Properties of the Higgs Boson, and its interpretation in Supersymmetry

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— The quartic Higgs self coupling and Supersymmetry

— The Next-to-Minimal Supersymmetric Standard Model

— Higgs signal rates in $H \to \gamma\gamma$, $H \to ZZ/WW$, $H \to bb$ channels

— Additional Higgs bosons?

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 mass M_h of the Higgs boson in terms of the known Higgs 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

Supersymmetry

— one of the possible solutions of the hierarchy problem

— contains automatically a candidate for dark matter

— leads automatically to a "grand unification" of the gauge couplings

Up to now:
No sign of Susy partners ("sparticles") of the standard particles:

$$M_{\text{u-squark}},\ M_{\text{d-squark}},\ M_{\text{gluino}}\ \gtrsim\ 1\ \text{TeV}$$

But:
No sign of alternative solutions of the hierarchy problem
(compositeness $\to$ extra excited states;
large extra dimensions $\to$ Kaluza-Klein states...)

$\longrightarrow$The Higgs sector in Supersymmetry:

At least two Higgs doublets; the quartic Higgs self couplings are related by Supersymmetry to the electroweak gauge couplings, and to Higgs-higgsino Yukawa couplings (if they exist)

MSSM:

Two SU(2) doublets H_u and H_d, but no Higgs-higgsino Yukawa coupling;

$\longrightarrow$ the quartic Higgs self couplings are given by the electroweak gauge couplings

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

$$M_h \leq M_Z$$

But: Supersymmetry has to be (softly) broken by scalar mass terms/ trilinear scalar interactions/gaugino mass terms of $\mathcal{O}\left(M_{\text{Susy}}\right)$

$\longrightarrow$ Radiative corrections involving scales $Q < M_{\text{Susy}}$ modify the quartic Higgs self couplings

Dominant contributions from top quark/stop$_1$/stop$_2$ mass splittings (with the largest couplings to the Higgs bosons)

$\longrightarrow$ $M_h \sim 125$ GeV is possible, but only if M_{Susy} is large enough (in agreement with constraints from direct searches)

But: rad. corrs. $\sim M_{\text{Susy}}$ to the mass terms in the Higgs potential!

$v \ll M_{\text{Susy}}$ becomes unnatural, "little fine tuning problem"

The μ problem

The Higgs fields H_u and H_d have fermionic superpartners, the charged and neutral higgsinos ψ_u and ψ_d

Not observed at LEP $\longrightarrow$ a mass term $\mu\psi_u\psi_d$ must be present

μ appears also in the Higgs potential $\longrightarrow$ μ should be of $\mathcal{O}(M_{\text{weak}}...M_{\text{Susy}})$

But:

μ is not a soft Susy breaking term; how can it accidentically be of $\mathcal{O}(M_{\text{weak}}...M_{\text{Susy}})$???

The NMSSM

How to generate fermionic mass terms?

$\longrightarrow$ introduce a Yukawa coupling to a scalar (here: a gauge singlet S)

$$\lambda S \psi_u \psi_d$$

S has automatically a vev v_s of $\mathcal{O}(M_{\text{Susy}})$

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

$\longrightarrow$ Additional benefit: An extra quartic coupling $\lambda^2 H_u^2 H_d^2$ due to SUSY

$\longrightarrow$ Larger mass $M_h > M_Z$ at tree level!

$\longrightarrow$ $M_h \sim 125$ GeV does not require large (unnatural) radiative corrections!

Now: 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

Their 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 Higgs H (as in the MSSM)

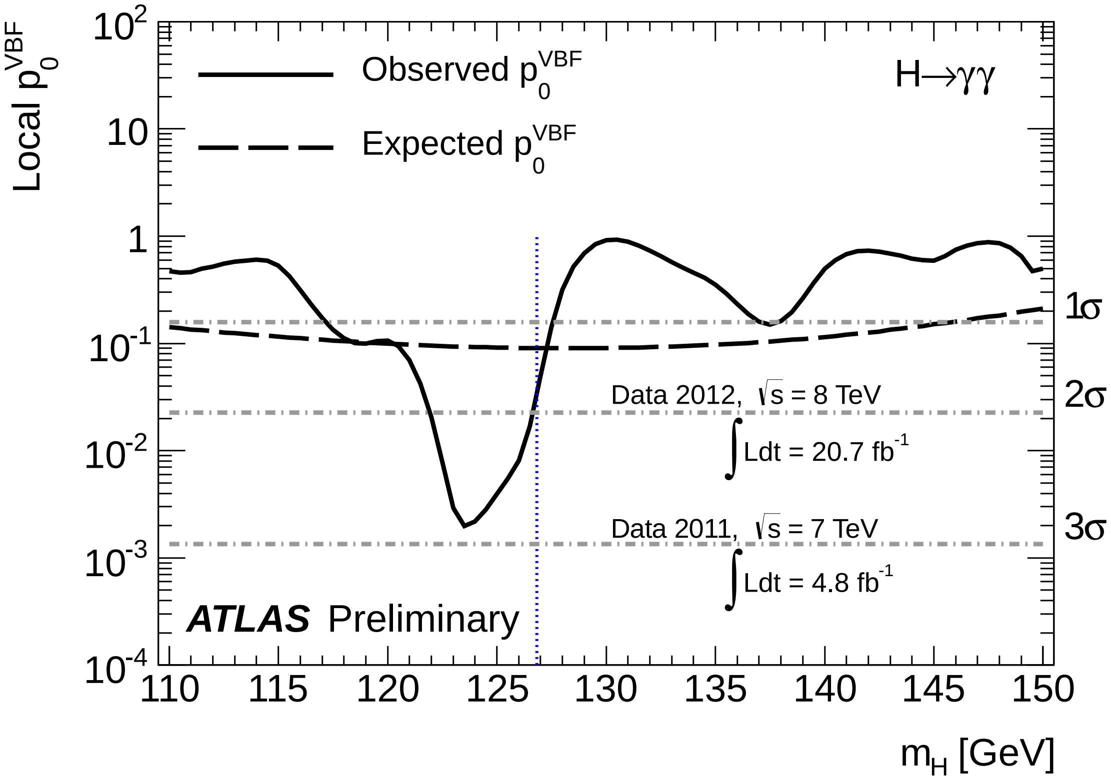
The tree level mass of the mostly SM like h_{SM} is

