Signals of CP Violation Beyond the MSSM in Higgs Physics

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Outline

1. Introduction: something beyond the MSSM?

- The lightest Higgs boson & the little hierarchy problem

2. Higgs collider phenomenology

- A heavy lightest Higgs boson
- Characteristic Higgs scenarios
- Reach of the 7 TeV LHC

3. Conclusions

Based on:

„Signals of CP violation beyond the MSSM in Higgs and flavor physics "

W.Altmannshofer, M.Carena, SG, A.dela Puente

arXiv: 1107:3814 (accepted for publication in PRD)

Introduction and motivations

What will the LHC find?

Nobody knows...

Among the known suggestions, supersymmetry is the most studied and most conventional possibility for LHC physics.

The MSSM has a set of predictions, e.g. a light Higgs boson

Leading to the little hierarchy problem

Barbieri, Strumia, 1998

What if LHC results do not agree with these predictions ?

Topic

What can we learn from a Susy effective field theory approach?

What if there are new sources of CP violation at (few) TeV energy scale?

BMSSM: the lagrangian

- Let us assume that at the (few) TeV scale (scale M) there are additional particles which interact with the Susy particles and that preserve the SU(3)×SU(2)×U(1) gauge group

What happens below the M scale?

Dine, Seiberg, Thomas, 2007

- In all generality, the superpotential at the leading order in 1/M:

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

Dimensionless and possibly **complex**

- Susy breaking parametrized by a chiral superfield spurion: $\mathcal{Z} = m_s \theta^2, \quad m_s \ll M$

with superpotential $$W_{\text{break}} = \alpha \frac{\omega}{2M} \mathcal{Z} (H_u H_d)^2$$

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- Tree level effective field theory obtained below the M scale (at the 1/M order):

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

Some definitions:

$$\lambda_5 = |\lambda_5| e^{i\phi_5} \equiv \frac{\alpha \omega m_s}{M}$$

$$\lambda_6 = |\lambda_6| e^{i\phi_6} \equiv \frac{\omega \mu^*}{M}$$

$$\lambda_8 \equiv |\omega|^2$$

ElectroWeak Symmetry Breaking

- λ_8 ensures that the potential is <u>bounded from below</u>
- At the minimum: $H_u = e^{i\theta_u}\begin{pmatrix} 0 \\ \frac{v_u}{\sqrt{2}} \end{pmatrix}, \quad H_d = e^{i\theta_d}\begin{pmatrix} \frac{v_d}{\sqrt{2}} \\ 0 \end{pmatrix}$ with non trivial θ_u, θ_d

1. $\theta_u - \theta_d$ is non physical (U(1) rotation)
2. $\theta_u + \theta_d \equiv \theta$ is instead physical and determined by

(Difference with the MSSM at the tree level)

$$\boxed{\frac{\partial V_{\rm ren}}{\partial \theta} = 0} \Rightarrow \boxed{v^2 c_\beta s_\beta |\lambda_5| \sin(\phi_5 + 2\theta) + v^2 |\lambda_6| \sin(\phi_6 + \theta) - 2B\mu \sin\theta = 0}$$

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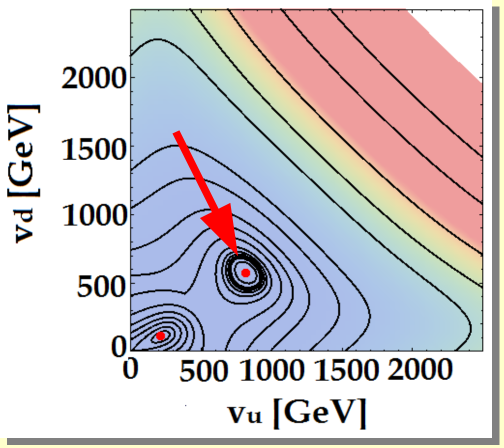
- The three conditions $\frac{\partial V_{\mathrm{ren}}}{\partial \mathrm{Re} H_u} = \frac{\partial V_{\mathrm{ren}}}{\partial \mathrm{Re} H_d} = \frac{\partial V_{\mathrm{ren}}}{\partial \theta} = 0$

and the requirement to have a positive definite hessian at v≠0 do <u>not</u> necessarily lead to a <u>unique solution</u>



Second minimum on the D-flat direction

see also Blum, Delaunay, Hochberg, 2009

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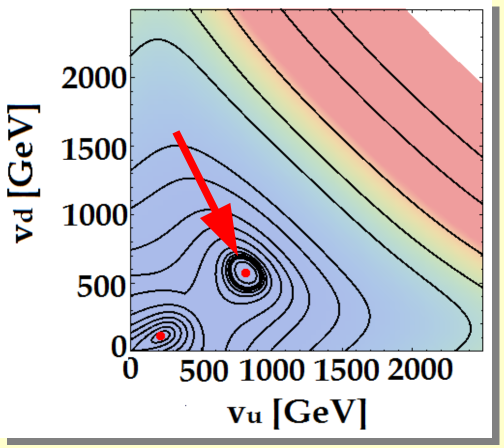

