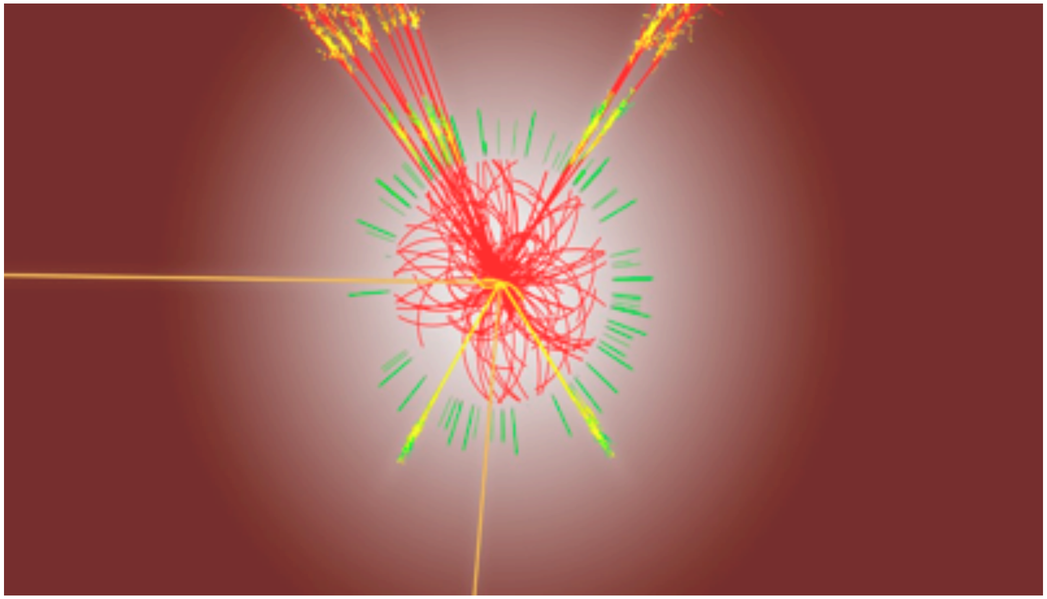
SUSY Signals of CP violation in Higgs and Flavor Physics



Marcela Carena

Theoretical Physics Department, Fermilab

Enrico Fermi Institute, University of Chicago

CERN Theory Institute

August 25, 2011

- LEP,Tevatron and LHC have cornered the SM-like Higgs

  114 GeV < m_{HSM} < 145 GeV
- Still room in the MSSM: M_h~(115-130) GeV (some fine tuning)
- Where can SUSY Higgs bosons be hiding ?

Extensions of the MSSM Higgs Sector

- MSSM with explicit CP violation (radiatively induced)
- Additional SM singlets; additional gauged U(1)'s
- Models with enhanced weak gauge symmetries
- Effective field theory with higher dimensional operators:
  - * A more model-independent approach
  - * Important effects on Higgs mass spectrum and collider signals
  - * CP violation at tree level
    - → relevant for Higgs and flavor physics
    - → enlarges the window for EW baryogenesis

More general MSSM Higgs extensions: EFT approach

- The non-minimal part of the Higgs sector is parametrically heavier than the weak scale (understood as v = 174 GeV)

- SUSY breaking is of order v, hence heavy masses nearly supersymmetric

  M : overall ``heavy'' scale SUSY breaking mass splittings $\Delta m \sim \mathrm{v} \ll M$

  In practice: formalism applies for e.g. M~ 1- few TeV

Low energy superpotential: at leading order in 1/M

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2$$

- can include SUSY breaking via a spurion X= $m_S\, \theta^2$ $W_X \supset \alpha_1 \frac{\omega_1}{2M} X (H_u H_d)^2$

  Only two new parameters order one: ω_1 and α_1

M.C, Kong, Ponton, Zurita
see also Dine, Seiberg, Thomas;
Antoniadis, Dudas, Ghilencea, Tziveloglou

- At NLO, Kähler potential only:

$$K = H_d^\dagger e^{2V} H_d + H_u^\dagger e^{2V} H_u + \Delta K^{\mathrm{CV}} + \Delta K^{\mathrm{Cust}}$$

Custodially violating (treel level) :

$$\Delta K^{\mathrm{CV}} = \frac{c_1}{2|M|^2}(H_d^\dagger e^{2V} H_d)^2 + \frac{c_2}{2|M|^2}(H_u^\dagger e^{2V} H_u)^2 + \frac{c_3}{|M|^2}(H_u^\dagger e^{2V} H_u)(H_d^\dagger e^{2V} H_d)$$

Custodially preserving (tree level) :

$$\Delta K^{\mathrm{Cust}} = \frac{c_4}{|M|^2}|H_u H_d|^2 + \left[\frac{c_6}{|M|^2} H_d^\dagger e^{2V} H_d + \frac{c_7}{|M|^2} H_u^\dagger e^{2V} H_u\right](H_u H_d) + \mathrm{h.c.}$$

Plus SUSY breaking terms obtained by multiplication by spurion, with new coefficients

$$X \to \gamma_i \ , \qquad X^\dagger X \to \beta_i$$

- EFT coefficients can be essentially arbitrary, if UV theory complicated enough
  - look at specific examples: Singlet, triplets with Y =0 ; ± 1, and extra gauge bosons-

Why to go beyond LO in the EFT approach

Quartic interactions of 2HDM can be written as

$$V \supset \frac{1}{2}\lambda_1(H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2(H_u^\dagger H_u)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u H_d)(H_u^\dagger H_d^\dagger)$$
$$+ \left\{\frac{1}{2}\lambda_5(H_u H_d)^2 + \left[\lambda_6(H_d^\dagger H_d) + \lambda_7(H_u^\dagger H_u)\right](H_u H_d) + \text{h.c.}\right\}$$

At O(1/M), only $\lambda_5, \lambda_6, \lambda_7$ modified

At O(1/M²) all λ_i's receive contributions

But at tree-level in MSSM: $\lambda_1, \lambda_2, \lambda_3, \lambda_4 \propto g^2$ (small)

NLO effects can be relevant without indicating breakdown of EFT

(however, higher order effects should be small...)

