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SUPERSYMMETRY AT THE PLC*

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In this talk I will begin with a very brief discussion as to why TeV scale Supersymmetry forms an important subject of the studies at all the current and future Colliders. Then, I will give different examples where the Photon Linear Collider, PLC, will be able to make unique contributions. PLC's most important role is in the context of Higgs Physics, due to its ability of accurate determination of $\Gamma_{\gamma\gamma}$ as well as the possibilities it offers for the determination of the CP property of the Higgs boson and of possible CP-mixing in the Higgs sector. Further, the PLC can provide probes of SUSY in the regions of the SUSY parameter space, which are either difficult or inaccessible at the LHC and also in the e^+e^- mode of the International Linear Collider (ILC).

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1. Introduction

In this talk I want to discuss the special role that the Photon Linear Collider (PLC) can play when it comes to Supersymmetry searches/studies at the future colliders. Before doing this, let us just briefly recapitulate the basics of Supersymmetry (SUSY), the attractions that the TeV scale Supersymmetry holds for the Particle Physics community and the reasons why the searches for SUSY form a significant part of the physics studies at the colliders: currently running and/or in planning/construction [1]. Supersymmetry, a symmetry transformation between fermions and bosons, is the only possible extension of the spacetime symmetries to particle interactions. In other words this is the only consistent way to combine spacetime symmetries with an internal symmetry. In addition Supersymmetric field theories are the only quantum field theories which remain "natural" [2] even in presence of scalars. As a result Supersymmetry helps stabilise the EW symmetry

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breaking scale against radiative corrections. SUSY thus provides a solution to the "naturalness" problem, which is theoretically very attractive and elegant. In these theories, associated with every standard model particle there is a supersymmetric partner, the sparticle, differing in spin by 1/2. The left-hand side panel in Fig. 1 indicates how the sparticle loops help cancel the large self energy corrections, keeping the Higgs mass "naturally" light. As a matter of fact in the limit of perfect supersymmetry, where the particle and sparticle masses are equal, these corrections will cancel each other exactly. Even if SUSY is broken, one can show that existence of TeV scale supersymmetry keeps the Higgs naturally light.

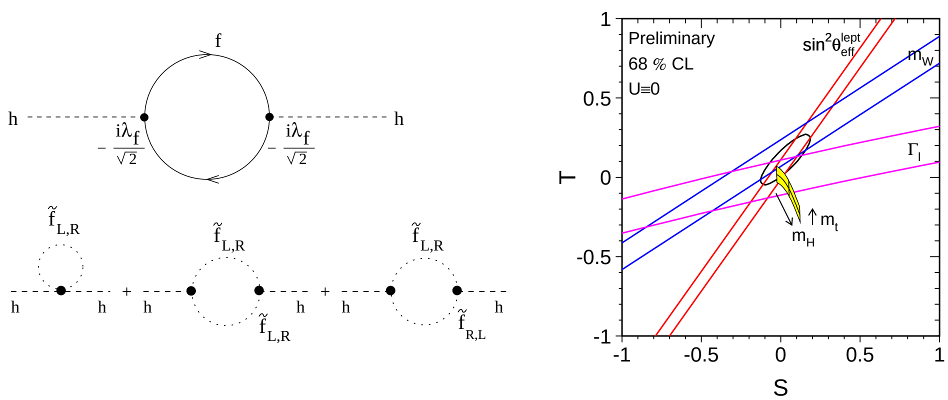

Fig. 1. Stabilisation of Higgs mass against radiative corrections and experimental evidence for a weakly coupled light Higgs.

The experiments of the past few decades, culminating in the high precision measurements at the colliders and the neutrino experiments, have established the correctness of both the gauge sector and the flavour sector of the SM Lagrangian given by

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + i\bar{\psi}\not{D}\psi + \psi^T \lambda \psi h + \text{h.c.} + |D_\mu h|^2 - V(h)\,. \tag{1.1}$$

