B-Physics, Direct Dark Matter Detection and Supersymmetric Higgs Searches at Colliders

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Rencontres de Moriond EW 2007,
La Thuile
March 11, 2007

Outline

- Introduction ==> **The connection between Higgs and Flavor Physics**
  -- The Flavour issue in Supersymmetry ==> Minimal Flavor Violation (MFV)

- The MSSM Higgs Bosons
  -- the impact of radiative corrections on Higgs-fermion couplings:
  Flavour conserving and FCNC effects

- SM-like Higgs and the $\mathrm{A/H} \to \tau\tau$ channels at the TeVatron and the LHC

- **B and Higgs Physics at the Tevatron and LHC**
  -- correlation between Bs mixing and $\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)$
  -- the impact of rare decays: $\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)$, $\mathrm{BR}(b \to s\gamma)$ and $\mathrm{BR}(B_u \to \tau\nu)$ on direct MSSM Higgs searches

- **The interplay between Collider Higgs Searches and Direct Dark Matter Searches**

The Connection between Higgs and Flavour Physics

The Flavor Structure in the SM

- In the mass eigenstate basis, the Higgs field interactions are also flavor diagonal

$$\bar{d}_i(m_i + h_i H) d_i, \qquad \text{with} \quad m_i = h_i v$$

Flavor Changing effects arise from charged currents, which mix left-handed up and down quarks: $\bar{u}_{L,i} V_{CKM}^{ij} \gamma_\mu d_{L,j} W_\mu^+ + h.c.$ where $V_{CKM} = U_L^\dagger D_L$

- The CKM matrix is almost the identity ==> Flavor changing transitions suppressed
- The Higgs sector and the neutral gauge interactions do not lead to FCNC

Flavor Beyond the Standard Model

Two Higgs doublet Models: Yukawa interactions ==> $\bar{d}_{R,i}(\hat{h}_{d,1}^{ij}\,\phi_1 + \hat{h}_{d,2}^{ij}\,\phi_2)\, d_{L,j}$

Different v.e.v.'s ==> $\hat{m}_d^{ij} = \hat{h}_{d,1}^{ij}\mathrm{v}_1 + \hat{h}_{d,2}^{ij}\mathrm{v}_2$

Diagonalization of the mass matrix will not give diagonal Yukawa couplings

==> will induce large, usually unacceptable FCNC in the Higgs sector

Solution: Each Higgs doublet couples only to one type of quarks ==> SUSY at tree level

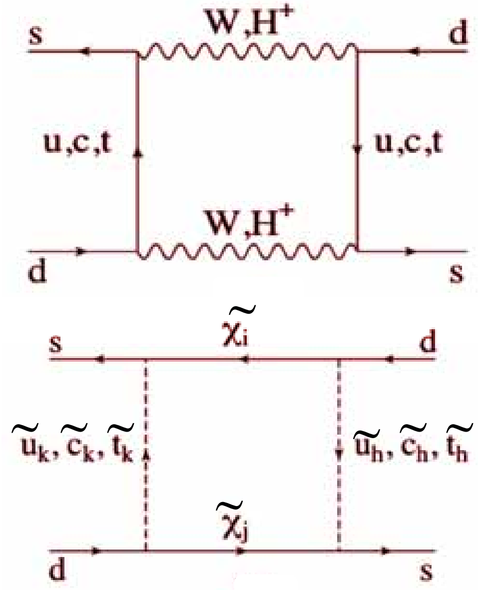
The Flavor Problem in SUSY Theories

SUSY mechanisms ==> can give rise to large FCNC effects

Minimal Flavor Violation

- At tree level: the quarks and squarks diagonalized by the same matrices $\tilde{D}_{L,R} = D_{L,R}; \quad \tilde{U}_{L,R} = U_{L,R}$

Hence, in the quark mass eigenbasis the only FC effects arise from charged currents via V_{CKM} as in SM. →



Isidori, Retico: Buras et al.

- At loop level: FCNC generated by two main effects:

1) Both Higgs doublets couple to up and down sectors
==> important effects in the B system at large tan beta

2) Soft SUSY parameters obey Renormalization Group equations:
given their values at the SUSY scale, they change significantly at low energies
==> RG evolution adds terms prop. to $h_d h_d^+$ and $h_u h_u^+$, and h.c.

In both cases the effective coupling governing FCNC processes

$$(X_{FC})_{ij} = (h_u^+ h_u)_{ij} \propto m_t^2 \, V_{3i}^{CKM*} V_{3j}^{CKM} \qquad \text{for } i \neq j$$

D'Ambrosio, Giudice, Isidori, Strumia

The Higgs Sector in Minimal Supersymmetric Standard Model

- 2 Higgs SU(2) doublets ϕ_1 and ϕ_2 :

→ 2 CP-even h, H with mixing angle α ,1 CP-odd A and a charged pair $H^{\pm}$

At tree level,

Masses and couplings given in terms of m_A and $\tan\beta = v_2/v_1$

Each Higgs doublet couples only to one type of quarks

$$\overline{\psi}_L^i = \begin{pmatrix} \overline{u}_L \\ \overline{d}_L \end{pmatrix}^i$$

$$-L = \overline{\psi}_L^i \left(\hat{h}_d^{ij^+} \phi_1 d_R^j + \hat{h}_u^{ij^+} \phi_2 u_R^j \right) + h.c.$$

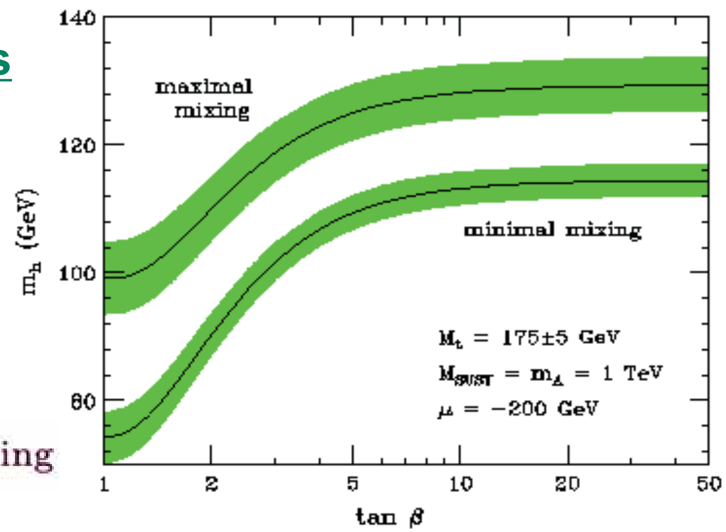
Up and down sectors diagonalized independently ==>Higgs interactions remain flavor diagonal.

Radiative Corrections to Higgs Boson Masses

Important effects due to incomplete cancellation of particles and superparticles in the loops

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2 g_2^2 m_t^4}{8\pi^2 M_W^2} \left[\ln(M_{\tilde{S}}^2/m_t^2) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right]$$

$$M_{\tilde{S}}^2 = \tfrac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) \text{ and } X_t = A_t - \mu/\tan\beta \longrightarrow \text{stop mixing}$$



After 2 -loop corrections $m_h \leq 135\text{GeV}$ ==> stringent test of the MSSM

Radiative Corrections to the Higgs Couplings

1) Through radiative corrections to the CP-even Higgs mass matrix δM_{ij}^2 ,
which defines the mixing angle α

$$\sin\alpha\cos\alpha = M_{12}^2 / \sqrt{\left(\mathrm{Tr}\, M^2\right)^2 - 4\det M^2}$$

The off diagonal elements are prop. to

M.C. Mrenna, Wagner

$$M_{12}^2 \propto -\left(m_A^2 + m_Z^2\right)\cos\beta\sin\beta + \frac{m_t^4}{16\pi^2 \mathrm{v}^2}\frac{\mu X_t}{M_S^2}\left(\frac{X_t^2}{M_S^2} - 6\right)$$

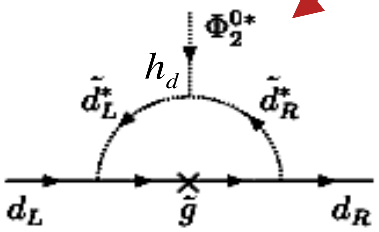
Important effects of rad. correc. on $\sin\alpha$ or $\cos\alpha$ depending on the sign of μX_t
and the magnitude of X_t / M_S

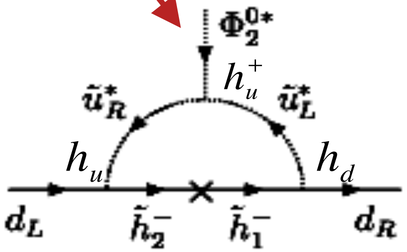
===> govern couplings of Higgs to fermions
===> via rad. correc. to $\cos(\beta - \alpha)$ and $\sin(\beta - \alpha)$ governs couplings to vector bosons

• If off-diagonal elements vanish (small m_A & large tan beta) ===> $\sin\alpha$ or $\cos\alpha$ vanish
===> strong suppression of SM-like Higgs boson coupling to b-quarks and tau-leptons

2) Vertex corrections to neutral Higgs-fermion couplings ($\tan\beta$ enhanced)

$$-L_{eff.} = \bar{d}_R^0 \hat{h}_d \left[\phi_1^{0^*} + \phi_2^{0^*} \left(\hat{\varepsilon}_0 + \hat{\varepsilon}_Y \hat{h}_u^+ \hat{h}_u \right) \right] d_L^o + \phi_2^0 \bar{u}_R^0 \hat{h}_u u_L^0 + h.c.$$





ε loop factors intimately connected to the structure of the squark mass matrices.

- **In terms of the quark mass eigenstates** Dedes , Pilaftsis

$$\mathrm{h_u = M_u / v_2}$$

$$-L_{eff} = \frac{1}{v_2}\left(\tan\beta\, \Phi_1^{0^*} - \Phi_2^{0^*}\right) \bar{d}_R M_d \left[V_{CKM}^+ R^{-1} V_{CKM} \right] d_L + \frac{1}{v_2} \Phi_2^{0^*} \bar{d}_R M_d d_L + \Phi_2^0 \bar{u}_R M_u u_L + h.c.$$

and $R = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |h_u|^2$ ➔ R diagonal with $R^{33} \equiv 1 + \Delta_b$

Dependence on SUSY parameters ➔

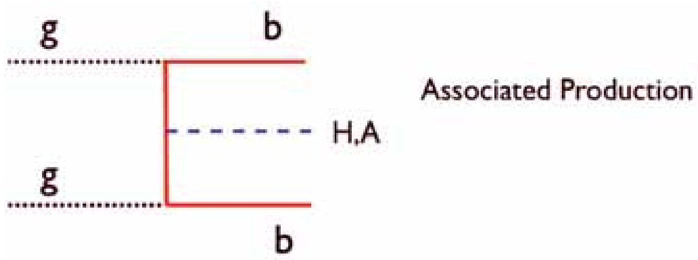
$$\varepsilon_0^i \approx \frac{2\alpha_s}{3\pi} \frac{\mu^* M_{\tilde{g}}^*}{\max\left[m_{\tilde{d}_1^i}^2, m_{\tilde{d}_2^i}^2, M_{\tilde{g}}^2 \right]} \qquad \varepsilon_Y \approx \frac{\mu^* A_t^*}{16\pi^2 \max\left[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2 \right]}$$

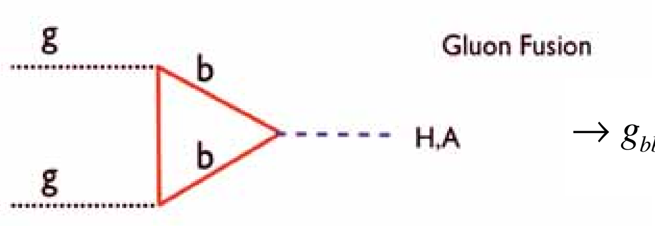
Non-Standard Higgs Production at the Tevatron and LHC

Looking at $V_{CKM} \cong I \Rightarrow$ Flavor Conserving Higgs-fermion couplings

- Important effects on couplings to b quarks and tau-leptons

destroy basic relation
$g_{\mathrm{h,H,Abb}} / g_{h,H,A\,\tau\tau} \propto m_b / m_\tau$





$$\rightarrow g_{bbA/H} \approx \frac{m_b \tan\beta}{(1+\Delta_b)\mathrm{v}}$$

- Considering value of running bottom mass and 3 quark colors

$$BR(A \rightarrow b\bar{b}) \cong \frac{9}{9+(1+\Delta_b)^2} \Rightarrow$$

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

$$BR(A \rightarrow \tau^+\tau^-) \cong \frac{(1+\Delta_b)^2}{9+(1+\Delta_b)^2} \Rightarrow$$

