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

Arjun Menon
Illinois Institute of Technology

Based on:

M. Carena, A. Menon, R. Noriega-Papaqui, A. Szynkman and C. Wagner,Phys.Rev.D74:015009,

[arXiv:hep-ph/0603107];

M. Carena, A. Menon and C. Wagner, Phys.Rev.D76:035004,2007,. [arXiv:0704.1143];

M. Carena, A. Menon and C. Wagner, Phys.Rev.D79:075025,2009,. [arXiv:0812.3594]

November 3, 2009

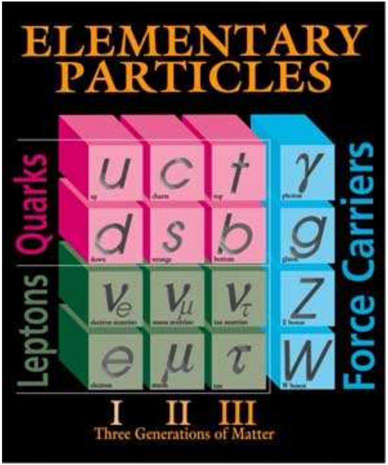
Outline

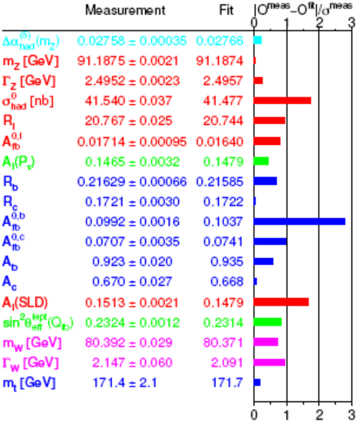
Outline

The Standard Model

- Gauge group:

$SU_C(3) \times SU_L(2) \times U_Y(1)$

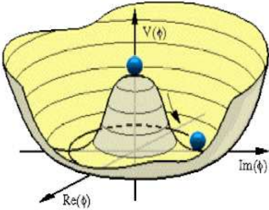




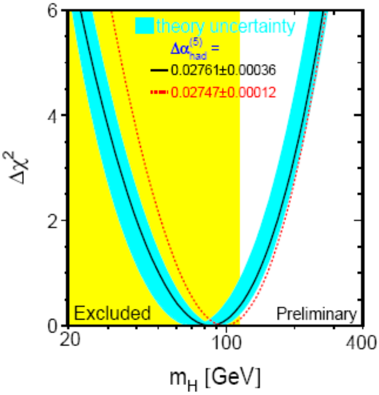
The Higgs and Flavor sector in the Standard Model

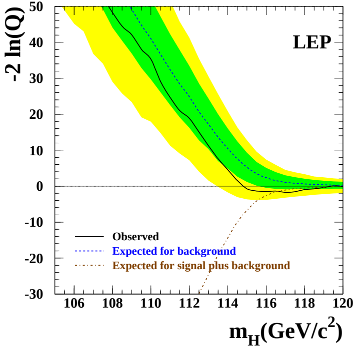
- The H doublet acquires a vev $\begin{pmatrix} 0 \\ v \end{pmatrix}$ at minimum.
- H gives the gauge bosons their mass and longitudinal components.
- Yukawa interactions with H give the quarks their masses.

- 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 $\propto V_{CKM} \sim \mathbf{1}$.
- All flavor physics observables are in good agreement with the SM.



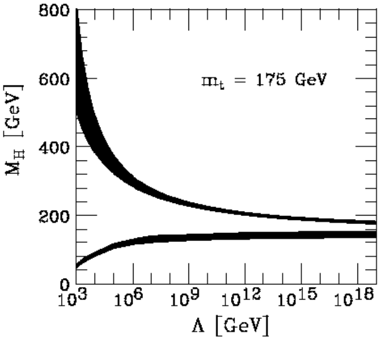
Experimental and Electroweak Precision Limits

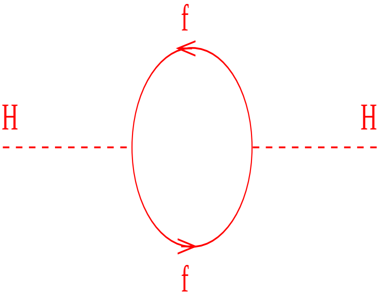




- Electroweak precision observables prefer $m_h \sim 100$ GeV, while the LEP Higgs mass bound $\Rightarrow m_h \geq 114.6$ GeV

