

# Higgs boson(s) in the NMSSM

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Supersymmetry had a bad press recently:

- No signs for squarks/gluino/charginos/neutralinos... at the LHC
- Conflict (?) between "naturalness" and the Higgs mass of  $\sim 126$  GeV

**Still:** No convincing alternatives solving the hierarchy problem, including dark matter, Grand Unification... (the "goodies" of supersymmetry)

**Moreover:** Supersymmetric extensions of the Standard Model are not unique (see talks by G. Ross, N. Weiner...)!

The minimal extension (MSSM) has its shortcomings (see below),

many constraints are MSSM specific;  
notably those from the Higgs mass of  $\sim 126$  GeV! **Why?**

## The quartic Higgs coupling

In the Standard Model, the “mexican hat” potential of the Higgs field  $V(H) = -m^2|H|^2 + \lambda^2|H|^4$  allows to express the physical Higgs mass  $M_h$  in terms of the known vacuum expectation value  $v$  (given by the  $Z/W$  masses) and  $\lambda$ :

$$M_h^2 = 2\lambda^2 v^2$$

- Larger  $M_h$  corresponds to larger  $\lambda$
- If we would have known the coupling  $\lambda$ , we could have predicted the Higgs mass  $M_h$

MSSM: two SU(2) doublets  $H_u, H_d$ :

The quartic self couplings are given by the electroweak gauge couplings

- upper tree level bound on the lighter Higgs mass

$$M_h \leq M_Z$$

- Large (unnatural?) radiative corrections needed for a 126 GeV Higgs

## The NMSSM

Note: The SU(2) doublets  $H_u$  and  $H_d$  of the MSSM have neutral and charged fermionic superpartners  $\Psi_{H_u}$ ,  $\Psi_{H_d}$  which are not observed at LEP

- a fermionic *supersymmetric* mass term  $\mu \Psi_{H_u} \Psi_{H_d}$  with  $\mu \sim \mathcal{O}(M_{Weak})$  must be present ( $\mu$  appears also in the scalar potential)
- an accident? (The “ $\mu$ -problem”, see Kim+Nilles 1984)

Better: recall how fermionic mass terms are generated in the SM:

- introduce a Yukawa coupling  $\lambda S \Psi_{H_u} \Psi_{H_d}$  to a scalar (here: a gauge singlet  $S$ )

$S$  has automatically a vev  $v_s$  of  $\mathcal{O}(M_{Susy})$  due to the soft Susy breaking terms

- generates a mass term  $\mu_{eff} = \lambda v_s$  of the desired order

## Additional benefits of the NMSSM:

An extra quartic coupling  $\lambda^2 H_u^2 H_d^2$  due to SUSY

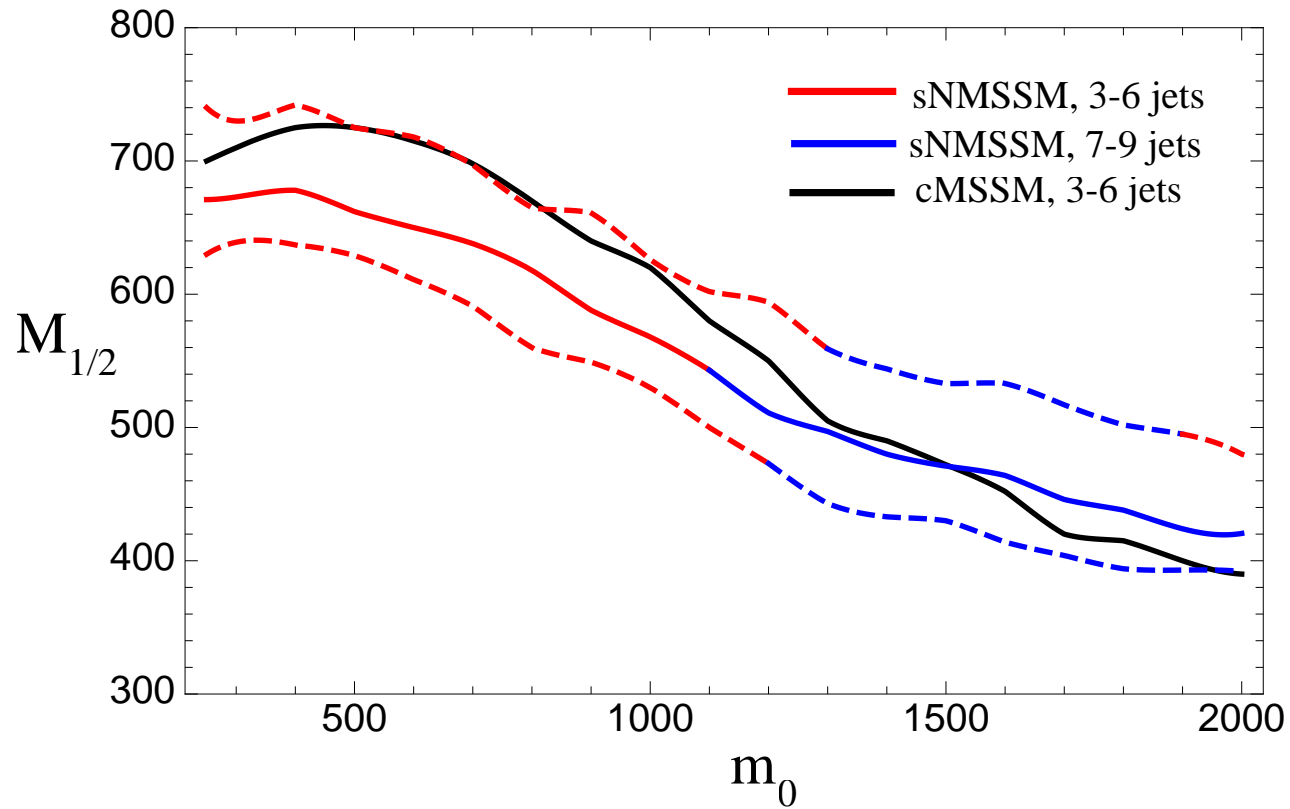
→ Larger mass  $M_{h_{SM}} > M_Z$  at tree level (if  $\tan \beta \lesssim 5$ ,  $\lambda \gtrsim 0.5$ )

An additional singlino  $\psi_S$  (mixes with higgsinos/bino → a good dark matter candidate)

→ complicates squark/gluino decay cascades;

→ weaker bounds from sparticle searches via  $E_T^{\text{miss}}$ ?