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

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

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

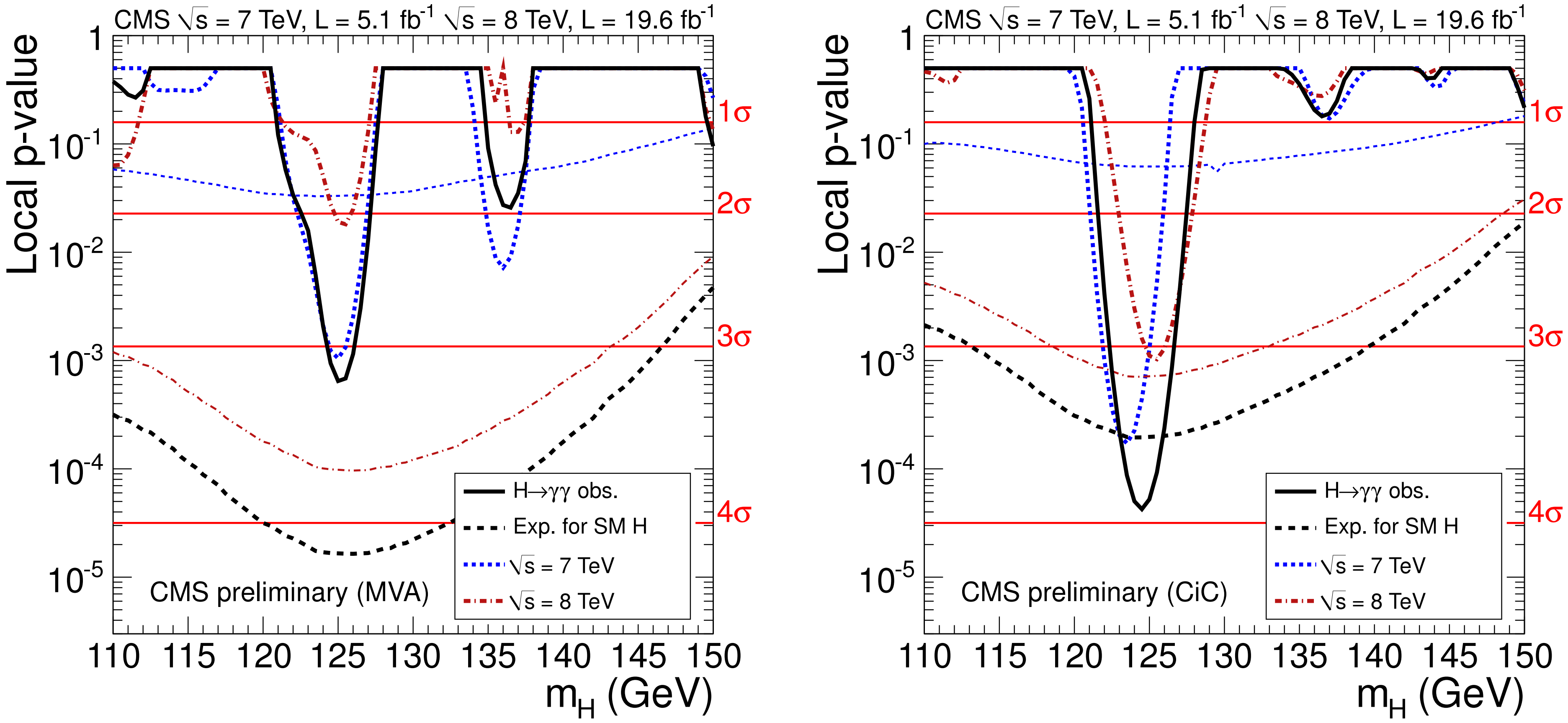
ATLAS (in Higgs production via Vector Boson Fusion, VBF):



After combining with Higgs production in 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)



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

The diphoton 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 Higgs)

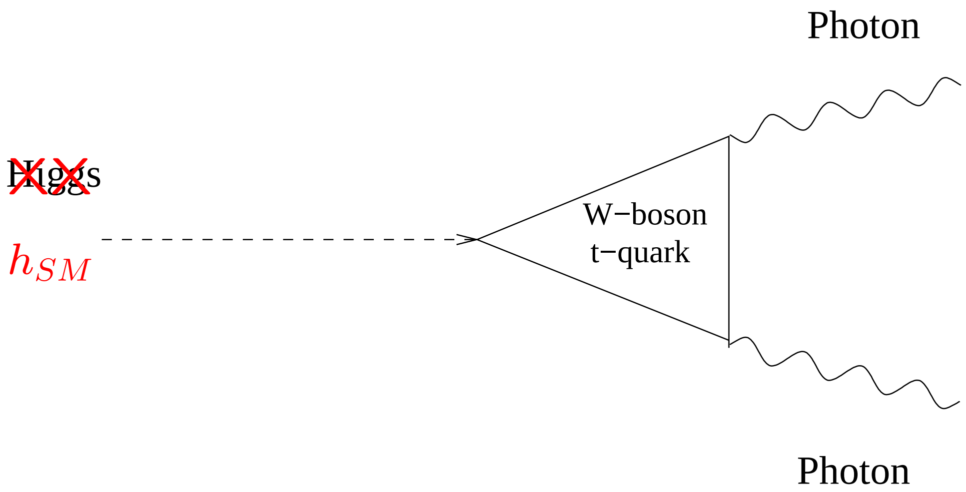
$\longrightarrow$ Due to the mixing of H_u, H_d, S it is easily possible that, in the NMSSM, the mostly SM–like h_{SM} has

— 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 diphoton 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

h_{SM} signal rates in other channels

(with G. Bélanger, B. Dumont, J. Gunion, S. Kraml)

$R^{VV}(gg)$: ZZ/WW signal rate in gluon fusion (relative to the SM)
Combining ATLAS + CMS: $R^{VV}(gg) \sim 0.91 \pm 0.16$

