Non SM Higgs phenomenology 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**

PRD85:035007, 2012, arXiv:1111.2049, LPN 11-60

and work in progress...

E. Weihs, J.Z: **JHEP 1202 (2012) 041, arXiv:1110.5909, LPN 11-56**

LHC Phenonet Annual Meeting 2012, 21st March 2012

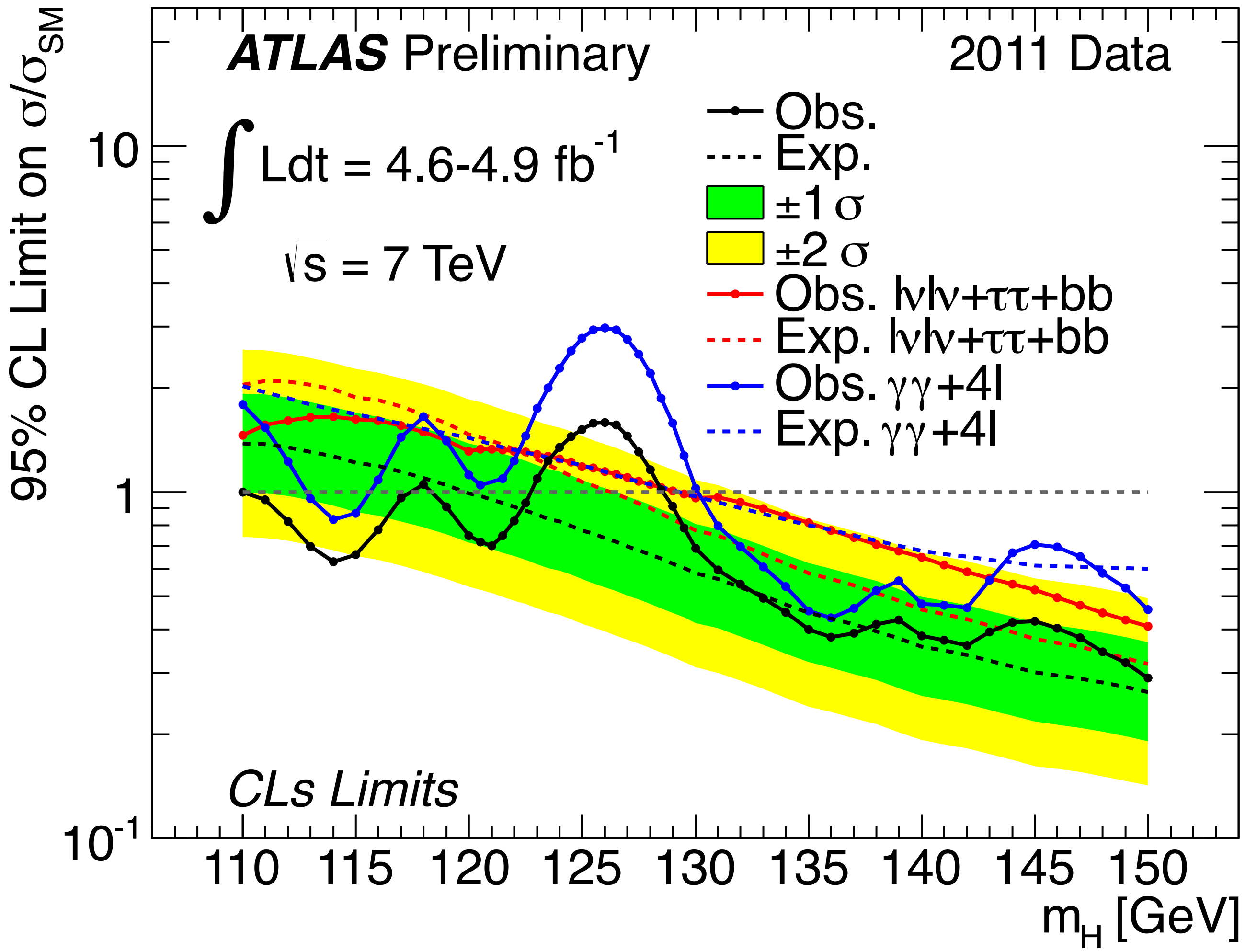
Outline

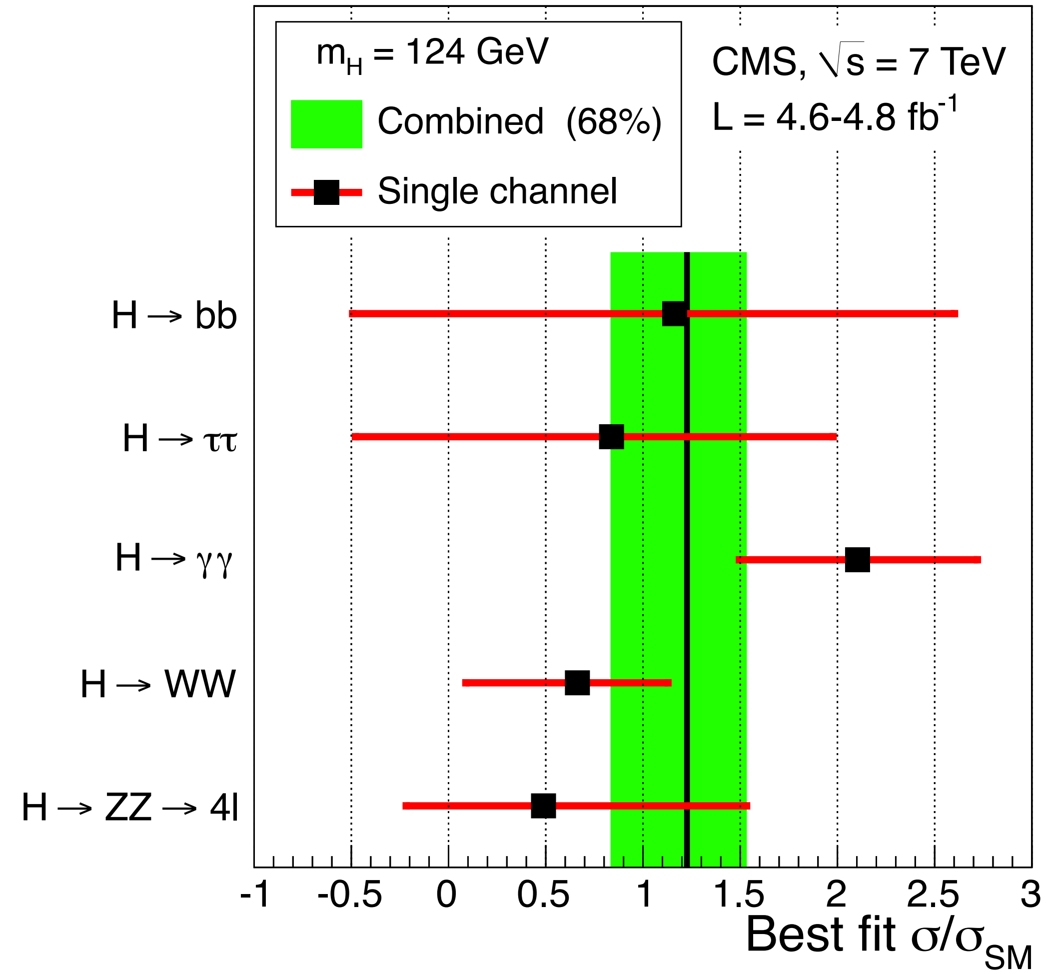
- Higgs searches at the LHC
- Non SM Higgs Sectors:
  - BMSSM (Beyond MSSM)
  - Higgs Portal
- Conclusions

SM Higgs @ LHC

ATLAS-CONF-2012-019

arXiv: 1202.1488





- 99% C.L exclusion: 130-486 GeV (ATLAS) and 129-525 GeV (CMS)
- Hints for a Higgs boson at 125 GeV (compatible with SM).
- Data suggests enhanced rate in the diphoton channel.

