SUSY Frameworks at Hadron Colliders

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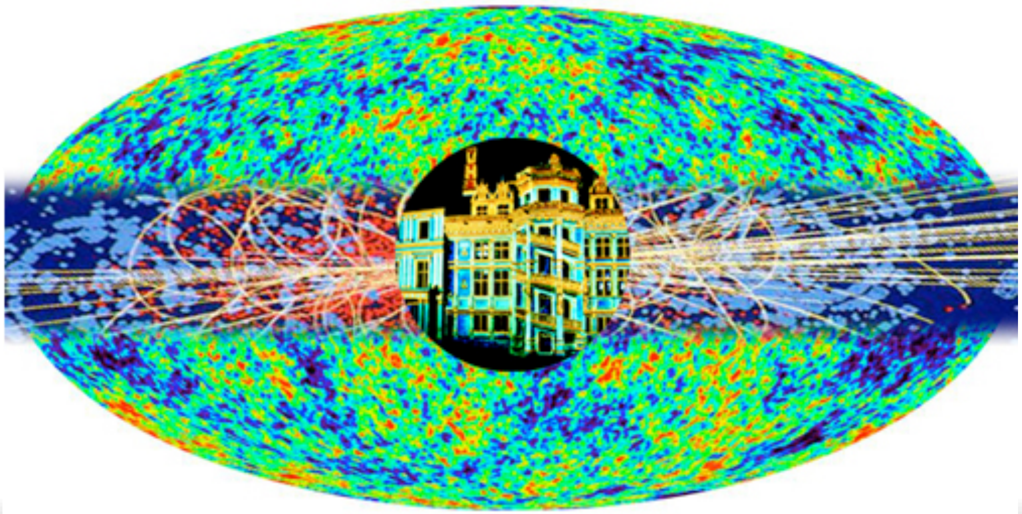
22nd Rencontres de Blois

Particle Physics and Cosmology: first results from the LHC

Chateau Royal de Blois



July 19, 2010

Outline

- Introduction:

  SUSY facts, SUSY problems

- SUSY Breaking and Renormalization Group invariants

  High scale characteristics from LHC low energy measurements

  SUSY breaking structure and the Messenger Scale

- MSSM Higgs Extensions: A model-independent approach

  The EFT at NLO

  Masses and couplings

  Collider phenomenology

SUSY facts

- SUSY is a framework for an infinite number of models with an extended space-time symmetry
- SUSY can provide solutions to EWSB, the hierarchy problem, unification and cosmology:
- SUSY must be broken:

IF SUSY were an exact symmetry, the SM particles and their superpartners would have the exactly same masses.

$$m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_e = 0.511 \text{ MeV}$$

$$m_{\tilde{u}_L} = m_{\tilde{u}_R} = m_u$$

$$m_{\tilde{g}} = m_{\text{gluon}} = 0 + \text{QCD-scale effects}$$

No SUSY particles have been seen yet

How is SUSY broken? **Soft SUSY breaking**

=> give different masses to SM particles & their SUSY-partners, but preserving the **coupling** structure of the theory

-- secure solution to the hierarchy problem relying on equality of couplings and not on equality of the masses of the particles and their SUSY-partners --

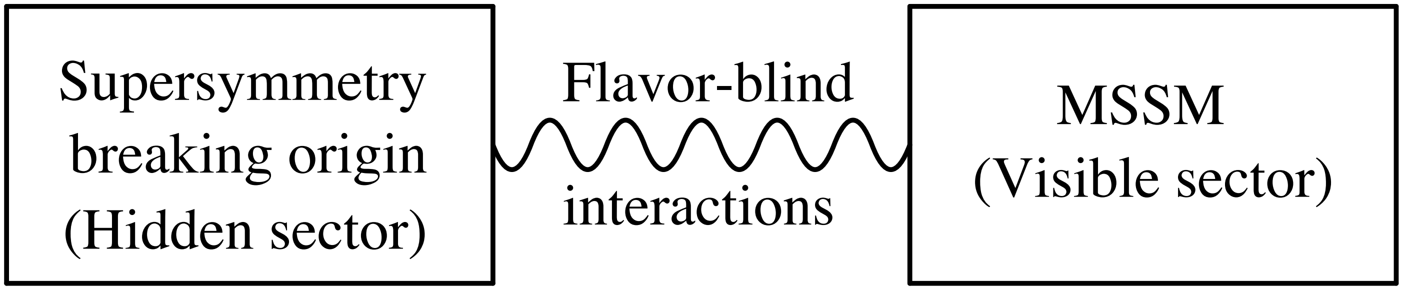
$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B})$$
$$-m_Q^2\tilde{Q}^\dagger\tilde{Q} - m_U^2\tilde{U}^\dagger\tilde{U} - m_D^2\tilde{D}^\dagger\tilde{D} - m_L^2\tilde{L}^\dagger\tilde{L} - m_E^2\tilde{E}^\dagger\tilde{E}$$
$$-m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (\mu B H_1 H_2 + cc.)$$
$$-(A_u h_u \tilde{U}\tilde{Q}H_2 + A_d h_d \tilde{D}\tilde{Q}H_1 + A_l h_l \tilde{E}\tilde{L}H_1) + c.c.$$

The scale of SUSY breaking must be of order 1 TeV, if SUSY is associated with the scale of electroweak symmetry breaking

Understanding the origins of Spontaneous SUSY breaking:

Soft SUSY breaking terms arise indirectly,

not through treel level, renormalizable couplings to the SUSY breaking sector



Spontaneous SUSY breaking occurs in a Hidden sector of particles, with none or tiny direct couplings to the MSSM particles, when some components of the hidden sector acquire a vev $\langle F \rangle \neq 0$.

One can think of Messengers mediating some interactions that transmit SUSY breaking effects indirectly from the hidden sector to the MSSM

- There are many possible SUSY breaking mechanisms, and many possible ways to mediate SUSY breaking to SM particles

- **Gravity mediation: SUSY breaking mediated by Planck-scale-suppressed couplings**

mSUGRA, anomaly mediation, stringy models,...

- **Gauge mediation: SUSY breaking mediated by loops containing heavy “messenger” fields**

GMSB: minimal, general, metastable...

- **Bulk mediation: We live on a “brane” in a larger (“bulk”) extra dimensional space; SUSY is broken on a different brane**

gaugino mediation, radion mediation,...

< SUSY can be also classified according to the particle content and/or how many independent SUSY breaking parameters appear in the SM sector >

MSSM, CMSSM, pMSSM, NMSSM, nMSSM...

Problems with SUSY Models

- **Why is the Z mass so light?**

$$M_Z^2 = -1.8\mu^2(\mathrm{UV}) + 5.9M_3^2(\mathrm{UV}) - 0.4M_2^2(\mathrm{UV}) - 1.2m_{H_U}^2(\mathrm{UV}) + 0.9m_{Q_3}^2(\mathrm{UV}) + 0.7m_{U_3}^2(\mathrm{UV}) - 0.6A_t(\mathrm{UV})M_3(\mathrm{UV}) - 0.1A_t(\mathrm{UV})M_2(\mathrm{UV}) + 0.2A_t^2(\mathrm{UV}) + 0.4M_2(\mathrm{UV})M_3(\mathrm{UV}) + \ldots$$

- **The "mu problem":** $\mu H_u H_d$
  Why is the mass scale of the supersymmetric mu parameter related to the effective scale of SUSY breaking and of EWSB?

- **The “flavor problem”:**

MSSM:105 new parameters not present in the SM

Why doesn’t SUSY breaking introduce new large sources of flavor (and CP) violation?

If the mediating interactions are flavor blind

(gravity/ordinary gauge interactions),

the MSSM soft SUSY breaking terms will also be flavor independent

(favored experimentally)

- **Why is the Higgs so heavy?**

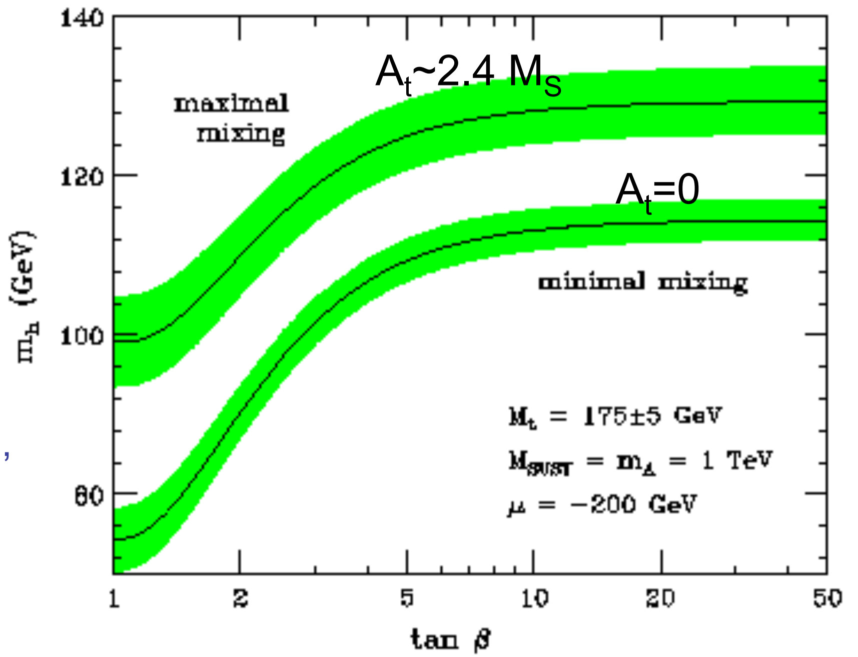
  - **For minimal SUSY models, the SM-like Higgs should have been discovered at LEP**
    -- little room left --

    after 2 -loop corrections:

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

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

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



  - **Much recent activity on SUSY models with extra stuff and/or with non-minimal Higgs sectors**

The SM-like SUSY Higgs boson becomes heavier, or is hidden from LEP

Dissecting SUSY at the LHC

Top-down approach:

Many possible SUSY breaking scenarios

$\Rightarrow$ limited number of parameters with boundary conditions at an specific SUSY breaking scale are fit to low scale data via RG evolution

Bottom-up approach:

Low energy SUSY particle masses converted to Lagrangian parameters and RG evolved to the SUSY breaking scale to analyze their structure

Shortcomes:

RG dependence, SUSY breaking scale dependence, MSSM parameters interconnected, experimental uncertainties in gauge/Yukawa couplings

A powerful approach based on RG invariants:

Determining the Structure (and Scale) of SUSY-Breaking & Testing Flavor

M.C. Draper, Shah, Wagner '10

Assumptions:

- EFT at the EW scale is the MSSM
- no new physics below the scale of SUSY breaking

Procedure:

- Study RG evolution of Soft Masses and Gauge Couplings
- **Define RG invariant combinations at one-loop**
- Use SUSY particle mass measurements at LHC to obtain low energy measurements of RG invariants

  ==> **Probe different high scale SUSY Breaking mechanisms**

  Determine parameter space and (sometimes) **SUSY breaking scale**
- Discuss two-loop effects and experimental uncertainties

Constructing RG Invariants

- use 1-loop RG evolution of soft masses and gauge couplings
- soft sfermion masses flavor diagonal.
- 1st and 2nd generation masses degenerate at the messenger scale.
- Neglect 1st and 2nd generation yukawa and trilinear couplings.

