CP violation in Supersymmetry,Higgs sector and the LHC.

- ♢ Introduction.
- ♢ Effects on CP violation on $\tilde{\chi}^{\pm}, \tilde{\chi}_2^0$ sector and the LHC.
- ♢ CP mixing induced in the Higgs sector due to CP violation in soft SUSY breaking parameters.
- ♢ Plugging the 'hole' in tan β–M_{H^+} plane at low neutral Higgs masses, ($\sim 10 - 50$)GeV through the charged Higgs decay at the LHC.
- ♢ Determination of CP of a Higgs at LHC,ILC and a $\gamma\gamma$ collider.
- ♢ Conclusions and & Summary.

Introduction

Why CP violation in SUSY?

Why study $\not{C}\not{P}$

The phenomenon still lacks a fundamental understanding

- CKM description vindicated by measurements of CP mixing in the B_0 sector.
- CKM $\not{C}\not{P}$ **not** sufficient to explain **quantitatively** why

$$\frac{N_b}{N_\gamma} \sim 6.1 \times 10^{-10} \qquad \frac{N_{\bar{b}}}{N_\gamma} \sim 0 \qquad (1)$$

- Sources of CP violation beyond the CKM?

$\not{CP}$ and SUSY

CP violation in SUSY: Ugly Duckling to Swan !

Large # (44 to be precise) of phases of the SUSY parameters $e.g. \mu, A_f, M_i, i = 1,3$ **can not** be rotated away by a simple redefinition of the fields.

Older days:

These generate unacceptably large electric dipole moments for fermions. Fine tune all the $\not{CP}$ phases in SUSY to zero.

Now:

Ibrahim et al 97,Brhlik et al 98,Bartl et al 99,Falk et al 98,99

It is possible for some combination of phases to be O (1) and yet satisfy *all* the constraints on EDM's provided the first two generation of squarks are heavy.

Why does that make $\not{CP}$ in MSSM a Swan?

A few more things about $\not{C}\not{P}$:

1. $\not{C}\not{P}$ in the Higgs sector is a theoretically attractive source of the additional $\not{C}\not{P}$ required to explain the Barayon Asymmetry in the Universe.

2. $\not{C}\not{P}$ posible only in Multi-Higgs models, of which SUSY is one example.

3. $\not{C}\not{P}$ in the MSSM, large number of available phases, possible to satisfy *all* the constraints and still have enough $\not{C}\not{P}$ to help Baryogenesis.

4. The MSSM $\not{C}\not{P}$ phases induce CP mixing in the Higgs sector (which has no CP mixing at the tree level) of the MSSM through loop effects Pilaftsis 98,Choi et al 00, Carena et al 00

5. CP mixing in the Higgs sector, one way for $\not{C}\not{P}$ in SUSY to manifest itself: can affect production rates at LHC as well. Dedes et al 99,Choi et al 01

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

Which phases can be large?

- $|\mu|, |A_f|$ and $|M_i|, i = 1, 2$.

♢ Can give rise to nonzero phases in the $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ sector.

- 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

Very often the CP-even variables, precision measurables, at $e^{+}e^{-}$ colliders offer a better probe of phases due to the larger size of the effects.

Hadronic Colliders? $\tilde{\chi}$ systems

♢ CP violating phases can change the dilepton invariant mass distribution.

— Effect on phenomenology of cascade decay.

— Can afford information on phase if *all* the SUSY parameters are known.

♢ For a $\bar{p}p$ possible to construct CP-odd quantities, for $\tilde{\chi}_{\pm}, \tilde{\chi}_0$ system. Guchait, Choi et al, 0007276,9904276, Kane et al, 99. Studied trilepton signal from $p\bar{p} \to \tilde{\chi}_2^0 \chi_1^{\pm}$.

♢ Effects on

- $\sigma(p\bar{p} \to \tilde{\chi}_1^- \tilde{\chi}_2^0)$
- $\mathcal{B}(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \nu)$, $\mathcal{B}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$

T-odd/CP-odd triple products

♢ For the $\bar{p}p$ case possible to construct T-odd variables using initial (anti)proton direction:

$$\mathcal{O}_T = \vec{p}_{_{\ell_1}} \cdot (\vec{p}_{_{\ell_3}} \times \vec{p}_{_{\ell_4}}),$$

$\ell_1 = \ell^-$ of the chargino decay $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \, \ell^- \bar{\nu}_\ell$, and $\ell_3 = \ell'^-$, $\ell_4 = \ell'^+$ of the neutralino decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \, \ell'^- \ell'^+$.

$$\mathcal{O}_T^{\ell\ell'} = \vec{p}_p \cdot (\vec{p}_\ell \times \vec{p}_{\ell'})$$

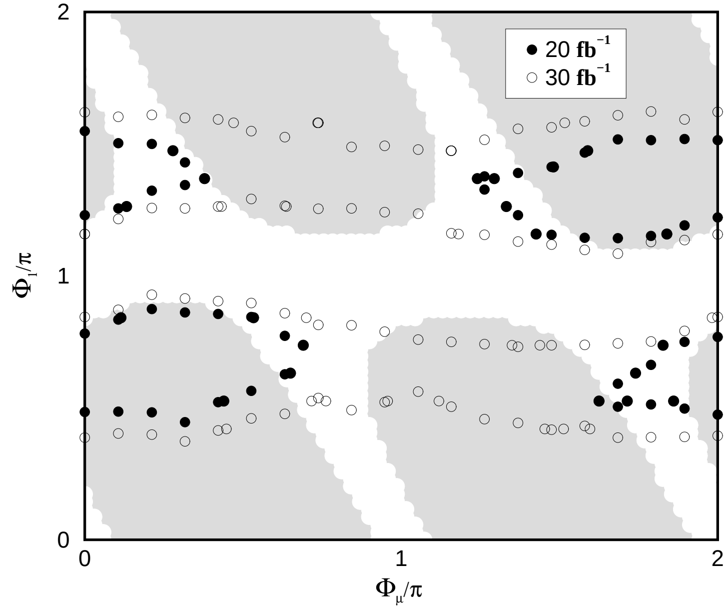
$\{\ell, \ell'\}$:any combination of two momenta among the three final lepton momenta.

The shaded areas ruled out by EDM constraints.

Contours show regions that can be probed at 5σ level, for a given luminosity.

Thus Tevatron can probe CP violation in the MSSM through such studies.

EDM constraints have been imposed on the SUSY phases.



What about LHC?

At the LHC the initial state is *not* a CP eigenstate.

So far *no studies* exist how one can use the $\tilde{\chi}$ sector to probe the $\not{C}\not{P}$ phases at the LHC.

Investigations to estimate the effect of these phases, on the studies using ,say, cascade decays at the LHC needed.

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 CP-even A CP-odd

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

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

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.

Three types of effects on Higgs production rates

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

II] $\not{CP}$ 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)....

