NMSSM and Multi-Higgs Scenarios and Implications

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Towards the NMSSM

The Higgs mass in the Standard Model:

Given a quartic Higgs self coupling λ^2, the Higgs mass M_h can expressed in terms of the known Higgs vev v and λ: $M_h = \lambda v$

$\longrightarrow$ If we would have known the coupling λ, we could have predicted the Higgs mass M_h

The Higgs mass in the 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

$\rightarrow$ Upper tree level bound on the lighter CP-even neutral scalar mass $M_h \leq M_Z$

$\rightarrow$ With radiative corrections involving large (unnatural?) Susy breaking top-stop and/or stop$_1$-stop$_2$ mass splittings: $M_h \sim 125$ GeV is possible

But: Need an "ad hoc" mass term $\mu \Psi_{H_u} \Psi_{H_d}$ for the higgsinos, which contributes also to the Higgs potential $V(H_u, H_d) \rightarrow$ cannot be much larger than the weak scale, its order of magnitude is difficult to explain (*NOT* a soft Susy breaking term!)

NMSSM: Generate the μ-term through a Yukawa coupling and the vev of an extra scalar singlet S, $\langle S \rangle = v_s$: $\mu \Psi_{H_u} \Psi_{H_d} \rightarrow \lambda S \Psi_{H_u} \Psi_{H_d} \rightarrow \lambda v_s \Psi_{H_u} \Psi_{H_d}$ (v_s of $\mathcal{O}(M_{\mathrm{SUSY}}) \sim M_{weak}$ is automatic)

Benefit: The Yukawa coupling λ^2 contributes also to the quartic Higgs self couplings

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

Now: Three physical CP-even scalars, superpositions of H_u, H_d and S

Eigenstates of the 3×3 mass matrix:
h_{SM} (mostly SM like), H_{MSSM} (similar to the heavy Higgs H in the MSSM), h_S (mostly singlet like, its mass can be anywhere from $1 - 1000$ GeV)

Moreover: Two physical CP-odd scalars A_S (mostly singlet like) and A_{MSSM}

The tree level mass $M_{h_{SM}}$ of the mostly SM like h_{SM} is ($\tan\beta = \frac{v_u}{v_d}$)

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

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

Impact on the diphoton signal rate: (ATLAS: $\mu_{\gamma\gamma} = 1.65 \pm 2.3\sigma$)

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)

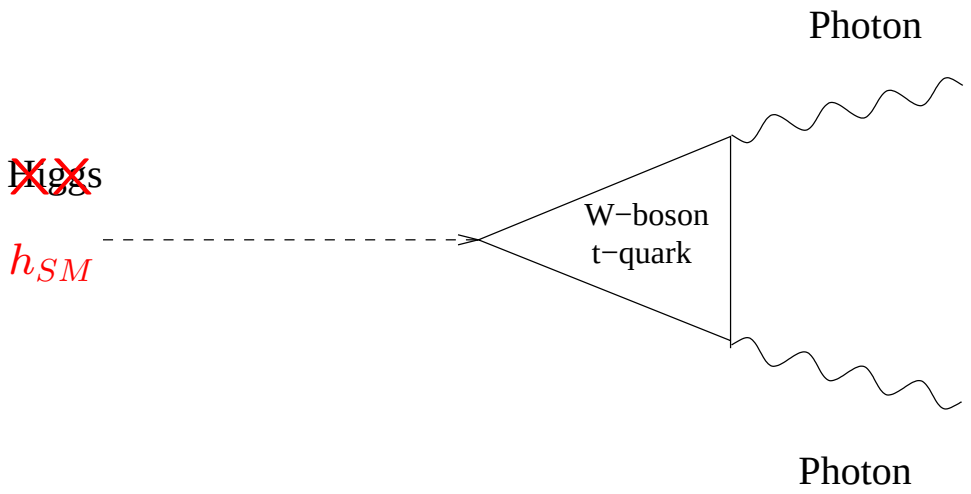
$\to$ Due to the mixing of H_u, H_d, S it is easily possible that, in the NMSSM, the mostly SM–like h_{SM} has

— a reduced coupling to bb, and hence a reduced width $\Gamma(h_{SM} \to bb)$
$\to$ 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
$\to$ 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 $\langle S \rangle$)

