Interplay of B Physics, Higgs Physics and Dark Matter constraints in MFV MSSM

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Based on:


Motivation

Hierarchy Problem

MSSM Parameters:

Yukawas: $Y_u$ and $Y_d$

Trilinears: $A_u$ and $A_d$

Soft squark mass parameters: $m_{Q}^{2}, m_{U}^{2}, m_{d}^{2}$

Soft gaugino mass parameters: $M_3, M_2, M_1$

Higgs Sector: CP-even $m_h, m_H$ and CP-odd $M_A$.

Ratio of Higgs boson VEV’s $\frac{v_u}{v_d} = \tan \beta$.

Higgsino mass parameter $\mu$.

Many Parameters!

Sensitivity of and constraints?
Outline

1) Higgs and Flavor Physics in the SM

2) The MSSM Higgs sector and its couplings.

3) B-physics in the MSSM.

4) Dark matter searches in the MSSM.

5) B-physics, Higgs search and Direct Dark Matter detection constraints.

6) Conclusions.
The Standard Model
The Higgs and Flavor in the Standard Model

- The $H$ doublet acquires a vev $\left( \begin{array}{c} 0 \\ v \end{array} \right)$ at minimum.

- $H$ gives the gauge bosons their mass and longitudinal components.

- Yukawa interactions with $H$ give the quarks their masses.

- $H$ couples to both $u$ and $d$ $\Rightarrow$ no FCNCs (flavor changing neutral currents).

- Mismatch of the $U_L$ and $D_L$ rotations $\Rightarrow u_L W^+ d_L$ flavor changing couplings $\propto V_{CKM} \sim 1$.

- All flavor physics observables are in good agreement with the SM.
$b \to s\gamma$ in the Standard Model and Experiment

- **SM prediction:** Left-right operator $\Rightarrow \mathcal{B}\mathcal{R}(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$
  

- **Experimental measurement:** $\mathcal{B}\mathcal{R}(b \to s\gamma) = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$
  
  [Heavy Flavor Averaging Group (HFAG)], arXiv:hep-ex/0603003
Review of $B_s - \bar{B}_s$ Mixing

- The mesons $B_s = (\bar{b}s)$ and $\bar{B}_s = (b\bar{s})$ mix in the presence of flavor violation through the matrix

$$H = M - \frac{i}{2} \Gamma$$

where $M$ and $\Gamma$ are hermitian matrices with CPT invariance forcing $M_{11} = M_{22} = M$ and $\Gamma_{11} = \Gamma_{22} = \Gamma$.

- $|\Gamma_{12}| \ll |M_{12}|$ in the Standard Model because the charm box diagram is the dominant contribution to $\Gamma_{12}$. Therefore the mass splitting in the $B_s$ meson eigenstates is

$$\Delta M_s = 2\Re \left( \sqrt{(M_{12} - \frac{i}{2} \Gamma_{12})(M_{12}^* - \frac{i}{2} \Gamma_{12}^*)} \right) \approx 2|M_{12}|$$
**$\Delta M_s$ in the Standard Model and Experiment**

- **CKMfitter SM** prediction: $13.6 \text{ ps}^{-1} \leq (\Delta M_s)^{SM} \leq 28.6 \text{ ps}^{-1}$ at $2\sigma$

- **UtFit SM** prediction: $\Delta M_s = 20.9 \pm 2.6 \text{ ps}^{-1}$ at 95 % C.L.

- **Experimental measurement**: $\Delta M_s = (17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}))$.

$B_s \rightarrow \mu^+\mu^-$ in the Standard Model and Experiment

- **SM prediction:** $\mathcal{BR}(B_s \rightarrow \mu^+\mu^-) = (3.8 \pm 0.1) \times 10^{-9}$

- **Experimental bound (CDF):** $\mathcal{BR}(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8}$ at 95% C.L.
\( B_u \rightarrow \tau \nu \) in the Standard Model and Experiment

- **SM prediction:** \( \mathcal{BR}(B_u \rightarrow \tau \nu) = (1.09 \pm 0.40) \times 10^{-4} \) using average HFAG \( |V_{ub}| = (3.98 \pm 0.45) \times 10^{-4} \) and the value of \( f_B = (189 \pm 27) \text{ MeV} \) from LQCD.