Only the scalar sector remains without direct evidence. The Tevatron and the LEP/SLC give "indirect" bounds on the Higgs mass. Analysis of precision measurements from LEP in terms of the Oblique parameters, S, T, U [3], constrain strongly any **nondecoupling NEW** physics beyond the SM. The plot in the right-hand side panel of Fig. 1, taken from the `http://lepewwwg.web.cern.ch`, illustrates these constraints. This indirect upper bound on the Higgs mass at 95% c.l. is 251 GeV, whereas the direct searches give a lower bound of 114 GeV. Thus the precision measurements like a "light" Higgs. As a matter of fact, theorists like a "light" Higgs as well. If the SM is an effective theory, then we expect $180 < m_h < 200$ GeV. Further, in a model independent analysis [4], one can show that if the scale for New Physics $\Lambda_{\rm NP} < 10\,{\rm TeV}$, then one expects, demanding "naturalness" $195 < m_h < 215$; SUSY being a particular example of the New Physics which keeps the Higgs "naturally" light. These experimental indications of a "light" Higgs make SUSY theoretically very attractive. The search for SUSY is thus the case of experiments chasing a beautiful theoretical idea. Even if it is a symmetry of nature, it is clearly broken. Further, all the experimental searches so far have yielded only negative results, giving only **lower** limits on the sparticle masses. The only, *very indirect* indication for SUSY at present seems to be the absence of the unification of the three gauge couplings in the SM, whereas in the MSSM the three do unify. This is illustrated in the left-hand side panel of Fig. 2. It is imperative to find "direct" evidence for SUSY. As a result, SUSY searches have been an important benchmark against which the capabilities and physics potential of the upcoming colliders such as the LHC or the ones in future such as the ILC, have been evaluated.

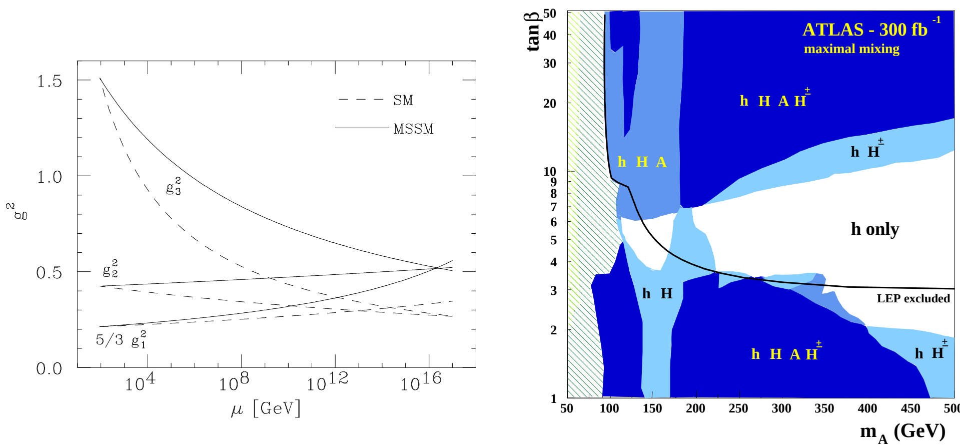

Fig. 2. The (non) unification of the three gauge couplings in the (SM) MSSM (left-hand side panel) and the reach of LHC for the MSSM Higgs [5] (right-hand side panel).

The sparticle mass spectrum depends on the mechanism responsible for SUSY breaking and can vary widely, but the sparticle spins and couplings are predicted unambiguously. With the help of the LHC and the ILC in the e^+e^-*mode* [1, 5–7] we hope to find the sparticles, measure their masses, spins and couplings. The masses and the couplings of the $\tilde\chi^\pm, \tilde\chi^0_l$ and the supersymmetric partners of the third generation of the quarks/leptons, can depend on the SUSY breaking mechanism and parameters. The LHC will be able to "see" the strongly interacting sparticles if the SUSY breaking scale is TeV. If the sparticle mass is within the kinematic reach of the ILC, we should be able to make accurate mass measurements and spin determination. The LHC and the ILC together can even help us determine the SUSY model parameters and hence the SUSY breaking mechanism [7]. On this background it is important to enquire about the special role, if any, that the PLC can play in this context.

There are certain regions in the SUSY parameter space where the LHC and the ILC in e^+e^- mode may be blind and or the signal may be lost. The $\gamma\gamma$ mode and $e\gamma$ mode does provide possibilities to search for SUSY in this case. However, a more important question to ask is what are the unique possibilities offered by the PLC. Almost all of these come in the context of the Supersymmetric Higgs sector; especially in the context of Higgs sector with CP violation. The PLC with its option of having highly polarised photons, offers some unique possibilities. Some of these have already been discussed in the meeting [8–10]. In the next section we would discuss these one by one.