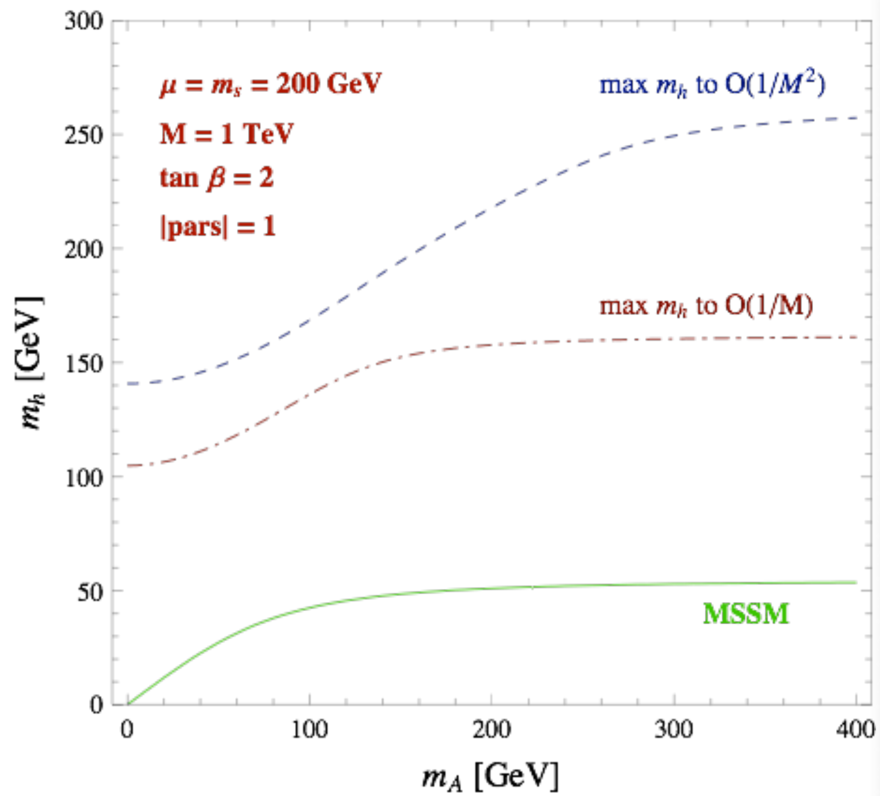
Higgs Spectra in EFT extensions of the MSSM

The lightest tree level Higgs mass can be well above the LEP bound!!.

Expansion parameters: μ/M and m_S/M (m_S is the spurion F term)

Second order terms can have a relevant impact.

Large deviations from the MSSM mass values specially for low tanb



M.C, Kong, Ponton, Zurita

Higgs Spectra in EFT extensions of the MSSM

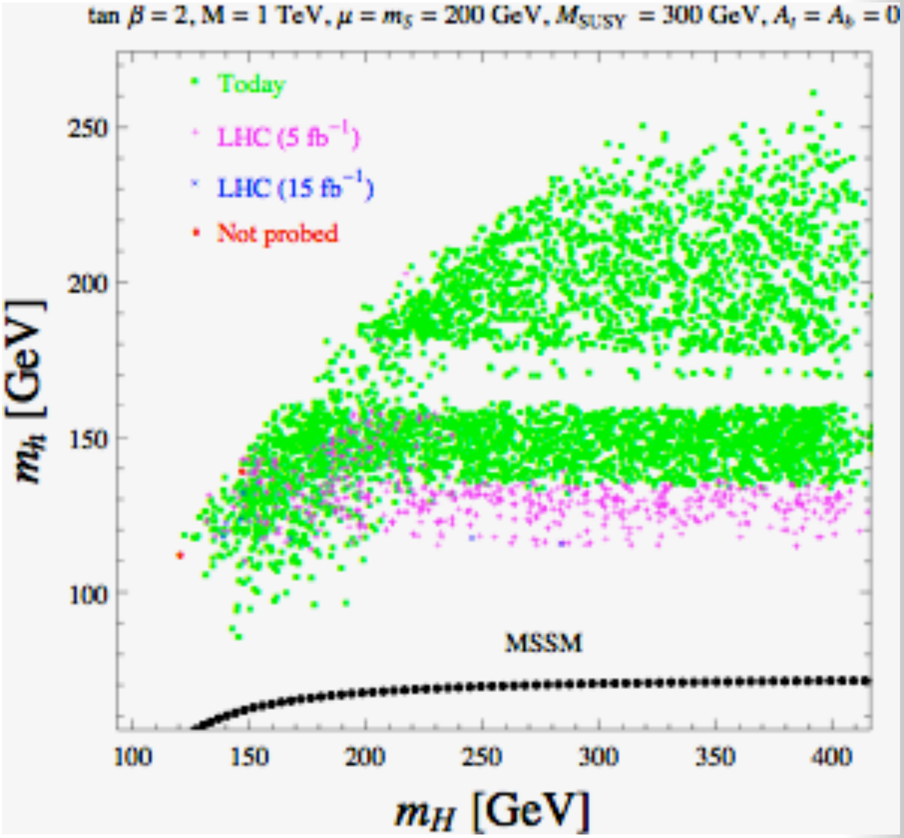
The lightest tree level Higgs mass can be well above the LEP bound.

Expansion parameters: μ/M and m_S/M (m_S is the spurion F term)

Scanning over model parameters

$$|\alpha_1|, |\beta_i|, |\gamma_i|, |\delta_i| \in [1/3, 1] \text{ for } i = 1, 2, 3, 4, 6, 7$$

$$|\omega_1|, |c_i| \in [0, 1]$$



Most regions of parameter Space are being tested at LHC

Using many different channels
h/H → WW/ZZ
h → diphotons
h/H/A → tau pairs
t → H^+ b

M.C, Ponton, Zurita

Additional Sources of CP Violation in the EFT

Altmannshofer, M.C, Gori, de la Puente

- O(1/M) higher dimensional operators in the superpotential and including SUSY breaking via a spurion, with complex coefficients ω_1 and α_1

$$V_{\rm ren} = V_{\rm MSSM} + \left(\alpha \frac{\omega m_S}{2M} (H_u H_d)^2 - \frac{\omega \mu^*}{M} (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) \ + \ h.c. \right)$$

Parametrizing the complex coefficients in term of λ_i's

$$\lambda_5 = |\lambda_5| e^{i\phi_5} \equiv \frac{\alpha \omega m_s}{M} \qquad \lambda_6 = |\lambda_6| e^{i\phi_6} \equiv \frac{\omega \mu *}{M}$$

CP violating tree level 1/M effects,
can be stronger than MSSM radiatively induced ones .
Different effects in Higgs pheno, EWBG, EDM’s, B observables

Electroweak Symmetry Breaking

- Parametrizing the Higgs fields as

$$H_u^T = e^{i\theta_u}(H_u^+, \frac{v_u + h_u + ia_u}{\sqrt{2}}) \quad H_d^T = e^{i\theta_d}(\frac{v_d + h_d + ia_d}{\sqrt{2}}, H_d^-)$$

$$v_d = v\cos\beta \quad v_u = v\sin\beta$$

The relative phase $\theta = \theta_u - \theta_d$ can be rotated away by a U(1) transformation