III] Effects on the couplings with b

Enhanced production cross-sections through b-fusion: hep-ph 0401024, F. Borzmuati, J.S. Lee and W. Y. Song

A few details of the mixing.

General two-Higgs-doublet Model:

Two complex $Y = 1$, $SU(2)_L$ doublet scalar fields, Φ_1 and Φ_2

Most general Higgs potential is:

$$\begin{aligned} V &= {m_{11}}^2\Phi_1^\dagger\Phi_1 + {m_{22}}^2\Phi_2^\dagger\Phi_2 - [{m_{12}}^2\Phi_1^\dagger\Phi_2 + h.c.] \\ &+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + h.c.\right\} \end{aligned}$$

$$\text{Unitarity} \Rightarrow V \in \Re \Rightarrow \begin{cases} \{m_{11}, m_{22}, \lambda_{1-4}\} \in \Re \\ \{m_{12}, \lambda_{5-7}\} \in \mathcal{C} \end{cases}$$

Notice that with one Higgs doublet, we can have no CP violation.

MSSM:

Higgs potential as 2HDM above with

$$
\begin{array}{ll}
m_{11}^2 = -m_1^2 - |\mu|^2 & \lambda_1 = \lambda_2 = -(g^2 + g^{'2})/8 \\
m_{22}^2 = -m_2^2 - |\mu|^2 & \lambda_3 = -(g^2 - g^{'2})/4 \\
m_{12}^2 = \mu B & \lambda_4 = g^2/2 \\
 & \lambda_5 = \lambda_6 = \lambda_7 = 0
\end{array}
$$

Vacuum expectation values:

$$
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} e^{i\xi} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

At tree-level:

Minimisation conditions $\Rightarrow \arg(m_{12}^2 e^{i\xi}) = 0$

Rotate phase away with an appropriate choice of Φ_2

$$\boxed{\Phi_2 \to e^{-i\xi}\Phi_2 \Rightarrow \arg(m_{12}) = 0}$$

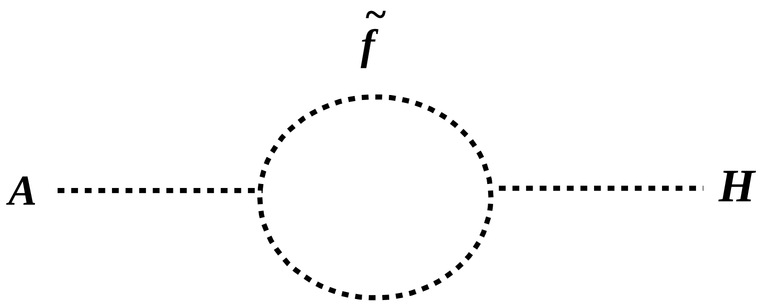
No CP-violation in tree-level Higgs sector

Higgs bosons are CP-eigenstates

At one-loop:

Now have $\arg(m_{12}^2 e^{i\xi}) \neq 0$

Potentially have CP-violation from soft-susy breaking terms $A_{t,b,\tau}$, M_3



$$\propto \frac{m_f^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \Im m(A_f \mu)$$

write $A_f = |A_f| e^{i\Phi_{A_f}}$, $M_3 = |M_3| e^{i\Phi_3}$ and $\mu = |\mu| e^{i\Phi_\mu}$

CP-violation parameterised by $\{\Phi_{A_f}, \Phi_3, \Phi_\mu\}$

Higgs bosons are NOT CP-eigenstates

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:

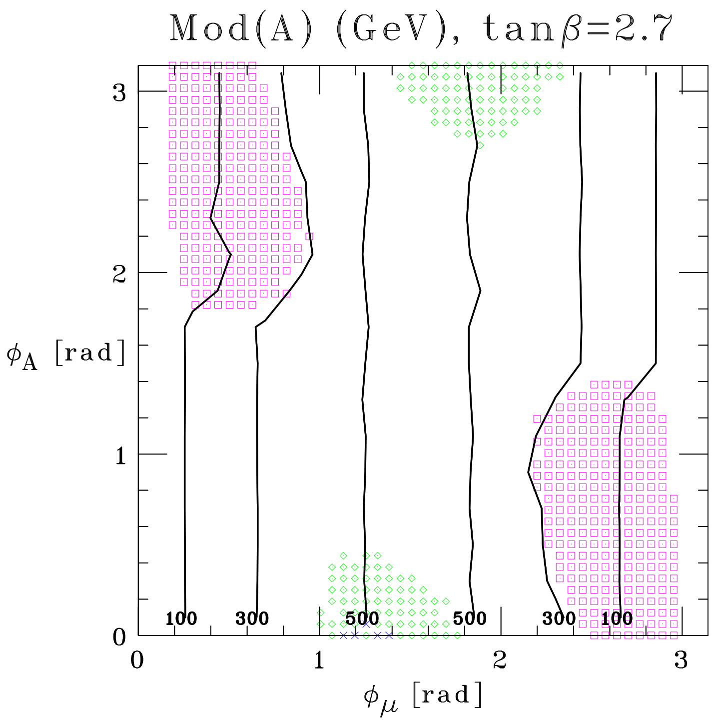
$$|d_e|_{\text{exp}} \leq 4.3 \times 10^{-27} e\,\text{cm} \qquad |d_n|_{\text{exp}} \leq 6.3 \times 10^{-26} e\,\text{cm}$$

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

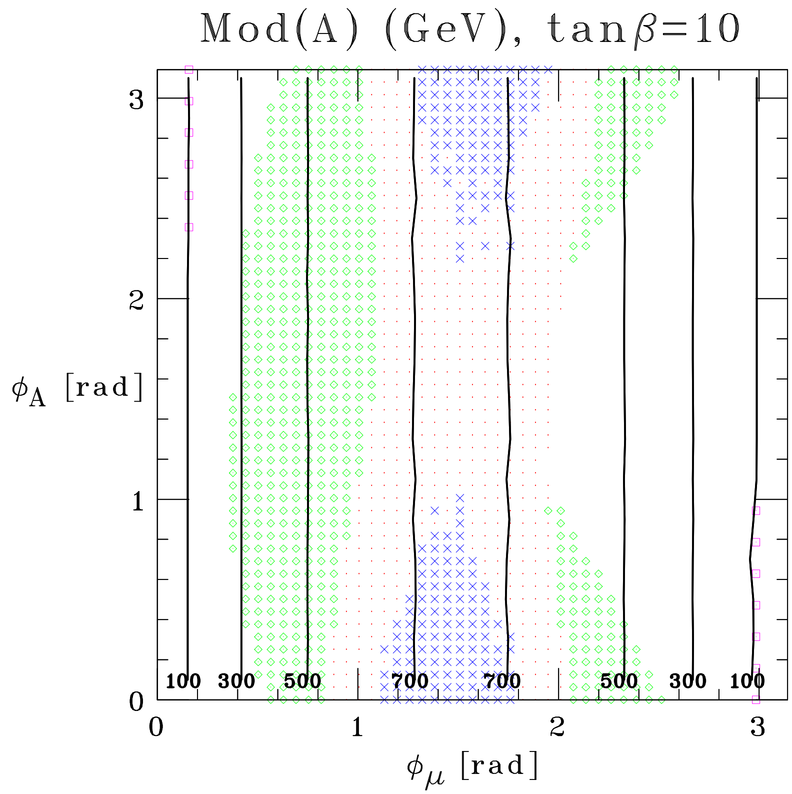


Higher $\tan\beta$ more difficult

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

shaded areas excluded

Require $|A| >$ contour



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

The CPX Scenario

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

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

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

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

Allow the following parameters to vary:

