SUSY and New Physics at the Photon Collider.

- ♢ Introduction. Choice of topics in new physics! .
- ♢ What special rôle can a photon collider play in the context?
  - a Searching for sparticles at $\gamma\gamma$ colliders *directly*
  - b Study of the Heavy Higgs H/A sector and CP-mixing if $\not{C}\not{P}$ in SUSY. WW/ZZ final states, t/τ polarisation.
  - c SUSY parameter determination: PLC can help probe the regions of the SUSY parameter space which are difficult and/or inaccessible for the LHC and/or in the e^+e^- mode.
  - d New physics via anomalous couplings, extra dimensions?

Asked to talk about SUSY and new physics at the $\gamma\gamma$ collider.

SUSY is one of the most popular template for new physics.

New physics can be discussed in two contexts.

i) Specific Models, Some well motivated, some speculative. Extra dimensions, noncommmutative theories,unparticles... Many of these give addiitonal contributions to jet, $t\bar{t}$ production in $\gamma\gamma$ collisions and /or produce effects on the Higgs channel(eg. effects of radion).

ii) Model indpendent formulations.

I will pick some combination of topics..but will mainly concentrate on sparticle and Higgs (both SUSY and non SUSY BSM Higgs).

Try to evaluate where the $\gamma\gamma$ collider has a distinct advantage and higher reach.

Thanks to a lot of work by a lot of people,

- 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 colliders we hope to find the sparticles, measure their masses **AND** measure their spins and couplings.

- For $\tilde{\chi}^{\pm}, \tilde{\chi}_l^0$ as well as the supsesymmetric partners of the third generation of the quarks/leptons, the masses as well as the couplings can depend on the SUSY breaking mechanism and parameters.

- The LHC will be able to 'see' the strongly interacting sparticles if the SUSY scale is TeV.

- If the sparticle mass is within the kinematic reach of the ILC, we will be able to make accurate mass measurements, spin determination.

- LHC + ILC can even help us determine the SUSY model parameters and hence the SUSY breaking mechanism.

- SPA project.

BUT

LHC+ILC (e^+e^-) mode though very exhaustive, may have holes.

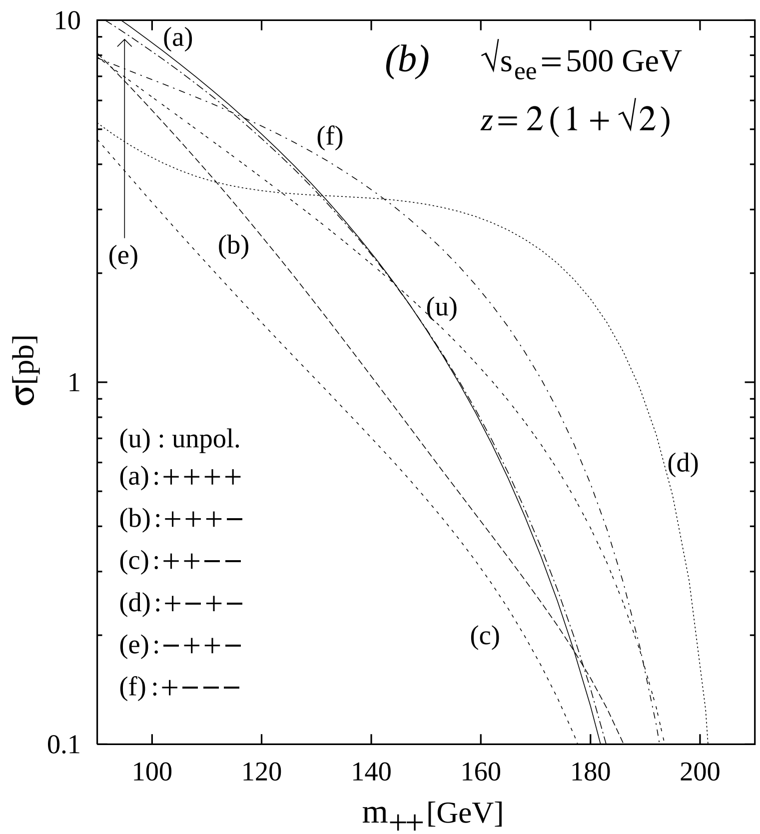
- LHC/ILC is 'blind' to some regions of SUSY parameter space. PLC can help.

- Does the PLC offer any Unique possibllities for SUSY?Yes in the Higgs sector with polarisation: CP violation.

- can the PLC help extend the reach for sparticle masses *for the same e^+e^- beam energy?*Yes, upto a factor of 1.6 for the Higgs. Also in $e^-\gamma \to \tilde{e}_R\tilde{\chi}_1^+$ which was mentioned by Klaus Moenig.

Will discuss some of these some with a few details.

Charged Scalars: Higgses, sfermions...
$\gamma\gamma \to s^+ s^-$
Q_s is the electromagnetic charge: $\gamma\gamma$ rates enhanced by Q_s^2 compared to e^+e^-.
Relevant, for example, in the little higgs models etc., where one may have doubly charged higgses.
Choice of laser and $e^\pm$ polarisation can enhance the cross-section.