$\longrightarrow$ 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

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

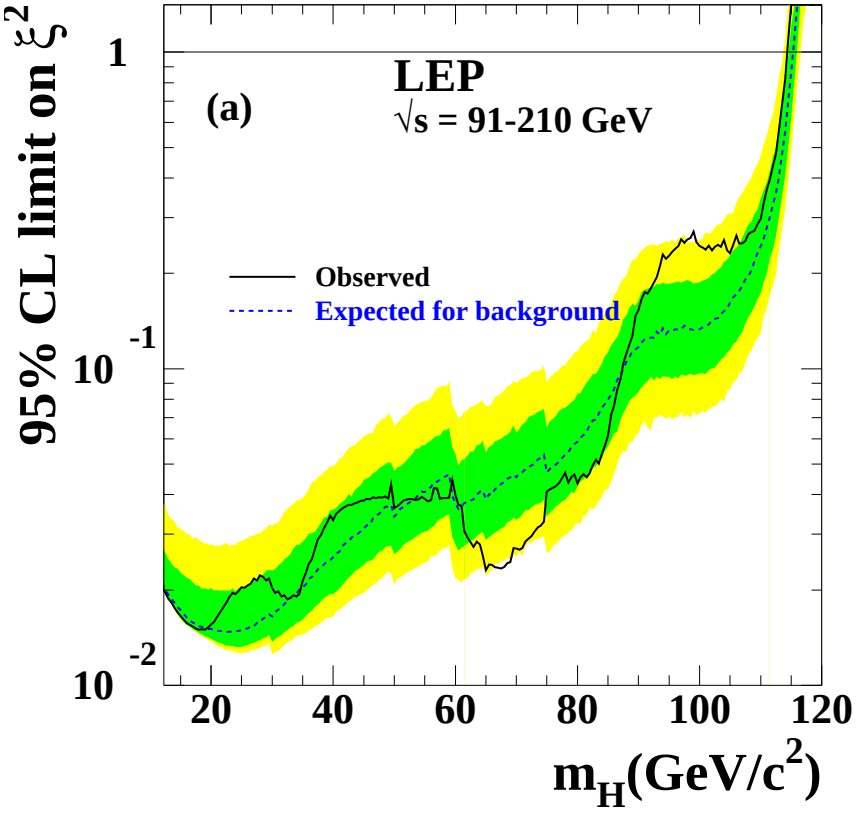
$\longrightarrow$ Are there hints for (at least weak bounds on) such a state?

Unfortunately: The couplings/signal rates of such a state are typically reduced relative to the ones of h_{SM}, but it can still be visible in SM Higgs search channels

Moreover: Higgs-to-Higgs decays become likely!
(Gunion, Haber Moroi, 1996;
Dobrescu, Landsberg, Matchev, 2000: in particular into a light a_1
U.E., Gunion, Hugonie, Moretti, 2003-04; ...)

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:

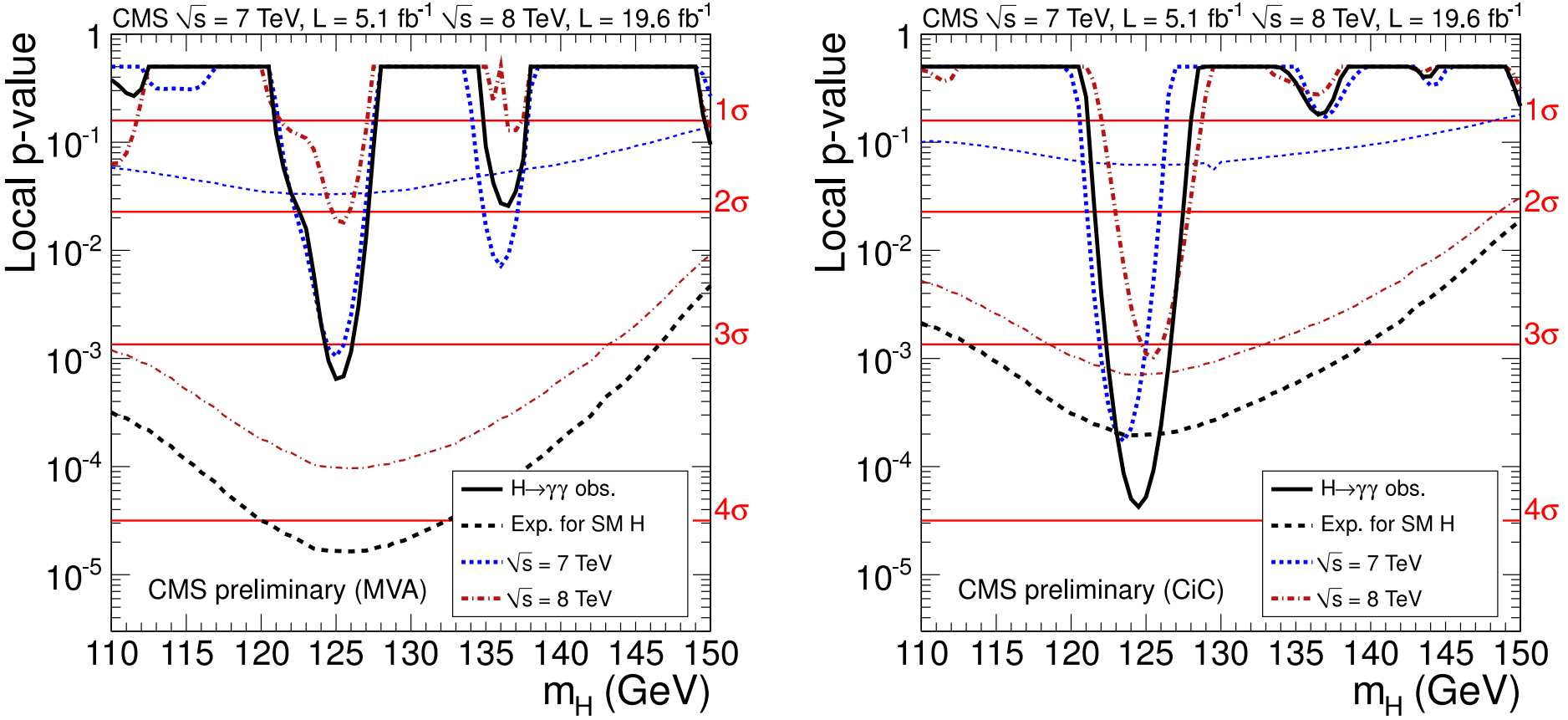
$\longrightarrow$ If $\xi^2(h_S) \sim 0.2$:
Compatible with the
weak bounds ($\sim 2\sigma$ excess)
around 95 GeV
(R. Dermisek, J.-F. Gunion)



