Interplay for Higgs Boson Searches in the MSSM at Hadron Colliders

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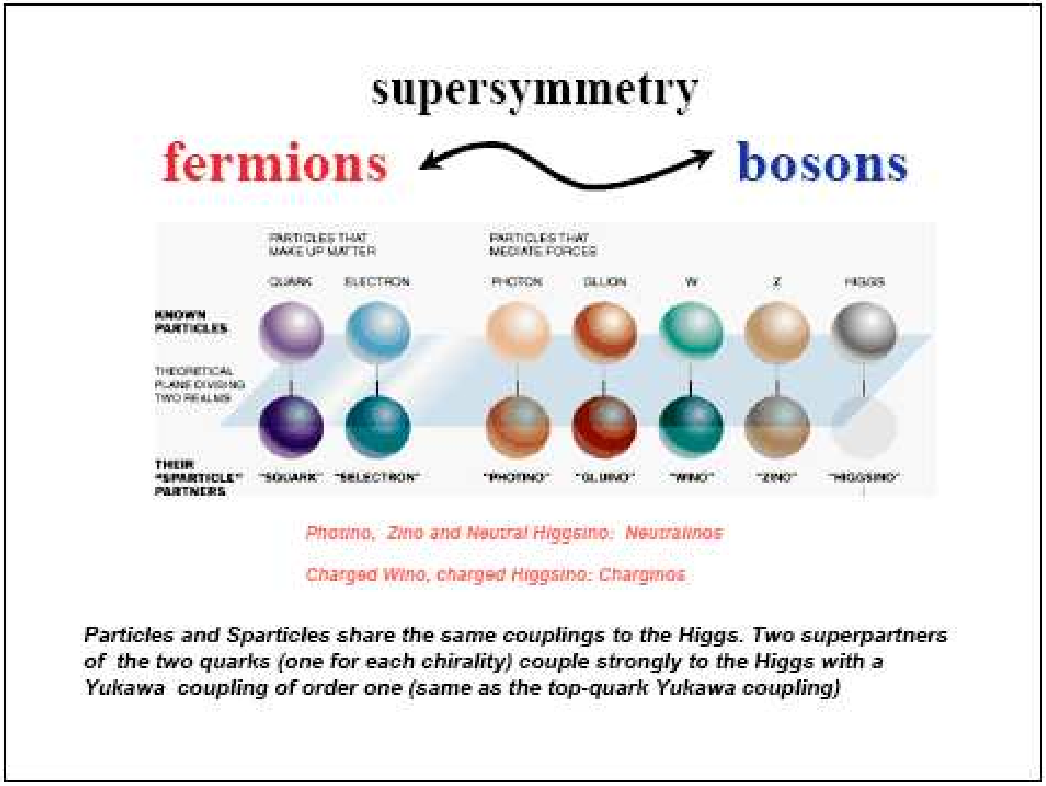
Based on:

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, arXiv:0704.1143 [hep-ph].;

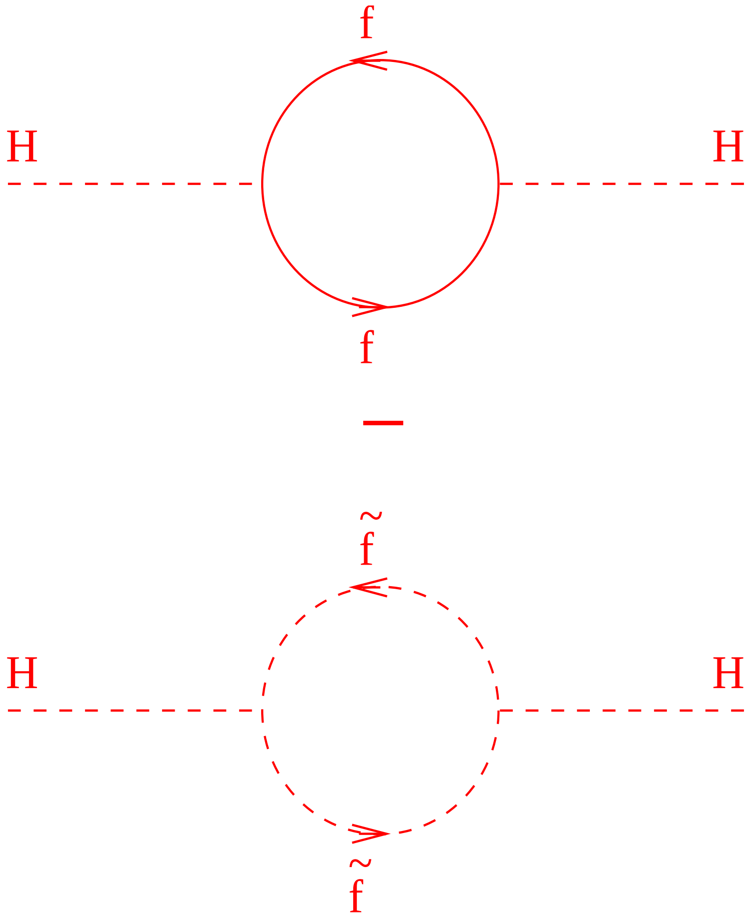
The Minimal Supersymmetric Standard Model: a solution



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)



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

SUSY breaking and Soft Mass terms

- SUSY breaking and weak scale stabilization $\Rightarrow$ only couplings of positive mass dimension.

- Squark mass matrices:

$$\begin{aligned}
M_U^2 &= \begin{pmatrix} \hat{\mathbf{M}}^{\mathbf{2}}_{\tilde{\mathbf{u}}_{\mathbf{L}}} & \frac{v_2}{\sqrt{2}} X_u \hat{\mathbf{Y}}_{\mathbf{u}} \\ \frac{v_2}{\sqrt{2}} X_u^* \hat{\mathbf{Y}}^\dagger_{\mathbf{u}} & \mathbf{M}^{\mathbf{2}}_{\tilde{\mathbf{u}}_{\mathbf{R}}} \end{pmatrix} \\
M_D^2 &= \begin{pmatrix} \hat{\mathbf{M}}^{\mathbf{2}}_{\tilde{\mathbf{d}}_{\mathbf{L}}} & \frac{v_1}{\sqrt{2}} X_d \hat{\mathbf{Y}}_{\mathbf{d}} \\ \frac{v_1}{\sqrt{2}} X_d^* \hat{\mathbf{Y}}^\dagger_{\mathbf{d}} & \mathbf{M}^{\mathbf{2}}_{\tilde{\mathbf{d}}_{\mathbf{R}}} \end{pmatrix} .
\end{aligned}$$

