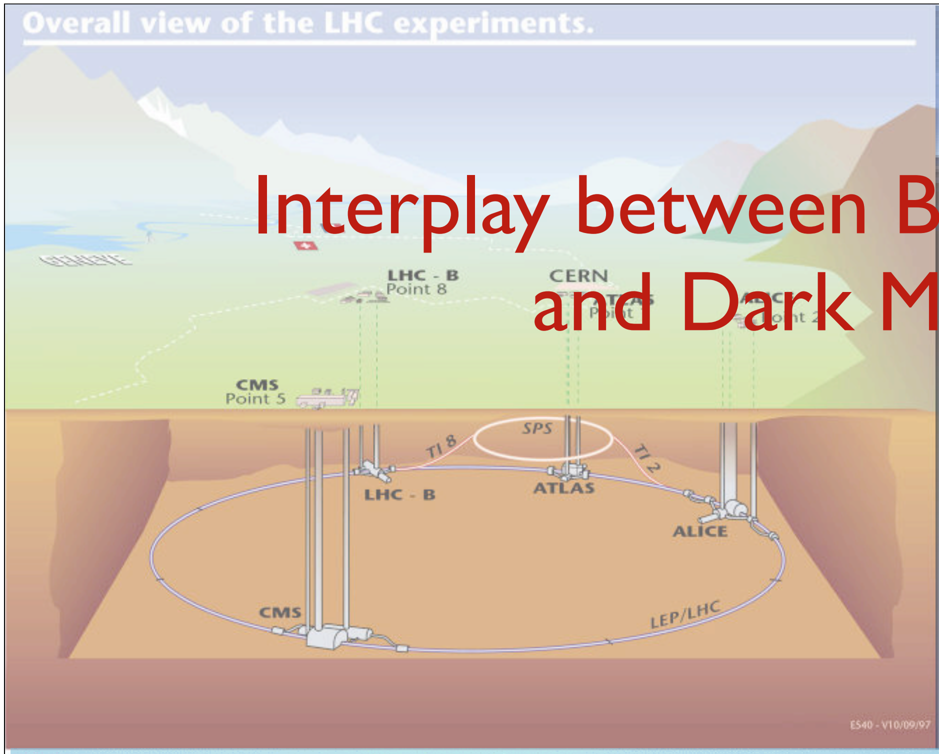
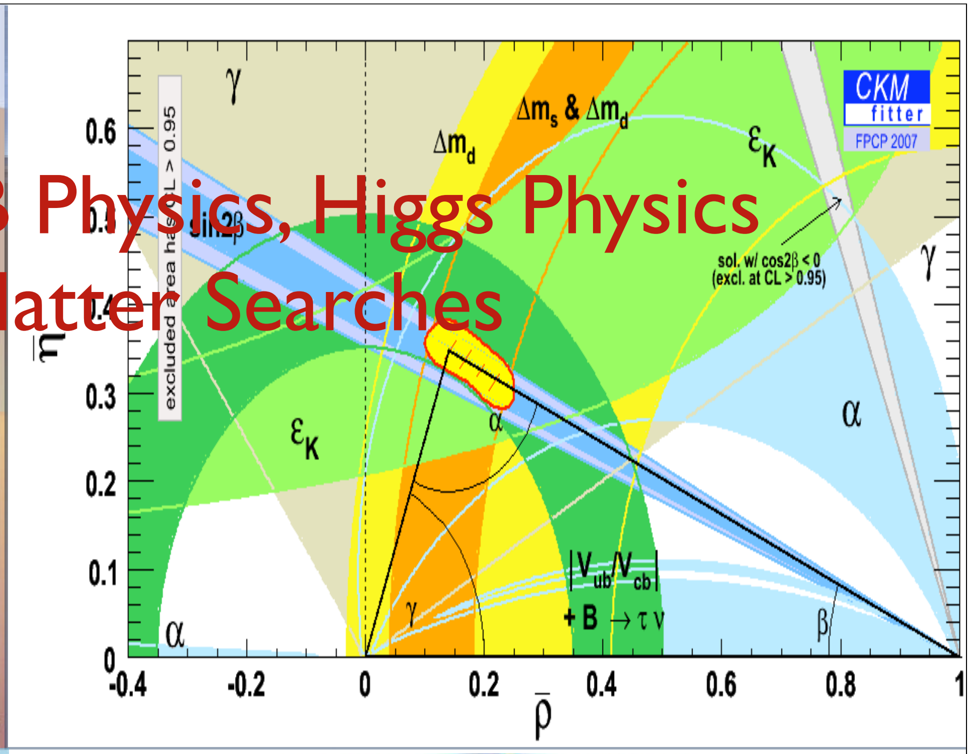
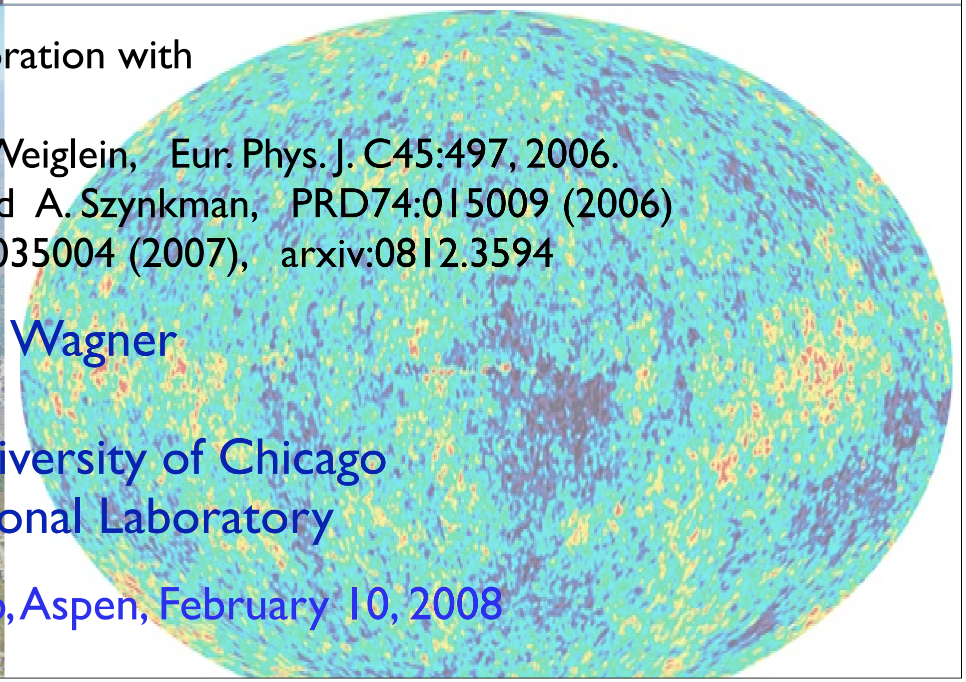
Interplay between B Physics, Higgs Physics and Dark Matter Searches







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), arxiv:0812.3594

C.E.M. Wagner

EFI and KICP, University of Chicago
Argonne National Laboratory

Aspen Winter Workshop, Aspen, February 10, 2008

Higgs Physics in the Standard Model

- In the SM, the Higgs couples to fermions with a strength proportional to the fermion mass. One can start from arbitrary Yukawas

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

- 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.

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

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

- 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 $\boxed{\tan\beta = \frac{v_2}{v_1}}$ $\qquad$ $< H_i^0 >= v_i$

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

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

$$m_H^2 \simeq m_A^2 \qquad\qquad m_{H^+}^2 \simeq m_A^2 + m_W^2$$

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

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

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

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

- h is SM-like, while H and A have enhanced couplings to down quarks
- Trilinear interactions of Higgs with sfermions. In the simplest case,

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

Mass of the SM-like Higgs h

- Most important corrections come from the stop sector,

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

where the off-diagonal term depends on the stop-Higgs trilinear couplings, $X_t = A_t - \mu^* / \tan\beta$

- For large CP-odd Higgs boson masses, and with $M_S = m_Q = m_U$ dominant one-loop corrections are given by,

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right) \right)$$

- 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:

