Fermion polarisation probes MSSM w/o CP conservation at LC.

- Introduction.
- τ polarisation in $\tilde{\tau}$ decays at e^+e^- colliders: CP conserving case.
- $\tau(t)$ polarisation in $\tilde{\tau}(\tilde{t})$ decays at the e^+e^- colliders: CP violating case.
- CP mixing induced in the Higgs sector due to CP violation in soft SUSY breaking parameters.
- Probing CP violation in the Higgs sector through τ polarisation at $\gamma\gamma$ colliders.
- Conclusions.

Some of the refs:

S. Kraml, D. Miller, M. Krawczyck and R. Godbole Contribution to the LHC/LC studies, [arXiv:hep-ph/0404024].

M. Guchait, D.P. Roy and R.G. (Manuscript in preparation)

S. Kraml, T. Gadosijk, R.G., JHEP **0409**, 051 (2004) [arXiv:hep-ph/0405167].

S. Kraml, R.K. Singh and R.G. [arXiv:hep-ph/0409199], Talk given at International Conference on Linear Colliders (LCWS 04), Paris, France, 19-24 Apr 2004, (Manuscript in preparation.)

Introduction

Why study τ $/(t)$ polarisation?

- Large mass of the third generation fermions means large coupling to a Higgs. Third generation fermions useful to probe Higgs physics.

- $f\bar{f}$ pair produced via gauge interactions will have opposite handedness, produced via Yukawa interactions will have the same handedness. A correlation between polarisation of f and $\bar{f}$ can be a probe of Higgs contribution.

- τ (t) polarisation probes chirality structure of $\tau(t)$ production process, may it be Higgs physics, new physics : eg. $H^{\pm} \to \tau\nu_\tau$ decay Vs $W \to \tau\nu_\tau$. τ's produced in the former(latter) are right(left) handed, modulo m_τ effects, CP violation in the Higgs sector will reflect in the decay τ $/(t)$ polarisation.

• Large mass of the top $\Rightarrow t$ decays before hadronisation. The decay l can retain the memory of the t polarisation.

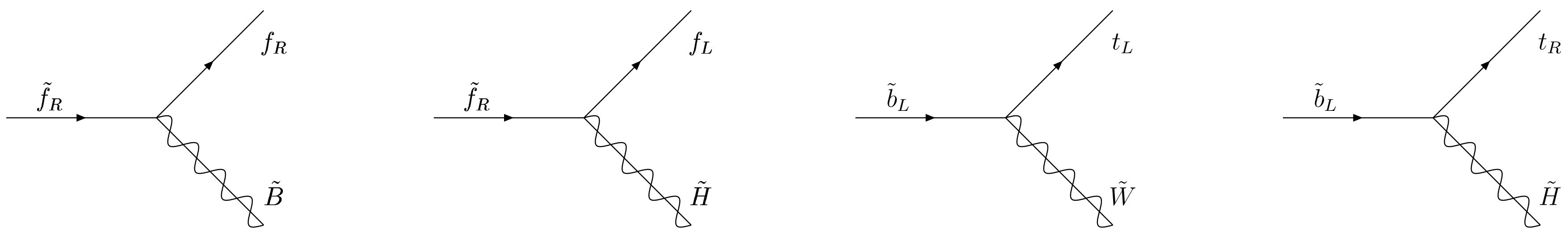
• τ has hadronic decay modes. The energy distribution of the π produced in the decay, $\tau \to \nu_\tau \pi$ as well as those in $\tau \to \rho \nu_\tau, \tau \to A_1 \nu_\tau$ depends on the handedness of the τ. Thus τ polarisation can be determined using decay π energy distribution. K. Hagiwara, A.D. Martin and D. Zeppenfeld, PLB **235** 198 (1990), B.K.Bullock, K.Hagiwara and A.D.Martin, PRL **67**, 3055 (1991), NPB **395**, 499 (1993).

• If $m_h < 2m_t$ then τ is the only fermion whose polarisation can be determined and into which a Higgs decays may be somewhat substantial.

♢ Thus t and τ polarisation are a very good probe for new and Higgs physics.

τ (t) produced in stau/stop decay. M. Nojiri, PRD **51** (1995) 6281 [hep-ph/9412374]

$f = t/\tau$



- In MSSM mass eigenstates $\tilde{f}$–sleptons/squarks $(\tilde{f}_1, \tilde{f}_2)$, mixtures of $\tilde{f}_L$ and $\tilde{f}_R$, $f = t, \tau$.