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

The 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 a CP odd Higgs A, a charged Higgs H^+ and two CP even Higgs bosons h, H

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

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

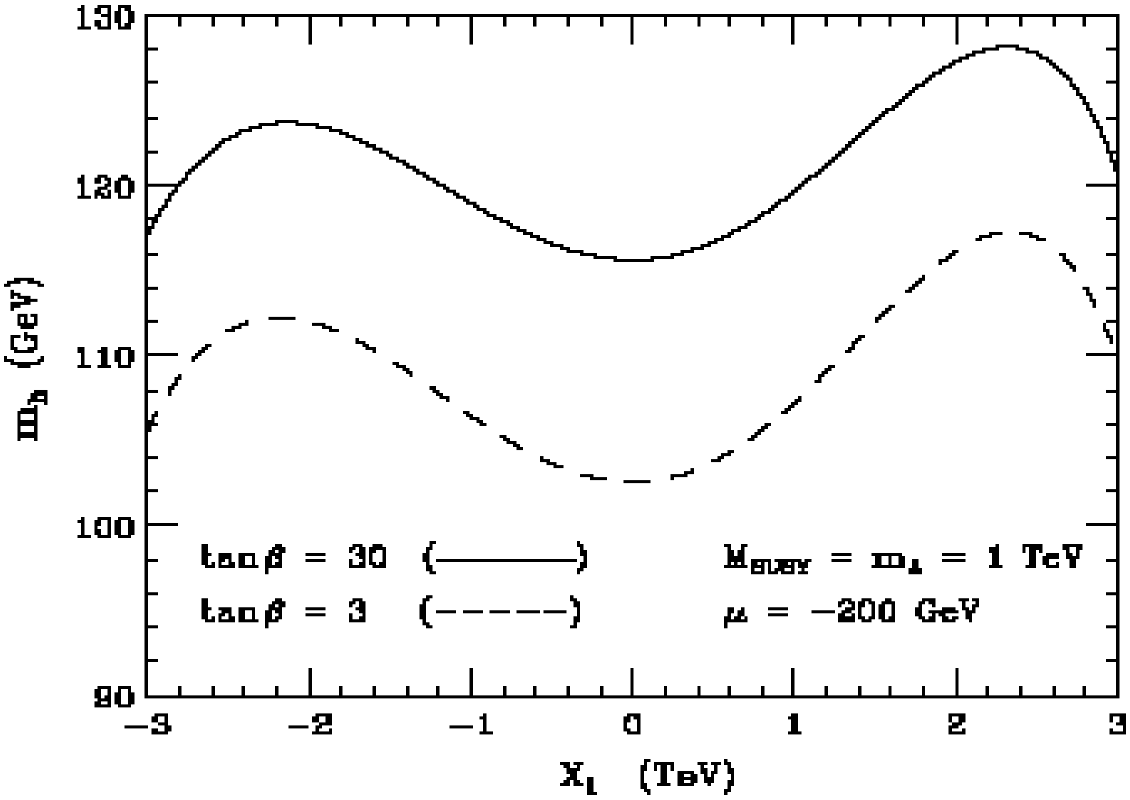
- Gauge coupling $\sim 1 \Rightarrow$ SM-like Higgs while gauge coupling $\sim 0 \Rightarrow$ CP odd Higgs.

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

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

where $\tilde{X}_t = 2a^2(1 - a^2/12)$, M_{SUSY} is the 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 ⇒ maximum value of the Higgs mass ⇒ $X_t \sim 2.4 M_{SUSY}$
- Minimal mixing scenario ⇒ minimum value of the Higgs mass ⇒ $X_t \sim 0$

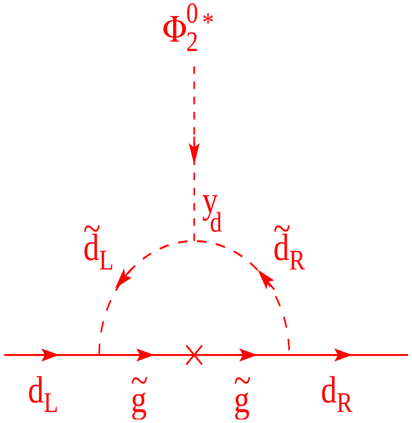
The Flavor Problem and Minimal Flavor Violation in the MSSM

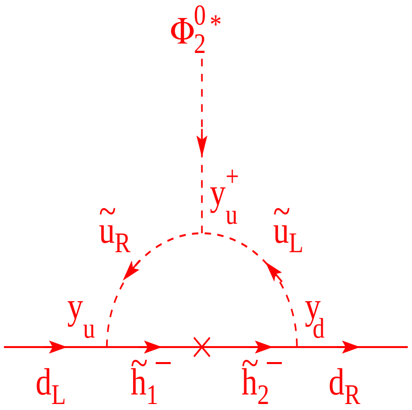
- No tree-level flavor changing neutral currents as: $\mathcal{L} = \bar{Q}_L(\hat{Y}_d \Phi_d d_R + \hat{Y}_u \Phi_u u_R) + h.c.$, but Loop suppression effects offset by large $\tan\beta$ effects.

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

$$-\mathcal{L}_{eff} = \bar{d}^0_R \hat{\mathbf{Y}}_\mathbf{d}[\mathbf{\Phi}^{0*}_d + \mathbf{\Phi}^{*0}_u \left(\hat{\epsilon}_\mathbf{0} + \hat{\epsilon}_\mathbf{Y} \hat{\mathbf{Y}}^\dagger_\mathbf{u} \hat{\mathbf{Y}}_\mathbf{u}\right)]d^0_L + h.c.$$

where the ϵ loop factors are:





and have the structure:

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

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

- In quark mass basis:

$$-\mathcal{L}_{\mathrm{mass}} = \frac{v_d}{\sqrt{2}} \bar{d}_R \mathbf{Y}_\mathbf{d}[1 + \tan\beta \left(\epsilon_\mathbf{0} + \mathbf{V}_\mathbf{0}^\dagger \epsilon_\mathbf{Y} |\mathbf{Y}_\mathbf{u}|^2 \mathbf{V}_\mathbf{0}\right)]d_L + h.c.$$

