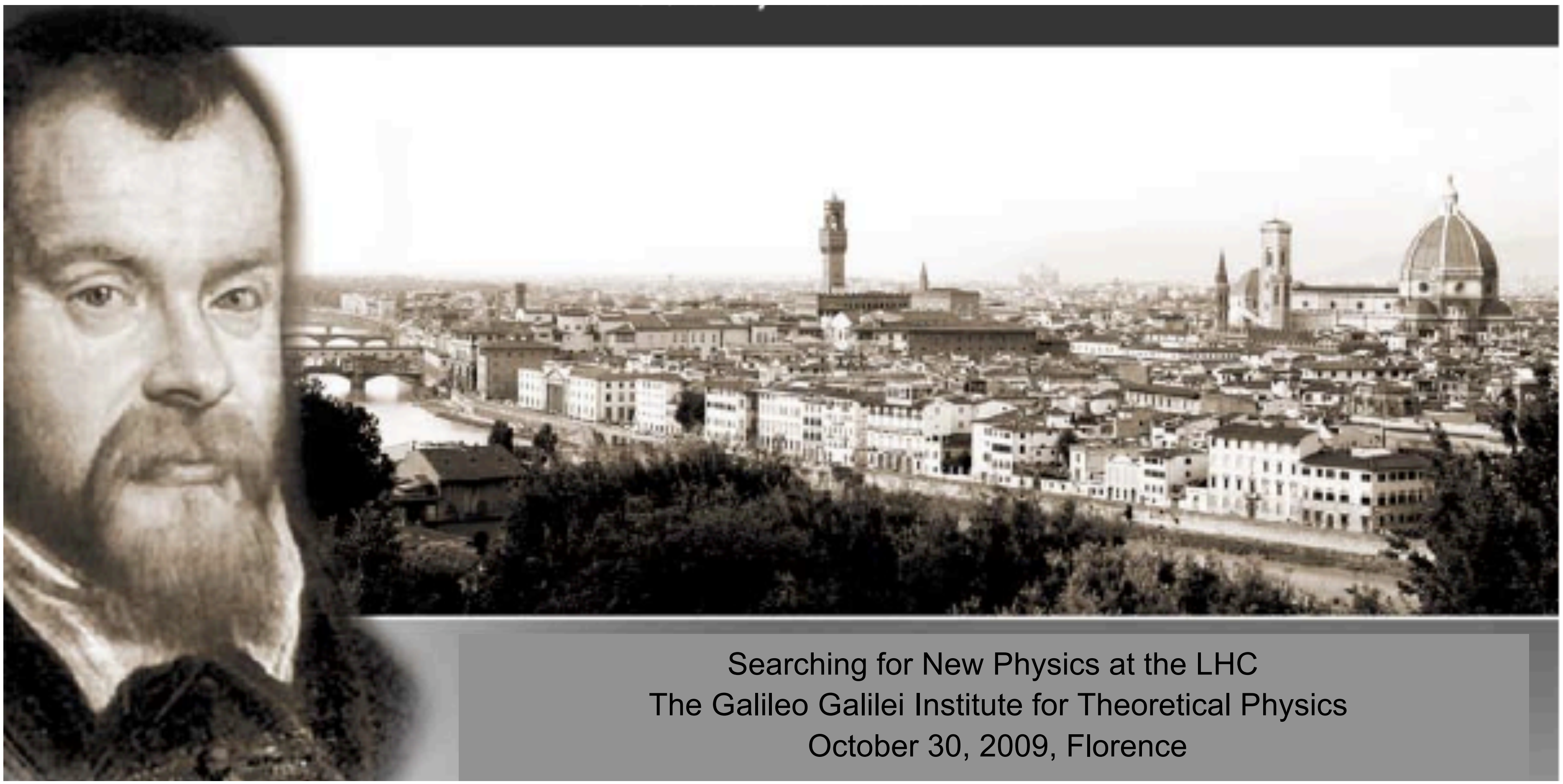
Supersymmetric Higgs

Marcela Carena
Theoretical Physics Department, Fermilab
Enrico Fermi Institute, University of Chicago



Outline

- The SM-like Higgs Boson: state of the art

- The MSSM Higgs Bosons

  -- Basics

  -- The impact of radiative corrections on masses & couplings

  -- Collider searches

- MSSM Higgs Extensions: A model-independent approach

  -- The EFT at NLO

  -- Masses and Couplings

  -- Comments on collider phenomenology

The Standard Model Higgs Mechanism

- One physical state -- ***the Higgs Boson*** -- left in the spectrum

First evidence of EWSB ==> masses of gauge bosons

Measuring the WWH and ZZH couplings is essential to identify the Higgs as the agent of EWSB: without a v.e.v, no such trilinear coupling at tree level

==> we need to detect the Higgs in association with gauge bosons

==> if the theory remains perturbative, the top mass will mainly come from a Higgs with SM-like couplings to W and Z

The search for the SM Higgs: state of the art

$e^+e^- \xrightarrow{Z^*} H_{SM} Z$ with $H_{SM} \to b\bar{b}, \tau^+\tau^-$

Gluon-gluon fusion with $H \to WW$

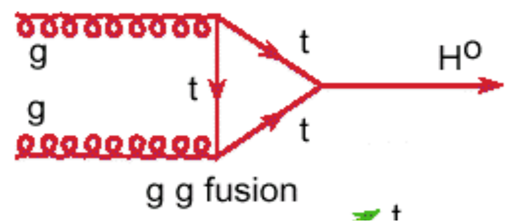
2 isolated leptons + missing Energy

Constraints on m_H from precision tests of the SM

SM Higgs production processes at hadron colliders

Much progress recently in computing NLO and NNLO QCD and EW corrections

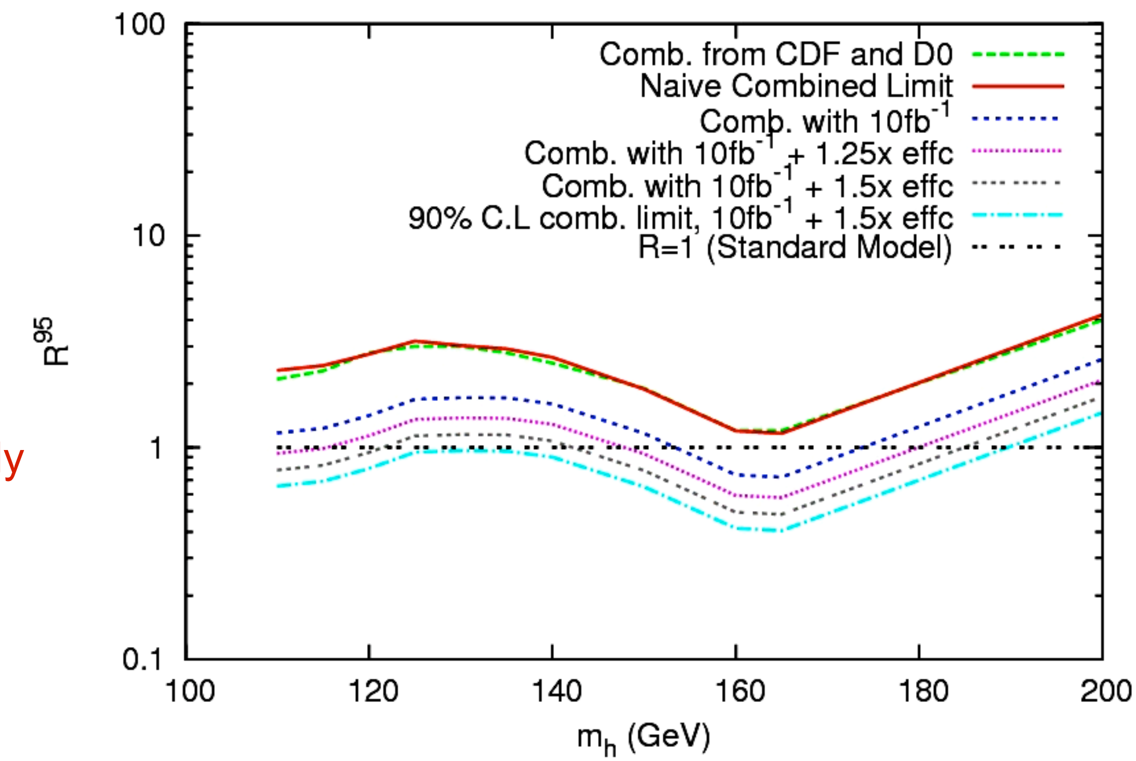
with H ⟶ bb, WW*



with H ⟶ $WW^{(*)}$.

The Tevatron Projections

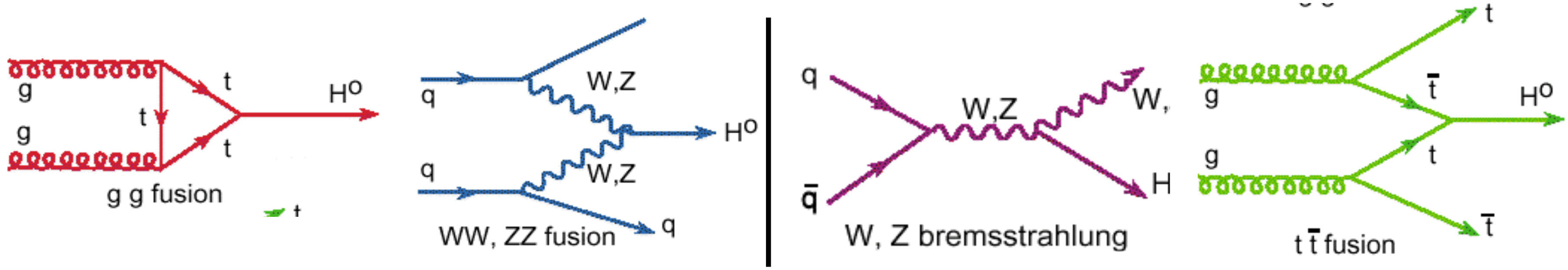
based on improvements already achieved for some analysis, extending them to the rest-

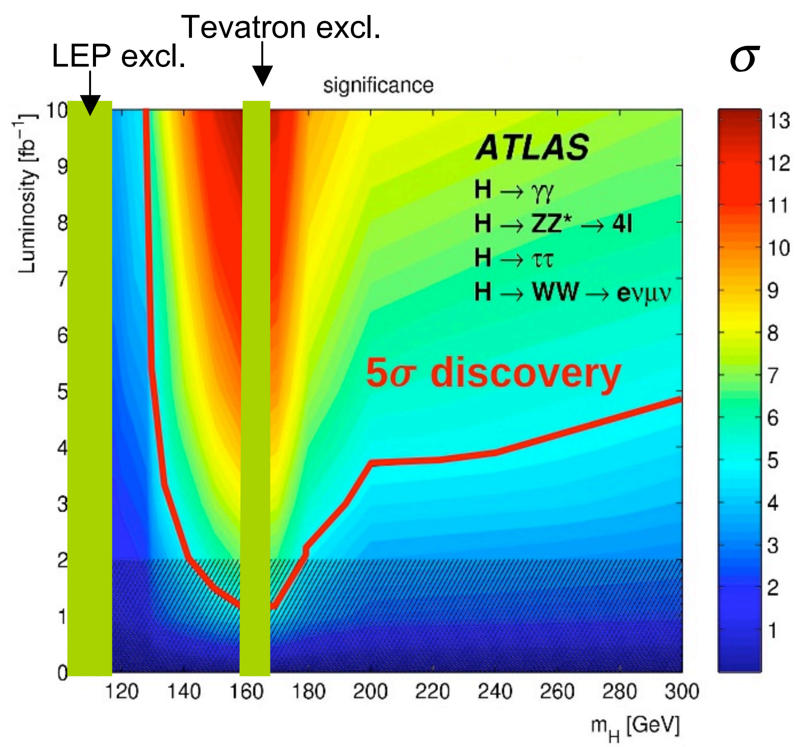


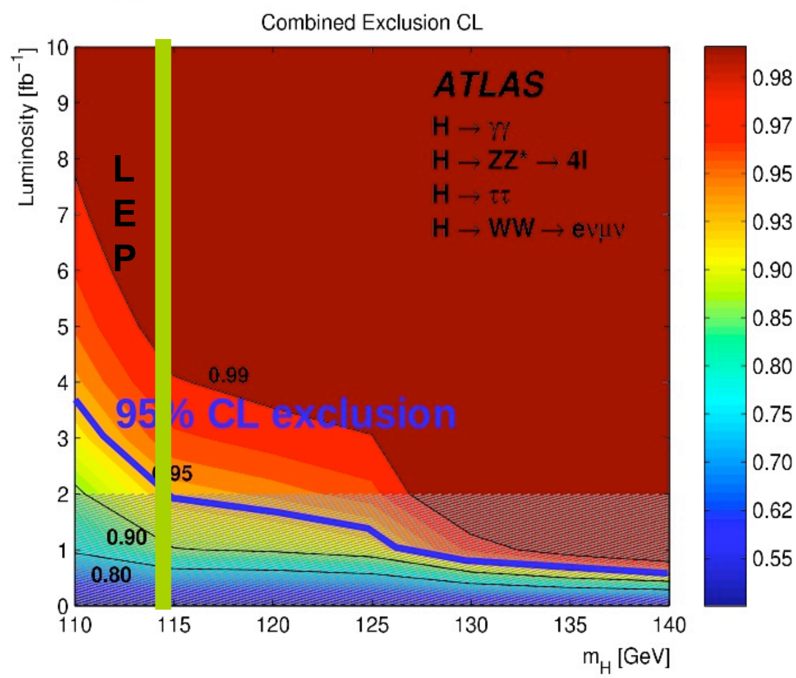
$R^{95}_i = S^{95}_i / S_i^{SM}$

The SM Higgs LHC potential

Talk by A. Nisati





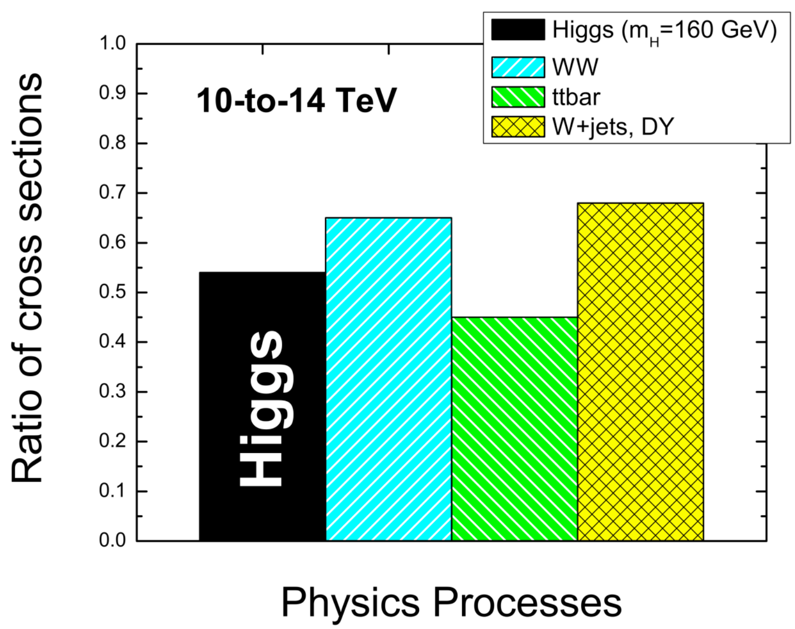


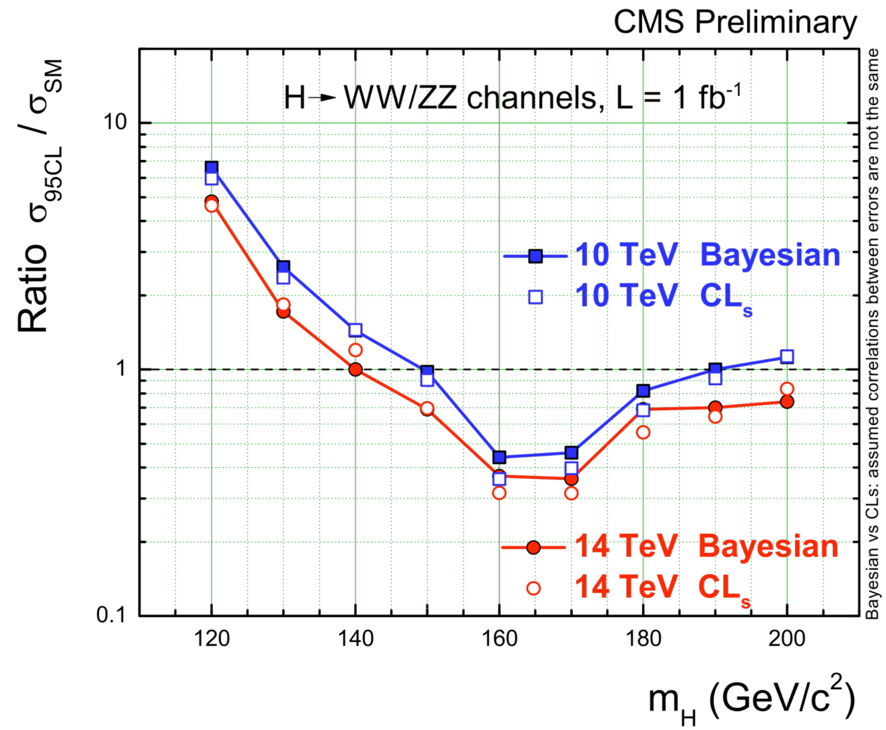
With 10 fb^{-1}, discovery for m_h [~125,~500] GeV range;
With 1-2 fb^{-1}, some reach in the H to WW channel (2 fb^{-1}:exclusion for all m_h)

What can the LHC do with 10 TeV and $1fb^{-1}$?

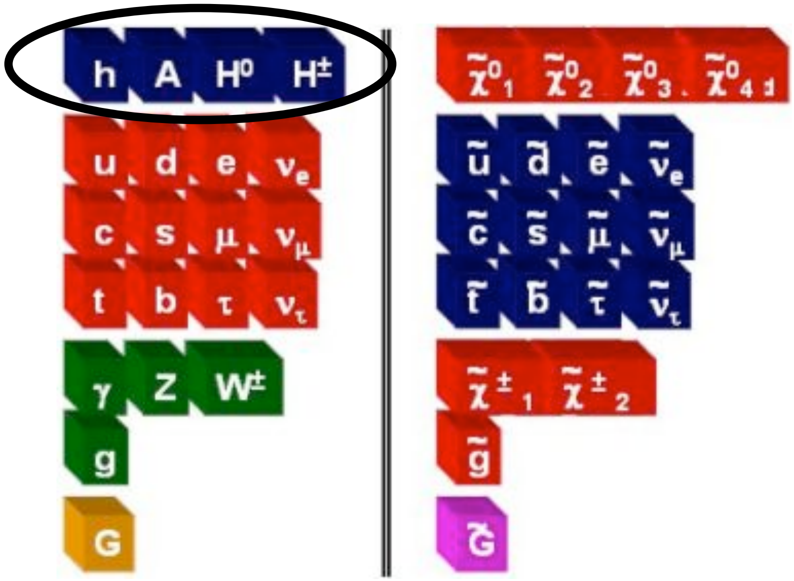
Looking at the golden channel H→ WW/ZZ

Main Backgrounds increase relative to the signal





Comparable to Tevatron reach with 10 fb^{-1} and 1.5 efficiency factor improvement



Supersymmetric Higgs ?

The Higgs Sector in the Minimal Supersymmetric SM

2 Higgs SU(2) doublets ϕ_1 and ϕ_2: after Higgs Mechanism

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

$$\tan\beta = \mathrm{v}_2/\mathrm{v}_1$$

$$\Rightarrow \mathrm{v} = \sqrt{\mathrm{v}_1^2 + \mathrm{v}_2^2} = 246 \text{ GeV}$$

At tree level,
one Higgs doublet couples only to down quarks, the other couples only to up quarks

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

Since the up and down sectors are diagonalized independently, the Higgs interactions remain flavor diagonal at tree level.

