Signals of CP Violation
Beyond the MSSM at the LHC

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1. Introduction: something beyond the MSSM?
   - The little hierarchy problem
   - CP violation in the $B_s$ mixing system

2. The BMSSM at low $\tan\beta$
   - A heavy lightest Higgs boson
   - Characteristic Higgs scenarios
   - Reach of the LHC

3. The BMSSM at sizable $\tan\beta$
   - $B_s$ 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?
LHC is running...

What will it find?

Nobody knows...
LHC is running...

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?

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

In the MSSM at the tree level: \( m_h \leq m_Z \cos 2\beta \)

The lightest Higgs is SM like in most of the parameter space

LEP bound: \( m_h \geq 114.4 \text{ GeV} \)

Need of large loop contributions

\[
\Delta m_h^2 \sim \frac{3\alpha}{2\pi \sin^2 \theta} \frac{m_t^4}{m_W^2} \log \left( \frac{m_t^2}{m_Z^2} \right)
\]

Relatively heavy stops (\( \sim \text{TeV} \)) 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 ??

Barbieri, Strumia, 1998

\( m_h \leq 120 \text{GeV} \)
A heavier Higgs boson at the tree level

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

Some possibility:

- **U(1) gauge extensions:**
  \[
  m_h^2 \leq \left( m_Z^2 + \frac{g_X^2 v^2}{2 \left( 1 + \frac{M^2}{2 M^2} \right)} \right) \cos^2(2\beta)
  \]
  See also Bellazzini, Csaki, Delgado, Welier (2009)

- **SU(2) gauge extensions:**
  \[
  m_h^2 \leq m_Z^2 g'^2 + \eta g^2 \cos^2(2\beta)
  \]
  \[
  \eta = \frac{1 + \frac{g^2 M^2}{g^2 M^2}}{1 + \frac{M^2}{M^2}}
  \]

- **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 $S_{ \psi \phi}$ ($B_s$ 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, $\mu$)

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 $\Delta F=2$ flavor observables as $S_{\psi \phi}$ are really limited

$$S_{\psi \phi} \sim 0.2$$

is still allowed by present experiments (LHCb)

(LHCb-CONF-2011-056)

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

Beyond the MSSM (theory)
BMSSM: the lagrangian

Let us assume that at the \textit{(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.

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 \textbf{complex}

Susy breaking parametrized by a chiral superfield spurion: \[ Z = m_s \theta^2, \quad m_s \ll M \]

with superpotential

\[
W_{\text{break}} = \alpha \frac{\omega}{2M} Z (H_u H_d)^2
\]

What happens below the M scale?

Dine, Seiberg, Thomas, 2007
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Tree level effective field theory obtained below the M scale (at the 1/M order):

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

$$+ \frac{\omega}{M^2} |H_u H_d|^2 (H_u^\dagger H_u + H_d^\dagger H_d)$$

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

- $\lambda_8$ ensures that the potential is bounded from below

- At the minimum of the potential: $H_u = e^{i\theta_u} \left( \begin{array}{c} 0 \\ \frac{v_u}{\sqrt{2}} \end{array} \right)$, $H_d = e^{i\theta_d} \left( \begin{array}{c} \frac{v_d}{\sqrt{2}} \\ 0 \end{array} \right)$ with non trivial $\theta_u, \theta_d$

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
The three conditions
\[
\frac{\partial V_{\text{ren}}}{\partial \text{Re} H_u} = \frac{\partial V_{\text{ren}}}{\partial \text{Re} H_d} = \frac{\partial V_{\text{ren}}}{\partial \theta} = 0
\]
and the requirement to have a positive definite hessian at \( v \neq 0 \) do not necessarily lead to a unique solution.
The three conditions

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and the requirement to have a positive definite hessian at \( v \neq 0 \) do not necessarily lead to a unique solution.

If the quartic couplings along the D-flat direction are negative, a second minimum in the \( v_u, v_d \) plane can appear.