$\theta = \theta_u + \theta_d$ is a physical phase

Minimization conditions trade soft masses by v, tanb and m_{H+}, and determine θ

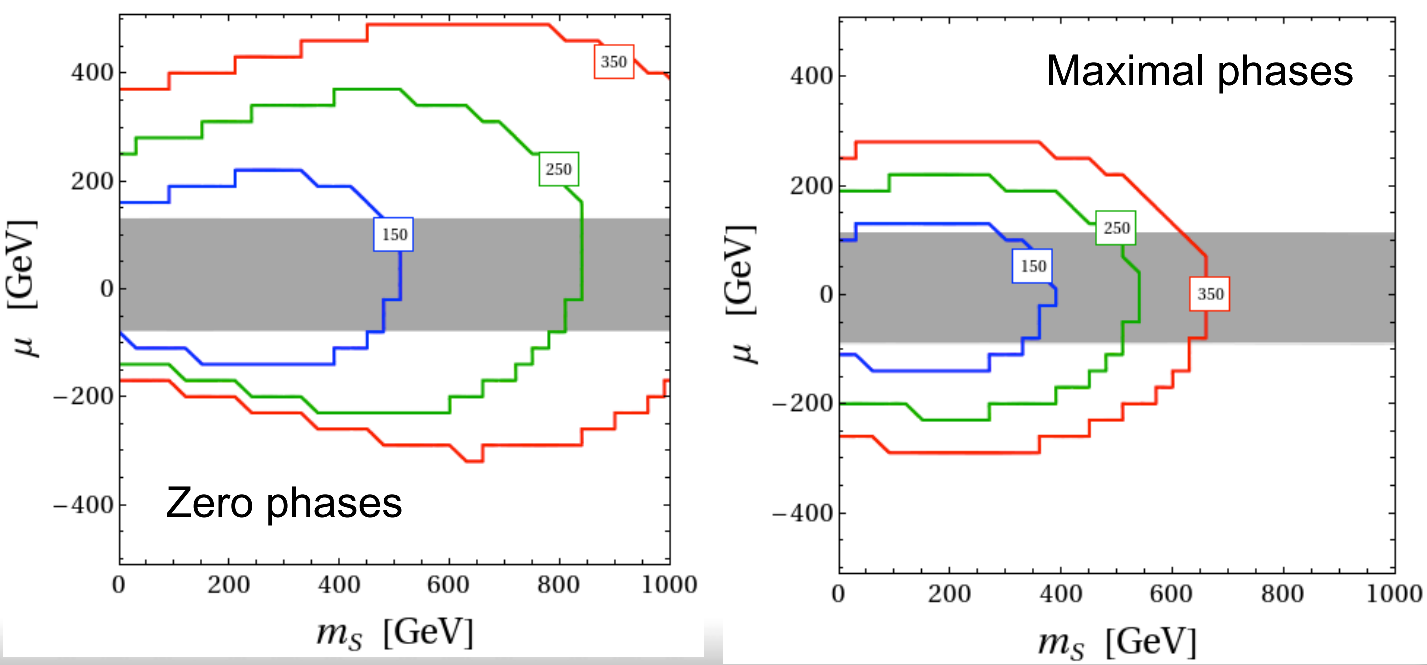
$$v^2 c_\beta s_\beta |\lambda_5| \sin(\phi_5 + 2\theta) + v^2 |\lambda_6| \sin(\phi_6 + \theta) - 2B\mu \sin\theta = 0$$

Vacuum stability constrains

$M = 2$ TeV

$\tan\beta = 2$

$|\alpha| = |\omega| = 1$



Higgs Spectrum

- CP violation leads to scalar-pseudoscalar mixing

$$M_H^2 = \begin{pmatrix} M_h^2 & 0 & M_{hA}^2 \\ 0 & M_H^2 & M_{HA}^2 \\ M_{hA}^2 & M_{HA}^2 & M_A^2 \end{pmatrix}$$

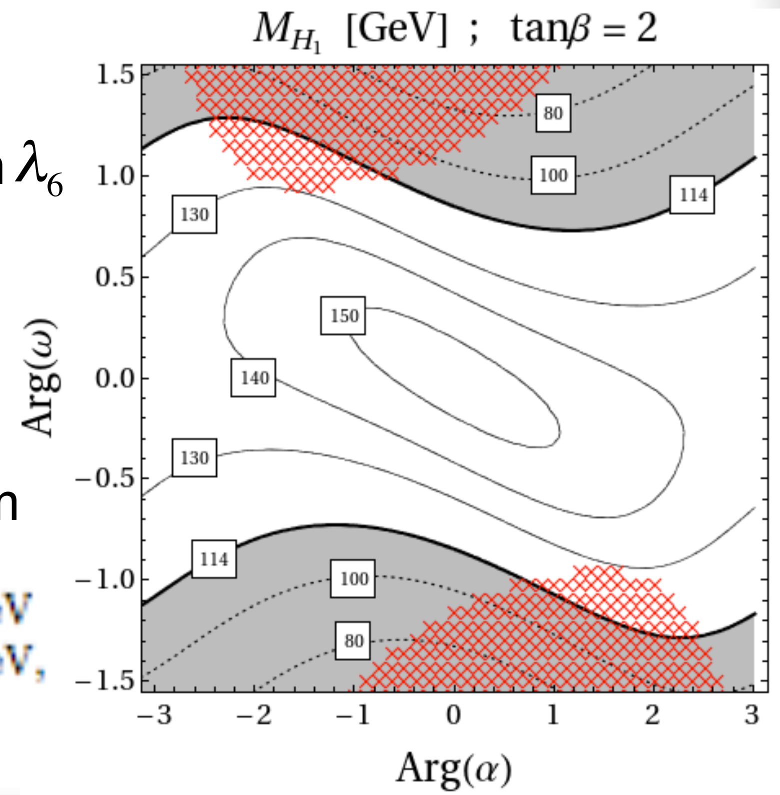
$$M_{hA}^2 = -\frac{v^2}{2}\left(c_{\beta+\alpha}|\lambda_5|\sin(\phi_5+2\theta) - 2s_{\beta-\alpha}|\lambda_6|\sin(\phi_6+\theta)\right)$$

$$M_{HA}^2 = -\frac{v^2}{2}\left(s_{\beta+\alpha}|\lambda_5|\sin(\phi_5+2\theta) - 2c_{\beta-\alpha}|\lambda_6|\sin(\phi_6+\theta)\right)$$

Lightest Higgs mass depends mainly on λ_6
dependence on λ_5 and its phase
is $1/\tan\beta^2 M$ suppressed