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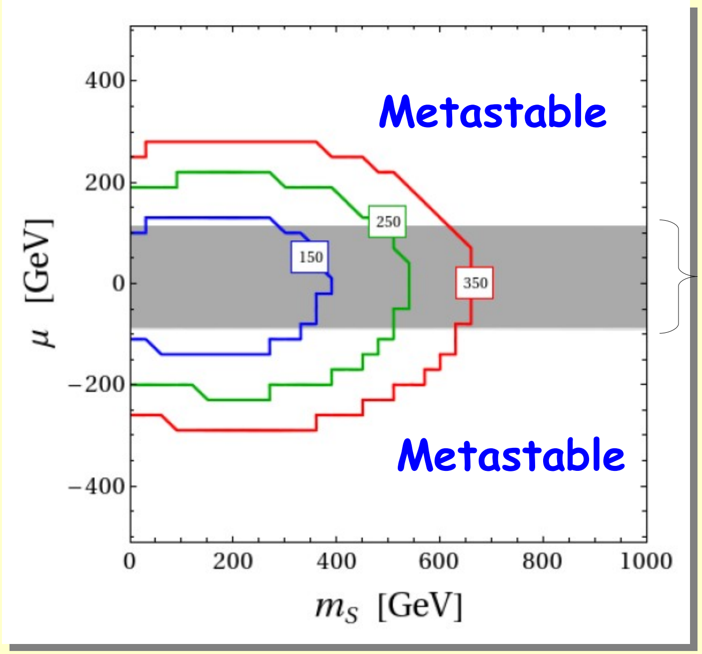


Chargino mass bound

The Higgs spectrum (1)

- In the MSSM at the tree level: $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_u \\ h_d \end{pmatrix}, \begin{pmatrix} G \\ A \end{pmatrix} = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} a_u \\ a_d \end{pmatrix}$

- In our BMSSM, thanks to the new sources of CP violation at the tree level all the three Higgs bosons mix

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

$$O^T \mathcal{M}_H^2 O = \mathrm{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2)$$

- <u>The lightest Higgs boson mass:</u>

Expanding in $1/t_\beta$ and $1/M$ (and assuming the decoupling limit):

$$M_{H_1}^2 \simeq M_Z^2 + \frac{4v^2}{\tan\beta}|\lambda_6|\cos(\phi_6+\theta) + \frac{v^4}{M_A^2}|\lambda_6|^2\cos^2(\phi_6+\theta)$$

The NP effects decouple with $\tan\beta$ and with M

- <u>The splitting between the two heavier Higgs bosons:</u>

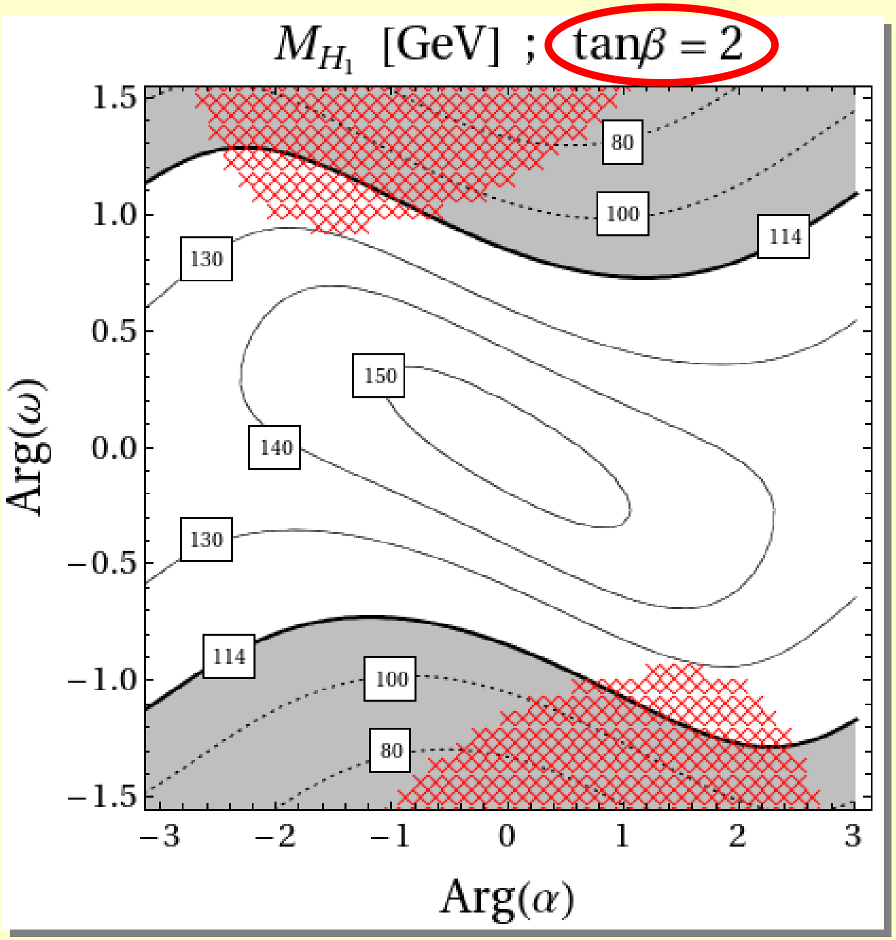
$$M_{H_3}^2 - M_{H_2}^2 \simeq v^2 \frac{|\alpha\omega| m_s}{M}$$

