Signals of CP Violation Beyond the MSSM at the LHC

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Outline

1. Introduction: something beyond the MSSM?

- The little hierarchy problem
- CP violation in the B_s mixing system

2. The BMSSM at low tanβ

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

3. The BMSSM at sizable tanβ

- B_s mixing phase

4. 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)

LHC is running...

What will it find?

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Nobody knows...

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What will it 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

What if LHC does not satisfy these predictions?

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

Two issues in the MSSM

1. In the MSSM:

Very well motivated model but

Little hierarchy problem:

Problem of fine tuning,

arising because the lightest Higgs boson is too light

What about a Susy effective field theory with a heavy lightest Higgs boson & new sources of CP violation?

The little hierarchy problem

Barbieri, Strumia, 1998

- In the MSSM at the tree level: $m_h \leq m_Z \cos 2\beta$ but
- The lightest Higgs is SM like in most of the parameter space

→ LEP bound: $m_h \geq 114.4\ \mathrm{GeV}$

- Need of large loop contributions

$$\Delta m_h^2 \sim \frac{3\alpha}{2\pi \sin^2\theta} \frac{m_t^4}{m_W^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

⇒ Relatively heavy stops (~ TeV) are required (or heavily mixed)

But also

$$\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1}$$

Quadratic dependence on the stop mass

Fine tuning!

MSSM after LEP

Perturbativity

Unification

EWPT

DM ?

Naturalness ??

$m_h \leq 120\mathrm{GeV}$

A heavier Higgs boson at the tree level

A rich literature on extensions of the MSSM which increase the tree level Higgs boson mass

Enhancing the quartic coupling:

Some possibility:

- U(1) gauge extensions: $$m_h^2 \leq \left(m_Z^2 + \frac{g_X^2 v^2}{2\left(1 + \frac{M_X^2}{2M_\Phi^2}\right)} \right) \cos^2(2\beta)$$

  Batra, Delgado, Kaplan, Tait (2004)

  See also Bellazzini, Csaki, Delgado, Welier (2009)

- SU(2) gauge extensions: $$m_h^2 \leq m_Z^2 \frac{g'^2 + \eta g^2}{g'^2 + g^2} \cos^2(2\beta) \qquad \eta = \frac{1 + \frac{g_I^2 M_\Xi^2}{g^2 M_X^2}}{1 + \frac{M_\Xi^2}{M_X^2}}$$

  Batra, Delgado, Kaplan, Tait (2004),
  Maloney, Pierce, Wacker (2006)

- NMSSM & λSusy: $$m_h^2 \leq m_Z^2 \left(\cos^2(2\beta) + \frac{2\lambda^2}{g^2 + g'^2} \sin^2(2\beta) \right)$$

  Harnik, Kribs, Larson, Murayama (2004)
  Barbieri, Hall, Nomura, Rychkov (2007)

  See also Franceschini, Gori (2010)

...

What can we say model independently?

Two issues in the MSSM

1. In the MSSM:

Very well motivated model but

Little hierarchy problem:

Problem of fine tuning,

arising because the lightest Higgs boson is too light

2. CP violation & the MSSM:

- The SM CP violation is not sufficient to generate the baryon-antibaryon asymmetry

and

- Also the MSSM has problems generating a correct asymmetry

- Still some NP room in some CP violating observables as $S_{\psi\varphi}$ (B_s mixing phase)

What about a Susy effective field theory with a heavy lightest Higgs boson & new sources of CP violation?

CP violation

- In the **SM** there are only two sources of CP violation:
  - CKM phase
  - Strong CP phase

→ Not sufficient to fit the baryon asymmetry of the universe

- In the **MSSM** there are plenty of new sources of CP violation (soft masses, trilinear terms, μ)

Carena, Nardini, Quiros and Wagner, 2008

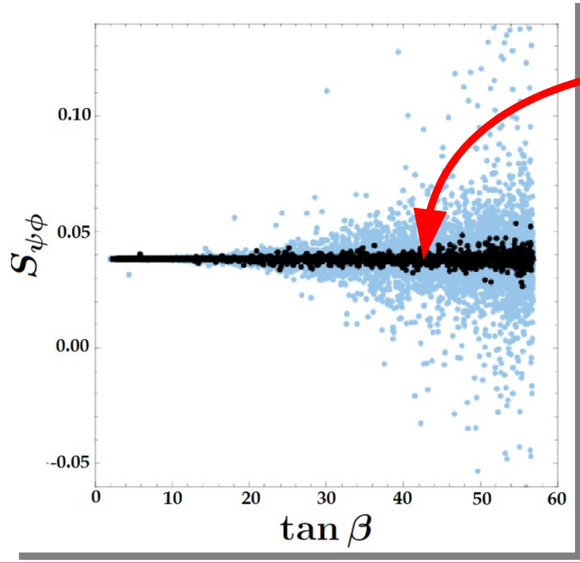
Still, to reproduce the correct baryon-antibaryon asymmetry, a very light stop is needed

difficult!

In addition, assuming a Minimal Flavor Violating (MFV) structure, New Physics (NP) contributions to ΔF=2 flavor observables as $S_{\psi\varphi}$ are really limited

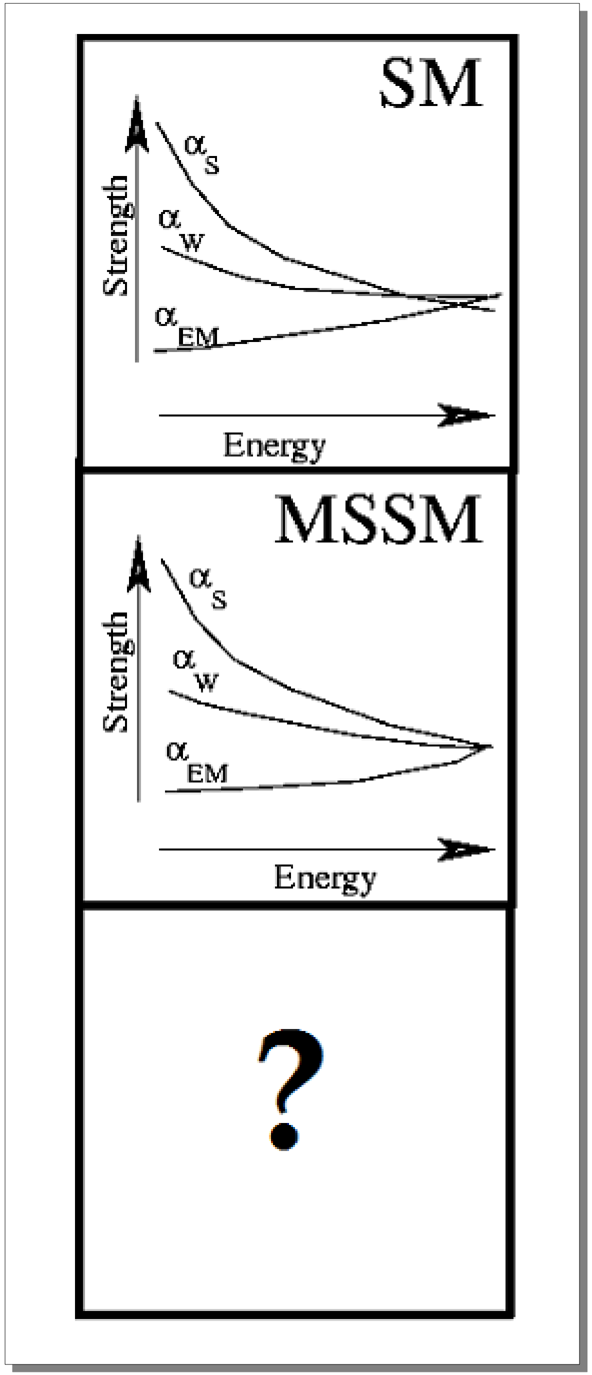
$S_{\psi\varphi} \sim 0.2$
is still allowed
by present experiments
(LHCb)

(LHCb-CONF-2011-056)



Points satisfying the constraints from $BR(B_s \to \mu\mu)$ and $BR(b \to s\gamma)$

Altmannshofer, Buras, SG, Paradisi, Straub, Nucl.Phys.B830:17-94,2010



Beyond the MSSM (theory)

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

Dine, Seiberg, Thomas, 2007

What happens below the M scale?

- 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):

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

Some definitions:

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

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

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

EWSB: a physical phase at the minimum

- λ_8 ensures that the potential is bounded from below

- At the minimum of the potential: $H_u = e^{i\theta_u}\begin{pmatrix} 0 \\ \frac{v_u}{\sqrt{2}} \end{pmatrix}, \quad H_d = e^{i\theta_d}\begin{pmatrix} \frac{v_d}{\sqrt{2}} \\ 0 \end{pmatrix}$ 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

$$\frac{\partial V_{\text{ren}}}{\partial \theta} = 0$$

Contrary to the MSSM at the tree level

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

This phase will be crucial for EDMs

EWSB: the metastable case (1)

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

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

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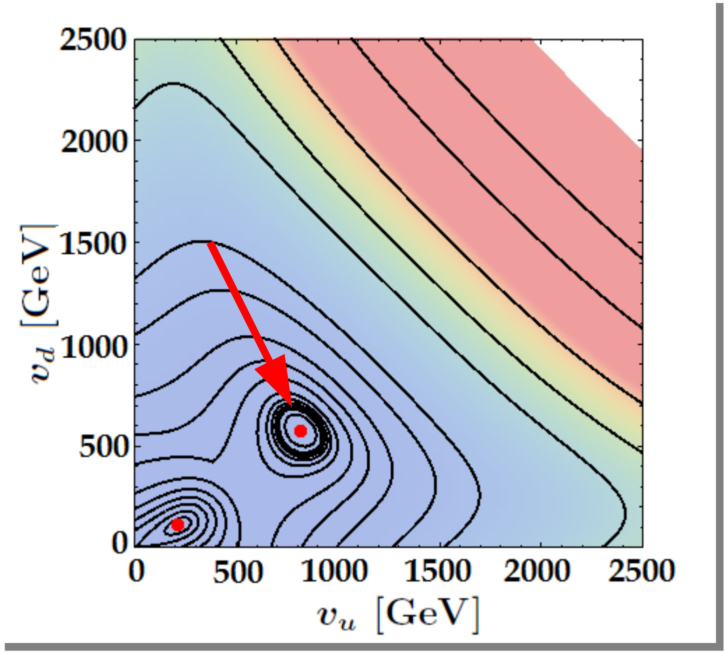
  and the requirement to have a positive definite hessian at v≠0 do not necessarily lead to a unique solution

