



Higgs Decays in the NMSSM

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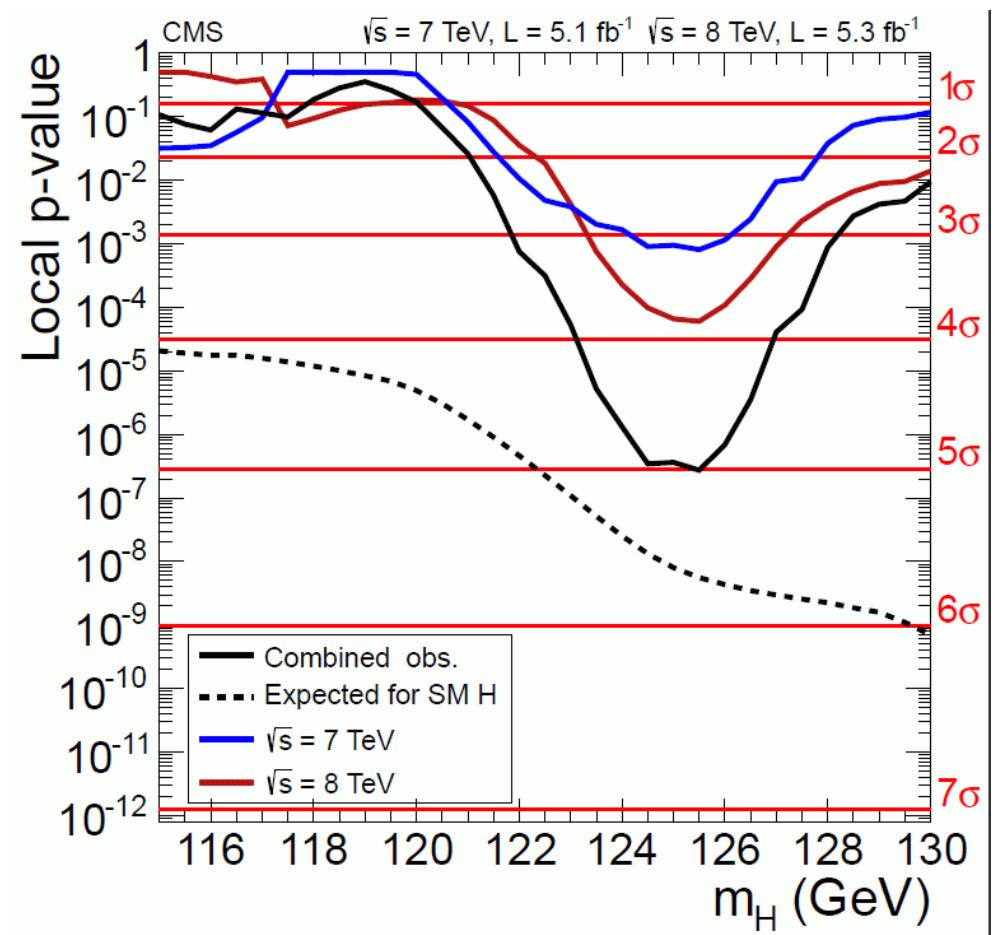
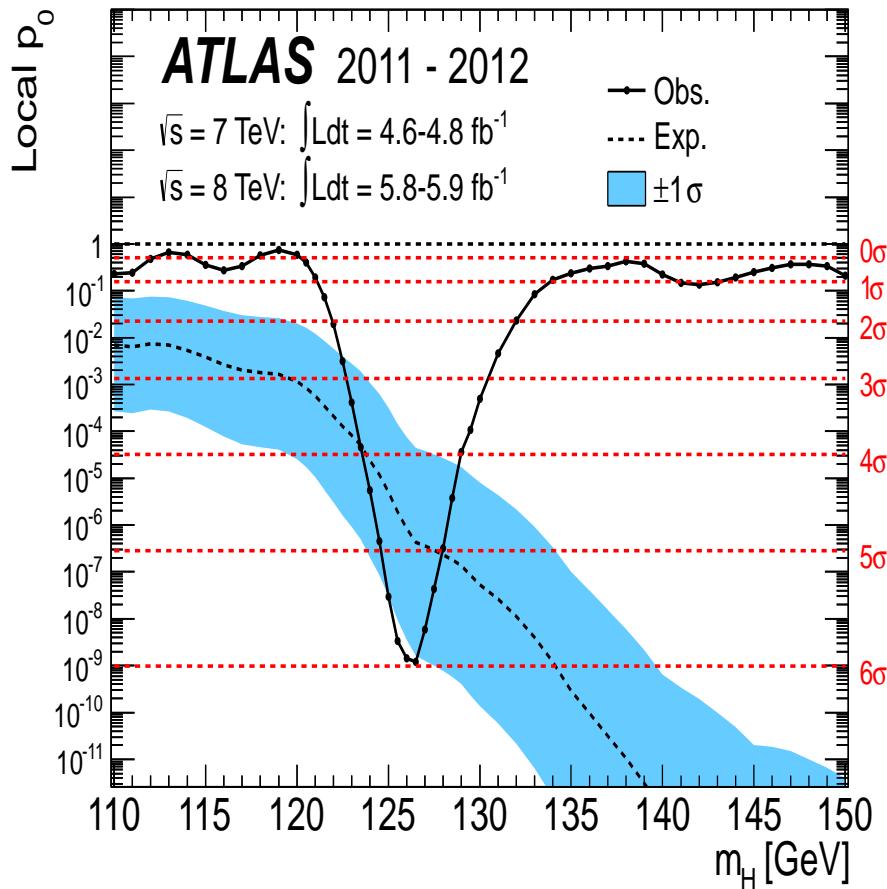
Based on a collaboration with
F. Domingo, S. Paßehr, and G. Weiglein

- Motivation
- Higgs decays in the (N)MSSM
- $\phi_{96} \rightarrow \gamma\gamma$
- Conclusions

1. Motivation

Fact I:

We have a discovery!



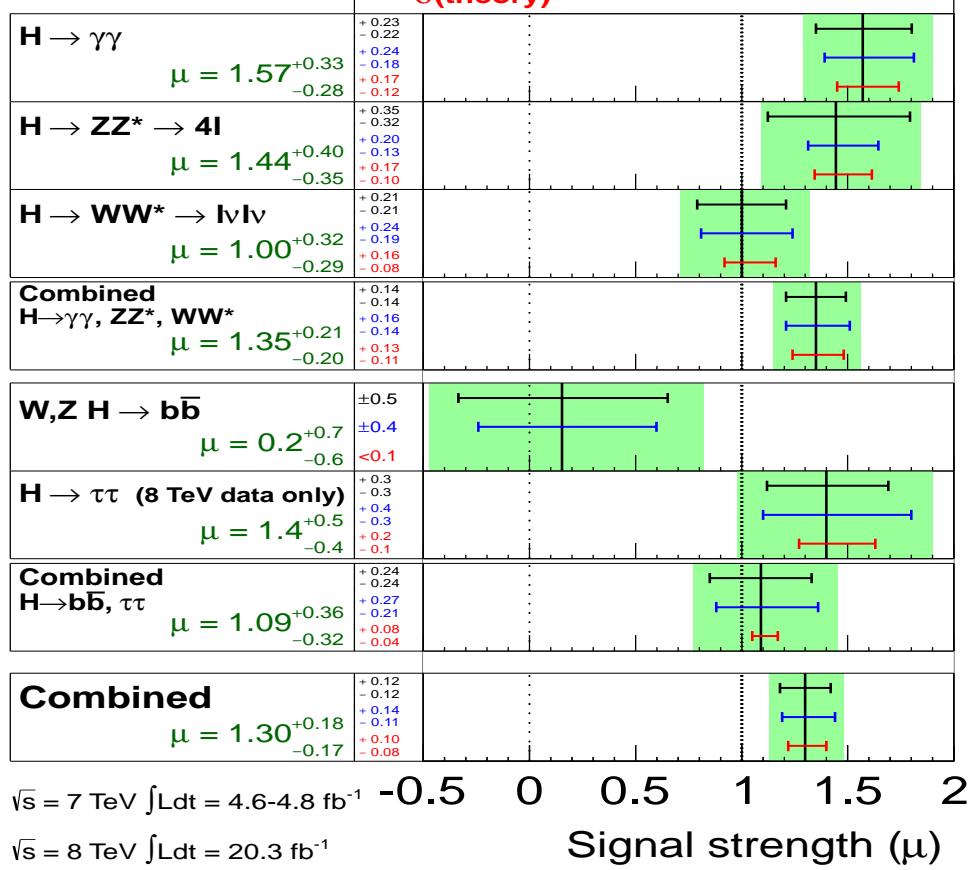
1. Motivation

Fact I:

We have an SM-like discovery!

