Higgs Beyond the MSSM

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Outline

- Introduction:

  The minimal SUSY model (MSSM)

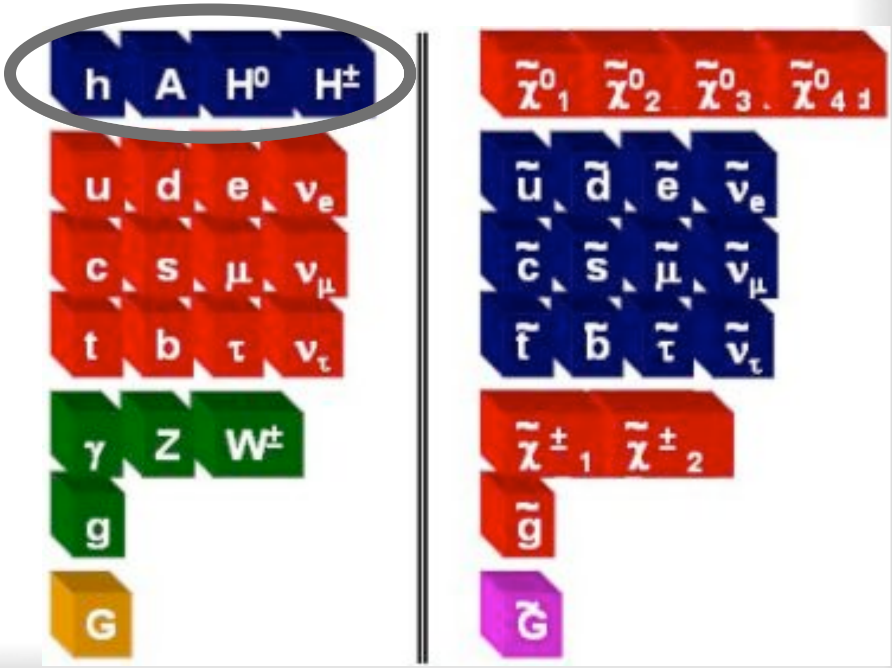
  Collider searches and the naturalness problem

- MSSM Higgs Extensions: A model-independent approach

  The EFT at NLO

  Masses and couplings

  Collider phenomenology



The Higgs Sector in the Minimal Supersymmetric SM

2 Higgs SU(2) doublets ϕ_1 and ϕ_2

$$\tan\beta = v_2/v_1$$

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

$$\Rightarrow v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

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)

hZZ, hWW, ZHA, $WH^{\pm}H$ $\longrightarrow \sin(\beta - \alpha)$
HZZ, HWW, ZhA, $WH^{\pm}h$ $\longrightarrow \cos(\beta - \alpha)$

(h,H,A) $u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \sin\alpha/\sin\beta,\ 1/\tan\beta$
(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

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

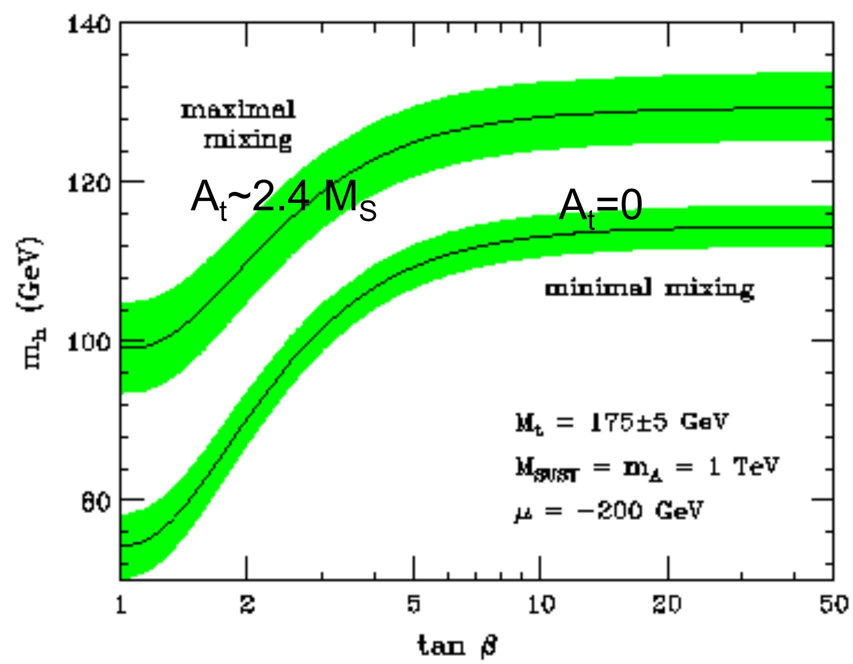
$M_S^2 = \frac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2)$ and $X_t = A_t - \mu/\tan\beta \longrightarrow$ stop mixing

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

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

$$M_S = 1 \to 2\ \text{TeV} \Longrightarrow \Delta\, m_h \simeq 2 - 5\ \text{GeV}$$

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



Radiative Corrections to the Higgs Couplings

1) Important effects through radiative corrections to the CP-even mass matrix, which defines the mixing angle $\alpha \longrightarrow \alpha_{\text{eff}}$

2) Important vertex corrections to Higgs fermion couplings from SUSY loops, relevant for large tanb (induce FCNC and CC effects)

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

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

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

destroy basic relation

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

$$\Delta_b = \left(\varepsilon_0^3 + \varepsilon_Y h_t^2\right)\tan\beta$$

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

Strong suppression of h(H) -bottom coupling

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

SM-like Higgs decays into b- and tau-pairs can be drastically changed

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

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

SUSY benchmark scenarios

M.C.,Heinemeyer, Wagner,Weiglein

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

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

$g_{hbb}, g_{h\tau\tau} \sim \sin\alpha_{eff}, / \cos\beta$ *enhanced* 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.

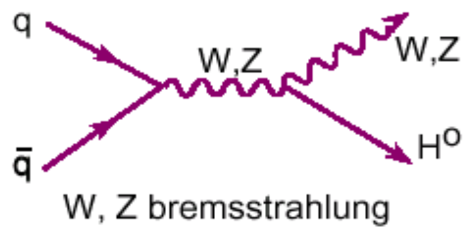
- The small $\sin\alpha_{eff}$ scenario:

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

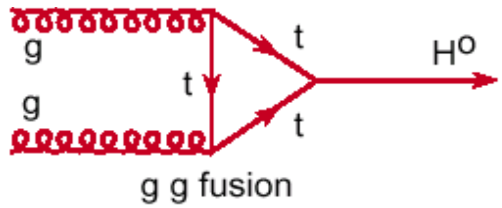
hence, BR($h \to \gamma\gamma$) and BR($h \to WW$) enhanced with respect to SM

SM-like Higgs production processes at the Tevatron



W, Z bremsstrahlung

with H → bb, WW*



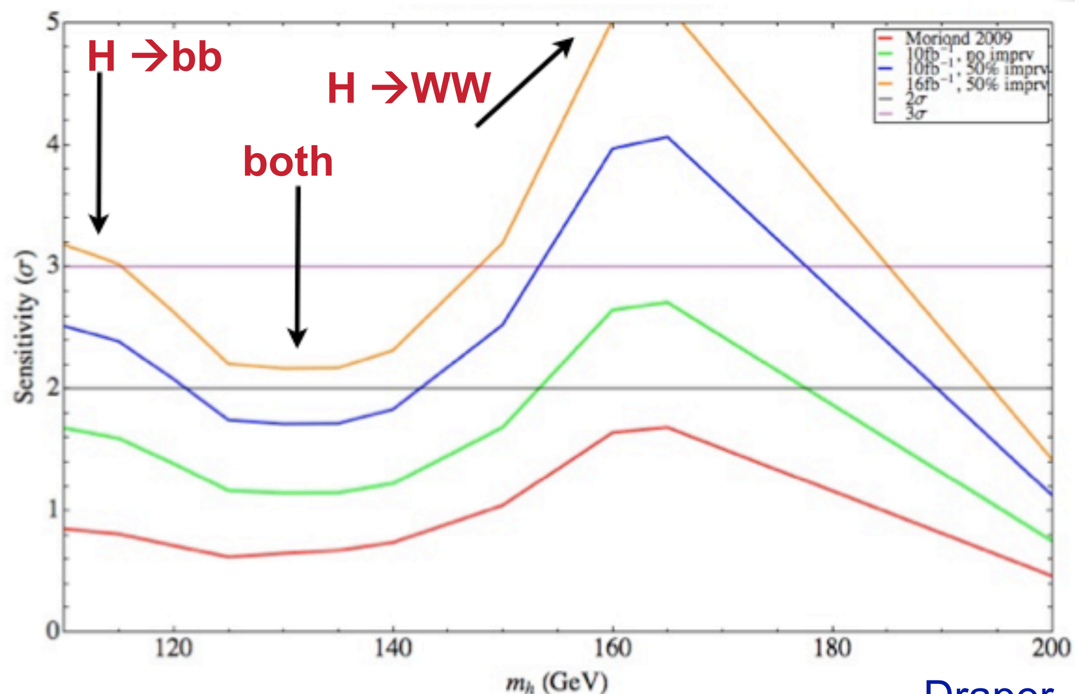
g g fusion

with H → WW(*).

The Tevatron projections for a SM-like Higgs

2011 and $\mathcal{L}$ = 10 fb^{-1}

(2014 and $\mathcal{L}$ = 16 fb^{-1})

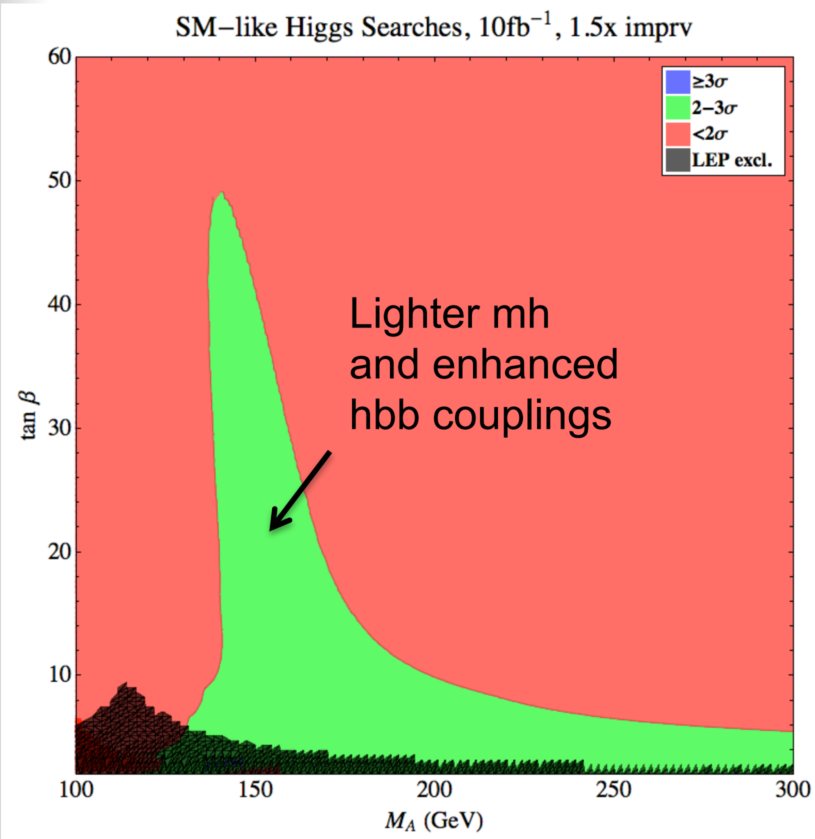


Draper

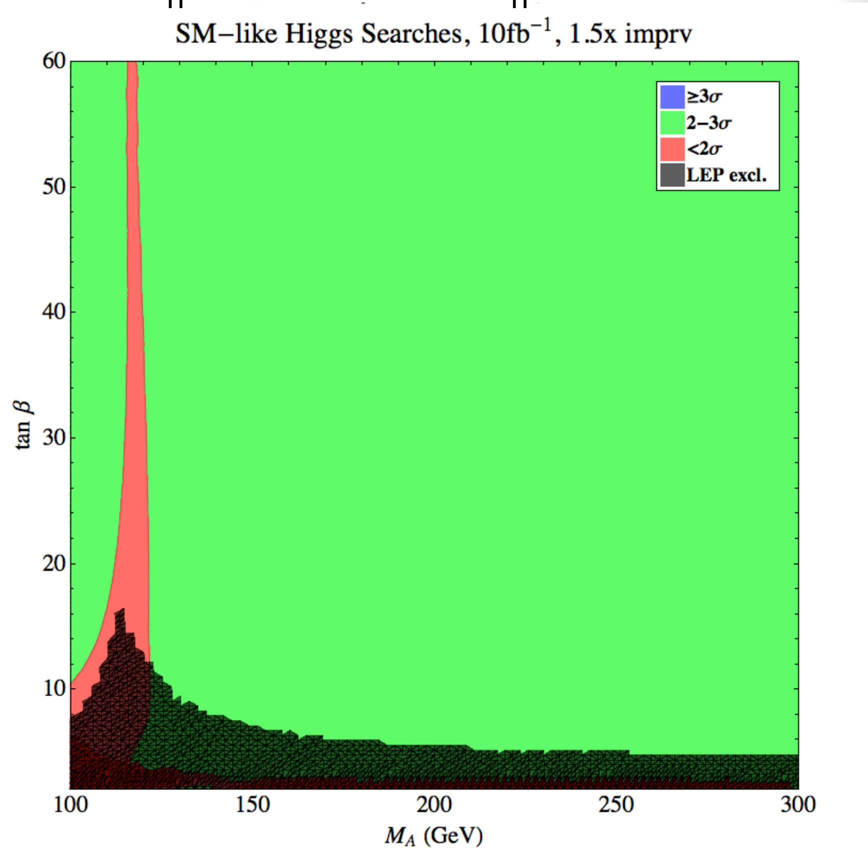
Tevatron reach for the MSSM SM-like Higgs

All channels included in CDF/DO combination.