Couplings to
gauge bosons & fermions
(SM normalized)

$$\mathrm{hZZ,\ hWW,\ ZHA,\ WH^{\pm}H} \longrightarrow \sin(\beta - \alpha)$$
$$\mathrm{HZZ,\ HWW,\ ZhA,\ WH^{\pm}h} \longrightarrow \cos(\beta - \alpha)$$
$$\mathrm{(h,H,A)}\ u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$$
$$\mathrm{(h,H,A)}\ d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta$$

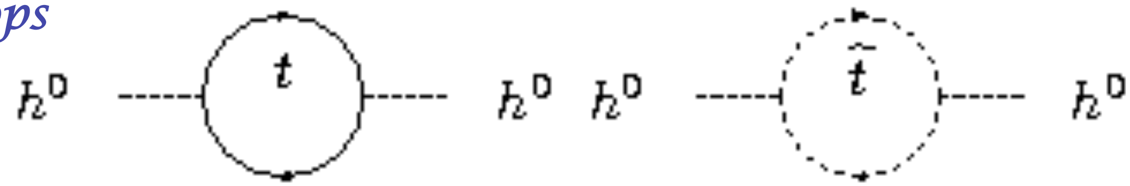
Decoupling limit $m_A >> m_Z$

Lightest (SM-like) Higgs $m_h \leq m_Z$, others heavy and roughly degenerate

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



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

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

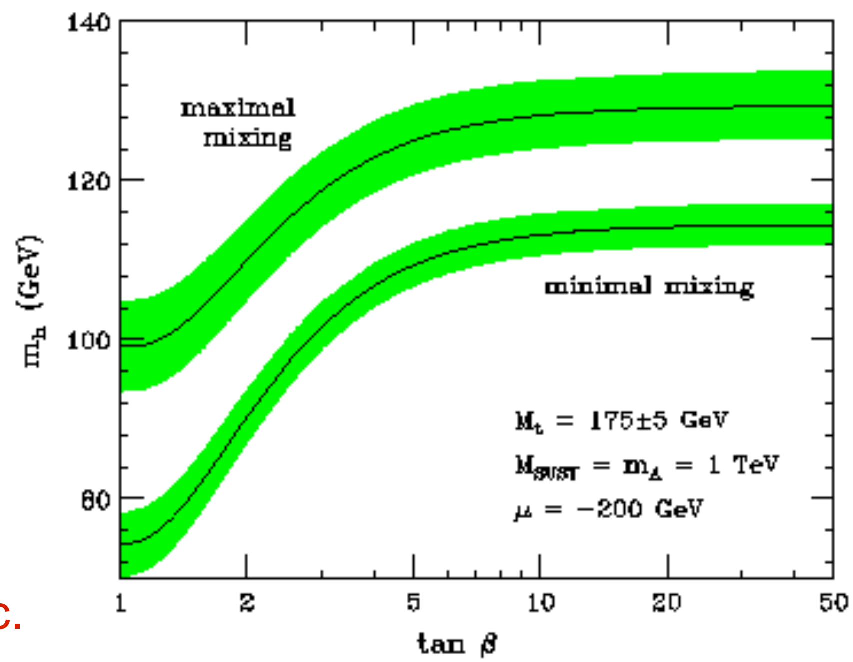
- m_t^4 enhancement
- log sensitivity to stop masses M_S
- depend. on stop mass mixing X_t

2 -loop corrections: $m_h \leq 135\text{GeV}$

Brignole, M.C., Degrassi, Ellis, Haber, Hempfling, Heinemeyer, Hollik, Espinosa, Martin, Quiros, Ridolfi, Slavich, Wagner, Weiglein, Zhang, Zwirner, …

- If 3rd gen. scalar masses > tens of TeV need to resum large logs for reliable m_h calc.

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



Radiative Corrections to the Higgs Couplings

1) Important effects through radiative corrections to the CP-even 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

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

M.C. Mrenna, Wagner

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 and μ / M_S

===> govern couplings of Higgs to fermions and vector bosons

When off-diagonal elements vanish, either $\sin\alpha$ or $\cos\alpha$ vanish

===> strong suppression of the SM-like Higgs boson coupling to b-quarks and taus

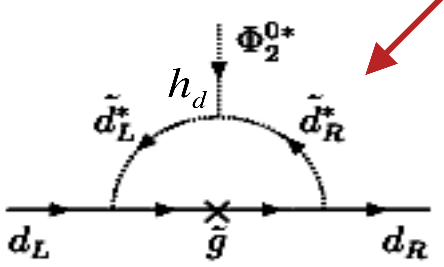
Enhancement of BR (h/H --> WW/ γγ) for $m_{h/H}$ < 135 GeV

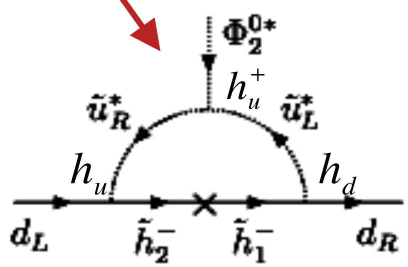
2) Important Vertex corrections to Higgs-fermion couplings from SUSY loops

- relevant for sizeable $\tan\beta$ -

Can induce Flavor changing neutral and charged current effects

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





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

- **In terms of the quark mass eigenstates**

$$-L_{eff} = \frac{1}{\mathrm{v}_2}\left(\tan\beta\ \Phi_1^{0*} - \Phi_2^{0*}\right) \bar{\mathrm{d}}_R \mathrm{M}_d \left[\mathrm{V}_{CKM}^+ \mathrm{R}^{-1} \mathrm{V}_{CKM}\right] \mathrm{d}_L + h.c. + \ldots$$

Dedes, Pilaftsis

and $\mathrm{R} = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |\mathrm{h}_u|^2$ ➔ R diagonal

Dependence on SUSY param.

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

Higgs Physics strongly connected to flavor physics and to the ~~SUSY~~ mechanism

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:

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

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

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

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

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

M.C. Mrenna, Wagner; Haber,Herrero, Logan, Penaranda, Rigolin, Temes
Noth, Spira: Muhlleitner, Rzehak, Spira

Strong suppression of h(H) -bottom coupling

$\tan\alpha \simeq \Delta_b / \tan\beta \;\rightarrow g_{hb\bar{b}} \simeq 0;\; g_{h\tau\tau} \simeq \Delta_b m_\tau / v$ (Similar for H)

Radiative corrections ⟶ main decay modes of the SM-like MSSM Higgs into b- and tau-pairs can be drastically changed

What can the Tevatron say about an SM-like MSSM Higgs?

Different SUSY benchmark scenarios will yield very different results

M.C.,Heinemeyer, Wagner,Weiglein

- The m_h^{max} scenario: [Maximizes m_h]

$$M_S = 1\ \mathrm{TeV};\quad X_t = 2.4\ M_S;\quad m_{\tilde{g}} = 0.8\ M_S;\quad M_2 = -\mu = 200\mathrm{GeV};\quad A_t = A_b$$

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

hence, strong suppression of BR($h \to \gamma\gamma$) and BR($h \to WW$) with respect to SM

- The m_h^{min} scenario: [zero mixing in the stop sector]

Similar coupling's behaviour as m_h^{max}, but minimizes m_h.

- The small $\sin\alpha_{eff}$ scenario:

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

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

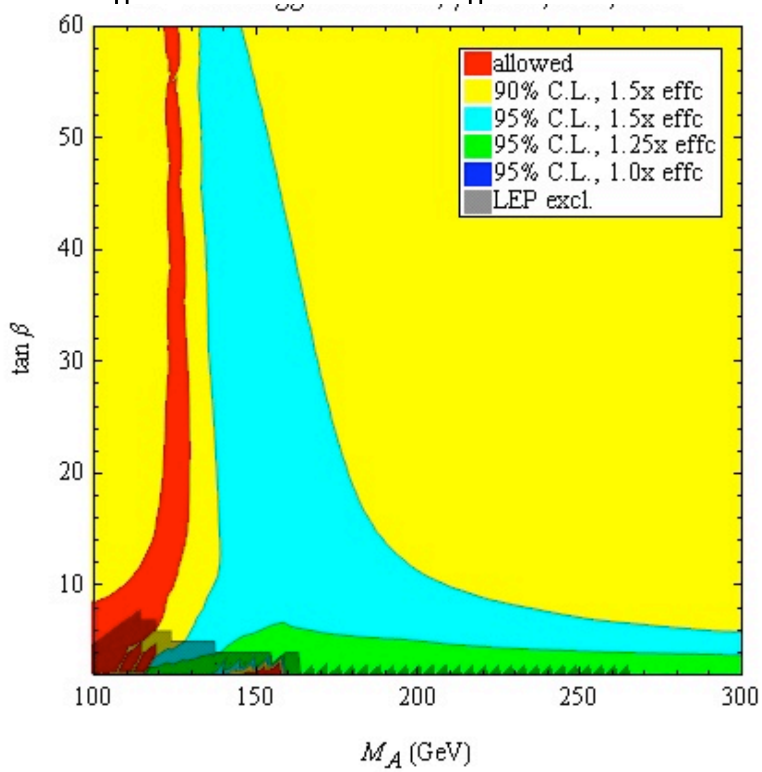
hence, BR($h \to \gamma\gamma$) and BR($h \to WW$) enhanced with respect to SM

Tevatron reach for the MSSM SM-like Higgs

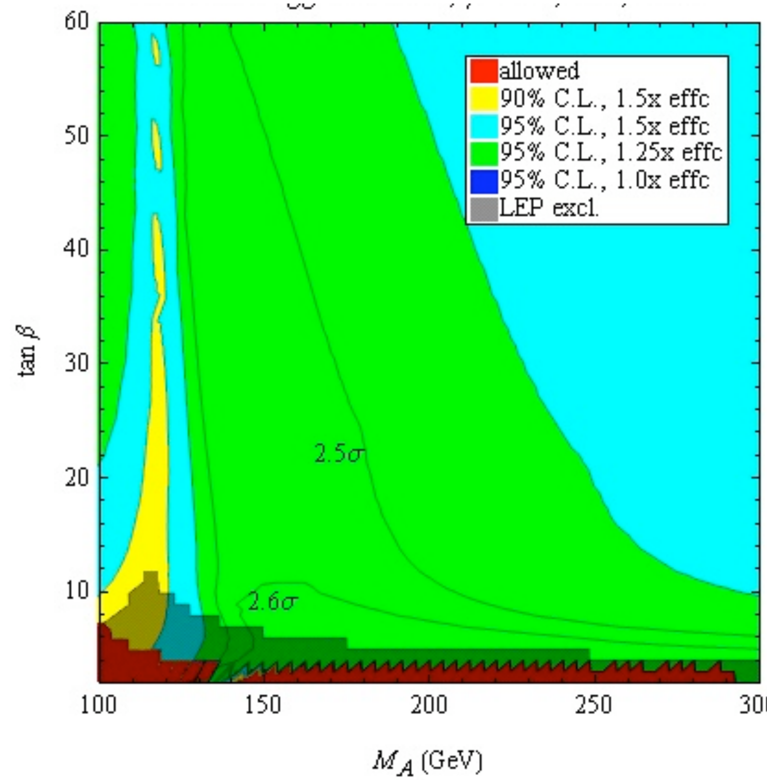
All channels included in CDF/DO combination.

95% C.L. Exclusion- 10 fb^{-1}.

The m_h^{max} scenario: m_h ~ 125 GeV



The m_h^{min} scenario: m_h < 120 GeV



No reach at present

BUT with the expected improvement factor of 1.5 assumed ⟶ good/full coverage

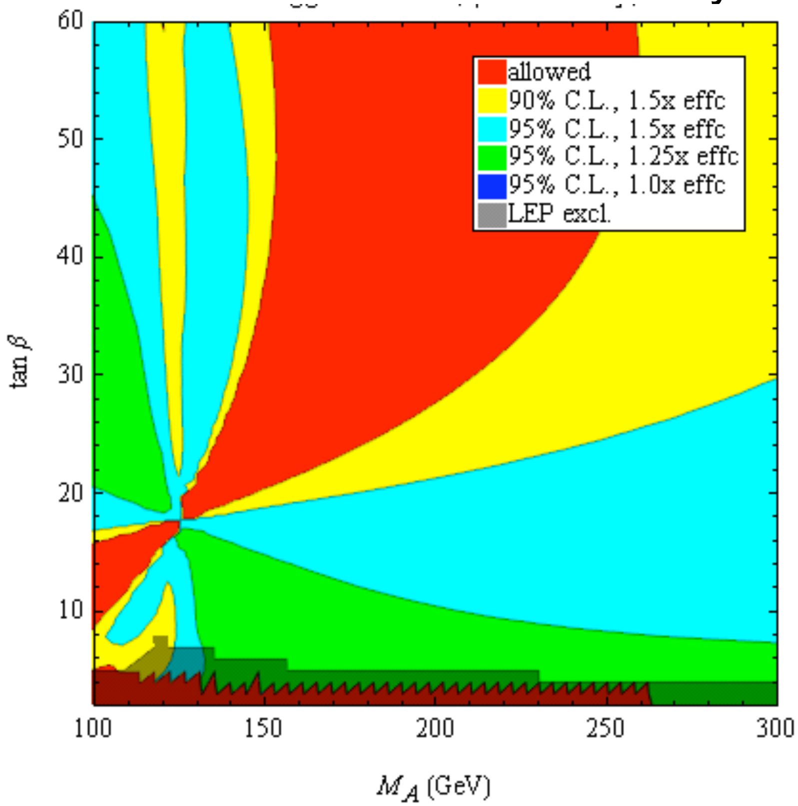
Draper, Liu, Wagner

An interesting case: The small $\sin\alpha_{eff}$ scenario

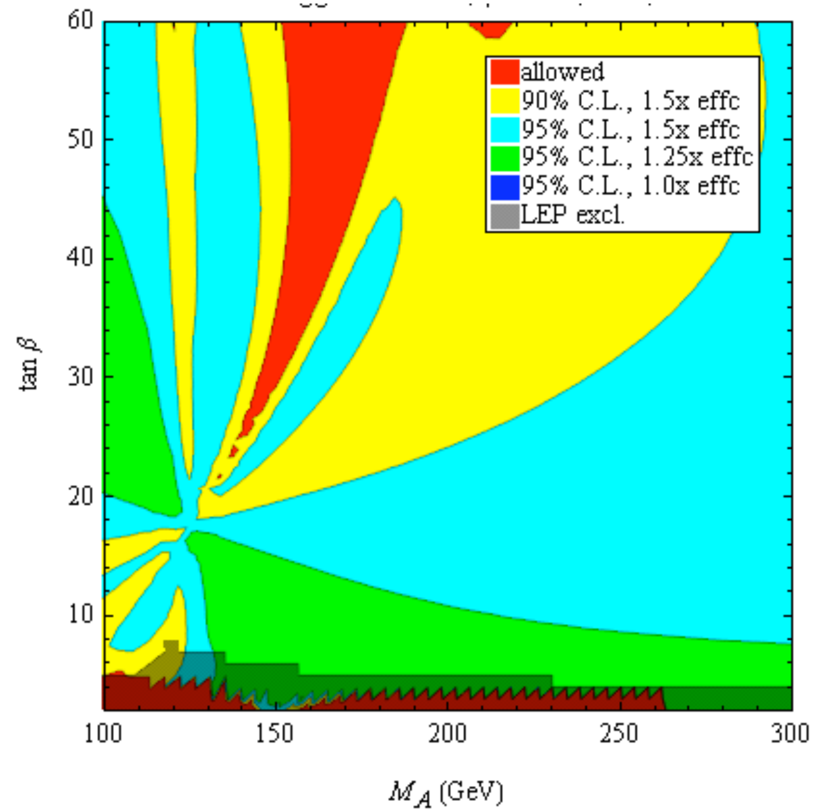
CDF/DO combination: 95% C.L. Exclusion- 10 fb^{-1}.

Draper, Liu, Wagner

H/h → bb final channel only



H/h → bb + WW channels

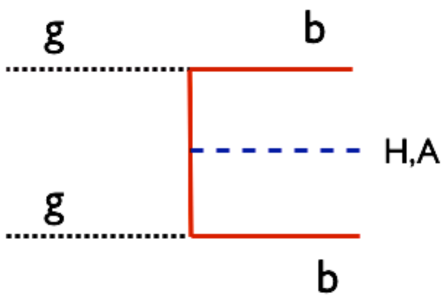


- Useful h → WW Tevatron search for a low mass MSSM SM-like Higgs
- Full coverage of the MSSM plane once the tan beta enhanced channels $\tau\tau$ inclusive, b$\tau\tau$, and bbb, with present efficiency and 10fb^{-1}, are included

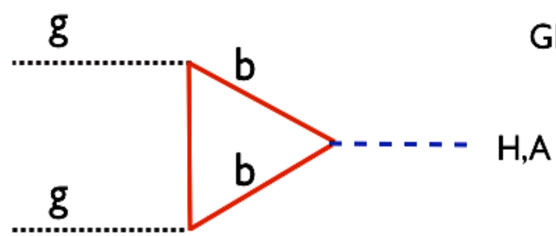
Non-Standard Higgs Production at the Tevatron and LHC

- Enhanced couplings to b quarks and tau-leptons
- Considering value of running bottom mass and 3 quark colors

$$BR(A \to b\bar{b}) \cong \frac{9}{9 + (1+\Delta_b)^2} \qquad BR(A \to \tau^+\tau^-) \cong \frac{(1+\Delta_b)^2}{9 + (1+\Delta_b)^2}$$



Associated Production



Gluon Fusion

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

Strong dependence on the SUSY parameters in the bb channel.

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

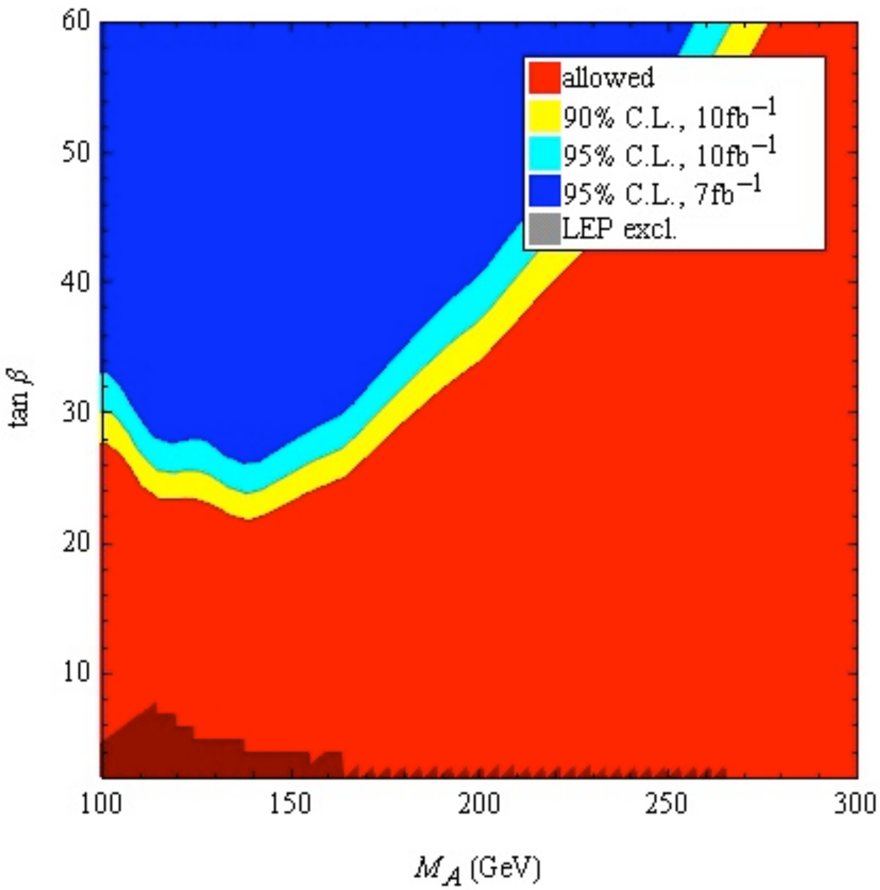
Robust predictions in the tau-tau channel

