Distinguishing Non-minimal Higgs sectors via precise measurements of a light neutral Higgs boson

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Contents

- SUSY phases in MSSM
- Scalar-pseudoscalar mixing
- Case of large phases and large M_{SUSY}
- Phenomenology of H_1
- Conclusions

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2 Higgs doublet models

2 Higgs doublets models contain CP even fields and CP odd fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 + ia_1 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 + ia_2 \end{pmatrix}$$

- *CP conserving 2HDM*:
Neutral Higgs mass eigenstates are either pure CP even or pure CP odd:
$H_i = f(\phi_i^0)$ or $H_i = f(a_i)$

- *CP violating 2HDM*:
Neutral Higgs mass eigenstates are mixtures of CP even and CP odd fields:
$H_i = f(\phi_i^0, a_i)$

scalar-pseudoscalar mixing

MSSM Higgs potential

The most general 2HDM potential is given by:

$$V = \mu_1^2(\Phi_1^+\Phi_1) + \mu_2^2(\Phi_2^+\Phi_2) + \lambda_1(\Phi_1^+\Phi_1)^2 + \lambda_2(\Phi_1^+\Phi_1)^2 + \lambda_3(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) + \lambda_4|\Phi_1^+\Phi_2|^2 + \{m_{12}^2(\Phi_1^+\Phi_2) + h.c\} + [\lambda_5(\Phi_1^+\Phi_2)^2 + h.c] + [\lambda_6(\Phi_1^+\Phi_1)(\Phi_1^+\Phi_2) + h.c] + [\lambda_7(\Phi_2^+\Phi_2)(\Phi_2^+\Phi_1) + h.c]$$

In the MSSM tree level potential (V_0) one has:

$\mu_i^2 = -m_i^2 - |\mu|^2$, $\lambda_1 = \lambda_2 = -\frac{1}{8}(g^2 + g'^2)$

$\lambda_3 = -\frac{1}{4}(g^2 - g'^2)$, $\lambda_4 = \frac{1}{2}g^2$, $\lambda_5 = \lambda_6 = \lambda_7 = 0$

No Explicit CP violation in V_0 (all real parameters)

In 1-loop potential V_1:

$$\lambda_5, \lambda_6, \lambda_7 \neq 0$$

from radiative corrections from $t, \tilde{t}, b, \tilde{b}$ etc

Effective potential technique employed:

$$\lambda_5, \lambda_6, \lambda_7 = f(\mu, A_t, A_b, M_{SUSY}...)$$

$\lambda_5, \lambda_6, \lambda_7$ can be complex if SUSY parameters complex
$\rightarrow$ scalar-pseudoscalar mixing

The neutral Higgs boson mass squared matrix in basis (A^0, ϕ_1, ϕ_2):

$$M_N^2 = \begin{pmatrix} M_P^2 & M_{SP}^2 \\ M_{PS}^2 & M_S^2 \end{pmatrix}$$

where $M_{PS} = (M_{SP})^T$

In terms of λ_i:

$$M_{PS}^2 = v^2 \begin{pmatrix} Im(\lambda_5)\sin\beta + Im(\lambda_6)\cos\beta \\ Im(\lambda_5)\cos\beta + Im(\lambda_7)\sin\beta \end{pmatrix}$$

In CP conserving MSSM:

- $M^2_{PS} = (0,0)$, corresponding to real $\lambda_5, \lambda_6, \lambda_7$
- $M^2_P = M^2_A$
- Pure CP–even h^0, H^0 and pure CP–odd A^0

In CP violating MSSM (i.e. $arg(\mu)$, $arg(A_t) \neq 0$):

- $Im(\lambda_5), Im(\lambda_6), Im(\lambda_7) \neq 0$
- $O^T M^2_N O =$ Diag$(M^2_{H_1}, M^2_{H_2}, M^2_{H_3})$, with $M_{H_1} < M_{H_2} < M_{H_3}$
- H_1, H_2, H_3 are mixed states of CP: $H_i = f(A^0, \phi_1, \phi_2)$