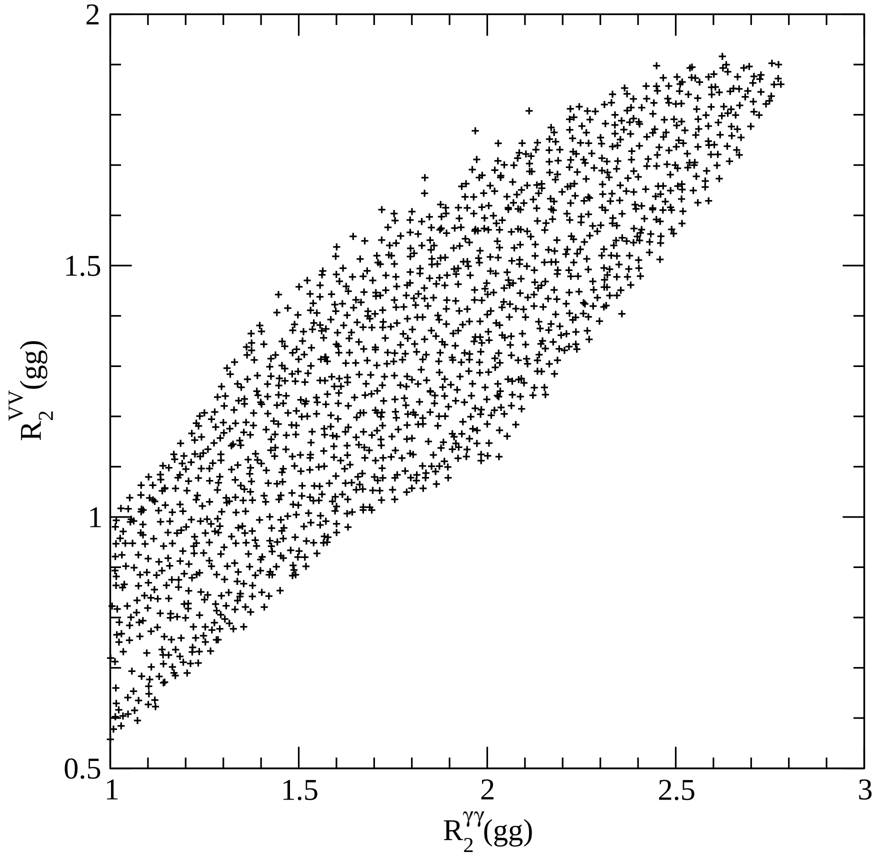
$R^{bb}(VH)$: bb signal rate in associate production with a $V = Z$ or W boson
Combining ATLAS, CMS, Tevatron: $R_2^{bb}(VH) \sim 1.13 \pm 0.43$

Examples in the parameter space of the NMSSM with universal squark/slepton masses and gaugino masses at the GUT scale
(Supergravity motivated sources of Susy breaking, with C. Hugonie)

Imposing $M_{h_{SM}} \sim 125$ GeV, good dark matter relic density
The mostly SM like h_{SM} is the next-to-lightest H_2
The mostly singlet like h_s is the lightest H_1
(satisfying constraints from LEP, see later)

Studies of $R_2^{\gamma\gamma}(gg)$, $R_2^{VV}(gg)$, $R_2^{bb}(VH)$:

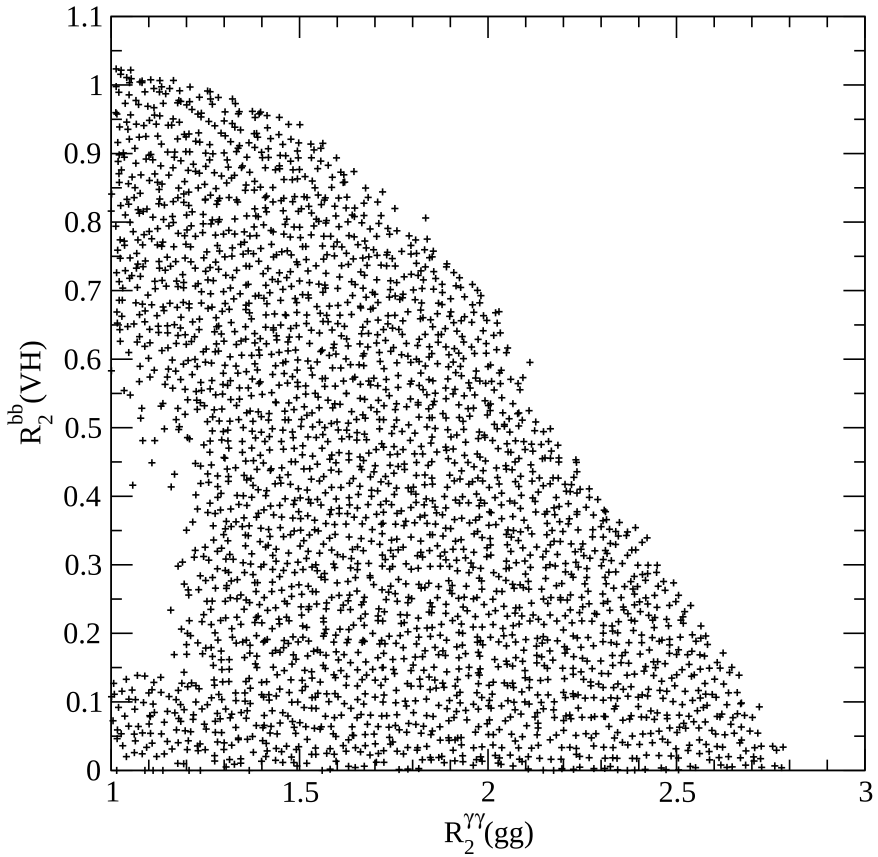
$R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$ against $R_2^{\gamma\gamma}(gg)$:



$\longrightarrow$ $R_2^{\gamma\gamma}(gg)$ 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