Excellent coverage at both colliders in the di-tau inclusive channel

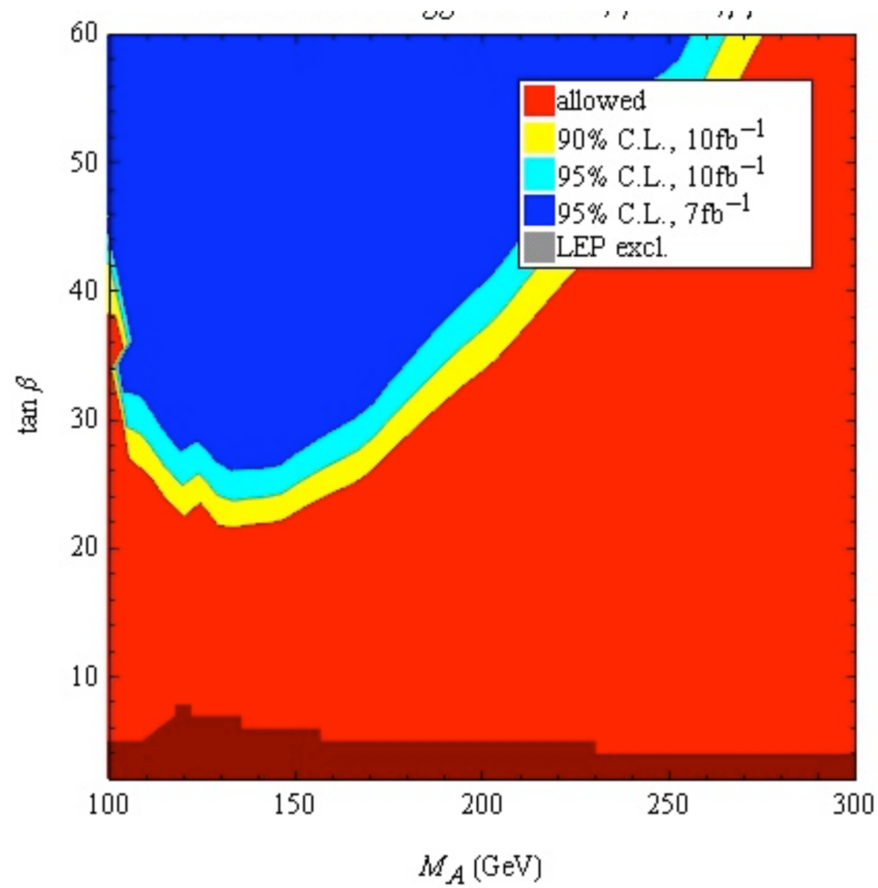
M.C, Heinemeyer, Weiglein, Wagner

MSSM Higgs at the Tevatron

H/A ⟶ tau pairs, with both exp. and for 10 fb^{-1} Draper, Liu, Wagner



M_h^{max}. Scenario



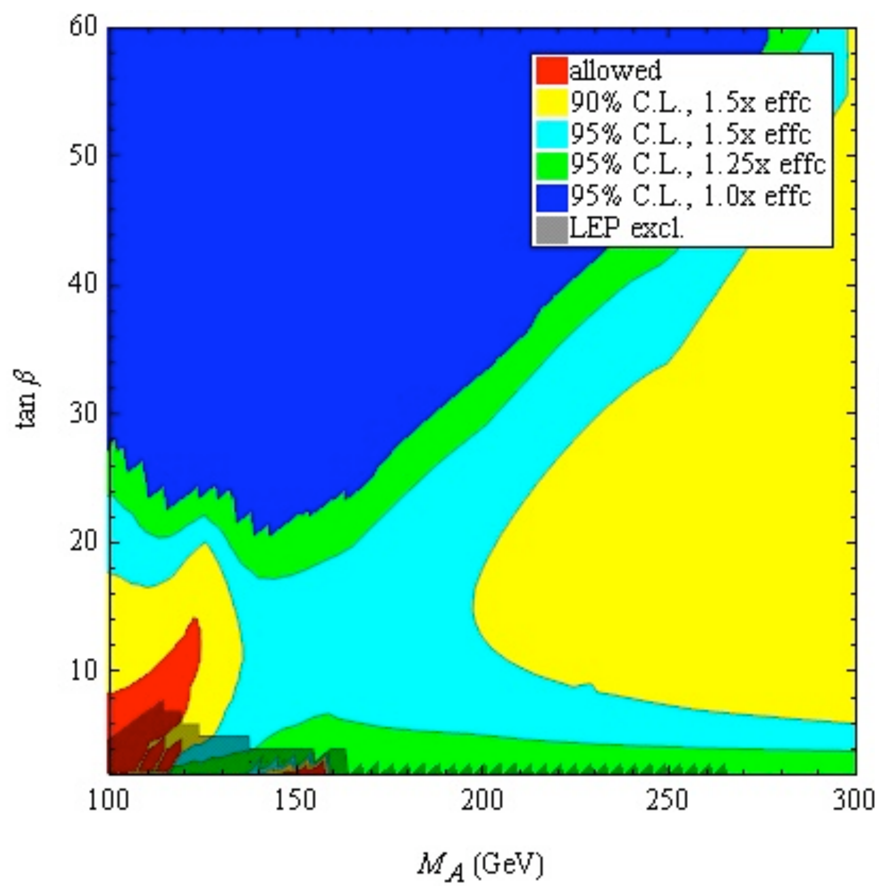
Small $\sin\alpha_{eff}$. scenario

Limits are robust under variation of SUSY parameters

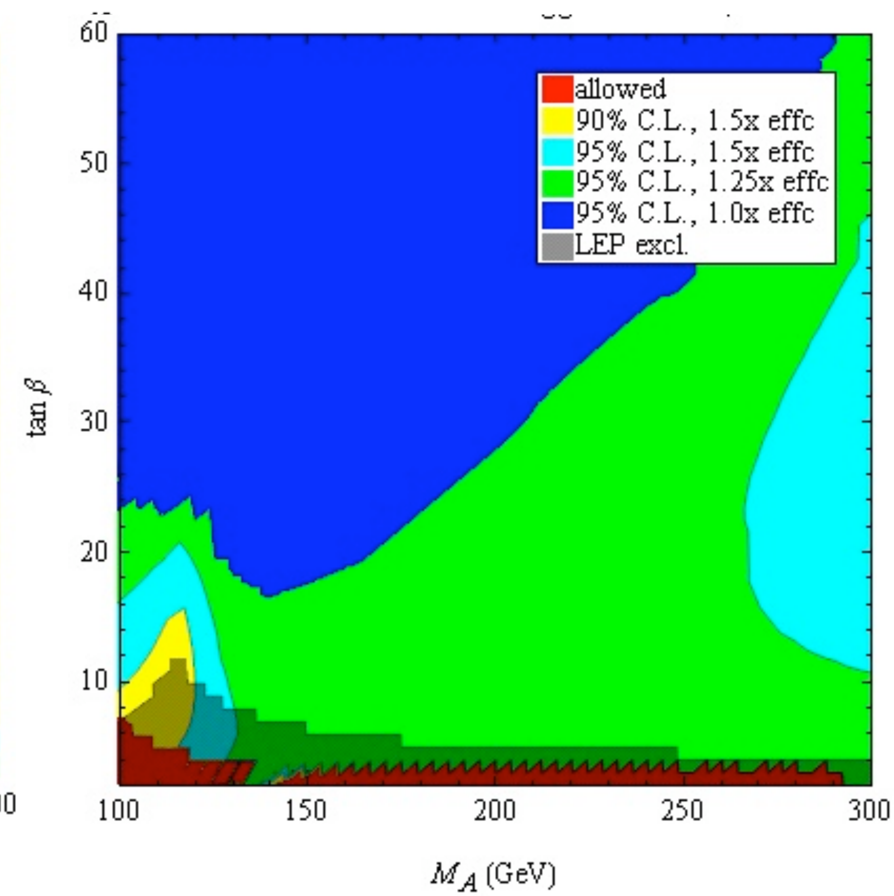
MSSM Higgs at the Tevatron

All channels combined both exp. and for 10 fb^{-1}

Draper, Liu, Wagner



M_h^{max} scenario



M_h^{min} scenario

Extensions of the MSSM Higgs Sector

- MSSM with Explicit CP violation

- Additional SM singlets

- Additional gauged U(1)’s

- Models with enhanced weak gauge symmetries

- Effective field theory with higher dimensional operators:
  A more model-independent approach

More general MSSM Higgs extensions: EFT approach

- The non-minimal part of Higgs sector is parametrically heavier than the weak scale (understood as v = 174 GeV)

- SUSY breaking is of order v, hence heavy masses nearly supersymmetric

M : overall ``heavy" scale SUSY breaking mass splittings $\Delta m \sim \mathrm{v} \ll M$

In practice: formalism applies for e.g. $M \sim 1 \text{ TeV}$

Low energy superpotential: at leading order in 1/M

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2$$

- can include SUSY breaking via a spurion X= $m_S\, \theta^2$ $\quad W_X \supset \alpha_1 \frac{\omega_1}{2M} X (H_u H_d)^2$

Only two new parameters: ω_1 and X

M.C, Kong, Ponton, Zurita

see also Dine, Seiberg, Thomas; Antoniadis, Dudas, Ghilencea, Tziveloglou

- At NLO, Kähler potential only:

$$K = H_d^\dagger e^{2V} H_d + H_u^\dagger e^{2V} H_u + \Delta K^{\rm CV} + \Delta K^{\rm Cust}$$

Custodially violating (treel level) :

$$\Delta K^{\rm CV} = \frac{c_1}{2|M|^2}(H_d^\dagger e^{2V} H_d)^2 + \frac{c_2}{2|M|^2}(H_u^\dagger e^{2V} H_u)^2 + \frac{c_3}{|M|^2}(H_u^\dagger e^{2V} H_u)(H_d^\dagger e^{2V} H_d)$$

Custodially preserving (tree level) :

$$\Delta K^{\rm Cust} = \frac{c_4}{|M|^2}|H_u H_d|^2 + \left[\frac{c_6}{|M|^2} H_d^\dagger e^{2V} H_d + \frac{c_7}{|M|^2} H_u^\dagger e^{2V} H_u\right](H_u H_d) + \text{h.c.}$$

Plus SUSY breaking terms obtained by multiplication by spurion, with new coefficients

$$X \to \gamma_i \ , \qquad X^\dagger X \to \beta_i$$

- EFT coefficients can be essentially arbitrary, if UV theory complicated enough

Examples

Example 1: singlets

B_μ-term

$$W = \mu H_u H_d + \frac{1}{2} M_S S^2 + \lambda_S S H_u H_d - X \left(a_1 \mu H_u H_d + \frac{1}{2} a_2 M_S S^2 + a_3 \lambda_S S H_u H_d \right)$$

$$K = H_u^\dagger e^V H_u + H_d^\dagger e^V H_d + S^\dagger S - X^\dagger X \left(b_1 H_d^\dagger H_d + b_2 H_u^\dagger H_u + b_3 S^\dagger S \right)$$

Soft masses: $m^2_{H_d}, m^2_{H_u}, m^2_S$

Integrating out the singlet:

$$M = M_S \;, \qquad \omega_1 = -\lambda_S^2 \;, \qquad \alpha_1 = a_2 - 2a_3 \;,$$

$$c_4 = |\lambda_S|^2 \;, \qquad \gamma_4 = a_2 - a_3 \;, \qquad \beta_4 = |a_2 - a_3|^2 - b_3$$

Note $c_4 > 0$, other arbitrary

Example 2: triplets with $Y = \pm 1$

$$W \supset M_T T\bar{T} + \frac{1}{2}\lambda_T H_u T H_u + \frac{1}{2}\lambda_{\bar{T}} H_d \bar{T} H_d$$
$$+ X\left(a_2 M_T T\bar{T} + \frac{1}{2}a_3\lambda_T H_u T H_u + \frac{1}{2}a_4\lambda_{\bar{T}} H_d \bar{T} H_d\right)$$
$$K \supset T^\dagger e^{2V} T + \bar{T}^\dagger e^{2V}\bar{T} + XX^\dagger\left(b_3 T^\dagger T + b_4 \bar{T}^\dagger \bar{T}\right)$$

Integrating out the triplets:

$$\left.\begin{array}{lll} M = M_T\ , & \omega_1 = \frac{1}{4}{}_T{}^{\bar{T}}\ , & \alpha_1 = a_2 - a_3 - a_4\ , \\ c_1 = \frac{1}{4}|\lambda_{\bar{T}}|^2\ , & \gamma_1 = a_2 - a_4\ , & \beta_1 = |a_2 - a_4|^2 - b_3\ , \\ c_2 = \frac{1}{4}|\lambda_T|^2\ , & \gamma_2 = a_2 - a_3\ , & \beta_2 = |a_2 - a_3|^2 - b_4\ , \end{array}\right\}$$

Induce custodially violating ops.

Note $c_1, c_2 > 0$, other arbitrary

$(\Delta T < 0)$

For triplets with $Y = 0 \quad \longrightarrow \quad \lambda_T H_u T H_d$

$$\left.\begin{array}{lll} M = M_T\ , & \omega_1 = -\frac{1}{4}\lambda_T^2\ , & \alpha_1 = a_2 - 2a_3\ , \\ c_3 = \frac{1}{2}|\lambda_T|^2\ , & \gamma_3 = a_2 - a_3\ , & \beta_3 = |a_2 - a_3|^2 - b_3\ , \\ c_4 = -\frac{1}{4}|\lambda_T|^2\ , & \gamma_4 = a_2 - a_3\ , & \beta_4 = |a_2 - a_3|^2 - b_3\ , \end{array}\right\}$$

Induce custodially violating ops.

Note $c_3 > 0$ $(\Delta T > 0)$,

and $c_4 < 0$!

Why to go beyond LO in the EFT approach

Quartic interactions of 2HDM can be written as

$$V \supset \frac{1}{2}\lambda_1(H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2(H_u^\dagger H_u)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u H_d)(H_u^\dagger H_d^\dagger)$$
$$+ \left\{\frac{1}{2}\lambda_5(H_u H_d)^2 + \left[\lambda_6(H_d^\dagger H_d) + \lambda_7(H_u^\dagger H_u)\right](H_u H_d) + \text{h.c.}\right\}$$

At O(1/M), only $\lambda_5, \lambda_6, \lambda_7$ modified

At O(1/M^2) all λ_i's receive contributions

But at tree-level in MSSM: $\lambda_1, \lambda_2, \lambda_3, \lambda_4 \propto g^2$ (small)

NLO effects can be relevant without indicating breakdown of EFT

(however, higher order effects should be small...)

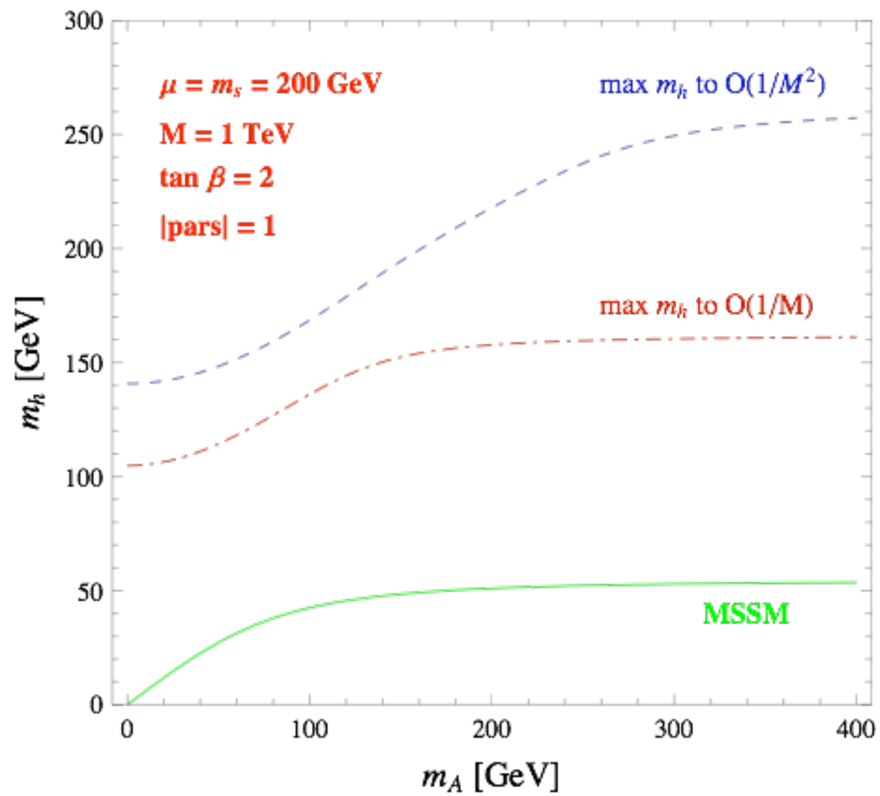
Higgs Spectra in EFT extensions of the MSSM

The lightest tree level Higgs mass can be well above the LEP bound!!.

Expansion parameters: μ/M and m_S/M (m_S is the spurion F term)

Second order terms can have a relevant impact.

Large deviations from the MSSM mass values, specially for low tanb



Higgs Spectra in EFT extensions of the MSSM

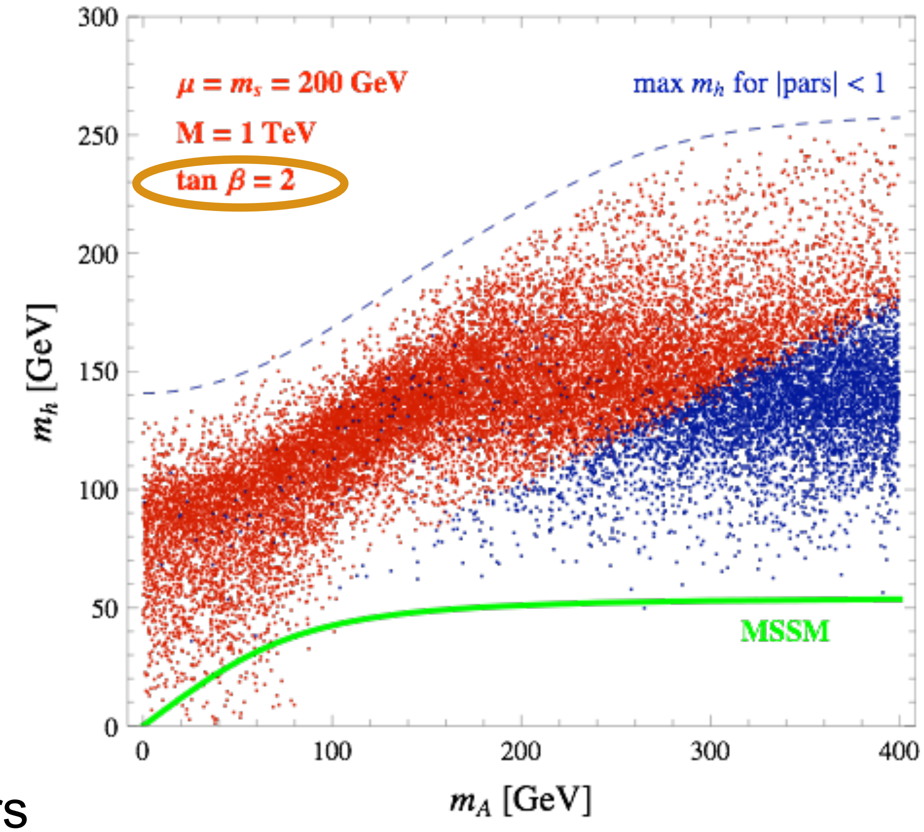
M.C., Kong, Ponton, Zurita

The lightest tree level Higgs mass is well above M_Z.

Expansion parameters: μ/M and m_s/M

Second order terms can have a relevant impact.

Large deviations from the MSSM mass values, specially for low tanb



Scanning over model parameters

Scan: $|\omega_1|, |c_i| \in [0,1]$ and $|\alpha_1|, |\beta_i|, |\gamma_i|, |\delta_i| \in [1/3, 1]$ for $i = 1, 2, 3, 4, 6, 7$

Higgs Spectra in EFT extensions of the MSSM

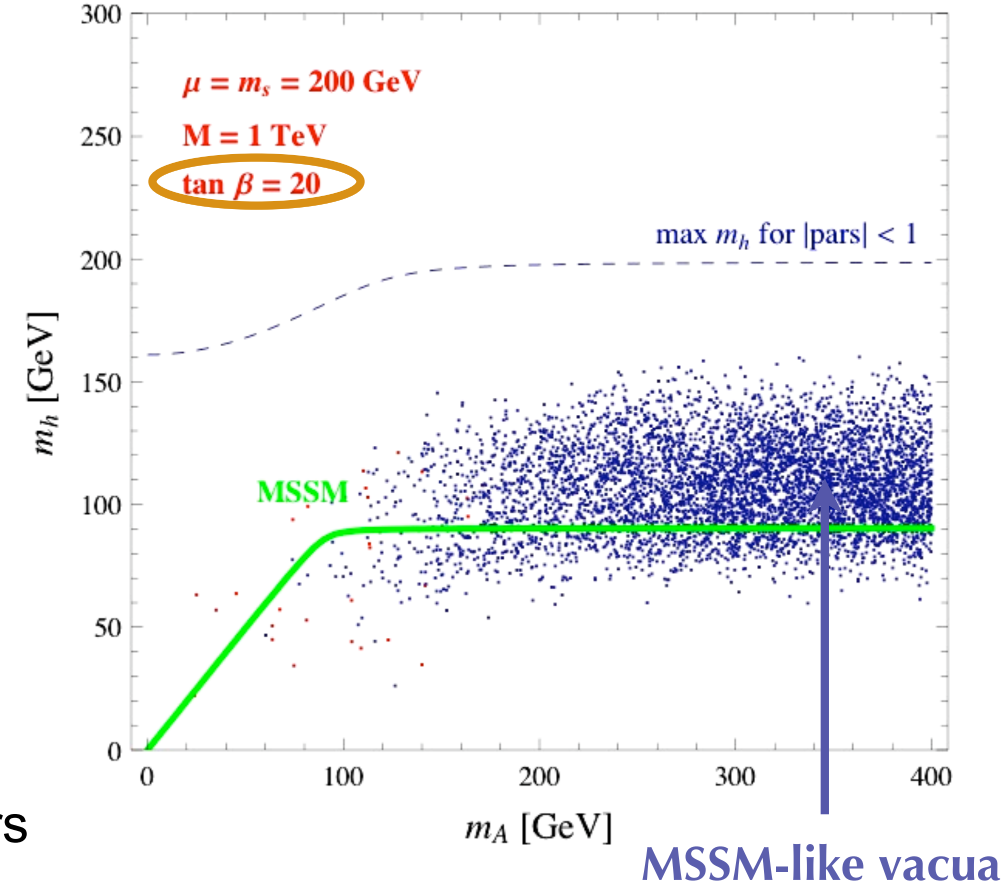
M.C., Kong, Ponton, Zurita

The lightest tree level Higgs mass is well above M_Z.

Expansion parameters: μ/M and m_s/M

Second order terms can have a relevant impact.

Smaller effects for large tanb main contributions proportional to $1/M^2$.