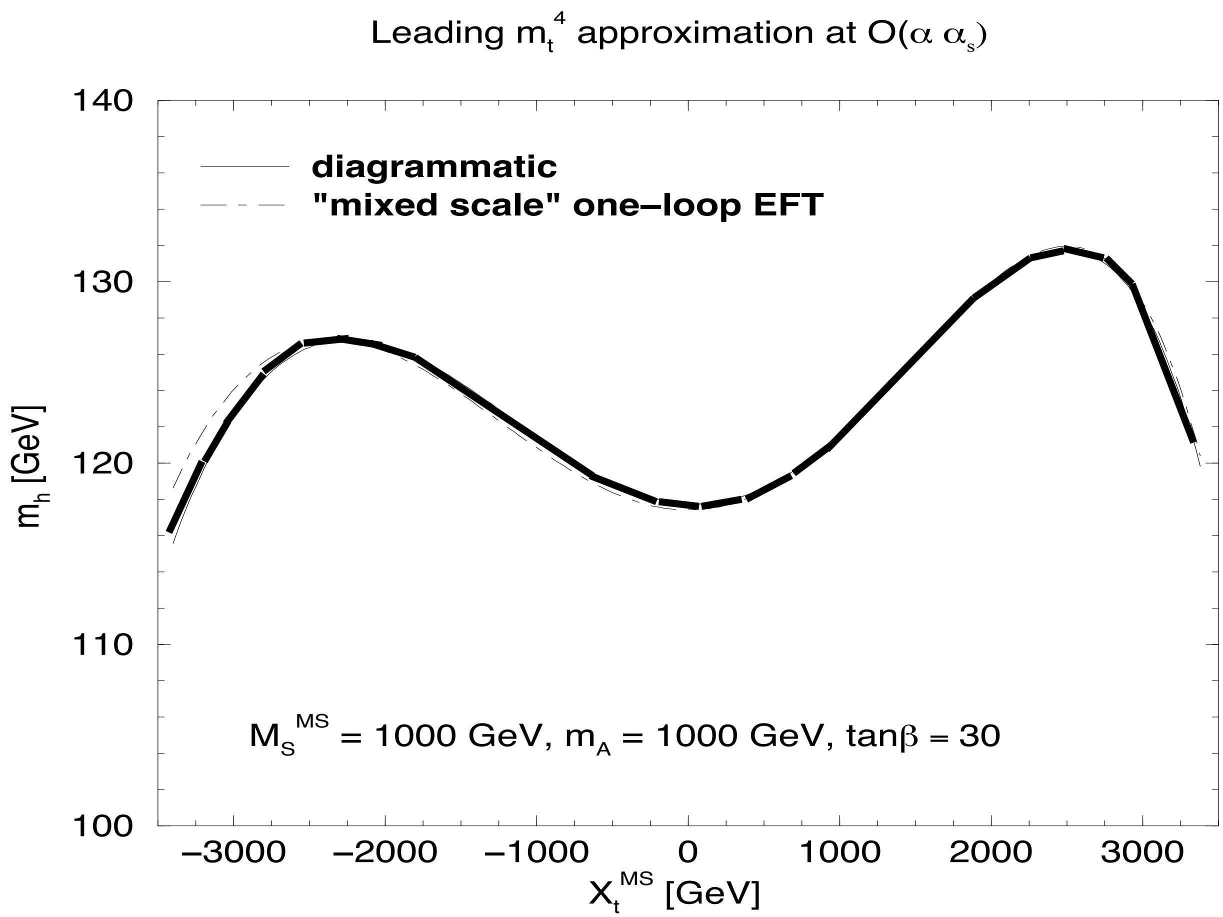
<u>$m_h \lesssim 135$ GeV</u>

$M_S = 1 \rightarrow 2$ 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

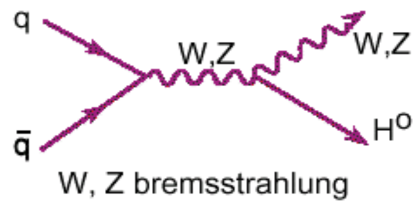


$X_t = A_t - \mu/\tan\beta, \quad X_t = 0$: No mixing; $\quad X_t = \sqrt{6} M_S$: Max. Mixing

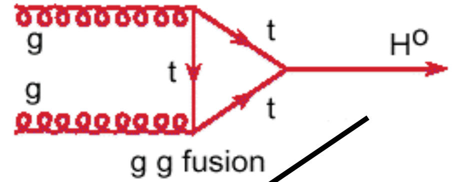
Direct Higgs searches at the Tevatron

Tevatron can search for the Higgs in all the mass range preferred by precision data

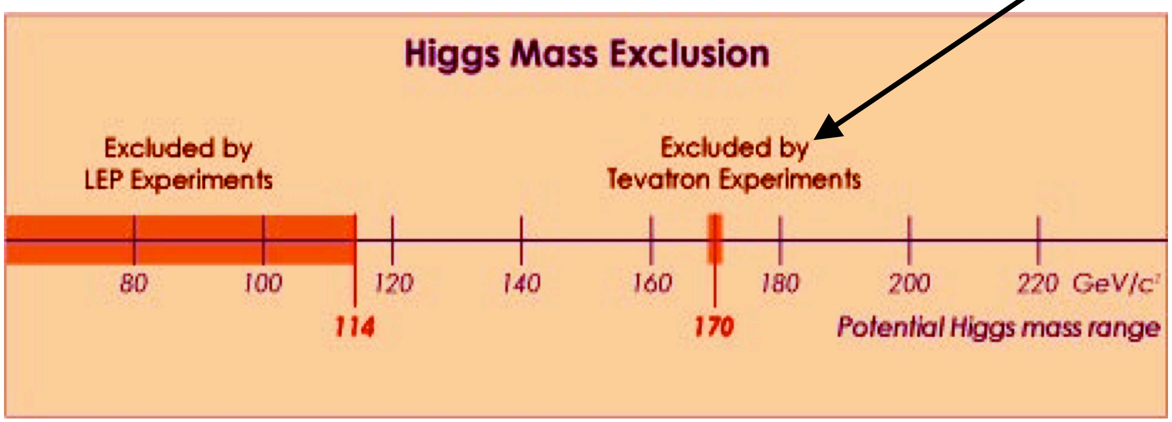
Some Possible production Processes



with $H \to b\bar{b}$, WW



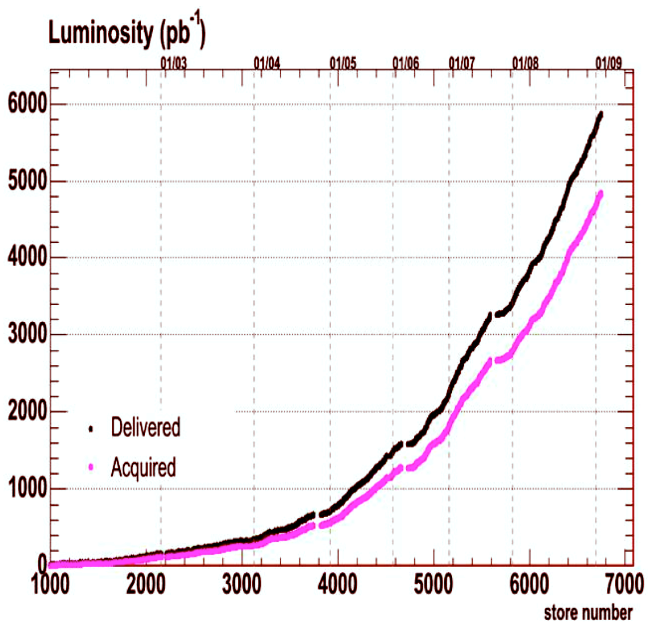
with $H \to WW$

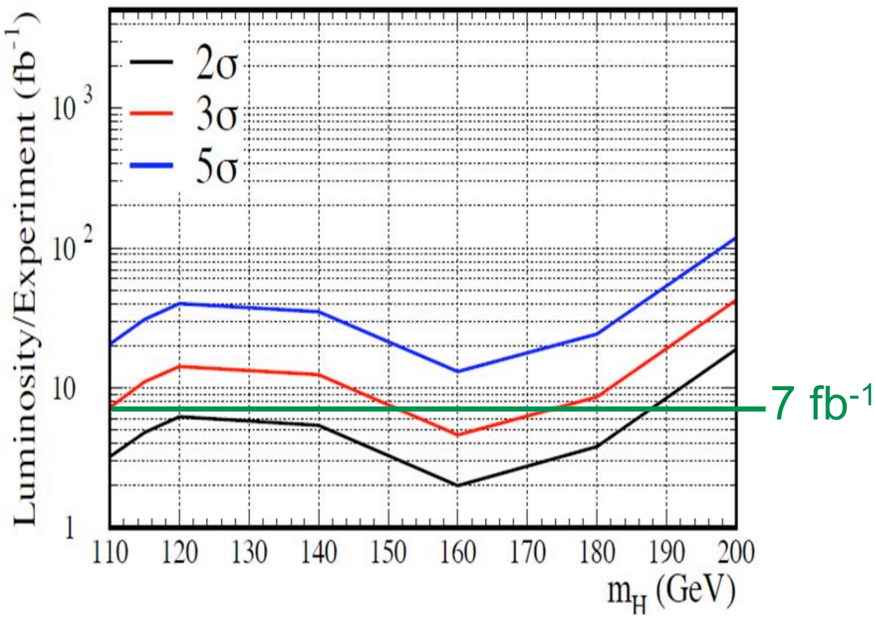


Press release: 9/08

Tevatron achieves sensitivity to exclude a Higgs with mass 170 GeV

Higgs mass reach at the Tevatron: exciting times ahead





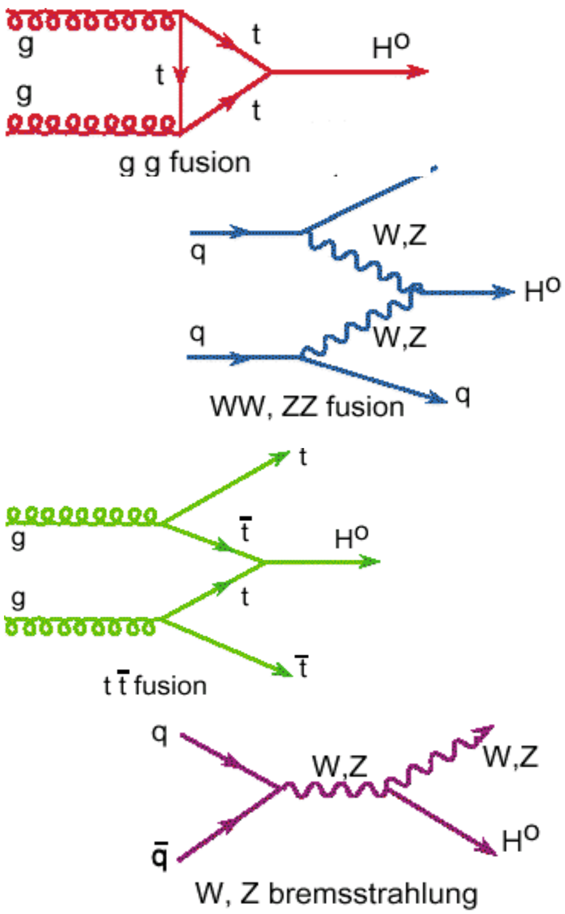
Accelerator performance implies 9fb^{-1} of data available in 2010

Expected detector/analysis performance

==> $m_H < 185$ GeV will to be probed at the Tevatron

Evidence of a signal will mean that the Higgs has SM-like couplings to the W and Z