Non-SM Higgs sector

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

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

BMSSM Higgs sectors

Higgs in the MSSM

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

$h,\ H$ → scalars A → pseudoscalar

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

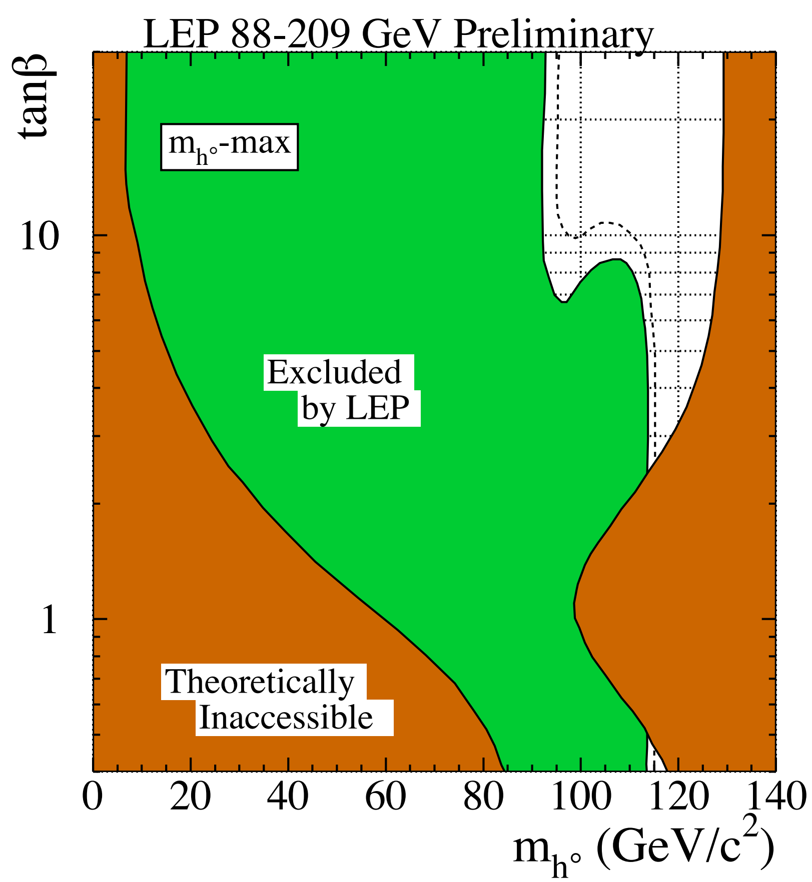
Tree level: $m_h^{(0)} \leq m_Z |\cos(2\beta)|$

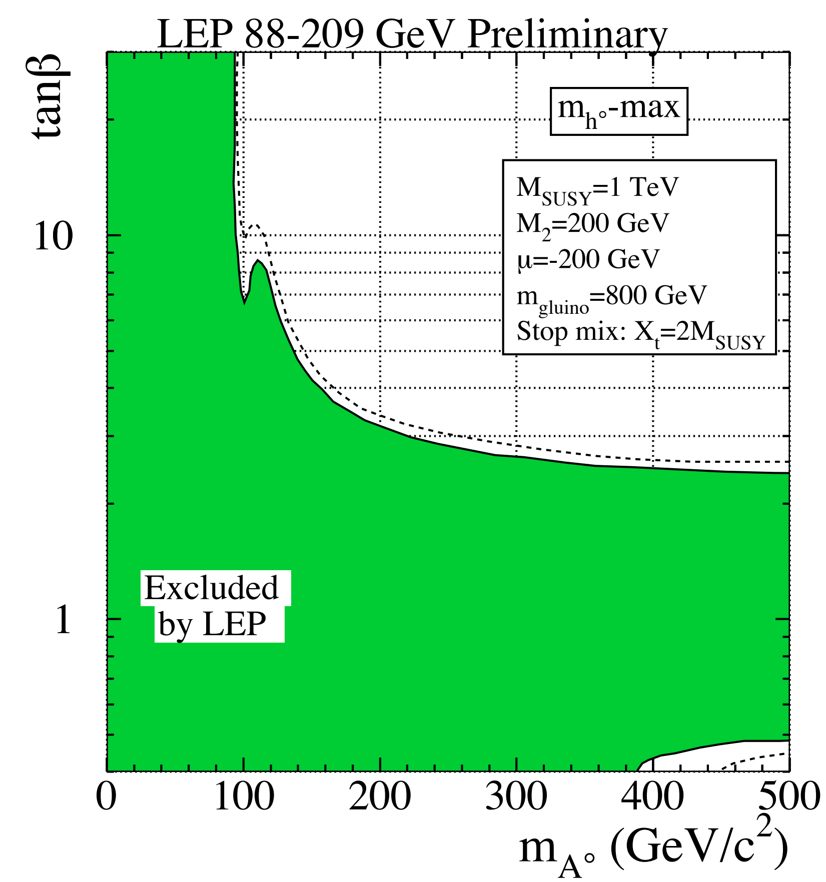
2-loops: $m_h < 135$ GeV

m_S, A_t, A_b

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

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





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).

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.

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)

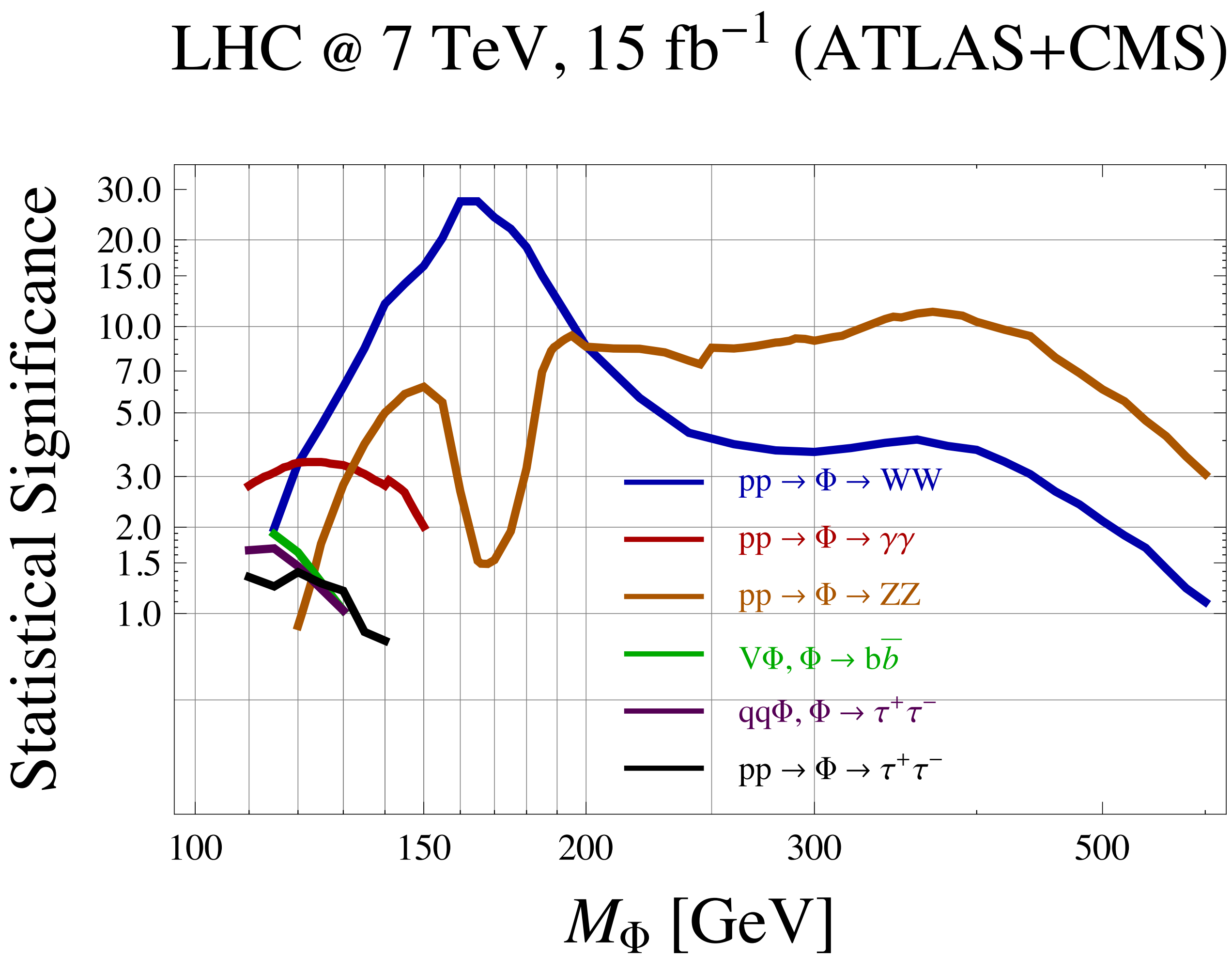
- Experimental Bounds: HiggsBounds v2.1.0 (LEP and Tevatron)