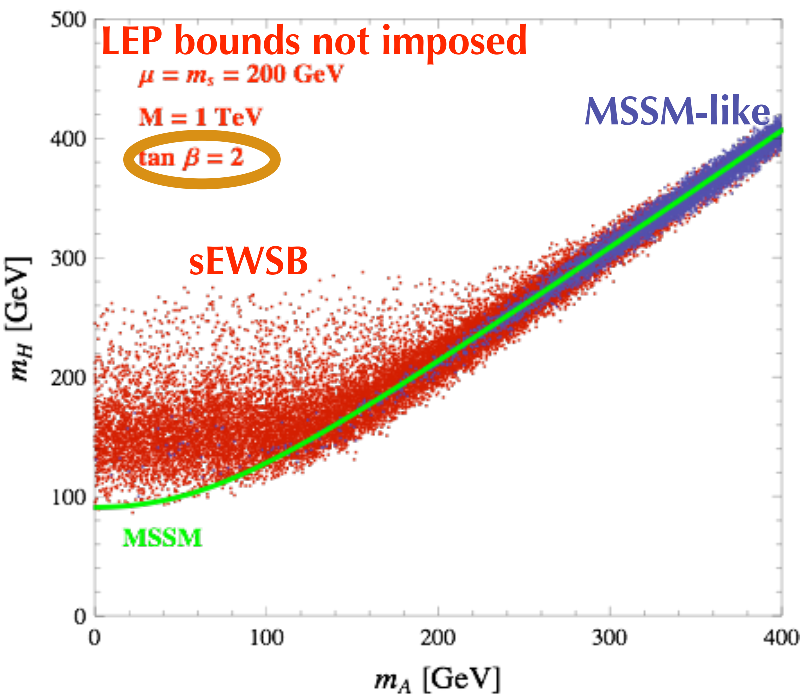
Scanning over model parameters

Scan: $|\omega_1|, |c_i| \in [0,1]$ and $|\alpha_1|, |\beta_i|, |\gamma_i|, |\delta_i| \in [1/3, 1]$ for $i = 1,2,3,4,6,7$

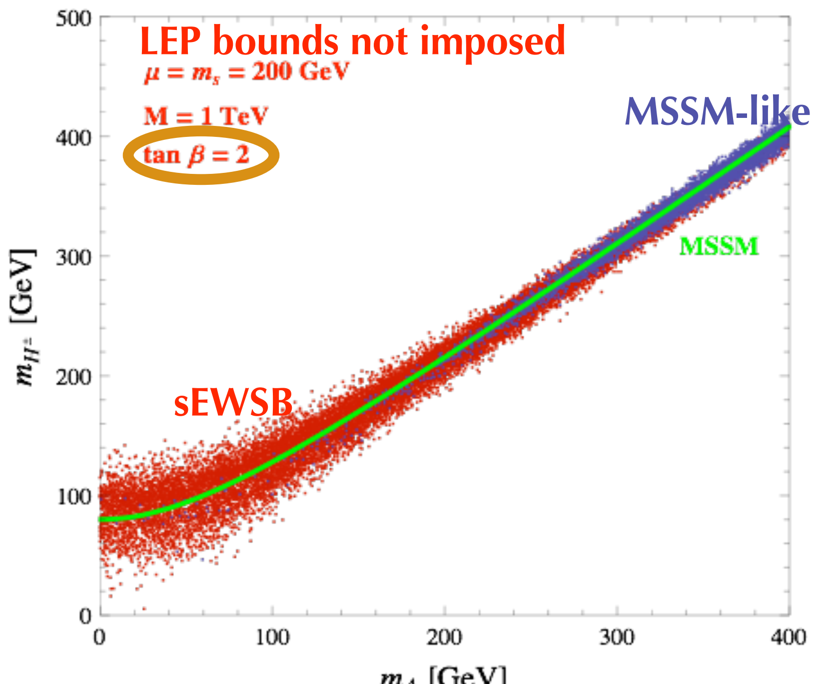
Heavy CP Even and Charged Higgs Masses

H and $H^{\pm}$ follow MSSM trend (with m_A), but

- large spreading at smaller m_A (heavier H)
- non-negligible deviations throughout



Heavy CP-even Higgs



Charged Higgs

Precision Electroweak Constraints

1. Tree-level effects due to new physics:

$$\alpha T^{\rm Tree} = -\frac{v^2}{2M^2}\sin^4\beta\left[c_2 - 2(\tan\beta)^{-2}c_3 + (\tan\beta)^{-4}c_1\right]$$

2. Effects from MSSM Higgs sector:

- Heavier SM-like Higgs
- Mass splittings among non-standard Higgses

} Loop-level contr. to S and T

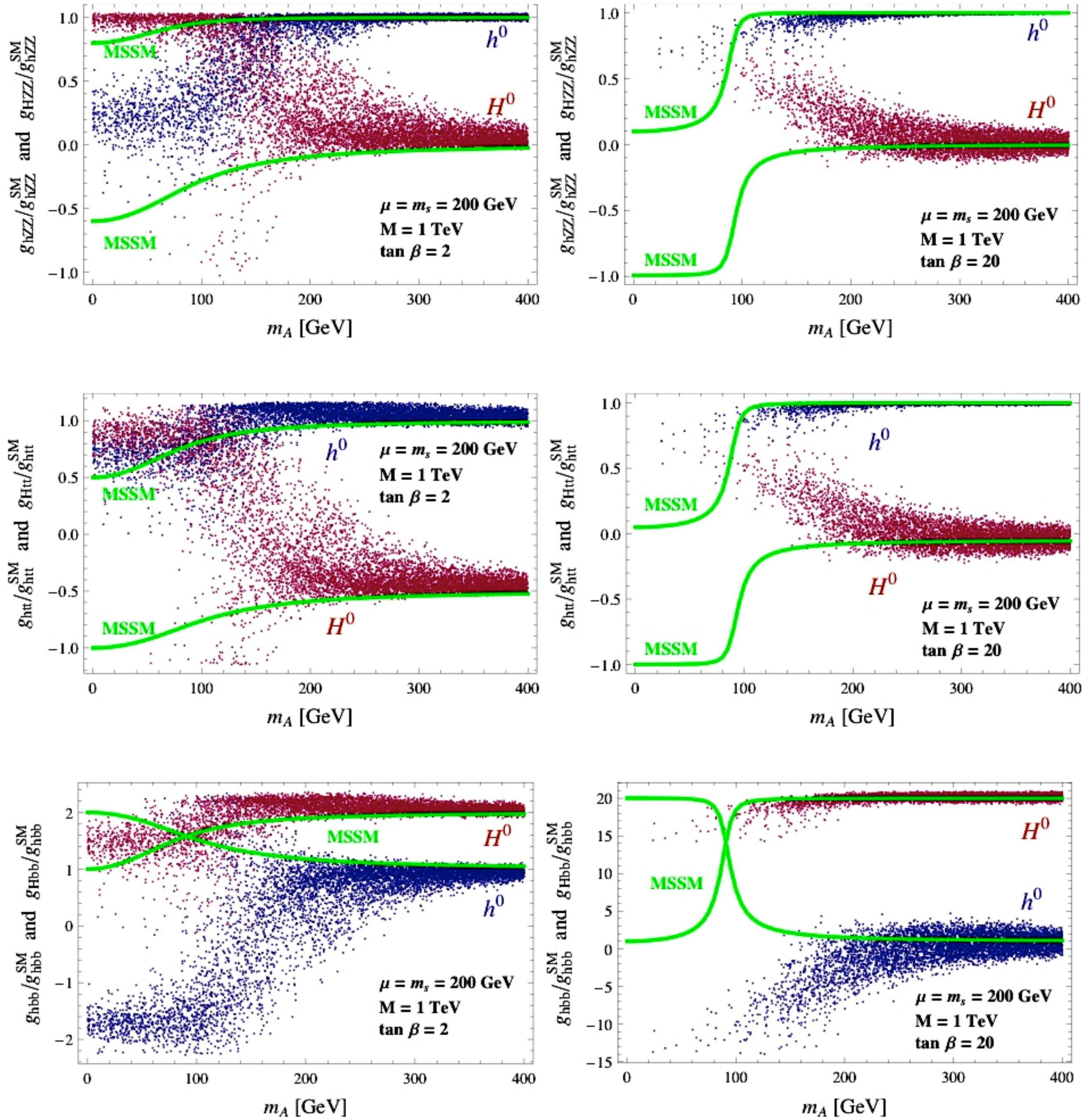
3. Custodially violating mass splittings in SUSY sector — Medina, Shah, Wagner

Here: require that $-0.4 < T^{\rm Tree} + T^{\rm Higgs} < 0.3$ (S is small)

Consistent with $-0.2 < T^{\rm Total} < 0.3$ $(95\%\ C.L.)$ for $0 < T^{\rm SUSY} < 0.2$

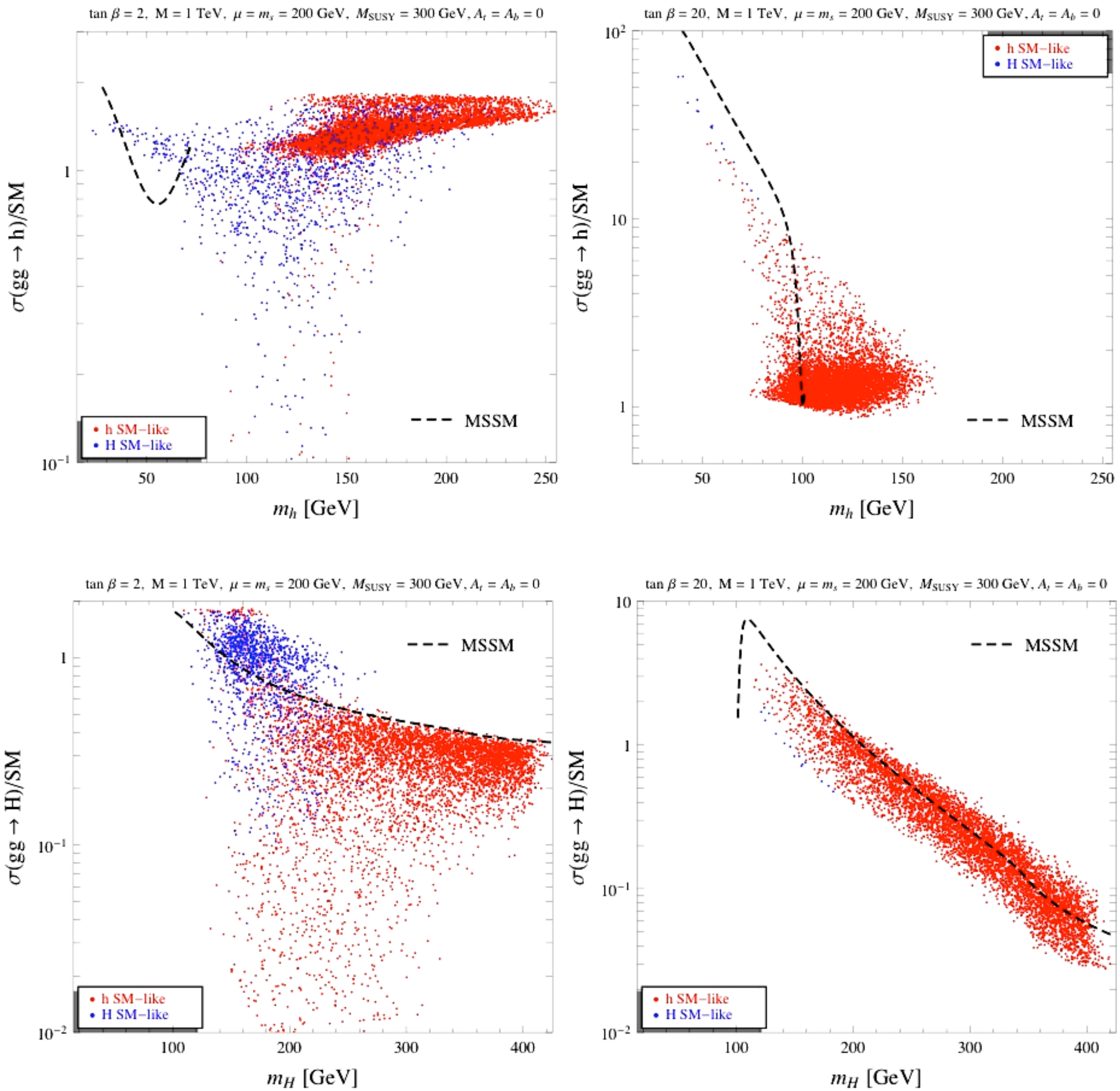
CP-even Higgs Couplings to gauge bosons and fermions

Variations of couplings with respect to SM and MSSM can lead to important variations in the production processes and BR's relevant for Higgs searches



Gluon Fusion Production

A generic enhancement of the production for the Higgs that is SM-like (the one with largest coupling to WW/ZZ)



- The couplings of the CP-odd and charged Higgs bosons differ from the MSSM due to corrections to their kinetic terms only at order $1/M^2$

  ➔ much less significant

- The main effects involving A and H^{+-} are those related to new decay modes due to variations in the mass spectrum

- New decay channels such as H → AA/AZ, h→ AA and H^+→ W^+A open with BR's of order one

- Regular MSSM channels with decays into h are closed at low tanb and open at large tan beta: $A \to hZ; \quad H^{\pm} \to W^{\pm}h; \quad H \to hh$

- At sufficiently large m_A (> 300 GeV) behavior similar to MSSM

• Many models for which BR's into bb/tau-pairs are significantly enhanced or suppressed with respect to SM ones,
leading to important variations of BR's into golden modes WW/ZZ

• Models with enhancement in BR's to cc/gg/di-photons
-sometimes challenging dominant decay into jets-

In the following: Full study with LEP and Tevatron bounds using **Higgsbounds**

Bechtle, Brein, Heinemeyer, Weiglein, Williams

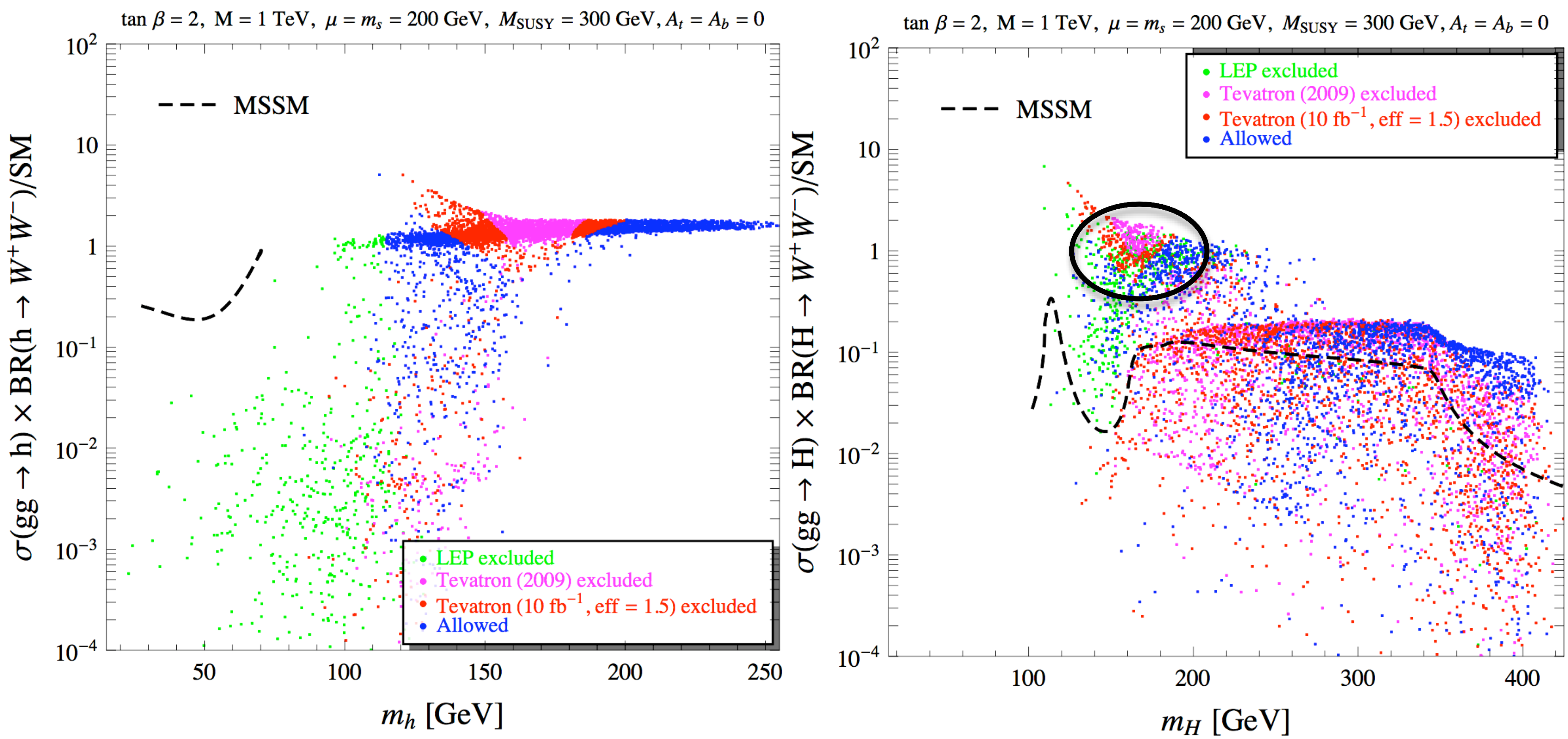
plus Tevatron projections based on SM Higgs present reach and projections

[Tevatron projections based on heavy MSSM Higgs searches underway]

All the above for our specific multi parameter SUSY scenarios

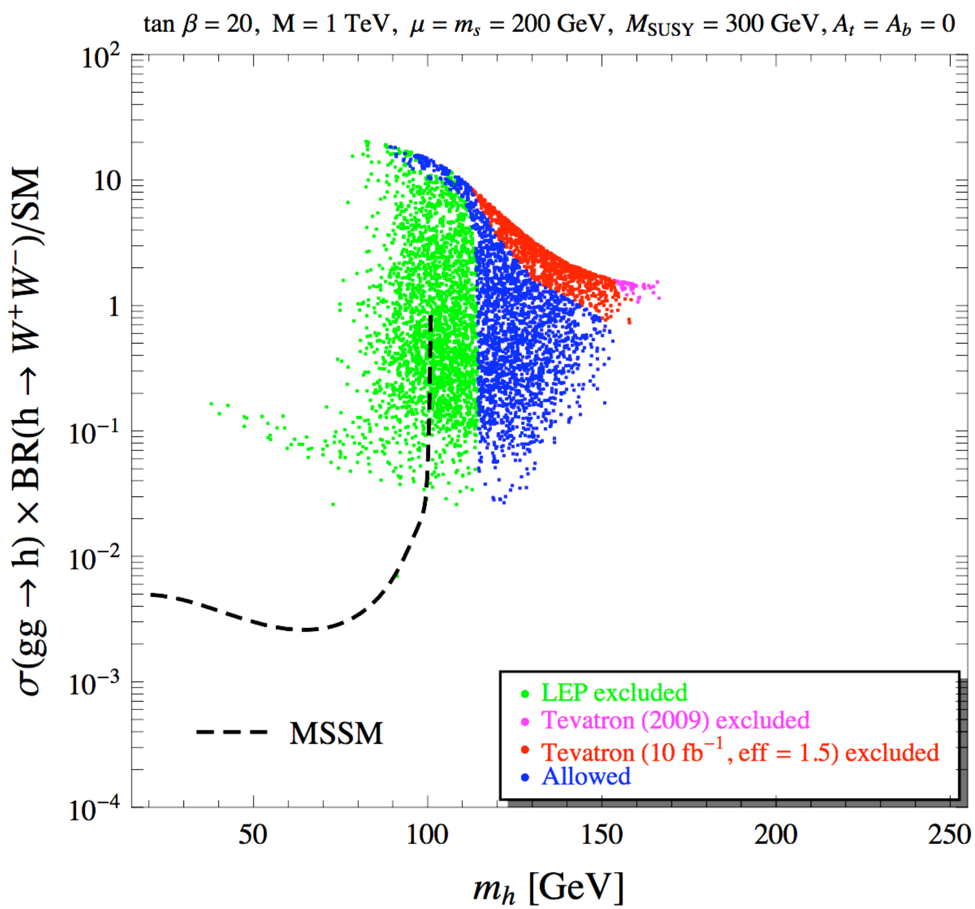
CP-even Higgs Bosons: low tanb

Tevatron searches in the h/H →WW channel effective, (h/H→ bb remains borderline)



CP-even Higgs Bosons: large tanb

- Excellent reach in the h →WW channel at the Tevatron

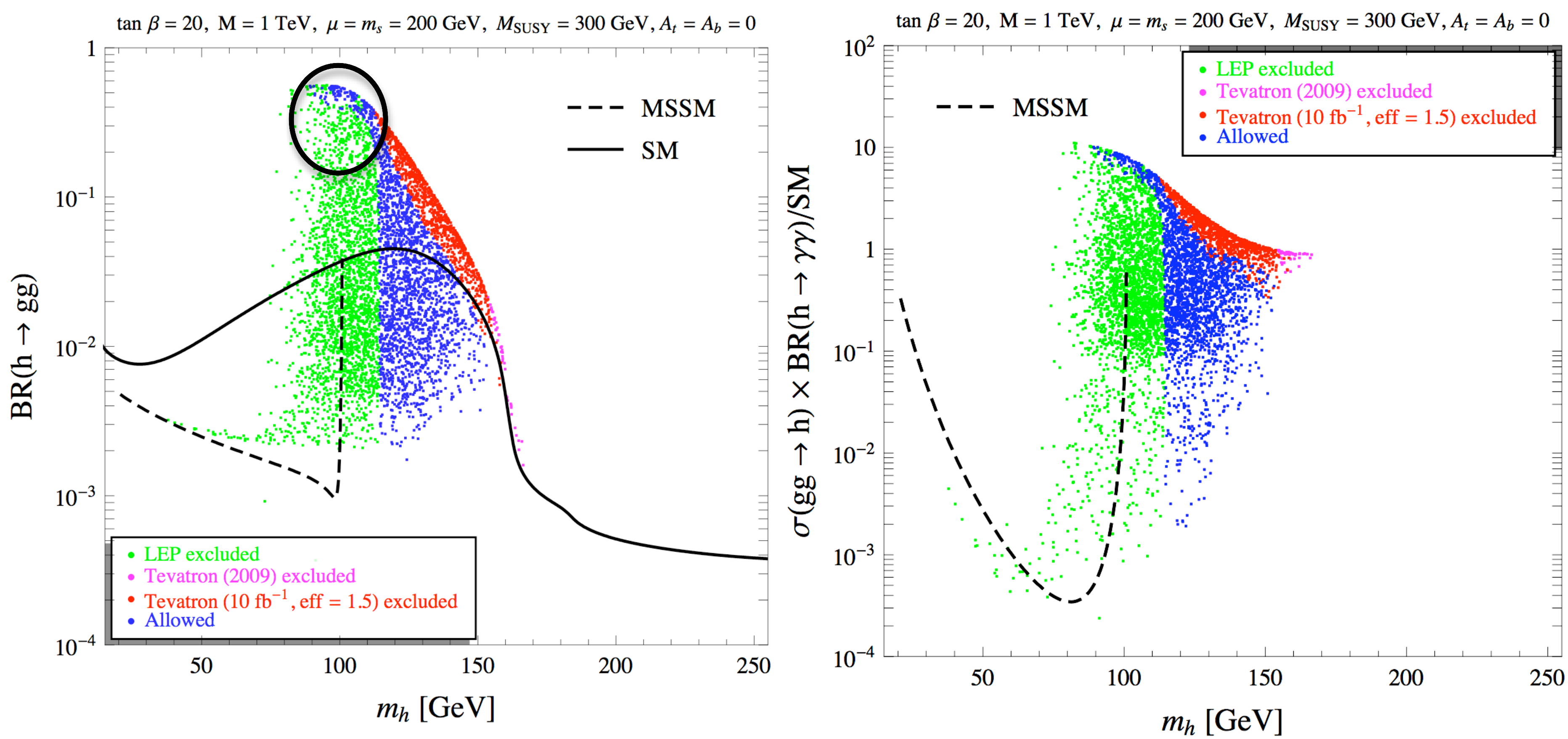


H always MSSM-like behavior in dominant bb, tau pair channels
➔ at the Tevatron reach for sufficiently large tanb.