- Mixing affects Gauge couplings of $\tilde{f}_i, i = 1,2$ and hence the production rates.

- The $\tilde{\chi}^{\pm}_j, j = 1,2$, $\tilde{\chi}^0_j, j = 1,4$ are mixtures of Higgsinos and Gauginos.

- Couplings of sfermions with Higgsinos flip chirality whereas those with gauginos do not.

- Net helicity of produced f in the decay $\tilde{f}_i \to \tilde{\chi}^0_j f$ AND $\tilde{f}_i \to \tilde{\chi}^{\pm}_j f'$ depends on the L–R mixing in the sfermion sector and gaugino-higgsino mixing.

- A lot of analyses of τ polarisation and hence of the MSSM parameter determination at LC exist. Use the $\tau \to \rho/A\nu_\tau$ (multiprong) mode.

- Our New work: (M. Guchait, D.P. Roy and R.G.) Developed a new variable for τ polarisation analysis.

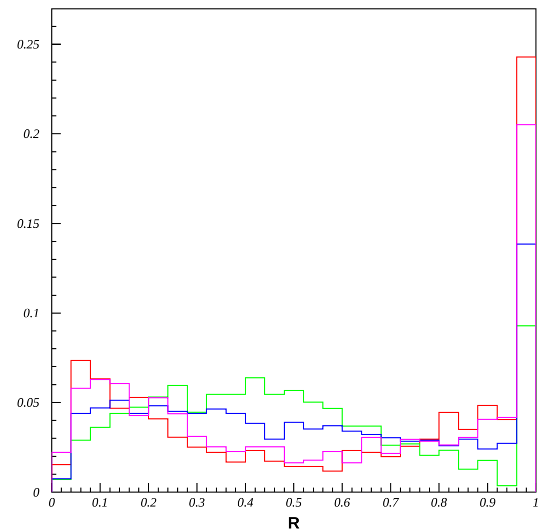
- Look at $R = \frac{E_\pi}{E_{jet}}$. and study

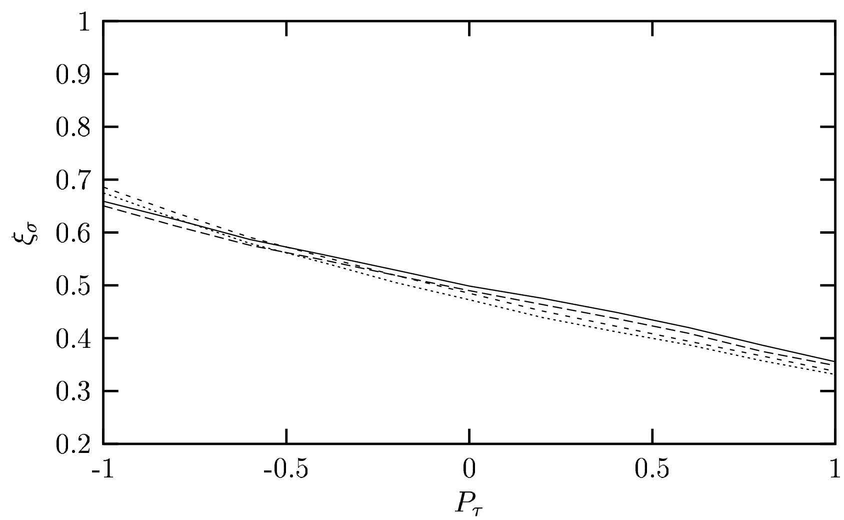
$$\xi = \frac{\#(0.2 < R < 0.8)}{\#total}$$

- ξ a good discriminator of τ polarisation, hence of SUSY models.

Top :Distribution in R. Different curves for values of polarisation $p_\tau = -1, -.5, 0.5, 1.0$. Bottom: ξ as a function of P_τ, band: theoretical uncertainty, obtained using Tauola.

- Detailed application of this variable to MSSM parameter analysis in progress.