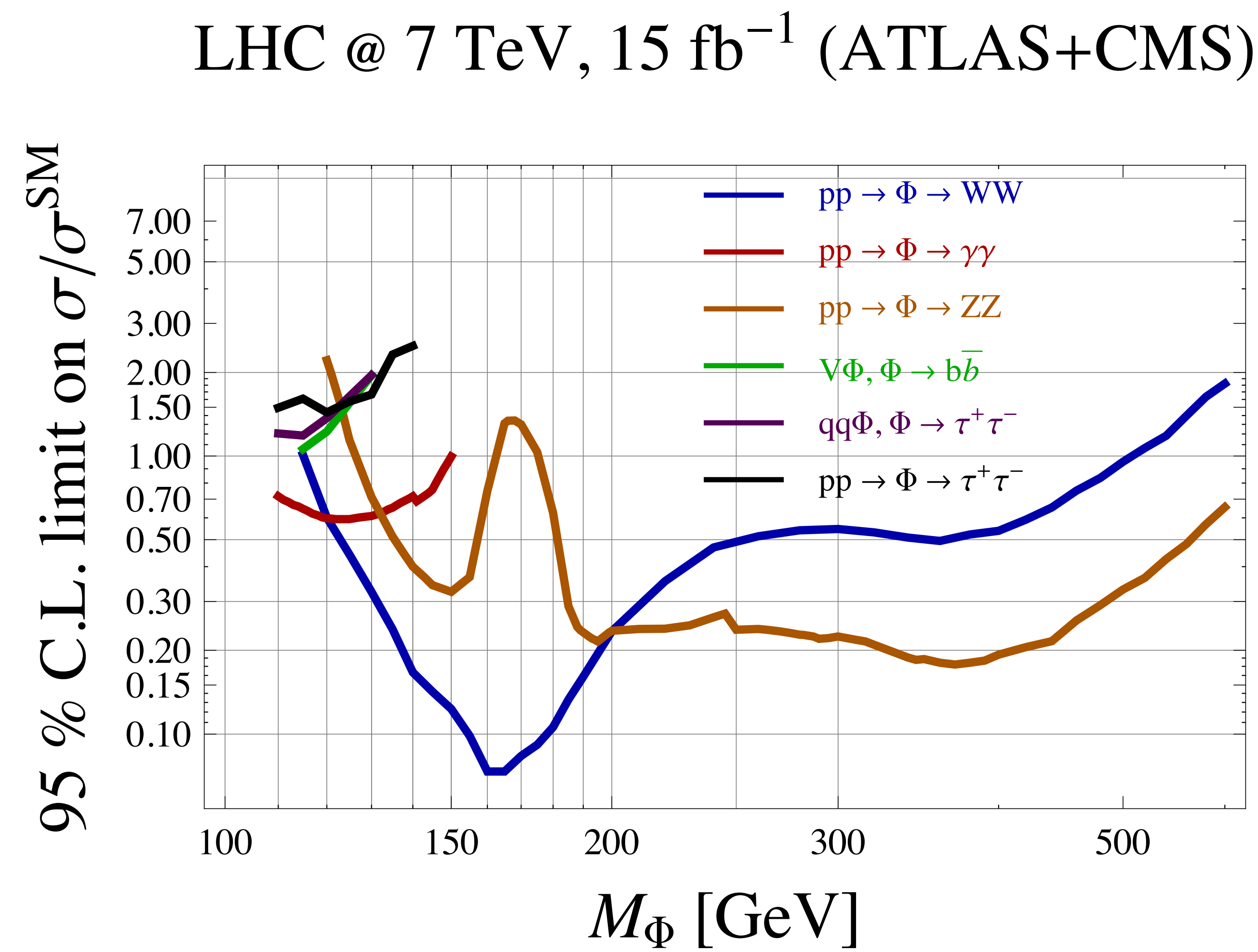
P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K. E. Williams

+ Electroweak precision data + LHC data from HCP 2011 (pre D-13).

BMSSM @ LHC: phenomenology

SM-like Higgs searches @ LHC





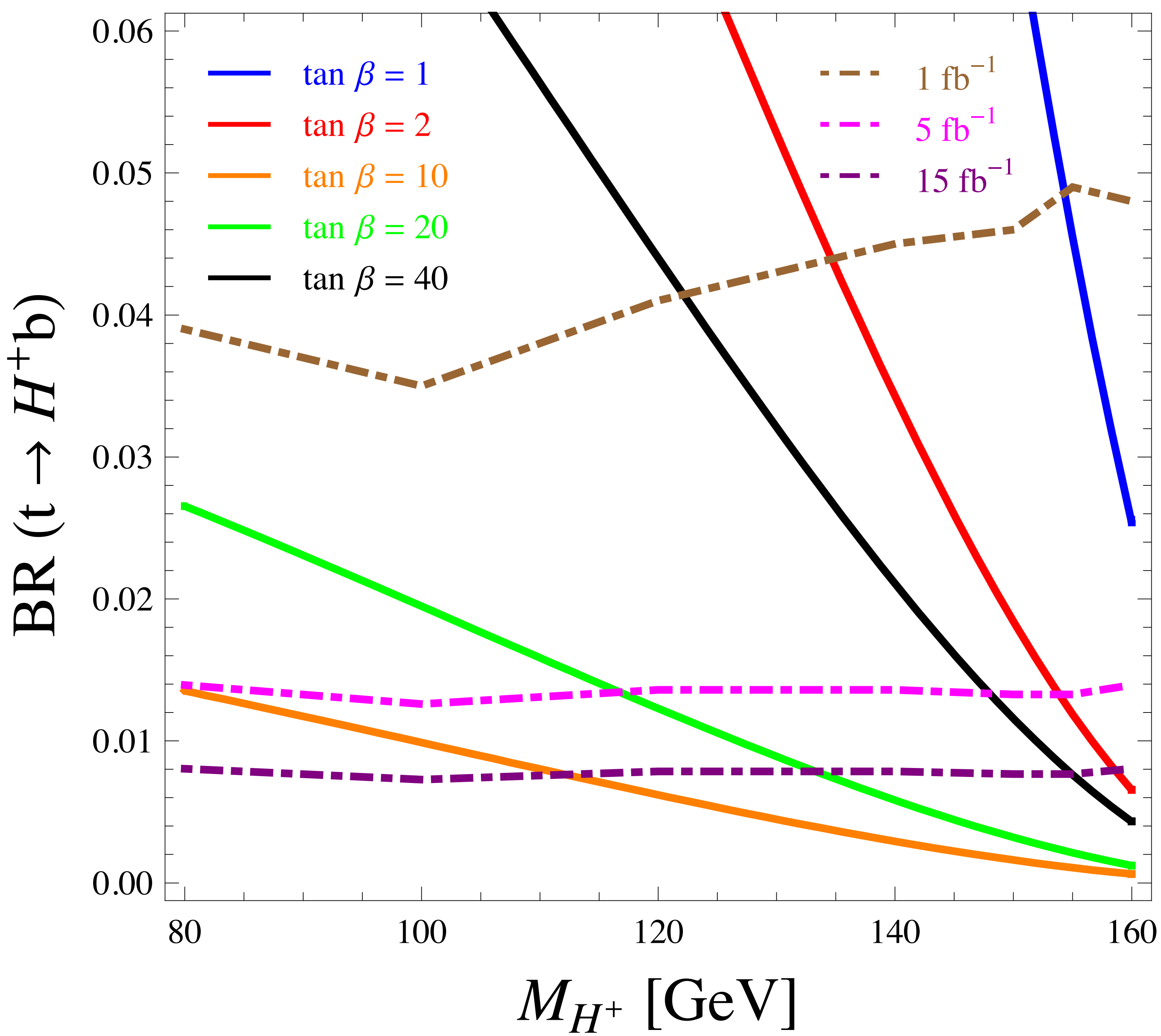
E. Weihs, J.Z (2011)

- Extrapolation of LHC data presented in summer 2011.
- Naive combination of CMS and ATLAS data channel by channel.
- Comparison to official combination (HCP): accuracy better than 10%.