- If the quartic couplings along the D-flat direction are negative, a second minimum in the vu, vd plane can appear



$$M_A = M_{H^\pm} = 275 \text{ GeV}, \ \tan\beta = 2, \ \alpha = -1, \ \omega = 1,$$

$$m_{\tilde{t}} = A_t = 500 \text{ GeV}, \ \mu = m_s = 200 \text{ GeV}, \ M = 1 \text{ TeV}$$

Different from the MSSM:

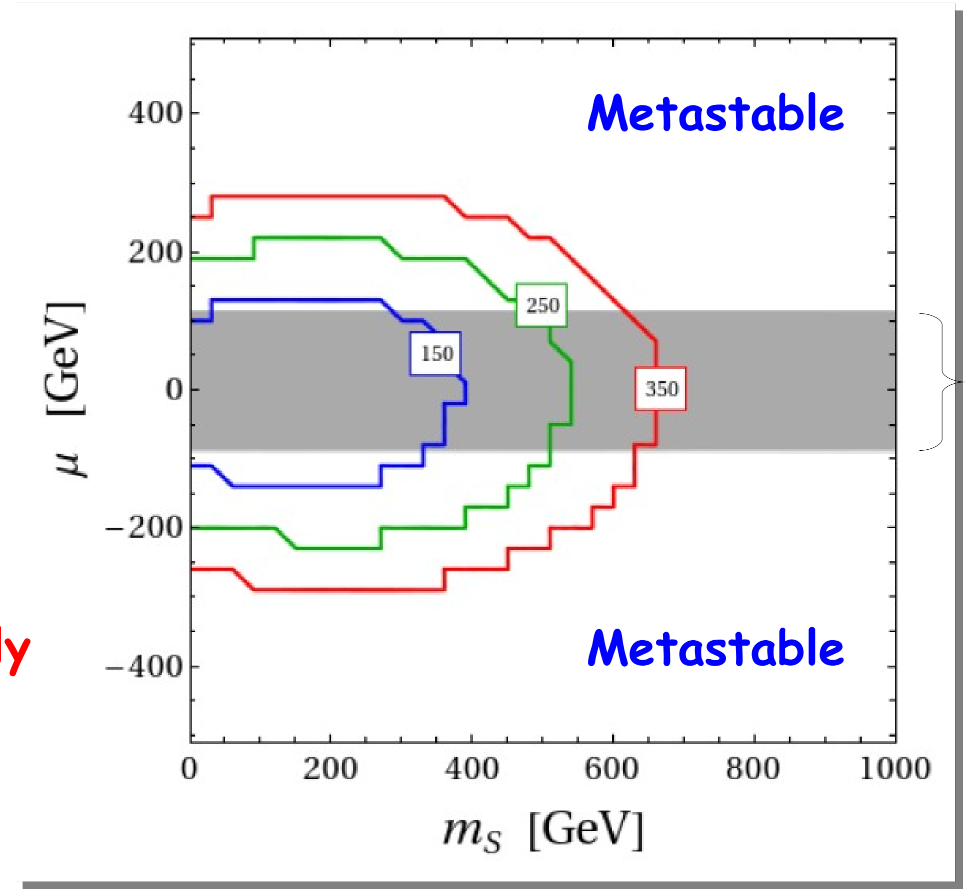
$$V^4_{\rm BMSSM} = \alpha \frac{\omega m_s}{2M}(H_u H_d)^2 - \frac{\omega \mu^*}{M}(H_u H_d)(|H_u|^2 + |H_d|^2) \ + \ h.c.$$

$$V^4_{\rm MSSM} = \frac{g_2^2}{8c_W}\left(|H_u|^2 - |H_d|^2\right)^2 + \frac{g_2^2}{2}|H_u^\dagger H_d|^2 \geq 0$$

EWSB: the metastable case (2)

This second minimum can be deeper than the EW minimum at v=246GeV ⇒ **The EW minimum is metastable**

Requirement of absolute stability of the EW minimum →



LEP Chargino mass bound

The chargino mass is strongly bounded from above

$$M = 2\,\text{TeV},\ \tan\beta = 2,\ |\omega| = |\alpha| = 1,$$
$$m_{\tilde t} = 800\,\text{GeV},\ \text{Arg}(\alpha) = \text{Arg}(\omega) = \pi/2$$

see also Blum, Delaunay, Hochberg, 2009

The Higgs spectrum (1)

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

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

$$\mathcal{M}_H^2 = \begin{pmatrix} M_h^2 & 0 & M_{hA}^2 \\ 0 & M_H^2 & M_{HA}^2 \\ M_{hA}^2 & M_{HA}^2 & M_A^2 \end{pmatrix} \qquad O^T \mathcal{M}_H^2 O = \mathrm{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2)$$

- The lightest Higgs boson mass:

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 tanβ and with M

- The splitting between the two heavier Higgs bosons:

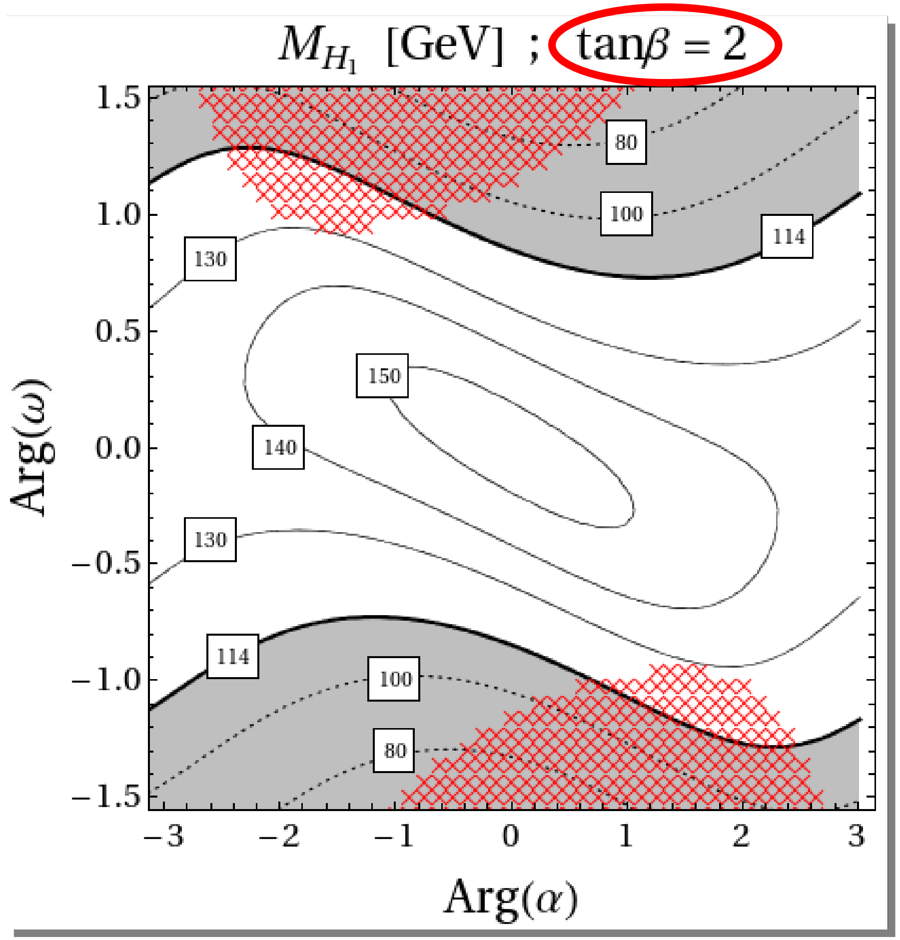
$$M_{H_3}^2 - M_{H_2}^2 \simeq v^2 \frac{|\alpha\omega| m_s}{M}$$

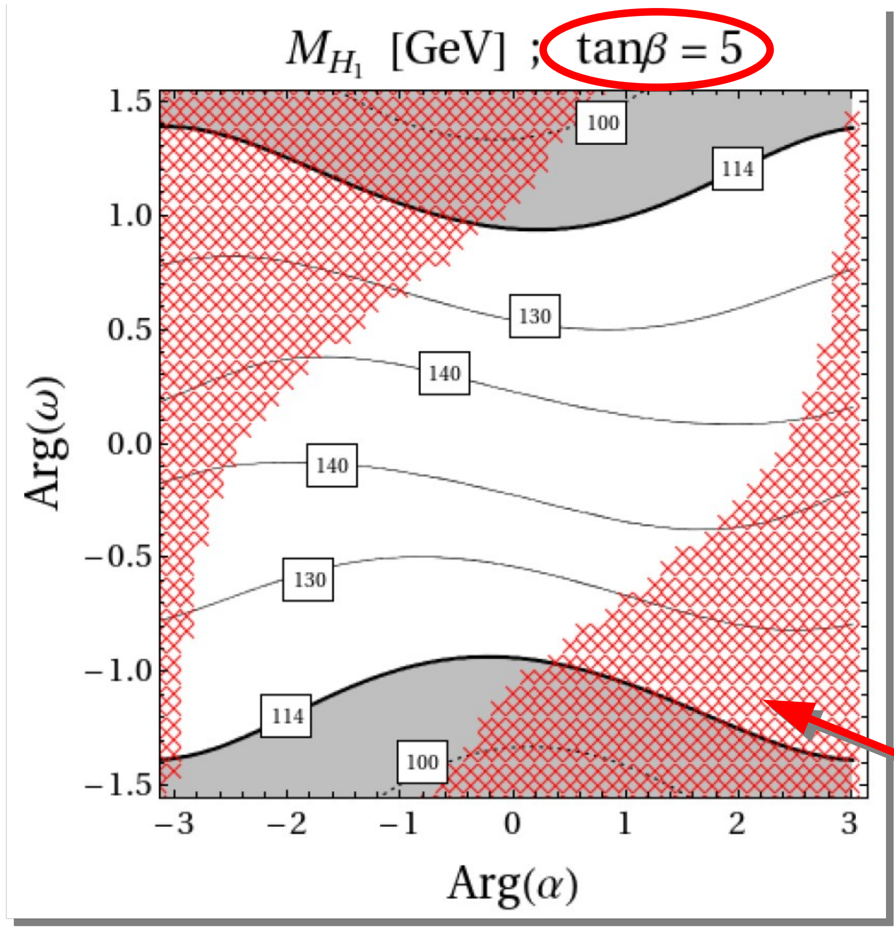
It can be much larger than the splitting one can get in the MSSM (m_W^2/t_β^2 suppressed)

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

The Higgs spectrum (2)