Or: could be very close to 125 GeV?
(See the talk by S. Kraml)

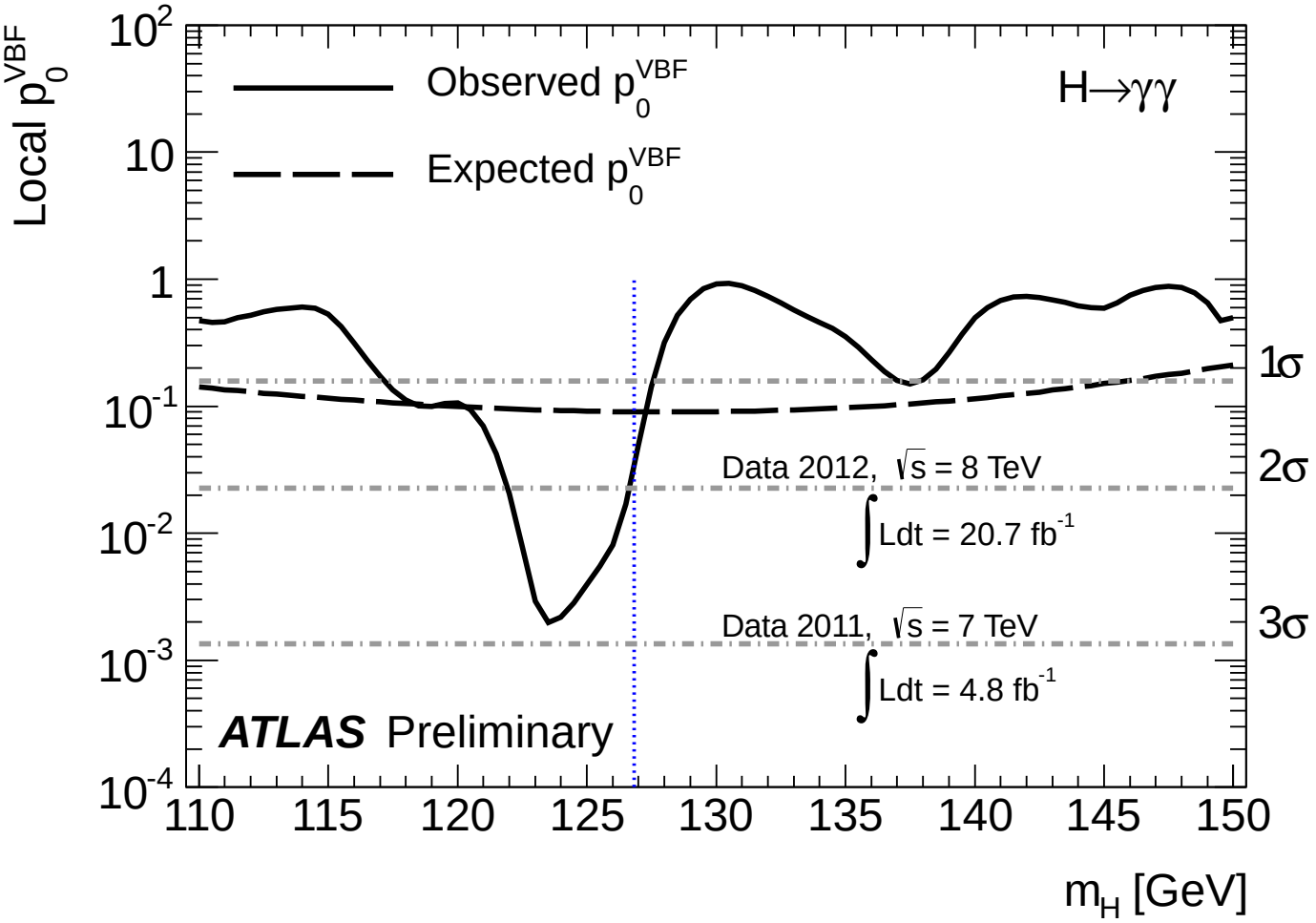
Or: above 125 GeV? hints?

CMS $H \to \gamma\gamma$ (HIG-13-001-PAS)