Red region:
EWSB vacuum is only a local minimum

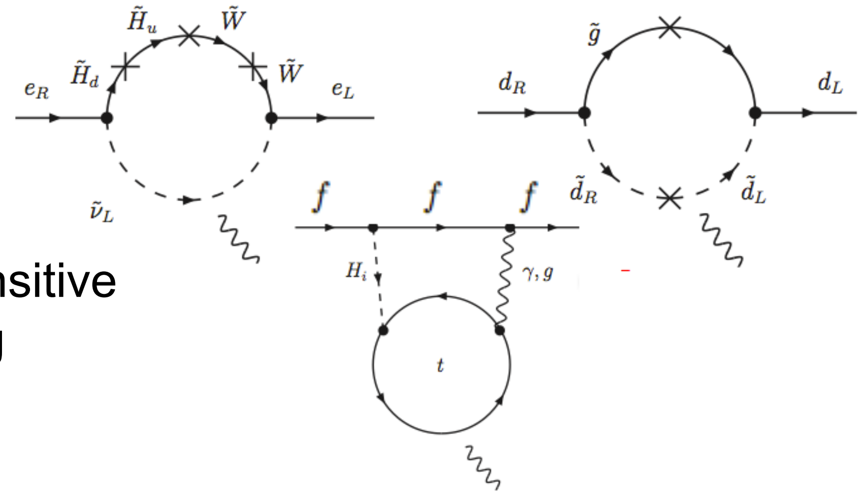
$M = 1.5$ TeV, $M_{H^\pm} = 200$ GeV
$|\alpha| = |\omega| = 1$, $\mu = m_S = 150$ GeV,
$m_{\tilde{t}} = 800$ GeV, $A_t = 2m_{\tilde{t}}$

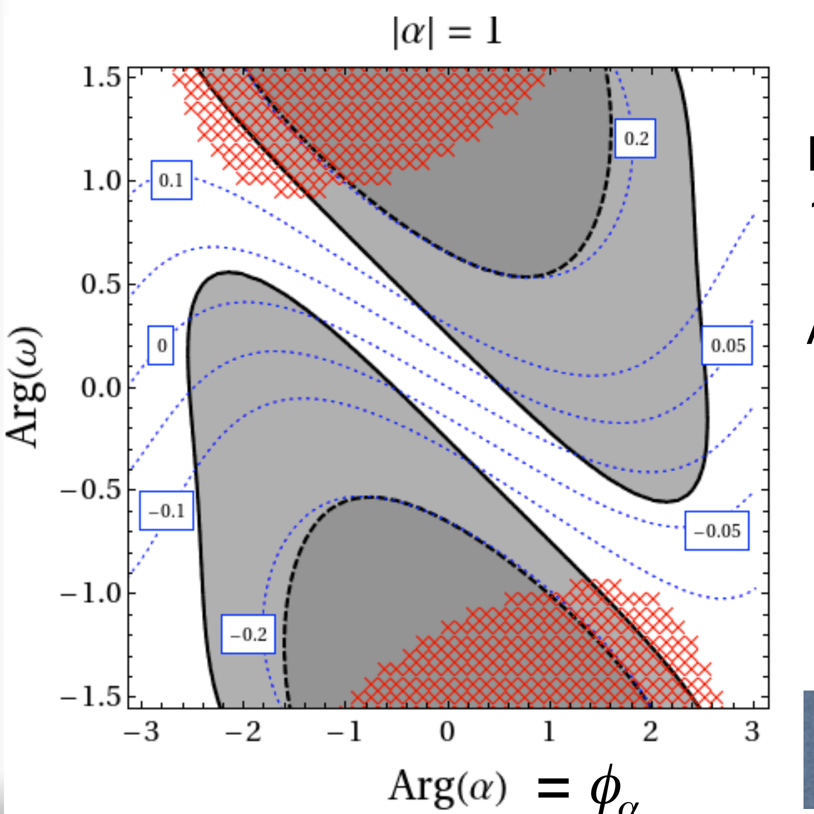


Constraints on phases from EDM's

One loop EDMs mainly induced by Higgs vev and are tanb enhanced

Two loop EDMs due to Bar-Zee, sensitive to Higgs scalar-pseudoscalar mixing





Main constraints from Thalium EDM from 1-loop chargino contribution

↓

Allowed region for small Higgs vev phase

In the absence of other MSSM phases, full allowed range of ϕ_α for given ϕ_ω

$$\sin\phi_\omega = -s_\beta c_\beta \frac{|\alpha| m_S}{\mu} \sin(\phi_\alpha + \phi_\omega)$$

$\tan\beta = 2$
$\omega = 1$

$M_{H+} = 200$ GeV
$M = 1.5$ TeV

$\mu = m_s = 150$ GeV

Study the regions of BMSSM parameter space as a function

of production and decay processes that may be probed at the LHC

- Impose constraints from LEP and the Tevatron [Higgsbounds] Bechtle, Brein,Heinemeyer, Weiglein, Williams

  plus implement latest Tevatron results (Hdecay, HiGlu, CPsuperH)

  Spira et al, Lee et al.

- Combined latest CMS and ATLAS results for SM-like Higgs and heavy Higgs with tanb enhanced couplings

- Impose bounds from vacuum stability and EDM's

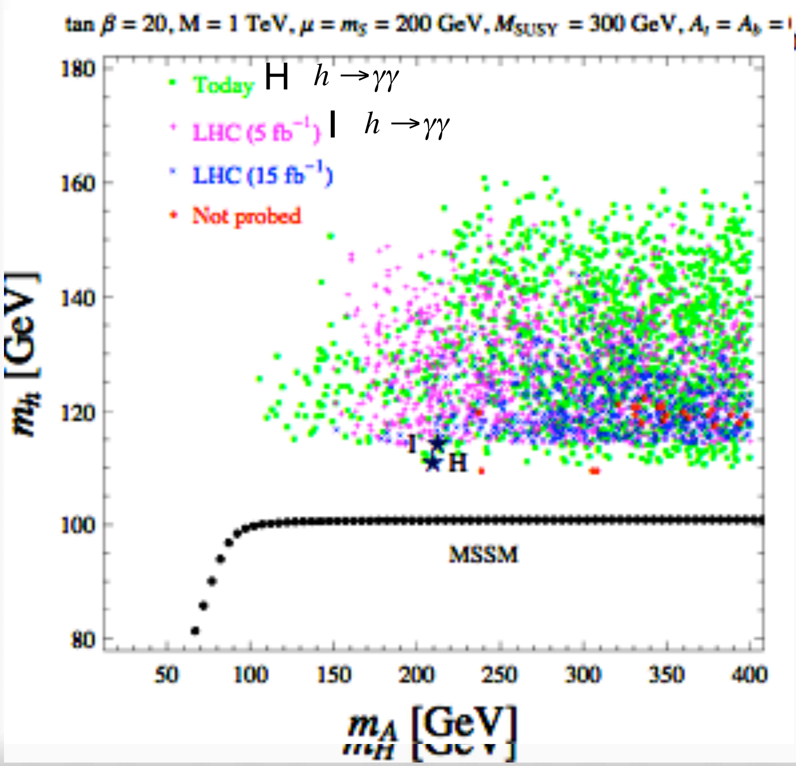
Hard to distinguish CP conserving from CP violating case in a generic scanning - specially for the lightest and heaviest Higgs - CP behavior obscured by parameter scan