□ Polarisation of $f(f')$ produced in $\tilde{f}_i \to f\tilde{\chi}^0_j$, $\tilde{f}_i \to \tilde{\chi}^{\pm}_j f'$, depends on L–R mixing and Guagino/higgsino content

♢ CP-violating phases of A_f, μ, M_i in MSSM affect L–R mixing and Guagino/higgsino content

□ Polarisation of f, f' can carry information on CPV phases as well.

♢ NOTE: polarisation itself is a CP-even variable

• Our study: Kraml, T. Gadosijk, R.G JHEP **0409**, 051 (2004) How well does the P_f probe the CPV phases?

• An example for $\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0$

$$P_f = \frac{Br(\tilde{f}_1 \to \tilde{\chi}_1^0 f_R) - Br(\tilde{f}_1 \to \tilde{\chi}_1^0 f_L)}{Br(\tilde{f}_1 \to \tilde{\chi}_1^0 f_R) + Br(\tilde{f}_1 \to \tilde{\chi}_1^0 f_L)}$$

• Take A_f, M_2, M_1, μ complex. Safe to choose μ real $\Leftarrow$ (EDM CONSTRAINTS).

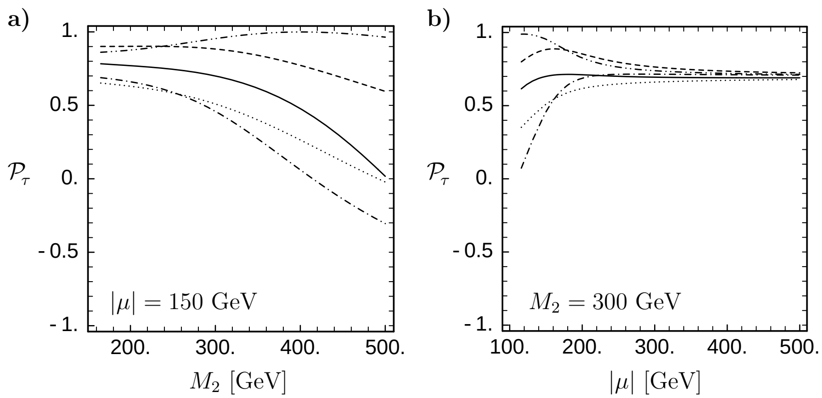
♢ P_f sensitive to CPV and nonzero even if ONLY one phase (either in sfermion sector or gaugino sector) is nonzero. $m_{\tilde{f}}$ not relevant for predictions of P_f.

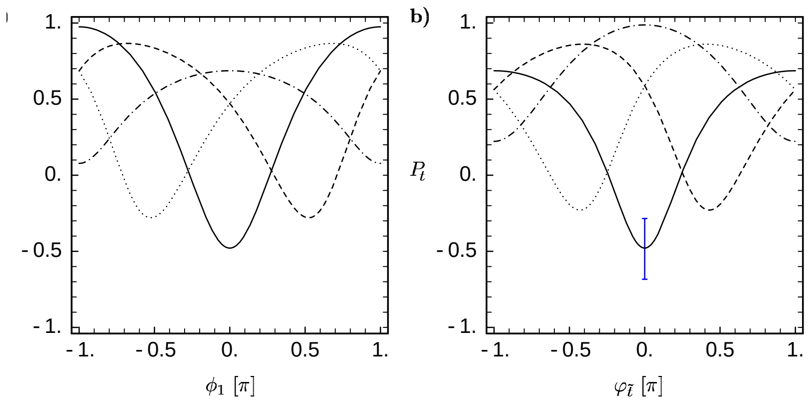
• Effects large for larger Yukawa Couplings and enhanced if $\tilde{\chi}_1^0$ is a guagino-higgsino mixed state.

□ P_t has significant dependence on the phases even when $\mu \simeq M_2$

♢ P_f can be used to extract information on phases ONLY in conjunction with other observabels which will give info. on μ, M_2, M_1 etc.

♢ Polarisation information need be included in a global analysis of MSSM parameter determination at ILC.





Some Results:

Average polarisation for τ for $\theta_{\tilde{\tau}} = 130°$ and $\tan\beta = 10$: in a) as a function of M_2 for $|\mu| = 150$ GeV, in b) as a function of $|\mu|$ for $M_2 = 300$ GeV. The full, dashed, dotted, dash-dotted, and dash-dot-dotted lines are for $(\phi_1, \varphi_{\tilde{\tau}}) = (0,0)$, $(0, \frac{\pi}{2})$, $(\frac{\pi}{2}, 0)$, $(\frac{\pi}{2}, \frac{\pi}{2})$, and $(\frac{\pi}{2}, -\frac{\pi}{2})$.