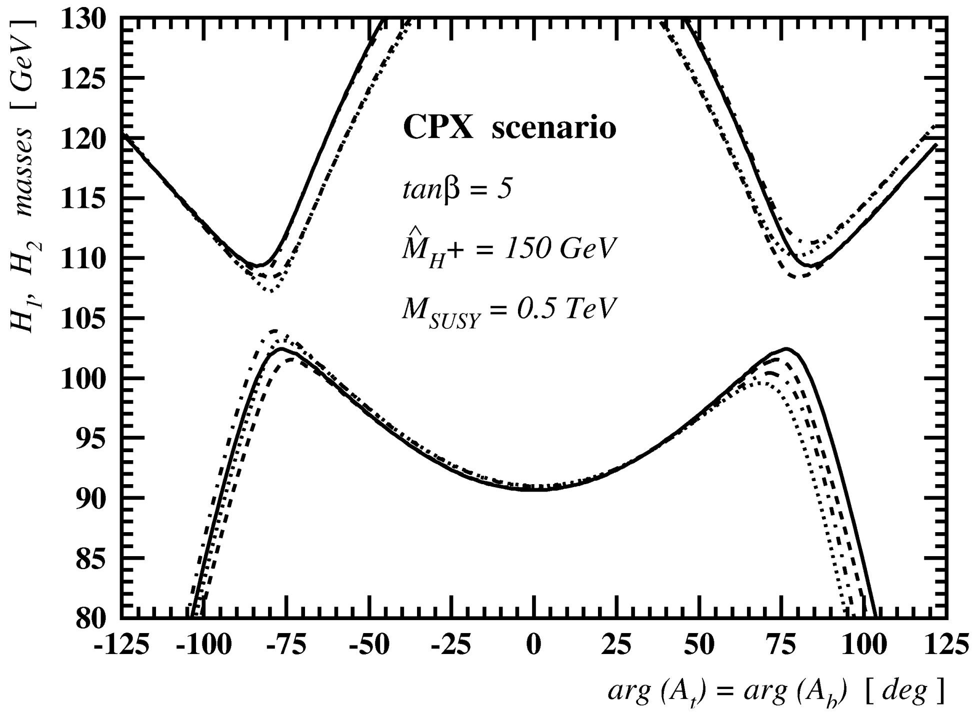
$$\tan\beta, \quad M_{H^\pm}, \quad M_{\mathrm{SuSy}},$$

$$\{\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}\}, \quad \Phi_3, \quad \Phi_\mu$$

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

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

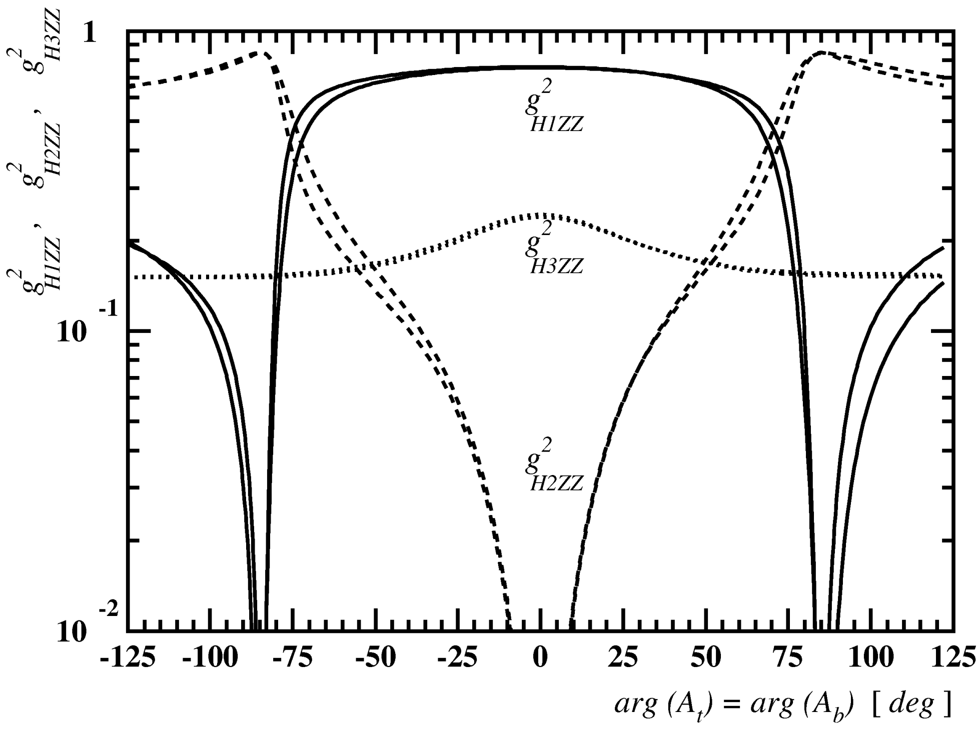
masses:



$M_{H_3} \sim 150$ GeV

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

couplings to VV:



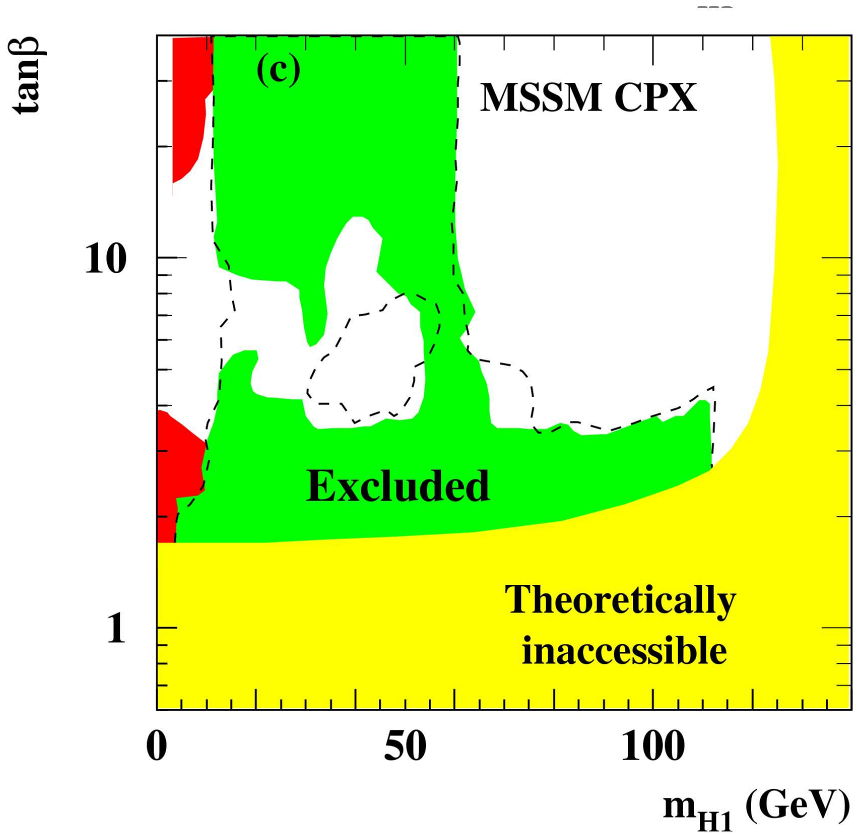
Sum rule for couplings

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

Often $g_{\phi_i ZZ}$ vanishes!

$\Rightarrow$ light Higgs may have escaped LEP limits

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



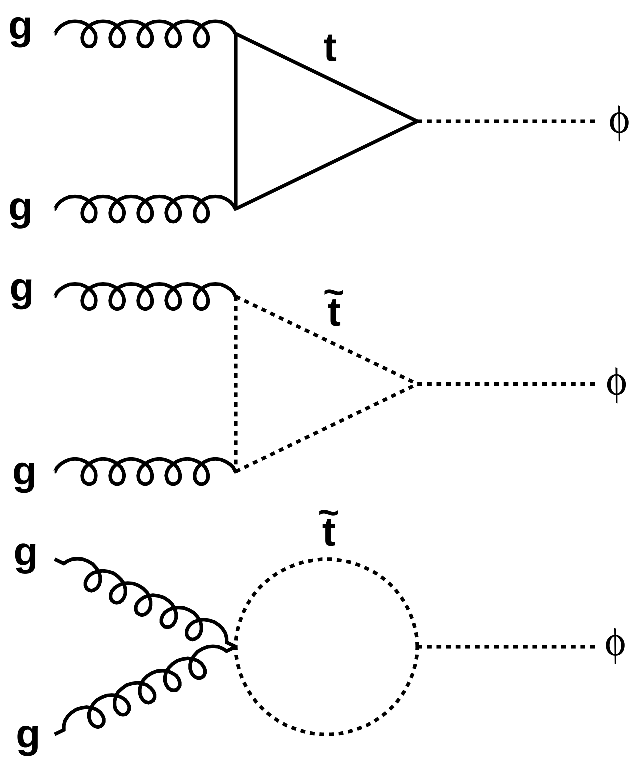
$$\Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau} = \Phi_{\tilde{g}} = \frac{\pi}{2}$$

$$\Phi_\mu = 0$$

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

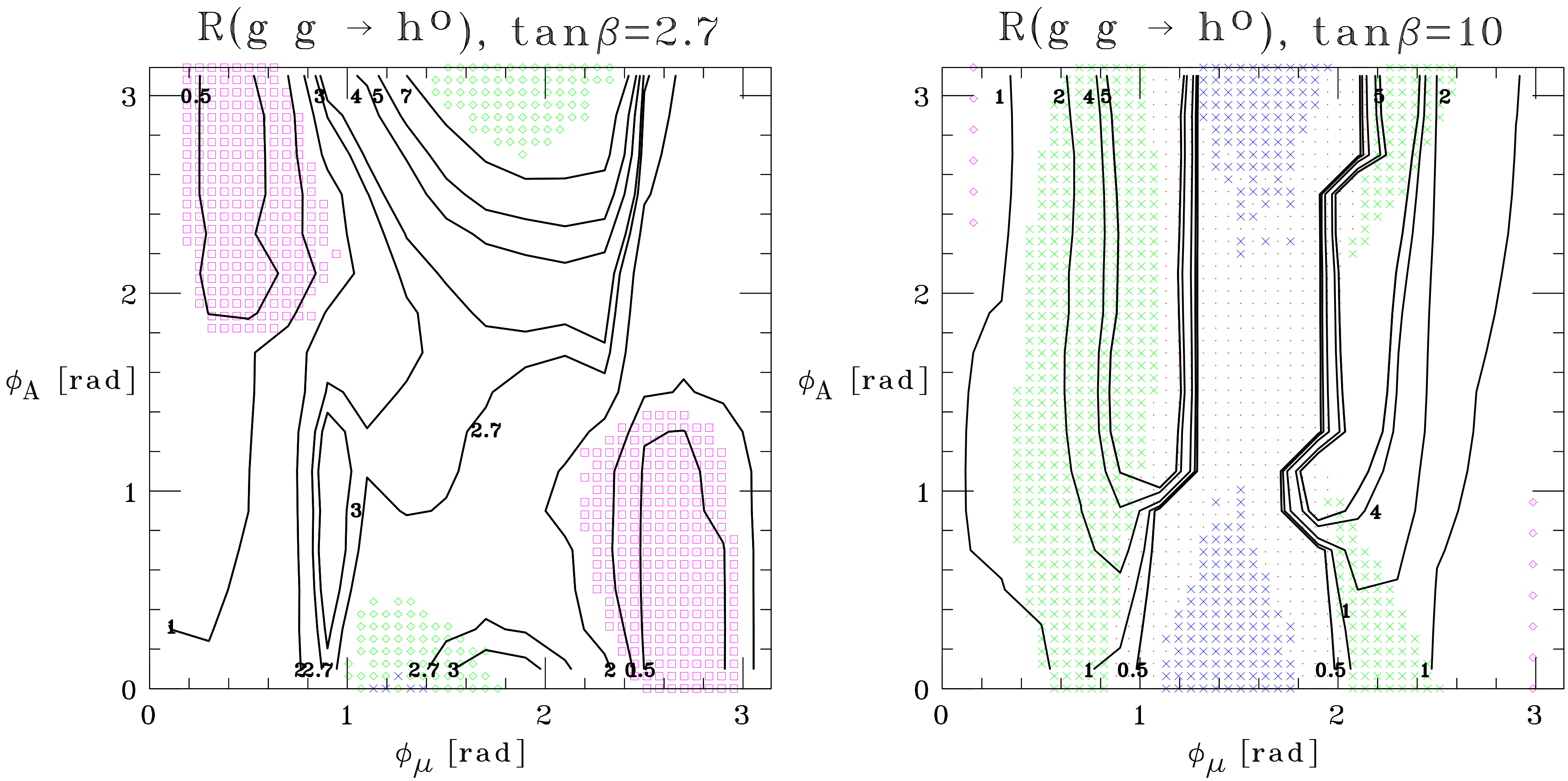
Even have gaps at 0–50 GeV!