E.g. in the  $m_0 - M_{1/2}$  plane (with D. Das, A. Teixeira):



→ Slightly lower bounds on  $M_{1/2}$  for  $m_0 \lesssim 1$  TeV  
stronger reduction possible if constraints at the GUT scale are relaxed

**NMSSM:** Three physical scalars, superpositions of  $H_u$ ,  $H_d$  and  $S$  with vevs  $v_u$ ,  $v_d$ ,  $v_s$  where  $v_u^2 + v_d^2 = v_{SM}^2$ , but  $v_u/v_d \equiv \tan \beta$  and  $v_s$  unknown

**Moreover:** Two physical pseudoscalars, possibly a very light one

The scalar masses have to be obtained by diagonalising a  $3 \times 3$  mass matrix, typically:

- a mostly SM like eigenstate  $h_{SM}$ ,
- a mostly singlet like eigenstate  $h_S$ ,
- a heavy MSSM-like scalar  $H$

The tree level mass of the mostly SM like  $h_{SM}$  is

$$M_{h_{SM}}^2 = M_Z^2 \cos^2 2\beta + \lambda^2 (v_u^2 + v_d^2) \sin^2 2\beta \pm ( \dots )$$

$\pm ( \dots )$ : From mixing of the mostly SM like scalar  $h_{SM}$  with the mostly singlet like scalar  $h_S$  (dep. on unknown parameters);

positive if  $M_{h_S} < M_{h_{SM}}$ !

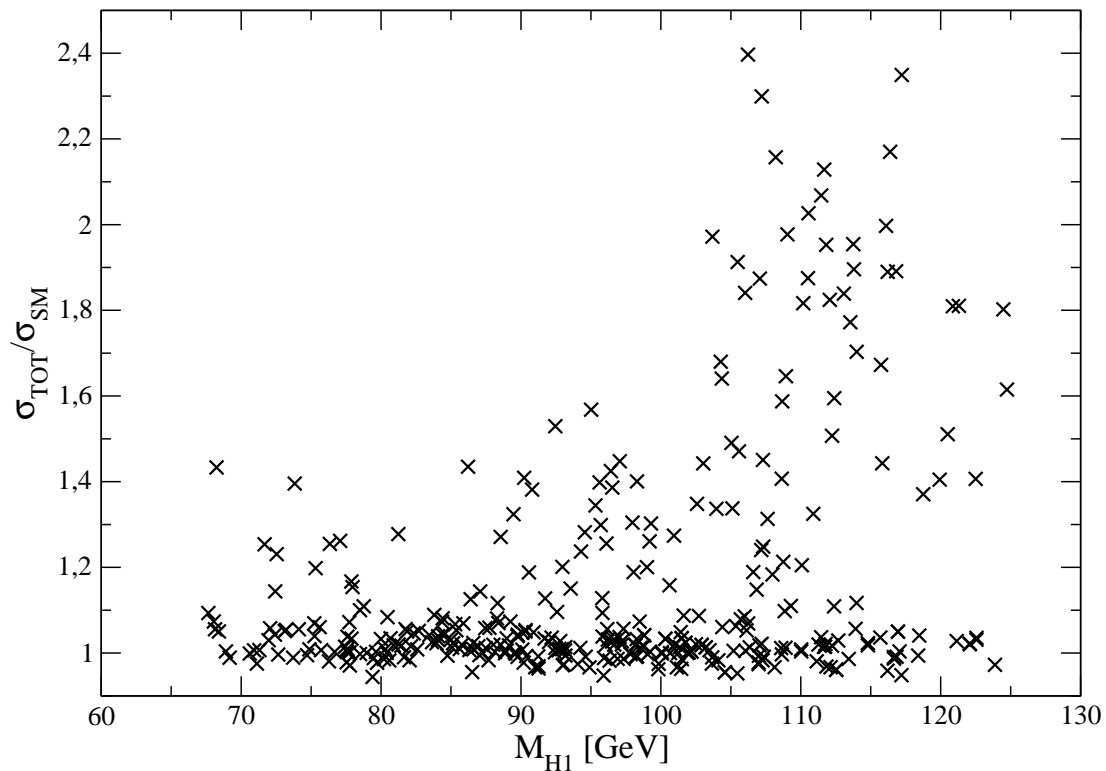
→ Larger mass  $M_{h_{SM}} > M_Z$  at tree level, all in all:

$M_{h_{SM}} \sim 126$  GeV does not require large (unnatural) radiative corrections

If  $M_{h_S} < M_{h_{SM}}$ :

Visible in Higgs pair production/measurements of triple Higgs coupling(s)?

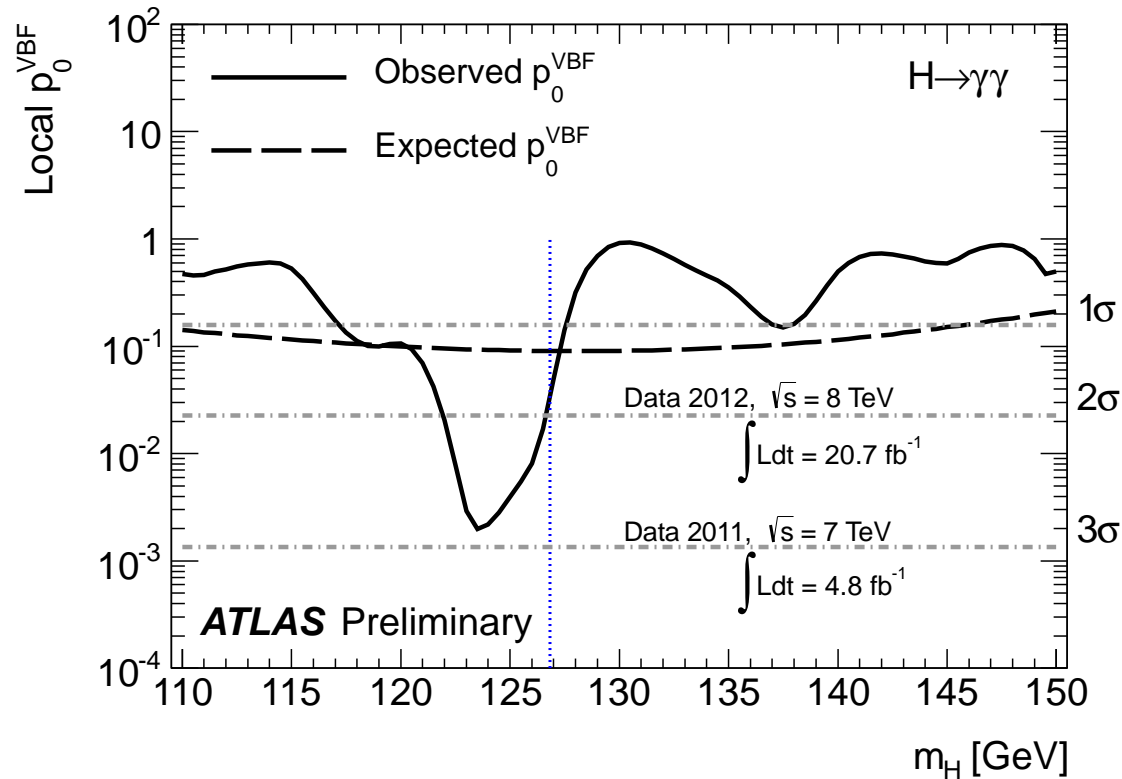
$(h_S + h_S) + (h_S + h_{SM}) + (h_{SM} + h_{SM})$  production cross section relative to the SM as function of  $h_S = 65 \dots 125$  GeV (U.E. 1306.5541):



→ Possibly, but not necessarily enhanced

# The measured signal rate in $H \rightarrow \gamma\gamma$

ATLAS-CONF-2013-012 (in Higgs prod. via Vector Boson Fusion, VBF):