Charged Higgs reach

Search channel: $t \to H^+b,\ H^+ \to \tau^+\nu_\tau$

CMS-PAS-HIG-11-008

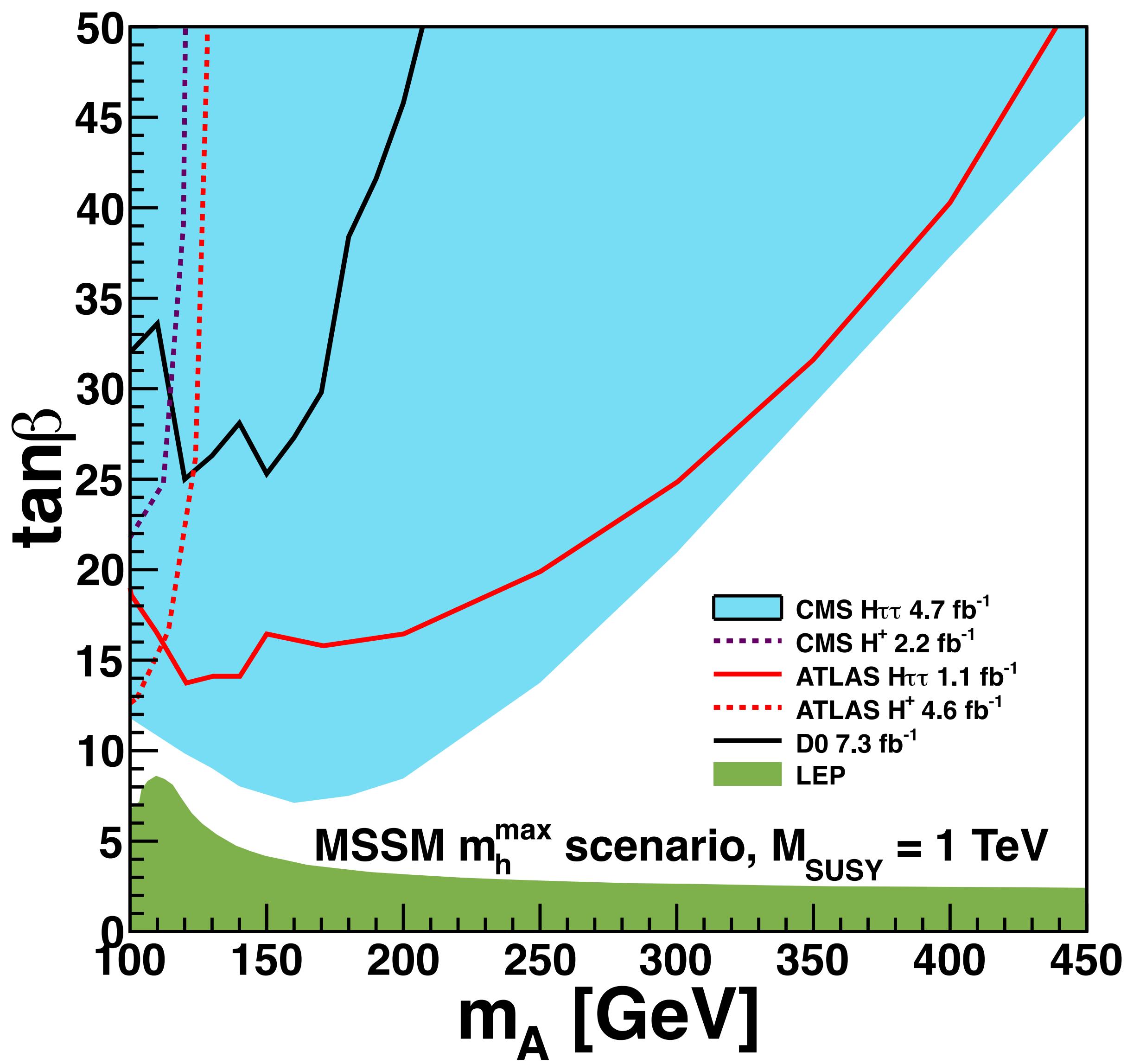


M. Carena, E. Pontón, J. Z (2011)

- 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.

MSSM Higgs searches

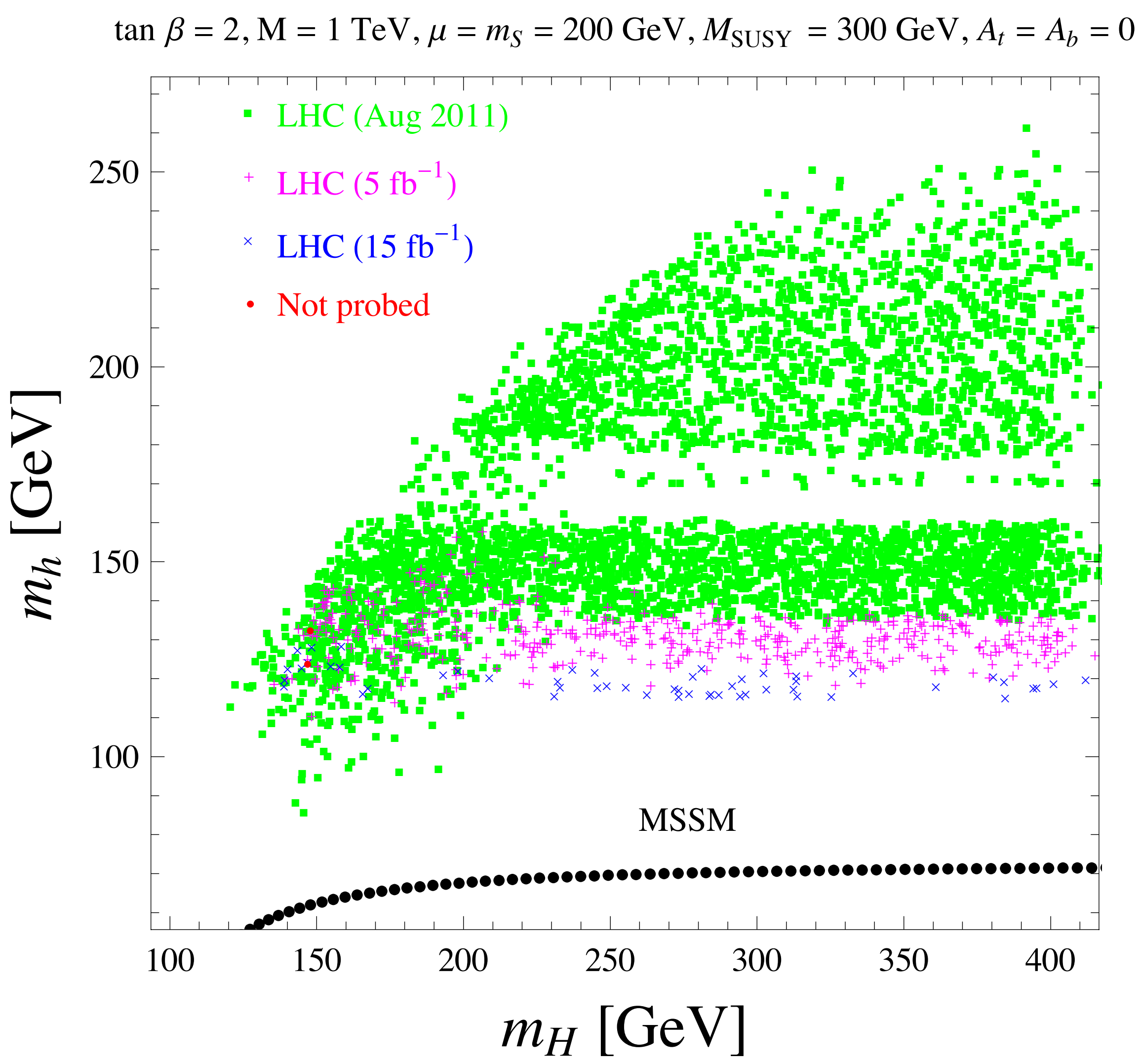
arXiv 1202.4083, ATLAS CONF-2012-011 CMS-PAS-HIG-11-008

