CP studies in the Higgs sector

Meeting on CP studies and Nonstandard Higgs

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in collaboration with

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Introduction

- Importance of the study of the CP properties in the Higgs sector.
- CP violation in the Higgs sector.
- Principles used in different studies to determine the CP properties / CP mixing in the Higgs sector.
- A summary of different studies available.

CP Violation

$\not{CP}$: The phenomenon still lacks a fundamental understanding

1. CKM description vindicated by measurements of CP mixing in the B_0 sector.
2. CKM $\not{CP}$ **not** sufficient to explain quantitatively $\frac{N_b}{N_\gamma} \sim 6.1 \times 10^{-10}$
3. $\not{CP}$ in the Higgs sector is a theoretically attractive source of the additional $\not{CP}$ required to explain the Barayon Asymmetry in the Universe.
4. $\not{CP}$ posible only in Multi-Higgs models.
5. $\not{CP}$ in the MSSM, **large #** of available phases, possible to satisfy *all* the constraints and still have enough $\not{CP}$ to help Baryogenesis.

Higgs Studies at the Colliders

1. Studies of the Higgs sector is indeed the **raison d'etre** of all the accelerators under discussion and we hope they will provide the evidence for scalar(s)
2. Discovery is not enough, need to profile the Higgs: determine its properties such as spin, couplings to fermions, gauge bosons in detail.
3. The studies of CP properties of the Higgs sector : An important issue for studies at the Colliders when mature, to *prove* the SM or find evidence for BSM physics.
4. CP Studies in the Higgs Sector: good time to concentrate efforts now.

CP study in the Higgs sector

Three aspects of the CP studies in the Higgs sector:

1. Effect of $\not{CP}$ on different aspects of Higgs phenomenology: such as production rates, branching ratios; note even DM detection rates etc. could be affected in $\not{CP}$ MSSM.
2. Determination of the CP properties of the Spin 0 particle(s) which we hope will be discovered at the future colliders.
3. Determination of the CP mixing if discovered scalars ($\simeq$ Higgses) **NOT** CP eignestates.

Establish tensor structure for $\phi_i f \bar{f}$, $\phi_i VV$ vertex.
ϕ_i : a generic Higgs.

General strategy for CP study

Study $\not{C}\not{P}$ in a model indpendent way (most studies so far)

$$\phi_i f \bar{f} \quad : \quad -\bar{f}(v_f + i a_f \gamma_5)\frac{g m_f}{2 m_W},$$

$$V V \phi_i \quad : \quad c_V \frac{g m_V^2}{m_W} g_{\mu\nu} (\mathrm{V = W/Z, g : tree/loop\ level})$$

$$: \quad \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma (\mathrm{loop\ level})$$

1. SM: $v_f = c_V = 1, a_f = 0$,i = 1.
2. $v_f = c_V = 0$ and $a_f \neq 0$ for the CP odd Higgs, for general CP conserving multi-Higgs models.
3. Pseudoscalar $\epsilon^{\mu\nu\rho\sigma}$: only at loop level in MSSM and CP conserving 2HDM.
4. Generically CP mixing is a loop effect, hence small.

General strategy (con.)

CP conserving MSSM/ 2HDM : Three Neutral Higgses

h,H A

CP-even CP-odd

CP violation : ϕ_1, ϕ_2, ϕ_3

no fixed CP property

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

Sum rules exist for $\phi_i f \bar{f}$, $\phi_i VV$

(A. Mendez and A. Pomarol, PLB **272** (1991) 313. J.Gunion, H. Haber and J. Wudka, PRD **43** (1991) B.Grzadkowski, J.Gunion and J. Kalinowski, PRD **60** (1999) 075011)

e.g. in a 2HDM,

$$g^2_{\phi_i WW} + g^2_{\phi_j WW} + g^2_{\phi_k WW} = g^2 m^2_W, i \neq j \neq k$$

Observation of *all* the three in $e^+e^- \Rightarrow \not{C}\not{P}$.

Main recent theoretical developement

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

1] $\not{C}\not{P}$ phases in MSSM $\Rightarrow$ $\not{C}\not{P}$ in $\tilde{q}\tilde{q}\phi$ couplings $\Rightarrow$ affect the ggh_i coupling: A. Dedes and S. Moretti, PRL **84** (2000) 22,...