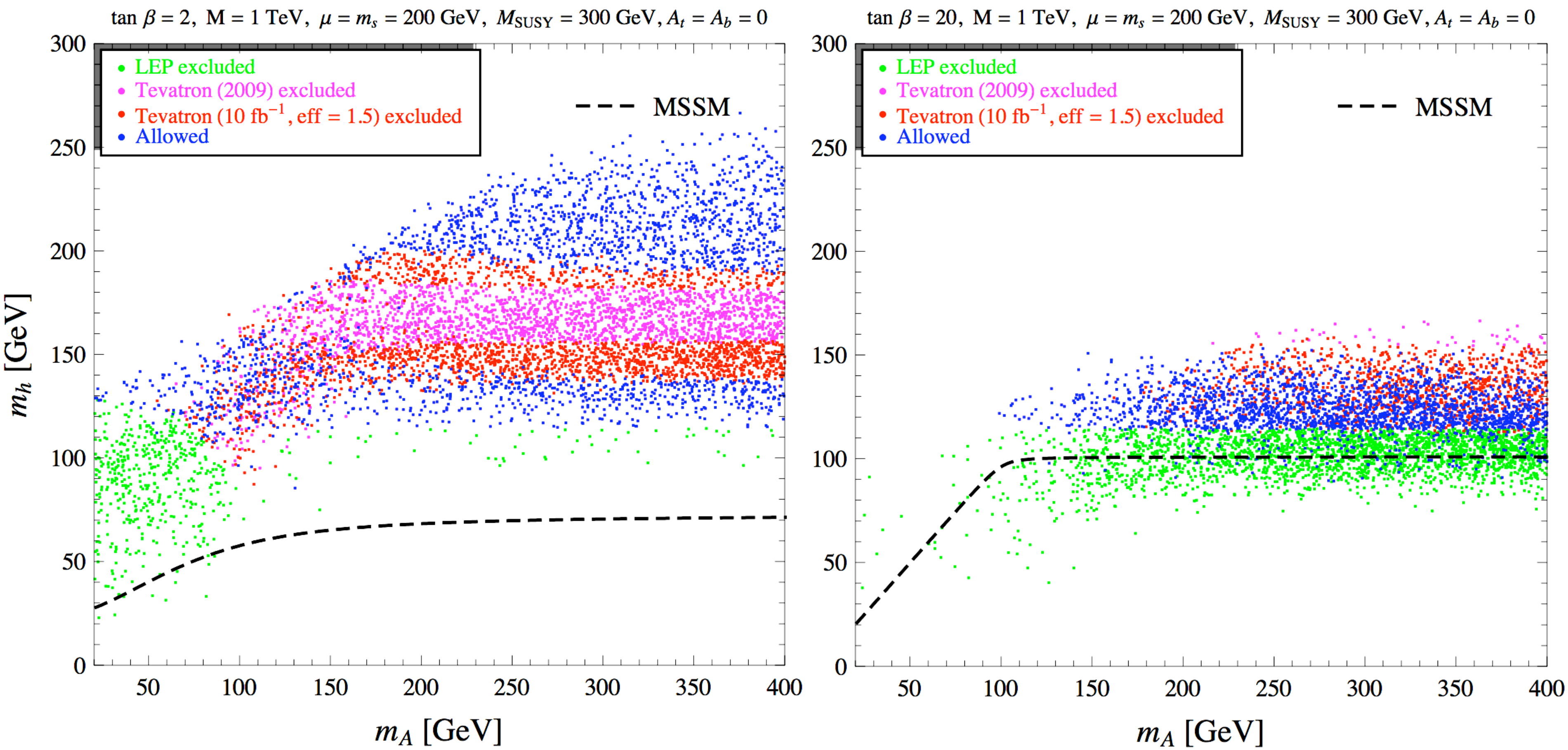
A challenge for the LHC: lightest CP-even Higgs, large tanb

- BR(h→cc,gg,diphotons) can be significantly enhanced with respect to SM ones
  => challenging dominant decay into jets

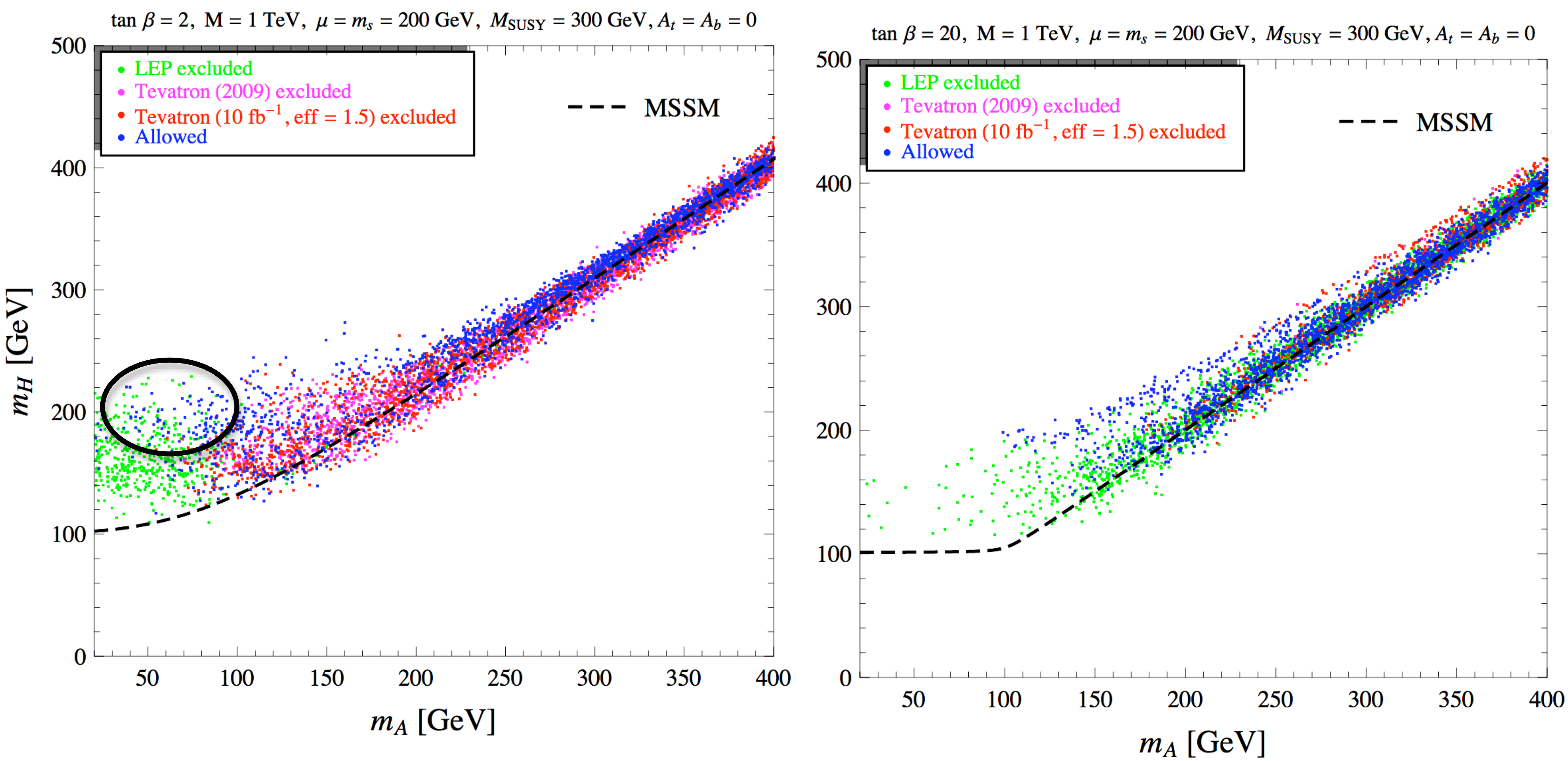
Enhanced reach in h→diphoton at LHC (only possible channel in many scenarios)



Lightest Higgs Mass in the light of collider searches



Heavy CP-even Higgs mass as a function of M_A.



Outlook

Some type of SM-like Higgs is probably around the corner

The Higgs sector can shed light to many SM puzzles
the origin of mass, flavor, dark matter …

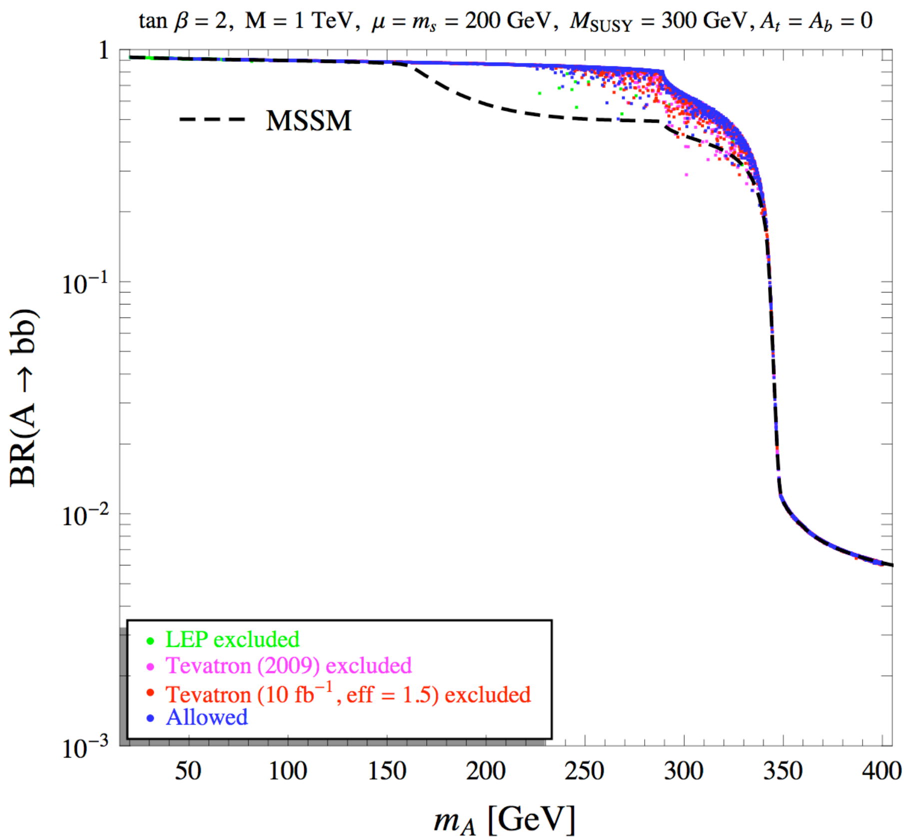
Many types of experiments are exploring the Higgs sector
-impressive results from the Tevatron-

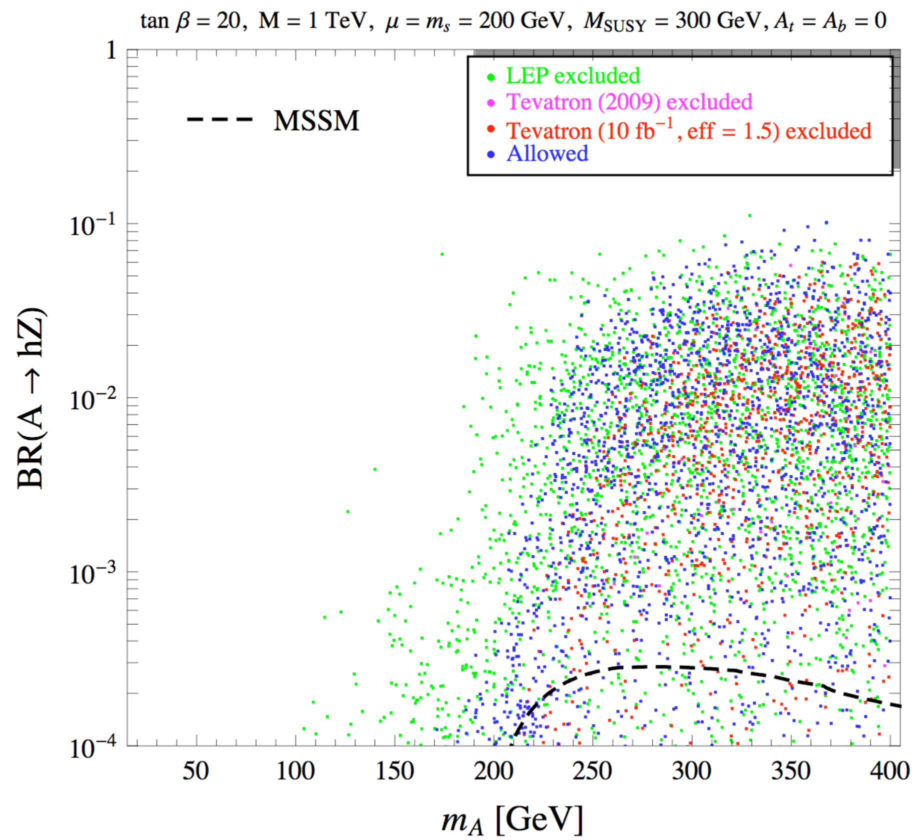
The SM and many new physics models,
in particular SUSY Models, are being constrained

Let's make a wish for Multi -HIGGS discoveries !

CP-odd and Charged Higgs behave MSSM like, but

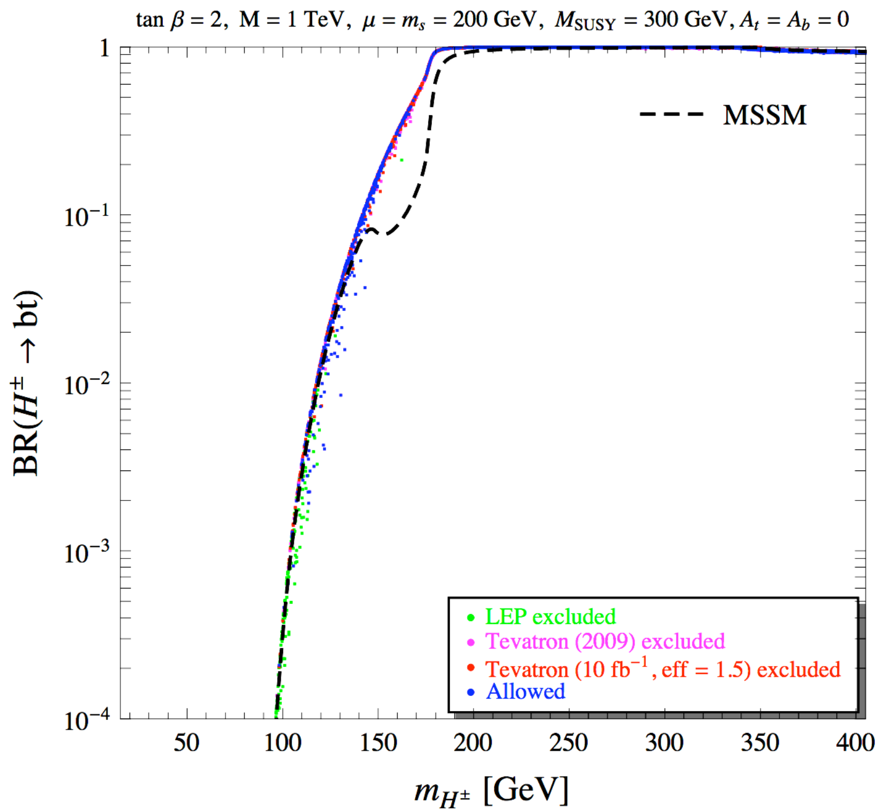
- For low tanb: enhanced BR's: $A \to b\bar{b}, \tau^+\tau^-$, due to closed channel $A \to hZ$
- For large tanb the above h channel contribute moderately

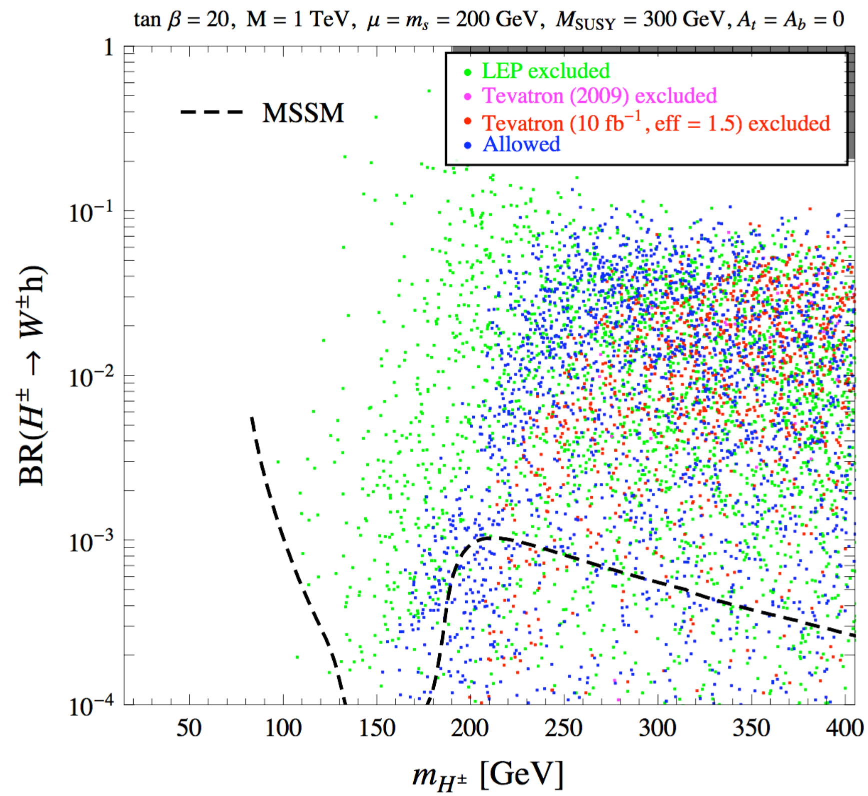




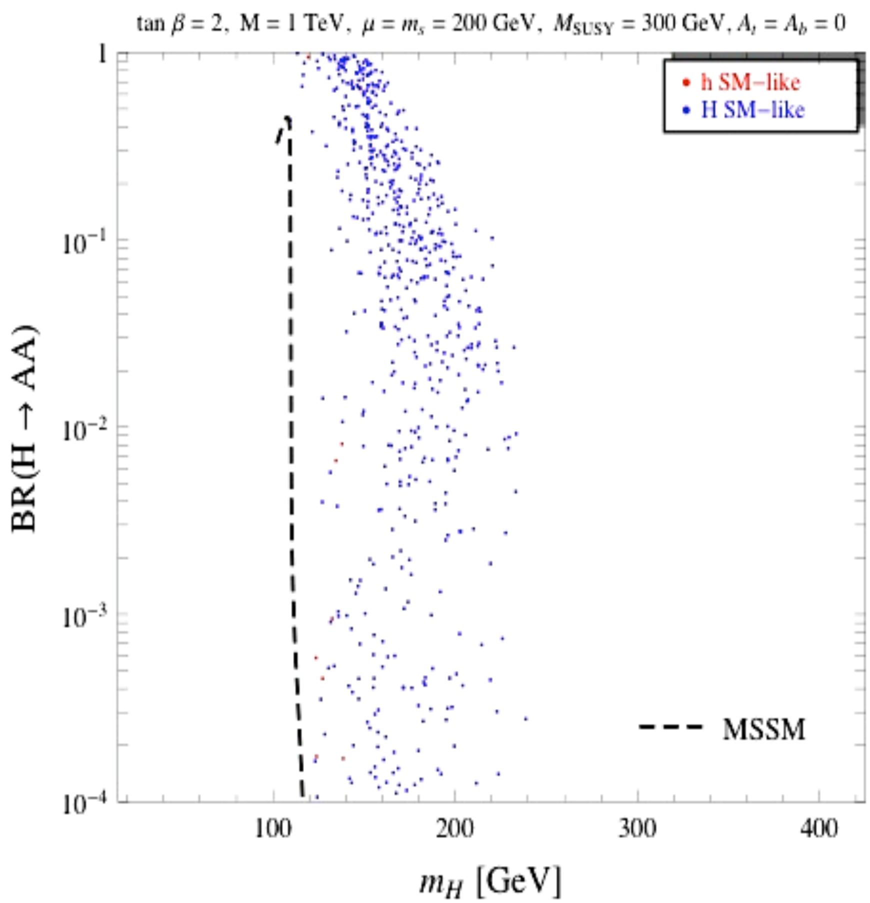
CP-odd and Charged Higgs behave MSSM like, but