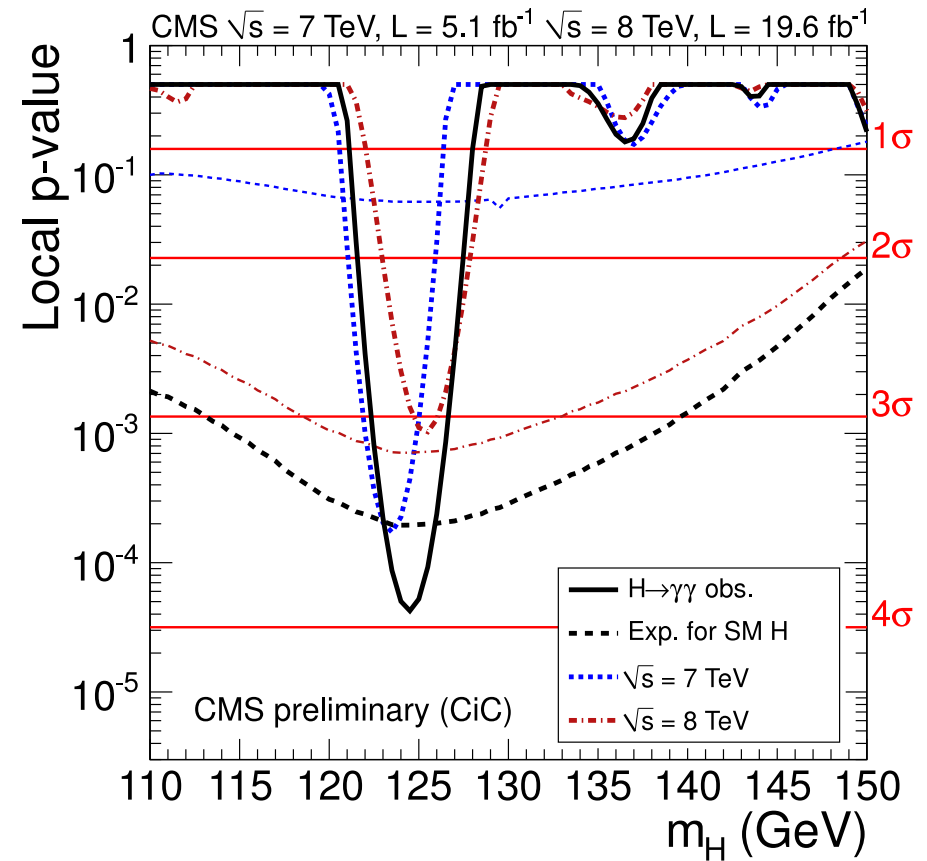
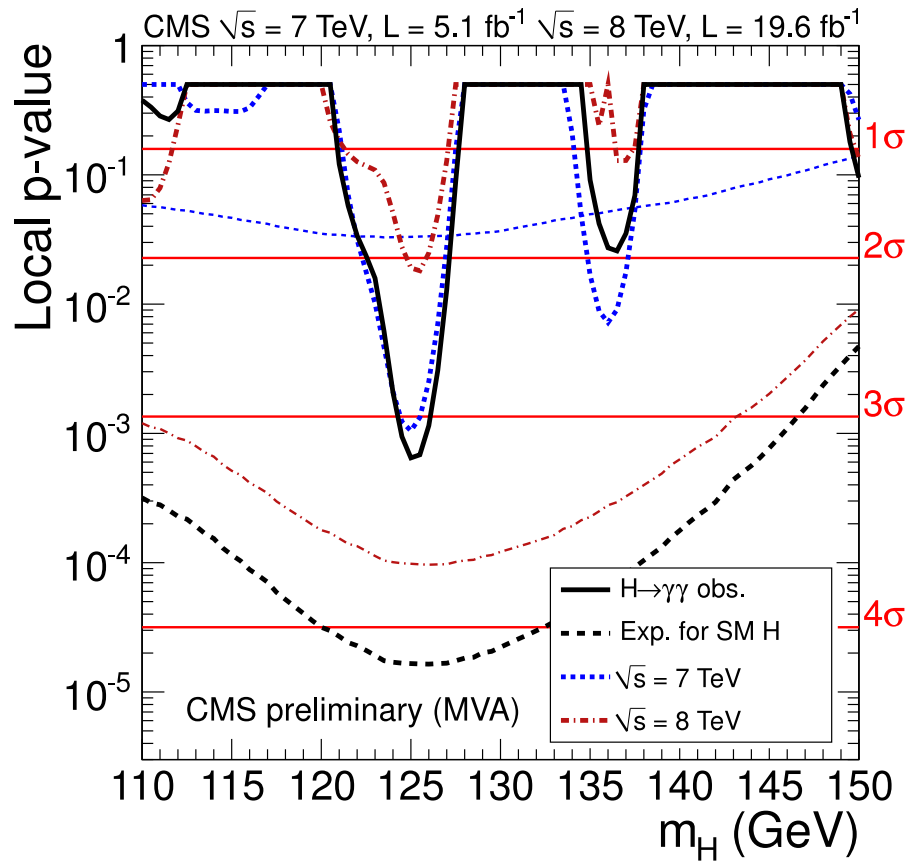


After combining with Higgs production via gluon fusion:

$$R_{\gamma\gamma} \equiv \frac{\text{measured signal rate}}{\text{Standard Model signal rate}} = 1.65 \pm 0.32$$



# CMS $H \rightarrow \gamma\gamma$ (HIG-13-001-PAS, comb. VBF+ggF)



→ Confirmation of the enhanced  $\gamma\gamma$  rate in the cutbased analysis (r.h.s.), but not in the MVA analysis (l.h.s.)

# The $\gamma\gamma$ signal rate in the NMSSM

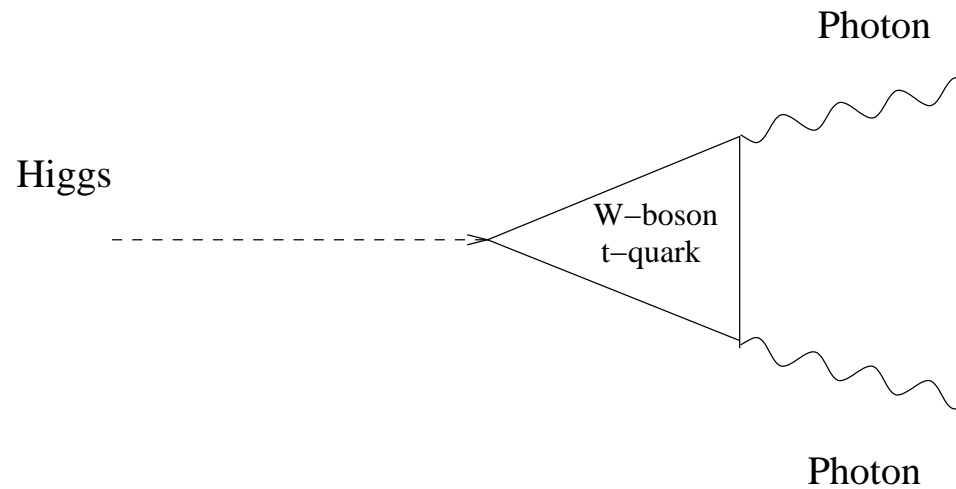
1) Recall:

$$BR(H \rightarrow \gamma\gamma) = \frac{\Gamma(H \rightarrow \gamma\gamma)}{\Gamma(H \rightarrow bb) + \dots}$$