II] $\not{C}\not{P}$ phases in MSSM $\Rightarrow$ *explicit* CP mixing for Higgses

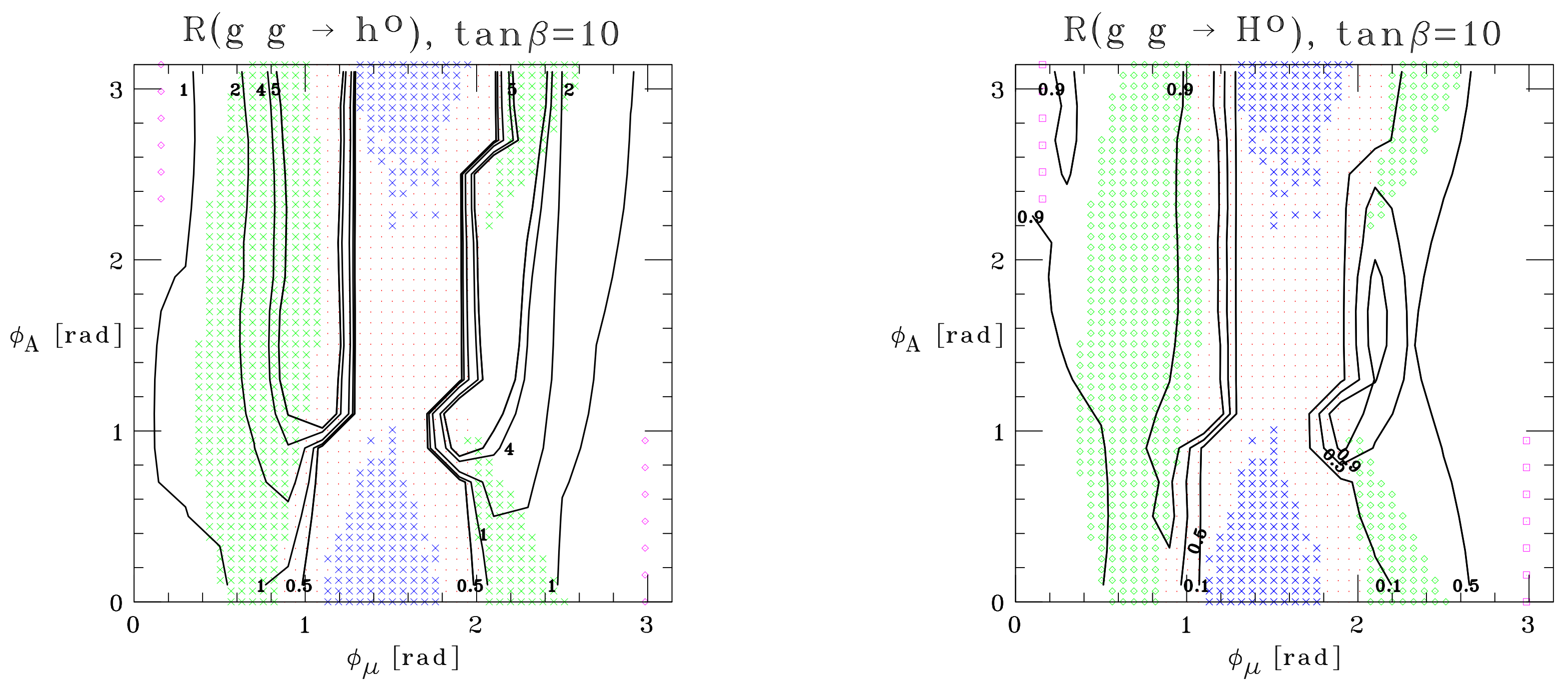
A. Pilaftsis, PLB **435** (1998) 88, A. Pilaftsis, C. E. Wagner, NPB **553**, 3 (1999), S. Y. Choi, M. Drees and J. S. Lee, PLB **481**, 57 (2000)....

$\phi_i, i = 1, 3$ share the VV couplings.