Chakrabarti, Godbole, Choudhury, Mukhopadhyaya

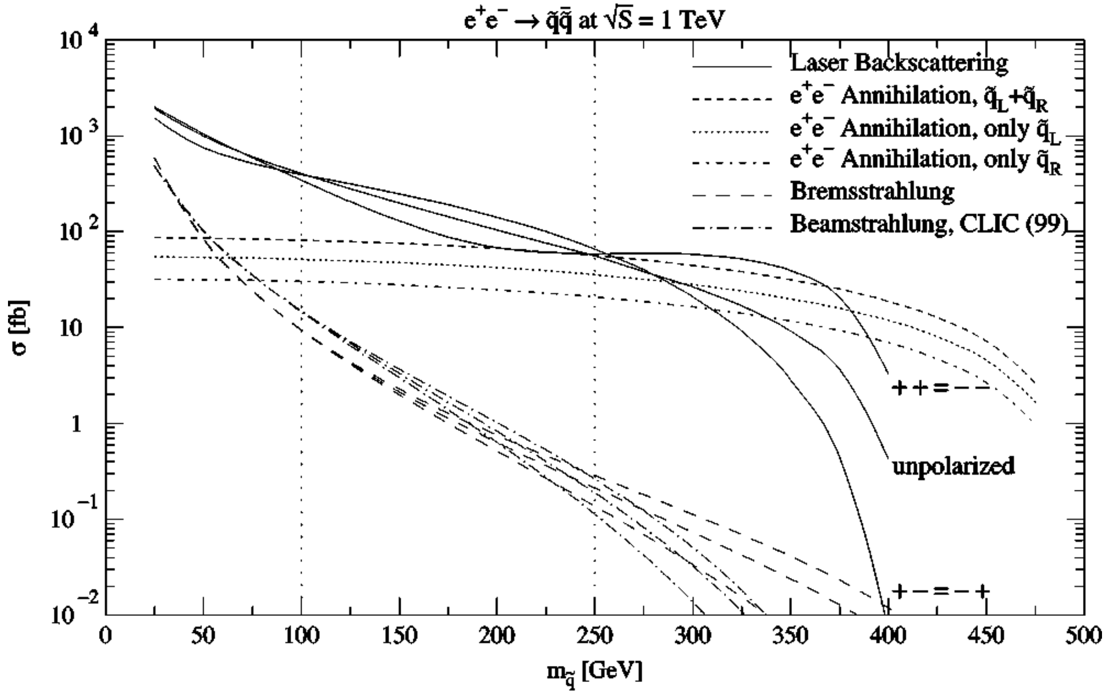
Berge/Klassen

Polarisation dependence can be used to enhance the cross-section

At $\sqrt{s} = 1$ TeV the squark production cross-section stays larger than the annihilation process.

May be one needs to study also kinematic distribution whether this can help further to get addiitonal information.

Zerwas/Freitas: Isolate difft. helicity amplitudes to probe the sector in slepton production.



Contribution from the PLC in SUSY in the Higgs sector is very significant.

In Supesymmetric theories there are (at least) five scalar states:

h, H, A and $H^{\pm}$. h, H : CP even, A : CP odd. M_h is bounded from above. In the decoupling limit h will look/smell like a SM Higgs.

SUSY parameters relevant for this sector:

$\tan\beta$ (the ratio of vacuum expectation values), Higgsino mass term μ, M_A.

What special features of the PLC relevant for these studies?

i) Accurate measurements ($\sim 2\%$) of the $\Gamma_{\gamma\gamma}$ decay width possible.

ii) Polarisation of the laser and the e^+/e^- beam can be tuned.

These two offer special control.

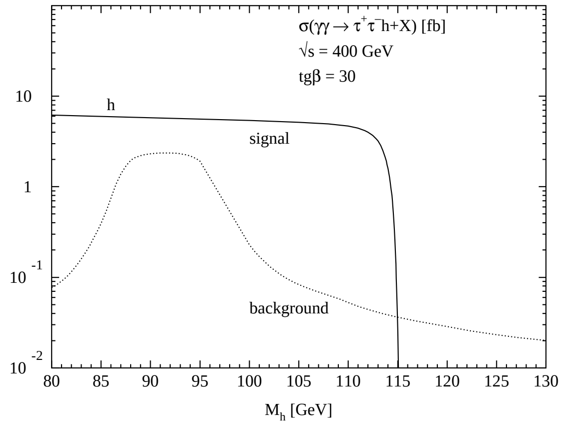
Determination of CP property of the Higgs in the most unambigious way is possible by studying $t\bar{t}H$ production and its production at the $\gamma\gamma$ collider. Reason : the H/A couples democratically to $t\bar{t}$ and $\gamma\gamma$ pair.

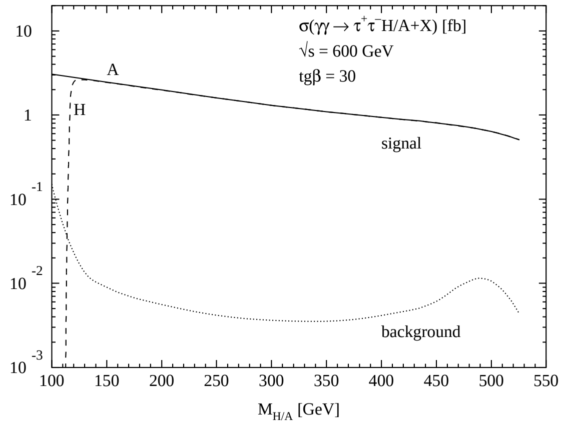
Already discussed by Klaus.