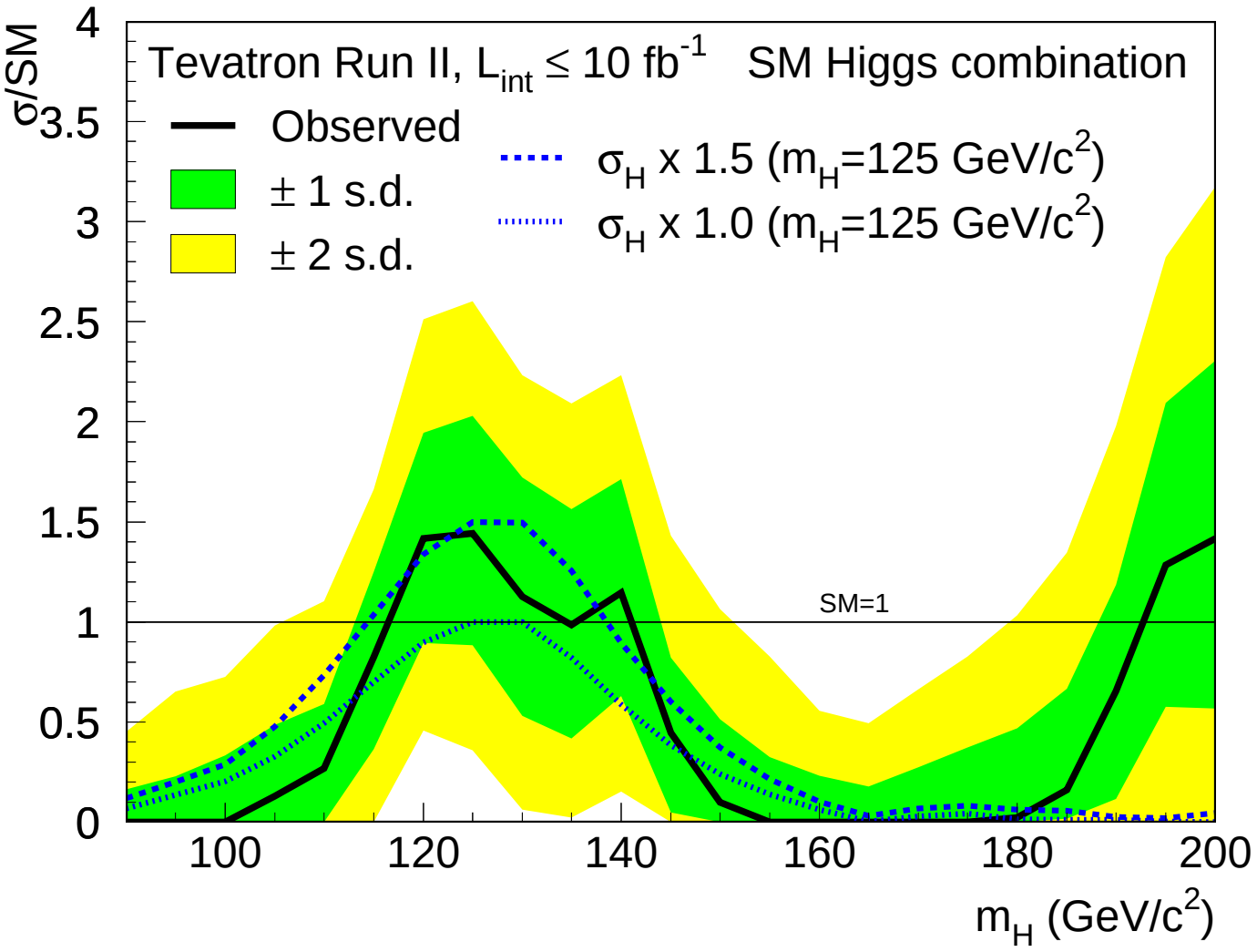
Either: an additional $\sim 2\sigma$ excess around $M_H \sim 136$ GeV
(MVA analysis, l.h.s.), or
confirmation of the enhanced $\gamma\gamma$ rate of the 125 GeV Higgs
(cutbased analysis, r.h.s.; still: $\sim 1\sigma$ excess around $M_H \sim 136$ GeV)

ATLAS $H \to \gamma\gamma$ in VBF (ATLAS-CONF-2013-012):



small additional excess around $M_H \sim 137$ GeV

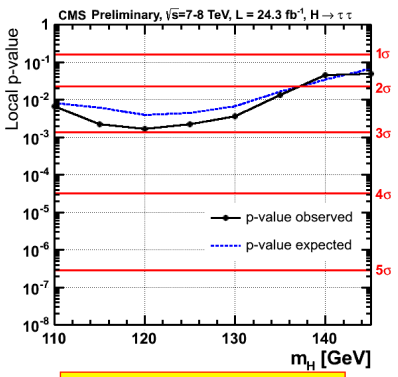
Tevatron $VH \to bb$ (1303.6346):



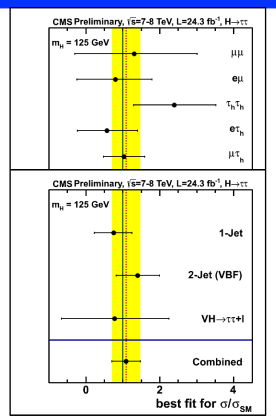
small additional excess around $M_H \sim 140$ GeV (low mass resolution)

CMS $H \to \tau\tau$ (talk by Korytov):

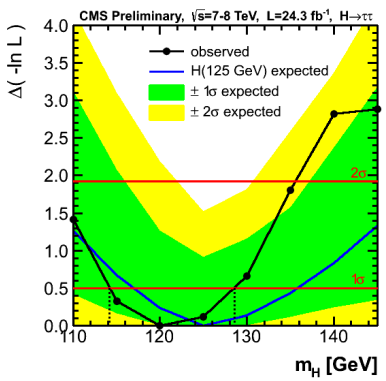
H → ττ: results



Z_{obs} = 2.9 σ
Z_{exp} = 2.6 σ (m = 125)



μ = 1.1 ± 0.4
(m = 125 GeV)