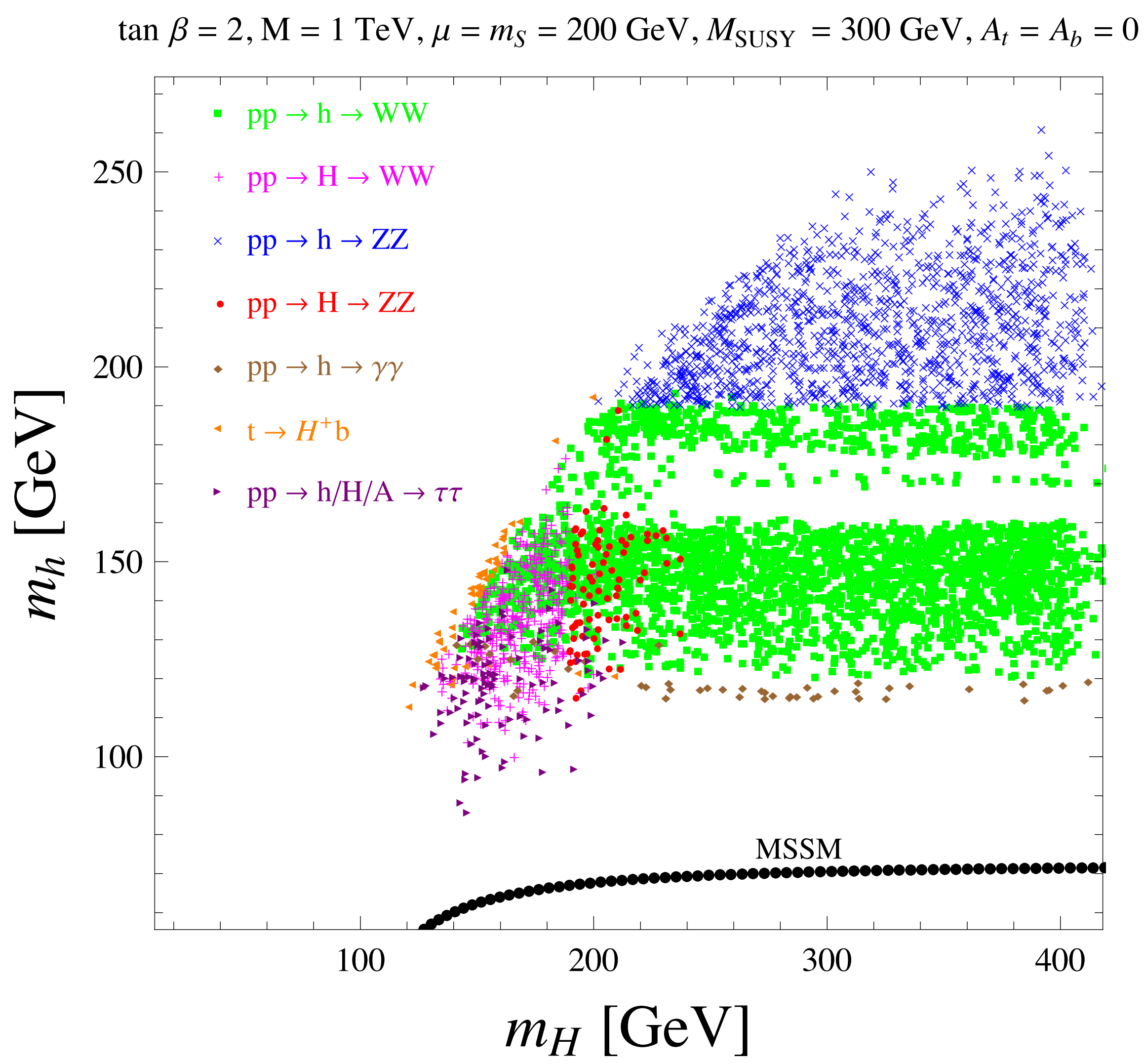


- Important for large tangent beta.
- Low tangent beta: SM-like channels.

In between:
the "wedge region".

