

CP violation in the Higgs sector at the LHC?.

- ◇ Introduction.
- ◇ Two parts:
 - i Model independent determination of the HZZ coupling of a Higgs with/out determinate CP. Use of $H \rightarrow ZZ(Z^*) \rightarrow l^+l^-l'^+l'^-$
 - ii Model dependent, in the context of CP violating MSSM.
- ◇ Conclusions and & Summary.

Some references :

1) R.G., D. Miller, M. Muhelleitner, S. Moretti, [hep-ph/0608079](#) and [hep-ph/0602198](#) ; CPNSH report and Les Houches proceedings CP and CPV in the Higgs sector at LHC, a model independent analysis.

2) R.G.. D. Miller and M.Muhlleitner, Anomalous HZZ vertex and the LHC. A model independent analysis. ([hep-ph/0708.0458](#))

3)D. Ghosh, D.P. Roy and R.G., *Phys. Lett. B* 628, 131, 2005.

4) B. Dev, A. Djouadi, RG, M.Muehleitner, S.Rindani, **ILC Model indep. analysis** $e^+e^- \rightarrow t\bar{t}H$ ([hep-ph/0707.2848](#)) (will not have time for it!)

General Ref.: [R.G, S.Kraml, M.Krawczyk, D.J.Miller, P.Nieczurawski and A.F.Zarnecki](#) in (*Phys. Rept.* 426 (2006) 47 and [hep-ph/0404024](#).); ([hep-ph/0608079](#)) CPNSH report.

Why study CP of Higgs? Why \mathcal{CP} in Higgs sector and in SUSY?

- Just the discovery of the Higgs boson is not sufficient to validate the minimal SM.
- In SM, the **only** fundamental neutral scalar has $J^{PC} = 0^{++}$ state arising from an $SU(2)_L$ doublet with $Y = +1$.
- Various extensions of the SM can have several Higgs bosons with different CP properties: e.g. MSSM has two CP -even and one CP -odd states.
- Therefore, should a neutral spin-0 particle be detected, a study of its CP -properties would be essential to establish it as *the* SM Higgs boson.
- To study the *New Physics* effects beyond SM, we need to establish the CP eigenvalues for the Higgs states if CP is conserved, and measure the mixing between CP -even and CP -odd states if it is not.
- CP violation in the Higgs sector can be an alternative source of CP violation beyond the SM, required to explain the observed baryon asymmetry in our universe. [Accomando et al., *CERN 2006-009* (2006)]

Effect of SUSY \mathcal{CP} on Higgs phenomenologyMSSM \mathcal{CP} phases \Rightarrow \mathcal{CP} in the Higgs sector:

CP conserving MSSM 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](#))

$$g_{\phi_i WW}^2 + g_{\phi_j WW}^2 + g_{\phi_k WW}^2 = g^2 m_W^2, i \neq j \neq k$$

First proposed in a model independent way.

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

Predictions in terms of SUSY \mathcal{CP} phases in the MSSM for this mixing.

CP Study in the Higgs sector

(R.G., Kraml, Krawczyck, Miller et al in LHC/LC study group report.

1. Effect of \mathcal{CP} on different aspects of Higgs phenomenology: such as production rates, branching ratios; note even DM detection rates etc. could be affected in \mathcal{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 eigenstates.

Establish tensor structure for $\phi_i f \bar{f}$, $\phi_i VV$ vertex.

ϕ_i : a generic Higgs.

General Strategy for CP determination:Study \mathcal{CP} in a model independent way (most studies so far)

$$\phi_i f \bar{f} : -\bar{f}(v_f + ia_f \gamma_5) \frac{gm_f}{2m_W},$$

$$VV\phi_i : a_V \frac{gm_V^2}{m_W} g_{\mu\nu} (V = W/Z, g : \text{tree/loop level})$$

$$: c_V \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma / m_Z^2 (\text{loop level})$$

1. SM: $v_f = a_V = 1, a_f = 0, i = 1$.
2. $v_f = a_V = 0$ 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. c generally small.
4. If c_V has both real and imaginary parts, v_f, a_f both are nonzero \Rightarrow CP violation.

- Use kinematic distribution of the decay products of the Higgs: $H \rightarrow f\bar{f}$ ($f = t, \tau$), $H \rightarrow ZZ(Z^*) \rightarrow f\bar{f}f'\bar{f}'$.
- What distributions: Angular distributions, invariant mass distributions, angular correlations.
- Kinematics of the production process, threshold rise.
- Spin information of the fermions produced in the decay of Higgs or the fermions which are produced in association with the Higgs.

CP studies and the LHC

- 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

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

ILC and $\gamma\gamma$ colliders best, but LHC is the only collider we have for sure!

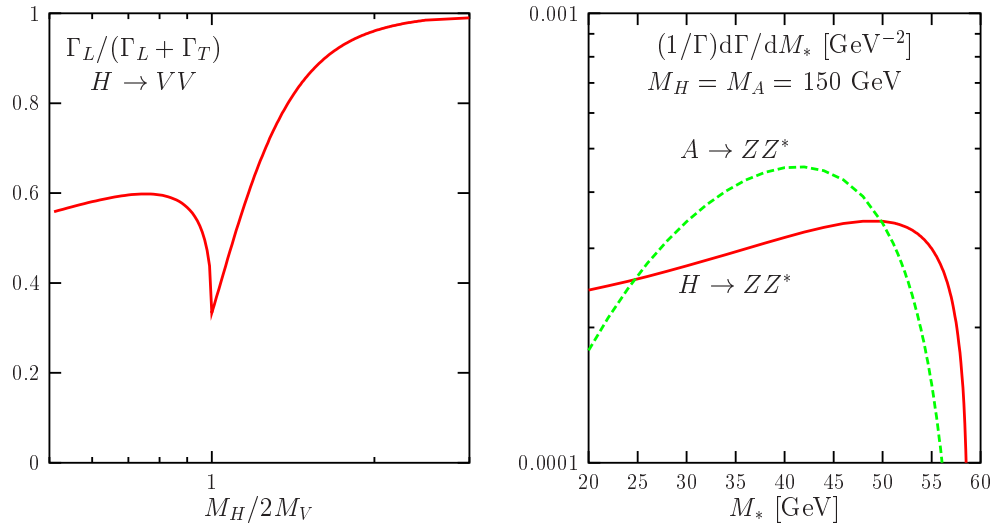
A small example of the dependence on the CP property of the Higgs

$$\Gamma_{\text{Born}}(H \rightarrow f\bar{f}) = \frac{G_{\mu}N_c}{4\sqrt{2}\pi} M_H m_f^2 \beta_f^3$$

$$\Gamma_{\text{Born}}(A \rightarrow f\bar{f}) = \frac{G_{\mu}N_c}{4\sqrt{2}\pi} M_H m_f^2 \beta_f$$

Surely one recalls $e^+e^- \rightarrow \gamma^* f\bar{f}(s\bar{s})$ have different energy dependence, near threshold, one proportional to one power of c.m. momentum and one to the third. Follows from angular momentum and parity conservation.

Similar things happen for Higgs production.