Theoretical Limits: Naturalness and Triviality





- Unitarity of vector boson scattering $\Rightarrow m_h \lesssim \mathcal{O}(1\text{ TeV})$.
- Triviality and stability of the Higgs potential $\Rightarrow 130\text{ GeV} \lesssim m_h \lesssim 200\text{ GeV}$.
- Naturalness: For $m_h \sim \mathcal{O}(1\text{ TeV}) \Rightarrow \Lambda \sim 1\text{ TeV}$.

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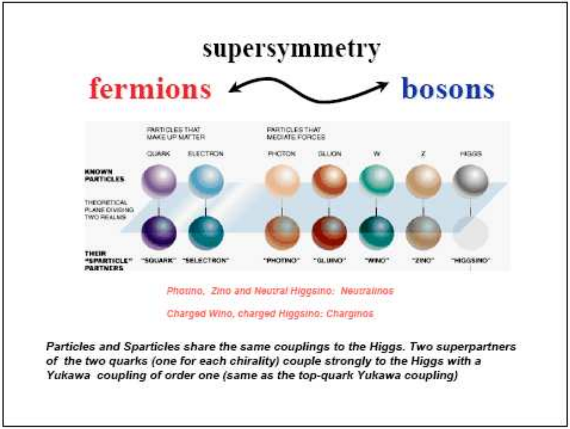
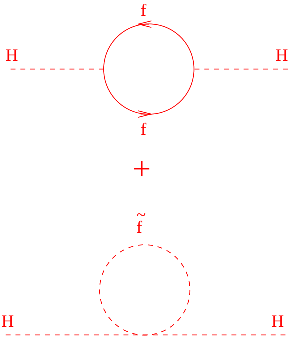
The Supersymmetric Extension of the Standard Model





- Relative sign between squark and quark loops $\Rightarrow$ cancellation of the quadratic dependence of m_h on Λ.
- The superpotential characterizes SUSY interactions

$$W_{MSSM} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

MSSM parameters: Tree-level Higgs Sector

- 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
  1 charged Higgs H^+, and
  2 CP even Higgs bosons h, H

- The angle α rotates the CP-even Higgs mass matrix to give the eigenvalues

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

  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:

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

MSSM parameters: Sfermions and Neutral(charg)inos

- Squark mass matrices:

$$M^2_{U,D} = \begin{pmatrix} \mathbf{\hat{M}^2_{\tilde{u}_L,\tilde{d}_L}} & \frac{v_{u,d}}{\sqrt{2}} X_{u,d} \mathbf{\hat{Y}_{u,d}} \\ \frac{v_{u,d}}{\sqrt{2}} X^*_{u,d} \mathbf{\hat{Y}^\dagger_{u,d}} & \mathbf{M^2_{\tilde{u}_R,\tilde{d}_R}} \end{pmatrix} .$$

where $X_u = \left(A_u - \frac{\mu}{\tan\beta}\right)$ and $X_d = (A_d - \mu \tan\beta)$ flip squark chirality.

- Neutralino states: μ controls amount of Higgsino component in LSP $\Rightarrow$ strong constraints from DM searches on low values of μ
- Chargino states: μ flips chirality between $\tilde{h}_u^+$ and $\tilde{h}_d^-$.

Number of parameters $\sim 10^2$!

How are experimental observables and SUSY parameters?

Outline

Synopsis of this Section

• The B Physics observables:
1. $b \to s\gamma$: either needs a cancellation between the charged-Higgs and chargino-stop contributions or small individual contributions.
2. $B_u \to \tau\nu$: two reqions are allowed (i.e. where Standard contribution $\gg$ MSSM one or vice verse).
3. $B_s \to \mu^+\mu^-$: prefers low or moderate values of the stop trilinear A_t.
4. ΔM_s: correlation with $B_s \to \mu^+\mu^-$ prevents large SUSY contributions.
• Hints of the scale of SUSY breaking may be observed in B physics observables.