Another aspect where $\gamma\gamma$ collider plays a special role is in studying CP violation in the Higgs sector.

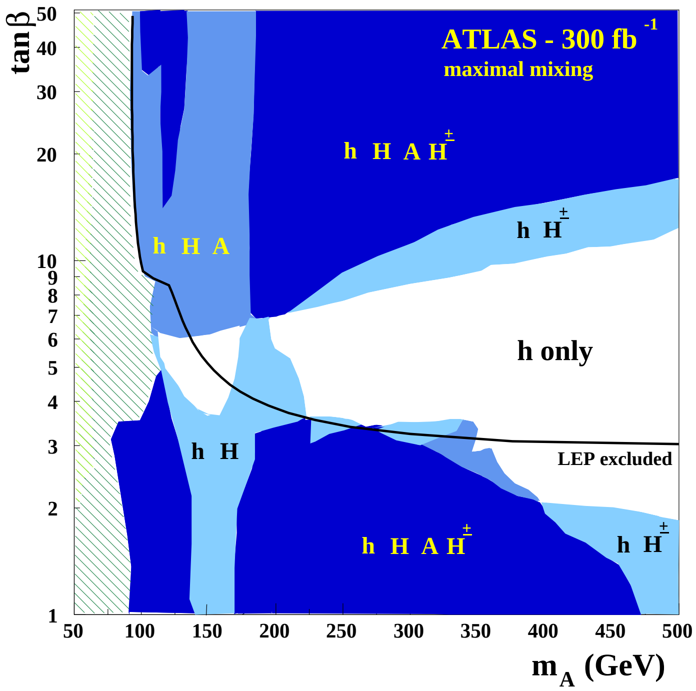
Studies of the $\tilde{\chi}^+\tilde{\chi}^-, \tilde{\chi}^0_j\tilde{\chi}^0_i$ at e^+e^- can not give accurate determination of $\tan\beta$ at large values accurately mainly because the obsevable involves $\cos 2\beta$. Muhelleitner, Kalinowksi, Choi, Zerwas. $\gamma\gamma \to \tau^+\tau^-\phi \to \tau^+\tau^- b\bar{b}$

Very good measurement of $\tan\beta$. Need simulations. At $\tan\beta = 30, \Delta\tan\beta = 0.9$–1.3.





Very good measurement of $\tan\beta$.



$\tan\beta \simeq 4 - 10$, $M_A, M_H >$ 200–250 GeV, LHC will see only on Higgs and H, A not accessible for first generation LC. So called LHC-wedge.

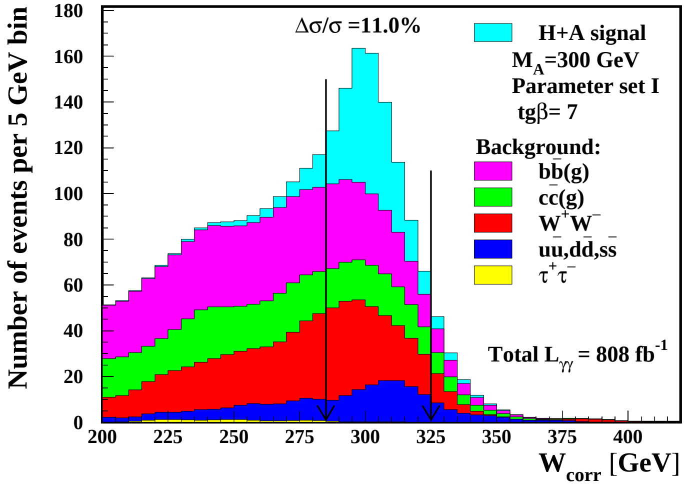
single H/A production (Muheleitner et al) increases the reach from $0.5\sqrt{s} \rightarrow 0.8\sqrt{s}$.

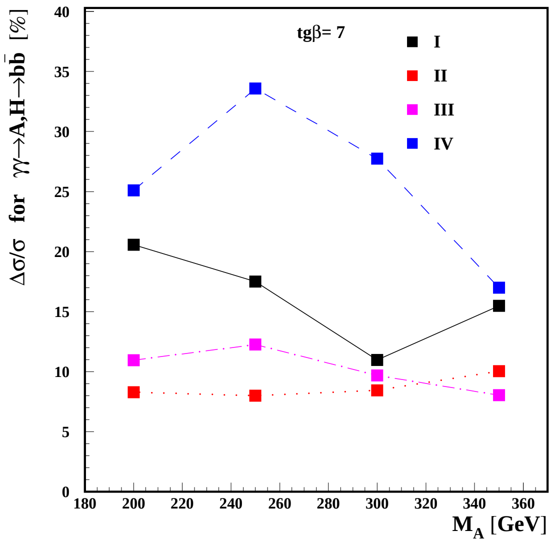
large $\tan\beta$: $b\bar{b}$ final state useful.

Small $\tan\beta$, $b\bar{b}$ coupling reduces, QED bkgd. larger for $t\bar{t}$ final state.

For small $\tan\beta$ the $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_j^0\tilde{\chi}_i^0$ decays can be used. (Muehelleitner et al).

$b\bar{b}$ final state: Detailed simulations: Niezurawski et al; Spira, Krawzyck





Light Higgs: $\gamma\gamma$ rates could be measured $\simeq 2\%$. For H/A measurement precision somewhat worse : $\sim 11\%$–21% .