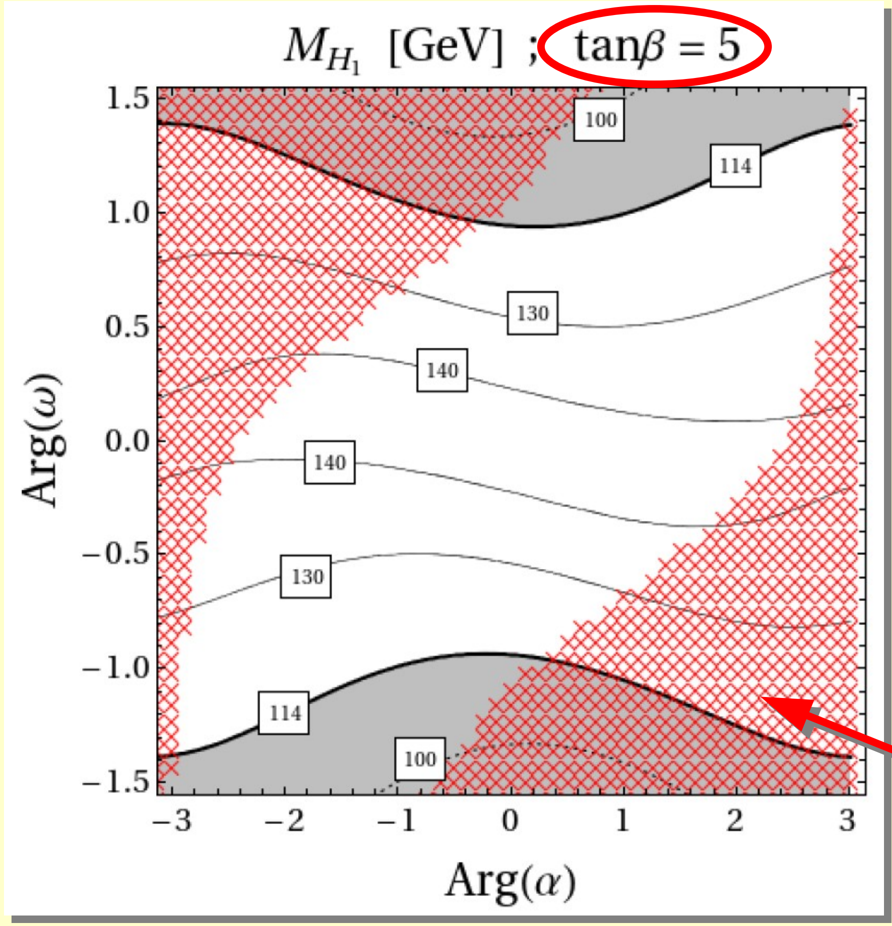
It can be much larger than the splitting one can get in the MSSM (m_W^2/t_β^2 suppressed) (important for flavor physics)

The interesting regime for Higgs physics is low tanβ and low values of M ((2-3)TeV)

The Higgs spectrum (2)

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





The EW minimum is metastable

The little hierarchy problem can be easily addressed
(both in the CP conserving and CP violating case)

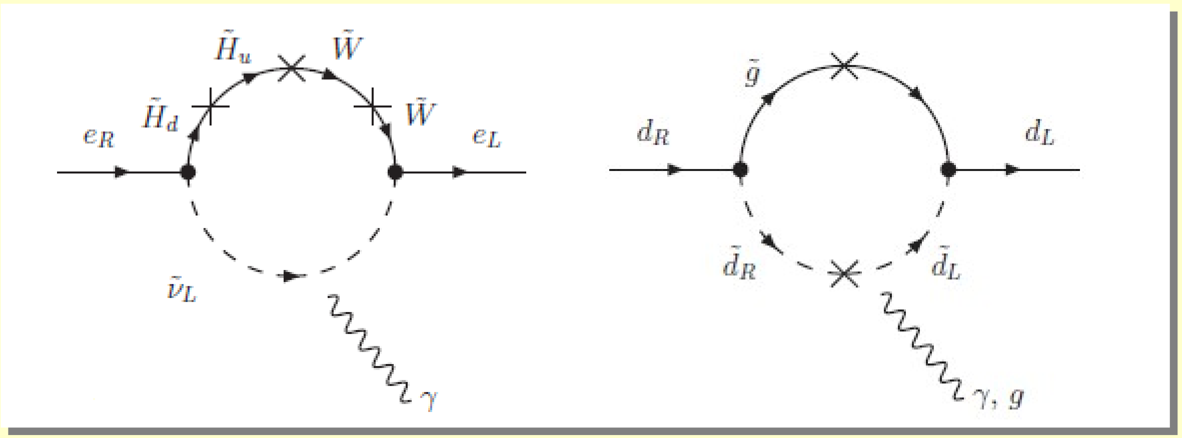
Experimental constraints on the NP phases

- Constraints from flavor observables (e.g. BR($B_s \to \mu\mu$)) are very mild since we are considering very low values of $\tan\beta$

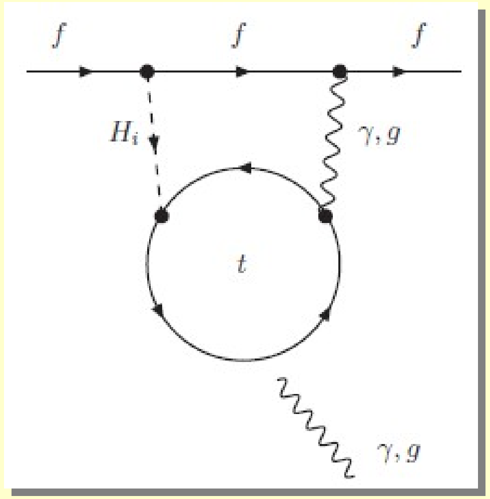
- Electric dipole moments (EDMs) instead...

