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 $\sim$ 125 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!

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

many constraints are MSSM specific;
notably those from the Higgs mass of $\sim$ 125 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 λ:

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

$\longrightarrow$ Larger M_h corresponds to larger λ

$\longrightarrow$ If we would have known the coupling λ, 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

$\longrightarrow$ upper tree level bound on the lighter Higgs mass

$$M_h \leq M_Z$$

$\longrightarrow$ Large (unnatural?) radiative corrections needed for a 125 GeV Higgs

The NMSSM

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

$\longrightarrow$ a fermionic *supersymmetric* mass term $\mu\Psi_{H_u}\Psi_{H_d}$ with $\mu \sim \mathcal{O}(M_{Weak})$ must be present (μ appears also in the scalar potential)

$\longrightarrow$ an accident? (The "μ-problem", see Kim+Nilles 1984)

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

$\longrightarrow$ 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 $\mathcal{O}(M_{\text{Susy}})$ due to the soft Susy breaking terms
$\longrightarrow$ generates a mass term $\mu_{\text{eff}} = \lambda v_s$ of the desired order

Additional benefits of the NMSSM:

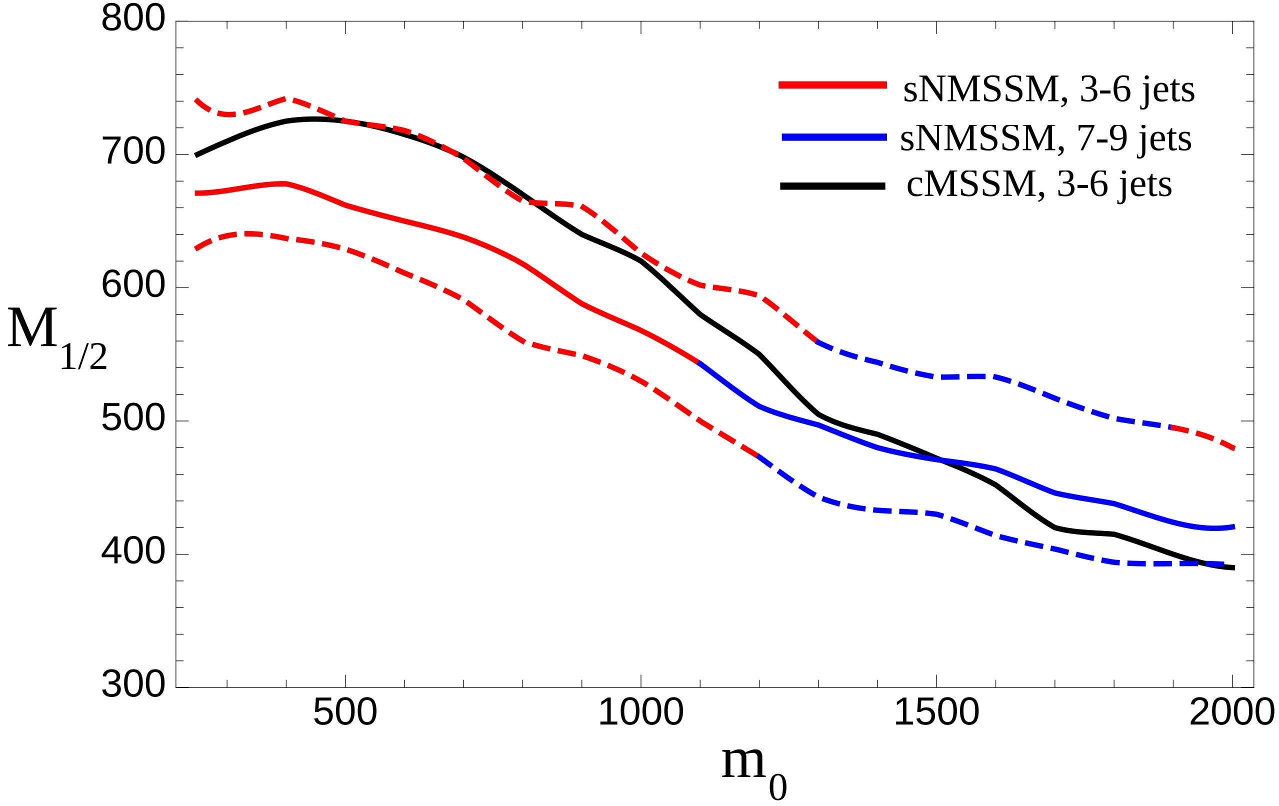
An extra quartic coupling $\lambda^2 H_u^2 H_d^2$ due to SUSY

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

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

$\longrightarrow$ complicates squark/gluino decay cascades;
$\longrightarrow$ weaker bounds from sparticle searches via E_T^{miss}?

E.g. in the $m_0 - M_{1/2}$ plane (with D. Das, A. Teixeira, 1301.7584):



$\longrightarrow$ Slightly lower bounds on $M_{1/2}$ for $m_0 \lesssim 1$ TeV
stronger alleviation 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 3×3 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