( $\Gamma(H \rightarrow bb)$  gives  $\sim 58\%$  of the total width for a 126 GeV SM Scalar)

- Due to the mixing of  $H_u, H_d, S$  it is easily possible that, in the NMSSM, the mostly SM-like  $h_{SM}$  has
  - a reduced coupling to  $bb$ , and hence a reduced width  $\Gamma(h_{SM} \rightarrow bb)$ 
    - an enhanced  $BR(h_{SM} \rightarrow \gamma\gamma)$
  - nearly SM-like couplings to the top quark (whose loops induce the coupling to gluons) and to the electroweak gauge bosons
    - the production rates in gluon fusion and/or VBF are hardly reduced
- The  $\gamma\gamma$  signal rate is enhanced (U.E. 2010)

2) Recall: In the SM,  $\Gamma(H \rightarrow \gamma\gamma)$  is induced via  $W$ -boson (and top quark) loops:

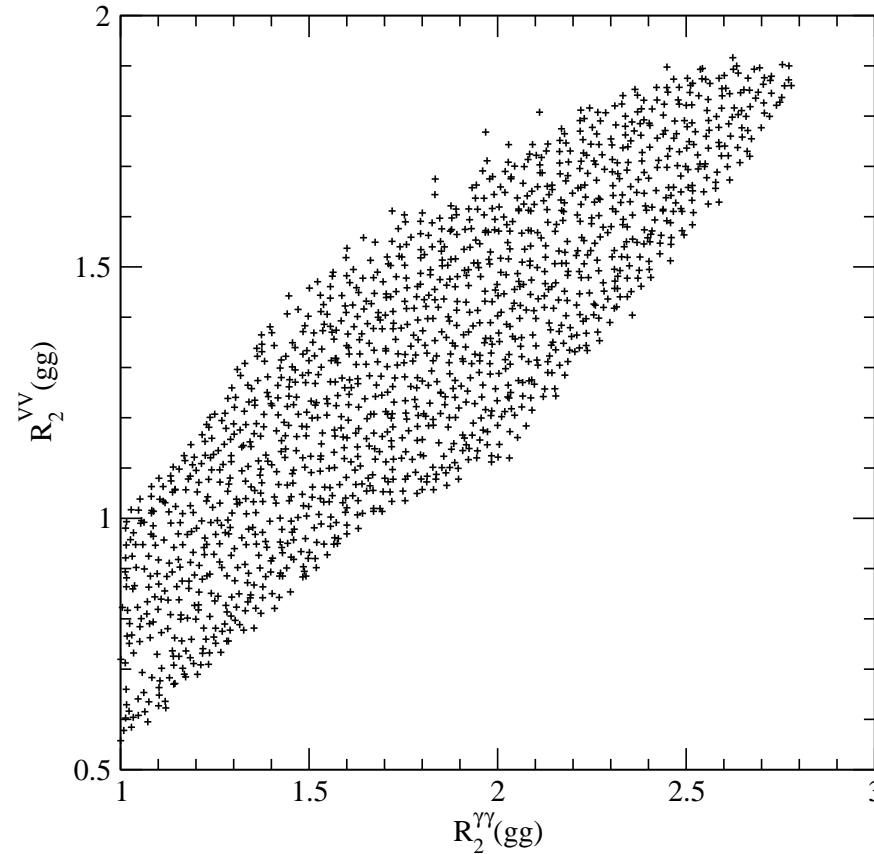


In the NMSSM, the singlet  $S$  couples to the (charged) higgsinos  $\psi_{H_u}, \psi_{H_d}$ :

$\lambda S \psi_{H_u} \psi_{H_d}$  (recall the generation of the  $\mu$ -term through  $v_s$ )

→ If  $h_{SM}$  has a  $S$ -component, charged higgsinos contribute to the loop and to  $\Gamma(h_{SM} \rightarrow \gamma\gamma)$  unless  $\lambda$  is small or the higgsinos are heavy

Plot of the possible signal rates in the  $\gamma\gamma$  and  $VV \equiv ZZ, WW$  final states relative to the SM: (semi-constr. NMSSM, with C. Hugonie, 1203.5048)

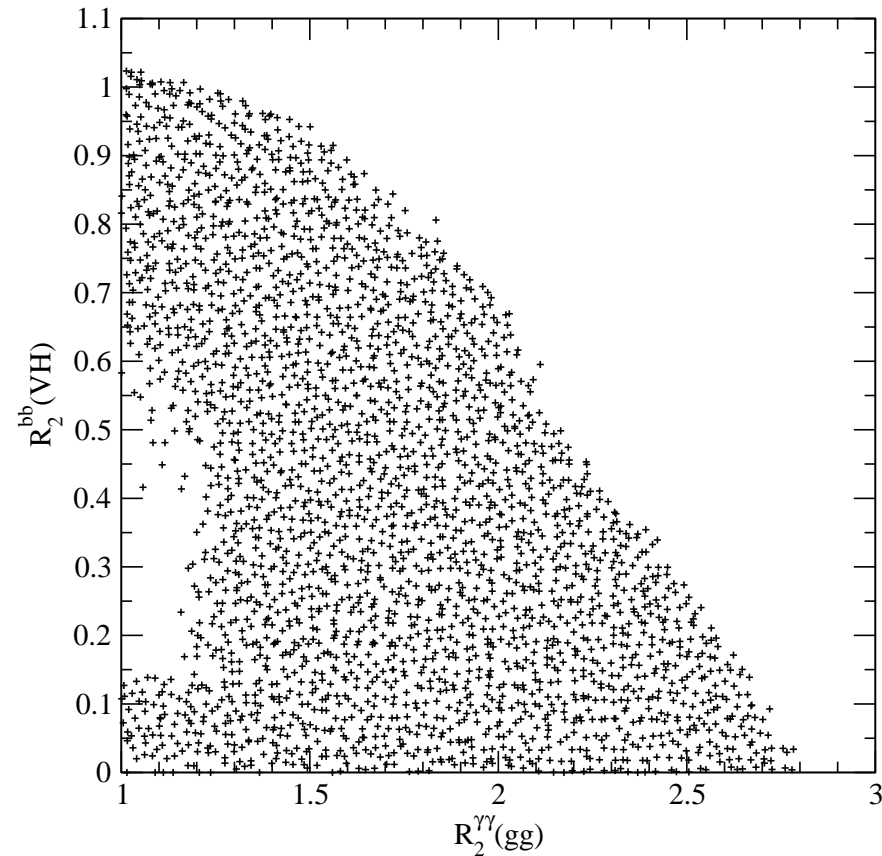


→  $R_2^{\gamma\gamma}(gg)$  can be enhanced by a factor 2 (or larger); both mechanisms 1) and 2) contribute!