A decays only into transverse V and H into both transverse and longitudinal, fraction changing with V^* for a fixed M_ϕ .

$$\frac{d\Gamma(H \rightarrow VV^*)}{dM_*^2} = \frac{3G_\mu^2 M_V^4}{16\pi^3 M_H} \delta'_V \frac{\beta_V (M_H^4 \beta_V^2 + 12M_V^2 M_*^2)}{(M_*^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \quad \frac{d\Gamma(A \rightarrow VV^*)}{dM_*^2} = \frac{3G_\mu^2 M_V^6}{8\pi^3 M_A} \delta'_V \eta^2 \frac{M_*^2 \beta_V^3}{(M_*^2 - M_V^2)^2 + M_V^2 \Gamma_V^2}$$

with $\beta_V^2 = [1 - (M_V + M_*)^2/M_H^2][1 - (M_V - M_*)^2/M_H^2]$.

The $ZZ\phi$ Coupling $\diamond \phi \rightarrow ZZ^{(*)} \rightarrow 4l$ Choi, D. Miller, Mühlleitner & Zerwas

$$\phi VV : \quad ag_{\mu\nu} + b \frac{p_\mu p_\nu}{M_Z^2} + c \epsilon_{\mu\nu\rho\sigma} \frac{p^\rho k^\sigma}{M_Z^2}$$

$$[p \equiv p_{Z_1} + p_{Z_2}, k \equiv p_{Z_1} - p_{Z_2}]$$

Note:

- Many other formulations:

eg. Plehn, Rainwater, Zeppenfeld use higher dimensional operators to motivate

$$aV_{\mu\nu}V^{\mu\nu} + bV_{\mu\nu}\tilde{V}^{\mu\nu} \rightsquigarrow (g_{\mu\nu}p_1 \cdot p_2 - p_1^\mu p_2^\nu) + b\epsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma$$

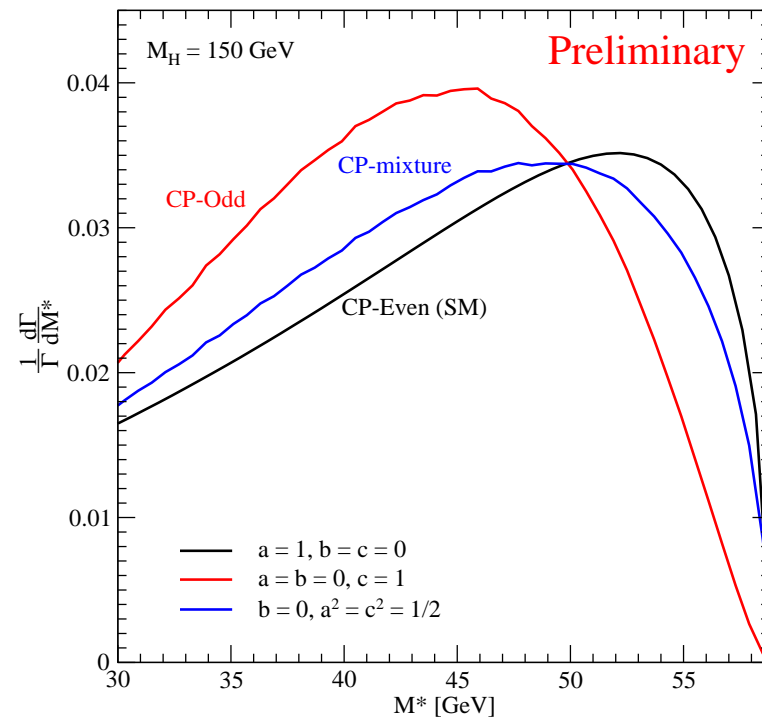
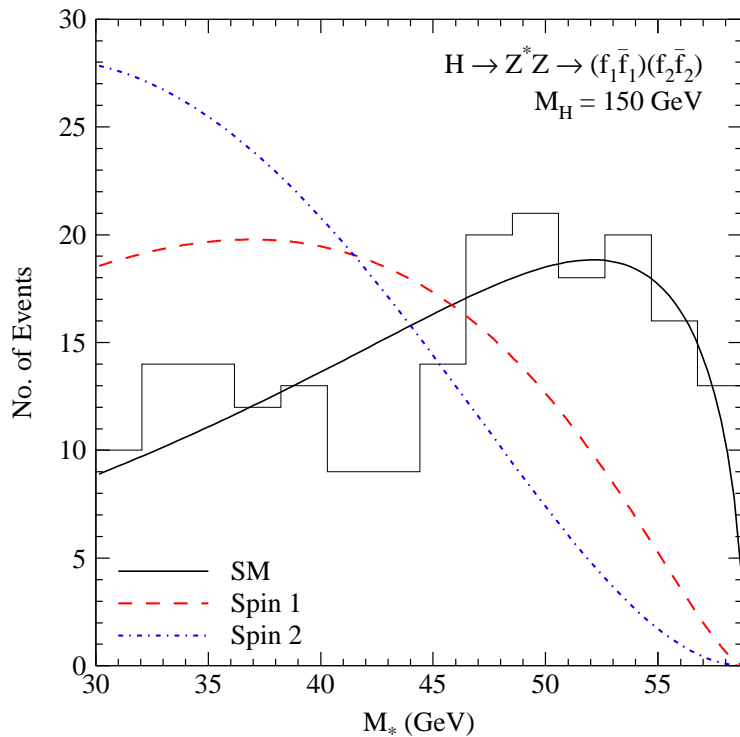
Can be obtained from the above by appropriate mappings of coefficients

- In SM and 2HDMs, the pseudoscalar coupling is missing (ie. $c = 0$) at tree-level

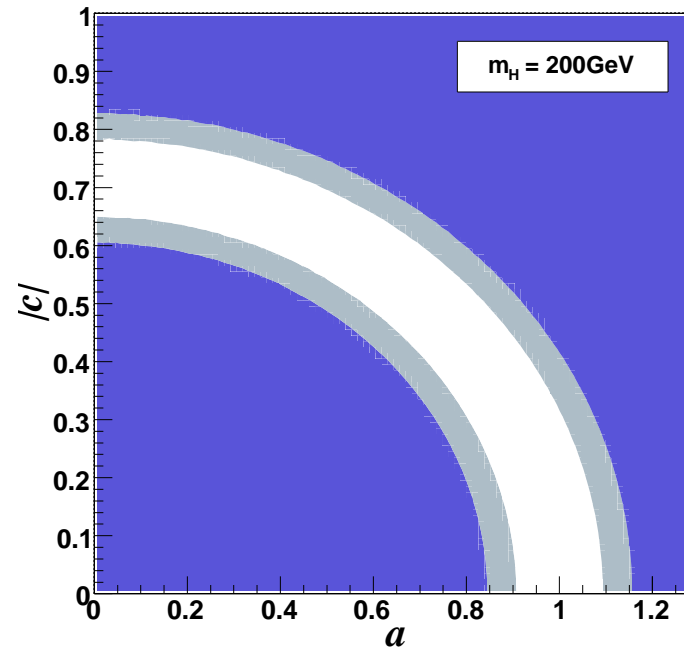
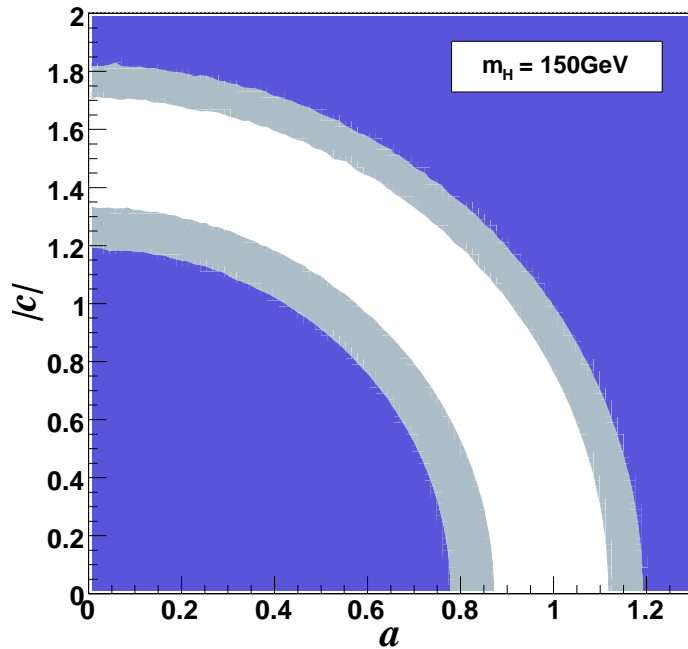
\Rightarrow expect c to be small