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



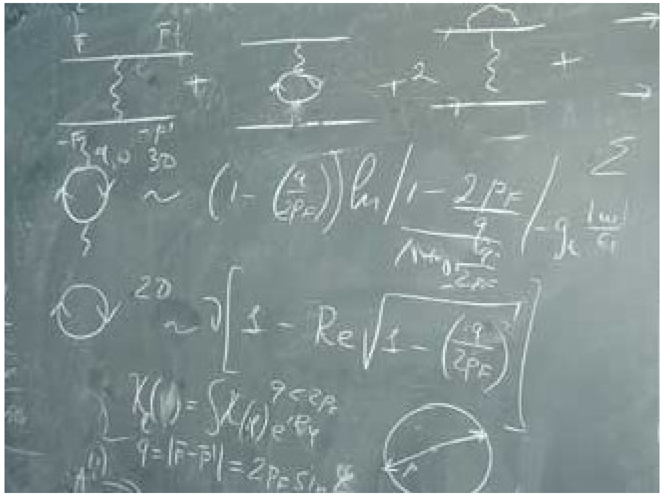


The EW minimum is metastable

The little hierarchy problem can be easily addressed

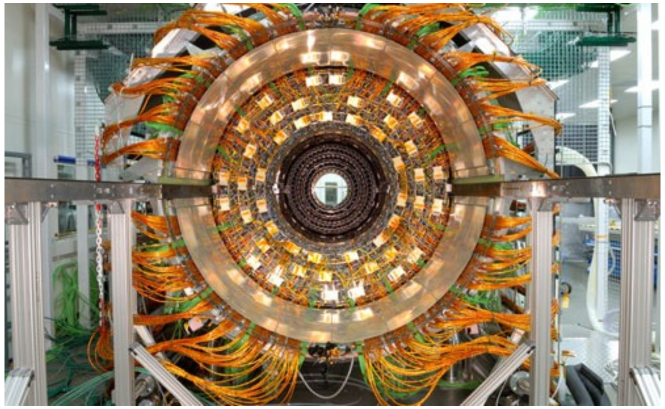
(both in the CP conserving and CP violating case)

Theory



vs.

Experiment



Is the model viable?

Brief summary:

EDMs

LEP and Tevatron constraints on the Higgs boson

LHC constraints (Higgs + superparticles)

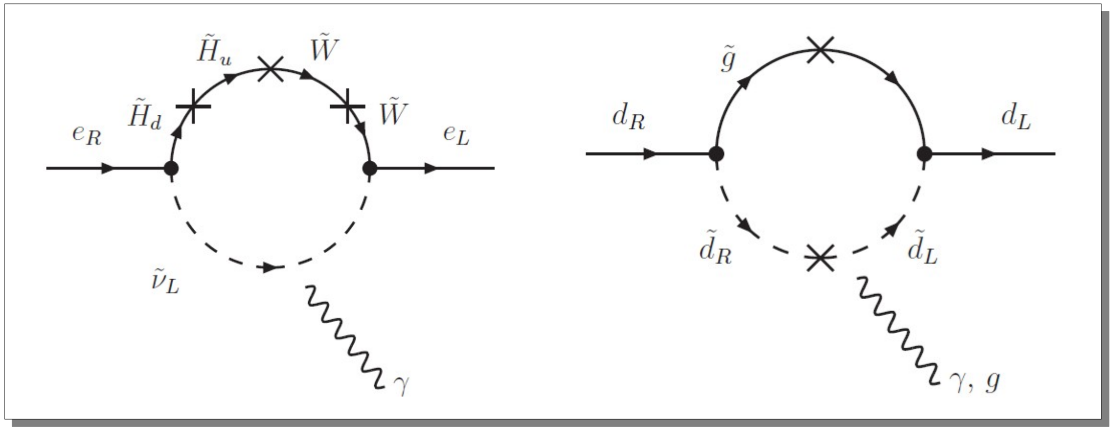
Electric Dipole Moments (1)

Experimental status and theoretical prediction:

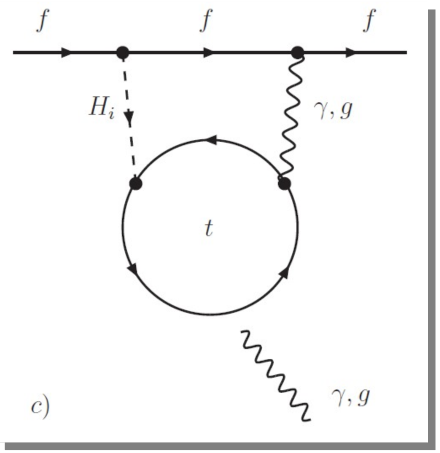
Usually they represent very strong constraints on new CP violating phases

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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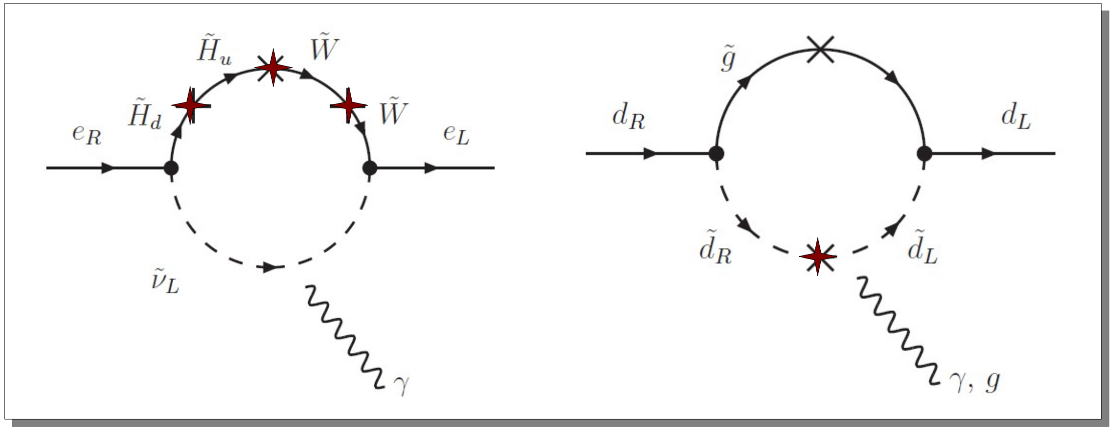

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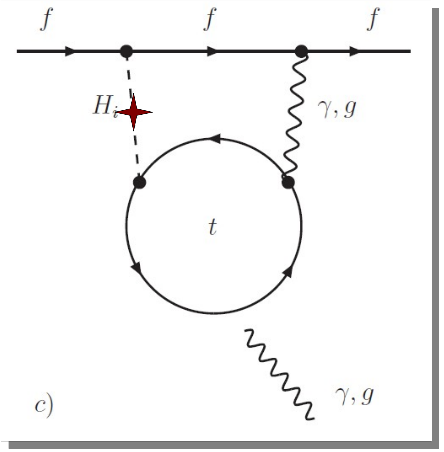
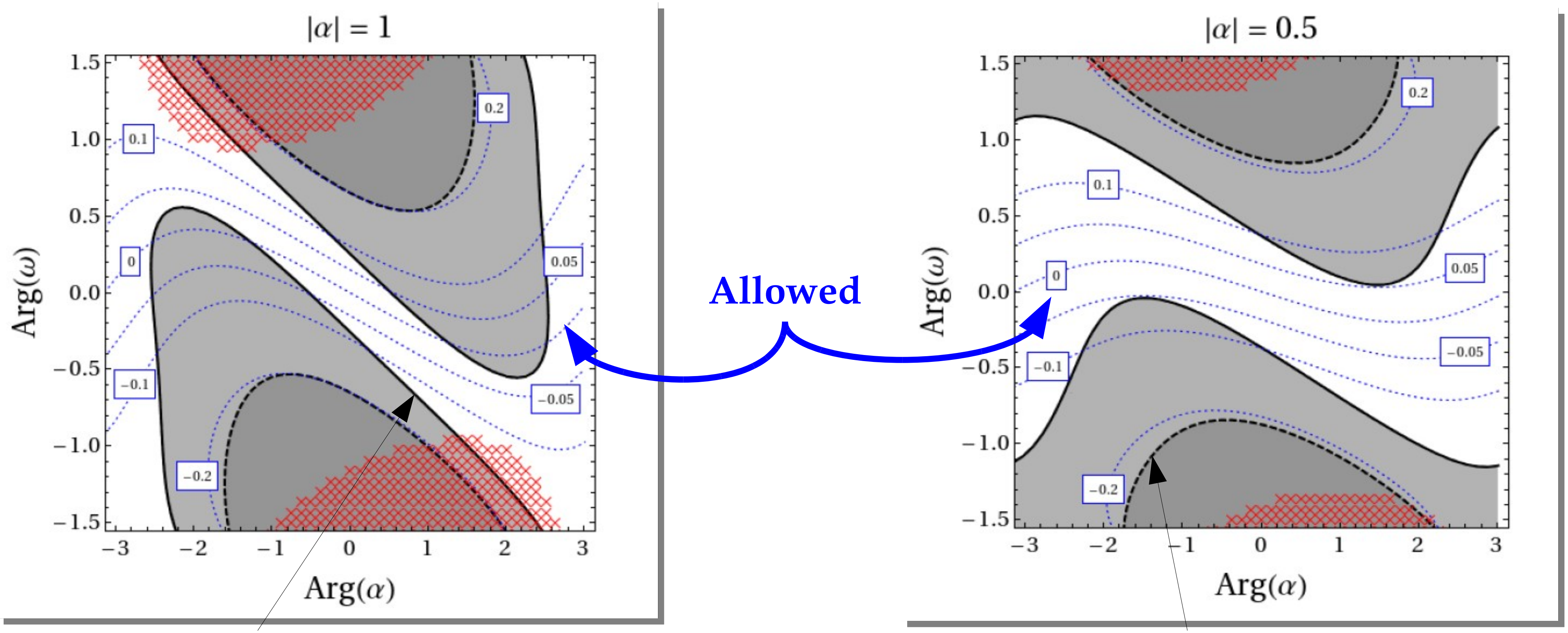


Barr-Zee contributions at 2-loops

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 Moments (2)

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



Most constraining is the Thallium EDM

Mercury EDM

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

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

Small values of θ are preferred

Still θ =0 is not the perfect solution, because of the 1/M suppressed correction to the Higgsino mass

