BMSSM Higgs bosons at the LHC

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M. Carena, K.C. Kong, E. Pontón, J.Z: **PRD81:015001, 2010 (arXiv:0909.5434)**

M. Carena, E. Pontón, J.Z: **PRD82:055025, 2010 (arXiv:1005.4887) and arXiv:1111.2049**

CERN EP-Seminar, 29th November 2011

Outline

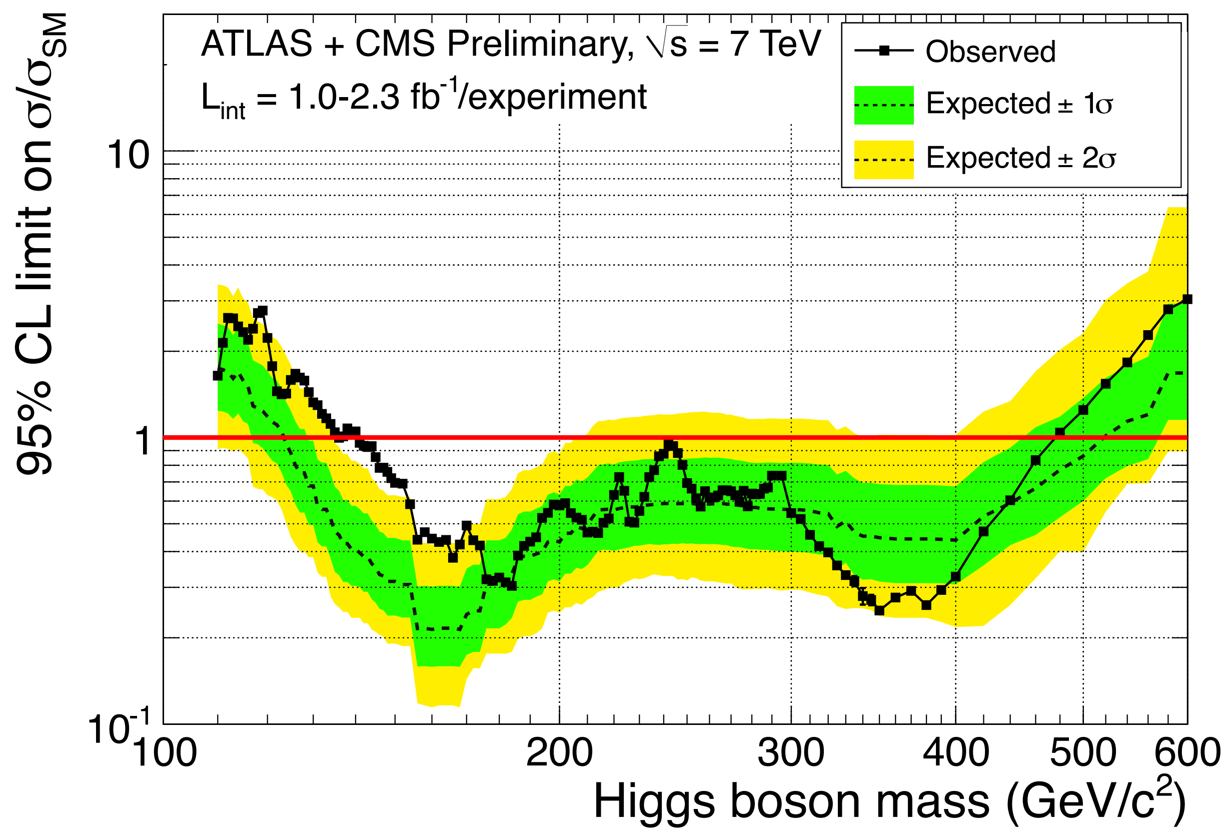
- Motivation
- Higgs Physics in the SM and in the MSSM
- BMSSM Higgs sectors
- LHC phenomenology
- Conclusions

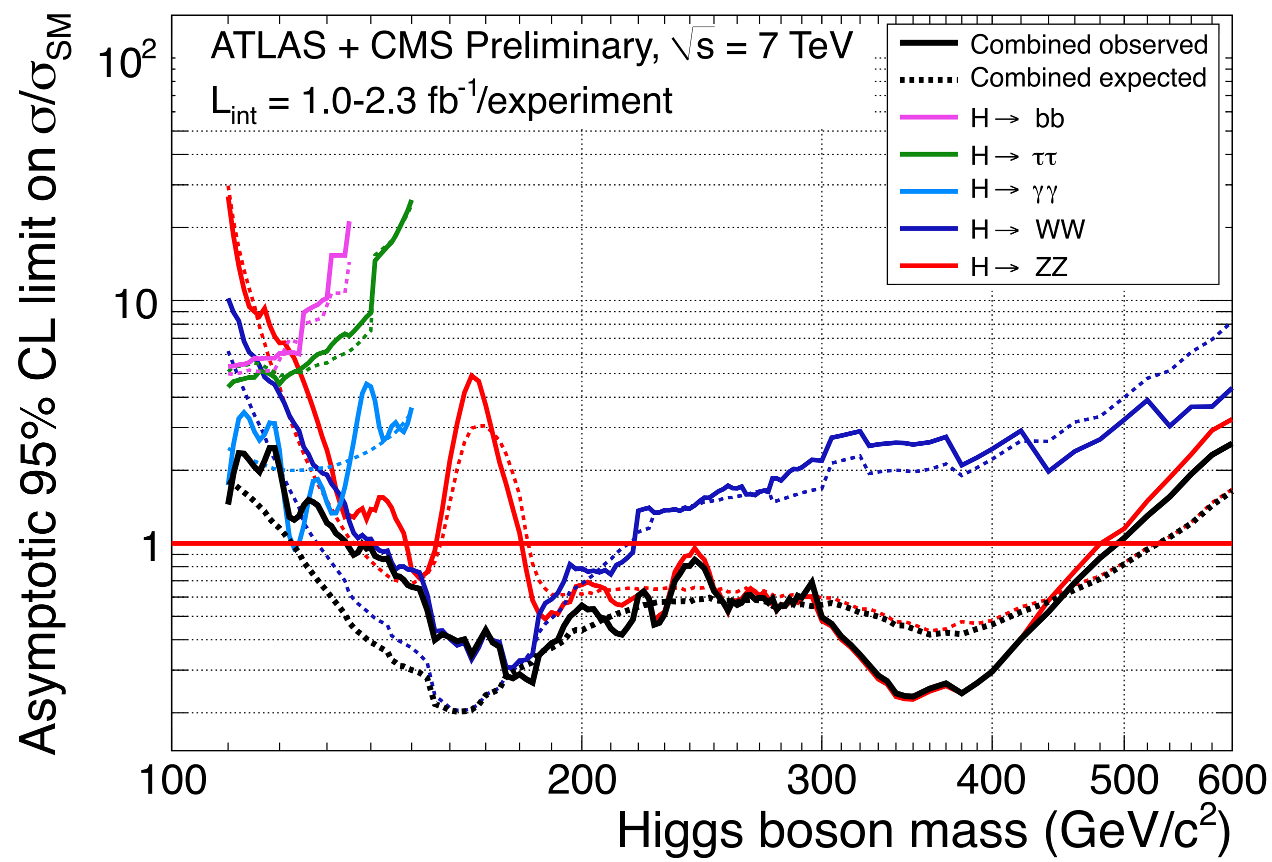
Why to go Beyond the MSSM?

- MSSM Higgs sector is strongly constrained:
  - LEP search: $m_h > 90 - 114 \text{ GeV}$
  - MSSM 2 loops: $m_h < 135 \text{ GeV}$
- Tension can be relaxed with new degrees of freedom like singlet(s) , triplets, extra gauge symmetries.
- Effective Field Theory (EFT): capture the features of MSSM extensions where supersymmetry breaking is treated as a perturbation and the extra physics "lives" at a scale M. B(eyond)MSSM.

Brignole, Casas, Espinosa, Navarro (2003), Dine, Seiberg, Thomas (2007).

Higgs @ LHC





Obs: $114\ \mathrm{GeV} < \mathrm{m_h} < 141\ \mathrm{GeV}$ (@ 95% C.L)

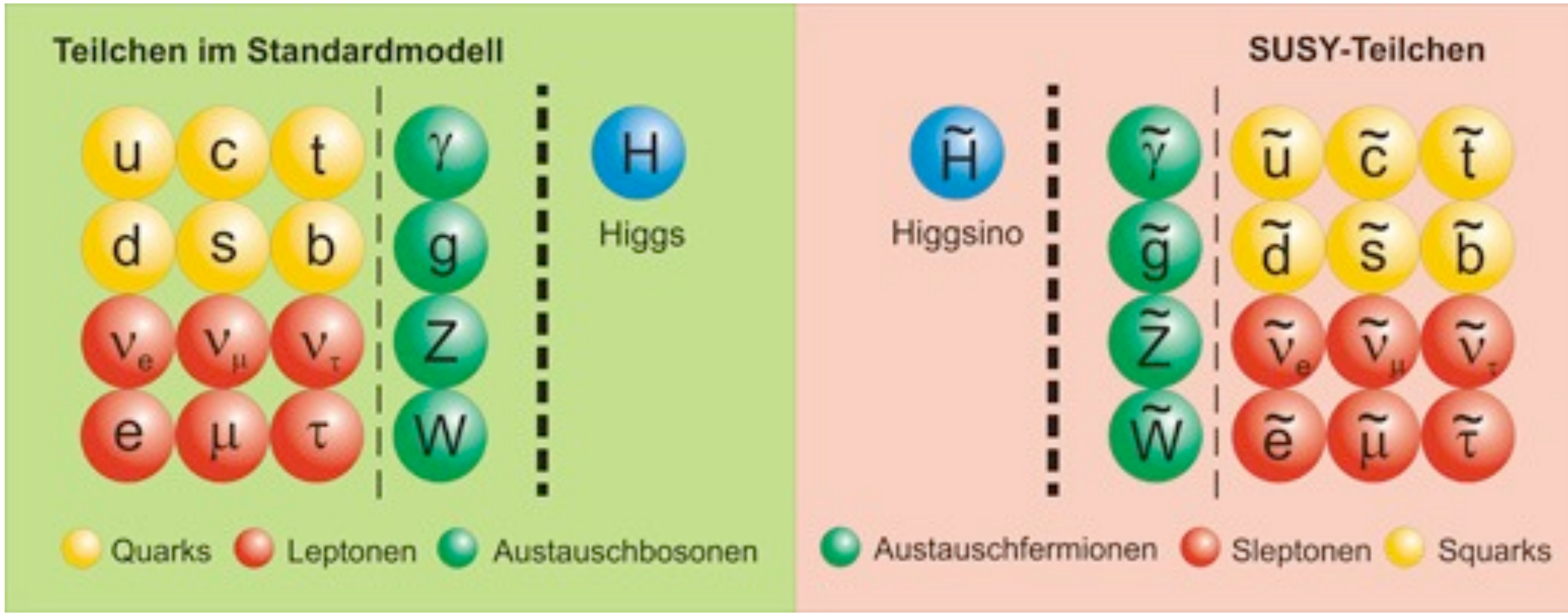
A broad excess (about 2σ) → Something hiding there?

→ What about the 5/fb data?

Why Supersymmetry?

- Possible explanation the hierarchy problem.
- Gauge coupling unification.
- Provides a DM candidate.
- Includes gravity.
- Provides radiative electroweak symmetry breaking
- etc...

MSSM



- Supersymmetrized version of the SM.
- Fermion ⟷ Sfermion (scalar)
- Gauge boson ⟷ Gaugino (fermion)

Since no scalar particle with the electron mass and charge has been detected... ⇒ SUSY is broken

MSSM Lagrangian

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft} \longrightarrow$$

$$\begin{aligned}\mathcal{L}_{\rm soft}^{\rm MSSM} = & -\frac{1}{2}\Big(M_3\widetilde{g}g + M_2 W\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + {\rm c.c}\Big) \\ & -\Big(\widetilde{u}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{d}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{e}\,\mathbf{a_e}\,\widetilde{L}H_d + {\rm c.c}\Big) \\ & -\widetilde{Q}^\dagger\,\mathbf{m^2_{\widetilde{Q}}}\,Q - \widetilde{L}^\dagger\,\mathbf{m^2_{\widetilde{L}}}\,\widetilde{L} - \widetilde{u}\,\mathbf{m^2_u}\,\widetilde{u}^\dagger - \widetilde{d}\,\mathbf{m^2_d}\,d^\dagger - \widetilde{e}\,\mathbf{m^2_e}\,\widetilde{e}^\dagger \\ & - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + {\rm c.c})\,.\end{aligned}$$

Soft Terms

- Sparticle masses $m_{\tilde{t}},\ m_{\tilde{g}}$
- Yukawa couplings $A_t,\ A_b$

Usually one writes down $\mathcal{L} = \int d^2\theta d^2\bar{\theta}\, K + (\int d^2\theta\, W + c.c)$

K: Kähler potential (kin. terms and gauge int.)

W: Super potencial (Yukawa-like interactions)

Higgs in the MSSM

$$H_u,\, H_d \rightarrow h,\, H,\, A,\, H^{\pm} \qquad v^2 = v_u^2 + v_d^2$$

scalars ($h,\, H$) — pseudoscalar (A)

Tree level: $\tan\beta = v_u/v_d$, m_A

$$\begin{aligned} V &= m_{11}^2 H_u^\dagger H_u + m_{22}^2 H_d^\dagger H_d - [b H_u H_d + \mathrm{c.c}] \\ &+ \frac{1}{2}\lambda_1 (H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2 (H_u^\dagger H_u)^2 + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u H_d)(H_u^\dagger H_d^\dagger) \\ &+ \left\{ \frac{1}{2}\lambda_5 (H_u H_d)^2 + \left[\lambda_6 (H_d^\dagger H_d) + \lambda_7 (H_u^\dagger H_u)\right] (H_u H_d) + \mathrm{c.c} \right\}. \end{aligned}$$

MSSM: $\lambda_1 = \lambda_2 = (g_1^2 + g_2^2)/4, \quad \lambda_3 = (g_2^2 - g_1^2)/4, \quad \lambda_4 = -g_2^2/4, \quad \lambda_5 = \lambda_6 = \lambda_7 = 0$

Tree level: $m_h^{(0)} \leq m_Z |\cos(2\beta)|$ **2-loops:** $m_h < 135\ \mathrm{GeV}$

m_S, A_t, A_b

Higgs in the MSSM

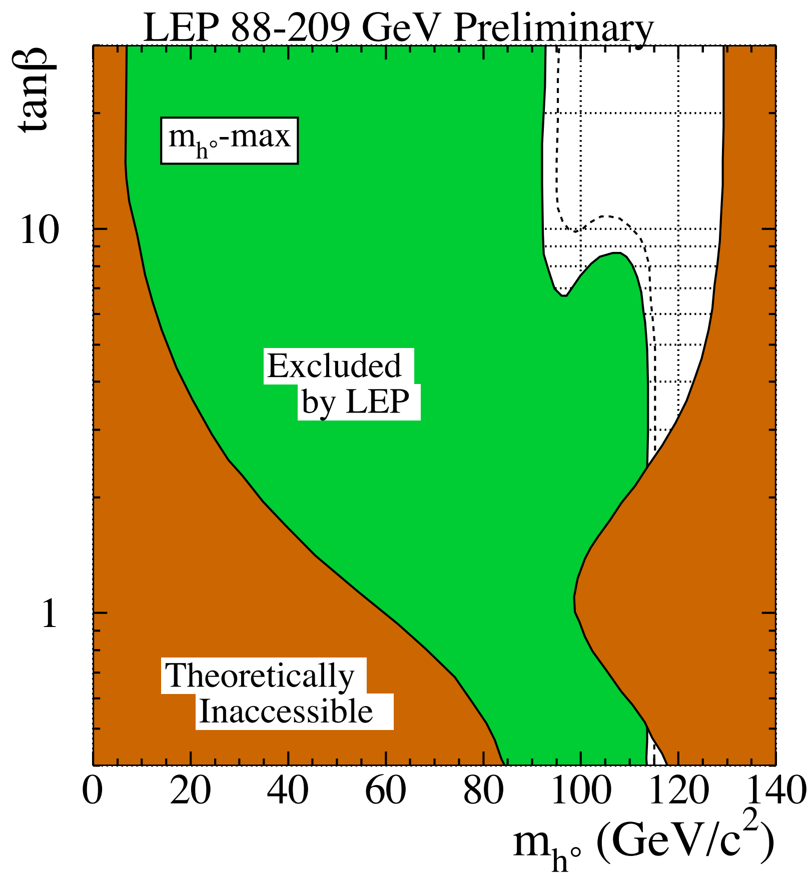
Tree level: $m_h^{(0)} \leq m_Z |\cos(2\beta)|$