Average polarisation of top for $\theta_{\tilde{t}} = 130°$, and $\tan\beta = 10$: in a) as a function of ϕ_1 for $M_2 = 225$ GeV and $|\mu| = 200$ GeV; in b) as a function of $\varphi_{\tilde{t}}$ for $|\mu| = 200$ GeV and M_2 adjusted such that $m_{\tilde{\chi}_1^0} = 100$ GeV. The full, dashed, dotted, and dash-dotted lines are for $\varphi_{\tilde{t}}$ $(\phi_1) = 0, \frac{\pi}{2}, -\frac{\pi}{2}, \pi$ in a (b).

MSSM $\not{C}\not{P}$ phases $\Rightarrow$ $\not{C}\not{P}$ in the Higgs sector:

CP conserving MSSM Three Neutral Higgses h,H CP-even A CP-odd

CP violation : ϕ_1, ϕ_2, ϕ_3 no fixed CP property

$m_{\phi_1} < m_{\phi_2} < m_{\phi_3}$

The h, H, A now all mix and share the couplings with vector boson pair VV. Will affect production rates.

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

May escape detection at e^+e^- collider, but can still be produced at a $\gamma\gamma$ collider.

Predictions in terms of SUSY $\not{C}\not{P}$ phases in the MSSM for this mixing.

Tools

CPSuperH	FeynHiggs
Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner	Hahn, Heinemeyer, Hollik & Weiglein
http://theory.ph.man.ac.uk/~jslee/CPsuperH.html	http://www.feynhiggs.de

low energy parameters $\longrightarrow$ masses, BR's, couplings...

RG improved effective potential for masses & couplings	Feynman–diagrammatic approach for masses & couplings
leading log approx for one-loop	full one-loop
leading log approx for O($\alpha_s\alpha_t, \alpha_t^2$), but full phase dependence	full O($\alpha_s\alpha_t, \alpha_t^2$) but approx phase dependence

O($\alpha_s\alpha_t$) has $(\alpha_s \tan\beta)^n$ resummation and full complex phase dependence

CPX Scenario [Carena, Ellis, Pilaftsis & Wagner, Phys. Lett. **B495** (2000) 155]

"designed to showcase the effects of CP violation in the MSSM"

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\mathsf{SuSy}}$$

$$\mu = 4M_{\mathsf{SuSy}}, \quad |A_{t,b,\tau}| = 2M_{\mathsf{SuSy}}, \quad |M_3| = 1TeV, \ |M_1| = |M_2| = 200GeV$$

Allow the following parameters to vary:

$\tan\beta$,	$M_{H^\pm}$,	M_{SuSy},
$\{\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}\}$,	Φ_3,	Φ_μ

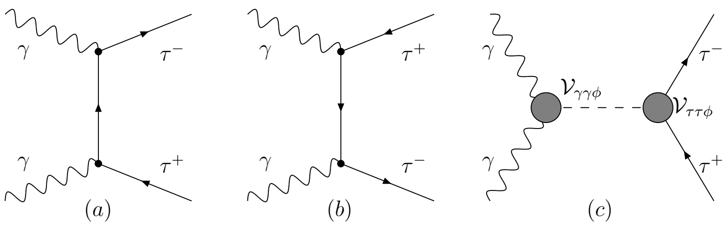
What have we done?

Kraml, R.Singh, R.G, [arXiv:hep-ph/0409199]

τ pair production as a probe of the Higgs contribution and CP structure of its coupling. Studied

$$\gamma\gamma \to \phi \to \tau^+\tau^-$$

.



The Higgs contribution treated in a model independent way.

$$\mathcal{V}_{\tau^+\tau^-\phi} = -ie\frac{m_\tau}{M_W}\left(S_\tau + i\gamma^5 P_\tau\right),$$

$$\mathcal{V}_{\gamma\gamma\phi} = \frac{-i\sqrt{s}\alpha}{4\pi}\left[S_\gamma(s)\left(\epsilon_1.\epsilon_2 - \frac{2}{s}(\epsilon_1.k_2)(\epsilon_2.k_1)\right) - P_\gamma(s)\frac{2}{s}\epsilon_{\mu\nu\alpha\beta}\epsilon_1^\mu\epsilon_2^\nu k_1^\alpha k_2^\beta\right].$$

$\{S_\tau, P_\tau, S_\gamma, P_\gamma\}$ depend upon the MSSM parameters.