→ If  $R_2^{\gamma\gamma}(gg) \lesssim 2$ :  $R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$  is not necessarily enhanced

$R_2^{bb}(VH)$  against  $R_2^{\gamma\gamma}(gg)$ :

In conflict with the SM-like signal rate  $h_{SM} \rightarrow bb$ ?



→ If  $R_2^{\gamma\gamma}(gg) \lesssim 1.5$ :

$R_2^{bb}(VH)$  is not necessarily reduced, the enhancement of  $R_2^{\gamma\gamma}(gg)$  results from the additional higgsino loop, not from a reduction of  $\Gamma(h_{SM} \rightarrow bb)$

If  $h_{SM}$  mixes strongly with another mostly singlet-like scalar: The mass of this mostly singlet-like  $h_S$  should be not too far from  $M_{h_{SM}} \sim 126$  GeV

→ Are there hints for (at least weak bounds on) such a state?

Unfortunately: The couplings/signal rates of  $h_S$  are typically reduced relative to the ones of  $h_{SM}$ ,

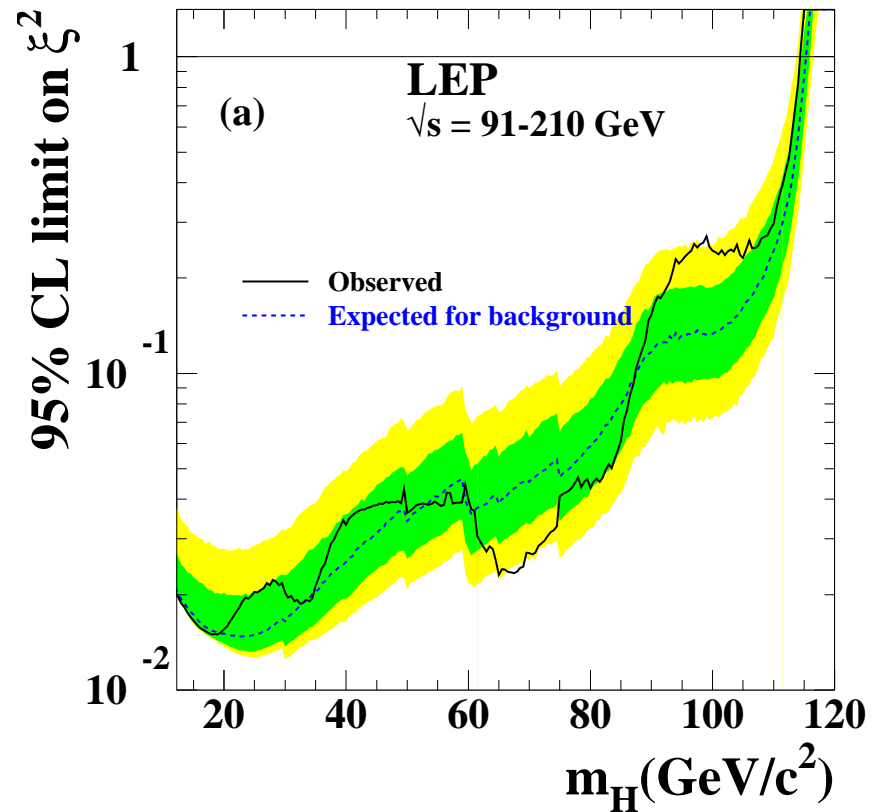
but it can still be visible in some SM Higgs search channels

If this state has a mass below 114 GeV:

Bounds on the signal rate  $\xi^2$  in  $Z^* \rightarrow Z + h_{SM}$  at LEP:

→ If  $\xi^2(h_S) \sim 0.2$ :

Compatible with the weak bounds ( $\sim 2\sigma$  excess) around 95 GeV



G. Belanger et al., 1210.1976:

$M_{h_S} \sim 95$  GeV with  $\xi^2(h_S) \sim 0.2$  is a possible scenario in the semi-constrained NMSSM

Or:

The 126 GeV signal could be due to the superposition of two scalars close in mass (J. Gunion et al., 1207.1545 and 1208.1817)

→ possible enhancement of the diphoton signal rate

(But: this would NOT resolve differences in mass measurements in the  $ZZ$  and  $\gamma\gamma$  channels (ATLAS)!) )

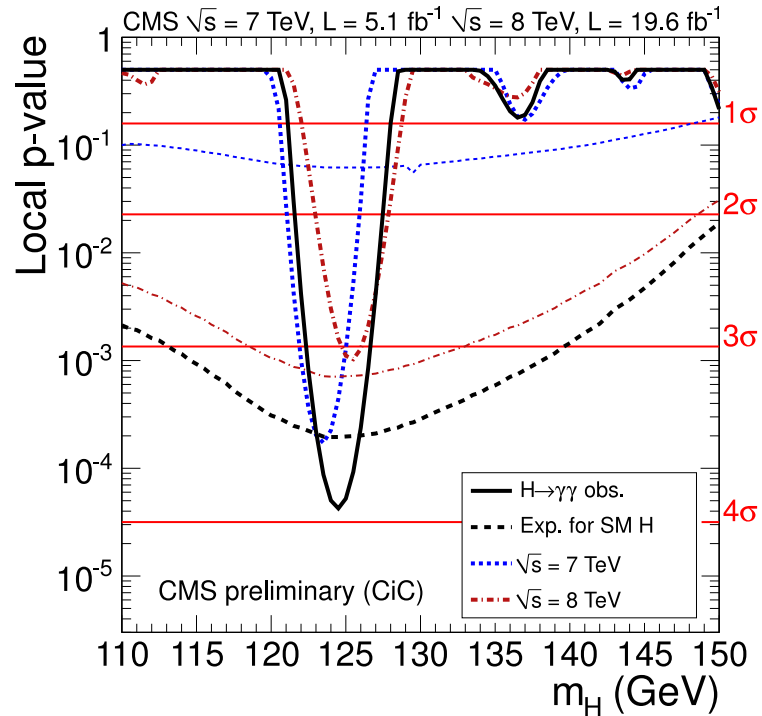
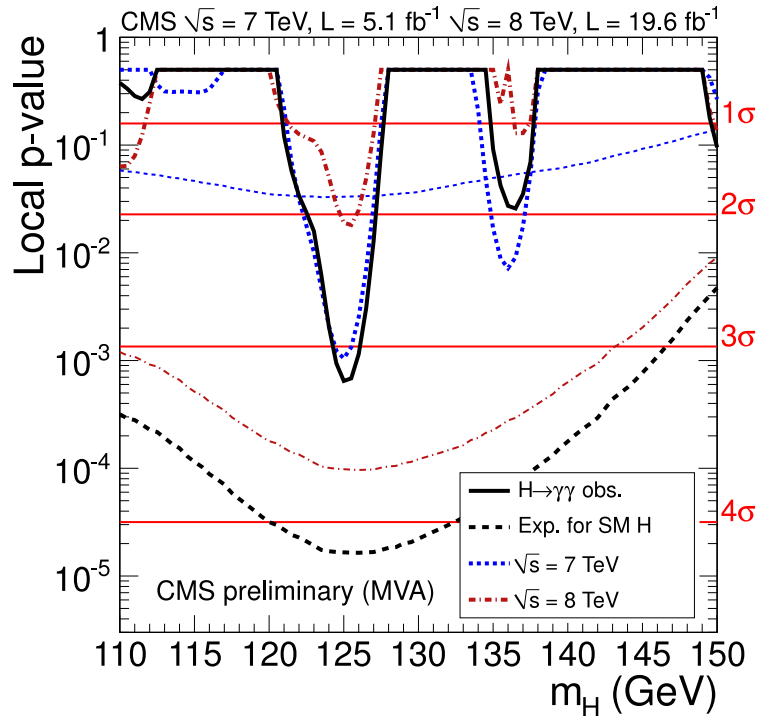
Or:

$h_S$  could be heavier than 126 GeV (G. Belanger et al., 1208.4952)?