- **Belle measurement:** \( \mathcal{BR}(B_u \rightarrow \tau \nu) = (1.79^{+0.86}_{-0.49}\text{(stat)}^{+0.46}_{-0.51}\text{(syst)}) \times 10^{-4} \).

- **Babar measurement:** \( \mathcal{BR}(B_u \rightarrow \tau \nu) = (1.20 \pm 0.54) \times 10^{-4} \).

- **Experimental Average:** \( \mathcal{BR}(B_u \rightarrow \tau \nu)^\text{Exp} = (1.41 \pm 0.43) \times 10^{-4} \).
The Higgs sector in the MSSM
The Tree-level Higgs sector in the MSSM

- **Neutral** components of the Higgs boson doublets acquire vevs $v_d$ and $v_u$ and their ratio is $\tan \beta = v_u/v_d$.

- Neglecting CP violation in the Higgs sector, electroweak breaking leaves:
  1. CP odd Higgs $A$
  2. Charged Higgs $H^+$, and
  3. CP even Higgs bosons $h, H$

- The angle $\alpha$ rotates the CP-even Higgs mass matrix to give the eigenvalues

$$\Rightarrow M^2_{h,H} = \frac{1}{2} \left( M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2M_A^2\cos^2 2\beta} \right)$$

while the charged Higgs mass is $M^2_{H^+} = M_A^2 + M_W^2$.

- The modified tree-level couplings of these Higgs bosons to gauge bosons are:

$$\frac{1}{(\phiVV)_{SM}} \begin{pmatrix} (hVV)_{MSSM} \\ (HVV)_{MSSM} \\ (AVV)_{MSSM} \end{pmatrix} = \begin{pmatrix} \sin(\beta - \alpha) \\ \cos(\beta - \alpha) \\ 0 \end{pmatrix}$$

- A gauge coupling $\sim 1 \Rightarrow$ SM-like Higgs while a gauge coupling $\sim 0 \Rightarrow$ CP odd Higgs.
The Loop corrected Higgs mass in the MSSM

- Tree-level SM-like Higgs mass $< M_Z < \text{LEP Higgs mass bound}$. 

- For large values of the CP odd Higgs mass $M_A$ the SM-like Higgs has a mass 

$$
(m_h^{\text{max}})^2 = M_Z^2 \cos^2(2\beta)(1 - \frac{3m_t^2}{8\pi^2v^2t}) + \frac{3m_t^4}{4\pi^2v^2} \left[ \frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left( \frac{3m_t^2}{2v^2} - 32\pi\alpha_3 \right) (\tilde{X}_tt + t^2) \right]
$$

where $\tilde{X}_t = 2a^2(1 - a^2/12)$, $M_{\text{SUSY}}$ is the uniform squark mass scale, $a = X_t/M_{\text{SUSY}}$ and $X_t = A_t - \mu/\tan \beta$. 

Benchmark scenarios in the MSSM

- **Maximal mixing scenario** ⇒ maximum value of the Higgs mass ⇒ $X_t \sim 2.4M_{\text{SUSY}}$
- **Minimal mixing scenario** ⇒ minimum value of the Higgs mass ⇒ $X_t \sim 0$

Non-standard Higgs boson production and decay

\[ g_{Abb} \simeq \frac{m_b \tan \beta}{(1 + \epsilon_3 \tan \beta) v}; \quad g_{A\tau\tau} \simeq \frac{m_\tau \tan \beta}{v}; \quad \text{BR}(A \to \tau^+\tau^-) \simeq \frac{(1 + \epsilon_3 \tan \beta)^2}{9 + (1 + \epsilon_3 \tan \beta)^2}; \]

\[ \sigma(b\bar{b}, gg \to A) \times \text{BR}(A \to \tau\tau) \propto \frac{\tan^2 \beta}{(1 + \epsilon_3 \tan \beta)^2 + 9} \]

- Estimate the MSSM signal significance using the ratio:

\[ r = \frac{\sigma(P\bar{P} \to XA)_{MSSM} \text{BR}(A \to Y)_{MSSM}}{\sigma(P\bar{P} \to X\phi)_{SM} \text{BR}(\phi \to Y)_{SM}} \]
Flavor in the MSSM
The Flavor Problem and Minimal Flavor Violation in the MSSM

- No tree-level flavor changing neutral currents as:
  \[ \mathcal{L} = \bar{Q}_L(\hat{Y}_d \Phi_d d_R + \hat{Y}_u \Phi_u u_R) + h.c. \]

- Flavor structure of soft SUSY breaking terms can induce large flavor changing effects through loops.