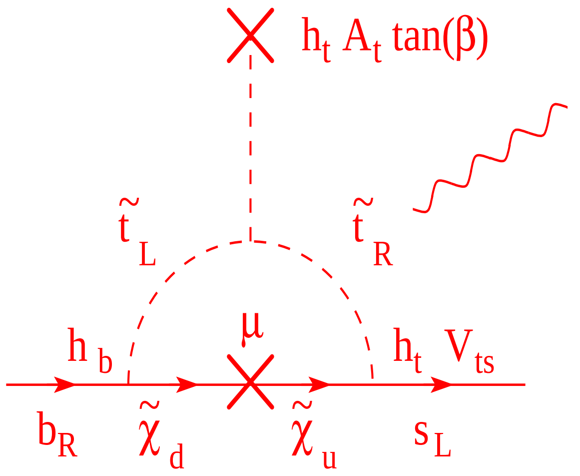
Similarly there is ϵ'_0 and ϵ'_Y for up-type quarks.

B physics experimental limits and the SM predictions

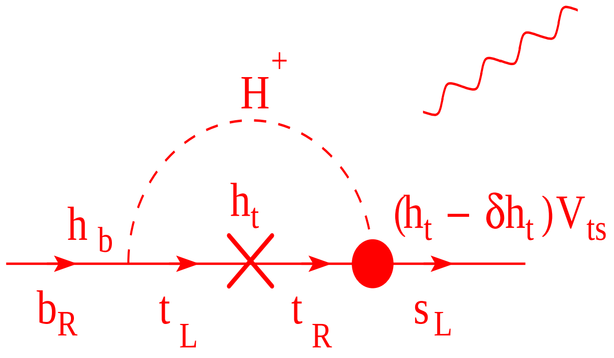
Quantity	SM prediction	Exp. meas./limit
$\mathcal{BR}(b \to s\gamma)$	$(2.98 \pm 0.26) \times 10^{-4}$	$(3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$
ΔM_s CKMfitter	$13.4\ \mathrm{ps}^{-1} \leq (\Delta M_s)^{SM} \leq 31.1\ \mathrm{ps}^{-1}$ at 2σ	$\Delta M_s = (17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst}))$.
ΔM_s UTfit	$\Delta M_s = 20.9 \pm 2.6\ \mathrm{ps}^{-1}$ at 95 % C.L.	
$\mathcal{BR}(B_s \to \mu^+\mu^-)$	$(3.8 \pm 0.1) \times 10^{-9}$	$< 1 \times 10^{-7}$ at 95% C.L

Quantity	SM prediction	Exp. meas.
$\mathcal{BR}(B_u \to \tau\nu)$	$(0.85 \pm 0.13) \times 10^{-4}$ $\vert V_{ub}\vert$ fit	$\mathcal{BR}(B_u \to \tau\nu) = (1.79^{+0.86}_{-0.49}(\mathrm{stat})^{+0.46}_{-0.51}(\mathrm{syst})) \times 10^{-4}$ Belle
	$(1.39 \pm 0.44) \times 10^{-4}$ $\vert V_{ub}\vert$ ext.	$\mathcal{BR}(B_u \to \tau\nu) = (0.88^{+0.68}_{-0.67}(\mathrm{stat}) \pm 0.11) \times 10^{-4}$ Babar

$b \to s\gamma$ in the MSSM with MFV

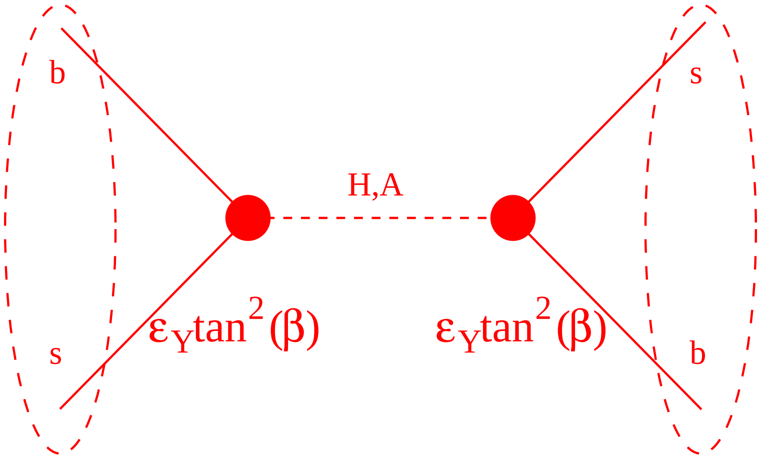


$\propto \frac{\mu A_t \tan\beta}{1+\epsilon_3 \tan\beta}$



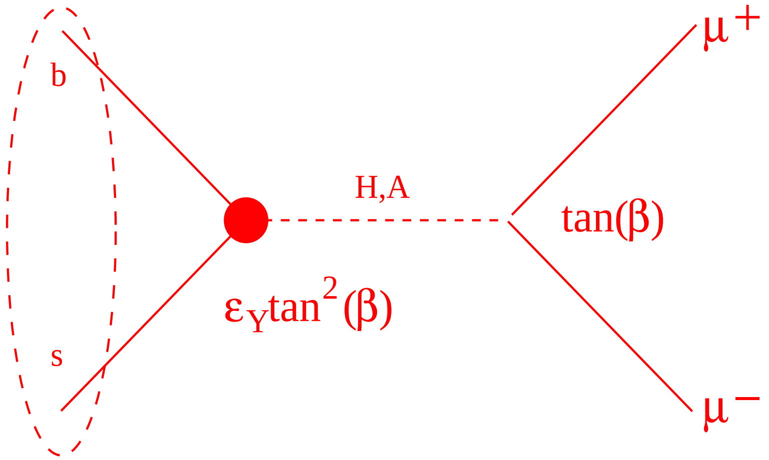
$\propto \frac{h_t - \delta h_t \tan\beta}{(1+\epsilon_3 \tan\beta)}$ where $\frac{\delta h_t}{h_t} \propto \frac{\alpha_s}{3\pi} \mu M_3 \epsilon_0'$

