Interplay of B and Higgs Physics in Minimal Supersymmetric Models

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in collaboration with

M. Carena, S. Heinemeyer and G. Weiglein, Eur. Phys. J. C45:497, 2006.
M. Carena, A. Menon, R. Noriega and A. Szynkman, PRD74:015009 (2006)
M. Carena, A. Menon, PRD76:035004 (2007)

Workshop on Interplay of Flavor and Collider Physics,
CERN, December 3, 2007

Flavor Structure of the SM

- The complete fermion Lagrangian reads

$$\mathcal{L} = \sum_i \bar{\Psi}^i_{L,R} \mathcal{D}^\mu \gamma_\mu \Psi^i_{L,R} + \sum_{i,j} \left(\bar{\Psi}^i_L h^d_{ij} H d^j_R + \bar{\Psi}^i_L h^u_{ij} (i\sigma_2 H^*) u^j_R + h.c. \right)$$

- Once we diagonallize the mass matrix, the interactions of the Higgs field are also diagonal in flavor.

- For instance, in the mass eigenstate basis what we get is

$$\bar{d}_i(\hat{m}_i + \hat{h}_i H^0) d_i, \qquad \text{with} \quad \hat{m}_i = \hat{h}_i v$$

where $\hat{m}_i$ and $\hat{h}_i$ are the diagonal masses and Yukawa couplings of the down quarks.

Flavor Changing Effects

- Flavor changing effects in the SM arise from the charged currents, which mix left-handed u and d quarks

$$\bar{u}_{L,i} V^{ij}_{CKM} \gamma_\mu d_{L,j} W^+_\mu + h.c. \qquad \text{(Responsible for } n \to p e \bar{\nu}\text{)}$$

where $V_{CKM} = U_L^\dagger D_L$.

- The CKM matrix is very close to the identity, and hence transitions between different flavors are suppressed in the SM

- The Higgs sector, as well as the neutral gauge interactions do not lead to FCNC.

Two Higgs doublet Models

- Now, imagine there are two Higgs doublets.

$$\bar{d}_{R,i}\left(h^{ij}_{d,1}H_1 + h^{ij}_{d,2}H_2\right)d_{L,j}$$

- Both Higgs doublets will acquire different v.e.v.'s. The mass matrix will be equal to

$$m_d^{ij} = h^{ij}_{d,1}v_1 + h^{ij}_{d,2}v_2$$

- It is clear that the diagonalization of the mass matrix will lead to the diagonalization of neither of the Yukawa couplings. This will induce large, usually unacceptable FCNC in the Higgs sector.

- Easiest solution: Up and down quarks should couple to only one of the Higgs bosons. This is what happens in the MSSM at tree-level.

MSSM Higgs Boson Spectrum

- Two Higgs doublets: Two CP-even, a CP-odd and a charged Higgs. The CP-even Higgs bosons

$$h \simeq \cos\beta \; Re(H_1^0) + \sin\beta \; Re(H_2^0)$$

$$H + iA \simeq \sin\beta \; H_1^0 - \cos\beta \; H_2^0$$

where $\boxed{\tan\beta = \frac{v_2}{v_1}}$

- Similarly, the charged CP-odd and charged Higgs bosons

$$H^{\pm} = \sin\beta H_1^{\pm} - \cos\beta H_2^{\pm}$$

Higgs Couplings to (s)fermions

- At tree level, only one of the Higgs doublets couples to down-quarks and leptons, and the other couples to up quarks

$$\mathcal{L} = \bar{\Psi}^i_L \left(h_{d,ij} H_1 d_R + h_{u,ij} H_2 u_R\right) + h.c.$$

- Since the up and down quark sectors are diagonalized independently, the interactions remain flavor diagonal.

$$\bar{d}_L \frac{\hat{m}_d}{v} \left(h + \tan\beta \left(H + iA\right)\right) d_R + h.c.$$

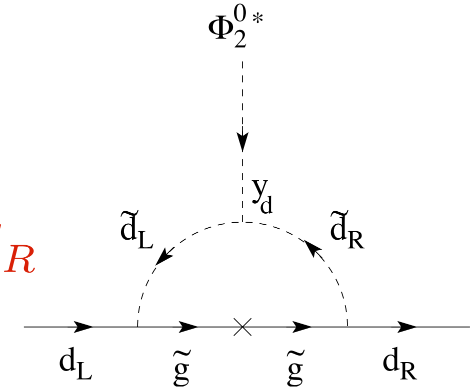
- Trilinear interactions of Higgs with sfermions. In the simplest case,

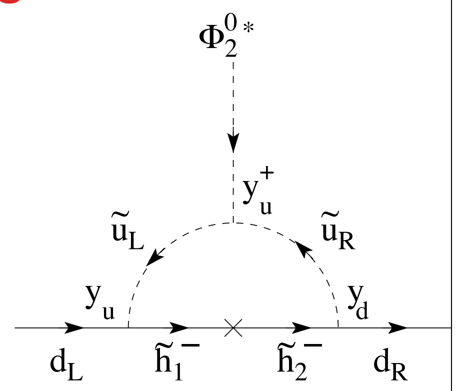
$$\tilde{u}^*_L h_u (A_u H_2 - \mu^* H_1) \tilde{u}_R + \tilde{d}^*_L h_d (A_d H_1 - \mu^* H_2) \tilde{d}_R + h.c.$$

Radiative Corrections to Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L(h_d H_1^0 + \Delta h_d H_2^0) d_R$$





- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

Searches for Non-Standard Higgs bosons

- Non-standard Higgs bosons are characterized by enhanced couplings to the b-quarks and tau-leptons.

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

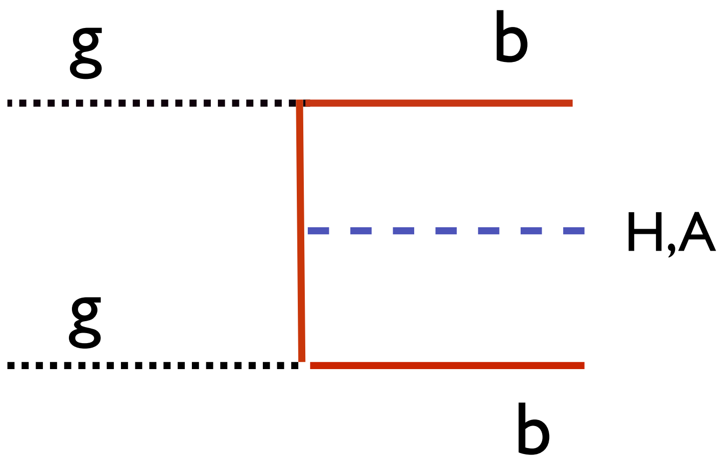
- Couplings to gauge bosons and other fermions are suppressed.

- Considering the values of the running bottom and tau masses and the fact that there are three colors of quarks, one gets

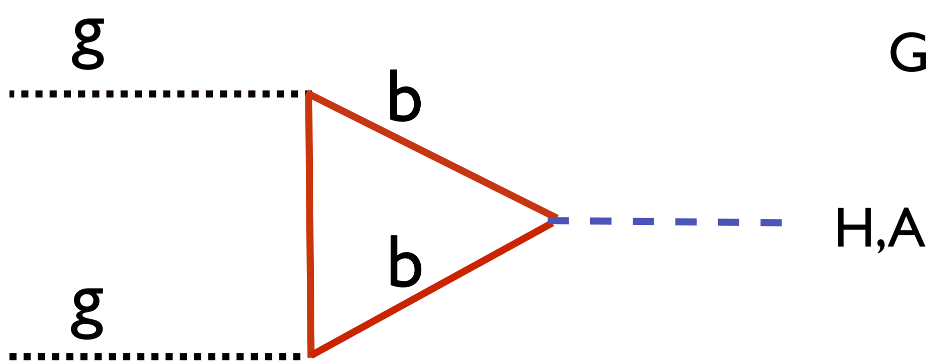
$$\mathrm{BR}(A \to bb) \simeq \frac{9}{9+(1+\Delta_b)^2}, \qquad \mathrm{BR}(A \to \tau\tau) \simeq \frac{(1+\Delta_b)^2}{9+(1+\Delta_b)^2}$$

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D.Wackeroth, hep-ph/0603112



Associated Production



Gluon Fusion

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

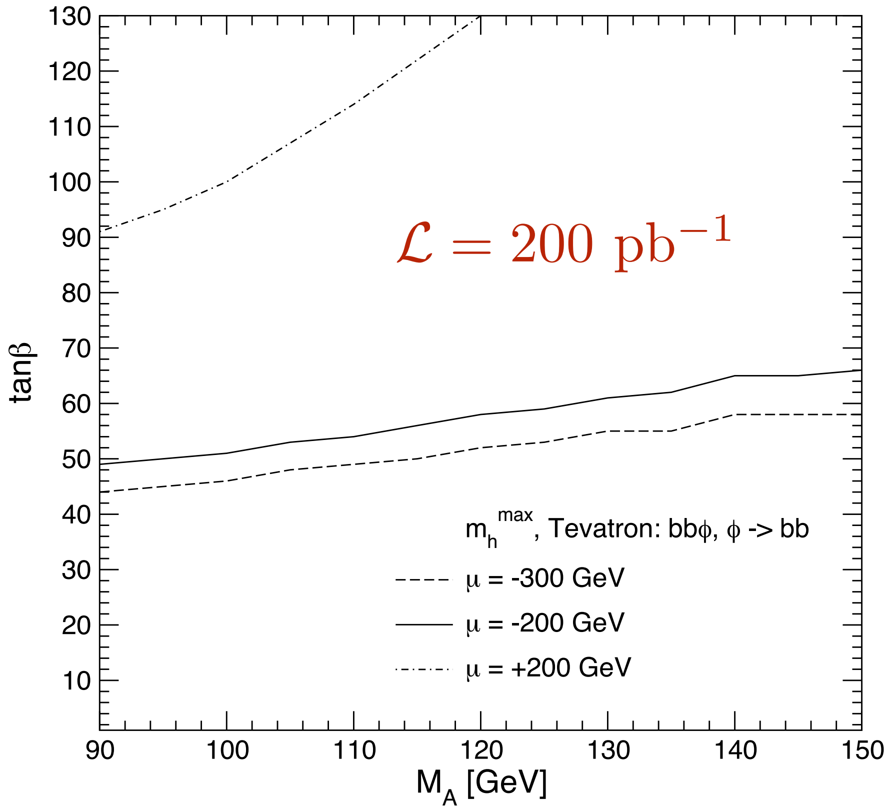
$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9}$$