Rather accurate	$-585 d_e \simeq d_{\mathrm{Tl}} \leq 9.4 \times 10^{-25}\, e\,\mathrm{cm}$ @ 90% C.L.
Factor 2-3 uncertainty	$7 \times 10^{-3} e(\tilde{d}_u - \tilde{d}_d) + 10^{-2} d_e \simeq d_{\mathrm{Hg}} \leq 3.1 \times 10^{-29}\, e\,\mathrm{cm}$ @ 95% C.L.
50% uncertainty	$1.4(d_d - 0.25 d_u) + 1.1 e(\tilde{d}_d + 0.5\tilde{d}_u) \simeq d_n \leq 2.9 \times 10^{-26}\, e\,\mathrm{cm}$ @ 90% C.L.

Main Susy contributions:



1-loop contributions



Barr-Zee contributions at 2-loops

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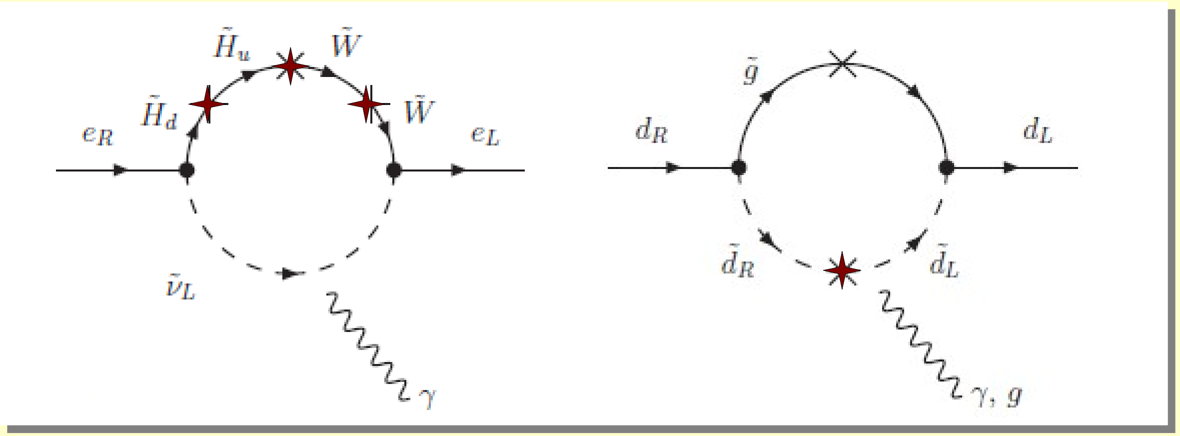
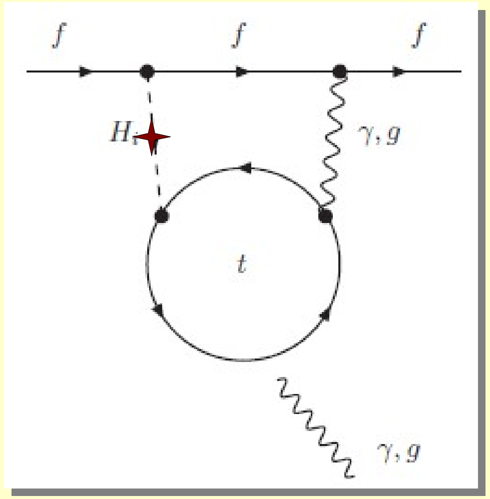