Use of initial state polarisation to reduce the QED background.

$A(H)$ will contribute if polarisation vectors of the two photons are perpendicular (parallel): but $q\bar{q}$ background will increase.

There exist regions in the SUSY parameter space where the masses of sparticles are large enough to elude detection BUT effect on $\Gamma_{\gamma\gamma}$ is still a few percent (A. Djouadi; F.Boudjema, Belanger, R.G.)

CP violation in MSSM. Possible for some phases to be large and still satisfy the constraints on EDM's

The MSSM $\not{CP}$ phases induce CP mixing in the Higgs sector (which has no CP mixing at the tree level) of the MSSM through loop effects

Pilaftsis ,Choi et al , Carena et al

CP mixing in the Higgs sector, one way for $\not{CP}$ in SUSY to manifest itself: can affect production rates at LHC as well. Dedes et al, Choi et al

MSSM : Three neutral Higgs h,H CP-even A CP-odd

CP violation : ϕ_1, ϕ_2, ϕ_3 no fixed CP property $m_{\phi_1} < m_{\phi_2} < m_{\phi_3}$

ϕ_i coupling to gauge bosons and fermions changes with CP violation.

$$g^{VV\phi_1} < g^{VVH_{SM}} \Rightarrow \sigma(e^+e^- \to Z^* \to Z\phi) < \sigma(e^+e^- \to Z^* \to ZH_{SM})$$

Such a light higgs may have been missed at LEP for tan β : 3–5, M_{H+} : $50 - 100$ GeV. (Pilaftsis et al, OPAL)

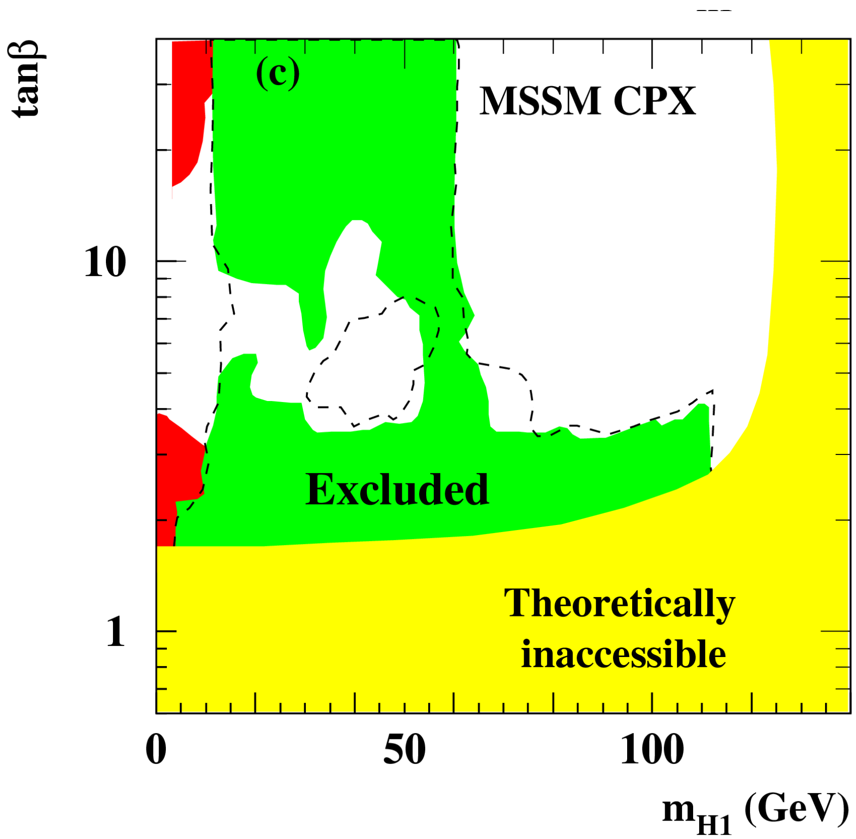
May escape detection at the LHC as well since $t\bar{t}\phi_1$ coupling also reduced (Pilaftsis etal, ATLAS).

Production through $t \to bH^+ \to bW\phi_1$ at the LHC can fill part of the 'hole' (D.P.Roy, D. Ghosh and R.G)

Can always be produced at a $\gamma\gamma$ collider.

LEP Limits

Preliminary OPAL results : hep-ex/0406057



$$\Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau} = \Phi_{\tilde{g}} = \frac{\pi}{2}$$

$$\Phi_\mu = 0$$

$$M_{\mathsf{SuSy}} = 500 \text{ GeV}$$

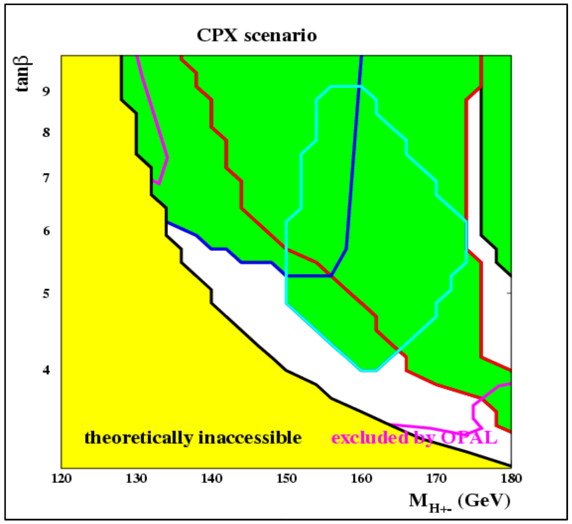
Even have gaps at 0–50 GeV!