ATLAS Prelim.

$m_H = 125.5 \text{ GeV}$



$19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$

CMS

$m_H = 125 \text{ GeV}$

$p_{\text{SM}} = 0.96$

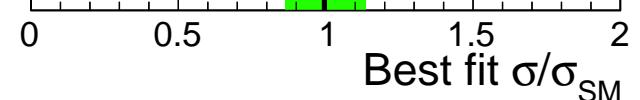
$H \rightarrow \gamma\gamma$ tagged
 $\mu = 1.12 \pm 0.24$

$H \rightarrow ZZ$ tagged
 $\mu = 1.00 \pm 0.29$

$H \rightarrow WW$ tagged
 $\mu = 0.83 \pm 0.21$

$H \rightarrow \tau\tau$ tagged
 $\mu = 0.91 \pm 0.28$

$H \rightarrow bb$ tagged
 $\mu = 0.84 \pm 0.44$



Fact II:

The SM cannot be the ultimate theory!

Some facts:

1. gravity is not included
2. the hierarchy problem
3. Dark Matter is not included
4. neutrino masses are not included
5. anomalous magnetic moment of the muon shows a $\sim 4\sigma$ discrepancy

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be “the SM Higgs” !

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Q: Does the BSM physics have any (relevant) impact on the Higgs?

Q': Which model?

Fact I & II:

We have a discovery!

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Q: Does the BSM physics have any (relevant) impact on the Higgs?

Q': Which model?

A1: check changed properties

A2: check for additional Higgs bosons

A2': check for additional Higgs bosons above and below 125 GeV

Which model should we focus on?

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

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⇒ **good motivation to look at SUSY! :-)**

2. NMSSM Higgs boson decays

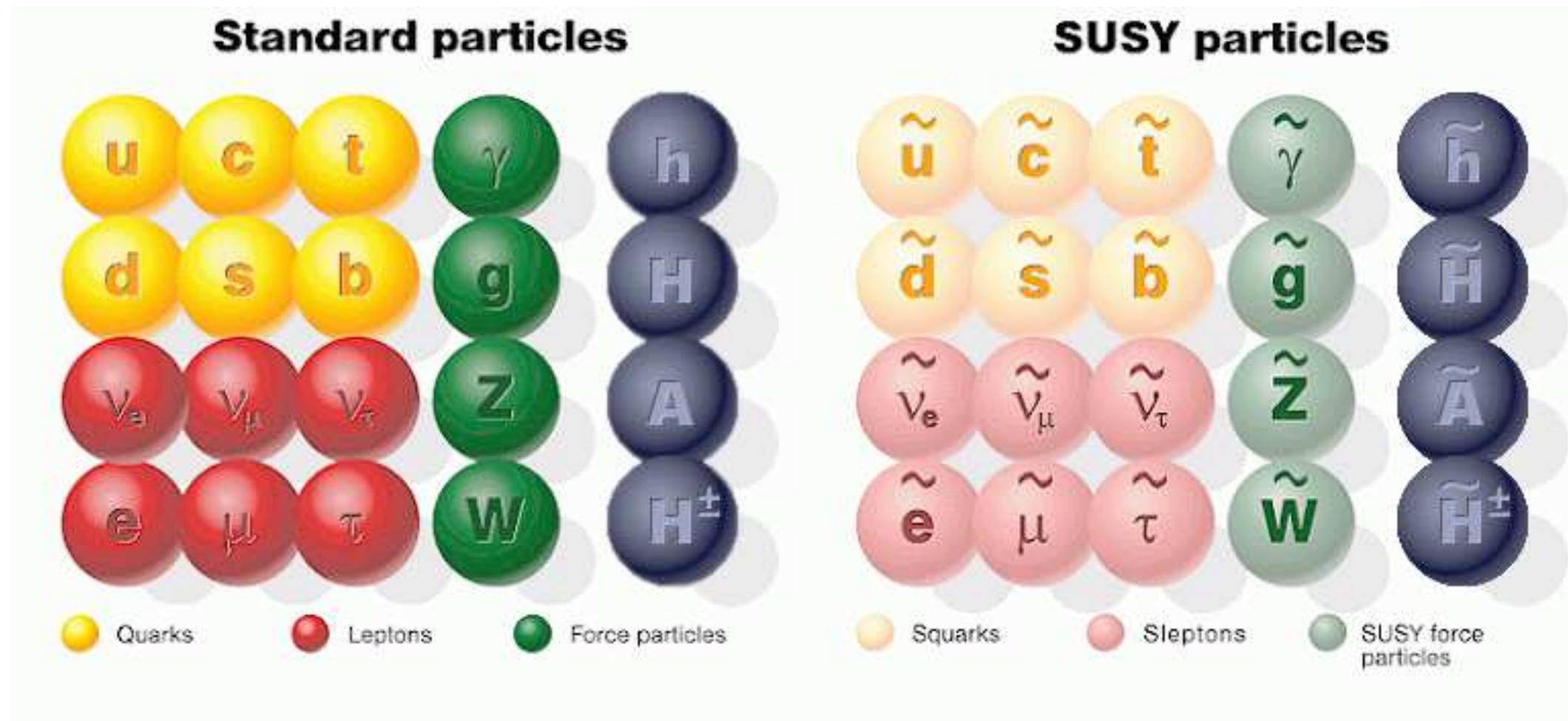
Needed for LHC/ILC/CLIC/... physics:

Precise and consistent prediction of

- Higgs boson masses
 - Higgs boson mixings
 - Higgs boson couplings
 - Higgs boson production cross sections
 - Higgs boson decay widths/branching ratios \Leftarrow focus here
 - ...
- ⇒ (partially) provided by FeynHiggs

The MSSM:

→ Superpartners for Standard Model particles



MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: h^0, H^0, A^0, H^\pm

Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

NMSSM Higgs sector (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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$$\begin{aligned} V = & (\tilde{m}_1^2 + |\mu_1|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu_2|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ & + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \end{aligned}$$

NMSSM Higgs sector (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$S = v_s + S_R + IS_I$$

$$V = (\tilde{m}_1^2 + |\mu \lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu \lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

$$+ |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})$$

Free parameters:

$$\lambda, \kappa, A_\kappa, M_{H^\pm}, \tan \beta, \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

\mathcal{CP} -even : h_1, h_2, h_3

\mathcal{CP} -odd : a_1, a_2

charged : H^+, H^-

Goldstones : G^0, G^+, G^-

Neutralinos:

$$\mu \rightarrow \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\rightarrow \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the lightest \mathcal{CP} -even Higgs:

$$m_{h,\text{tree},\text{NMSSM}}^2 = m_{h,\text{tree},\text{MSSM}}^2 + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the \mathcal{CP} -odd Higgs:

MSSM : $M_A^2 = -m_{12}^2(\tan \beta + \cot \beta) = \mu B(\tan \beta + \cot \beta)$

NMSSM : " M_A^2 " = $\mu_{\text{eff}} B_{\text{eff}} (\tan \beta + \cot \beta)$

with $B_{\text{eff}} = A_\lambda + \kappa s$, $\mu_{\text{eff}} = \lambda s$ \Rightarrow one very light a_1

Mass of the charged Higgs:

MSSM : $M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2}v^2 g^2$

NMSSM : $M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$

Mass of the lightest \mathcal{CP} -even Higgs:

$$m_{h,\text{tree,NMSSM}}^2 = m_{h,\text{tree,MSSM}}^2 + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

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$$\text{NMSSM} : M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

$$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \leq M_{h_1}^{\text{NMSSM,tree}}, \text{ one light } a_1, M_{H^\pm}^{\text{MSSM,tree}} \geq M_{H^\pm}^{\text{NMSSM,tree}}$$

The FeynHiggs Ansatz for masses (taken from talk by [P. Dreyse '16])

General idea: treat the MSSM part exactly as in the MSSM

- ▶ full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}(k^2) = i \left[k^2 \mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}_{\phi\phi}^{(1L)}(k^2)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}_{\phi\phi}^{(2L)}(k^2 = 0)}_{\text{MSSM/FEYNHIGGS}} \right]$$

- ▶ included corrections from FEYNHIGGS at 2-loop order:
 - ▶ orders $\mathcal{O}(\alpha_s \alpha_t, \alpha_s \alpha_b, \alpha_t^2, \alpha_t \alpha_b)$
 - ▶ resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it ...