Below $\phi \rightarrow ZZ$ threshold, one Z is virtual \rightarrow can examine threshold behaviour (Zerwas, Miller, Choi..) to determine the spin.

Can we determine Higgs CP parity also like this: (D. Miller, M Muhleitner + R.G)



Can one distinguish CP-odd from CP-even how about mixtures?



Total rate CP even. Can not test the CP odd coupling

Depends on the CP-even a , $\Re(b)$, $|b|$ and $|c|$.

Plots are for $b = 0$.

Assume that the effect of the cuts on the observable cross-sections is the same as for the SM and take the expected numbers from an ATLAS study

Regions that can be excluded at 5 and 3 σ level.

All such studies look for difference caused by the different tensor structure to kinematical distributions.

Effect caused by CP mixing in MSSM, on the other hand will only affect normalisations mostly.

CP-violating observables: constructed for ILC Hagiwara et al, Han et al, Biswal et al.

For the PLC Hagiwara et al, Singh et al, Krawzyck et al.

For the LHC Buszello et al, Zhang et al

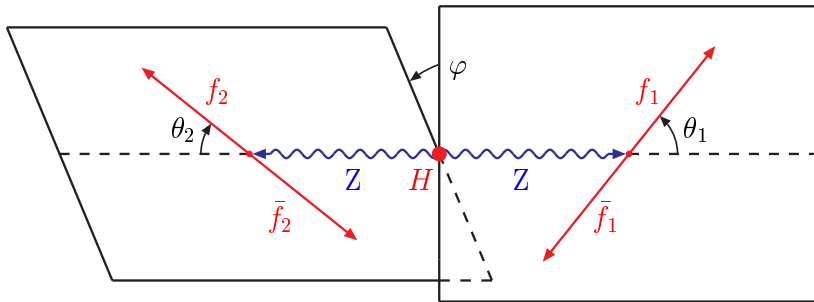
Our analysis Miller, Moretti, Muhelleitner and R.G. in CPNSH report and in Les Houches proceedings (hep-ph/0608079 and hep-ph/0602198):

Miller, Muehlleitner and RG: in preparation

Construct variables such that each probes one part of the anomalous coupling; thus CP violating variables to probe CP mixing.

- \tilde{T} : Naive time reversal operation.
- Cross-sections integrated over $CPT\tilde{T}$ symmetric phase space will probe only the CP – even, \tilde{T} –even couplings, in the approximation that the anomalous couplings are small.
- Partially integrated cross-sections will be able to probe these. for example to probe a P -odd coupling we construct Forward-Backward asymmetry.
- Constructed different observables out of the available momenta such that they have specific CP and \tilde{T} transformation properties.
- Look at expectation value of 'sign' of these observables. These asymmetries, are proportional to the part of the anomalous coupling which has the **same** CP and \tilde{T} transformation properties as the observable, to leading order in the anomalous coupling.

The definition of the polar angles θ_i ($i = 1, 2$) and the azimuthal angle φ for the sequential decay $H \rightarrow Z^{(*)}Z \rightarrow (f_1\bar{f}_1)(f_2\bar{f}_2)$ in the rest frame of the Higgs boson.



With these angles construct two observables:

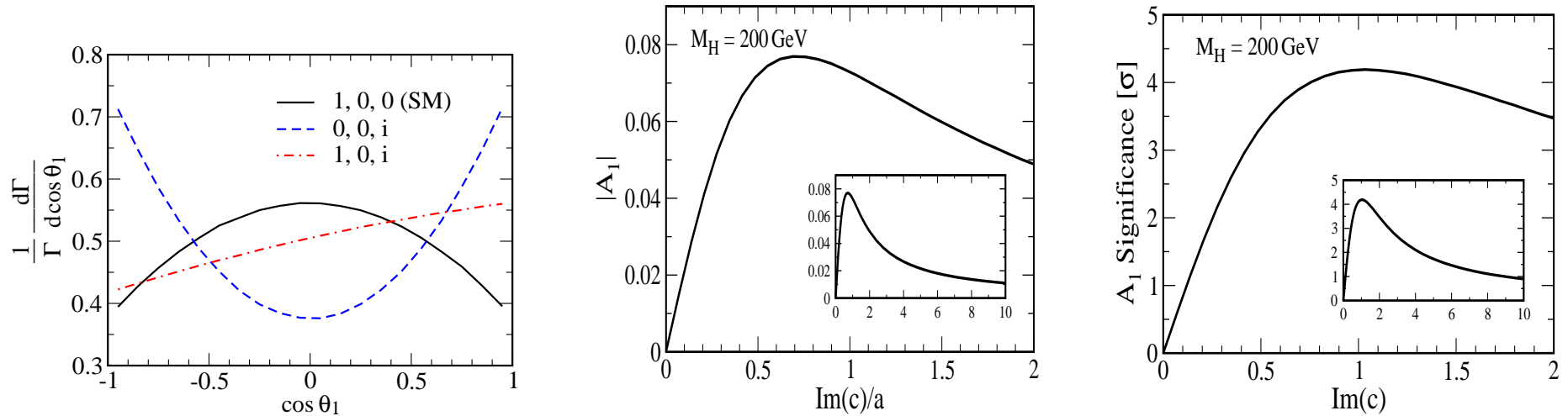
$$O_1 \equiv \cos \theta_1 = \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}) \cdot (\vec{p}_{\bar{f}_2} + \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}| |\vec{p}_{\bar{f}_2} + \vec{p}_{f_2}|}$$

Need to distinguish between f_1 and \bar{f}_1 .

One Z decays to $f_1\bar{f}_1$ and other two $f_2\bar{f}_2$.

$$\mathcal{A}_1 = \frac{\Gamma(\cos \theta_1 > 0) - \Gamma(\cos \theta_1 < 0)}{\Gamma(\cos \theta_1 > 0) + \Gamma(\cos \theta_1 < 0)}.$$

If $\Im m(c) \neq 0$ this will mean $\mathcal{A}_1 \neq 0$.



The normalized differential width for $H \rightarrow ZZ \rightarrow (f_1 \bar{f}_1)(f_2 \bar{f}_2)$. The solid (black) curve: the SM ($a = 1, b = c = 0$), Dashed (blue) curve: pure CP-odd state ($a = b = 0, c = i$). The dot-dashed (red) curve is for a state with a CP violating coupling ($a = 1, b = 0, c = i$). One can clearly see an asymmetry about $\cos\theta_1 = 0$ for the CP violating case.