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



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



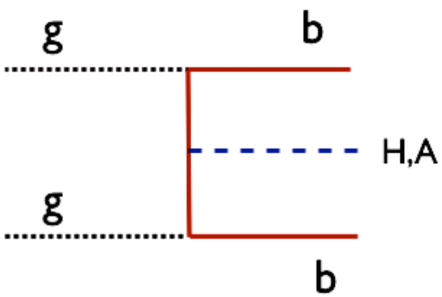
The small $\sin\alpha_{eff}$: interesting coverage from h→WW for low mass range

Draper, Liu, Wagner + MC

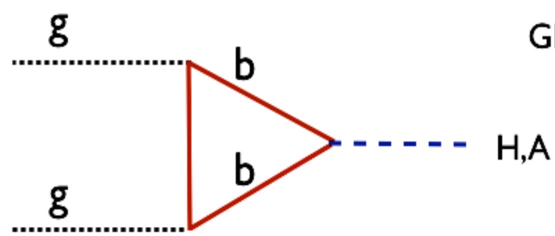
Non-Standard Higgs Production at the Tevatron and LHC

- 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.

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

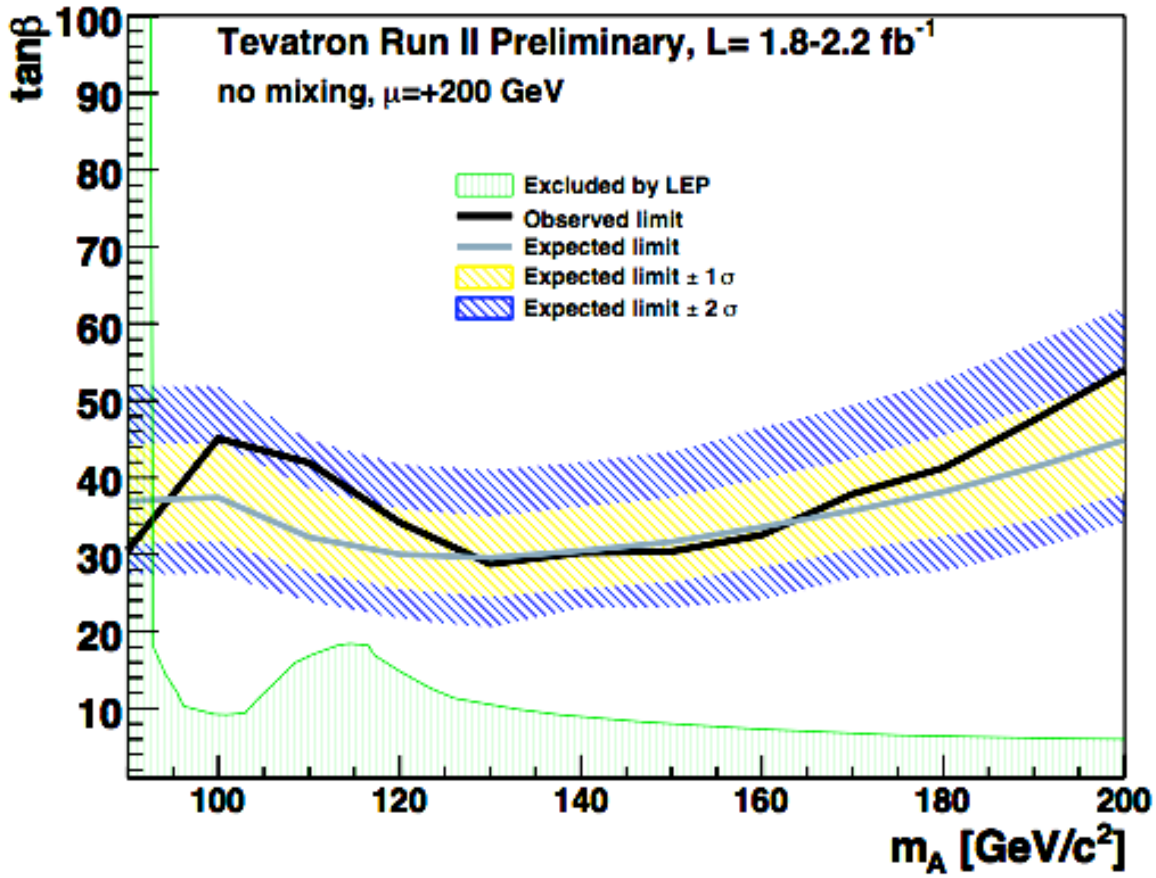
Robust predictions in the tau-tau channel

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

M.C, Heinemeyer, Weiglein, Wagner

MSSM Higgs at the Tevatron

CDF + D0 combination: A/H → di-taus

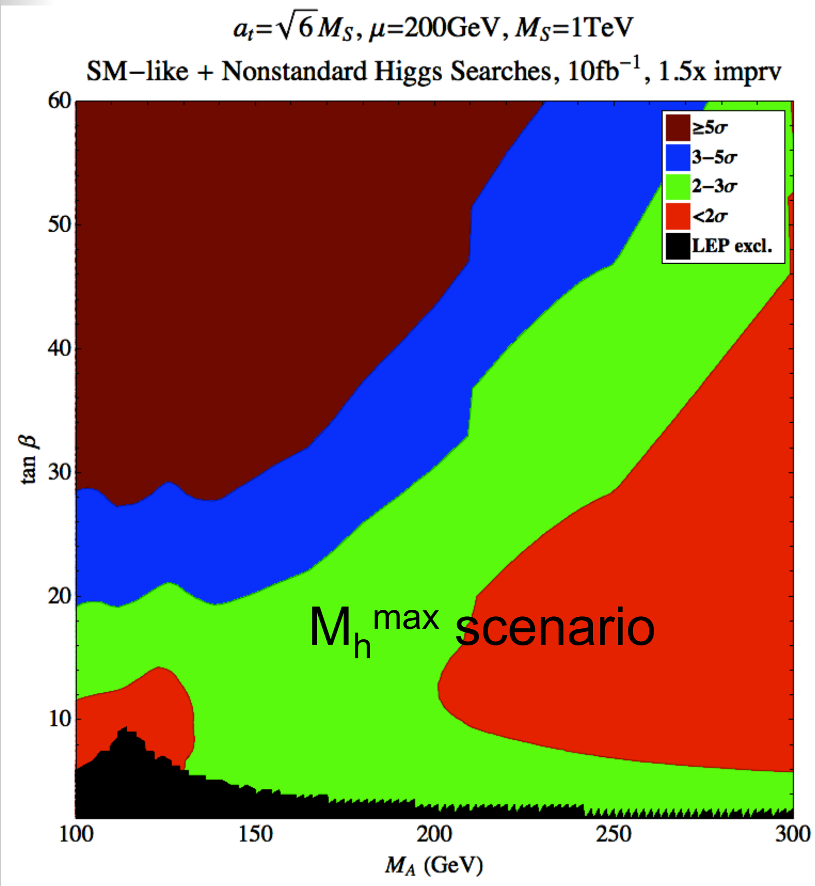


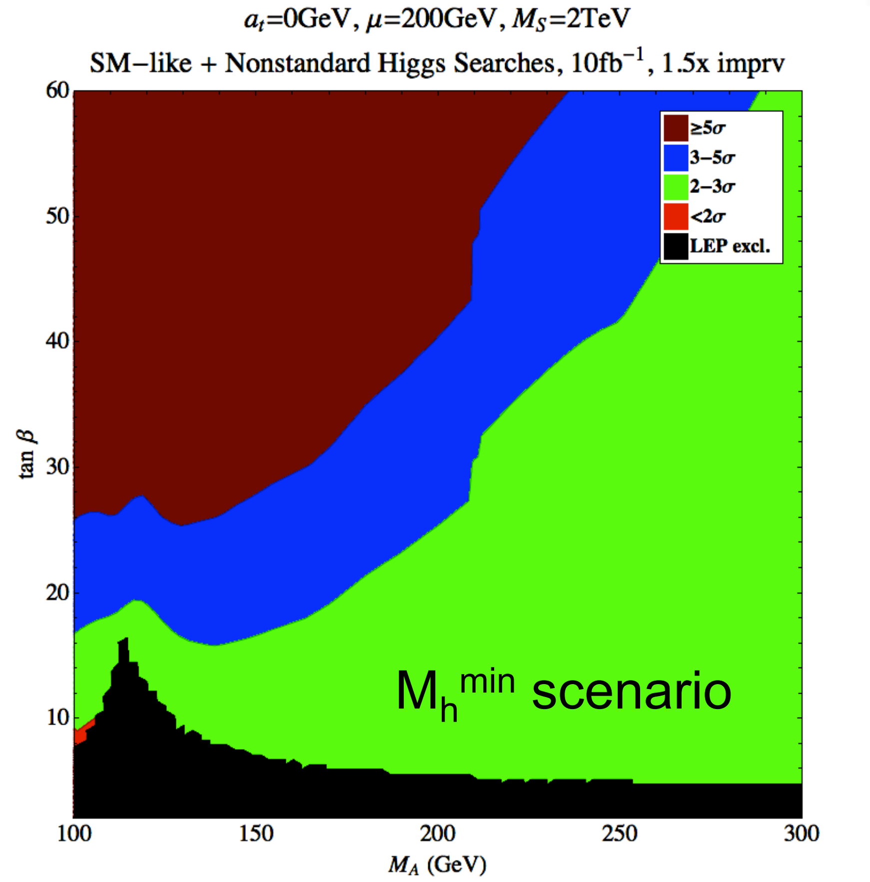
Limits are robust under variation of SUSY parameter space

MSSM Higgs at the Tevatron

All channels combined: H/A to tau pairs plus SM-like Higgs searches, CDF + D0 projections for 10 fb^{-1}

Draper, Liu, Wagner





By end of 2011, the Tevatron will have explored the majority of MSSM Higgs parameter space. With 3 more years → more that 3 sigma evidence or exclusion

Specific SUSY breaking scenarios:

CMSSM (similar situation for Minimal Gauge Mediation)

$$A_t \simeq A_0\left(1-y_t^2\right) - 2M_{1/2}$$
$$m_Q^2 \simeq m_0^2\left(1-y_t^2/2\right) + 5.5M_{1/2}^2$$
$$m_U^2 \simeq m_0^2\left(1-y_t^2\right) + 5M_{1/2}^2$$
$$m_{H_u}^2 \simeq m_0^2\left(1-3y_t^2/2\right) - 3M_{1/2}^2$$

M.C, Pokorski, Chankowski, Wagner

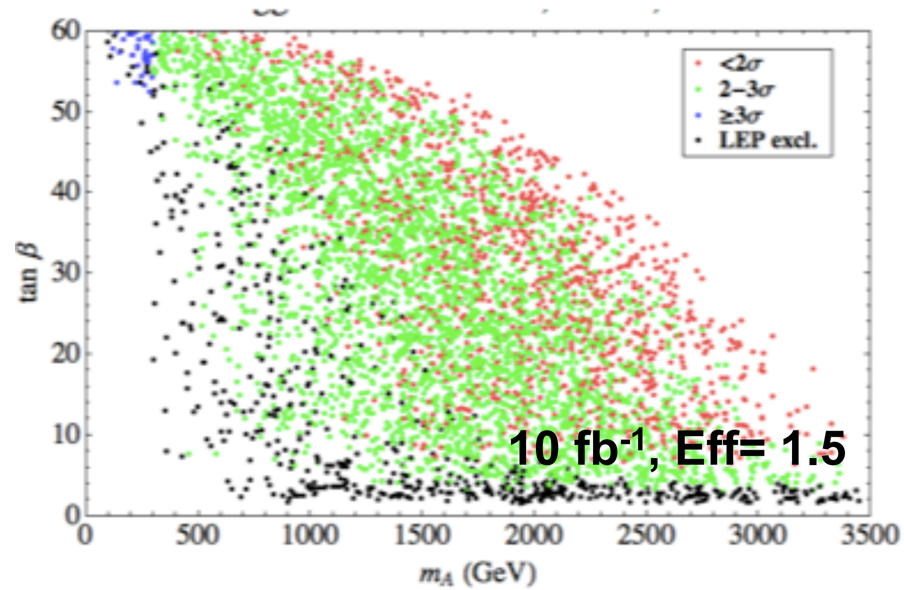
$$\mu^2 \simeq -M_Z^2/2 - m_{H_u}^2$$
$$m_A^2 \simeq -M_Z^2 + (m_{H_d}^2 - m_{H_u}^2)$$

$y_t^2 \sim 2/3$

Closer to minimal than to maximal mixing unless A0 is large.

$$50\ \text{GeV} < m_0 < 2\ \text{TeV}$$
$$50\ \text{GeV} < m_{1/2} < 2\ \text{TeV}$$
$$-3\ \text{TeV} < A_0 < 3\ \text{TeV}$$
$$1.5 < \tan\beta < 60$$

Red points fully tested by Tevatron only if 16 fb-1 of data



M.C, Draper, Heinemeyer, Liu, Wagner, Weiglein

LEP bounds on SM-like Higgs are in tension with upper bound on m_h in the MSSM

Tevatron data is further increasing that tension

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= $m_S\, \theta^2$ $W_X \supset \alpha_1 \frac{\omega_1}{2M} X (H_u H_d)^2$

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

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...)