Different from the MSSM:

\[
V_{\text{BMSSM}}^4 = \alpha \frac{\omega m_s}{2M} (H_uH_d)^2 \\
- \frac{\omega \mu^*}{M} (H_uH_d)(|H_u|^2 + |H_d|^2) + h.c.
\]

\[
V_{\text{MSSM}}^4 = \frac{g_2^2}{8c_W} (|H_u|^2 - |H_d|^2)^2 + \frac{g_2^2}{2} |H_u^+H_d|^2 \geq 0
\]

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

\( m_t = A_t = 500 \text{ GeV}, \; \mu = m_s = 200 \text{ GeV}, \; M = 1 \text{ TeV} \)
This second minimum can be deeper than the EW minimum at $v=246\text{GeV}$

Requirement of absolute stability of the EW minimum

The chargino mass is strongly bounded from above

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

see also Blum, Delaunay, Hochberg, 2009
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

\[
M^2_H = \begin{pmatrix}
  M^2_h & 0 & M^2_{hA} \\
  0 & M^2_H & M^2_{HA} \\
  M^2_{hA} & M^2_{HA} & M^2_A
\end{pmatrix}
\quad
O^T M^2_H O = \text{diag}(M^2_{H1}, M^2_{H2}, M^2_{H3})
\]

The lightest Higgs boson mass:

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

\[
M^2_{H1} \approx M^2_Z + \frac{4v^2}{\tan \beta} |\lambda_6| \cos(\phi_6 + \theta) + \frac{v^4}{M^2_A} |\lambda_6|^2 \cos^2(\phi_6 + \theta)
\]

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

The splitting between the two heavier Higgs bosons:

\[
M^2_{H3} - M^2_{H2} \approx v^2 \frac{|\alpha \omega| m_s}{M}
\]

It can be much larger than the splitting one can get in the MSSM ($m^2_W/t^2_\beta$ suppressed)

The interesting regime for Higgs physics is low $\tan \beta$ and low values of $M$ ((2-3)TeV)
The Higgs spectrum (2)

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

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

The EW minimum is metastable

The EW minimum is metastable
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:

- Rather accurate: $-585d_e \simeq d_{T1} \leq 9.4 \times 10^{-25} \text{ e cm @ 90\% C.L.}$
- Factor 2-3 uncertainty: $7 \times 10^{-3}e(\tilde{d}_u - \tilde{d}_d) + 10^{-2}d_e \simeq d_{Hg} \leq 3.1 \times 10^{-29} \text{ e cm @ 95\% C.L.}$
- 50\% uncertainty: $1.4(d_d - 0.25d_u) + 1.1e(\tilde{d}_d + 0.5\tilde{d}_u) \simeq d_n \leq 2.9 \times 10^{-26} \text{ e cm @ 90\% C.L.}$

Main Susy contributions:

- 1-loop contributions
- Barr-Zee contributions at 2-loops
Electric Dipole Moments (1)

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1-loop contributions

Barr-Zee contributions at 2-loops

Large effects may arise 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 \(\omega, \alpha\) and \(\theta\))
Most constraining is the **Thallium** EDM

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

Small values of \( \theta \) are preferred

Still \( \theta = 0 \) is not the perfect solution, because of the \( 1/M \) suppressed correction to the Higgsino mass

Assuming the presence of CP phases only in \( \omega, \alpha \)

\[ \mu e^{i\theta} \rightarrow \mu e^{i\theta} - \omega \frac{v^2}{M} s_\beta c_\beta e^{2i\theta} \]
Most constrained decay mode: $H_i \rightarrow W^+W^-$

(T$_{\beta} = 2$)

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

Points excluded by LEP

Orange: CP conserving case
Green: CP violating case

Plenty of points with large CP violating phases in $\omega, \alpha$ are allowed
The **Higgs Boson** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.999% the speed of light.

*Wool felt with gravel fill for maximum mass.*

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**Characteristic Higgs scenarios**
A great scenario for the LHC (1)

Three Higgs bosons with $M_{hi} \gtrsim 140 \text{ GeV}$ 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?
   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

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

$$\sum_i \xi_{WWH_i}^2 = 1$$

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 $M_{h_1} \gtrsim 140$ GeV and all mixed/decaying strongly into $WW$

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

$\tan \beta = 2$

$\xi_{ZZH_1}^2 = 0.94$
$\xi_{ZZH_2}^2 = 0.02$
$\xi_{ZZH_3}^2 = 0.04$
A more hidden scenario for LHC (1)

Three Higgs bosons rather close in mass $145 \lessapprox M_{h_i} \lessapprox 160$ GeV and heavily mixed/decaying mainly into $\text{bb}$.