The search for the Standard Model Higgs at the LHC

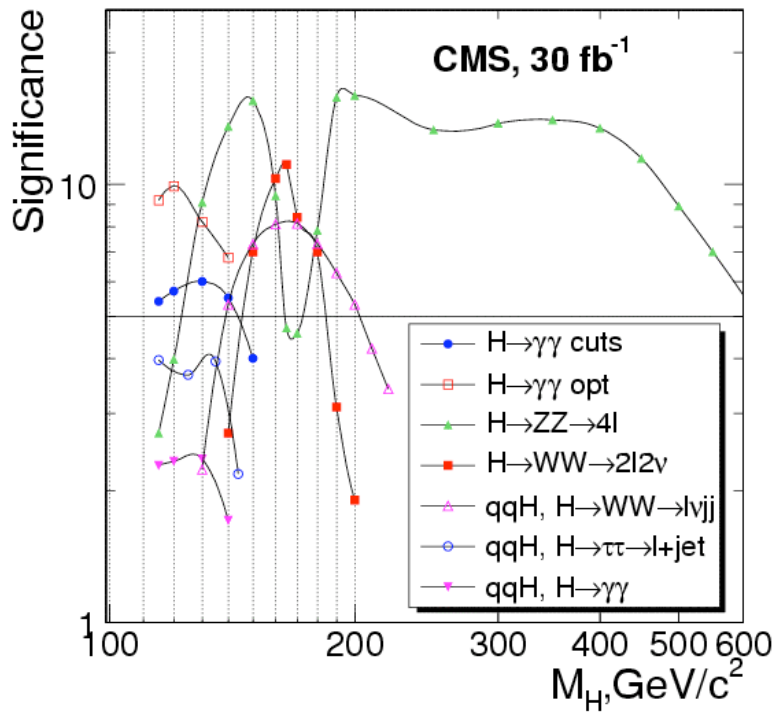


- **Low mass range** $m_{H_{SM}}$ < 200 GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

- **High mass range** $m_{H_{SM}}$ > 200 GeV

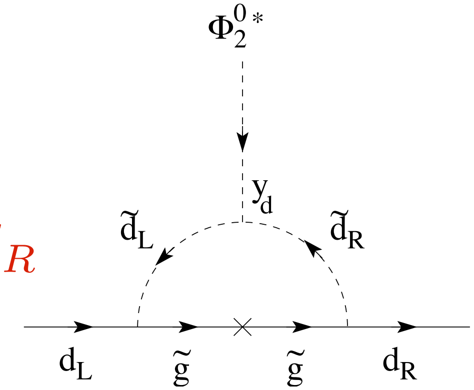
$$H \to WW,\ ZZ$$

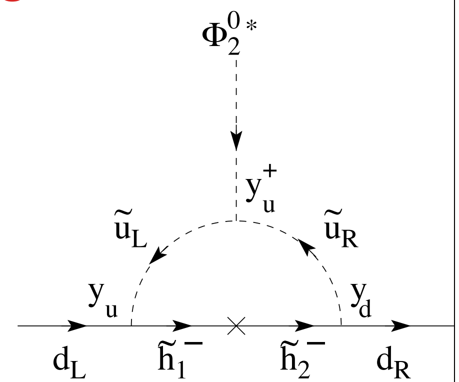


Radiative Corrections to Higgs Couplings

- 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

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

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

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

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

Searches for Non-Standard Higgs bosons

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

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

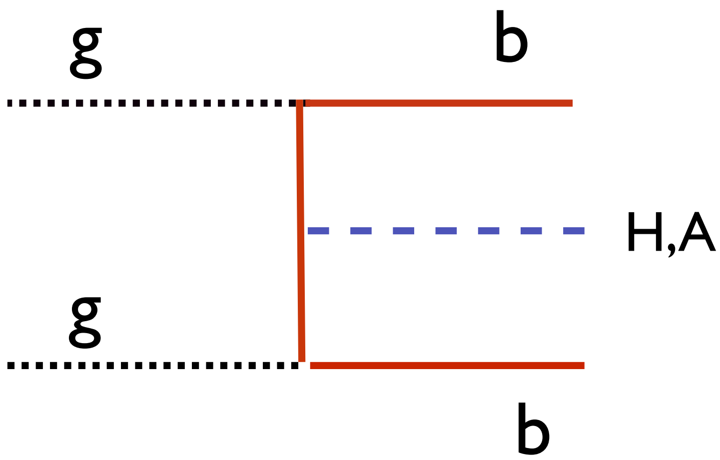
- Couplings to gauge bosons and other fermions are suppressed.

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

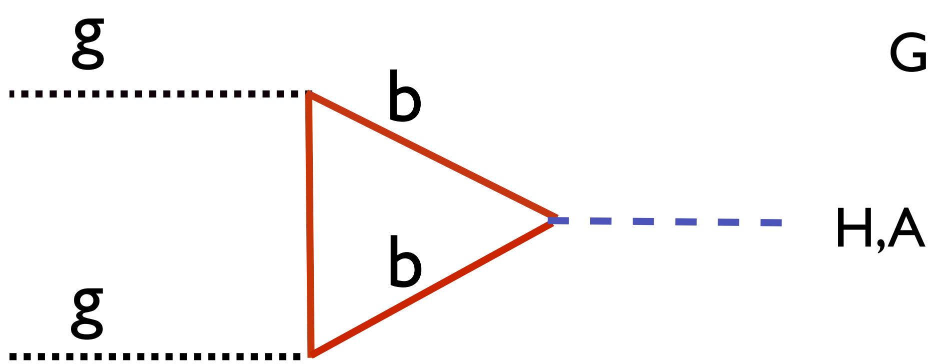
$$\mathrm{BR}(A \to bb) \simeq \frac{9}{9+(1+\Delta_b)^2}, \qquad \mathrm{BR}(A \to \tau\tau) \simeq \frac{(1+\Delta_b)^2}{9+(1+\Delta_b)^2}$$