The MSSM Flavor Problem and Minimal Flavor Violation

- 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.
- Flavor Problem: $\mathcal{O}(1)$ flavor violation leads $M_{SUSY} \sim 100$ TeV.
- 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

- Corrections due to running soft squark masses:

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

M. Dugan et. al., '85.

- $M \sim M_{SUSY}$ 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

$$\tilde{d}_L^i \rightarrow U_L d_L^i$$

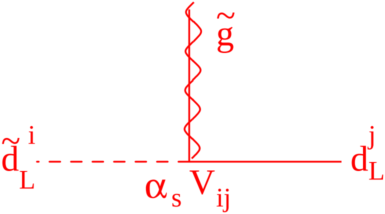
rather than in the basis

$$\tilde{d}_L^i \rightarrow D_L d_L^i$$

MSSM: Tree-level flavor violating charged currents

- Both $M \sim M_{SUSY}$ and $M \sim M_{GUT}$ have V_{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 $M \sim M_{GUT}$ there is a flavor violating gluino vertex:

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



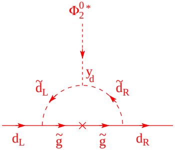
- In this basis additional off-diagonal L-R down squark mass terms:

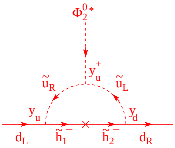
$$\mathcal{L}_{mass} \supset (\tilde{d}_L^*)^I (m_Q^2)^I (\tilde{d}_L)^J + (\tilde{d}_R^*)^I (m_R^2)^I (\tilde{d}_R)^J + \tilde{\mu}^* (\tilde{d}_L^*)^I V_{CKM}^{IJ} m_{d_J} (\tilde{d}_R)^I + h.c.$$

MSSM: Flavor Changing Neutral Currents

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

$$-\mathcal{L}_{eff} = \bar{d}_R^0 \hat{\mathbf{Y}}_{\mathbf{d}} [\Phi_d^{0*} + \Phi_u^{*0} \left(\hat{\epsilon}_{\mathbf{0}} + \hat{\epsilon}_{\mathbf{Y}} \hat{\mathbf{Y}}_{\mathbf{u}}^{\dagger} \hat{\mathbf{Y}}_{\mathbf{u}} \right)] d_L^0 + h.c.$$





  and have the structure:

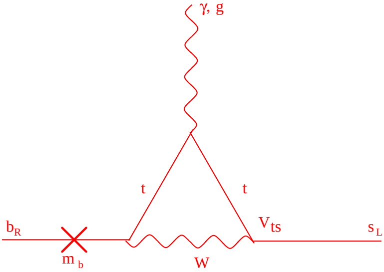
$$\epsilon_0^I \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0(m^2_{\tilde{d}_1^I}, m^2_{\tilde{d}_2^I}, M_3^2)$$

$$\epsilon_Y \approx \frac{1}{16\pi^2} A_t \mu C_0(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)$$

Kolda, Babu, Buras, Roszkowski...

- ϵ_0' and ϵ_Y' for up-type quarks completely parameterize all FCNC effects.
- Low scale flavour structure of the squark masses determines the flavor structure of ϵ-loop factors.

$b \to s\gamma$: Standard Model vs Experiment

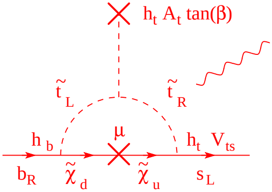


- SM prediction: Left-right operator
  $\Rightarrow \mathcal{BR}(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$

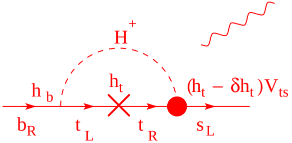
  M. Misiak *et al.*, Phys. Rev. Lett. **98**, 022002 (2007)
- Experimental measurement:
  $\mathcal{BR}(b \to s\gamma) = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$

  [Heavy Flavor Averaging Group (HFAG)], arXiv:hep-ex/0603003

$b \to s\gamma$: MFV MSSM



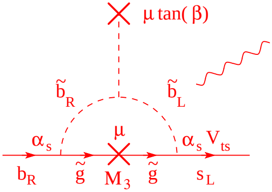
$\propto \mu A_t \tan\beta$



$\propto h_t - \delta h_t \tan\beta$ where

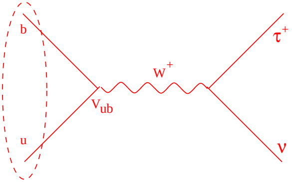
$\frac{\delta h_t}{h_t} \propto \frac{\alpha_s}{3\pi}\mu M_3 \epsilon_0'$

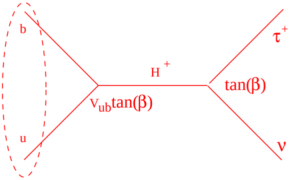
M. Carena et. al. Phys. Lett. B **499**, 141 (2001)



$\propto \mu M_3 (m_0^2 - m_{Q_3}^2) \tan\beta$ only for the $M \simeq M_{GUT}$ scenario.