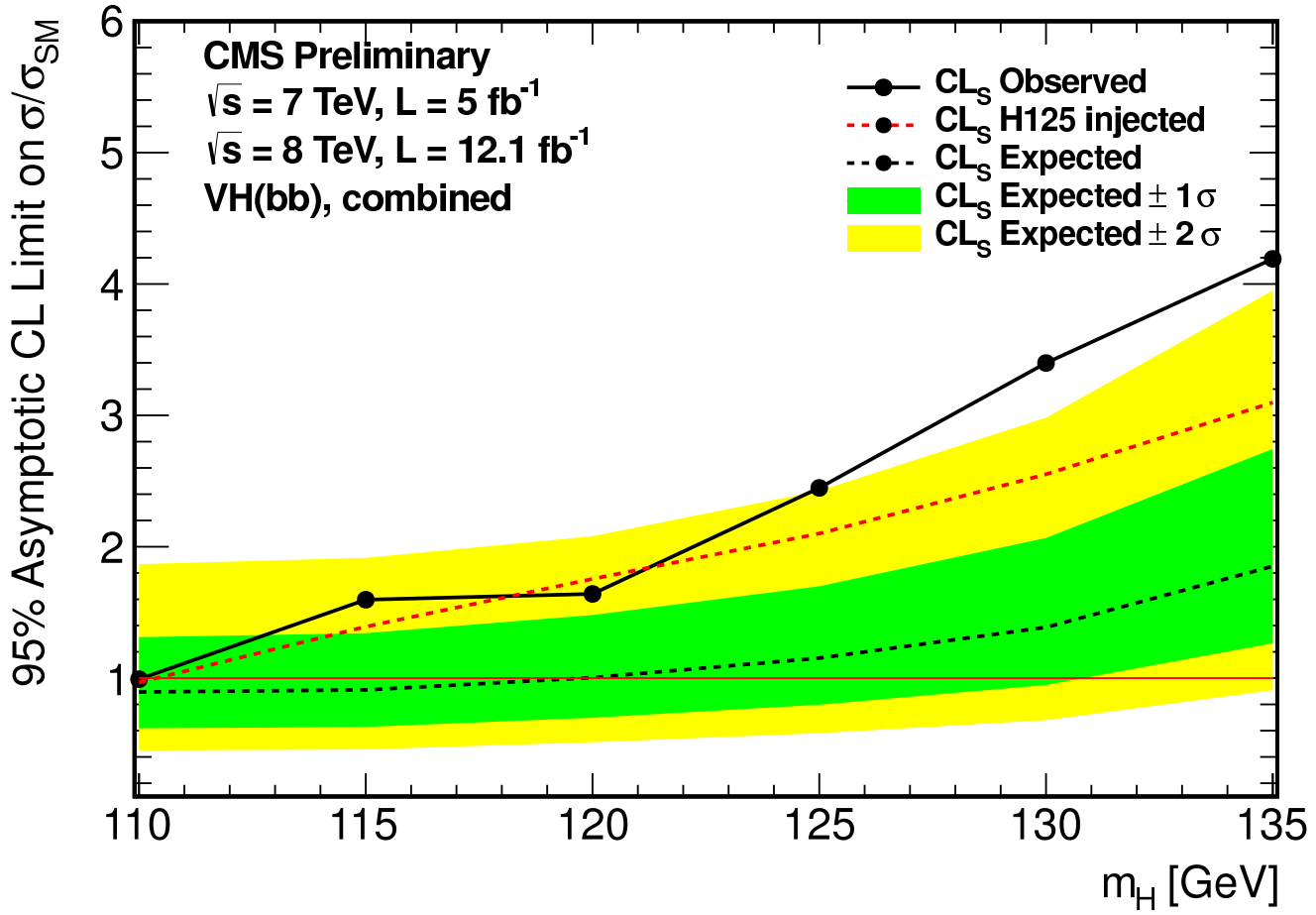
$m_X = 120\ ^{+9}_{-7}$ GeV

Points to note:

- broad access (poor mass resolution), consistent with **SM Higgs rate**
- close to reaching a 3σ-sensitivity: **fair sensitivity for measurements**
- 1-jet channel has a respectable weight in the search (cf. ±δμ for 1-jet and 2-jet channels)
- **VH(ττ) analysis is updated too**; its sensitivity can be seen in the μ-compatibility plot
- despite poor mass resolution, the TauTau channel is **not completely mass-blind** !