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

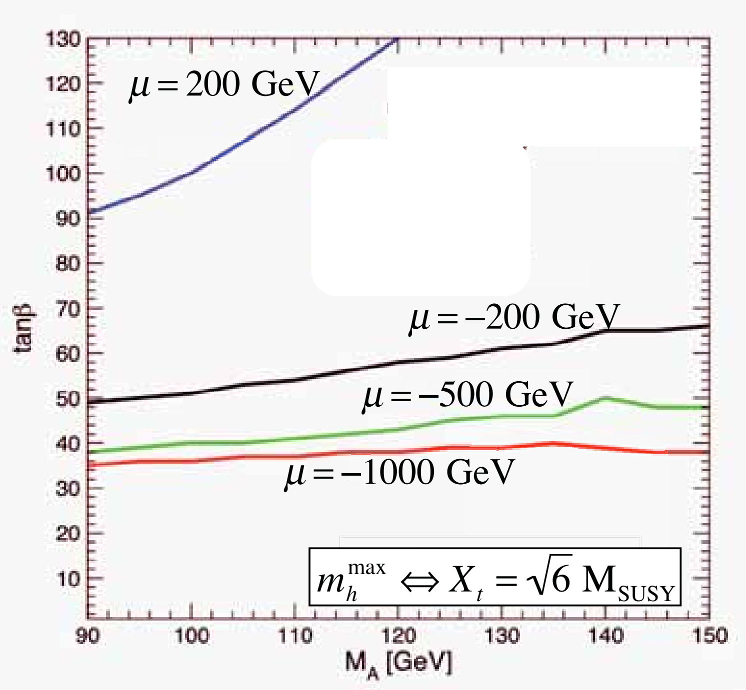
There is a strong dependence on the SUSY parameters in the bb search channel.
This dependence is much weaker in the tau-tau channel

Searches for Non-Standard Higgs bosons at the Tevatron

A) In the bb mode $p\bar{p} \to b\bar{b}\phi, \;\; \phi \to b\bar{b}$

==> probe large region of $\tan\beta - m_A$ plane

$\Rightarrow$ based on D0 $\to 260\text{pb}^{-1}$



- Enhanced reach for negative values of μ
- Strong dependence on SUSY parameters

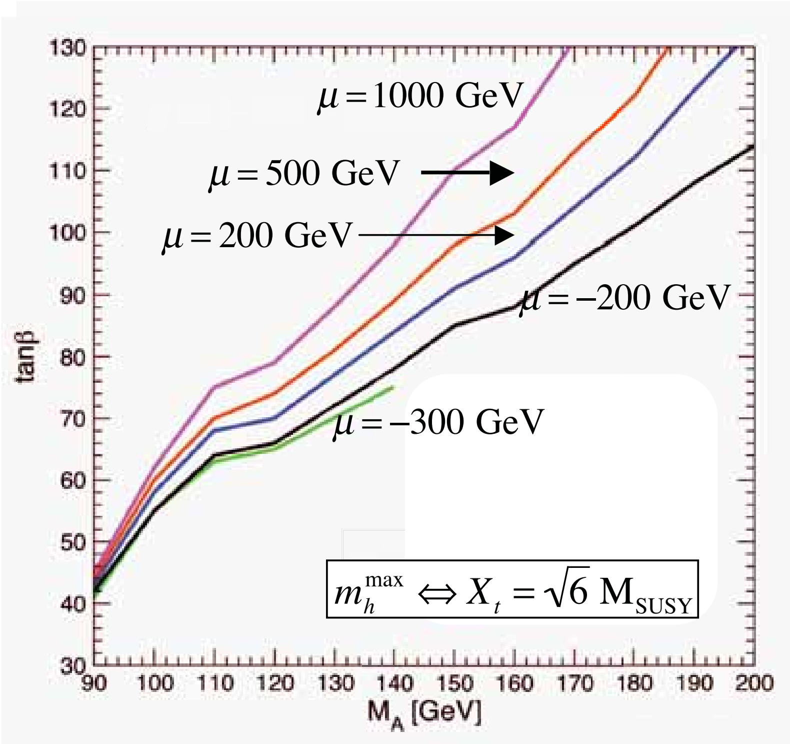
$$\sigma(b\bar{b}\phi) BR(\phi \to b\bar{b}) \propto 1/(1+\Delta_b)^2$$

$\Rightarrow$ enhanced for $\Delta_b < 0 \;\; \Leftrightarrow \mu < 0$ (if A_t and $M_{\tilde{g}} > 0$)

B) In the tau tau inclusive mode

$$p\bar{p} \to X\phi, \;\; \phi \to \tau^+\tau^-$$

$\Rightarrow$ based on CDF: 310pb^{-1}

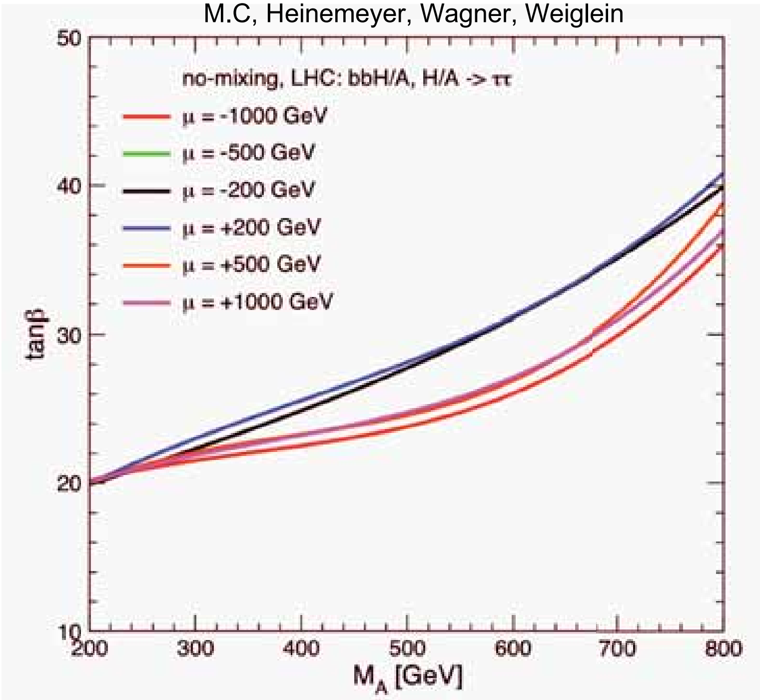


- Important reach for large tanb, small m_A
- Weaker dependence on SUSY parameters via radiative corrections

M. C., Heinemeyer, Wagner, Weiglein '05

Searches for Non-Standard Neutral Higgs bosons at the LHC

$pp \to A/H\,X,\ \ A/H \to \tau^+\tau^-,$ rescaling CMS prospects for 30 fb^{-1} (similar for ATLAS)

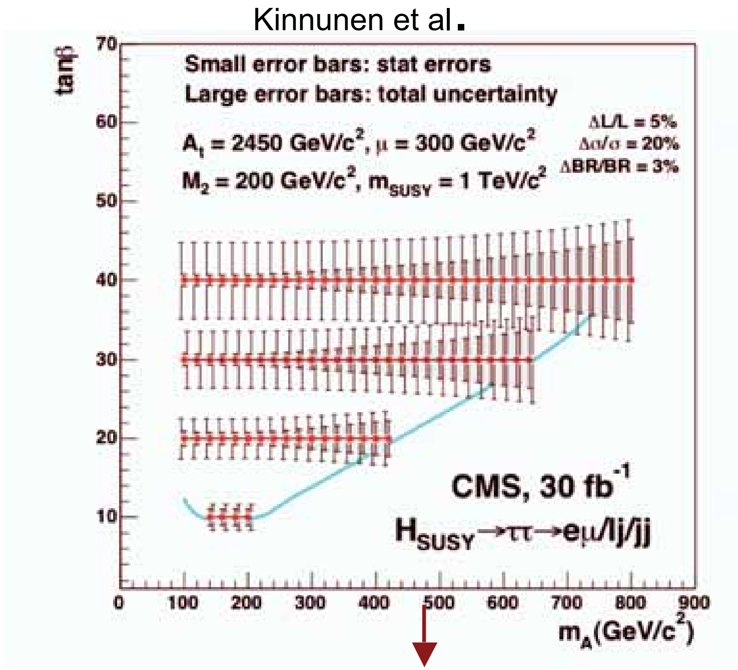


- Enhancement of Hbb and Abb couplings by factor $\tan\beta$ compared with SM Higgs.

  ==> large production cross section

  ==> decay dominated by $A/H \to \tau^+\tau^-$

  (with different decay modes of tau leptons)



Cancellation of Δ_b effects ==> projections stable under variations of SUSY space ==> $\Delta \tan\beta \approx 8$

main variation ==> $A/H \to \tilde{\chi}_i^0 \tilde{\chi}_j^0,\ \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$

Robustness of results under variations of SUSY space ==>handle on tan beta

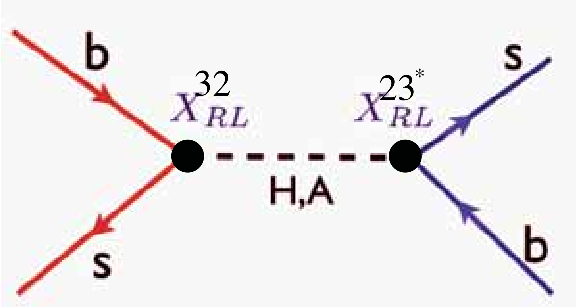
B and Higgs Physics at the Tevatron and the LHC

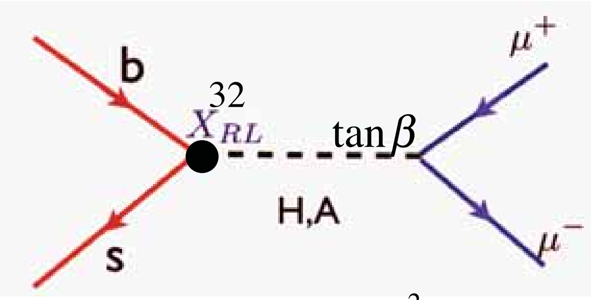
explore complementary regions of SUSY parameter space

Important Flavor Changing effects: 1) tree level ==> charged Higgs induced via V_{CKM}
2) tan beta enhanced loop corrections both in the neutral and charged Higgs sectors

- Loop-induced Higgs mediated FCNC in the down-quark sector

Correlation between Bs mixing and $\mathrm{BR}(B_S \to \mu^+\mu^-)$





$$\left(\Delta M_{B_S}\right)^{SUSY} \propto \ominus \frac{X_{RL}^{32} X_{LR}^{32}}{m_A^2}$$

Negative sign with respect to SM

$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto \frac{\left|X_{RL}^{32}\right|^2 \tan\beta^2}{m_A^4} \propto \frac{\left|\mu A_t\right|^2 \tan\beta^6}{m_A^4}$$

with $$\left(\mathrm{X}_{\mathrm{RL}}^{\mathrm{H/A}}\right)^{ji} \approx -\frac{\bar{m}_{d_j}\; h_t^2 \; \varepsilon_Y \; x_{\phi_1}^{H/A} \tan\beta^2}{\mathrm{v}\left(1+\varepsilon_0^{\mathrm{j}}\tan\beta\right)\left(1+\Delta_b\right)} \mathrm{V}_{\mathrm{CKM}}^{3\mathrm{j}^*} \mathrm{V}_{\mathrm{CKM}}^{3\mathrm{i}} \Longrightarrow \frac{\Delta M_{B_S}}{BR(B_S \to \mu^+\mu^-)} \propto \frac{m_A^2}{\tan\beta^2}$$

SUSY contributions strongly correlated

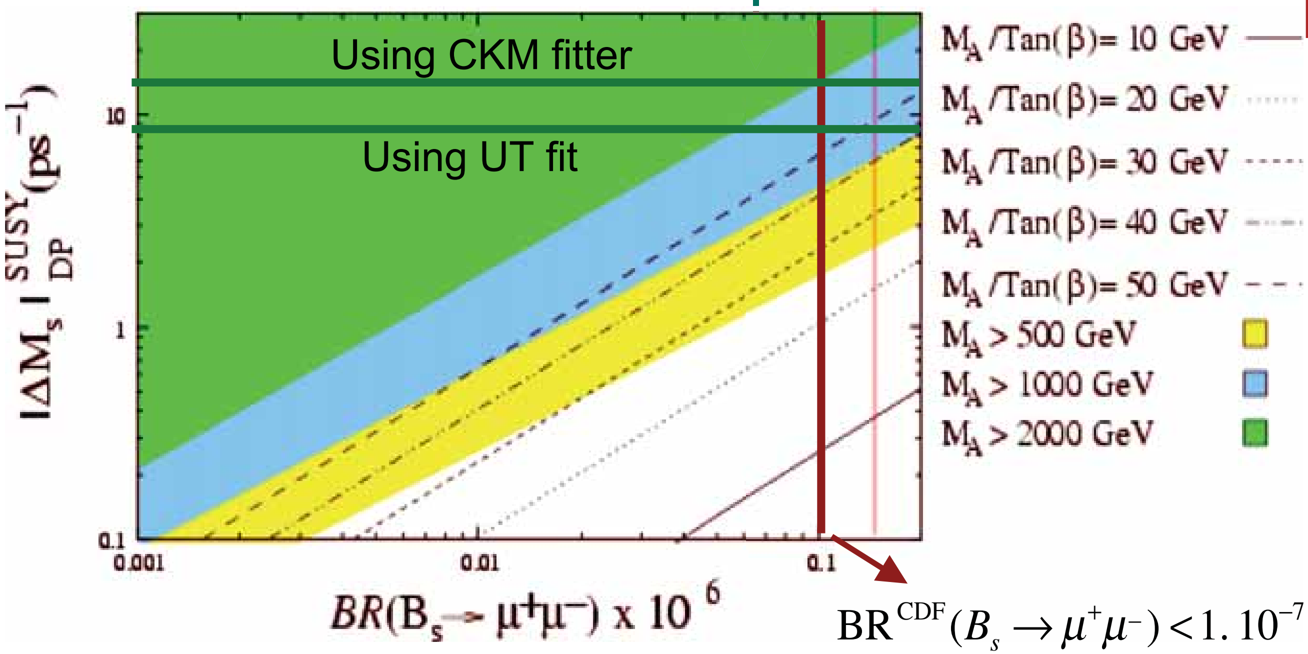
What can we learn from Bs-mixing?