ΔM_s in the MSSM with MFV



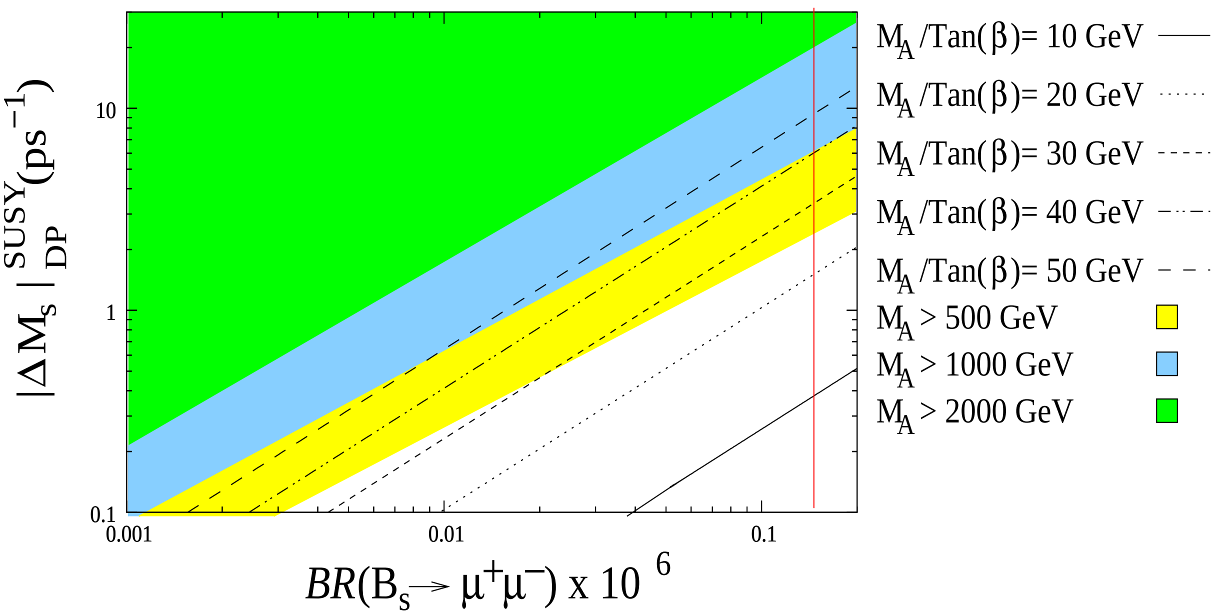
$$(\Delta M_s)^{DP} = -12.0\text{ps}^{-1}\left[\frac{\tan\beta}{50}\right]^4\left[\frac{F_{B_s}}{230MeV}\right]^2\left[\frac{V_{ts}}{0.04}\right]^2$$
$$[\frac{\bar{m}_b(\mu_s)}{3.0GeV}][\frac{\bar{m}_s(\mu_s)}{0.06GeV}][\frac{\bar{m}_t^4(\mu_s)}{M_W^2 M_A^2}]\frac{(16\pi^2\epsilon_Y^2)^2}{(1+\epsilon_3\tan\beta)^2(1+\epsilon_0\tan\beta)}$$

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



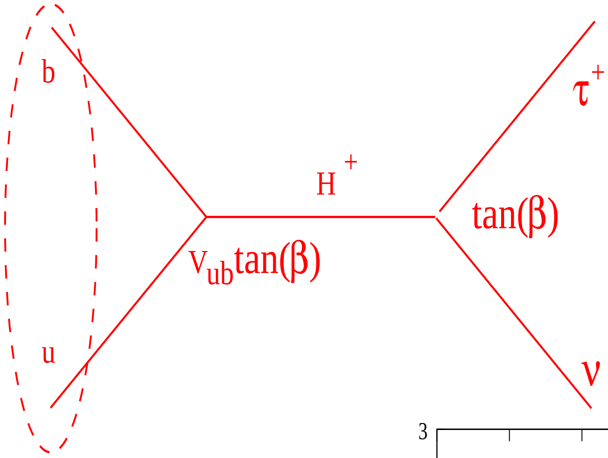
$$\begin{aligned} \mathcal{BR}(B_s \to \mu^+\mu^-) &= 3.5 \times 10^{-5} \left[\frac{\tan\beta}{50}\right]^6 \left[\frac{\tau_{B_s}}{1.5\mathrm{ps}}\right] \left[\frac{F_{B_s}}{230\mathrm{MeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 \\ &\times \frac{m_t^4}{M_A^4} \frac{(16\pi^2\epsilon_Y)^2}{(1+\epsilon_3\tan\beta)^2(1+\epsilon_0\tan\beta)^2} \end{aligned}$$

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

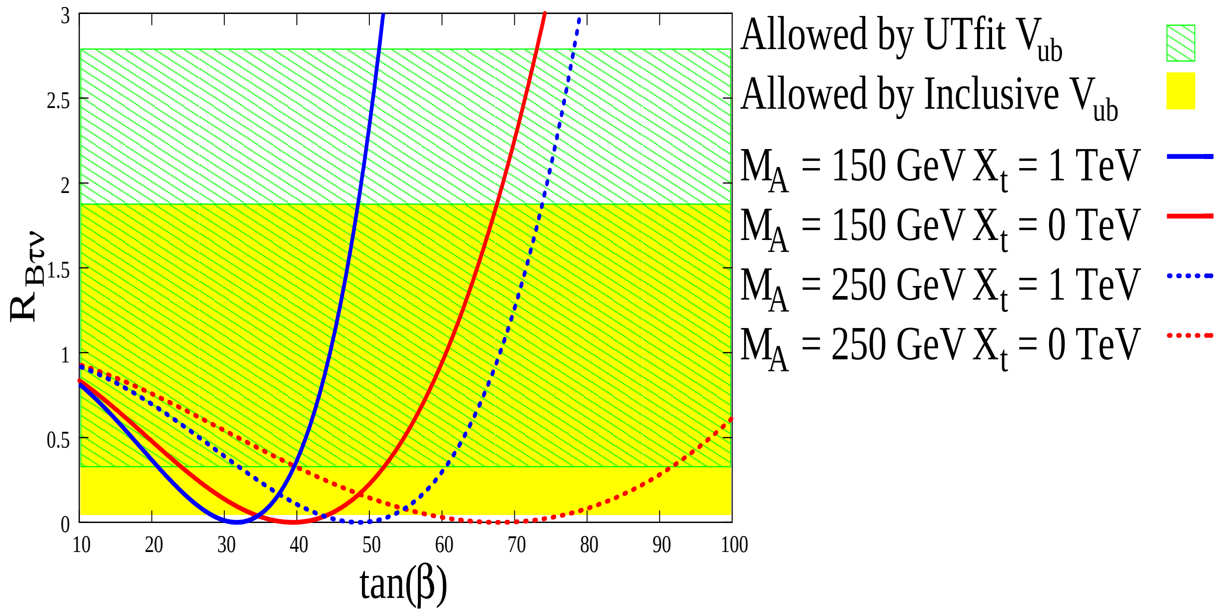


$$\frac{|(\Delta M_s)^{SUSY}_{DP}|}{\mathcal{BR}(B_s \to \mu^+\mu^-)_{SUSY}} \sim \frac{0.034(\mathrm{ps})^{-1}}{10^{-7}} \frac{M_A^2}{M_W^2} \left(\frac{50}{\tan\beta}\right)^2$$