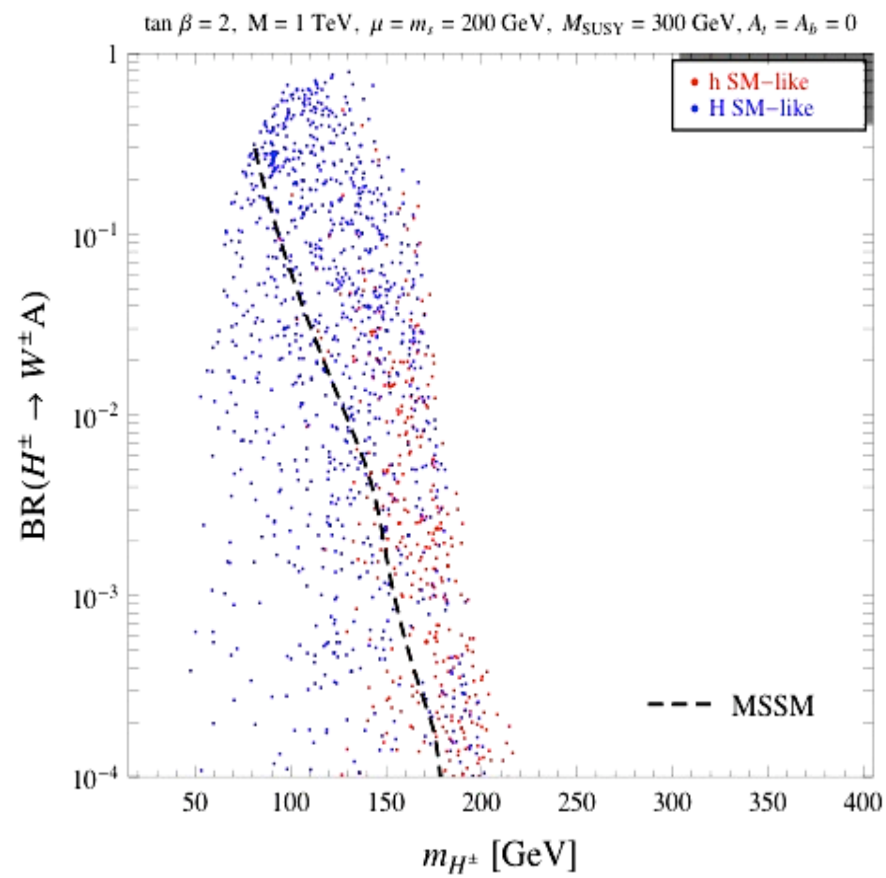
- For low tanb: enhanced BR's: $H^{\pm} \to bt, \tau^{\pm}\nu$ due to closed channel $H^{\pm} \to W^{\pm}h$ (MSSM for low m_h specific). Recall, new channel $H^{\pm} \to W^{\pm}A$
- For large tanb the above h channel contributes moderately



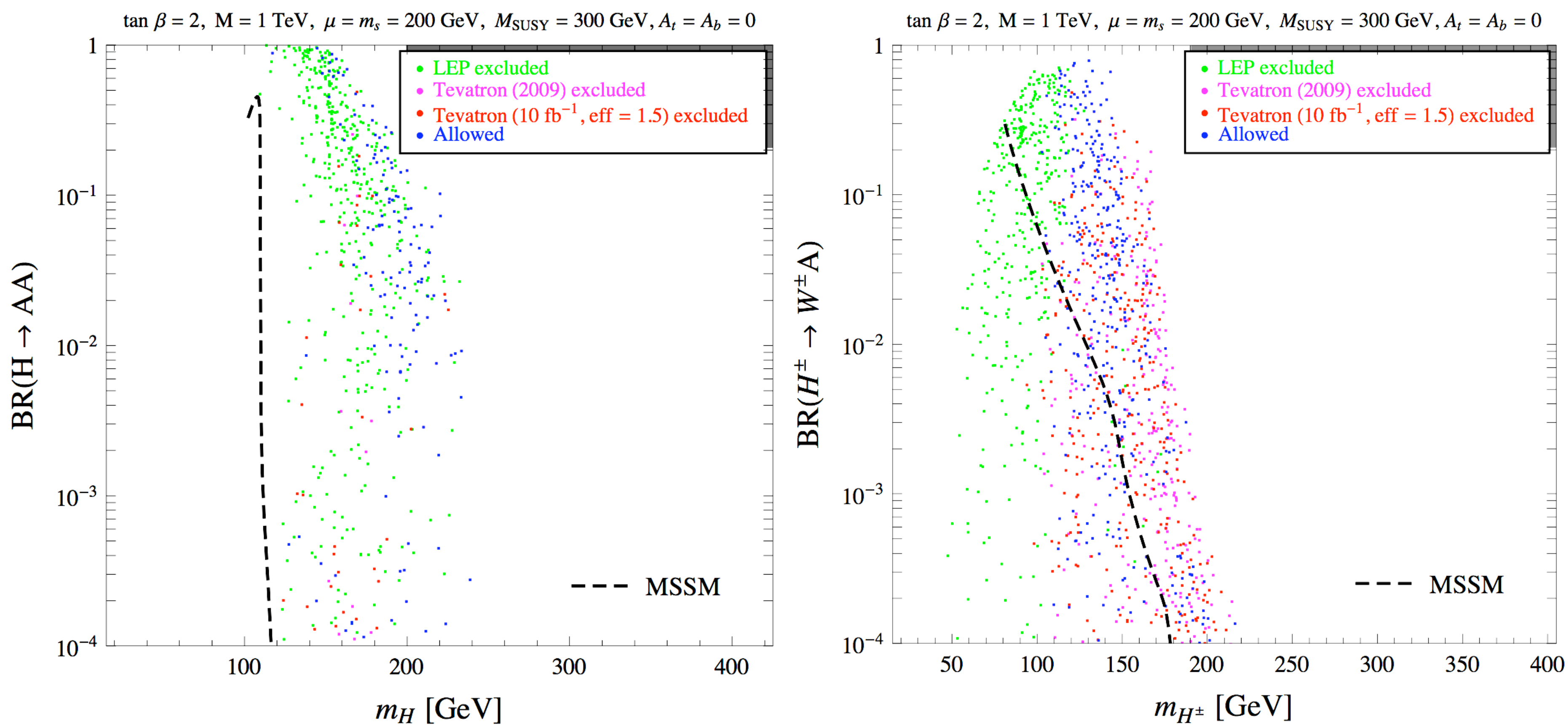


- New decay channels such as H → AA/AZ, H^+ → W^+A



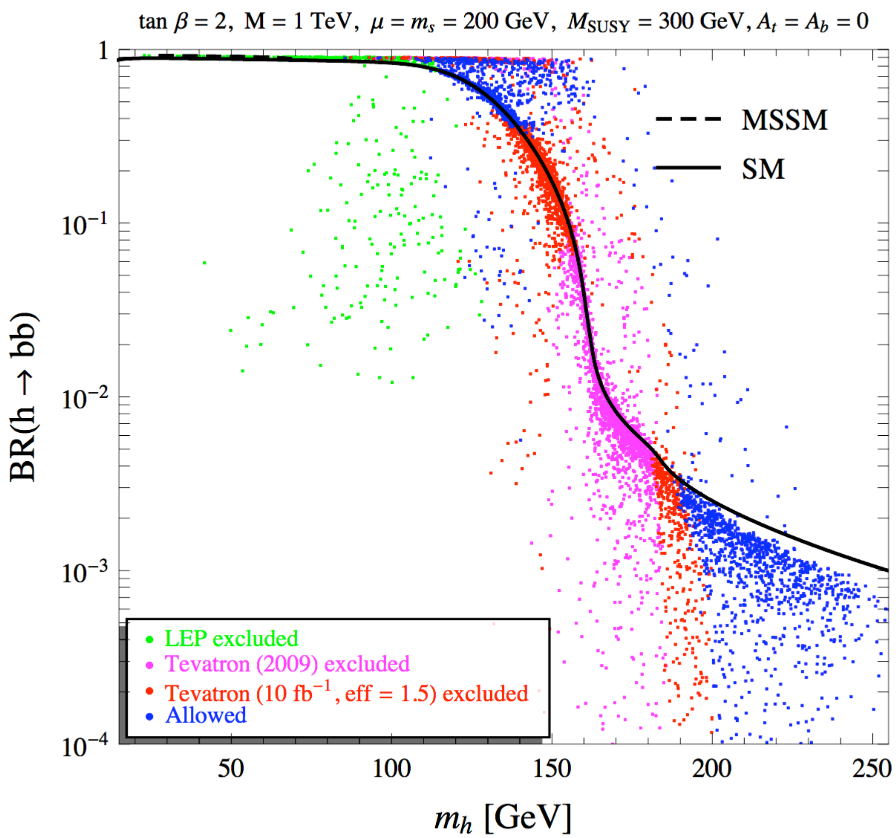


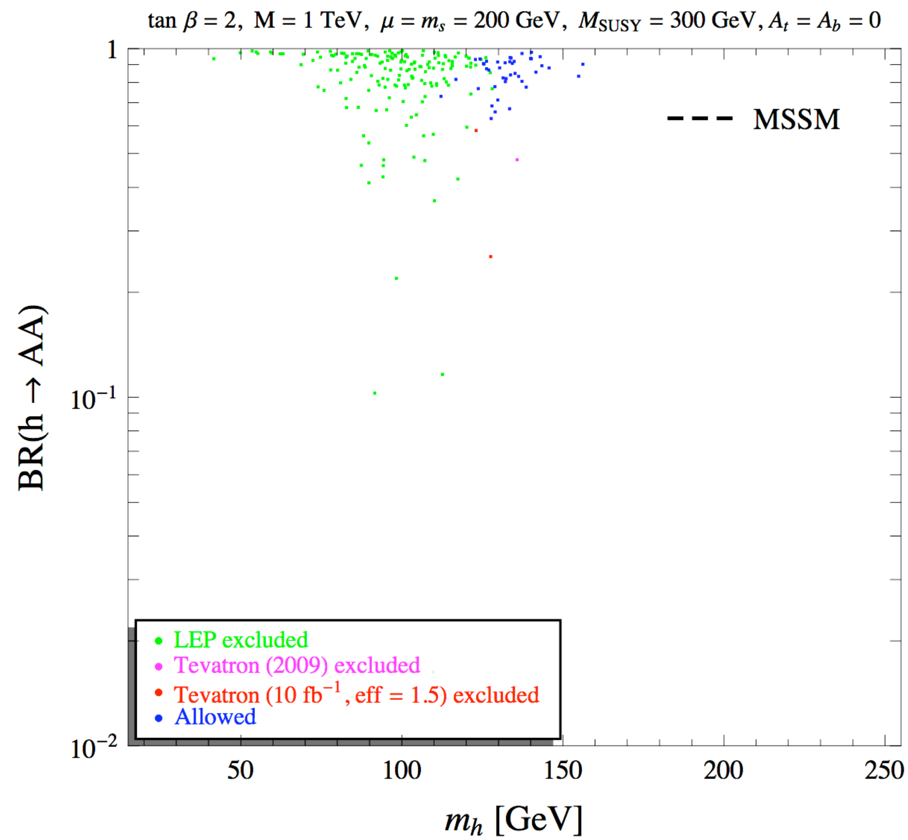
- New decay channels such as $H \rightarrow AA/AZ$, $H^{+} \rightarrow W^{+}A$



CP-even lightest Higgs: low tanb

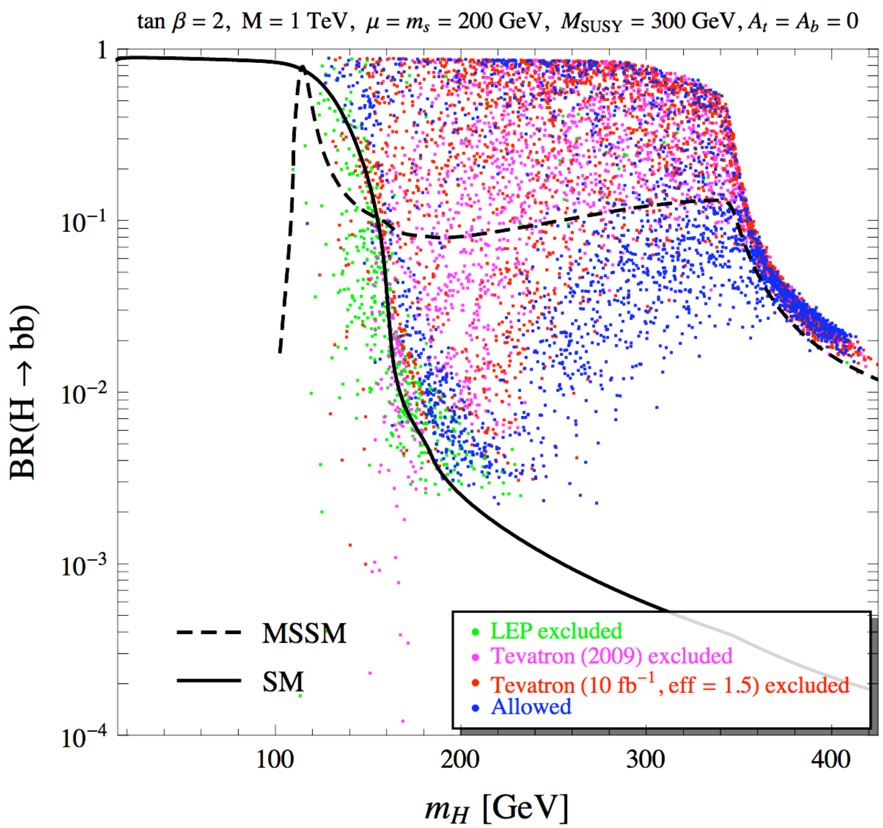
- BR(h→WWZZ) and BR(h→bb/tau's) can be significantly enhanced or suppressed with respect to SM ones
- BR(h→AA) of order one for a small parameter region with mh < 150 GeV

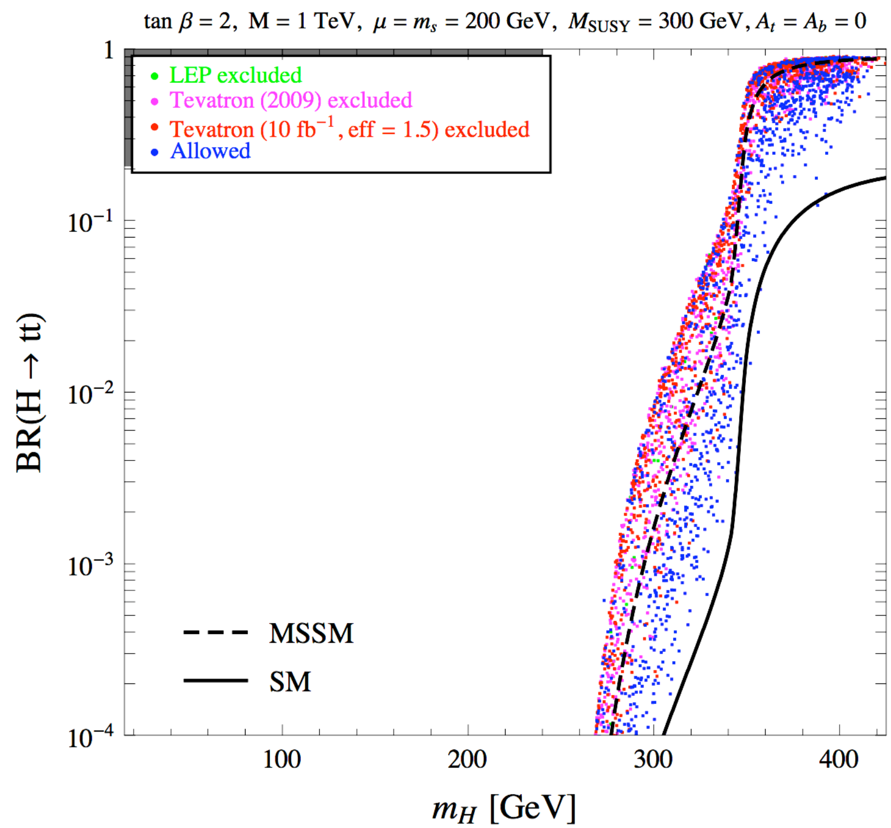




CP-even Heavy Higgs Boson: low tanb

- BR(H→WW/ZZ/bb/tau's) enhanced above the MSSM due to H→hh suppression
- H→AA/AZ open in a moderate region of parameter space.
- BR(H→tt) fluctuations around MSSM values above tt-threshold)

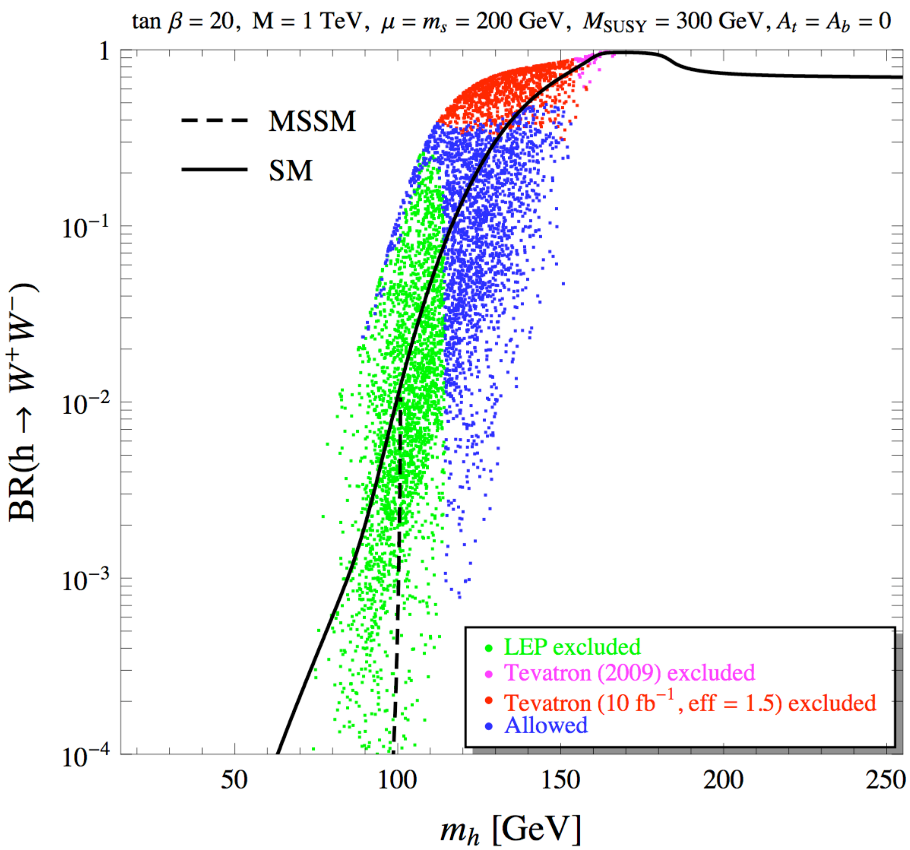


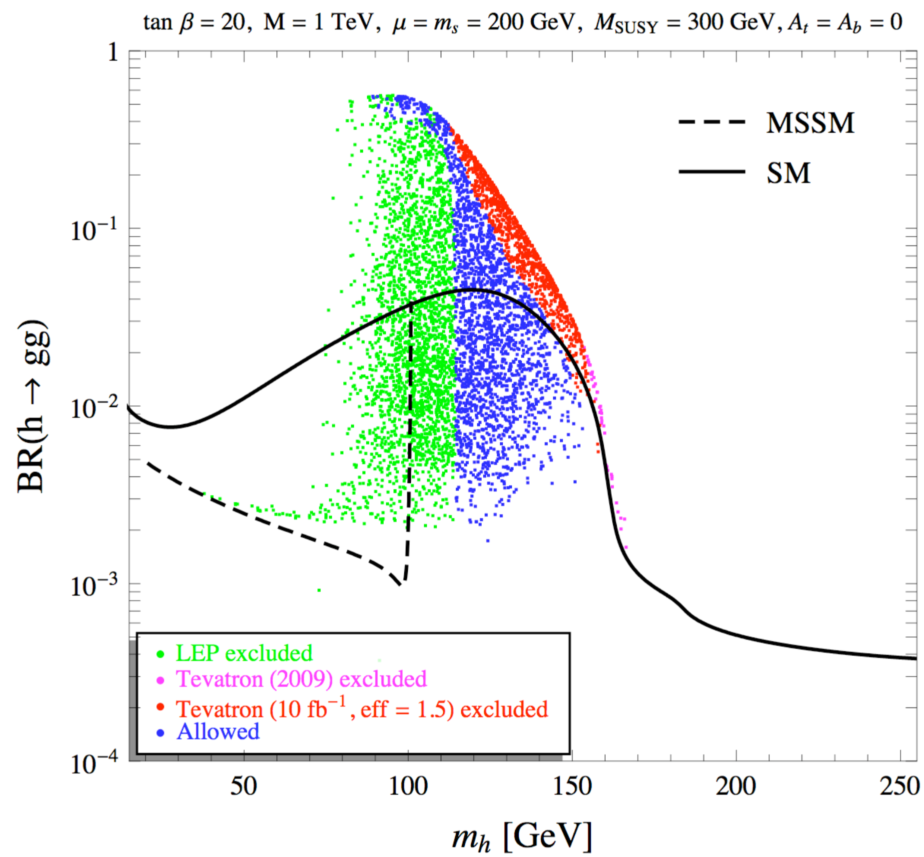


Lightest CP-even Higgs: large tanb

- BR(h→WW/ZZ) and BR(h→bb/tau's) can be significantly enhanced or suppressed with respect to SM ones
- BR(h→cc,gg,diphotons) can be significantly enhanced with respect to SM ones