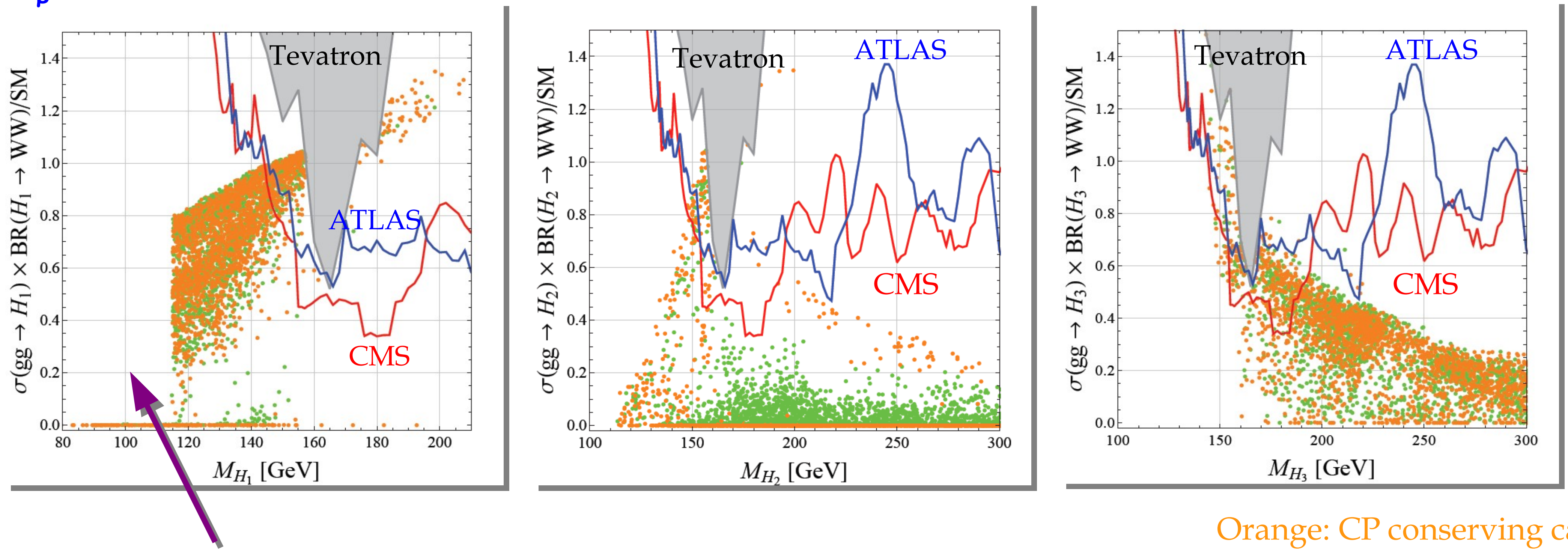
$$\mu e^{i\theta} \to \mu e^{i\theta} - \omega \frac{v^2}{M} s_\beta c_\beta e^{2i\theta}$$

LEP-Tevatron-LHC Higgs searches

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

Orange: CP conserving case
Green: CP violating case

Plenty of points with large CP violating phases in ω, a are allowed

Characteristic Higgs scenarios

A great scenario for the LHC (1)

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

Why is it interesting?

Such a scenario is not possible either in the MSSM,
or in the BMSSM without CP violation

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 mixed

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

If the three Higgs bosons are all 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

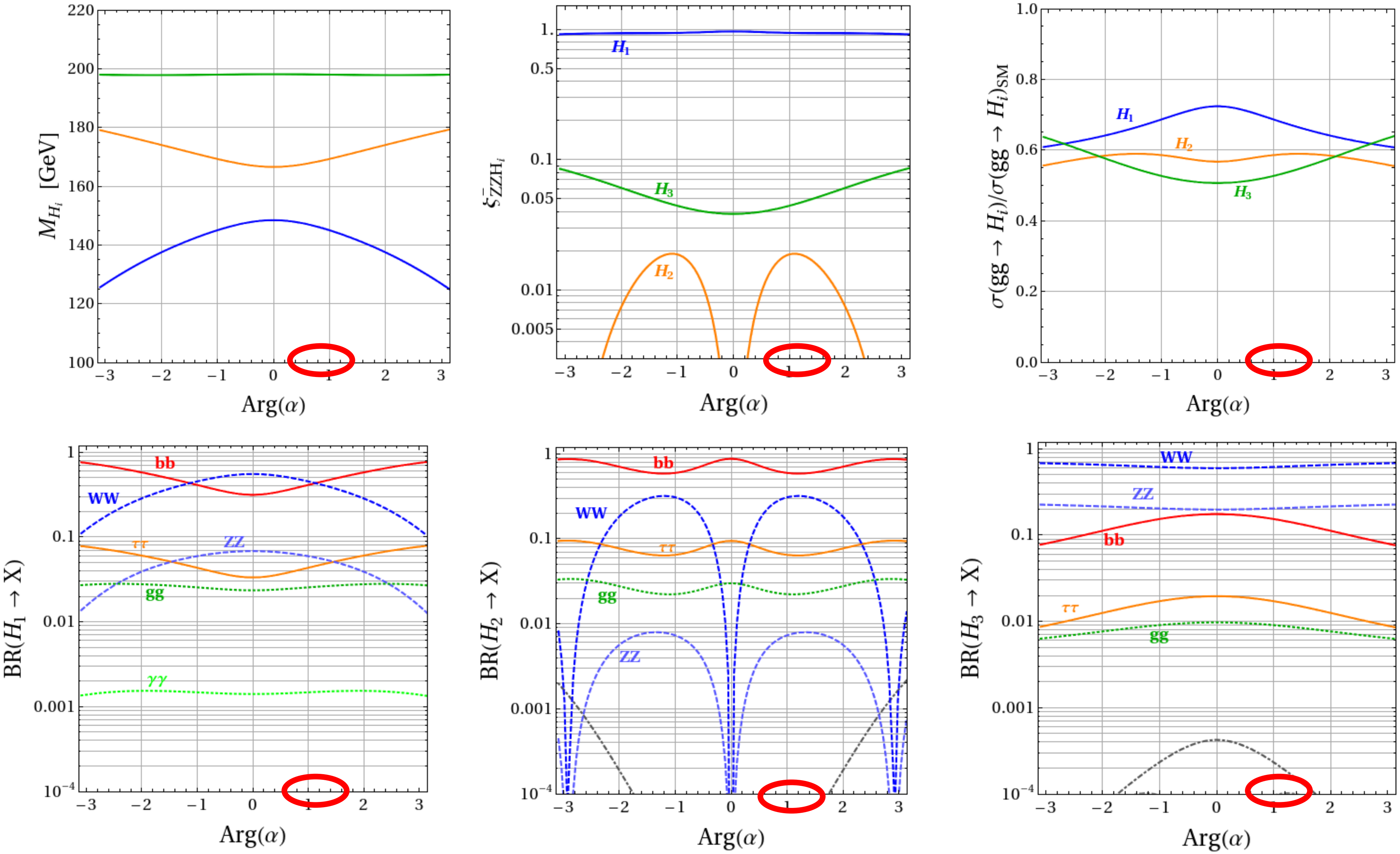
⇨ Bounds coming from LHC Higgs searches are rather severe

A great scenario for the LHC (2)

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

$\mathrm{Arg}(\omega) = -\mathrm{Arg}(\alpha)/5$

$\tan\beta = 2$



$\xi^2_{ZZH_1} = 0.94$

$\xi^2_{ZZH_2} = 0.02$

$\xi^2_{ZZH_3} = 0.04$

A more hidden scenario for LHC (1)

Three Higgs bosons rather close in mass $145 \lesssim M_{hi} \lesssim 160$ GeV

and heavily mixed/decaying mainly into bb

WW channel is kinematically suppressed

Why is it interesting?

Such a scenario is not possible either in the MSSM, or in the BMSSM without CP violation

1. What is the main difference with the BMSSM without CP violation?

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(see also Carena, Ponton, Zurita, 2010)

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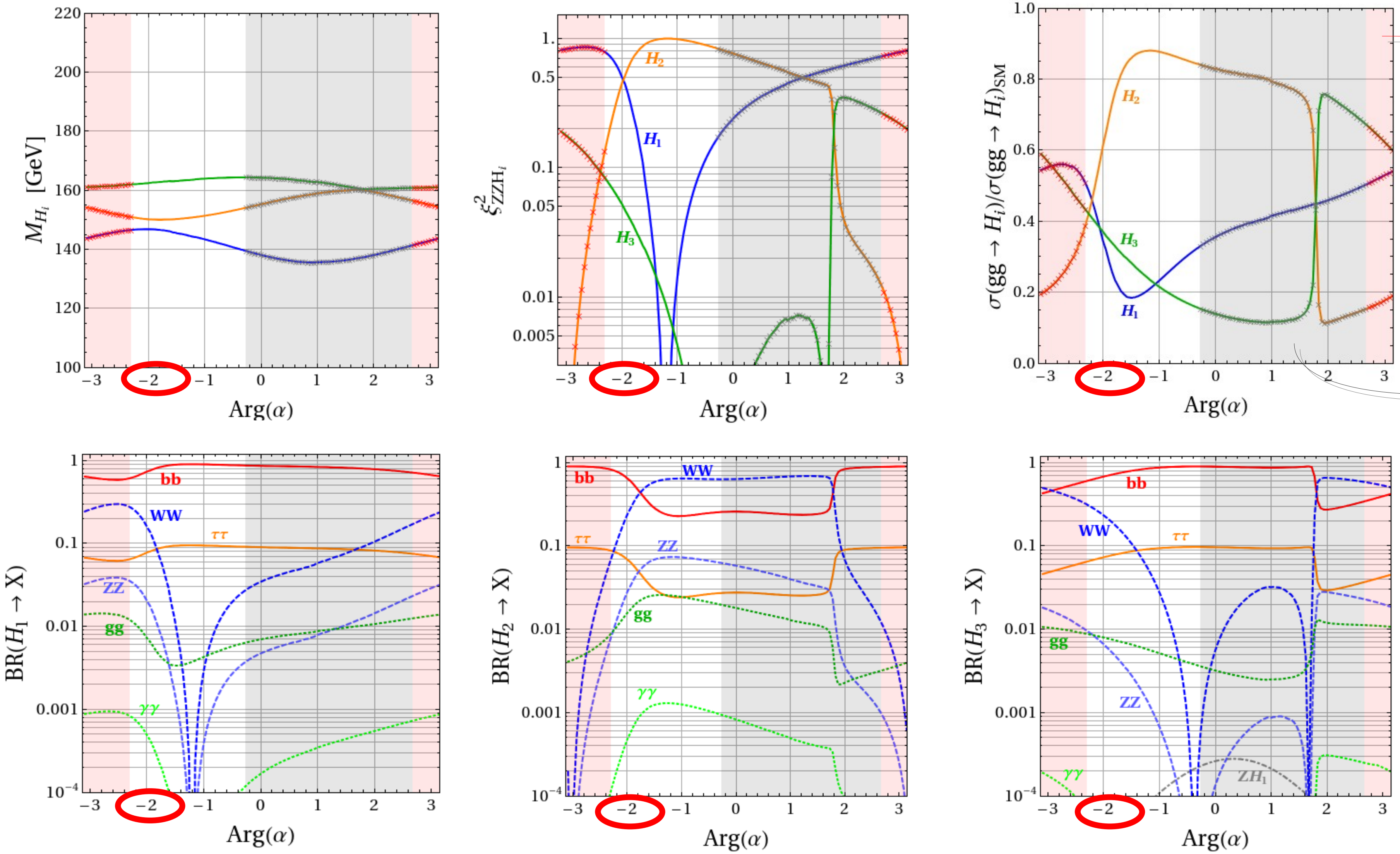
they can equally share the coupling with WW