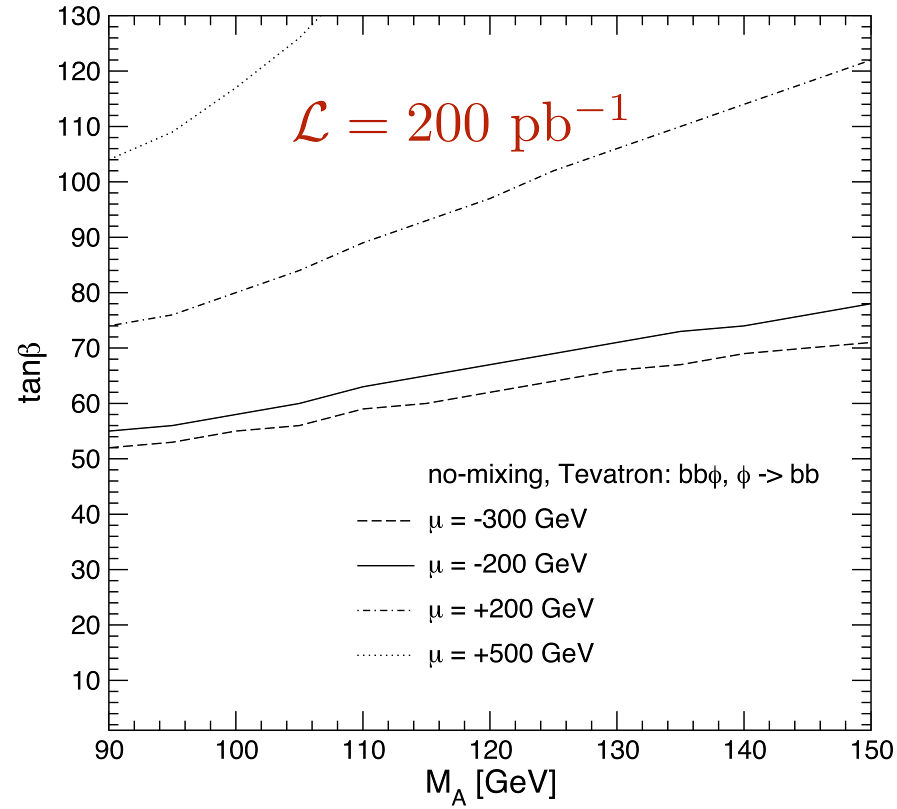
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Searches at the Tevatron in the bb mode. Current limits from D0

$$p\bar{p} \longrightarrow b\bar{b}\ \Phi,\ \ \Phi \longrightarrow b\bar{b}$$

M. Carena, S. Heinemeyer, G.Weiglein,C.W., EJPC'06

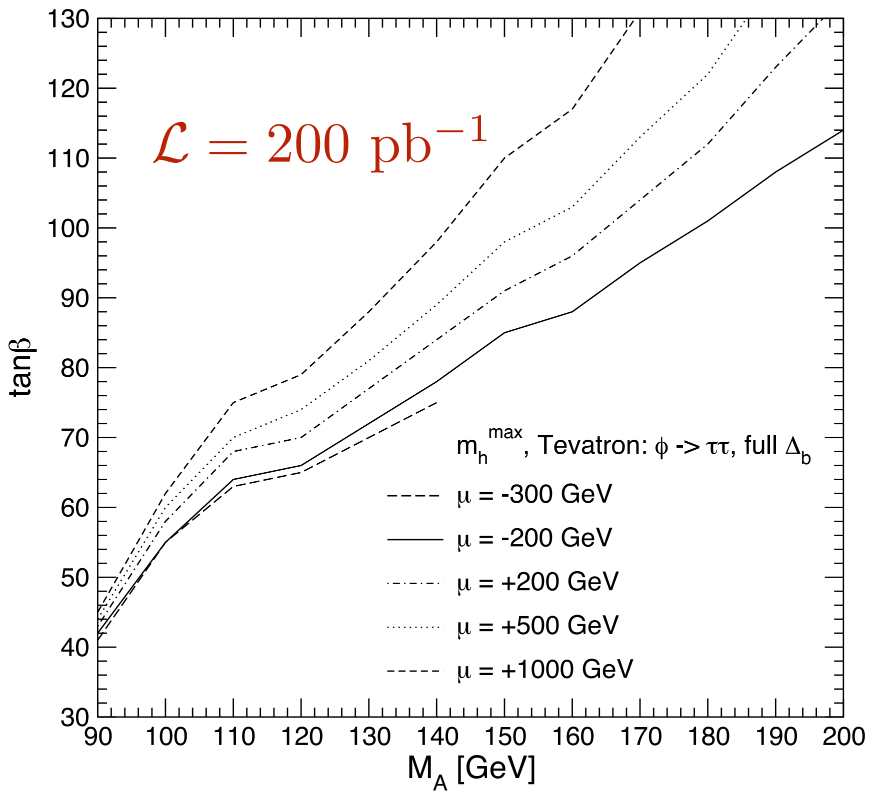


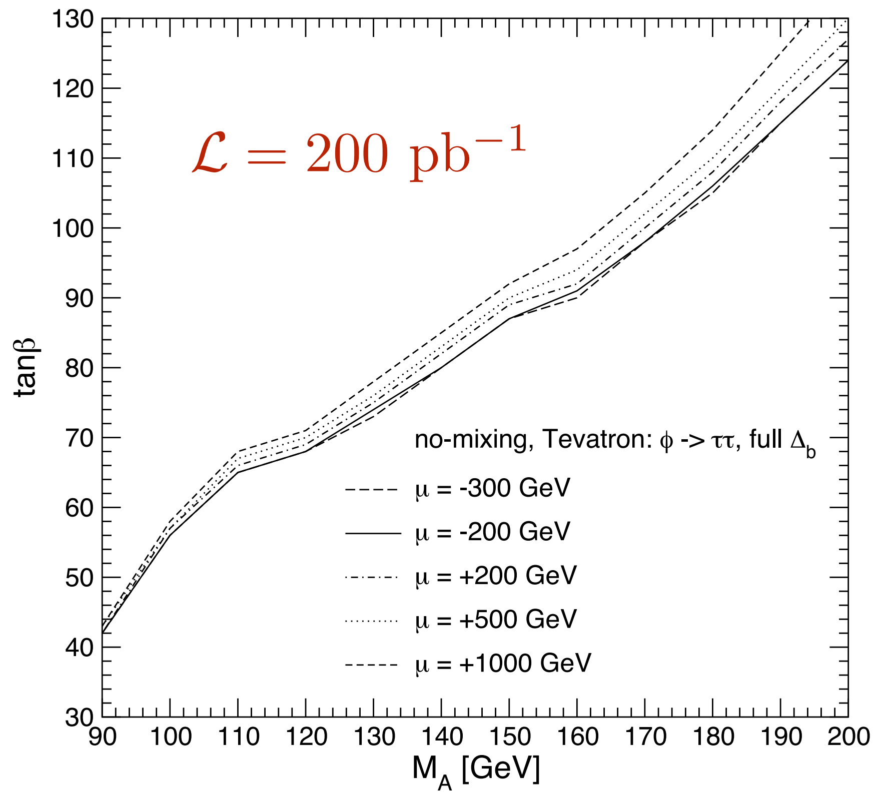


Searches at the Tevatron in the tau tau mode

$$p\bar{p} \rightarrow \Phi, \quad \Phi \rightarrow \tau^+\tau^-$$

M. Carena, S. Heinemeyer, G.Weiglein,C.W, EJPC06





Flavor Changing Neutral Currents

- As described above, since at the loop level the down quarks couple to both Higgs fields, there will be FCNC in the Higgs sector

$$\bar{d}_R \left(D_R^\dagger h_d D_L \right) D_L^\dagger \left[H_1^0 + (E_g + E_u h_u^\dagger h_u) H_2^0 \right] D_L d_L + h.c.$$

Babu and Kolda'00, A. Buras et al'02; Dedes and Pilaftsis'03, Foster et al'05

- We need that, when the Higgs field are replaced by v.e.v.'s, the whole expression becomes diagonal, and equal to the masses. We also know that $D_L^\dagger h_u^\dagger h_u D_L = V_{CKM}^\dagger |\hat{h_u}|^2 V_{CKM}$
- Hence, $D_R^\dagger h_d D_L \simeq \frac{\hat{m}_d}{v_1} V_{CKM}^\dagger \left(1 + \tan\beta (E_g + E_t h_t^2)\right)^{-1} V_{CKM}$
- Keeping only the non-diagonal, flavor changing interactions, we get

$$\mathcal{L}_{FCNC} \simeq \bar{d}_R \frac{\hat{m}_d}{v_1} \left(1 + \tan\beta V_{CKM}^\dagger (E_g + E_t \hat{h_t}^2) V_{CKM}\right)^{-1} d_L \left(H_1^0 - \frac{H_2^0}{\tan\beta} \right)$$

Flavor Violating b s couplings

As described above, since at the loop level the down quarks couple to both Higgs fields, there will be FCNC in the Higgs sector

$$\bar{b}_R X_{RL} s_L H + h.c. = \bar{b}_R \frac{m_b \tan\beta}{v} \frac{E_t h_t^2 \tan\beta \, V_{ts}}{(1+\Delta_b)(1+E_g \tan\beta)} s_L \; H + h.c.$$

$$\Delta_b = (E_g + E_t h_t^2) \tan\beta$$

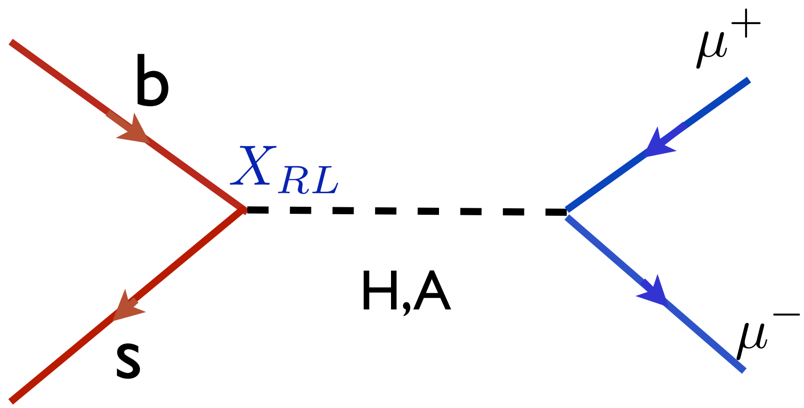
$E_t \propto X_t (\text{stop mixing parameter})$

An interesting correlation appears between the SUSY contribution to different processes

$$BR(B_s \to \mu^+\mu^-) \simeq \frac{|X_{RL}|^2 \tan^2\beta}{m_A^4}$$

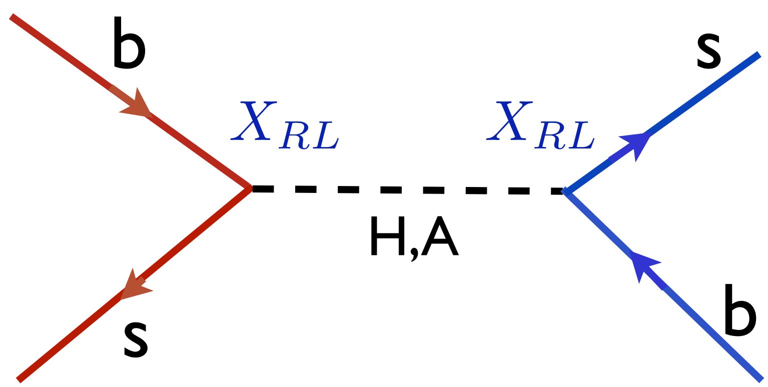
$$(\Delta M_{B_s})^{\rm SUSY} \simeq -\frac{|X_{RL}|^2}{m_A^2}$$