Some “appetizers” :

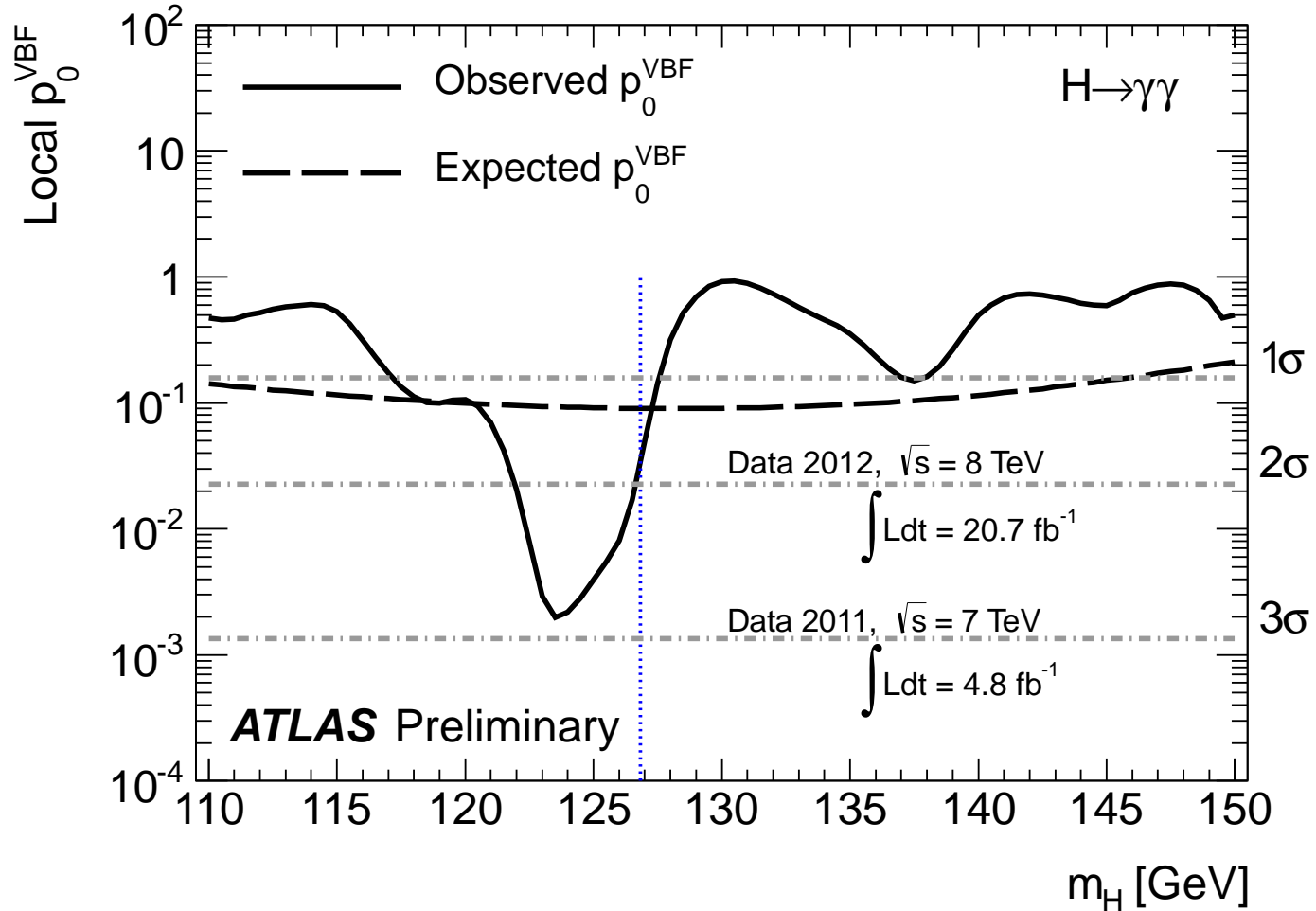


Recall:  $H \rightarrow \gamma\gamma$  at CMS (1303.4571):



Additional  $\sim 2\sigma$  excess around  $M_H \sim 136$  GeV (MVA analysis, l.h.s.)  
 or: confirmation of the enhanced  $\gamma\gamma$  rate of the 126 GeV Scalar in cut-based analysis, r.h.s.; still:  $\sim 1\sigma$  excess around  $M_H \sim 136$  GeV