RG inv. D_G associated to global symmetries of the Yukawa potential, with vanishing mixed anomalies with the SM gauge groups

Sfermion Mass Invariants

$$D_{B_{13}} = 2m^2_{\tilde{Q}_1} - m^2_{\tilde{u}_1} - m^2_{\tilde{d}_1} - 2m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + m^2_{\tilde{d}_3}$$

$$D_{L_{13}} = 2m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1} - 2m^2_{\tilde{L}_3} + m^2_{\tilde{e}_3}$$

$$D_{Y_{13H}} = m^2_{\tilde{Q}_1} - 2m^2_{\tilde{u}_1} + m^2_{\tilde{d}_1} - m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1} - \frac{10}{13}\left(m^2_{\tilde{Q}_3} - 2m^2_{\tilde{u}_3} + m^2_{\tilde{d}_3} - m^2_{\tilde{L}_3} + m^2_{\tilde{e}_3} + m^2_{H_u} - m^2_{H_d}\right) .$$

$$D_{\chi_1} = -6m^2_{\tilde{Q}_1} - 3m^2_{\tilde{u}_1} + 9m^2_{\tilde{d}_1} + 6m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1} .$$

$$D_Z \equiv 3m^2_{\tilde{d}_3} + 2m^2_{\tilde{L}_3} - 2m^2_{H_d} - 3m^2_{\tilde{d}_1} .$$

Gauge Coupling/Gaugino Mass Invariants

$$I_{Y\alpha} \equiv \frac{D_Y}{g_1^2} = \left(m^2_{H_u} - m^2_{H_d} + \sum_{gen}(m^2_{\tilde{Q}} - 2m^2_{\tilde{u}} + m^2_{\tilde{d}} - m^2_{\tilde{L}} + m^2_{\tilde{e}})\right)/g_1^2$$

$$I_{g_2} \equiv \frac{1}{g_1^2} - \frac{33}{5g_2^2} \sim -11 \qquad I_{g_3} \equiv \frac{1}{g_1^2} + \frac{33}{15g_3^2} \sim 6.2 \qquad I_{B_r} \equiv M_r/g_r^2 \ .$$

Gaugino/Sfermion Mass Invariants

$$I_{M_1} \equiv M_1^2 - \frac{33}{8}\left(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1}\right) ,$$

$$I_{M_2} \equiv M_2^2 + \frac{1}{24}\left(9(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1}) + 16m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1}\right) ,$$

$$I_{M_3} \equiv M_3^2 - \frac{3}{16}\left(5m^2_{\tilde{d}_1} + m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1}\right) .$$

14 RG invariants as a function of
low energy soft SUSY breaking masses and gauge couplings

Once we have measured SUSY masses at the LHC

1) Test if SUSY model is Flavor Blind

$D_{B_{13}}$ = 0 ? $D_{L_{13}}$ = 0 ?

2) Check the Structure of the SUSY Breaking Mechanism

★ Other zeroes of the RG inv. (D_{χ_1} = 0 in GMG)

★ Consistency relations among RG inv. (if too many RG inv. for the # of high energy param.)

★ Determine high energy parameters & the SUSY breaking scale

Examples

General Gauge Mediation (GGM): 8 high energy parameters

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} g_r^4 C_r(f) A_r \qquad M_r = g_r^2 M B_r \qquad m_{H_d}^2 = m_{\tilde{L}_3}^2 + \delta_d$$

$$m_{H_u}^2 = m_{\tilde{L}_3}^2 + \delta_u$$

GGM is flavor-blind ==> $D_{B_{13}}$ = $D_{L_{13}}$ = 0 In addition: D_{χ_1} = 0

- **3 RGI's sufficient to rule out GGM or show consistency with data**
- **Non-zero RGI's at the messenger scale determine all other param.**

$$A_1 = \frac{10}{33}\left(\frac{I_{M_1}}{g_1^4} - I_{B_1}^2\right), \qquad M B_r = I_{B_r} \qquad g_1^2(M) = \frac{13}{10}\frac{D_{Y_{13H}}}{I_{Y\alpha}}$$

$$A_2 = 2\left(\frac{I_{M_2}}{g_2^4} - I_{B_2}^2\right), \qquad \delta_u = -\frac{1}{2}D_Z - \frac{13}{10}D_{Y_{13H}}$$

$$A_3 = \frac{2}{3}\left(\frac{-I_{M_3}}{g_3^4} + I_{B_3}^2,\right) \qquad \delta_d = -\frac{1}{2}D_Z$$

↓ Including the scale M

Constrained MSSM with Non-Universal Higgs Masses (CMSSM + NUHM):

only 4 high energy parameters, m_0, $m_{1/2}$, δ_u, δ_d, and $g_1(M)$

also flavor-blind ==> $D_{B_{13}} = D_{L_{13}} = 0$

- **Non-zero RGI's at the messenger scale overconstrain the system**

-- multiple ways of testing consistency and extracting parameters--

$$m_0^2 = \frac{D_{\chi_1}}{5} \qquad m_{1/2}^2 = I_{M_1} - \frac{33}{40} D_{\chi_1}$$

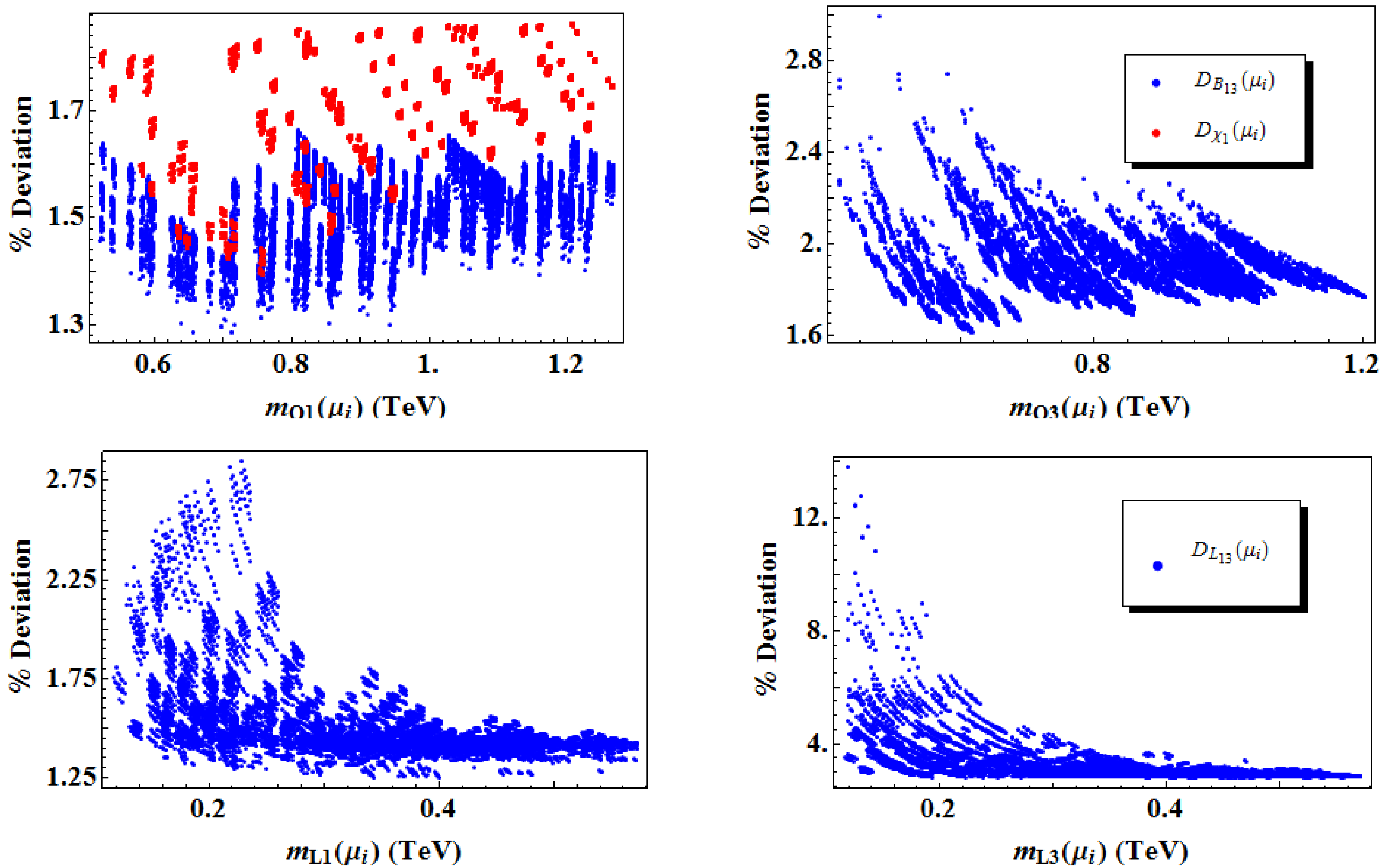
$$D_Z = -2\delta_d \qquad D_{Y_{13H}} = -\frac{10}{13}(\delta_u - \delta_d)$$

$$g_1^2 = \frac{\sqrt{4I_{M_1} - \frac{33}{10} D_{\chi_1}}}{2I_{B_1}}.$$

plus 5 consistency relations:

provide strong constraints that make it highly unlikely for a generic flavor blind or GGM spectrum to mimic CMSSM + NUHM