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⇒ same Ansatz for Higgs decays!

What is included in FeynHiggs (so far):

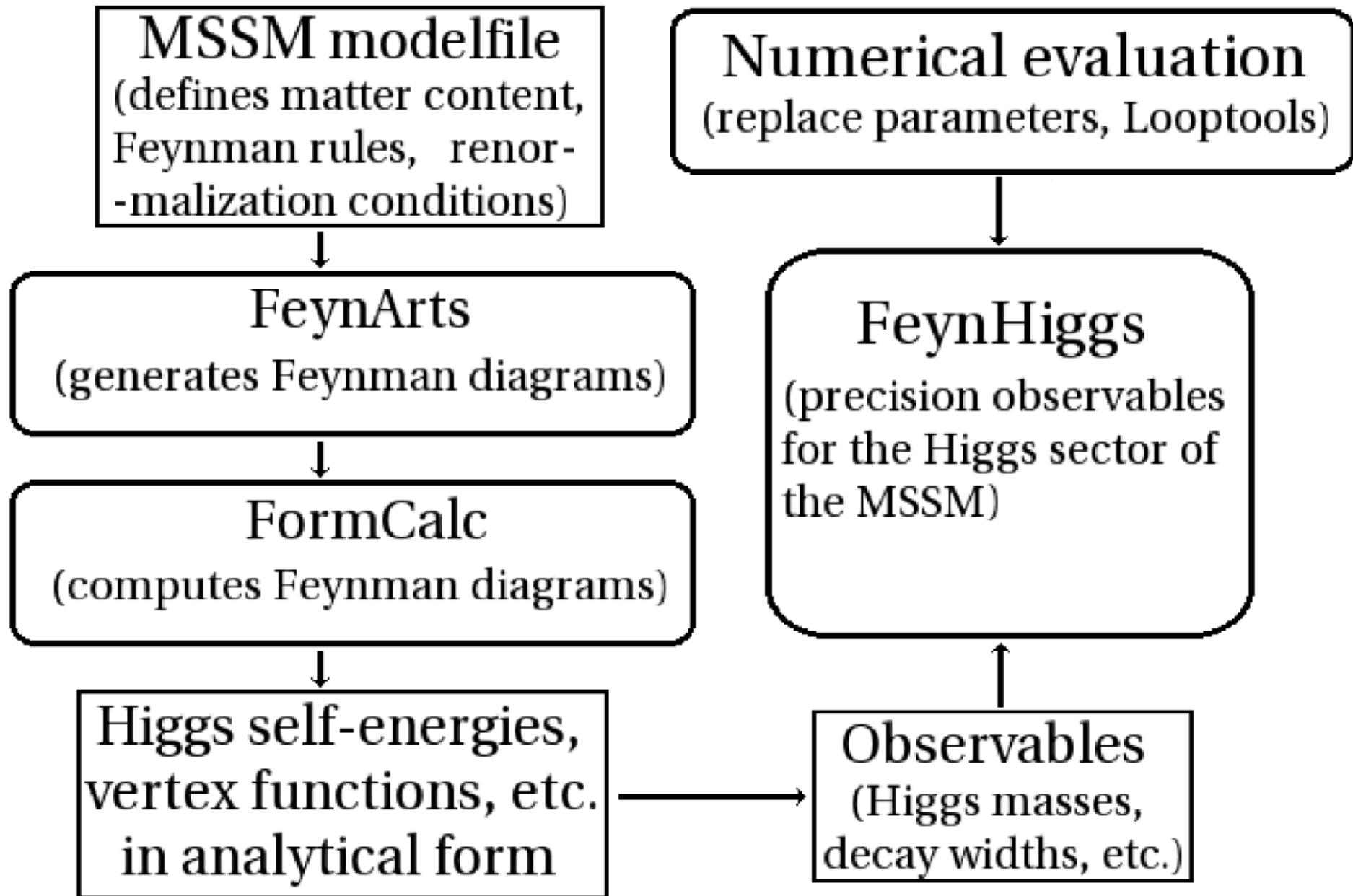
Evaluation of all MSSM Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}, \alpha_{\text{eff}}, Z_{ij}, U_{ij}, \dots \Rightarrow$ precision discussed before

Evaluation of all neutral MSSM Higgs boson decay channels (so far)

- total decay width Γ_{tot}
- $\text{BR}(h_i \rightarrow f\bar{f})$: decay to SM fermions: full 1L, running m_q at 3L, Z_{ij}
- $\text{BR}(h_i \rightarrow Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)})$: decay to massive SM gauge bosons:
Prophecy4f \oplus coupling factors, U_{ij}
- $\text{BR}(h_i \rightarrow \gamma\gamma, gg)$: decay to massless SM gauge bosons:
NLO QCD, gg : NNLO, NNLL from SM, U_{ij}
- $\text{BR}(h_i \rightarrow h_j Z^{(*)}, h_j h_k)$: decay to gauge and Higgs bosons:
 $h_j Z^{(*)}$: U_{ij} , $h_j h_k$: full 1L, log-resum, Z_{ij}
- $\text{BR}(h_i \rightarrow \tilde{f}_i \tilde{f}_j)$: decay to sfermions: U_{ij}
- $\text{BR}(h_i \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$: decay to charginos, neutralinos: U_{ij}

FeynHiggs “workflow”:



- Renormalization of the CP-conserving Higgs-sector
[Drechsel, Galeta, Heinemeyer, Weiglein, (2016)];
- CP-violating NMSSM, on-shell neutral Higgs
[Drechsel, F.D., Paßehr (2017)];
- Neutral Higgs decays into SM particles at full one-loop order
[F.D., Heinemeyer, Paßehr, Weiglein, (2018)];
- Higgs-to-Higgs + Higgs-to-SUSY on-going...
- Inclusion within FeynHiggs in an unforseeable future...

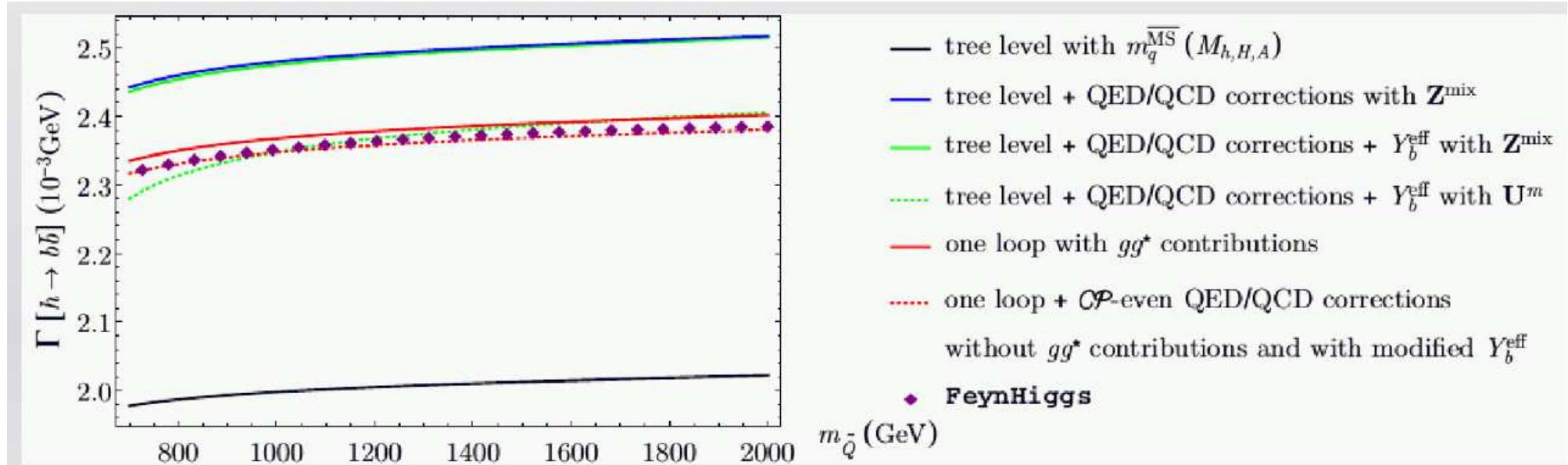
*Learn from MSSM and adapt to the NMSSM.
+ Re-juvenile MSSM from NMSSM.*