Magnitude of scalar-pseudoscalar mixing

Pilaftsis 98, Pilaftsis,Wagner 99, Choi,Lee,Drees 00

$$M_{PS}^2 = \left(\frac{m_t^4}{v^2} \frac{|\mu||A_t|}{32\pi^2 M_{SUSY}^2} \right) \sin\phi_{CP} \times f(M_{SUSY}, A_t, \mu, \tan\beta)$$

where $\phi_{CP} = arg(A_t\mu)$

Optimal M_{PS}^2 requires:

- Large $|\mu|/M_{SUSY}$,
- Large $|A_t|/M_{SUSY}$
- moderate to large $\sin\phi_{CP}$

Constraints on $\sin\phi_{CP}$

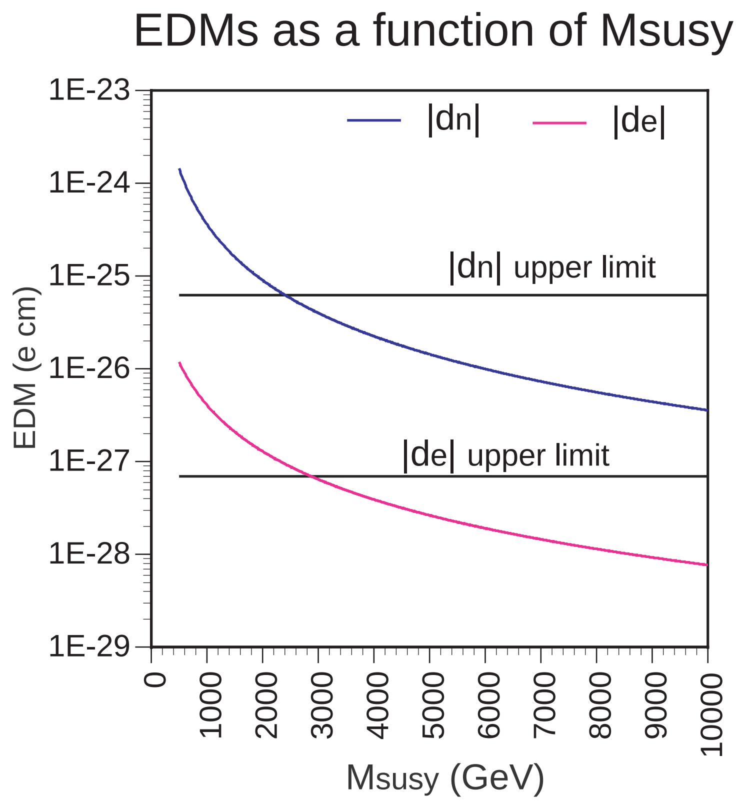
$\sin\phi_{CP}(=arg(\mu A_t))$ strongly constrained by EDMs of the neutron and electron