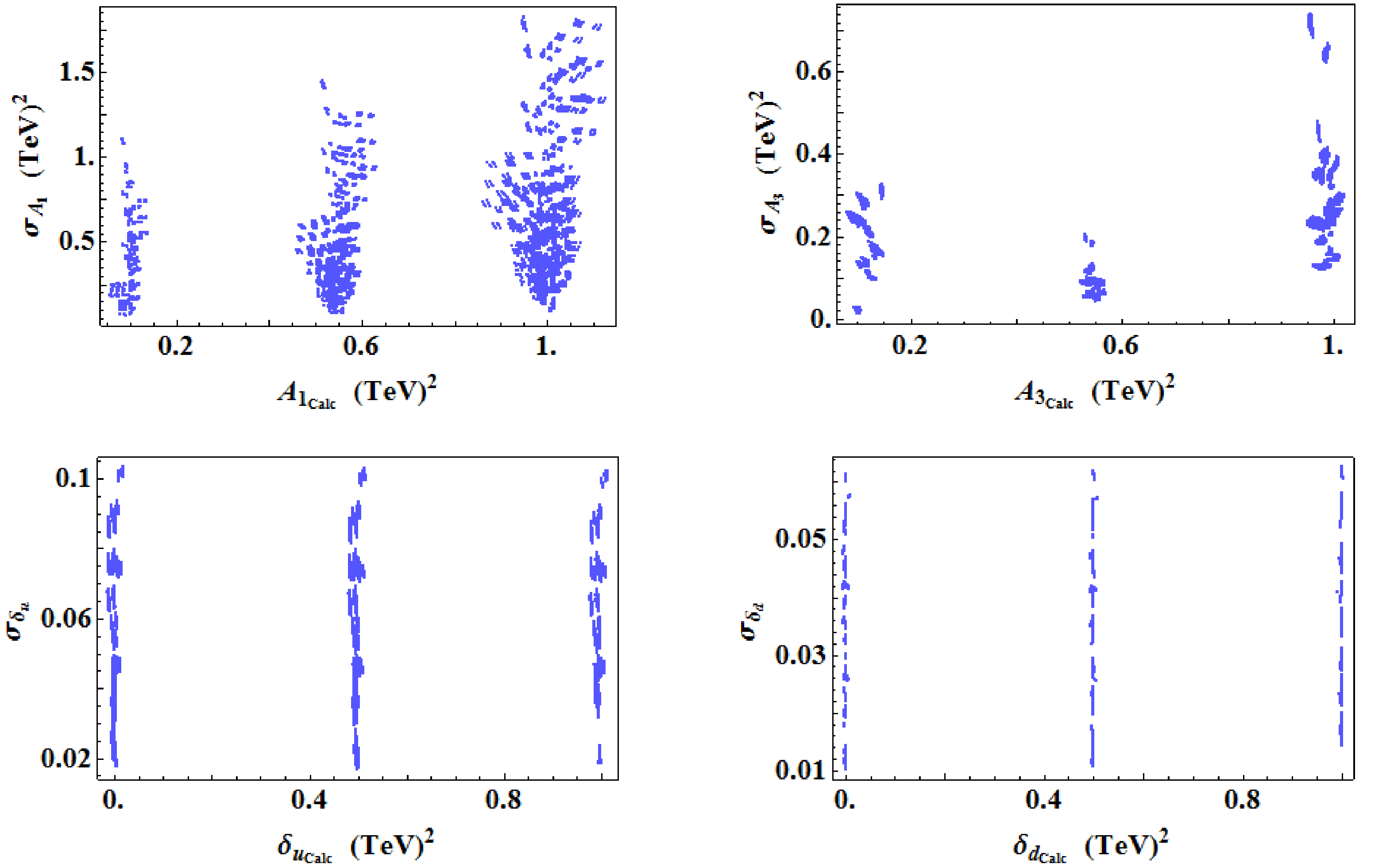
Discriminating power of null RGI's in GGM



Percent deviation in the soft SUSY breaking parameters that would lead to 1σ departure from zero

M.C. Draper, Shah, Wagner.

Experimental prospects for GGM parameter measurements via RGI reconstruction



M.C. Draper, Shah, Wagner.

- 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 the 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. $M \sim 1$ 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

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/M²) 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)

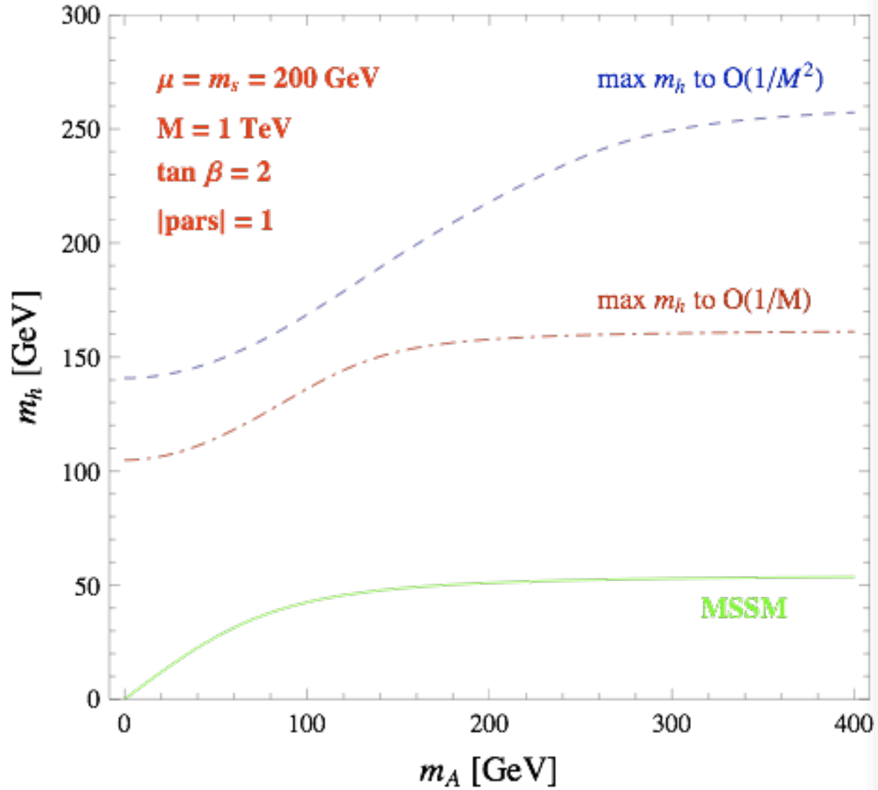
Higgs Spectra in EFT extensions of the MSSM

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



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

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

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 $i = 1, 2, 3, 4, 6, 7$

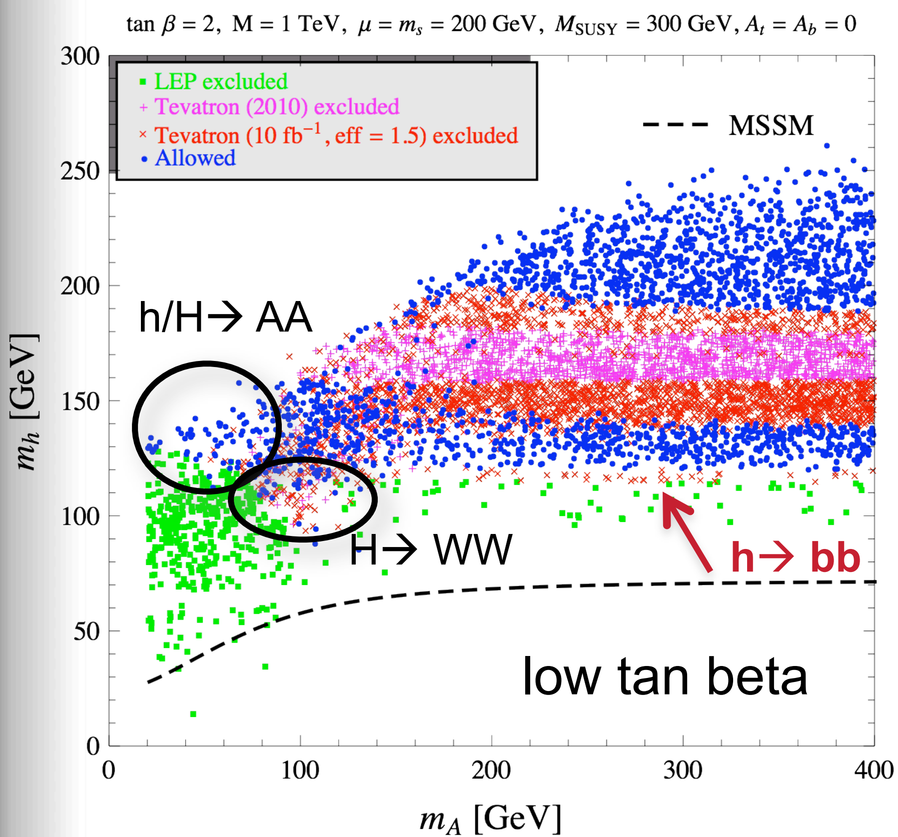
Lightest Higgs Mass after LEP and the Tevatron