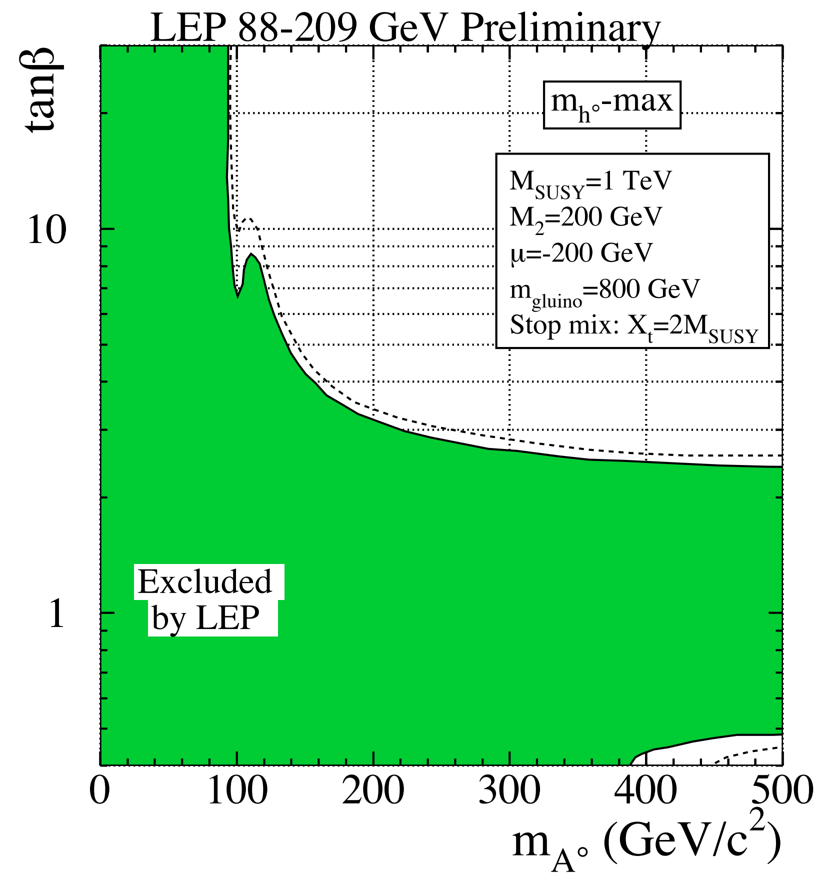
2-loops: $m_h < 135\ \mathrm{GeV}$

↑ m_S, A_t, A_b

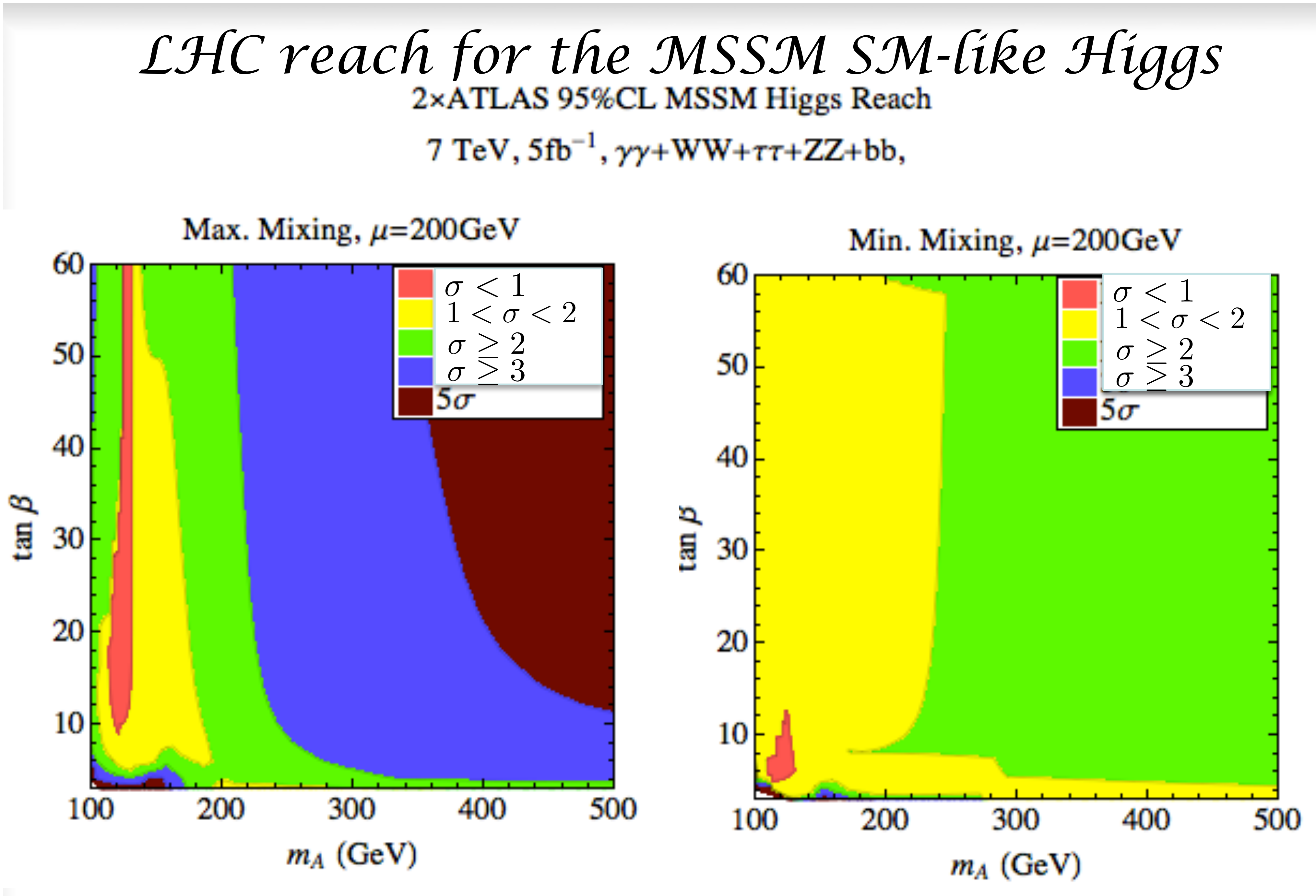
$$\begin{array}{llll} m_h^{(0)} & \approx & 0, & \tan\beta \approx 1 \\ m_h^{(0)} & \approx & m_Z, & \tan\beta > 10 \end{array}$$

Brignole, Carena, de Grassi, Diaz, Ellis, Haber, Hempfling, Heinemeyer, Hollik, Espinosa, Martin, Quiros, Ridolfi, Slavich, Wagner, Weiglein, Zhang, Zwirner,...





Higgs in the MSSM: 7 TeV LHC



Carena, Draper, Liu, Wagner (2011)

"With 10 (15)/fb per experiment 2 sigma (3 sigma) possible".

Carena's talk in HiggsDays (Santander, 2011)

BMSSM Higgs sectors

BMSSM

Starting point: Effective theory (valid below scale M)

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(1 + \alpha_1 X)(H_u H_d)^2$$

M. Dine, N. Seiberg, S. Thomas (2007)

Only 2 parameters: $\omega_1, \alpha_1 \sim \mathcal{O}(1)$ Spurion: $X = m_S\, \theta^2$

$$\Delta\lambda_5 = \alpha_1 \omega_1 \frac{m_S}{M} \qquad \Delta\lambda_6 = \Delta\lambda_7 = \omega_1 \frac{\mu}{M} \qquad \mathcal{O}(1/M) \equiv \mathrm{Dim5}$$

Our choices:
- $\mu = m_S = 200\ \mathrm{GeV}$ and $M = 1\ \mathrm{TeV}$
- $\tan\beta = 2\ (20)$: Low (large) $\tan\beta$ regime.

Related work in HDO

- MSSM: Antoniadis, Dudas, Ghilencea, Tziveloglou (‘08, ’09), Strumia (’99).
- Stability: Blum, Delaunay, Hochberg (’09).
- Fine tuning: Casas, Espinosa, Hidalgo (’04), Cassel, Ghilencea, Ross (’10), Cassel, Ghilencea (’11).
- DM: Cheung, Choi, Song (’09), Berg, Edsjo, Gondolo, Lundstrom, Sjors (’09), Bernal, Goudelis (’10).
- Cosmology: Bernal, Blum, Losada, Nir (’09).
- EW baryogenesis: Grojean, Servant, Wells (’05), Bodeker, Fromme, Huber, Seniuch (’05), Delaunay, Grojean, Wells (’08), Noble, Perelstein (’08), Grinstein, Trott (’08), Blum, Delaunay, Nir, Losada, Tulin (’10).
- S(upersymmetric)EWSB vacua: Batra, Pontón (’09).
- Flavour: Bernal, Losada, Mahmoudi (’11).
- CP-violation: Altmannshofer, Carena, de la Puente, Gori (’11)

Dimension 6 Lagrangian

$$
\begin{aligned}
K &= H_d^\dagger e^V H_d + H_u^\dagger e^V H_u \\
&+ \frac{c_1}{M^2}(1+\gamma_1(X+X^\dagger)+\beta_1 X X^\dagger)(H_d^\dagger e^V H_d)^2 \\
&+ \frac{c_2}{M^2}(1+\gamma_2(X+X^\dagger)+\beta_2 X X^\dagger)(H_u^\dagger e^V H_u)^2 \\
&+ \frac{c_3}{M^2}(1+\gamma_3(X+X^\dagger)+\beta_3 X X^\dagger)(H_u^\dagger e^V H_u)(H_d^\dagger e^V H_d) \\
&+ \frac{c_4}{M^2}(1+\gamma_4(X+X^\dagger)+\beta_4 X X^\dagger)(H_u H_d)(H_u H_d)^\dagger \\
&+ \{[\frac{c_6}{M^2}(1+\beta_6 X X^\dagger+\gamma_6 X+\delta_6 X^\dagger)H_d^\dagger e^V H_d \\
&+ \frac{c_7}{M^2}(1+\beta_7 X X^\dagger+\gamma_7 X+\delta_7 X^\dagger)H_u^\dagger e^V H_u](H_u H_d) + h.c\}\,,
\end{aligned}
$$

$\mathcal{O}(1/M^2)$: 20 extra free parameters.

Are dim 6 operators necessary?

Recall: in the MSSM (dimension 4 operators only)

$$\lambda_{1,4}^{(4)} \sim g^2 \qquad \lambda_{5,7}^{(4)} = 0$$

Turning on dimension 5 operators

$$\Delta\lambda_{1,4}^{(5)} = 0 \qquad \Delta\lambda_{5,7}^{(5)} \neq 0$$

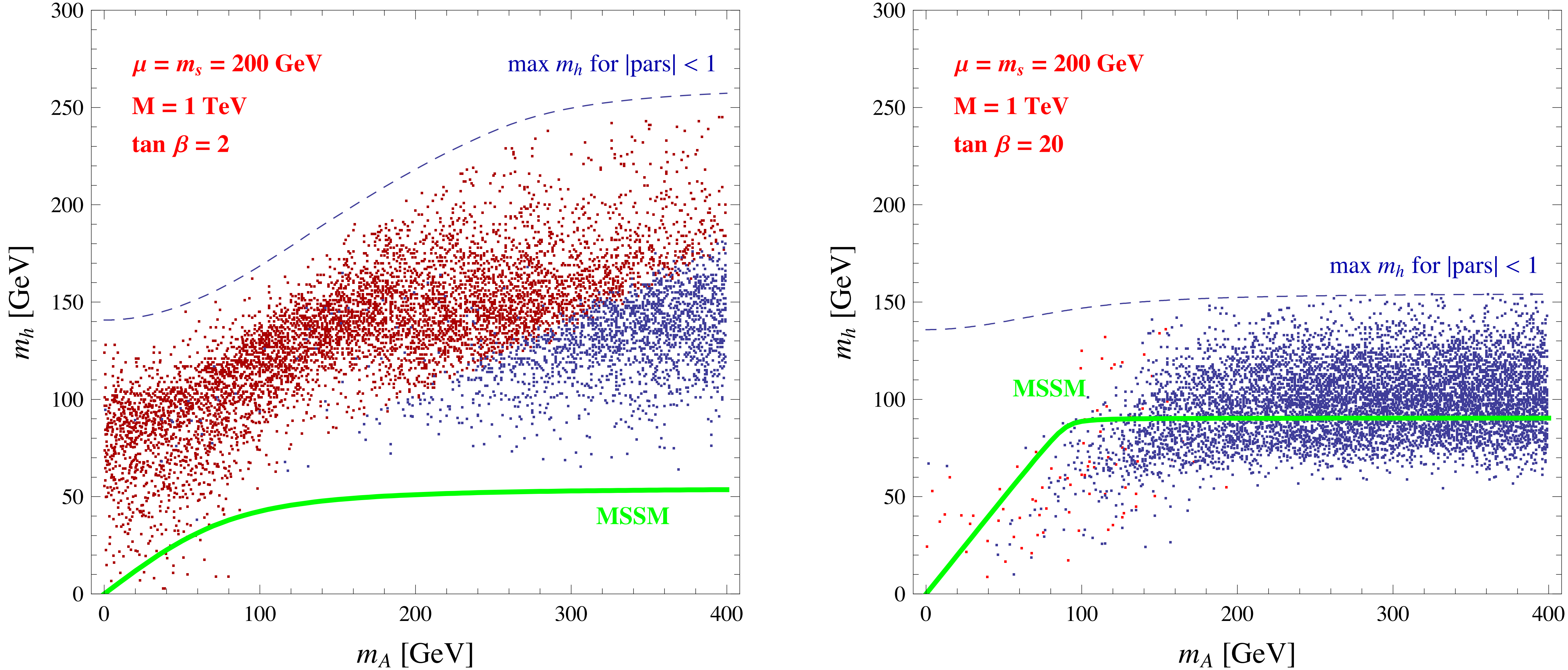
Dimension 6: first corrections to all quartic couplings

Therefore: Dimension 6 analysis is needed !

For the Higgs sector, see:

- Carena, Kong, Pontón, J.Z (2009)
- Antoniadis, Dudas, Ghilencea, Tziveloglou (2009)

Lightest Higgs Mass

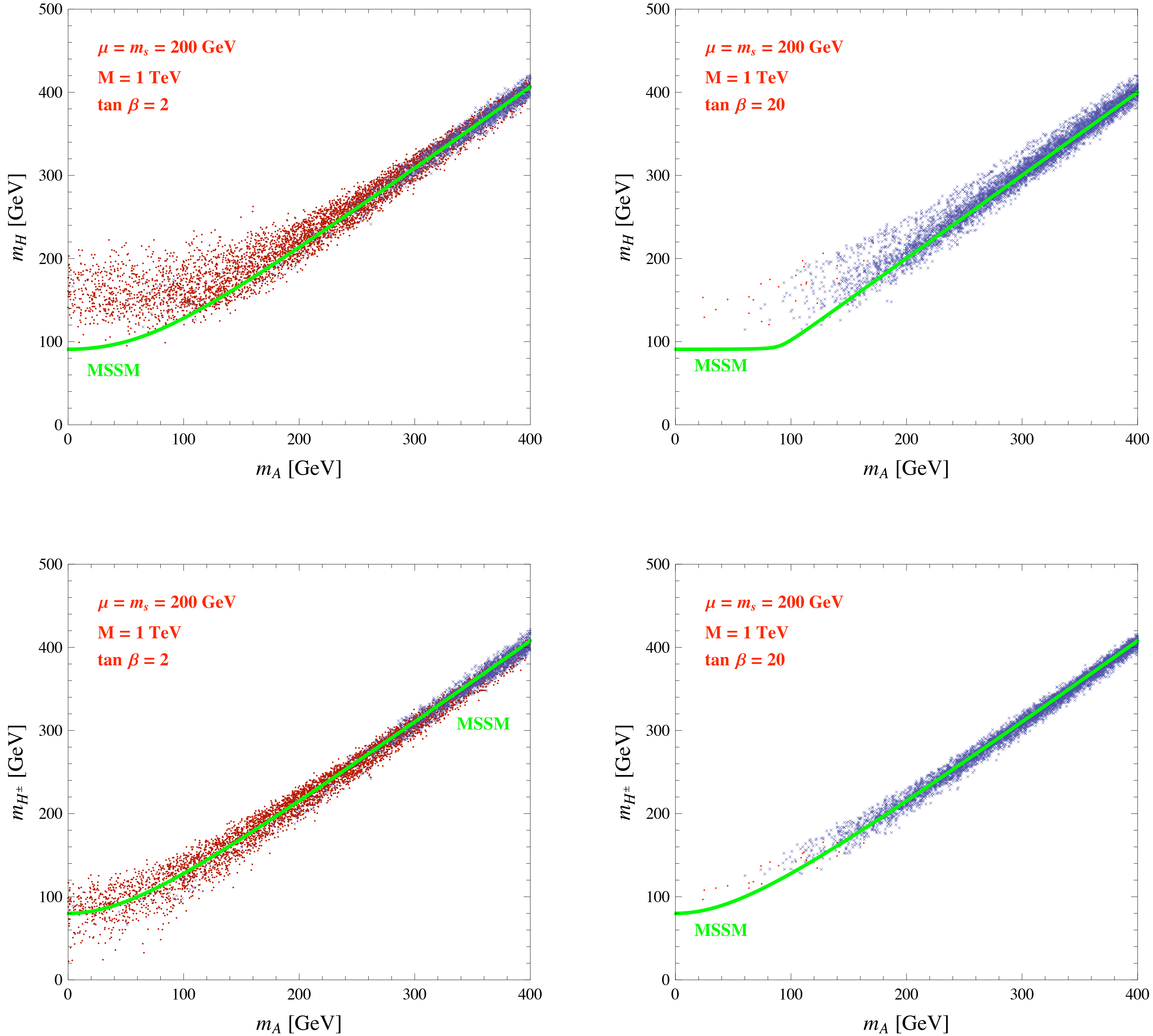


■ sEWSB vacua ■ MSSM vacua

M. Carena, K. Kong, E. Pontón, J. Z (2009)

- The lightest Higgs can be well above the LEP bound (specially for low tangent beta).
- The lightest Higgs mass is also larger than the MSSM theoretical upper bound.