How strong is the bound on $\mathrm{BR}(B_s \to \mu^+\mu-)$?

Upper bound on NP from CDF ==> $\Delta M_S = 17.7 \pm 0.10 \pm 0.07\, ps^{-1}$

$\Delta M_S^{CKM} = 18.9^{+12.2}_{-5.5}\, ps^{-1}$

$\Delta M_S^{UT} = 20.9 \pm 5.2\, ps^{-1}$



$\mathrm{BR}^{\mathrm{CDF}}(B_s \to \mu^+\mu^-) < 1.\, 10^{-7}$

M. C., Menon, Papaqui, Zsynkman, Wagner 06

$\mathrm{BR}(B_s \to \mu^+\mu-)_{SM}$ of order 10^{-9}

↓

at the reach of LHC with about $10 fb^{-1}$

↓

SUSY corrections can enhance it by 2 orders of magnitude.

For natural values of m_A< 1000 GeV ==> largest contributions at most a few ps-1

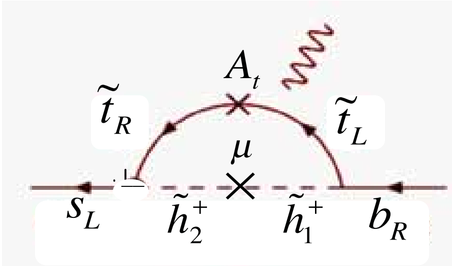
↕

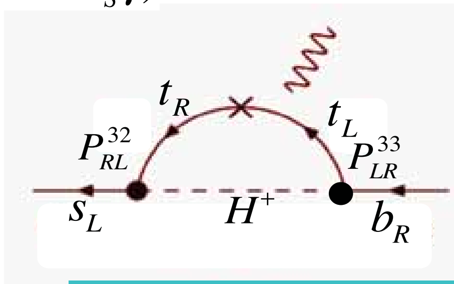
A/H at the reach of the Tevatron or the LHC <==> strong constraints on $|\Delta M_S|^{\mathrm{SUSY}}_{\mathrm{DP}}$

Similar to the neutral Higgs case ==> tanb enhanced SUSY loop corrections

Flavor Changing in the charged Higgs coupling:

- **Important SUSY contributions to** $BR(B \to X_S \gamma)$





$$\delta h_t \propto h_t \frac{2\alpha_S}{3\pi} \mu^* M_{\tilde{g}}$$

$$A_{\chi^+} \propto \frac{\mu A_t \tan\beta \, m_b}{(1+\Delta_b)} \, h_t^2 f[m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu] \, V_{ts}$$

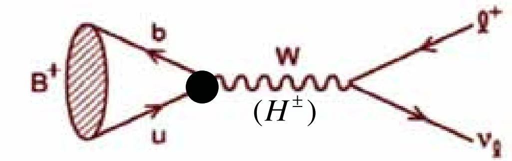
$$A_{H^+} \propto \frac{(h_t - \delta h_t \tan\beta) \, m_b}{(1+\Delta_b)} \, g[m_t, m_{H^+}] \, V_{ts}$$

If At ~0 + large $\mu M_{\tilde{g}} > 0$ ==> NO constraint on tanb-ma plane from $b \to s\gamma$

$$0.92 \le \ \mathrm{BR}(B \to X_S\gamma)^{MSSM} / \mathrm{BR}(B \to X_S\gamma)^{SM} \le \ 1.46 \qquad 2\sigma \text{ range}$$

Becher and Neubert '06

- $B_u \to \tau\nu$ **transition**



In the MSSM ==> charged Higgs contribution interferes destructively with SM one.

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

Belle + Babar averaged:

$$BR(B_u \to \tau\nu)^{\exp} = (1.31 \ \pm 0.48) \ 10^{-4}$$

$$\Rightarrow 0.32 \le R_{B_u \to \tau\nu} \le 2.77 \quad \text{at } 2\ \sigma$$

Interplay between Higgs and B physics searches in different SUSY scenarios

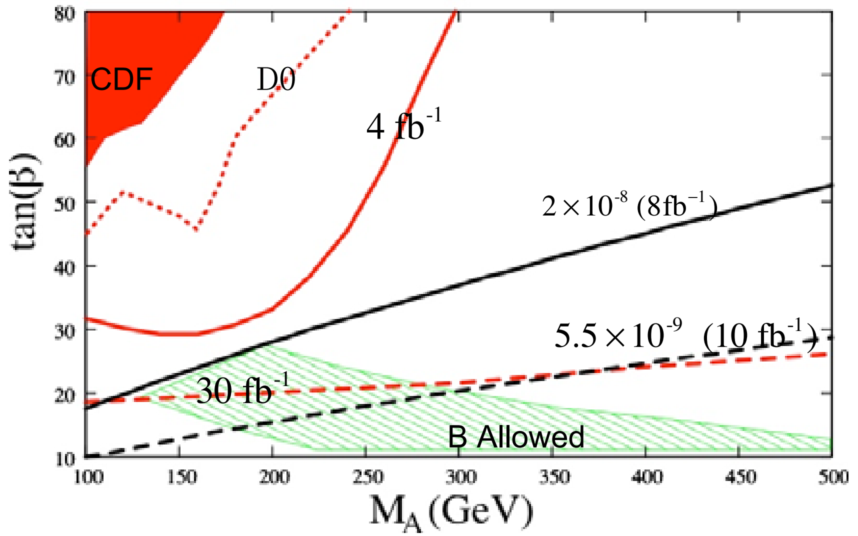
1) Non-SM-like Higgs and B-meson Searches

Large to moderate values of X_t ==> SM like Higgs heavier than 120 GeV

$BR(B_S \to \mu^+\mu^-) \propto |\mu A_t|^2 \Rightarrow$ Experimental bound ==> small μ

Small $\mu < 0$ ==> $\cong$ constant H^+ and enhanced negative $\chi^+ - \tilde{t}$ contributions to $BR(b \to s\gamma)$

M. C. et al. hep-ph/0603106 and in preparation



Red $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
-- 1 fb^{-1} (CDF and D0 excluded)
-- projected 4 fb^{-1} at the Tevatron
-- projected 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} ($10 fb^{-1}$)

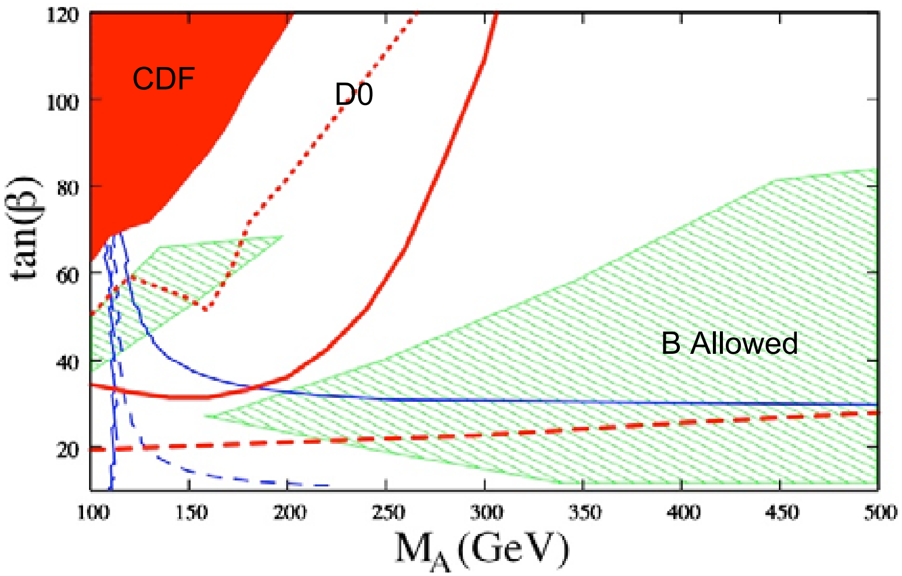
Hatched Area: Allowed regions by $BR(B_u \to \tau\nu)$, $BR(b \to s\gamma)$ and $BR(B_S \to \mu^+\mu^-)$

- Sizeable LR stop mixing <==> small/moderate mu

  ==> **B searches more powerful than Non-SM like Higgs searches**

- **Small X_t, sizeable μ ==> No mixing scenario**
  - Interesting region since light SM-like Higgs lighter than 125 GeV
  - **No constraints from** $\mathrm{BR}(B_s \to \mu^+\mu^-)$
  - Mild constraints from $\mathrm{BR}(b \to s\gamma)$ if large $\mu\, M_{\tilde{g}} > 0$
  - Important constraint from recent measurement of $\mathrm{BR}(B_u \to \tau\nu)$

M.C., Menon, Wagner



Red: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
-- 1 fb^{-1} (CDF and D0 excluded)
-- projected 4 fb^{-1} at the Tevatron
-- projected 30 fb^{-1} at the LHC

Green: Allowed by B physics constraints

Blue: LEP Excluded from Higgs searches

↓

Already strong bounds on SM-like Higgs from LEP

==> Non-SM like neutral Higgs searches can cover areas compatible with B physics constraints

Discovery reach for a SM-like MSSM Higgs at the Tevatron

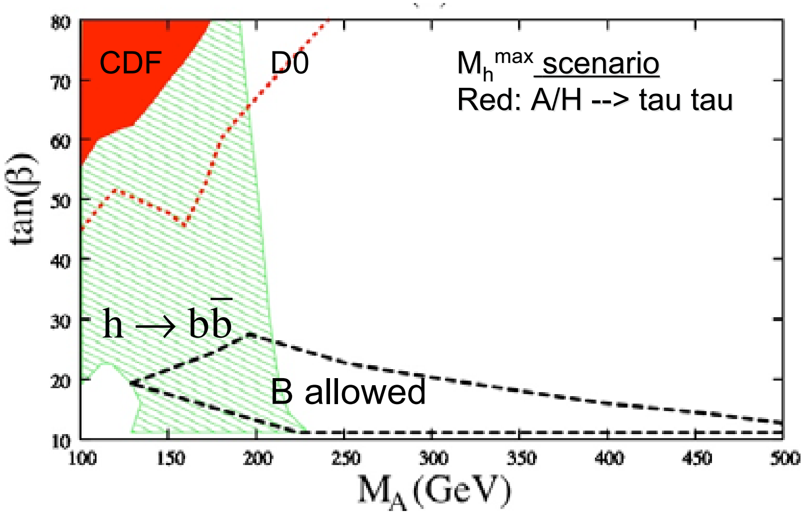
$p\bar{p} \to W/Z\, h$ with $h \to b\bar{b}$ with 4 fb^{-1}