Flavor Changing Transitions mediated by X_{RL}



$$B_s \to \mu^+\mu^-$$

$$\left(g_{A\mu\mu} = \frac{m_\mu \tan\beta}{v} \right)$$



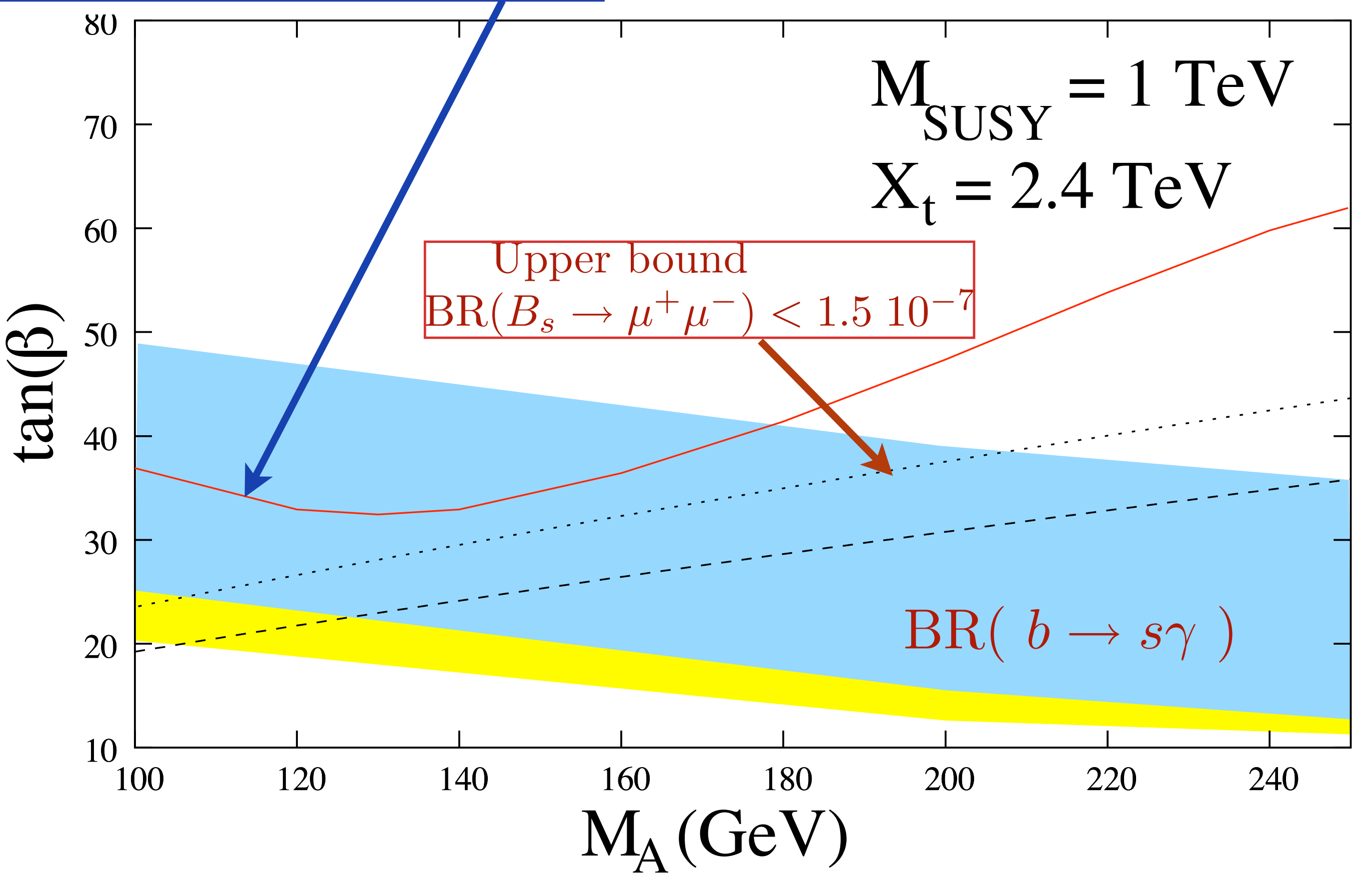
$$\Delta M_s$$

Interplay of B-Physics and Higgs Searches

Experimental Constraints (mid'06)

Higgs Tevatron reach with $1 fb^{-1}$ ($\tau^+\tau^-$ mode)

Top (bottom) lines (countors) $\mu = -100$ GeV (-200 GeV)



$$\mathcal{A}^{b\to s\gamma}_{\rm SUSY} \simeq C_1 X_{RL} + C_2 \frac{m_t^2}{m_{H^+}^2} \ll \mathcal{A}_{SM}$$

M. Carena, A.Menon, A. Szynkman, R. Noriega, C.W.'06

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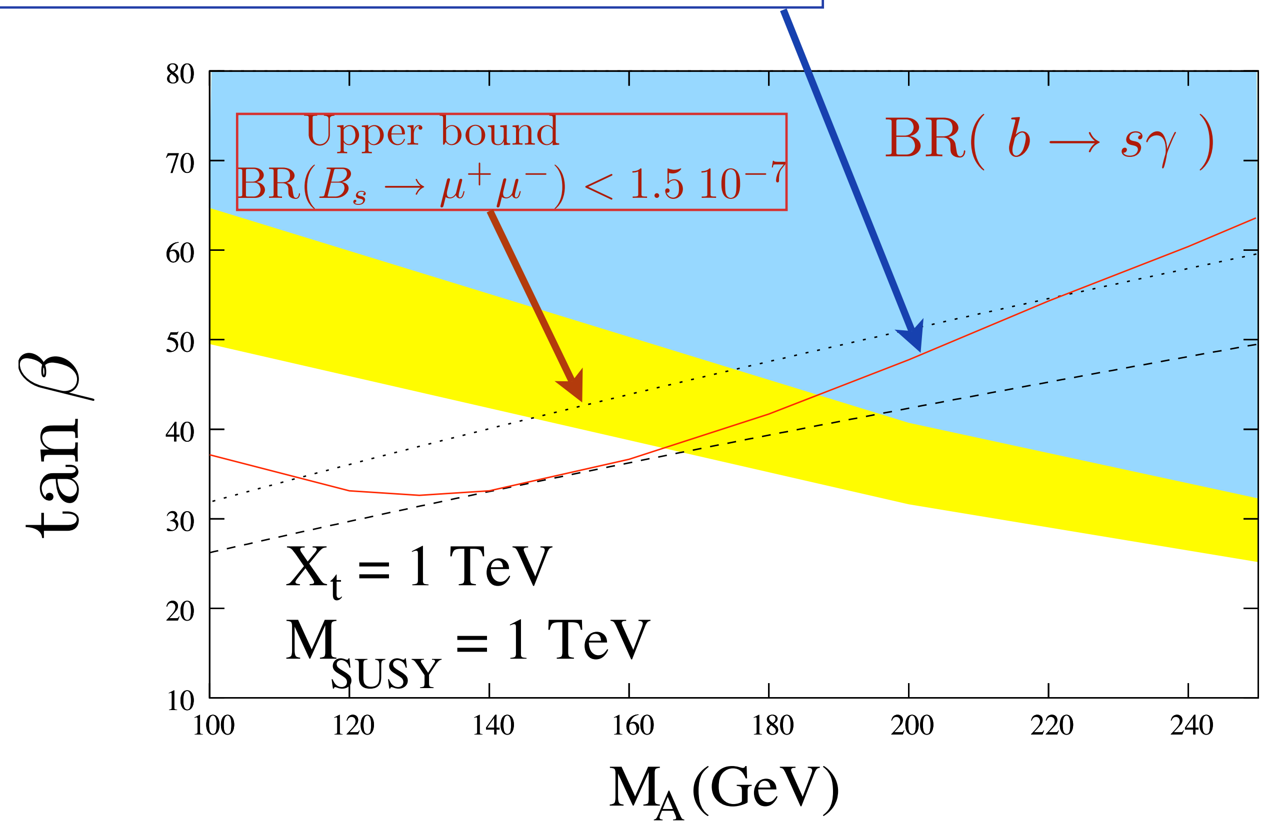


For moderate values of μ and X_t, B physics puts strong constraints on the region of parameters for which signatures of non-standard Higgs bosons may be observed at the Tevatron collider

$$\mathcal{A}^{b\to s\gamma}_{\rm SUSY} \simeq C_1 X_{RL} + C_2 \frac{m_t^2}{m_{H^+}^2} \ll \mathcal{A}_{SM}$$

M. Carena, A. Menon, A. Szynkman, R. Noriega, C.W.'06

Comments

- Constraints are weaker for small values of X_t
- Small values of X_t are also associated with the smallest values of the SM-like Higgs mass, for which the Tevatron sensitivity increases.
- Observation of a non-Standard Higgs signal at the Tevatron collider would increase the probability of detecting a SM-like signal (and $B_s \to \mu^+\mu^-$)

Loop Corrections to Higgs boson masses

- Most important corrections come from the stop sector,

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} \mathbf{m}^2_Q + \mathbf{m}^2_t + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}^2_U + \mathbf{m}^2_t + \mathbf{D}_R \end{pmatrix}$$

where the off-diagonal term depends on the stop-Higgs trilinear couplings, $\mathbf{X}_t = \mathbf{A}_t - \mu^* / \tan\beta$

- For large CP-odd Higgs boson masses, and with $\mathbf{M}_S = \mathbf{m}_Q = \mathbf{m}_U$ dominant one-loop corrections are given by,

$$\mathbf{m}^2_h \approx \mathbf{M}^2_Z \cos^2 2\beta + \frac{3\mathbf{m}^4_t}{4\pi^2 \mathbf{v}^2}\left(\log\left(\frac{\mathbf{M}^2_S}{\mathbf{m}^2_t}\right) + \frac{\mathbf{X}^2_t}{\mathbf{M}^2_S}\left(1 - \frac{\mathbf{X}^2_t}{12\,\mathbf{M}^2_S}\right) \right)$$

- After two-loop corrections:

M.Carena, J.R. Espinosa, M. Quiros, C.W.'95
M. Carena, M. Quiros, C.W.'95

- upper limit on Higgs mass:

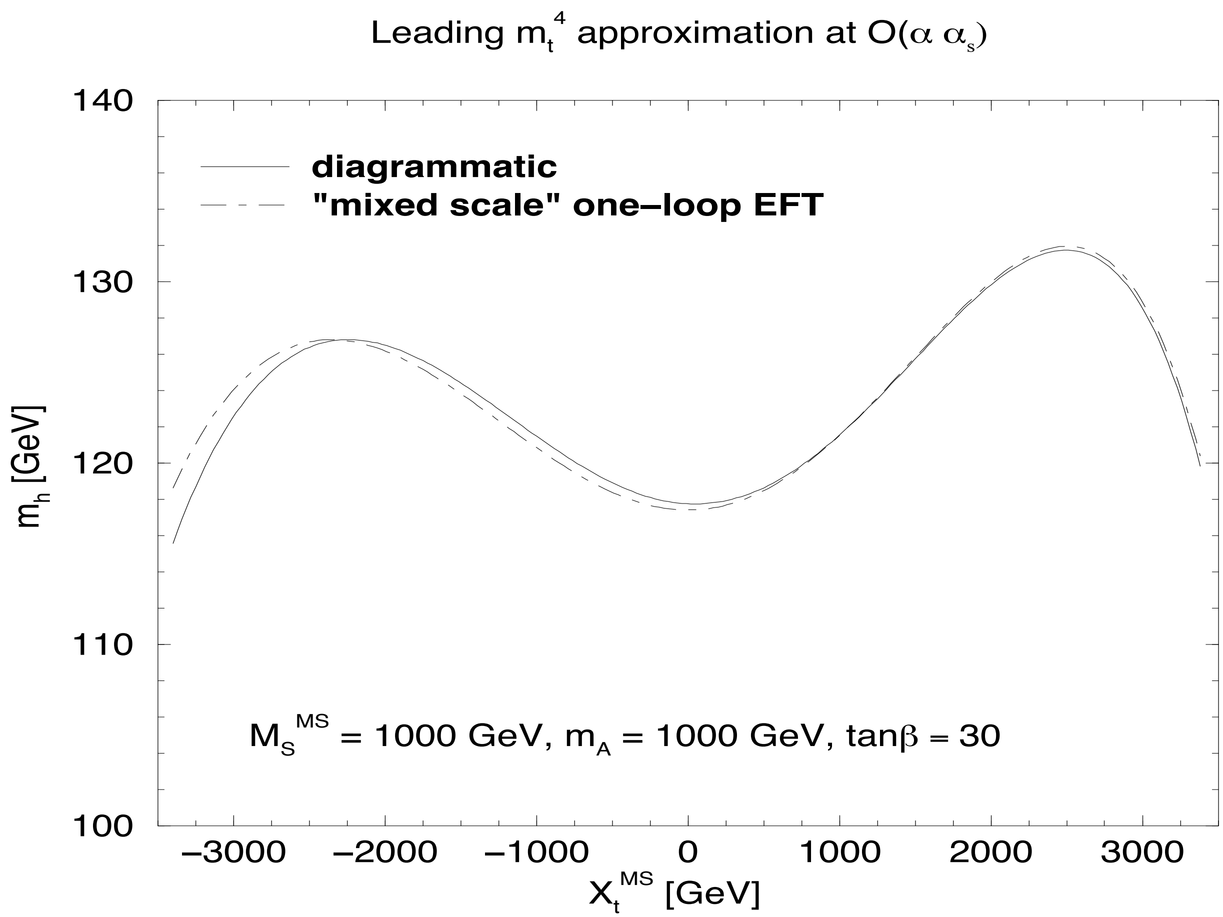
$m_h \lesssim 135$ GeV

$M_S = 1 \to 2$ TeV $\Longrightarrow \Delta m_h \simeq 2-5$ GeV

$\Delta m_t = 1$ GeV $\Longrightarrow \Delta m_h \sim 1$ GeV

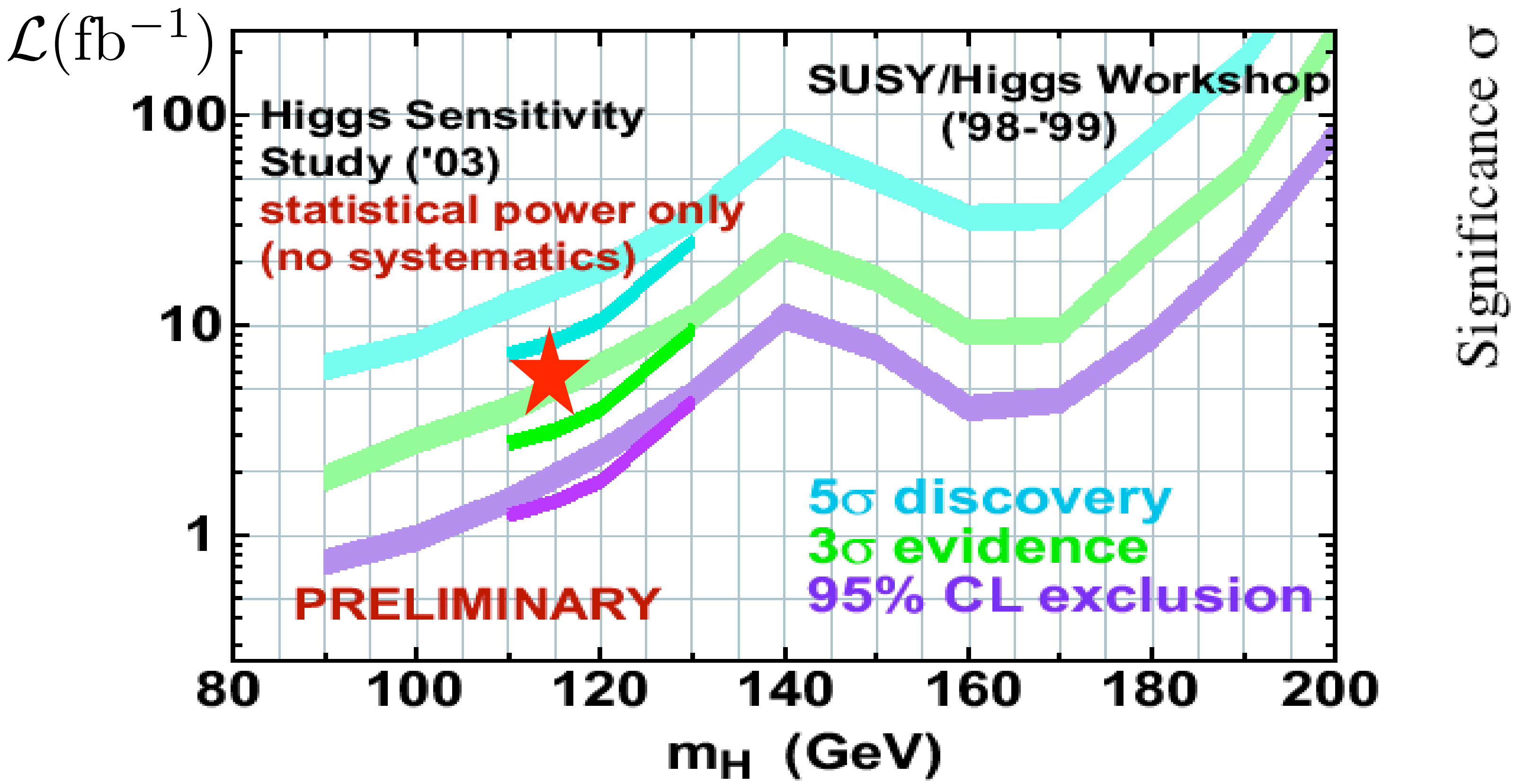
Standard Model-like Higgs Mass

Carena, Haber, Heinemeyer, Weiglein, C.W.'00



$X_t = A_t - \mu/\tan\beta, \quad X_t = 0$: No mixing; $\quad X_t = \sqrt{6}M_S$: Max. Mixing

Tevatron SM Higgs Sensitivity



Systematic errors tend to worsen the results by about 40 percent. Tevatron sensitivity increases if Higgs mass is close to present LEP bound, $m_h > 114$ GeV

Small values of Xt increase significantly the Tevatron sensitivity

Current Theory and Experimental results

Bs Mixing:

$$\Delta M_s = (17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst}))\mathrm{ps}^{-1}.$$ (CDF'06)

$$(\Delta M_s)^{SM} = (20.9 \pm 2.6)\mathrm{ps}^{-1}$$ (UTFit'06)

$BR(b \to s\gamma)$:

$$\mathcal{BR}(b \to s\gamma)^{exp} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}.$$

$$0.89 \leq \frac{\mathcal{BR}(b \to s\gamma)^{MSSM}}{BR(b \to s\gamma)^{SM}} \leq 1.39$$

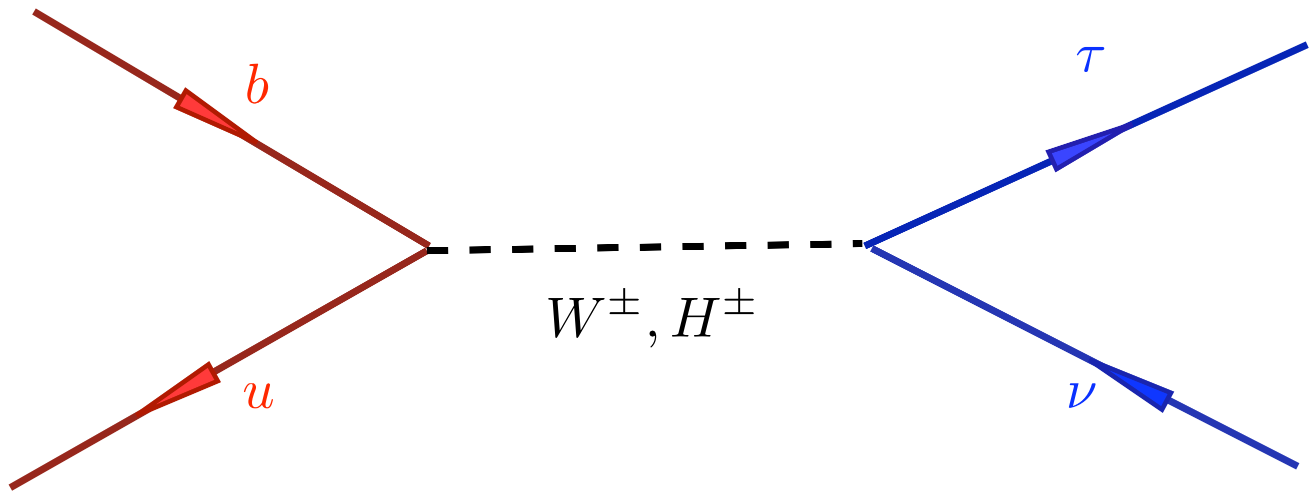
$$\mathcal{BR}(b \to s\gamma)^{SM} = (3.15 \pm 0.26) \times 10^{-4}.$$ Misiak'06; Neubert,Becher'06

$B_s \to \mu^+\mu^-$

$$\mathcal{BR}(B_s \to \mu^+\mu^-) \leq 1 \times 10^{-7},$$ (CDF'06) $5.8\ 10^{-8}$ (CDF'07)

$$\mathcal{BR}(B_s \to \mu^+\mu^-)_{SM} = (3.8 \pm 0.1) \times 10^{-9}.$$ (UTFit'06)

Additional Flavor Constraints



$$\frac{BR(B_u \to \tau\nu)^{\rm MSSM}}{BR(B_u \to \tau\nu)^{\rm SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right) \frac{\tan^2\beta}{(1 + E_g \tan\beta)}\right]^2$$

$$\mathcal{BR}(B_u \to \tau\nu)^{\rm Exp} = (1.31 \pm 0.48) \times 10^{-4}.$$ **(Belle-Babar'06)**

$$\mathcal{BR}(B_u \to \tau\nu)^{\rm SM} = (0.85 \pm 0.13) \times 10^{-4}.$$ **(UTFit'07)**

$$R_{B\tau\nu} = \frac{\mathcal{BR}(B_u \to \tau\nu)^{\rm MSSM}}{\mathcal{BR}(B_u \to \tau\nu)^{\rm SM}} \qquad 0.32 \leq R_{B\tau\nu} \leq 2.77.$$

Charged Higgs contributions to $\mathrm{BR}(\ b \to s\gamma\ )$

- Charged Higgs contributions to $\mathrm{BR}(\ b \to s\gamma\ )$ involve the couplings

$$\bar{t}_R H^+ s_L \ \ (1/\tan\beta \text{ suppressed}) \text{ and}$$
$$\bar{t}_L H^+ b_R \ \ (\tan\beta \text{ enhanced})$$

- The suppression arises due to the fact that that coupling is proportional to the charged Higgs component on H_2^+. loop corrections induce a coupling to H_1^+

