CP violation at the LHC.

CP **studies** and violation **the Higgs sector** at the LHC

- ♢ Introduction.
- ♢ Two parts:
  - i Model independent discussion : $HZZ, Ht\bar{t}$ coupling of a Higgs with/out determinate CP.
  - ii Model dependent, in the context of CP violating MSSM. But pointing out a scenario which CAN be generic.
- ♢ 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 indpendent analysis. (hep-ph/0708.0458), JHEP **0712**, 031.

3) B. Dev, A. Djouadi, RG, M.Muehlleitner, S.Rindani, **ILC Model indep. analysis** $e^+e^- \to t\bar{t}H$(hep-ph/0707.2848) Phys. Rev. Lett. **100**, 051801.

4)D. Ghosh, D.P. Roy and R.G., Phys. Lett. B 628, 131, 2005. (CP violating MSSM)

General Ref.: R.G, S.Kraml, M.Krawczyk, D.J.Miller, P.Niezurawski 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 $\not{C}\!P$ 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 may be an alternative source of CP violation beyond the SM, required to explain the observed baryon asymmetry in our universe.

CP Study in the Higgs sector

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

1. Effect of $\not{C}\not{P}$ on different aspects of Higgs phenomenology: such as production rates, branching ratios; note even DM detection rates etc. could be affected in $\not{C}\not{P}$ 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 determination:

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

$$\begin{aligned}
\phi_i f \bar{f} &: \quad -\bar{f}(v_f + i a_f \gamma_5)\frac{g m_f}{2 m_W}, \\
V V \phi_i &: \quad a_V \frac{g m_V^2}{m_W} g_{\mu\nu} (\mathrm{V = W/Z, g : tree/loop\ level}) \\
&: \quad c_V \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma / m_Z^2 (\mathrm{loop\ level})
\end{aligned}$$

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 both the CP even and CP odd couplings simultaneoulsy nonzero $\Rightarrow$ CP violation.

- Use kinematic distribution of the decay products of the Higgs: $H \to f\bar{f} (f = t, \tau)$, $H \to ZZ(Z^*) \to f\bar{f}f'\bar{f}'$.

- 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 and Measurement of Mixing
LHC	$t\bar{t}h$ production: gg initial state. $f\bar{f}$ final state : gg initial state.
	VV final state: initial state VV fusion : $f\bar{f}$ final state.

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

Pioneering studies: J. Gunion and X. He, PRL 76 (1996) 4468; J. Gunion and J. Pliszka, PLB 444 (1998) 136.

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

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

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

Surely one recalls $e^+e^- \to \gamma^* f\bar{f}(s\bar{s})$ 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.

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

$$\boxed{\phi VV: \qquad a g_{\mu\nu} + b\frac{p_\mu p_\nu}{M_Z^2} + c\,\epsilon_{\mu\nu\rho\sigma}\frac{p^\rho k^\sigma}{M_Z^2}}$$

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

Note:

- Many other formulations:

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

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

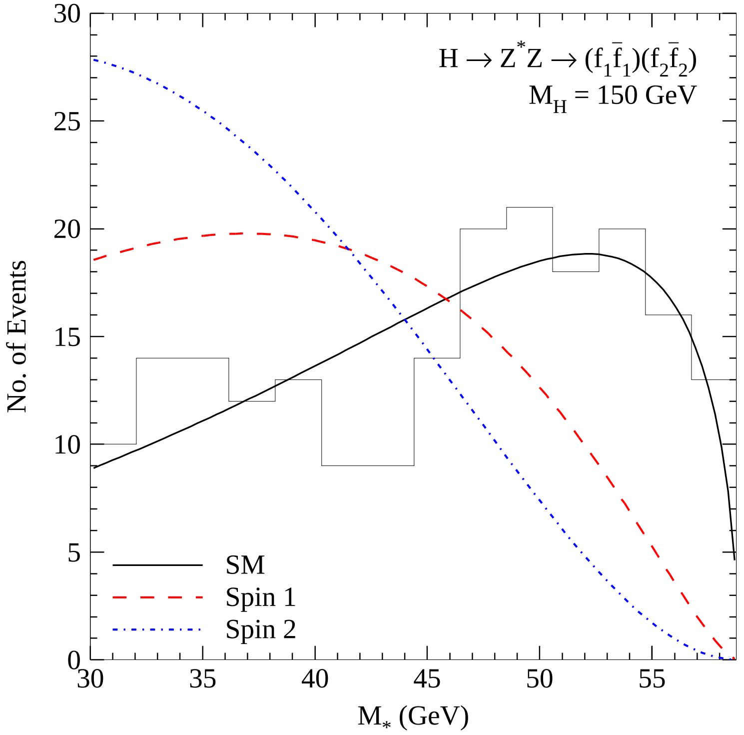
Can be obtained from the above by appropriate mappings of coefficients

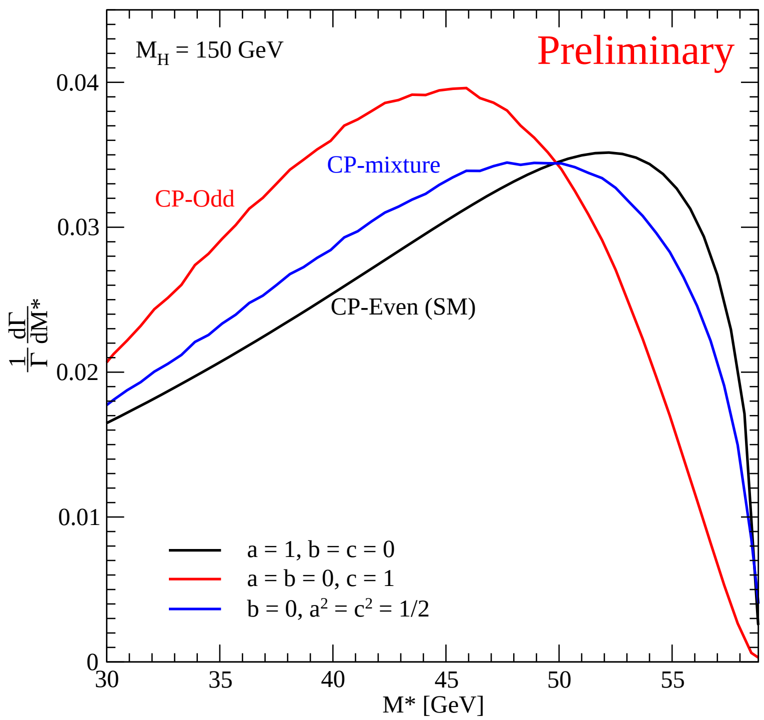
- In SM and 2HDMs, the pseudoscalar coupling is missing (ie. $c = 0$) at tree-level

$\Rightarrow$ expect c to be small

Below $\phi \to ZZ$ threshold, one Z is virtual → 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)



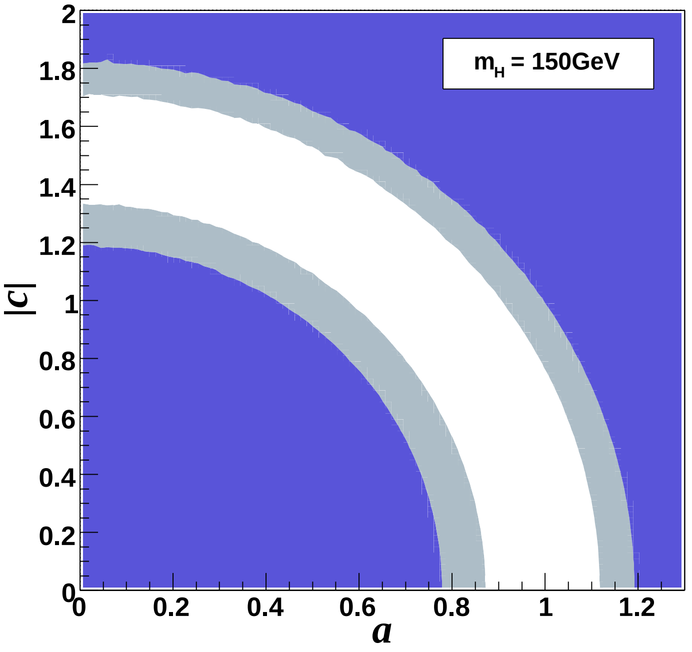


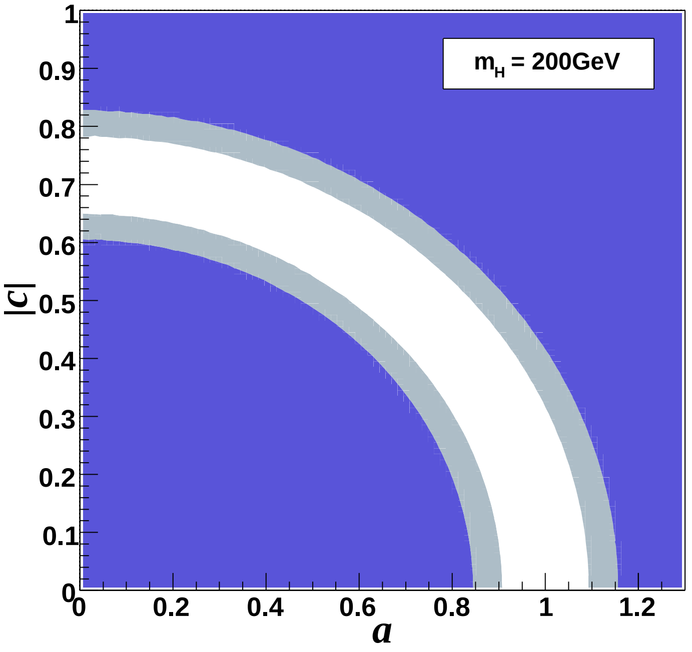
Can one distinguish CP-odd from CP-even how about mixtures?