Low tan beta

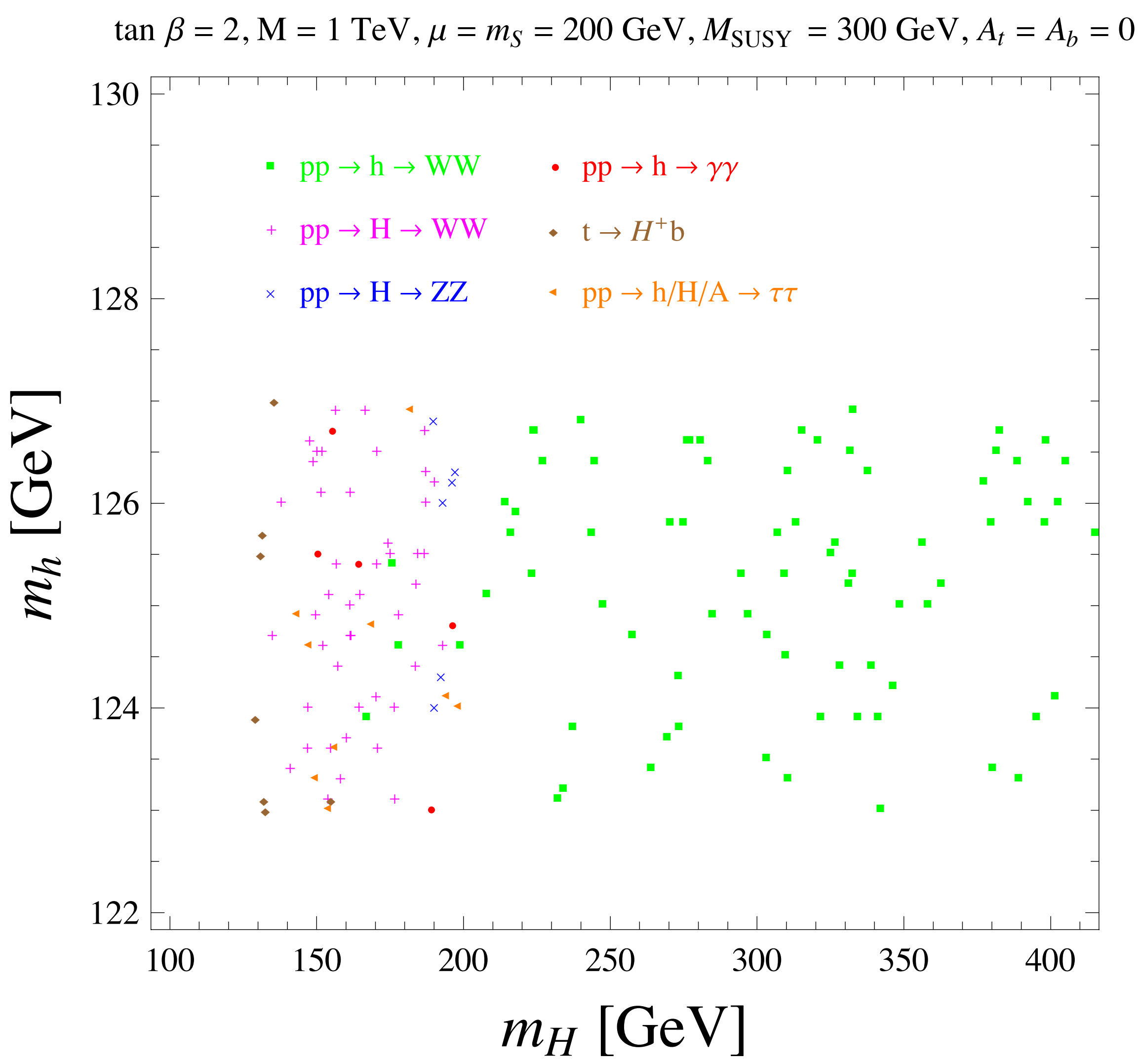


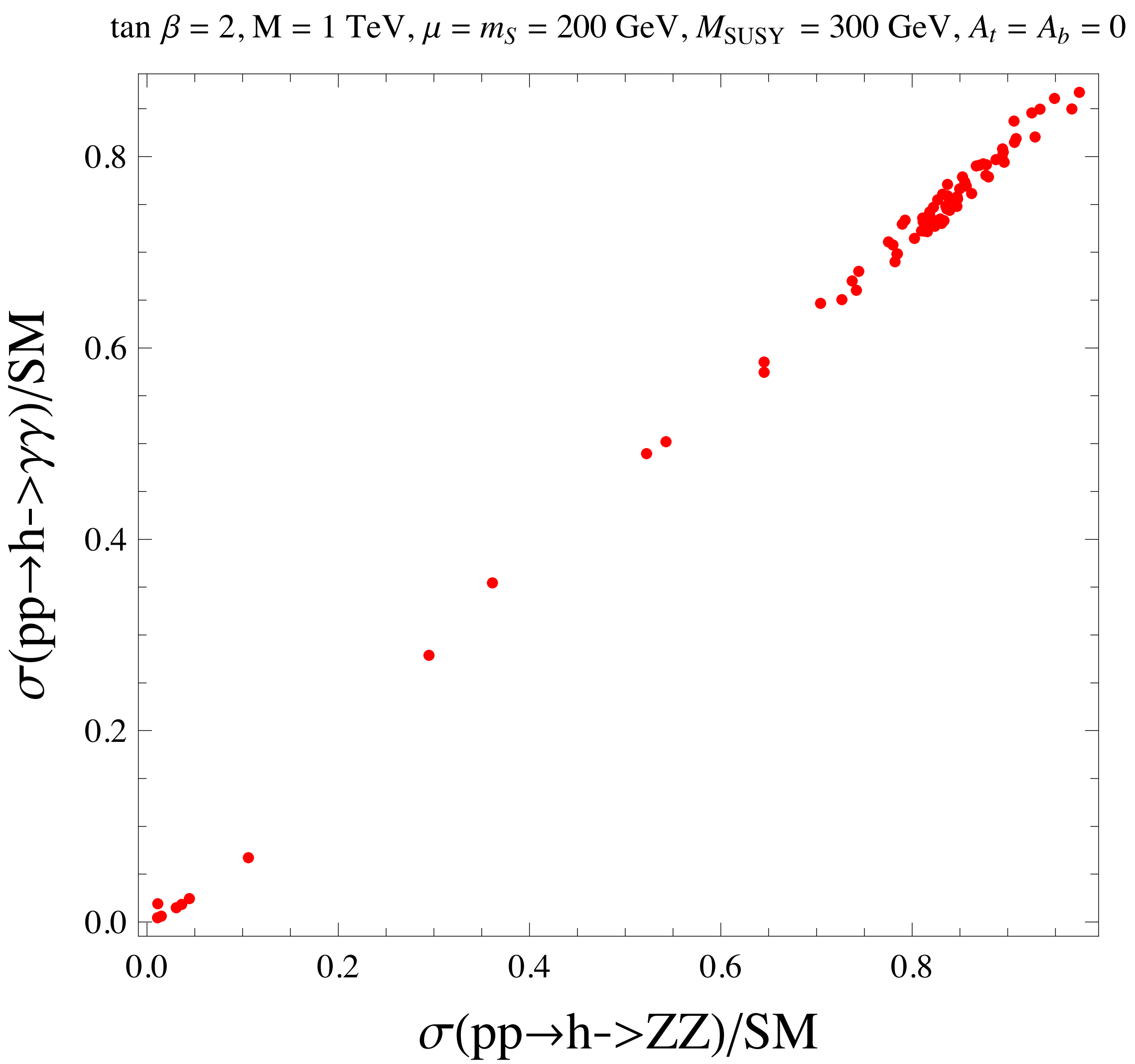


Most important channels: di-bosons.

Charged Higgs and tau tau important for low mh values.