Corrected for change in the production rate due to our non-standard couplings as compared to the SM rate. For 100 fb^{-1}

May be improved by using jets instead of f_2 as the asymmetry does not require charge determination. One essentially means 'b'-jets. ATLAS study demonstrates it is possible to see the signal in $Z \rightarrow b\bar{b}$.

For $\Re(c)$ one needs an observable which is CP odd and \tilde{T} odd.

$$O_2 \equiv \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}) \cdot (\vec{p}_{\bar{f}_2} \times \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}| |\vec{p}_{\bar{f}_2} \times \vec{p}_{f_2}|}$$

$$\mathcal{A}_2 = \frac{\Gamma(O_2 > 0) - \Gamma(O_2 < 0)}{\Gamma(O_2 > 0) + \Gamma(O_2 < 0)}$$

Need to distinguish between f_2 and \bar{f}_2 as well. Hence, jets can not be used.

Significance for this never more than 0.6! Essentially because of the small vector coupling of Z to leptons.

One probe or $\Re(c)$ which does not have this suppression:

$$O_3 = \cos \theta_1 \sin \theta_2 \cos \theta_2 \sin \phi .$$

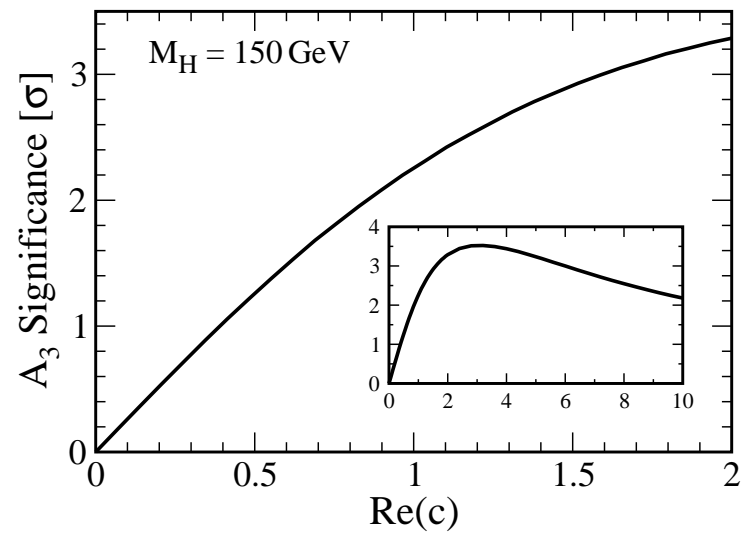
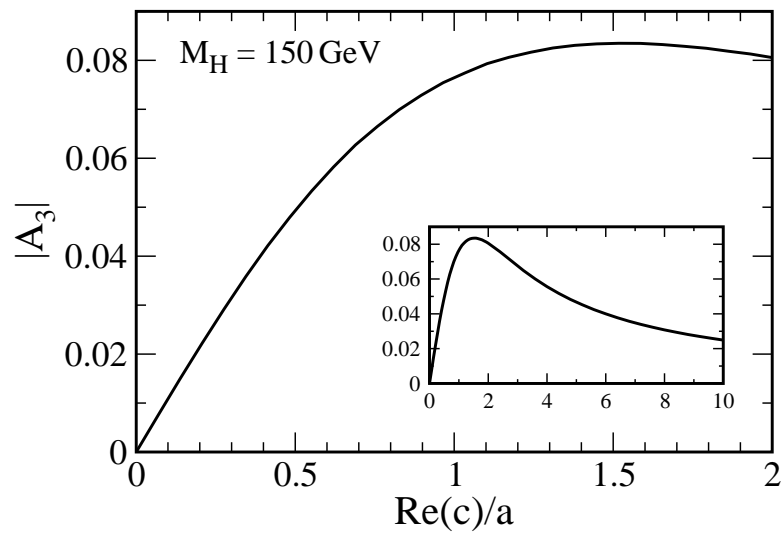
and

$$\mathcal{A}_3 = \frac{\Gamma(O_3 > 0) - \Gamma(O_3 < 0)}{\Gamma(O_3 > 0) + \Gamma(O_3 < 0)}.$$

We get,

$$\mathcal{A}_3 = \frac{1}{\Gamma} \int dPSP \frac{-256}{9} m_1^3 m_2^3 (v^2 + a^2)^2 \gamma_a \gamma_b (a \Re(c) - \Re(bc^*) m_1 m_2 \frac{\gamma_b^2}{\gamma_a})$$

The asymmetry is proportional to $a \Re(c)$ and $\Re(bc^*)$. In linear approximation for anomalous coupling it is then a probe of $\Re(c)$. **Does not have the suppression that \mathcal{A}_2 has.**

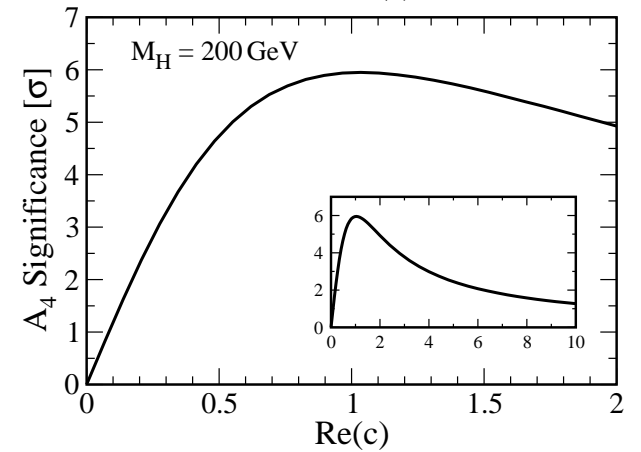
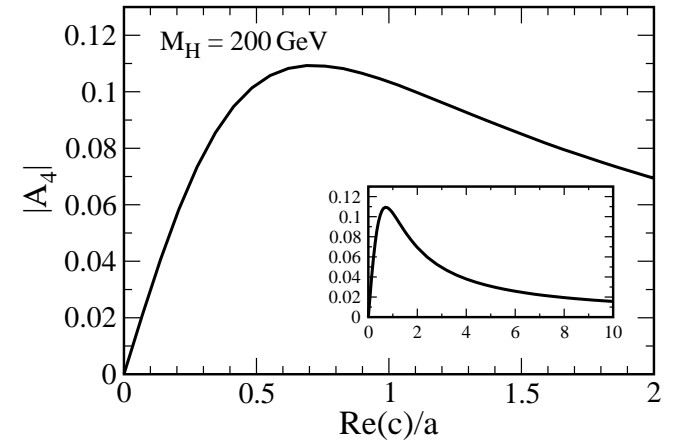


Expected significance for 100 fb^{-1} not bad!

$$O_4 = \frac{16[(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot \vec{p}_{1H}][(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot (\vec{p}_{1H} \times \vec{p}_{2H})]}{|\vec{p}_{3H} + \vec{p}_{4H}|^2 |\vec{p}_{1H} + \vec{p}_{2H}| |\vec{p}_{3Z} - \vec{p}_{4Z}|^2 |\vec{p}_{1Z} - \vec{p}_{2Z}|^2}$$

In terms of the angles it reads

$$O_4 = \sin^2 \theta_1 \sin^2 \theta_2 \sin \phi \cos \phi.$$



$$O_5 = \sin \theta_1 \sin \theta_2 \sin \phi [\sin \theta_1 \sin \theta_2 \cos \phi + \cos \theta_1 \cos \theta_2]$$

and can be constructed from the three-vectors by

$$O_5 = \frac{[(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot \vec{p}_{1H}][(\vec{p}_{1Z} - \vec{p}_{2Z}) \cdot \vec{p}_{3Z}]}{|\vec{p}_{3H} + \vec{p}_{4H}| |\vec{p}_{3Z} - \vec{p}_{4Z}|^2 |\vec{p}_{1Z} - \vec{p}_{2Z}|^2}.$$

The related asymmetry

$$A_5 = \frac{\Gamma(O_5 > 0) - \Gamma(O_5 < 0)}{\Gamma(O_5 > 0) + \Gamma(O_5 < 0)}$$

A_5 is even better than A_4 for smaller Higgs masses.