A few observations

• Small regions in $\tan\beta, M_{H+}$ plane where LHC,TEVATRON will have no reach

• Caused by reduced ϕ_1 coupling to W/Z AND *top*.

What happens to LHC discvoery plots?



preliminary results presented by M. Schumacher at the meeting on 'CP violation and nonstandard Higgs' //http://kraml.home.cern.ch/kraml/CPstudies/

NOT the official ATLAS results.

A hole in the $\tan\beta - M_{H^+}$ plane: for $m_{\phi_1} < 50, 100 < m_{\phi_2} < 110$ and $130 < m_{\phi_3} < 180$.

Suggestion to fill the hole via H^+ decays

D. Ghosh, R.G. and D.P. Roy,

Small $\tan\beta$, light $M_{H^+} \Rightarrow$ large $B.R.(H^+ \to \phi_1 W)$.

Use $t\bar{t}$ production with :

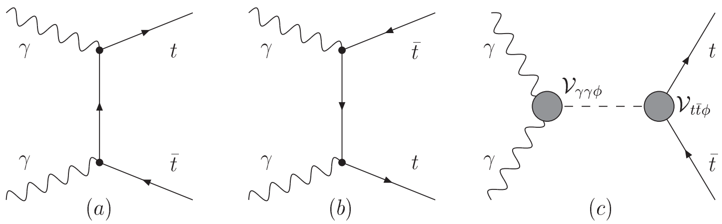
$t \to \bar{b}H^+ \to \bar{b}\phi_1 W \to \bar{b}b\bar{b}W$ and $\bar{t} \to \bar{b}W$, with one W decaying leptonically the other hadronically. Hence both $W's$ can be reconstructed.

Look at the $WWbbbb$ events, 3 tagged $b's$.

The mass of the $b\bar{b}$ pair with the smallest value will cluster around m_{ϕ_1} and $b\bar{b}W$ around M_{H^+}.

Some part of the hole still not plugged in. $\gamma\gamma$ collider can help.

$f\bar{f}$ pair production as a probe of the Higgs contribution.



Higgs contribution in general can be written as.

$$\begin{aligned}\mathcal{V}_{f\bar{f}\phi} &= -ie\frac{m_f}{M_W}\left(S_f + i\gamma^5 P_f\right), \\ \mathcal{V}_{\gamma\gamma\phi} &= \frac{-i\sqrt{s}\alpha}{4\pi}\left[S_\gamma(s)\left(\epsilon_1.\epsilon_2 - \frac{2}{s}(\epsilon_1.k_2)(\epsilon_2.k_1)\right) - P_\gamma(s)\frac{2}{s}\epsilon_{\mu\nu\alpha\beta}\epsilon_1^\mu\epsilon_2^\nu k_1^\alpha k_2^\beta\right].\end{aligned}$$

$\{S_f, P_f, S_\gamma, P_\gamma\}$ 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.

Combinations of form-factors that appear in the helicity amplitude.

Combinations	Aliases	CP-property	Combinations	Aliases	CP-property
$S_f \Re(S_\gamma)$	x_1	even	$S_f \Re(P_\gamma)$	y_1	odd
$S_f \Im(S_\gamma)$	x_2	even	$S_f \Im(P_\gamma)$	y_2	odd
$P_f \Re(P_\gamma)$	x_3	even	$P_f \Re(S_\gamma)$	y_3	odd
$P_f \Im(P_\gamma)$	x_4	even	$P_f \Im(S_\gamma)$	y_4	odd

QED background : P, CP and chirality conserving.
Higgs exchange diagram violates these symmetries,
$\{x_i, y_j\} \neq 0 \Rightarrow$ Chirality flipping interaction $\Rightarrow$ fermion-polarisation affected.

Polarised photons :

(J.S. Lee, Pilaftsis et al, Choi, Kalinowksi,Zerwas et al, Asakawa et al, Singh,Rindani,Kraml, R.G.)

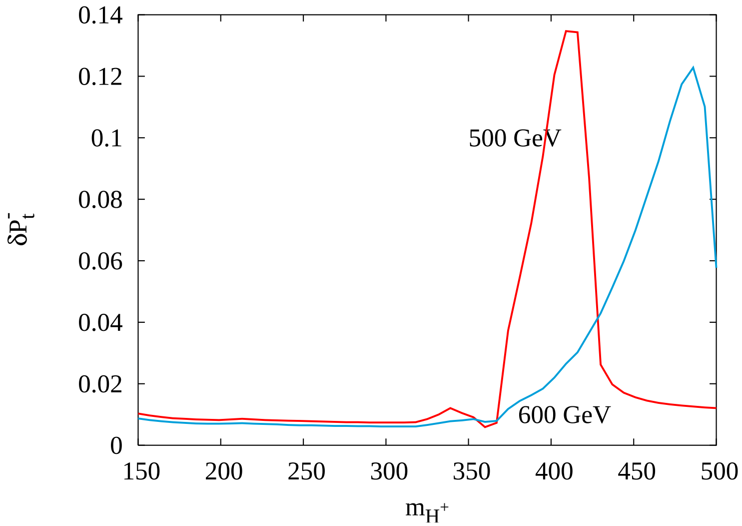
• P_f^{++}, P_f^{--} : finite for QED diagrams alone.
P invariance of QED $\Rightarrow P_f^{++} = -P_f^{--} \Rightarrow P_f^{++} + P_f^{--} = 0$

$P_f^{++} + P_f^{--} \neq 0 \Rightarrow$ signal of $\not{P}$
In case of C invariance $\Rightarrow$ signal of CP violation.