$B_u \to \tau\nu$: Standard Model vs MSSM and Experiment





- SM prediction: $\mathcal{BR}(B_u \to \tau\nu) = (1.09 \pm 0.40) \times 10^{-4}$.
- Belle measurement: $\mathcal{BR}(B_u \to \tau\nu) = (1.79^{+0.86}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})) \times 10^{-4}$.
- Babar measurement: $\mathcal{BR}(B_u \to \tau\nu) = (1.20 \pm 0.54) \times 10^{-4}$.
- Experimental Average: $\mathcal{BR}(B_u \to \tau\nu)^{\text{Exp}} = (1.41 \pm 0.43) \times 10^{-4}$.

- SUSY: $R_{B\tau\nu} = \frac{\mathcal{BR}(B_u \to \tau\nu)^{\text{MSSM}}}{\mathcal{BR}(B_u \to \tau\nu)^{\text{SM}}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right) \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta}\right]^2$

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

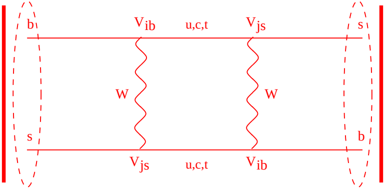
$$\mathbf{H} = \mathbf{M} - \frac{\mathbf{i}}{\mathbf{2}}\boldsymbol{\Gamma}$$

where M and Γ 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 Γ_{12}. Therefore the mass splitting in the B_s meson eigenstates is

$$\begin{aligned} \Delta M_s &= 2\Re\left(\sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}\right) \\ &\approx 2|M_{12}| \end{aligned}$$

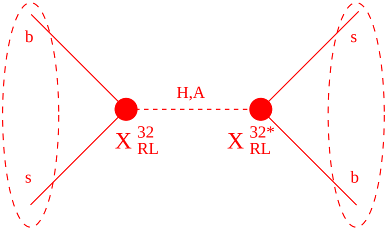
ΔM_s in the Standard Model and Experiment



- CKMfitter SM prediction:
  $13.6\ \mathrm{ps}^{-1} \leq (\Delta M_s)^{SM} \leq 28.6\ \mathrm{ps}^{-1}$ at 2σ
- UtFit SM prediction: $\Delta M_s = 20.9 \pm 2.6\ \mathrm{ps}^{-1}$ at 95 % C.L.
- Experimental measurement:
  $\Delta M_s = (17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst}))$.

S. Giagu [CDF Collaboration], arXiv:hep-ex/0610044.

ΔM_s in the MSSM with MFV



- In MFV MSSM the dominant ΔM_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 $M \sim M_{SUSY}$:

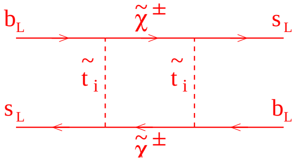
$$X_{RL}^{32} \propto \frac{\epsilon_Y \tan^2\beta}{(1+\epsilon_0^3\tan\beta)(1+\epsilon_3\tan\beta)} V_{eff}^{33*} V_{eff}^{32}$$

- When $M \sim M_{GUT}$:

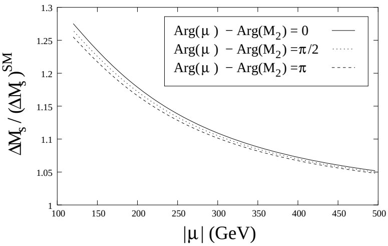
$$X_{RL}^{32} \propto \frac{(\epsilon_0^3+\epsilon_Y-\epsilon_0)\tan^2\beta}{(1+\epsilon_0^3\tan\beta)(1+\epsilon_3\tan\beta)} V_{eff}^{33*} V_{eff}^{32}$$