- Minimal Flavor Violation is the scheme in which in the only source of flavor and CP violation is the CKM matrix.

- Flavor violating effects can be large due to loop suppression being offset by large \( \tan \beta \).
RGE evolution of the soft squarks masses

- Running of the soft squark masses induces the corrections:

  \[
  \Delta M^2_{\tilde{Q}} \approx -\frac{1}{8\pi^2} \left[ (2m_0^2 + M^2_{H_u}(0) + A_0^2) Y_u^\dagger Y_u + (2m_0^2 + M^2_{H_d}(0) + A_0^2) Y_d^\dagger Y_d \right] \log\left(\frac{M}{M_{SUSY}}\right),
  \]

  \[
  \Delta M^2_{\tilde{u}_R} \approx -\frac{2}{8\pi^2} \left[ (2m_0^2 + M^2_{H_u}(0) + A_0^2) Y_u Y_u^\dagger \log\left(\frac{M}{M_{SUSY}}\right) \right]
  \]

  \[
  \Delta M^2_{\tilde{d}_R} \approx -\frac{2}{8\pi^2} \left[ (2m_0^2 + M^2_{H_d}(0) + A_0^2) Y_d Y_d^\dagger \log\left(\frac{M}{M_{SUSY}}\right) \right]
  \]


- \( M \sim M_{SUSY} \) corrections are small and the squark masses remain diagonal.

- \( M \sim M_{GUT} \) corrections are significant and the down squark mass matrix is approximately diagonal in the basis

  \[
  \tilde{d}_L^i \rightarrow U_L d_L^i
  \]

  rather than in the basis

  \[
  \tilde{d}_L^i \rightarrow D_L d_L^i
  \]
Tree-level flavor violating charged currents in the MSSM

- Both $M \sim M_{\text{SUSY}}$ and $M \sim M_{\text{GUT}}$ have $V_{\text{CKM}}$ proportional couplings in the charged Higgs-top-strange quark ($H^+ts$) vertex and in the chargino-stop-strange ($\tilde{\chi}^\pm\tilde{t}s$) vertex.

- Additionally, for $M \sim M_{\text{GUT}}$ there is a flavor violating gluino vertex:

\[ \mathcal{L}_g \supset \sqrt{2} g_3 \tilde{g}^a \left( (V_{\text{CKM}})^J I (\tilde{d}_L^*)^J T^a d_L^I - (\tilde{d}_R^*)^I T^a d_R^I \right) \]

- In this basis additional off-diagonal L-R down squark mass terms:

\[ \mathcal{L}_{\text{mass}} \supset (\tilde{d}^*_L)^I (m_Q^2)^I(\tilde{d}_L)^J + (\tilde{d}^*_R)^I (m_R^2)^I(\tilde{d}_R)^J + \tilde{\mu}^* (\tilde{d}_L^*)^I V_{\text{CKM}}^{IJ} m_{d_J} (\tilde{d}_R)^I + \text{h.c.} \]
Flavor Changing Neutral Currents in MFV MSSM

- Including 1-loop effects both quarks couple to both the Higgs bosons so that:

\[-L_{eff} = \overline{d}^0_R \hat{Y}_d [\Phi^0_d + \Phi^*_u \left( \hat{c}_0 + \hat{c}_Y \hat{Y}_u^\dagger \hat{Y}_u \right)] d^0_L + h.c.\]

The \(\epsilon\) loop factors correspond to the diagrams:

\[\epsilon_I \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0 \left( m_{\tilde{d}_1}^2, m_{\tilde{d}_2}^2, M_3^2 \right)\]

\[\epsilon_Y \approx \frac{1}{16\pi^2} A_t \mu C_0 \left( m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2 \right)\]

- Similar \(\epsilon'_I\) and \(\epsilon'_Y\) for up-type quarks which completely parameterize all FCNC effects in MFV.

- Low scale flavour structure of the squark masses after RG evolution determines which of these \(\epsilon\)-loop factors induce flavour violation.