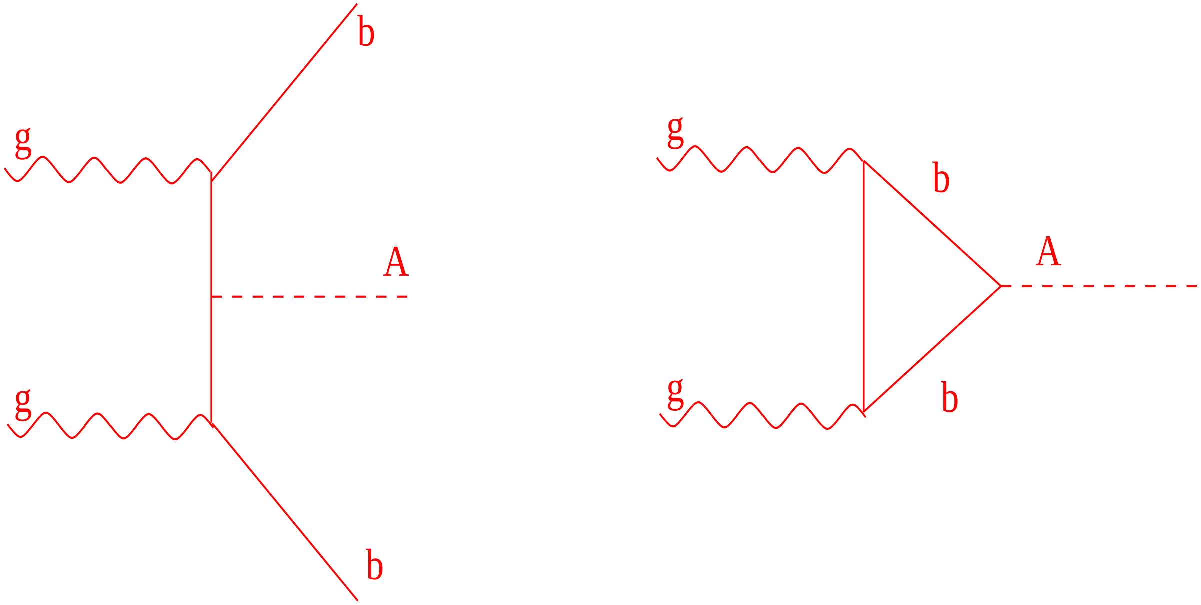
$B_u \to \tau\nu$ in the MSSM with MFV



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



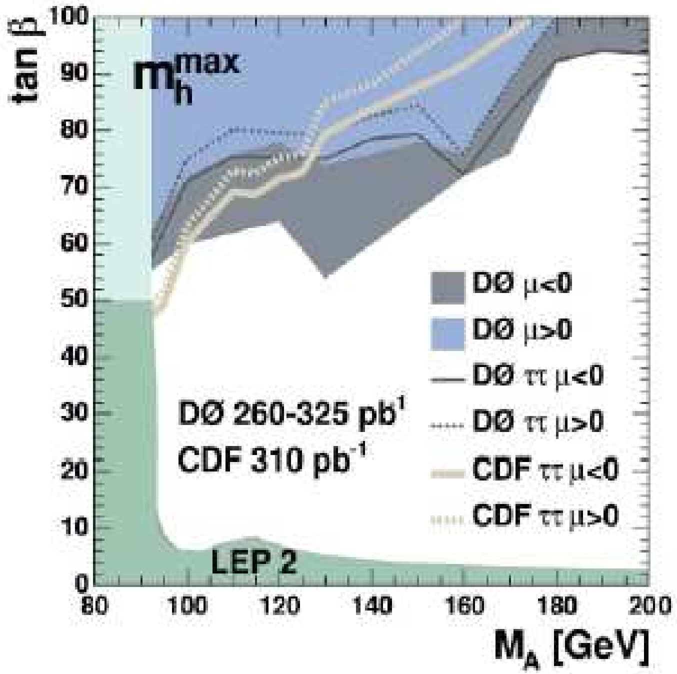
Non-standard Higgs boson production and decay