In the future: **FeynHiggs 3.0**

⇒ few numerical examples for the Higgs decays

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[slide from F. Domingo]

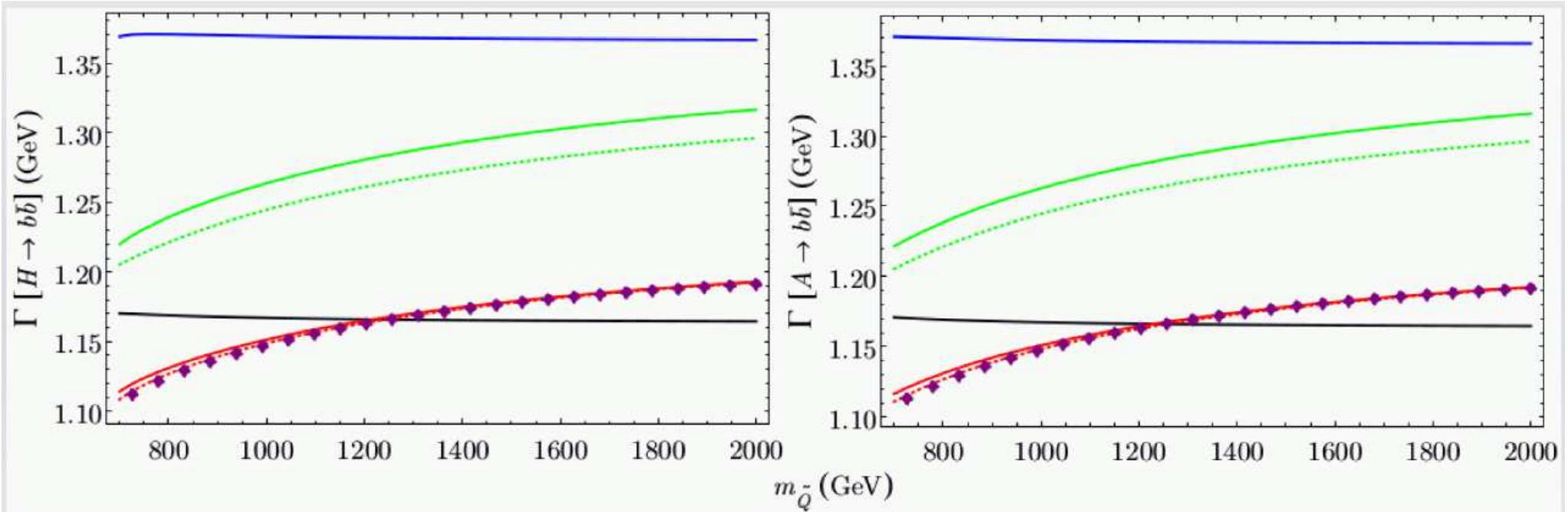


SM-like Higgs state

- Radiative corrections dominated by QCD-corrections;
- Unitary tree-level approximation works well;
- Difference wrt. FH (small): $h \rightarrow g(g^* \rightarrow b\bar{b})$
(whether $h \rightarrow b\bar{b}$ or $h \rightarrow gg$ is an experimental question).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[slide from F. Domingo]

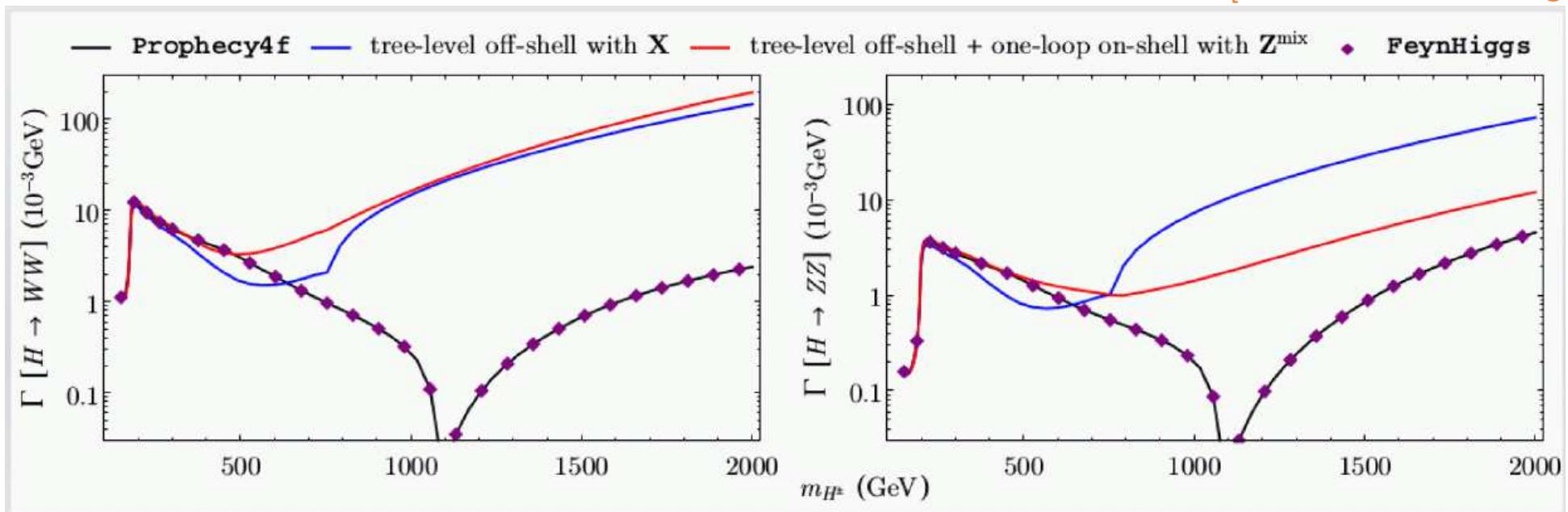


Heavy doublet Higgs states at ~ 1 TeV

- Sizable EW corrections due to Sudakov logarithms;
- Unitary tree-level approximation ‘fails’ $\sim 10\%$ off;
- Difference wrt. FH (minor): UV scale in Δ_b (higher-order).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[slide from F. Domingo]