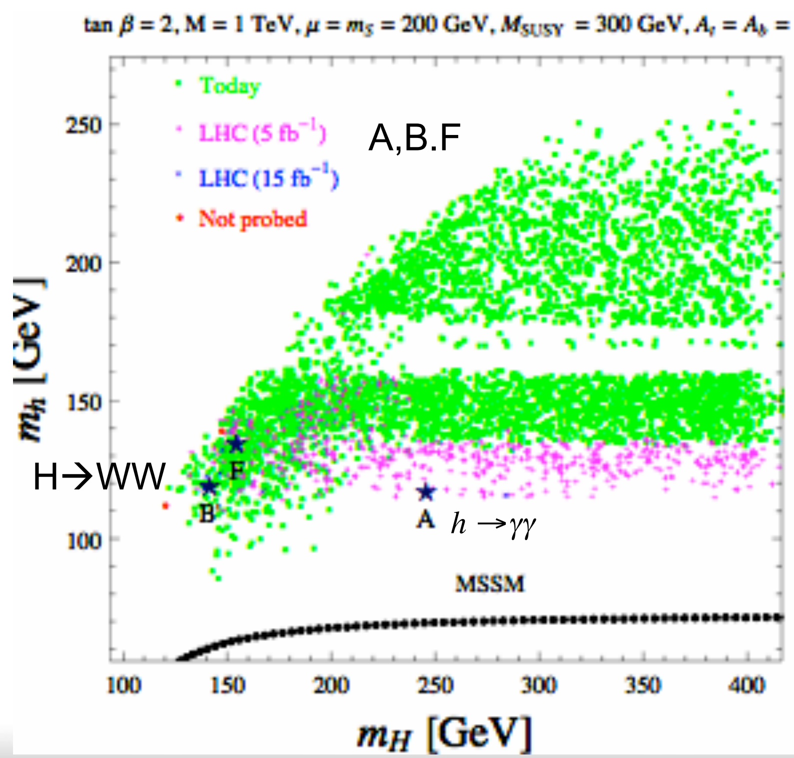
Consider a few distinctive signals at LHC

Distinctive LHC signals of BMSSM Higgs bosons with and without CP violation

- CP conserving scenarios:

- Enhanced di-photon signals → due to suppression in bb-Higgs coupling which is hard to achieve in CP violating scenarios
- Higgs cascade decays → possible due to large splitings in masses : h/H→ AA In CP violating case: hard to have light H_1 < 114 GeV





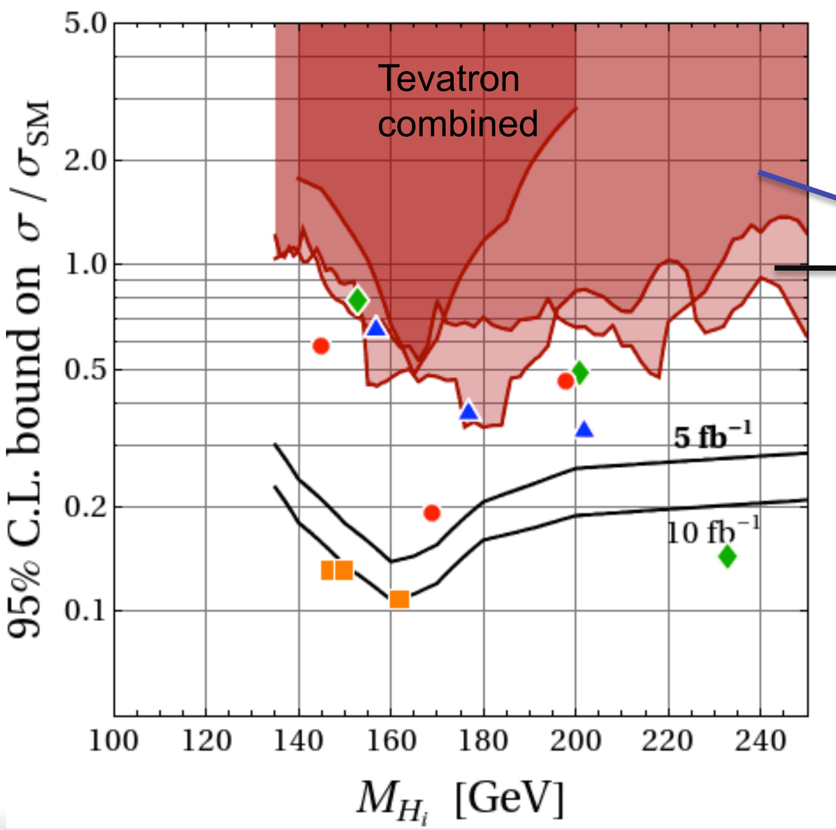
- Carachteristic CP violating scenarios

- 3 Heavy Higgs bosons (mHi > 140 GeV)

→ due to scalar- pseudoscalar mixing

a) all 3 Hi couple to WW (main search channel)

b) all 3 Hi decay mainly into bb; still with ~ 10 fb^{-1} can be seen in WW decays