An asymmetry to probe $\Im m(b)$:

$$\begin{aligned}
 O_6 &= \frac{[(\vec{p}_{1Z} - \vec{p}_{2Z}) \cdot (\vec{p}_{3H} + \vec{p}_{4H})][(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot \vec{p}_{1H}]}{|\vec{p}_{1Z} - \vec{p}_{2Z}|^2 |\vec{p}_{3H} + \vec{p}_{4H}|^2 |\vec{p}_{3Z} - \vec{p}_{4Z}|} \\
 &= \cos \theta_1 \sin \theta_2 \sin \phi
 \end{aligned}$$

And the asymmetry reads

$$\mathcal{A}_6 = \frac{\Gamma(O_6 > 0) - \Gamma(O_6 < 0)}{\Gamma(O_6 > 0) + \Gamma(O_6 < 0)}$$

Asymmetry/form factor	a	$\Re(b)$	$\Im(b)$	$\Re(c)$	$\Im(c)$
\mathcal{A}_1	x				x
\mathcal{A}_3	x	x	x	x	x
\mathcal{A}_4	x			x	
\mathcal{A}_5	x	x	x	x	x
\mathcal{A}_6	x		x		

The dependence of the asymmetries \mathcal{A}_1 and \mathcal{A}_3 to \mathcal{A}_6 on the form factors a, b, c of the general HZZ coupling.

Not presenting the significances for O_5, O_6 .

Distribution in ϕ ; the angle between the planes of the fermion pairs coming from the Z boson decays.

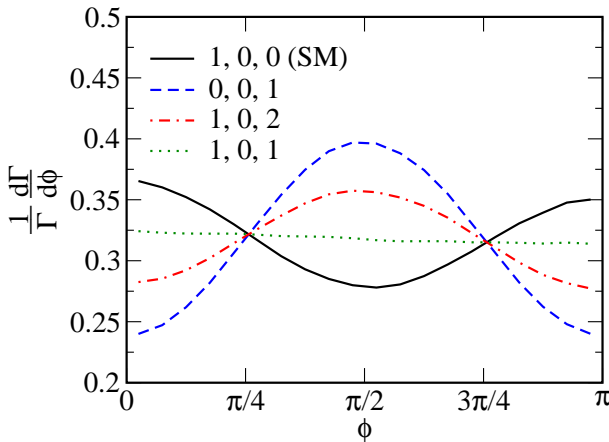
In the SM

$$\frac{d\Gamma}{d\phi} \sim 1 + A \cos \phi + B \cos 2\phi$$

A, B are functions of M_H, M_Z . the ϕ dependence will vanish for larger Higgs masses.

For CP odd case:

$$\frac{d\Gamma}{d\phi} \sim 1 - \frac{1}{4} \cos 2\phi$$



Mixed CP case : the ϕ distribution can be used to get the information. Has been studied by a few authors. Van der Bijj et al

Mixed CP case : the ϕ distribution can be used to get the information.
Has been studied by a few authors.

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 $gg \rightarrow \phi + 2 \text{ jets}$, 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)

Warning: All the above processes use ϕZZ coupling for production. Which means for a pseudoscalar the strength is necessarily small as loops are involved. For a state of mixed CP, only the CP-even part gets projected out in production. This is true of all the various studies suggested above.

$t\bar{t}\phi$ production treats the scalar and the pseudoscalar democratically.

$\gamma\gamma$ colliders have the same good feature. But we may never have it!

Can LHC do something? $t\bar{t}H$ needed!!!!

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

“designed to showcase the effects of CP violation in the MSSM”

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

$$\mu = 4M_{\text{SuSy}}, \quad |A_{t,b,\tau}| = 2M_{\text{SuSy}}, \quad |M_3| = 1\text{TeV}$$

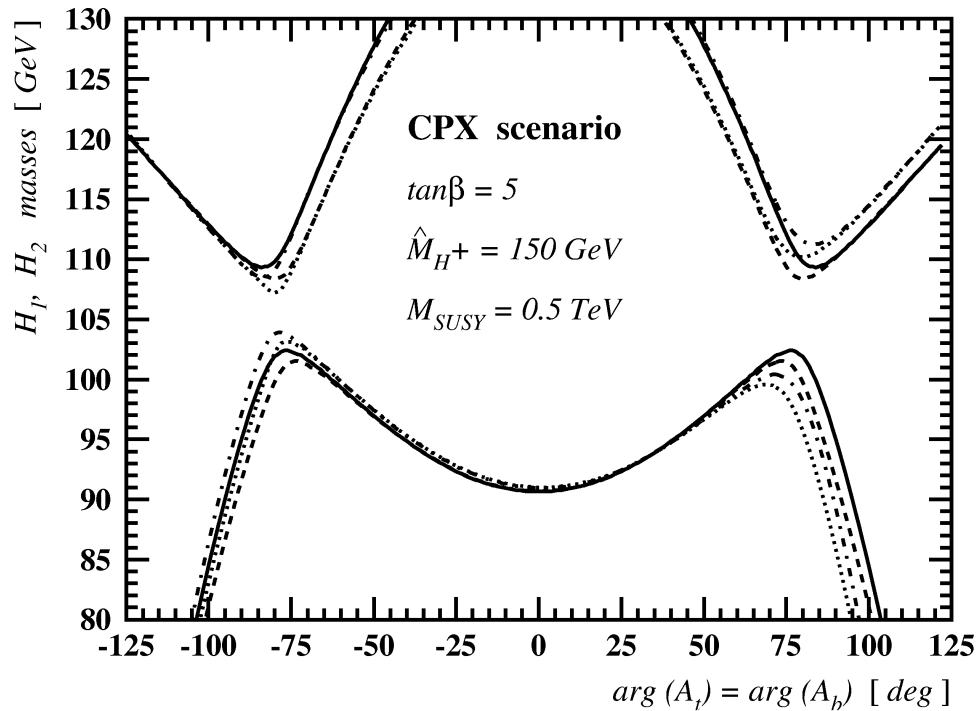
Allow the following parameters to vary:

$\tan \beta,$	$M_{H^\pm},$	$M_{\text{SuSy}},$
$\{\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}\},$	$\Phi_3,$	Φ_μ

Masses and couplings[Carena, Ellis, Pilaftsis & Wagner, Nucl. Phys. B **625** (2002) 345]

CPX scenario with $\tan\beta = 5$, $M_{H^\pm} = 150\text{GeV}$, $M_{\text{SUSY}} = 500\text{GeV}$,
 $\Phi_\mu = 0$, $\Phi_{\tilde{g}} = 0$ and $\pi/2$.