2. CP conserving MSSM Higgs sector and the PLC

The PLC provides truly unique possibilities in probing the Higgs sector in the MSSM [1, 11]. In Supersymmetric theories there are (at least) five scalar states: h, H, A and $H^{\pm}$. h, H are CP even whereas A is CP odd and the M_h is bounded from above. In the decoupling limit h will have properties very similar to a SM Higgs. The MSSM parameters relevant for this sector are: $\tan\beta$ (the ratio of vacuum expectation values), higgsino mass term μ and M_A.

The special features of a $\gamma\gamma$ collider that are of special help, are:

1. Accurate measurements ($\sim 2\%$) of the $\Gamma_{\gamma\gamma}$ decay width is possible.
2. Polarisation of the laser and as well as that of the e^+/e^- beam can be tuned.
3. The $e\gamma$ option where polarised electron is scattered off the high energy backscattered photon provides an extra channel.

Below I will discuss three examples where the PLC can cover regions of SUSY parameter space which will be inaccessible to the LHC and the ILC in e^+e^- mode.

2.1. Higgs production through τ-fusion mechanism

Studies of the $\tilde{\chi}^+\tilde{\chi}^-, \tilde{\chi}^0_j\tilde{\chi}^0_i$ at e^+e^- colliders provide possibilities of the determination of SUSY parameters, μ, M_1, M_2 and $\tan\beta$. However, accuracy of the $\tan\beta$ determination is degraded at large $\tan\beta$ mainly because the observable involves $\cos 2\beta$. A recent suggestion [12] is to use the τ-fusion process $\gamma\gamma \to \tau^+\tau^-\phi \to \tau^+\tau^- b\bar{b}$; where ϕ denotes the Higgs boson.

Plots in Fig. 3 show that indeed for all the three Higgs states, the signal is substantially above the background. One can see that the process offers a possibility of accurate $\tan\beta$ determination at large $\tan\beta$. For example, at $\tan\beta = 30, \Delta\tan\beta = 0.9$–$1.3$. This has to be contrasted with the precision of $\Delta\tan\beta \sim 10$–20 that can be reached at the e^+e^- option [13]. The conclusions of this very interesting study need to be confirmed by simulations.

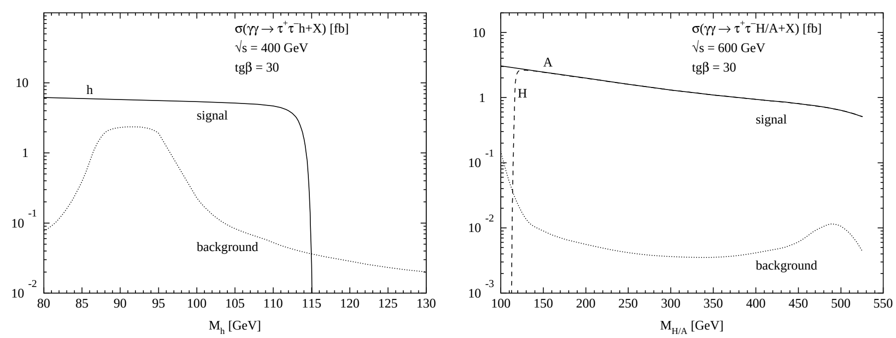

Fig. 3. τ-fusion production rates for h and H/A production, along with the background at the PLC shown in the left-hand side and the right-hand side panel, respectively. The peaked photon spectrum is used [12].

2.2. Covering the LHC-wedge for the MSSM

As is seen in the right-hand side panel of Fig. 2, in a plot taken from the TESLA-TDR [5], for $\tan\beta \simeq 4$–10, $M_A, M_H > 200$–250 GeV, LHC will see only one spin 0 state and the H, A are not accessible for the first generation ILC. This region is referred to as the LHC-wedge. The $\gamma\gamma$ colliders offer unique possibilities of exploring this region. Since H/A can be produced singly at a $\gamma\gamma$ collider, the reach in mass extends to $0.8\sqrt{s}$ at the $\gamma\gamma$ option compared to the $0.5\sqrt{s}$ at the e^+e^- option. $\sqrt{s}$ of course is the cm energy of the parent e^+e^- collider. The QED background can be reduced by appropriately choosing the laser photon and the electron helicities. For the larger $\tan\beta$ range, $b\bar{b}$ final state can be utilised effectively. However, for the smaller $\tan\beta$ values the $b\bar{b}$ coupling reduces and ,since the QED background being much higher for the $t\bar{t}$ final state (due to the larger charge of the t quark), this latter channel cannot be used effectively either. In this region decays of H/A into the $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_j^0\tilde{\chi}_i^0$ may be used [14].