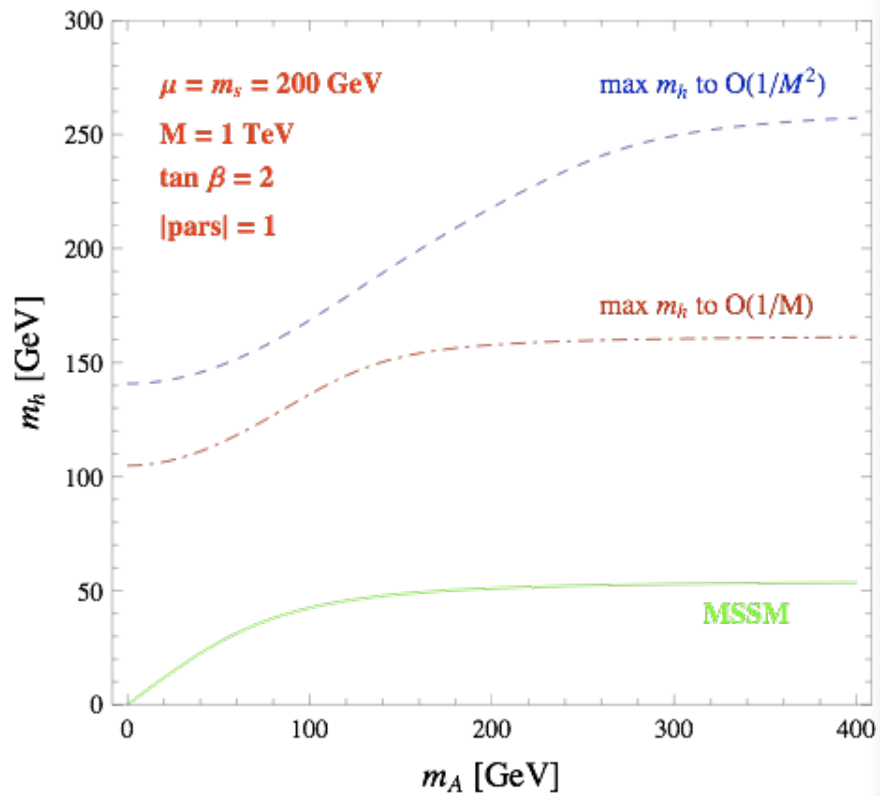
Higgs Spectra in EFT extensions of the MSSM

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

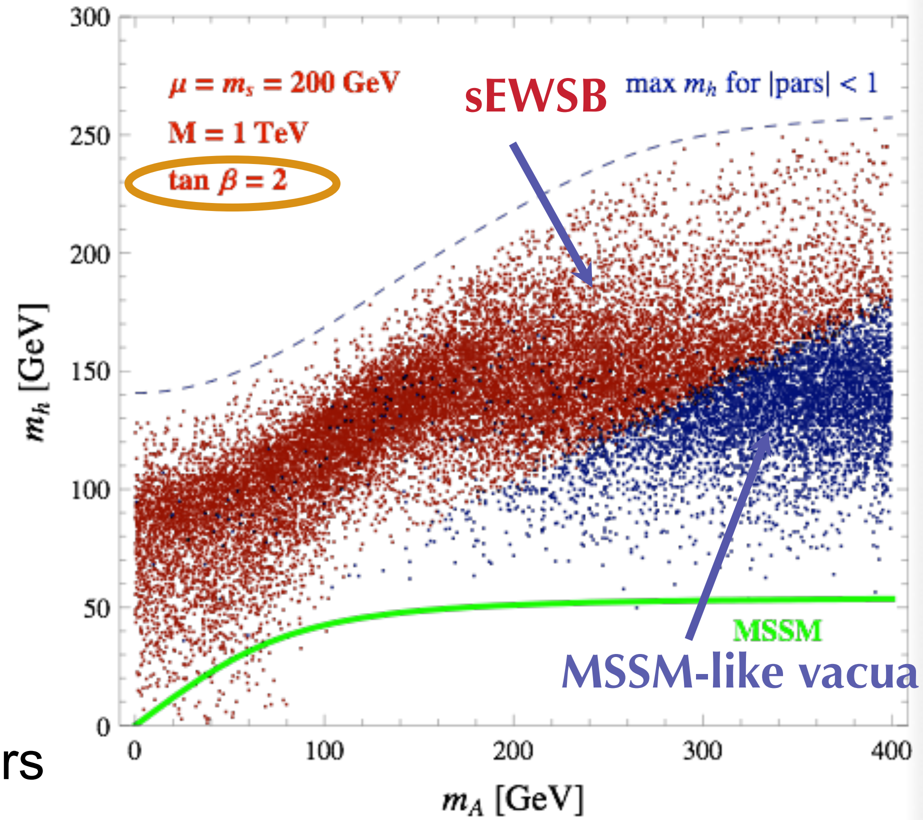
M.C., Kong, Ponton, Zurita

The lightest tree level Higgs mass is well above M_Z.

see Ponton's talk

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

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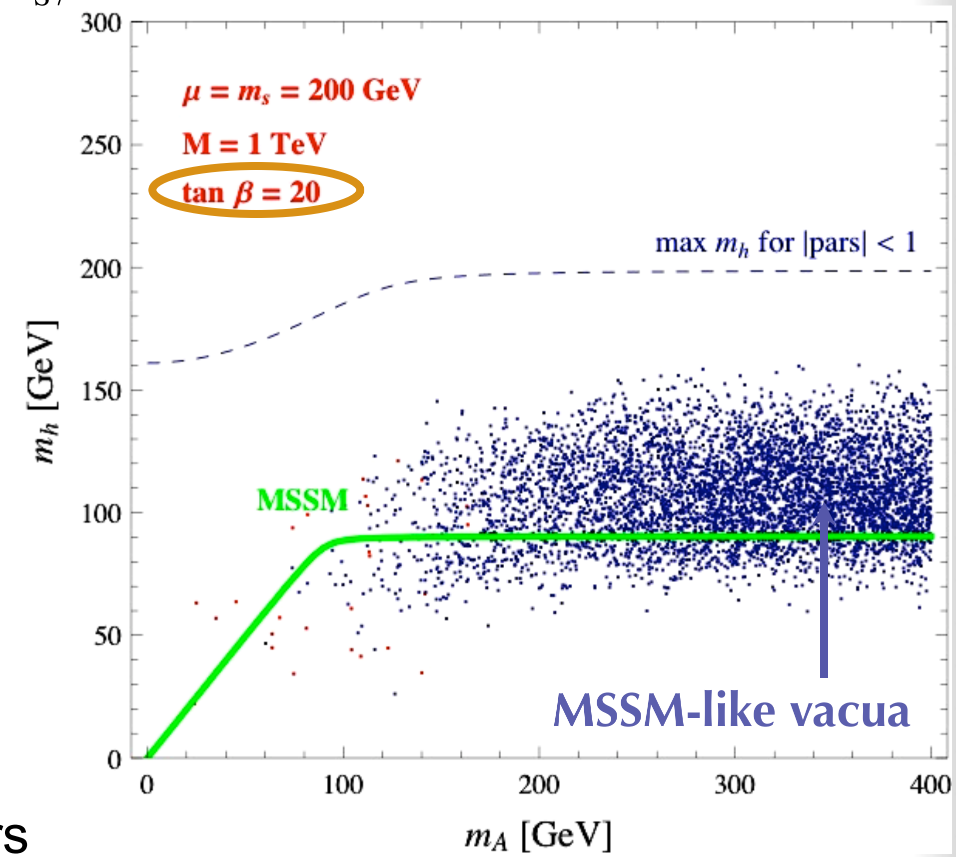


Second order terms can have a relevant impact.

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

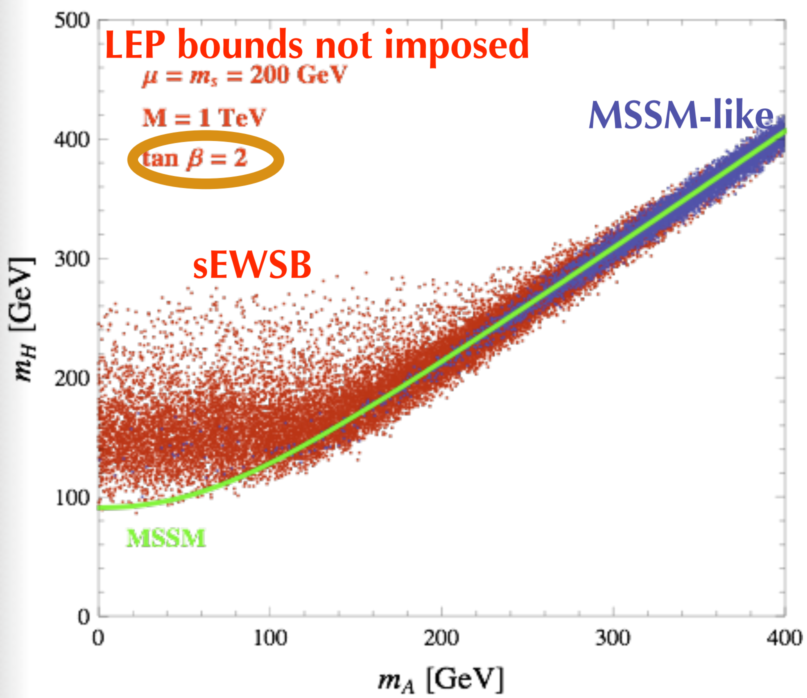
Scanning over model parameters

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

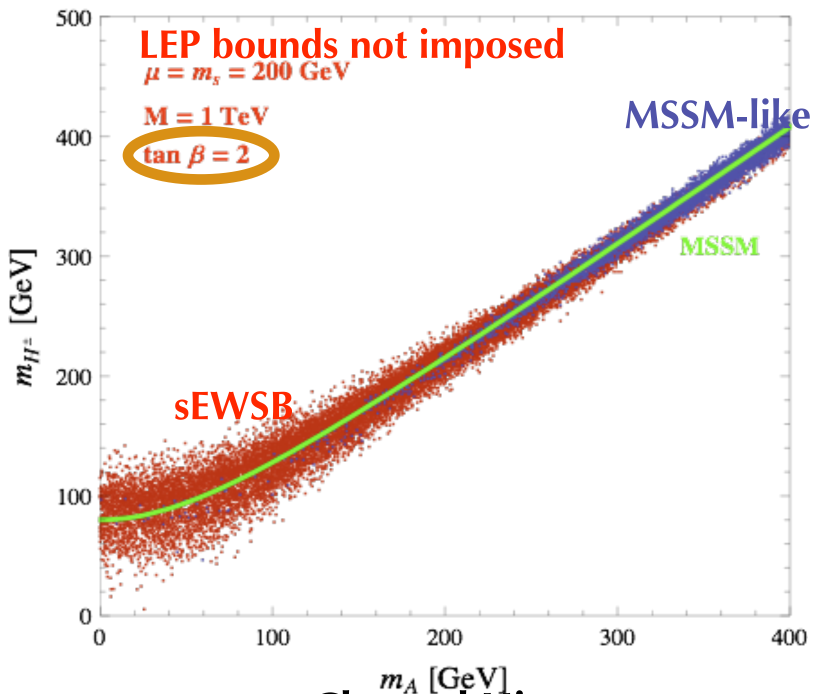
Heavy CP Even and Charged Higgs Masses

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:

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

2. Effects from MSSM Higgs sector:

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

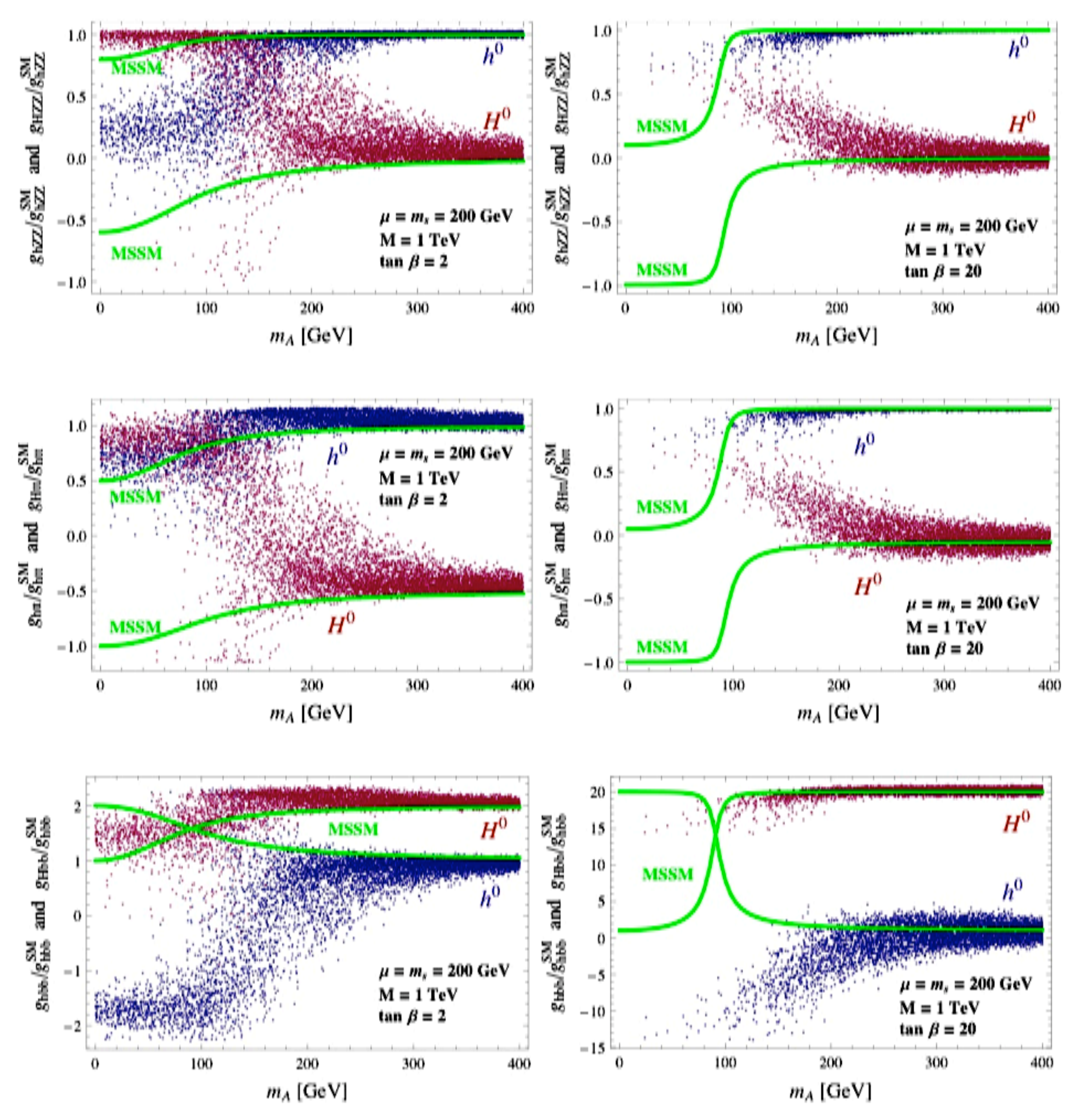
} Loop-level contr. to S and T

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

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

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

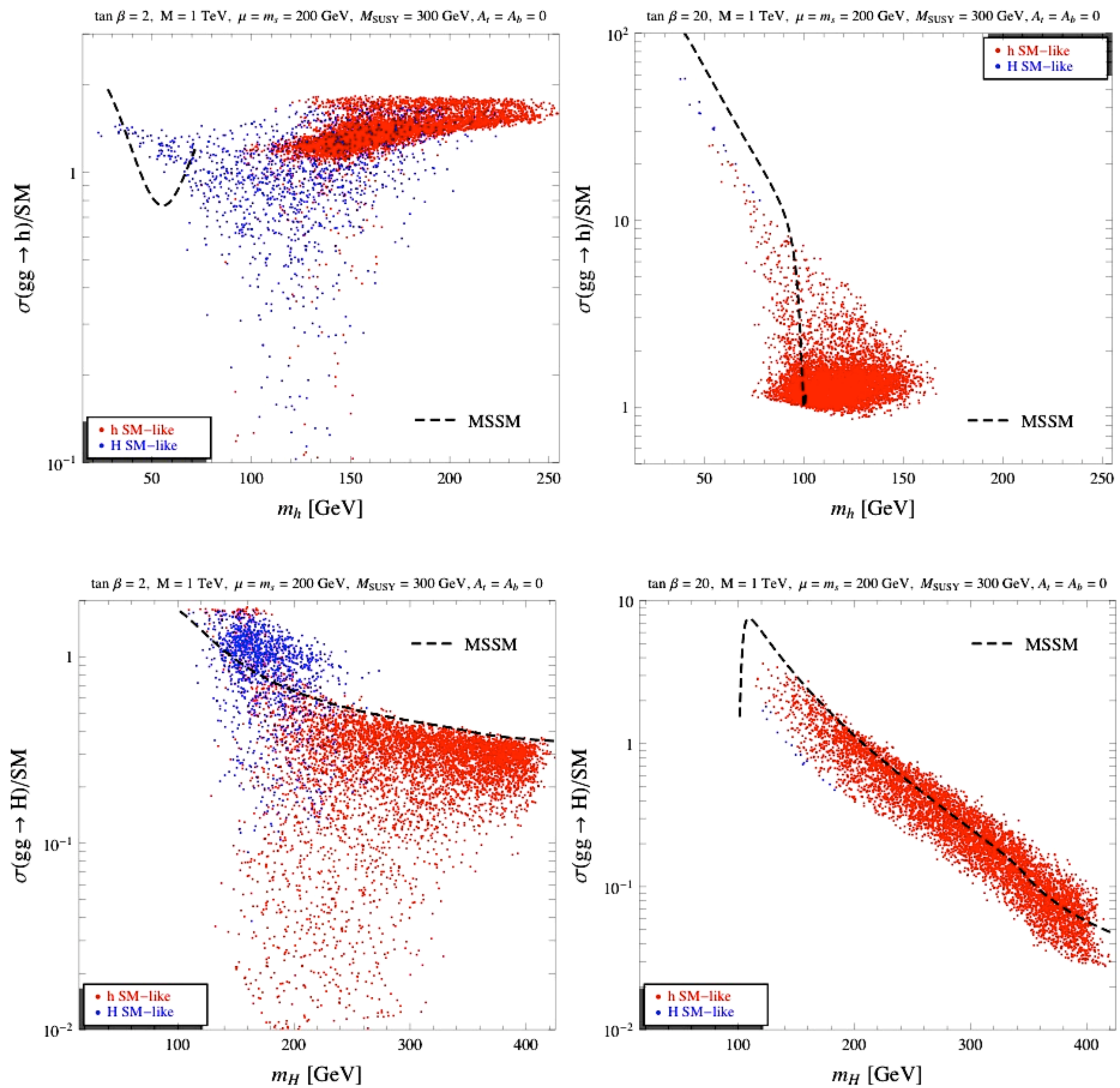
CP-even Higgs Couplings to gauge bosons and fermions



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 (low tanb, A/h inversion)

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

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

In the following:

Full study with LEP and Tevatron bounds using

Higgsbounds Bechtle, Brein, Heinemeyer, Weiglein, Williams

+ charged Higgs at LEP

+ latest Tevatron SM h/H→ WW and A/H to tau pair results

Also Tevatron projections based on

SM-like and MSSM Higgs bosons present reach

All the above for our specific multi-parameter SUSY scenarios

in collaboration with Ponton and Zurita

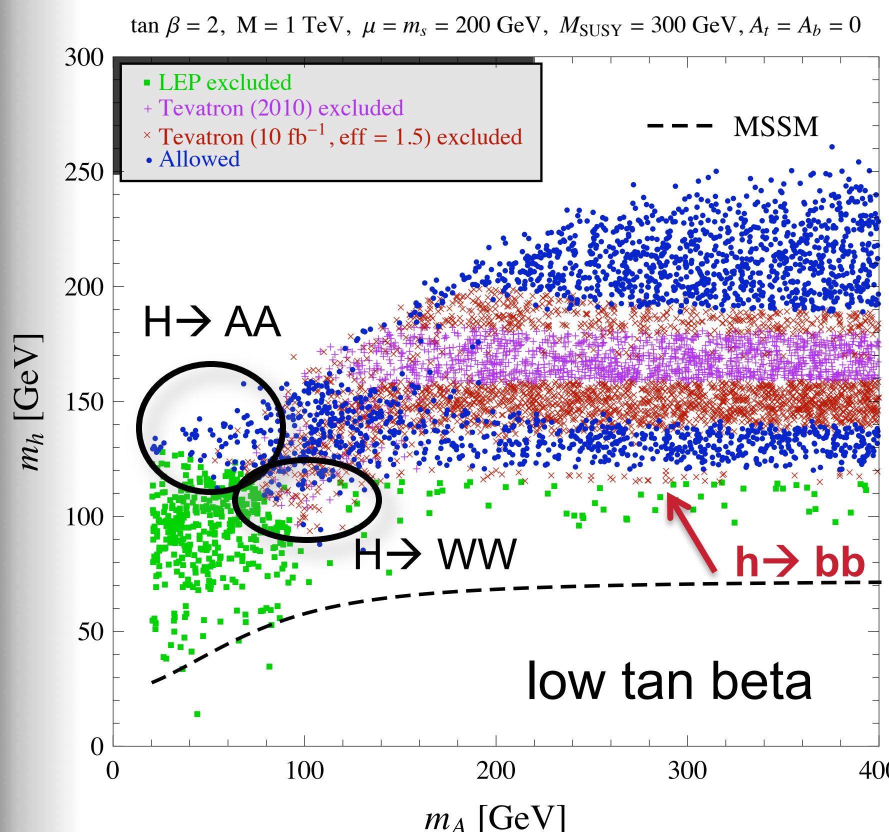
Lightest Higgs Mass after LEP and the Tevatron

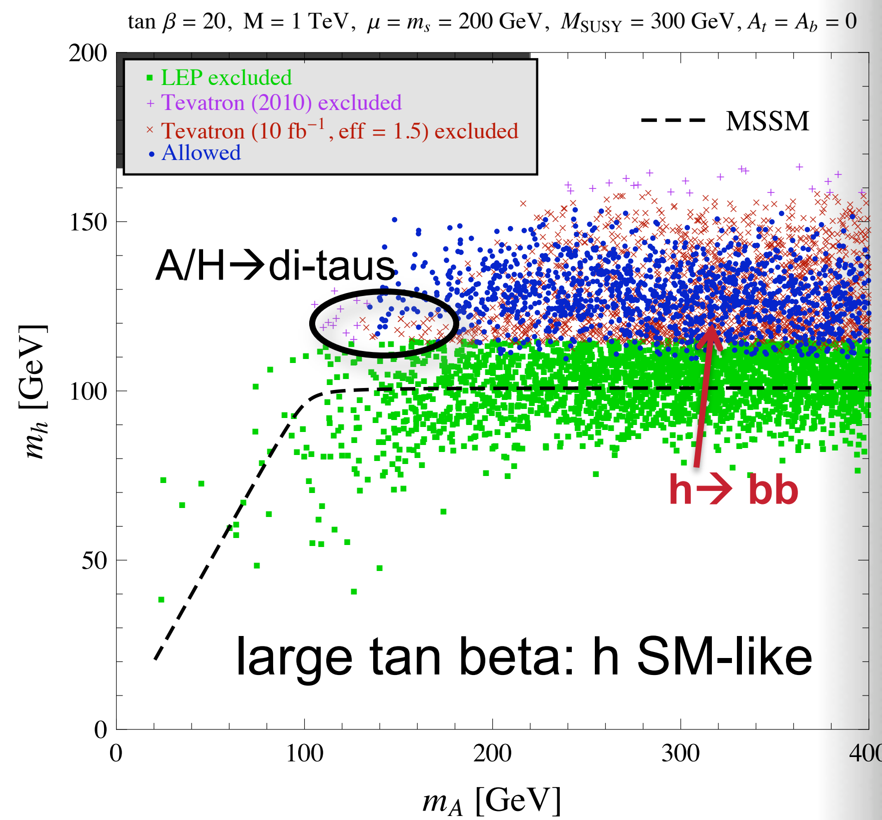
GREEN → LEP excluded

RED → Tevatron with 10 fb-1 and eff. = 1.5

MAGENTA → Tevatron excluded

BLUE → Beyond Tevatron





Most magenta and red regions at Tevatron reach in the h→WW channel

BMSSM Higgs at the Tevatron and LHC

- **At Tevatron reach**:

SM-like searches: 1) h→ bb 2) h→ WW 3) H→ WW

Disjoint reach since in no region of parameter space are they simultaneously effective

Non-SM-like searches: A, H and h to tau pairs,

- **At the LHC:**

SM-like reach in d-iphotons, tau pairs and di-bosons

Non-SM-like Higgs bsoson in di-tau pairs or top-bottom and tau-neutrinos

Multi-Higgs chain decays

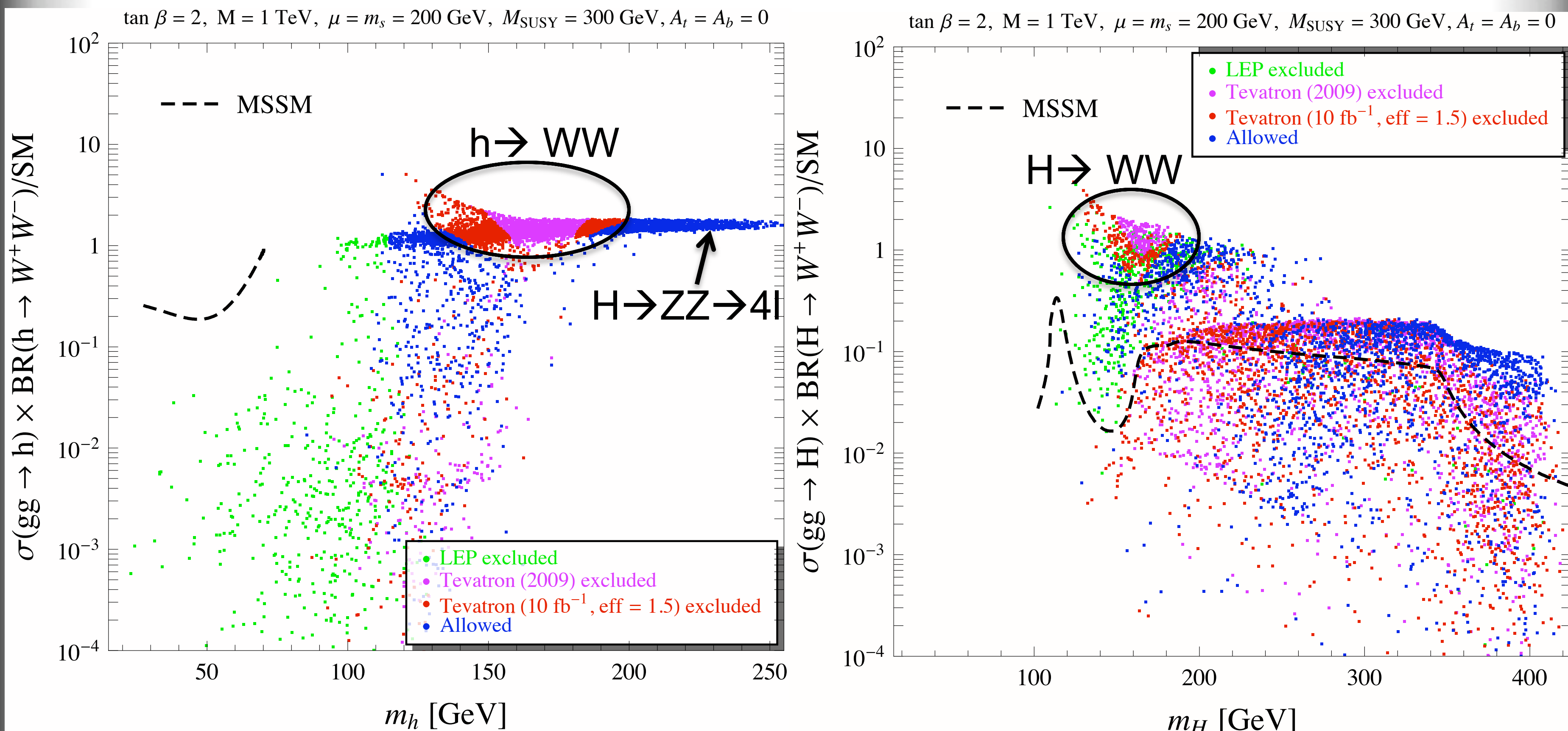
Benchmark Scenarios

Many benchmarks similar to MSSM ones, or with larger mass splitting in the A/H/H+ system (MSSM with C̸P)→ need to detect light SUSY spectra.