Good points:

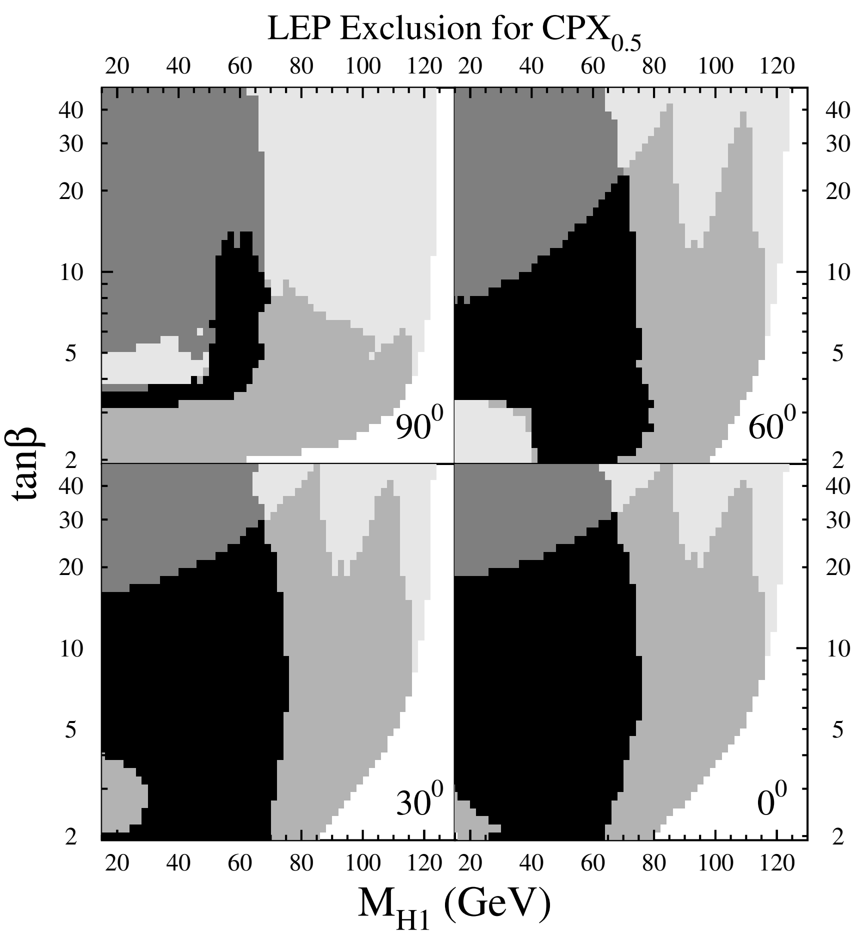
1. Gives a template for $\not{C}\not{P}$ in the Higgs sector.
2. $\not{C}\not{P}$ in the Higgs sector related to $\not{C}\not{P}$ in other sectors of the model

Effect on Cross sections



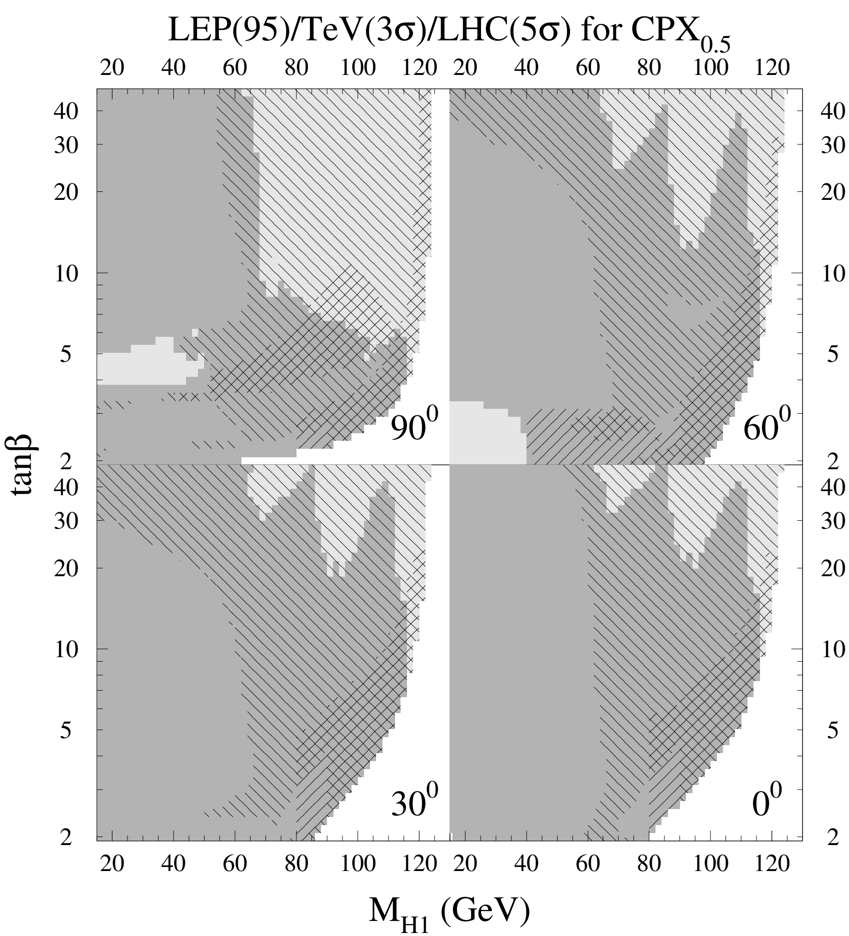
- The ratio is the $ggh/H0$ coupling compared to the MSSM with $\Phi_\mu, \Phi_A = 0.0$.
- Region of the MSSM parameter space where these effects dominate over the CP mixing induced by the nonzero MSSM phases.