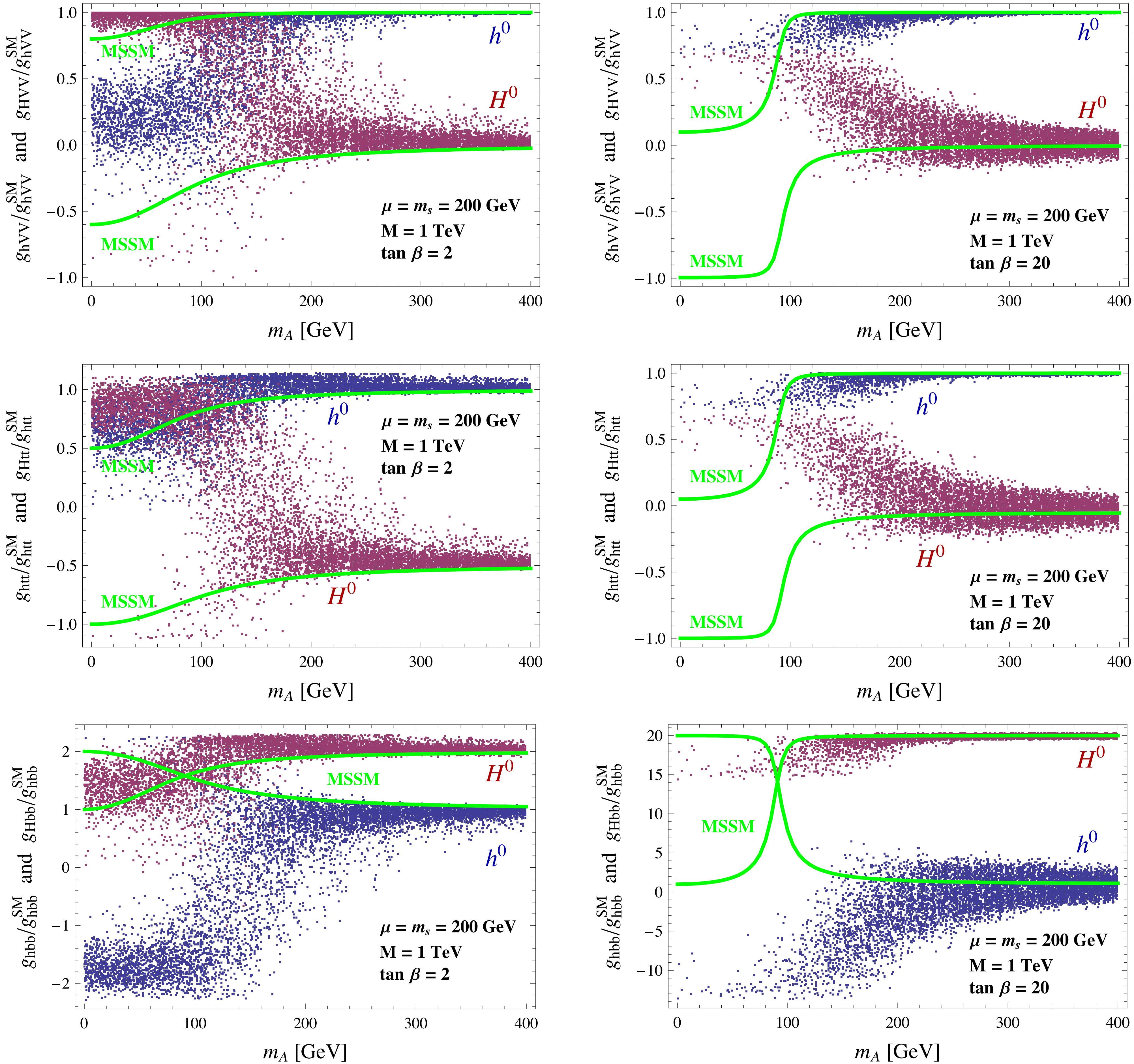
Heavy CP-even and charged Higgs masses



- The other Higgs bosons follow the MSSM trend with the CP-odd mass.
- Large spreading at smaller m_A .
- New decay channels, i.e: $H \to AZ$
  $H^+ \to AW^+$
  $H/h \to AA$

CP-even Higgs couplings to gauge bosons and fermions can change significantly w.r.t both SM and MSSM.

Important variations in the production processes and the decay branching ratios.



Combining with radiative corrections

$$\lambda_i = \lambda_i^{(4)} + \Delta\lambda_i^{(5)} + \Delta\lambda_i^{(6)} + \Delta\lambda_i^{(1-loop-MSSM)}$$

- Obtain masses and couplings of the Higgs sector

- BRs: Modifying HDECAY v 3.4 A. Djouadi, J. Kalinowski, M. Spira (1996)

- Experimental Bounds: HiggsBounds v2.1.0 (LEP and Tevatron)

P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K. E. Williams

+ Electroweak precision data + LHC data from EPS 2011, LP 2011.

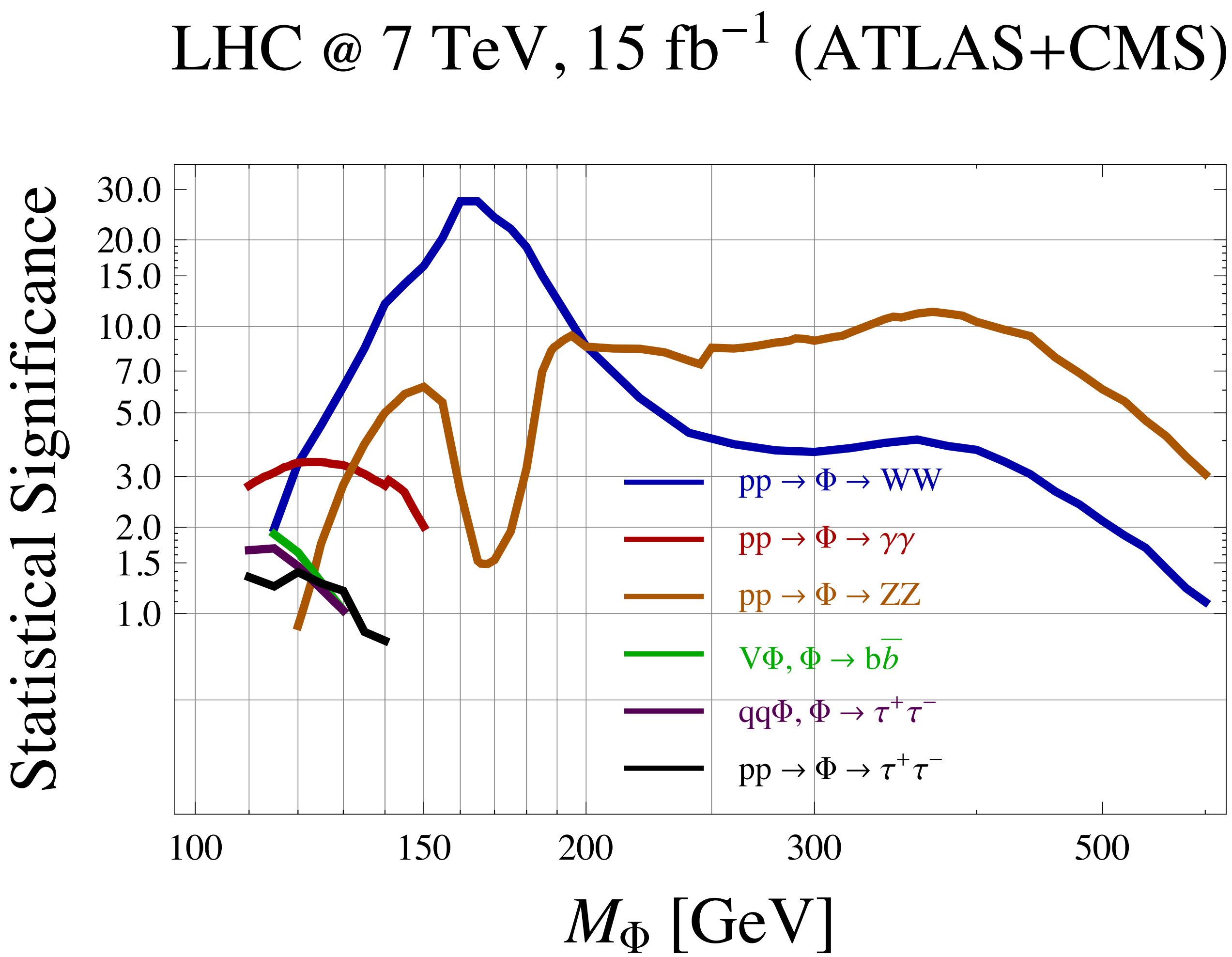
LHC phenomenology

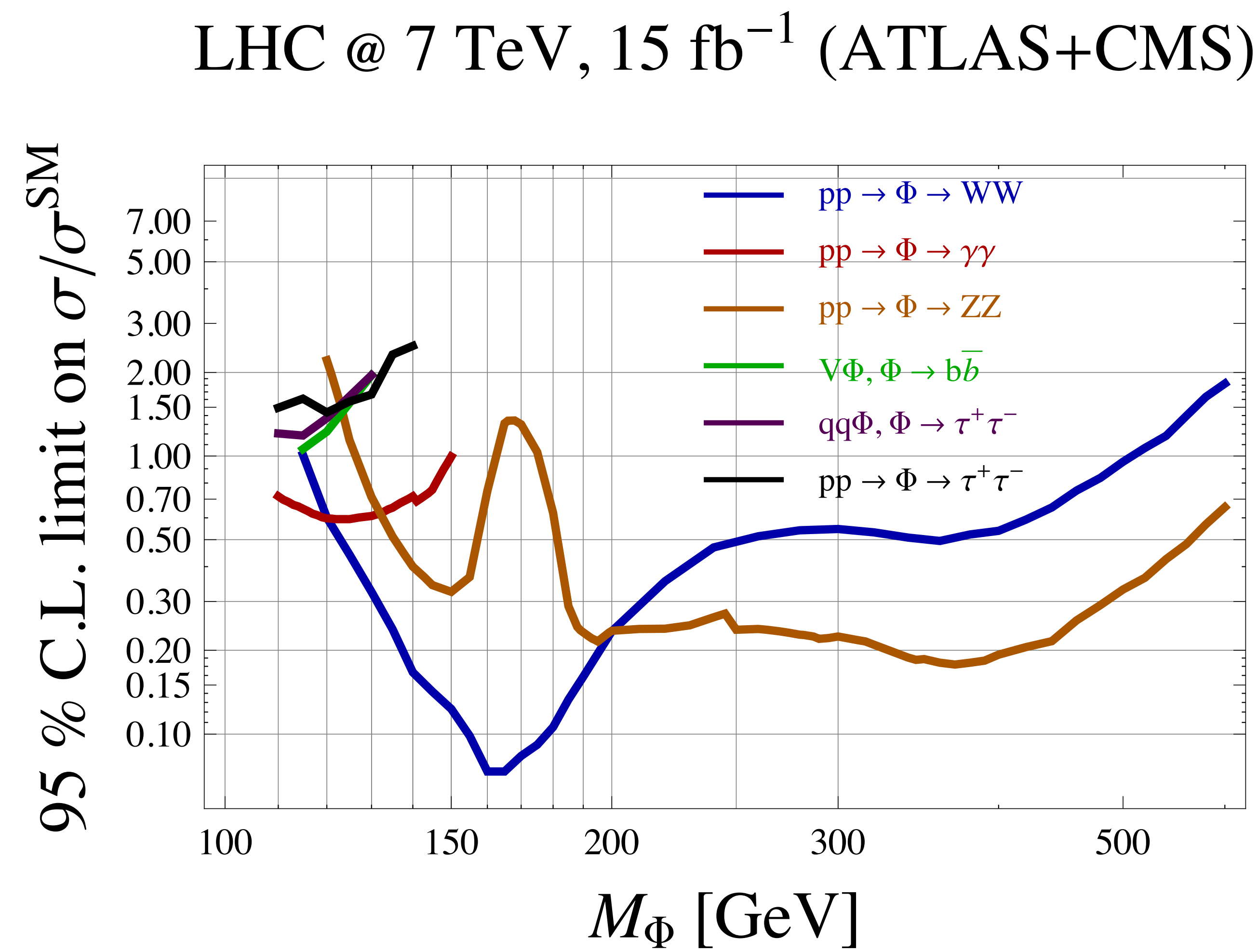
Extended Higgs sector

- What is measured is XS x BR.
- SM is taken as the reference model.
- Extended Higgs sectors:
  - a) H couplings to SM (modifies XS and partial widths)
  - b) new (non-SM) decay channels (change BRs)
- Parametrized by *effective couplings*: $g_{hVV}, g_{hf\bar{f}}, \cdots$

$$g_{hXX} = \frac{\Gamma^{BMSSM}(h \to XX)}{\Gamma^{SM}(h \to XX)}$$

SM Higgs at the 7 TeV LHC





E. Weihs, J.Z (2011)

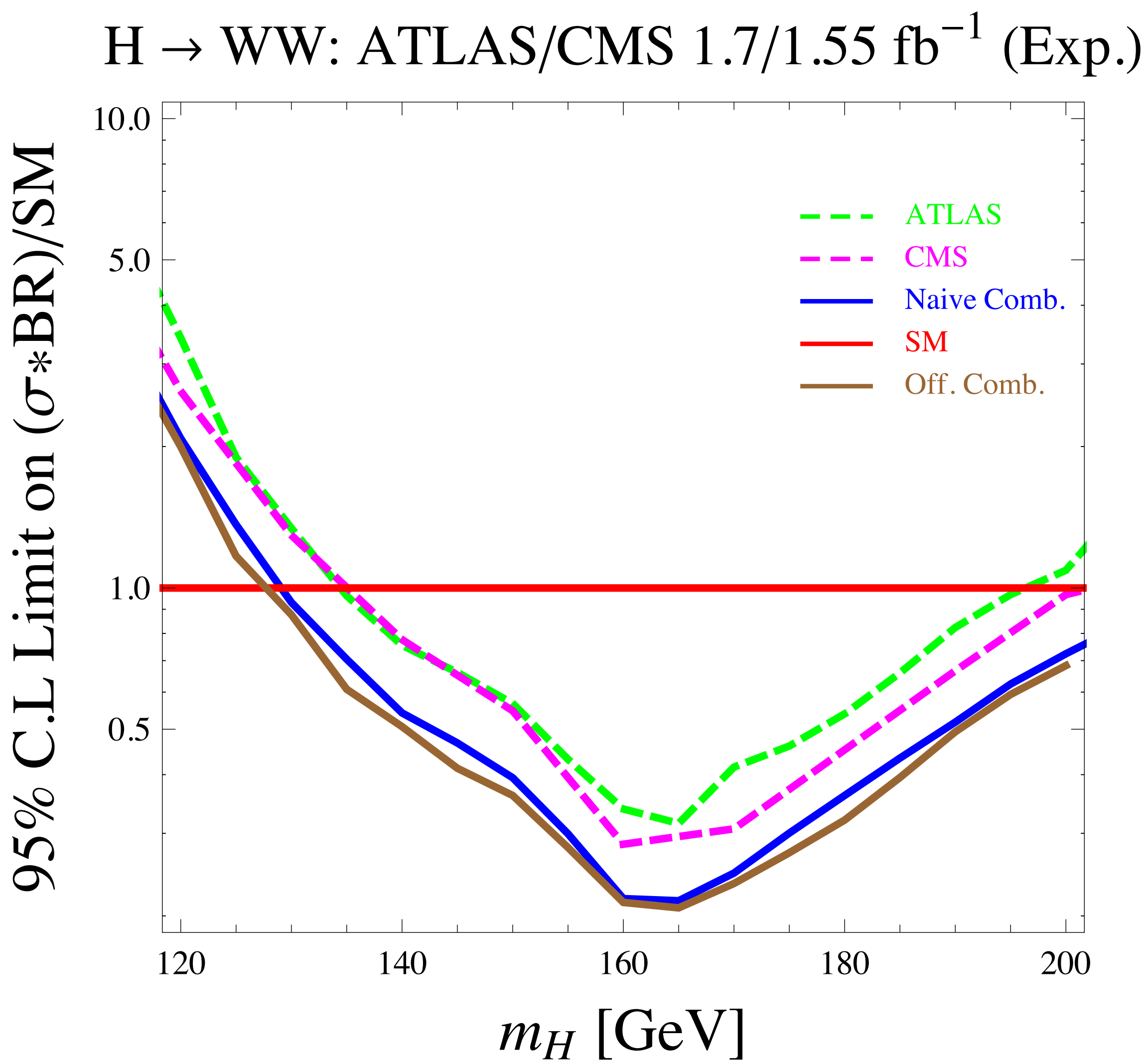
- LHC data presented in summer 2011.
- Combination of CMS and ATLAS data.