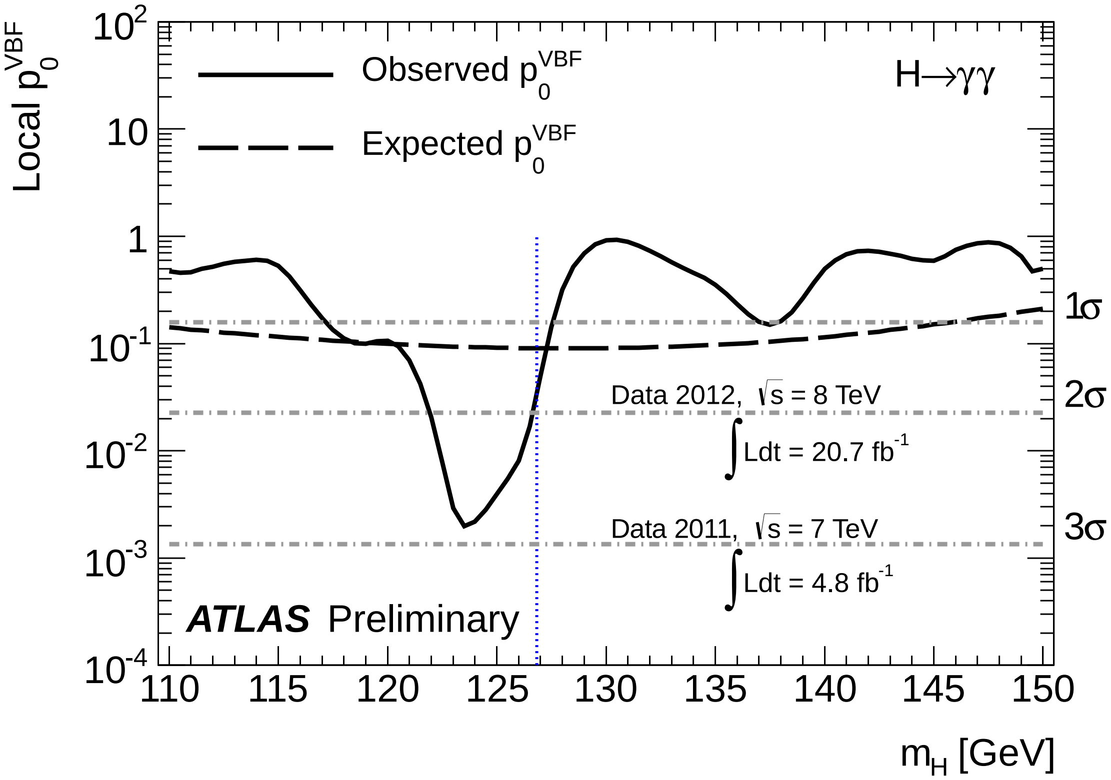
$$M_{h_{SM}}^2 = M_Z^2 \cos^2 2\beta + \lambda^2 (v_u^2 + v_d^2) \sin^2 2\beta \pm (\ . \ . \ . \ )$$

$\pm (\ . \ . \ . \ )$: From mixing of the mostly SM-like scalar h_{SM} with the mostly singlet-like scalar h_S (dep. on unknown parameters);
positive if $M_{h_S} < M_{h_{SM}}$!

$\longrightarrow$ Larger mass $M_{h_{SM}} > M_Z$ at tree level, all in all:
$M_{h_{SM}} \sim 125$ GeV does not require large (unnatural) radiative corrections

The measured signal rate in $H \to \gamma\gamma$

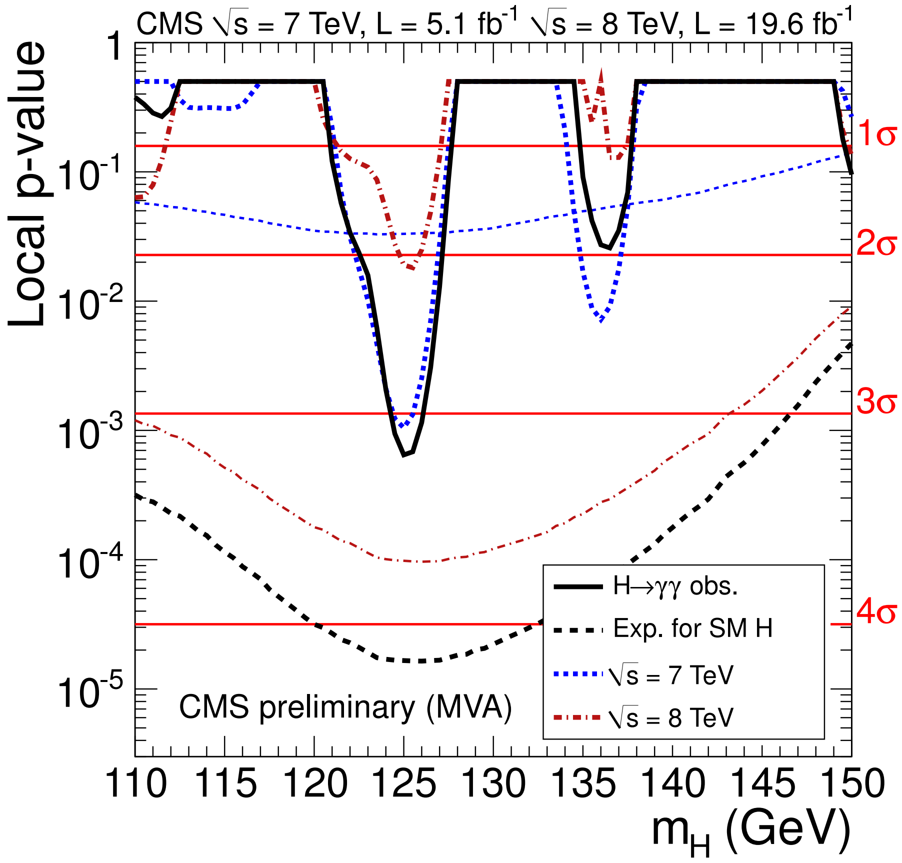
ATLAS-CONF-2013-012 (in Higgs prod. via Vector Boson Fusion, VBF):