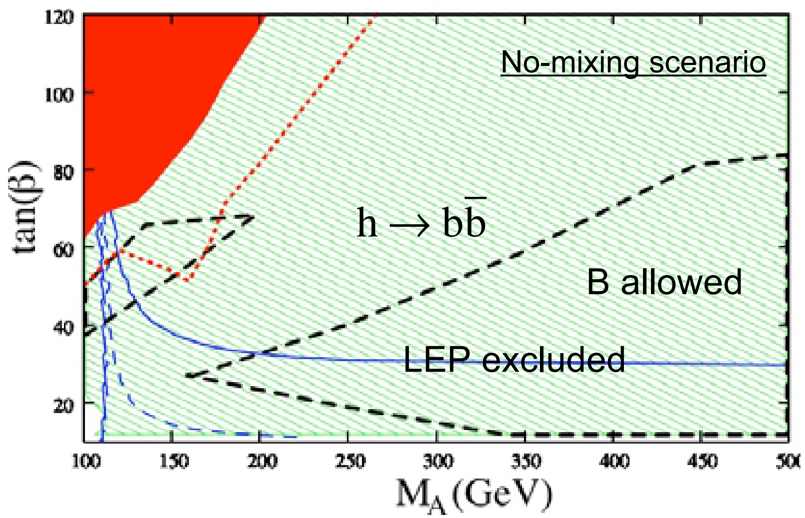
•The m_h^{max} scenario: $M_S = 1$ TeV ; $X_t = 2.4\, M_S$; $m_{\tilde{g}} = -0.8\, M_S$; $M_2 = -\mu = 200$GeV; $A_t = A_b$

-- Maximizes m_h and allows conservative tan beta bounds

-- $g_{hbb}, g_{h\tau\tau}$ enhanced due to $\sin\alpha_{eff}, / \cos\beta$ factor for low m_A and intermediate and large tan beta (analogous for H if $m_A < m_h^{max}$)

==> strong suppression of $h \to \gamma\gamma$





•The No-Mixing scenario: X_t=0 ==> lightest Higgs mass < 120 GeV

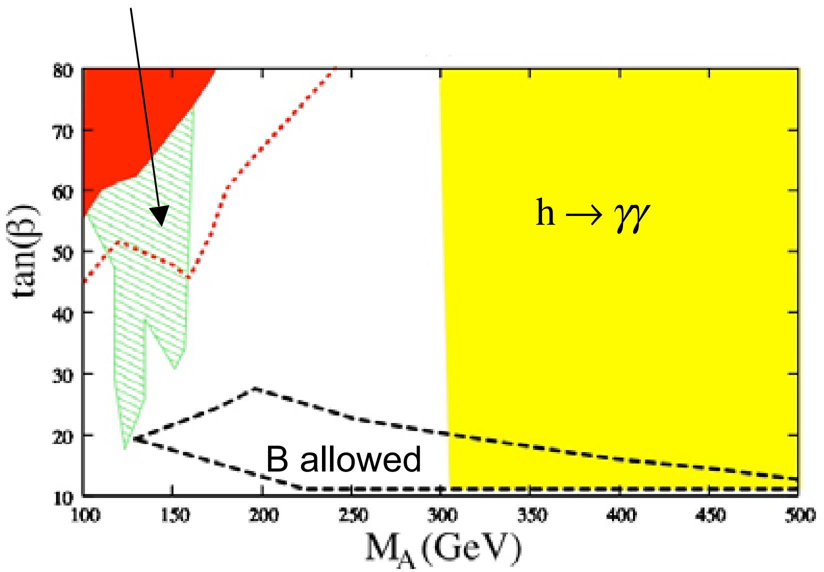
==> similar behavior for Higgs couplings to tau leptons, bottom quarks and photons. Tevatron may have sensitivity to discover all 3 MSSM neutral Higgs bosons

Discovery reach for SM-like MSSM Higgs at the LHC with 30 fb-1

•The m_h^{max} scenario: $M_S = 1$ TeV ; $X_t = 2.4\ M_S$; $m_{\tilde{g}} = 0.8\ M_S$; $M_2 = -\mu = 200$GeV; $A_t = A_b$

Production and decay channels: $t\bar{t}\,h\ (h \to b\bar{b})$; $q\bar{q}h \to q\bar{q}\ \tau^+\tau^-$ and $h \to \gamma\gamma$ inclusive

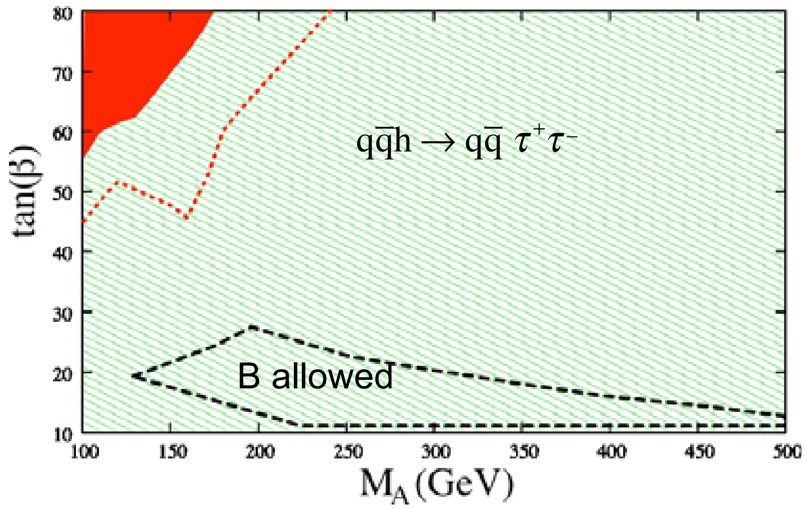
$q\bar{q}h \to q\bar{q}\ \tau^+\tau^-$ CMS Projections



First, full simulation analysis of qqH, H->ττ->l+jet,
Optimized Nikitenko, ICHEP 06

ATLAS Projections

re-evaluating Higgs studies at present



CMS can cover small part of B allowed region, with $h \to \gamma\gamma$ and $h \to \tau\tau$;

ATLAS tau tau channel seems to have full coverage with $h \to \tau\tau$

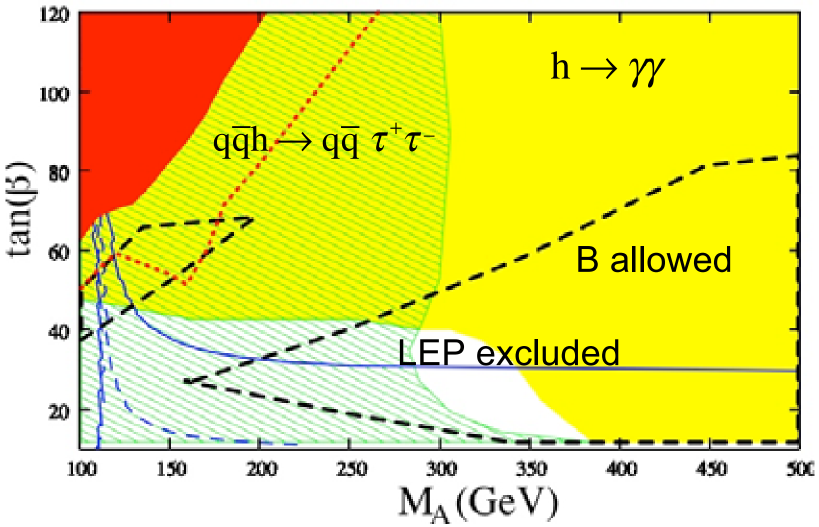
Discovery reach for SM-like MSSM Higgs at the LHC with 30 fb-1

- The No mixing scenario:

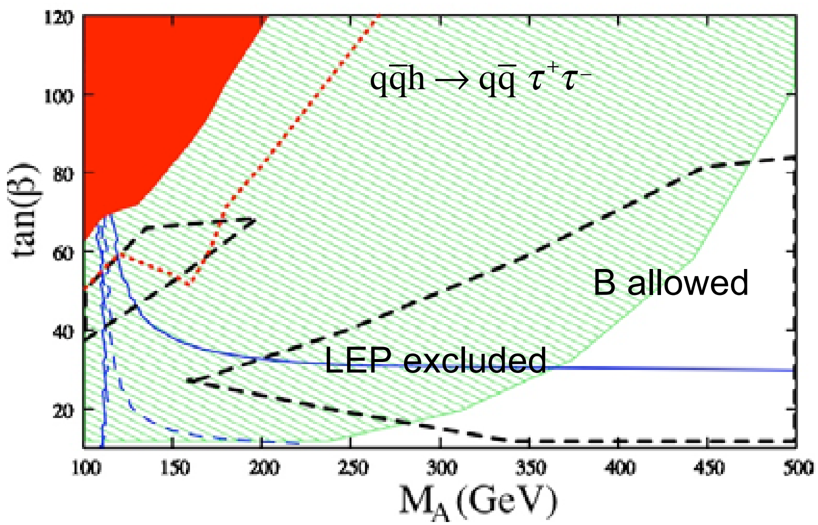
$$M_S = 1\ \text{TeV}\ ;\quad X_t = 0\ ;\ m_{\tilde g} = 0.8\ M_S\ ;\ M_2 = 200\text{GeV};\ A_t = A_b;\ \mu = 1.5\ \text{TeV}$$

Production and decay channels: $t\bar{t}\,h\ (h \to b\bar{b})$; $q\bar{q}h \to q\bar{q}\ \tau^+\tau^-$ and $h \to \gamma\gamma$ inclusive

CMS Projections



ATLAS Projections



SM-like Higgs needs di-tau and di-photon channels to secure discovery with 30fb^{-1}
some B allowed regions remain uncovered

Prospects for SM–like Higgs searches at Tevatron and LHC for:

- The small $\sin\alpha_{eff}$ (rad.correc. α) scenario:

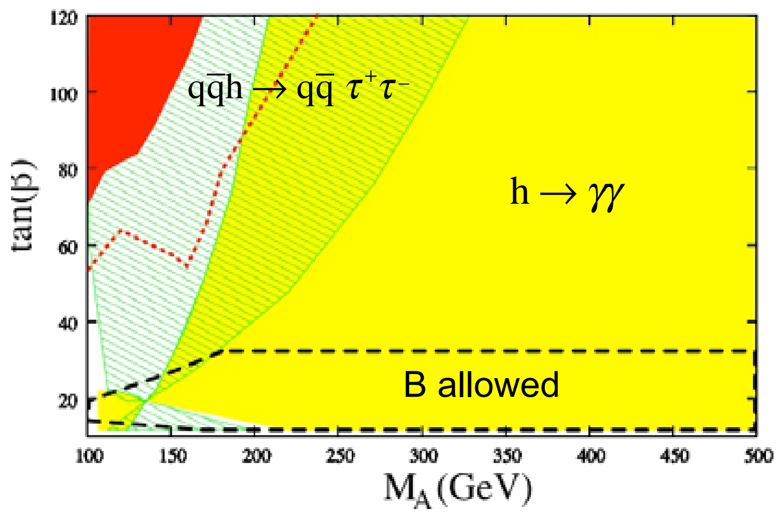
$$M_S = 800\ \text{GeV}\ ; \quad X_t = -1.2\ \text{TeV}\ ; \ \mu = 2.5\ M_s\ ; \ m_{\tilde{g}} = M_2 = 500\text{GeV}; \ A_t = A_b$$

==> $g_{hbb}, g_{h\tau\tau}$ importantly suppressed for large tan beta and small m_A, and in different ways due to Δ_b corrections

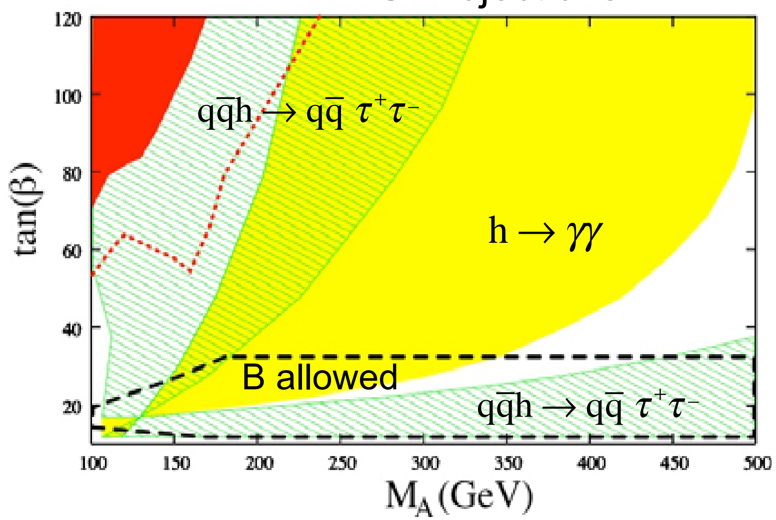
hence, $h \to \gamma\gamma$ channel enhanced with respect to SM