Calculated $\Gamma(H \to ZZ^* \to f_1\bar{f}_1 f_2\bar{f}_2)$ Total rate CP even. Can not test the CP odd coupling Depends on the CP-even $a, \Re e(b), |b|$ and $|c|$.

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.

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

For the PLC Gunion and collab., Hagiwara et al, Singh et al, Krawzyck et al.

For the LHC Gunion et al., 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: JHEP **0712**, 031.

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.

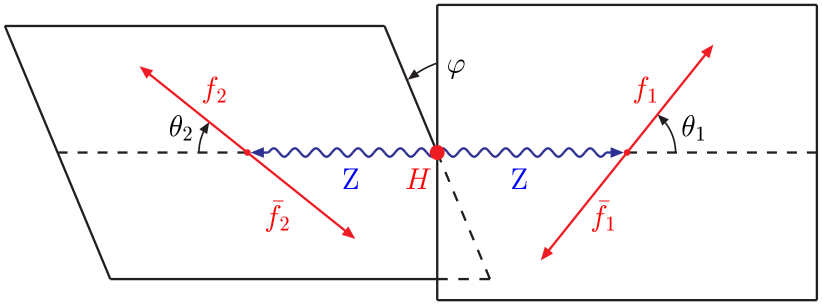
- Cross-sections integrated over $CP\tilde{T}$ symmetric phase space will probe only the $CP-even$, $\tilde{T}$–even couplings, in the approximation that the anomalous couplings are small.

- Partially integrated cross-sections will be able to probe these. for example to probe a P-odd cpupling 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 expectaion 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. In the rest frame of H.



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

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

Available complete analytic expression for the triple diff. crosssection $\frac{d^3\Gamma}{dc_{\theta_1}\,dc_{\theta_2}d\phi}$

With these angles consruct observables:

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

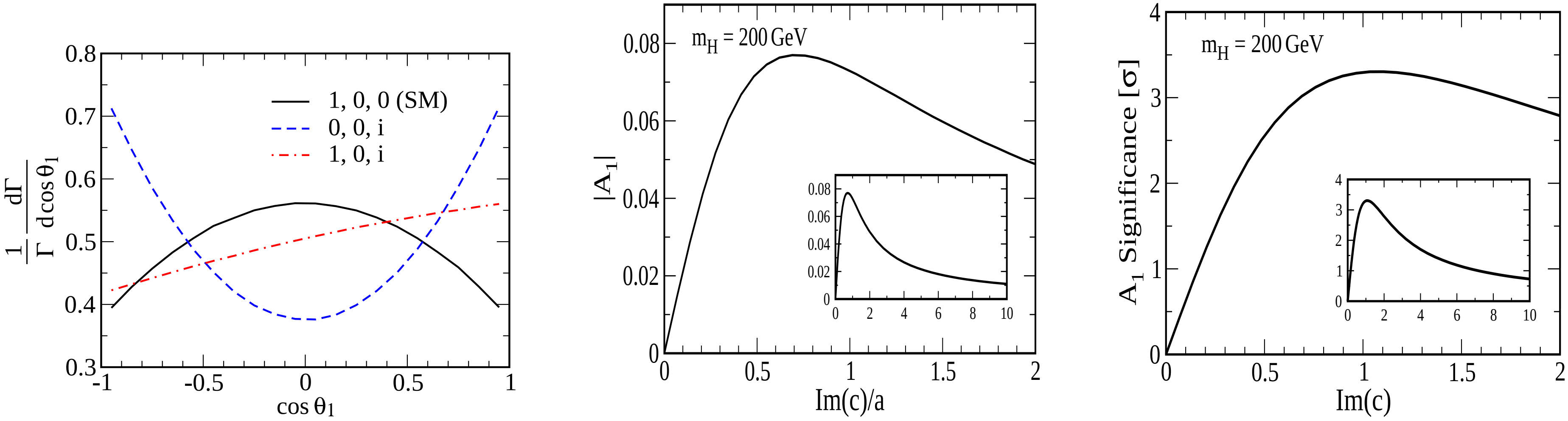
Calculate $< (sgn(\mathcal{O}_1)) >$

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

Expect this to be nonzero ONLY if $\Im m(c)$ is nonzero.

$\mathcal{A}_1 \propto \int d^2\mathcal{P}(-3\Im m(c))v_1 f_1$

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



The normalized differential width for $H \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ 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 $Z \to b\bar{b}$.

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

$$O_2 \equiv \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}) \cdot (\vec{p}_{\bar{f}_2} \times \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}||\vec{p}_{\bar{f}_2} \times \vec{p}_{f_2}|} \equiv -\sin\phi \sin\theta_1$$

$$\mathcal{A}_2 = \frac{\Gamma(O_2 > 0) - \Gamma(O_2 < 0)}{\Gamma(O_2 > 0) + \Gamma(O_2 < 0)} \propto v_1 a_1 v_2 a_2$$

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 $\Re e(c)$ which does not have this suppression:

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

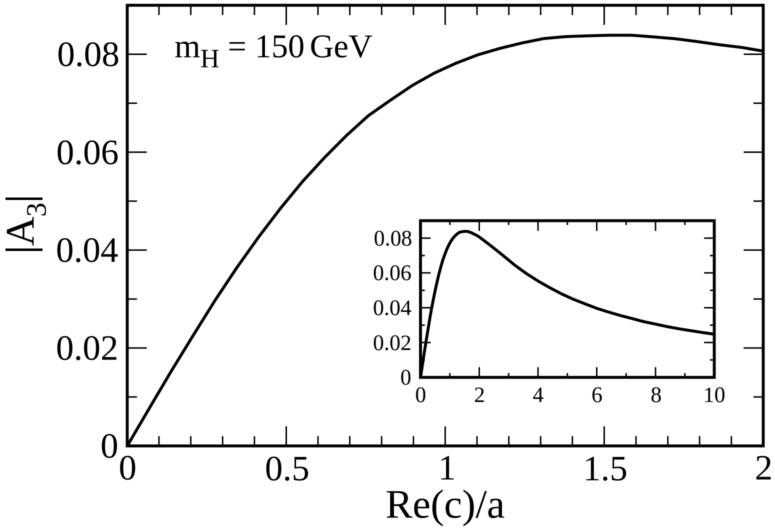
and

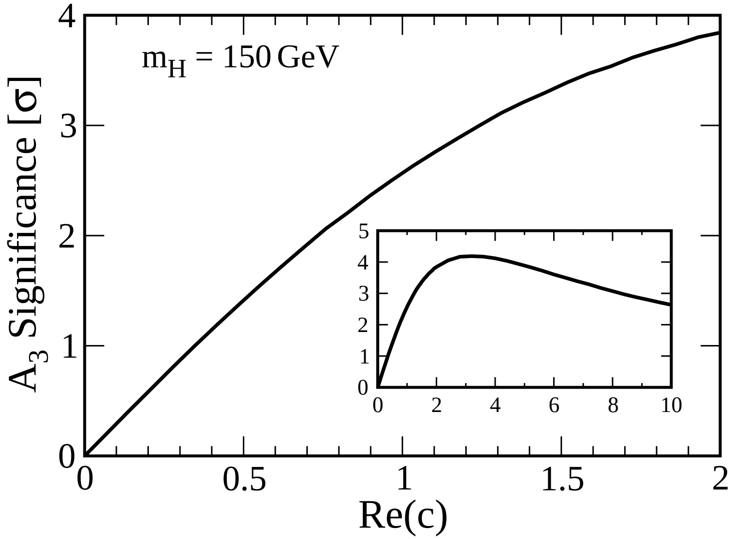
$$\mathcal{A}_3 = \frac{\Gamma(O_3 > 0) - \Gamma(O_3 < 0)}{\Gamma(O_3 > 0) + \Gamma(O_3 < 0)}.$$