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 tau tau mode

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

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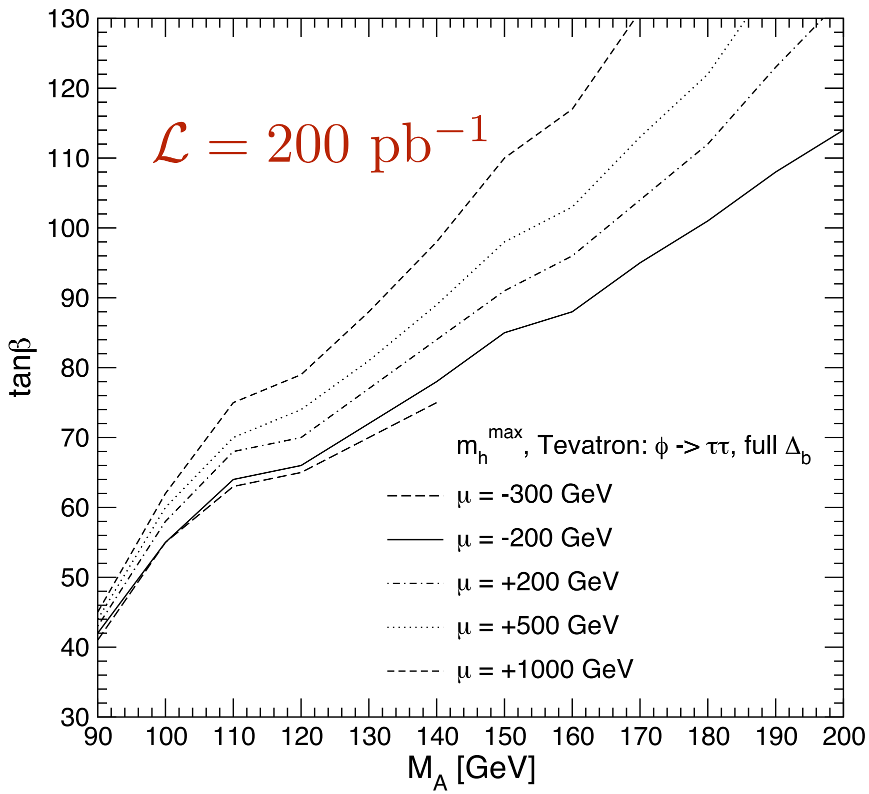
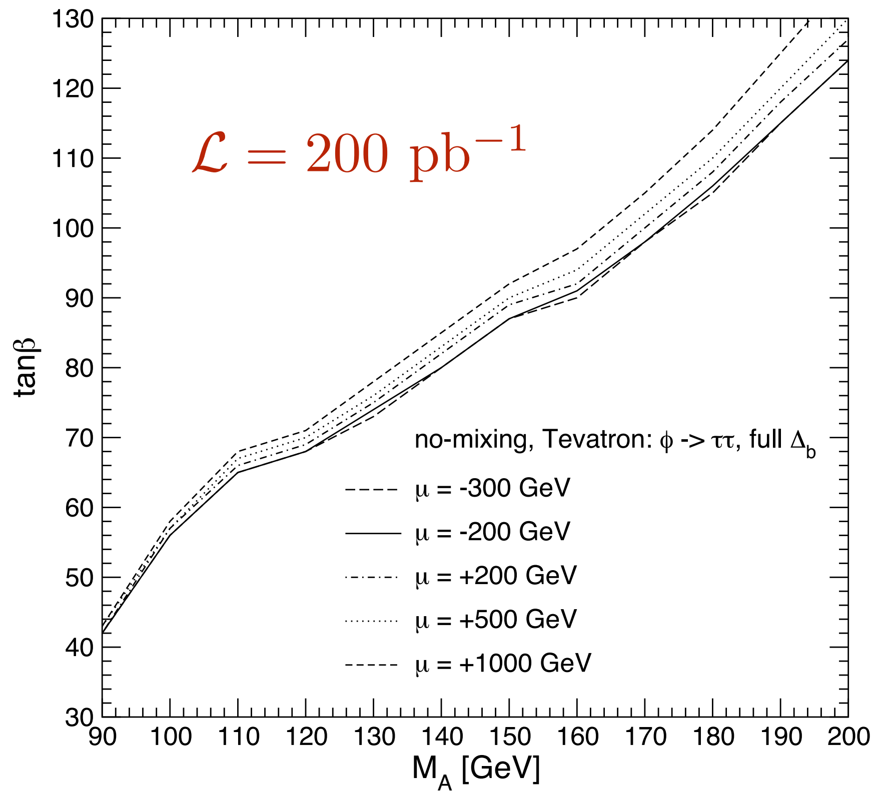
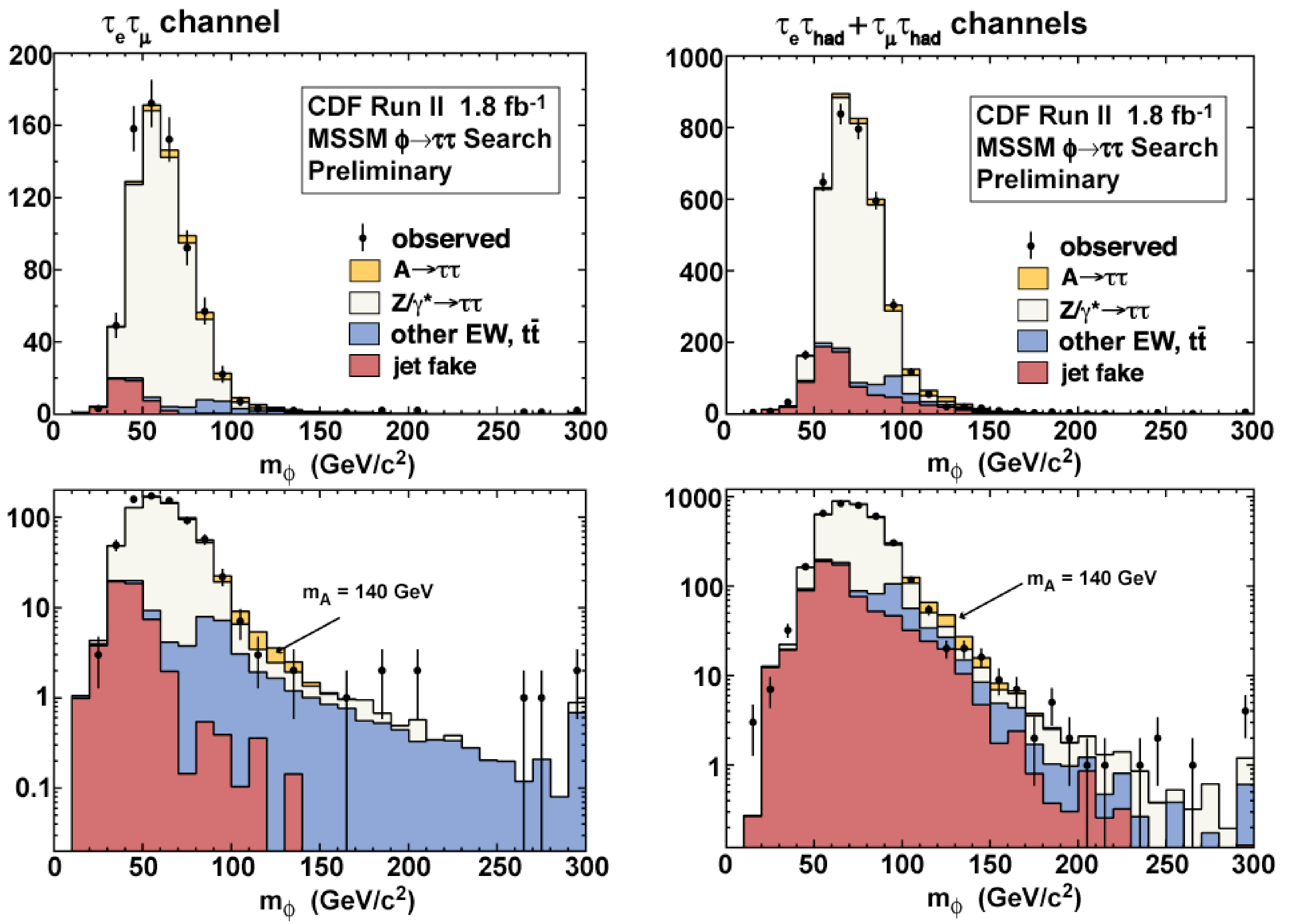




Updated CDF Higgs Search Results



Non-standard Higgs FCNC: 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. In the absence of FC couplings in the gluino sector:

Babu and Kolda'00, A. Buras et al'02; Dedes and Pilaftsis'03, Foster et al'05, Lunghi et al'06

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

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

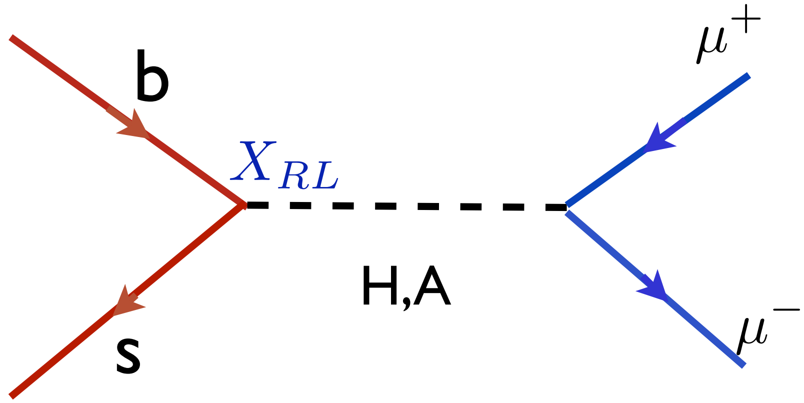
$E_t \propto X_t$(stop mixing parameter)

An interesting correlation appears between the SUSY contribution to different processes

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

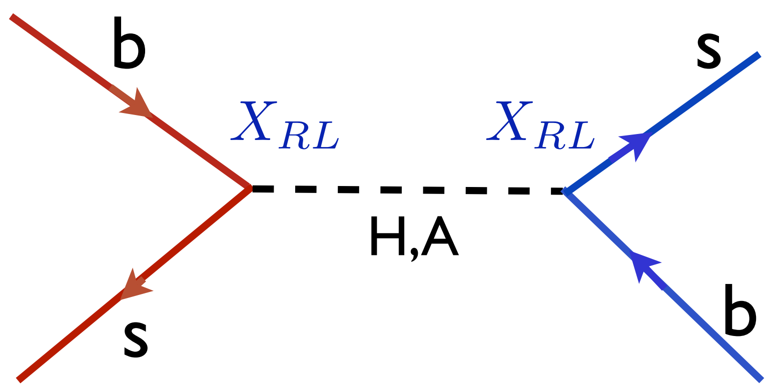
$$(\Delta M_{B_s})^{\text{SUSY}} \simeq -\frac{|X_{RL}|^2}{m_A^2}$$

Flavor Changing Transitions mediated by X_{RL}



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

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



$$\Delta M_s$$

Current Theory and Experimental results

Bs Mixing:

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

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

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

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

$$0.89 \leq \frac{\mathcal{BR}(b \to s\gamma)^{MSSM}}{BR(b \to s\gamma)^{SM}} \leq 1.36$$

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

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

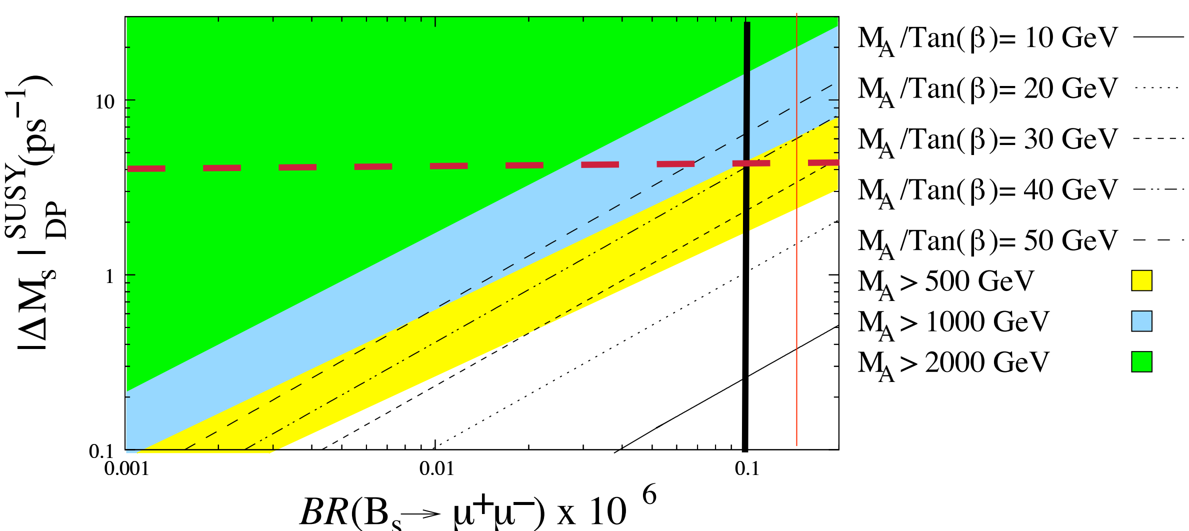
$$\mathcal{BR}(B_s \to \mu^+\mu^-) \leq 1 \times 10^{-7},$$ (CDF'06) $5.8\ 10^{-8}$ (CDF'07)

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

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.