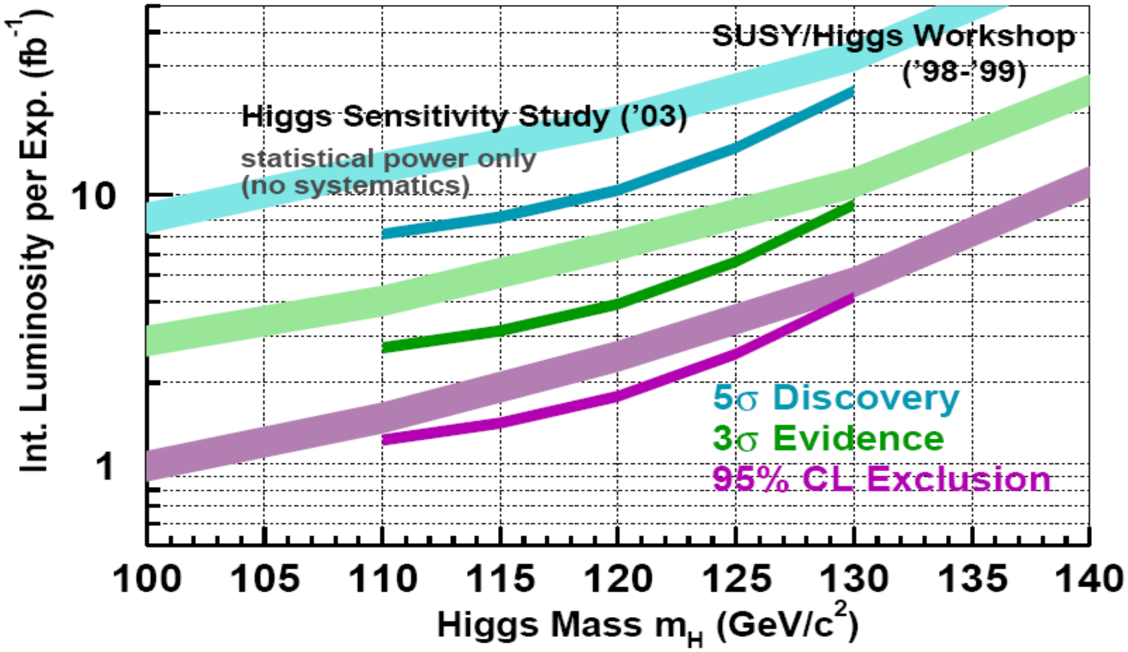


$$g_{Abb} \simeq \frac{m_b \tan\beta}{(1+\epsilon_3 \tan\beta) v}; \qquad g_{A\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}; \qquad \mathcal{BR}(A \to \tau^+\tau^-) \simeq \frac{(1+\epsilon_3 \tan\beta)^2}{9 + (1+\epsilon_3\tan\beta)^2};$$

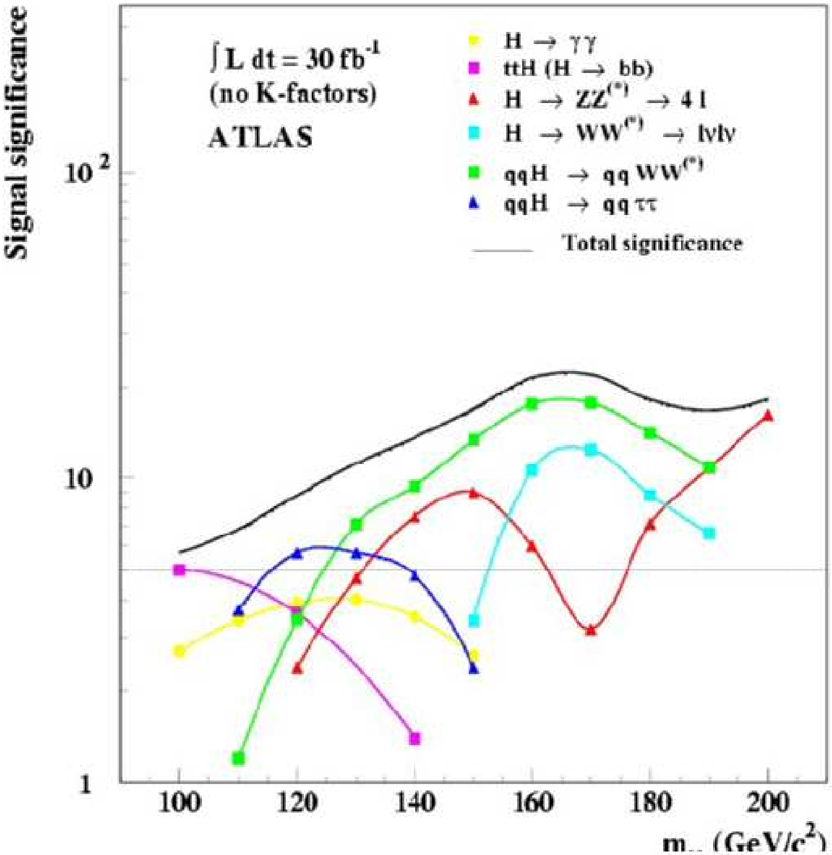
$$\sigma(b\bar{b}, gg \to A) \times \mathcal{BR}(A \to \tau\tau) \propto \frac{\tan^2\beta}{(1+\epsilon_3\tan\beta)^2 + 9}$$