Here, only present examples of non-MSSM like scenarios

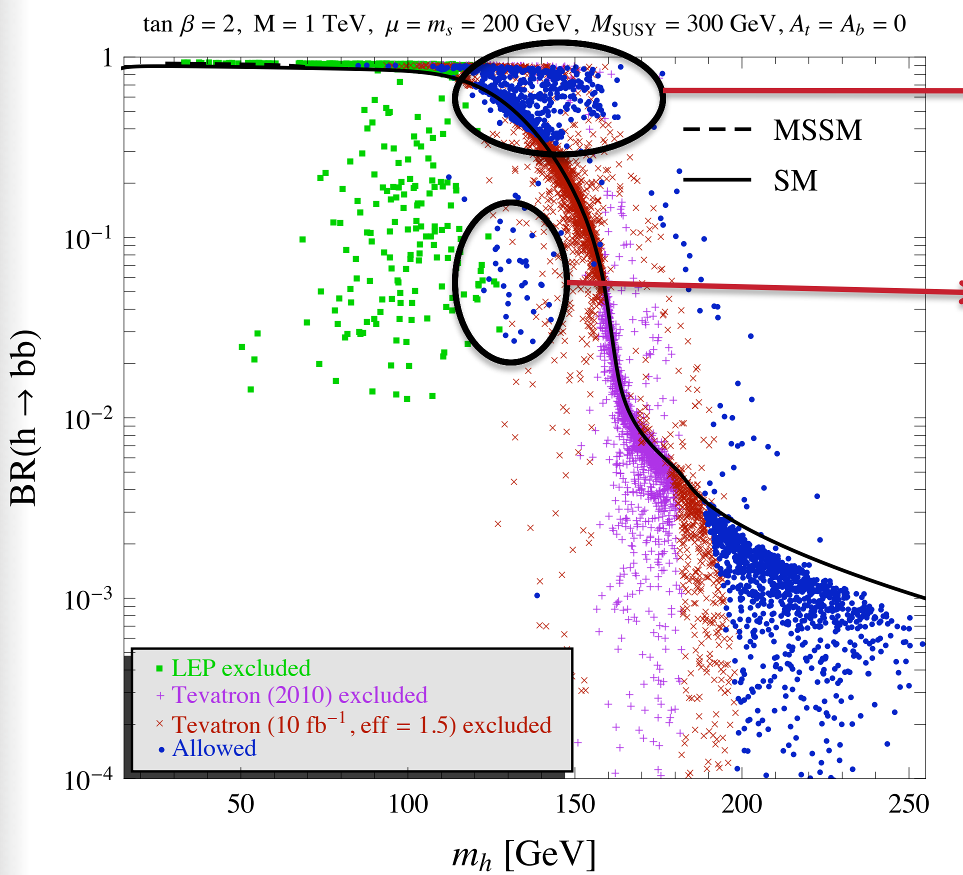
CP-even Higgs Bosons: low tanb

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



Lightest Higgs Boson: low tanb

- Important variations in the BR of h into bottom pairs



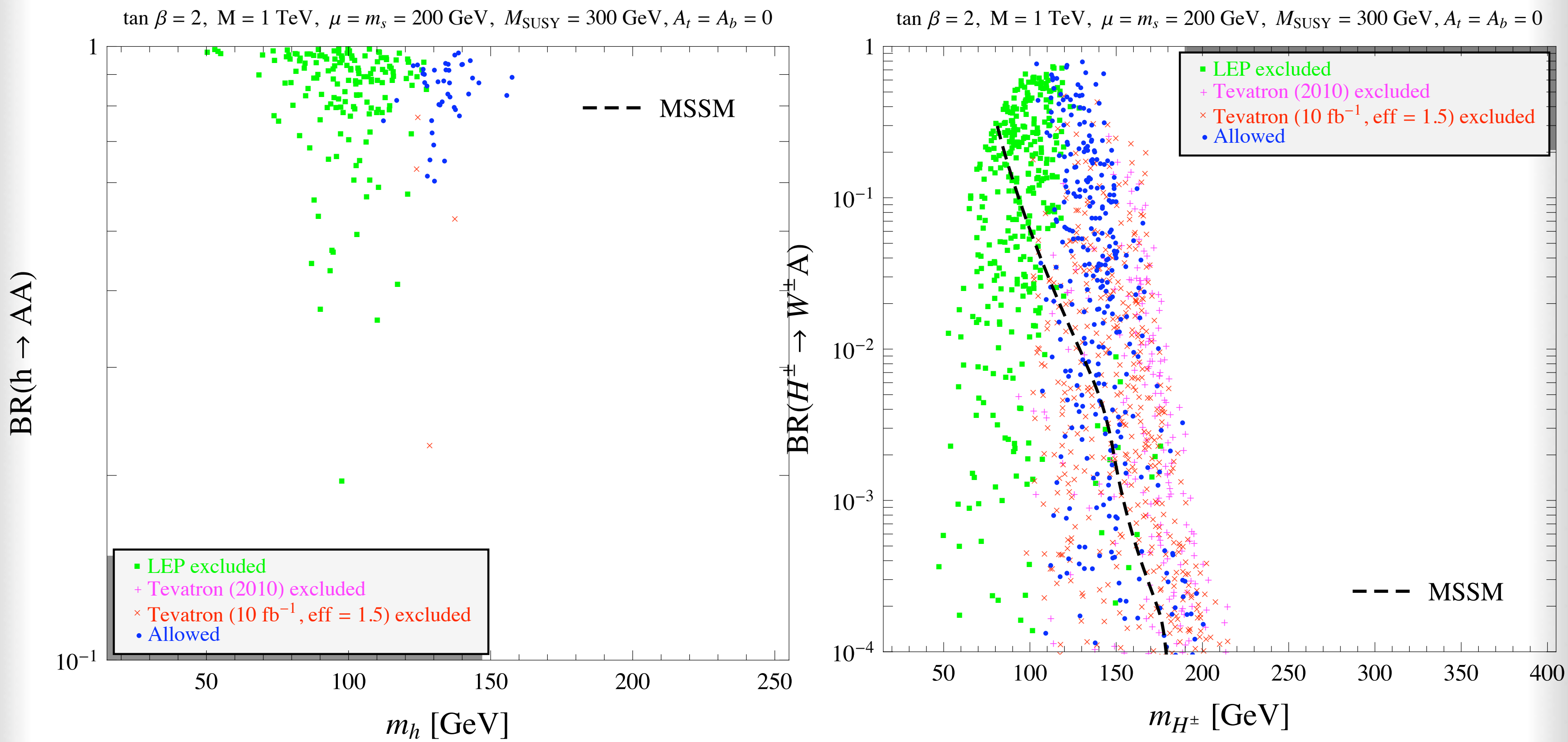
reduced BR (h-> WW)

strong suppression of h into bb
In mass region mh ~ 120-150

BR in tau-tau channel
follows closely the bb behavior

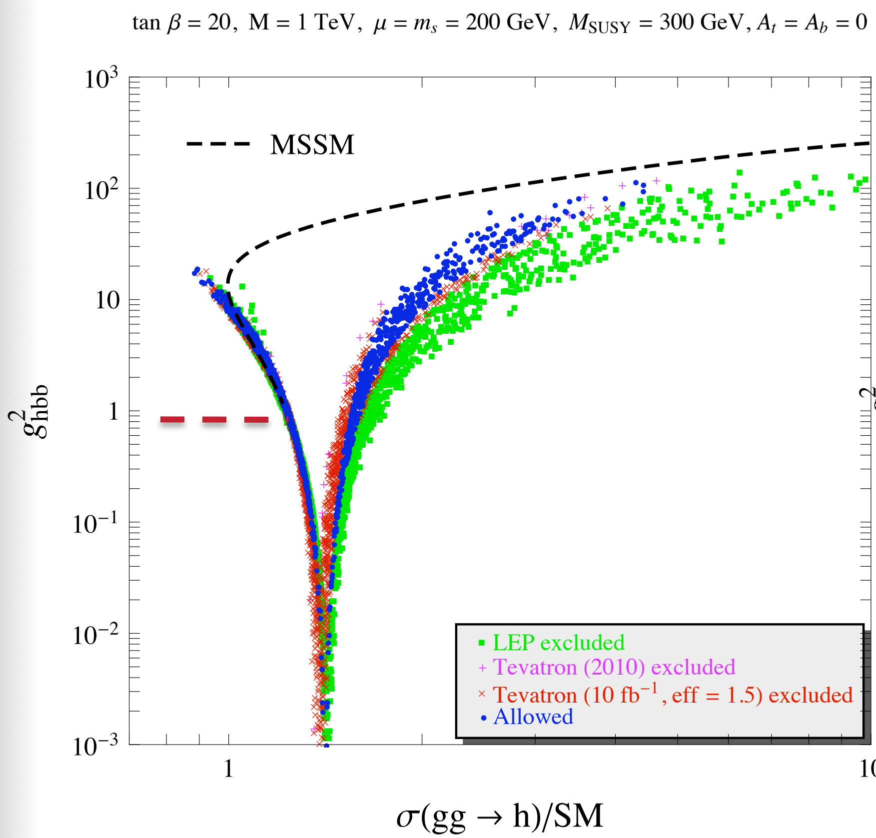
- In small regions of parameter space, enhancement of order 2 in BR (h → di-photons) ➔ at Tevatron reach in the near future

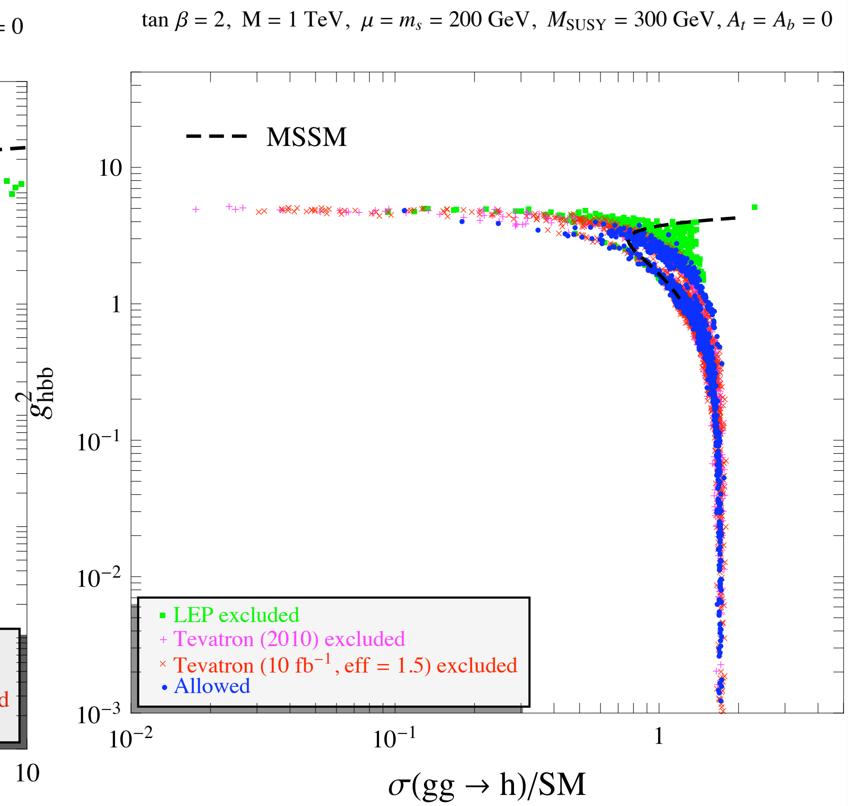
A-h inversion of hierarchy at low tanb



The MSSM channels A/H → hh and H⁺ → hW⁺
replaced by h/H → AA and H⁺ → AW⁺ in BMSSM
with parameter sets of BR's of order one