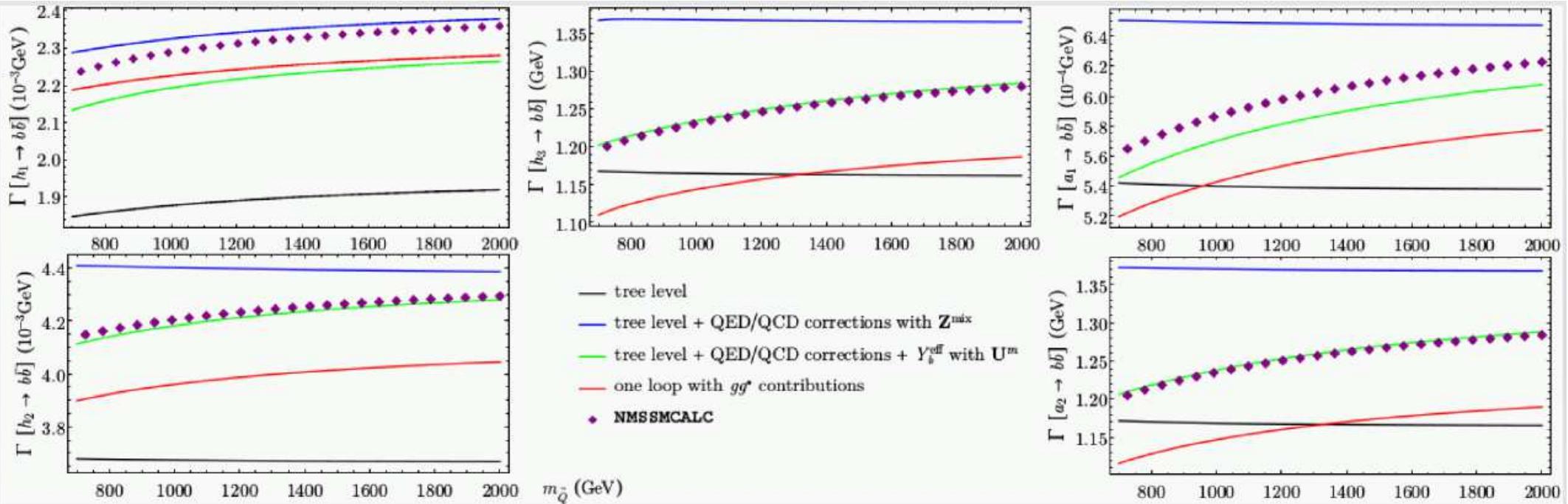


Heavy CP-even doublet Higgs state

- black curve: SM 1L prediction of Prophecy4f rescaled (as FH);
- Red curve: full one-loop (on-shell);
- Rescaling procedure fails for a decoupling state
 $g^{HVV}/g^{H_{\text{SM}}VV} \simeq 0$.

Bringing the NMSSM to the same level: NMSSM

[slide from F. Domingo]

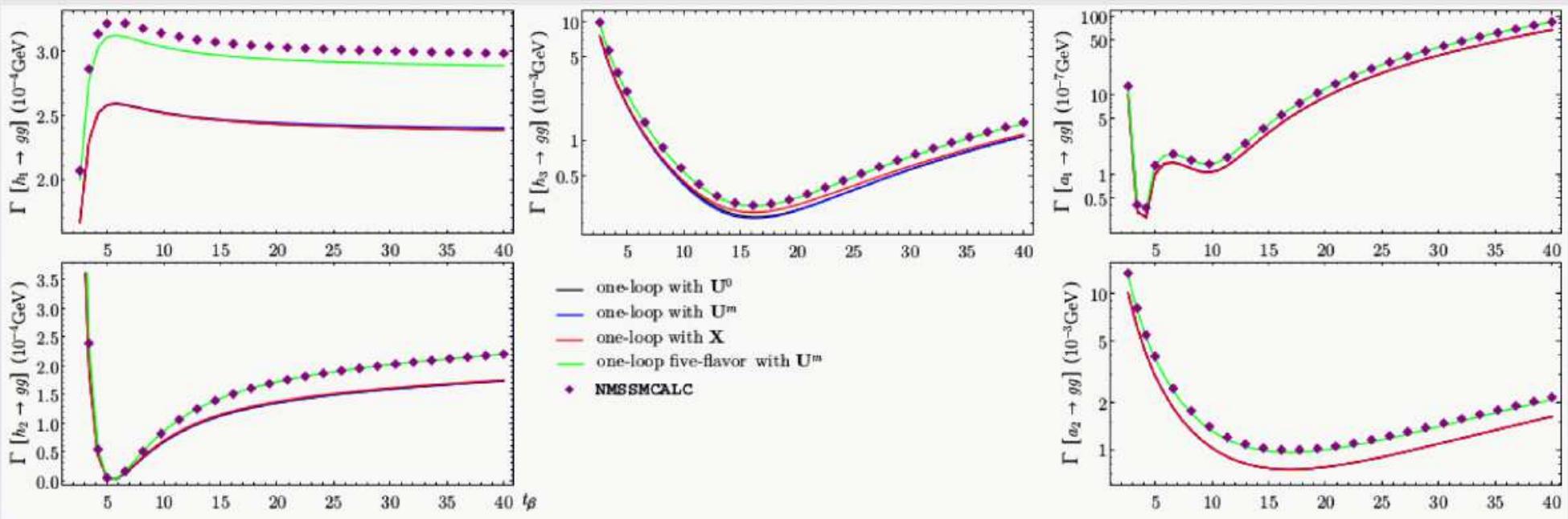


- HDECAY provides a QCD/large $\tan\beta$ -corrected width (including SQCD) \simeq our green line;
- Full one-loop shows EW Sudakov logarithms for heavy states.

Here: h_1 SM-like; h_2 (640 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).

Bringing the NMSSM to the same level: NMSSM

[slide from F. Domingo]



- HDECAY performs at the same order as us with 5-flavor radiation;
- $\sim 4\%$ deviation due to normalization factor (difference of EW 2-loop and QCD 3-loop order).

Here: h_1 SM-like; h_2 (650 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).

Overall (N)MSSM Higgs decay uncertainty estimates

- $h_i \rightarrow q\bar{q}$: SM-like: SM NNLO QCD, EW NNLO, SUSY 2L: $\sim 5\%$
heavy: as SM-like, Sudakov logs: $\sim 5 - 10\%$
- $h_i \rightarrow \ell\bar{\ell}$: SM-like: $\lesssim 1\%$
heavy: Sudakov logs for very heavy Higgses $\lesssim 10\%$
- $h_i \rightarrow WW^{(*)}, ZZ^{(*)}$: SM-like: $\lesssim 1\%$
heavy: missing 2L (very small width): $\lesssim 50\%$
- $h_i \rightarrow \gamma\gamma, gg, \gamma Z$: $\gamma\gamma$: NNLO QCD, EW: $\lesssim 4\%$
 gg : NNLO QCD, EW: $\lesssim 4\%$
 γZ : NLO: $\sim 5\%$
- $h_i \rightarrow \text{SUSY SUSY}$: [S.H., C. Schappacher '14-'16]
1L effects $10 - 20\%$, 2L?
- all decays: U_{ij}, Z_{ij} : few %, effects close to threshold?

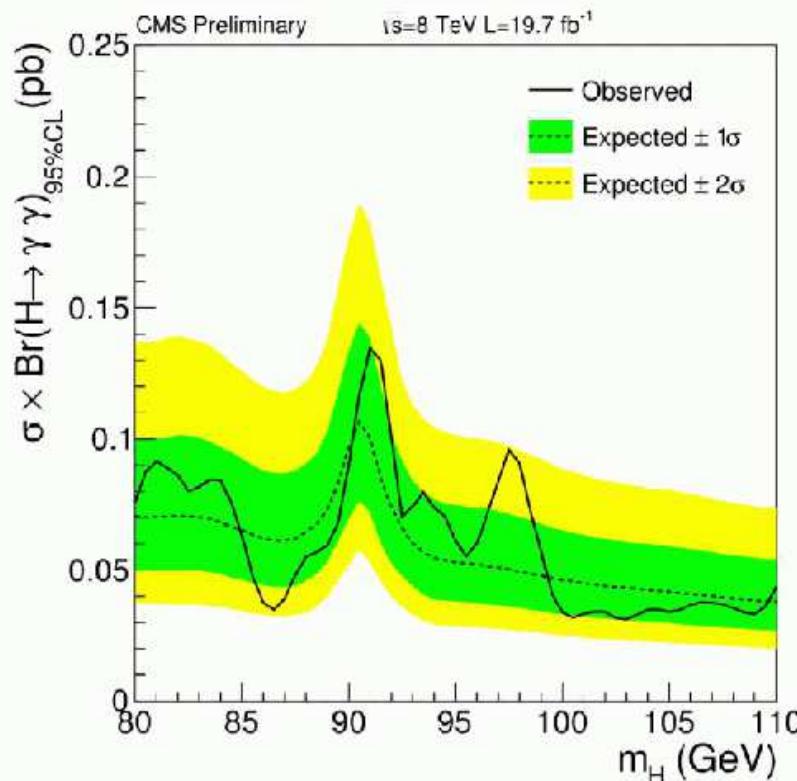
⇒ approaching LC precision for SM-like Higgs (not for heavy Higgses yet)

3. $\phi_{96} \rightarrow \gamma\gamma$

- What was seen in Run I?
- What was seen in Run II?
- What was seen at LEP?
- Should we get excited?
- What about the NMSSM?