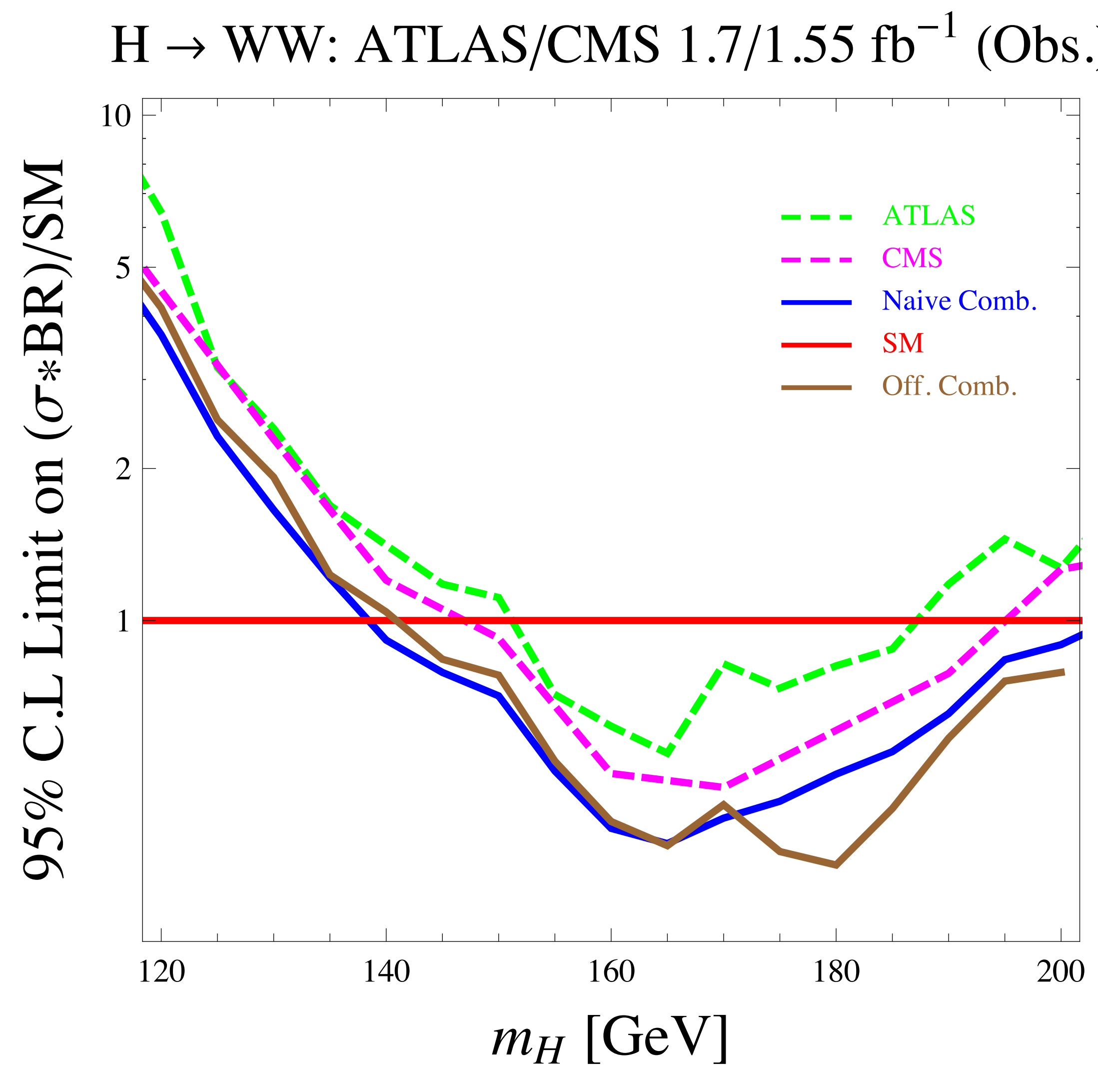
- SM Higgs can be:

a) excluded 115-600 GeV

b) discovered 125-550 GeV

Naïve combination





$$R_i^{95} = S_i^{95} / S_i^{SM}$$

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

If $R^{model} > R^{95}$
the model is excluded.

$$R \sim \sqrt{\mathcal{L}}$$

List of channels

Channel	Lum. (fb^{-1}) ATLAS	CMS	Mass range (GeV)	Ref.
$pp \to \Phi \to WW$	1.7	1.55	115-600	[8–10]
$pp \to \Phi \to ZZ$	1.04 –2.28	1.1 –1.7	120-600	[11–14]
$pp \to \Phi \to \gamma\gamma$	1.08	1.7	110-150	[15, 16]
$pp \to \Phi \to \tau^+\tau^-$	1.06	1.6	90-600	[17, 18]
$V\Phi, \Phi \to b\bar{b}$	–	1.1	110-135	[19]
$qq\Phi, \Phi \to \tau^+\tau^-$	1	–	110-130	[28]
$t \to H^+b, H^+ \to \tau^+\nu_\tau$	–	1.1	80 - 160	[20]

[8] ATLAS collaboration, ATLAS-CONF-2011-134.

[9] ATLAS Collaboration, [arXiv:1109.3615 [hep-ex]].

[10] CMS collaboration, CMS-PAS-HIG-11-014.

[11] G. Aad *et al.* [ATLAS Collaboration], [arXiv:1109.5945 [hep-ex]].

[12] ATLAS. Collaboration, [arXiv:1109.3357 [hep-ex]].

[13] G. Aad *et al.* [ATLAS Collaboration], [arXiv:1108.5064 [hep-ex]].

[14] CMS collaboration, CMS-PAS-HIG-11-013; CMS-PAS-HIG-11-015; CMS-PAS-HIG-11-016; CMS-PAS-HIG-11-017.

[15] ATLAS. Collaboration, [arXiv:1108.5895 [hep-ex]].

[16] CMS collaboration, CMS- PAS-HIG-11-021.

[17] ATLAS collaboration, ATLAS-CONF-2011-132.

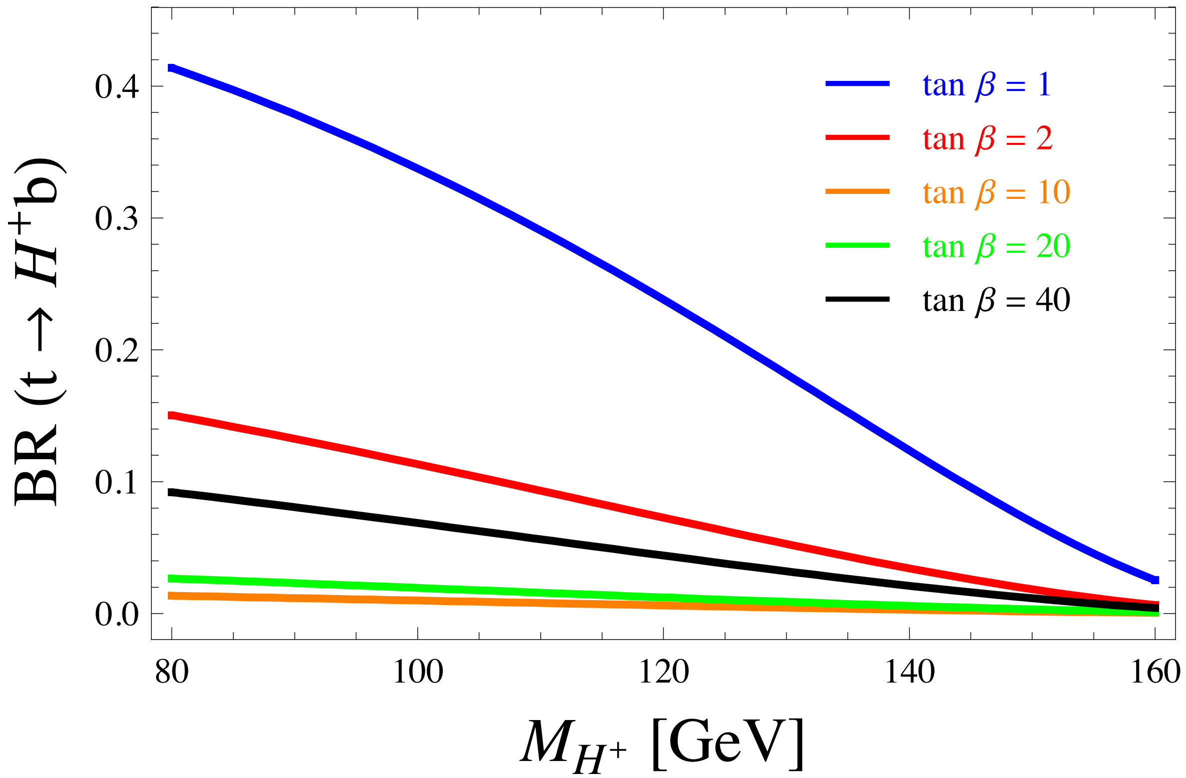
[18] CMS collaboration, CMS-PAS-HIG-11-020.

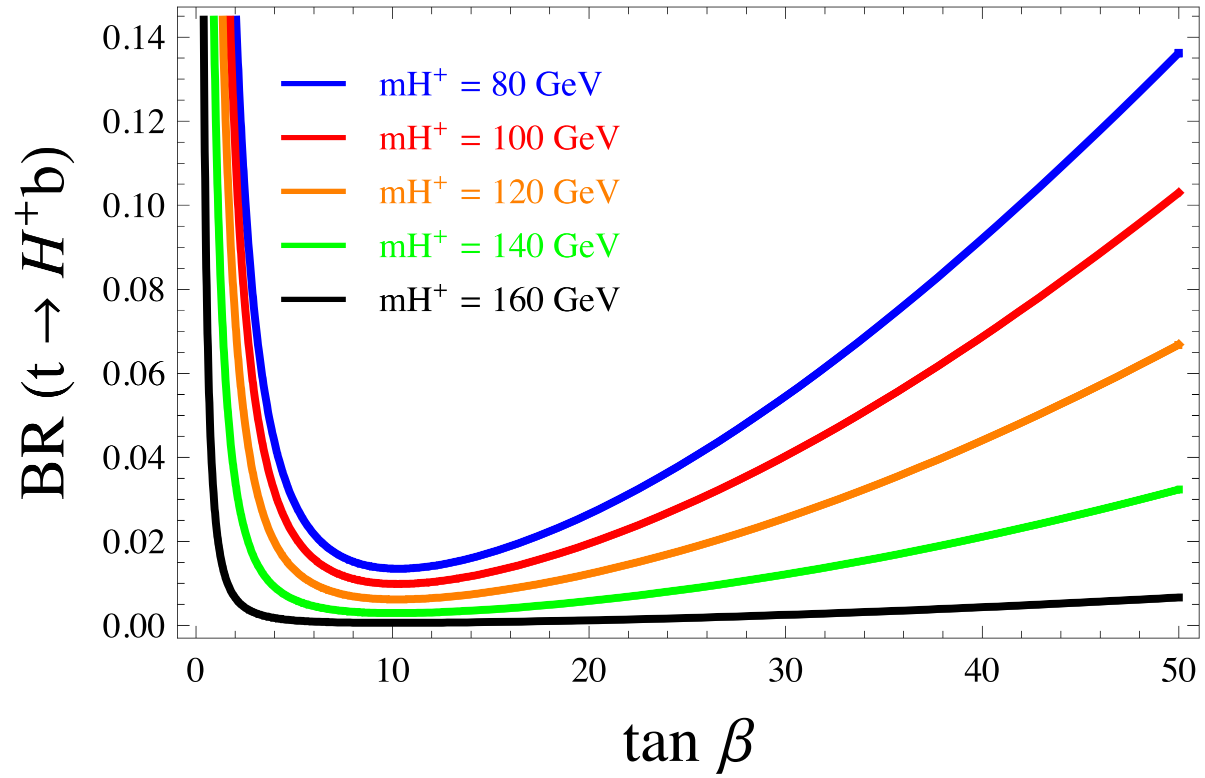
[19] CMS collaboration, CMS-PAS-HIG-11-012.

[20] CMS collaboration, CMS-PAS-HIG-11-008.

[28] ATLAS collaboration, ATL-PHYS-PUB-2010-015.

Charged Higgs





M. Carena, E. Pontón, J. Z (2011)

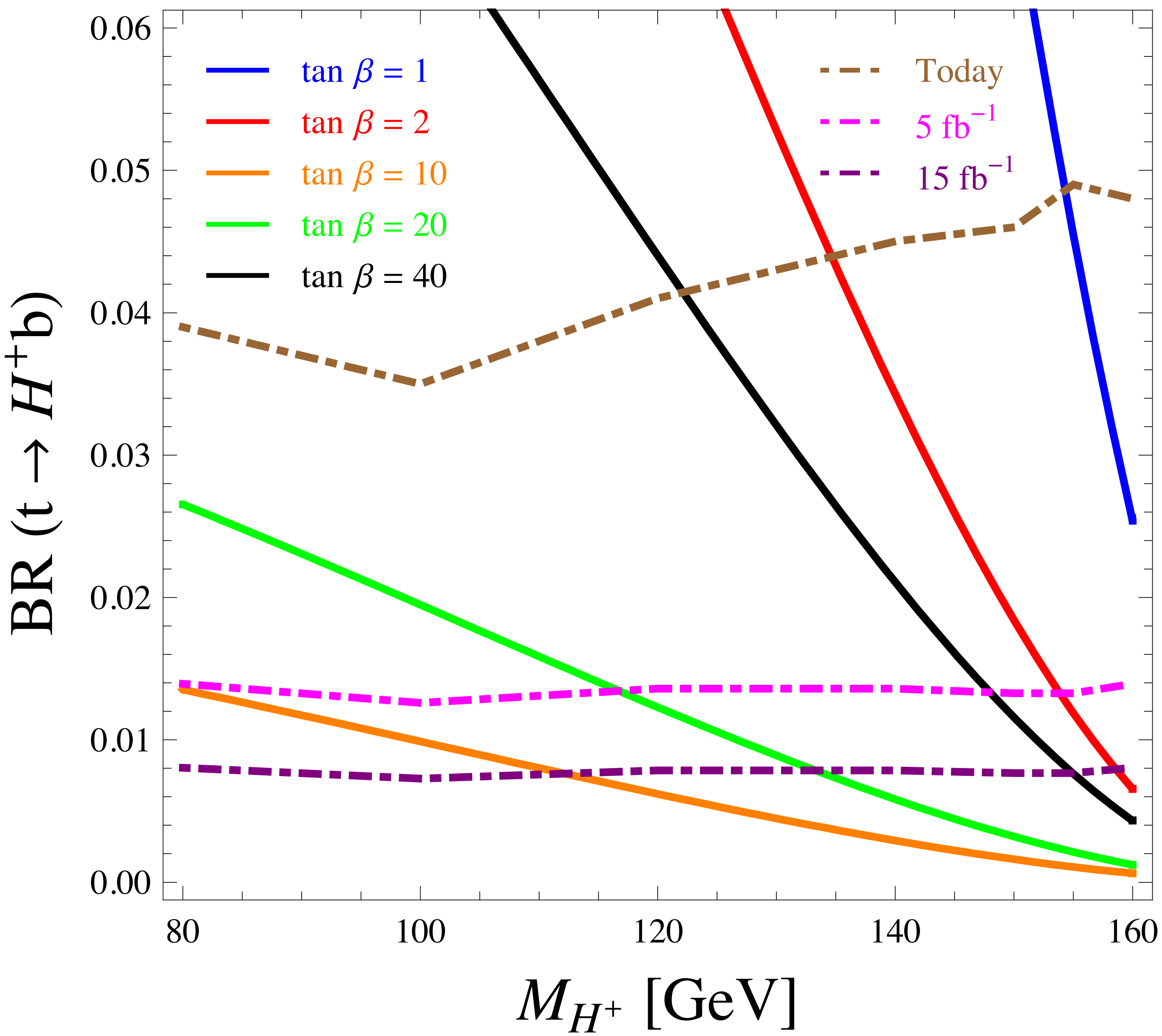
Search channel: $t \to H^+ b,\ H^+ \to \tau^+ \nu_\tau$ CMS-PAS-HIG-11-008

BMSSM effects in charged Higgs sector are smaller.