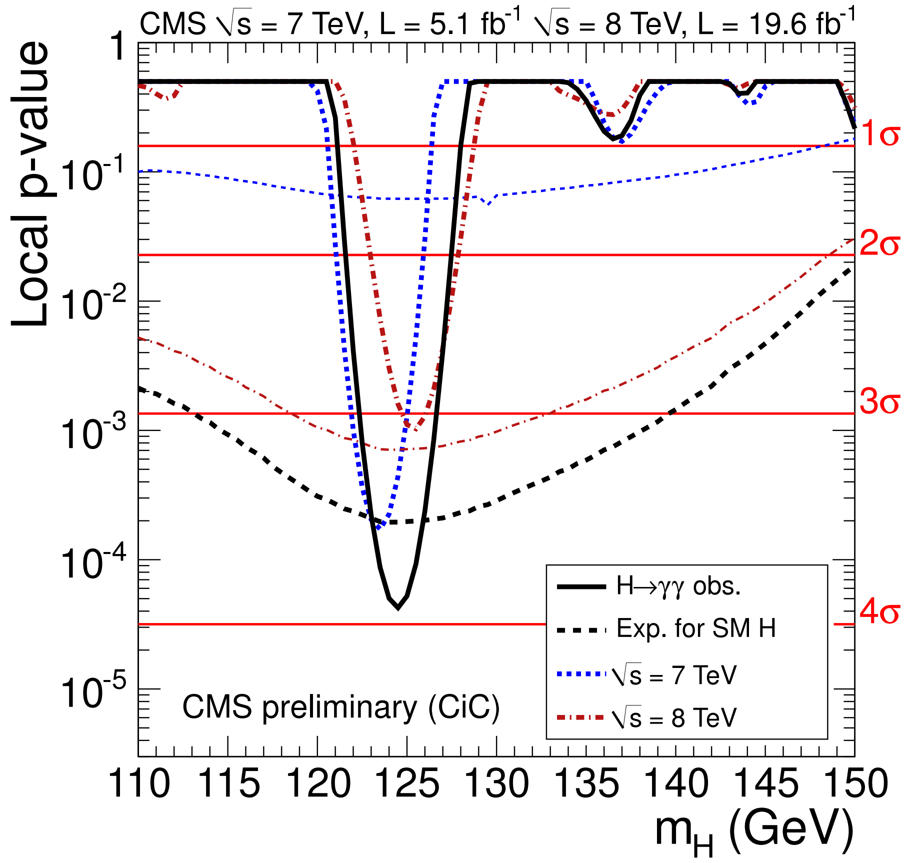


After combining with Higgs production via gluon fusion:

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

CMS $H \to \gamma\gamma$ (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 "official" MVA analysis (l.h.s.)

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

1) Recall:

$$BR(H \to \gamma\gamma) = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to bb) + \ldots}$$

($\Gamma(H \to bb)$ gives $\sim 58\%$ of the total width for a 125 GeV SM Scalar)

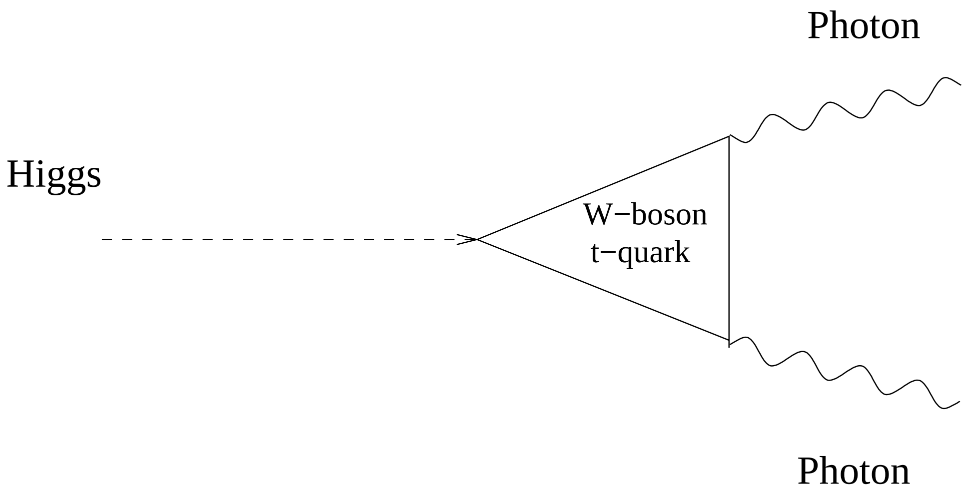
$\longrightarrow$ Due to the mixing of H_u, H_d, S it is easily possible that, in the NMSSM, the mostly SM–like h_{SM} has

— a reduced coupling to bb, and hence a reduced width $\Gamma(h_{SM} \to bb)$
$\longrightarrow$ an enhanced $BR(h_{SM} \to \gamma\gamma)$

— nearly SM–like couplings to the top quark (whose loops induce the coupling to gluons) and to the electroweak gauge bosons
$\longrightarrow$ the production rates in gluon fusion and/or VBF are hardly reduced

$\to$ The $\gamma\gamma$ signal rate is enhanced (U.E. 2010)

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

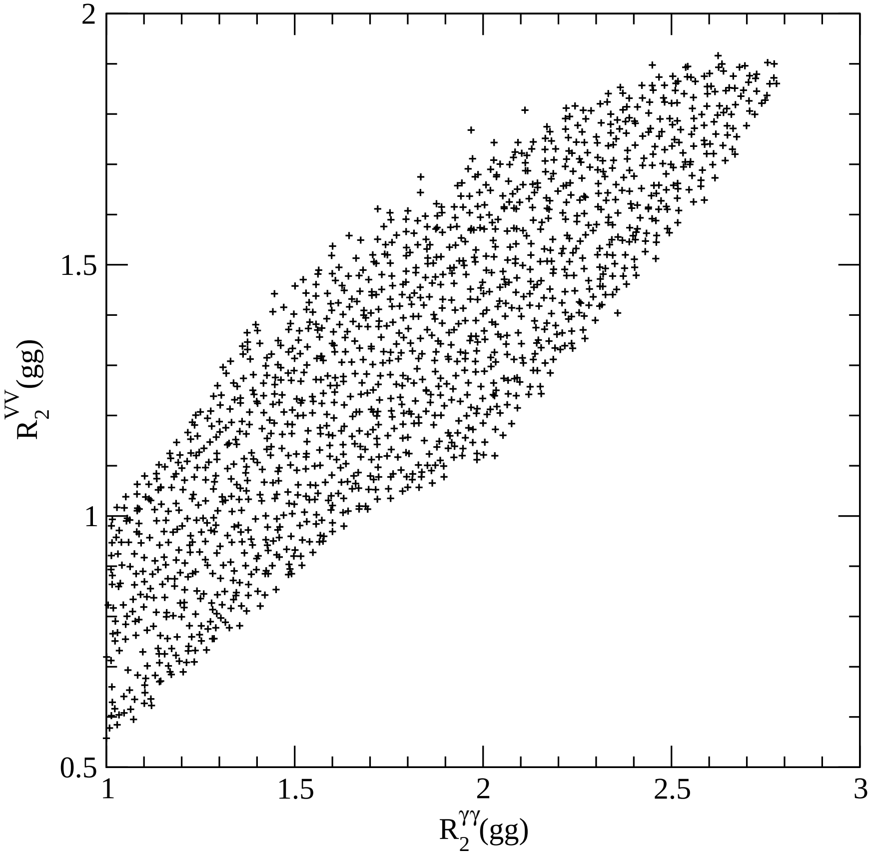


In the NMSSM, the singlet S couples to the (charged) higgsinos ψ_{H_u}, ψ_{H_d}:

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

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

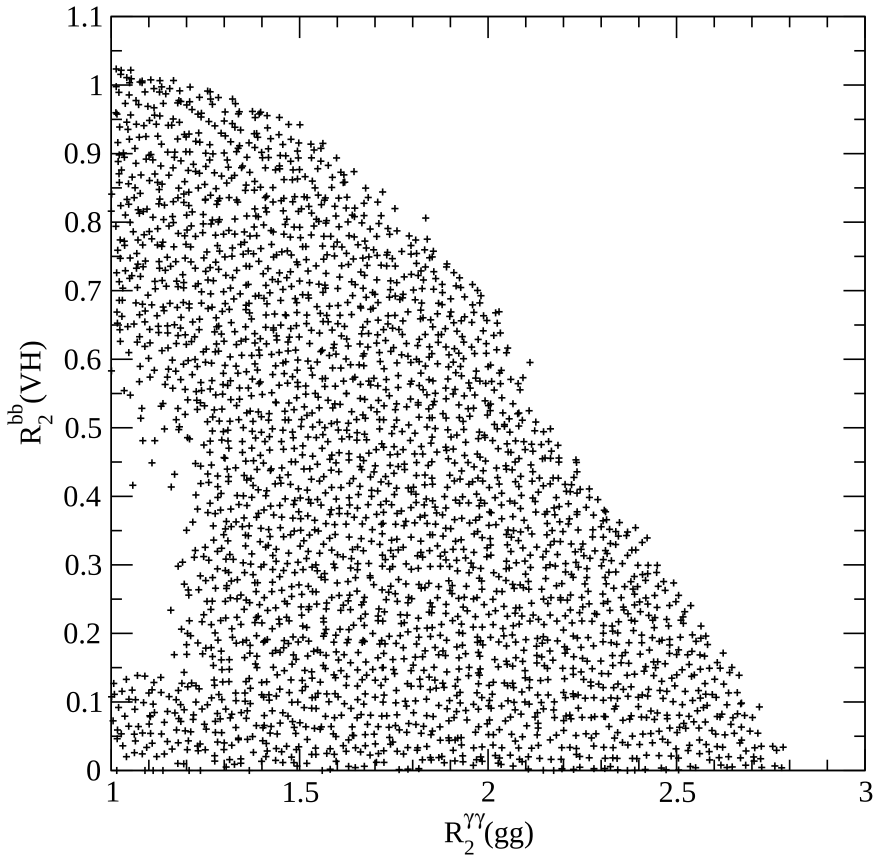
Plot of the possible signal rates in the $\gamma\gamma$ and $VV \equiv ZZ,\ WW$ final states relative to the SM: (semi-constr. NMSSM, with C. Hugonie, 1203.5048)



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

$\longrightarrow$ 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 $h_{SM} \to bb$?



$\longrightarrow$ 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 $\Gamma(h_{SM} \to bb)$

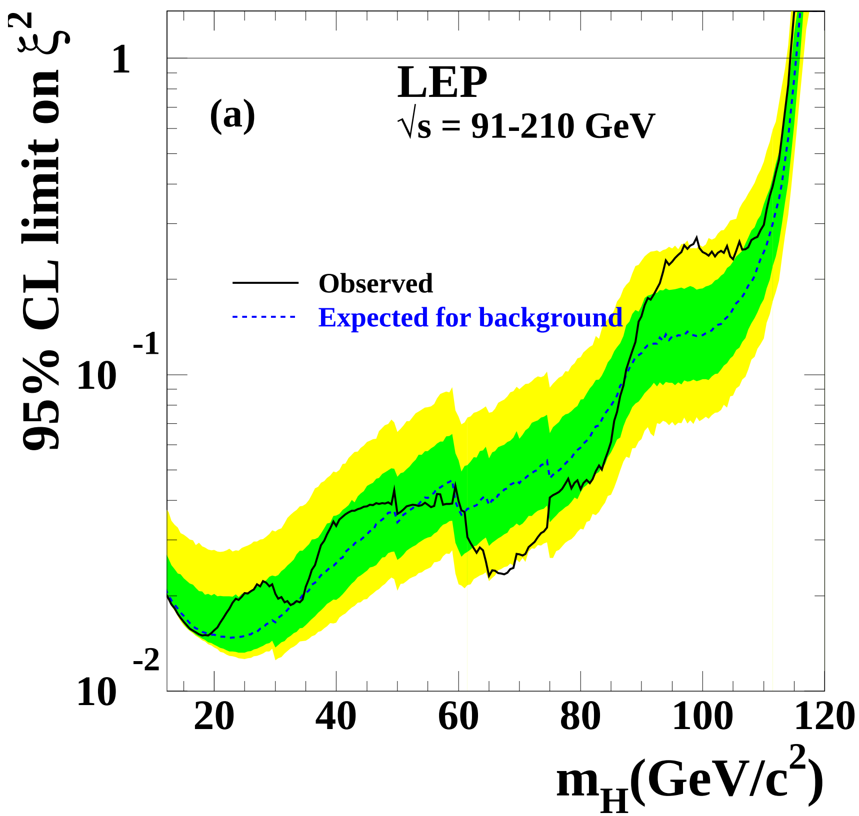
If h_{SM} mixes strongly with another mostly singlet-like scalar: The mass of this mostly singlet-like h_S should be not too far from $M_{h_{SM}} \sim 125$ GeV

$\longrightarrow$ 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 ξ^2 in $Z^* \to Z + h_{SM}$ at LEP:

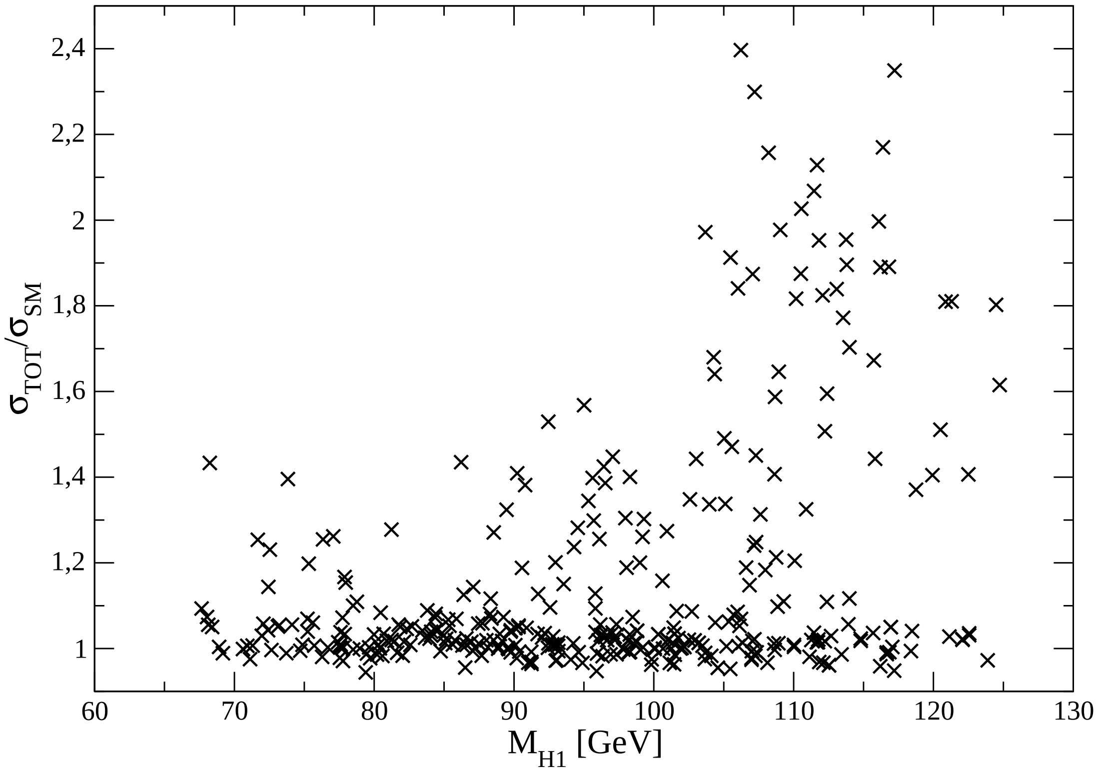


$\rightarrow$ If $\xi^2(h_S) \sim 0.2$:
Compatible with the weak bounds ($\sim 2\sigma$ excess) around 95 GeV

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

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 $h_S = 65...125$ GeV (U.E. 1306.5541):



→ Possibly, but not necessarily enhanced

Or:

The 125 GeV signal could be due to the superposition of two scalars close in mass (J. Gunion et al., 1207.1545 and 1208.1817)
$\rightarrow$ possible enhancement of the diphoton signal rate

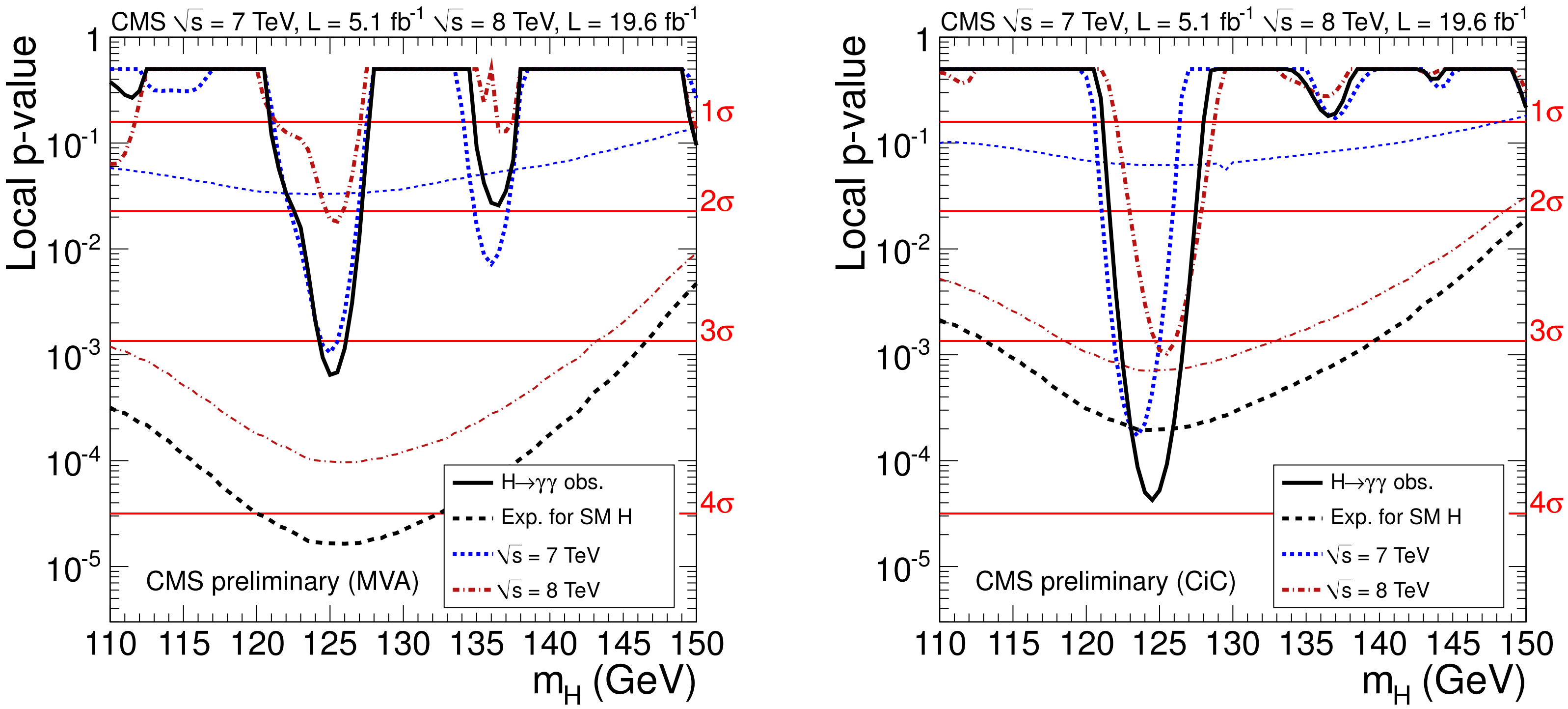
(But: this would NOT resolve differences in mass measurements in the ZZ and $\gamma\gamma$ channels (ATLAS)!)

Or:

h_S could be heavier than 125 GeV (G. Belanger et al., 1208.4952)?