**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? Possibility of having the three neutral Higgs bosons all heavily mixed.

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If the three Higgs bosons are heavily mixed then

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

$$\sum_i \xi_{WWH_i}^2 = 1$$

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 $\text{bb}$ channel is studied by Tevatron only for masses $\lessapprox 140$ GeV.

(see also Carena, Ponton, Zurita, 2010)
A more hidden scenario for LHC (2)

Three Higgs bosons rather close in mass $145 \lesssim M_{h_i} \lesssim 160$ GeV and heavily mixed/decaying mainly into $bb$

Arg($\omega$) = $\pi/20$
\[\tan \beta = 3\]

Excluded by vacuum stability
Excluded by EDMs

$\xi_{ZZH_1}^2 = 0.62$
$\xi_{ZZH_2}^2 = 0.32$
$\xi_{ZZH_3}^2 = 0.06$
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 10 fb⁻¹ are needed to probe all the three Higgs bosons.
The model at large $\tan \beta$: 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 $S_{\psi\phi}$ + Direct CP asymmetry in D decays

\begin{equation}
\begin{aligned}
\text{Schrödinger equation describing the } B_s \text{ mixing:} \\
\frac{d}{dt} \left( \begin{array}{c} B_s(t) \\ \bar{B}_s(t) \end{array} \right) = \left( M_s + \frac{i}{2} \Gamma_s \right) \left( \begin{array}{c} B_s(t) \\ \bar{B}_s(t) \end{array} \right) \\
\end{aligned}
\end{equation}

\begin{align*}
\text{Physical observables:} & \\
1. \text{Mass and width difference}: & \Delta M_s = 2 |M_{12}^s|, \Delta \Gamma_s = 2 |\Gamma_{12}^s| \cos \phi_s \\
2. \text{CP asymmetry}: & \alpha_{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)} = \frac{\Gamma_{12}^s}{M_{12}^s} \sin \phi_s = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi_s \\
& \text{or} \quad 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) \\
\text{Model-independent relation} & \\
(\text{Ligeti, Papucci, Perez '06; Grossman, Nir, Perez '09}) \\
\alpha_{SL}^s &= - \frac{\Gamma_{12}^s}{M_{12}^s}^{SM} S_{\psi\phi} = - \frac{\Delta \Gamma_s}{\Delta M_s} \frac{S_{\psi\phi}}{\sqrt{1 - S_{\psi\phi}^2}} \\
\end{align*}
The CP asymmetry of the $B_s$ mixing system (2)

- Small SM prediction for $S_{\psi\phi}$
  \[ S_{\psi\phi}^{\text{SM}} = \sin(2|\beta_s|) \approx 0.038, \quad V_{ts} = -|V_{ts}|e^{-i\beta_s} \]

- The measurement of $S_{\psi\phi}$ and $a_s^{\text{SL}}$:
  - **2009**: status of the measurements:
    - Data from CDF and D0 seem to hint towards a large CP asymmetry $S_{\psi\phi}$
    - (2-3 $\sigma$ deviation from the SM prediction)
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    ($\sim 1\sigma$ deviation)
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  - **2010**: status of the measurements:
    - updates from CDF and D0 for $S_{\psi \phi}$ are in better agreement with the SM prediction ($\sim 1\sigma$ deviation)
    - new result from D0 on the like sign dimuon charge asymmetry $A_{\text{SL}}^b$ shows a 3.2$\sigma$ deviation from the SM for $S_{\psi \phi}$

(arXiv:1005.2757 [hep-ex])
The CP asymmetry of the $B_s$ mixing system (2)

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  - **2010**: status of the measurements:
    - updates from CDF and D0 for $S_{\psi\phi}$ are in better agreement with the SM prediction (~1σ deviation)
    - new result from D0 on the like sign dimuon charge asymmetry $A_{SL}^b$ shows a 3.2σ deviation from the SM for $S_{\psi\phi}$