We get,

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

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



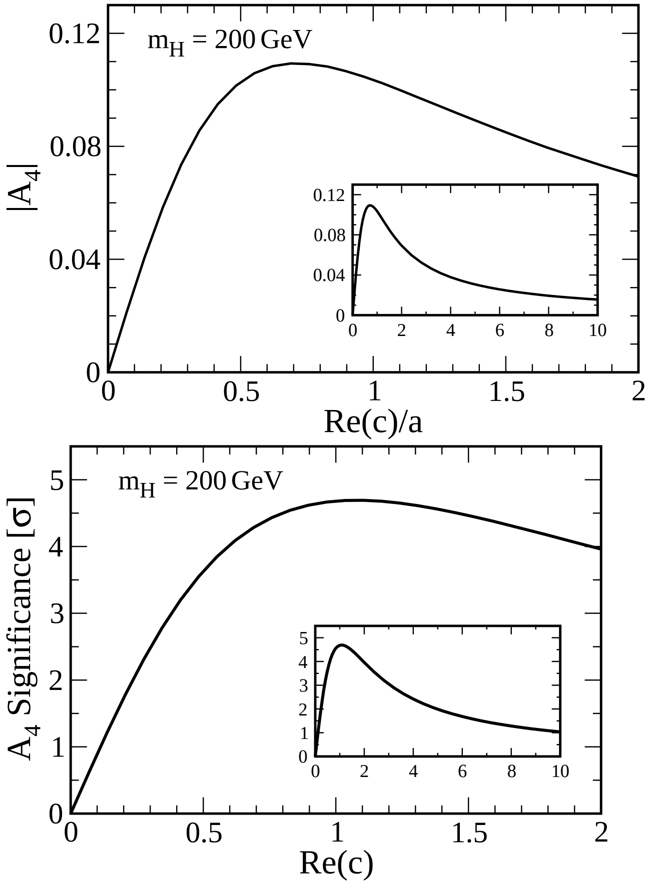


Expected signficance for 100 fb^{-1} not bad!

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

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

$$\mathcal{A}_5 = \frac{\Gamma(O_5 > 0) - \Gamma(O_5 < 0)}{\Gamma(O_5 > 0) + \Gamma(O_5 < 0)}$$

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	$\Re e(b)$	$\Im m(b)$	$\Re e(c)$	$\Im m(c)$
$\mathcal{A}_1$	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.

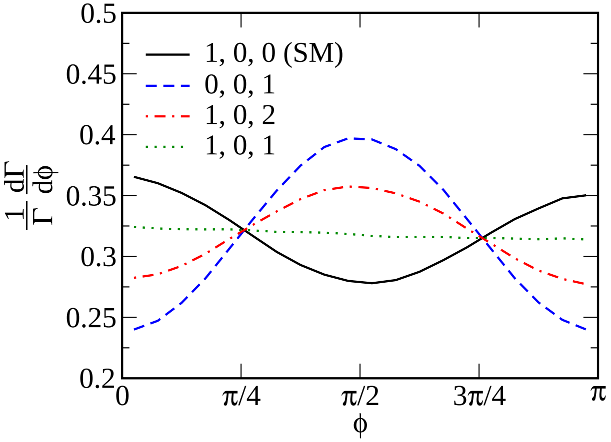
In the SM

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

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

For CP odd case:

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



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

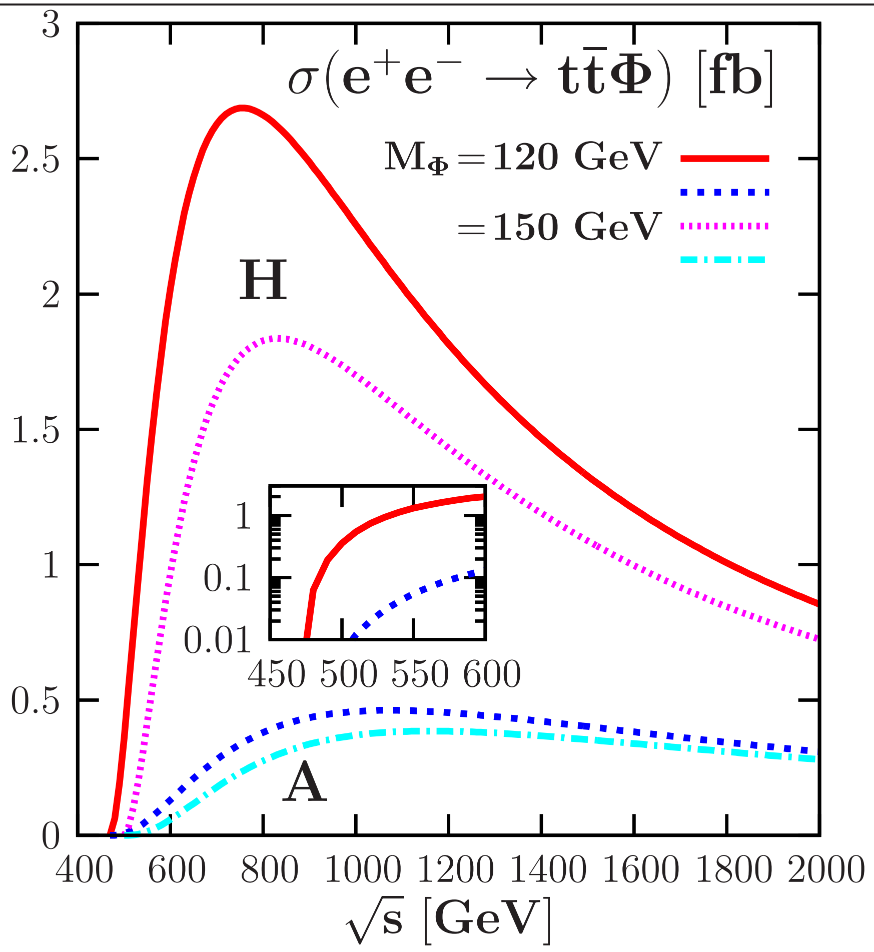
Same true for $gg \to \phi+$ 2 jets, QCD corrections ??? V. Del Duca, W. Kilgore, C. Oleari, C. R. Schmidt and D. Zeppenfeld [arXiv:hep-ph/0109147] K. Odagiri, JHEP **0303**, 009 (2003)

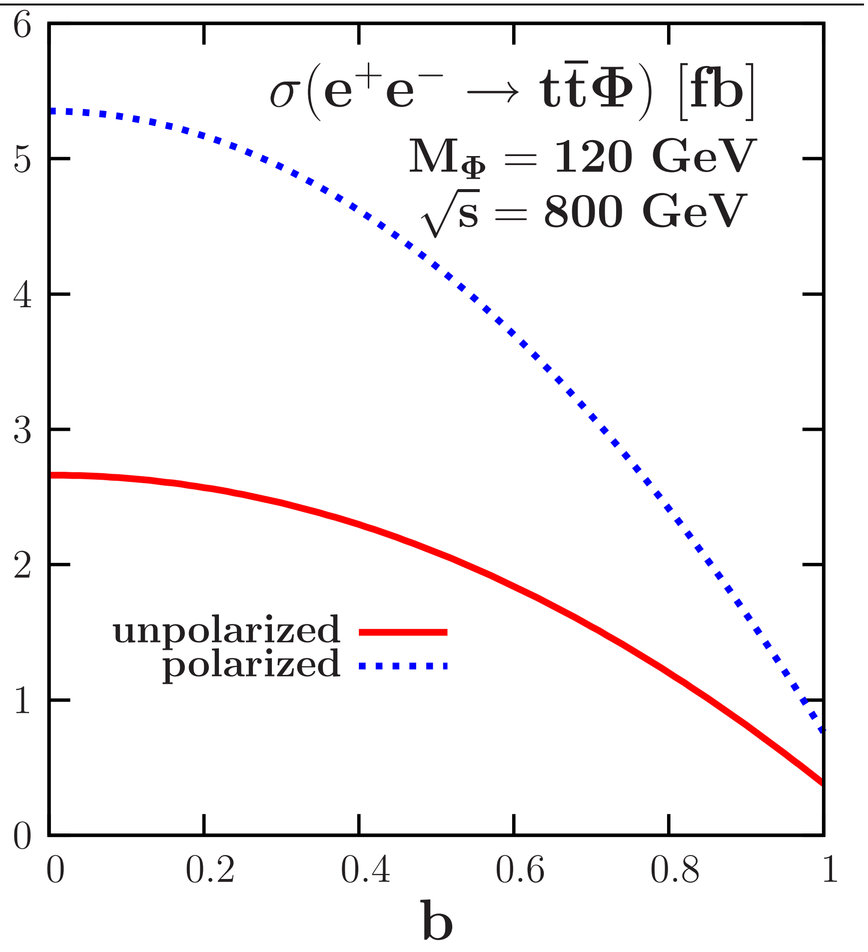
Warning: If we use ϕZZ coupling for production. it means for a pseudoscalar the strength is necessarily small as loops are involved. For a state of mixed CP, only the CP-even part gets projected out in production.