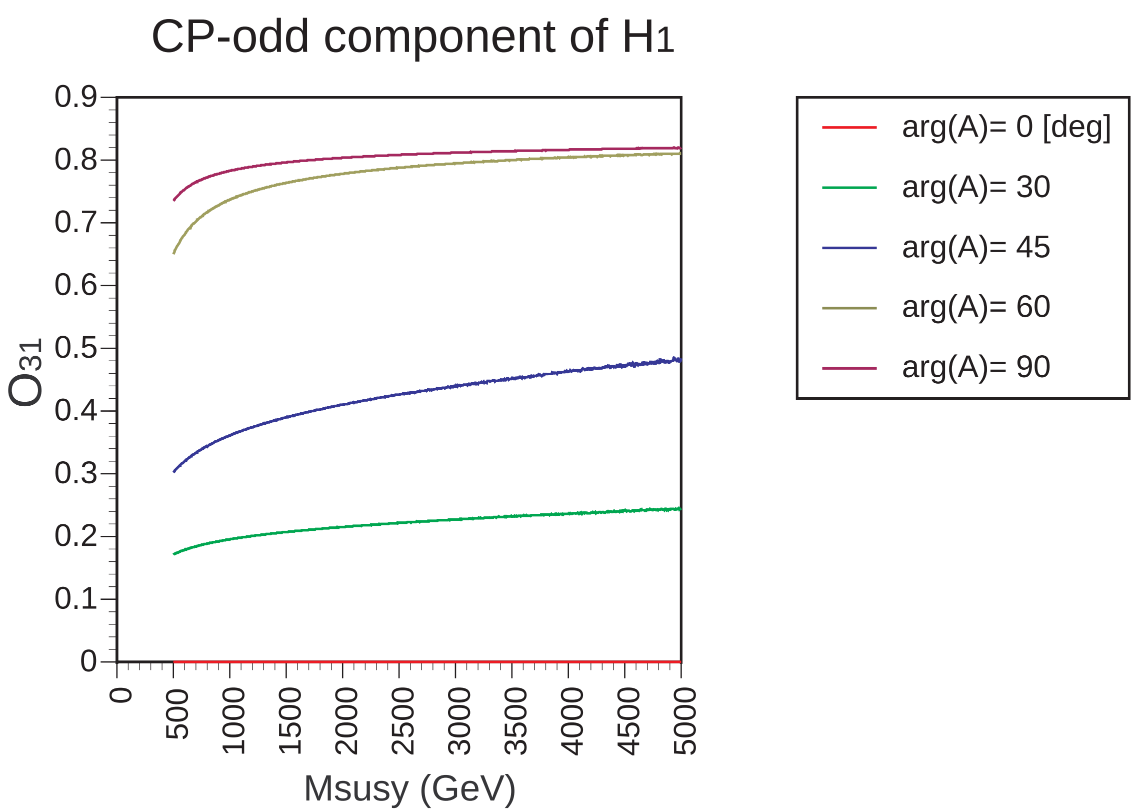
Phenomenology often done for $M_{SUSY} < 1000$ GeV case:

- $arg(\mu)$ strongly constrained by 1-loop EDM diagrams
- $arg(A_t)$ relatively unconstrained by 1-loop EDM $\rightarrow$ 2-loop graphs important (Chang,Keung,Pilaftsis, 99)
- Large $\sin\phi_{CP}$ due to cancellation mechanism (Nath,Ibrahim 98) or fine tuning of phases

We are interested in $M_{SUSY} > 2000$ GeV case: (Ibrahim 01)

- Constraints on $arg(\mu)$,$arg(A_t)$ are weakened $\sim 1/M^2_{SUSY}$
- CP violation in Higgs sector remains as $M_{SUSY} \rightarrow$ large
- Aim to see if pseudoscalar-scalar mixing can be sizeable even if SUSY partices out of range at LHC/Linear Collider


EDMs as a function of Msusy
|dn|
|de|
|dn| upper limit
|de| upper limit
EDM (e cm)
1E-23
1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Msusy (GeV)


CP-odd component of H1
O31
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Msusy (GeV)
arg(A)= 0 [deg]
arg(A)= 30
arg(A)= 45
arg(A)= 60
arg(A)= 90

Scalar-pseudoscalar mixing in H_1

We focus on H_1

(i) In MSSM with $\phi_{CP} = 0$:

$$H_1 = O_{11}\Phi_1 + O_{21}\Phi_2$$

(ii) In MSSM with $\phi_{CP} \neq 0$:

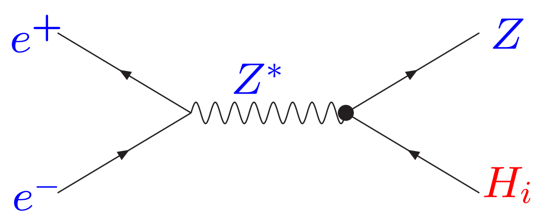
$$H_1 = O_{11}\Phi_1 + O_{21}\Phi_2 + O_{31}A^0$$