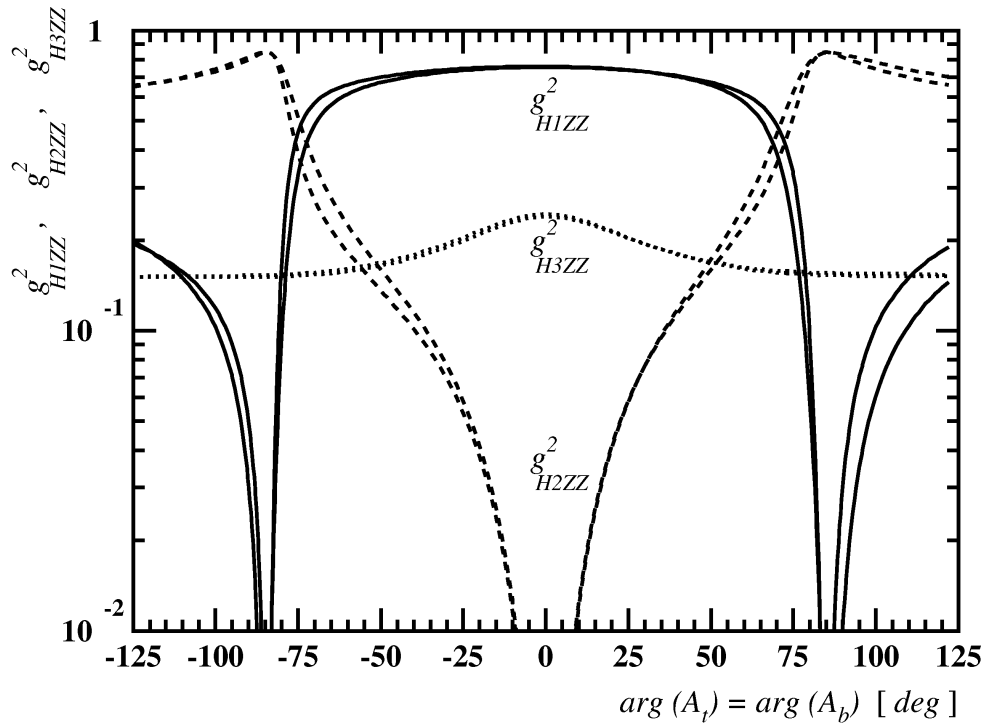
masses:



$$M_{H_3} \sim 150\text{ GeV}$$

$\Phi_{\tilde{g}}$ does not have
 a big effect (two-loop)

couplings to VV:

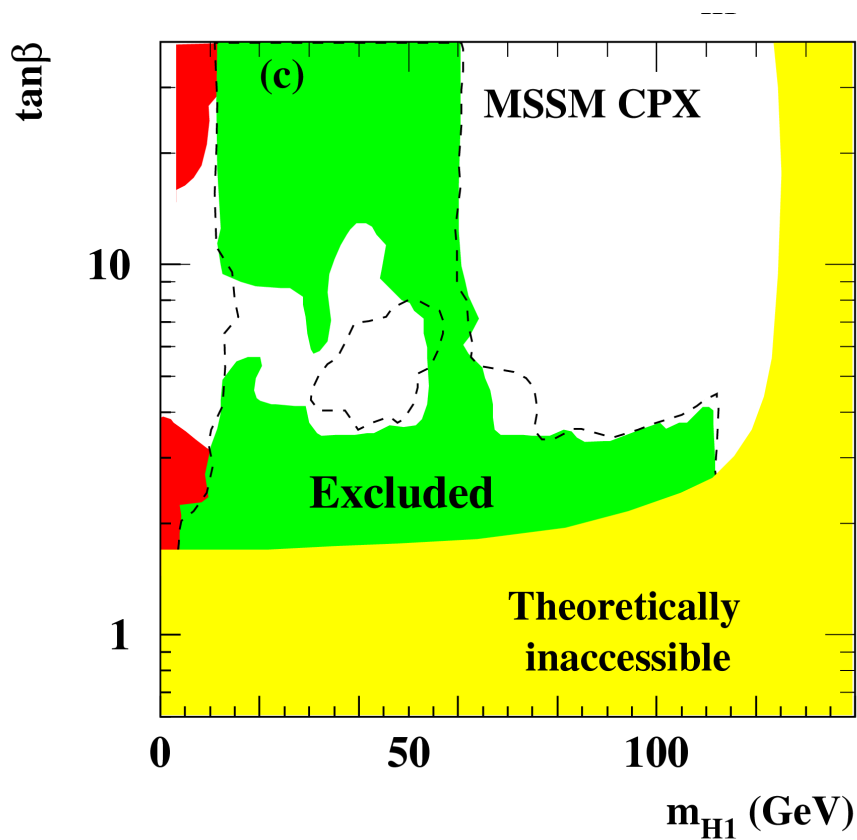


Sum rule for couplings

$$\sum_{i=1}^3 g_{\phi_i VV}^2 = g_{\phi_i VV}^2 (SM)$$

Often $g_{\phi_i ZZ}$ vanishes!
 \Rightarrow light Higgs may have
escaped LEP limits

[LEP Limits](#) Preliminary OPAL results :hep-ex/0406057, EJPC 37, 2004,49; LHWG-Note 2004-01



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

$$\Phi_\mu = 0$$

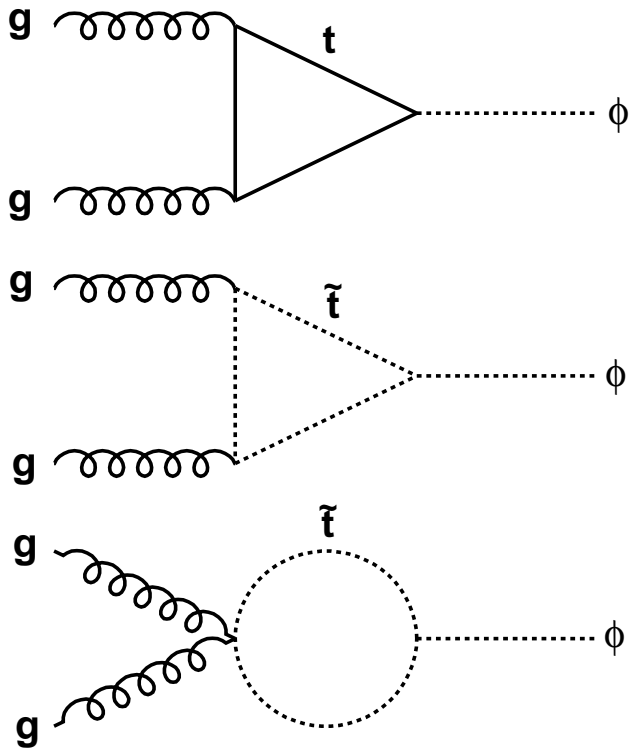
$$M_{\text{SuSy}} = 500 \text{ GeV}$$

Even have gaps at 0–50 GeV!