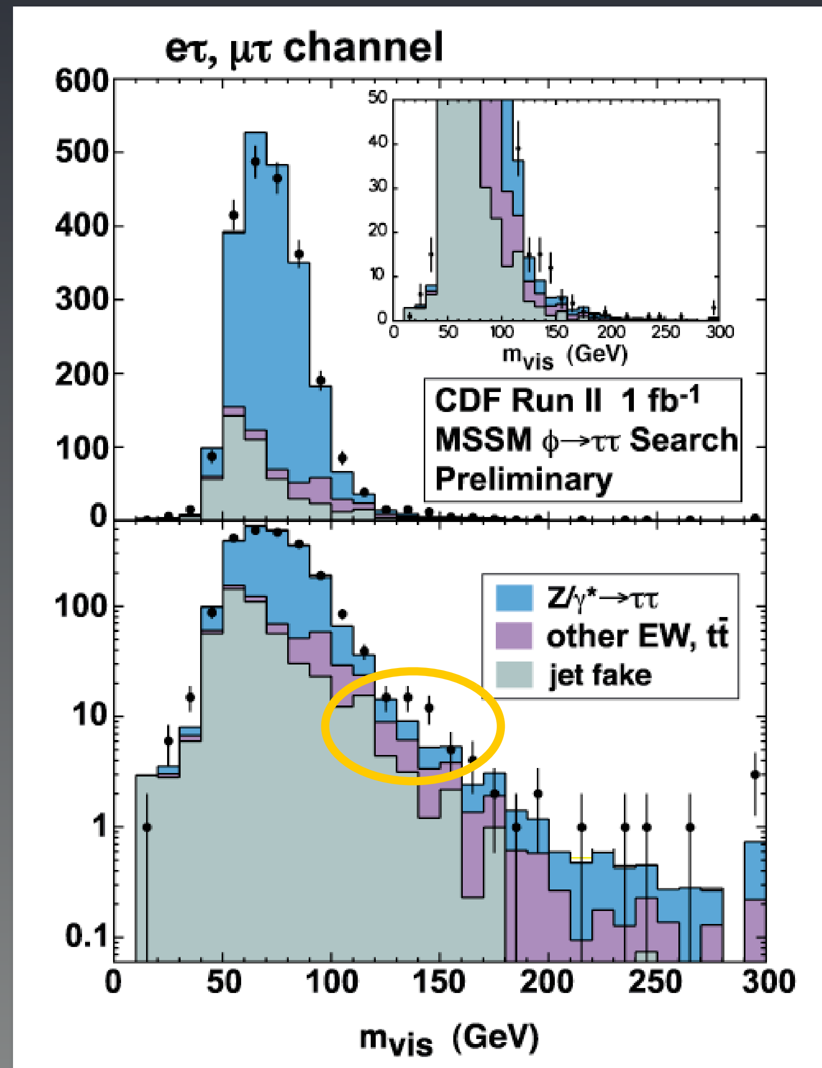
- The amplitude becomes proportional to

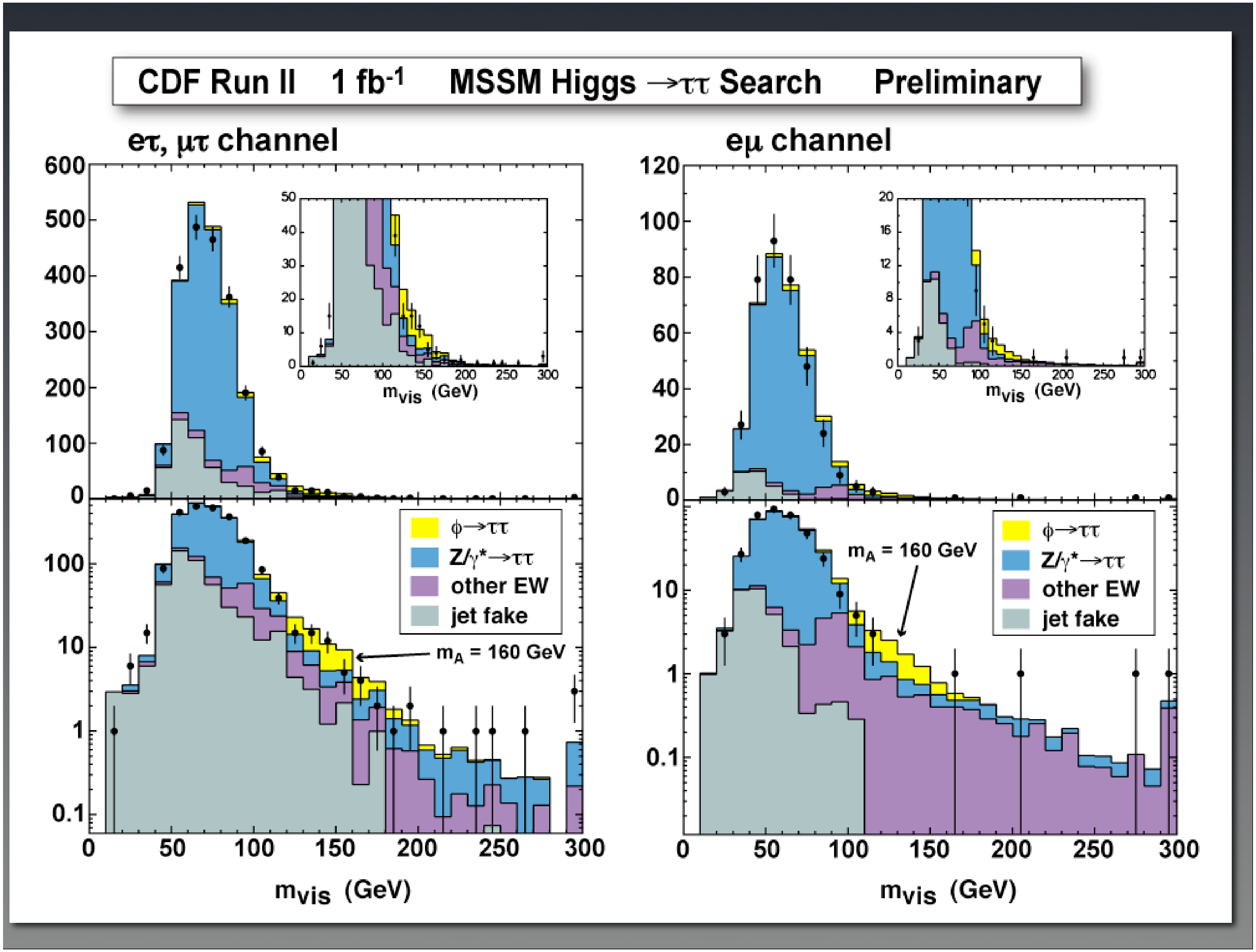
$$\mathcal{A}_{H^+} \simeq \frac{1}{\tan\beta}\left(1 - \frac{2\alpha_3}{3\pi}\frac{\mu M_3 \tan\beta}{\max(m_{\tilde{q}}^2, M_3^2)}\right)$$

- For small values of X_t and large values of $|\mu|$, cancellations between both contibutions may appear. At the same time, the stop-chargino contribution becomes small.

- performed analysis "blind" with respect to setting cuts, method, etc.
- opened the box in December and this is what we saw!

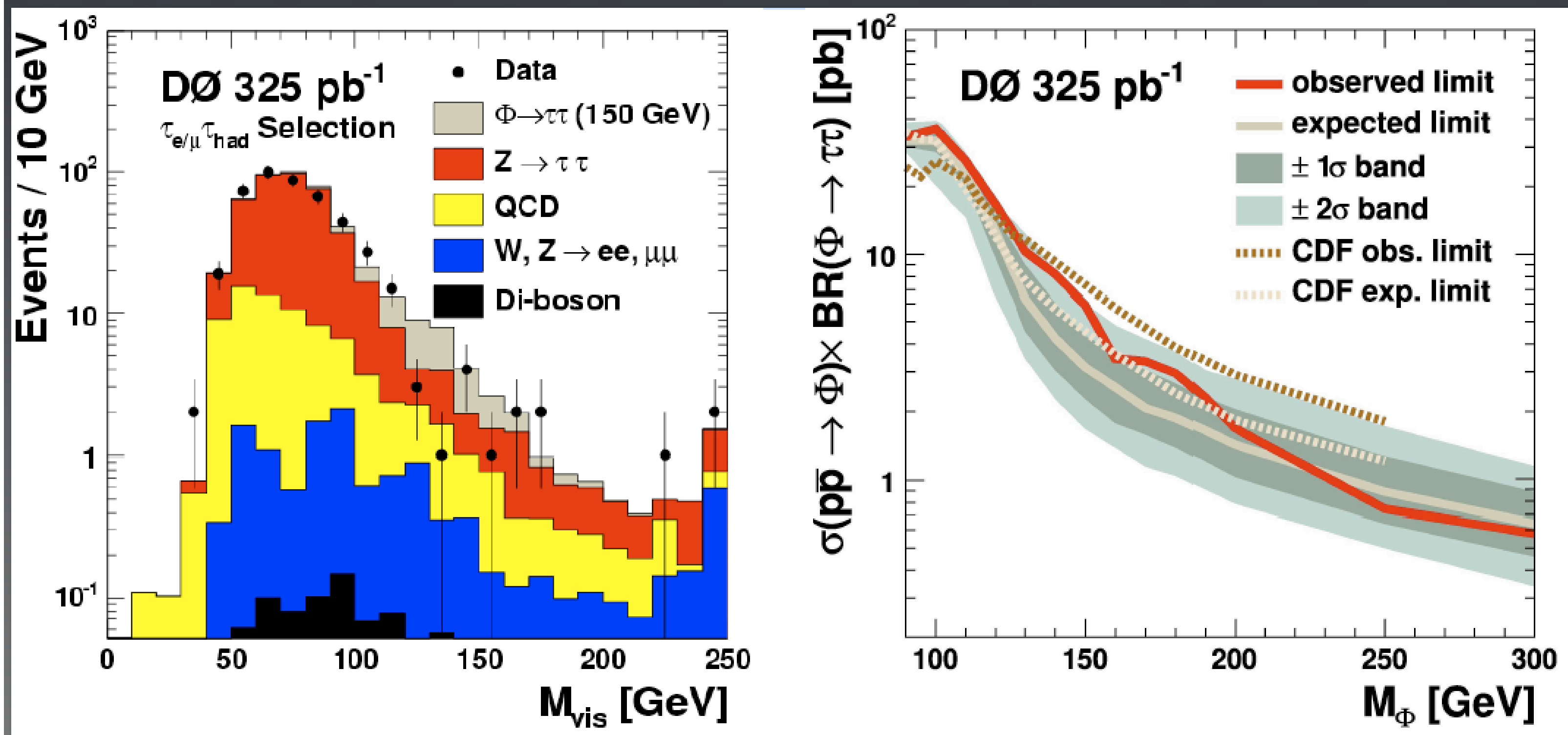
Tevatron , $\mathcal{L} = 1\text{fb}^{-1}$



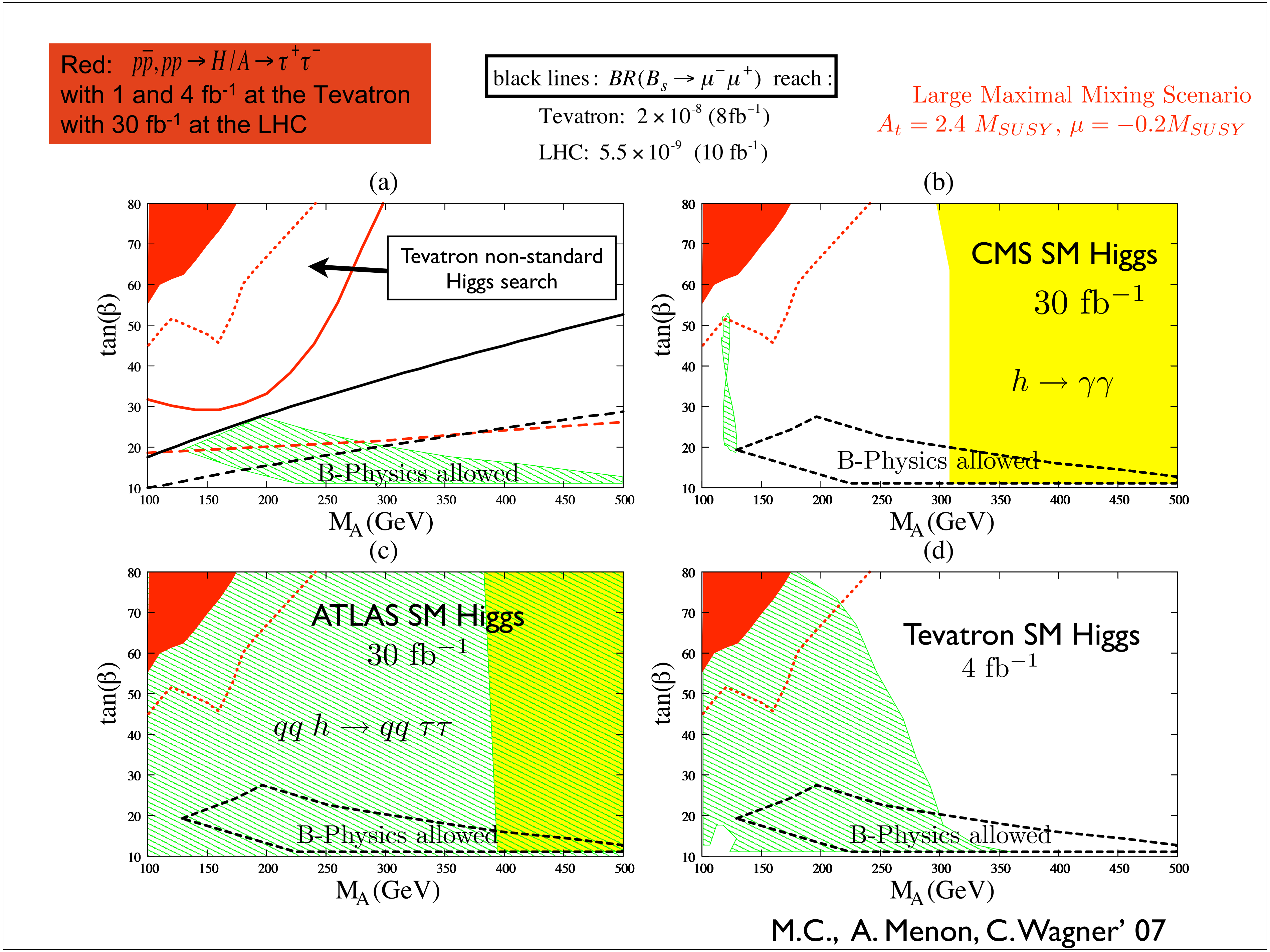


J. Conway, 2007 Aspen Winter Conference

D0 - 350 pb^{-1} eτ, μτ result



Looking forward to 1 fb^{-1} update!