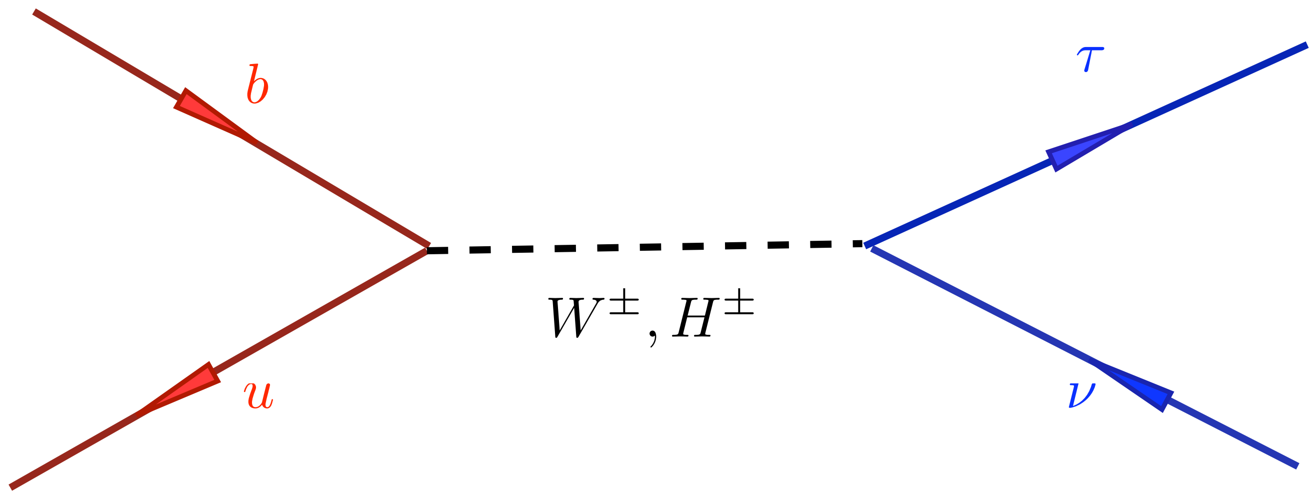
$$\Delta M_s \simeq (17.77 \pm 0.25)\ \mathrm{ps}^{-1}; \qquad (\Delta M_s)^{\mathrm{SM}} \simeq (20.9 \pm 5.2)\ \mathrm{ps}^{-1}\ (\mathrm{UTFIT}, 2\sigma\ \mathrm{range})$$



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

Buras et al'07; U. Nierste et al'08

Additional Flavor Constraints



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

$$\mathcal{BR}(B_u \to \tau\nu)^{\rm Exp} = (1.41 \pm 0.43) \times 10^{-4}.$$ **(Belle-Babar)**

$$\mathcal{BR}(B_u \to \tau\nu)^{\rm SM} = (1.09 \pm 0.40) \times 10^{-4}$$

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

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

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

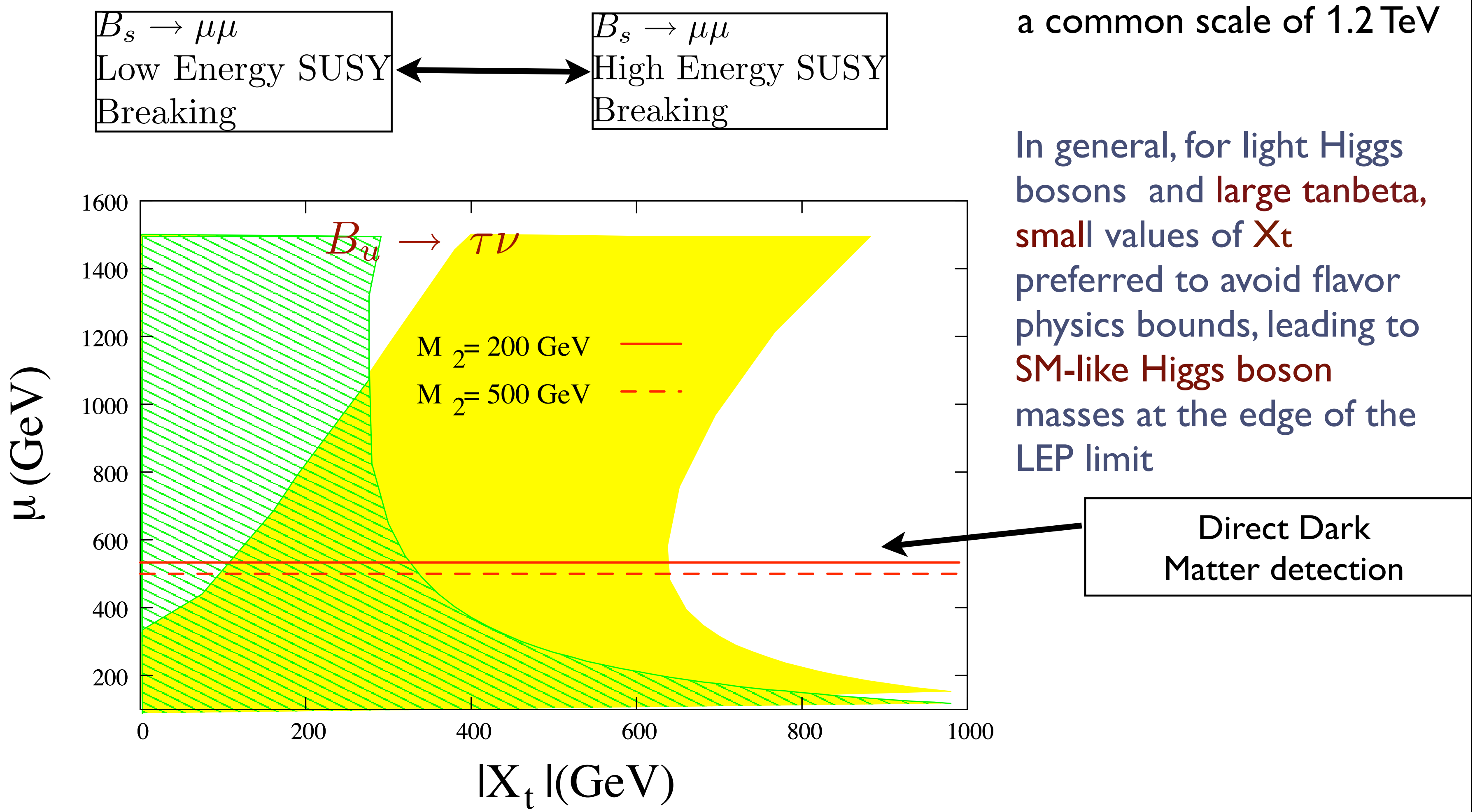
Dedes and Pilaftsis'03

A delicate cancellation may occur between these contributions

- 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 X_t–μ plane

$M_A = 200$ GeV $\quad \tan\beta = 55$



Third generation squarks at a common scale of 1.2 TeV

In general, for light Higgs bosons and large tanbeta, small values of Xt preferred to avoid flavor physics bounds, leading to SM-like Higgs boson masses at the edge of the LEP limit

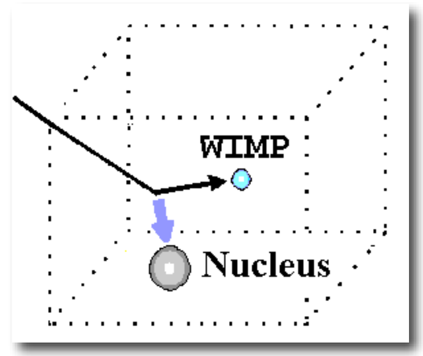
Direct Detection Dark Matter Experiments

• Collider experiments can find evidence of DM through $\not{E}_T$ signature but no conclusive proof of the stability of a WIMP

- Direct Detection Experiments can establish the existence of Dark Matter particles

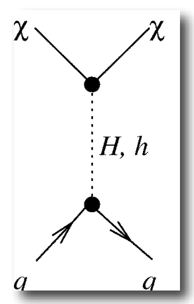
WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

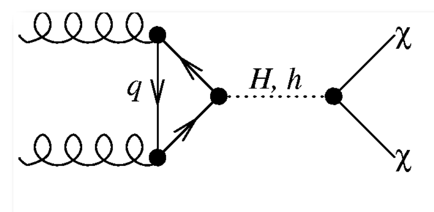
$$R = \sum_i N_i \; \eta_\chi \langle \sigma_{i\chi} \rangle$$



Direct DM experiments:
sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8}\, pb$)