M.C., Menon. Wagner
In preparation

CMS Projections



ATLAS Projections



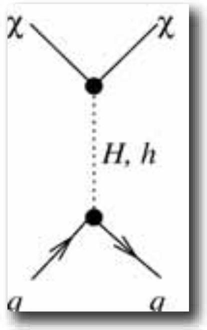
-- The Tevatron has almost no chance due to the suppressed hbb coupling
-- LHC: Complementarity in coverage
-- One can see a SM-like Higgs in the $\gamma\gamma$ channel and not in the $\tau^+\tau^-$ channell

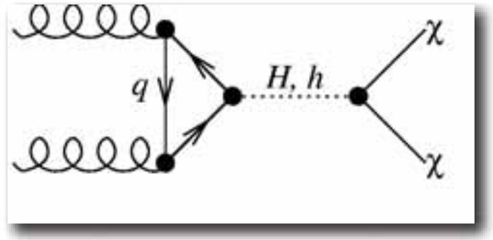
Direct DM searches Vs the Tevatron and LHC H/A searches

Direct DM experiments: CDMS, ZEPLIN, EDELWEISS, CRESST,WARP,…
sensitive mainly to spin-independent elastic scattering cross section $\longrightarrow \sigma_{SI} \leq 10^{-8}\, pb$

==> dominated by virtual exchange of H and h,
coupling to strange quarks and to gluons
via bottom loops

$\tan\beta$ enhanced couplings for H





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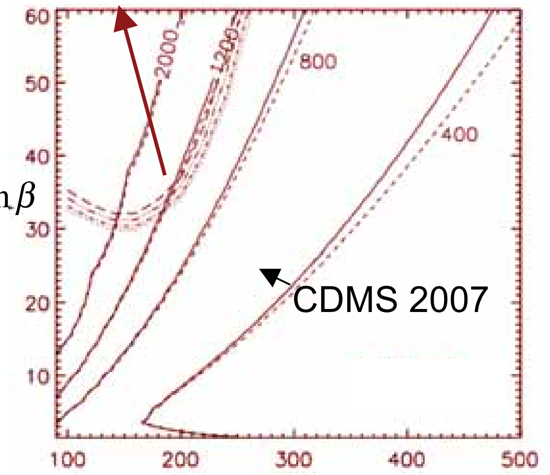
Both MSSM Higgs searches and neutralino direct DM searches depend on m_A and $\tan\beta$

H/A $\rightarrow \tau\tau$ at Tevatron 4 fb^{-1}

$\tan\beta$



m_A[GeV]

For $\mu = 400, 800, 1200, 2000$ GeV

Smaller μ values imply

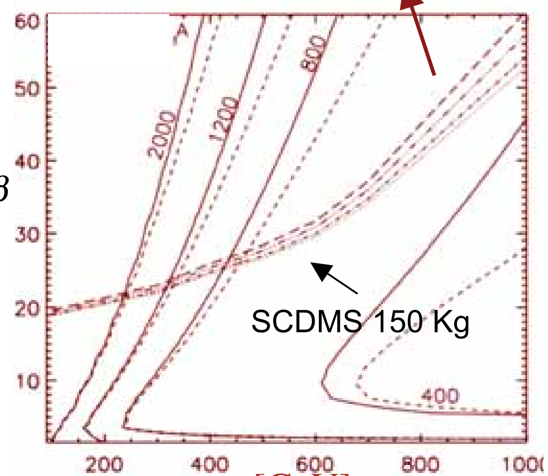
larger Higgsino component of the LSP

==> larger σ_{SI}

Direct detection of DM
<==> detection of A/H
at the Tevatron and LHC

H/A $\rightarrow \tau\tau$ at LHC 30 fb^{-1}

$\tan\beta$



m_A[GeV]

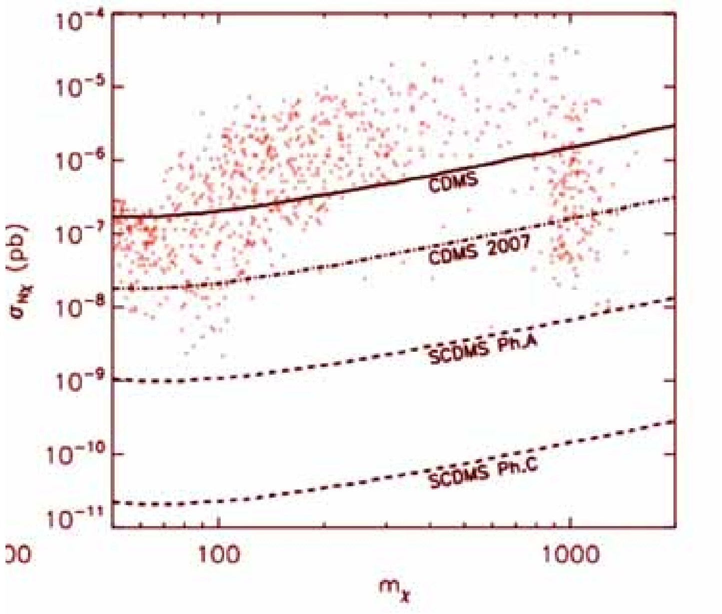
CDMS DM searches Vs the Tevatron and LHC H/A searches

•If the lightest neutralino makes up the DM of the universe

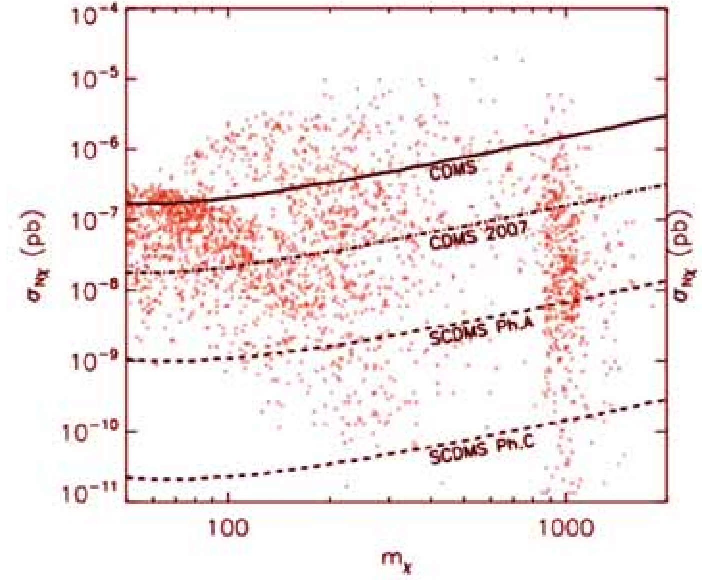
==> Evidence for H/A at the Tevatron (LHC) predict neutralino cross sections typically within the reach of present (future) direct DM detection experiments.

(strong μ dependence)

Tevatron reach



LHC reach



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Conclusions

- SUSY SM-like Higgs ==> strong variation in the discovery reach depending on SUSY parameter space via radiative corrections

  Complementarity of channels important for early Higgs discovery

- Other MSSM Higgs bosons ==> Need sizeable $\tan\beta$ enhancement for discovery

  $A/H \to \tau^+\tau^-$ and $\mathrm{H}^\pm \to \tau\nu \to$ robust results under variation of SUSY space

  ↓

  moderate sensitivity to tan beta

- The Non-Standard MSSM Higgs searches at the LHC can be strongly constrained by B physics measurements depending on the SUSY parameter space.

- **Tevatron results will yield important information for the LHC** and may help to understand the type of Supersymmetry that may be realized in nature

Supersymmetry is a leading candidate for a theory beyond the Standard Model

==> it opens the possibility of a more complex Higgs structure and connects Higgs physics with Flavor physics and Cosmology

EXTRAS

The flavor problem in SUSY Theories

SUSY breaking mechanisms ==> can give rise to large FCNC effects

- Novel sfermion-gaugino-fermion interactions, e.g. for the down sector

$$\bar{d}^i_{L,R}\ \tilde{\lambda}\ \tilde{d}^j_{L,R} \rightarrow \bar{d}_{L,R} D^+_{L,R} \tilde{D}_{L,R} \tilde{\lambda}\ \tilde{d}_{L,R}$$

recall $V_{CKM} = U^+_L D_L$

where $\tilde{D}_{L,R}$ come from the block diagonalization of the squark mass matrix

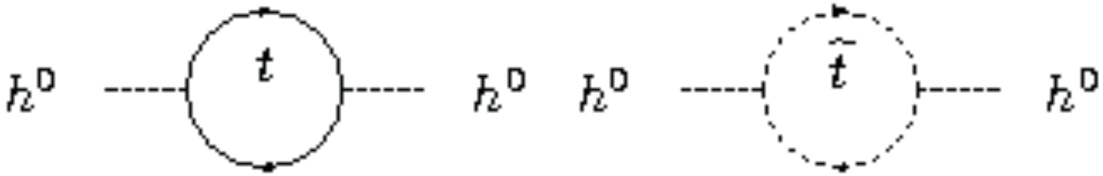
$$\begin{pmatrix} \tilde{d}^{i\,*}_L & \tilde{d}^{i\,*}_R \end{pmatrix} \begin{pmatrix} M^2_Q + \mathrm{v}_1^2 \hat{h}^+_d \hat{h}_d + D_{\tilde{d}_L} & \mathrm{v}_1 \left(A^*_d - \mu \tan\beta \right) \hat{h}^+_d \\ \mathrm{v}_1 \hat{h}_d \left(A_d - \mu^* \tan\beta \right) & M^2_D + \mathrm{v}_1^2 \hat{h}_d \hat{h}^+_d + D_{\tilde{d}_R} \end{pmatrix} \begin{pmatrix} \tilde{d}^i_L \\ \tilde{d}^i_R \end{pmatrix}$$

- The diagonal entries are 3x3 matrices with M^2_Q, M^2_D the soft SUSY breaking mass matrices and the rest proportional to the Yukawa or I
- The off-diagonal matrices are proportional to the Yukawa and to the soft SUSY breaking matrices A_d coming from the trilinear interactions of the Higgs doublets with the sfermions

$$\tilde{u}^*_L \left(A^*_u \phi_2 - \mu \phi_1 \right) \hat{h}^+_u \tilde{u}_R + \tilde{d}^*_L \left(A^*_d \phi_1 - \mu \phi_2 \right) \hat{h}^+_d \tilde{d}_R + h.c.$$

Radiative Corrections to Higgs Boson Masses

Important quantum corrections due to incomplete cancellation of particles and superparticles in the loops



Main effects: stops;
and sbottoms at large tan beta

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2\, M_W^2} \left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12\, M_S^2} \right) \right] + \text{h.o.}$$

$$M_S^2 = \tfrac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) \text{ and } X_t = A_t - \mu/\tan\beta \longrightarrow \text{stop mixing}$$

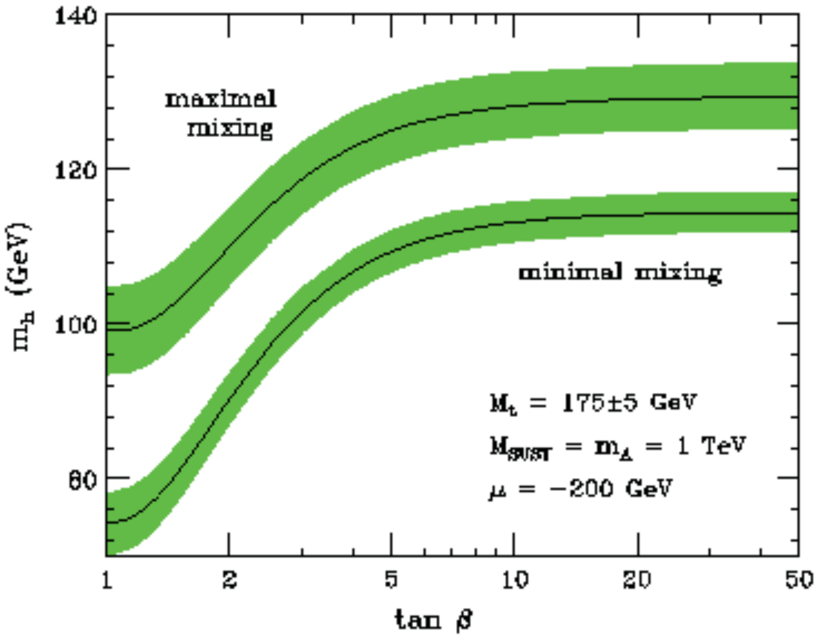
- m_t^4 **enhancement**
- **log sensitivity to stop masses** M_S
- **depend. on stop mass mixing** X_t

After 2 -loop corrections

$$m_h \leq 135\text{GeV}$$

stringent test of the MSSM

$$M_S = 1 \rightarrow 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2 - 5 \text{ GeV}$$
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$