⇒ The main constraint from the scenario comes still from LHC searches of Higgs to WW, since the bb channel is studied by Tevatron only for masses $\lesssim$140GeV

Three Higgs bosons rather close in mass $145 \lesssim M_{hi} \lesssim 160$ GeV

and heavily mixed/decaying mainly into bb



$\mathrm{Arg}(\omega) = \pi/20$

$\tan\beta = 3$

Excluded by vacuum stability

Excluded by EDMs

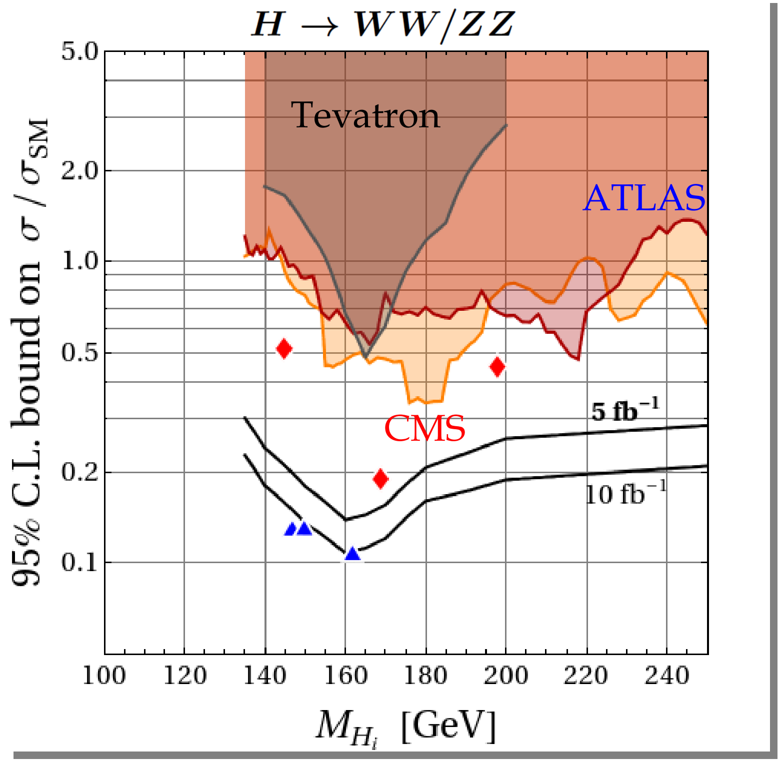
$\xi^2_{ZZH_1} = 0.62$

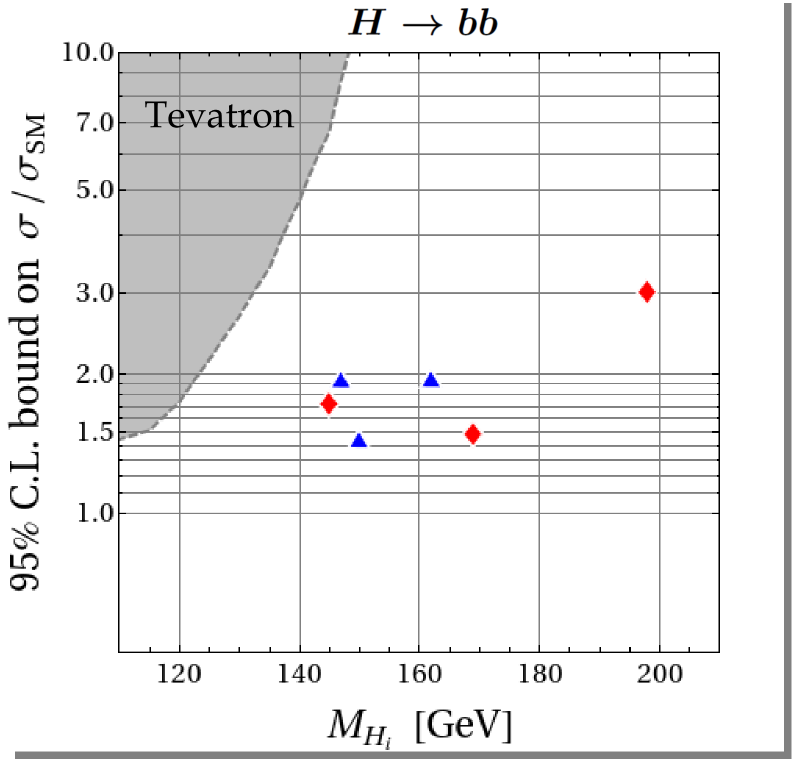
$\xi^2_{ZZH_2} = 0.32$

$\xi^2_{ZZH_3} = 0.06$

Sensitivity of the 7 TeV LHC

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



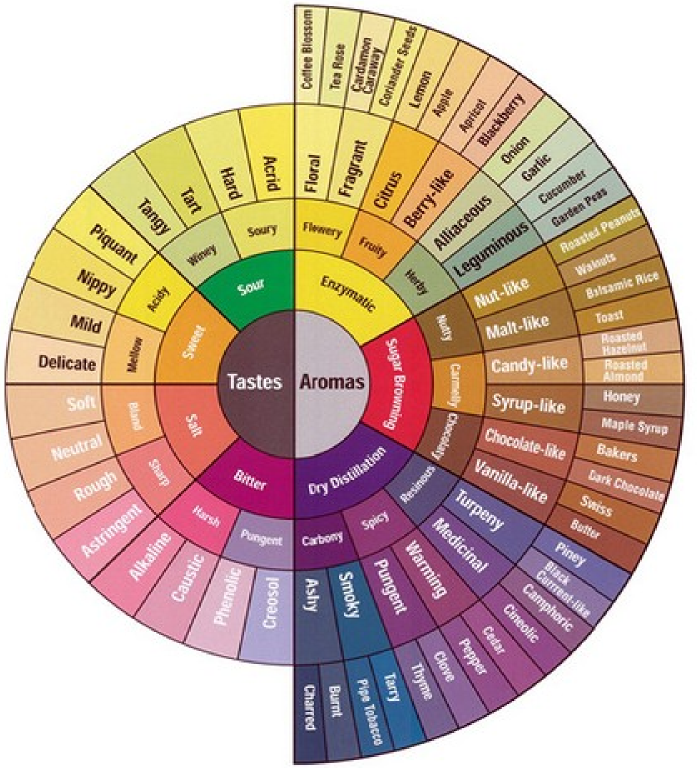


Scenario I:

- 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



The model at large tanβ: What about flavor?

The CP asymmetry of the B_s mixing system (1)

Status of flavor physics in two sentences

- Very stringent constraint coming from the measurement of many flavor observables, e.g. $\Delta M_{s,d},\ \varepsilon_K,\ b \to s\gamma$
- Some other observables have not been measured precisely yet

→ Still room for NP, e.g. in $S_{\psi\phi}$ + New! Direct CP asymmetry in D decays

- Schrödinger equation describing the B_s mixing

$$i\partial_t \begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix} = \left(M^s + \frac{i}{2}\Gamma^s \right) \begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix} \Rightarrow |M_{12}^s|,\ |\Gamma_{12}^s|,\ \phi_s = -\arg\left(\frac{M_{12}^s}{\Gamma_{12}^s}\right)$$

- Physical observables:

1. Mass and width difference: $\Delta M_s = 2\,|M_{12}^s|,\quad \Delta\Gamma_s = 2\,|\Gamma_{12}^s| \cos\phi_s$

2. CP asymmetry: $a_{SL}^s \equiv \frac{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)}{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)} = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$ (Semileptonic asymmetry)

or

$$S_{\psi\phi} = \frac{1}{\sin(\Delta M_s t)} \cdot \frac{\Gamma(\bar{B}_s \to \psi\phi) - \Gamma(B_s \to \psi\phi)}{\Gamma(\bar{B}_s \to \psi\phi) + \Gamma(B_s \to \psi\phi)} \sim -\sin(\phi_s)$$

- Model-independent relation

(Ligeti, Papucci, Perez '06; Grossman, Nir, Perez '09)

$$a_{SL}^s = -\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|^{SM} S_{\psi\phi} = -\frac{\Delta\Gamma_s}{\Delta M_s}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi}^2}}$$

(In the assumption of small φ_s^{SM})

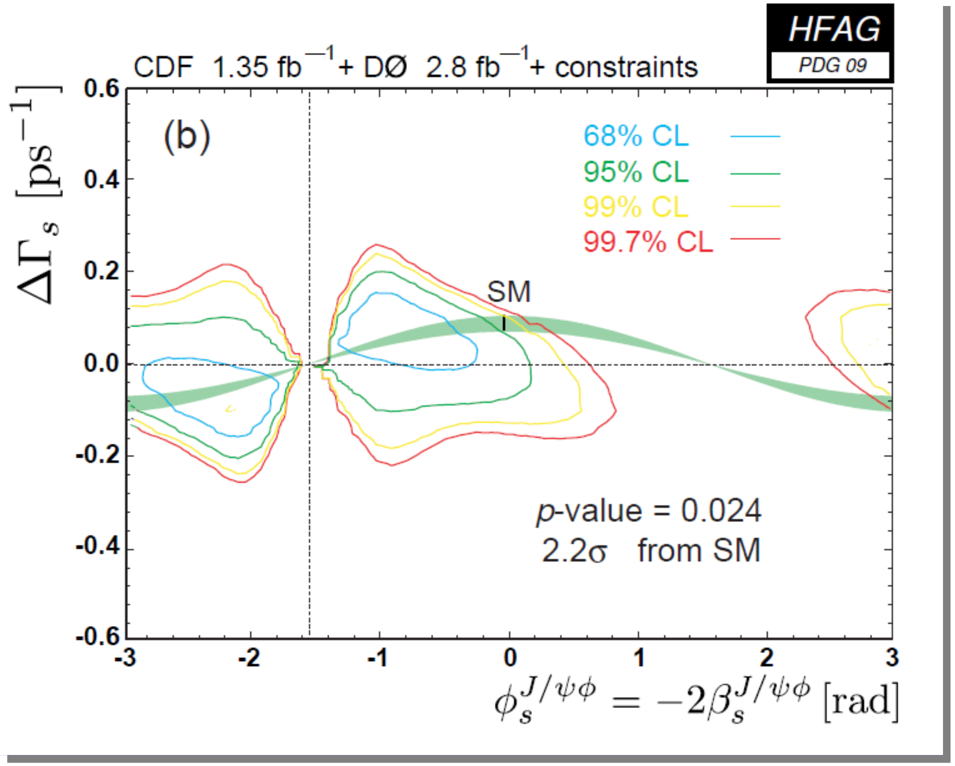
The CP asymmetry of the B_s mixing system (2)