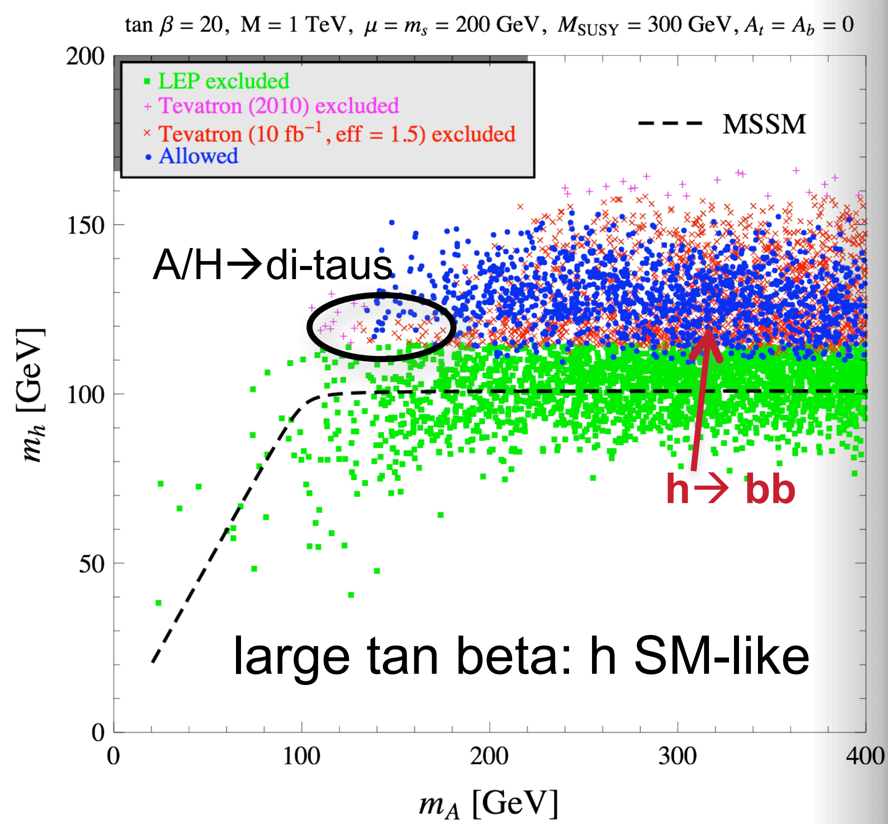
GREEN → LEP excluded

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

MAGENTA → Tevatron excluded

BLUE → Beyond Tevatron





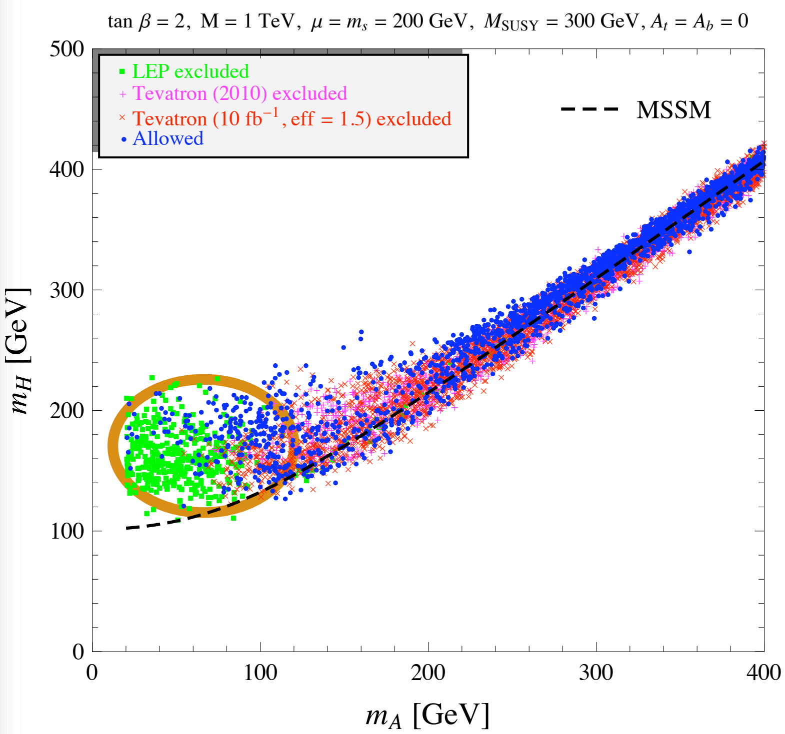
Most magenta and red regions at Tevatron reach in the h→WW channel

M.C,Ponton, Zurita

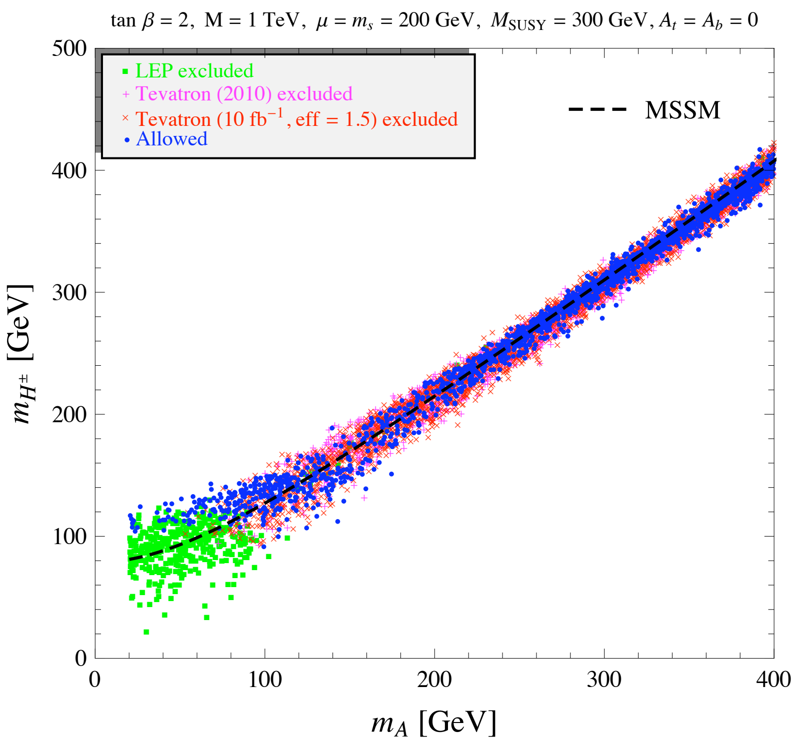
Heavy CP Even and Charged Higgs Masses

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

- **CP-even Higgs boson**: deviations from MSSM and SM fermions and gauge bosons couplings lead to important variations in production processes and BR's

- **CP-odd and charged Higgs boson** couplings 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: $A \to hZ; \quad H^\pm \to W^\pm h; \quad H \to hh$

BMSSM Higgs at the Tevatron and LHC

- **At Tevatron reach**:

SM-like searches: 1) $h \to bb$ 2) $h \to WW$ 3) $H \to WW$

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 di-photons, tau pairs and di-bosons

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

Multi-Higgs chain decays

Benchmark Scenarios

Many benchmarks are similar to MSSM ones, or with larger mass splitting

Benchmark point 1 (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)
$h \to WW$ $H \to WW$ $A \to b\bar{b}$	0.73 (0.72) 0.70 (0.71) 0.87	$h \to ZZ$ $H \to ZZ$ $H^+ \to t\bar{b}$	0.25 (0.27) 0.29 (0.29) 0.99

tanb = 2

- All Masses in similar mass range. Lightest Higgs ~ 200 GeV
- BR(h/H→ WW/ZZ) ~ SM value but hWW rather 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 2 (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 with large luminosity (about 100 fb^{-1})
- ***H^+ → A W^+ possible***

Benchmark point 3 (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

Measuring sufficient number of super-particle masses
we may test essential features of the SUSY breaking structure
and the scale of SUSY breaking

If SUSY is richer at a much lower energy scale
many mysteries may be hiding in the details
of the EWSB sector

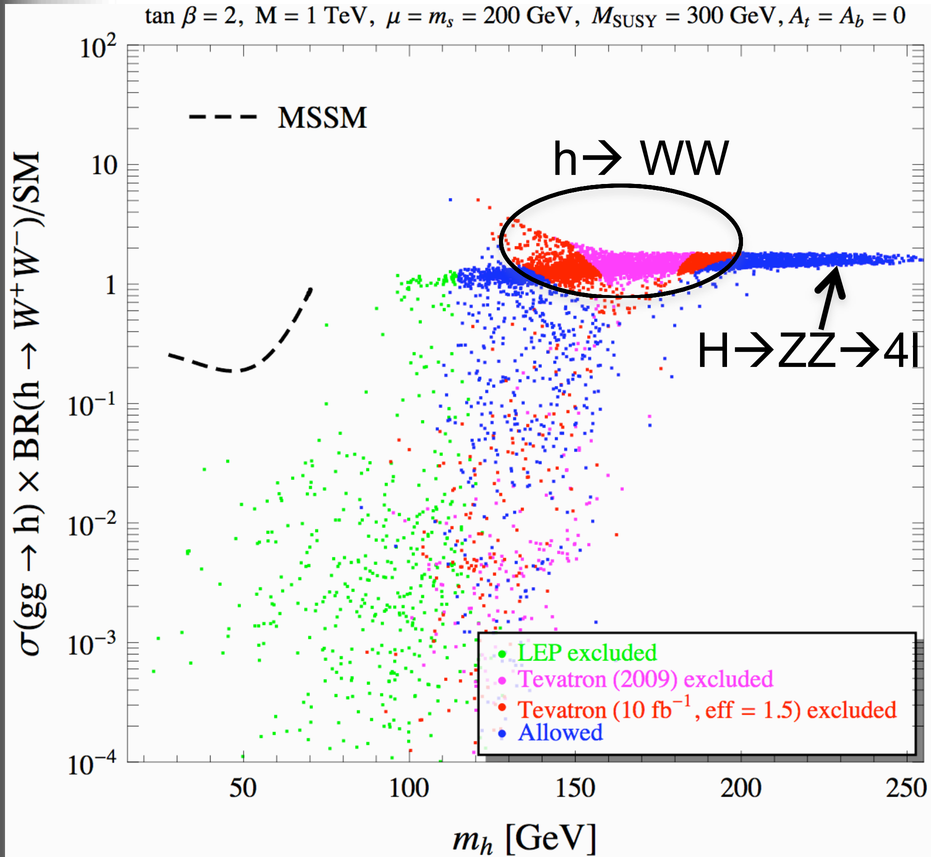
Some type of SUSY may be discovered soon at the LHC
it will probably be more complex than we anticipate it
Let's try to be ready