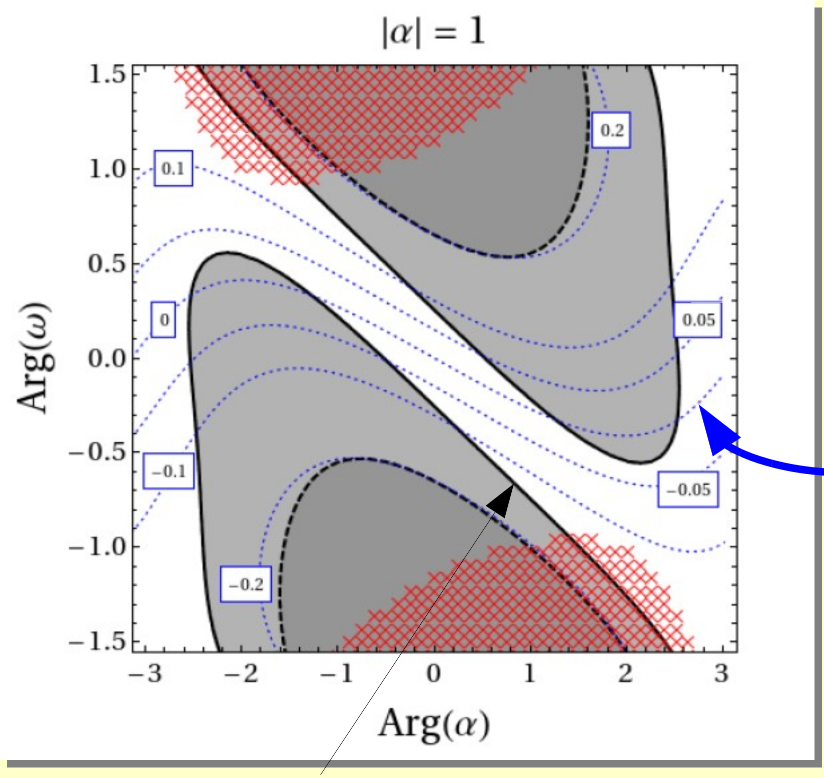
1-loop contributions

Barr-Zee contributions at 2-loops

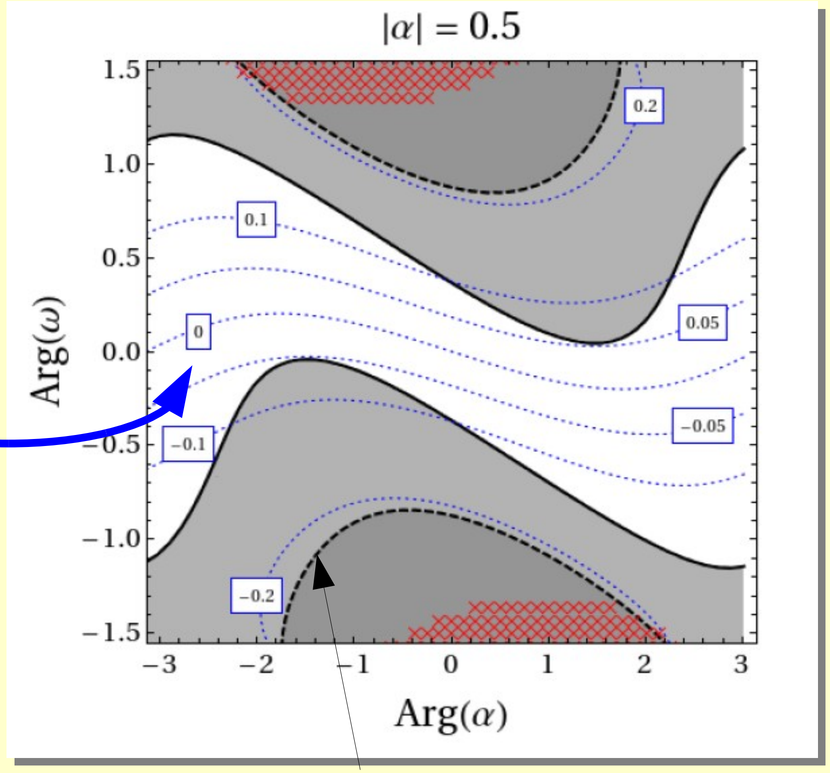
Large effects may arrise because of the presence of complex phases in Higgsino, chargino and squark mass matrices and of the scalar-pseudoscalar mixing in the Higgs sector (coming because of ω, α and θ)

Electric Dipole Moment constraint

$\tan\beta = 2,\ |\omega| = 1,\ \mu = m_s = 150\ \text{GeV},\ M = 1.5\ \text{TeV},$
$M_{H^\pm} = 200\ \text{GeV},\ \tilde{m} = 800\ \text{GeV},\ M_{\tilde{g}} = 1.2\ \text{TeV}$



Allowed



Most constraining is the Thallium EDM

Mercury EDM

(Assuming the presence of CP phases only in ω, α)

$$d_e^{\tilde{H}}/e \simeq \frac{\alpha_2}{4\pi}\, m_e\, \mathrm{Im}\left[e^{i\theta}\,\frac{t_\beta}{1+\epsilon_\ell t_\beta}\right]\frac{\mu M_2}{\tilde{m}^4}\, f_e(x_\mu, x_2)$$

Small values of θ are preferred

Interesting Higgs scenario (I)

1. What is the main difference with the BMSSM without CP violation? (see also Carena, Ponton, Zurita, 2010)
   Possibility of having the three neutral Higgs bosons all heavily mixed

2. What is the main differencewith the MSSM with CP violation?
   Possibility of having the lightest Higgs boson rather heavy

If the three Higgs bosons are heavily mixed then

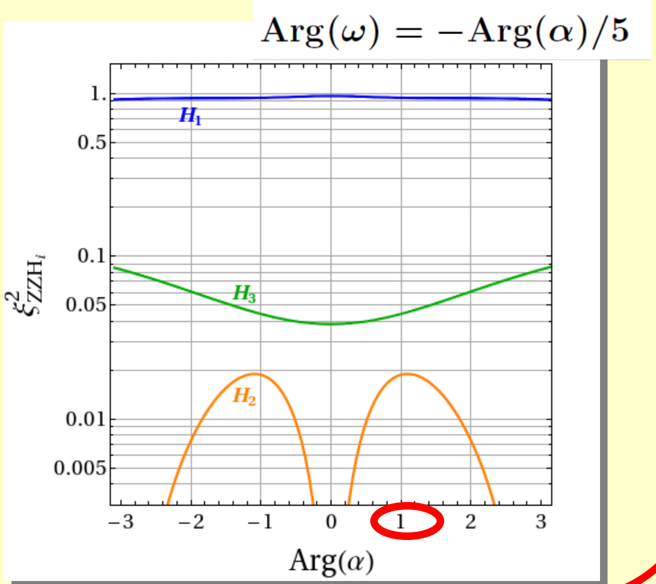
$$\xi_{WWH_i} = s_{\beta-\alpha} O_{1i} + c_{\beta-\alpha} O_{2i}$$
$$\sum_i \xi^2_{WWH_i} = 1$$

they can equally share the coupling with WW

Three Higgs bosons with $M_{hi} \gtrsim 140$ GeV and strongly mixed/decaying into WW

Scenario I	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)

In parenthesis the SM prediction for a Higgs boson of such a mass



Interesting Higgs scenario (II)

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they can equally share the coupling with WW

Three Higgs bosons $145 \lesssim M_{hi} \lesssim 160$ GeV and strongly mixed/decaying into bb