$gg \rightarrow \phi$ cross-sections

[Dedes, Moretti, Nucl. Phys. B **576** (2000) 29

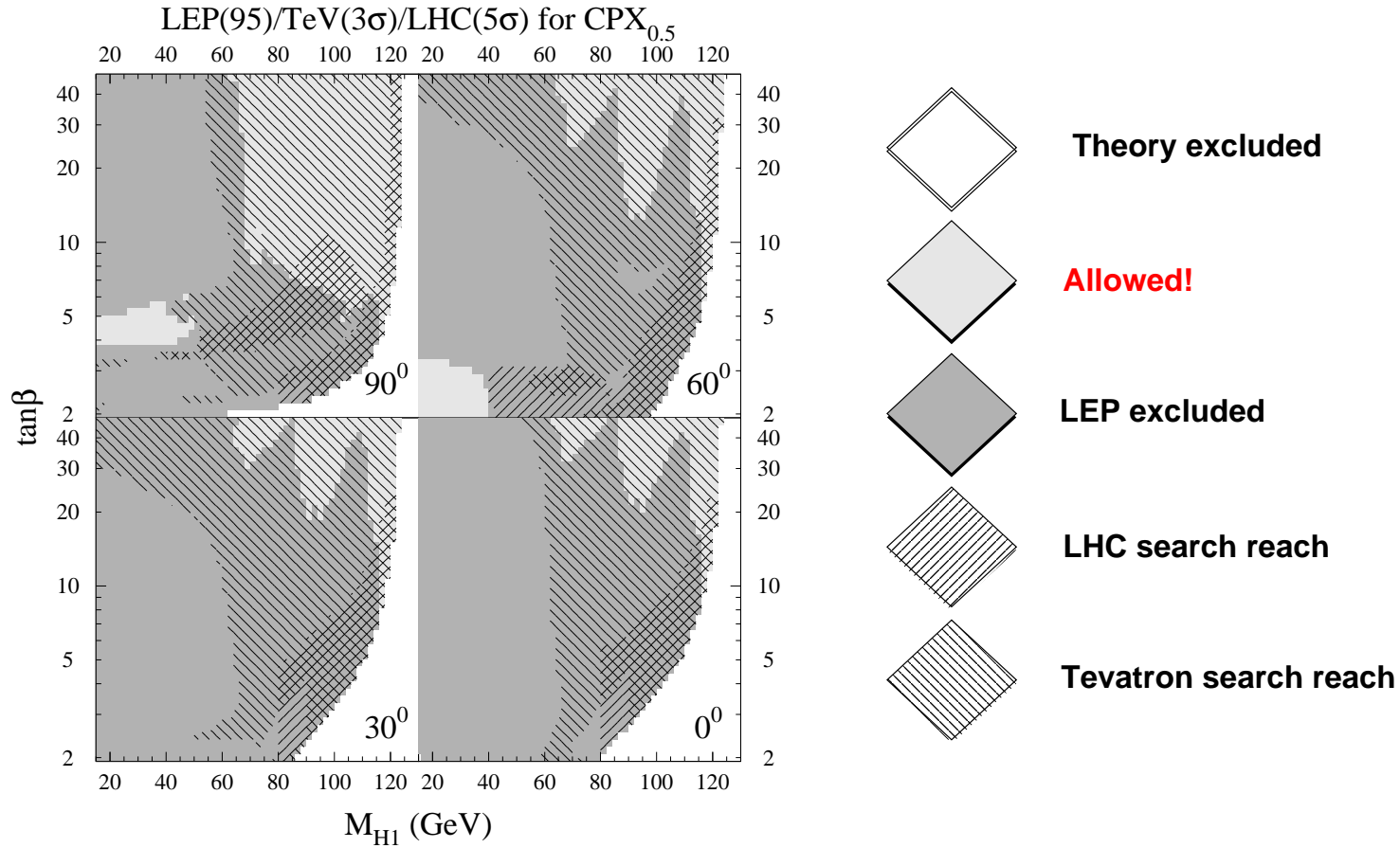
Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner, Comput. Phys. Commun. **156** (2004) 283]



$$g_{h\tilde{t}_L\tilde{t}_R^*} = \frac{igm_t}{2M_W \sin \beta} (\mu^* \sin \alpha - A_t \cos \alpha)$$

$gg \rightarrow \phi$ cross-sections may be altered

[Carena, Ellis, Mrenna, Pilaftsis & Wagner, Nucl. Phys. B **659** (2003) 145]



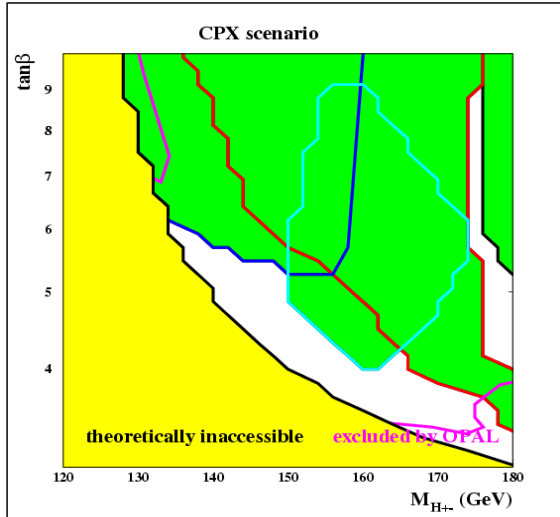
Gaps in coverage! Need to look at the light higgs searches again.

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 .

The higgs searches in $\emptyset P$ scenario need to be looked at carefully.

What happens to discovery reaches our LHC friends present?



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

Warning by M.S.: 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 $130 < m_{\phi_3} < 180$.

The results of theory analysis verified.

Suggestion to fill the hole via h^+ decays

D. Ghosh, R.G. and D.P. Roy, Phys. Lett. B: 658

Observation:

There exists a sum rule for the couplings.

$$g_{\phi_i VV}^2 + |g_{\phi_i H^+ W}|^2 = 1.$$

Since the couplings of ϕ_1 with $VV, gg, t\bar{t}$ are suppressed, ϕ_1 coupling to $H^+ W$ is large.

More important in this scenario the H^+ is light too.

In the 'window' where higgs signal might have been lost at LEP: Look for ϕ_1 production in H^+ decay, which in turn is produced in t decay.

(actually this would be true even in noncp violating supersymmetric scenarios as well if a non-chiral higgs singlet is present: D.P., P.N. Pandita, Sudhir Vempati; D.P. Roy, R.G.)

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

Small $\tan\beta$, light H^\pm , ($M_{H^+} < M_t$) $\Rightarrow H^\pm$ can be produced in the top decay