Low tan beta

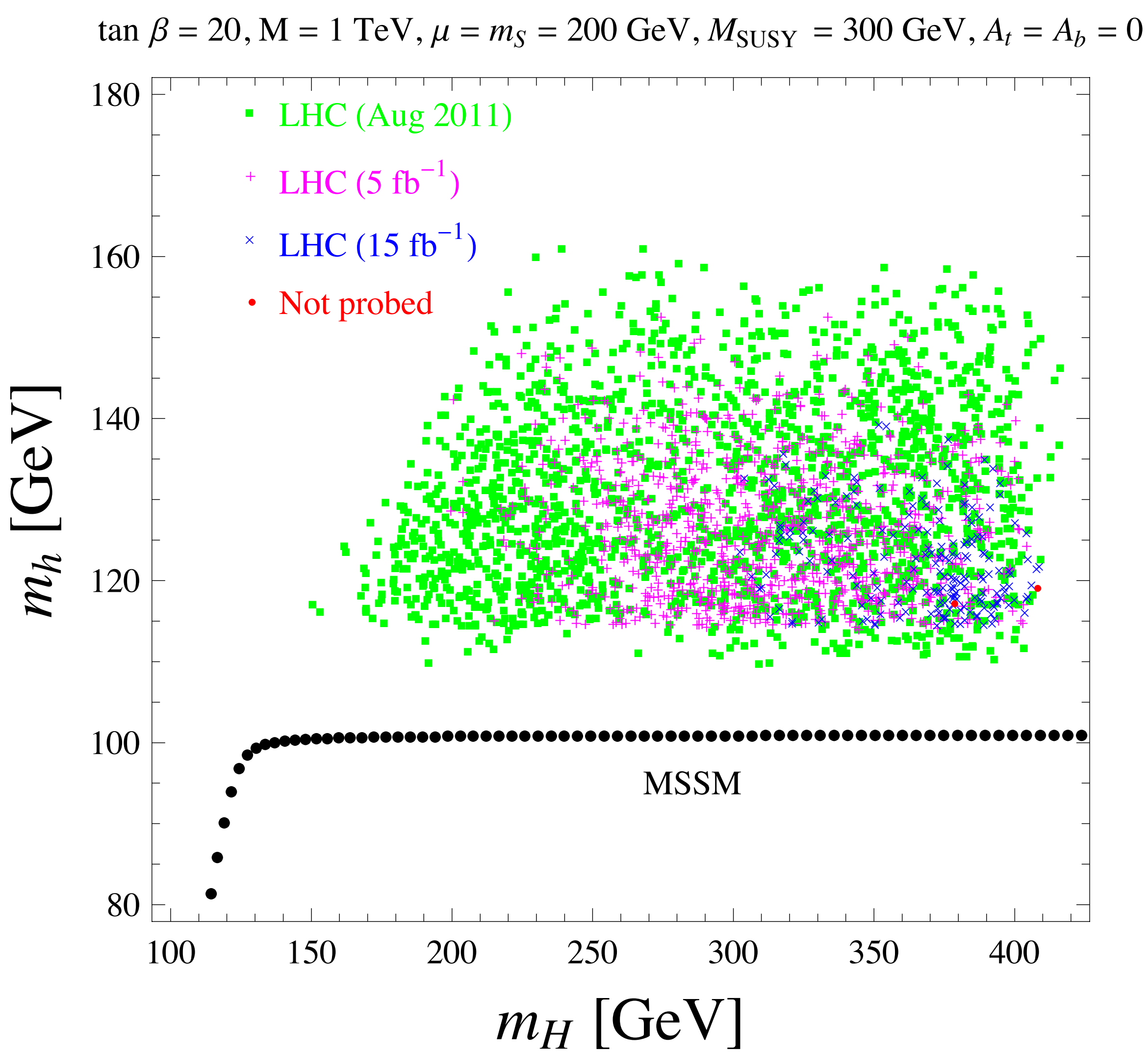


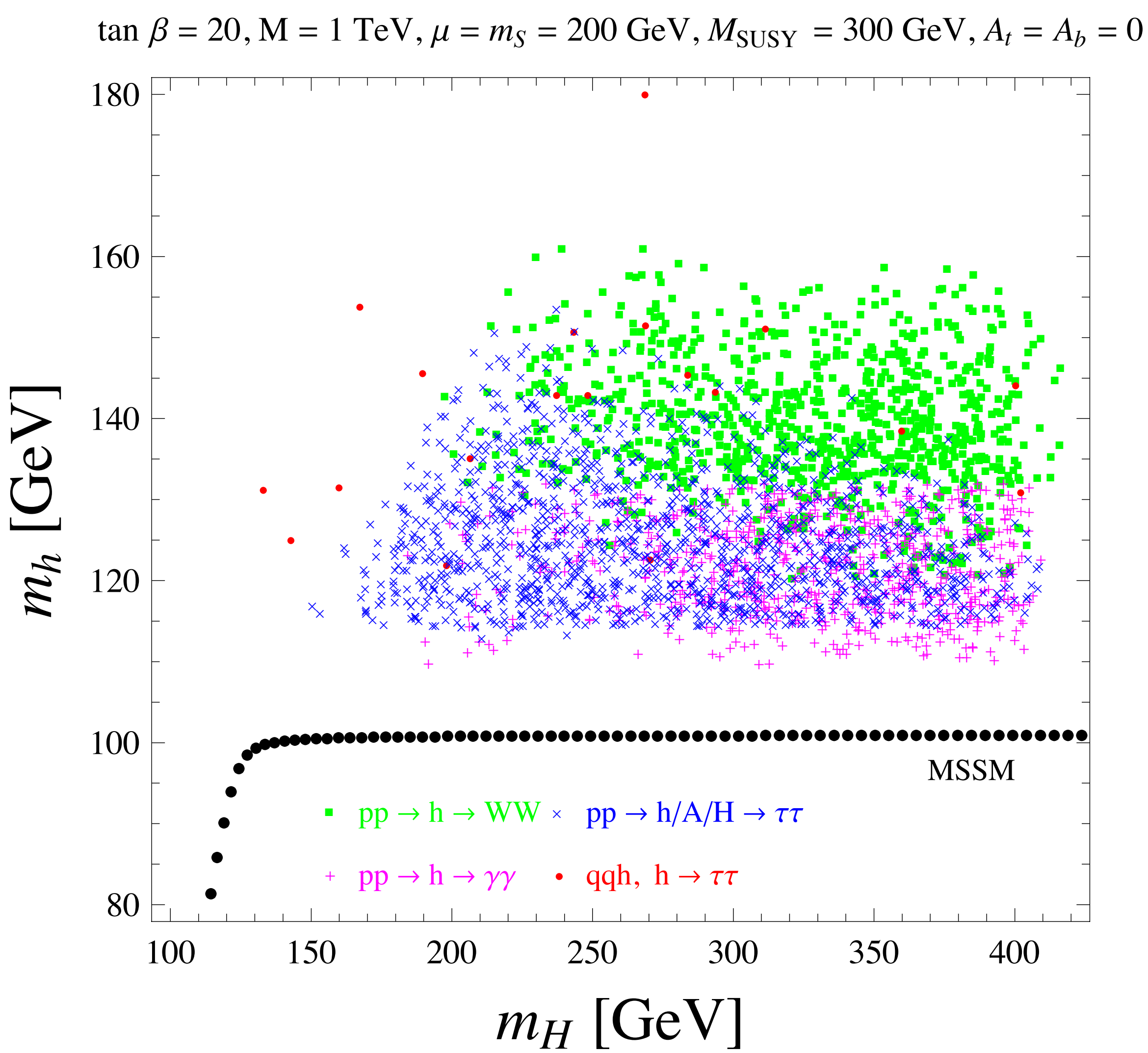


Points tested by diphoton, H can be as low as 150 GeV ⟶ Non-MSSM feature

Diphoton and ZZ channel highly correlated, rates > 1 not achievable.

Large tan beta

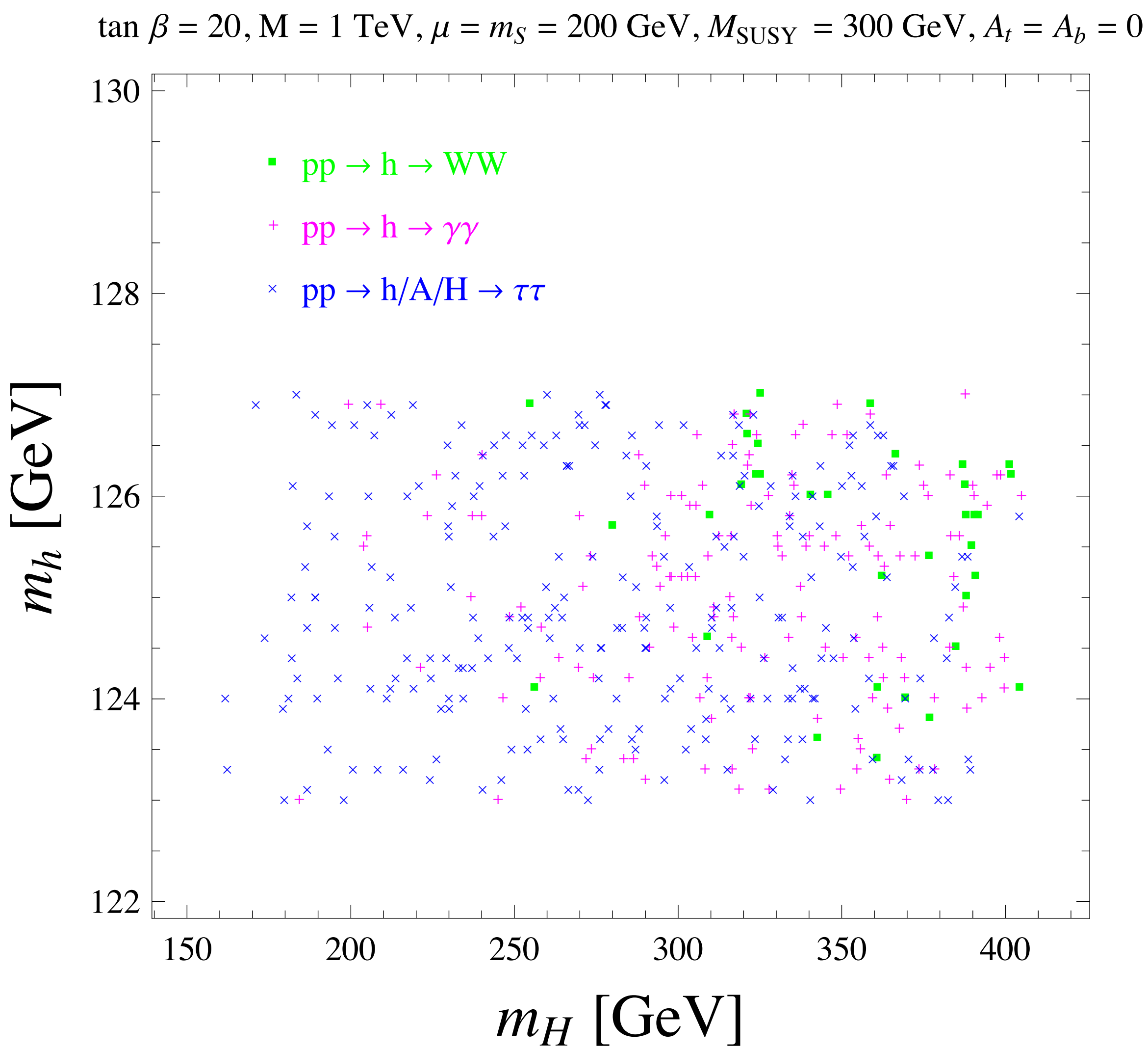


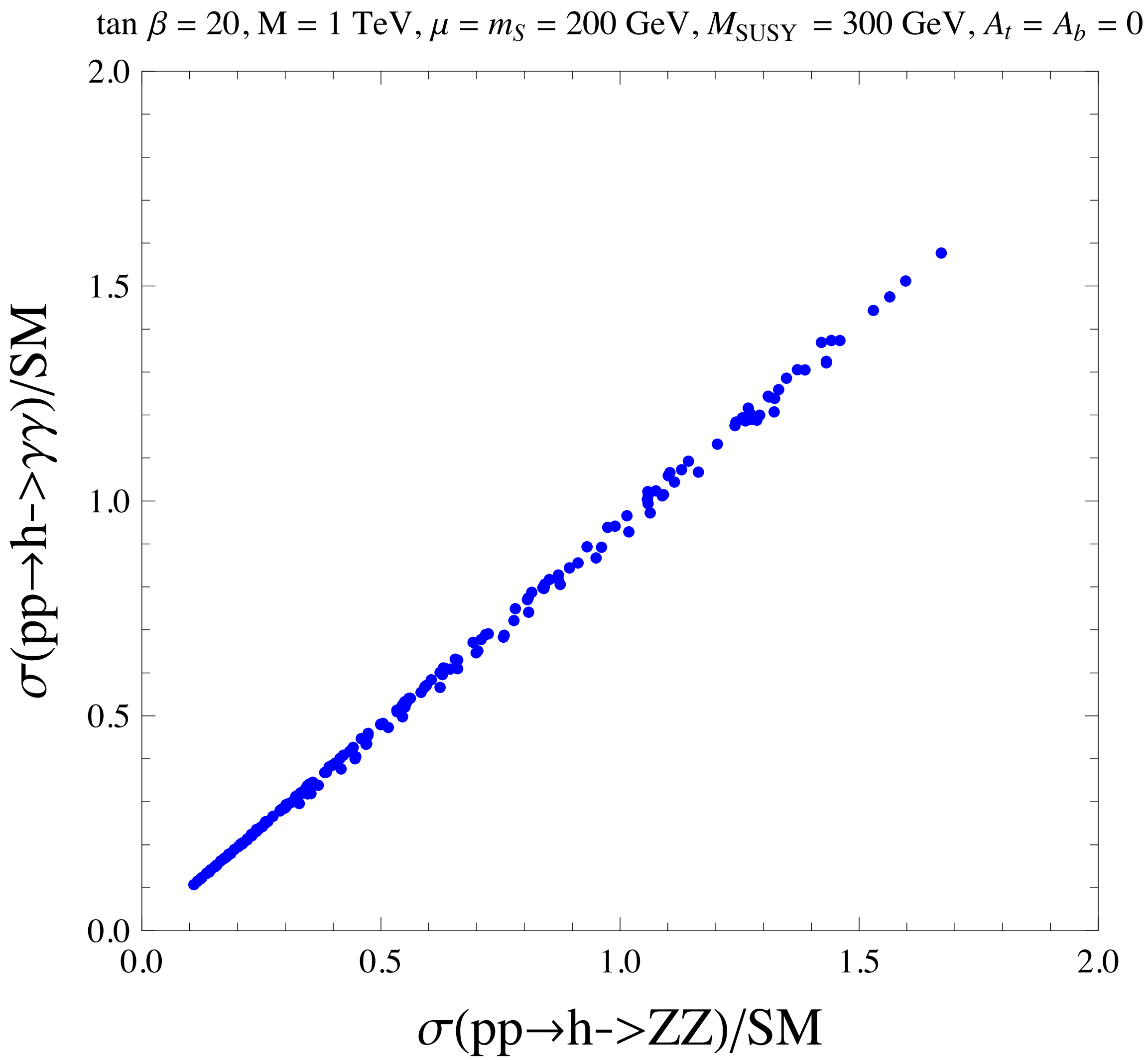


BMSSM effects less relevant than for low tangent beta.