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
$\mathrm{BR}(H_i \to bb)$	69%(22%)	72%(16%)	65%(2%)
$\mathrm{BR}(H_i \to WW)$	20%(63%)	17%(69%)	26%(94%)
$\mathrm{BR}(H_i \to ZZ)$	3%(8%)	2%(8%)	1%(3%)
$\mathrm{BR}(H_i \to \gamma\gamma) \times 10^4$	6(16)	3(13)	0.5(4)

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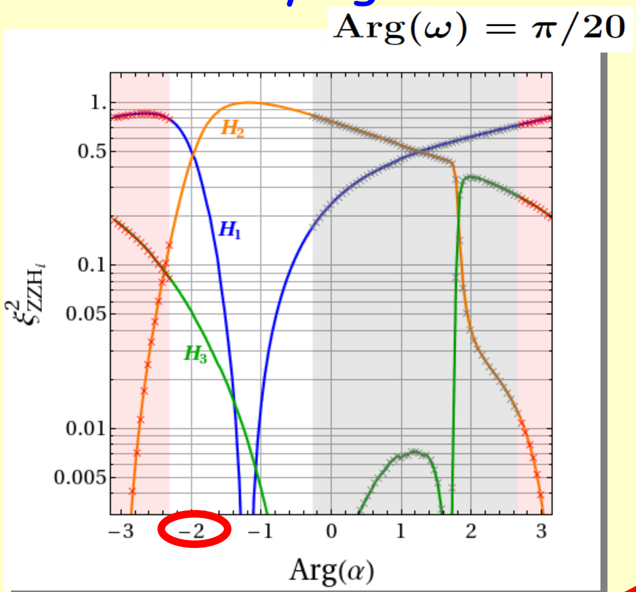
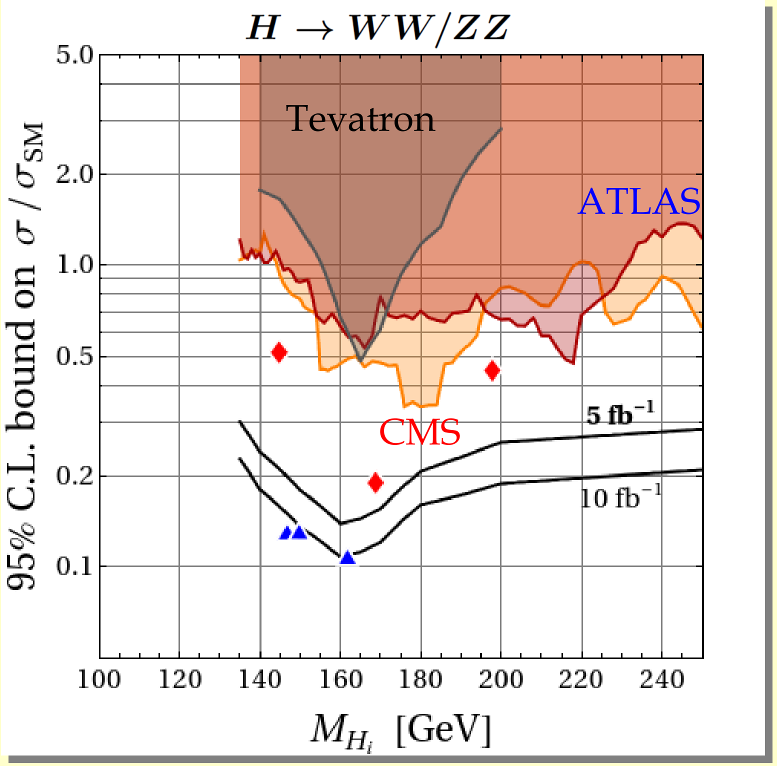
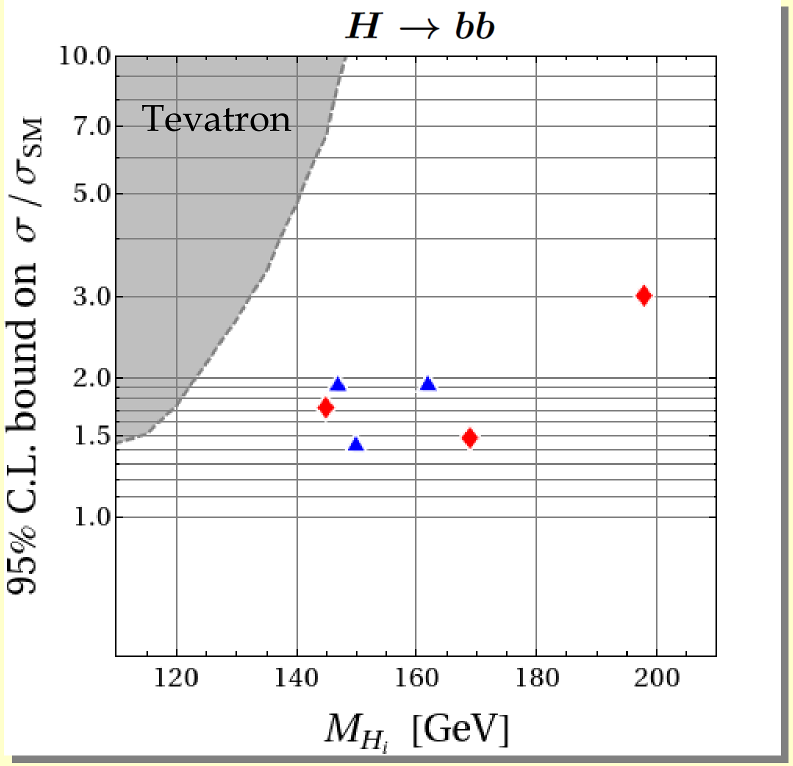


Sensitivity of the 7 TeV LHC

What are the chances for the LHC to discover these two scenarios in the near future?