==> dominated by virtual exchange of H and h



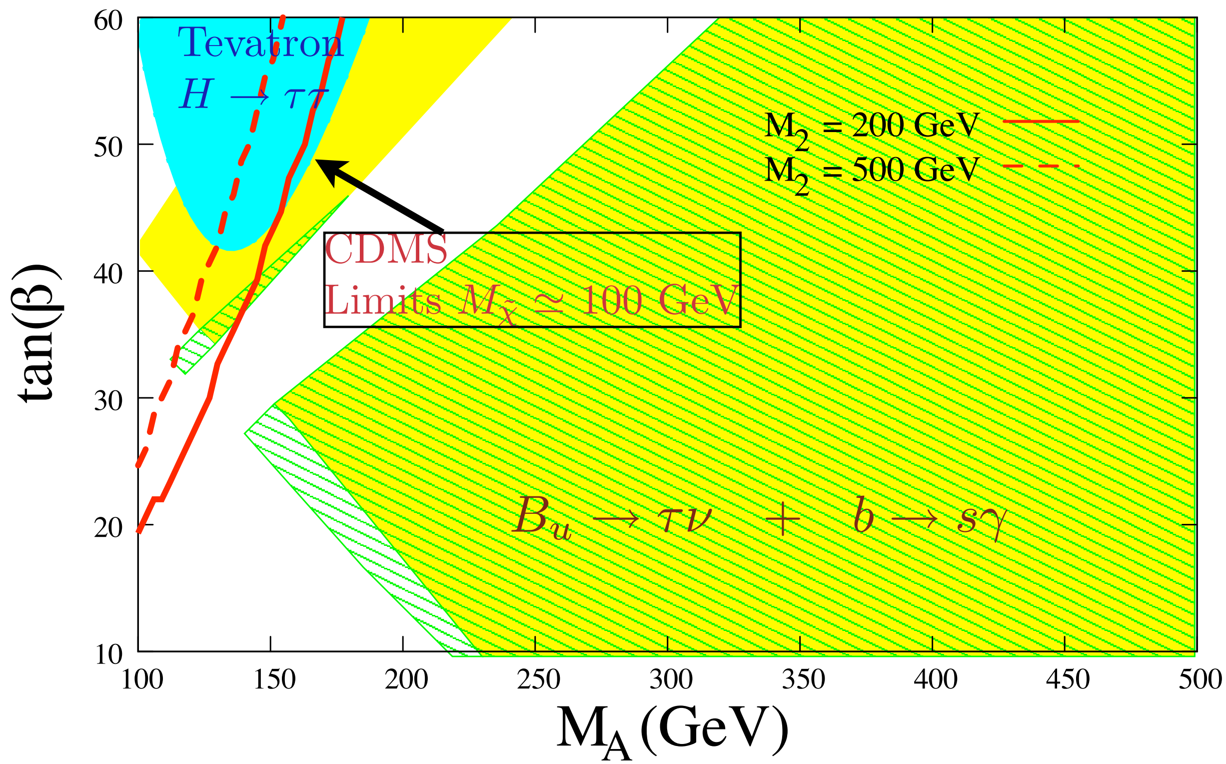


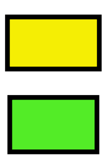
- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops

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

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

$X_t = -400$ GeV $\mu = 800$ GeV $M_3 = 800$ GeV





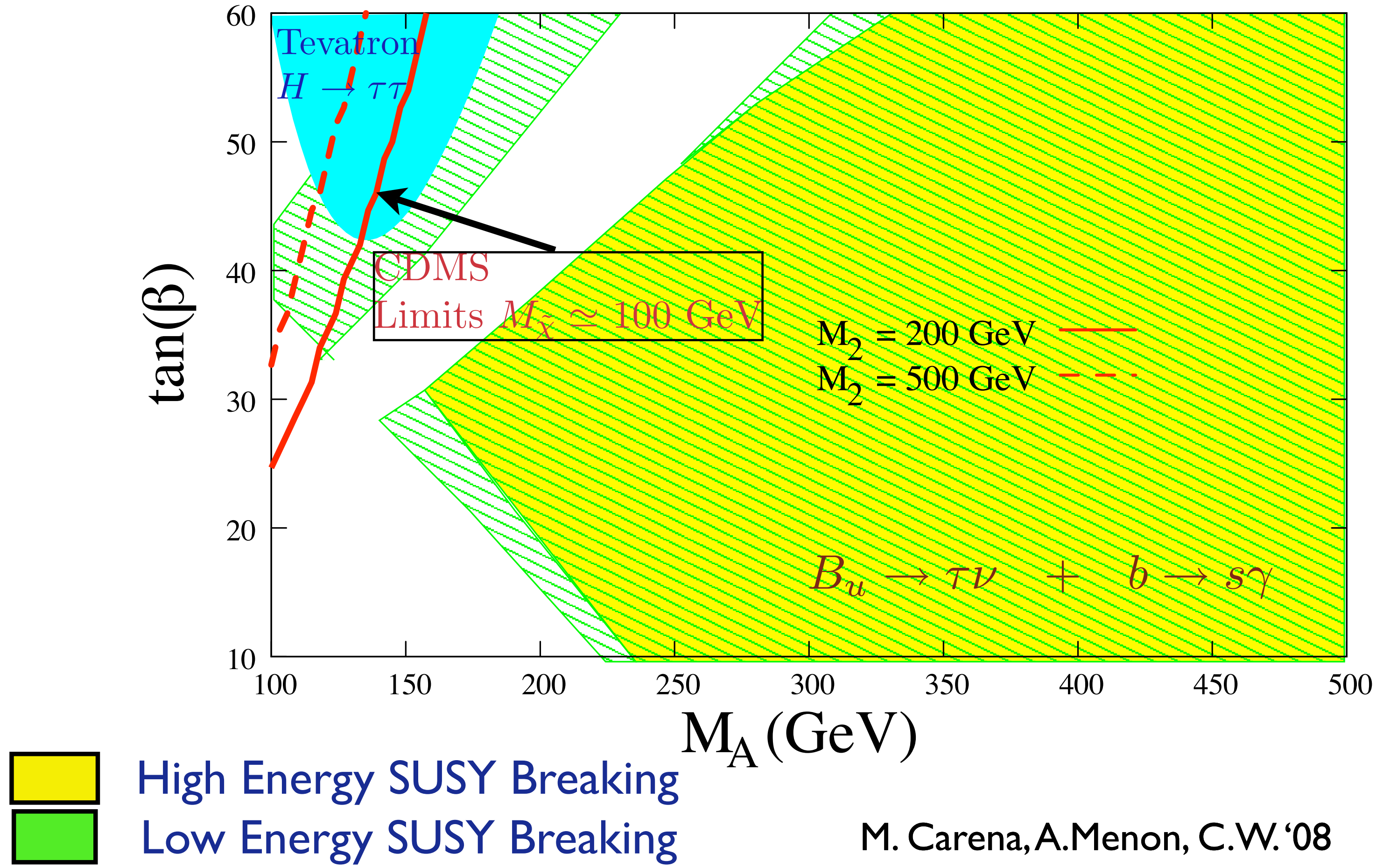
High Energy SUSY Breaking

Low Energy SUSY Breaking

M. Carena, A.Menon, C.W. '08

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

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



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Higgs and Dark Matter Searches

- Tevatron Higgs searches with $4\text{–}8\ \mathrm{fb}^{-1}$ are sensitive to values of $\tan\beta$ order 30 and m_A of about 250 GeV
- CDMS and XENON experiments will improve their dark matter searches sensitiviy by a factor 3 to an order of magnitude by the end of this year
- It is therefore expected that relevant information may be obtained from these experiments in the near future
- For instance, if any of those experiments would see a signature, then in the assumption of MFV one would obtain relevant information on the parameters in the Higgs sector and, possibly, on the scale of supersymmetry breaking !

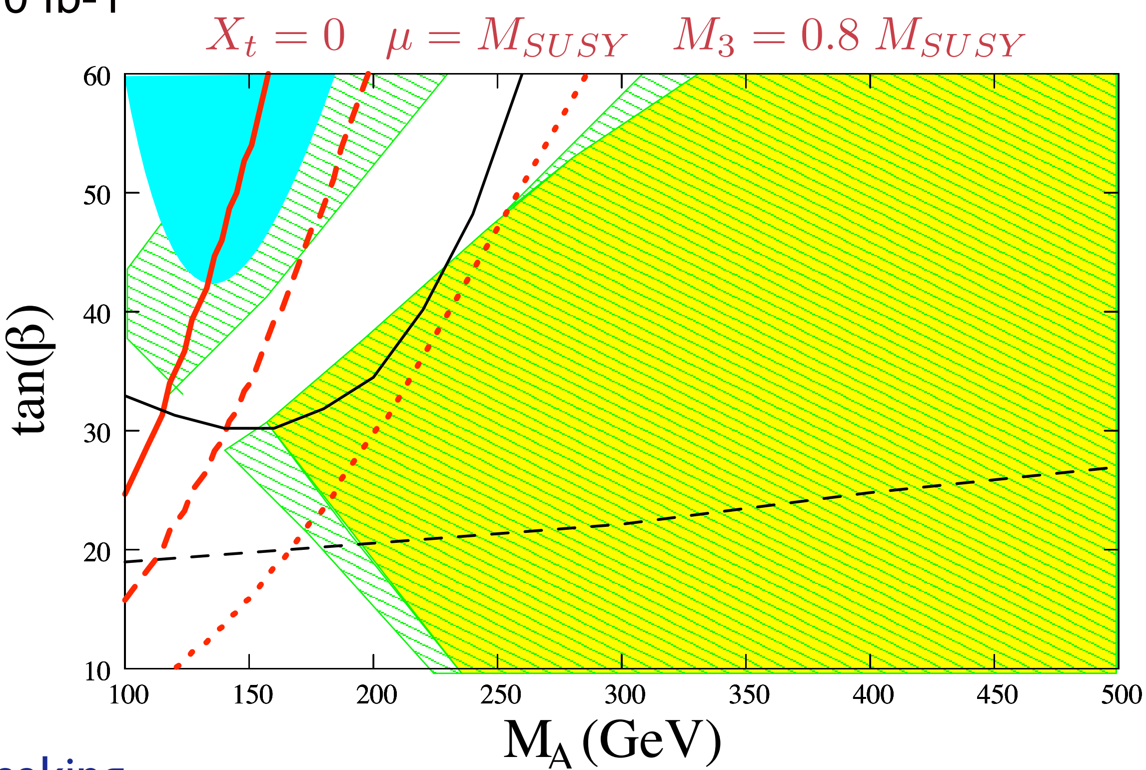
Expected Reach of Higgs and Dark Matter Searches (by the beginning of 2010)