$gg \to \phi$ cross-sections [Dedes, Moretti, Nucl. Phys. B **576** (2000) 29
Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner, Comput. Phys. Commun. **156** (2004) 283]

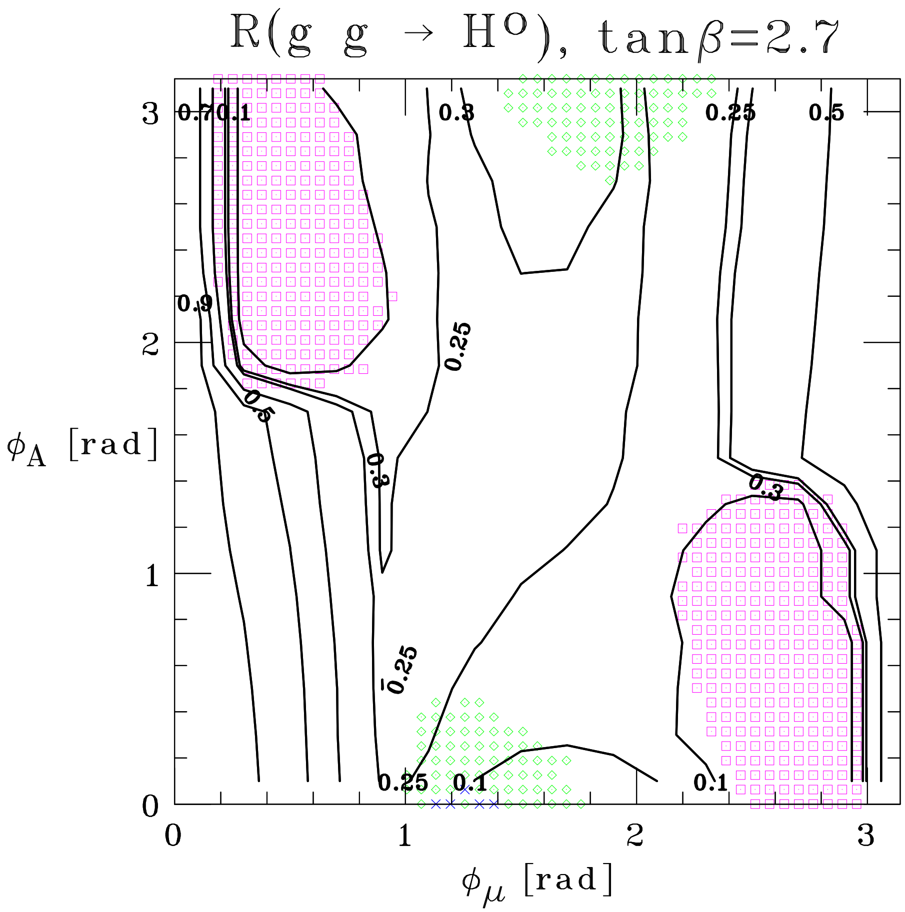


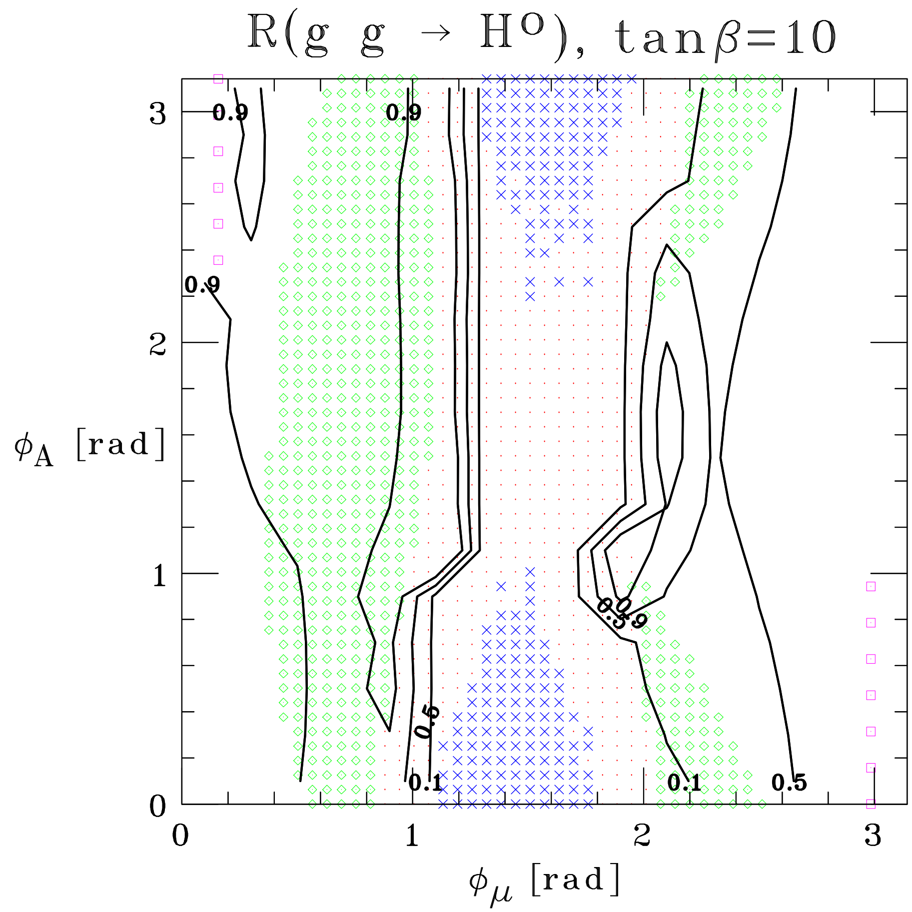
$$g_{h\tilde{t}_L\tilde{t}^*_R} = \frac{igm_t}{2M_W \sin\beta}(\mu^* \sin\alpha - A_t \cos\alpha)$$