A detailed simulation of the $b\bar{b}$ final state for this LHC-wedge region has been performed [15, 16]. A summary of the conclusion of these papers is that for the light Higgs the $\gamma\gamma$ width can be measured $\simeq 2\%$, however in the case of H/A the precision is somewhat worse: $\sim 11\%$–21%. As said

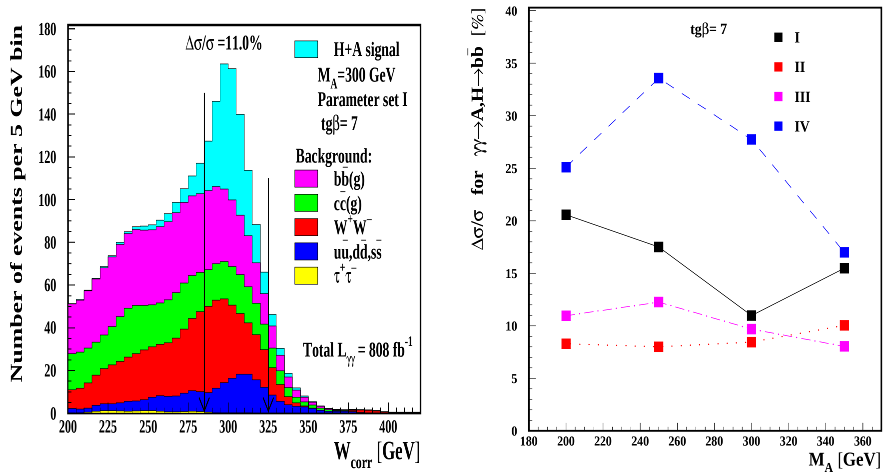

Fig. 4. Precision possible in the measurement of $\gamma\gamma \to H/A \to b\bar{b}$ [16].

earlier, one can handle the QED background, by adjusting the helicities of the two photons. For the A/H there were suggestions to separate the two by choosing the polarisation vectors of the two photons to be perpendicular and parallel. However, in this case the QED background cannot be handled easily.

The precise measurement of the width $\Gamma_{\gamma\gamma}$ at the PLC can offer a probe of the contribution due to SUSY particles in the loop to the Higgs width [11, 17, 18].

3. CP determination of the Higgs and the PLC

CP violation in SUSY used to be an embarrassment of riches, as there exists large number (44 to be precise) of phases of the SUSY parameters, *e.g.* $\mu, A_f, M_i, i = 1$–3, which cannot be rotated away by a simple redefinition of the fields. These can generate unacceptably large electric dipole moments for fermions and hence one of the solutions normally used was to fine tune all the $\not{C}\not{P}$ phases in SUSY to zero. It has been shown that it is possible for some combination of these phases to be O (1) and yet satisfy *all* the constraints on the EDM's provided the first two generation of squarks are heavy [19]. It has been demonstrated that such $\not{C}\not{P}$ phases can induce CP-mixing in the Higgs sector of the MSSM [20–22]. This leads to mixing between the CP-even h, H and the CP-odd A in the MSSM. The couplings of the three mass eigenstates ϕ_1, ϕ_2, ϕ_3, ($m_{\phi_1} < m_{\phi_2} < m_{\phi_3}$), are modified compared to the CP-conserving case. In particular, the ϕ_1 may develop a large pseudoscalar component, giving $g^{VV\phi_1} < g^{VVH_{\rm SM}}$ and hence $\sigma(e^+e^- \to Z^* \to Z\phi_1) < \sigma(e^+e^- \to Z^* \to Zh_{\rm SM})$. This is the simplest way in which CP violation may invalidate the lower limits on the Higgs mass obtained by LEP. The LEP data can now allow a much lighter Higgs with a mass $\lesssim$ 40–50 GeV [23–25] due to a reduction in the $\phi_1 ZZ$ coupling in the CPX scenario [22]. The latter corresponds to a certain choice of the CP-violating SUSY parameters, chosen so as to showcase the CP violation in the Higgs sector in this case. In a large portion of this region all the usual search channels of such a light Higgs at the LHC are also not expected to be viable [23] due to the simultaneous reduction in the coupling of the Higgs to a vector boson pair as well as the $t\bar{t}$ pair. As a matter of fact for $\tan\beta$: 3–5, M_{H^+}: 50–100 GeV, there may exist a hole in the SUSY parameter space in case of CP violation. Part of this hole can be filled up, by taking advantage of the light H^+ which can be produced in the top decay and which in turn has a large branching ratio in the $\phi_1 W$ channel [26]. Even after this, some part of this "hole" still remains.