Kolda, Babu, Buras, Roszkowski...
$b \rightarrow s\gamma$ for in MFV

\[ \propto \mu A_t \tan \beta \]

\[ \propto h_t - \delta h_t \tan \beta \text{ where } \frac{\delta h_t}{h_t} \propto \frac{\alpha_s}{3\pi} \mu M_3 \epsilon_0' \]


\[ \propto \mu M_3 (m_0^2 - m_0^2) \tan \beta \text{ only for the } M \simeq M_{GUT} \text{ scenario.} \]
\( \Delta M_s \) in the MSSM with MFV

- In MFV MSSM the dominant \( \Delta M_s \) contribution comes from double penguin diagrams.
- For uniform squark masses:
  \[
  (\Delta M_s)^{DP} \propto \frac{|X_{RL}^{32}|^2}{M_A^2}
  \]
- When \( M \sim M_{SUSY} \):
  \[
  X_{RL}^{32} \propto \frac{\epsilon_Y \tan^2 \beta}{(1 + \epsilon_0^3 \tan \beta)(1 + \epsilon_3 \tan \beta)} V_{33}^{3^\ast} V_{32}^{32} V_{eff}^{3^\ast} V_{eff}^{32}
  \]
- When \( M \sim M_{GUT} \):
  \[
  X_{RL}^{32} \propto \frac{(\epsilon_0^3 + \epsilon_Y - \epsilon_0) \tan^2 \beta}{(1 + \epsilon_0^3 \tan \beta)(1 + \epsilon_3 \tan \beta)} V_{33}^{3^\ast} V_{32}^{32} V_{eff}^{3^\ast} V_{eff}^{32}
  \]
Stop-Chargino Contributions to $\Delta M_s$ in MFV

- Light stops and charginos can give substantial contributions to $\Delta M_s$ even for low values of $\tan \beta$.

- These kinds of SUSY particle spectra can also induce large contributions to $\epsilon_K$.

- The experimentally measured value of $\epsilon_K = (2.282 \pm 0.014) \times 10^{-3}$
$B_s \rightarrow \mu^+\mu^-$ in the MSSM with MFV

- In MFV MSSM, $BR(B_s \rightarrow \mu^+\mu^-)$ gets an extra contribution which comes from penguin diagrams.

- For uniform squark masses:

\[
BR(B_s \rightarrow \mu^+\mu^-) = 4.64 \times 10^{-6} M_{B_s}^2 \left( \frac{4\pi^2 m_\mu \tan \beta}{\bar{m}_b M_W^2 2^{7/4} G^{3/2} |V_{32}|} \right)^2 |(X_{RL}^A)^{32}|^2 \frac{M_A^4}{M_A^4}
\]
Correlation between $\Delta M_S$ and $B_S \to \mu^+ \mu^-$

- For uniform squark masses the correlation between $\Delta M_S$ and $B_R(B_S \to \mu^+ \mu^-)$ is:

\[
\frac{|(\Delta M_S)_{SUSY}^{DP}|}{B_R(B_S \to \mu^+ \mu^-)_{SUSY}} \sim 0.034(\text{ps})^{-1} \frac{M_A^2}{10^{-7} M_W^2} \left( \frac{50}{\tan \beta} \right)^2
\]

- The bound on $B_R(B_S \to \mu^+ \mu^-)$ implies double penguin contributions to $\Delta M_S \sim 2 \text{ ps}^{-1}$
$B_u \to \tau \nu$ in the MSSM with MFV

\[ R_{B_{\tau \nu}} = \frac{\mathcal{B}(B_u \to \tau \nu)^{\text{MSSM}}}{\mathcal{B}(B_u \to \tau \nu)^{\text{SM}}} = \left[ 1 - \left( \frac{m_B^2}{m_{H^\pm}^2} \right) \tan^2 \beta \left( 1 + \epsilon_0 \tan \beta \right) \right]^2 \]
Dark Matter Searches
Direct Dark Matter Detection in the MSSM

\[ \chi \xrightarrow{\text{N}_{13}} \chi \]

\[ \Rightarrow \frac{\sigma_{SI}}{A^4} \approx \frac{0.1 g_1^2 g_2^2 N_{11}^2 N_{13}^2 m_p^4 \tan^2 \beta}{4 \pi m_W^2 M_A^4} \]