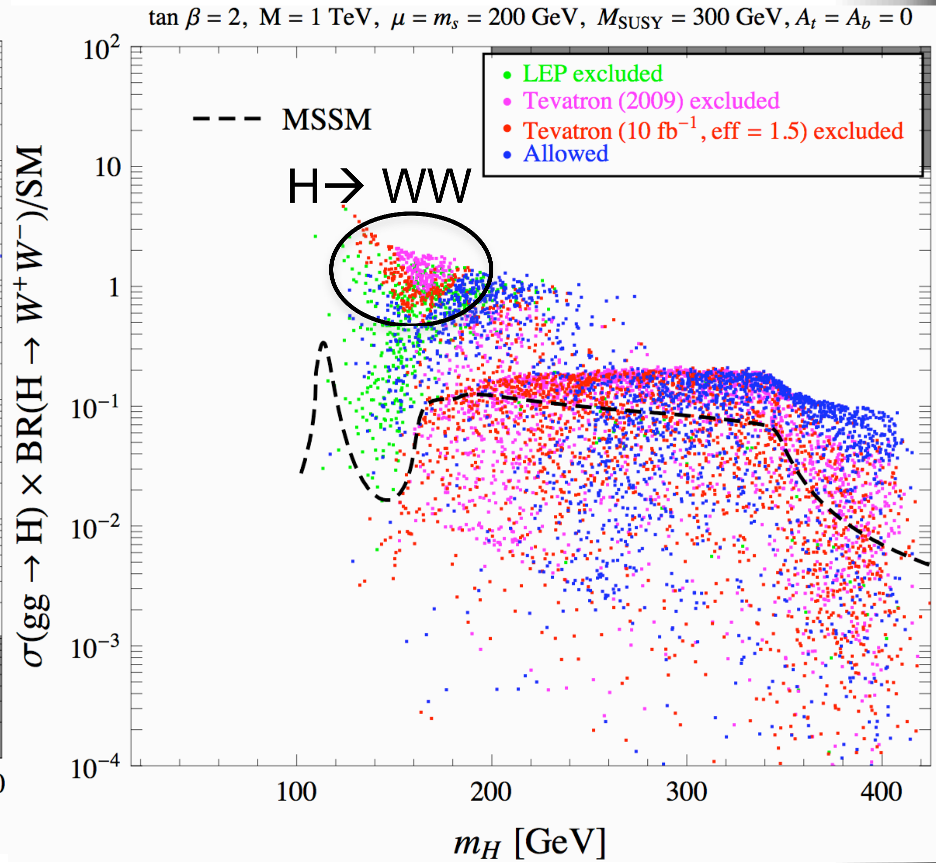
Extras

CP-even Higgs Bosons: low tanb

Tevatron searches in the h/H →WW channel,

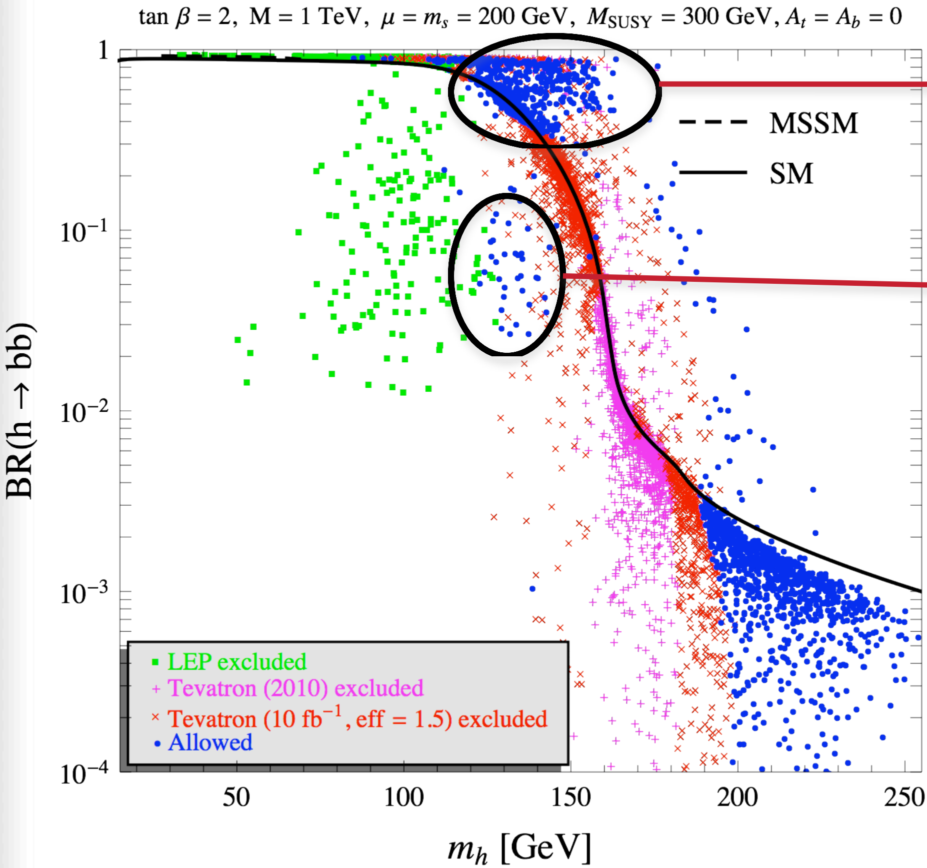
(h/H→ bb remains borderline)





Lightest Higgs Boson: low tanb

- Important variations in the BR of h into bottom pairs



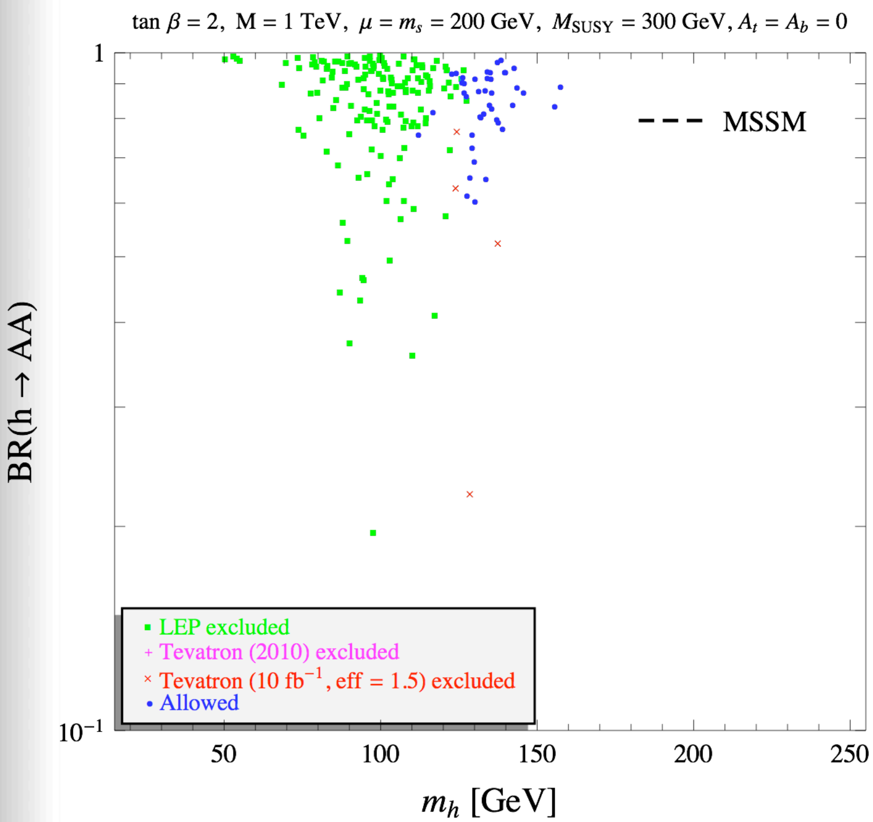
reduced BR (h-> WW)

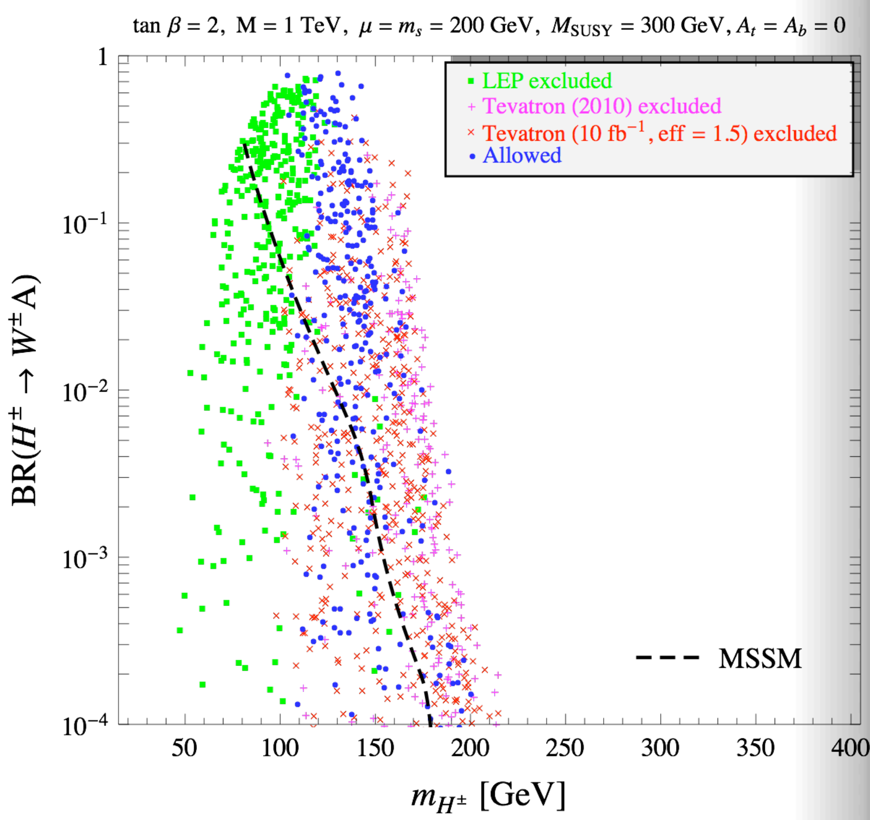
strong suppression of h into bb
In mass region mh ~ 120-150

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)