A PLC will be able to produce such a neutral Higgs in all cases; independent of whether it is a state with even/odd or indeterminate CP parity. It is possible to determine the CP-mixing, if present, by using the polarisation of the initial state γ or that of the fermions into which the ϕ_i decays [27–32]. A unique feature of the PLC is that the two photons can form a $J_z = 0$ state with both even and odd CP. As a result the PLC has a similar level of sensitivity for both the CP-odd and CP-even components of a CP-mixed state:

$$\begin{aligned} \text{CP-even}: \;\; \varepsilon_1 \cdot \varepsilon_2 \; &= \; -\frac{(1+\lambda_1\lambda_2)}{2}\,, \\ \text{CP-odd}: \;\; [\varepsilon_1 \times \varepsilon_2] \cdot k_\gamma \; &= \; \omega_\gamma i \lambda_1 \frac{(1+\lambda_1\lambda_2)}{2}\,, \end{aligned} \tag{3.1}$$

ω_i and λ_i denoting the energies and helicities of the two photons, respectively; the helicity of the system is equal to $\lambda_1 - \lambda_2$. This contrasts the e^+e^- case, where it is easy to discriminate between CP-even and CP-odd particles but may be difficult to detect small CP-violation effects for a dominantly CP-even Higgs boson [7,33,34]. For the PLC, one can form three polarisation asymmetries in terms of helicity amplitudes which give a clear measure of CP-mixing [27]. Note however that these require linearly polarised photons in addition to the circularly polarised photons. One can also use information on the decay products of WW, ZZ, $t\bar{t}$ or $b\bar{b}$ coming from the Higgs decay. Even with just circular beam polarisation almost mass degenerate (CP-odd) A and (CP-even) H of the MSSM may be separated [14–16, 28]. In the situation that the mass difference between the H and A is less than the sum of their widths, a coupled channel analysis technique [35] has to be used.

The authors of Ref. [31] and [32] explore this situation whereas the use of decay fermion polarisation for determination of the Higgs CP property for a generic choice of the MSSM parameters is explored in Ref. [36].

The process $\gamma\gamma \to f\bar{f}$ receives contribution from the process where the ϕ is exchanged in the s-channel and thus probes the $\phi\gamma\gamma$ and $\phi f\bar{f}$ couplings:

$$\mathcal{V}_{f\bar{f}\phi} = -i\, e \frac{m_f}{M_W} \left(S_f + i\gamma^5 P_f\right) \,,$$

and

$$\mathcal{V}_{\gamma\gamma\phi} = \frac{-i\sqrt{s}\alpha}{4\pi}\left[S_\gamma(s)\left(\varepsilon_1\cdot\varepsilon_2 - \frac{2}{s}(\varepsilon_1\cdot k_2)(\varepsilon_2\cdot k_1)\right) - P_\gamma(s)\frac{2}{s}\varepsilon_{\mu\nu\alpha\beta}\varepsilon_1^\mu\varepsilon_2^\nu k_1^\alpha k_2^\beta\right].$$