However they do constraint the parameter space, specially for low tan beta.

Analysis assumes $BR(H^+ \to \tau^+ \nu_\tau) = 1$ Bound applied if $BR(H^+ \to \tau^+ \nu_\tau) = 0.9$

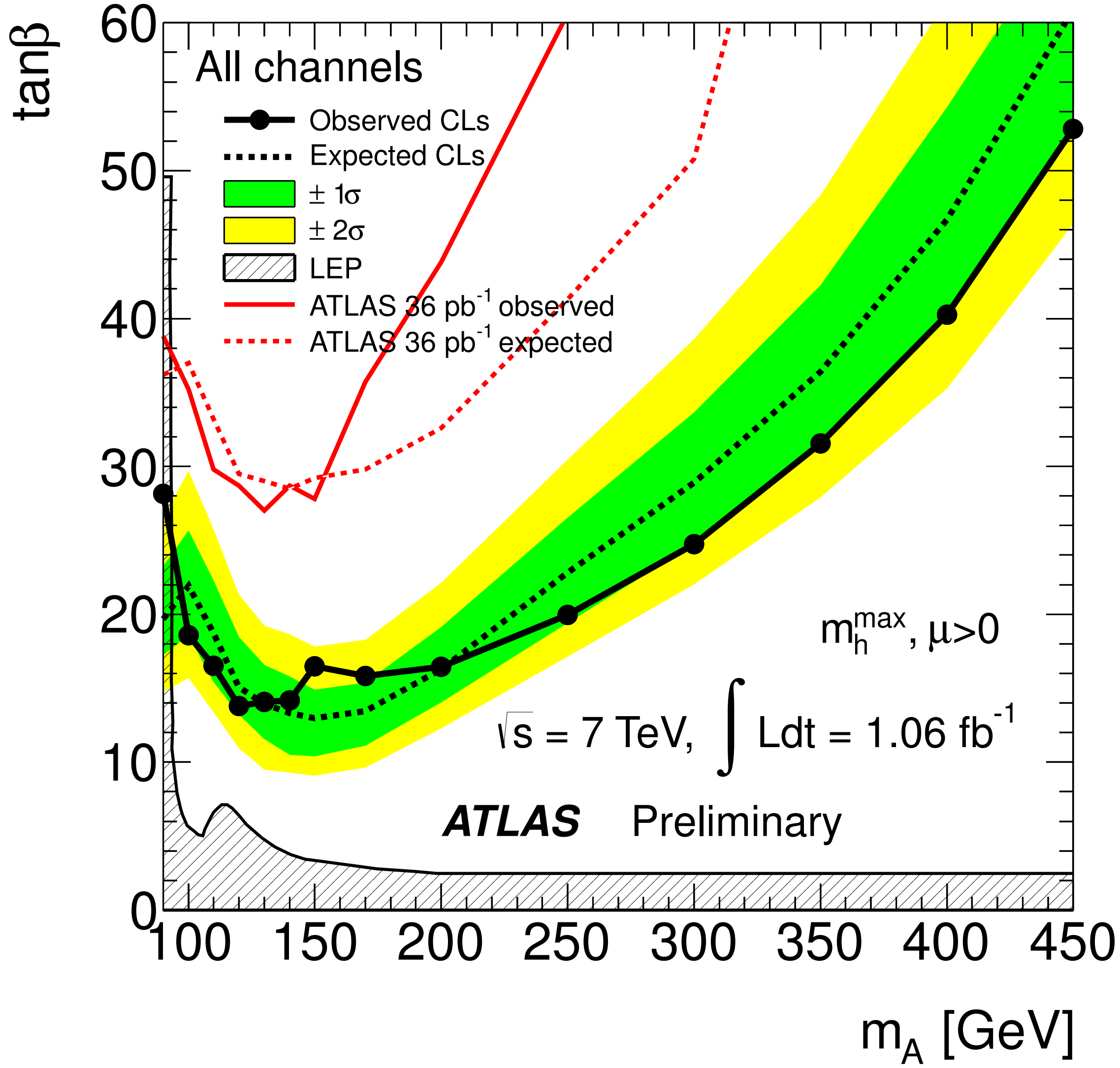
Charged Higgs reach

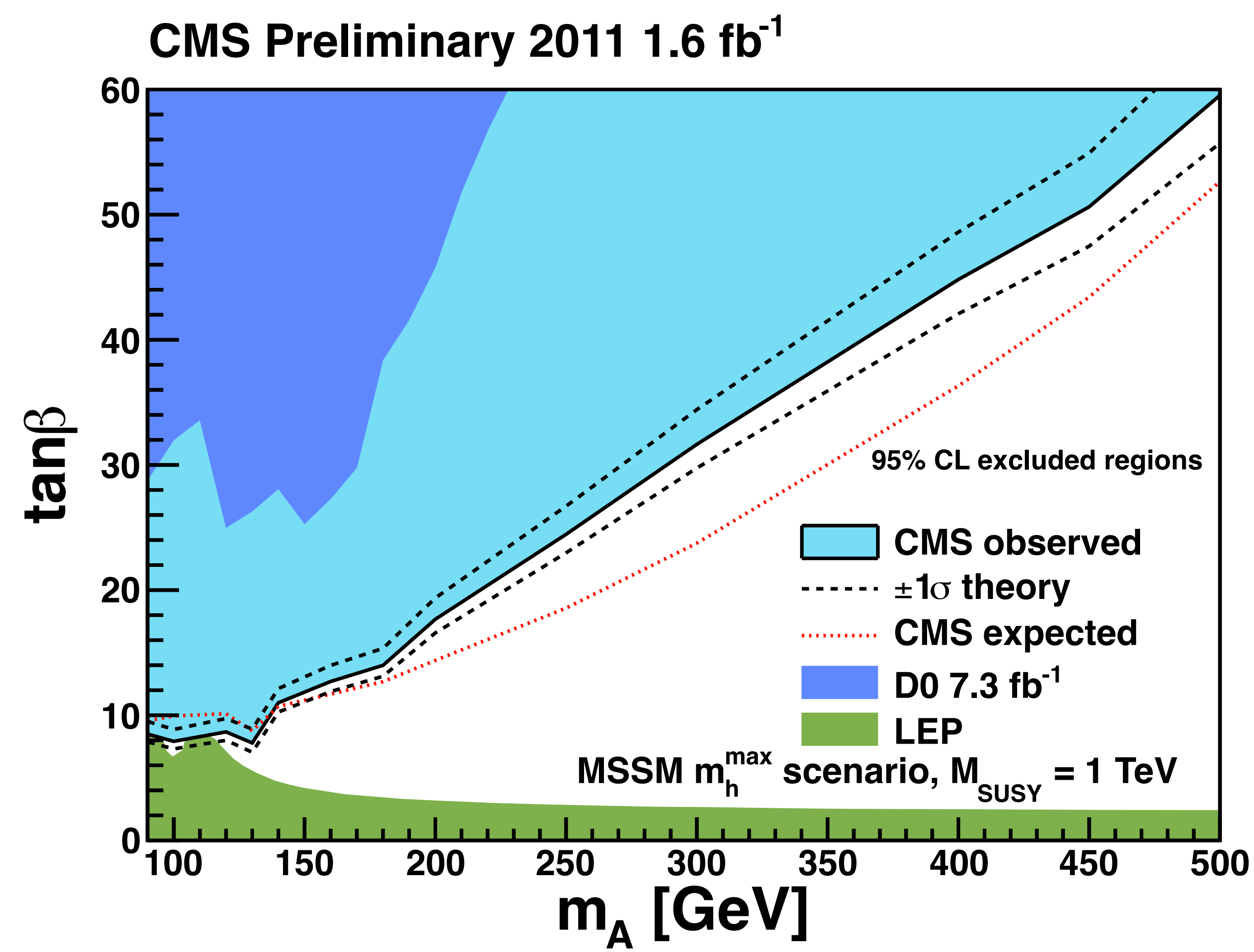


M. Carena, E. Pontón, J. Z (2011)

- NLO QCD corrections included
- SUSY QCD corrections depend non trivially on SUSY spectrum (not shown, but included in our analysis).
- They can have a large impact on the bottom Yukawa coupling
- Exclusion is stronger for extreme values of tan beta.

Tau-tau channel





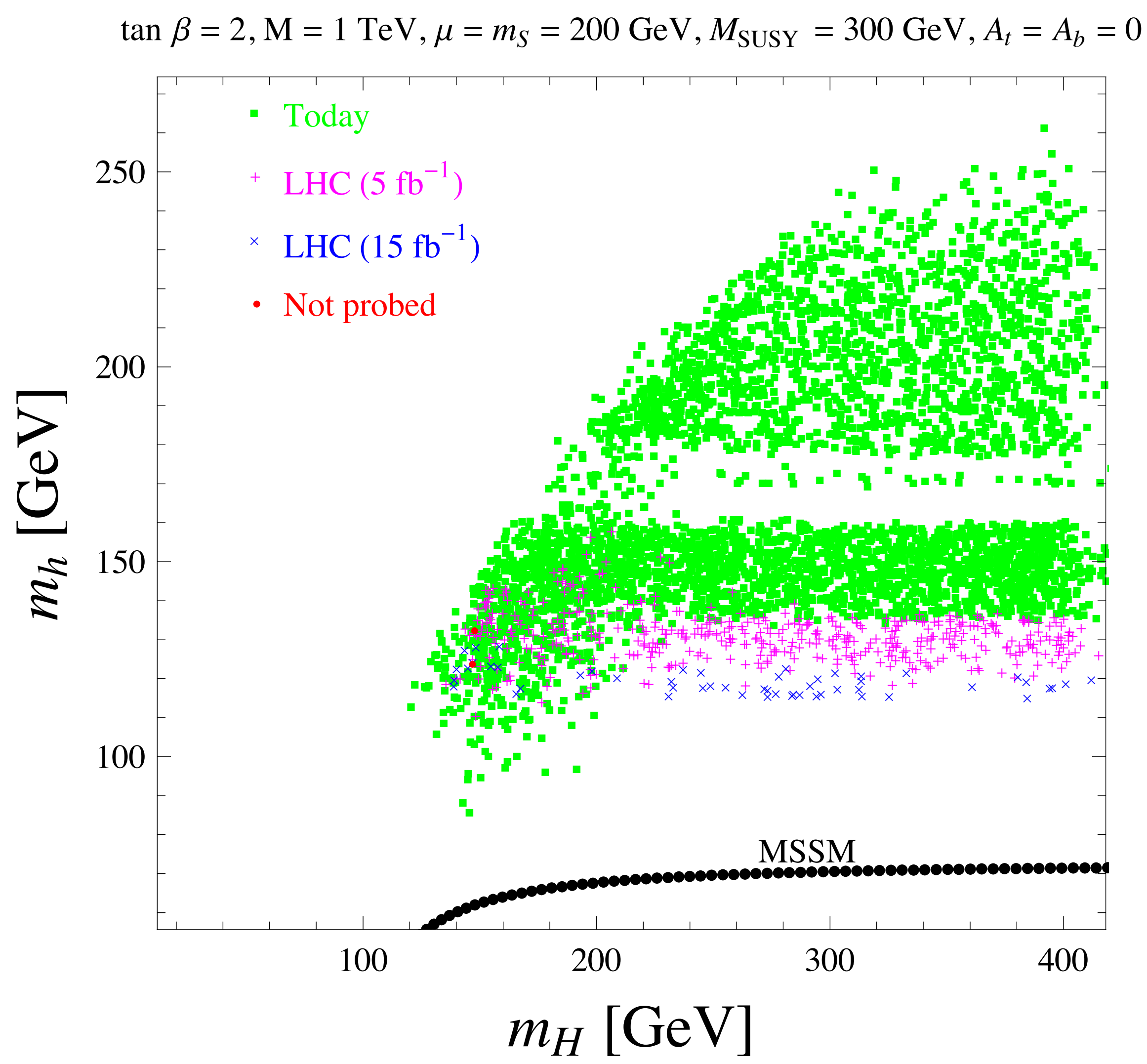
- Important for large tangent beta.
- Low tangent beta: other channels.

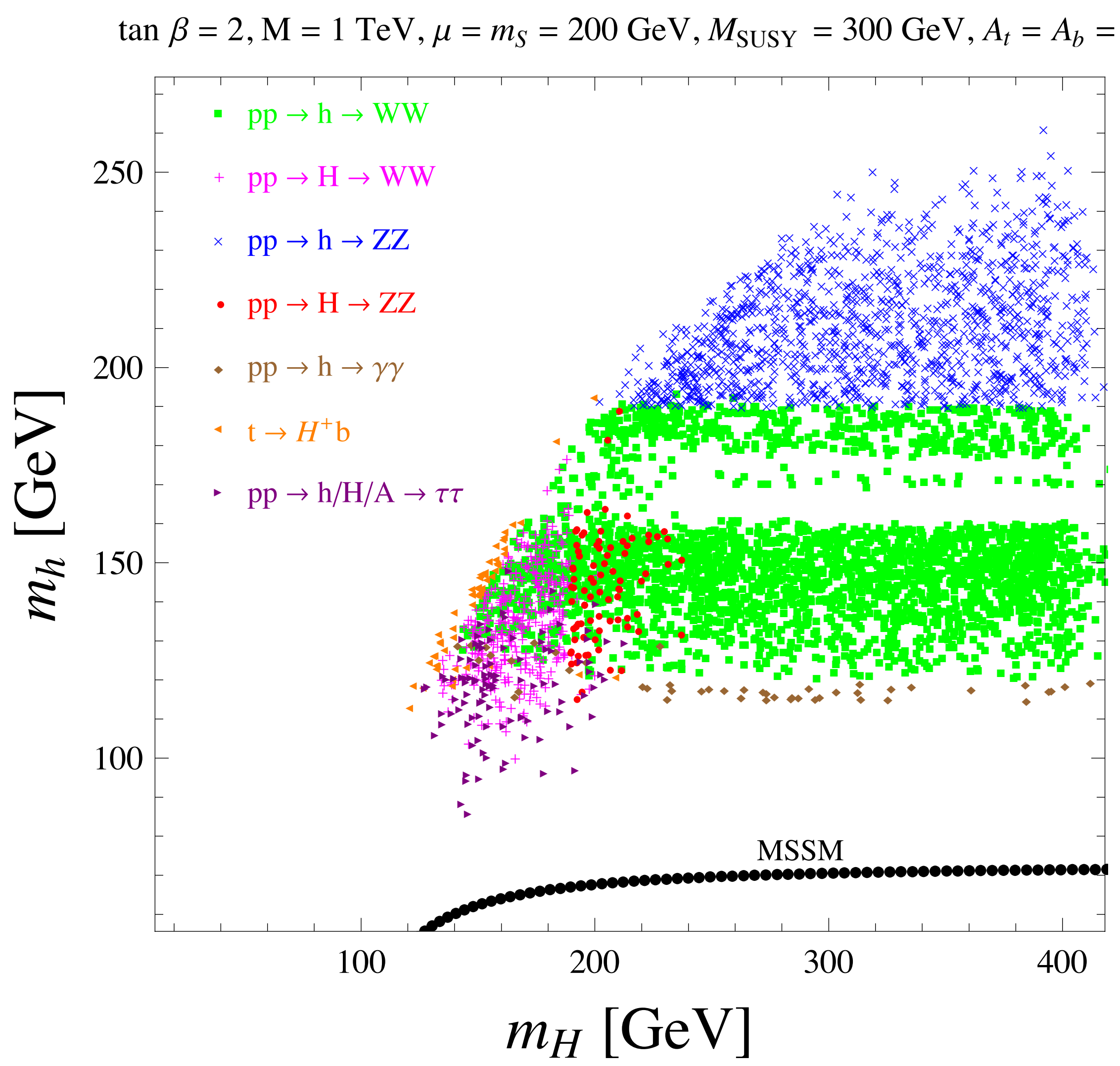
In between:
the "wedge region".

General features

- Lightest Higgs mass enhanced (especially for low tan beta).
- H, H^+ masses follow MSSM trend, except for low m_A.
- CP-even Higgs couplings can vary significantly w.r.t both SM and MSSM.
- A and H^+ couplings only corrected at $1/M^2$
- New decay channels open, like $h/H \to AA$, $H \to AZ$, $H^+ \to W^+ A$.
- At large m_A (> 300 GeV) behaviour is similar to MSSM.
- Decoupling slower than in the MSSM (m_A > 200 GeV).