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

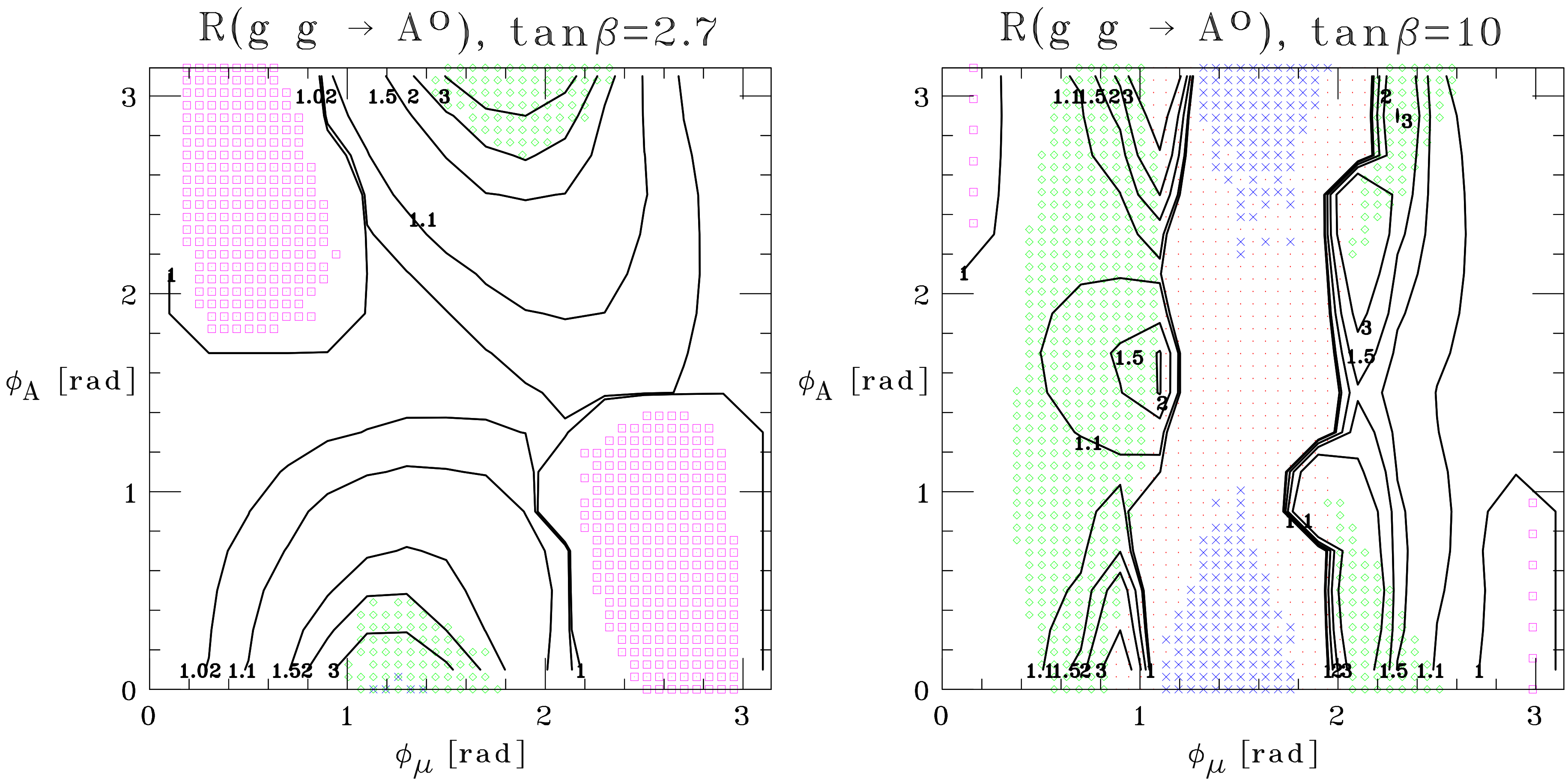


Fortunately, $gg \to h$ only <u>increases</u> in allowed regions



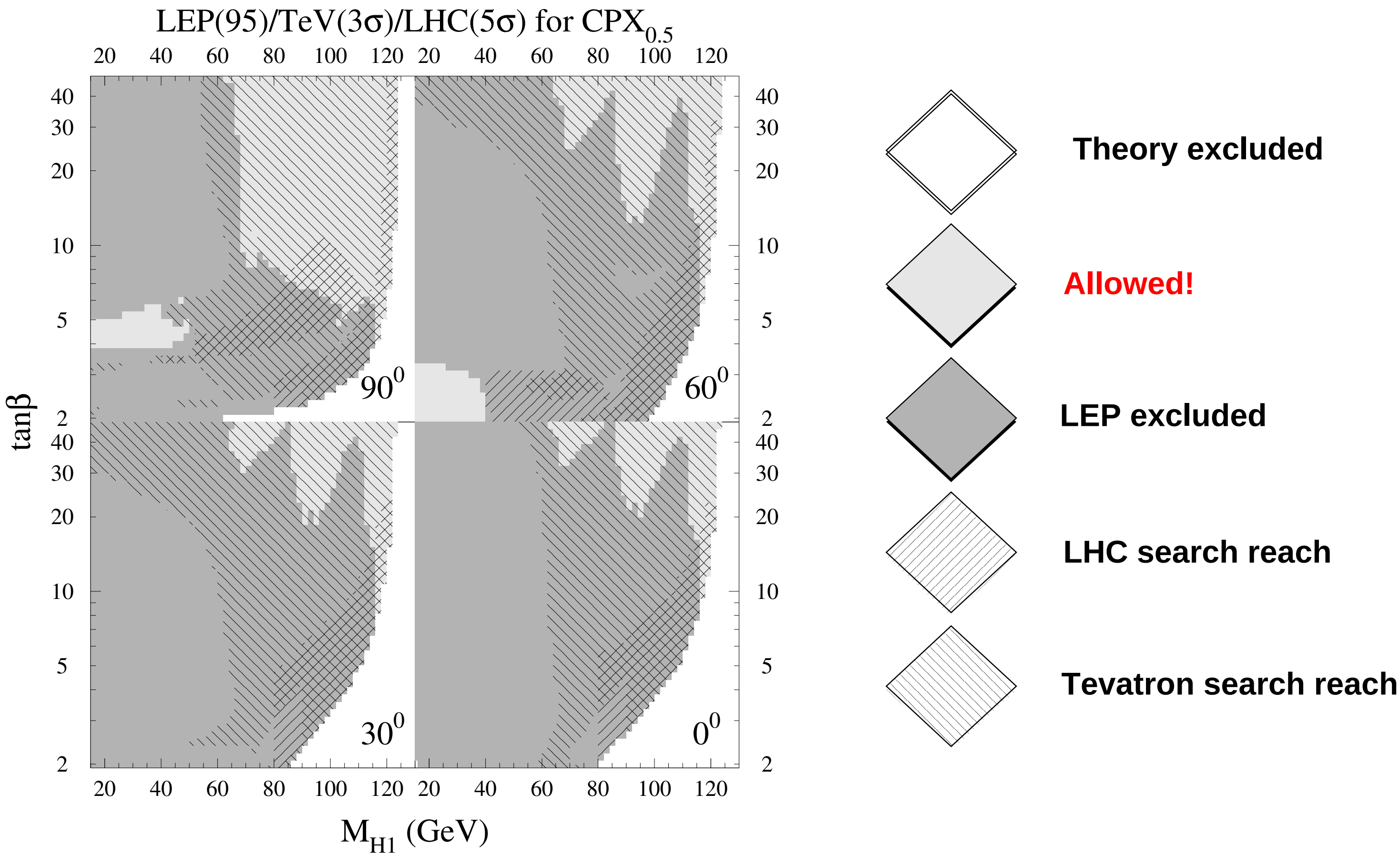


$gg \rightarrow H$ decreases (as expected from coupling sum rules)