$\{S_f, P_f, S_\gamma, P_\gamma\}$ depend upon m_{H^+}, $\tan\beta$, μ, $A_{t,b,\tau}$, $\Phi_{t,b,\tau}$, $M_{\tilde{q}}$, $M_{\tilde{l}}$ *etc.* in (CP-violating) MSSM. The helicity amplitudes involve four CP-even and CP-odd combinations of the different form factors, x_i, y_i, $i = 1,\ldots,4$, respectively. The QED background is P, CP and chirality conserving, while the ϕ exchange diagram violates these symmetries. Thus nonzero values of $\{x_i, y_j\}$ indicate existence of chirality flipping interactions as opposed to the chirality conserving QED interactions. As a result the fermion polarisation can be a probe of the ϕ contribution as well as any possible CP violation in the $\phi\gamma\gamma$ and $\phi t\bar{t}$ coupling. The polarisation of the initial state γ can be controlled by adjusting the initial laser and the e polarisation. The ϕ contribution is enhanced using the combination $\lambda_e \times \lambda_l = -1$. One can construct observables, with unpolarised and polarised laser and e beams: P_f^U and $\delta P_f^{\rm CP} = P_f^{++} + P_f^{--}$ which are both probes of CP-violating interaction, and $\delta P_f^{+} = P_f^{++} - (P_f^{++})^{\rm QED}$ $\delta P_f^{-} = P_f^{--} - (P_f^{--})^{\rm QED}$ which are probes of chirality flipping interactions. Here $+/-$ in the (double) superscripts of P_f refer to the polarisation of the e, λ_e. Left panel of Fig. 5 shows the predicted value of δP_t^- as a function of m_{H^+} for $E_{\rm cm} = 500\,{\rm GeV}$ and $600\,{\rm GeV}$, using the ideal back-scattered photons, with $x_c = 4.8$. The peak occurs when the average mass of ϕ_2 and ϕ_3 ($\bar{m}_\phi$) matches with the $\sqrt{s}_{\gamma\gamma}$ value where the backscattered laser photon luminosity peaks. The right-hand side panel shows the expected values of the CP-violating asymmetry $\delta P_t^{\rm CP}$ as a function of the two MSSM parameters, $\tan\beta$ and μ, for $\Phi = 90^\circ$. $E_{\rm cm}$ is adjusted for each point in the scan such that the peak of the photon spectrum matches with scaled mass $\bar{m}_\phi$. Nowhere in this range of the parameters are the two states extremely degenerate, and hence a coupled channel analysis is not required. We see that even in this case, the size of the expected asymmetries is not too small. Thus in a generic case of CPV MSSM the PLC can probe this CP-mixing in the Higgs sector.

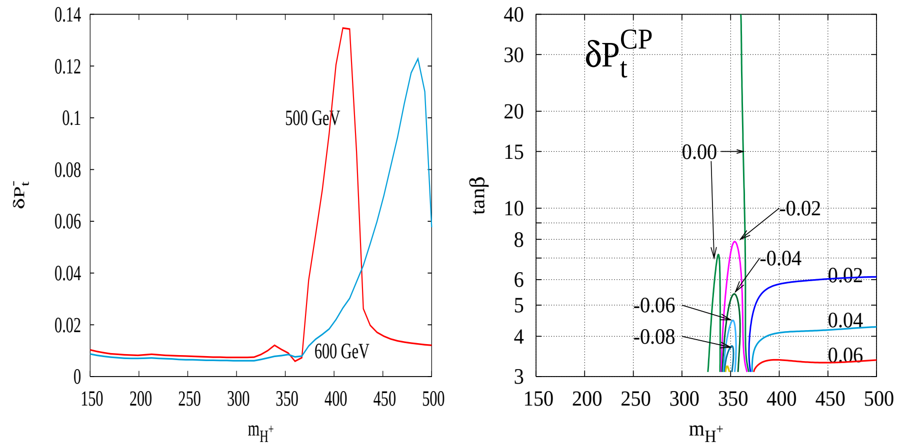

Fig. 5. Left-hand side panel shows δP_t^- as a function of m_{H^+} for $E_{\rm cm} = 500\,$GeV and 600 GeV, while the right-hand side panel shows $\delta P_t^{\rm CP}$ over the $\tan\beta$–m_{H^+} plane for CP-violating phase $\Phi = 90°$, in the CPX scenario [22].

The case of extreme degeneracy has been studied for the PLC in [31,32]. Fig. 6 shows the CP-violating asymmetries:

$$\mathcal{A}_1 \equiv \frac{\hat{\Delta}_1}{\hat{\sigma}_{++} + \hat{\sigma}_{--}}\,, \qquad \mathcal{A}_2 \equiv \frac{\hat{\Delta}_2}{\hat{\sigma}_{+-} + \hat{\sigma}_{-+}}\,.$$

Here $\hat{\varDelta}_i, i = 1, 2$ have been constructed out of cross-sections with final quarks in different helicity states. $+/-$ refer to photon and the final state quark helicities. For the chosen values of the parameters, the asymmetries are sizable only near the ϕ_2 mass.