- Small SM prediction for $S_{\psi\varphi}$

$$S_{\psi\phi}^{\rm SM} = \sin(2|\beta_s|) \simeq 0.038, \quad V_{ts} = -|V_{ts}|e^{-i\beta_s}$$

- The measurement of $S_{\psi\varphi}$ and a^s_{SL}:
  - 2009: status of the measurements:

    Data from CDF and D0 seem to hint towards a large CP asymmetry $S_{\psi\varphi}$ (2-3 σ deviation from the SM prediction)



(PDG 2009)

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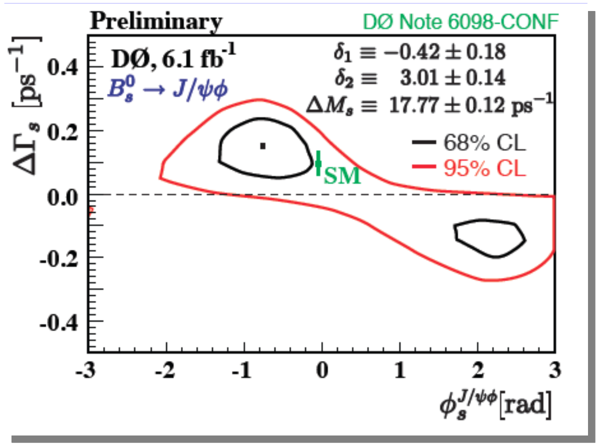
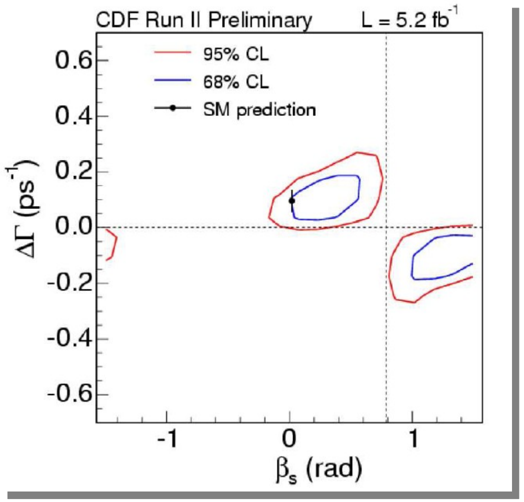


D0



CDF

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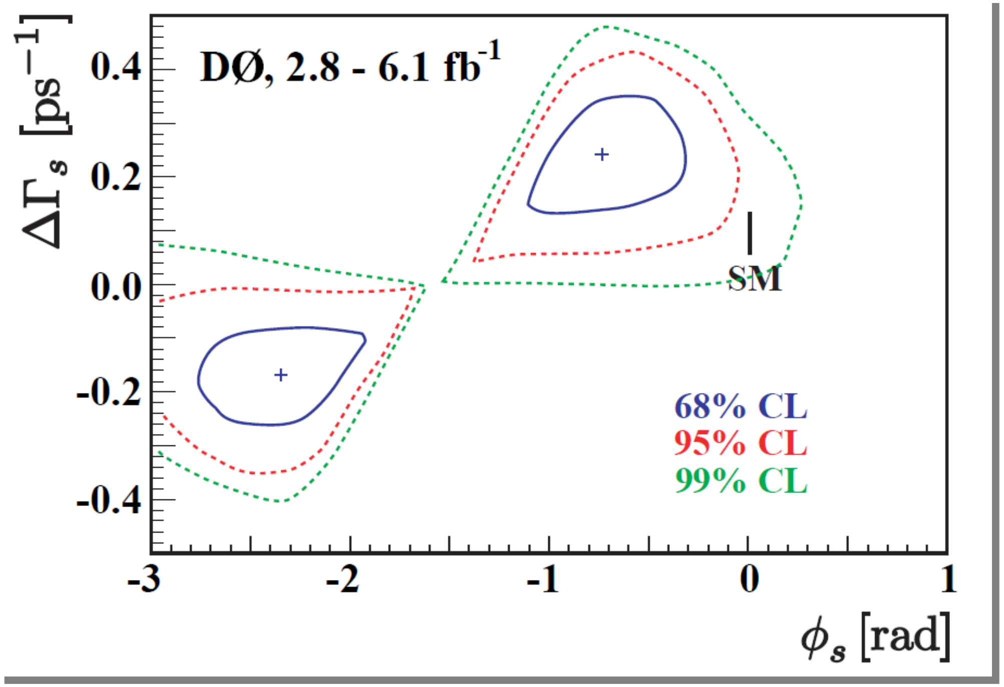

(arXiv:1005.2757 [hep-ex])

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  - global fits prefer sizable phase in B_s mixing
    (Ligeti, Papucci, Perez, Zupan '10
    Lenz, Nierste, CKMfitter '10, ...)

$$S_{\psi\phi} \simeq 0.5$$

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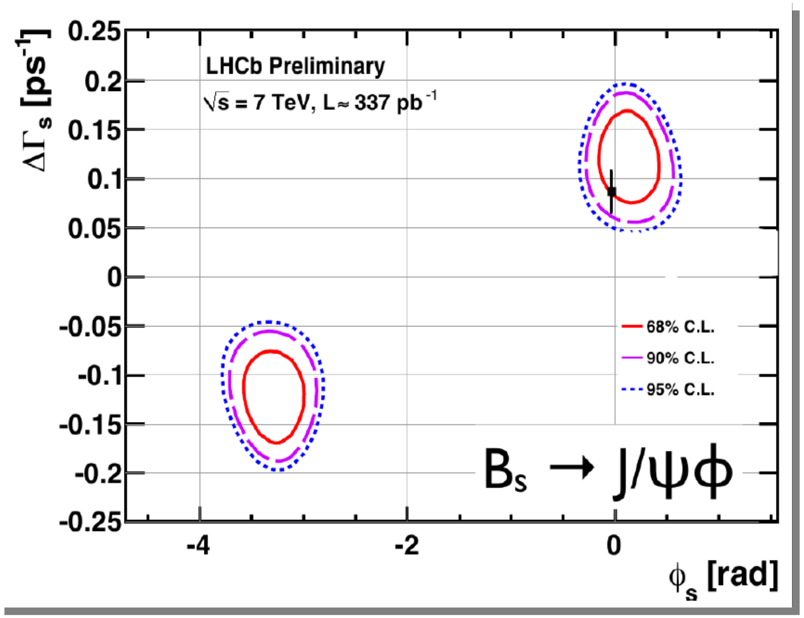
  - New 2011: status of the measurements:

    First results from LHCb: combining results on

$$B_s \to \psi\phi, \; B_s \to \psi f_0 \qquad \phi_s^{\rm LHCb} = 0.03 \pm 0.16 \pm 0.07$$

Significant improvements from LHCb are expected!



The Bs mixing phase in the MFV MSSM

What is the Minimal Flavor Violating (MFV) MSSM?

Chivukula, Georgi '95
D'Ambrosio et al. '02

MFV The global $SU(3)^3$ flavor symmetry of the gauge sector is only broken by the SM Yukawa couplings

MSSM with MFV Important implications on the structure of soft masses and trilinear terms

e.g. $m^2_{\tilde{D}_R} = \tilde{m}^2 \left(a_3 \mathbb{I} + b_6 Y_d^\dagger Y_d \right), \; A_D = A \left(a_5 \mathbb{I} + b_8 Y_u Y_u^\dagger \right) Y_d$

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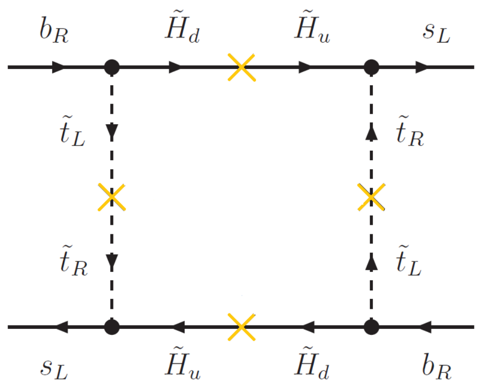
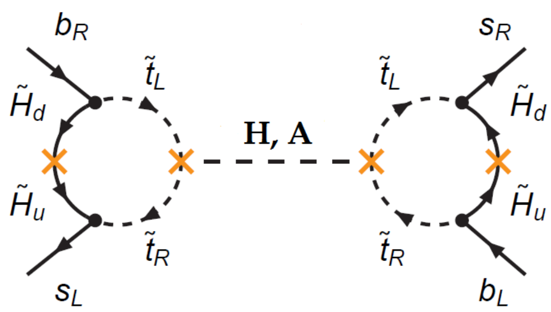
NP effects in the Bs mixing phase in this framework



$$\tilde{O}_3 = \left(\bar{b}^\alpha P_L s^\beta \right) \left(\bar{b}^\beta P_L s^\alpha \right)$$

$$\tilde{C}_3 \propto \alpha^2 \left(V_{tb} V_{ts}^* \right) m_b^2 t_\beta^2 \frac{\mu^2 A_t^2}{\tilde{m}^8}$$



Additional gluino contributions in case of squark mass splitting

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

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

Not sensitive to NP phases of the MSSM
(only through higher order tanβ resummation factors)