Low tan beta

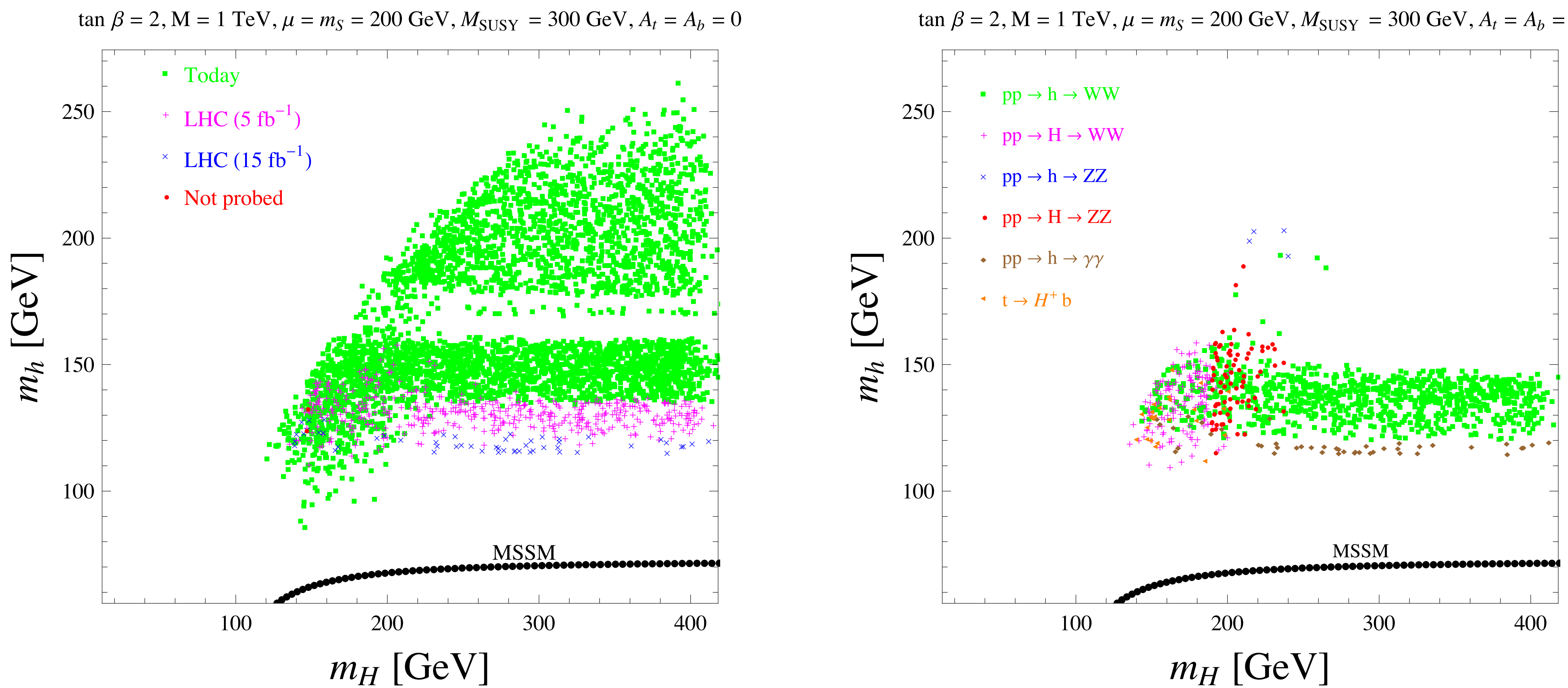




Most important channels: di-bosons

Charged Higgs and tau tau important for low mh values

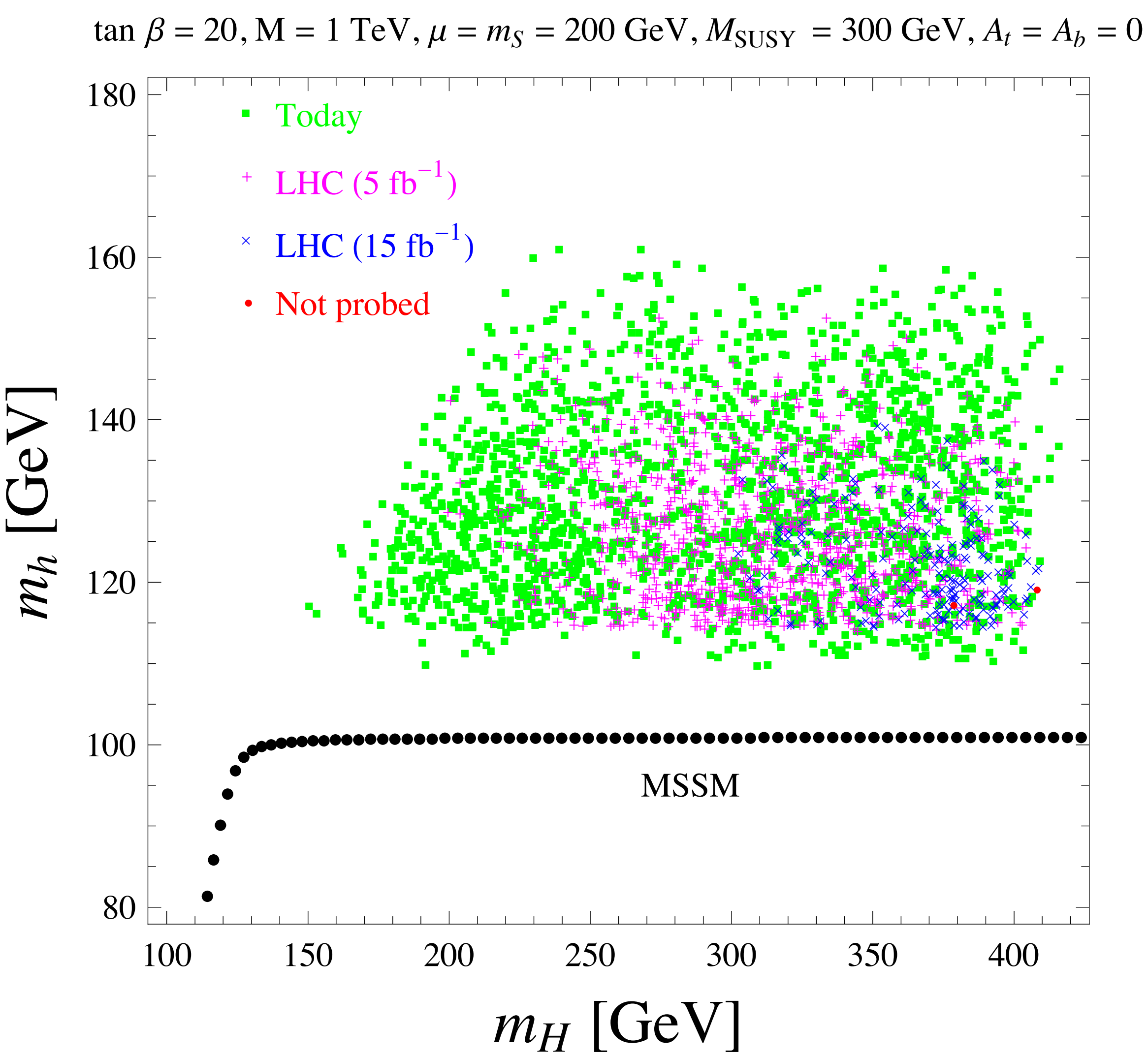
Low tan beta

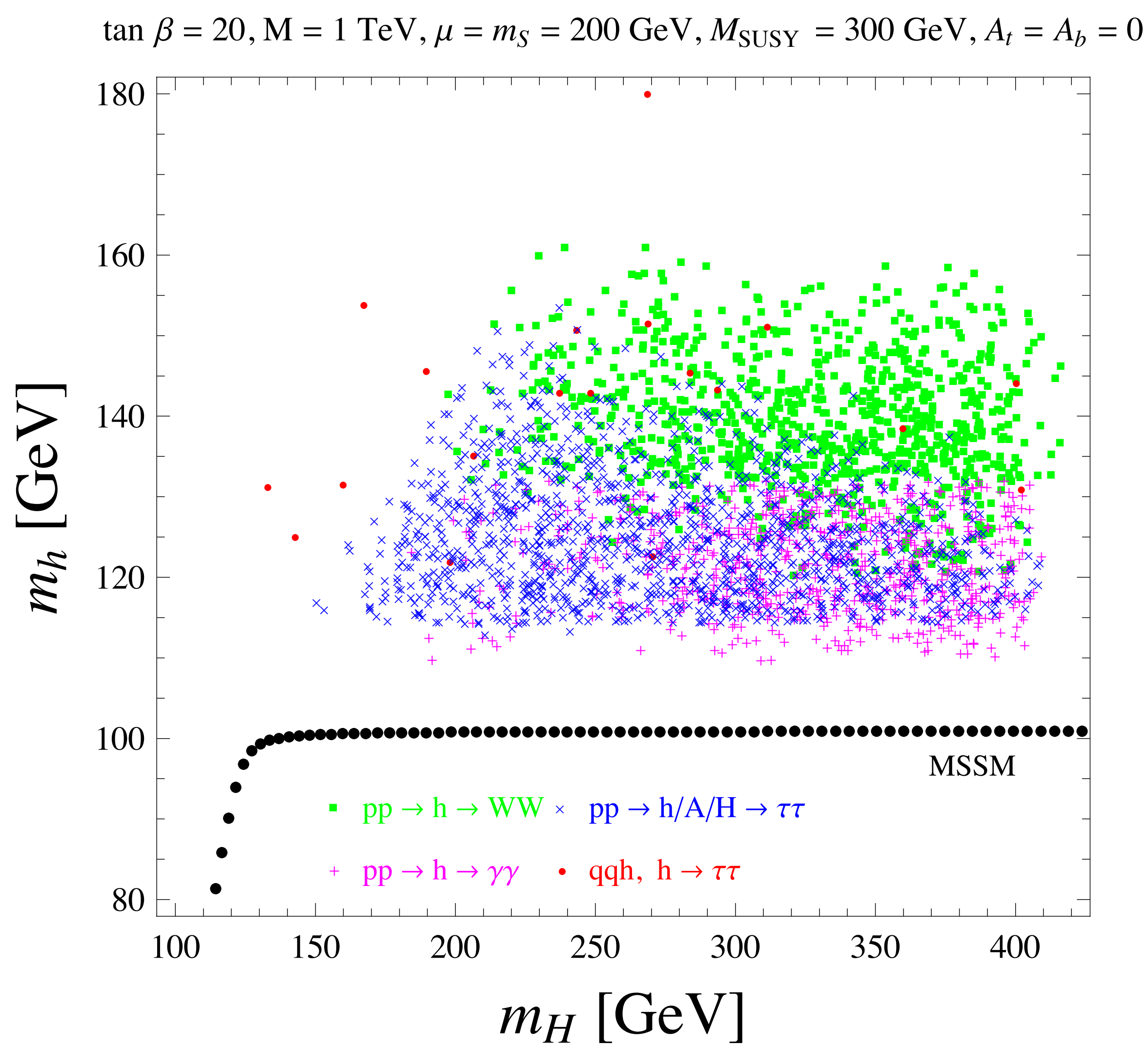


Enhanced couplings to b's dilutes di-boson signal.

15/fb probe allmost all points at the 2 sigma level (for low tangent beta)

Large tan beta

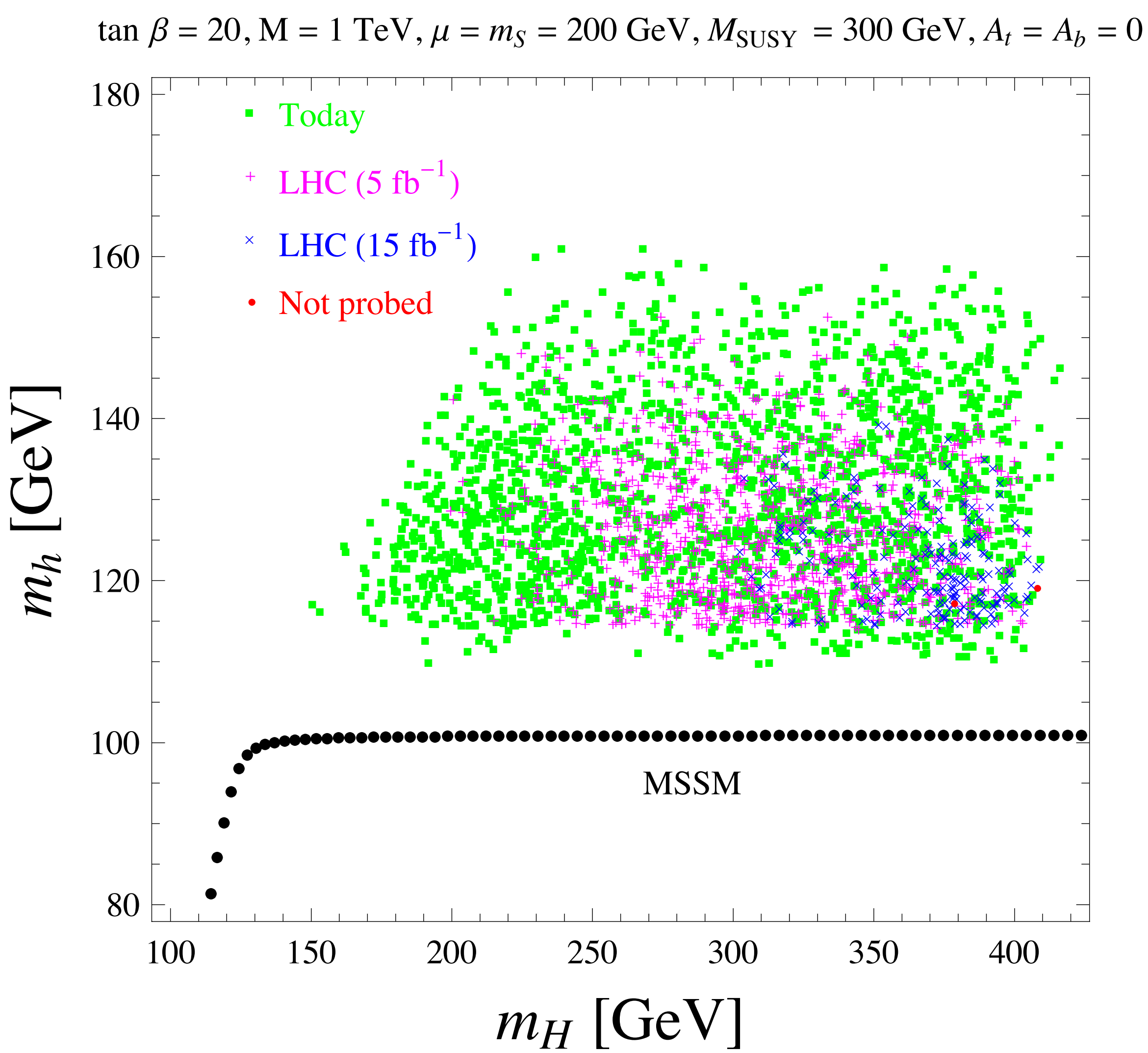


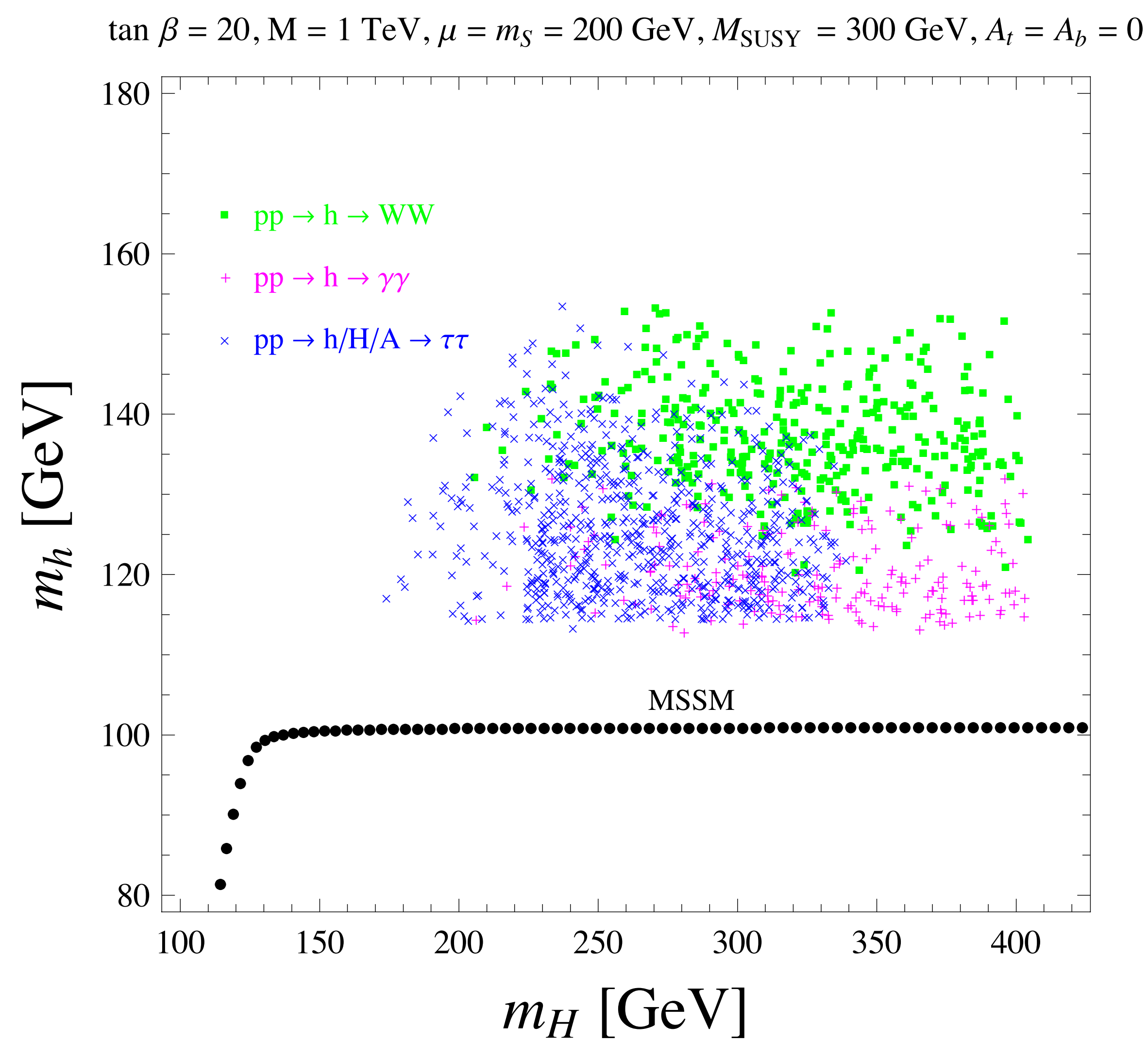


BMSSM effects less relevant than for low tangent beta.