Suppression of the hbb couplings: both for large and (unlike the MSSM) low tanb

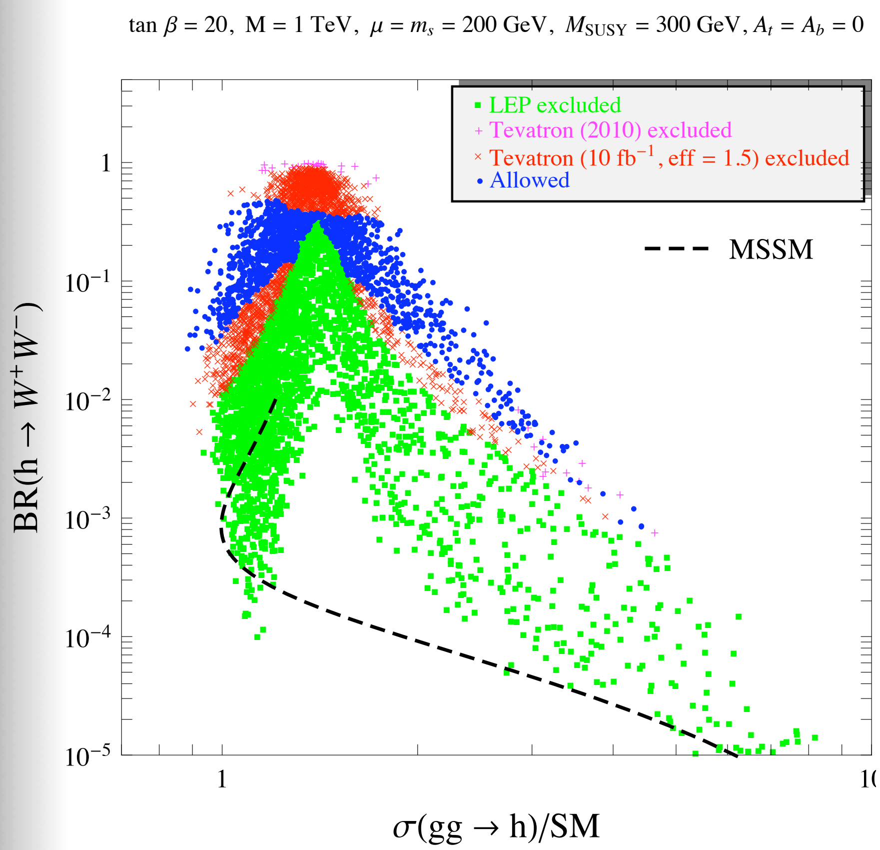


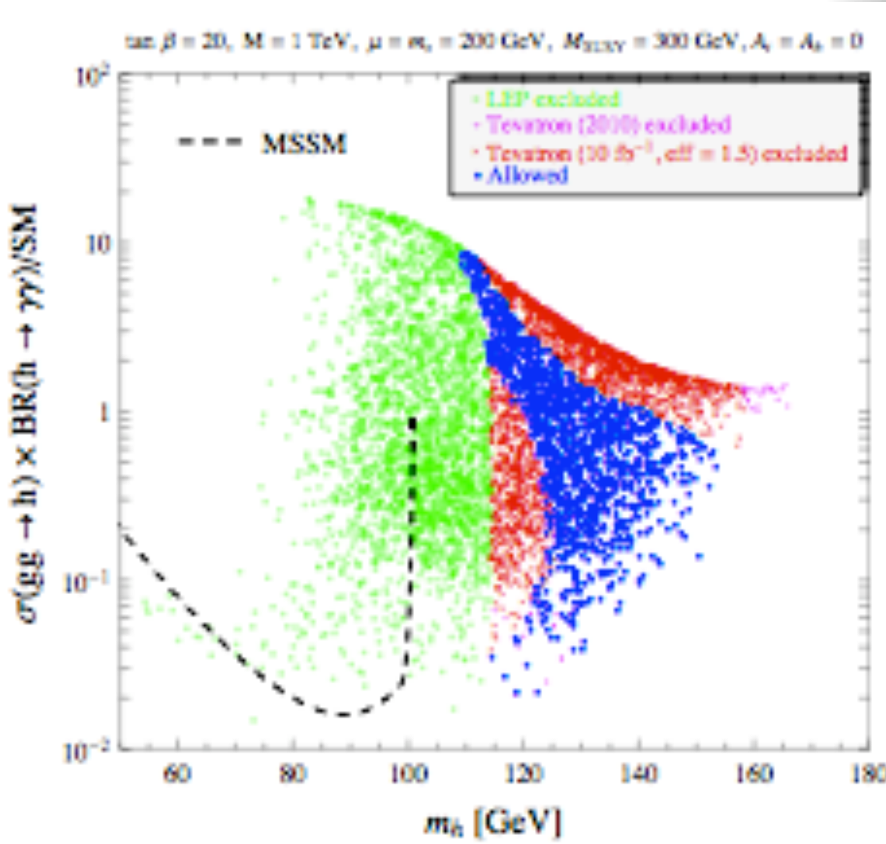


Cancellation between tree level and h.o. operators contributions yields enhancement in gluon fusion: lack of b-loops + light SUSY

For large tanb: enhanced hbb coupling as in the MSSM, when h is non-SM like

Enhancement of h→ WW/ZZ and h→ di-photon channels
(also due to hbb coupling suppression)





Interesting reach in h→ WW and in di-photon signals at the Tevatron and of course at the LHC

Benchmark point 1a (Tevatron signal)

Heavy Higgs SM-like, but Tevatron reach in h → WW

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
135	174	186	164
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.11	0.89	1.05	0.65
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.12 (0.01)	$h \to WW$	0.84 (0.96)
$H \to WW$	0.81 (0.82)	$H \to ZZ$	0.17 (0.17)
$A \to b\bar{b}$	0.90	$A \to \tau\bar{\tau}$	0.10
$H^+ \to \tau\nu_\tau$	0.59	$H^+ \to t\bar{b}$	0.38

tanb = 2

- All Higgs CP-even Higgs masses well above the MSSM limit and $m_h > m_A$
- hWW coupling very suppressed but still sizable BR(h→ WW)
- H→ WW too heavy for the Tevatron, but good at LHC in H→ZZ→ 4-leptons

Not such a heavy SM-like Higgs in the MSSM, specially with light SUSY

Benchmark point 1b (LHC signal)

Heavy h and H, non-SM like h in WW/ZZ channel at LHC

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
134	181	205	165
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.03	0.95	0.79	0.99
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.23 (0.005)	$h \to \tau\bar{\tau}$	0.03 (0.0005)
$h \to WW$	0.68 (0.92)	$h \to ZZ$	0.04 (0.07)
$H \to WW$	0.72 (0.73)	$H \to ZZ$	0.27 (0.27)
$A \to b\bar{b}$	0.89	$A \to \tau\bar{\tau}$	0.10
$H^+ \to t\bar{b}$	0.57	$H^+ \to \tau\nu_\tau$	0.40

tanb = 2

- H very SM–like, first to be seen at LHC
- hWW/hZZ very suppressed, still h → ZZ and possibly h →WW at LHC reach

Benchmark point 2 (LHC signal)

No Tevatron reach. Two ZZ → 4 lepton peaks at the LHC

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
184	204	234	203
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.3	0.7	1.39	0.36
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to WW$	0.73 (0.72)	$h \to ZZ$	0.25 (0.27)
$H \to WW$	0.70 (0.71)	$H \to ZZ$	0.29 (0.29)
$A \to b\bar{b}$	0.87	$H^+ \to t\bar{b}$	0.99

tanb = 2

- All Masses in similar mass range. Lightest Higgs ~ 200 GeV
- BR(h/H→ WW/ZZ) ~ SM value but hWW suppressed
- Any decay H/A/H⁺ → h X is closed due to heavy h

Two Higgs signals in the ZZ channel at LHC, both in the 200 GeV range

Benchmark point 3 (LHC signal)
Multi Higgs signal: chain decays

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
64	135	155	125
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.002	0.991	0.65	1.17
channel	BMSSM	channel	BMSSM
$h \to b\bar{b}$	0.15	$h \to AA$	0.84
$H \to WW$	0.12	$H \to AA$	0.84
$H \to b\bar{b}$	0.02	$A \to b\bar{b}$	0.92
$H^+ \to \tau\nu_\tau$	0.56	$H^\pm \to W^\pm + A$	0.40

tanb = 2

- h → AA and H→ AA, with subsequent decays into di-taus + b pairs
- Also gg → H → WW but needs large luminosity (about 100 fb^{-1})
- ***H^+ → A W^+ possible***

Benchmark point 4 (LHC signal)
SM-like light higgs with enhanced di-photon signal

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
210	111.3	215	225
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.98	0.02	1.39	0.84
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.03 (0.79)	$h \to \gamma\gamma/10^{-3}$	12.1 (2.1)
$h \to$ jets	0.56 (0.07)	$h \to WW$	0.36 (0.05)
$H \to b\bar{b}$	0.86	$H \to \tau\bar{\tau}$	0.14
$A \to b\bar{b}$	0.86	$A \to \tau\bar{\tau}$	0.14
$H^\pm \to \tau\nu_\tau$	0.35	$H^\pm \to t\bar{b}$	0.64

tanb = 20

- strong suppression of h→bb channel (escaped LEP bound)

- ***Similar scenario with heavier A/H will allow A/H → hh decays***

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

Some corners of SUSY parameter space may be elusive

But the Tevatron and ultimately the LHC will have the final word on multi Higgs searches

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: $m_{H_d}^2, m_{H_u}^2, m_S^2$

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 $Y = \pm 1$

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

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 $Y = 0$ $\longrightarrow$ $\lambda_T H_u T H_d$

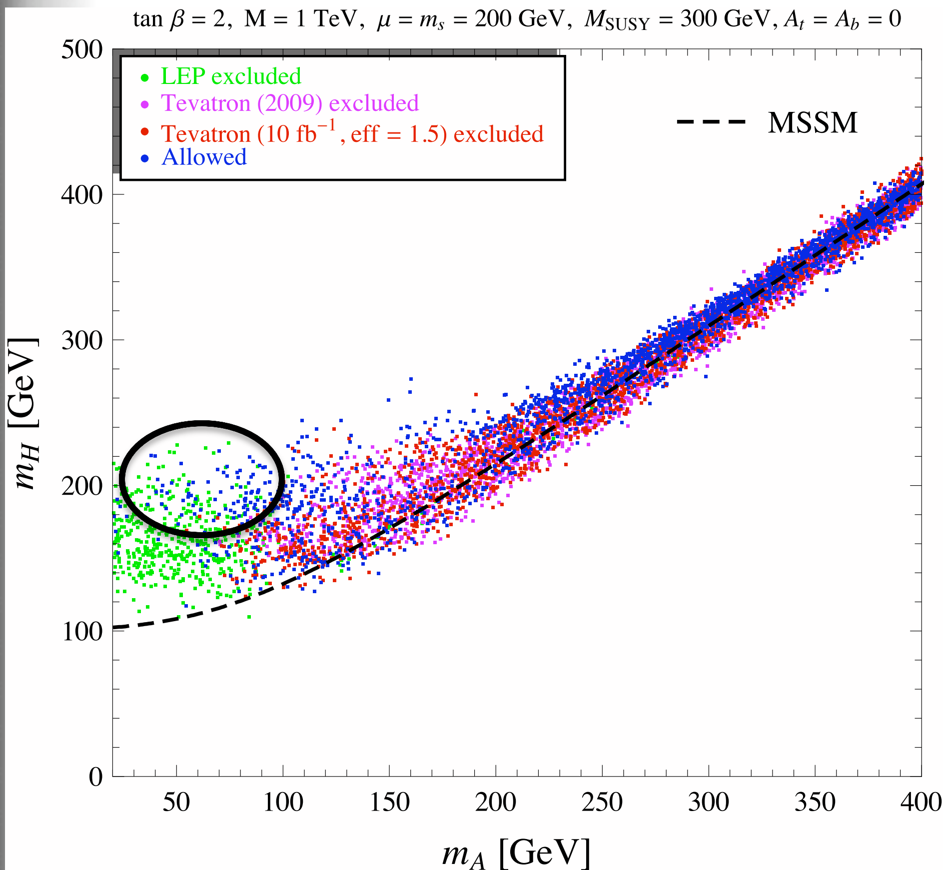
$$\left.\begin{array}{lll} M = M_T\ , & \omega_1 = -\frac{1}{4}\lambda_T^2\ , & \alpha_1 = a_2 - 2a_3\ , \\ c_3 = \frac{1}{2}|\lambda_T|^2\ , & \gamma_3 = a_2 - a_3\ , & \beta_3 = |a_2 - a_3|^2 - b_3\ , \\ c_4 = -\frac{1}{4}|\lambda_T|^2\ , & \gamma_4 = a_2 - a_3\ , & \beta_4 = |a_2 - a_3|^2 - b_3\ ,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

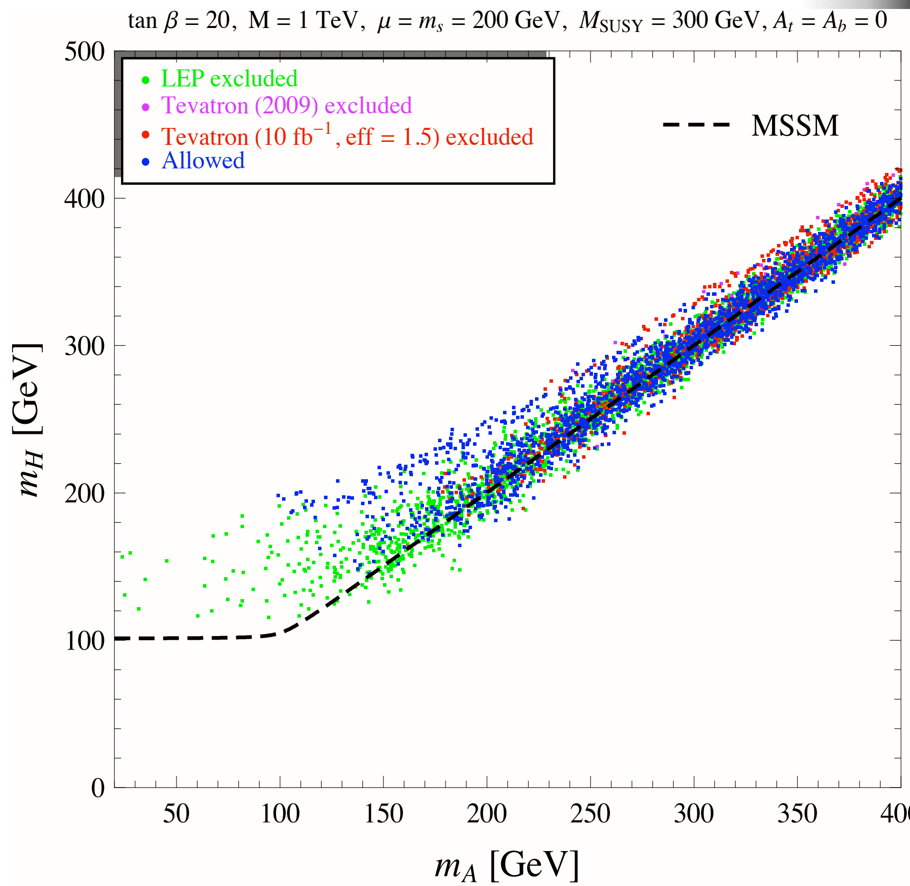
Induce custodially violating ops.