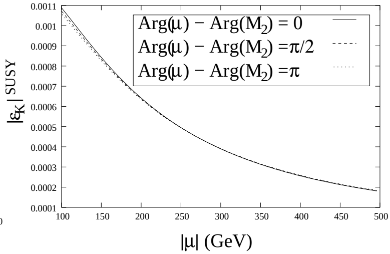
Stop-Chargino Contributions to ΔM_s in MFV

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

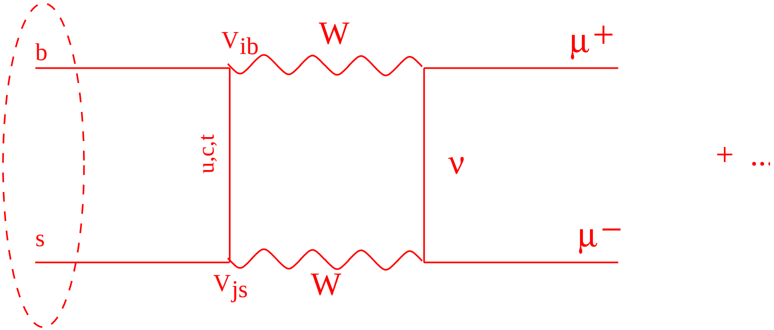


- These kinds of SUSY particle spectra can also induce large contributions to ϵ_K.
- The Experimental value of $\epsilon_K = (2.282 \pm 0.014) \times 10^{-3}$



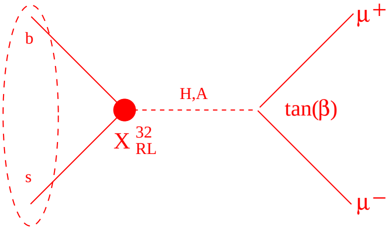


$B_s \to \mu^+\mu^-$ in the Standard Model vs Experiment



- SM prediction: $\mathcal{BR}(B_s \to \mu^+\mu^-) = (3.8 \pm 0.1) \times 10^{-9}$
- Experimental prediction: $\mathcal{BR}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ at 95% C.L.

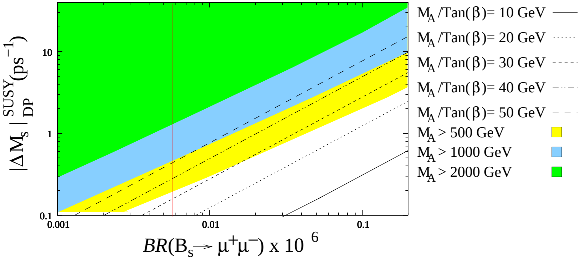
$B_s \to \mu^+\mu^-$ in the MSSM with MFV



- In MFV MSSM, $\mathcal{BR}(B_s \to \mu^+\mu^-)$ gets an extra contribution which comes from penguin diagrams.
- For uniform squark masses:

$$\mathcal{BR}(B_s \to \mu^+\mu^-)_{MSSM} \propto \frac{|(X^A_{RL})^{32}|^2 \tan^2\beta}{M_A^4} \propto \frac{\tan^6\beta}{M_A^4}$$

Correlation between ΔM_s and $B_s \to \mu^+\mu-$



- For uniform squark masses the correlation between ΔM_s and $\mathcal{BR}(B_s \to \mu^+\mu^-)$ is:

$$\frac{|(\Delta M_s)^{SUSY}_{DP}|}{\mathcal{BR}(B_s \to \mu^+\mu^-)_{SUSY}} \sim \frac{0.034(\mathrm{ps})^{-1}}{10^{-7}} \frac{M_A^2}{M_W^2} \left(\frac{50}{\tan\beta}\right)^2$$

- The bound on $\mathcal{BR}(B_s \to \mu^+\mu^-)$ implies an atmost 2 ps^{-1} double penguin contributions to $\Delta M_s \sim$

B Physics observables and SUSY Parameters

- Large values of pseudo-scalar mass M_A and low values of $\tan\beta$ are not greatly constrained by flavor physics.
- $\mathcal{BR}(B_u \to \tau\nu)$ independent of μ and X_t
- For large $\tan\beta$ and small M_A B physics constraints are important, especially for searches at the Tevatron.