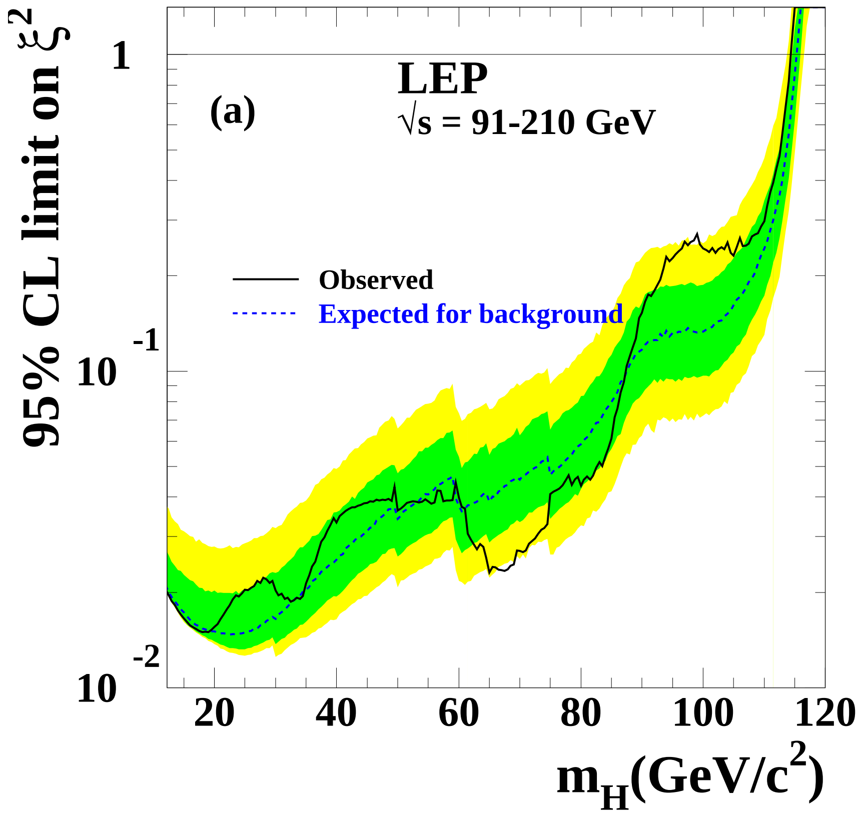
$\longrightarrow$ Are there hints for (at least weak bounds on) such a state?

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 SM Higgs search channels

If this state has a mass below 114 GeV:

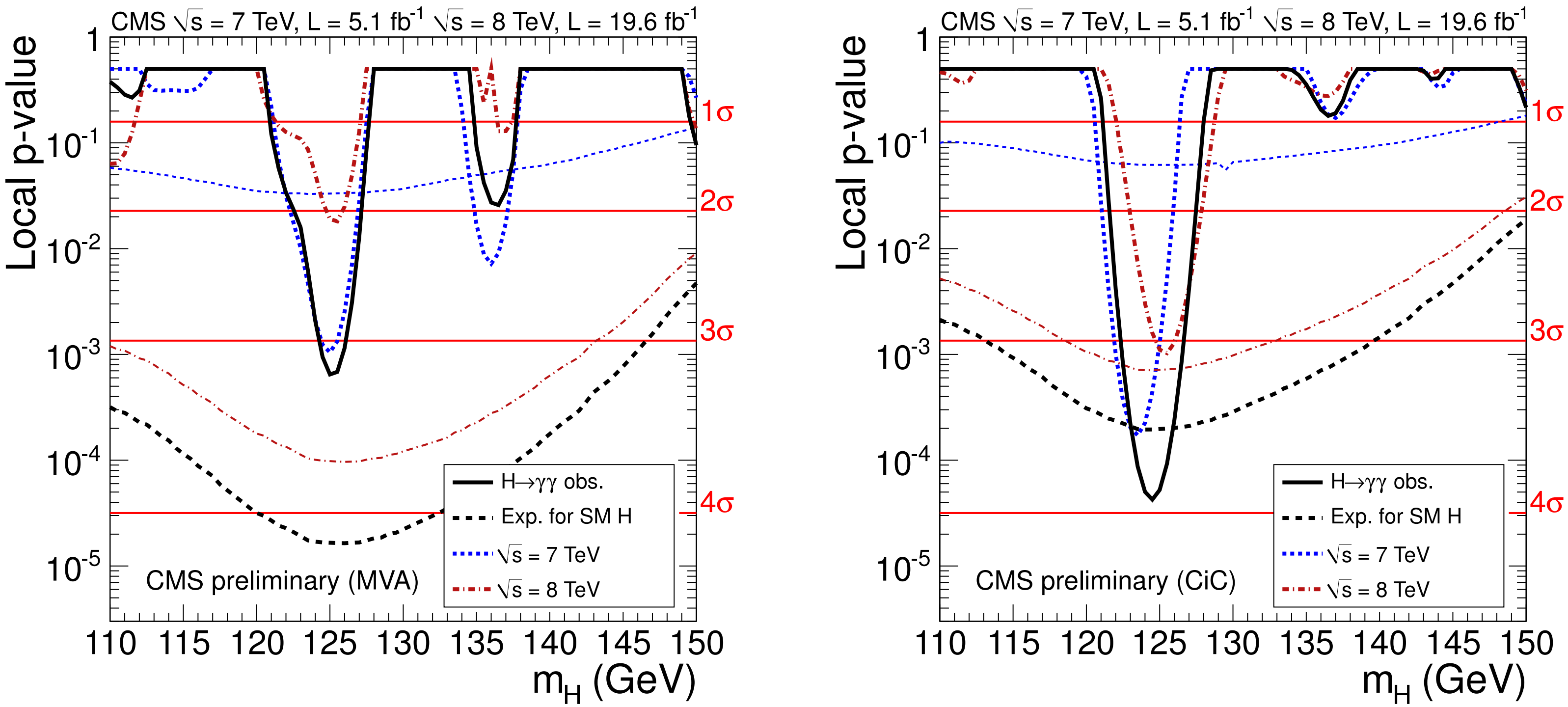
Study the bounds on the signal rate ξ^2 in $Z^* \to Z + h_{SM}$ at LEP:

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



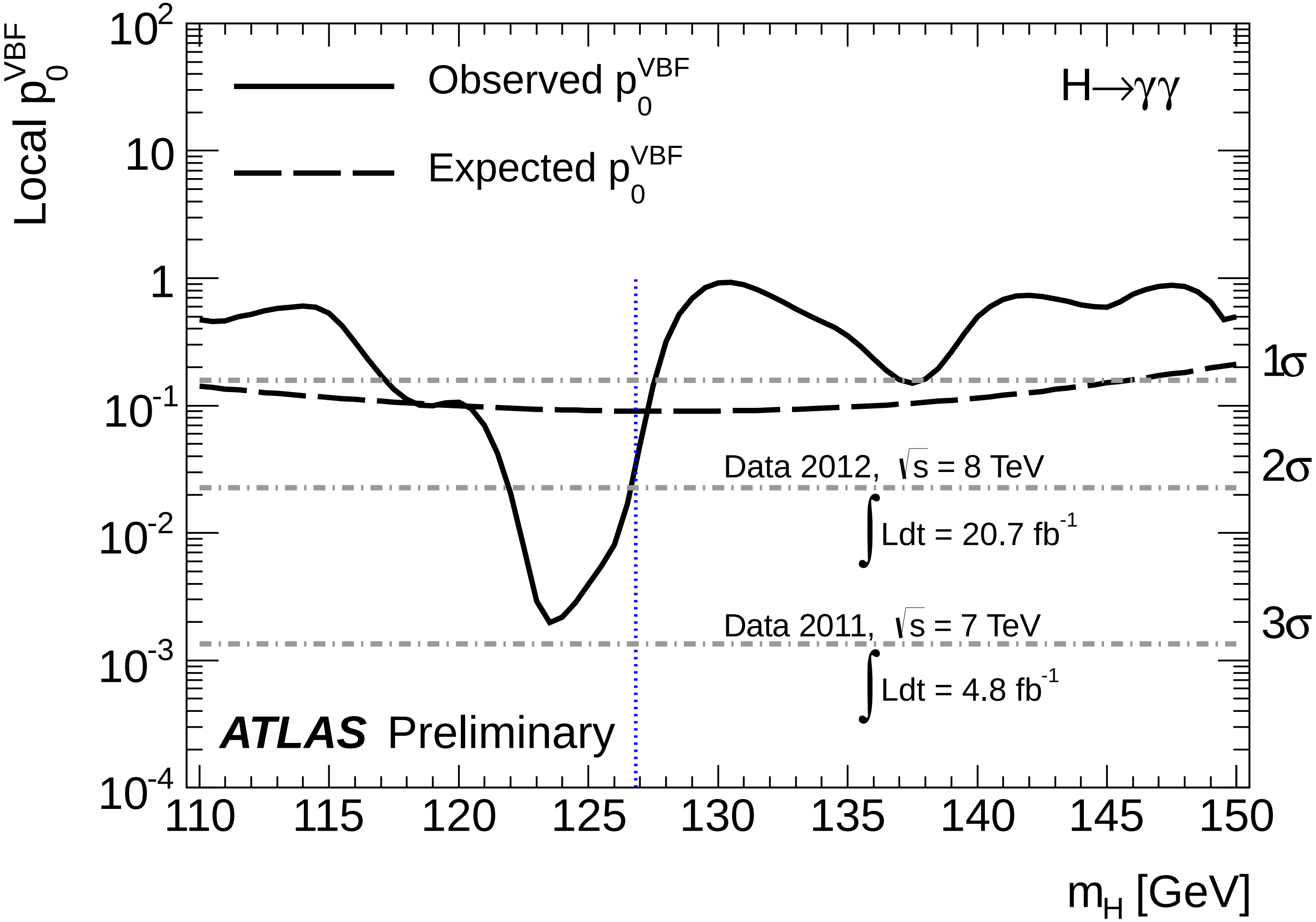
Or: above 125 GeV? hints?

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 Higgs in cutbased analysis, r.h.s.; still: $\sim 1\sigma$ excess around $M_H \sim 136$ GeV

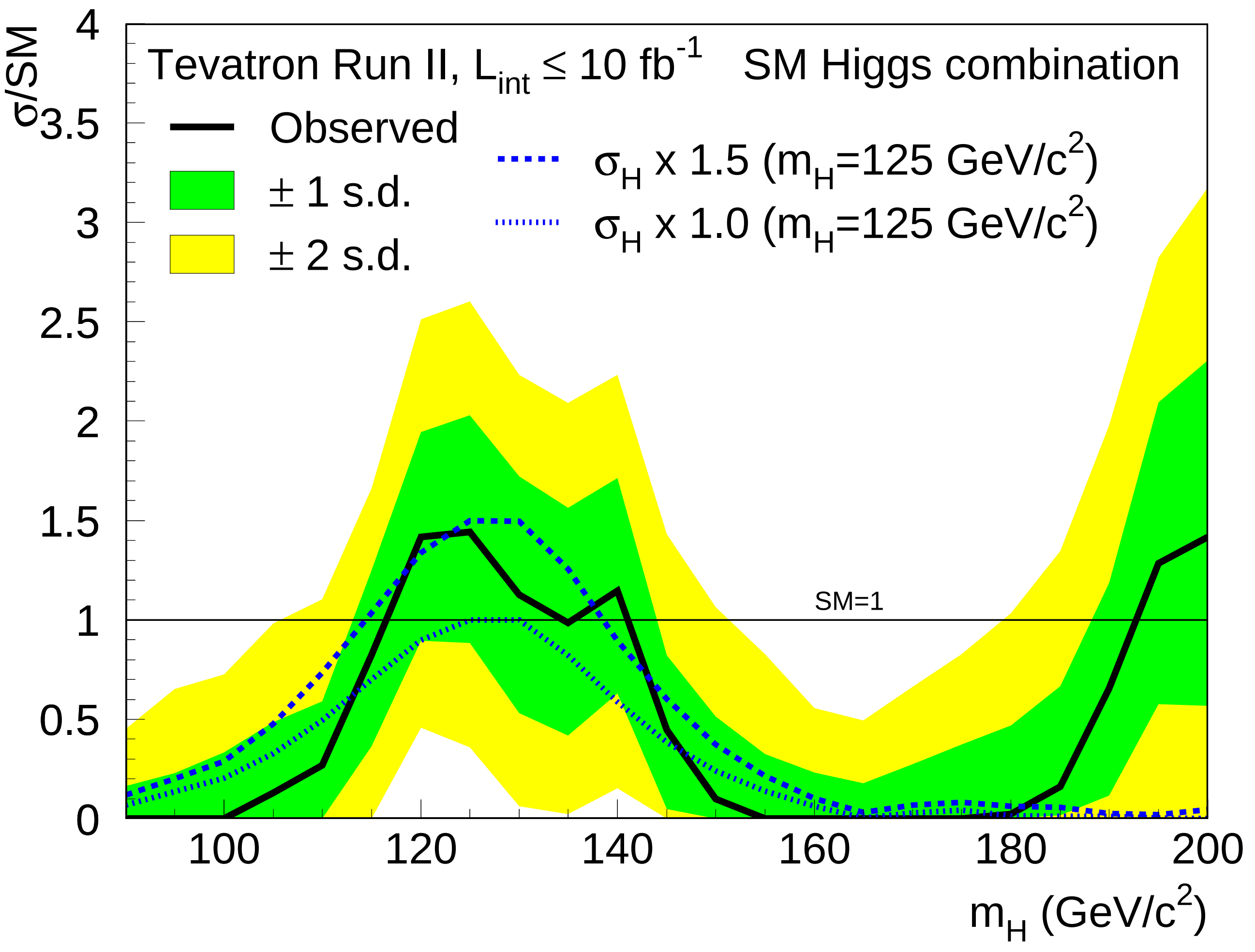
Recall: $H \to \gamma\gamma$ at ATLAS (ATLAS-CONF-2013-012):