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

Combinations	Aliases	CP-property	Combinations	Aliases	CP-property
$S_\tau \Re(S_\gamma)$	x_1	even	$S_\tau \Re(P_\gamma)$	y_1	odd
$S_\tau \Im(S_\gamma)$	x_2	even	$S_\tau \Im(P_\gamma)$	y_2	odd
$P_\tau \Re(P_\gamma)$	x_3	even	$P_\tau \Re(S_\gamma)$	y_3	odd
$P_\tau \Im(P_\gamma)$	x_4	even	$P_\tau \Im(S_\gamma)$	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, $\Rightarrow$ τ-polarisation affected.

Polarisation of τ:

$$P_\tau^{IJ} = \frac{N_+^{IJ} - N_-^{IJ}}{N_+^{IJ} + N_-^{IJ}}$$

$I, J = +, -, U$ Polarisation of parent e^+/e^- beam.
$N_+^{IJ} = \#$ of τ_R, $N_-^{IJ} = \#$ of τ_L.

◇ $P_\tau^U = 0$: for QED contribution.

◇ $P_\tau^U = 0$: even with Higgs contribution, if $y_j = 0$; i.e. Higgs is a CP eigenstate.

□ $P_\tau^U \propto m_\tau \Rightarrow$ small **even** with CPV.

□ P_τ^U a 'poor' but 'pure' probe of CPV in the Higgs sector.

Move to polarised photons :

- P_τ^{++}, P_τ^{--} : finite for QED diagrams alone.

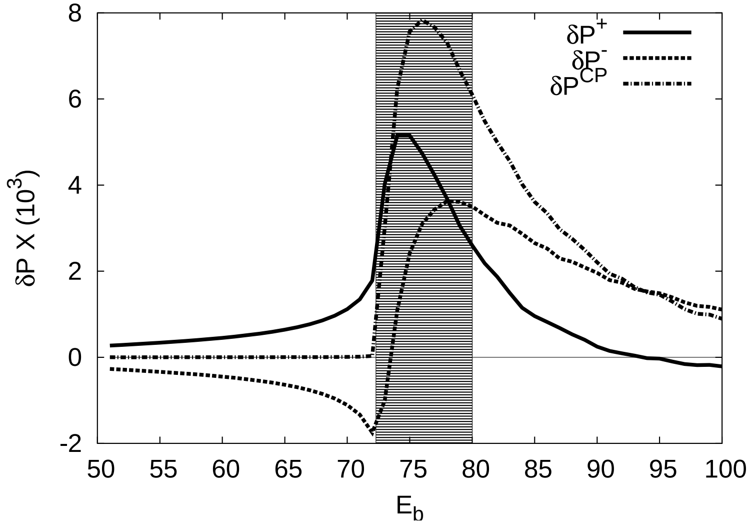
P invariance of QED $\Rightarrow P_\tau^{++} = -P_\tau^{--} \Rightarrow P_\tau^{++} + P_\tau^{--} = 0$

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

- P_τ^{++} : modified by the Higgs contribution.

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

Observables	Interaction probed
P_τ^U	CP-violating interaction
$\delta P_\tau^{CP} = P_\tau^{++} + P_\tau^{--}$	CP-violating interaction
$\delta P_\tau^{+} = P_\tau^{++} - (P_\tau^{++})^{QED}$	Chirality flipping interaction
$\delta P_\tau^{-} = P_\tau^{--} - (P_\tau^{--})^{QED}$	Chirality flipping interaction



$\delta P_\tau^+, \delta P_\tau^{CP}$ as a function of E_b

m_{ϕ_1}=120 GeV for a chosen CP violating MSSM point.