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

and $c_4 < 0$!

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

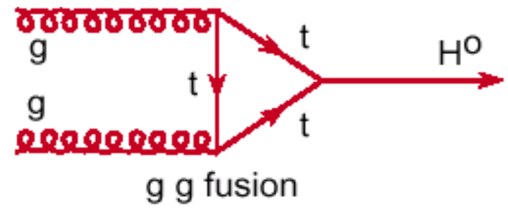




SM-like Higgs production at hadron colliders

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

with H → bb, WW*



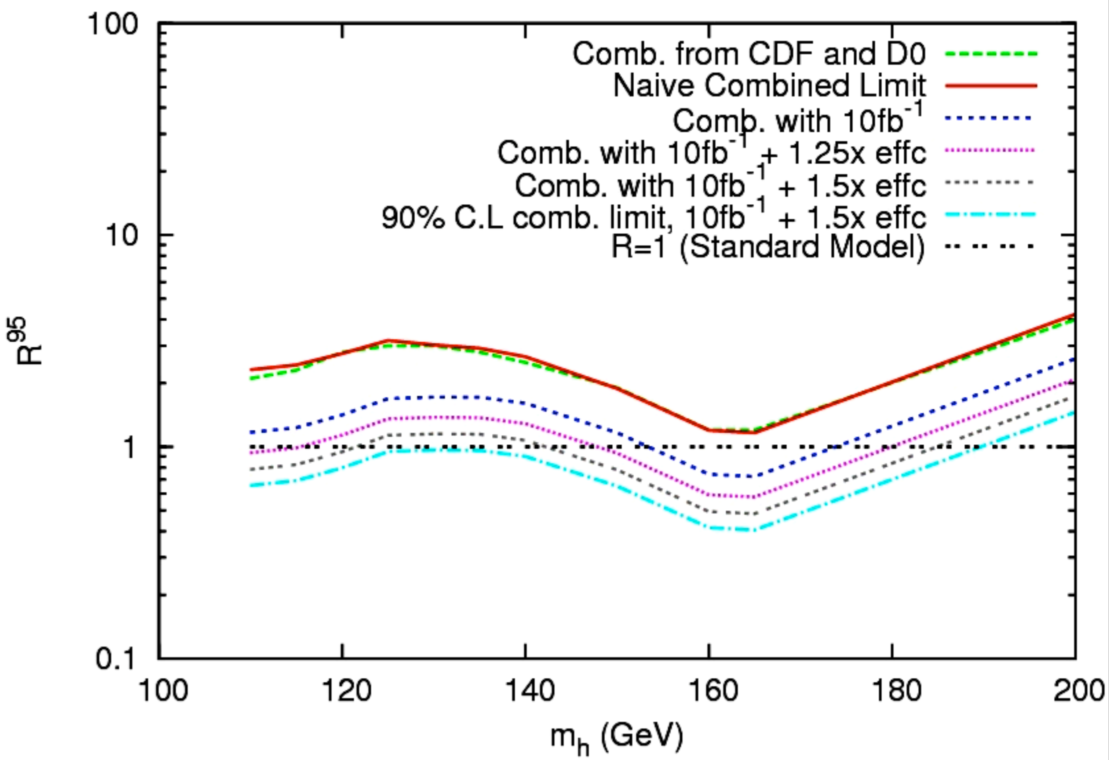
with H → $WW^{(*)}$.

The Tevatron Projections

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

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

$$\frac{1}{(R^{95})^2} \sum_i \frac{1}{(R_i^{95})^2}$$



If $R^{Model} > R^{95}$, then the Model is excluded

Draper, Liu, Wagner

Tevatron reach for the MSSM SM-like Higgs

All channels included in CDF/DO combination.

Draper, Liu, Wagner

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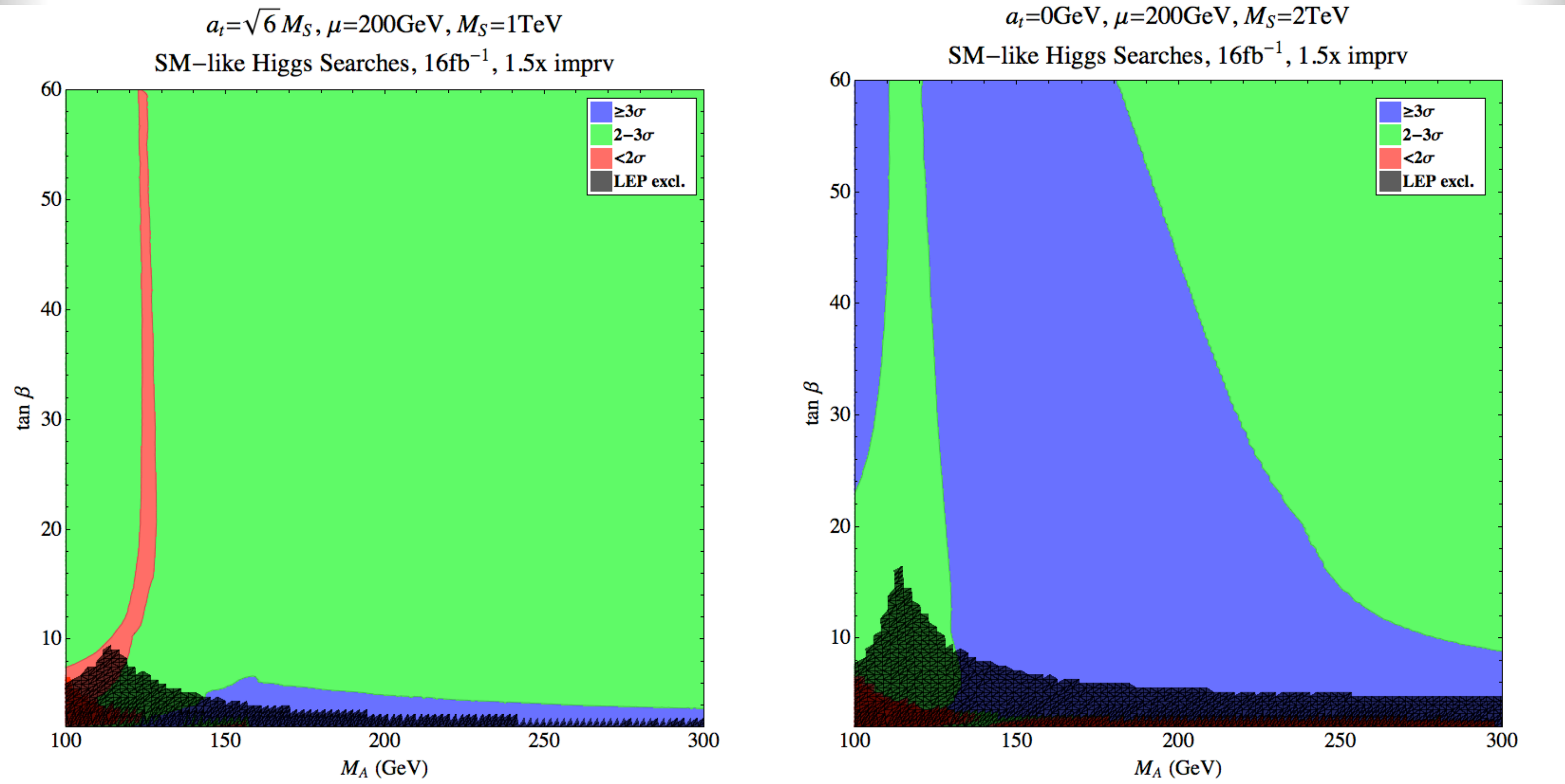


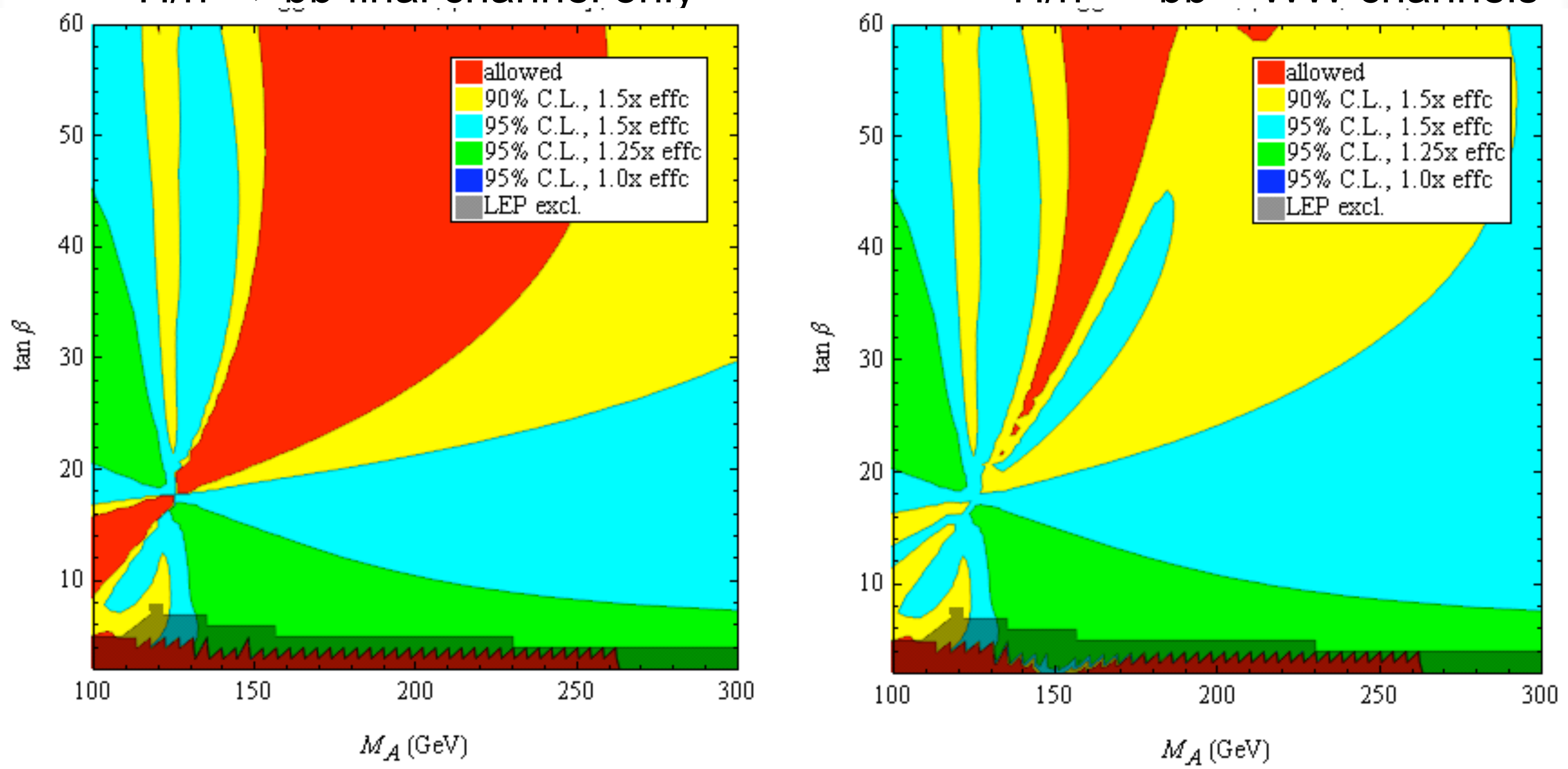
Even with only SM channels and 2011 run, 2 sigma sensitivity is achieved in most parameter space. Evidence may be achieved with further running.