Observable($M \sim M_{SUSY}$)	μ	X_t
$b \to s\gamma$ $B_s \to \mu^+\mu^-$	large or moderate small	small or moderate small
Observable($M \sim M_{GUT}$)		
$b \to s\gamma$ $B_s \to \mu^+\mu^-$	moderate moderate	small or moderate moderate

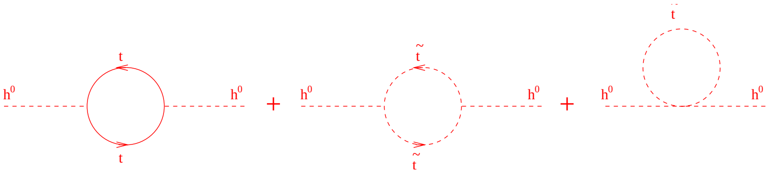
Outline

Synopsis of this Section

- Loop corrections to the Higgs mass are controlled by the stop trilinear X_t
- Non-standard Higgs bosons have $\tan\beta$ enhanced couplings to bottom quarks and τ leptons.

The Loop corrected Higgs mass in the MSSM

- Tree-level SM-like Higgs mass $< M_Z <$ LEP Higgs mass bound.

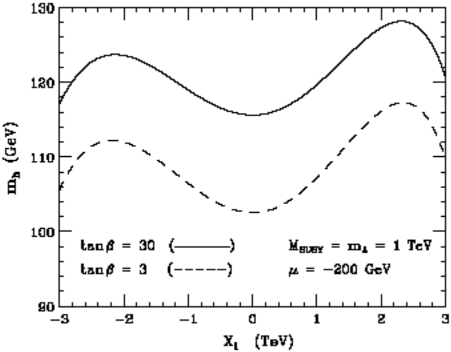


- For large values of the CP odd Higgs mass M_A the SM-like Higgs has a mass

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

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

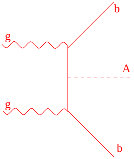
Benchmark scenarios in the MSSM

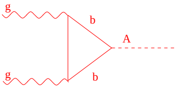


M. Carena et. al., Prog. Part. Nucl. Phys. **50**, 63 (2003).

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

Non-standard Higgs boson production and decay



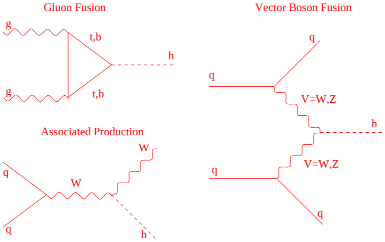


$$g_{Abb} \simeq \frac{m_b \tan\beta}{(1+\epsilon_3 \tan\beta)v};\, g_{A\tau\tau} \simeq \frac{m_\tau \tan\beta}{v};$$

$$\mathcal{BR}(A \to \tau^+\tau^-) \simeq \frac{(1+\epsilon_3 \tan\beta)^2}{9+(1+\epsilon_3 \tan\beta)^2};$$

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

SM-like Higgs boson production and decay



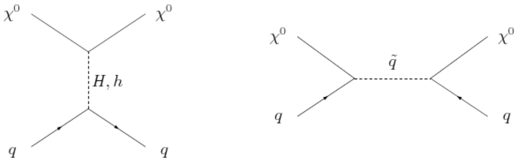
- At the Tevatron, for $m_h \lesssim 135$ GeV the channel $q\bar{q} \to Wh(h \to b\bar{b})$ is dominant, where the Higgs is produced in association with W and decays into $b\bar{b}$.
- At the LHC, for $m_h \lesssim 135$ GeV the $gg \to h(h \to \gamma\gamma)$ and $q\bar{q} \to q\bar{q}h(h \to \tau\bar{\tau})$ channels are important.

Outline

Synopsis of this Section

- The size of neutralino-nucleon spin-independent cross-section is mostly determine by the amount of Higgsino component in the Lightest SUSY Particle or the size of μ.