Relevant for large values of tanβ

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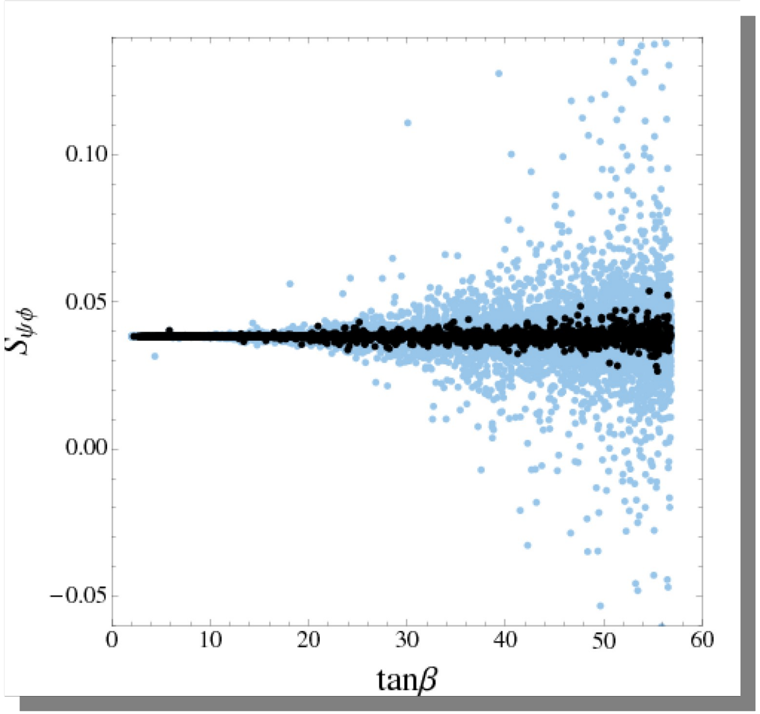
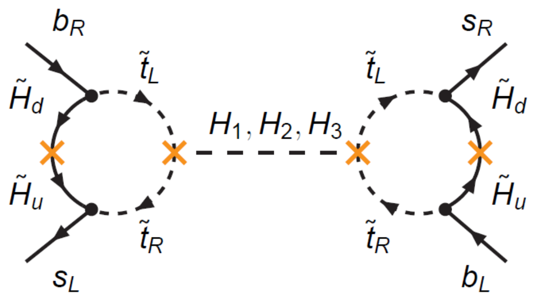


The constraints from both $BR(B_s \to \mu\mu)$ and $BR(b \to s\gamma)$ become very powerful at large tanβ.

SM like $S_{\psi\varphi}$

BMSSM contributions to the Bs mixing phase

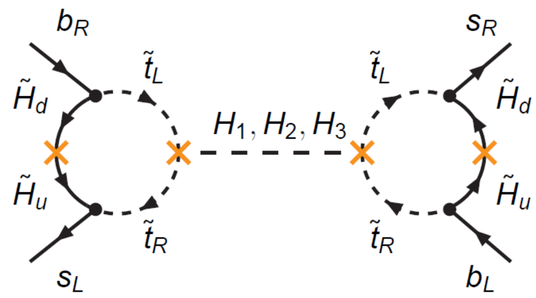


$$O_4 = (\bar{b}_R s_L)\,(\bar{b}_L s_R)$$

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

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

BMSSM contributions to the Bs mixing phase



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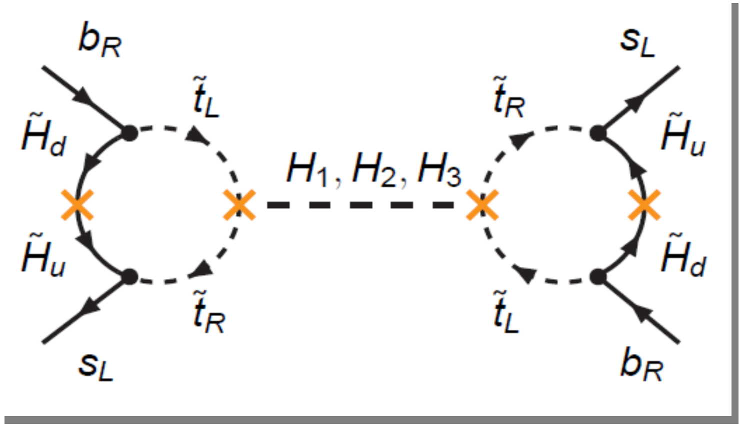
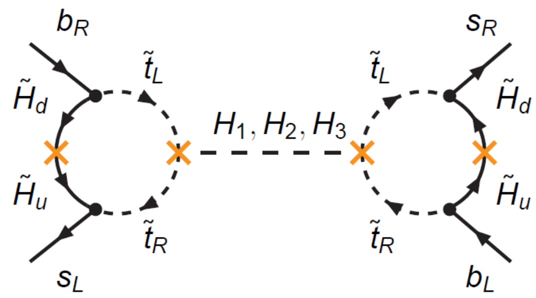
See also Altmannshofer, Carena (2011)





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

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

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

- 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)

See also Altmannshofer, Carena (2011)

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

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

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

Strong constraint from $B_s \to \mu\mu$

Present situation of theory and experiment

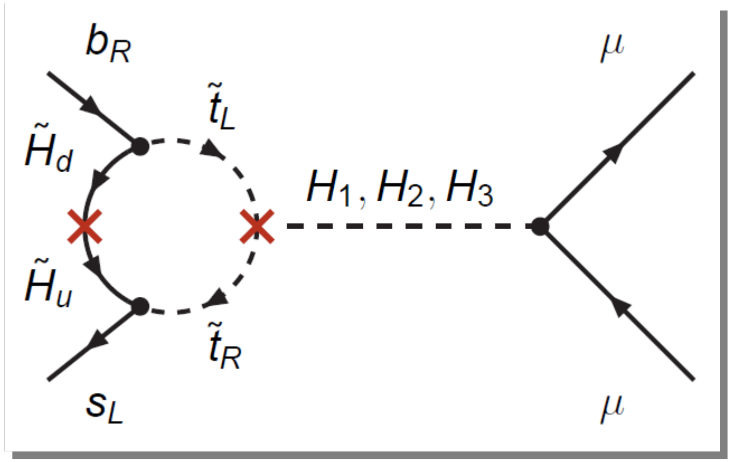
$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{SM}} = (3.2 \pm 0.2) \cdot 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \cdot 10^{-8}$$ CDF, July 2011

New

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.1 \cdot 10^{-8}$$ LHCb, CMS, August 2011

The main contribution is given by the same diagram as in the MSSM



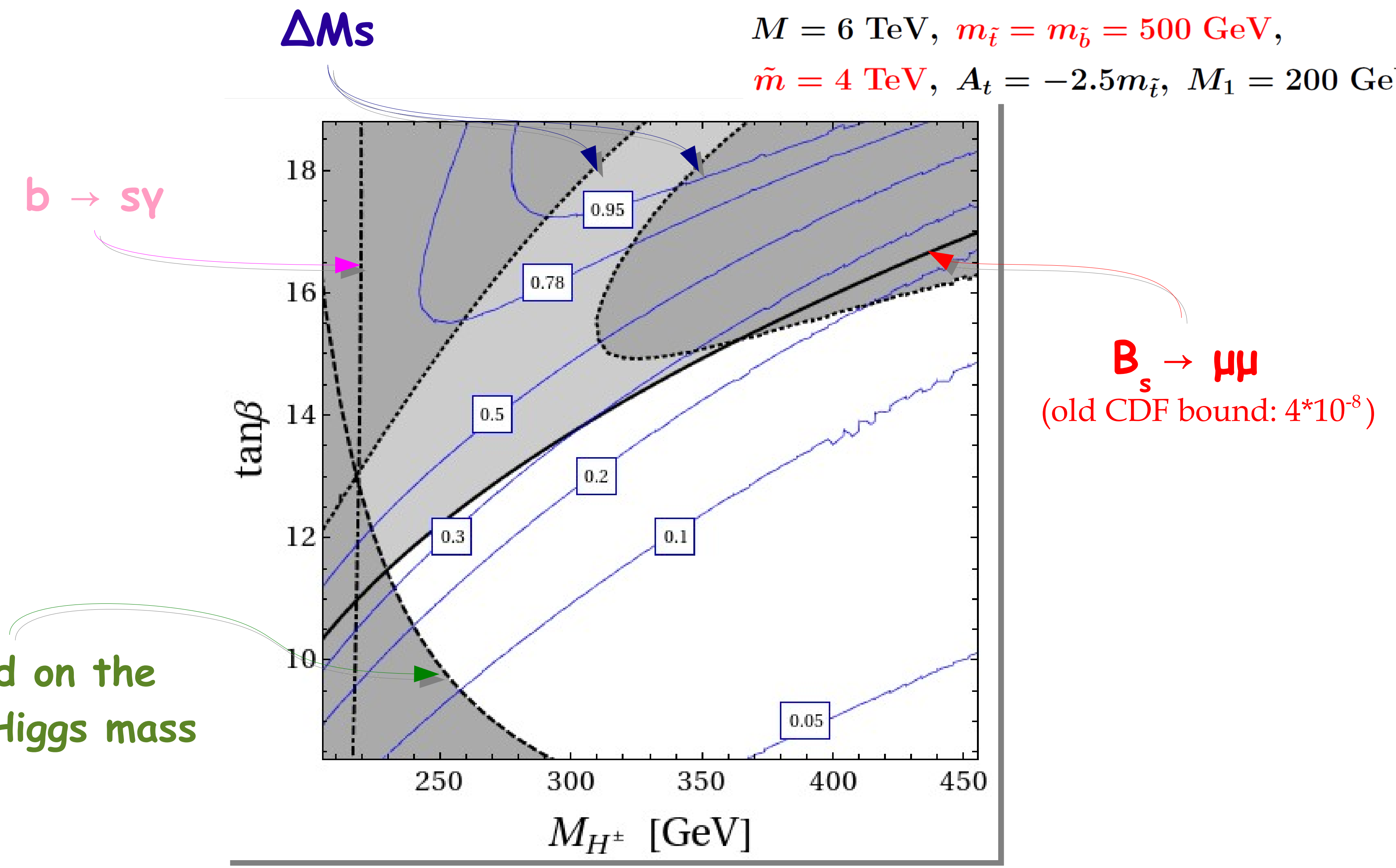
$$\propto \frac{\alpha_2}{4\pi} \frac{1}{M_A^2} V_{tb} V_{ts}^* \frac{m_b m_\mu}{M_W^2} t_\beta^3 \frac{A_t \mu}{\tilde{m}^2}$$

Best choice to maximize the B_s mixing phase and being in agreement with the constraint on $B_s \to \mu\mu$