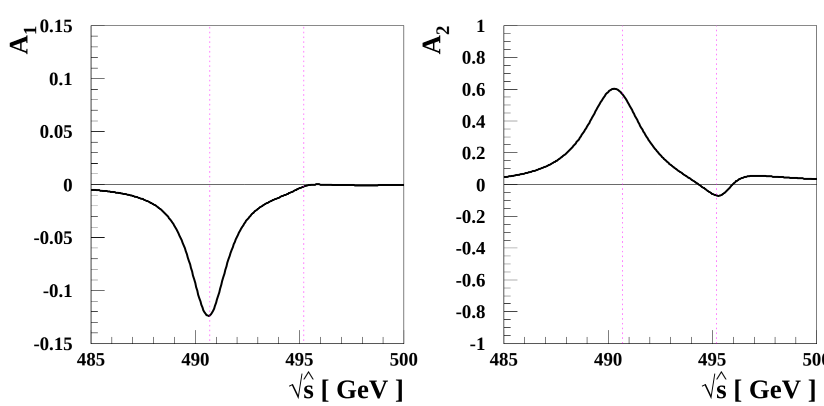

Fig. 6. The asymmetries wrt to photon helicities [31].

The analysis of Ref. [32] investigates the asymmetries constructed using linearly polarised photons. Fig. 7 taken from Ref. [32] shows the correlators

$$\mathcal{C}_{\parallel} = -\frac{2\,\Re\mathrm{e}\sum\langle +,\lambda\rangle\langle -,\lambda\rangle^*}{\sum\left(|\langle +,\lambda\rangle|^2+|\langle -,\lambda\rangle|^2\right)}\,, \tag{3.2}$$

$$\mathcal{C}_{\perp} = +\frac{2\,\Im\mathrm{m}\sum\langle +,\lambda\rangle\langle -,\lambda\rangle^*}{\sum\left(|\langle +,\lambda\rangle|^2+|\langle -,\lambda\rangle|^2\right)}\,, \tag{3.3}$$

as a function of the CP-violating phase Φ_A and the $t\bar{t}$ centre of mass energy.

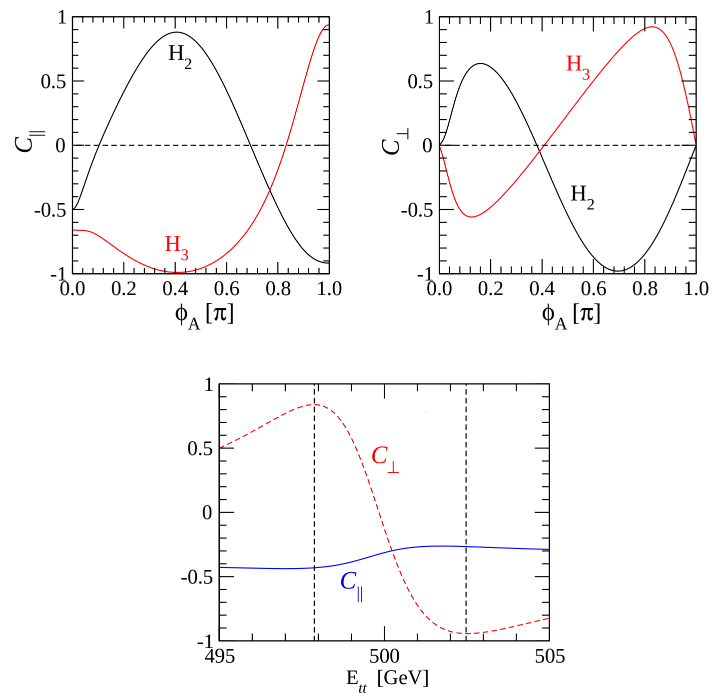

Fig. 7. CP-violating correlators constructed using linearly polarised photons, as a function of the CP-violating phase Φ_A and the $t\bar{t}$ centre of mass energy [32].