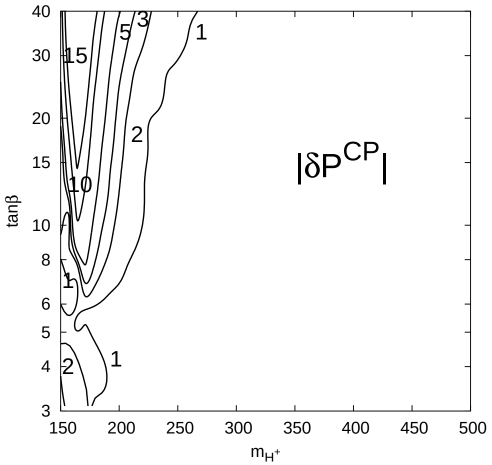
Ideal back-scattered photons, $x_c = 4.8$.

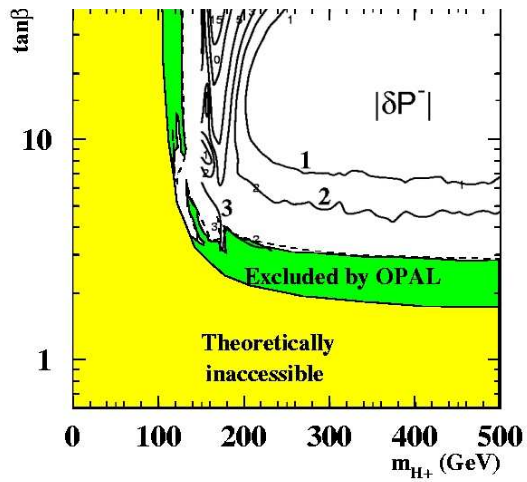
$\delta P_\tau^+, \delta P_\tau^{CP}$ peak for $E_b \approx (m_h/2)/f$ where $0.75 < f < 0.83$. This is the grey region.

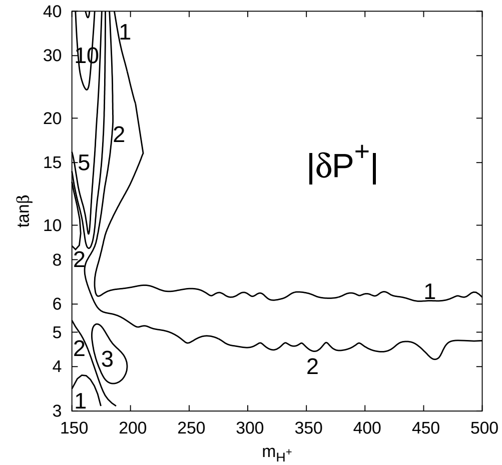
Beam energy can be chosen to maximise the sensitivity

Main contribution from off-shell Higgs ⇒ large statistics available.

Contribution from ϕ_2, ϕ_3 may be important if they are close to ϕ_1 in mass.







- Contribution from all the three ϕ_i included. Over the scanned region of the parameter space the degeneracy of the three states not high,i.e. $\delta m = m_{\phi_i} - m_{\phi_j} \gg \Gamma_{\phi_i} + \Gamma_{\phi_2}$

- δP_τ^{CP} is sensitive to some part of region. δP_τ^- is sensitive to most of the region. Only two of the three P_τ^X linearly indpendent.

- If sensitivity of $P_\tau^{IJ} \approx 0.001$, the observables can probe all the OPAL allowed region of the MSSM parameter space.

Conclusions:

• τ/t polarisation a very useful probe of different aspects of Higgs physics.

• Fraction of events in the inlcusive pion spectrum with $0.2 < R < 0.8$ where $R = \frac{E_\pi}{E_{jet}}$, is correated nicely with τ polarisation. This is a new observable to measure the τ polarisation.

• CP violating phases in the MSSM affect the CP–even polarisation of $\tau(t)$ produced in stau/stop/sbottom decays. Effects larger for the t due to larger Yukawa coupling. Effects larger when $\tilde{\chi}_j^0, \tilde{\chi}_i^\pm$ is a mixed gaugino–higgsino state. Determination of CP phases requires combining the polarisation information with knowledge of magnitudes of MSSM parameters from other observables.

• Program of global determination of SUSY parameters at the ILC should include polarisation information.

• Have constructed probes of CP violation and chirality flipping interactions in $\gamma\gamma \to \tau^+\tau^-$.

♢ δP_τ^- requires one measurement, δP_τ^{CP} requires two measurements. Both cover large regions of the OPAL allowed MSSM parameter space in CPX scenario.

♢ τ polarisation as a probe of CP properties of neutral Higgs holds promise