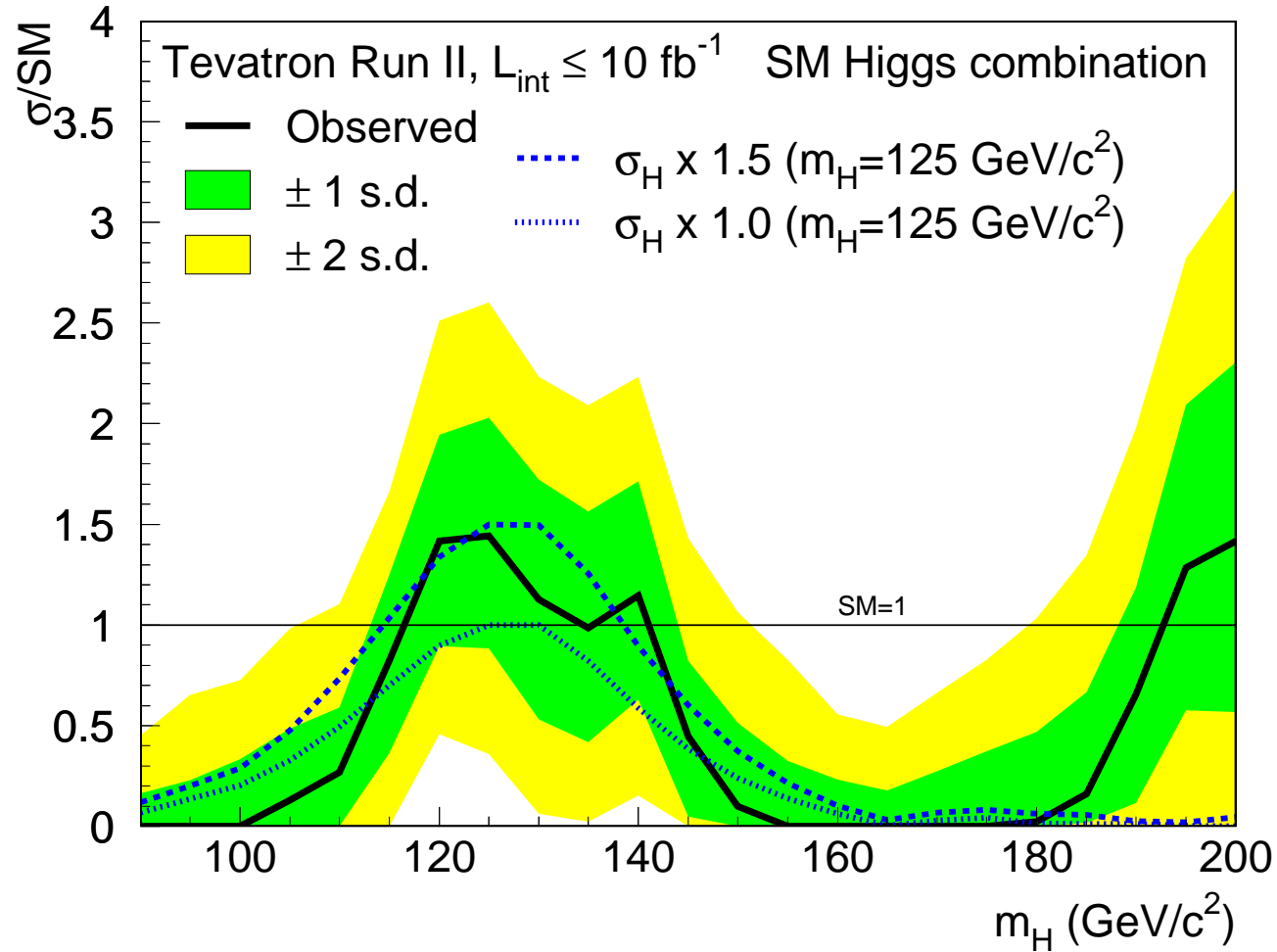
Recall:  $H \rightarrow \gamma\gamma$  at ATLAS (ATLAS-CONF-2013-012):



small additional excess around  $M_H \sim 137$  GeV

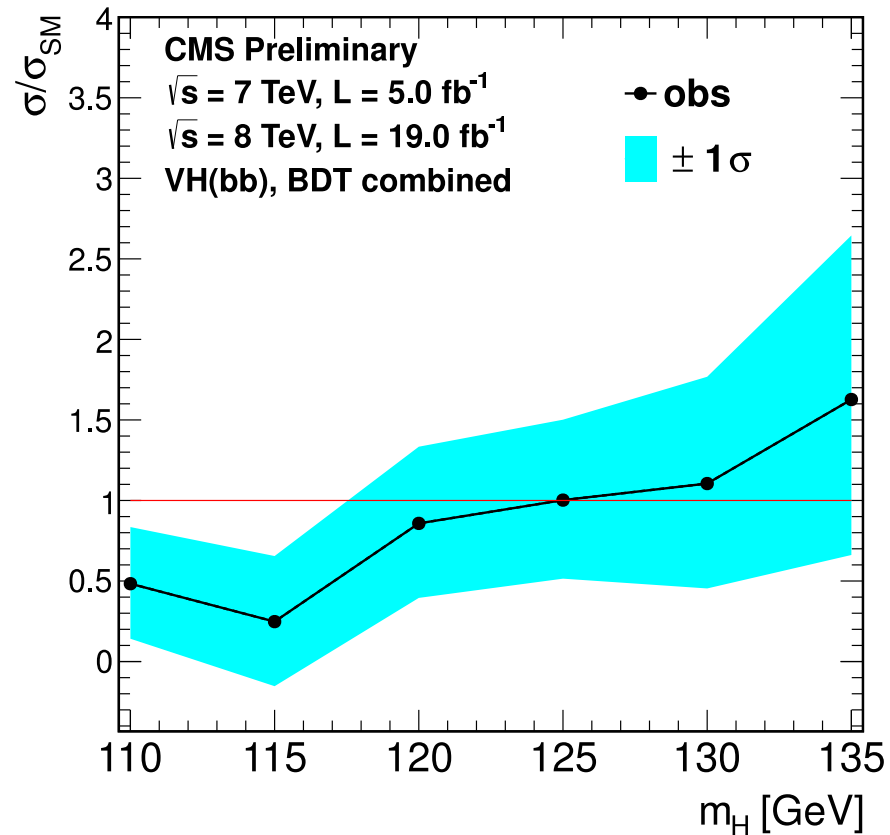
Tevatron  $VH \rightarrow bb$  (1303.6346):

(Fits to the measured signal rate relative to the SM)



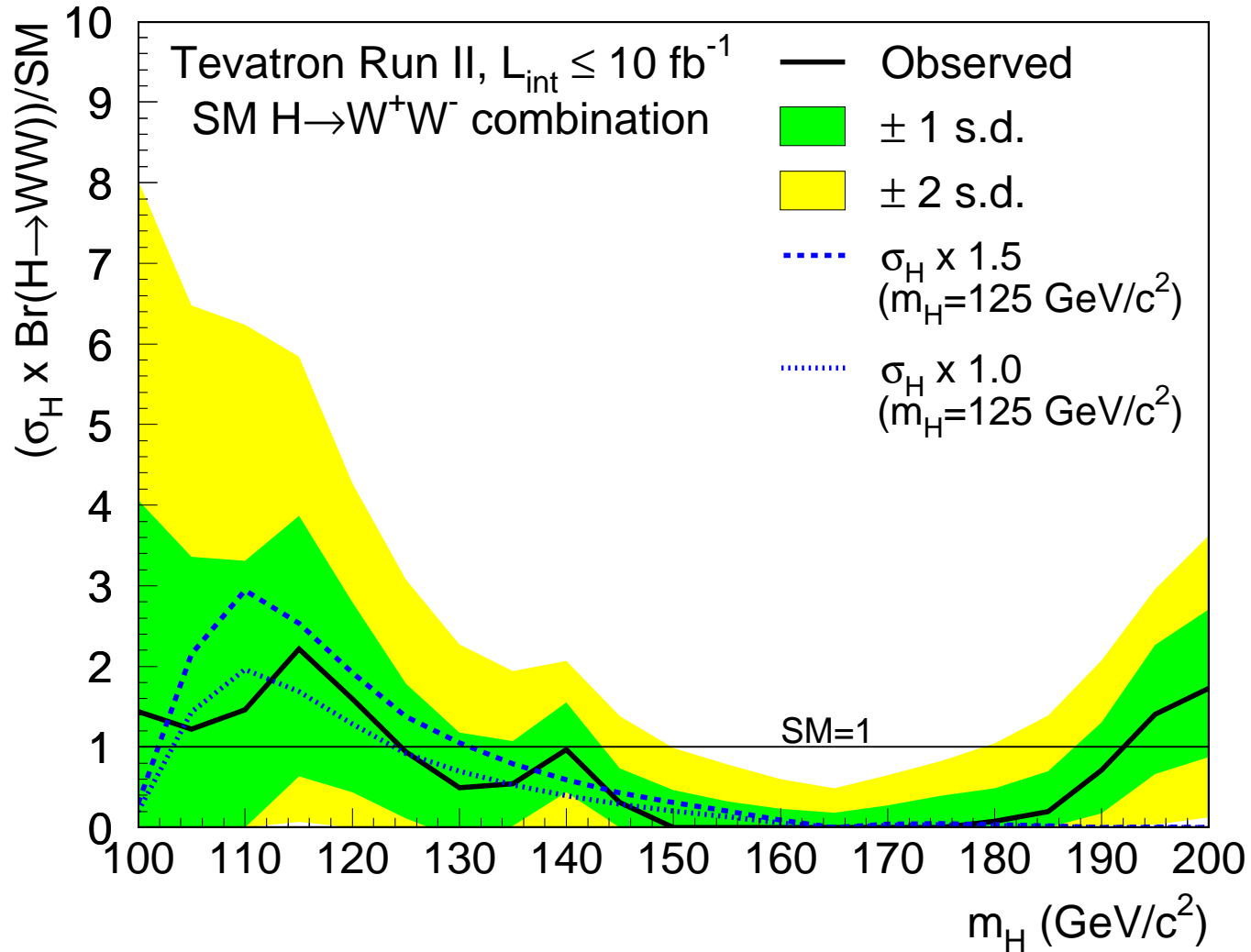
small additional excess around  $M_H \sim 140 \text{ GeV}$  (low mass resolution)