Scenario I:

- All the three Higgs bosons can be easily probed at the LHC with a luminosity of 5 fb^{-1}

Scenario II:

- The main search channel is still the WW channel
- More than 10fb^{-1} are needed to probe all the three Higgs bosons

Conclusions and remarks

What:

Phenomenological study of a Susy effective field theory arising if BMSSM degrees of freedom are present at a few TeV scale (M), introducing new sources of CP violation

Higgs:

If M and tanβ are not too large:

- Lightest Higgs boson is naturally heavy

  Solution of the little hierarchy problem

- Large splitting between the two heavier Higgs bosons

  (effects in flavor physics)

- Interesting scenarios are found

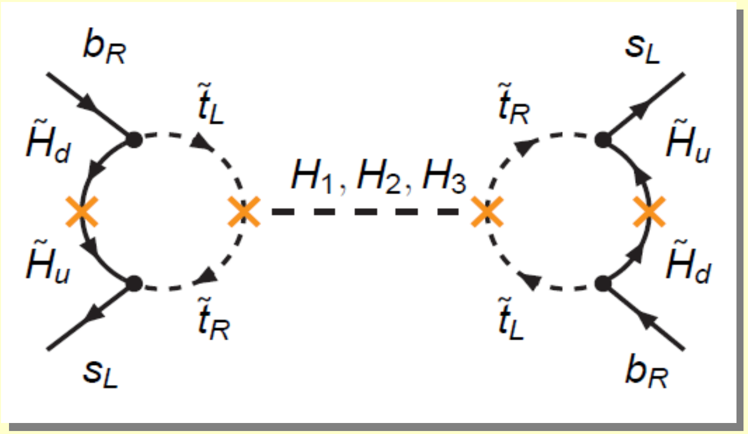
  All three Higgs bosons are heavily mixed and

  I. Decaying into WW — The discovery is around the corner

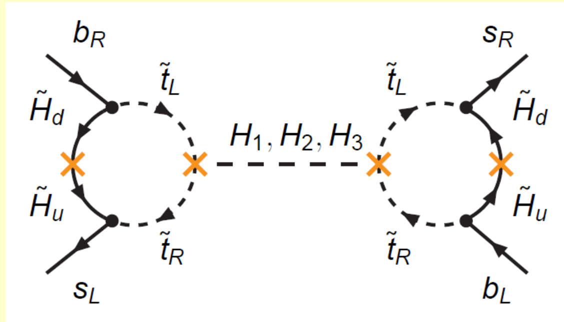
  II. Decaying into bb — More hidden to the LHC

Peculiar scenarios of the BMSSM with CP violation

BMSSM contributions to the Bs mixing phase



$$\tilde{O}_2 = \left(\bar{b}_R s_L\right)^2$$



$$O_4 = \left(\bar{b}_R s_L\right)\left(\bar{b}_L s_R\right)$$

$$C_4 \propto \frac{\alpha^3}{4\pi}\frac{1}{M_A^2}\left(V_{tb}V_{ts}^*\right)\frac{m_b m_s}{M_W^2}\, t_\beta^4\, \frac{|\mu A_t|}{\tilde{m}^4}\left(1 + \mathcal{O}\left(\frac{1}{M}\right)\right)$$

- In the MSSM, the contribution of the heavy scalar cancels approximately the contribution of the pseudoscalar (being the two Higgs almost degenerate)

same contribution as in the MSSM
(corrected only at the 1/M level)

- In the CP violating BMSSM, the sizable splitting between the two Higgs bosons brings to