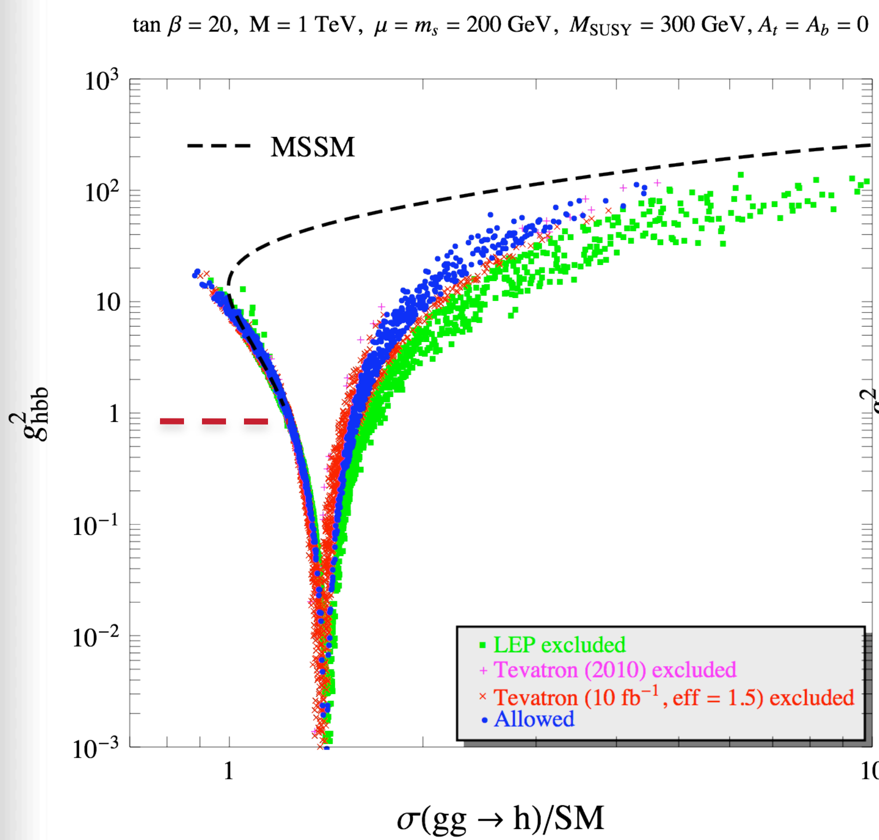
A-h inversion of hierarchy at low tanb

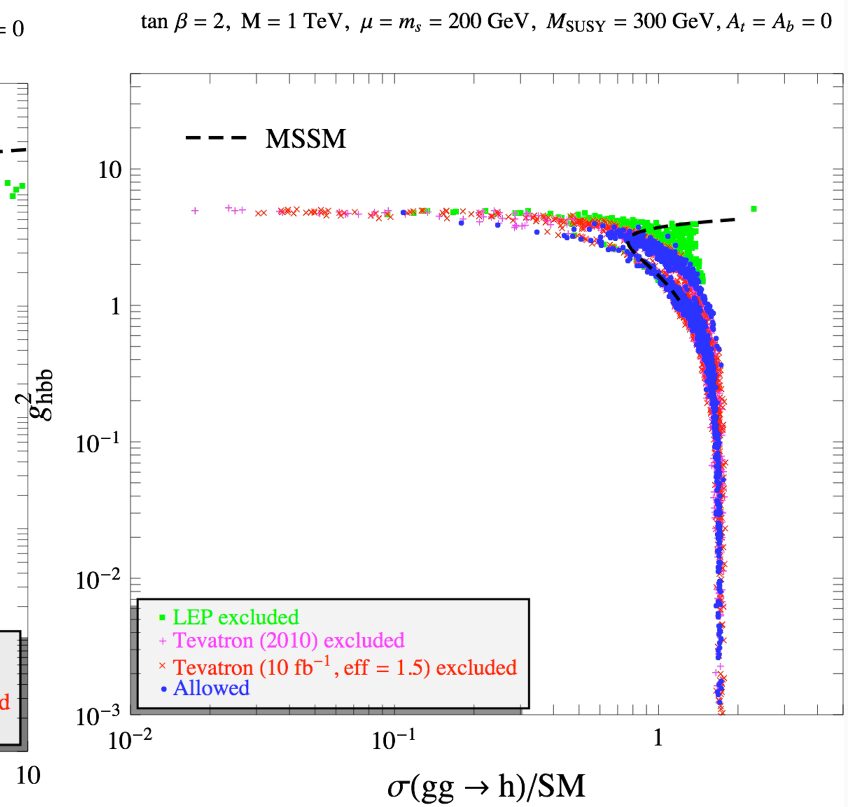




The MSSM channels A/H → hh and H^+ → hW^+
replaced by h/H → AA and H^+ → AW^+ in BMSSM
with parameter sets of BR's of order one

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

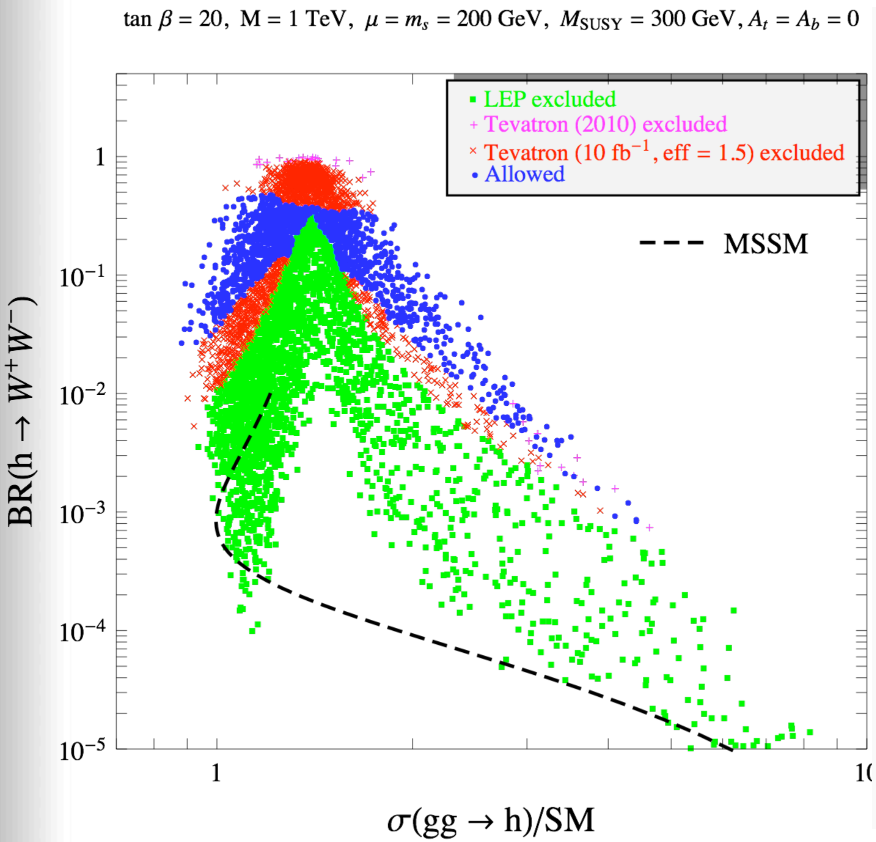


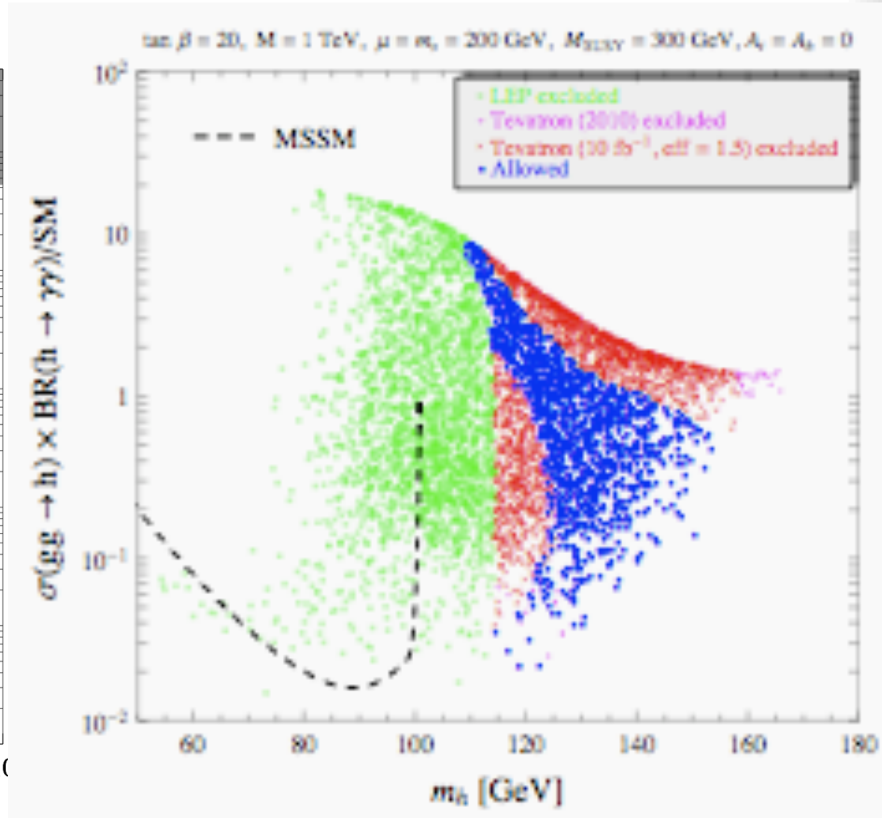


Cancellation between tree level and h.o. operators contributions yields enhancement in gluon fusion: lack of b-loops + light SUSY

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 2a (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 2b (LHC signal)

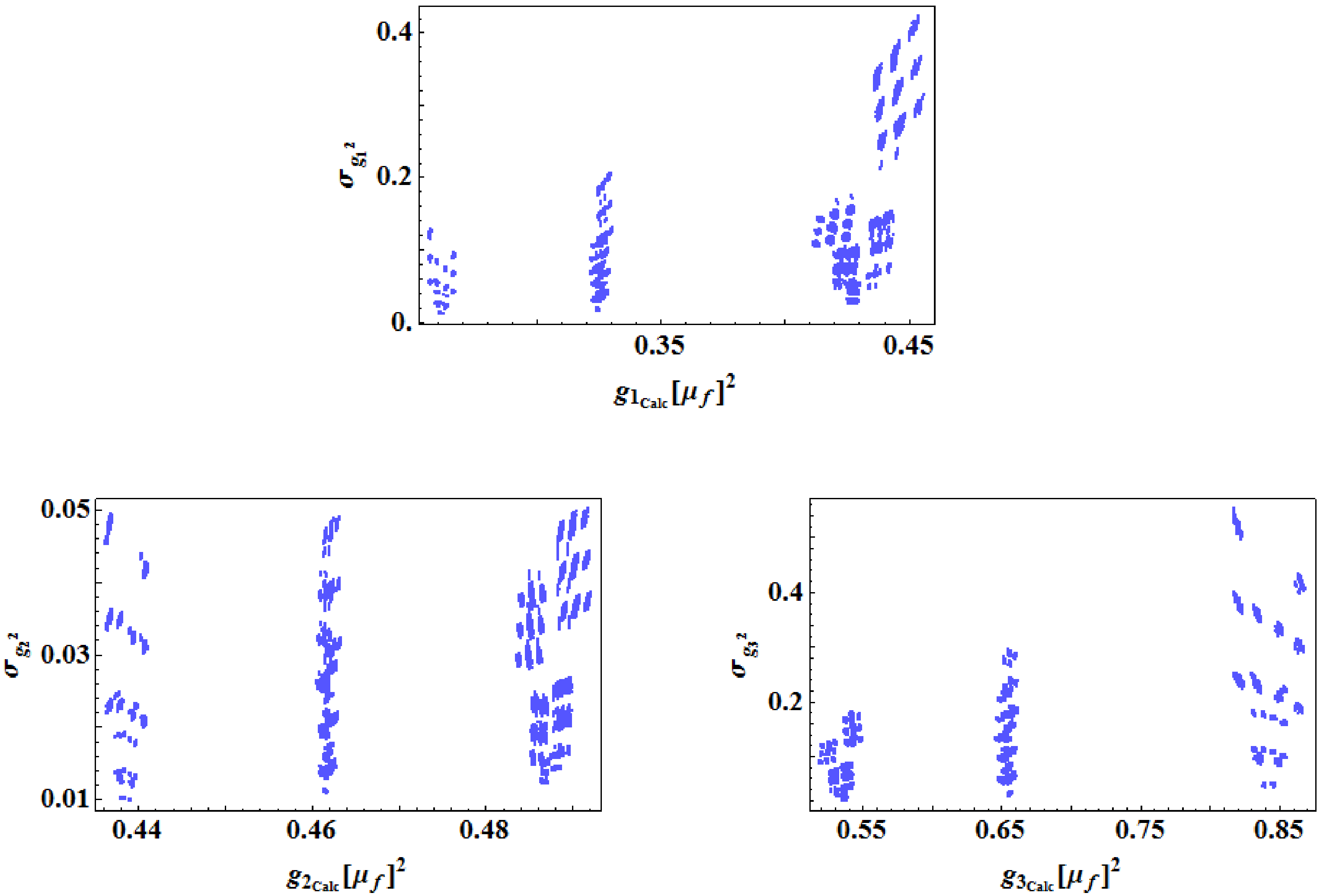
Heavy h and H, non-SM like h in WW/ZZ channel at LHC