Looking at $V_{CKM} \cong I \Rightarrow$ Flavor Conserving Higgs-fermion couplings

$$-L_{eff} = \frac{1}{v_2}\left(\tan\beta\,\Phi_1^{0^*} - \Phi_2^{0^*}\right)\bar{b}_R M_b \frac{1}{R^{33}} b_L + \frac{1}{v_2}\Phi_2^{0^*}\bar{b}_R M_d b_L + h.c.$$

$$R^{33} = 1 + \left(\varepsilon_0^3 + \varepsilon_Y h_t^2\right)\tan\beta \equiv 1 + \Delta_b$$

In terms of h,H and A:

$$\phi_1^0 = -\sin\alpha\, h + \cos\alpha\, H + i\,\sin\beta\;\; A$$
$$\phi_2^0 = \cos\alpha\, h + \sin\alpha\, H\; - \; i\,\cos\beta\;\; A$$

Hence:

$$g_{hbb} \approx \frac{-m_b \sin\alpha}{(1+\Delta_b)\ v\ \cos\beta}\left(1 - \Delta_b / \tan\alpha \tan\beta\right)$$

$$g_{Hbb} \approx \frac{m_b \cos\alpha}{(1+\Delta_b)\ v\ \cos\beta}\left(1 - \Delta_b \tan\alpha / \tan\beta\right)$$

$$g_{Abb} \approx \frac{m_b \tan\beta}{(1+\Delta_b) v}$$

M.C. Mrenna, Wagner

destroy basic relation

$g_{h,H,Abb} / g_{h,H,A\,\tau\tau} \propto m_b / m_\tau$

At large $\tan\beta \Rightarrow g_{Hbb} \approx g_{Abb}$

- strong suppression of coupling of h (H) to bottoms if
  $\tan\alpha \simeq \Delta_b / \tan\beta \quad \longrightarrow g_{h\,b\bar{b}} \simeq 0 \;\; ; \; g_{h\,\tau\tau} \simeq -\frac{m_\tau}{v}\Delta_b$ (similar for H)

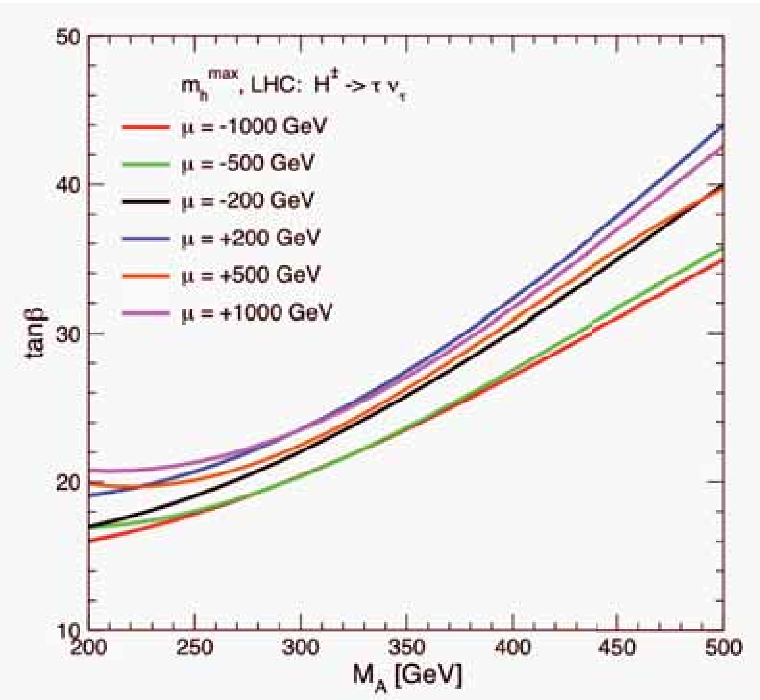
$\Longrightarrow$ main decay modes of SM-like MSSM Higgs: $b\bar{b} \sim 80\%$ $\quad \tau^+\tau^- \sim 7-8\%$
drastically changed $\Longrightarrow$ other decay modes enhanced

Charged Higgs searches at the LHC

- Similarly to the neutral Higgs case, there are tan beta enhanced loop corrections which depend on SUSY parameters

For $m_{H^\pm} > m_t + m_b$ expect $H^\pm \to tb$ decay, however

$$\sigma(gb \to H^\pm t) \times BR(H^\pm \to \tau\nu) \propto \frac{\tan\beta^2}{(1+\Delta_b)^2} \frac{(1+\Delta_b)^2}{(1+\Delta_b)^2 + 9\left(1 - m_t^2/m_{H^\pm}^2\right)^2}$$



Much more robust under radiative corrections

$$\Delta \tan\beta \leq 10$$

Including variation due to charged Higgs decay into SUSY particles for small mu

M.C., Heinemeyer, Wagner, Weiglein

B and Higgs Physics at the Tevatron and the LHC

explore complementary regions of SUSY parameter space

Important Flavor Changing effects: 1) tree level ==> charged Higgs induced via 2) tan beta enhanced loop corrections both in the neutral and charged Higgs sectors

==> model dependent ==> assume Minimal Flavor Violation

- Loop-induced Higgs mediated FCNC in the down-quark sector

$$-L_{FCNC} = \overline{d}_R^{\,j} \left(X_{RL}^S\right)^{ji} d_L^i \; \phi_S + h.c. \qquad \text{with } i \neq j \quad \phi_S = h, H, A$$

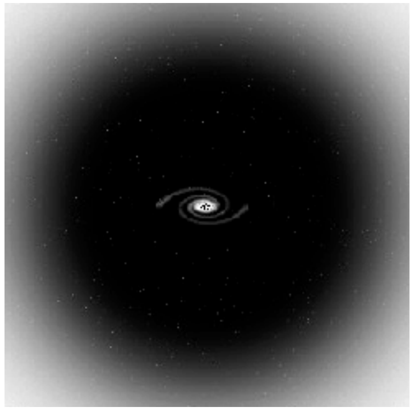
$$\text{and} \quad \left(X_{RL}^S\right)^{ji} = \frac{\overline{m}_{d\,j}\, h_t^2\, \varepsilon_Y \left(x_2^S - x_1^S \tan\beta\right)\tan\beta}{v\left(1+\varepsilon_0^j \tan\beta\right)\left(1+\Delta_b\right)} V_{CKM}^{3j^*} V_{CKM}^{3i}$$

Example: case of universal soft SUSY squark mass parameters

x_1^S, x_2^S are the components of the h, H and A in ϕ_1^0, ϕ_2^0

==> $\tan\beta^2$ enhanced coupling for H/A or h/A, depending on value of m_A

Indirect searches for MSSM Higgs bosons via direct Dark Matter experiments



Dark Matter: one of the fundamental open questions
==> demands new physics

• **Most suitable candidates beyond the Standard Model**:

==> Weakly interacting particles (WIMPS) with masses and interaction cross sections of order of the electroweak scale

SUSY with R-parity discrete symmetry conserved $R_P = (-1)^{3B+L+2S}$

==> naturally provides a neutral stable DM candidate: LSP ==> $\tilde{\chi}^0$

$\Omega_{CDM} \sim 1 / \int_0^{x_F} \langle \sigma_A v \rangle \, dx \qquad x \equiv \frac{M}{T}$

$0.089 < \Omega_{CDM} h^2 < 0.131$ WMAP at 3 σ

Many processes contribute to the $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ annihilation cross section: $\langle \sigma_A v \rangle$

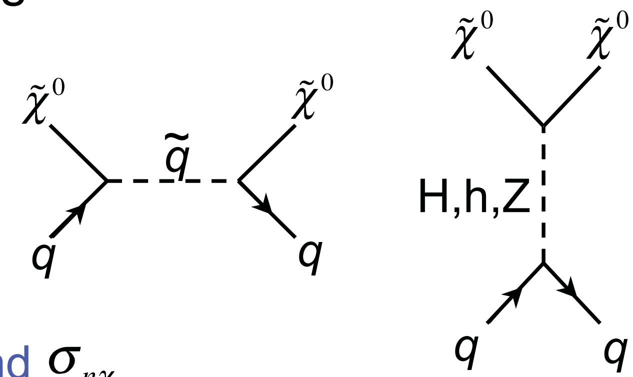
• **Collider experiments will find evidence of DM through $\not{E}_T$ signature**

knowledge of new physics particle masses and couplings will allow to compute DM-annihilation cross sections and elastic scattering WIMP -proton cross sections

But only Direct Detection Experiments will confirm the existence of Dark Matter particles

Direct Detection of WIMPs

- WIMPs elastically scatter off nuclei in targets, producing nuclear recoils with $\sigma_{n\chi} \Rightarrow$



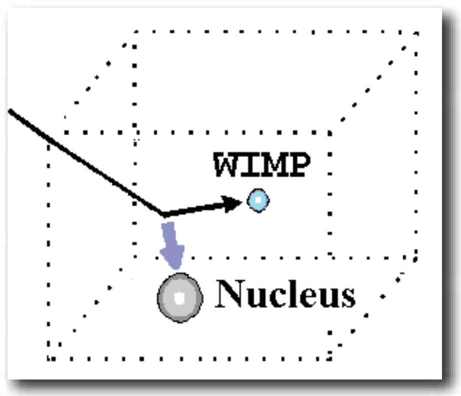
Main Ingredients to calculate signal:
Local density & velocity distribution of WIMPs and $\sigma_{n\chi}$
==> rate per unit time, per unit detector material mass

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

$\langle \sigma_{i\chi} \rangle$ → Scattering Cross section off nuclei averaged over relative wimp velocity

N_i → Number of target nuclei in the detector prop.to Detector mass/Atomic mass

η_χ → local WIMP density



<u>Direct detection has two big uncertainties</u>:

- The local halo density, inferred by fitting to models of galactic halo: assumed ==> $\eta_\chi \approx 0.3$ GeV / cm^3
- The galactic rotation velocity ≈ (230 +- 20) km/sec

Conclusions (continued)

- **The Non-Standard MSSM Higgs searches at the Tevatron and the LHC can be strongly constrained by B physics measurements depending on the SUSY parameter space.**

-- sizeable LR stop mixing <==> small/moderate mu ==> B searches more powerful

-- small stop mixing (Xt≈0) and large Higgsino mass parameter μ
==> good for the Tevatron ==> has sensitivity to discover all 3 MSSM neutral Higgs bosons

-- increasing the stop mixing for sizeable mu
==> Tevatron A/H searches become marginal, but excellent window of opportunity for LHC

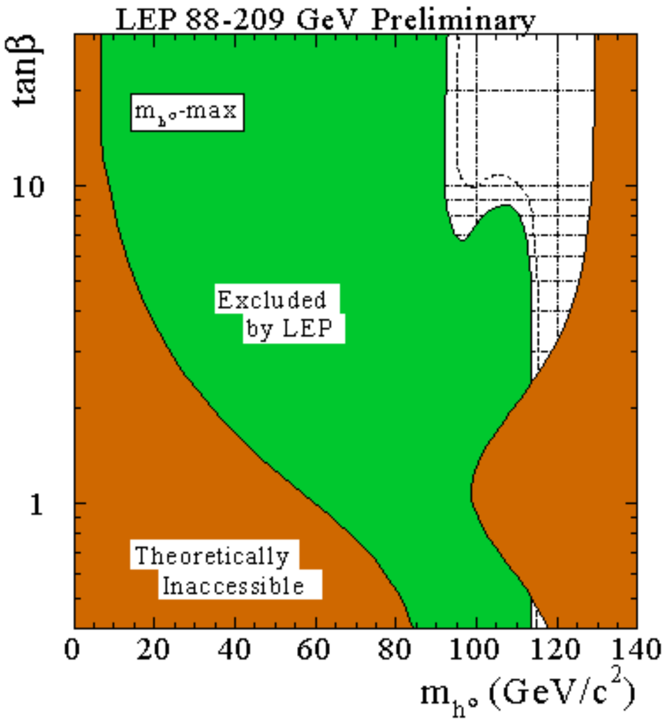
- **Tevatron results will yield important information for the LHC**