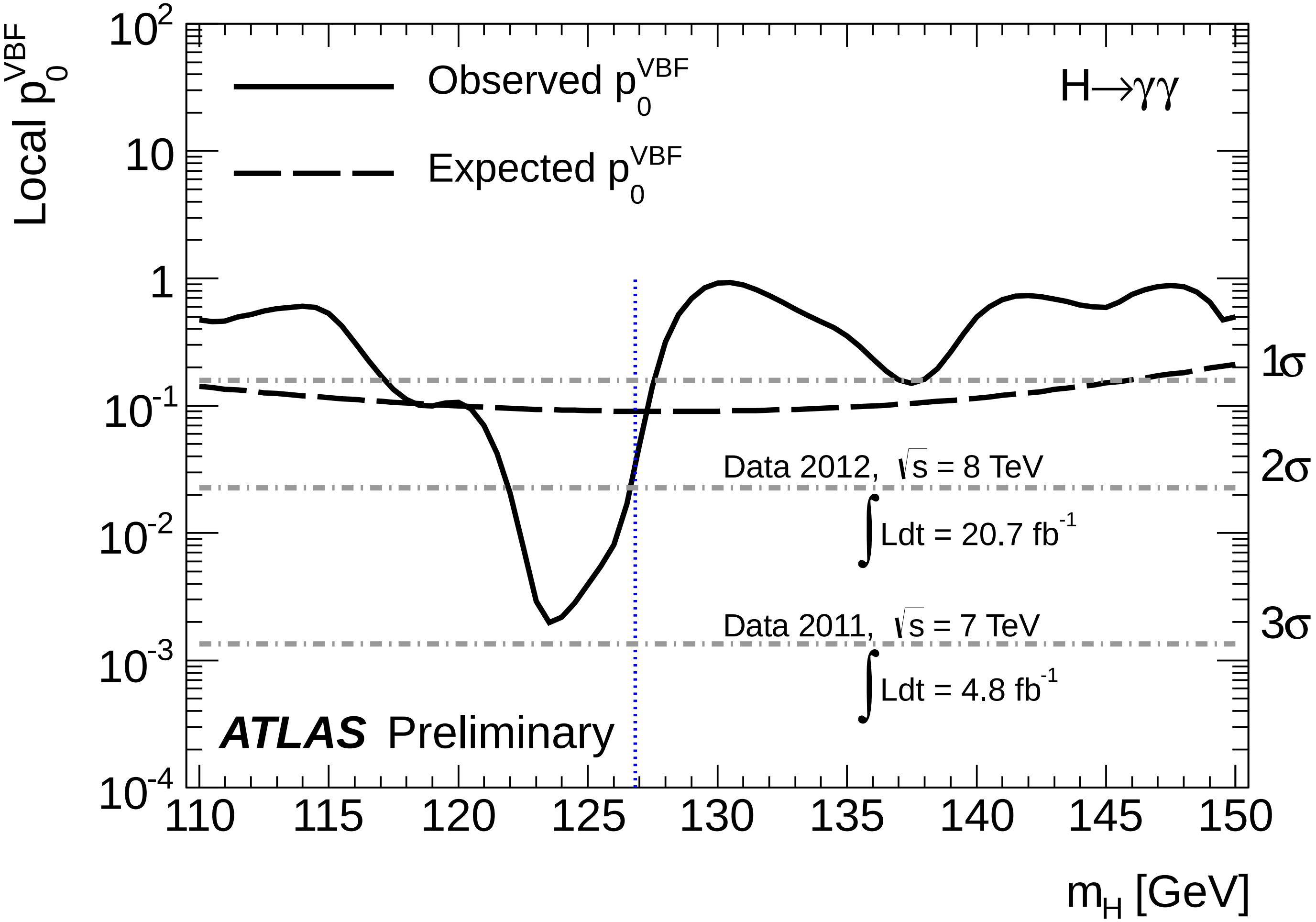
Some “appetizers”:

Recall: $H \to \gamma\gamma$ 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 125 GeV Scalar in cut-based analysis, r.h.s.; still: $\sim 1\sigma$ excess around $M_H \sim 136$ GeV

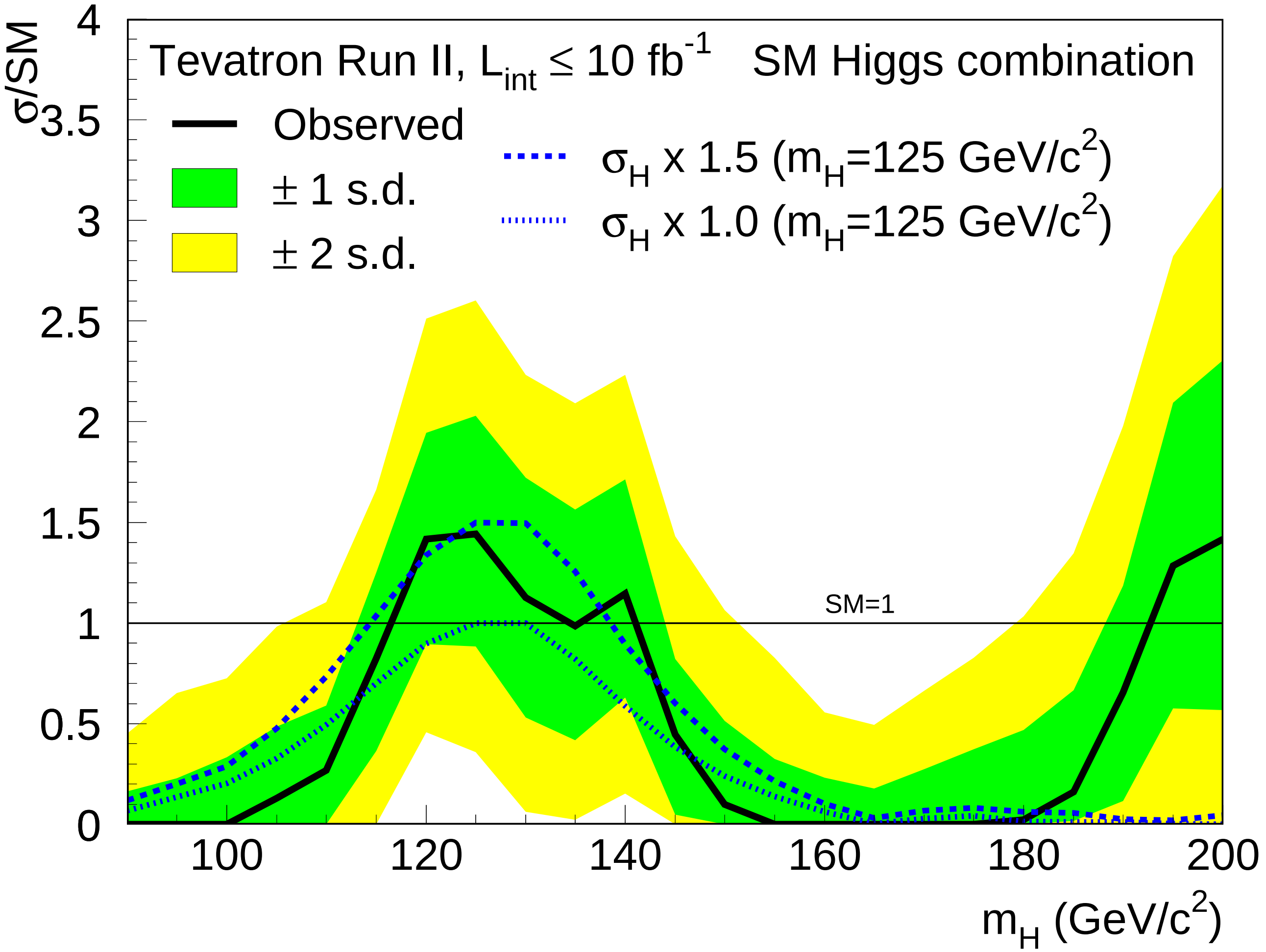
Recall: $H \to \gamma\gamma$ at ATLAS (ATLAS-CONF-2013-012):