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

\[ S_{\psi\phi} \approx 0.5 \]
The CP asymmetry of the $B_s$ mixing system (2)

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

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

- The measurement of $S_{\psi\phi}$ and $a^{s}_{SL}$:
  - **2009**: status of the measurements:
    - Data from CDF and D0 seem to hint towards a large CP asymmetry $S_{\psi\phi}$
      (2-3 $\sigma$ deviation from the SM prediction)
  - **2010**: status of the measurements:
    - updates from CDF and D0 for $S_{\psi\phi}$ are in better agreement with the SM prediction (~1$\sigma$ deviation)
    - new result from D0 on the like sign dimuon charge asymmetry $A_{\psi\phi}^{b}$ shows a 3.2$\sigma$ deviation from the SM for $S_{\psi\phi}$ (2011 update: 3.9$\sigma$ deviation)
  - **2011**: status of the measurements:
    - First results from LHCb: combining results on $B_s \rightarrow \psi\phi, B_s \rightarrow \psi f_0$
    - $\phi_{LHCb}^{S} = 0.03 \pm 0.16 \pm 0.07$

New

Significant improvements from LHCb are expected!
The Bs mixing phase in the MFV MSSM

What is the Minimal Flavor Violating (MFV) MSSM?

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

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

**with MFV** e.g. $m_{D_R}^2 = \tilde{m}^2 \left( a_3 \mathbb{I} + b_6 Y_d^\dagger Y_d \right)$, $A_D = A \left( a_5 \mathbb{I} + b_8 Y_u Y_u^\dagger \right) Y_d$

Chivukula, Georgi ‘95
D’Ambrosio et al. ’02
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NP effects in the Bs mixing phase in this framework

Additional gluino contributions in case of squark mass splitting

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

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

Not sensitive to NP phases of the MSSM (only through higher order $\tan\beta$ resummation factors)

Relevant for large values of $\tan\beta$
The Bs mixing phase in the MFV MSSM

What is the Minimal Flavor Violating (MFV) MSSM?

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

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

**with MFV** e.g. $m^2_{D_R} = \tilde{m}^2 \left( a_3 I + b_6 Y_d^\dagger Y_d \right), \quad A_D = A \left( a_5 I + b_8 Y_u Y_u^\dagger \right) Y_d$

NP effects in the Bs mixing phase in this framework

The constraints from both $\text{BR}(B_s \rightarrow \mu\mu)$ and $\text{BR}(b \rightarrow s\gamma)$
become very powerful at large $\tan\beta$.

SM like $S_{\psi\phi}$
BMSSM contributions to the Bs mixing phase

\[ O_4 = (\bar{b}_RS_L)(\bar{b}_LS_R) \]

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

same contribution as in the MSSM
(corrected only at the 1/M level)
BMSSM contributions to the $B_s$ mixing phase

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

\[
O_4 = (\bar{b}_R s_L) (\bar{b}_L s_R)
\]

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

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

See also Altmannshofer, Carena (2011)
In the MSSM, the contribution of the heavy scalar cancels approximately the contribution of the pseudoscalar (being the two Higgs almost degenerate).

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

$$O_4 = \langle \bar{b}_R s_L \rangle \langle \bar{b}_L s_R \rangle$$

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

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

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 $B_s \rightarrow \mu\mu$**

**Present situation of theory and experiment**

\[
\text{BR}(B_s \rightarrow \mu^+\mu^-)^{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9}
\]

\[
\text{BR}(B_s \rightarrow \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8} \quad \text{CDF, July 2011}
\]

\[
\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-8} \quad \text{LHCb, CMS, August 2011}
\]

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

![Diagram](image)

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

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

**Expected**
CP violation in $B_s$ mixing (1)

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

$\Delta M_s$

$b \rightarrow s \gamma$

$B_s \rightarrow \mu \mu$

(old CDF bound: $4 \times 10^{-8}$)

LEP bound on the lightest Higgs mass

$M_{H^\pm}$ [GeV]
CP violation in $B_s$ mixing (2)

$B_s \rightarrow \mu\mu$ severely 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 $S_{\psi\phi}$ 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 $\gamma\gamma$
- It may be observed in the $HV \rightarrow b\bar{b}$ channel using the full Tevatron data set
- $H_2$ and $H_3$ in the mass range (200-300) GeV and mainly decaying into $bb$ ($\tau\tau$ mode is the most promising)
- $BR(B_s \rightarrow \mu\mu)$ 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.