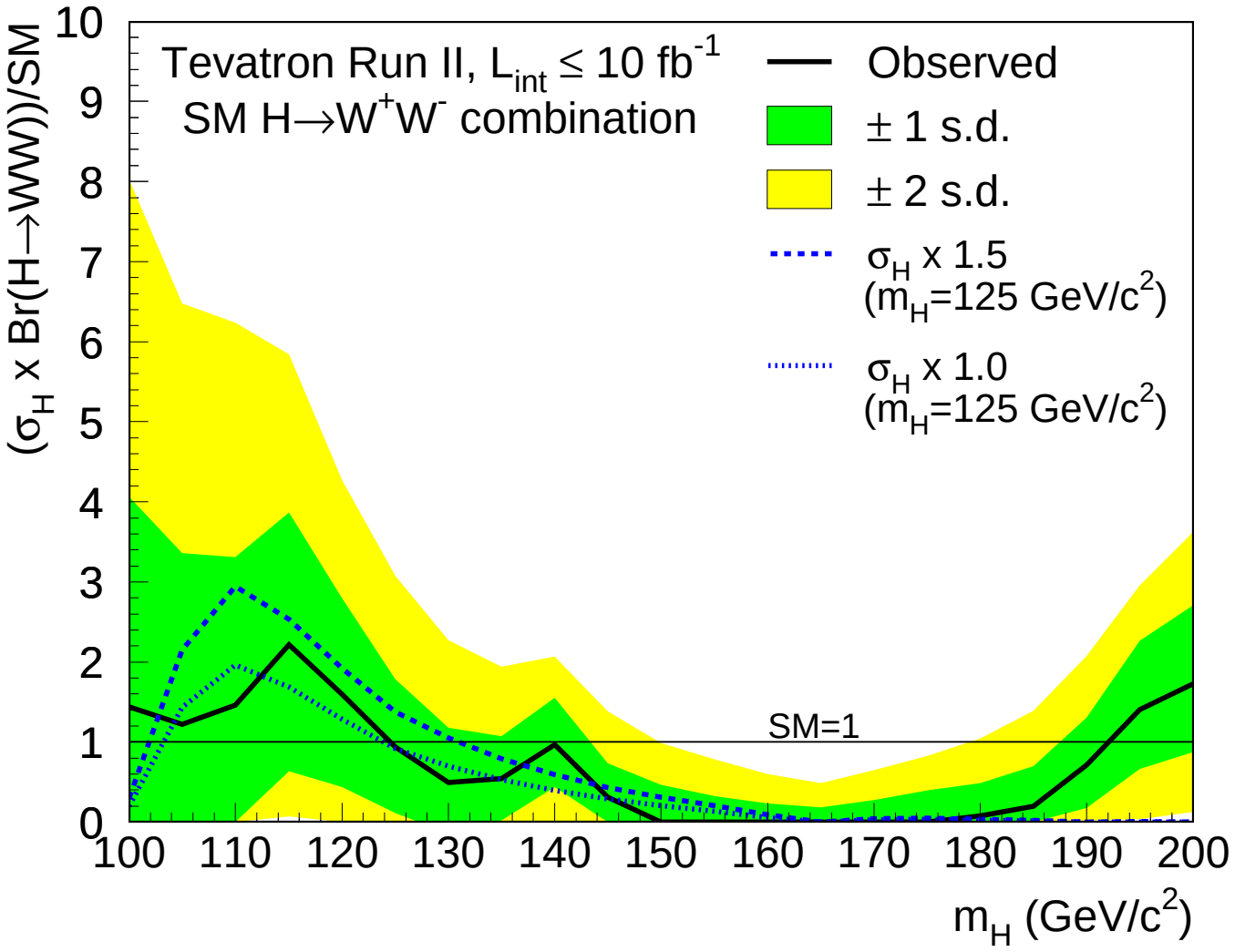
additional $\gtrsim 1$ sigma excess for $M_H \gtrsim 125$ GeV (low mass resolution)

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):



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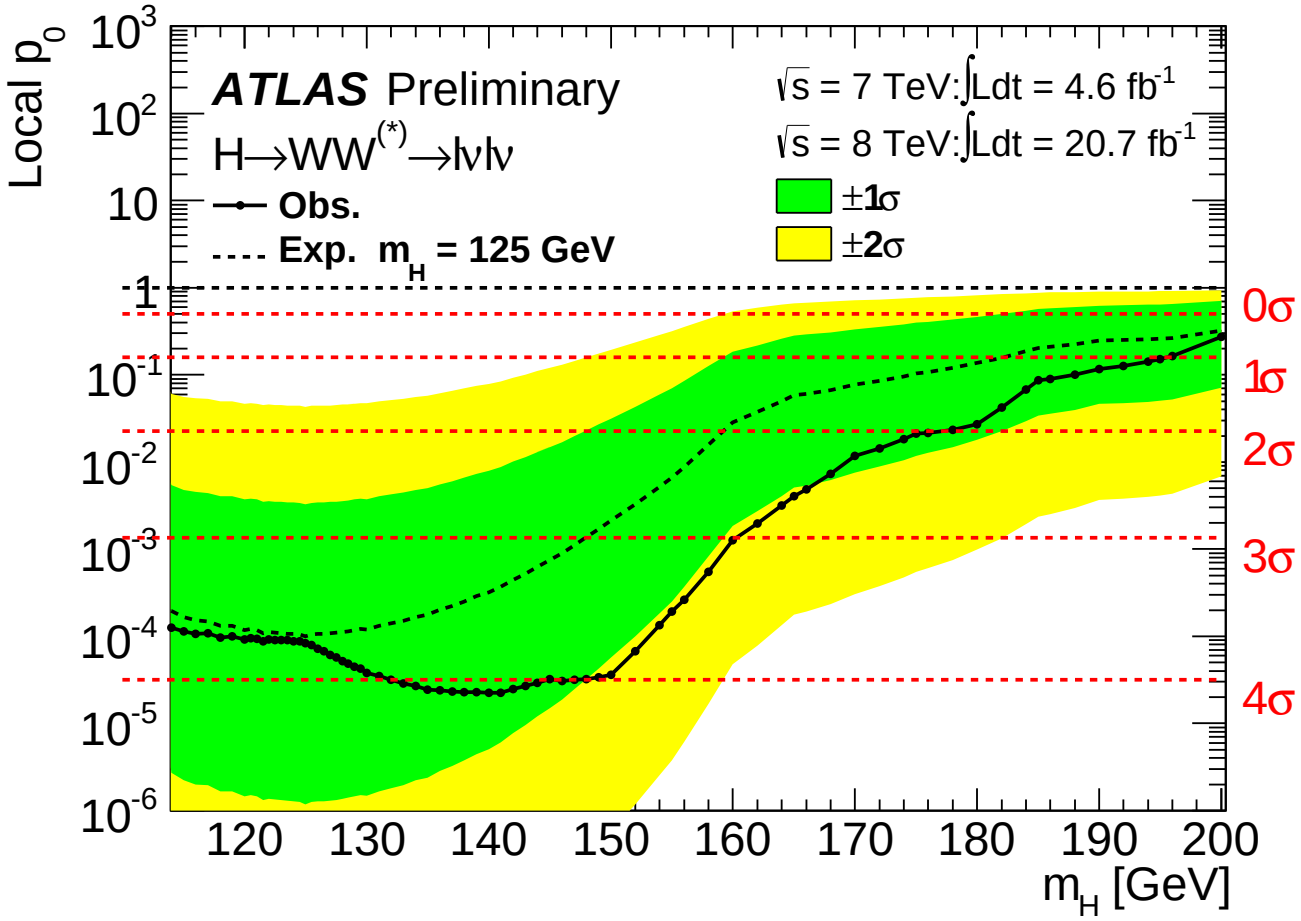
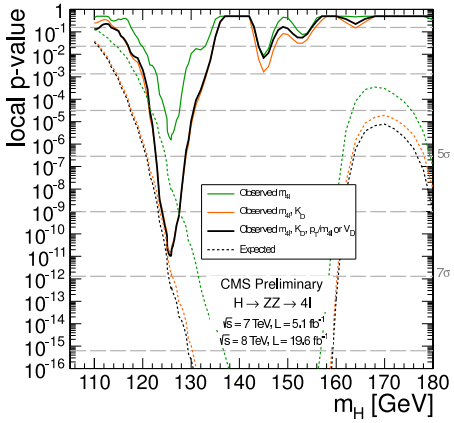
ATLAS $VH \to WW$ (ATLAS-CONF-2013-012):