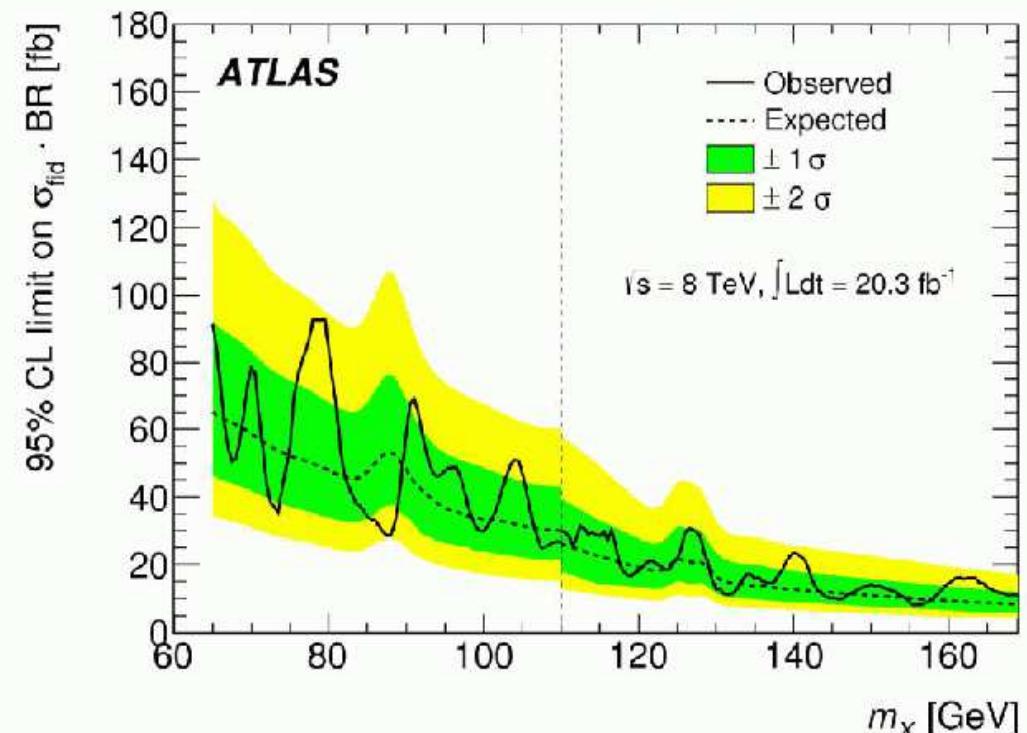


CMS PAS HIG-14-037



$h \rightarrow \gamma\gamma$ (65-110GeV) Run 1

PRL 113 171801 (2014)



- $\sim 2\sigma$ excursion @ $\sim 97.5 \text{ GeV}$

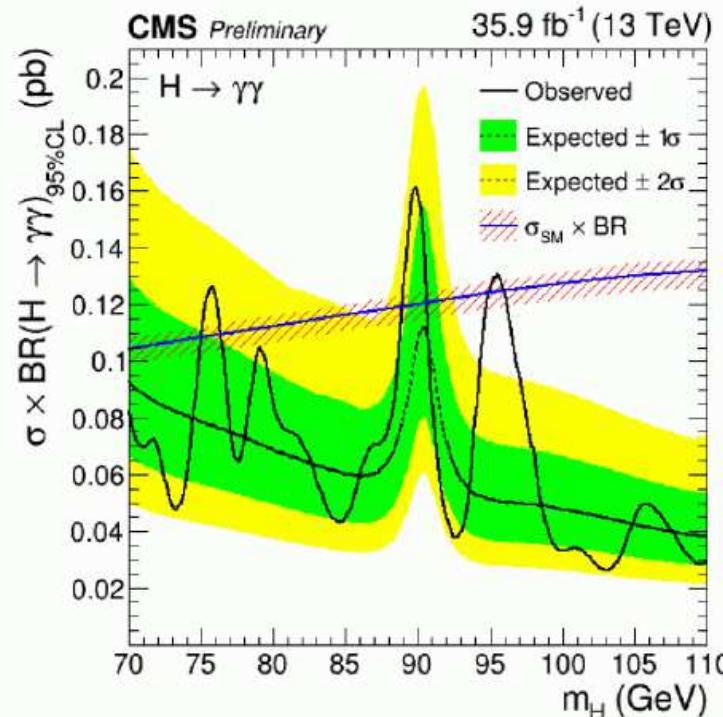
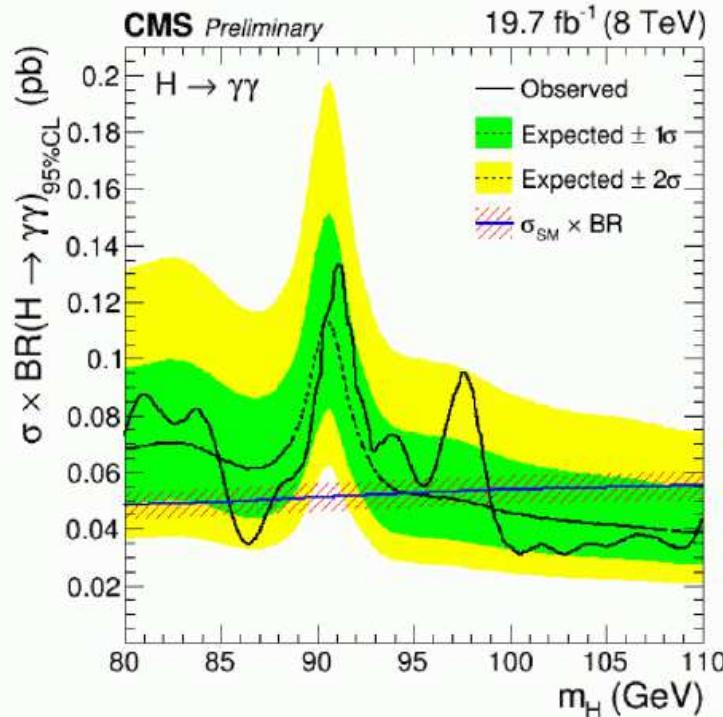
- $\sim 2\sigma$ excursion @ $\sim 80 \text{ GeV}$

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$h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+2



8 TeV:
minimum(maximum)
limit on $\sigma \times \text{Br}$:
 $31(133) \text{ fb}$ at
 $m=102.8(91.1) \text{ GeV}$

13 TeV:
minimum(maximum)
limit on $\sigma \times \text{Br}$:
 $26(161) \text{ fb}$ at
 $m=103.0(89.9) \text{ GeV}$

- 8 TeV limits on $\sigma \times \text{Br}$ redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

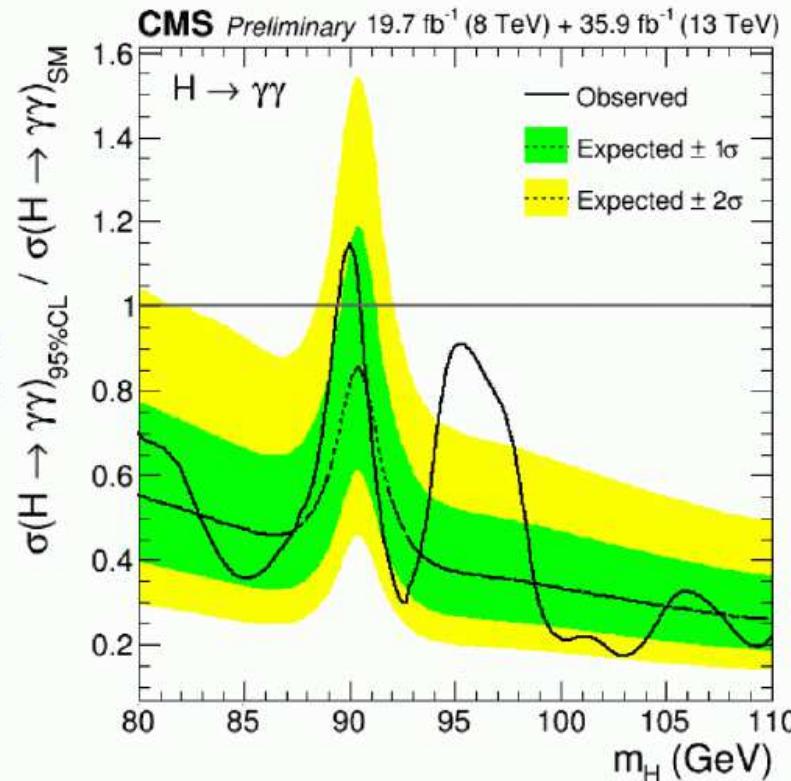
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$h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+2

All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).