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

Large tan beta





Diphoton points require H > 200 GeV: MSSM-like scenario .

Diphoton and ZZ: rates up to 1.5 are achievable, due to reduction of hbb.

Higgs Portal Models

Higgs Portal Models

Barbieri, Gregoire, Hall; Schabinger, Wells; Patt, Wilczek...

- Extra U(1) broken gauge symmetry: Z' and a "dark" Higgs.

- GeV-ish Z' motivation: Arkani-Hamed, Finkbeiner, Slatyer and Weiner (2008), Pospelov and Ritz (2008).

- $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Dark} + \mathcal{L}_{mix}$

- $\mathcal{L}_{Dark} = (D_\mu H_D)^\dagger (D_\mu H_D) + \mu_D H_D H_D^\dagger - \lambda_D (H_D H_D^\dagger)^2 - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \ldots$

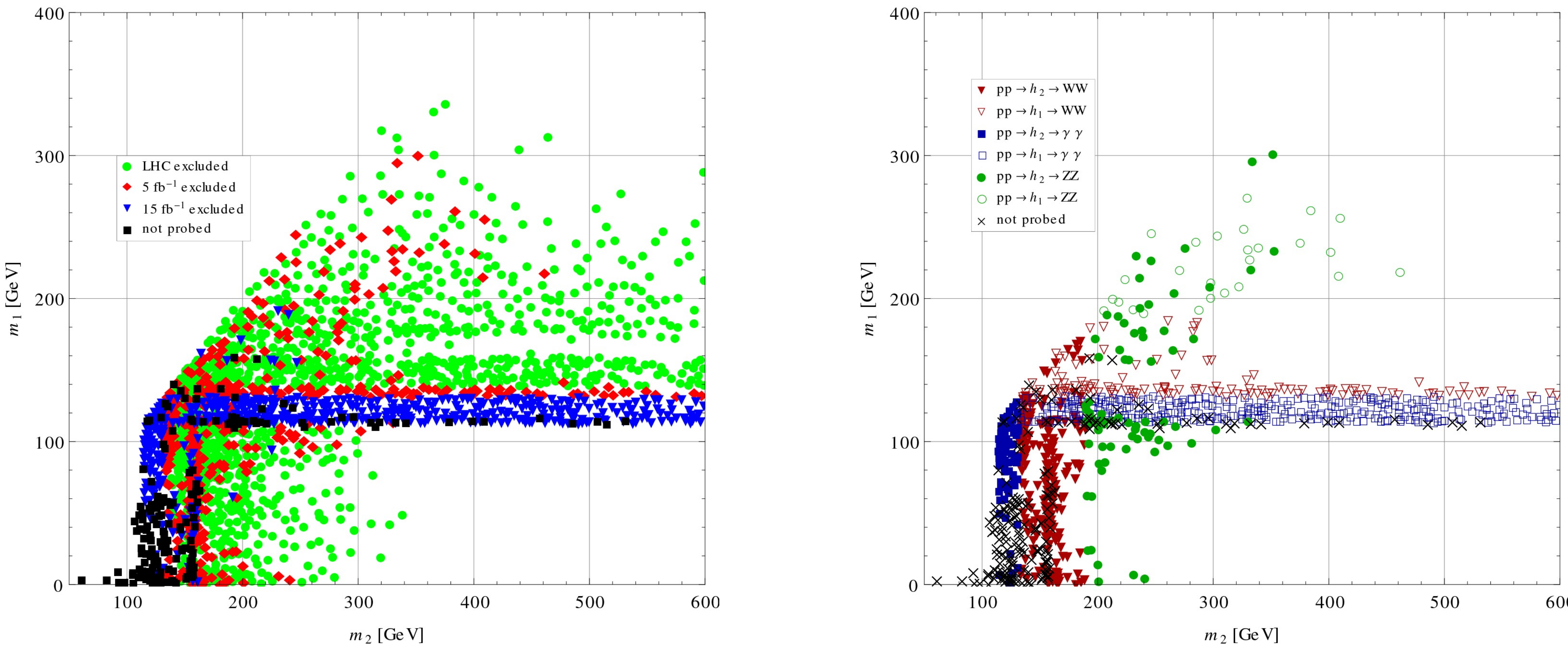
- $\mathcal{L}_{mix} = \frac{\epsilon_A}{2} B_{\mu\nu} X^{\mu\nu} + \epsilon_H (H H^\dagger)(H_D H_D^\dagger)$

- $\epsilon_A < 10^{-2} - 10^{-6}$ M. Ahlers, J. Jaeckel, J. Redondo and A. Ringwald (2008); A. Hook, E. Izaguirre and J. G. Wacker (2011).

- No constraints on ϵ_H.

$g_{h_1 XX} \approx \cos(\alpha)\,, \quad g_{h_2 XX} \approx \sin(\alpha)$ ⇒ All rates < SM.

Higgs Portal @ LHC



E. Weihs, J. Z (2011)

Unless mostly decoupled from the SM, $m_1 < 130$ GeV.

125 GeV hint for the SM-like Higgs boson (either h_2 or h_1.)

Conclusions

- We have studied the LHC reach on two non-SM Higgs sectors.
- BMSSM:
  - ZZ and diphoton channel are highly correlated.
  - No need for large radiative corrections to m_h from sparticles.
  - H does not have to be heavy (> 150 GeV).
- Higgs Portal:
  - $m_1 < 130\ \mathrm{GeV}$ (or h_1 is mostly decoupled from the SM).
  - 125 GeV Higgs could be either h_2 or h_1, with SM-like couplings.

Thanks!

Backup slides

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)

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.

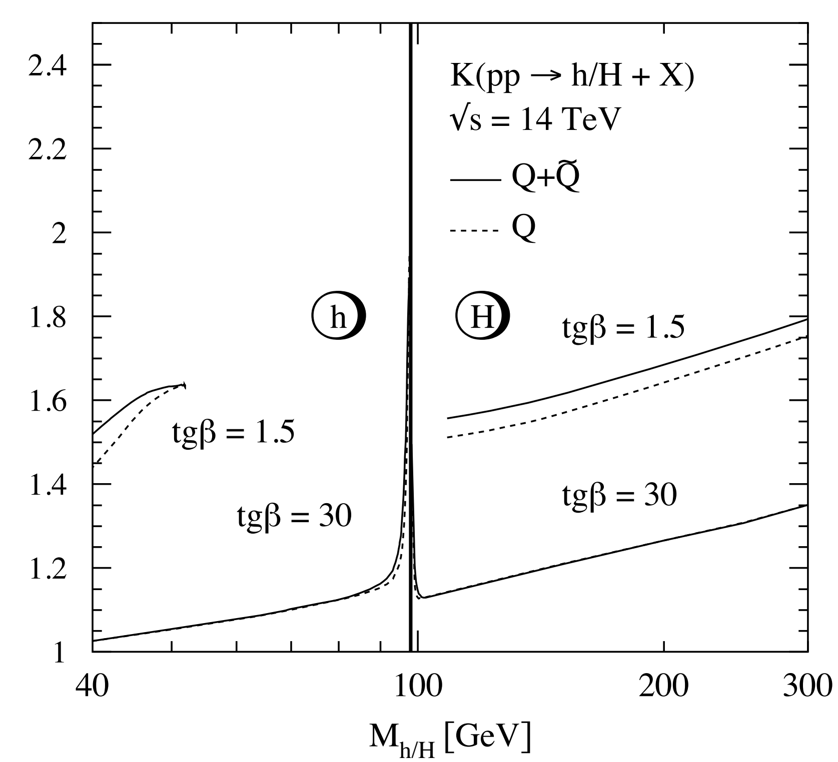
[28] ATLAS collaboration, ATL-PHYS-PUB-2010-015.

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:



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

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