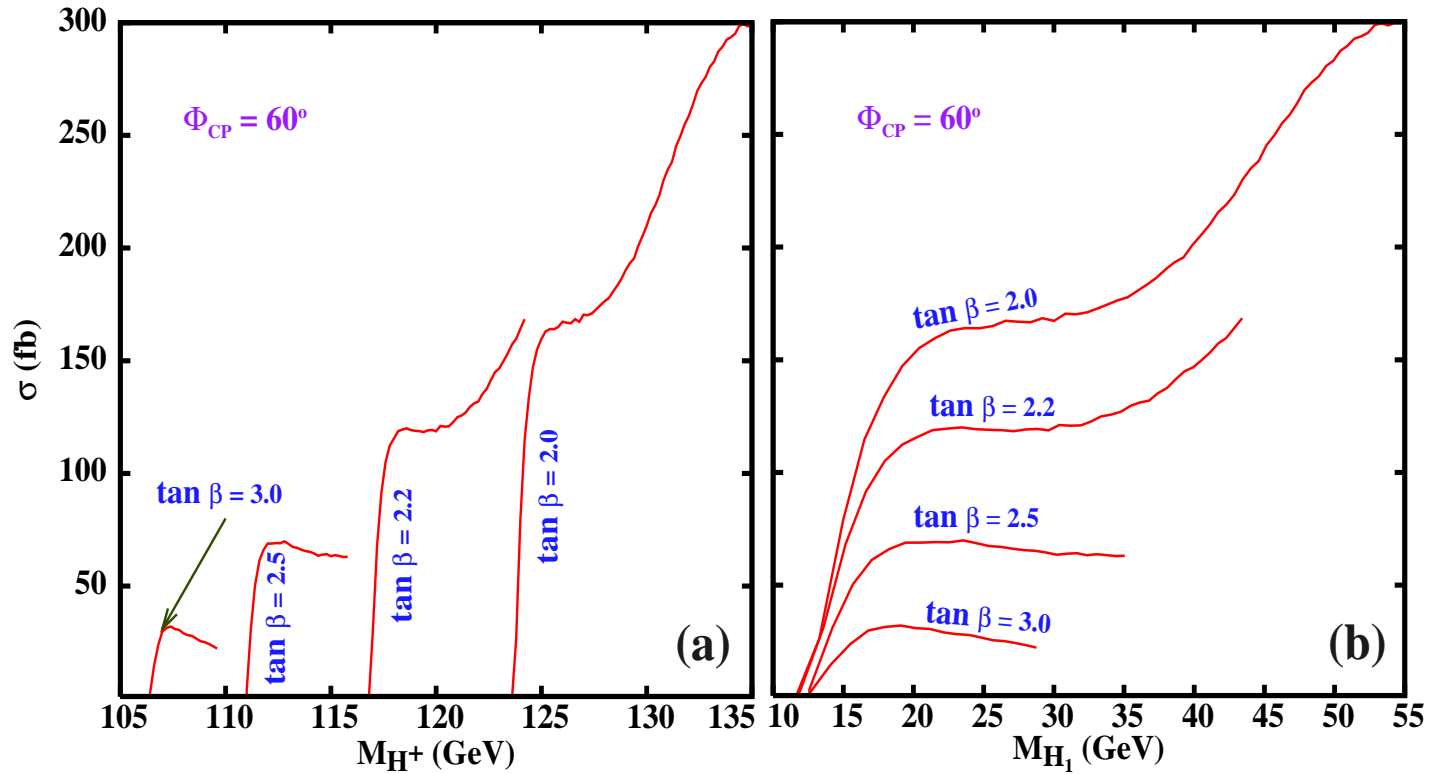
The sum rules on couplings means large $H^\pm W \phi_1$ coupling \Rightarrow large $B.R.(H^+ \rightarrow \phi_1 W)$

$$\Phi_{CP} = 90^\circ.$$

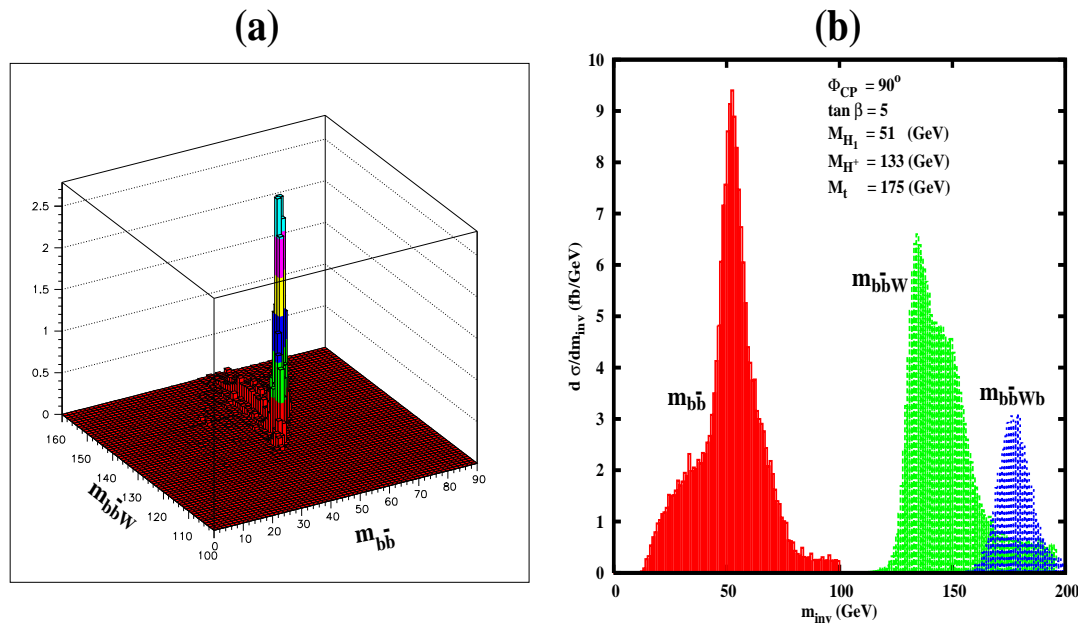
$\tan\beta$	3.6	4	5
$\text{Br}(H^+ \rightarrow \phi_1 W^+)(\%)$	$> 90(87.45)$	$> 90(57.65)$	$> 90(46.57)$
$\text{Br}(t \rightarrow bH^+)(\%)$	~ 0.7	$.7 - 1.1$	$1.0 - 1.3$
M_{H^+} (GeV)	< 148.5 (149.9)	< 139 (145.8)	< 126.2 (134)
M_{ϕ_1} (GeV)	< 60.62 (63.56)	< 49.51 (65.4)	< 29.78 (53.49)

The BR ($H^\pm \rightarrow \phi_1 W > 47\%$ over the *entire* kinematic region in the light ϕ_1 window still allowed by LEP. The BR of H^\pm in the usual $\tau\nu_\tau$ discovery channel **discussed at LHC for the charged higgs** suppressed by over an order of magnitude.

In the light ϕ_1 LEP window the H^\pm can also be NOT searched for using the usual strategies for $\emptyset P$ case.



Thus for $L = 30 \text{ fb}^{-1}$ luminosity, one expects about 1000 -5000 events!



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 $b\bar{b}W$ invariant mass at m_t . So detectability controlled by just the signal size.

The QCD bkgd can be removed by demanding that $b\bar{b}W$ mass within 25 GeV of m_t . Possible QCD background: cross-section as high as 8.5 pb After these cuts and reconstruction only 0.5 fb is left!

ATLAS has done some fast simulation analysis and CMS is doing it.

Conclusions

- ◇ The LHC can get information about the tensor structure of the coupling of the scalar to a pair of gauge bosons. But not so easy if the scalar has a mixed CP. Use of asymmetries may do it unambiguously. More theoretical and experimental work needed on the subject!
- ◇ colorblue For a light higgs, $m_\phi \sim 120$ GeV the e^+e^- colliders offer much better prospect of probing the anomalous ΦVV coupling. **This I did not tell you about!**
- ◇ CP violation in the MSSM will alter the sparticle phenomenology in a big way.
- ◇ Can affect the Higgs search drastically, a hole in the $\tan\beta - M_{H^+}$ plane, for a scenario in which the phase effects are maximised: LEP will have missed the signal and LHC/Tevatron will not see it.
- ◇ Production of ϕ_1 through the H^+ decay produced in the t decay, can perhaps help fill the hole.
- ◇ Many studies in the context of CPV SUSY and the Higgs sector still very preliminary, even the tools to calculate $\mathcal{O}P$ scenarios in SUSY-Higgs sector still need to be standardised.