Neutralino Spin-Independent Cross-section

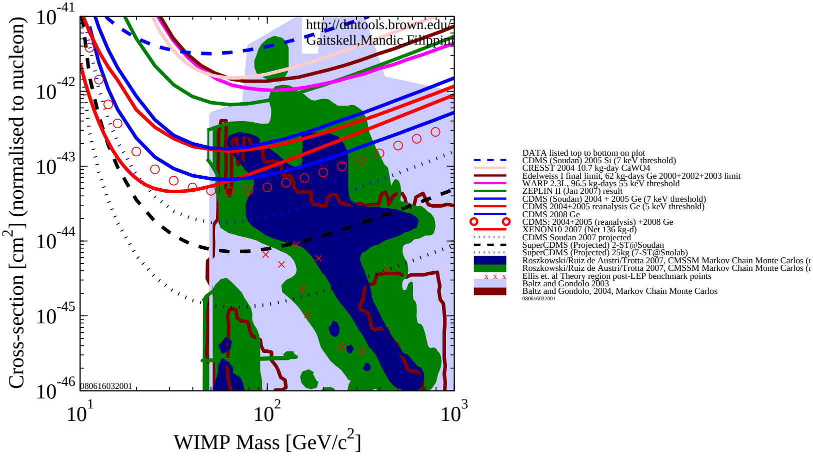


- The neutralino mass matrix

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_{\theta_W} & M_Z s_\beta s_{\theta_W} \\ 0 & M_2 & M_Z c_\beta c_{\theta_W} & -M_Z s_\beta c_{\theta_W} \\ -M_Z c_\beta s_{\theta_W} & M_Z c_\beta c_{\theta_W} & 0 & -\mu \\ M_Z s_\beta s_{\theta_W} & -M_Z s_\beta c_{\theta_W} & -\mu & 0 \end{pmatrix}$$

- Non-standard Higgs mediated scattering:
  $\sigma_{SI} \propto |N_{11}|^2 |N_{13}|^2 \frac{\tan^2\beta}{(1+\epsilon_0 \tan\beta) M_A^4}$
- Squark mediated scattering: $\sigma_{SI} \propto |N_{11}|^2 |N_{13}|^2 \frac{\tan^2\beta}{(1+\epsilon_0 \tan\beta) m_{\tilde{q}}^4}$

Direct Dark Matter Detection in the MSSM

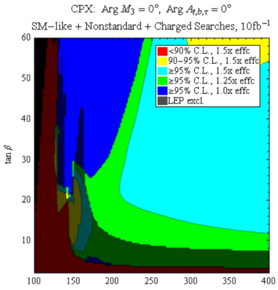


Outline

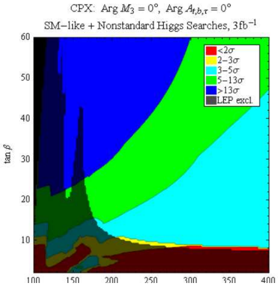
Combined Higgs Searches at the Tevatron and LHC

CPX Benchmark: $M_{SUSY} = 500$ GeV, $|A_t| = 1$ TeV, $\mu = 2$ TeV, $M_{1,2} = 200$ GeV and $M_3 = 1$ TeV

Tevatron Current/Projected



LHC Projected.



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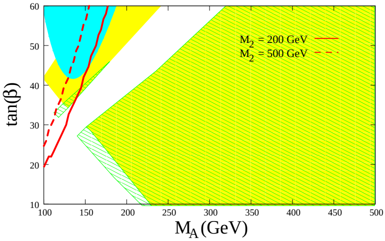
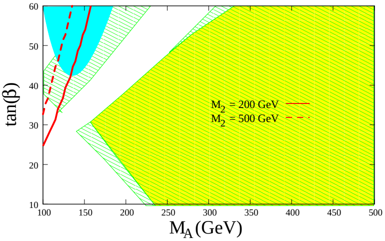
Most of MSSM parameter space will be probed 95% C.L. at the Tevatron!

B Physics and Dark Matter Constraints

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



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



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

- Region exclude by CDF/D0 in the $A \to \tau\tau$ channel at 2 fb^{-1}
- Region allowed by B Physics for $M \sim M_{SUSY}$
- Region allowed by B Physics for $M \sim M_{GUT}$
- Region below allowed by Direct Dark Matter Searches

Conclusions

- Within minimal flavor violating MSSM the double penguin contribution to ΔM_s is small due to $B_s \to \mu^+\mu^-$ constraint.
- We have showed that RG evolution has an impact of flavor observables and some interesting information about the scale of SUSY breaking maybe extracted from them.
- 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 Tevatron should be able to probe all of the allowed region of parameter space with 10 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.