small additional excess around $M_H \sim 137$ GeV

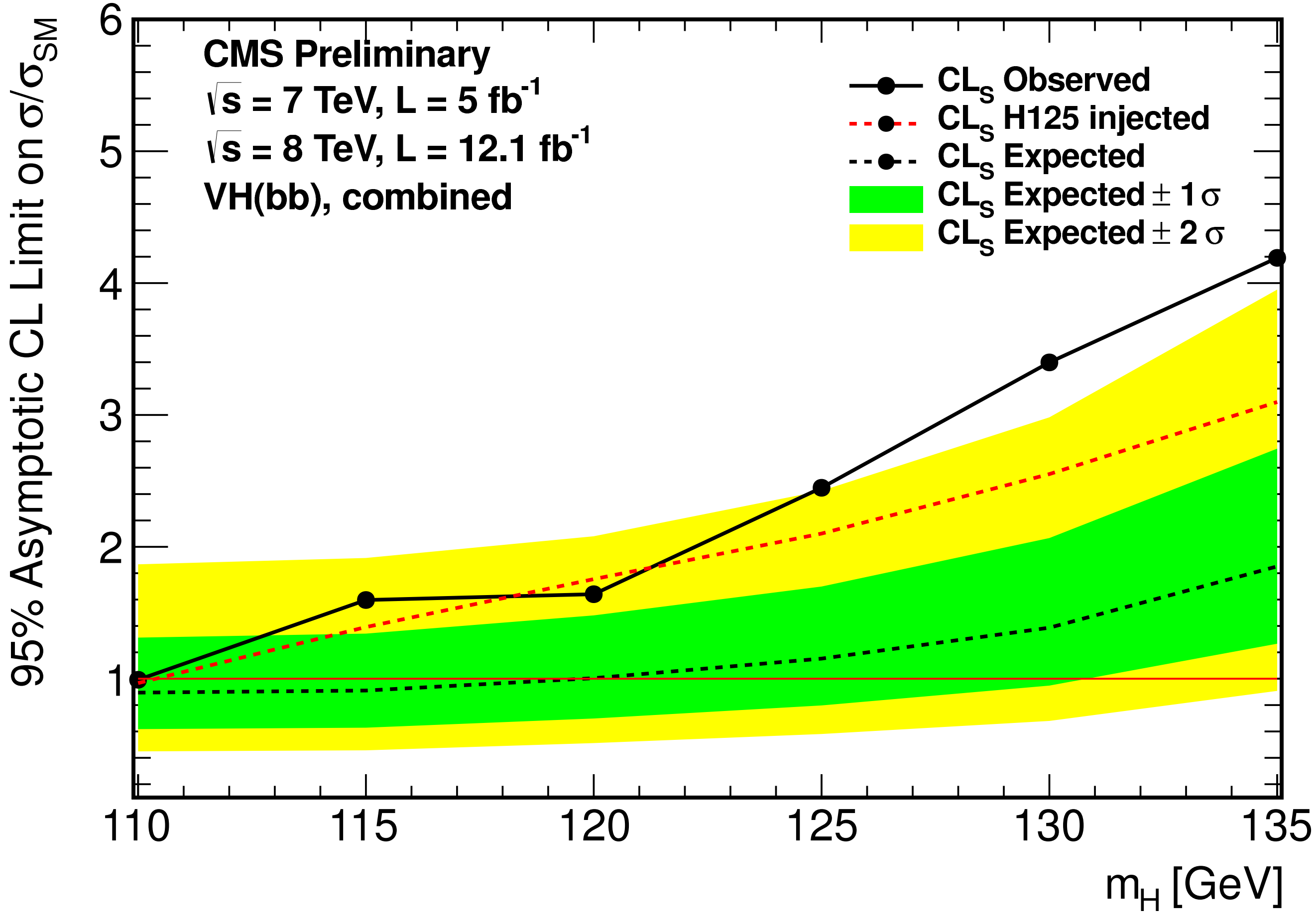
Tevatron $VH \to bb$ (1303.6346):