•P_f^{++} : modified by the Higgs contribution.

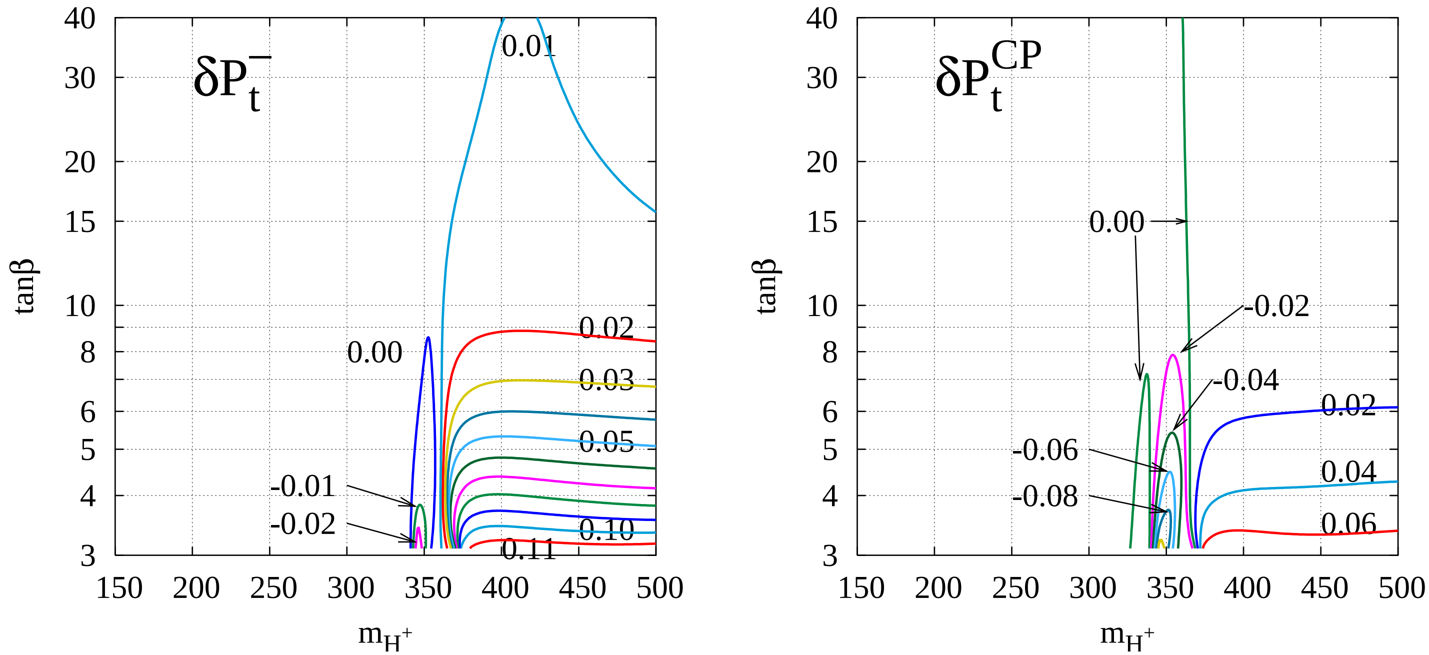
$P_f^{++} - (P_f^{++})^{QED} \neq 0$ even if ϕ is CP eigenstate, $\Rightarrow$probe of chirality flipping amplitude.

Observables	Description
P_f^U	Probe of CP violating interaction
$\delta P_f^{CP} = P_f^{++} + P_f^{--}$	Probe of CP violating interaction
$\delta P_f^{+} = P_f^{++} - (P_f^{++})^{QED}$	Probe of chirality flipping interaction
$\delta P_f^{-} = P_f^{--} - (P_f^{--})^{QED}$	Probe of chirality flipping interaction



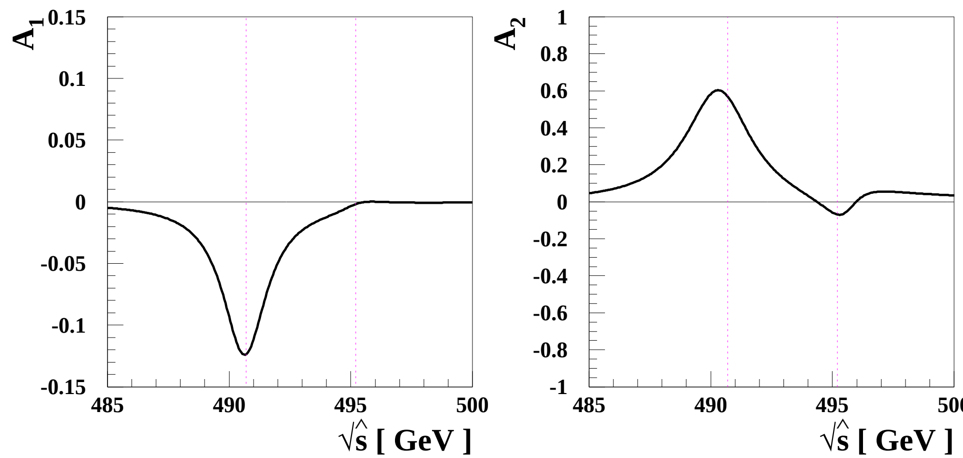
δP_t^- as a function of m_{H+} for $E_{cm} = 500$ GeV and 600 GeV.