The decay leptons from t-quark carry information about its polarisation. One can construct asymmetries combining charge of lepton and polarisation of the initial state e^- of the PLC. Parametring the cross-sections as $\sigma(\lambda_{e^-}, Q_\ell)$, one can define mixed charge-polarisation asymmetries:

$$\mathcal{A}_1 = \frac{\sigma(++)-\sigma(--)}{\sigma(++)+\sigma(--)}\,, \qquad \mathcal{A}_2 = \frac{\sigma(+-)-\sigma(-+)}{\sigma(+-)+\sigma(-+)}\,,$$

$$\mathcal{A}_3 = \frac{\sigma(++)-\sigma(-+)}{\sigma(++)+\sigma(-+)}\,, \qquad \mathcal{A}_4 = \frac{\sigma(+-)-\sigma(--)}{\sigma(+-)+\sigma(--)}\,.$$

Fig. 8 shows these asymmetries over the $\tan\beta$–m_{H^+} plane, for CPX scenario, for $\Phi = 90°$, and fixed beam energy. We see that the size of asymmetries goes as high as 10% and tracks the polarisation asymmetries shown in the earlier figures.

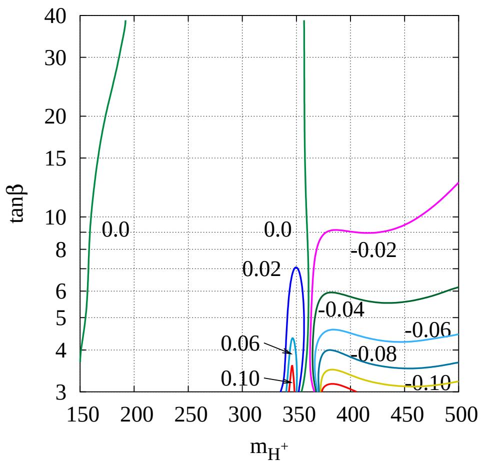

Fig. 8. Asymmetries using the initial state γ polarisation and final state lepton charge [36].

4. $e\gamma$, $\gamma\gamma$ collider and sparticle production

Production of the sparticles, at the $\gamma\gamma$ option [37–40] as well as that at the e–γ option [41–43] has been studied. The interesting thing about charged sparticle production at the $\gamma\gamma$ colliders is that the cross-sections, to leading order, are entirely determined by their charge and mass, as compared to the case of an e^+e^- collider where the cross-section may depend on the various mixing angles due to the presence of the weak gauge bosons. This property could provide us complementary information about the models, *e.g.*, universality of the masses for sleptons and squarks in the 1st and 2nd generations. It should be emphasised that, as the $\gamma\gamma$ cross sections involve an s-wave contribution, they will be much larger than that of e^+e^- if $\sqrt{s}$ is large compared to the mass threshold. In the e–γ option, a charged sfermion can be produced in association with a neutral gaugino or vice versa. If the mass difference between the two is large, then this offers a higher kinematical reach compared to the e^+e^- option. Further, use of polarisation allows to enhance the signal. Again, in this case the dependence of the cross-section on the SUSY parameters is reduced. For example, even in the case of (say) $\tilde{\chi}_1^0$ produced in association with a $\tilde{e}_R$ the production will involve only the Bino component of the $\tilde{\chi}_1^0$. The threshold dependence of the $\tilde{\nu}\tilde{\chi}_1$ production can be used for the determination of the sum of the two masses and hence can afford a good determination of the $\tilde{\nu}$ mass [43]. Single sneutrino production can be used to study SUSY at the PLC in the R-parity violating scenarios quite effectively [40].

5. Conclusion

Thus we see that the PLC can offer a chance of real improvements in the accuracy $\Delta\beta$ of $\tan\beta$ measurements at large $\tan\beta$ using $\tau\tau$ fusion. The PLC also provides major gains for the SUSY Higgs sector as it gives a reach for H/A in regions where the LHC does not have any. Further, the s-channel production mode increases the reach by a factor ~ 1.6 compared to the e^+e^- option. The advantages of a $\gamma\gamma$ collider are even more if CP violation is present. Polarisation asymmetries constructed using initial state photon polarisation and final state fermion polarisations, can be a very good probe of the CP violation in the Higgs sector. LHC/ILC are not very capable when it comes to probing CP-mixing. The H/A contribution can be probed through mixed polarisation-charge asymmetries, *i.e.* asymmetries in initial state polarisation and final state lepton charge. If CP violation makes the lightest Higgs dominantly pseudoscalar and hence "invisible" at LEP/ILC/LHC then $\gamma\gamma$ collider is the only place it can be produced. For SUSY searches, $\gamma\gamma$ and $e\gamma$ colliders can offer some interesting possibilities for sneutrino and gaugino searches; particularly the production cross-sections are independent of the the different mixing angles for the charged sparticles. Further the high polarisation of the backscattered laser can be put to very good use.

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