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



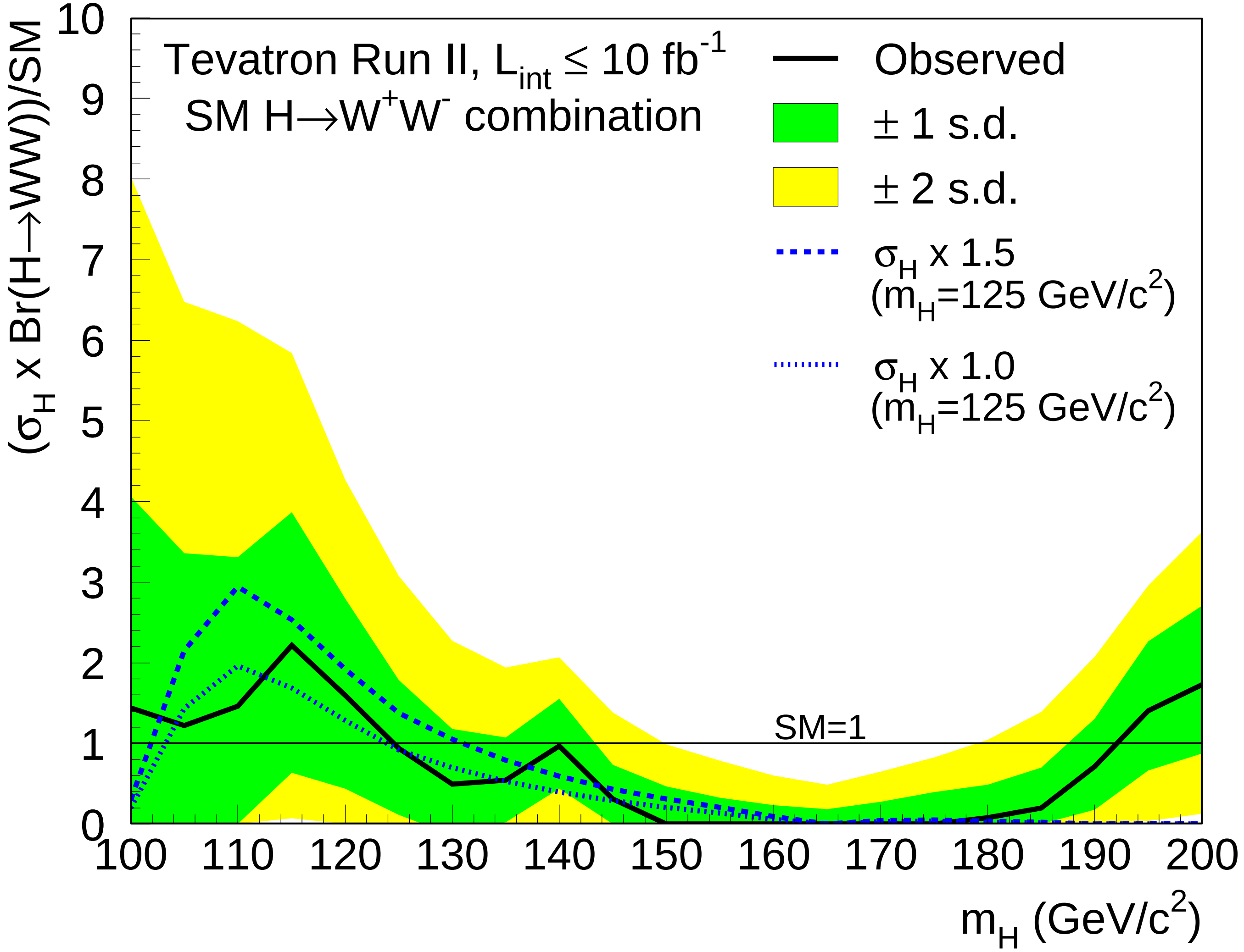
small additional excess around $M_H \sim 140$ GeV (low mass resolution)

CMS $VH \to bb$ (HIG-12-044-PAS):



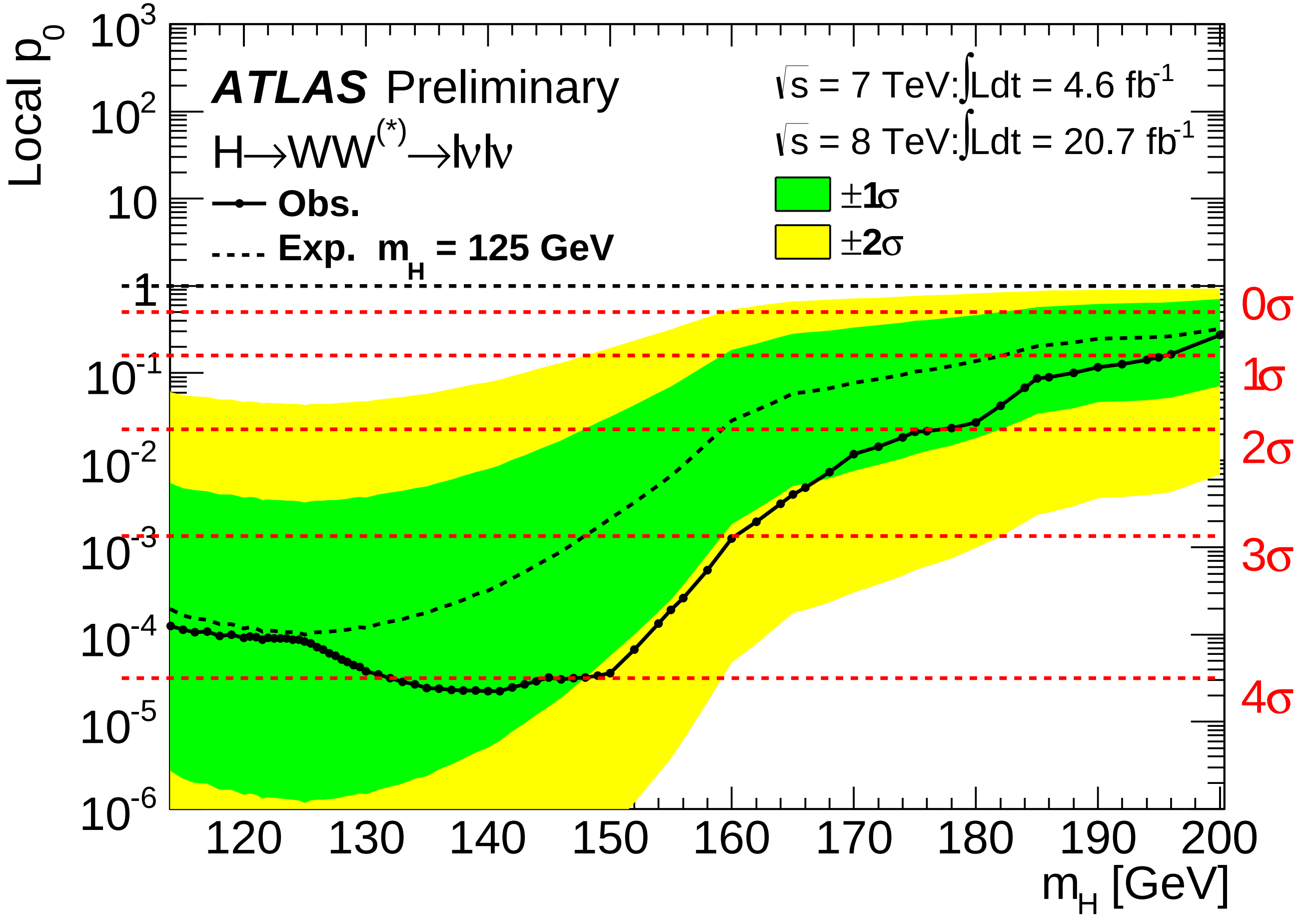
small additional excess for $M_H \gtrsim 130$ GeV (low mass resolution)

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 Higgs boson in $H \to ZZ$, $H \to \tau\tau$ (ATLAS, CMS)

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

Possibly the h_s of the NMSSM! (G. Belanger, U.E., J.F. Gunion, Y. Jiang, S. Kraml, 1208.4952)

$\to$ Keep on looking!