If M and $\tan\beta$ 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.

S. Gori
Signals of CP violation BMSSM @ LHC
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 $\tan \beta$ sizable:**

- The $B_s$ mixing phase can be non-standard, $S_{\psi\phi} \sim 0.15$, even assuming a *MFV* structure of soft masses and trilinear terms and being fine with the $B_s \rightarrow \mu\mu$ constraint

**Flavor:**

- Implication of a sizable $S_{\psi\phi}$
  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 tan$\beta$
### First Higgs scenario

<table>
<thead>
<tr>
<th>Scenario I</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$H_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{H_i}$ [GeV]</td>
<td>145</td>
<td>169</td>
<td>198</td>
</tr>
<tr>
<td>$ξ_{ZZH_i}^2$</td>
<td>0.94</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>$ξ_{ggH_i}^2$</td>
<td>0.68</td>
<td>0.59</td>
<td>0.53</td>
</tr>
<tr>
<td>BR($H_i \rightarrow bb$)</td>
<td>42% (23%)</td>
<td>59% (0.8%)</td>
<td>15% (0.2%)</td>
</tr>
<tr>
<td>BR($H_i \rightarrow WW$)</td>
<td>45% (60%)</td>
<td>31% (97%)</td>
<td>62% (74%)</td>
</tr>
<tr>
<td>BR($H_i \rightarrow ZZ$)</td>
<td>6% (8%)</td>
<td>0.7% (2.4%)</td>
<td>20% (26%)</td>
</tr>
<tr>
<td>BR($H_i \rightarrow \gamma\gamma \times 10^4$)</td>
<td>15 (17)</td>
<td>0.8 (1.6)</td>
<td>0.2 (0.5)</td>
</tr>
</tbody>
</table>

### Parameters

<table>
<thead>
<tr>
<th></th>
<th>Sc.I</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>α</td>
</tr>
<tr>
<td>$</td>
<td>ω</td>
</tr>
<tr>
<td>Arg($α$)</td>
<td>$\pi/3$</td>
</tr>
<tr>
<td>Arg($ω$)</td>
<td>$-\pi/15$</td>
</tr>
<tr>
<td>tan $β$</td>
<td>2</td>
</tr>
<tr>
<td>$M_{H^±}$ [GeV]</td>
<td>190</td>
</tr>
<tr>
<td>$M$ [TeV]</td>
<td>2.5</td>
</tr>
<tr>
<td>$μ$ [GeV]</td>
<td>150</td>
</tr>
<tr>
<td>$m_S$ [GeV]</td>
<td>150</td>
</tr>
</tbody>
</table>
# Second Higgs scenario

<table>
<thead>
<tr>
<th>Scenario II</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$H_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{H_i}$ [GeV]</td>
<td>147</td>
<td>150</td>
<td>162</td>
</tr>
<tr>
<td>$\xi_{ZZH_i}^2$</td>
<td>0.62</td>
<td>0.32</td>
<td>0.06</td>
</tr>
<tr>
<td>$\xi_{ggH_i}^2$</td>
<td>0.41</td>
<td>0.53</td>
<td>0.39</td>
</tr>
<tr>
<td>$\text{BR}(H_i \rightarrow bb)$</td>
<td>69% (22%)</td>
<td>72% (16%)</td>
<td>65% (2%)</td>
</tr>
<tr>
<td>$\text{BR}(H_i \rightarrow WW)$</td>
<td>20% (63%)</td>
<td>17% (69%)</td>
<td>26% (94%)</td>
</tr>
<tr>
<td>$\text{BR}(H_i \rightarrow ZZ)$</td>
<td>3% (8%)</td>
<td>2% (8%)</td>
<td>1% (3%)</td>
</tr>
<tr>
<td>$\text{BR}(H_i \rightarrow \gamma\gamma) \times 10^4$</td>
<td>6(16)</td>
<td>3(13)</td>
<td>0.5(4)</td>
</tr>
</tbody>
</table>

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