$t\bar{t}\phi$ 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!!!!!





$$b = p_t, a_t = \sqrt{(1 - p_t^2)} = \sqrt{(1 - b^2)}.$$

PRL08 : B. Dev. RG, A. Djouadi et al

Threshold dependence very different for scalar and pseudoscalar. Steep dependence (S vs P wave).

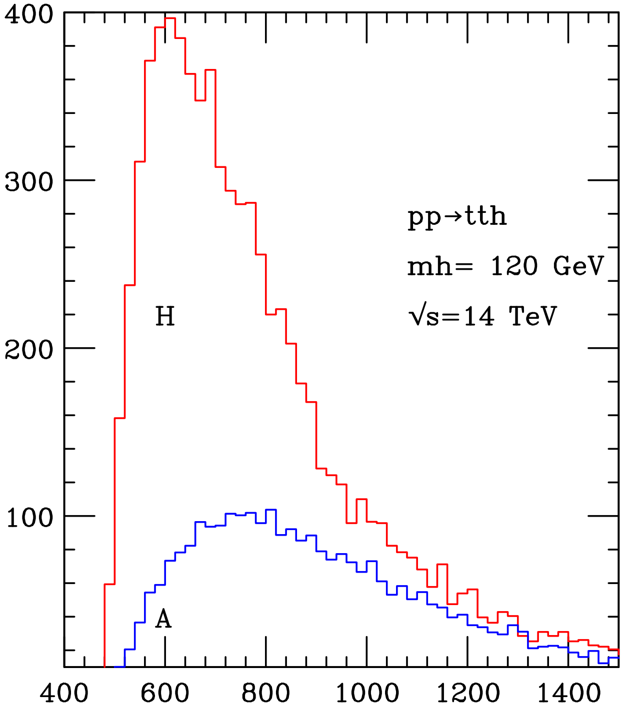
Define $\rho = 1 - 2m_t/\sqrt{s} - M_\Phi/\sqrt{s}$

$$F_1^H = -F_2^H \simeq 12\left[m_t^2/(M_H\sqrt{s})\right]^{3/2} \rho^2 \;\; F_1^A = -F_2^A \simeq 4\left[m_t^4/(M_A s\sqrt{s})\right]^{1/2} \rho^3.$$

May be just two measurements, at 500 and (say) 800, would see the difference. For $M_\phi = 120$ GeV, the ratios for H and A are 7.5 and 63, as $\sqrt{s}$ changes from 500 to 800 GeV. Recall: radiative corrections are also substantial. So taking ratios is a good idea.

What does it have to with LHC?

Interesting: The $pp \to t\bar{t}\phi$ shows the same behaviour!



Idea: can one use this feature to control the bkgd? The $b\bar{b}$ in the $t\bar{t}b\bar{b}$ QCd background is produced from a spin 1 gluon.

Djouadi, RG, Fabio Maltoni (in progress).

1) Clean variable to decide the CP at large luninosity

2)Perhaps use this feature to help clean up the signal?

Effects of CP violation in MSSM can affect Higgs sector nontrivially.

Due to mixing light Higgs may have escaped detection at LEP bound.

How to recover the ’lost’ reach of LHC for the Higgs in this case?

Effect of SUSY $\not{CP}$ on Higgs phenomenology

MSSM $\not{CP}$ phases $\Rightarrow$ $\not{CP}$ 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)

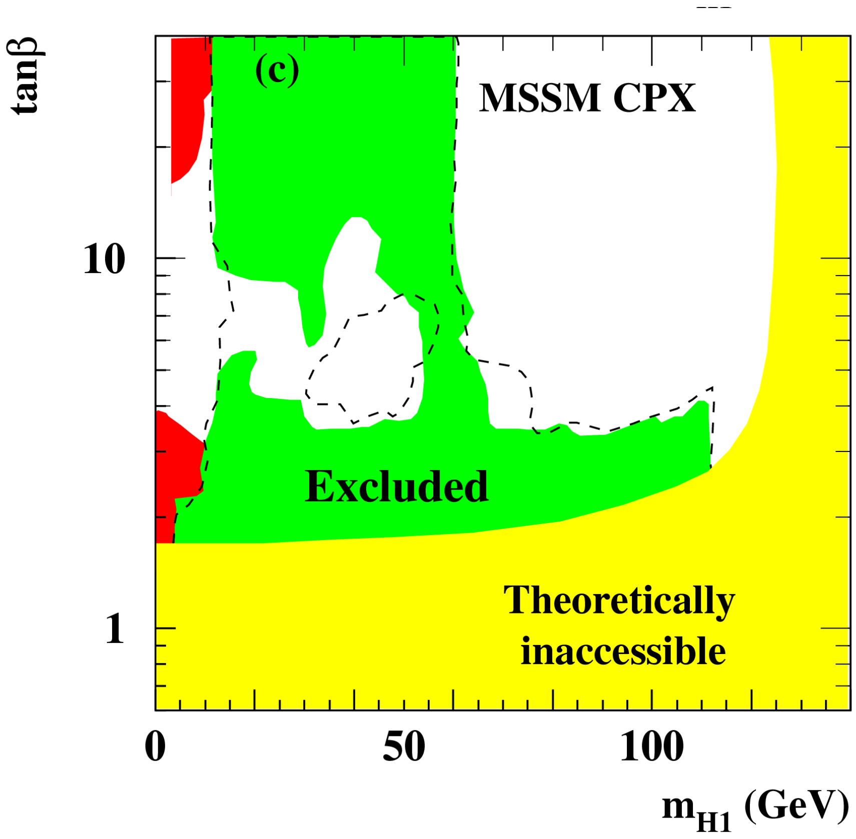
$$g^2_{\phi_i WW} + g^2_{\phi_j WW} + g^2_{\phi_k WW} = g^2 m^2_W, i \neq j \neq k$$

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 $\not{CP}$ phases in the MSSM for this mixing.

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



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

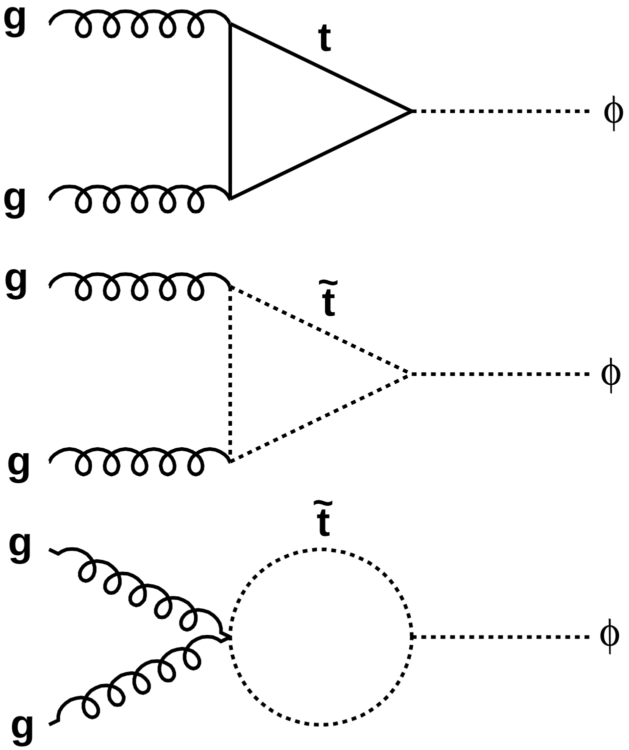
$$\Phi_\mu = 0$$

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

Even have gaps at 0–50 GeV!

$gg \to \phi$ cross-sections

[Dedes, Moretti, Nucl. Phys. B **576** (2000) 29
Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner, Comput. Phys. Commun. **156** (2004) 283]