small additional excess around $M_H \sim 137$ GeV

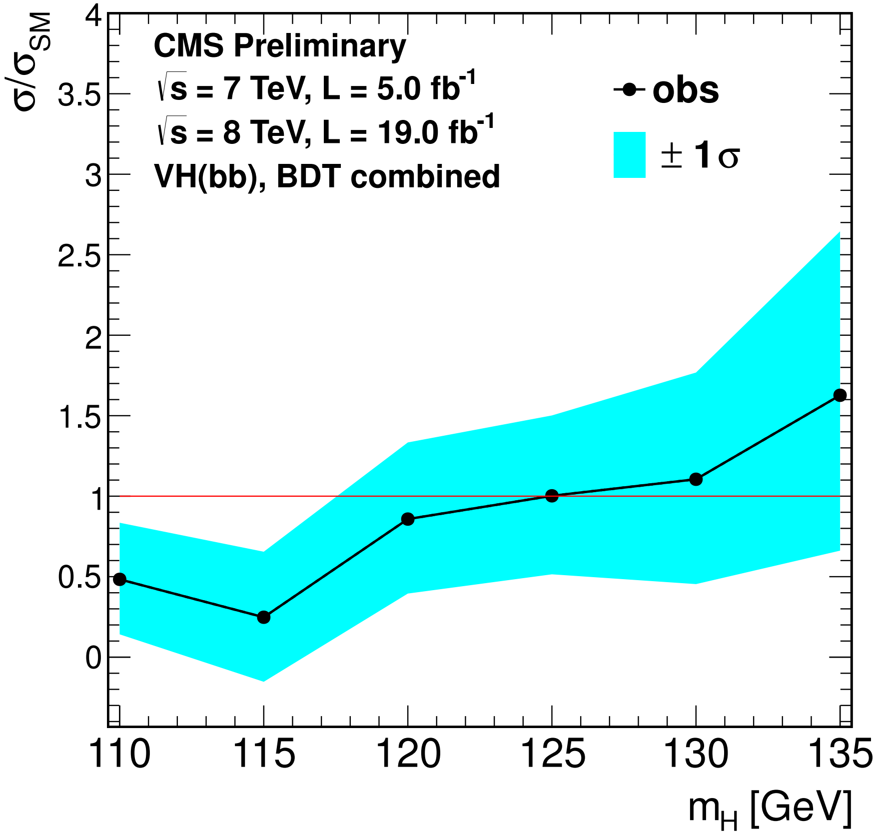
Tevatron $VH \to bb$ (1303.6346):

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



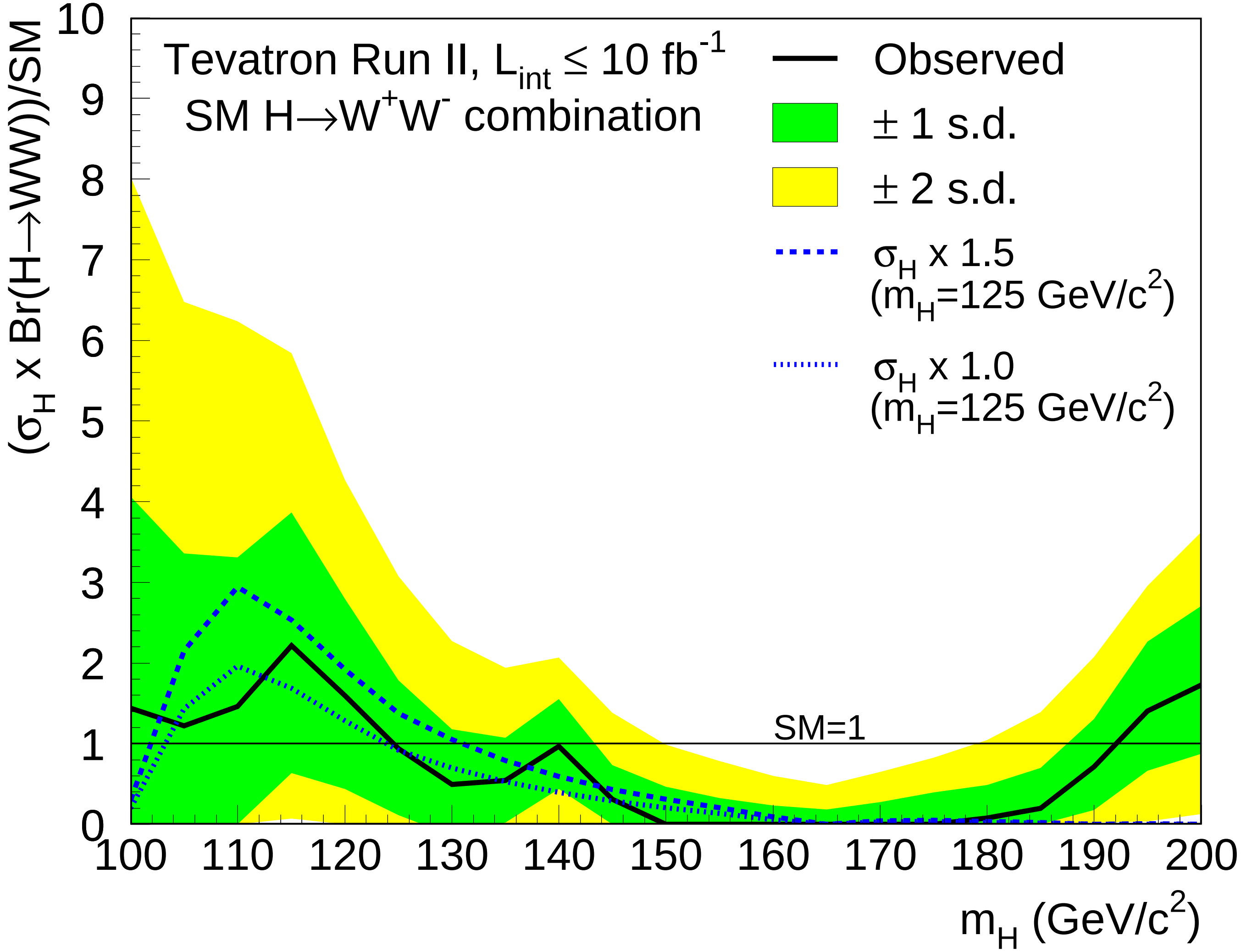
small additional excess around $M_H \sim 140$ GeV (low mass resolution)