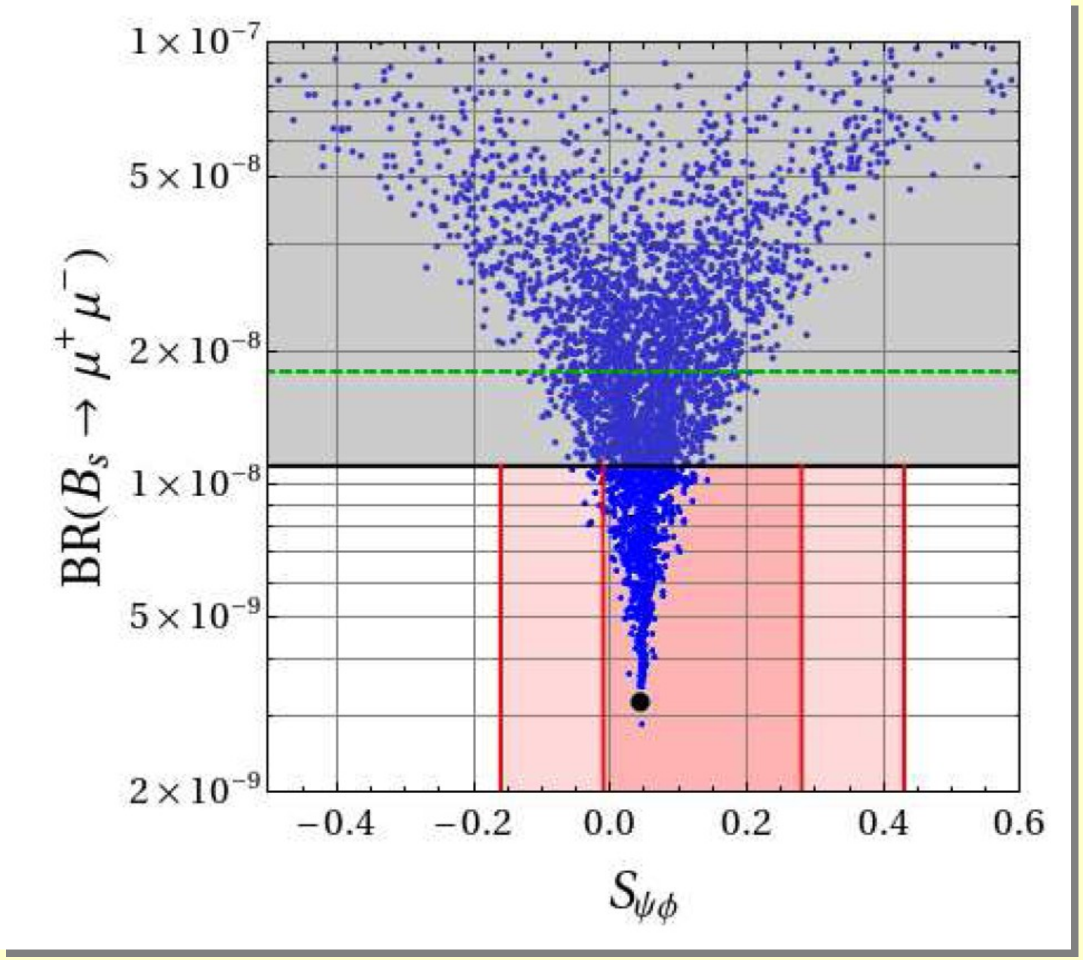
$$\tilde{C}_2 \propto \frac{\alpha^3}{4\pi}\frac{1}{M_A^2}\left(V_{tb}V_{ts}^*\right)\frac{m_b^2}{M_W^2}\, t_\beta^4\, \frac{(\mu A_t)^2}{\tilde{m}^4}\frac{\alpha\omega m_s}{M}\frac{v^2}{M_A^2}$$

Reminder:

$$M_{H_3}^2 - M_{H_2}^2 \simeq v^2\frac{|\alpha\omega| m_s}{M}$$

Main qualitative difference between the MSSM and the BMSSM in the flavor sector

CP violation in B_s mixing (2)



$B_s \to \mu\mu$ severly constrains possible values for the B_s mixing phase $\boxed{S_{\psi\phi} \lesssim 0.15}$

(still interesting in view of future LHCb sensitivity)

Higgs phenomenology: parameter scan

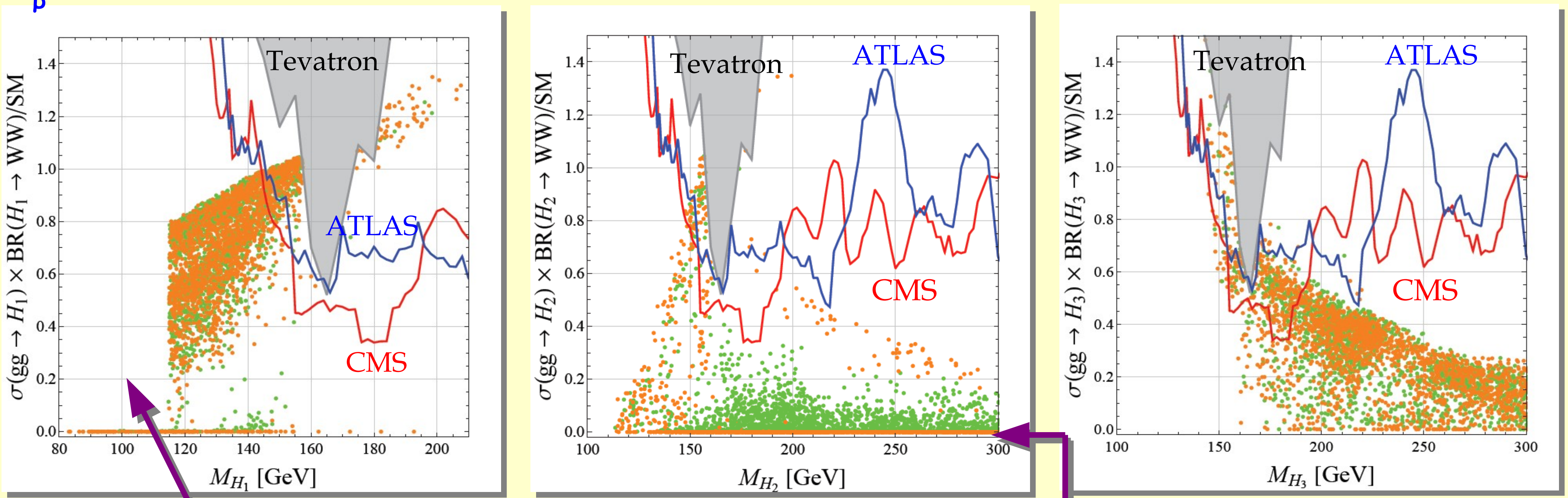
Most constrained decay mode: $H_i \to W^+W^-$

Tevatron bound: 8.2 fb^{-1}, arXiv:1103.3233

CMS bound: 1.7 fb^{-1}, CMS - PAS - HIG - 11 - 022

ATLAS bound: 2.3 fb^{-1}, ATL - CONF - 2011 - 135

(t_β=2)



Points excluded by LEP

Pseudoscalar Higgs boson

Orange: CP conserving case

Green: CP violating case

<u>Not too big differences</u> between the CP conserving and CP violating case, **but...**