Red: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
with 1 and 4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC
black lines: $BR(B_s \to \mu^-\mu^+)$ reach:
Tevatron: 2×10^{-8} (8fb^{-1})
LHC: 5.5×10^{-9} (10 fb^{-1})
Large Maximal Mixing Scenario
$A_t = 2.4\ M_{SUSY}$, $\mu = -0.2 M_{SUSY}$
(a)
Tevatron non-standard Higgs search
B-Physics allowed
tan(β)
M_A (GeV)
(b)
CMS SM Higgs
30 fb^{-1}
$h \to \gamma\gamma$
B-Physics allowed
tan(β)
M_A (GeV)
(c)
ATLAS SM Higgs
30 fb^{-1}
$qq\ h \to qq\ \tau\tau$
B-Physics allowed
tan(β)
M_A (GeV)
(d)
Tevatron SM Higgs
4 fb^{-1}
B-Physics allowed
tan(β)
M_A (GeV)
M.C., A. Menon, C.Wagner' 07

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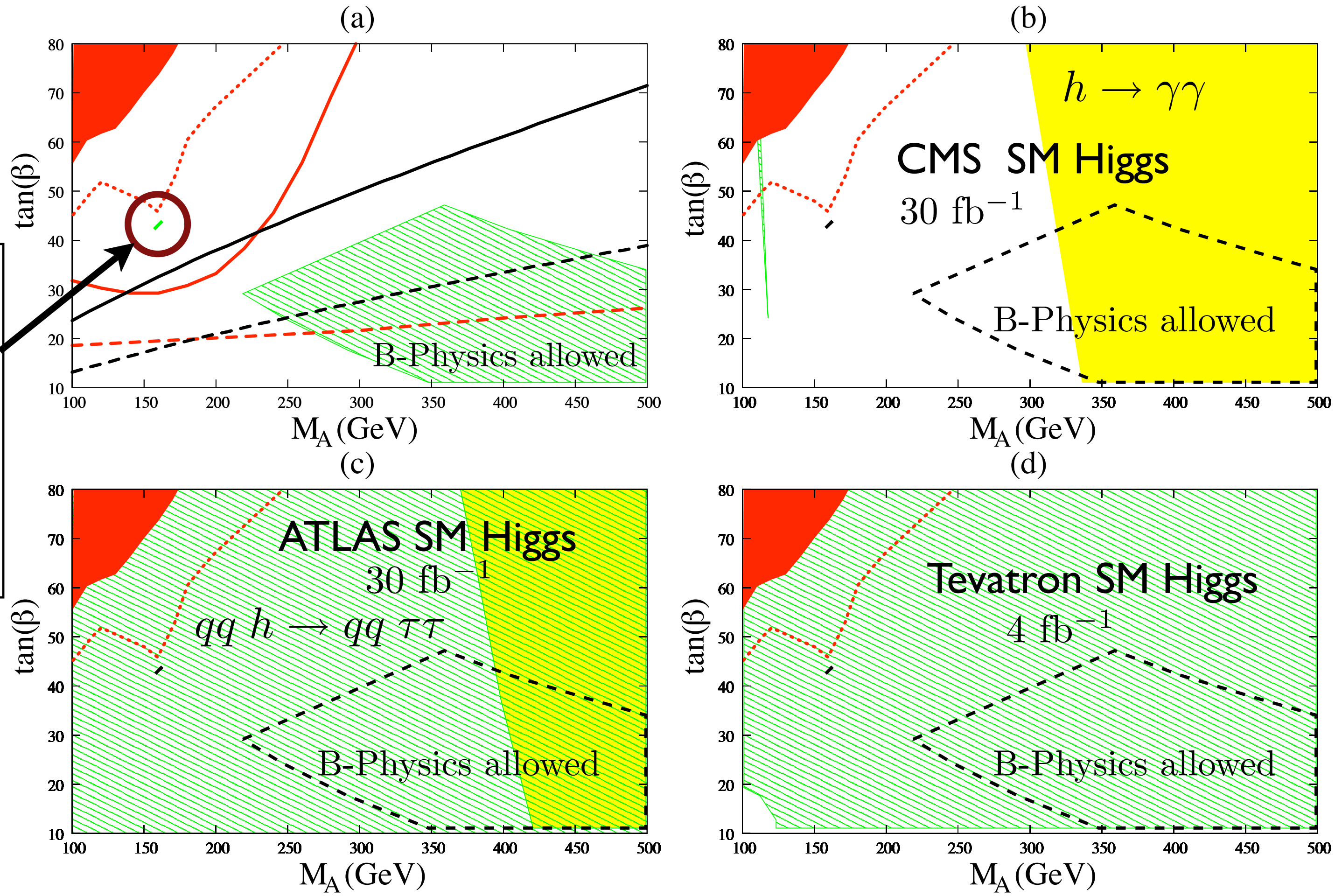
LHC: 5.5×10^{-9} ($10 fb^{-1}$)

Moderate Mixing Scenario
$A_t = -M_{SUSY}, \mu = 0.2 M_{SUSY}$

To be tested at the Tevatron by both Higgs searches and rare Bs decays.

Also found by Ellis et al'07



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Tevatron: 2×10^{-8} (8fb^{-1})

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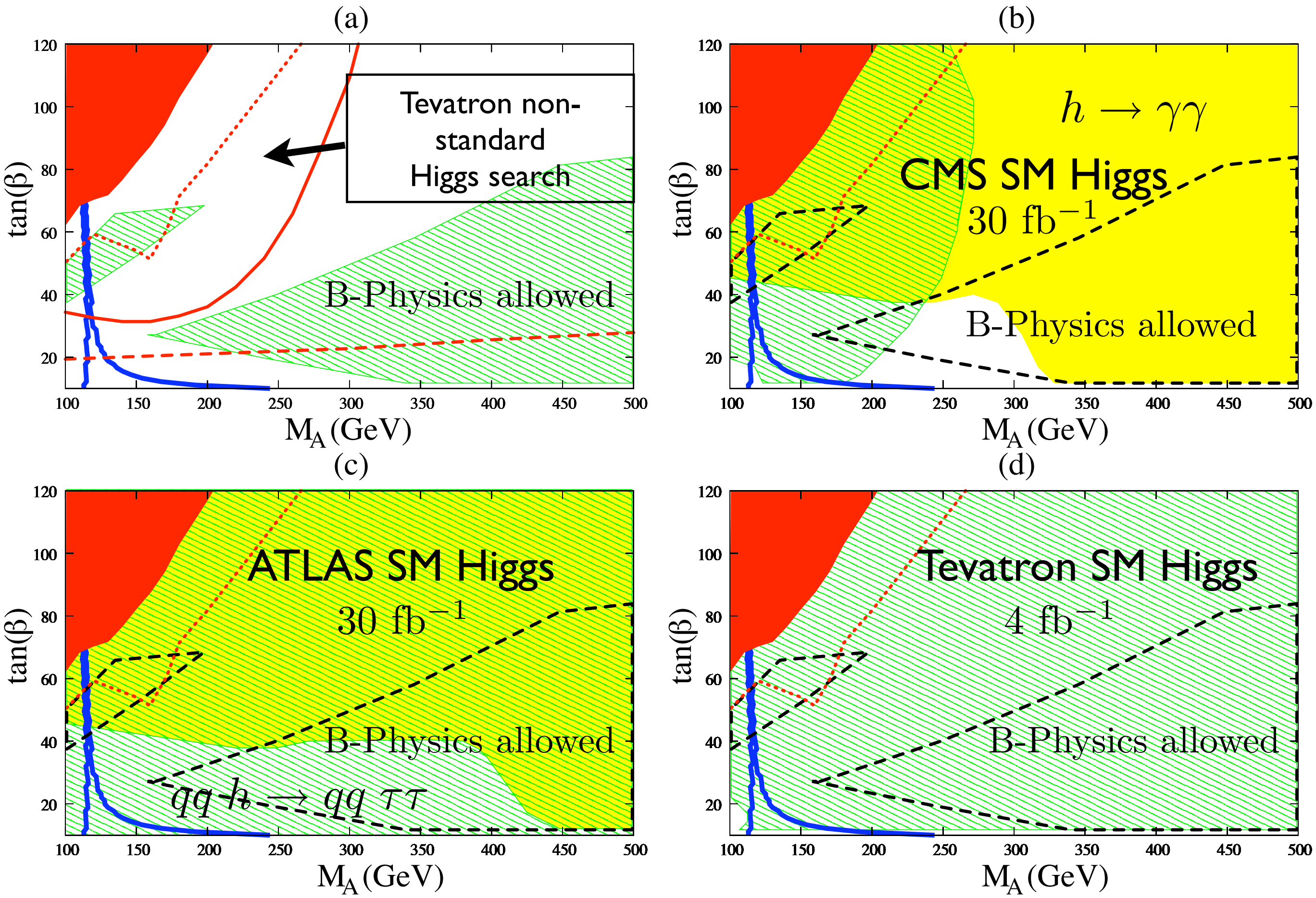
Minimal Mixing Scenario
$A_t = 0, \quad \mu = 1.5 M_{SUSY}$
$M_{SUSY} = 2$ TeV



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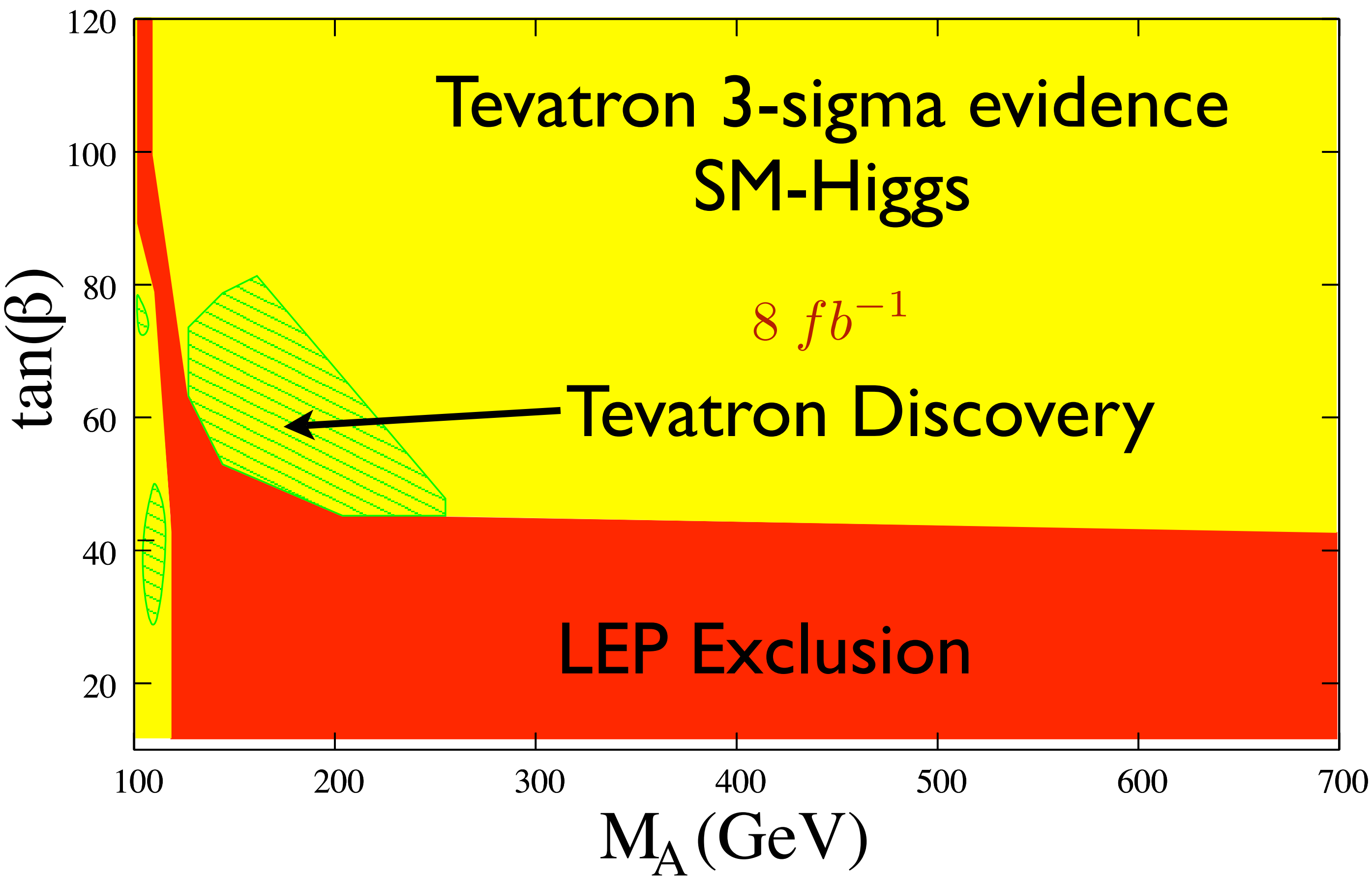
Tevatron SM-Higgs searches