--- Expected CDMS Limit

.... Expected Xenon Limit

— Expected Tevatron Bound 4fb-1

--- Expected LHC Bound 10 fb-1



High Energy SUSY Breaking

Low Energy SUSY Breaking

M. Carena, A.Menon, C.W.'08

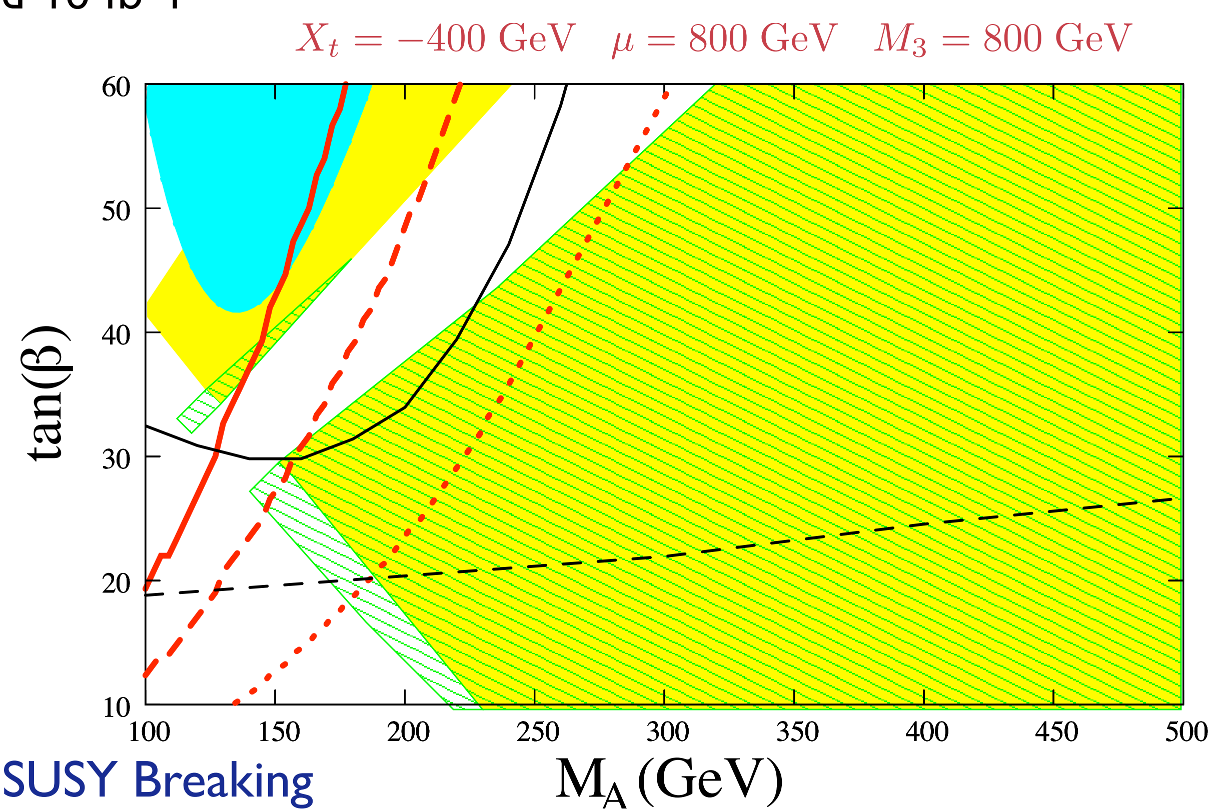
Expected Reach of Higgs and Dark Matter Searches (by the beginning of 2010)

-- Expected CDMS Limit

.... Expected Xenon Limit

— Expected Tevatron Bound 4fb-1

--- Expected LHC Bound 10 fb-1



High Energy SUSY Breaking

Low Energy SUSY Breaking

M. Carena, A. Menon, C.W. ‘08

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.

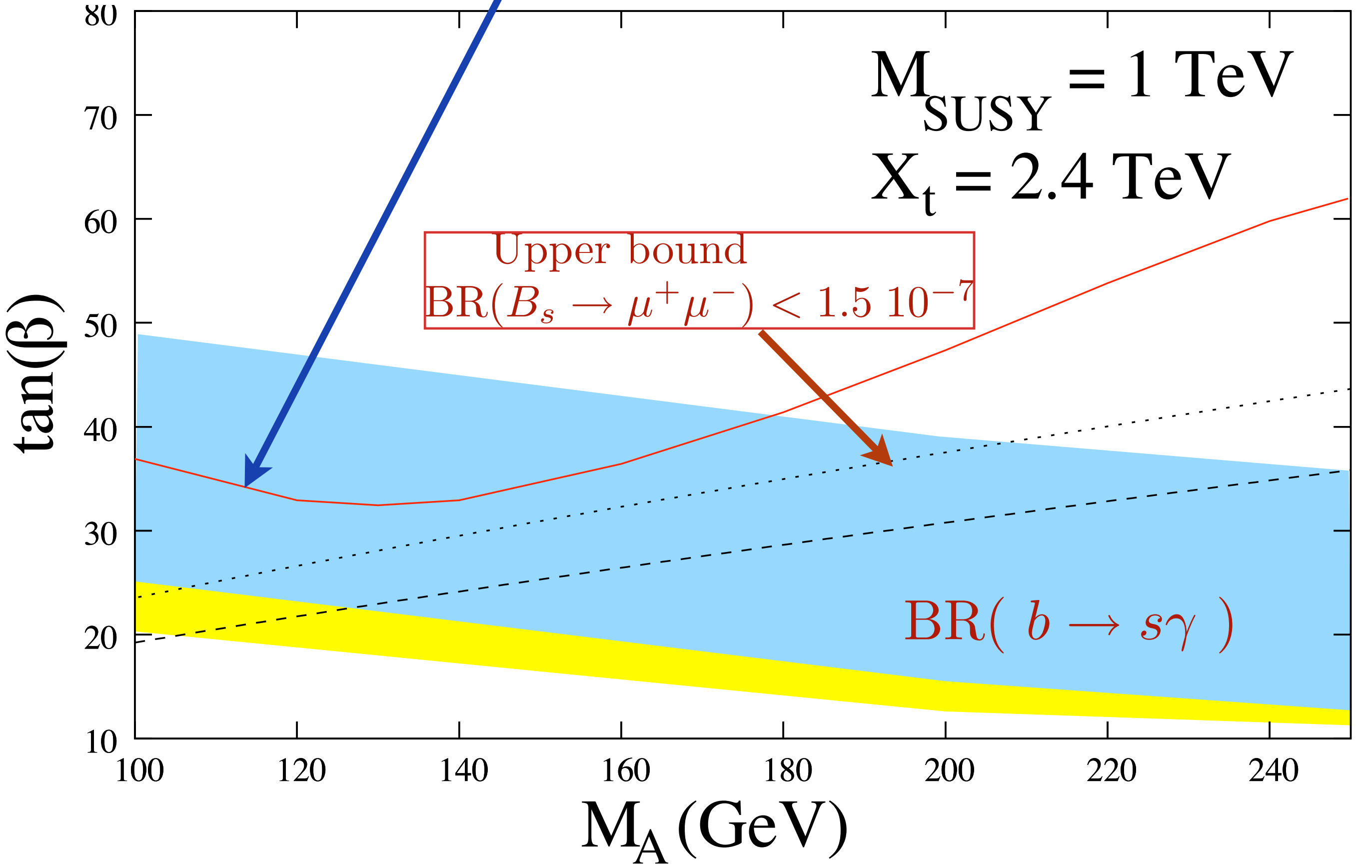
- Dark Matter searches would put further constraints scenarios of light Higgs spectrum and large $\tan\beta$. Complementarity of Higgs searches, flavor physics and dark matter searches can provide relevant information on Higgs parameters as well as, possibly, the scale of SUSY breaking.

Backup Slides

Experimental Constraints (mid'06)

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

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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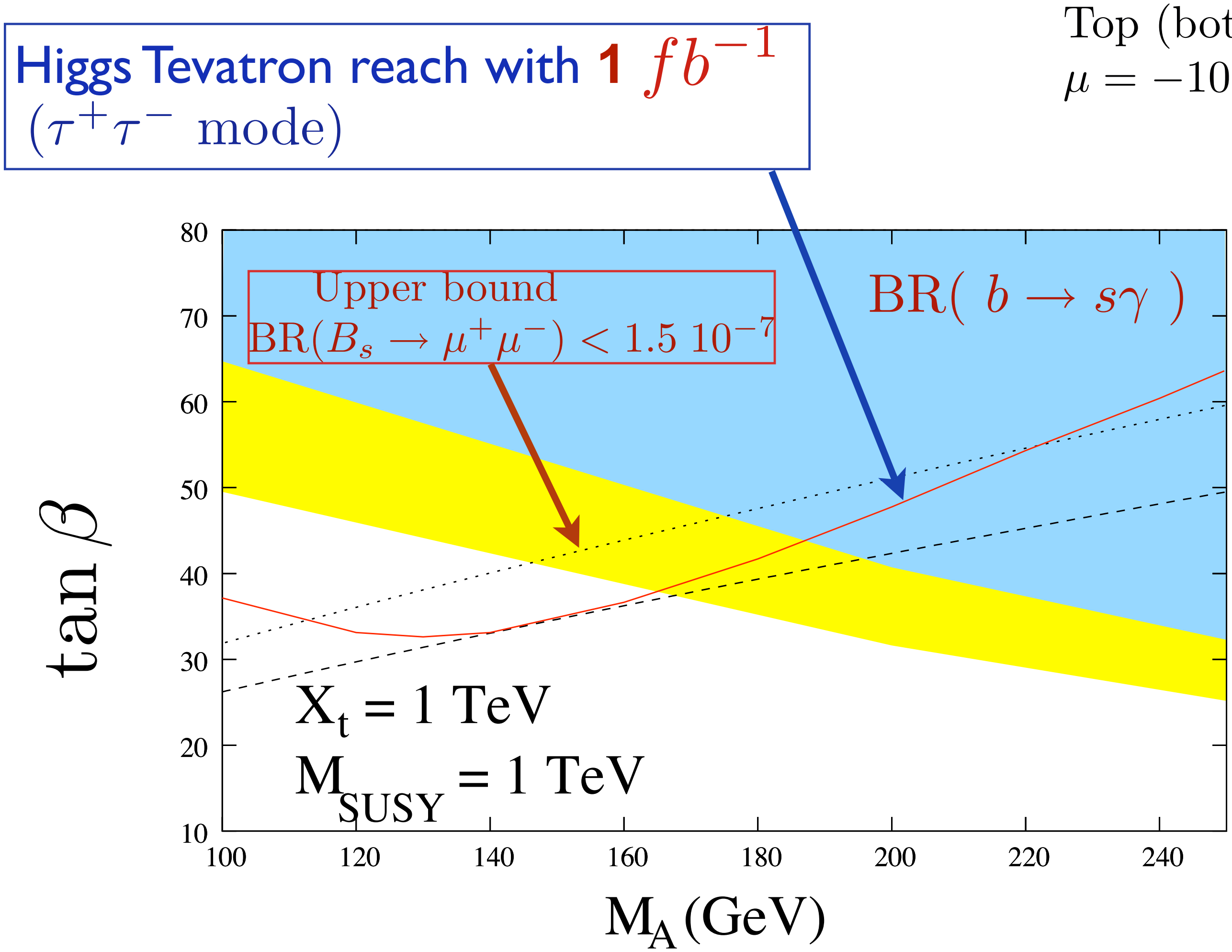