Effect on Cross-sec(cont)



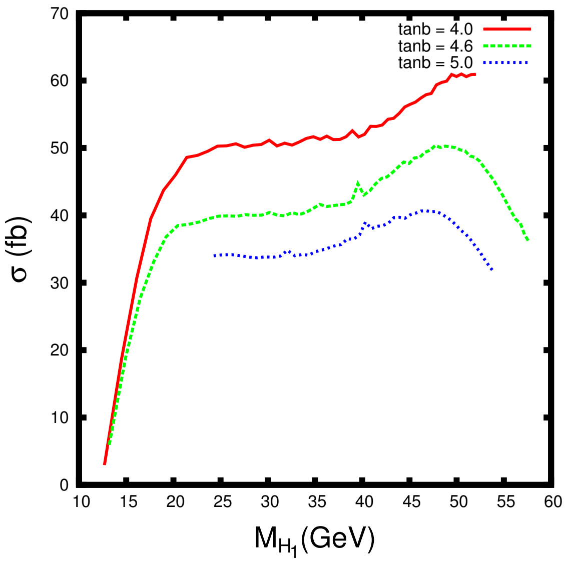
- Sum rules ⇒ modification in $ZZ\phi_i$ coupling.
- Higgs may escape detection at LEP
- J.Gunion, B. Grzadkowski, H.Haber, J. Kalinowski, PRL 79 (1997) 982: Model independent analysis,
- M. Carena, J. R. Ellis, S. Mrenna, A. Pilaftsis and C. E. Wagner, NPB 659, 145 (2003) ($\not{C}\not{P}$ MSSM)
- OPAL Collaboration, OPAL Physics Note PN524 (2003) (MSSM).

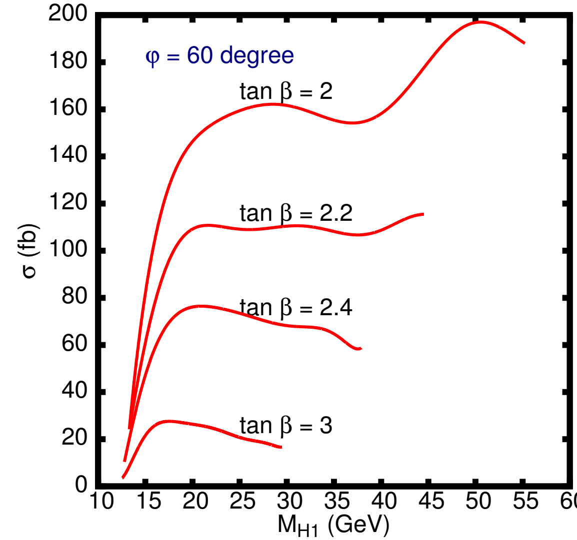
Effect on Cross-sec(cont)



- M. Carena, J. R. Ellis, S. Mrenna, A. Pilaftsis and C. E. Wagner, NPB **659**, 145 (2003)
- 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*.
- D. Ghosh, R.G. and D.P. Roy: Can recover the signal using large B.R. for $H^+ \rightarrow \phi_1 W$. $t\bar{t}$ production with one top decaying: $t \rightarrow \bar{b}H^+ \rightarrow \bar{b}\phi_1 W \rightarrow \bar{b}b\bar{b}W$
- Enhanced production cross-sections through b-fusion: hep-ph 0401024, F. Borzmuati, J.S. Lee and W. Y. Song

Effect on Cross-sec(cont)





LHC Signal : very clear clustering in the $b\bar{b}$, $b\bar{b}W$ invariant masses corresponding to m_{ϕ_1}, m_{H^+} also in $b\bar{b}bW$ invariant mass at m_t. So detectability controlled by just the signal size.