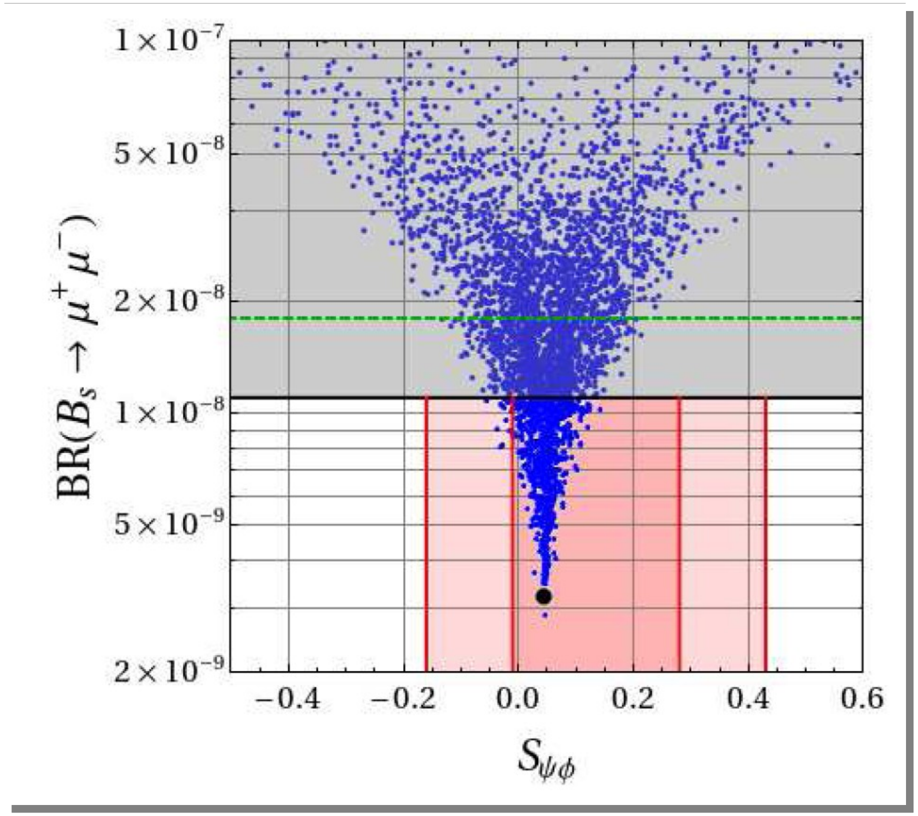
- Moderate $\tan\beta$
- Relatively light Higgs bosons H_2, H_3
- Large and negative value of μ

Expected

$|\omega| = 0.4,\ |\alpha\omega| = 2,\ \mathrm{Arg}(\omega) = -0.75,$
$\mathrm{Arg}(\alpha) = -2,\ \mu = -950\ \mathrm{GeV},\ m_s = 1\ \mathrm{TeV},$
$M = 6\ \mathrm{TeV},\ m_{\tilde{t}} = m_{\tilde{b}} = 500\ \mathrm{GeV},$
$\tilde{m} = 4\ \mathrm{TeV},\ A_t = -2.5 m_{\tilde{t}},\ M_1 = 200\ \mathrm{GeV}$



CP violation in B_s mixing (2)



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

(still interesting in view of future LHCb sensitivity)

Implications of a sizable $S_{\psi\varphi}$ in the model:

- Lightest Higgs boson close to the LEP bound $m_{H_1} \sim 114$ GeV
- Difficult to observe since mainly decaying into bb (suppressed decay into γγ)
- It may be observed in the $HV \to b\bar{b}$ channel using the full Tevatron data set
- H_2 and H_3 in the mass range (200-300) GeV and mainly decaying into bb (ττ mode is the most promising)
- $BR(B_s \to \mu\mu)$ close to the LHCb-CMS bound

Conclusions and remarks (1)

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

- Interesting scenarios are found

  All three Higgs bosons are heavily mixed and

  1. Decaying into WW — The discovery is around the corner
  2. Decaying into bb — More hidden to the LHC

Peculiar scenarios of the BMSSM with CP violation

Conclusions and remarks (2)

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

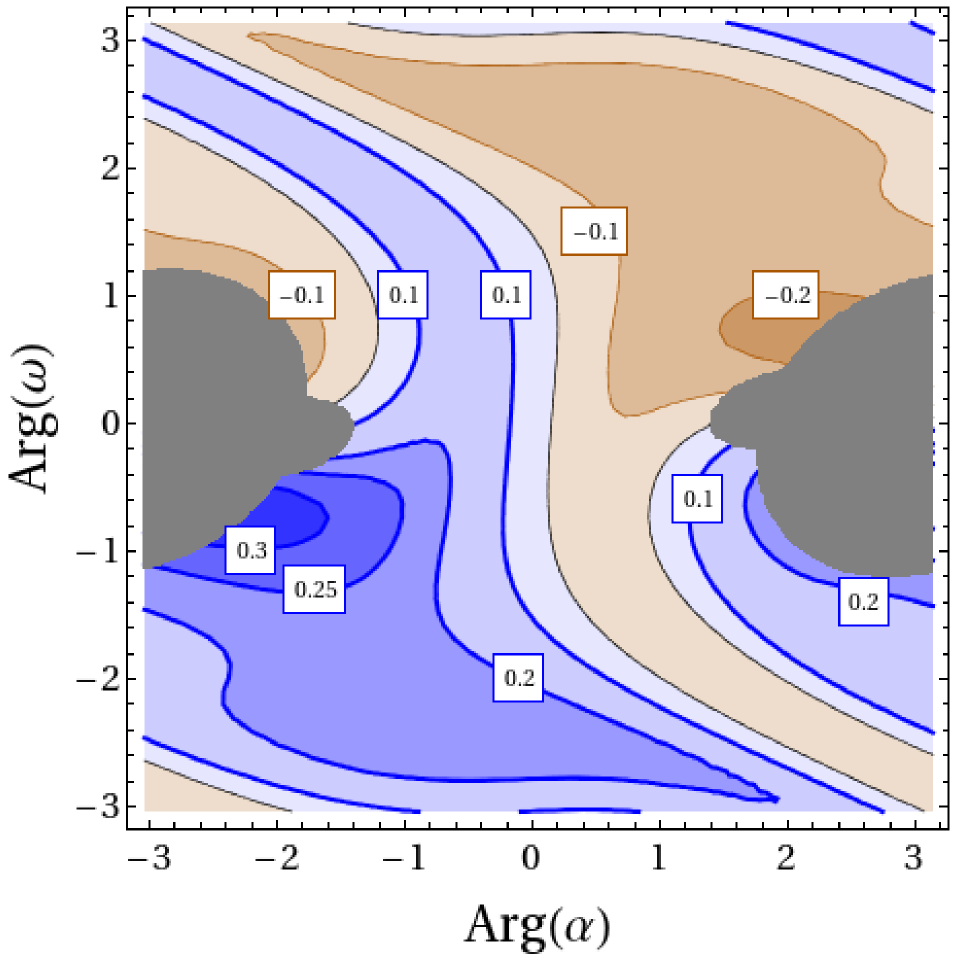
If M is not too large and tanβ sizable:

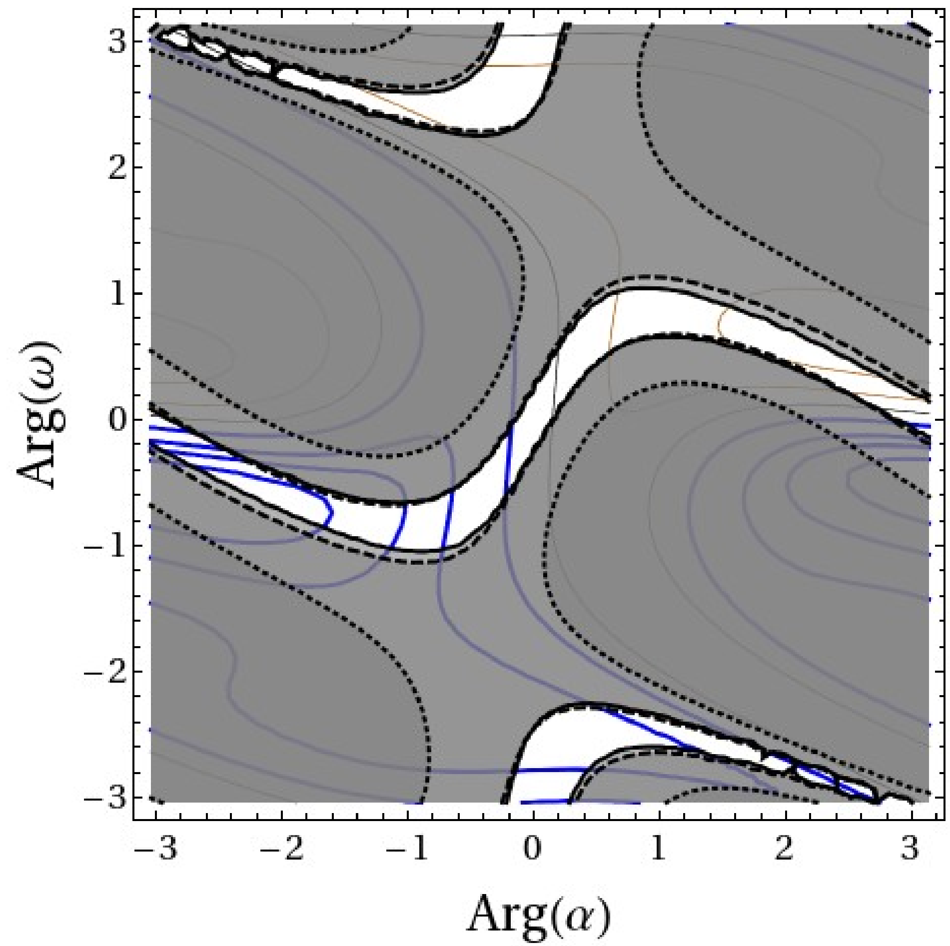
Flavor:

- The B_s mixing phase can be non-standard, $S_{\psi\varphi}$~0.15, even assuming a MFV structure of soft masses and trilinear terms and being fine with the $B_s \rightarrow \mu\mu$ constraint
- Implication of a sizable $S_{\psi\varphi}$
  1. Light and rather hidden lightest Higgs boson
  2. BR($B_s \rightarrow \mu\mu$) close to the LHCb, CMS upper bound

At odds with the MSSM with MFV structure

EDMs at large tanβ





Heavy first two generation squarks ⇒ two loop contributions are dominant

First Higgs scenario

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)

	Sc.I
$\vert\alpha\vert$	1
$\vert\omega\vert$	1.5
$\mathrm{Arg}(\alpha)$	$\pi/3$
$\mathrm{Arg}(\omega)$	$-\pi/15$
$\tan\beta$	2
$M_{H^\pm}$ [GeV]	190
M [TeV]	2.5
μ [GeV]	150
m_S [GeV]	150

Second Higgs scenario

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)

	Sc.II
$\lvert\alpha\rvert$	0.8
$\lvert\omega\rvert$	1.6
$\mathrm{Arg}(\alpha)$	$-2\pi/3$
$\mathrm{Arg}(\omega)$	$\pi/20$
$\tan\beta$	3
$M_{H^\pm}$ [GeV]	166
M [TeV]	2
μ [GeV]	140
m_S [GeV]	100