Ideal back-scattered photons, $x_c = 4.8$.



$\Phi = 90^\circ$

$E_{cm} = (m_{H_2} + m_{H_3})/4/0.8$ for each point in the scan. Folded with $\gamma\gamma$ spectrum, $\lambda_e \times \lambda_l = -1$, $+/-$ refer to λ_e



Coupled channel analysis if $M_H - M_A \sim \Gamma_{H/A}$. (J.S. Lee et al)

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

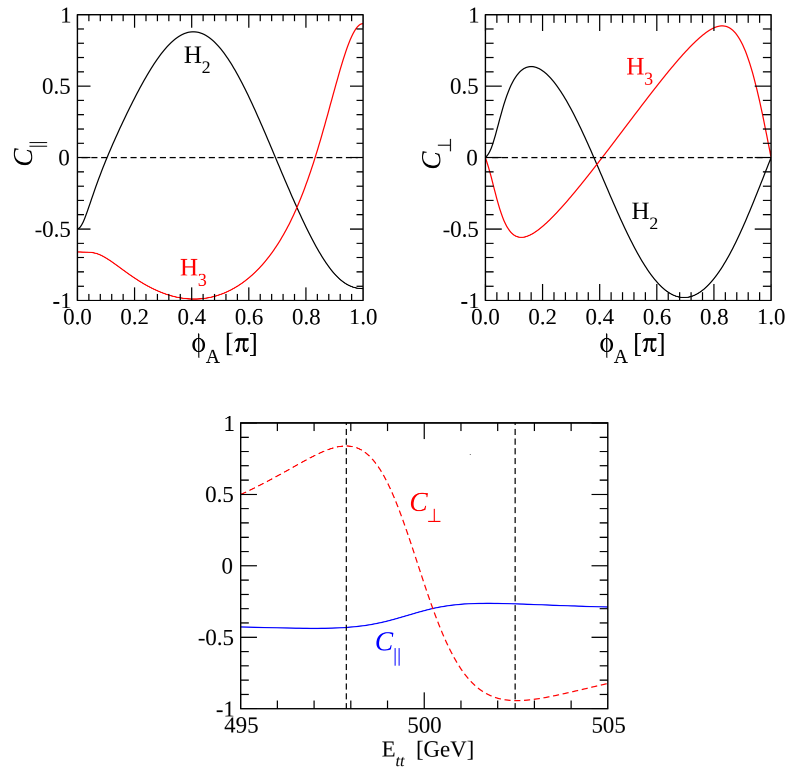
$+/-$ refer to photon helicities.

Analysis of the degeneate case: (Choi,Kalinowski,Zerwas et al)

$$\mathcal{C}_{\parallel} = -\frac{2\,\Re\mathrm{e}\sum\langle +,\lambda\rangle\langle -,\lambda\rangle^*}{\sum\left(|\langle +,\lambda\rangle|^2 + |\langle -,\lambda\rangle|^2\right)} \quad (1)$$

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

sum running over the two photon helicities.



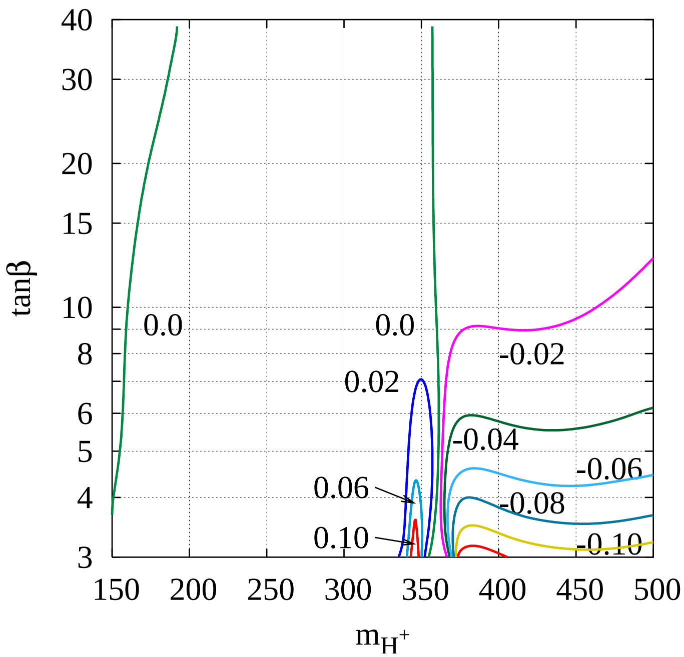
The decay leptons from t-quark carry information about its polarization. Can construct asymmetries combining charge of lepton and polarization of initial state e^- of the PLC.

We chose $\lambda_{e^-} (= \lambda_{e^+}) = -\lambda_1 (\lambda_2)$.

Thus cross-section can be parametrized as $\sigma(\lambda_{e^-}, Q_\ell)$.