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

- light Higgs heavier than A and H+
- H very SM –like, first to be seen at LHC
- hWW/hZZ very suppressed, still h at LHC reach

Invariant	Generic Flavor Blind Model	GGM	CMSSM with NUHM
$D_{B_{13}}$	0	0	0
$D_{L_{13}}$	0	0	0
D_{χ_1}	$9m_{\tilde{d}}^2 - m_{\tilde{e}}^2 + 6m_{\tilde{L}}^2 - 6m_{\tilde{Q}}^2 - 3m_{\tilde{u}}^2$	0	$5m_0^2$
$D_{Y_{13H}}$	$\frac{1}{13}\Big(3(m_{\tilde{d}}^2 + m_{\tilde{e}}^2 - m_{\tilde{L}}^2 + m_{\tilde{Q}}^2 - 2m_{\tilde{u}}^2) + 10(m_{H_d}^2 - m_{H_u}^2)\Big)$	$-\frac{10}{13}(\delta_u - \delta_d)$	$-\frac{10}{13}(\delta_u - \delta_d)$
D_Z	$2\left(m_{\tilde{L}}^2 - m_{H_d}^2\right)$	$-2\delta_d$	$-2\delta_d$
$I_{Y\alpha}$	$\Big(3(m_{\tilde{d}}^2 + m_{\tilde{e}}^2 - m_{\tilde{L}}^2 + m_{\tilde{Q}}^2 - 2m_{\tilde{u}}^2) - m_{H_d}^2 + m_{H_u}^2\Big)/g_1^2$	$(\delta_u - \delta_d)/g_1^2$	$(\delta_u - \delta_d)/g_1^2$
I_{B_r}	M_r/g_r^2	MB_r	$m_{1/2}/g_r^2$
I_{M_1}	$M_1^2 + \frac{33}{8}\left(m_{\tilde{e}}^2 + m_{\tilde{u}}^2 - m_{\tilde{d}}^2\right)$	$g_1^4\left((MB_1)^2 + \frac{33}{10}A_1\right)$	$m_{1/2}^2 + \frac{33}{8}m_0^2$
I_{M_2}	$M_2^2 + \frac{1}{24}\left(9m_{\tilde{d}}^2 - m_{\tilde{e}}^2 + 16m_{\tilde{L}}^2 - 9m_{\tilde{u}}^2\right)$	$g_2^4\left((MB_2)^2 + \frac{1}{2}A_2\right)$	$m_{1/2}^2 + \frac{5}{8}m_0^2$
I_{M_3}	$M_3^2 - \frac{3}{16}\left(5m_{\tilde{d}}^2 - m_{\tilde{e}}^2 + m_{\tilde{u}}^2\right)$	$g_3^4\left((MB_3)^2 - \frac{3}{2}A_3\right)$	$m_{1/2}^2 - \frac{15}{16}m_0^2$
I_{g_2}	≈ -10.9	≈ -10.9	≈ -10.9
I_{g_3}	≈ 6.2	≈ 6.2	≈ 6.2



0.4
0.2
0.
$\sigma_{g_1}{}^2$
0.35
0.45
$g1_{\text{Calc}}[\mu_f]^2$
0.05
0.03
0.01
$\sigma_{g_2}{}^2$
0.44
0.46
0.48
$g2_{\text{Calc}}[\mu_f]^2$
0.4
0.2
$\sigma_{g_3}{}^2$
0.55
0.65
0.75
0.85
$g3_{\text{Calc}}[\mu_f]^2$

Examples

Example 1: singlets

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

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

Examples

Example 1: singlets

B_μ-term

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

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

Examples

Example 1: singlets

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

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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

$(\Delta T < 0)$

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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 $c_4 < 0$!

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

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

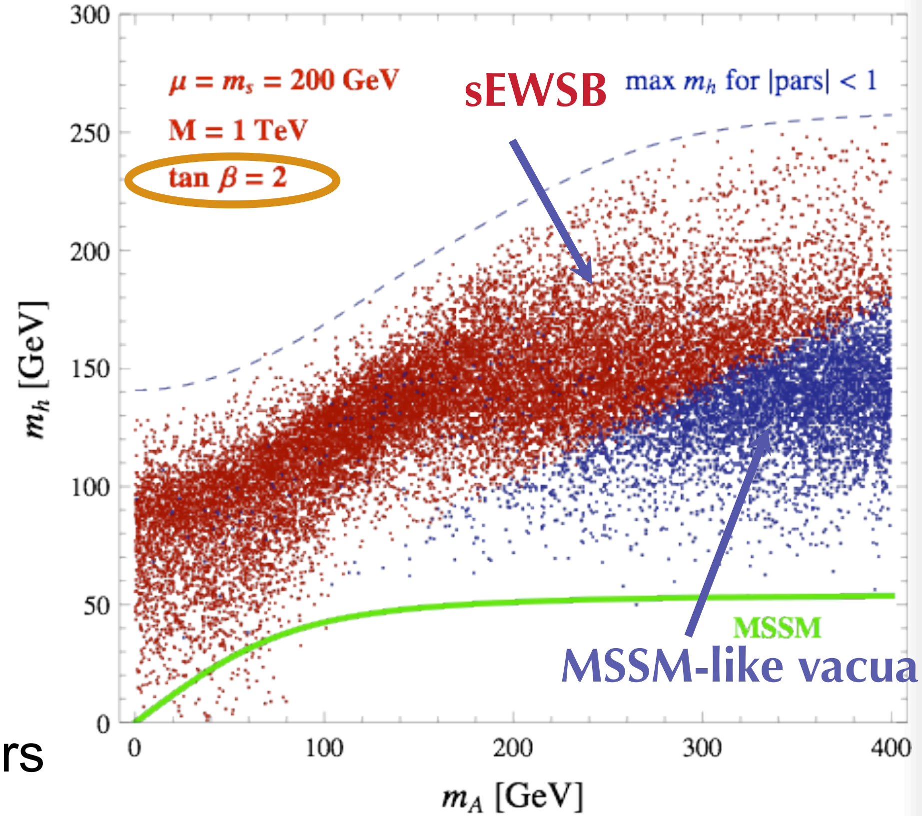
Higgs Spectra in EFT extensions of the MSSM

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.



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 $i = 1, 2, 3, 4, 6, 7$

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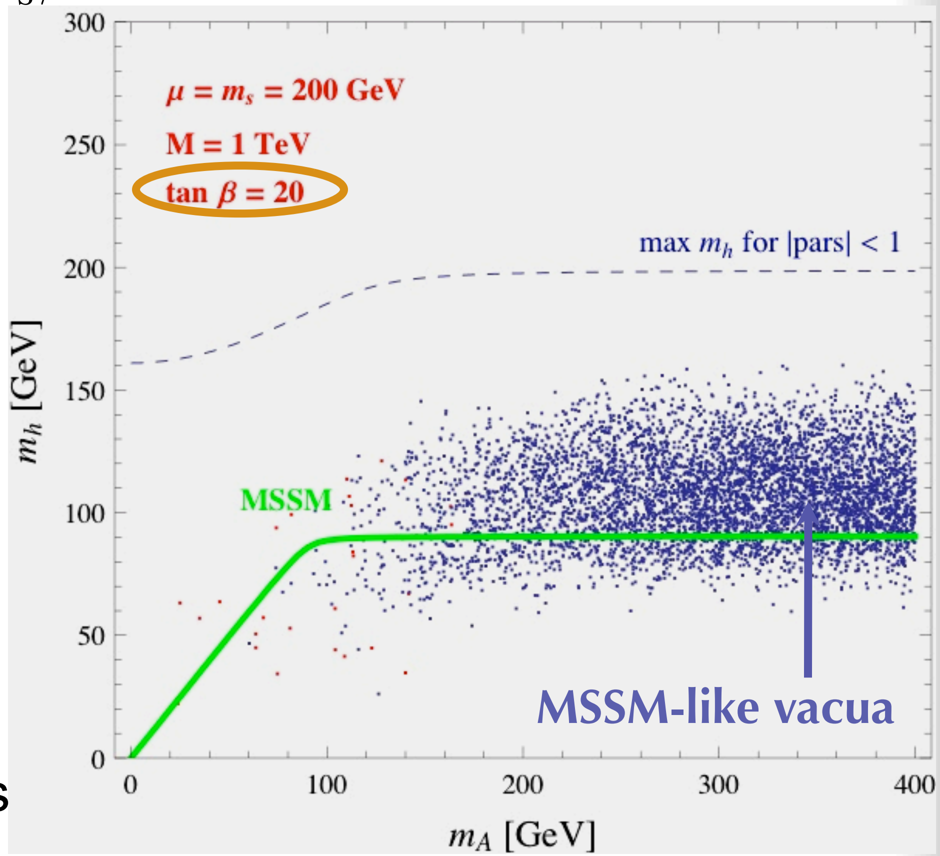
Smaller effects for large tanb main contributions proportional to $1/M^2$.