For moderate values of μ and X_t, B physics puts strong constraints on the region of parameters for which signatures of non-standard Higgs bosons may be observed at the Tevatron collider

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

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

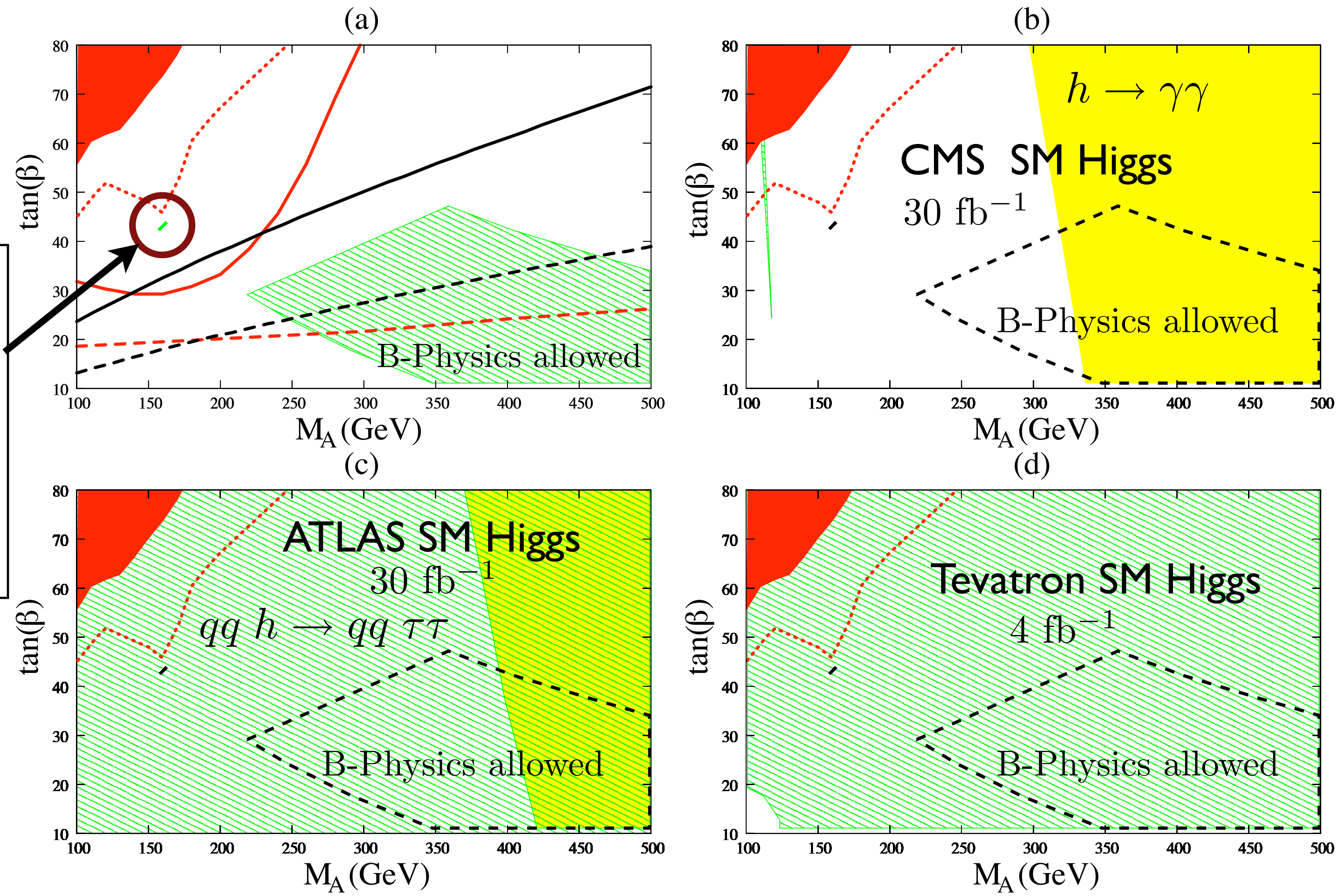
Red: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
with 1 and 4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC

black lines: $BR(B_s \to \mu^-\mu^+)$ reach:
Tevatron: 2×10^{-8} ($8 fb^{-1}$)
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



M.C., A. Menon, C. Wagner' 07

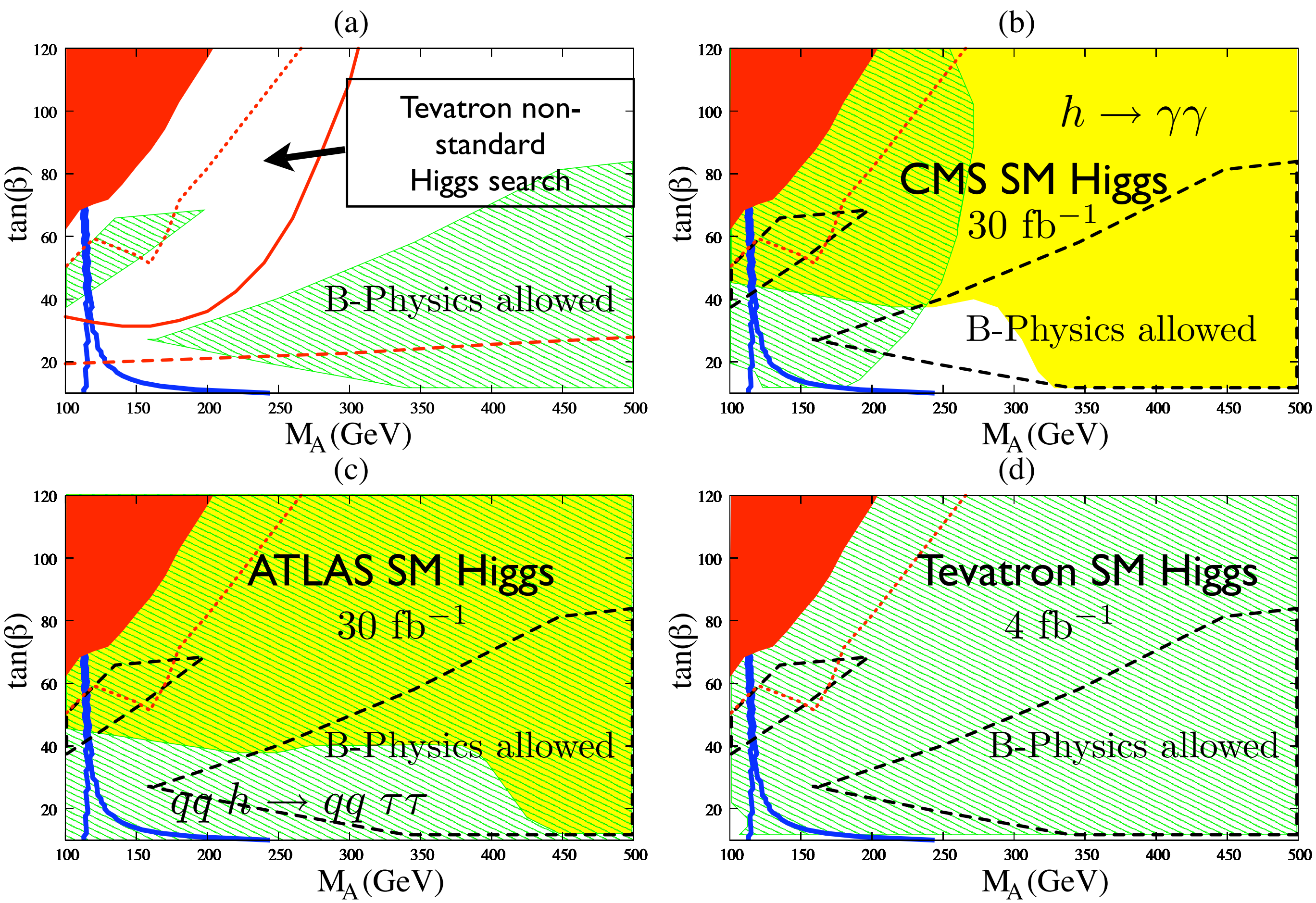
Red: $p\bar{p}, pp \rightarrow H/A \rightarrow \tau^+\tau^-$
with 1 and 4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC

black lines: $BR(B_s \rightarrow \mu^-\mu^+)$ reach:

Tevatron: 2×10^{-8} (8 fb^{-1})

LHC: 5.5×10^{-9} (10 fb^{-1})

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



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B