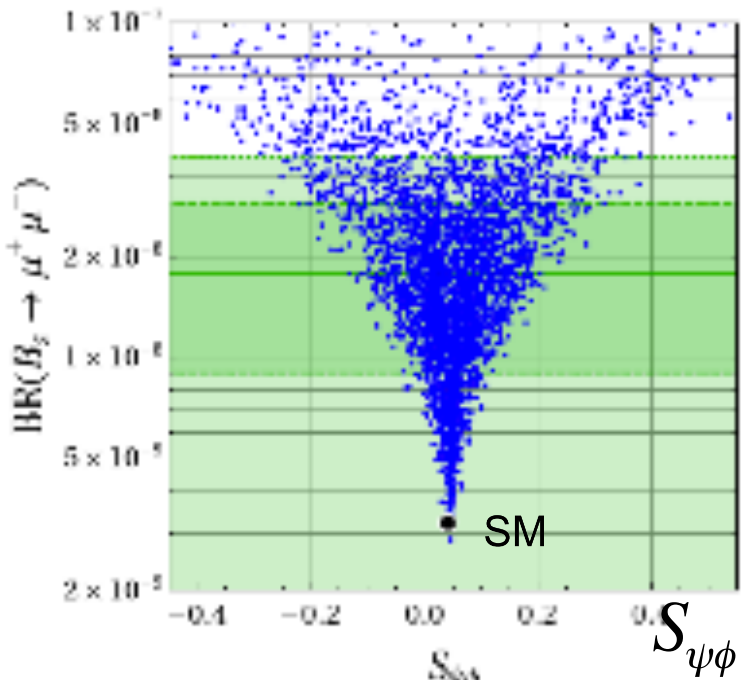


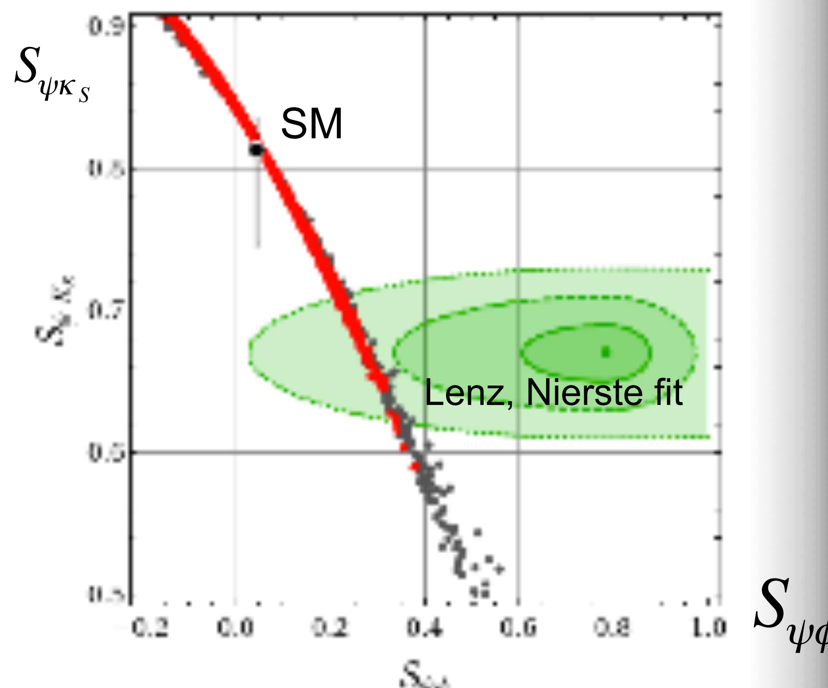
Atlas up to 2.3 fb-1

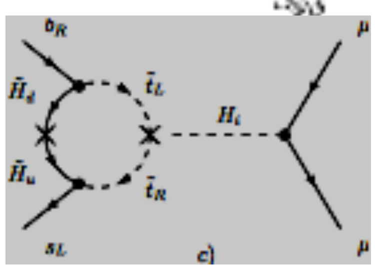
CMS up to 1.7 fb-1

BMSSM contributions to B Meson Mixing

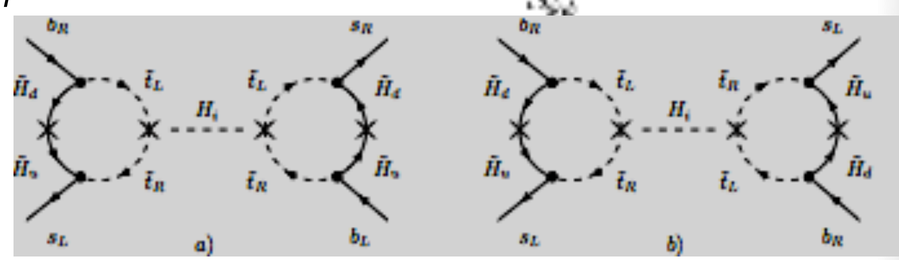
Deviation from SM only for tanb about 10: Lightest Higgs ~ 115 -118 GeV
Higgs direct searches MSSM like







$S, P \propto \tan^3\beta \frac{1}{M_A^2}$



$C_4 \propto \tan^4\beta \frac{1}{M_A^2}$, $\tilde{C}_2 \propto \tan^4\beta \frac{v^2}{M_A^4}$

Outlook

The Higgs sector can shed light to many SM puzzles
the origin of mass, flavor, dark matter …

Many types of experiments are exploring the Higgs sector
impressive results from LHC !

The SM and many new physics models,
in particular SUSY Models, are being constrained

Some corners of SUSY parameter space may be elusive, but

LHC will soon have the final word on multi Higgs searches

Study BMSSM parameter space as a function

of production and decay processes that may be probed at the LHC

- Impose constraints from LEP and the Tevatron [Higgsbounds] Bechtle, Brein,Heinemeyer, Weiglein, Williams

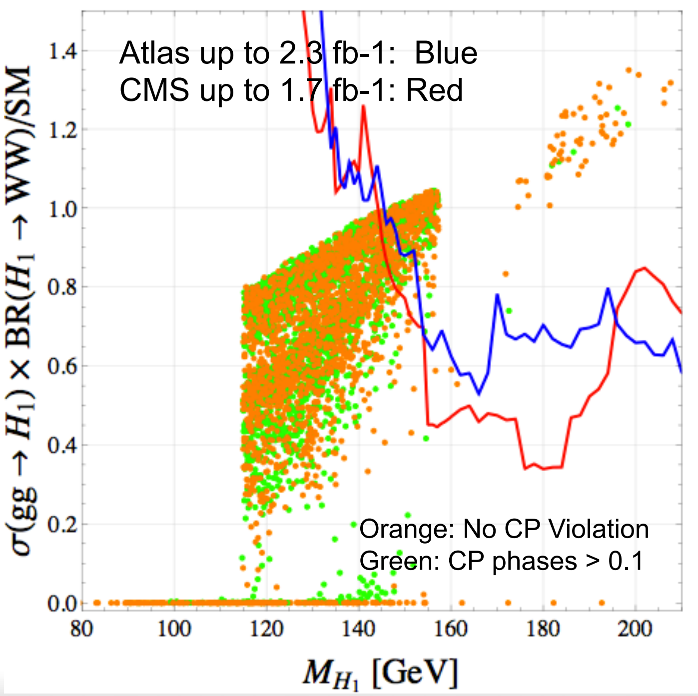
plus implement latest Tevatron results (Hdecay, HiGlu, CPsuperH) Spira et al, Lee et al.