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

But: only upper bounds $\sim 0.2\times$ SM on the signal rate of an additional 137 GeV Higgs boson in $H \to ZZ$ (see, e.g., CMS):



Still: at least $6 \times (\sim 1\ \sigma)$ excesses (– LLE) hinting for an additional ≈ 137 GeV Higgs

Possible in the NMSSM! (G. Belanger, U.E., J.F. Gunion, Y. Jiang, S. Kraml, 1208.4952)

$\to$ Keep on looking!

Higgs-to-Higgs decays:

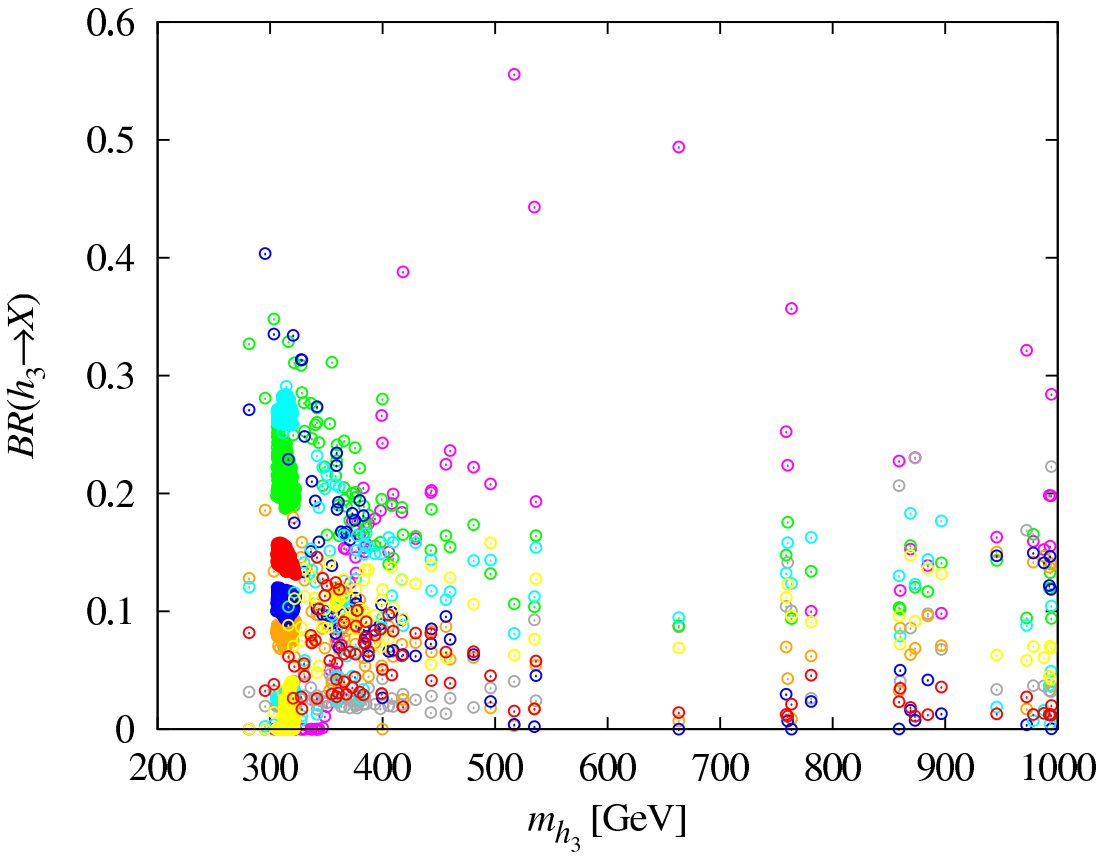
Recall: 3 CP-even, 2 CP-odd scalars in the NMSSM $\rightarrow$ many possibilities