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



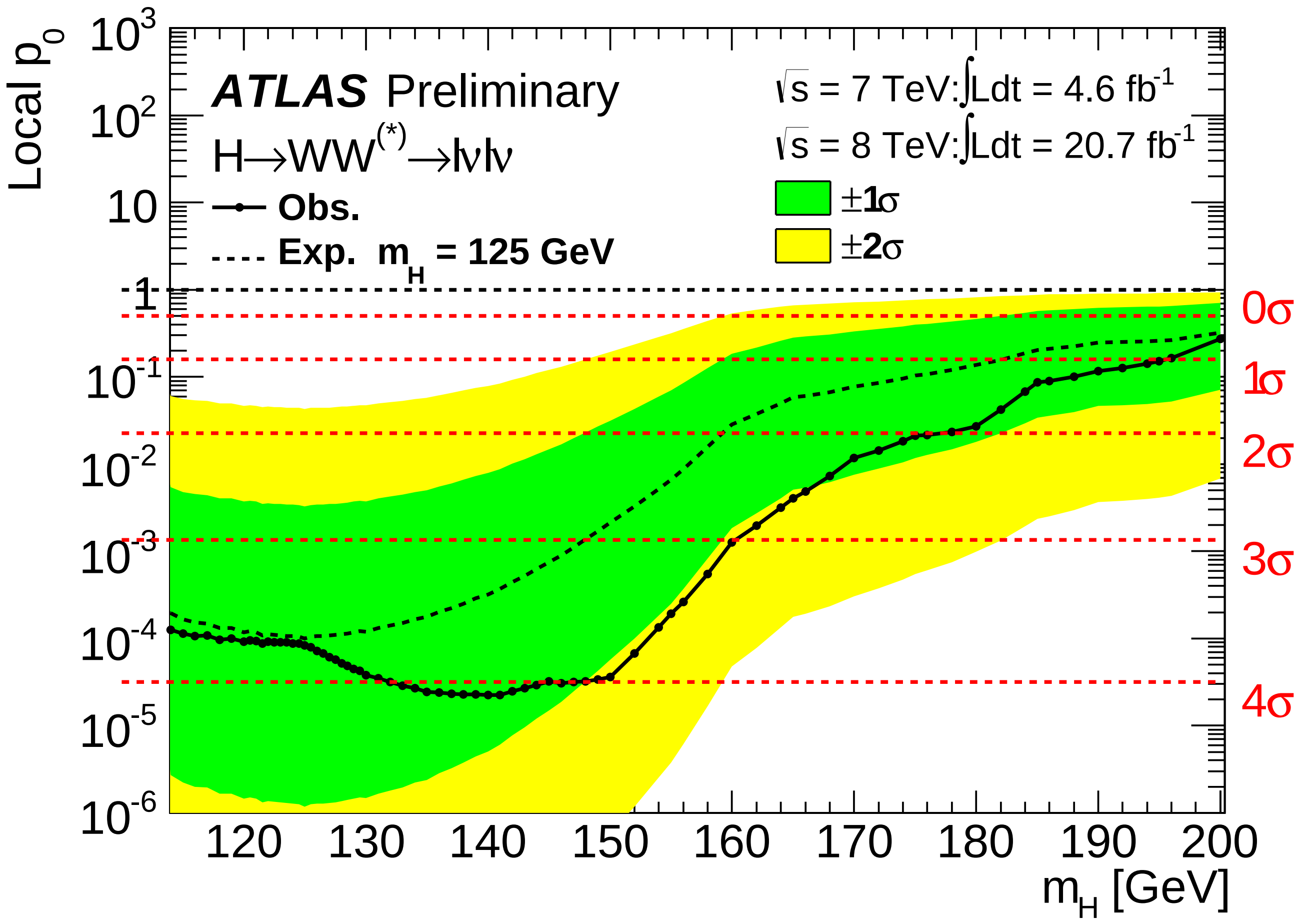
small additional excess for $M_H \gtrsim 130$ GeV (low mass resolution)

Tevatron $VH \to WW$ (1303.6346):



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

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



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

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

Still: at least $6 \times (\sim 1\ \sigma)$ excesses (− "look elsewhere effect") consistent with an additional ≈ 137 GeV Scalar

$\to$ 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 $M_{h_{SM}} \sim 125$ 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 masses somewhat below or above 125 GeV can be a hint for the NMSSM

Searches are ongoing...