$X_t = 0,\ \mu = 1.5\ \mathrm{TeV},\ M_S = 1\ \mathrm{TeV}$



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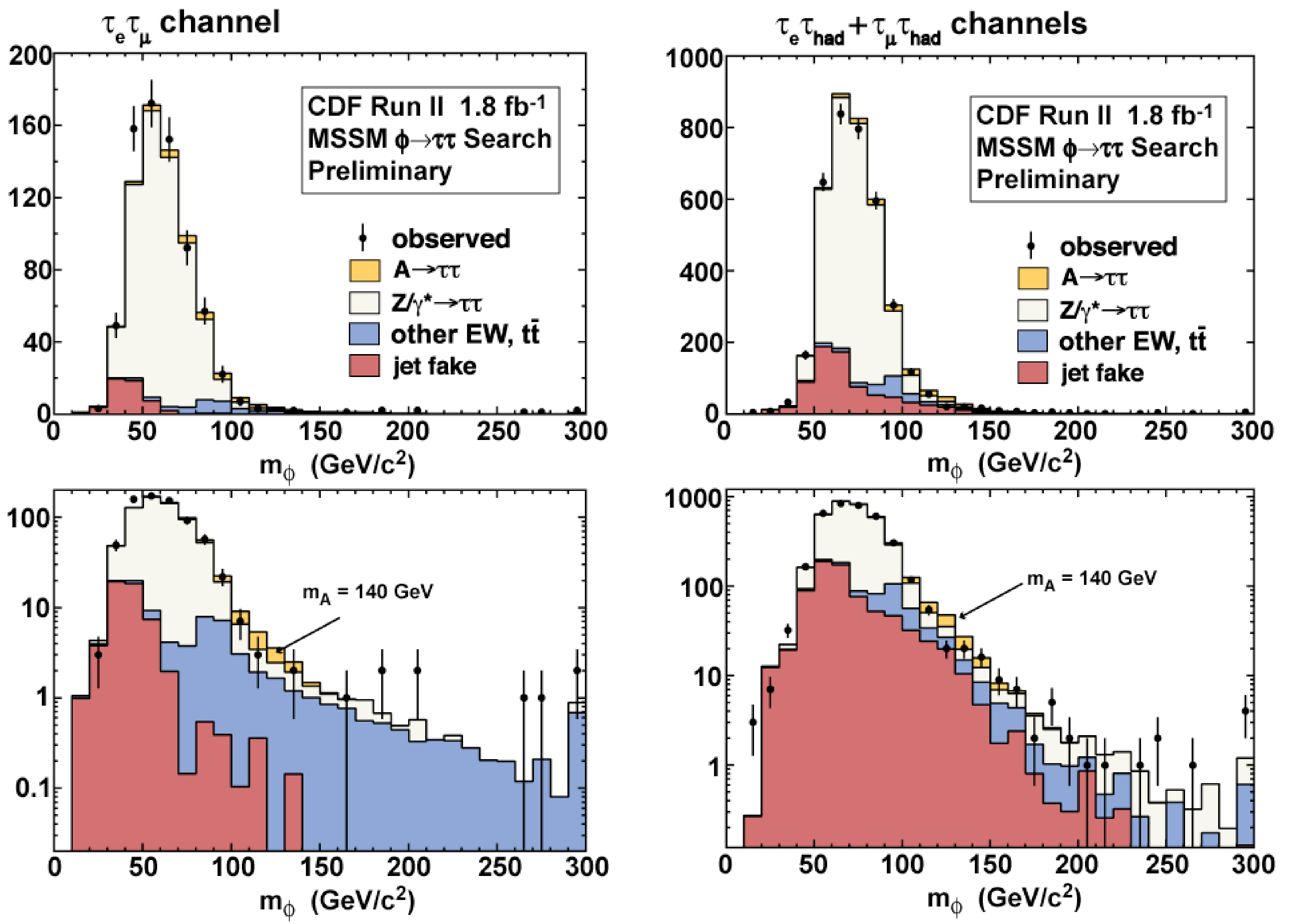
Updated CDF Higgs Search Results



Cancellations between Diagrams contributing to $\mathrm{BR}(B_s \to \mu^+\mu^-)$

- In models in which supersymmetry breaking is transmitted at high energies, even starting from universal masses, the Yukawa evolution of parameters induces flavor violation couplings in the left-handed gluino currents

- These are known to have small effects on $B_u \to \tau\nu \quad + \quad b \to s\gamma$, but may induce important contributions to $\mathrm{BR}(B_s \to \mu^+\mu^-)$

- Essentially, what happens is that the stop mixing dependence to the diagrams contributing to $\mathrm{BR}(B_s \to \mu^+\mu^-)$ is replaced by

$$X_{RL} \propto \frac{\left(E_t h_t^2 + E_{g,3} - E_{g,(1,2)}\right) \tan^2\beta}{\left(1 + E_{g,(1,2)} \tan\beta\right)(1 + \Delta_b)}$$

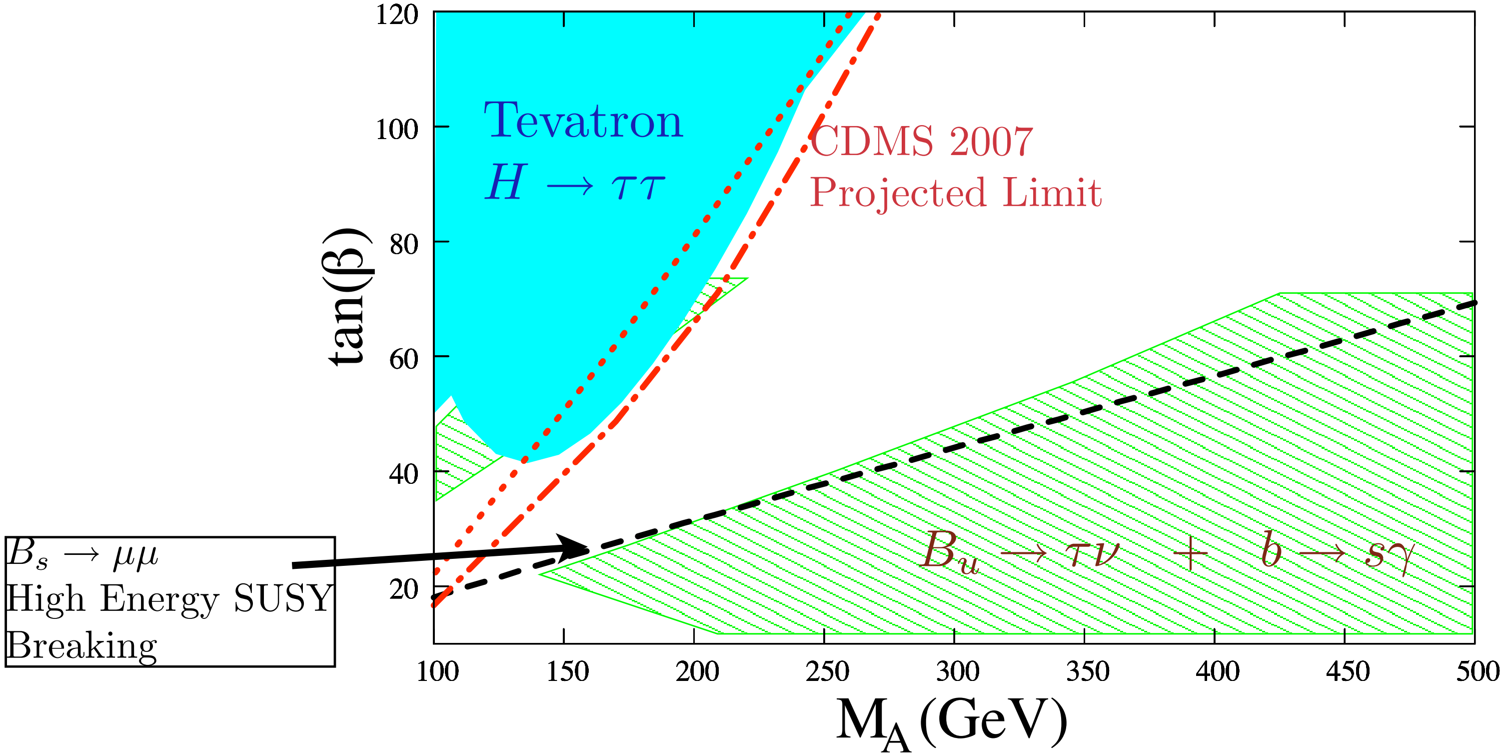
A delicate cancellation may occur between these contributions

Ellis, Heinemeyer, Olive, Weiglein'07

- In addition, dark matter searches start to constraint the parameter space with small values of the CP-odd Higgs mass and large values of $\tan\beta$

B-Physics and Higgs Constraints on the M_A–$\tan\beta$ plane

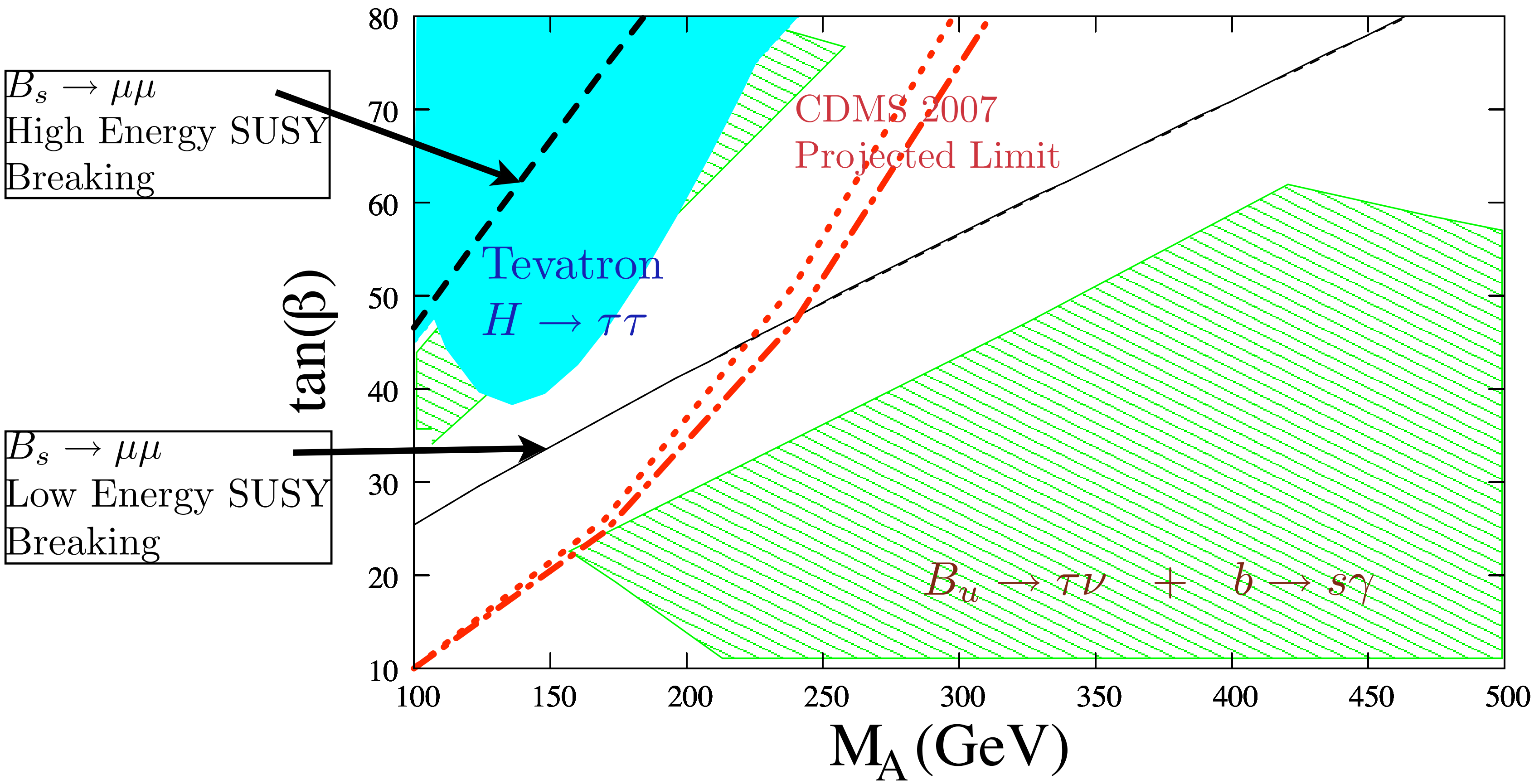
$X_t = 0 \quad \mu = M_{SUSY} \quad M_3 = 0.8\ M_{SUSY}$