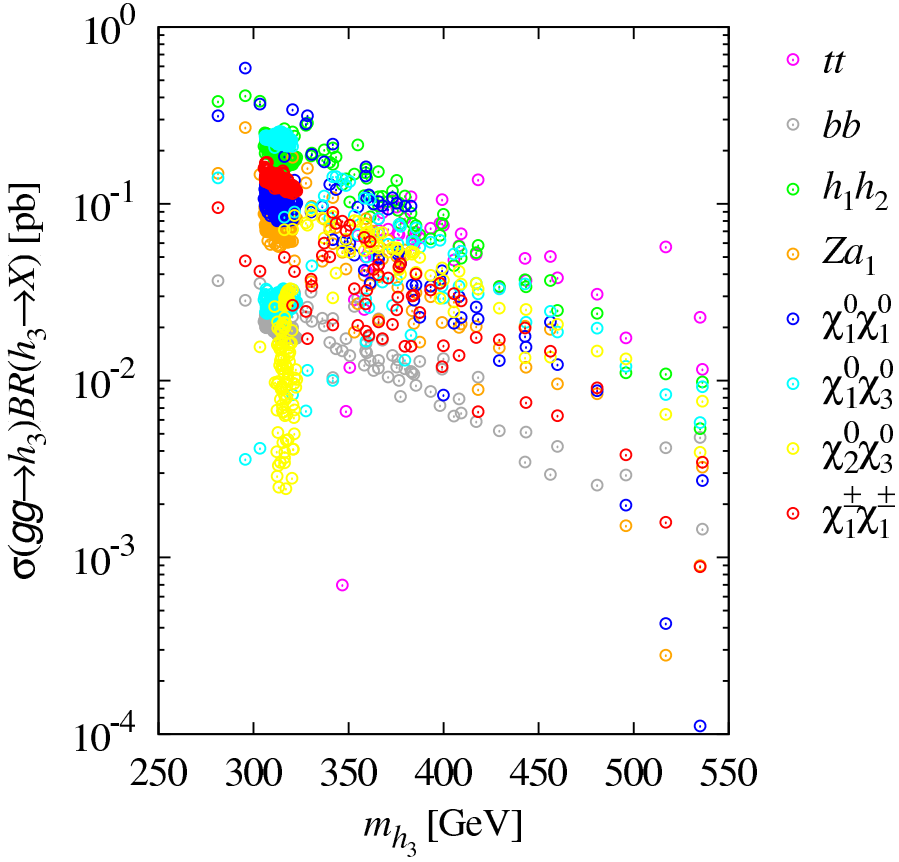
Several previous studies, but now we know that $M_{h_{SM}} \sim 125$ GeV

$\longrightarrow$ What can we expect?

G. Belanger, U.E., J.F. Gunion, Y. Jiang, S. Kraml, J. Schwarz:
Scan of the parameter space of the sNMSSM (unified soft breaking terms except for the Higgs sector), consistent with Higgs Bosons at 98 and 125 GeV

Decays and LHC cross sections in the gg fusion mode ($\sqrt{s} = 8$ TeV) for the heaviest h_3 (results for a_2 are similar):





Note: m_{h_3} not far above 300 GeV is more natural;
$h_3 \to h_1 + h_2$ (green) can be significant!
(Also: decays into neutralinos (blue)/charginos (red) are likely)

Recent simulations:

D. Cerdeño, P. Ghosh, C. B. Park (1301.1325) considered, on top of $m_{h_1} \sim 98$ GeV, $m_{h_2} \sim 125$ GeV, a light a_1 with $m_{a_1} < 2m_b$ (BMpoints consistent with LEP/LHC limits) and

$$gg \to h_1/h_2 \to 2a_1 \to 4\tau$$

After suitable cuts on M_{T2}, $m_{l^+l^-}$ etc.: background from DY, bb, tt, ZZ eliminated, up to 20 signal events at 8 TeV and 25 fb^{-1} (h_1 production is dominant!)

Z. Kang, J. Li, T. Li, D. Liu, J. Shu (1301.0453) studied

$$gg \to h_3 \to h_1 + h_2 \to bb + WW^* \to bb + l\nu + jj$$

using jet substructure $\to S/\sqrt{S+B} \gtrsim 4\sigma$ at 14 TeV, 500 fb^{-1} (!)

Conclusions

In the framework of supersymmetric extensions of the SM, the NMSSM explains most naturally a SM like Higgs boson with $M_{H_{SM}} \sim 125$ GeV;

— comes often hand-in-hand with an enhanced $\gamma\gamma$ signal rate;

— a "smoking gun" would be the discovery of at least one extra low-mass Higgs boson either
— in the search channels for a SM like scalar, both above and below 125 GeV or
— in dedicated Higgs-to-Higgs search channels
(also: including decays into/off neutralinos/charginos)

$\rightarrow$ More work is required!