CP studies and difft. colliders

- Different colliders have different sensitivity to different issues.

Collider	CP determination	Measurement of Mixing
LHC	$t\bar{t}h$ production $f\bar{f}$ final state	$t\bar{t}h$ production $f\bar{f}$ final state Simulation studies starting.
	VV final state VV fusion	Simulation studies of mixing required

$VV\phi$ pseduoscalar tensor structure is always loop suppressed.

Use of $f\bar{f}\phi$ coupling

- $f\bar{f}\phi$ coupling for heavy f:

1) large Yukawa coupling $\Rightarrow$ polarisation of f, $\Rightarrow$ spin-spin correlations for $\phi_1 \rightarrow f\bar{f}$ correlations , both CP determination and CP mixing can be studied.

W. Bernreuther, M. Flesch and P. Haberl, PRD **58** (1998) 114031 W. Bernreuther, A. Brandenburg and M. Flesch,arXiv:hep-ph/9812387. W. Khater and P. Osland, NPB **661**, 209 (2003)

2) $t\bar{t}h$ production at LHC

J. F. Gunion and X. G. He, PRL **76** (1996) 4468

Distinction bet. $CP = 1, -1$ is feasible, measurement of mixing seems challanging, 600 fb^{-1} to distinguish at 1.5 σ level.

Use of $VV\phi_i$ coupling.

- $VV\phi_i$ coupling:

1) Different tensor structure, pure scalar and pseduoscalar $\Rightarrow$ good distinction between them by angular distributions for the decay leptons and threshold behaviour of the ZZ^* inv. mass spectrum for $\phi \to ZZ^*$.

S.Y.Choi, D.J.Miller, M.M.Muhlleitner and P.M.Zerwas, PLB **553** (2003) 61, C.P.Buszello, I.Fleck, P.Marquard and J.J.van der Bij, EPJC **32** (2004) 209

2) Same for ϕ produced through VV fusion, Angular distribution of the forward/backward jets distinguish a scalar and a pseudoscalar.

T.Plehn, D.Rainwater and D.Zeppenfeld, PRL **88** (2002) 051801

Same true for $gg \to \phi +$ 2 jets, QCD corrections ???

V. Del Duca, W. Kilgore, C. Oleari, C. R. Schmidt and D. Zeppenfeld [arXiv:hep-ph/0109147]

K. Odagiri, JHEP **0303**, 009 (2003)

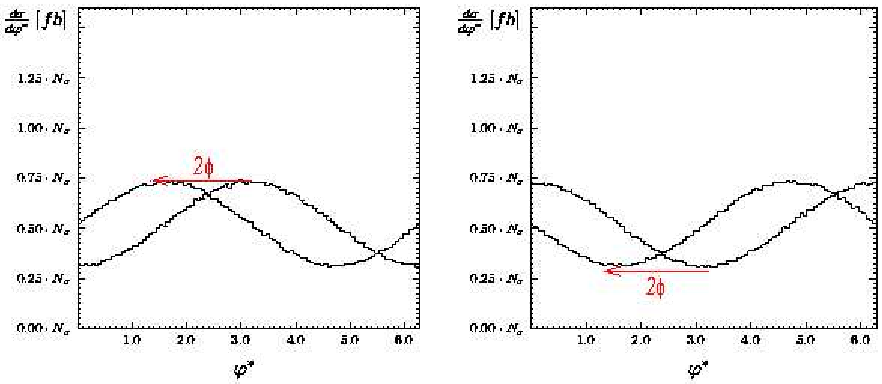
CP studies and difft. colliders

Collider	CP determination	Measurement of Mixing
LC	$f\bar{f}$ final state	$f\bar{f}$ final state
e^+e-	VV final state	Study of
	VV fusion	mixing difficult but possible.

