $M_A$ up to the kinematic limit, and the results are encouraging enough to start real experimental simulations.

### 3 Direct photon processes

As discussed above, the neutral Higgs boson can be produced via loops which is sensitive to new virtual particles arising in new physics beyond the SM. This process can be used to measure the $H \gamma \gamma$ magnitude from $\Gamma_{\gamma \gamma}$ and the phase $\Phi_{\gamma \gamma}$. According to the decay products of the Higgs boson, the investigations can be classified into: (1) $H \to heavy\ fermions$ and (2) $H \to VV$ with $V = W$ and $Z$.

#### 3.1 $H \to heavy\ fermions$

Usually the couplings of the Higgs boson with fermions are proportional to the fermion's mass, which is what makes the heavy fermion decay modes interesting\(^5,6\). For example, for $H \to bb$, a precision of 2-9% can be achieved on cross section measurements after one year of Photon Collider (PC) running for a SM Higgs mass between 120 to 160 GeV, while for MSSM Higgs bosons a measurement precision of 11-23% on the cross sections can be achieved for $M_A = 200 \sim 350$ GeV.$^5$

#### 3.2 $H \to VV$ with $V = W$ and $Z$

In the SM, from simultaneous fits to the $WW$ and $ZZ$ mass spectra, $\Gamma_{\gamma \gamma}$ and $\Phi_{\gamma \gamma}$ can be measured with precision of $\sim 4-9%$ and 40-120 mrad respectively\(^7\).

In the SM-like two Higgs doublet model [2HDM(II)] there is only one parameter, $\tan \beta$. But one can also introduce the additional CP-violating $H \to A$ mixing parameter $\Phi_{HA}$. Both $\tan \beta$ and $\Phi_{HA}$ can be measured to $\sim 10\%$ (for $\Phi_{HA} \sim 0$) and 0.1 rad if $\tan \beta$ is not too large\(^8\).

In the general 2HDM (II) one defines

$$\chi_x \equiv \frac{g_{Hxx}}{g_{Hxx}^{SM}}, \text{ with } H = H, h^0, A.$$ 

LHC measurements can constrain $\chi_U$ (Higgs boson production via top virtual loop where $U$ is for up-type quarks), the LC can constrain $\chi_V$ (Higgs boson radiating off $Z$ boson) and the PC can constrain both (Higgs boson production via gauge boson and quark loops). The combined analysis from the LHC, LC and PC, is depicted in Fig. 4. The average errors are:

$$< \Delta \chi_V > = 0.033$$

$$< \Delta \chi_U > = 0.12$$

$$< \Delta \Phi_{HA} > = 150 \text{ mrad}$$

for $\chi_V = 0.7$, $\chi_U = -1$ and $m_H = 250$ GeV$^9$.

In the generic model the $HVV$ couplings,
Figure 4. Taken from Ref. 9. Expected total error contours ($1\sigma$) in the determination of the basic Higgs-boson couplings to vector bosons ($\chi_V$) and up fermions ($\chi_u$) from combined fit to invariant mass distributions measured at LHC, LC and Photon Collider, for the CP-conserving (blue) and CP-violating (red) 2HDM (II). Production and decays of heavy Higgs boson are considered for $M_H = 250$ GeV.

$g_{HZZ}$ and $g_{HWW}$, can be written as

\[ ig \frac{m_Z}{\cos \theta_W} \left( g_{\mu H} \lambda_H + \lambda_A \epsilon_{\mu \rho \sigma} \epsilon_{\rho \sigma} \right) \]

\[ ig m_W \left( g_{\mu H} \lambda_H + \lambda_A \epsilon_{\mu \rho \sigma} \epsilon_{\rho \sigma} \right) \]

respectively, with $P_{\rho \sigma} = (p_1 + p_2)^\rho (p_1 - p_2)^\sigma$, $\lambda_H = \lambda \cos \Phi_{CP}$ and $\lambda_A = \lambda \sin \Phi_{CP}$. In the SM, $\lambda_H = 1$ and $\lambda_A = 0$. Detailed simulations, especially on the angular distributions, show that $\Delta \Phi_{CP} = 50 \text{ mrad}$ and $\lambda$ can be measured to several percents\(^{10}\).

4 Summary

We reviewed recent progress on Higgs physics at a photon colliders, especially Higgs physics in resolved photon processes. We can see that there is rich physics at the photon collider and much more investigation needs to be done.

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