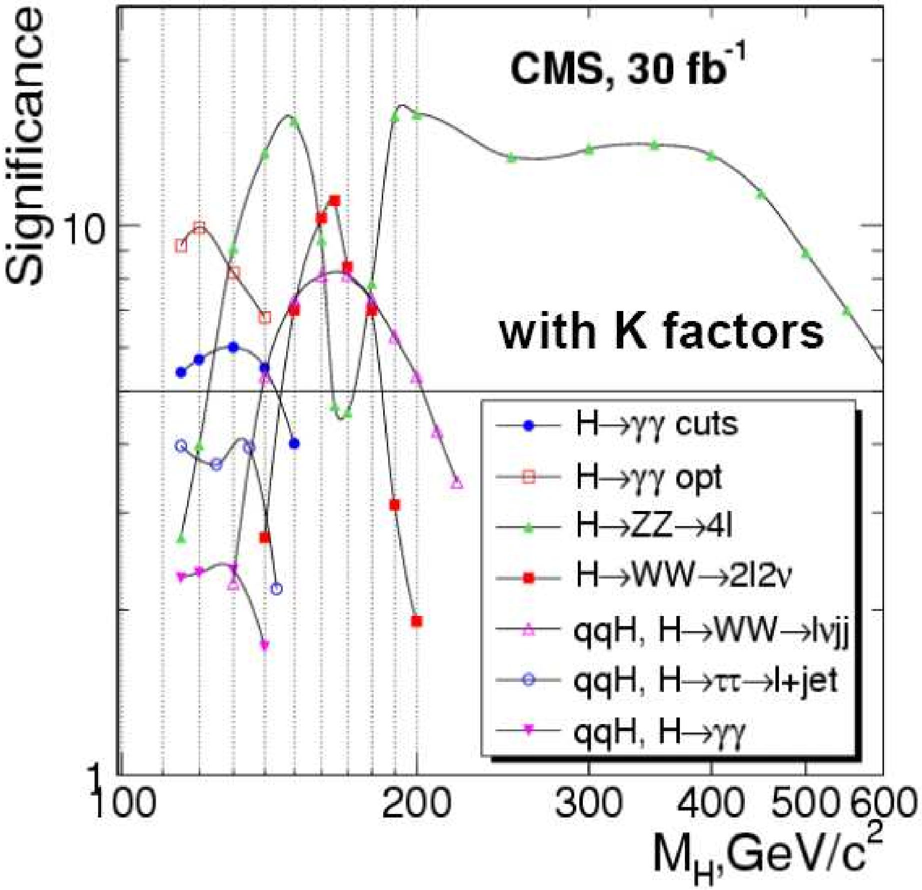
Tevatron limits and projections



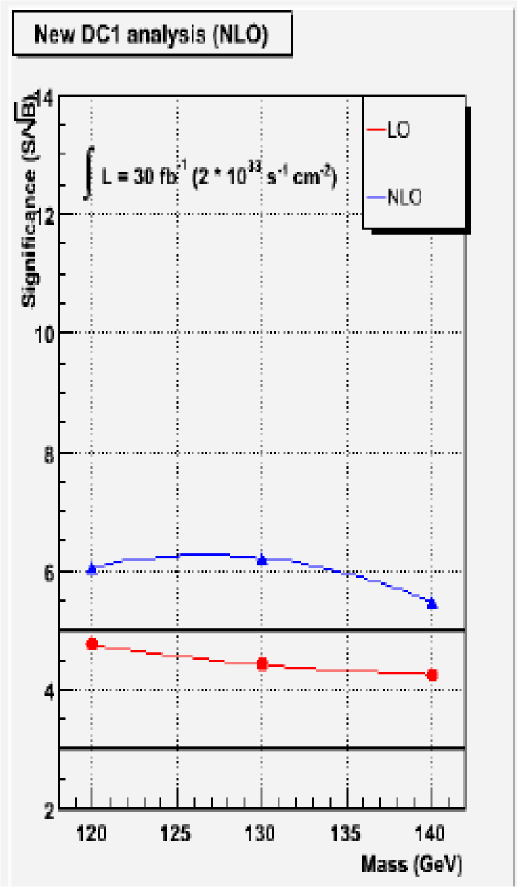


ATLAS and CMS projections





Updated ATLAS projections and Signal Significance in the MSSM



$$R = \frac{\sigma(P\bar{P}\to X\phi)_{MSSM}\mathcal{BR}(\phi\to Y)_{MSSM}}{\sigma(P\bar{P}\to X\phi)_{SM}\mathcal{BR}(\phi\to Y)_{SM}}$$

If $|m_h - m_h^{max}| \lesssim 10$ GeV

$$R = \frac{\sigma(P\bar{P}\to Xh)_{MSSM}\mathcal{BR}(h\to Y)_{MSSM}+\sigma(P\bar{P}\to XH)_{MSSM}\mathcal{BR}(H\to Y)_{MSSM}}{\sigma(P\bar{P}\to X\phi)_{SM}\mathcal{BR}(\phi\to Y)_{SM}}$$

Limits and constraints for maximal and minimal mixing

Maximal mixing: $X_t = 2.4$ TeV, $\mu = -100$ GeV:

- The $b \to s\gamma$ constraint $\Rightarrow$ charged Higgs cancels against chargino-stop or negative $sign(\mu A_t)$.

- The $B_s \to \mu^+\mu^-$ constraint is strong due to large A_t.

- The $B_u \to \tau\nu$ constraint dominated by SUSY contributions is strongly constrained by the $B_s \to \mu^+\mu^-$ constraint.

Minimal mixing: $X_t = 0$, μ large:

- $X_t \sim 0 \Rightarrow$ chargino-stop contribution is small, so $b \to s\gamma$ constraint $\Rightarrow$ charged Higgs contribution ~ 0 by cancellation due to corrected charged Higgs vertex.

- The $B_s \to \mu^+\mu^-$ constraint is weak due to small A_t.

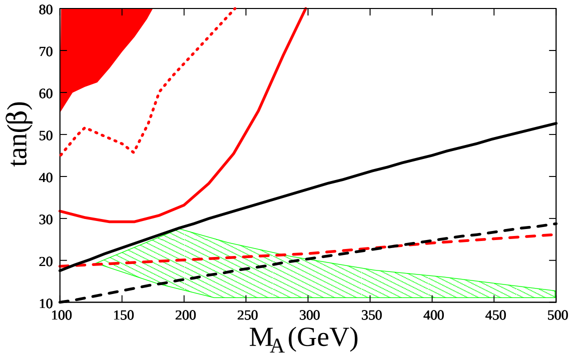
- For the $B_u \to \tau\nu$ constraint, the region dominated by SUSY contributions is interesting for the Tevatron.

Projection of constraints in the $M_A - \tan\beta$ plane for large X_t and small μ

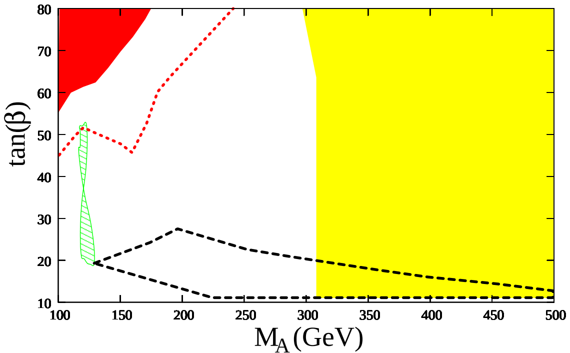
$$M_{SUSY} = 2.4\text{TeV}, \;\; |M_3| = 0.8 M_{SUSY}, \;\; \mu = -100\text{GeV}, \;\; X_t = A_t - \frac{\mu}{\tan\beta} = 1\text{TeV}$$

Fig	Green	Yellow
1	B-phys. allowed	N.A.
2	$q\bar{q}h(h \to \tau\bar{\tau})$	$ggh(h \to \gamma\gamma)$
3	$q\bar{q}h(h \to \tau\bar{\tau})$	$ggh(h \to \gamma\gamma)$
4	$W/Zh(h \to b\bar{b})$	N.A.