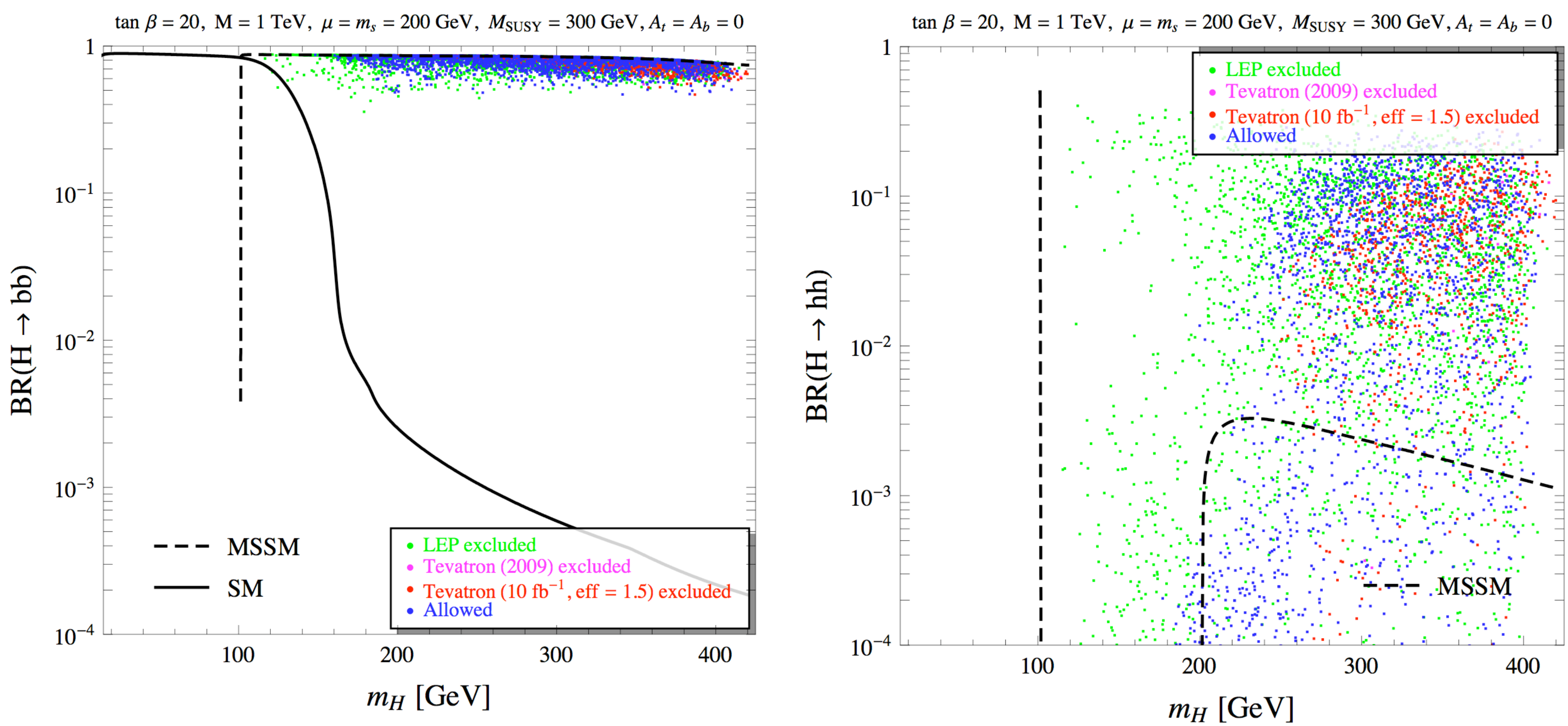
=> challenging dominant decay into jets





Heavy CP-even Higgs: large tanb

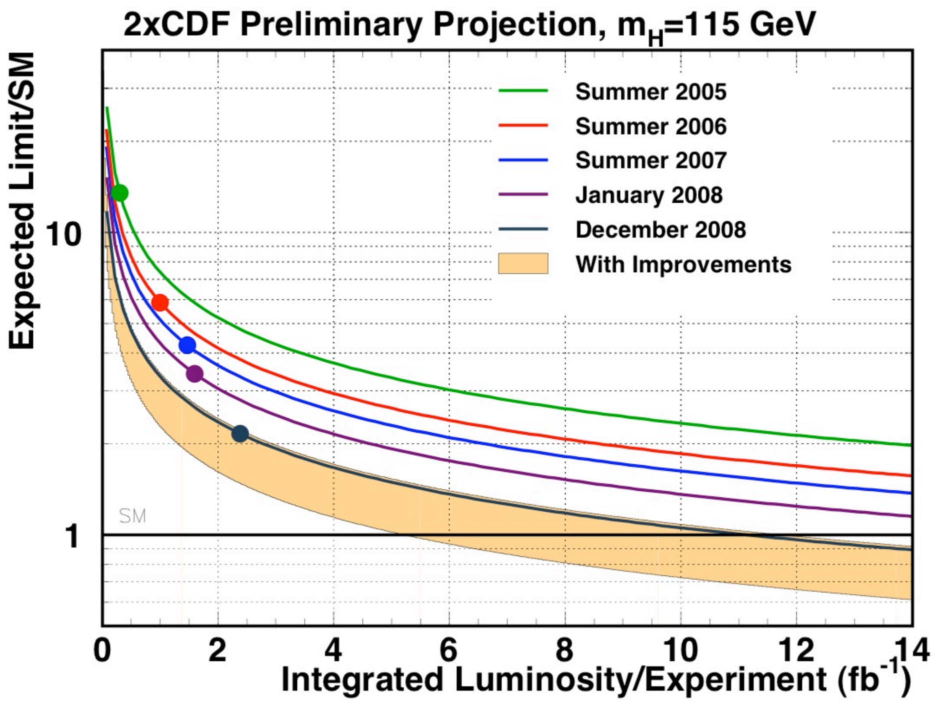
- H always MSSM-like behavior in dominant bb, tau pair channels
  ➔ at the Tevatron reach for sufficiently large tanb.
- BR(H→hh) can be sizable



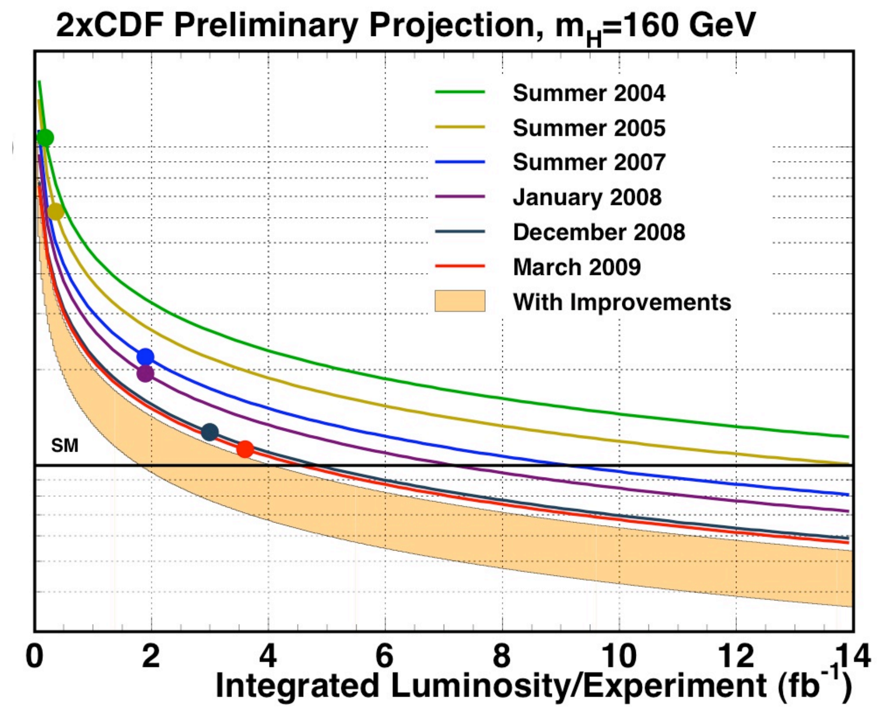
The Tevatron Projections

- based on improvements already achieved for some analysis, extending them to the rest-

Low mass regime

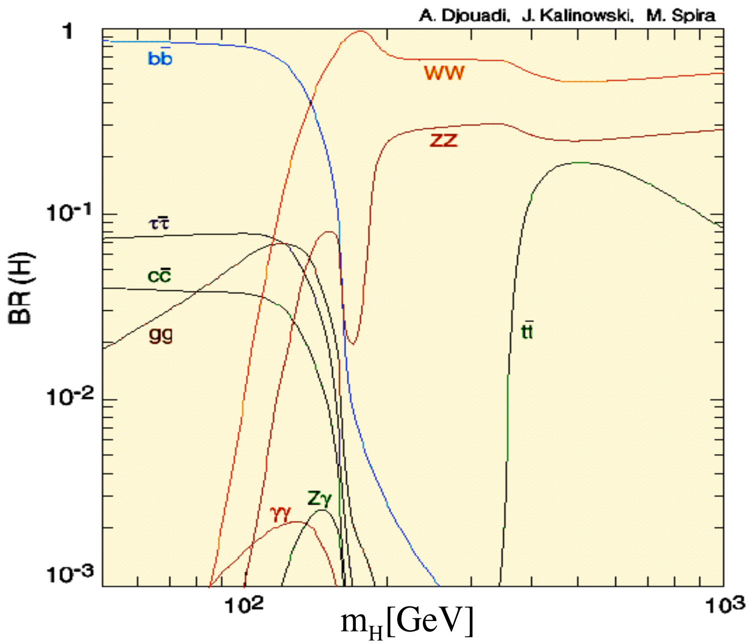


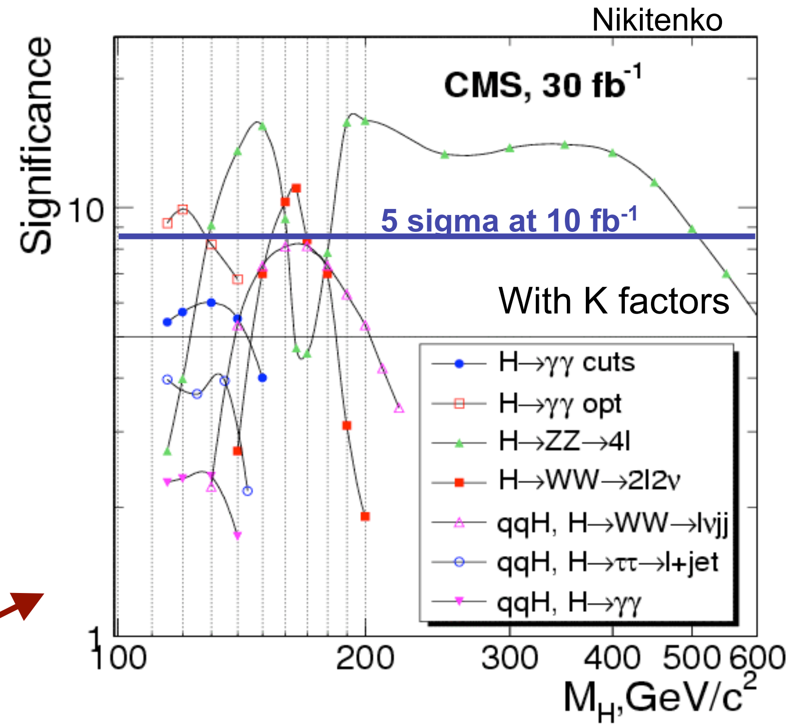
High mass regime



http://www-cdf.fnal.gov/physics/new/hdg/results/combcdf_mar09/#Projections

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→ l+l-	YES			

- **Intermediate mass range**

200 GeV < m_H < 700 GeV

Inclusive H → ZZ → 4l

- **Large mass range**: m_H > 700 GeV

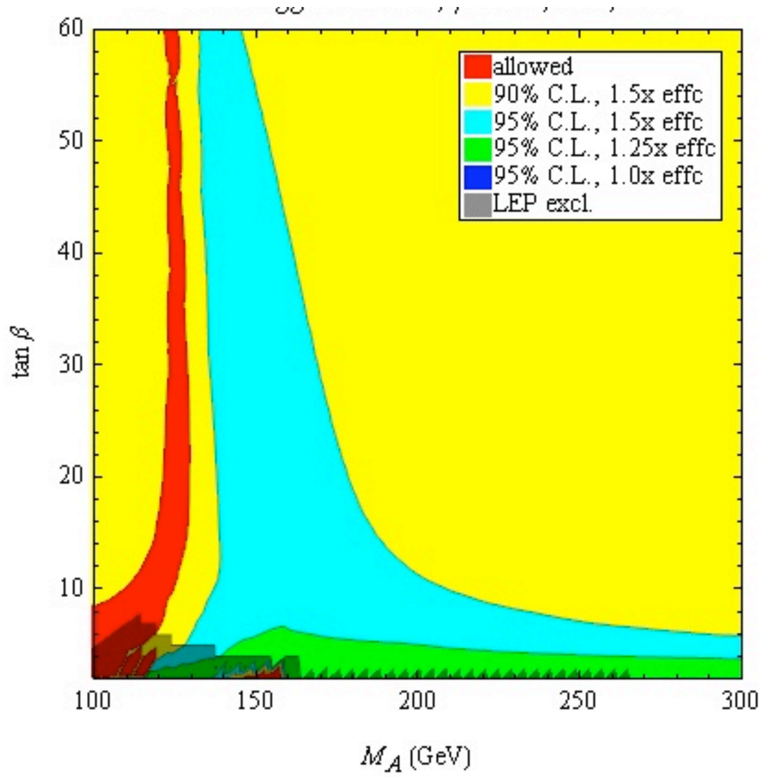
VBF with H → WW → lν jj

ZZ → ll νν

Tevatron reach for the MSSM SM-like Higgs

The m_h^{max} scenario: m_h ~ 125 GeV

All channels included in CDF/DO combination.
95% C.L. Exclusion- 10 fb^{-1}.



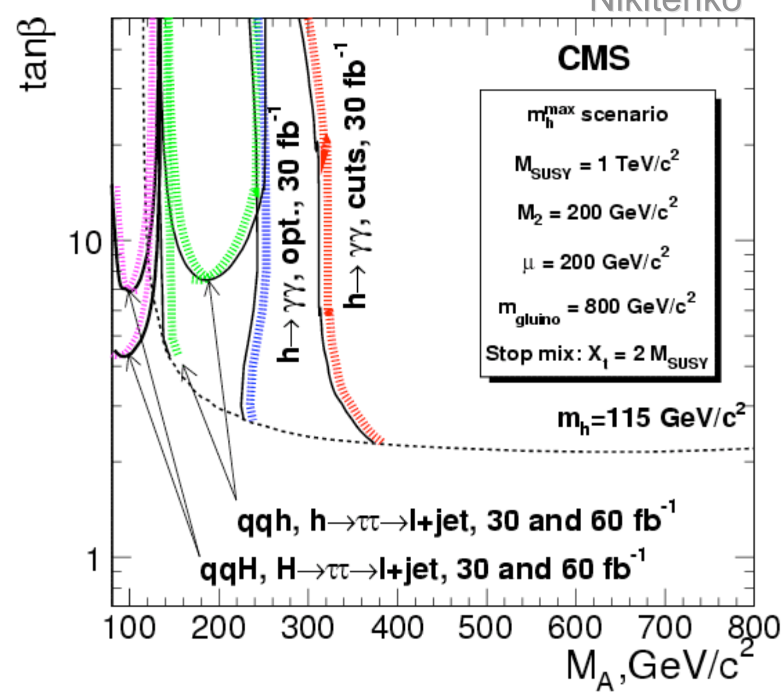
BUT with the expected improvement factor of 1.5 assumed ⟶ good coverage

Draper, Liu, Wagner

LHC projected reach for the same benchmark point

- First, full simulation analysis of qqH, H->ττ->l+jet
- Optimized NN with kinematics &γ isolation

Nikitenko



Indirect searches for MSSM Higgs bosons in B meson observables

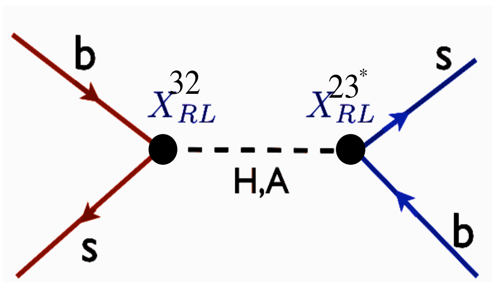
Important interplay between **B physics observables** and **SUSY Higgs searches at the Tevatron and the LHC**

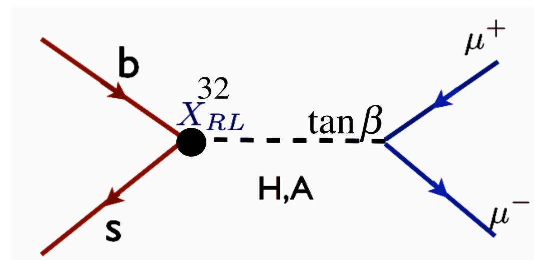
✦ Loop-induced A/H mediated FCNC's:

$$-L_{FCNC} = \bar{b}_R (X^S_{RL})^{bs} s_L \phi_S + h.c.$$

with

$$(X^{H/A}_{RL})^{bs} \approx -\frac{m_b}{v}\frac{h_t^2\ \varepsilon_Y\ \tan\beta^2}{(1+\varepsilon_0^3 \tan\beta)(1+\Delta_b)} V^{tb*}_{CKM} V^{ts}_{CKM}$$





$$(\Delta M_{B_S})^{SUSY} \propto \ominus \frac{X^{32}_{RL} X^{32}_{LR}}{m_A^2}$$

↓

Negative sign with respect to SM

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

A/H at collider reach:

strong constraints on $|\Delta M_S|^{SUSY}_{DP}$

good agreement with data

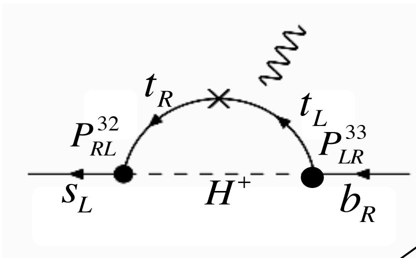
MFV: correlation between SUSY contributions

$$\frac{\Delta M_{B_S}}{BR(B_S \to \mu^+\mu^-)} \propto \frac{m_A^2}{\tan\beta^2}$$

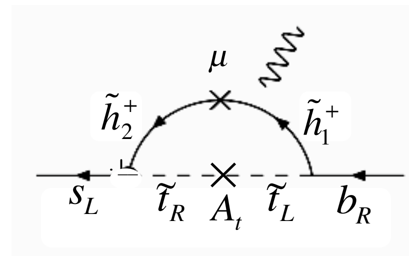
✦ Charged Higgs mediated flavor changing effects:

Similar to neutral Higgs case: tanb enhanced charged Higgs - squark loop corrections

- **Charged Higgs and chargino-stop contributions to** $BR(B \to X_s \gamma)$



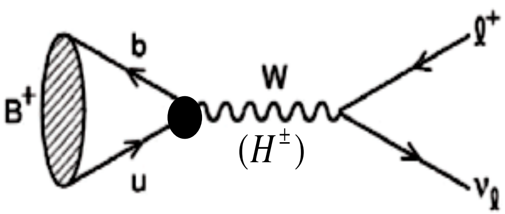
$$\delta h_t \propto h_t \frac{2\alpha_S}{3\pi} \mu^* M_{\tilde{g}}$$



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

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

- $B_u \to \tau\nu$ **transition** MSSM charged Higgs & SM contributions interfere destructively



$$R_{B_u \to \tau\nu} = \frac{\mathrm{BR}(B_u \to \tau\nu)^{MSSM}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right)\frac{\tan\beta^2}{(1+\varepsilon_0^3 \tan\beta)}\right]^2$$

In vast regions of SUSY space, indirect searches in B observables may be more powerful than direct Higgs searches