What about the "heavy" state H (both in the MSSM and NMSSM)?

— Nearly degenerate with a CP-odd state A and a charged Higgs $H^{\pm}$

— Nearly decoupled from electroweak gauge bosons Z, W,
but couples to top and bottom quarks

Recall: $m_b = h_b v_d$ where v_d is unknown in Susy

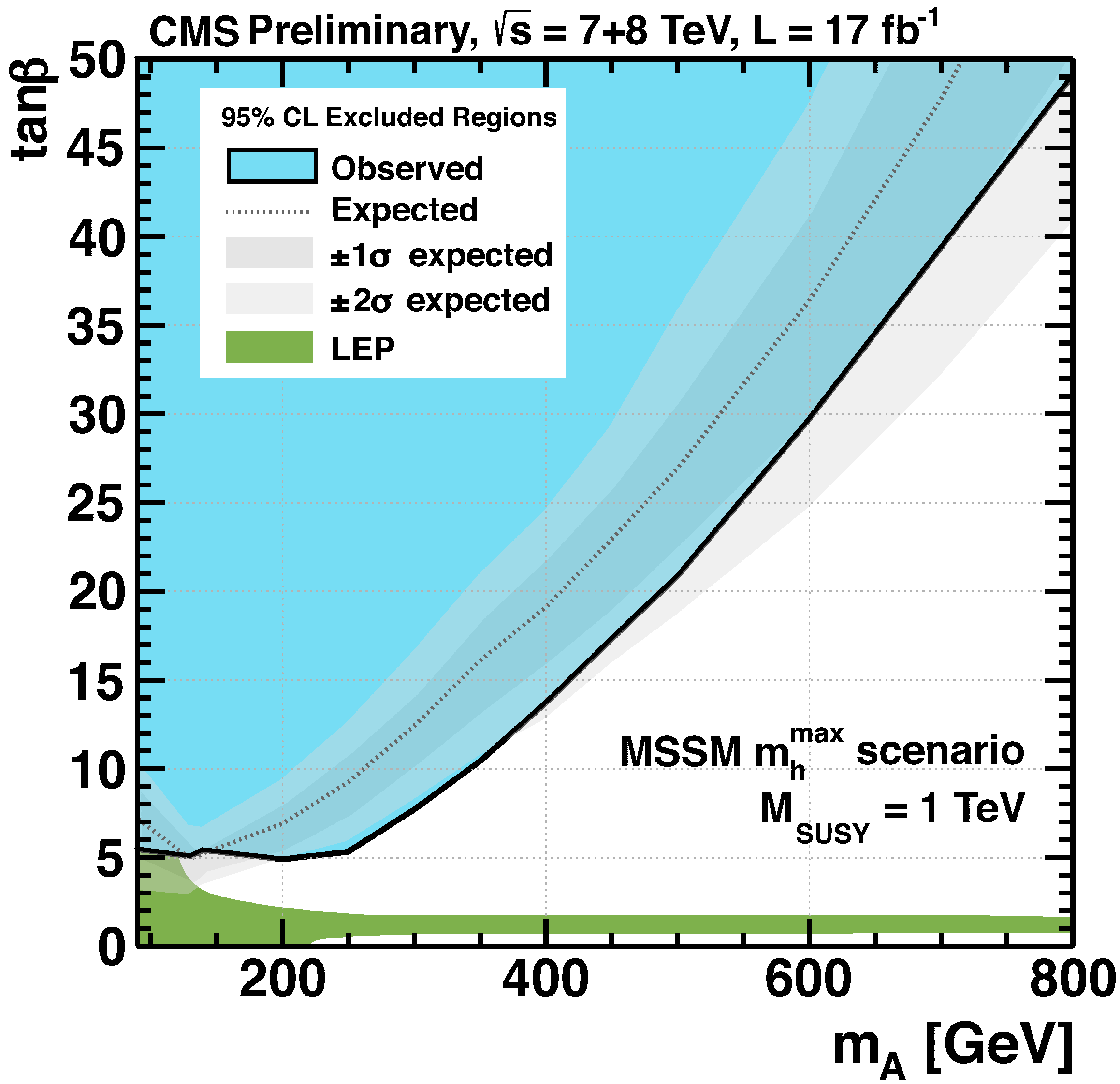
$\longrightarrow$ If v_d is small ($\tan\beta = \frac{v_u}{v_d}$ large, possibly up to 60), h_b is much larger than in the SM!

$\longrightarrow$ The couplings of H, A and $H^{\pm}$ to b quarks can be strongly enhanced

$\longrightarrow$ Constraints from b physics (typically: $M_{H^{\pm}} \sim M_A \gtrsim 300$ GeV)

$\longrightarrow$ Constraints from associate production of H, A with b quarks at the LHC (notably in the $H/A \rightarrow \tau\tau$ channel):

Constraints from CMS-PAS-HIG-12-050:



Note:

— m_h^{max} refers to a specific choice of stop masses in the MSSM

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

— expect large $\tan\beta$ in the MSSM in order to maximise $\cos^2 2\beta$
(no $\lambda^2(v_u^2 + v_d^2) \sin^2 2\beta$ term!)

— expect small $\tan\beta \approx 2$ in the NMSSM in order to maximise $\sin^2 2\beta$!

→ No constraints on the NMSSM (at present...)

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 very large top/stop mass splittings in order to explain the SM like Higgs mass, but gauge coupling unification and a good dark matter candidate as in the MSSM

— Nearly SM like Higgs signal rates are part of the parameter space of all Susy extensions of the SM, but an enhanced $\gamma\gamma$ signal rate of h_{SM} can be a hint for the NMSSM

— Additional below-the-SM signals in Higgs searches at low mass ($\lesssim 200$ GeV) can be a hint for the NMSSM