1) Different tensor structure, for pure scalar and pseduoscalar of $VV\phi$ coupling $\Rightarrow$ good distinction between them by angular distribution of Z, the lepton pairs and threshold behaviour of the ZZ^* inv. mass spectrum for $\phi \to ZZ^*$. D.J. Miller et al, M.T.Dova, P.Garcia-Abia and W.Lohmann, arXiv:hep-ph/0302113

CP asymmetries can be constructed from decay lepton distributions D. Choudhury, B. Mukhopadhyaya and R.K. Singh

LC (con.)



2) $f\bar{f}\phi$ coupling equally sensitive to CP even and CP odd part, better probe.

B. Grzadkowski and J.Gunion, PLB **350** (1995) 218 [arXiv:hep-ph/9501339]. J.Gunion,

B. Grzadkowski and X. G. He, PRL **77** (1996) 5172, [arXiv:hep-ph/9605326].

K.Desch, A.Imhof, Z.Was and M.Worek, arXiv:hep-ph/0307331.

Mixing angle to about 6^0 can be measured.

Caveat: production through VV fusion. so not equally sensitive to CP even and CP odd part.

$\gamma\gamma$ Collider

Collider	CP determination	Measurement of Mixing
LC	$f\bar{f}$ final state	$VV, f\bar{f}$ final state
$\gamma\gamma$	VV final state	Best for study
	VV fusion	of mixing

Most important advanatge: Production channel treats both the scalar and the pseudscalar the same way. Then use all the same methods as at other colliders. Arguably the best way to measure CP mixing.

$\gamma\gamma$ colliders possible with backscattered lasers at a parent e^+e^- collider.

$\gamma\gamma$ Collider

CP even (odd) combintaions couple to different combination of polarisation vectors. Polarisation dependence clearly measures CP mixing. B. Grzadkowski and J. F. Gunion, PLB **294** (1992) 361

Information from decay products of ϕ can be also used to determine the CP mixing.

MSSM H/A separation (CP conserving scenario) thro' decay to $b\bar{b}$. $\gamma\gamma$ covers an area of parameter space not accessible to LHC.

M.M.Muhlleitner, M.Kramer, M.Spira and P.M.Zerwas, PLB **508**, 311 (2001); P.Niezurawski, A.F.Zarnecki and M.Krawczyk, arXiv:hep-ph/0307180.

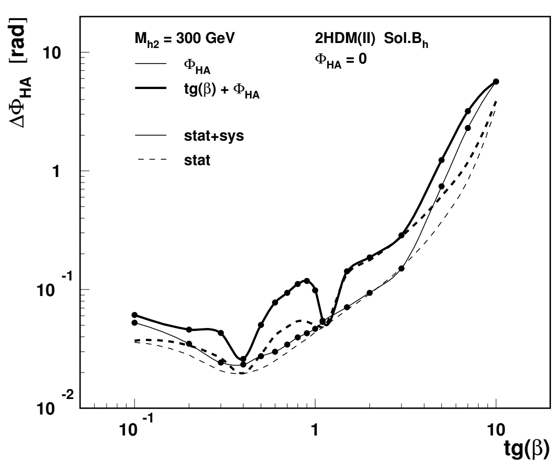
$\gamma\gamma$ (con.)

Can one do anything with only circular polarisation? Use the interference between the s-channel scalar exchange contribution and the QED/QFD processes.

$\gamma\gamma \to \phi_i \to VV, t\bar{t}, \tau\bar{\tau}$

P.Niezurawski, A.F.Zarnecki and M.Krawczyk, hep-ph/0307175;hep-ph/0403138;
E.Asakawa, S.Y.Choi, K.Hagiwara and J.S.Lee, PRD **62** (2000) 115005,

R.M.Godbole, S.D.Rindani and R.K.Singh, PRD **67** (2003) 095009.



Using the interference effects (Krawczyk et al) can determine Φ_{HA} to a good level.

Complete characterisation of the CP of the Higgs sector possible using $\gamma\gamma \to \phi_i \to t\bar{t}$ (Asakawa et al)

Conlcusions

- LHC and e^+e^- options offer good chance of determining the CP property of the Higgs. CP mixing studies possible only with decays into fermions or associate production with fermions. Many theorist's studies exist. Simualtions have now started for LHC.
- Higgs phenomenology affected quite strongly if $\not{C}\!\!\not{P}$ exists in the Higgs sector. In MSSM correlated studies with other sectors possible. Some exist, but not many.
- $\gamma\gamma$ colliders treat production of CP odd and even states democratically and offer the best chance to determine the CP mixing.
- There is lot to do!