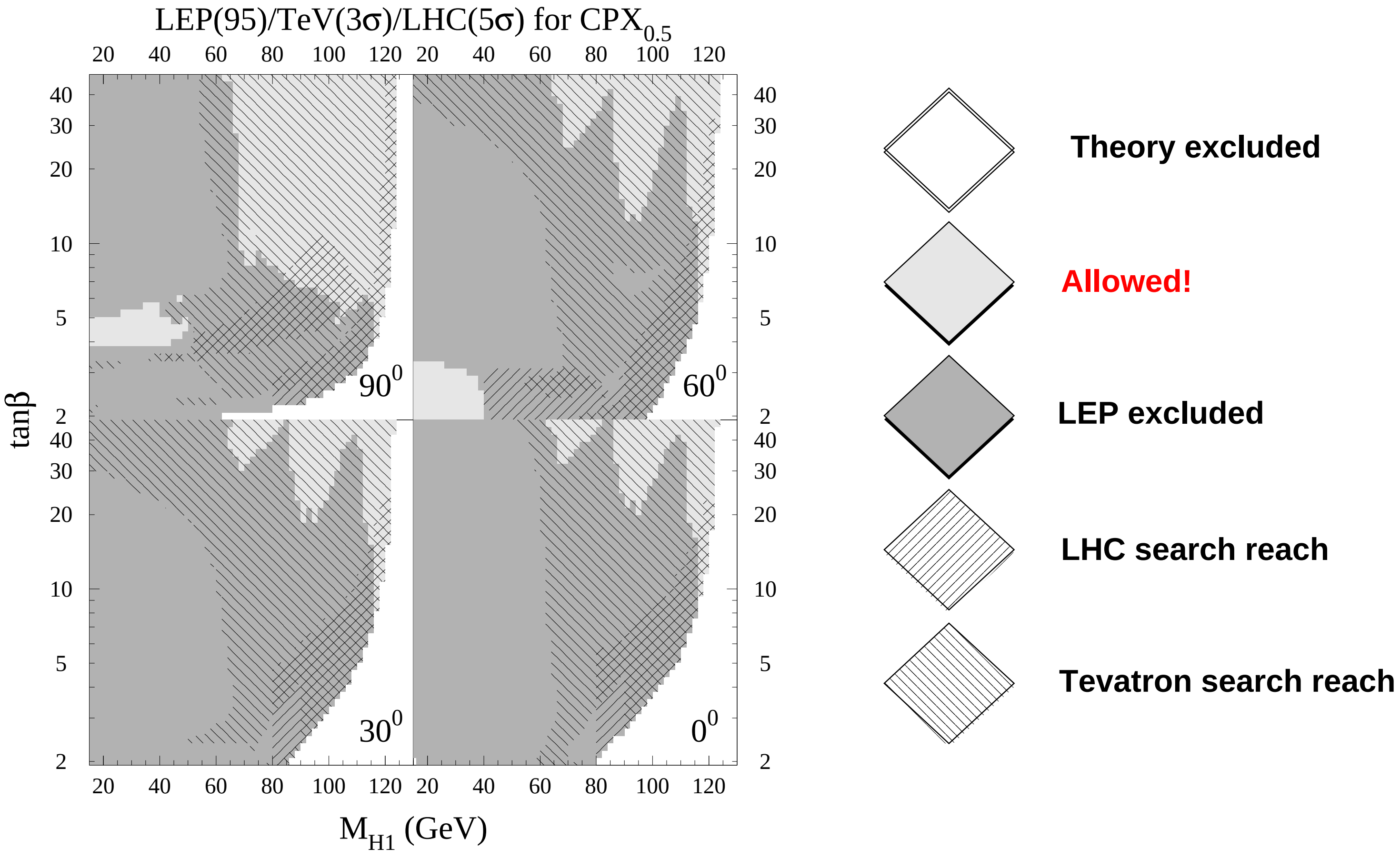


$$g_{h\tilde{t}_L\tilde{t}_R^*} = \frac{igm_t}{2M_W \sin\beta}(\mu^* \sin\alpha - A_t \cos\alpha)$$

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

LEP Allowed Window

[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

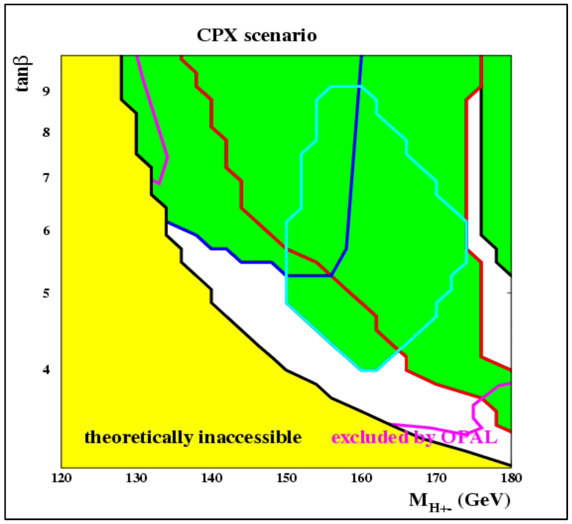
- Small regions in $\tan\beta, M_{H^+}$ plane where LHC,TEVATRON will have no reach

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

The higgs searches in $\not{C}\!P$ scenario need to be looked at carefully.

LEP Allowed Window

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.

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

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 $B.R.(H^+ \to \phi_1 W)$.

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 $B.R.(H^+ \to \phi_1 W)$

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

$\tan\beta$	3.6	4	5
Br($H^+ \to \phi_1 W^+$)(%)	$> 90(87.45)$	$> 90(57.65)$	$> 90(46.57)$
Br($t \to bH^+$)(%)	~ 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 ($H^\pm \to \phi_1 W > 47\%$ 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 $\not{C}\not{P}$ case.

Look at

$$\begin{array}{llllllll}
pp \to t & & & + & \bar{t} & + & X \\
\hookrightarrow b\,H^{+} & & & & \hookrightarrow \bar{b}\,W & & \\
& \hookrightarrow W & & H_1 & & \hookrightarrow q\bar{q}(\ell\nu) & \\
& & \hookrightarrow \ell\nu(q\bar{q}) & \hookrightarrow b\bar{b} & & &
\end{array}$$

Process allows a probe of a light $H^{\pm}$ **and** light neutral Higgs.

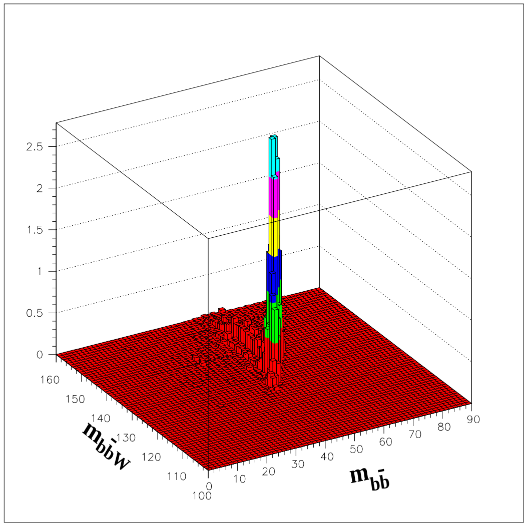
Use $t\bar{t}$ production with :

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

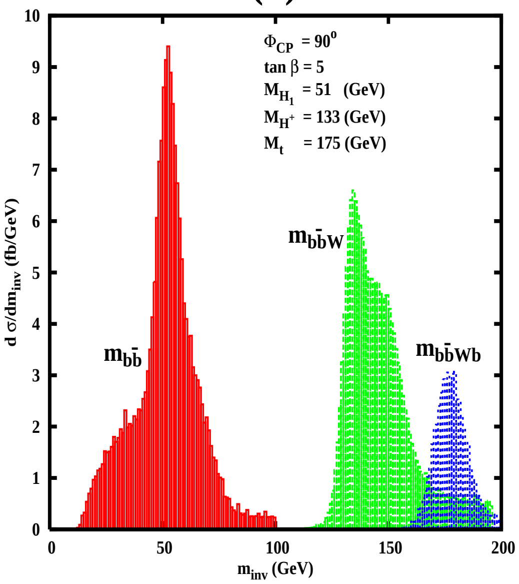
Look at the $WWbbbb$ events, demand three tagged $b's$.

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

(a)



(b)



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.

The QCD bkgd can be removed by demanding that bbbW 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 unambiguiously. More theoretical and experimental work needed on the subject!

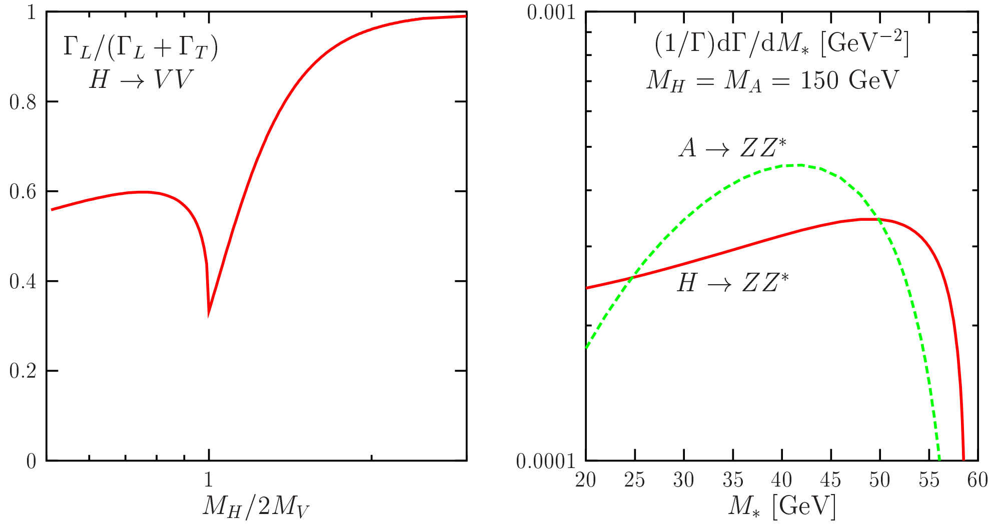
♢ For a light higgs, $m_\phi \sim 120$ GeV the the difference in the behaviour of $\sigma(t\bar{t}\phi)$ with energy for $\phi = H/A$ may be used to some effect to reduce signal/bkgd .