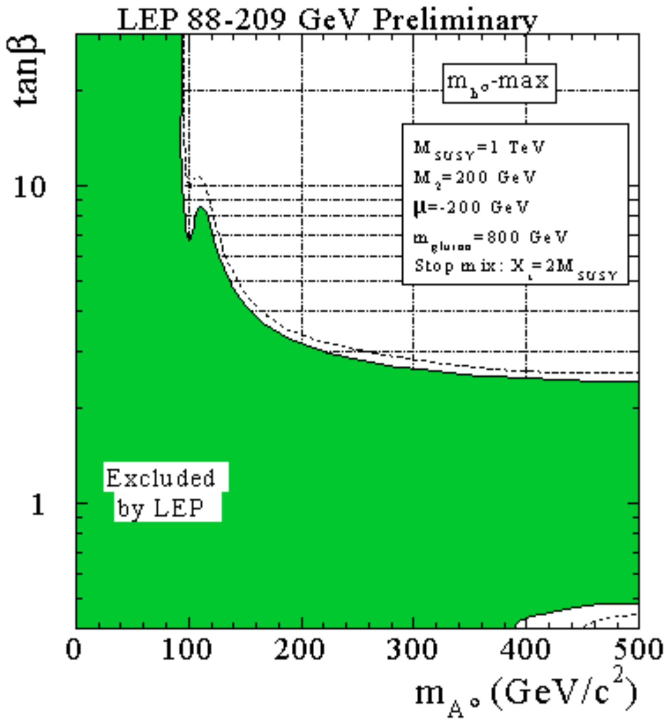
-- Non-observation of $B_s \to \mu^+\mu^-$ at the Tevatron ==> reduced parameter space for non-Standard MSSM Higgs searches at the LHC, specially for large X_t and $\mu < 0$

-- Discovery of H/A at the Tevatron, without positive results from leptonic rare Bs decay ==> small X_t an large μ or Deviations from MFV

$$e^+e^- \xrightarrow{Z^*} hZ, HZ, Ah, AH$$

main decay mode $h \to b\bar{b}$





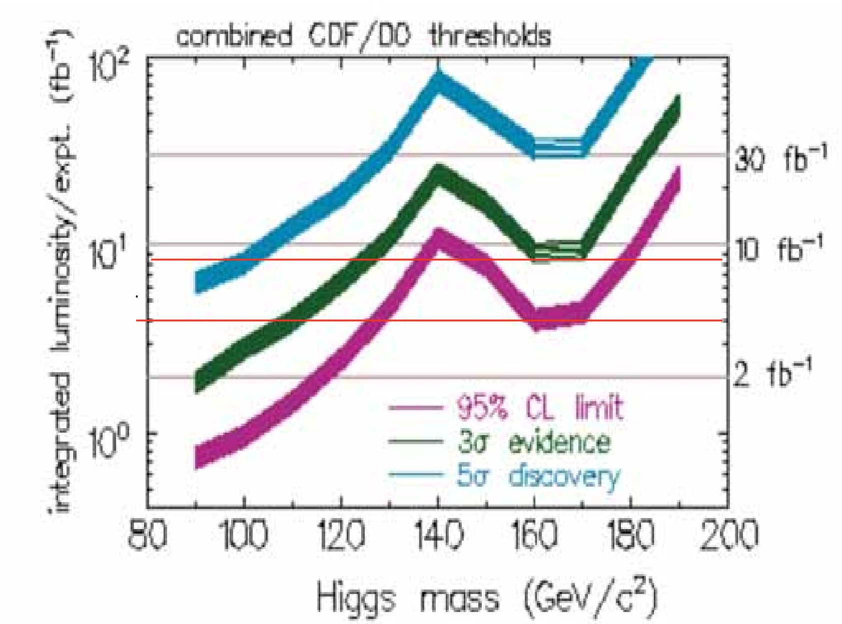
$$m_h > 91.0 GeV; m_A > 91.9 GeV$$

$$m_{H^\pm} > 78.6 GeV$$

$$m_h > 114.6 GeV$$

•**Tevatron can search for a Higgs in parts of the mass range preferred by precision data**

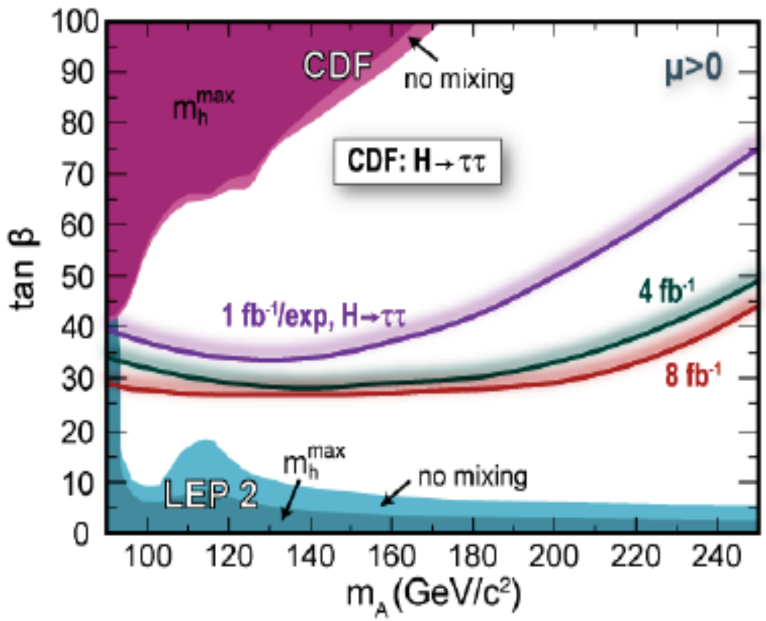
$p\bar{p} \to V\,H \to Vb\bar{b} \quad \text{with } V = W, Z$



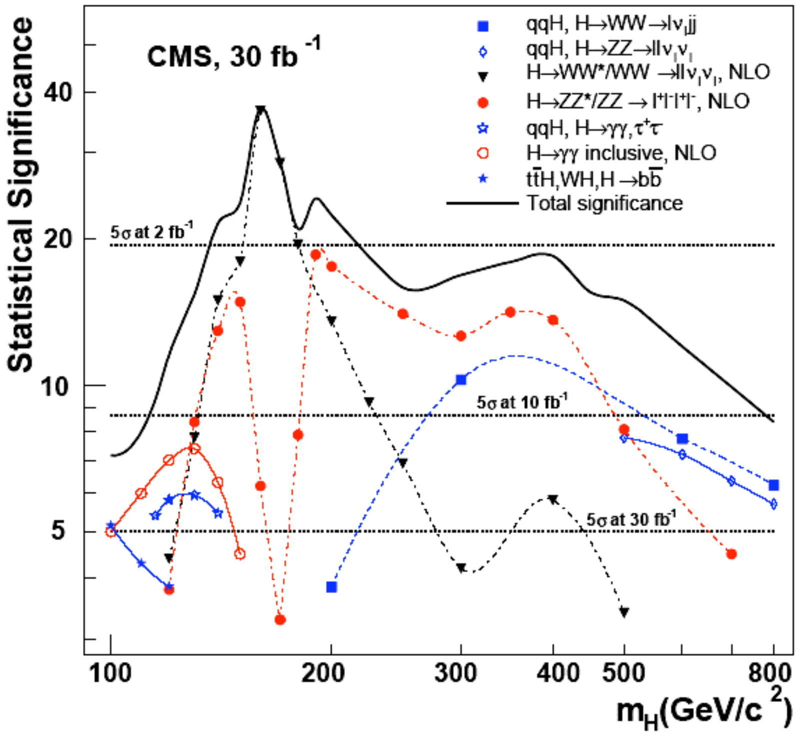
Quite challenging! Evidence of a signal will mean that the Higgs has strong (SM-like) couplings to W and Z

Heavy neutral MSSM Higgs searches

- $pp \to Ab+X \to bbb+X$
- $pp \to A+X \to \tau\tau + X$

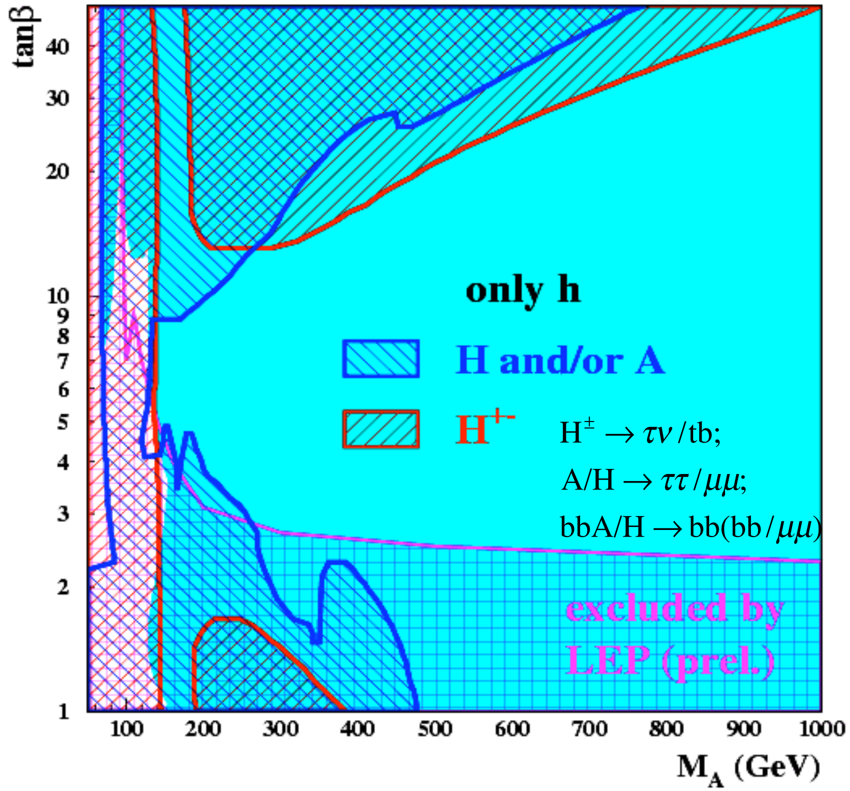


- LHC can search for a Higgs via many channels, already in the first few years

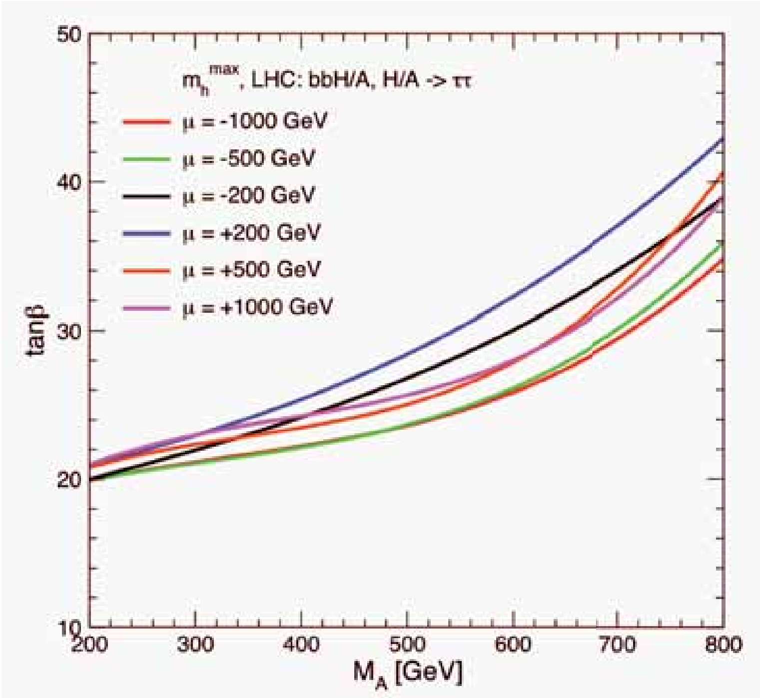


- Many SUSY Higgs production and decay processes accessible with full LHC potential