H and or A can only be tested via taus (as in the MSSM).

Large tan beta





BMSSM effects less relevant than for low tangent beta.

H and or A can only be tested via taus (as in the MSSM).

Benchmarks tb=2

POINT A' (2067)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
129	143	194	148
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.24	0.73	1.24	0.48
channel	BMSSM (SM)	channel	BMSSM (SM)
$h\to b\bar{b}$	0.62 (0.30)	$h\to WW$	0.21 (0.55)
$H\to WW$	0.74 (0.75)	$H\to ZZ$	0.24 (0.25)
$A\to b\bar{b}$	0.89	$A\to \tau\bar{\tau}$	0.10
$H^+\to\bar{\tau}\nu_\tau$	0.82	$H^+\to t\bar{b}$	0.15
$pp\to h\to WW$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.46	2.8	1.9	11.9

POINT A'' (570)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
111	127	144	145
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.95	0.08	0.86	0.86
channel	BMSSM (SM)	channel	BMSSM (SM)
$h\to b\bar{b}$	0.62 (0.59)	$h\to WW$	0.21 (0.25)
$H\to b\bar{b}/\tau\bar{\tau}$	0.81 / 0.09	$A\to b\bar{b}/\tau\bar{\tau}$	0.90 / 0.10
$H^+\to\bar{\tau}\nu_\tau$	0.81	$H^+\to t\bar{b}$	0.12
$pp\to h\to WW$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.45	1.16	11.2	70

- Tested in the h->WW channel in spite of its suppression (enhanced bb)
- Can be tested at the 2 sigma level with 2 (A') 11 (A'') inverse fb.
- Such masses can not be obtained in the MSSM.

POINT B' (1523)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
133	117	156	156
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.90	0.10	0.71	0.94
channel	BMSSM (SM)	channel	BMSSM (SM)
$h\to b\bar{b}$ $H\to b\bar{b}$ $H\to WW$ $H^+\to\bar{\tau}\nu_\tau$	0.84 (0.73) 0.64 (0.10) 0.23 (0.80) 0.72	$h\to\tau\bar{\tau}$ $H\to\tau\bar{\tau}$ $A\to b\bar{b}$ / $\tau\bar{\tau}$ $H^+\to t\bar{b}$	0.09 (0.08) 0.12 (0.01) 0.89 / 0.10 0.24
$pp\to H\to WW$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.27	2.8	1.9	12.0

POINT B'' (663)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
115	124	147	147
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.89	0.12	0.72	0.98
channel	BMSSM (SM)	channel	BMSSM (SM)
$h\to b\bar{b}$ $H\to b\bar{b}$ $H\to WW$ $H^+\to\bar{\tau}\nu_\tau$	0.80 (0.64) 0.74 (0.22) 0.12 (0.64) 0.81	$h\to\tau\bar{\tau}$ $H\to\tau\bar{\tau}$ $A\to b\bar{b}$ / $\tau\bar{\tau}$ $H^+\to t\bar{b}$	0.09 (0.07) 0.08 (0.02) 0.89 / 0.10 0.13
$pp\to H\to WW$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.18	1.2	9.7	60

Benchmarks tb=2

- Tested in the H->WW (enhanced hbb strongly suppress the photon channel)
- Can be tested at the 2 sigma level with 2 (B') 10 (B'') inverse fb.
- Such masses can not be obtained in the MSSM for tan beta=2

Benchmarks tb=2

POINT C' (964)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
203	118	222	225
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
1.0	$\lesssim 10^{-3}$	1.22	0.4
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.70 (0.72)	$h \to \tau\bar{\tau}$	0.07 (0.07)
$h \to WW$	0.13 (0.12)	$h \to \gamma\gamma$ ($\times 10^{-3}$)	2.1 (2.3)
$H \to b\bar{b}$ / $\tau\bar{\tau}$	0.81 / 0.10	$H \to WW$	0.04
$A \to b\bar{b}$ / $\tau\bar{\tau}$	0.87 / 0.10	$H^+ \to t\bar{b}$	1.0
$pp \to h \to \gamma\gamma$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
1.1	1.8	4.8	30

POINT C'' (3699)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
136	117.4	167	164
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
1.0	$\lesssim 10^{-3}$	1.11	0.53
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.76 (0.73)	$h \to \tau\bar{\tau}$	0.08 (0.08)
$h \to WW$	0.09 (0.11)	$h \to \gamma\gamma$ ($\times 10^{-3}$)	1.6 (2.3)
$H \to b\bar{b}$ / $\tau\bar{\tau}$	0.80 / 0.09	$H \to WW$	0.08
$A \to b\bar{b}$ / $\tau\bar{\tau}$	0.89 / 0.10	$H^+ \to \bar{\tau}\nu_\tau / t\bar{b}$	0.60 / 0.37
$pp \to h \to \gamma\gamma$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.76	1.18	10.7	67

- Tested in the diphoton channel.
- Can be tested at the 2 sigma level with 5 (C') 11 (C'') inverse fb.
- Such masses are difficult to obtain in the MSSM (H,A are too light)

Benchmarks tb=2

POINT F

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
64	135	155	125
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
$\le 10^{-2}$	0.99	0.59	1.14
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	$A\to b\bar{b}\ /\ \tau\bar{\tau}$	0.91 / 0.09
$H^+\to\bar{\tau}\nu_\tau$	0.56	$H^\pm\to W^\pm+A$	0.40
$pp\to H\to WW$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.18	1.8	4.9	30

h→AA and H→AA are the dominant decay modes.

Exclusion requires about 5/fb, discovery about 30/fb.

Any ongoing LHC searches for $b\bar{b}b\bar{b},\ b\bar{b}\tau\bar{\tau},\ \tau\bar{\tau}\tau\bar{\tau}$?

POINT L (810)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
256	129	278	275
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.99	0.02	1.6	0.86
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.70 (0.56)	$h \to \tau\bar{\tau}$	0.12 (0.06)
$h \to WW$	0.12 (0.28)	$H \to b\bar{b}$ / $\tau\bar{\tau}$	0.68 / 0.11
$H \to hh$	0.13	$A \to b\bar{b}$ / $\tau\bar{\tau}$	0.85 / 0.14
$H^+ \to \bar{\tau}\nu_\tau$	0.22	$H^+ \to t\bar{b}$	0.73
$\sigma(pp \to X \to \tau\bar{\tau})$ (pb)	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
A : 0.6	2.6	2.2	13.7
H : 0.3	1.6	5.9	37
h : 2.9	2.1	3.5	22.0

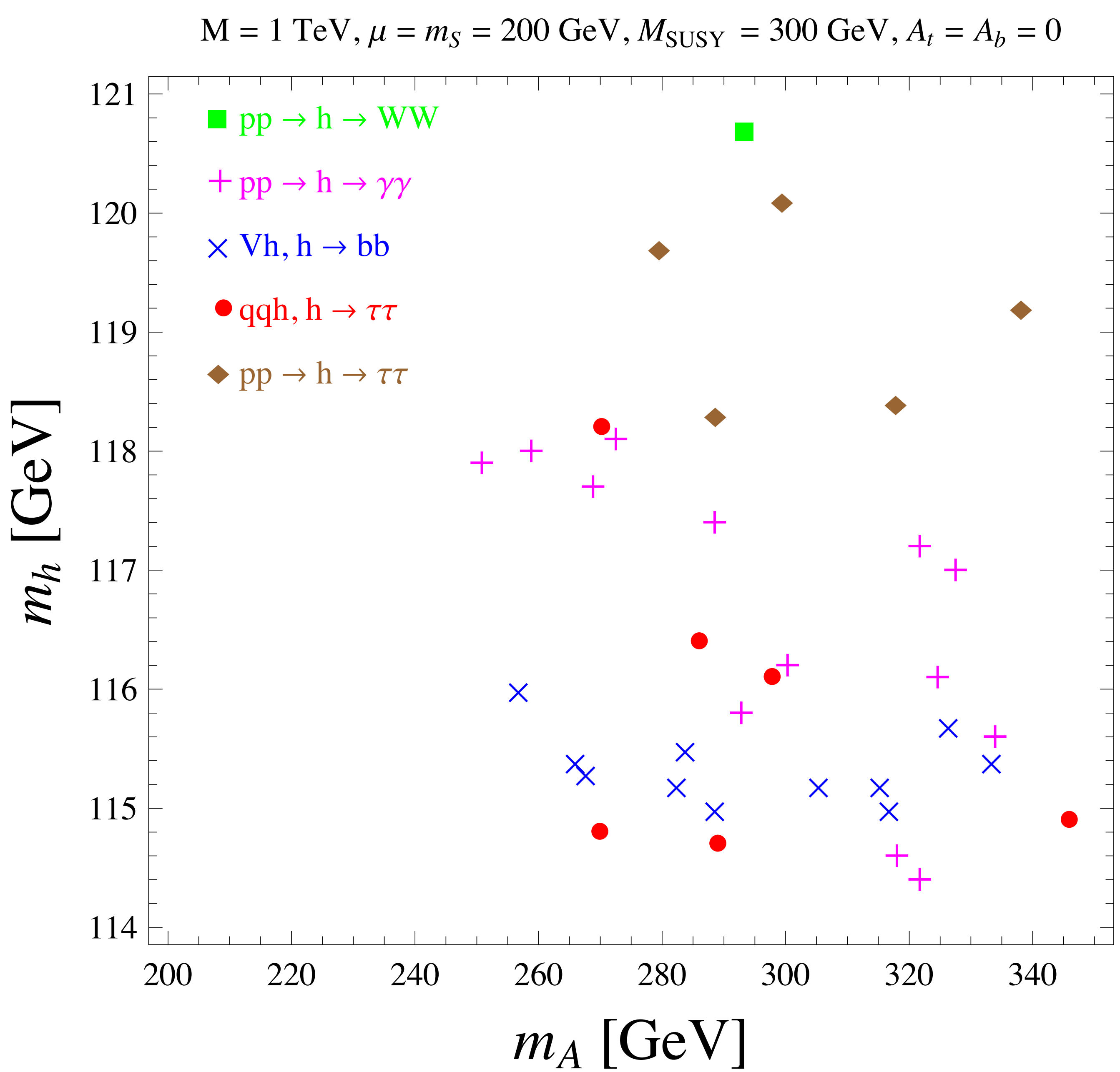
POINT L' (231)

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
359	133	333	345
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.99	$\leq 10^{-2}$	1.09	0.57
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.77 (0.48)	$h \to \tau\bar{\tau}$	0.10 (0.05)
$h \to WW$	0.10 (0.36)	$H \to b\bar{b}$ / $\tau\bar{\tau}$	0.71 / 0.12
$H \to hh$	0.10	$A \to b\bar{b}$ / $\tau\bar{\tau}$	0.73 / 0.13
$A \to hZ$	0.05	$H^+ \to t\bar{b}/\bar{\tau}\nu_\tau$	0.57 / 0.18
$\sigma(pp \to X \to \tau\bar{\tau})$ (pb)	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
H : 0.17	1.19	10.5	66
h : 1.49	1.17	10.9	68
A : 0.10	0.89	18.7	117

Benchmarks tb=20

- All neutral Higgs bosons are tested in the tau tau channel.
- Masses are well separated: they can be distinguished
- Can be around the corner (2/fb) or require more data (10/fb) for a 2 sigma exclusion

Intermediate tan beta region



- "Wedge region": where the large tan beta tau reach is ineffective, and the diboson search modes are not enough.

- Probed at the 2σ level with 20/fb.