- Combined 8 TeV+13 TeV $\sigma \times BR$ limit normalized to SM expectation (production processes assumed in SM proportions). No significant excess with respect to expected limits observed.



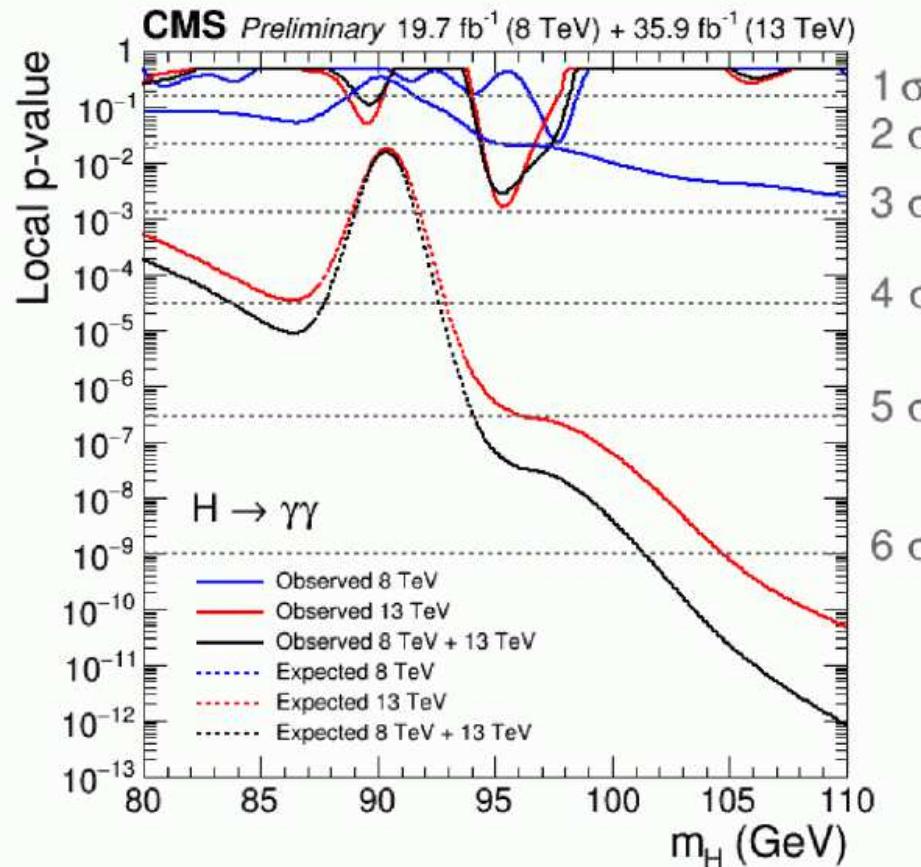
8 TeV+13 TeV:
minimum(maximum) limit
on $(\sigma \times Br) / (\sigma \times Br)_{SM}$:
0.17(1.15) at
 $m=103.0(90.0)$ GeV

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$h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+ 2



- Expected and observed local p-values for **8 TeV**, **13 TeV** and their combination

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8 TeV: Excess with $\sim 2.0 \sigma$ local significance at $m=97.6$ GeV

13 TeV: Excess with $\sim 2.9 \sigma$ local (1.47σ global) significance at $m=95.3$ GeV

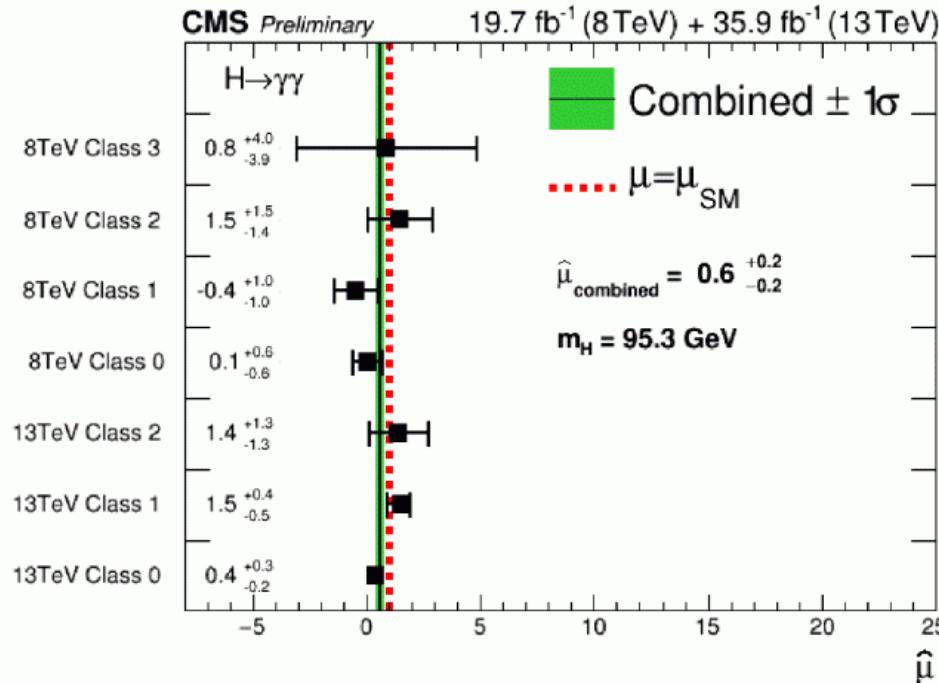
8TeV+13 TeV: Excess with $\sim 2.8 \sigma$ local (1.3σ global) significance at $m=95.3$ GeV

More data are required to ascertain the origin of this excess

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$h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+2



CMS PAS HIG-17-013

Excess here mostly driven by class 1 (&2) at 13 TeV

χ^2 probability for the seven individual values to be compatible with a single signal hypothesis: 41%

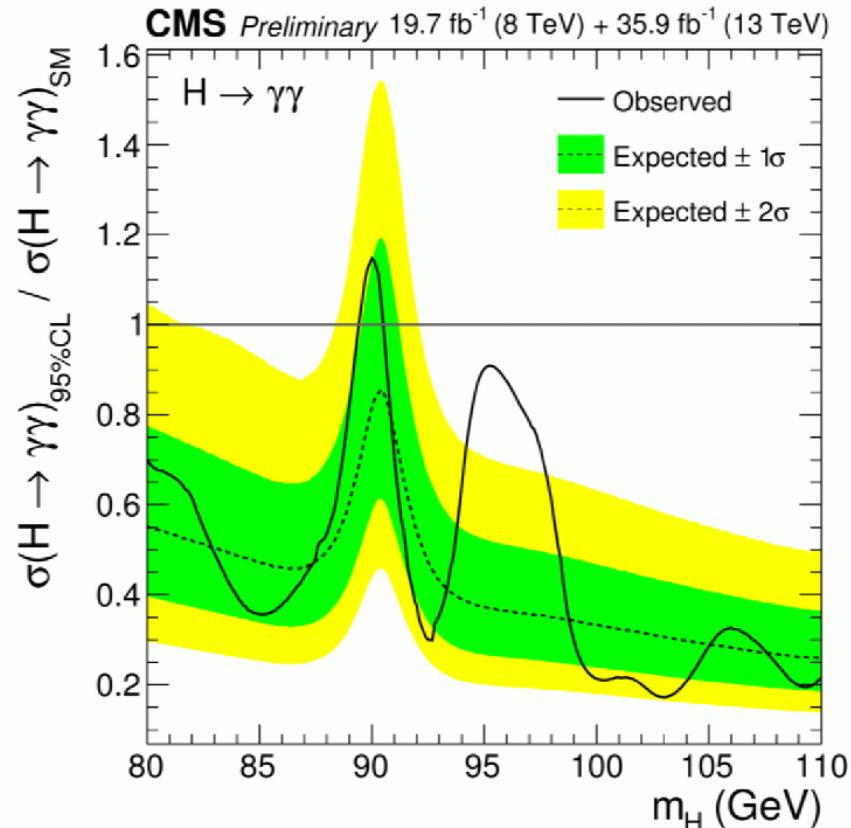
- ‘Signal’ strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing $m_H=95.3$ GeV
- More data are required to ascertain the origin of this excess