FCNC and the scale of SUSY Breaking

- FCNC's induced by Higgs-squark loops depend on the flavor structure of the squark soft SUSY breaking parameters

- **If ~~SUSY~~ is transmitted to the observable sector at high energies M~MGUT**

even starting with universal masses (MFV) in the supersymmetric theory:

Ellis, Heinemeyer, Olive, Weiglein
M.C, Menon, Wagner

Due to RG effects:

1) The effective FC strange-bottom-neutral Higgs is modified: $B_s \to \mu^+\mu^-$

$$\left(X_{RL}^{H/A}\right)^{bs} \approx -\frac{m_b}{v}\frac{(\varepsilon_0^3 - \varepsilon_0^{1,2} + h_t^2\varepsilon_Y)\ \tan\beta^2}{\left(1+\varepsilon_0^3\tan\beta\right)\left(1+\Delta_b\right)} V_{CKM}^{tb^*} V_{CKM}^{ts}$$

$\varepsilon_0^3 - \varepsilon_0^{1,2} > 0$ and proportional to $\mu M_{\tilde{g}}$

If $\mu A_t < 0$ and $\mu M_{\tilde{g}} > 0$

possible cancellation of effects

2) Flavor violation in the gluino vertex induces relevant contributions to $b \to s\gamma$

$$A_{\tilde{g}} \propto \alpha_S (m_0^2 - m_{Q_3}^2) M_{\tilde{g}}\mu\ \tan\beta\ F(m_0, m_R, m_{\tilde{b}_i}, m_{\tilde{d}_i}, M_{\tilde{g}})$$

Borzumati, Bertolini, Masiero,Ridolfi

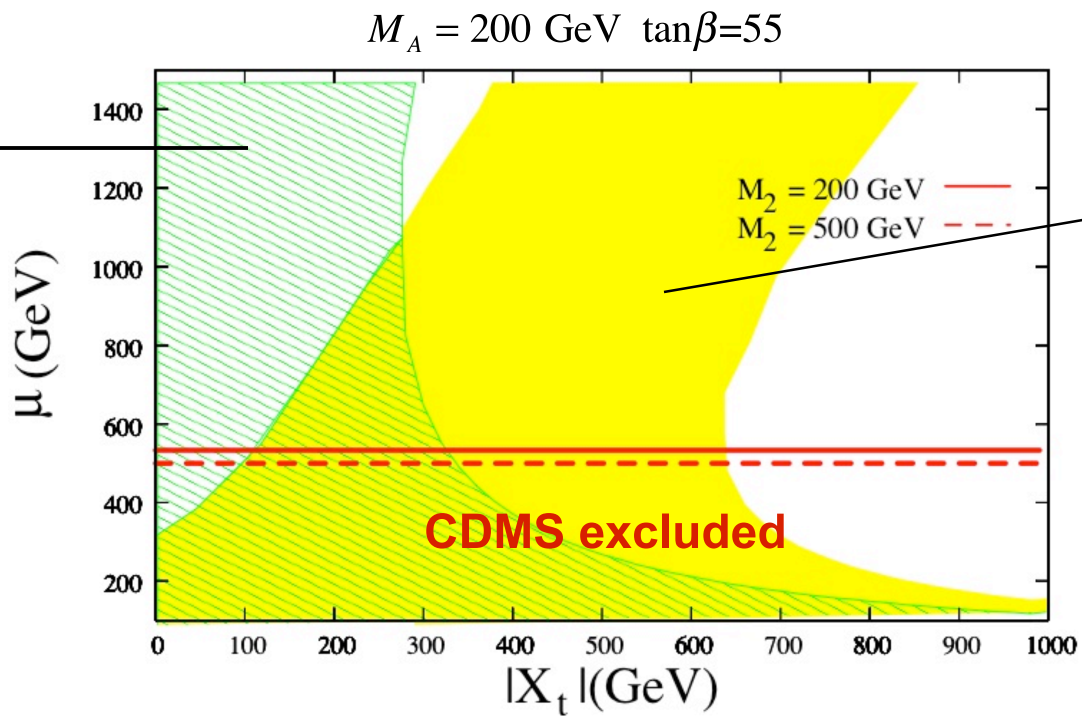
- **If ~~SUSY~~ is transmitted at low energies: M~ MSUSY,**

Squark mass matrices approx. block diag, only FC effects in the chargino-stop loop & via H^+

B physics constraints on the $X_t - \mu$ plane

Departures from MFV - the Scale of SUSY breaking

Allowed in low energy SUSY: $M = M_{SUSY}$



Allowed in high energy SUSY: $M = M_{GUT}$

M.C., Menon, Wagner

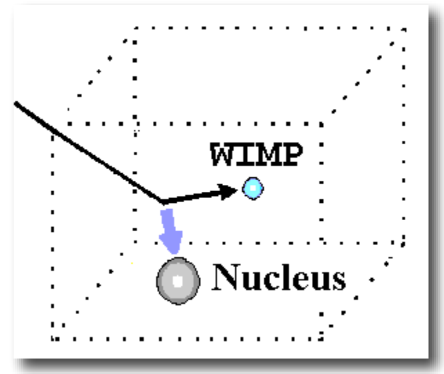
Independent of the scale at which SUSY breaking is transmitted

$$M \gg M_{SUSY} \text{ or } M \geq M_{SUSY}$$

Large stop mixing is disfavored ==> light Higgs mass below/about 120 GeV

Can be excluded by Tevatron; LHC discovery in di-tau and di-photon channels

Indirect searches for MSSM Higgs bosons in direct Dark Matter experiments



Direct DM experiments:

WIMPs elastically scatter off nuclei in target, producing nuclear recoils

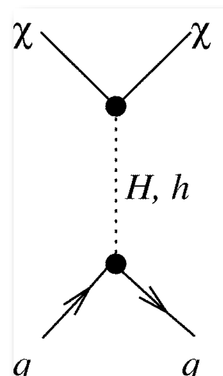
Sensitive mainly to spin-independent elastic scattering cross section $\longrightarrow \sigma_{SI} \leq 10^{-8}\, pb$

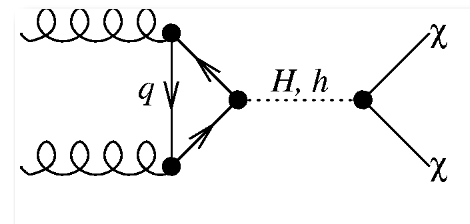
==> dominated by virtual exchange of H and h, coupling to strange quarks and to gluons via bottom loops

↓

$\tan\beta$ enhanced couplings for H

$$\sigma_{\chi N} \sim \frac{g_1^2 g_2^2 |N_{11}|^2 |N_{13}|^2\, m_N^4}{4\pi m_W^2 \cos^2\beta\, m_H^4} \left(f_{T_s} + \frac{2}{27} f_{TG} \right)^2$$





Indirect Higgs probes also in dark matter explanations of leptonic cosmic ray signals .

Non-SM-like Higgs and B-meson Constraints

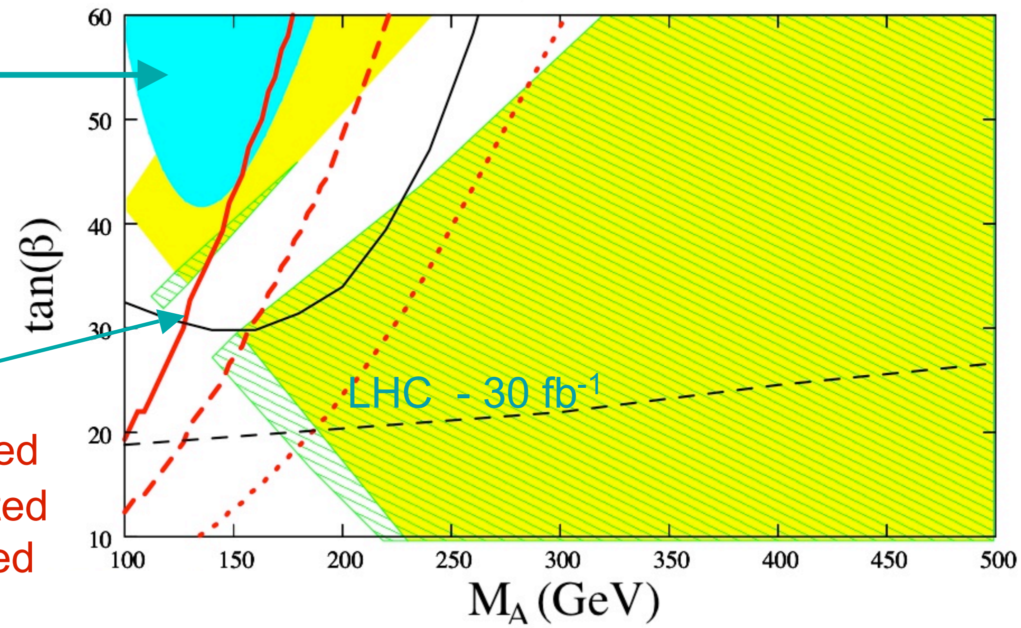
The effect of the SUSY breaking scenario in MFV

$X_t = -400$ GeV μ=800 GeV $M_{SUSY} = 1.5$TeV $M_{\tilde{g}}$=800 GeV $\mu A_t < 0$ and $\mu M_{\tilde{g}} > 0$

$p\bar{p} \to H/A \to \tau^+\tau^-$
excluded : 1.8 fb^{-1}

Tevatron - 4fb^{-1}

___CDMS excluded
- - - CDMS expected
.....Xenon expected



GREEN (hatched) region:
Allowed in low energy SUSY: M = M_{SUSY}

YELLOW region:
Allowed in high energy SUSY: M = M_{GUT}

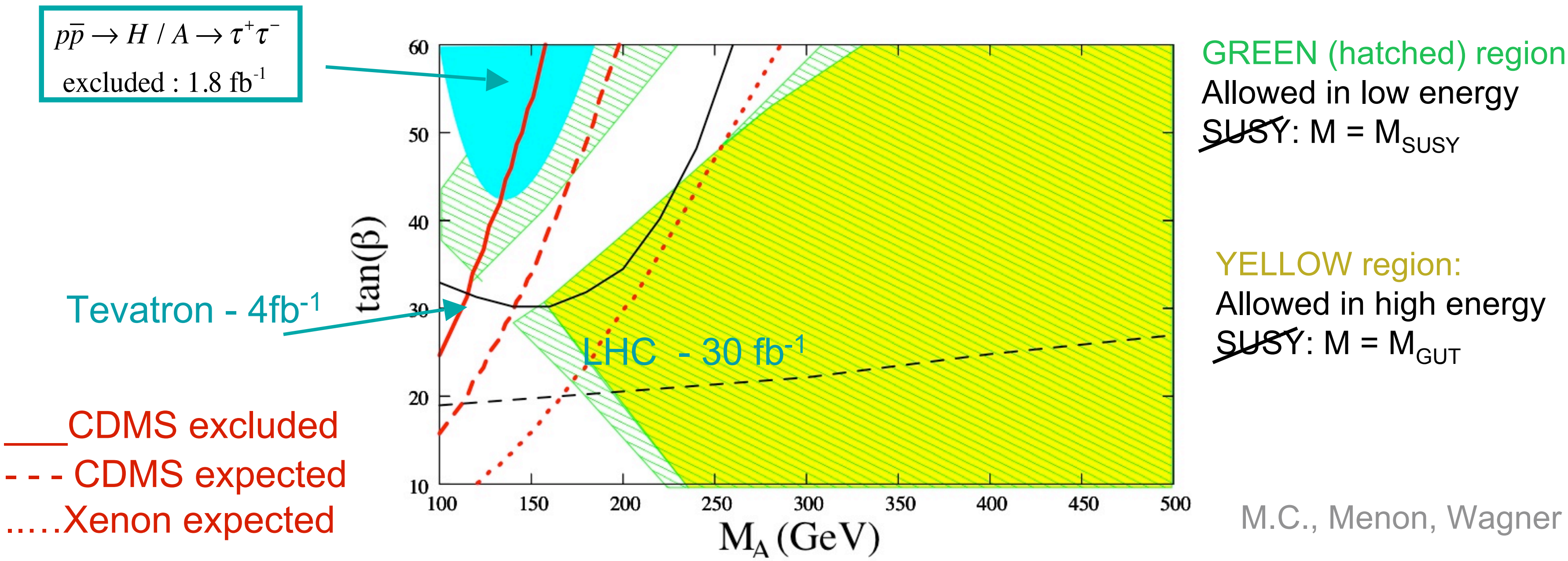
For M~M_{GUT}, parameter space less constrained for large tanb:
The chargino contribution cancels both, the gluino and charged Higgs ones to $b \to s\gamma$
Also, cancellation of $B_S \to \mu^+\mu^-$ due to mass splitting effect

For M~M_{susy}, parameter space more constrained for large tanb:
The chargino contribution cancels charged Higgs ones to $b \to s\gamma$ but $B_S \to \mu^+\mu^-$ very contrained due to non-vanishing A_t

Non-SM-like Higgs and B-meson Constraints

The effect of the SUSY breaking scenario in MFV: case 2

$X_t = 0 \quad \mu$=1000 GeV $\quad M_{SUSY} = 1.5$TeV $\quad M_{\tilde{g}}$=800 GeV



M.C., Menon, Wagner

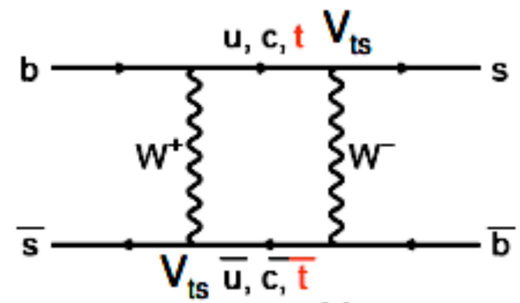
For M~M_{GUT}, parameter space STRONGLY constrained for large tanb:
The chargino and the charged Higgs contributions cancel individually, some contribution from the gluino to $b \rightarrow s\gamma$. Strong constrain from gluinos (no cancellation for At=0) to $B_S \rightarrow \mu^+\mu^-$

For M~M_{susy}, parameter space less constrained for large tanb:
The chargino and charged Higgs contributions to $b \rightarrow s\gamma$ (tend to) cancel individually and no constraint for At=0 to $B_S \rightarrow \mu^+\mu^-$

✦ Loop-induced A/H mediated FCNC can affect in a relevant way:

1) Bs mixing

$B_s^0 = (\bar{b}s) \qquad \bar{B}_s^0 = (b\bar{s})$



Flavor eigenstates mix via weak interactions →

Mass eigenstates: $B_H = pB_s^0 + q\bar{B}_s^0 \qquad B_L = pB_s^0 - q\bar{B}_s^0$

$$\Delta M_s = M_{B_H} - M_{B_L} = 2\,|M_{12}| = \frac{G_F^2}{6\pi^2}\eta_B m_{B_S} \underbrace{\hat{B}_{B_S} f_{B_S}^2}_{\text{lattice}} M_W^2 S_0(m_t)\,|V_{ts}|^2$$

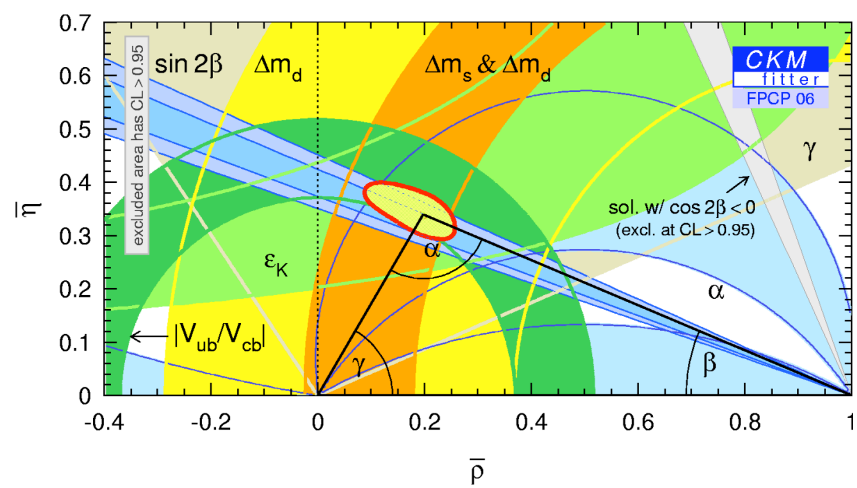
Short distance QCD corrections

Box-diagram

CDF: $\Delta M_S = 17.7 \pm 0.10 \pm 0.07\, ps^{-1}$

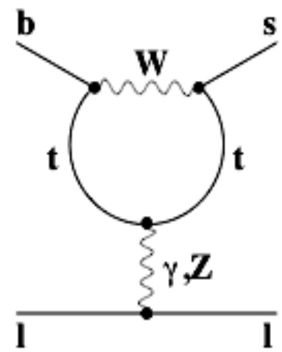
SM fit : $\Delta M_S^{CKM} = 18.9^{+12.2}_{-5.5}\, ps^{-1}$

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



2) Rare decay rate: $B_S \to \mu^+\mu^-$

Initial state $B_S = (\bar{b}s)$



Final state

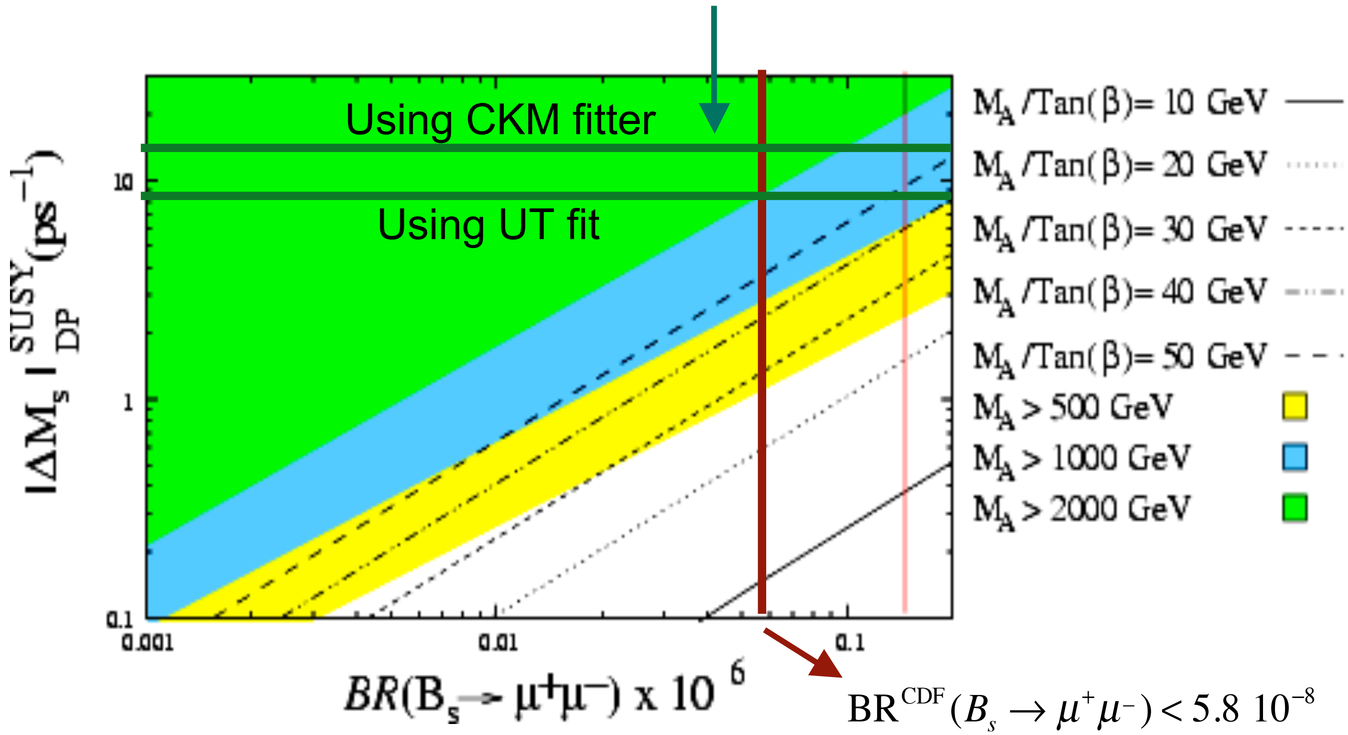
$$\text{SM amplitude} \propto V_{ts} \frac{m_\mu}{M_W}$$

$$BR(B_s \to \mu^+\mu^-)_{SM} \approx (3.8 \pm 1.0) \times 10^{-9}$$

- Present CDF limit:

$$BR(B_s \to \mu^+\mu^-) < 5.8\ 10^{-8} \quad \text{at 95\% C.L.}$$

LHCb will probe SM values with a few fb^{-1}


Using CKM fitter
Using UT fit
$|\Delta M_s|^{SUSY}_{DP}(ps^{-1})$
10
1
0.1
0.001
0.01
0.1
$BR(B_s \to \mu^+\mu^-) \times 10^6$
$M_A/Tan(\beta) = 10$ GeV
$M_A/Tan(\beta) = 20$ GeV
$M_A/Tan(\beta) = 30$ GeV
$M_A/Tan(\beta) = 40$ GeV
$M_A/Tan(\beta) = 50$ GeV
$M_A > 500$ GeV
$M_A > 1000$ GeV
$M_A > 2000$ GeV
$BR^{CDF}(B_s \to \mu^+\mu^-) < 5.8\ 10^{-8}$