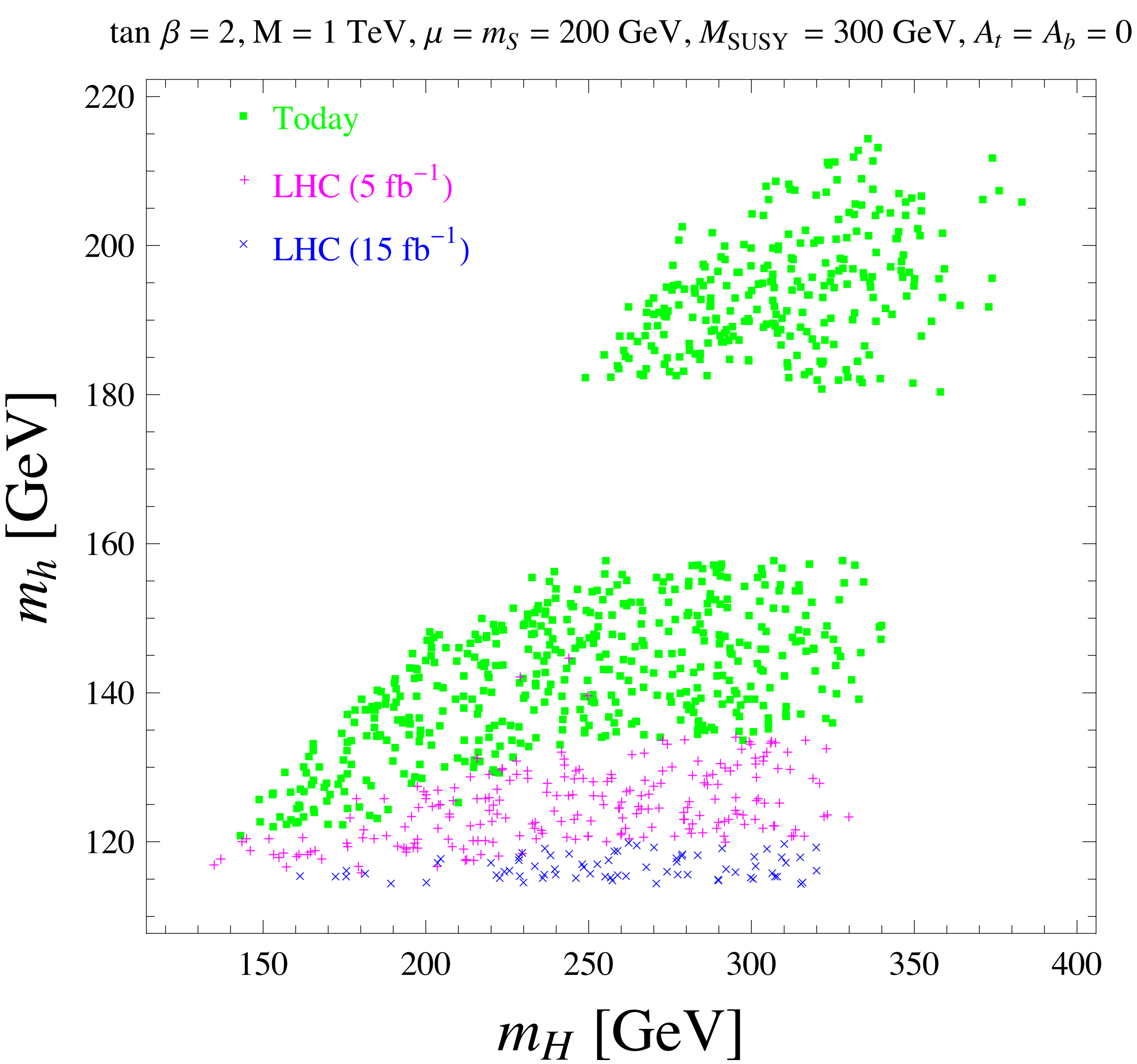
Benchmark for tan beta=6

POINT M

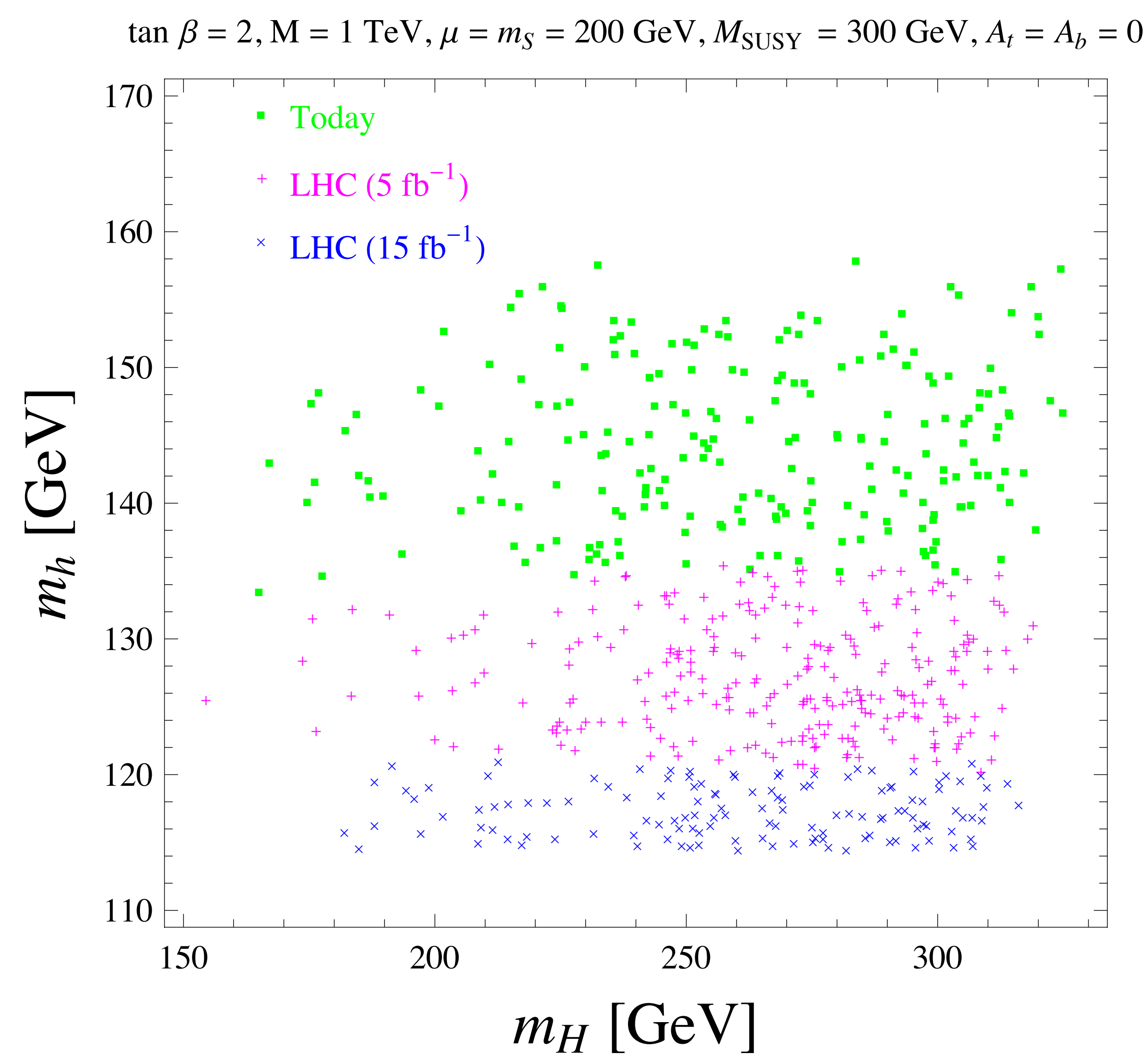
m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
200	115	193	203
g^2_{hWW}	g^2_{HWW}	$g^2_{pp\to h}$	$g^2_{pp\to H}$
0.99	$\leq 10^{-2}$	1.12	0.37
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$ $h \to WW$ $A \to b\bar{b}$ / $\tau\bar{\tau}$	0.82 (0.75) 0.05 (0.09) 0.88 / 0.12	$h \to \tau\bar{\tau}$ $H \to b\bar{b}$ / $\tau\bar{\tau}$ $H^+ \to \bar{\tau}\nu_\tau/t\bar{b}$	0.09 (0.08) 0.85 / 0.11 0.25 / 0.74
$Vh, h \to b\bar{b}$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
1.08	0.98	15.6	98
$qqh, h \to \tau\bar{\tau}$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
1.12	0.94	17	106
$pp \to h \to \gamma\gamma$	Q(15 fb^{-1})	$\mathcal{L}_2$ (fb^{-1})	$\mathcal{L}_5$ (fb^{-1})
0.56	0.83	22	137

Discovery is possible with about 100/fb, 7 TeV LHC.

UV completions (tanb=2)



MSSM + singlet



MSSM + triplets

Conclusions

- We have studied BMSSM extensions with an EFT approach up to the second order in the 1/M expansion.
- Modified phenomenology with respect to MSSM.
- Great rise of the lightest Higgs mass, specially for low tangent beta (relax the MSSM tension).
- LHC strongly constraints parameter space.
- Intermediate values of tan beta can avoid exclusion with 15/fb, but can be tested with 20/fb.
- Discovery might have to wait until 14 TeV Run.

Backup slides

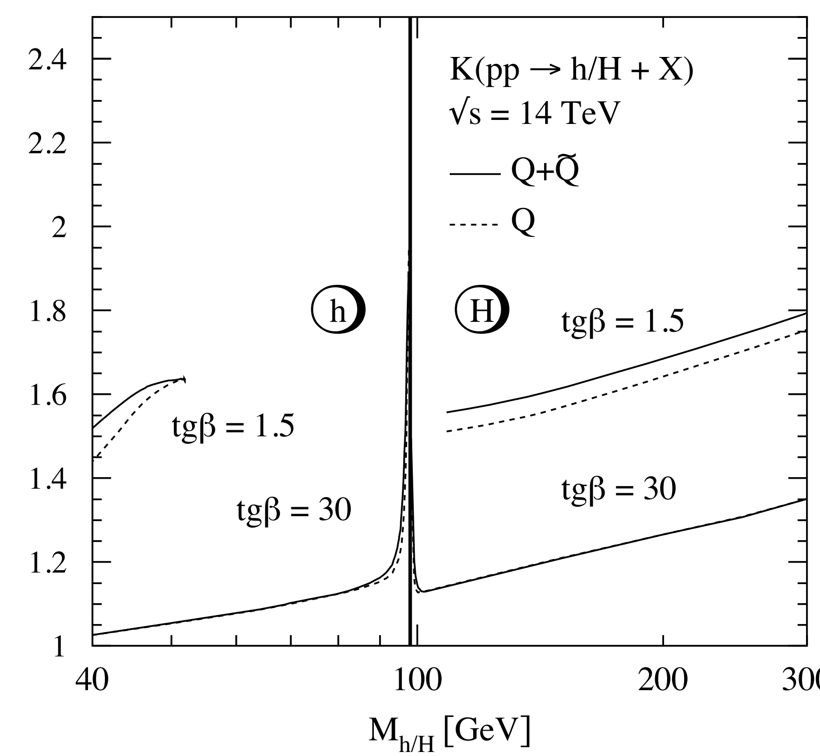
Production cross sections

- VBF, HS: scale by $(g_{hVV})^2$
- Gluon fusion: $\frac{\sigma^{model}(gg \to h)}{\sigma^{SM}(gg \to h)} \simeq \left(\frac{g^{model}_{ggh}}{g^{SM}_{ggh}}\right)^2 \equiv \frac{\Gamma^{model}_{h\to gg}}{\Gamma^{SM}_{h\to gg}}$ holds at LO

bottom loop (NLO):
K factors from
HIGLU (SM vs MSSM)

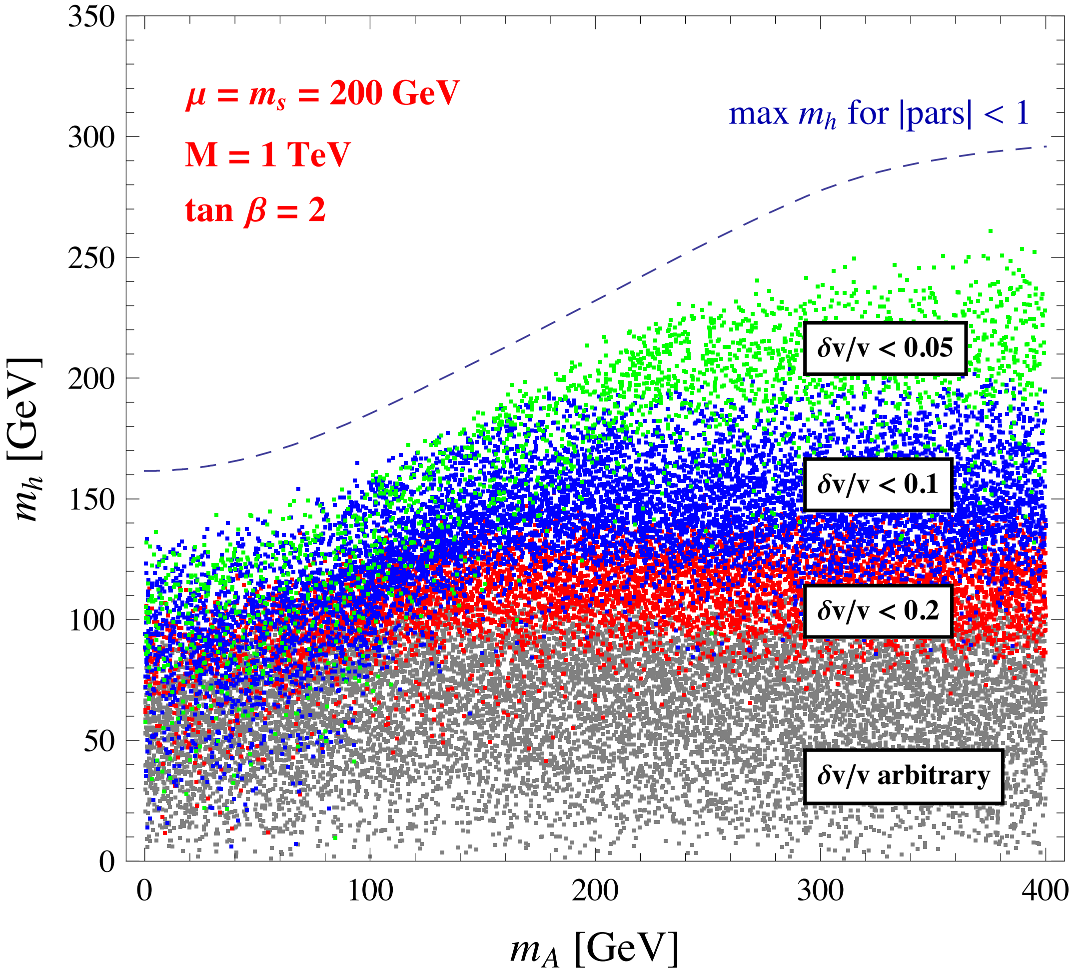
Sparticles:

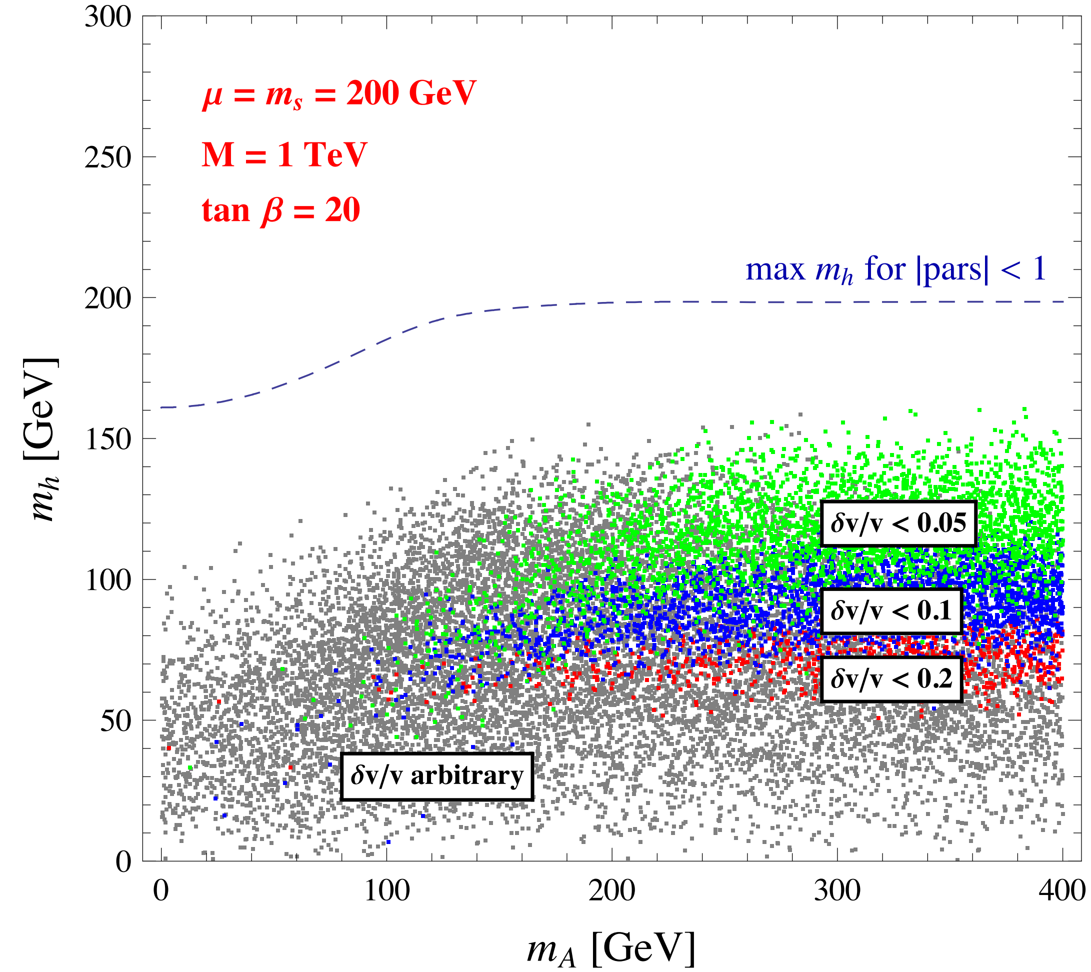
Effect	$\tan\beta = 2$	$\tan\beta = 20$
sparticles	3 %	negl.
bottom loop	< 5 %	20 %



M. Spira, Fortsch.Phys. 46 (1998)

Numerical Scan





- Keep if $\delta v/v < 10\%$ and $1.5(15) < \tan\beta < 2.5(25)$.
- Retain only global CP conserving minima.

Numerical scan

- Parameter region: $|\omega_1|,\ |c_1|,\ |c_2|,\ |c_3|,\ |c_4|,\ |c_6|,\ |c_7| \in [0,1].$

  $|\alpha_1|,\ |\beta_i|,\ |\gamma_i|,\ |\delta_6|,\ |\delta_7| \in [1/3,1]$ for $i = 1,2,3,4,6,7.$

- Convergence criteria:

$$\lambda_i \rightarrow \lambda_i \pm 2\,\mathrm{Max}\,\{|\omega_1|,|c_1|,|c_2|,|c_3|,|c_4|,|c_6|,|c_7|\}\left(\frac{\mu}{M}\right)^3 \ ,\ i = 1,\ldots 7\ ,$$

  Solve (with fixed params) for $v, \tan\beta$.

  Keep if $\delta v/v < 10\%$ and $1.5(15) < \tan\beta < 2.5(25)$.

- Only retain CP and charge conserving global minima.

- EW constraints: $-0.2 < T^{tree} + T^{Higgs} + T^{SUSY} < 0.3$

  $T^{SUSY} \sim 0.2$

Medina, Shah, Wagner ('09)