♢ CP violation in MSSM 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 $\not{C}\not{P}$ scenarios in SUSY-Higgs sector still need to be standardised.

Backup Slides



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

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

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

$$\begin{aligned}\Gamma_{H\to ZZ} \;=\; & \frac{G_F m_H^3}{16\sqrt{2}\pi}\,\beta\left\{a^2\left[\beta^2+\frac{12 m_1^2 m_2^2}{m_H^4}\right]+|b|^2\frac{m_H^4}{m_Z^4}\,\frac{\beta^4}{4}+|c|^2 x^2\, 8\beta^2\right.\\ & \left. + a\Re e(b)\frac{m_H^2}{m_Z^2}\,\beta^2\,\sqrt{\beta^2+4m_1^2 m_2^2/m_H^4}\right\} \qquad (1)\end{aligned}$$

and $\Gamma_{Z\to f_i\bar{f}_i}$ is the width for the decay of a Z boson to a fermion pair, $f_i\bar{f}_i$, as given in the SM,

$$\Gamma_{Z\to f_i\bar{f}_i}=\frac{G_F m_Z^2}{6\sqrt{2}\pi}\,m_Z\,(v_{f_i}^2+a_{f_i}^2)\;. \qquad (2)$$

$$
\begin{aligned}
\frac{d^3\Gamma}{dc_{\theta_1}\,dc_{\theta_2}d\phi} \;\sim\;& a^2\Bigg[s_{\theta_1}^2 s_{\theta_2}^2 - \frac{1}{2\gamma_a} s_{2\theta_1} s_{2\theta_2} c_\phi + \frac{1}{2\gamma_a^2}\Big[(1+c_{\theta_1}^2)(1+c_{\theta_2}^2) + s_{\theta_1}^2 s_{\theta_2}^2 c_{2\phi} \\
&\qquad - \frac{2\eta_1\eta_2}{\gamma_a}\left(s_{\theta_1} s_{\theta_2} c_\phi - \frac{1}{\gamma_a} c_{\theta_1} c_{\theta_2}\right)\Bigg] \\
&+\; |b|^2 \frac{\gamma_b^4}{\gamma_a^2}\, x^2\, s_{\theta_1}^2 s_{\theta_2}^2 \\
&+\; |c|^2 \frac{\gamma_b^2}{\gamma_a^2}\, 4x^2\, \Big[1 + c_{\theta_1}^2 c_{\theta_2}^2 - \frac{1}{2} s_{\theta_1}^2 s_{\theta_2}^2 (1 + c_{2\phi}) + 2\eta_1\eta_2 c_{\theta_1} c_{\theta_2}\Big] \\
&-\; 2a\Im m(b) \frac{\gamma_b^2}{\gamma_a^2}\, x\, s_{\theta_1} s_{\theta_2} s_\phi \Big[\eta_2 c_{\theta_1} + \eta_1 c_{\theta_2}\Big] \\
&-\; 2a\Re e(b) \frac{\gamma_b^2}{\gamma_a^2}\, x\, \Big[-\gamma_a s_{\theta_1}^2 s_{\theta_2}^2 + \frac{1}{4} s_{2\theta_1} s_{2\theta_2} c_\phi + \eta_1\eta_2 s_{\theta_1} s_{\theta_2} c_\phi\Big] \\
&-\; 2a\Im m(c) \frac{\gamma_b}{\gamma_a}\, 2x\, \Bigg[- s_{\theta_1} s_{\theta_2} c_\phi (\eta_1 c_{\theta_2} + \eta_2 c_{\theta_1})
\end{aligned}
$$

$$
\begin{aligned}
&\qquad\qquad\qquad + \frac{1}{\gamma_a}\left(\eta_1 c_{\theta_1}(1+c^2_{\theta_2}) + \eta_2 c_{\theta_2}(1+c^2_{\theta_1})\right)\Bigg] \\
- &\;\; 2a\Re e(c)\frac{\gamma_b}{\gamma_a}\,2x\, s_{\theta_1}s_{\theta_2}s_{\phi}\left[-c_{\theta_1}c_{\theta_2} + \frac{s_{\theta_1}s_{\theta_2}c_{\phi}}{\gamma_a} - \eta_1\eta_2\right] \\
+ &\;\; 2\Im m(b^*c)\frac{\gamma_b^3}{\gamma_a^2}\,2x^2\, s_{\theta_1}s_{\theta_2}c_{\phi}\left[\eta_2 c_{\theta_1} + \eta_1 c_{\theta_2}\right] \\
+ &\;\; 2\Re e(b^*c)\frac{\gamma_b^3}{\gamma_a^2}\,2x^2\, s_{\theta_1}s_{\theta_2}s_{\phi}\left[c_{\theta_1}c_{\theta_2} + \eta_1\eta_2\right]\ ,
\end{aligned}
$$

(3

The CPX Scenario

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

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

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

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

Allow the following parameters to vary:

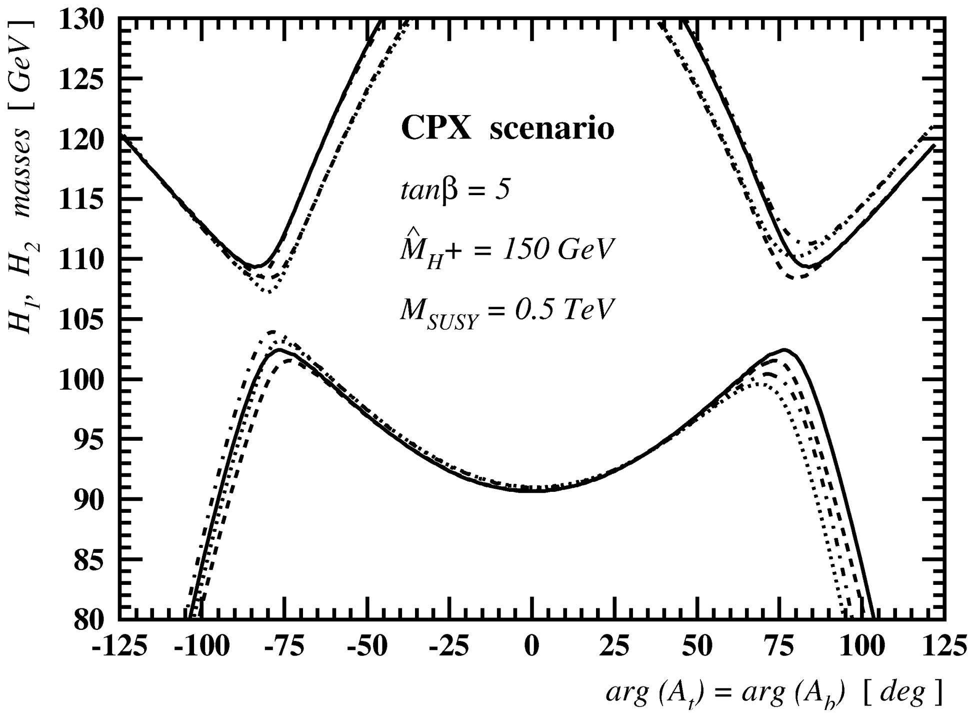
$$\boxed{\begin{array}{ccc} \tan\beta, & M_{H^\pm}, & M_{\mathsf{SuSy}}, \\ \{\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}\}, & \Phi_3, & \Phi_\mu \end{array}}$$

Masses and couplings

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

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

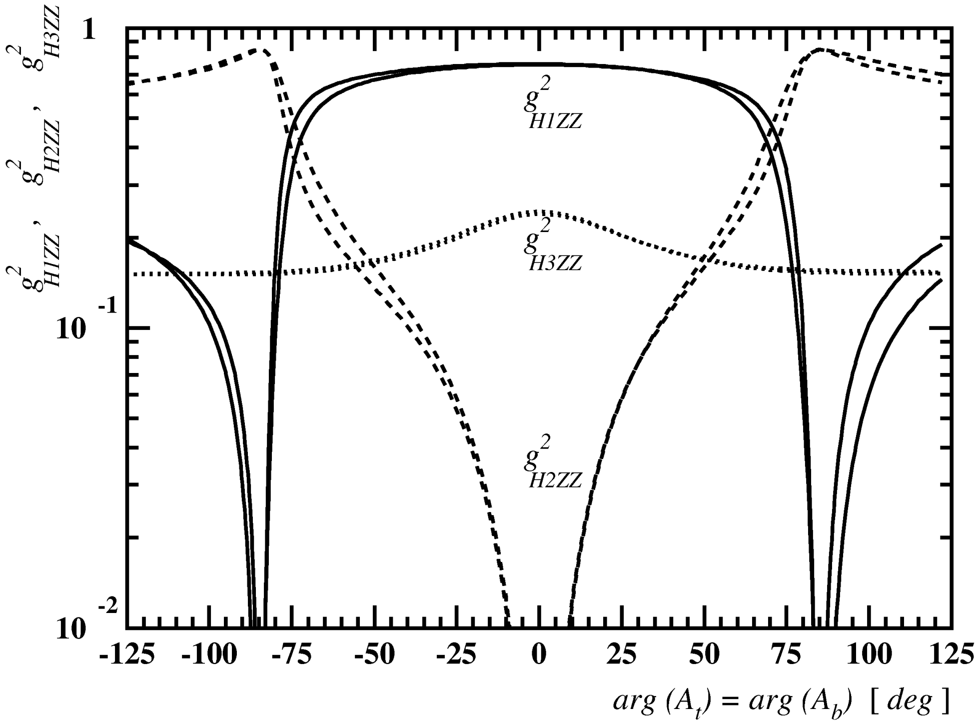
masses:



$M_{H_3} \sim 150$ GeV

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

couplings to VV:

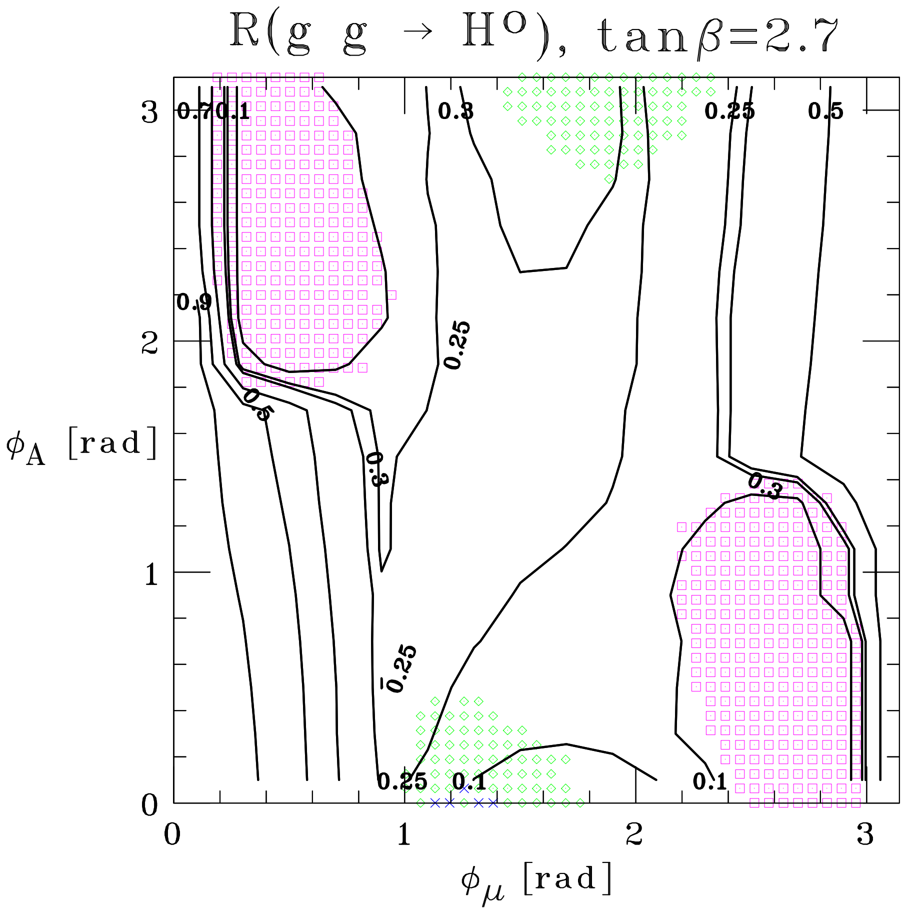


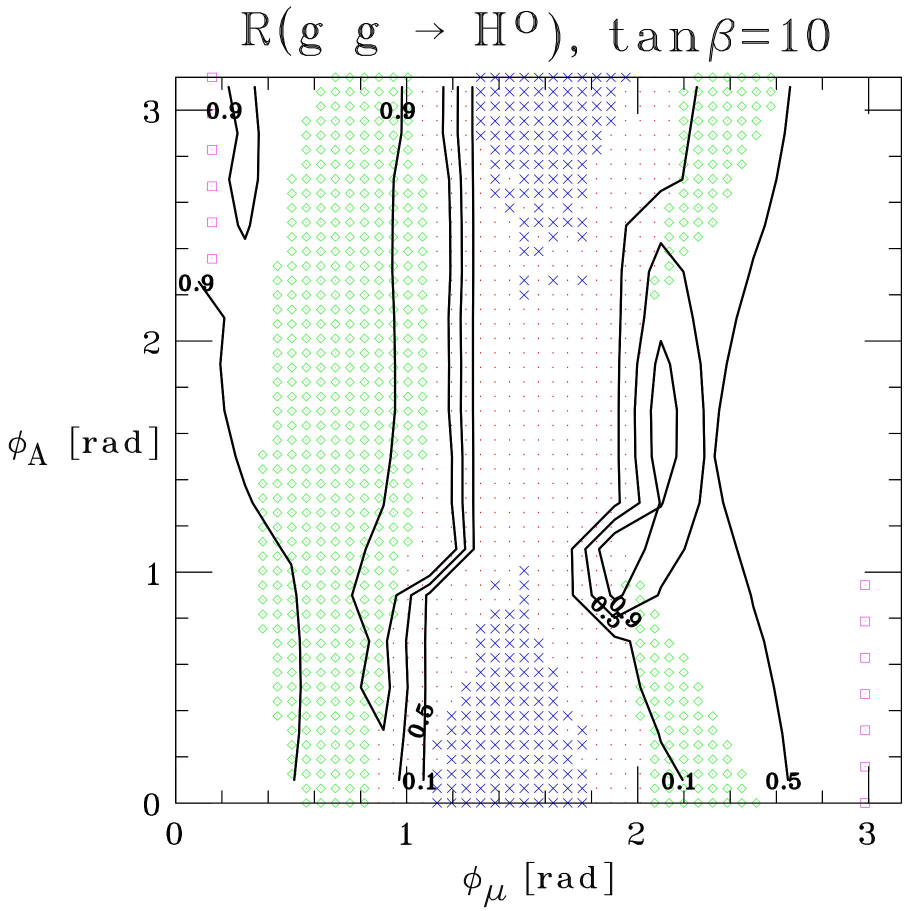
Sum rule for couplings

$$\boxed{\sum_{i=1}^{3} g^2_{\phi_i VV} = g^2_{\phi_i VV\,(SM)}}$$

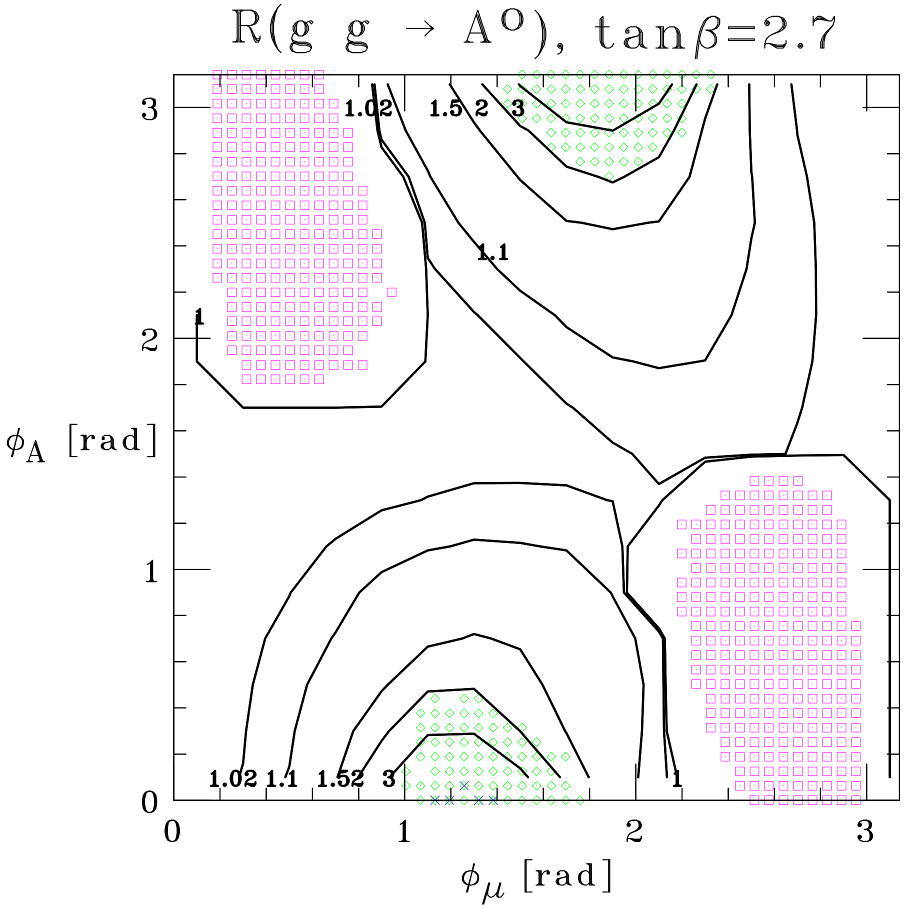
Often $g_{\phi_i ZZ}$ vanishes!