DATA listed top to bottom on plot
- CDMS (Soudan) 2005 Si (7 keV threshold)
- CRESST 2004 10.7 kg-day CaWO4
- Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
- WARP 2.3L, 96.5 kg-days 55 keV threshold
- ZEPLIN II (Jan 2007) result
- CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
- CDMS 2004+2005 reanalysis Ge (5 keV threshold)
- CDMS 2008 Ge
- CDMS: 2004+2005 (reanalysis) +2008 Ge
- XENON10 2007 (Net 136 kg-d)
- CDMS Soudan 2007 projected
- SuperCDMS (Projected) 2-ST@Soudan
- SuperCDMS (Projected) 25kg (7-ST@Snolab)
- Roszkowski/Ruiz de Austri/Trotta 2007, CMSSM Markov Chain Monte Carlos
- Roszkowski/Ruiz de Austri/Trotta 2007, CMSSM Markov Chain Monte Carlos (t)
- Ellis et. al Theory region post-LEP benchmark points
- Baltz and Gondolo 2003
- Baltz and Gondolo, 2004, Markov Chain Monte Carlos

080616032001
B-physics, Higgs search and Direct Dark Matter detection limits
The $M_A$ vs tan $\beta$ plane

$$(X_t, \mu) = (-400 \text{ GeV}, 800 \text{ GeV})$$

$$(X_t, \mu) = (0, 1000 \text{ GeV})$$

$M_3 = 800 \text{ GeV}, \tilde{m}_{Q_3} = 800 \text{ GeV}, \tilde{m}_d = \tilde{m}_{Q_1} = \tilde{m}_{Q_2} = 1 \text{ TeV}$

- The extra gluino contribution in the $M \sim M_{\text{GUT}}$ scenario slightly enhances the region allowed by $b \rightarrow s\gamma$.

- The $B_s \rightarrow \mu^-\mu^+$ constraint is strong in the $M \sim M_{\text{SUSY}}$ but weak for $M \sim M_{\text{GUT}}$ for $(X_t, \mu) = (-400 \text{ GeV}, 800 \text{ GeV})$ and the opposite is true for $(X_t, \mu) = (0, 1 \text{ TeV})$. 
The $X_t$ vs $\mu$ plane

$(M_A, \tan \beta) = (200 \text{ GeV}, 60)$

$(M_A, \tan \beta) = (110 \text{ GeV}, 40)$

$M_3 = 800 \text{ GeV}, \tilde{m}_{Q_3} = 800 \text{ GeV}, \tilde{m}_{d_i} = \tilde{m}_{Q_1} = \tilde{m}_{Q_2} = 1 \text{ TeV}$

- Large $X_t$ and $\mu \Rightarrow$ too small $BR(b \rightarrow s\gamma)$.

- For messenger scale $M \sim M_{SUSY} : X_t \gg 0 \Rightarrow$ large $BR(B_s \rightarrow \mu^+\mu^-)$

- For messenger scale $M \sim M_{GUT} : 2X_t \sim \mu \Rightarrow BR(B_s \rightarrow \mu^+\mu^-)$ is current limits.

- Dark matter direct detection limits exclude regions of small $\mu$. 

\[
\begin{align*}
\text{Region allowed by } b \rightarrow s\gamma \text{ for } M \sim M_{SUSY} \\text{Region allowed by } b \rightarrow s\gamma \text{ for } M \sim M_{GUT} \\
\text{Region below allowed by } B_s \rightarrow \mu^+\mu^- \text{ for } M \sim M_{SUSY} \\
\text{Region between allowed by } B_s \rightarrow \mu^+\mu^- \text{ for } M \sim M_{GUT} \\
\text{Region above allowed by Direct Dark Matter Searches}
\end{align*}
\]
Conclusions

- Within minimal flavor violating MSSM the double penguin contribution to $\Delta M_s$ is small due to $B_s \to \mu^+\mu^-$ constraint.

- We have showed that RG evolution has an impact on flavor observables and some interesting information about the scale of SUSY breaking maybe extracted from them.

- We also derived an analytic expression for the gluino-sbottom contribution to the $b \to s\gamma$ rare decay in the $M \sim M_{SUSY}$ scenario assuming that the first two generation left-handed squark masses and the right-handed sdown masses are uniform.

- B-physics and Non-standard Higgs search constraints disfavor scenarios of large $X_t$ like Maximal Mixing, making the SM-like Higgs mass $\lesssim 120$ GeV.

- SM-like Higgs boson searches at the LHC should be able to probe all of the allowed region of parameter space with $30 \text{ fb}^{-1}$.

- Scenarios like Minimal Mixing with $X_t \sim 0$ look more promising and non-standard Higgs searches at the Tevatron may still be able to probe regions of low $M_A$ and large $\tan \beta$ in the near future.