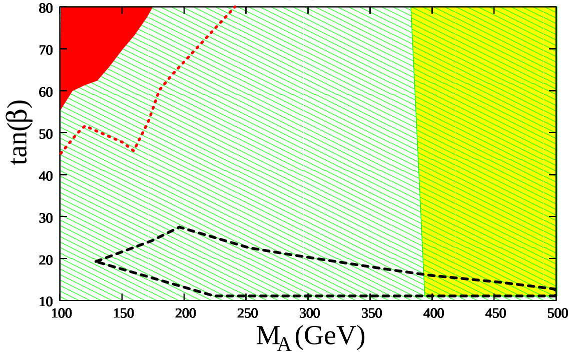
Non-standard Higgs searches



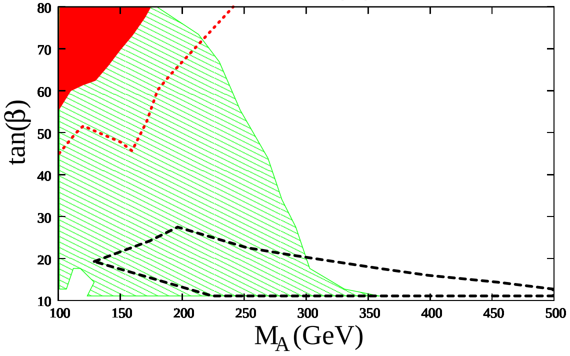
CMS SM Higgs searches



Altas SM Higgs searches



Tevatron SM Higgs searches



- Red region exclude by CDF by inclusive searches for $A \to \tau\tau$ at 1 fb^{-1}. Regions surrounded by black dashed curves in Fig. 2,3,4 are B-physics allowed

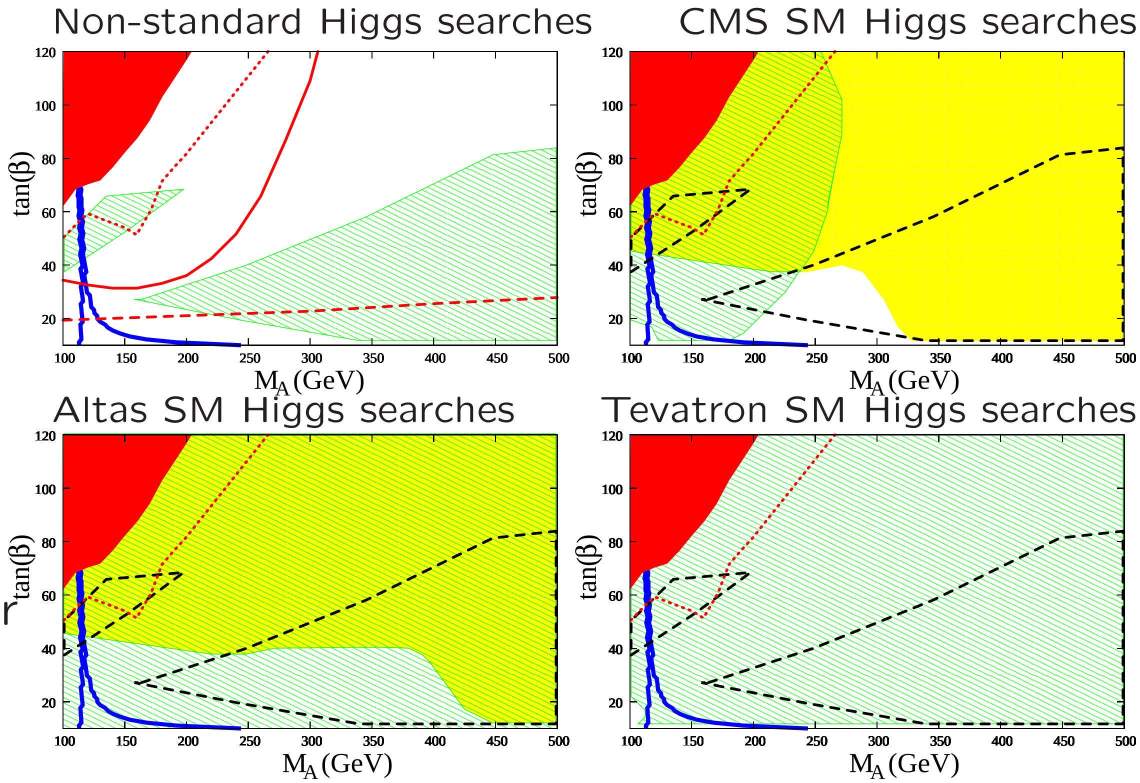
Line	solid	dashed	dotted
Excluded above red for inclusive $A \to \tau\tau$	4 fb^{-1} Proj. Tevatron	30 fb^{-1} Proj. LHC	1 fb^{-1} D0
Excluded below black for $B_s \to \mu^+\mu^-$	4 fb^{-1} Proj. Tevatron	10 fb^{-1} Proj. LHC	N.A.

Projection of constraints in the $M_A - \tan\beta$ plane for Minimal Mixing

The SUSY parameters are same except $X_t = 0$ $\mu = 1.5 M_{SUSY}$ and $M_{SUSY} = 2$ TeV.

Fig	Green	Yellow
1	B-phys. allowed	N.A.
2	$q\bar{q}h(h \to \tau\bar{\tau})$	$ggh(h \to \gamma\gamma)$
3	$q\bar{q}h(h \to \tau\bar{\tau})$	$ggh(h \to \gamma\gamma)$
4	$W/Zh(h \to b\bar{b})$	N.A.

- Red region exclude by CDF by inclusive searches for $A \to \tau\tau$ at 1 fb^{-1}. Regions surrounded by black dashed curves in Fig. 2,3,4 are B-physics allowed. Region under blue curve exclude by LEP Higgs mass bound. $X_t = 0 \Rightarrow B_s \to \mu^+\mu-$ constraint is weak


Non-standard Higgs searches

CMS SM Higgs searches

Altas SM Higgs searches

Tevatron SM Higgs searches

Line	solid	dashed	dotted
Excluded above red for inclusive $A \to \tau\tau$	4 fb^{-1} Proj. Tevatron	30 fb^{-1} Proj. LHC	1 fb^{-1} D0

Conclusions

- Within the MSSM the measurements of ΔM_s at D0 and CDF are consistent with the bound on $B_s \to \mu^+\mu^-$.

- Non-standard Higgs searches are highly constrained for the Maximal Mixing scenario as the B-physics favored regions are also those where non-standard Higgs searches are less efficient.

- SM-like Higgs boson searches, in the Maximal mixing scenario, the LHC experiments should be able to probe all of the allowed region of parameter space with 30 fb^{-1}, but the Tevatron collider may have difficulties doing this with 4 fb^{-1} of data.

- The Minimal Mixing scenario looks more promising especially for non-standard Higgs searches as the Tevatron is more sensitive at lower values of M_A.

- Observation of a non-standard Higgs at the Tevatron would imply either moderate values of X_t for small μ or small values of X_t and large values of μ.