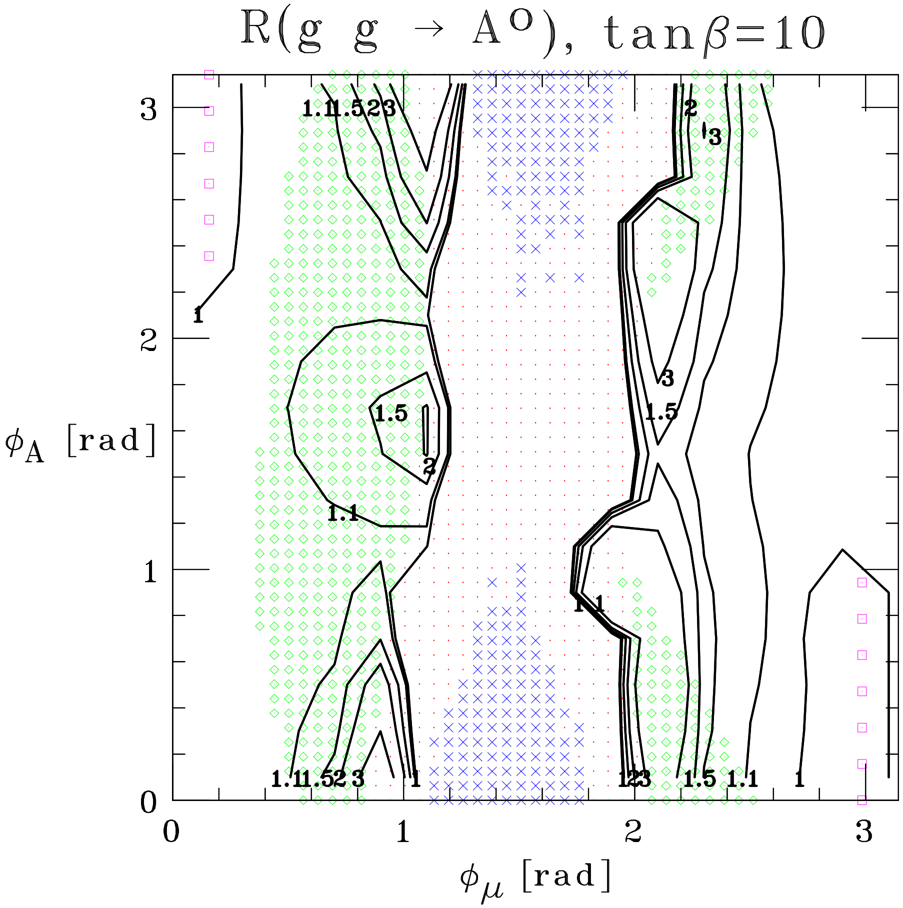
$\Rightarrow$ light Higgs may have escaped LEP limits





$gg \to H$ decreases (as expected from coupling sum rules)





$gg \to A$ doesn't change much

Electric Dipole Moments

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

Φ_μ and Φ_{A_f} are constrained by experimental limits of the EDMs of electron and neutron:

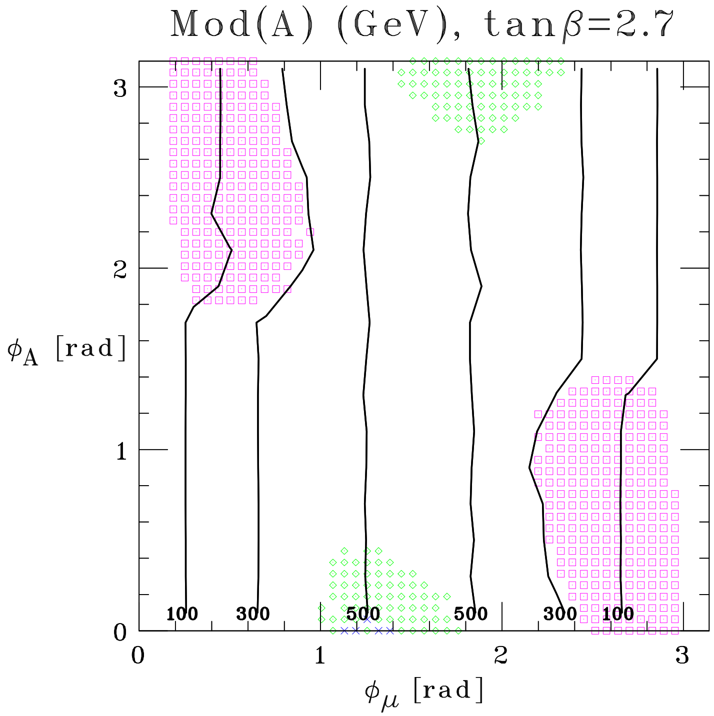
$$|d_e|_{\text{exp}} \leq 4.3 \times 10^{-27} e\,\text{cm} \qquad |d_n|_{\text{exp}} \leq 6.3 \times 10^{-26} e\,\text{cm}$$

e.g. at leading order:

$$\begin{aligned} \tan\beta &= 2.7 \\ |\mu| &= 600\text{GeV} \\ M_{\tilde{q}_{1,2}} &= 1000\text{GeV} \\ M_{\tilde{q}_3} &= 300\text{GeV} \\ M_{\tilde{g}} &= 300\text{GeV} \\ M_A &= 200\text{GeV} \end{aligned}$$

shaded areas excluded

Require $|A| >$ contour

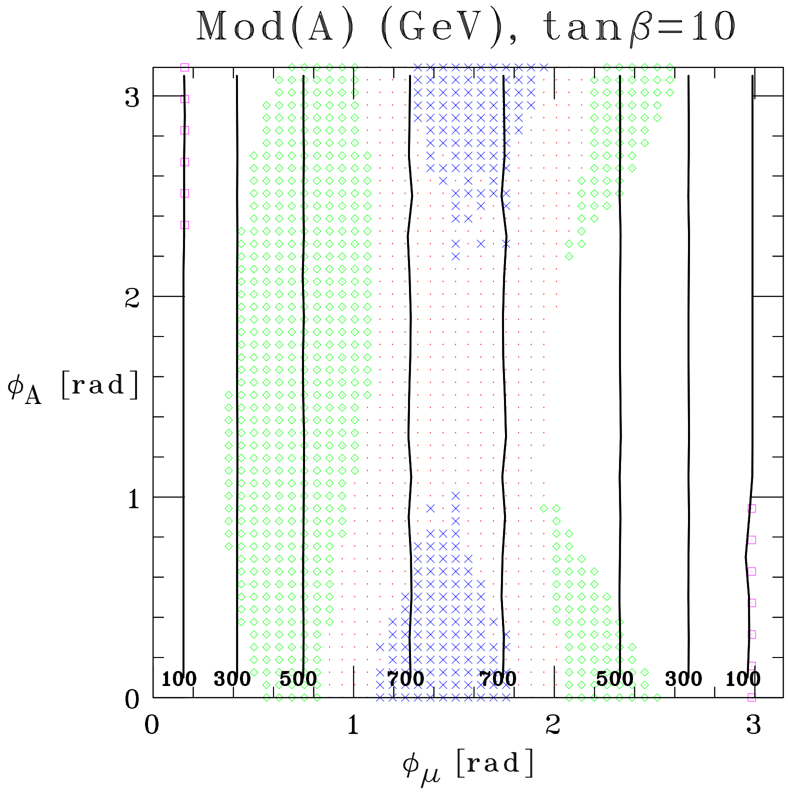


Higher $\tan\beta$ more difficult

$$\begin{aligned} \tan\beta &= 10 \\ |\mu| &= 600\text{GeV} \\ M_{\tilde{q}_{1,2}} &= 300\text{GeV} \\ M_{\tilde{q}_3} &= 300\text{GeV} \\ M_{\tilde{g}} &= 300\text{GeV} \\ M_A &= 200\text{GeV} \end{aligned}$$

shaded areas excluded

Require $|A| >$ contour



Much of the allowed region depends on accidental SuSy cancellations (fine tuning?)

Phenomenology of $\not{C}\not{P}$ violating MSSM at colliders.

Which phases can be large?

- $|\mu|, |A_f|$ and any two of the three gaugino masses M_1, M_2, M_3.
- Phases in the sfermion sector can also be non-zero.

♢ What can the phases do?

- They can affect the couplings, masses of the sparticles, affect CP-even variables the rates of production, decay widths, branching ratios.
- CP odd observables constructed out of final state decay products will have non-zero value

Exhaustive discussion for the e^+e^- case for the $\tilde{\chi}^\pm, \tilde{\chi}_0$ and the sfermions, charged Higgses.

Choi et al 98,00,01,03,04,Kneur99, Barger 01, Bartl et al 02,03, Christova + Kraml 02, RG + Kraml + Gadosijk