M. Carena, A.Menon, C.W., to appear

B-Physics and Higgs Constraints on the M_A–$\tan\beta$ plane

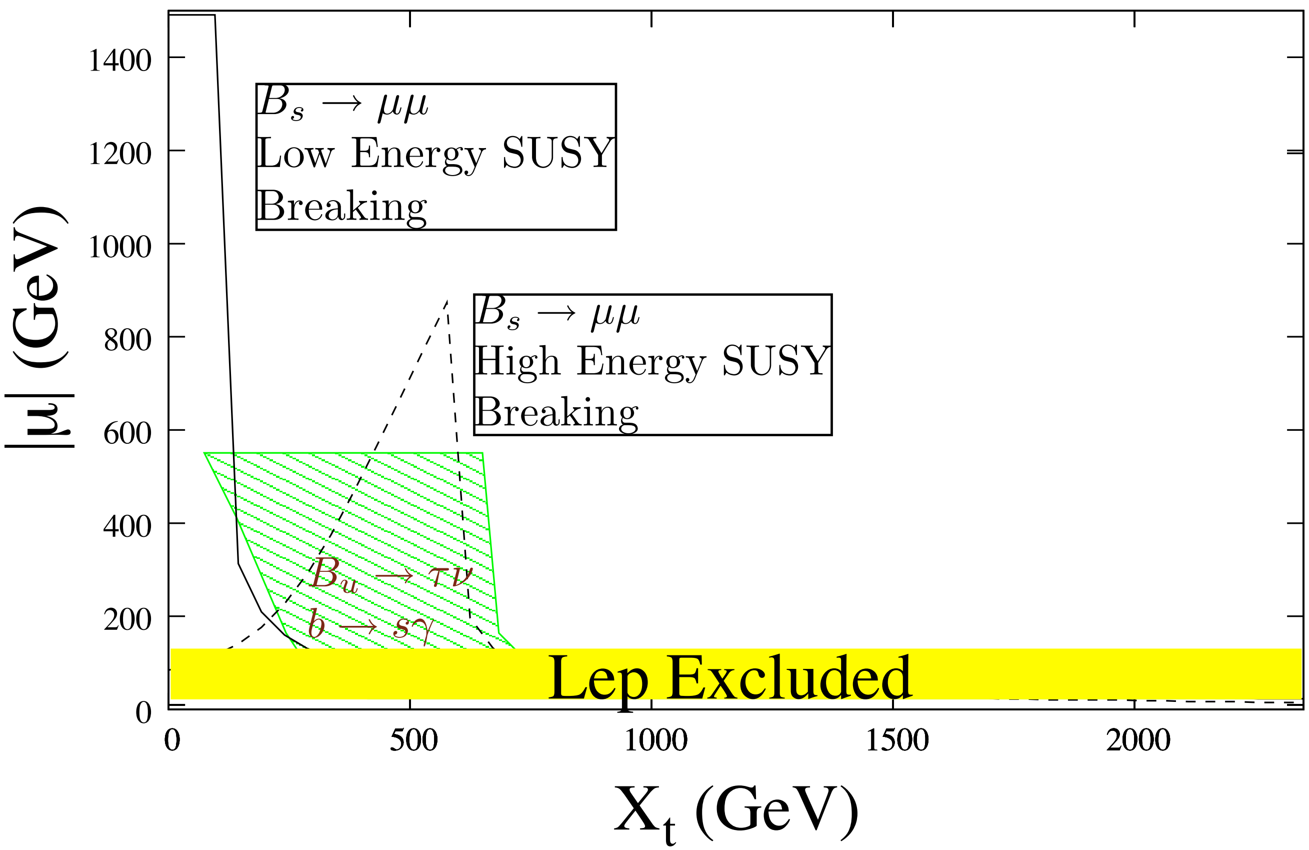
$X_t = -500$ GeV $\mu = 500$ GeV $M_3 = 800$ GeV



M. Carena, A.Menon, C.W., to appear

B-Physics and Higgs Constraints on the X_t–μ plane

$M_A = 200$ GeV $\tan\beta = 60$



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Conclusions

- MSSM Higgs sector includes two Higgs doublets, with flavor conserving couplings at tree-level
- In MFV SUSY models, loop corrections spoil this property and introduce interesting phenomenological consequences for Higgs searches and also for flavor violating process
- In particular, we have shown that the non-observation of the rare process $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at the Tevatron imposes strong constraints on the parameter space to be probed by the Tevatron in Higgs searches
- Best prospects are for small values of X_t, for which the SM-like Higgs boson becomes also light, or moderate values of X_t, when cancellations between stop and gluino induced FV diagrams may occur.
- Dark Matter searches would put further constraints scenarios of light Higgs spectrum and large $\tan\beta$
- Constraints at LHC become much weaker. Even in the case of non-observation of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at the LHC, a large parameter space remains to be probed by non-SM Higgs searches.

Correlation between observables

$$(\Delta M_{B_s})^{\rm SUSY} \simeq -\frac{|X_{RL}|^2}{m_A^2}$$

$$BR(B_s \to \mu^+\mu^-) \simeq \frac{|X_{RL}|^2 \tan^2\beta}{m_A^4}$$

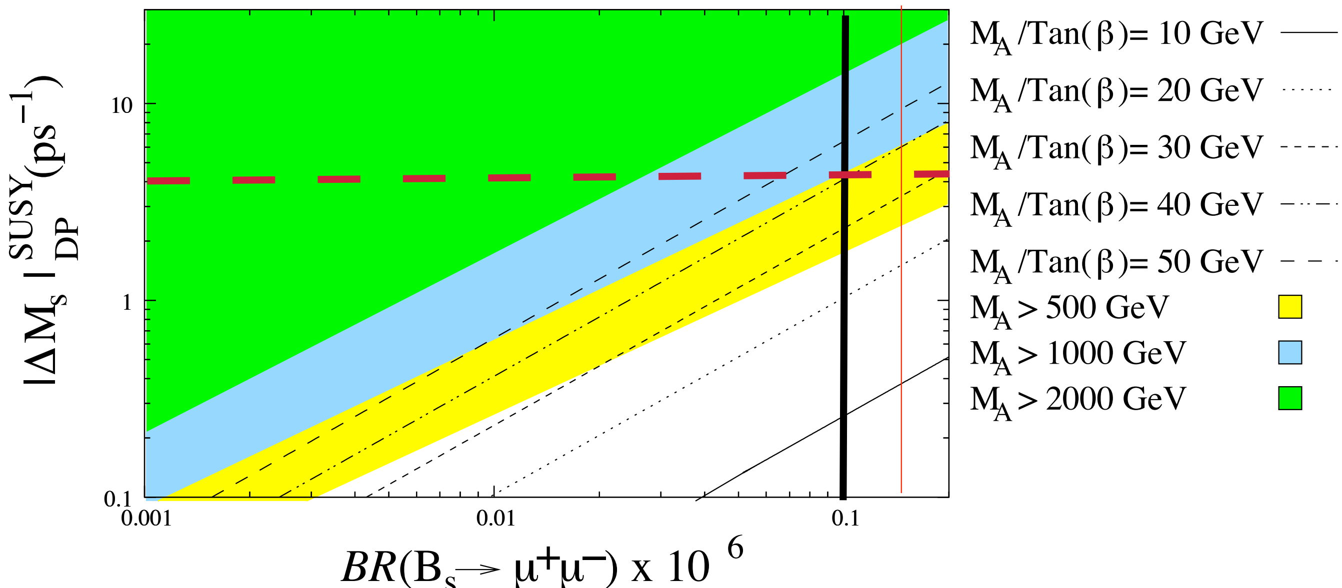
- For a given value of M_A, if one would like to maximize the negative shift of the mass eigenvalue difference without enhancing $B_s \to \mu^+\mu^-$, one needs to go to the smalles value of $\tan\beta$ possible

- This is achieved for the maximal (and negative) values of the loop parameters E_g and E_t

Correlation between Higgs mediated flavor violating effects

- Higgs mediated contribution to ΔM_s has opposite sign to the SM one.
- Recent measurement of ΔM_s is consistent with (a deviation of a few ps^{-1} with respect to) the SM prediction. A SUSY contribution of about a few ps^{-1} may only be obtained for parameters that would guarantee the observation of $B_s \to \mu^+\mu^-$ at the Tevatron collider.

$$\Delta M_s \simeq (17.77 \pm 0.25)\ \mathrm{ps}^{-1}; \qquad (\Delta M_s)^{\mathrm{SM}} \simeq (20.9 \pm 5.2)\ \mathrm{ps}^{-1}\ (\mathrm{UTFIT}, 2\sigma\ \mathrm{range})$$



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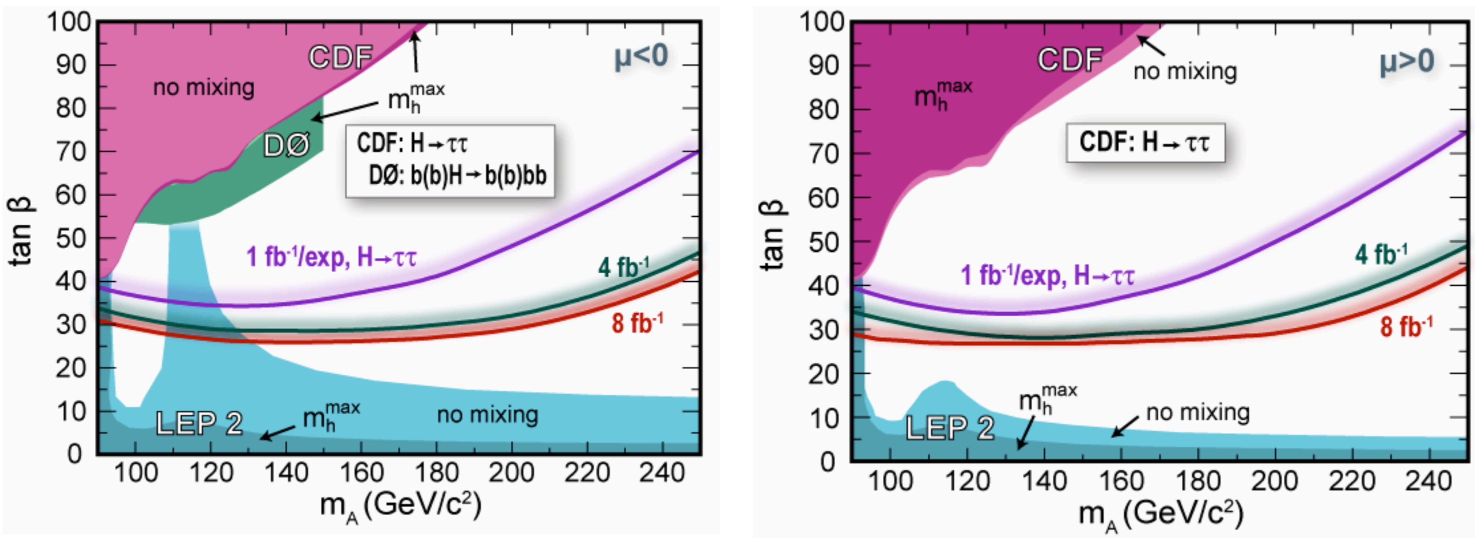
CDF observed, expected sensitivity



CDF: ττ result updated to 1 fb^{-1}