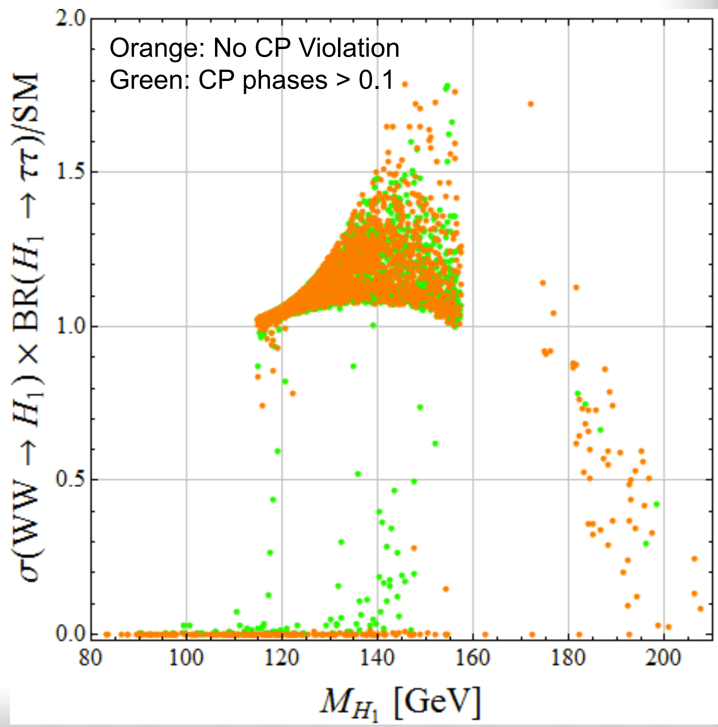
- Impose bounds from vacuum stability and EDM's
- Combined latest CMS and ATLAS results for SM-like Higgs and heavy Higgs with tanb enhanced couplings

Lightest BMSSM Higgs H_1

$H_1 \to \gamma\gamma$

Always suppressed with respect to SM case

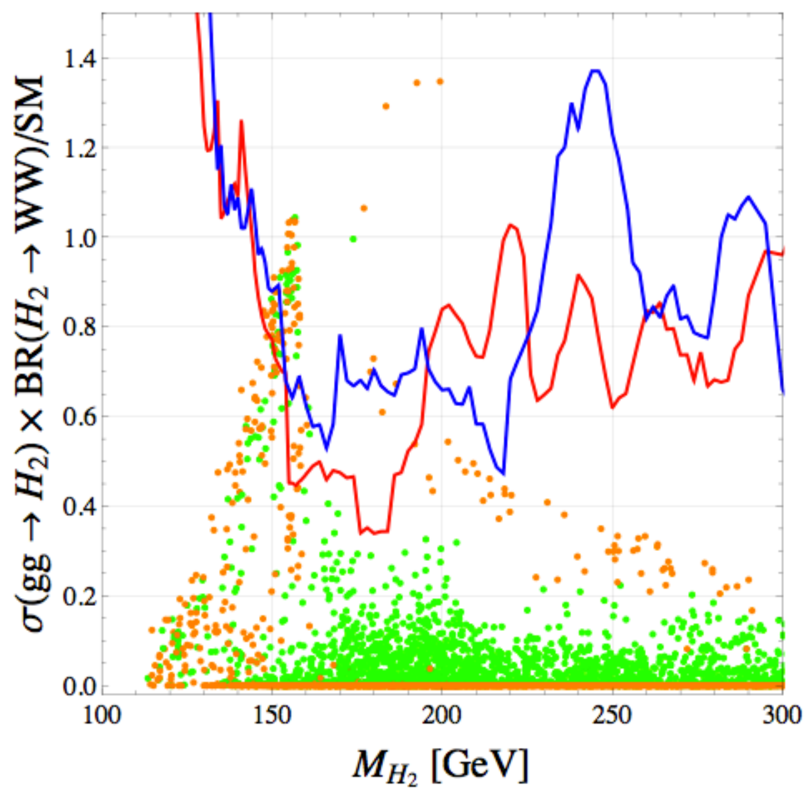


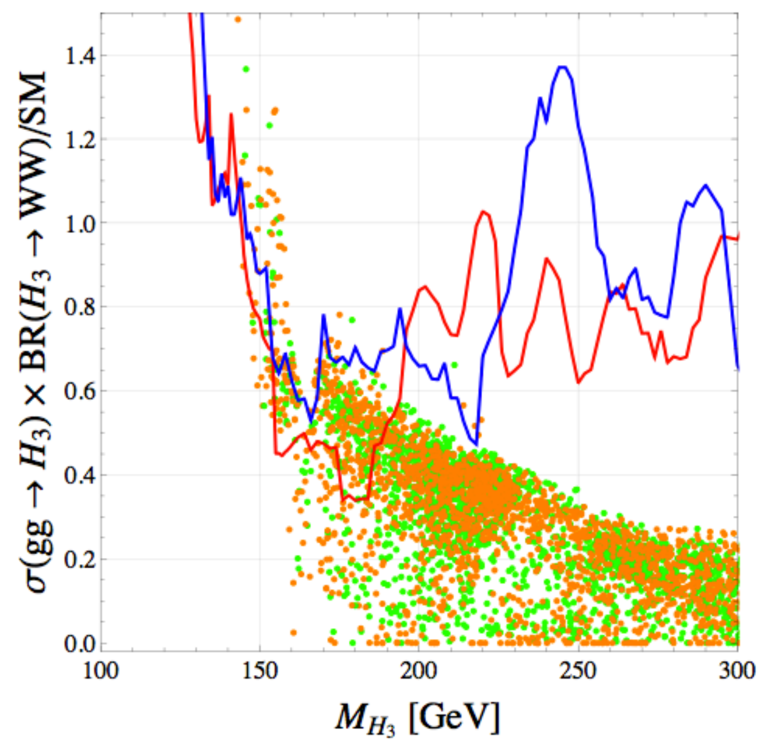


Study BMSSM parameter space in WW decays of H_2 and H_3

Orange: No CP Violation
Green: CP phases > 0.1

Atlas up to 2.3 fb-1: Blue
CMS up to 1.7 fb-1: Red





Hard to distinguish CP conserving from CP violating case:
specially for the lightest and heaviest Higgs
CP behavior obscured by parameter scan

CP Violating Benchmark Scenario

	Sc. Ia	Sc. Ib	Sc. II	Sc. III
$\lvert\alpha\rvert$	1	1	0.8	1
$\lvert\omega\rvert$	2	1	1.6	1.5
Arg(α)	$\pi/2$	$\pi/4$	$-2\pi/3$	$\pi/3$
Arg(ω)	$-\pi/10$	$-\pi/20$	$\pi/20$	$-\pi/15$
$\tan\beta$	2	2	3	2
$M_{H^\pm}$ [GeV]	195	225	166	190
M [TeV]	2.5	2	2	2.5
μ [GeV]	160	190	140	150
m_S [GeV]	160	400	100	150

Table 1: Input parameters. For all scenarios we choose a common squark mass of $\tilde{m} = 800$ GeV, a common slepton mass of $\tilde{m}_\ell = 1100$ GeV, trilinear couplings $A_t = 2\tilde{m}$, $A_b = A_\tau = 0$ and gaugino masses $M_{\tilde{g}} = 3M_2 = 6M_1 = 1200$ GeV.