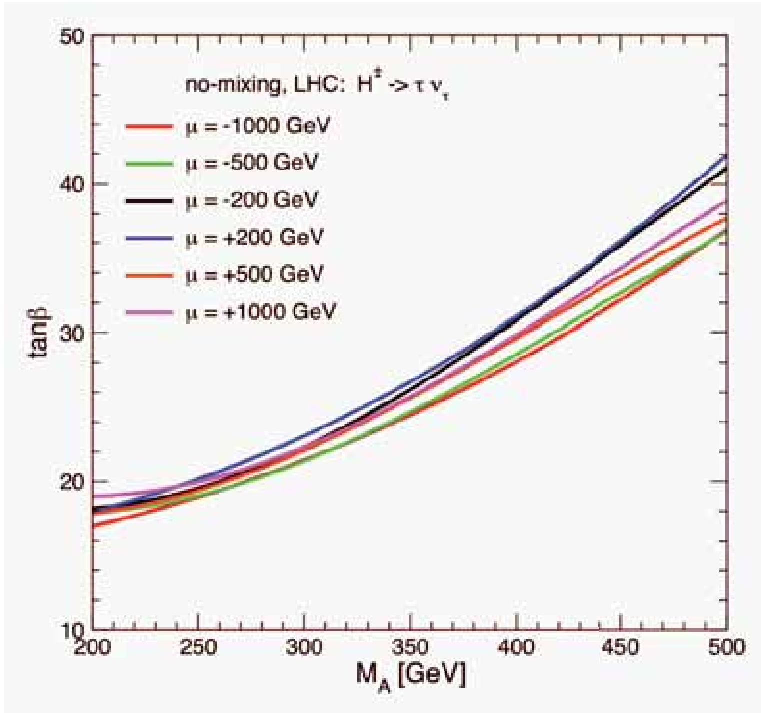
ATLAS and CMS with 300fb^{-1}



Still regions where only a SM-like Higgs is visible

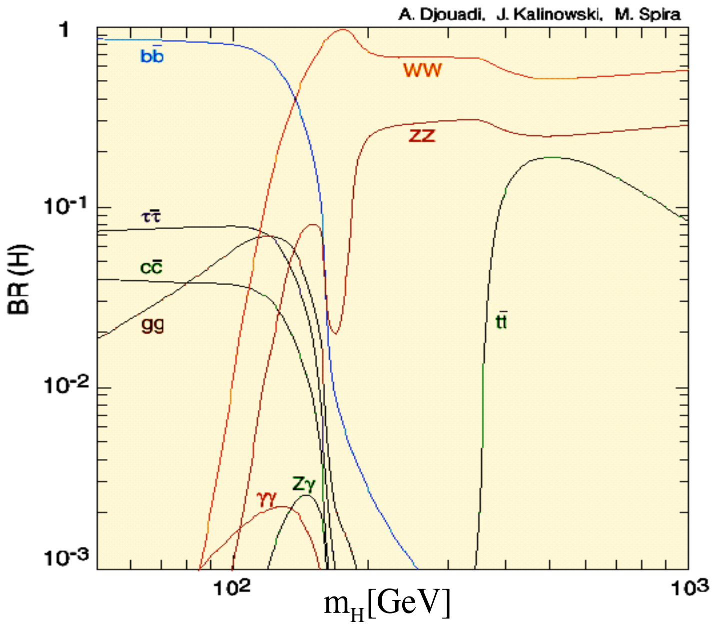


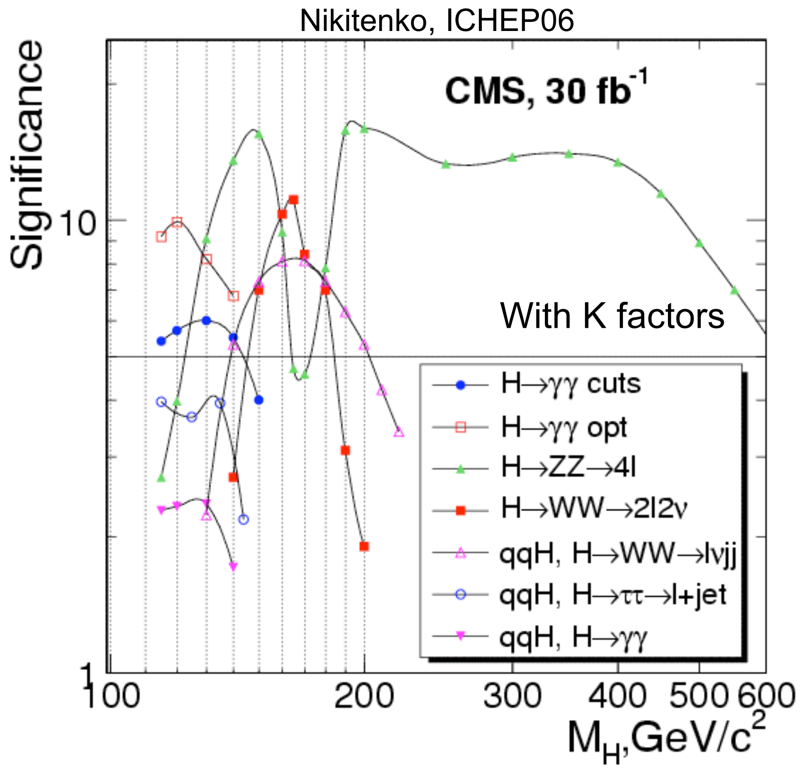
m_h^{max}, LHC: bbH/A, H/A -> ττ
μ = -1000 GeV
μ = -500 GeV
μ = -200 GeV
μ = +200 GeV
μ = +500 GeV
μ = +1000 GeV
tanβ
M_A [GeV]



no-mixing, LHC: $H^{\pm}$ -> τ ν_τ
μ = -1000 GeV
μ = -500 GeV
μ = -200 GeV
μ = +200 GeV
μ = +500 GeV
μ = +1000 GeV
tanβ
M_A [GeV]

Search Channels for the SM Higgs at the LHC



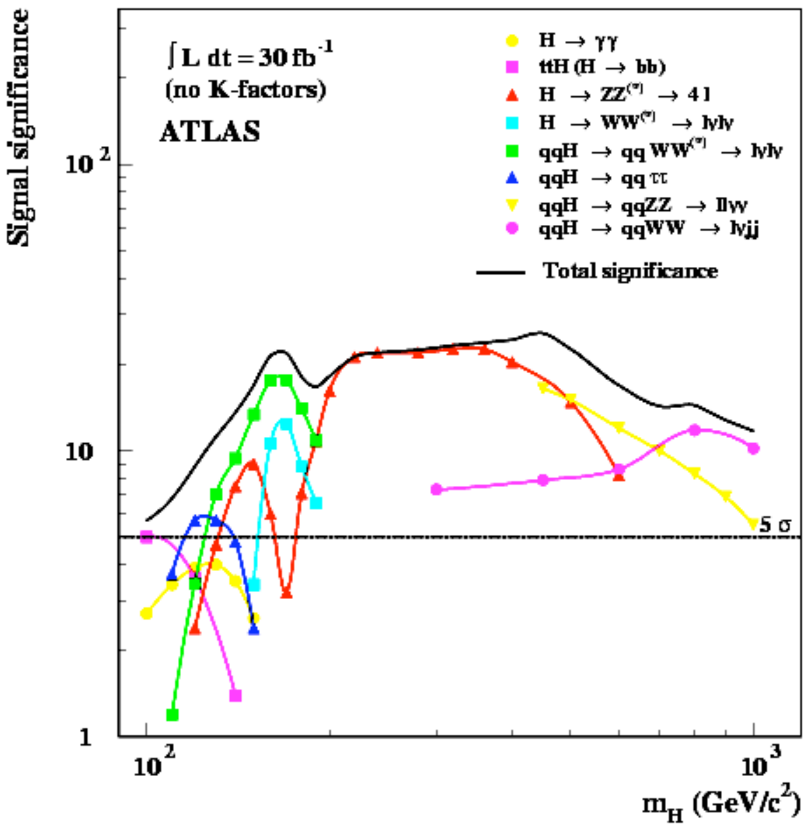


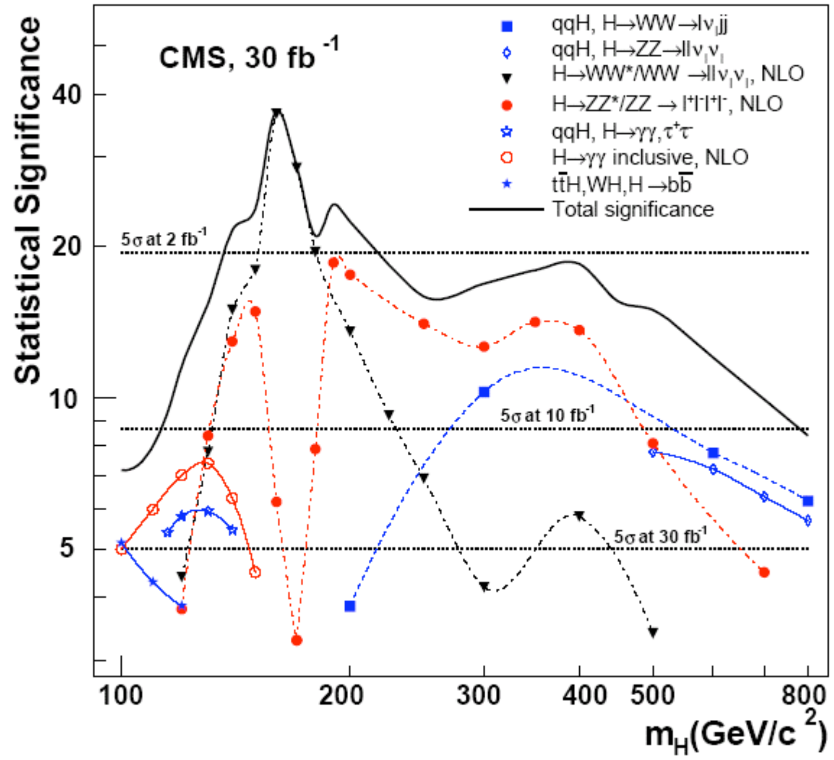
- **Low mass range** m_H < 200 GeV

Production / DECAY	Inclusive	VBF	WH/ZH	ttH
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$			YES	YES
$H \rightarrow \tau\tau$		YES		
$H \rightarrow WW^*$	YES	YES	YES	
$H \rightarrow ZZ^*$, $Z \rightarrow l^+l^-$	YES			

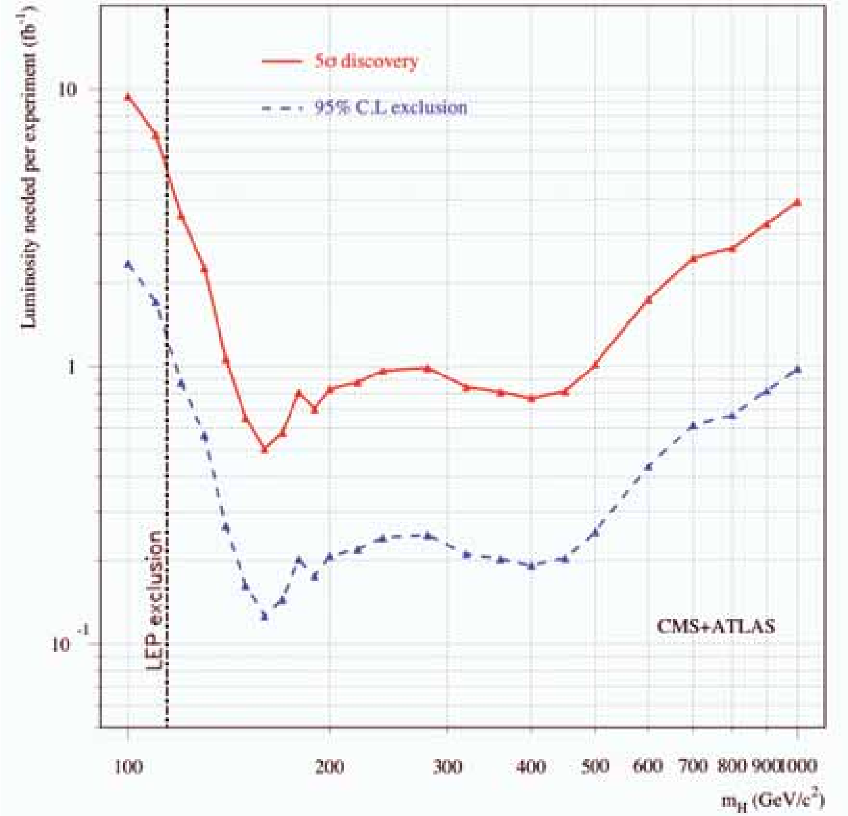
- **Intermediate mass range**
  200 GeV < m_H< 700 GeV
  Inclusive H ==>ZZ-->4l

- **Large mass range**: m_H> 700 GeV
  VBF with H ==>WW==>lv jj
  ZZ ==>ll vv


∫L dt = 30 fb-1
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
qqH → qq WW(*) → lνlν
qqH → qq ττ
qqH → qqZZ → llνν
qqH → qqWW → lνjj
Total significance
5 σ
Signal significance
mH (GeV/c2)


CMS, 30 fb-1
qqH, H→WW→lνjj
qqH, H→ZZ→llνν
H→WW*/WW →llνν, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ,τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H→bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
Statistical Significance
mH(GeV/c2)

The LHC potential



Total sensitivity combining all channels plus two experiments

5 σ discovery possible over the entire SM Higgs mass range of interest with 5 fb-1 (?)

==> For m_H~120 GeV combination of many different channels necessary, hence, requires a good understanding of the detectors.

==> The Tevatron may explore such region

Higgs mass resolution: 0.1 to 1%, combining most channels for 300 fb-1 and both experiments, using H-->ZZ--> 4l or H-->gamma gamma

Total Width resolution: 5-8 % for m_H > 300 GeV, ATLAS 300 fb-1, H-->ZZ--> 4l