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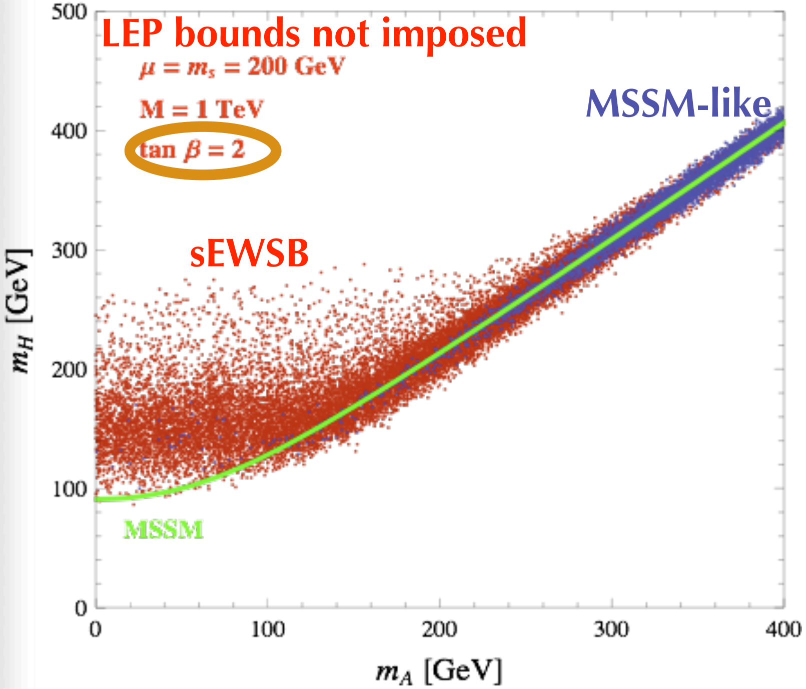
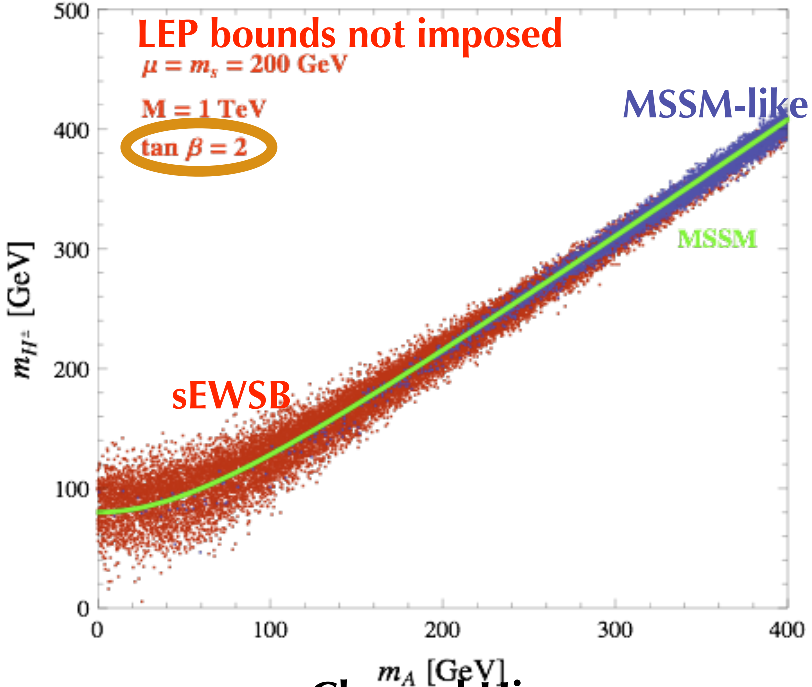
Heavy CP Even and Charged Higgs Masses

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

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



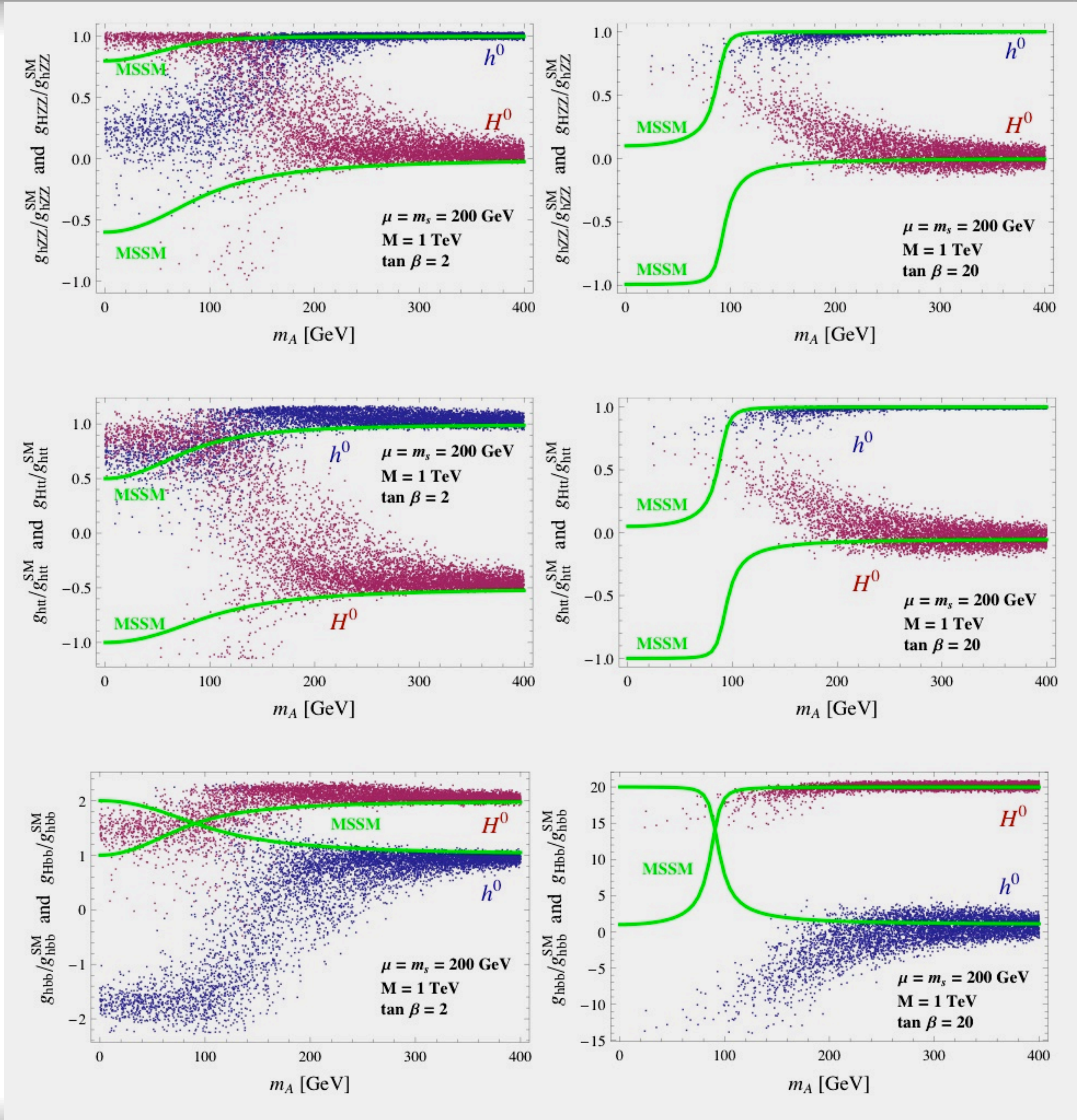
Heavy CP-even Higgs



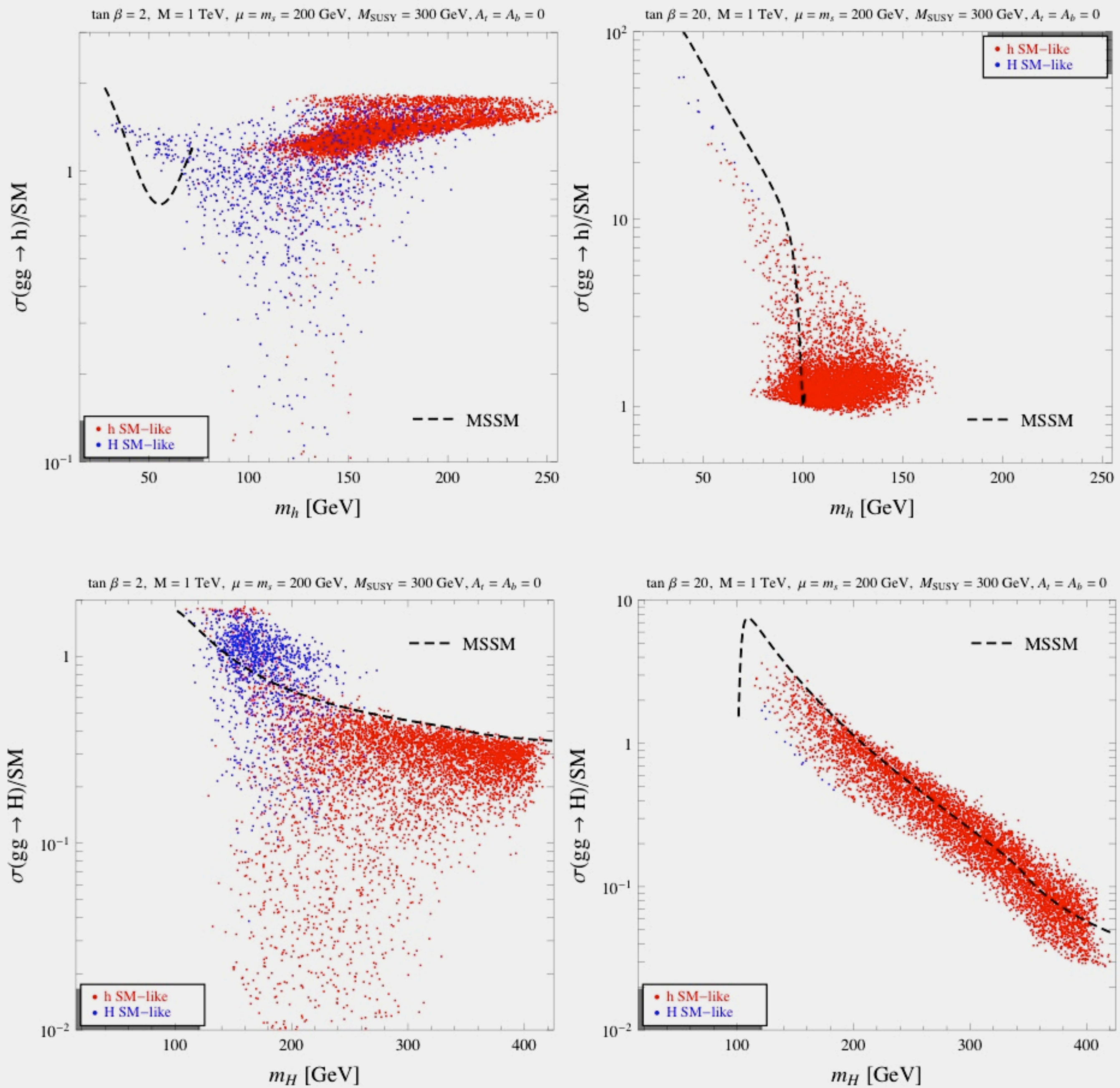
Charged Higgs

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)