	MSSM ($\phi_{CP} = 0$)	MSSM ($\phi_{CP} \neq 0$)
$H_1 b\bar{b}$	$O_{11}/\cos\beta$	$O_{11}/\cos\beta + O_{31}\tan\beta$
$H_1 VV$	$O_{11}\cos\beta + O_{21}\sin\beta$	$O_{11}\cos\beta + O_{21}\sin\beta$
$H_1 c\bar{c}$	$O_{21}/\sin\beta$	$O_{21}/\sin\beta + O_{31}\cot\beta$

Production at e^+e^- colliders

- Offers a clean environment in which to produce neutral Higgs bosons

- Is an ideal place to probe scalar-pseudoscalar mixing



$$\mathcal{L}_{H_iVV} = \frac{g m_W}{c_W^2} \sum_{i=1}^{3} C_i \; H_i Z_\mu Z^\mu$$

$$C_i = O_{1i} \cos\beta + O_{2i} \sin\beta \quad ,$$

- There exists the following sum rule:

$$C_1^2 + C_2^2 + C_3^2 = 1$$

Observables sensitive to $\sin\phi_{CP}$

Precision measurements of H_1

(i) $\sigma(e^+e^- \rightarrow H_1 Z)$

(ii) $\mathrm{BR}(H_1 \rightarrow b\bar{b})$

We aim to see if these observables can deviate from the $\sin\phi_{CP} = 0$ case for:

- Large $\sin\phi_{CP}$
- $M_{SUSY} >$ 2000GeV

Numerical results

We take the following input parameters:
$\widetilde{M}_Q = \widetilde{M}_t = \widetilde{M}_b = M_{SUSY} = 3$TeV,
$|A_t| = 1.5 M_{SUSY}$,$|\mu| = 10 M_{SUSY}$, $\tan\beta = 7$
$0 < \mathrm{Arg}(A_t) < 2\pi$

Fig.1: $\sigma(e^+e^- \to H_1 Z)$ as a function of m_{H_1} at $\sqrt{s} = 500$ GeV, for various ϕ_{CP}:

- $\sigma(e^+e^- \to H_1 Z)$ can be very suppressed for large ϕ_{CP}
- Suppression remains even for $m_{H_1} > 115$ GeV

Fig.2: $\sigma(e^+e^- \to H_1 Z)$ as a function of $m_{H^\pm}$ at $\sqrt{s} = 500$ GeV, for various ϕ_{CP}:

- Sizeable deviation from SM rate for $\sigma(e^+e^- \to H_1 Z)$ for $m_{H^\pm} < 230$ GeV

Fig.3: g_{bb} against g_{WW} varying $m_{H^\pm}$ for various ϕ_{CP}:

- g_{bb} for large $\sin\phi_{CP}$ can be much larger than for $\sin\phi_{CP} = 0$ case

Fig.1: $\sigma(e^+e^- \to H_1 Z)$ as a function of m_{H_1} at $\sqrt{s} = 500$ GeV, for various ϕ_{CP}:

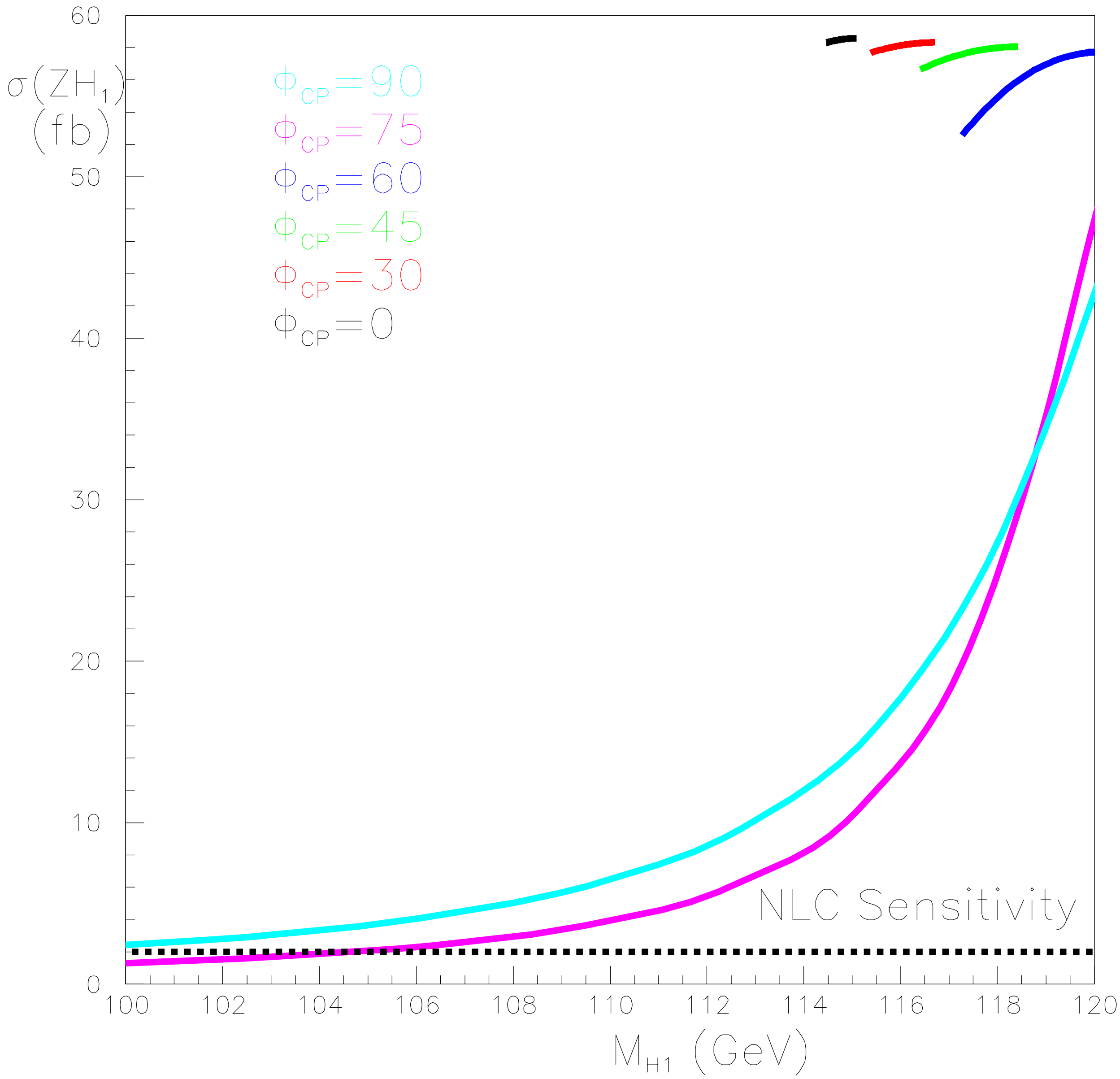


Fig.2: $\sigma(e^+e^- \to H_1 Z)$ as a function of $m_{H^\pm}$ at $\sqrt{s} = 500$ GeV, for various ϕ_{CP}:

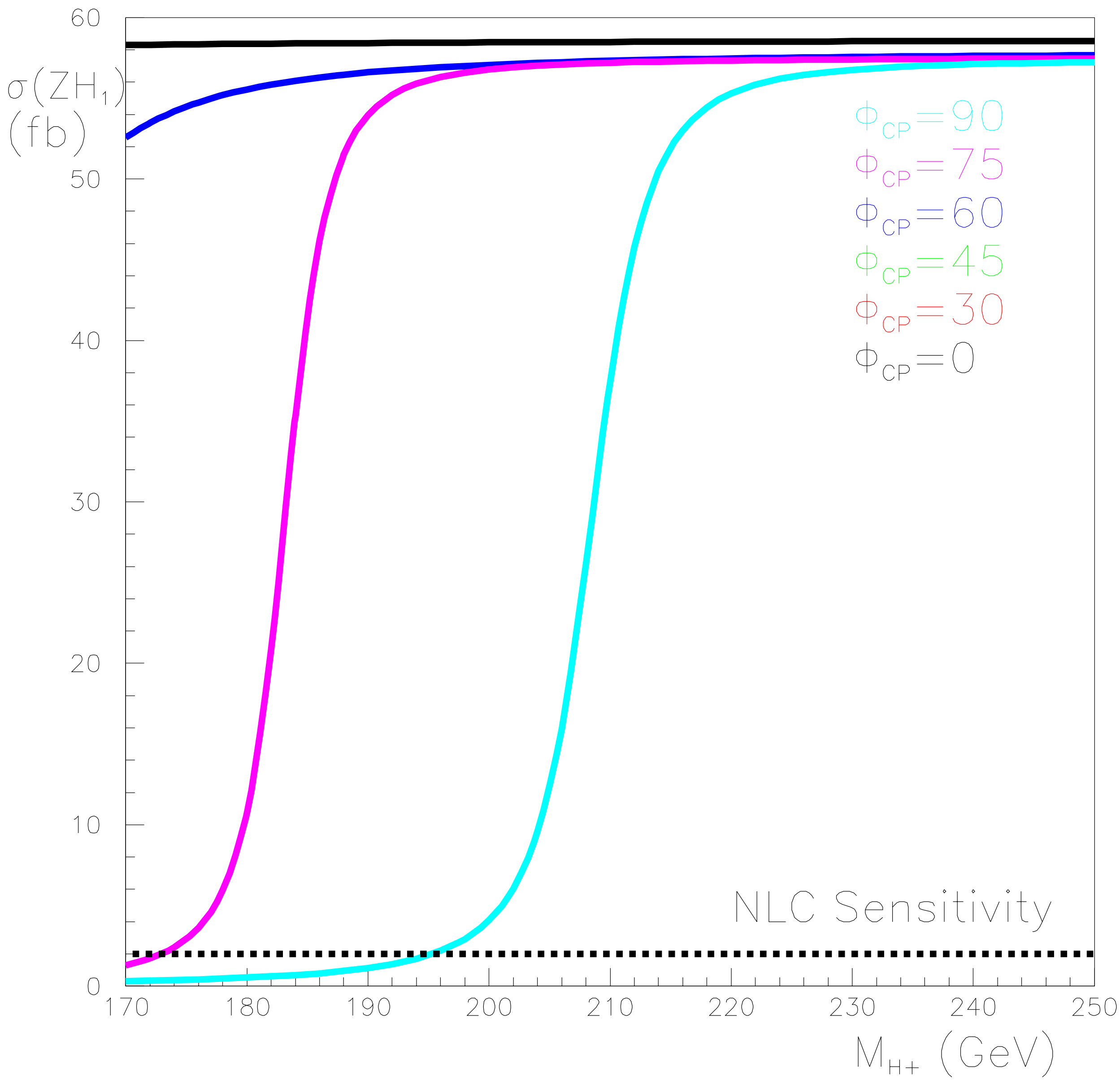
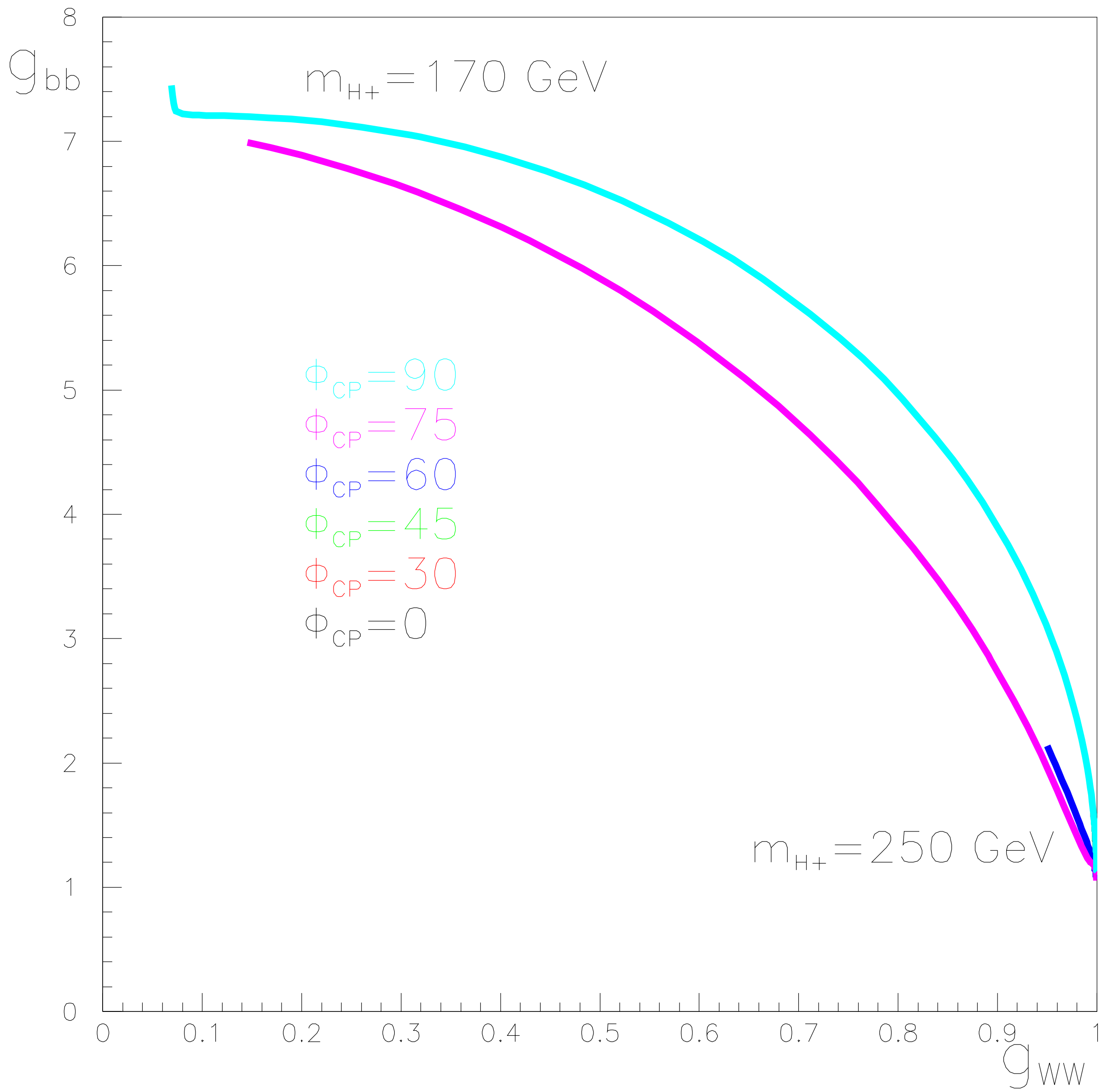


Fig.3: g_{bb} against g_{WW} varying $m_{H^\pm}$ for various ϕ_{CP}:



Conclusions

- SUSY phase $\phi_{CP} \neq 0 \to$ Scalar-pseudoscalar mixing
- Large A_t and μ required
- $M_{SUSY} > 2000$ GeV relaxes EDM constraints on ϕ_{CP}
- Large scalar-pseudoscalar mixing possible
- $\sigma(e^+e^- \to ZH_1)$ can be sizeably suppressed, even for $m_h \geq 115$ GeV
- Very different from MSSM with $\phi_{CP} = 0$