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

$$\mathcal{A}_3 = \frac{\sigma(++) - \sigma(-+)}{\sigma(++) + \sigma(-+)} \quad \mathcal{A}_4 = \frac{\sigma(+-) - \sigma(--)}{\sigma(+-) + \sigma(--)}$$


40
30
20
15
10
8
6
5
4
3
tanβ
150 200 250 300 350 400 450 500
m_{H^+}
0.0
0.0
0.02
0.06
0.10
-0.02
-0.04
-0.06
-0.08
-0.10

One can measure these with high accuracy at the ILC. Many studies: Hagiwara et al, Singh, Choudhury, RG et al, Biswal, Choudhury RG et al.

$$\Gamma_{\mu\nu} = g_V \left[a_V \; g_{\mu\nu} + \frac{b_V}{m_V^2}(k_{1\nu}k_{2\mu} - g_{\mu\nu} \; k_1 \cdot k_2) + \frac{\tilde{b}_V}{m_V^2} \; \epsilon_{\mu\nu\alpha\beta} \; k_1^\alpha k_2^\beta \right]$$

Study $e^+e^- \to f\bar{f}H$ to get information on WWH vertex for example.

There is no observable to constrain the $\tilde{T}$-odd couplings.

Mamta et al showed that in $e\gamma$ collider by using this process and its $P\tilde{T}$ conjugate process thet can probe different parts of the WWH couplings independently of other parts.

Talk by R. Santos.

Recall plot from M. Spira's talk for hhh couplings. The $\gamma\gamma \to hh$ process was shown to be a good probe of hhh couplings and comparable perhaps to other probes the LHC and the ILC.

Asakawa/Cornet calculated non decoupling effects.

If the modification of the hhh coupling is due to new particles in the spectrum, then it will also modify $h\gamma\gamma h$ as well $\gamma\gamma hh$. So in the framework of a Two Higgs Doublet Model they calculate the net change in the cross-section $\gamma\gamma \to hh$ and show that the sensitivities of the graph shown by M. Spira are enough to test the model.

Talk by Santos seems to demonstrate this.

Only one example.

Study contributions c

$\gamma\gamma$.

SM process loop level

show that $\gamma\gamma$ collider

case can be sensitiv

scale of 5 TeV for $\sqrt{s}$

GeV.

Plots show cross-sec

a fn. of $\gamma\gamma$ invarian

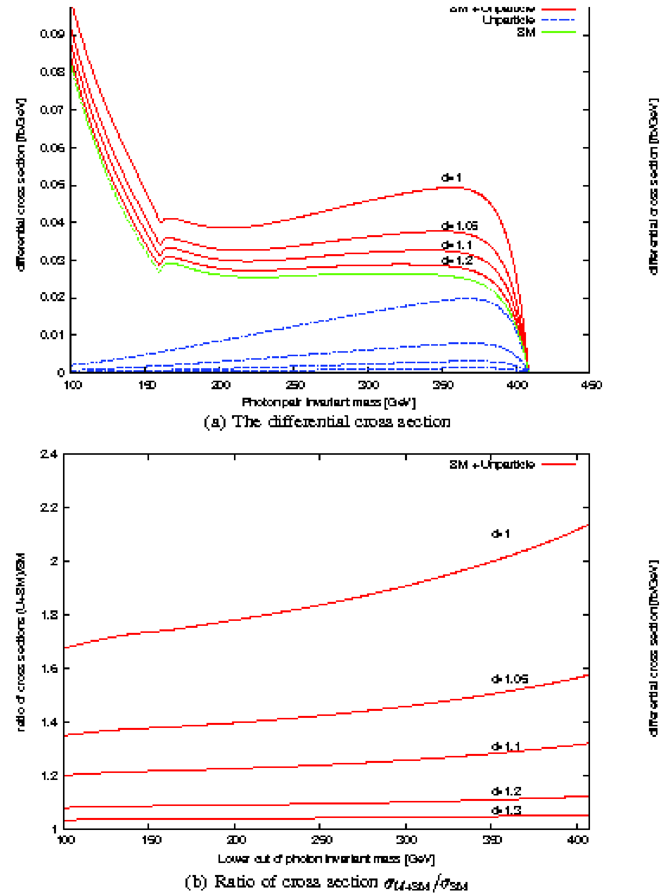
distribution , which i

the scaling dimension

particle.

The second plot show

of $\sigma_{\mathcal{U}} + \sigma_{SM}/\sigma_{SM}$



(a) The differential cross section

(b) Ratio of cross section $\sigma_{\mathcal{U}+SM}/\sigma_{SM}$

Conclusions:

- For SUSY searches, $\gamma\gamma$ collider can play a unique role for sfermion searches by providing clear signal in scenarios where ILC/LHC will have problems, by using more helicity amplitudes that are avaialble.

- $\Delta\beta \simeq 1$ at large $\tan\beta$ using $\tau\tau$ fusion.

- Major gains for the SUSY Higgs sector. Provides reach for H/A in regions where LHC does not have any. s channel production increase the reach by a factor ~ 1.6.

- Advantages of a $\gamma\gamma$ collider even more if CP violation is present.

- The 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 NOT very capable in 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 pseduoscalar and hence 'invisible' at LEP/ILC/LHC then $\gamma\gamma$ collider is the only place it can be produced

- Probing new physics *indirectly* via accurate measurement of $\Gamma_{\gamma\gamma}$ allows probe of new physics contribution in the loops.