$gg \to A$ doesn't change much

[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

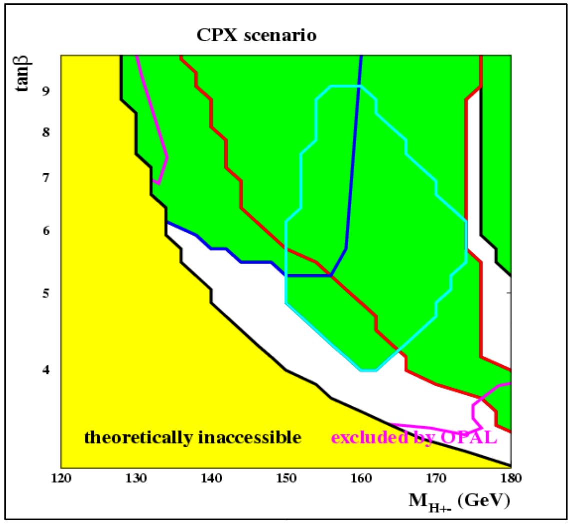
- Small regions in $\tan\beta, M_{H^+}$ plane where LHC,TEVATRON will have no reach

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

There are regions where the three states will be degenerate, just as earlier discussions of 'intense coupling' regime.

The higgs searches in $\not{C}\not{P}$ 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

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 nonsupersymmetric scenarios as well if a non-chiral higgs singlet is present: D.P., P.N. Pandita..etal)

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

$\tan\beta$	2	2.2	2.5	3.0
Br($H^+\phi_1 W$)(%)	> 90 (83.5)	> 90(80.32)	> 90 (73.85)	> 90 (63.95)
Br(tbH^+)(%)	4.0 – 4.2	4.9 – 5.1	4.8 – 5.11	4.0 – 4.3
M_{H^+}	< 133.6 (135.1)	< 122.7 (124.3)	< 113.8 (115.9)	< 106.6(109.7)
M_{H_1}	< 50.97 (54.58)	< 39.0 (43.75)	< 27.97 (35.44)	< 14.28 (29.21)

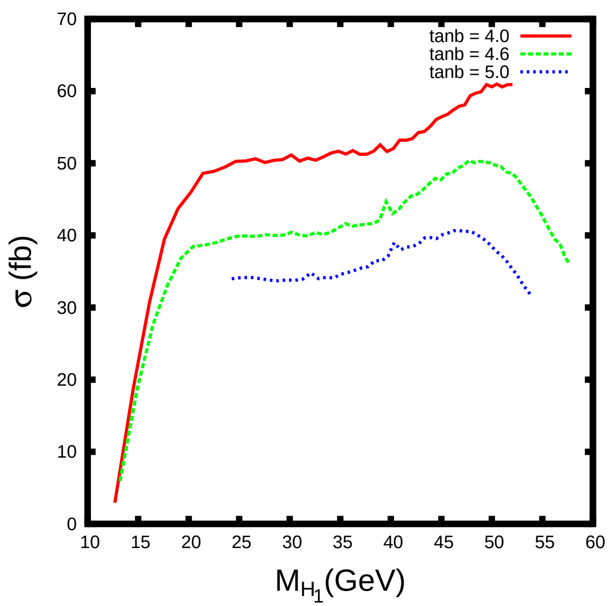
Small $\tan\beta$, light $M_{H^+} \Rightarrow$ large $B.R.(H^+ \to \phi_1 W)$ Use $t\bar{t}$ production with :

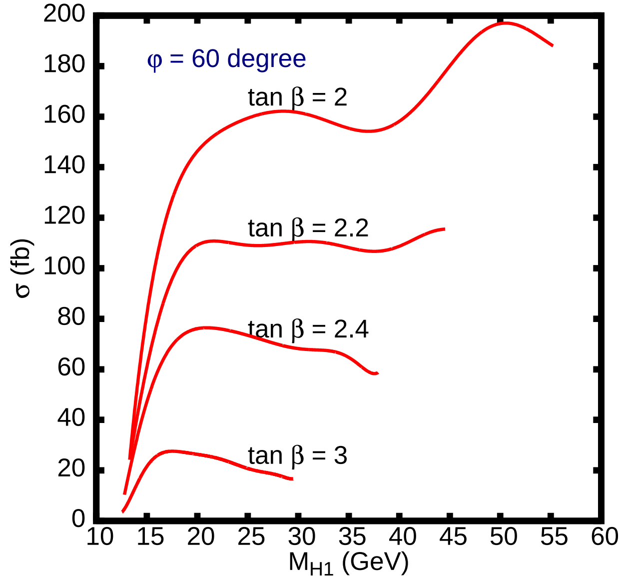
$t \to \bar{b}H^+ \to \bar{b}\phi_1 W \to \bar{b}b\bar{b}W$ and $\bar{t} \to \bar{b}W$, with one W decaying leptonically the other hadronically. Hence both $W's$ can be reconstructed.

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

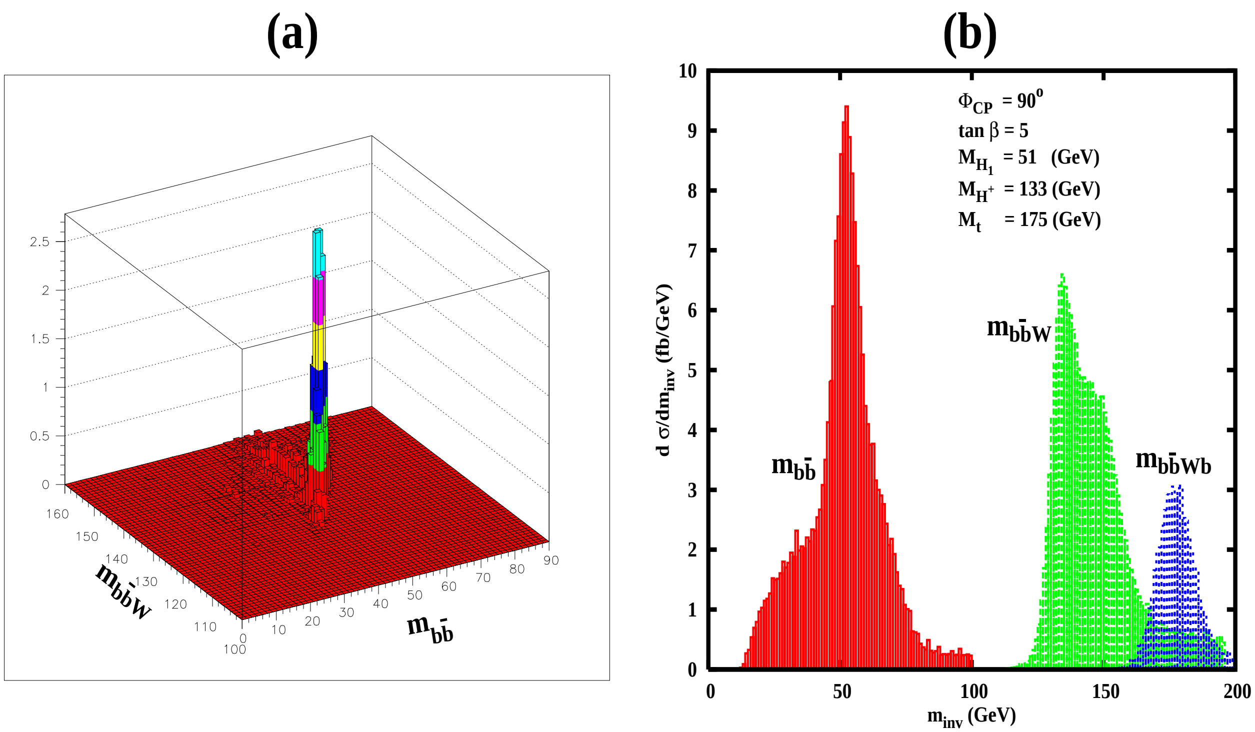
The mass of the $b\bar{b}$ pair with the smallest value will cluster around m_{ϕ_1} and $b\bar{b}W$ around M_{H^+}.