CMS  $VH \rightarrow bb$  (HIG-13-012-PAS):



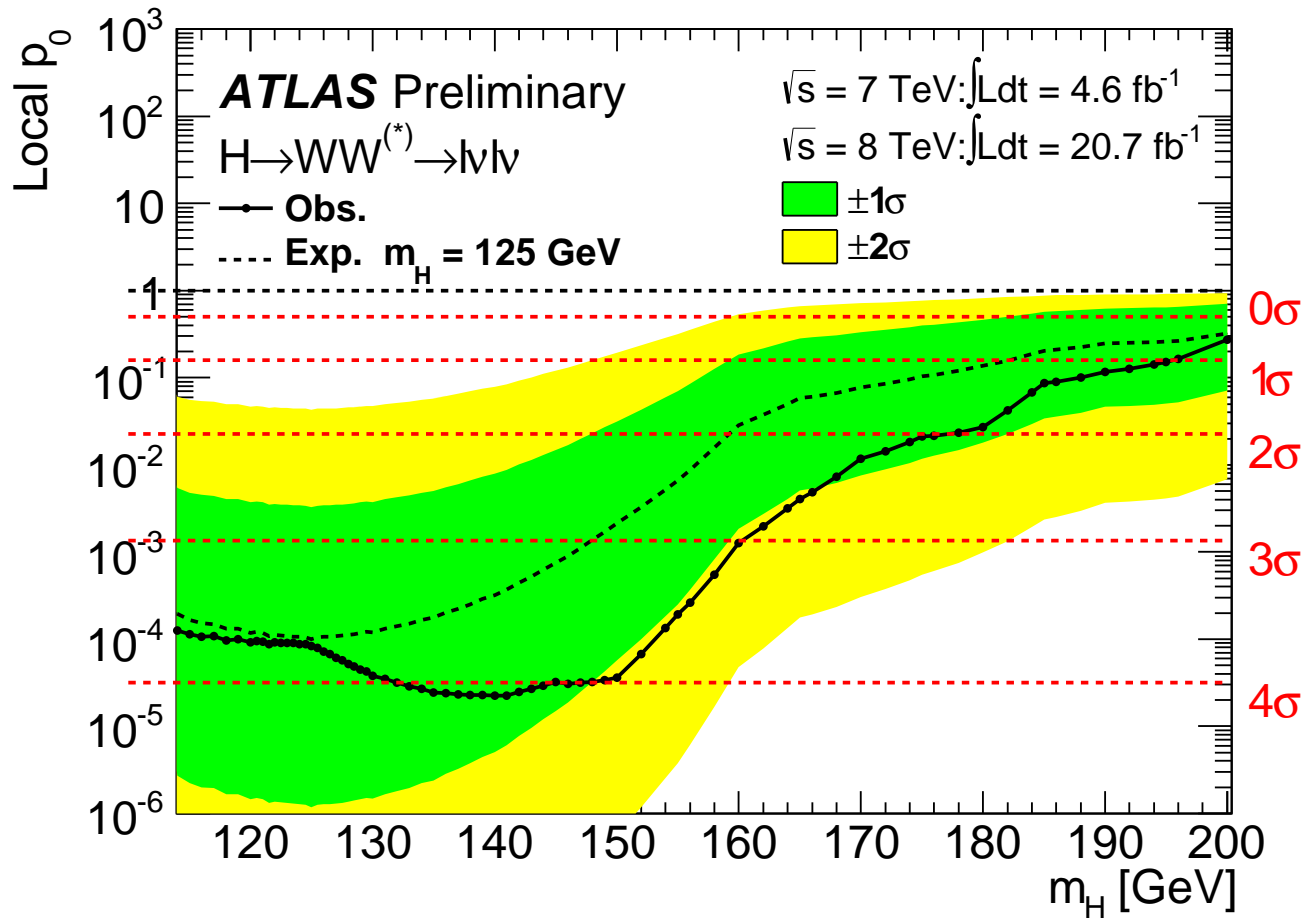
small additional excess for  $M_H \gtrsim 130 \text{ GeV}$  (low mass resolution)

Tevatron  $VH \rightarrow WW$  (1303.6346):



small additional excess around  $M_H \sim 140 \text{ GeV}$  (low mass resolution)

ATLAS  $VH \rightarrow WW$  (ATLAS-CONF-2013-012):



small additional excess for  $M_H \gtrsim 135$  GeV (low mass resolution)

But: only upper bounds  $\lesssim 0.2 \times \text{SM}$  on the signal rate of an additional 137 GeV boson in  $H \rightarrow ZZ, H \rightarrow \tau\tau$  (ATLAS, CMS)

Still: at least  $6 \times (\sim 1 \sigma)$  excesses (– “look elsewhere effect”)  
consistent with an additional  $\approx 137$  GeV Scalar

→ Notably in Higgs search channels with low mass resolution  $WW, bb$  and  $\tau\tau$ , the SM Higgs boson (assuming SM-like signal rates) should be considered as a background, allowing to set limits on/or find evidence for additional Higgs states with reduced couplings!

(Part of the “wishlist” of “On the presentation of the LHC Higgs Results”,  
F. Boudjema et al., 1307.5865)

# Conclusions

- Given  $M_{h_{SM}} \sim 126$  GeV, the NMSSM is the most natural SUSY extension of the SM: scale invariant SUSY interactions, no need for large radiative corrections, but gauge coupling unification and a good dark matter candidate as in the MSSM
- An enhanced Higgs pair production rate can be a hint for the NMSSM
- An enhanced  $\gamma\gamma$  signal rate of  $h_{SM}$  can be a hint for the NMSSM
- Additional signals (below the SM signal rate, channel dependent!) in Higgs searches at low mass below or above 126 GeV can be a hint for the NMSSM