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

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

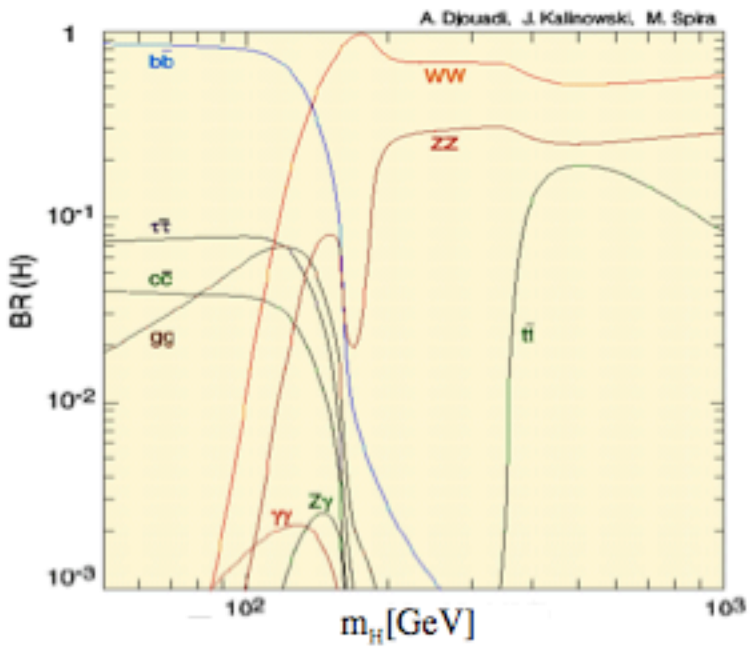
Draper, Liu, Wagner

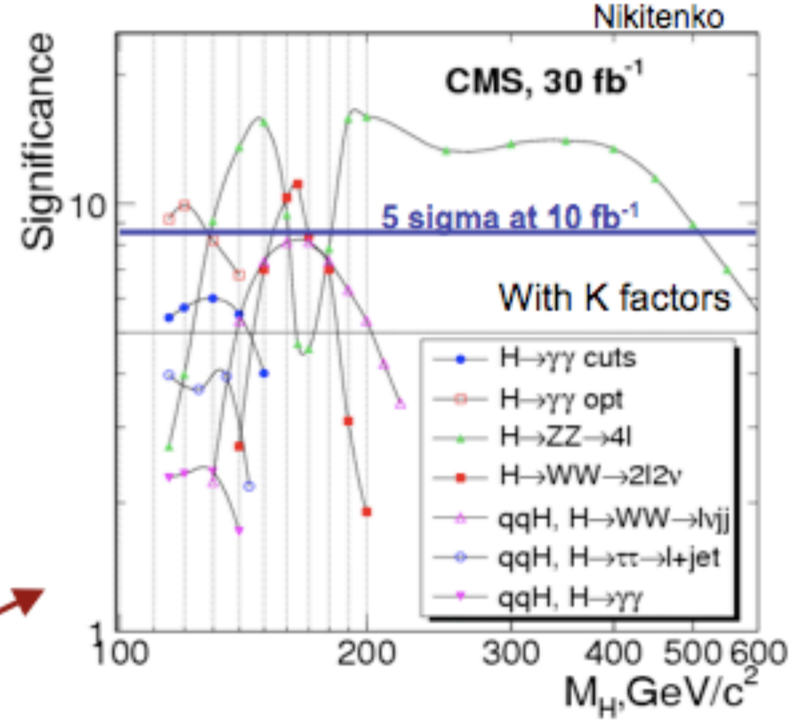
H/h → bb final channel only H/h → bb + WW channels



- 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

Search Channels for the SM Higgs at the LHC





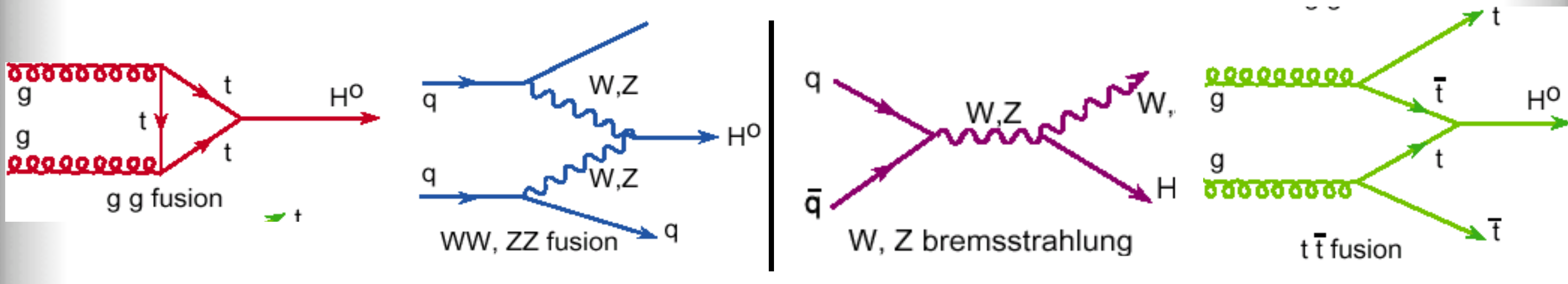
- **Low mass range** $m_H < 200$ GeV

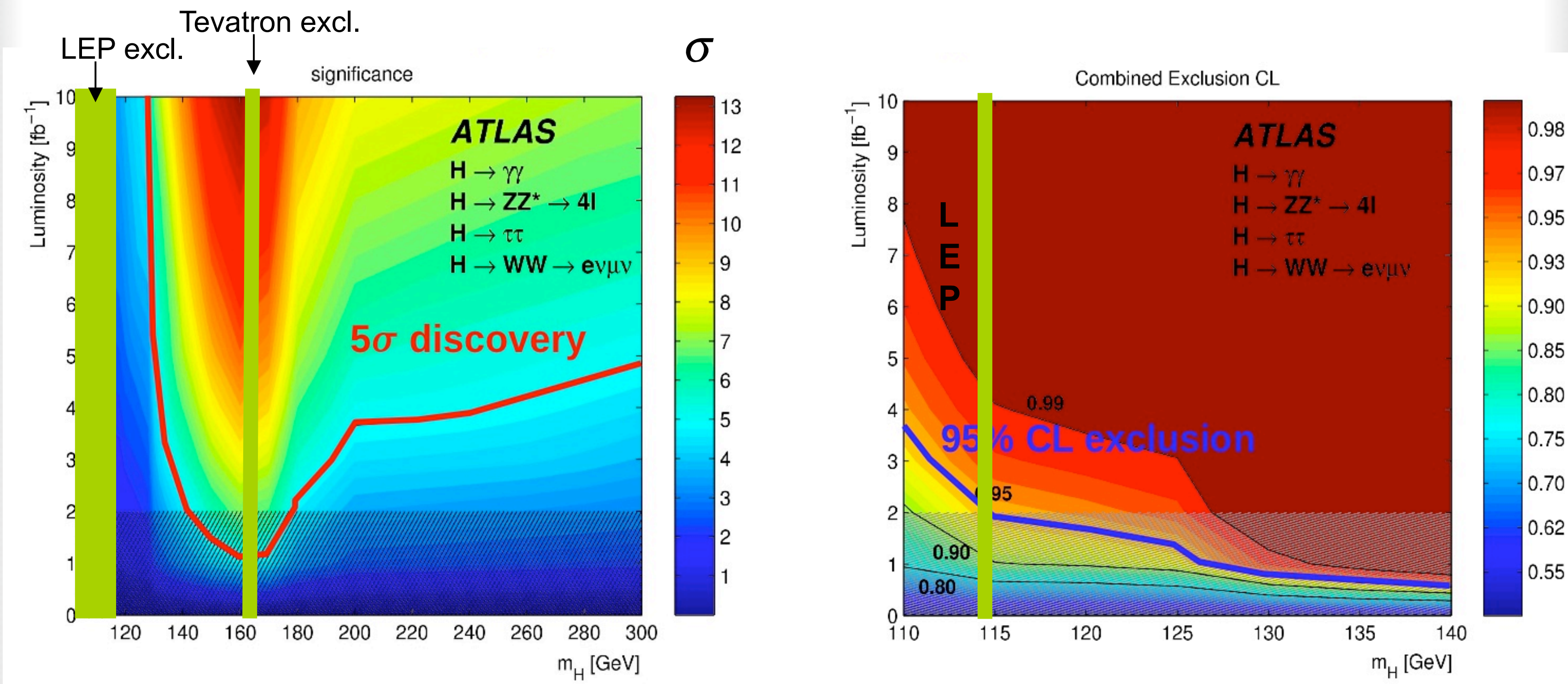
Production / DECAY	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	YES	YES	YES	YES
$H \to bb$			YES	YES
$H \to \tau\tau$		YES		
$H \to WW^*$	YES	YES	YES	
$H \to ZZ^*$, $Z \to l^+l^-$	YES			

- **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

The SM Higgs LHC potential (14 TeV)



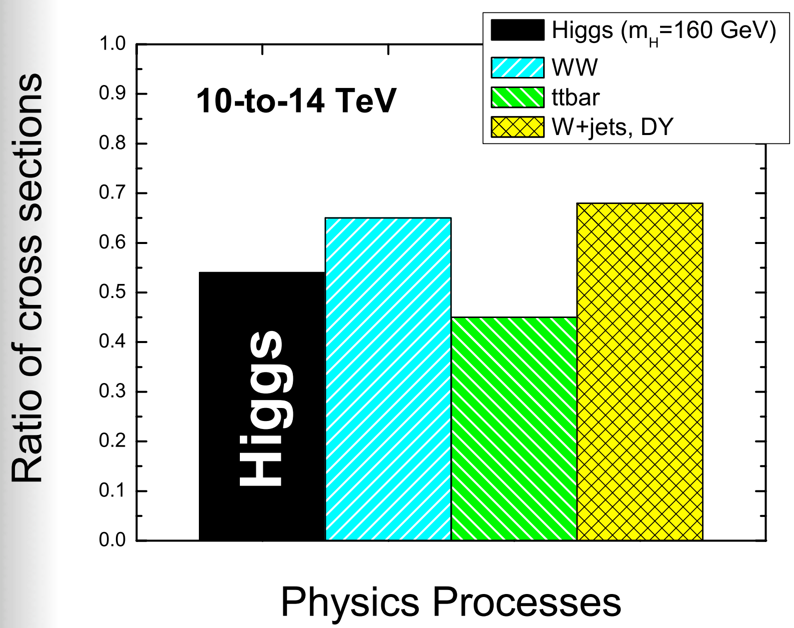


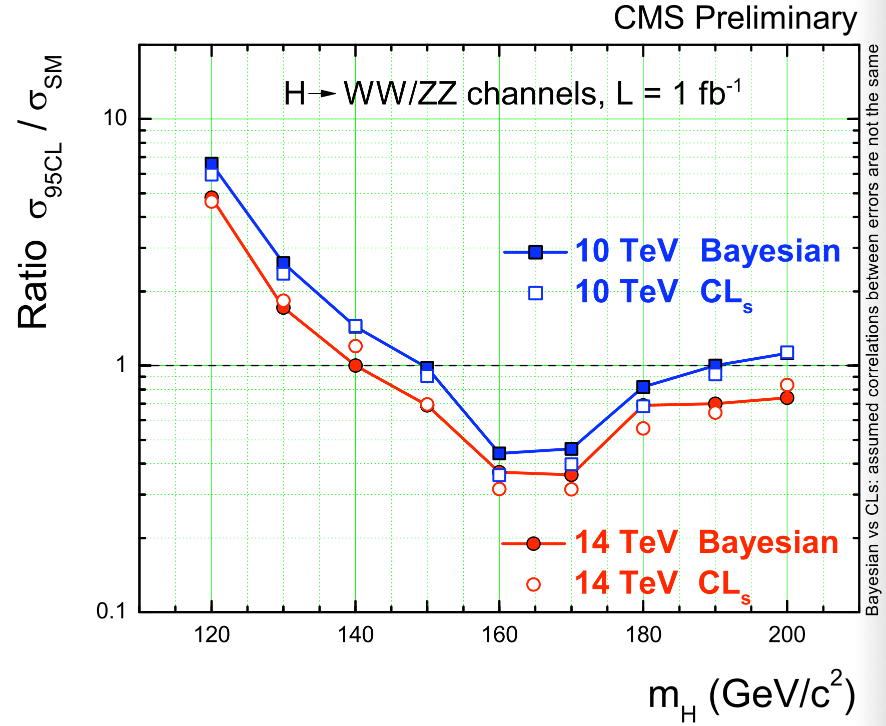
With 10 fb^{-1}, discovery for m_h [~125,~500] GeV range;
With 1-2 fb^{-1}, some reach in the H to WW channel (2 fb^{-1}:exclusion for all m_h)

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

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

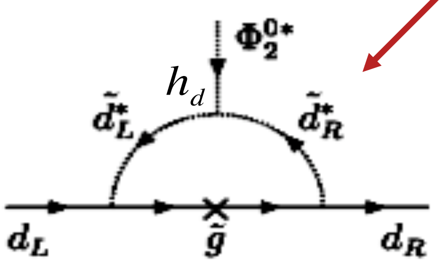
===> strong suppression of the SM-like Higgs boson coupling to b-quarks and taus

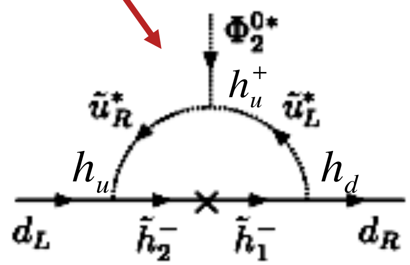
Enhancement of BR (h/H --> WW/ $\gamma\gamma$) for $m_{h/H}$ < 135 GeV

Radiative Corrections to Higgs-Fermion couplings

SUSY loop induced FCNC and charged current effects relevant for large $\tan\beta$

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





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

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

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

and $R = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |h_u|^2$ ➔ 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