Scenario III	H_1	H_2	H_3
M_{H_i} [GeV]	145	169	198
$\xi^2_{ZZH_i}$	0.94	0.02	0.04
$\xi^2_{ggH_i}$	0.68	0.59	0.53
BR($H_i \to bb$)	42% (23%)	59% (0.8%)	15% (0.2%)
BR($H_i \to WW$)	45% (60%)	31% (97%)	62% (74%)
BR($H_i \to ZZ$)	6% (8%)	0.7% (2.4%)	20% (26%)
BR($H_i \to \gamma\gamma$) $\times 10^4$	15 (17)	0.8 (1.6)	0.2 (0.5)

Scenario Ia	H_1	H_2	H_3
M_{H_i} [GeV]	157	177	202
$\xi^2_{ZZH_i}$	0.94	0.04	0.02
$\xi^2_{ggH_i}$	0.72	0.62	0.47
BR($H_i \to bb$)	15% (8%)	34% (0.6%)	24% (0.2%)
BR($H_i \to WW$)	76% (83%)	58% (95%)	53% (74%)
BR($H_i \to ZZ$)	6% (7%)	2% (4%)	19% (26%)
BR($H_i \to \gamma\gamma$) $\times 10^4$	9 (9)	0.8 (1.2)	0.2 (0.5)

Scenario Ib	H_1	H_2	H_3
M_{H_i} [GeV]	153	201	233
$\xi^2_{ZZH_i}$	0.96	0.03	0.004
$\xi^2_{ggH_i}$	0.84	0.64	0.35
BR($H_i \to bb$)	19% (13%)	21% (0.2%)	51% (0.1%)
BR($H_i \to WW$)	69% (74%)	56% (74%)	29% (71%)
BR($H_i \to ZZ$)	7% (8%)	19% (26%)	12% (29%)
BR($H_i \to \gamma\gamma$) $\times 10^4$	12 (12)	0.6 (0.5)	0.5 (0.3)

Scenario II	H_1	H_2	H_3
M_{H_i} [GeV]	147	150	162
$\xi^2_{ZZH_i}$	0.62	0.32	0.06
$\xi^2_{ggH_i}$	0.41	0.53	0.39
BR($H_i \to bb$)	69% (22%)	72% (16%)	65% (2%)
BR($H_i \to WW$)	20% (63%)	17% (69%)	26% (94%)
BR($H_i \to ZZ$)	3% (8%)	2% (8%)	1% (3%)
BR($H_i \to \gamma\gamma$) $\times 10^4$	6 (16)	3 (13)	0.5 (4)

Precision Electroweak Constraints

1. Tree-level effects due to new physics:

$$\alpha T^{\rm Tree} = -\frac{v^2}{2M^2}\sin^4\beta\left[c_2 - 2(\tan\beta)^{-2}c_3 + (\tan\beta)^{-4}c_1\right]$$

2. Effects from MSSM Higgs sector:

$$\left.\begin{array}{l}\bullet\ \text{Heavier SM-like Higgs}\\ \bullet\ \text{Mass splittings among non-standard Higgses}\end{array}\right\}\ \text{Loop-level contr. to S and T}$$

3. Custodially violating mass splittings in SUSY sector Medina, Shah, Wagner

Here: require that $-0.4 < T^{\rm Tree} + T^{\rm Higgs} < 0.3$ $\quad(S \text{ is small})$

Consistent with $-0.2 < T^{\rm Total} < 0.3\ (95\%\ C.L.)$ for $0 < T^{\rm SUSY} < 0.2$

Examples

Example 1: singlets

B_μ-term

$$W = \mu H_u H_d + \frac{1}{2} M_S S^2 + \lambda_S S H_u H_d - X\left(a_1 \mu H_u H_d + \frac{1}{2} a_2 M_S S^2 + a_3 \lambda_S S H_u H_d \right)$$

$$K = H_u^\dagger e^V H_u + H_d^\dagger e^V H_d + S^\dagger S - X^\dagger X \left(b_1 H_d^\dagger H_d + b_2 H_u^\dagger H_u + b_3 S^\dagger S \right)$$

Soft masses: $m_{H_d}^2, m_{H_u}^2, m_S^2$

Integrating out the singlet:

$$M = M_S\ , \qquad \omega_1 = -\lambda_S^2\ , \qquad \alpha_1 = a_2 - 2a_3\ ,$$

$$c_4 = |\lambda_S|^2\ , \qquad \gamma_4 = a_2 - a_3\ , \qquad \beta_4 = |a_2 - a_3|^2 - b_3$$

Note $c_4 > 0$, other arbitrary

Example 2: triplets with $Y = \pm 1$

$$
\begin{aligned}
W &\supset M_T T\bar{T} + \frac{1}{2}\lambda_T H_u T H_u + \frac{1}{2}\lambda_{\bar{T}} H_d \bar{T} H_d \\
&\quad + X\left(a_2 M_T T\bar{T} + \frac{1}{2}a_3\lambda_T H_u T H_u + \frac{1}{2}a_4\lambda_{\bar{T}} H_d \bar{T} H_d\right) \\
K &\supset T^\dagger e^{2V} T + \bar{T}^\dagger e^{2V}\bar{T} + XX^\dagger\left(b_3 T^\dagger T + b_4 \bar{T}^\dagger \bar{T}\right)
\end{aligned}
$$

Integrating out the triplets:

$$
\left.
\begin{array}{lll}
M = M_T\,, & \omega_1 = \frac{1}{4}{}_T{}^{\bar{T}}\,, & \alpha_1 = a_2 - a_3 - a_4\,, \\
c_1 = \frac{1}{4}|\lambda_{\bar{T}}|^2\,, & \gamma_1 = a_2 - a_4\,, & \beta_1 = |a_2 - a_4|^2 - b_3\,, \\
c_2 = \frac{1}{4}|\lambda_T|^2\,, & \gamma_2 = a_2 - a_3\,, & \beta_2 = |a_2 - a_3|^2 - b_4\,,
\end{array}
\right\}
$$

Induce custodially violating ops.

Note $c_1, c_2 > 0$, other arbitrary

$(\Delta T < 0)$

For triplets with $Y = 0$ $\longrightarrow$ $\lambda_T H_u T H_d$

$$
\left.
\begin{array}{lll}
M = M_T\,, & \omega_1 = -\frac{1}{4}\lambda_T^2\,, & \alpha_1 = a_2 - 2a_3\,, \\
c_3 = \frac{1}{2}|\lambda_T|^2\,, & \gamma_3 = a_2 - a_3\,, & \beta_3 = |a_2 - a_3|^2 - b_3\,, \\
c_4 = -\frac{1}{4}|\lambda_T|^2\,, & \gamma_4 = a_2 - a_3\,, & \beta_4 = |a_2 - a_3|^2 - b_3\,,
\end{array}
\right\}
$$

Induce custodially violating ops.

Note $c_3 > 0$ $(\Delta T > 0)$,

and $c_4 < 0$!