Same parameter range, the branching ratio of $H^\pm \to \tau\nu$ also decreases. Hence, this is also a search strategy for a light charged $H^\pm$ also.





Thus for L = 30 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 $b\bar{b}bW$ invariant mass at m_t. So detectability controlled by just the signal size.

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)

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

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.

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.

The $VV\phi$ Coupling

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

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

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

Note:

• Many other formulations:

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

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

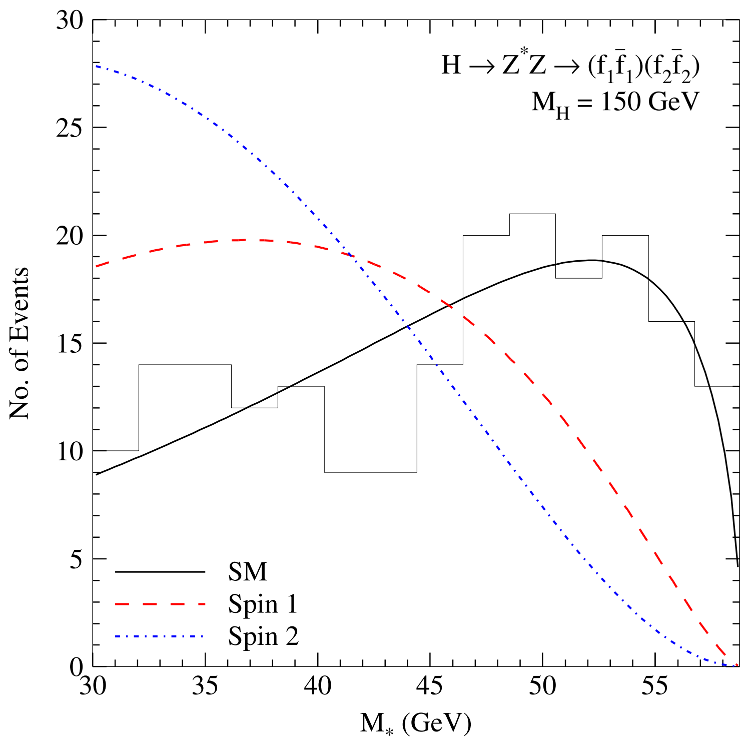
Can be obtained from the above by appropriate mappings of coefficients

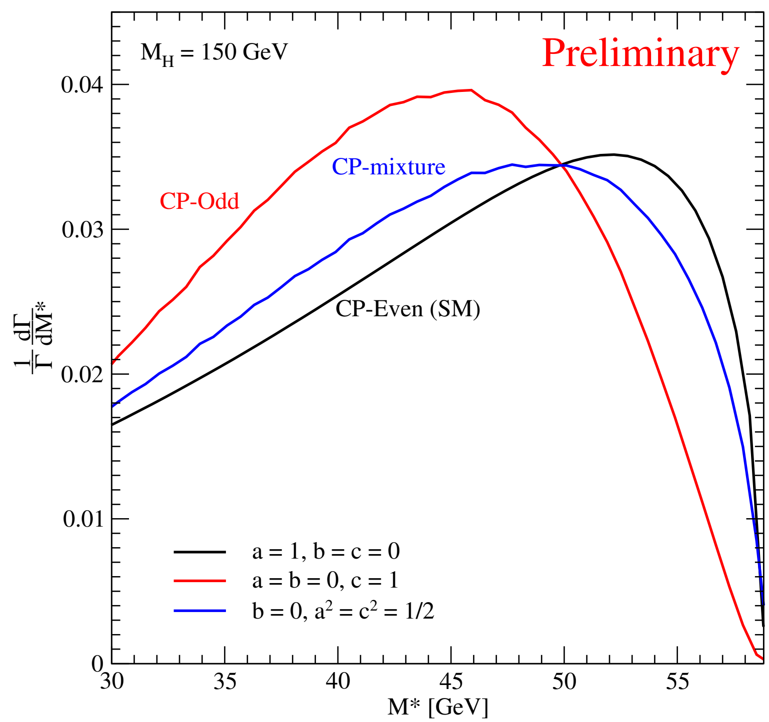
• In SM and 2HDMs, the pseudoscalar coupling is missing (ie. $c = 0$) at tree-level

$\Rightarrow$ expect c to be small

Below $\phi \to ZZ$ threshold, one Z is virtual $\to$ can examine threshold behaviour

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





Can distinguish CP-odd from CP-even easily, but not good for mixtures

Linear Collider: LC & $\gamma\gamma$

e^+e^- option: Gunion et al, Desch et al... If one uses production through VV fusion and decay into fermions pairs, CP studies possible but not equally sensitive to CP even and CP odd part. Associated production with $f\bar{f}$ pair offers a good chance.

$\gamma\gamma$ collider

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

$\gamma\gamma$ collider

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.G, S.D.Rindani and R.K.Singh, PRD **67** (2003) 095009,
R.G., S. Kraml and R.K. Singh, [arXiv:hep-ph/0409199].

Why decay τ /(t) polarisation is a probe of Higgs physics?

• 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.

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...

CPSuperH	FeynHiggs
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

Conclusions

♢ CP violation in the MSSM will alter the sparticle phenomenology in a big way.

♢ Possibilities of probing/measuring this at hadronic colliders have not yet been explored.

♢ 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.

♢ ILC and $\gamma\gamma$ colliders provide the best bet!