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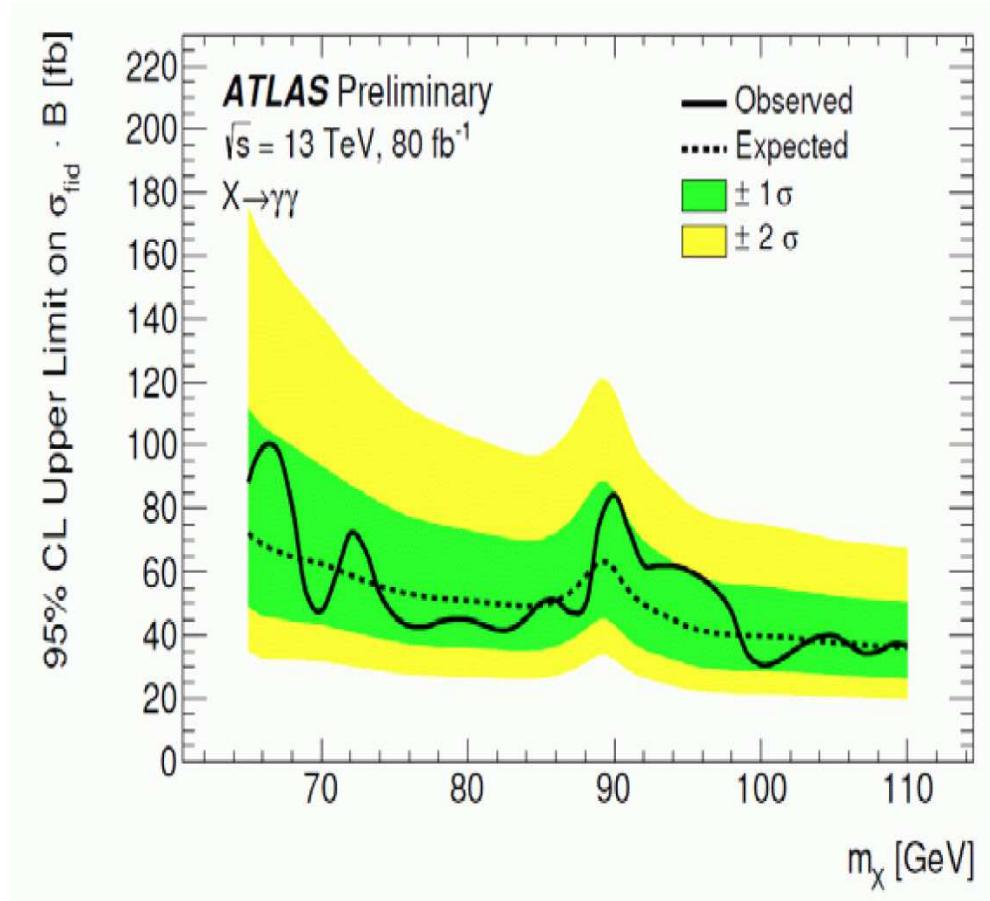
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$$\mu_{\text{CMS}}(96 \text{ GeV}) = [\sigma(pp \rightarrow h_1) \times \text{BR}(h_1 \rightarrow \gamma\gamma)]_{\text{exp/SM}} = 0.6 \pm 0.2$$

What about ATLAS?



CMS PAS HIG-17-013

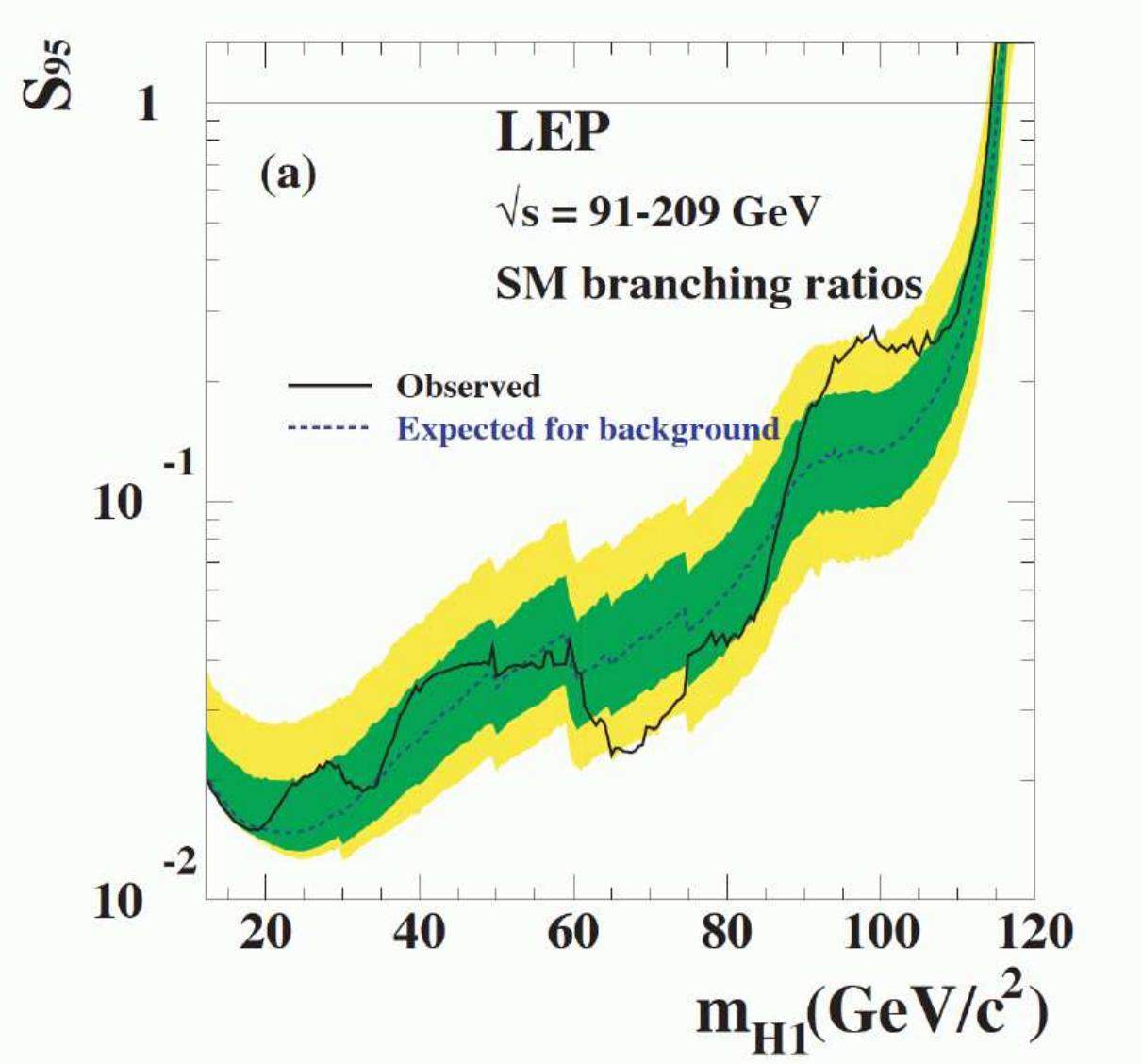


Note: ATLAS gives fiducial cross section! Conversion factor: $1/0.45$

⇒ ATLAS and CMS exclusion limit **identical!** (120 fb)

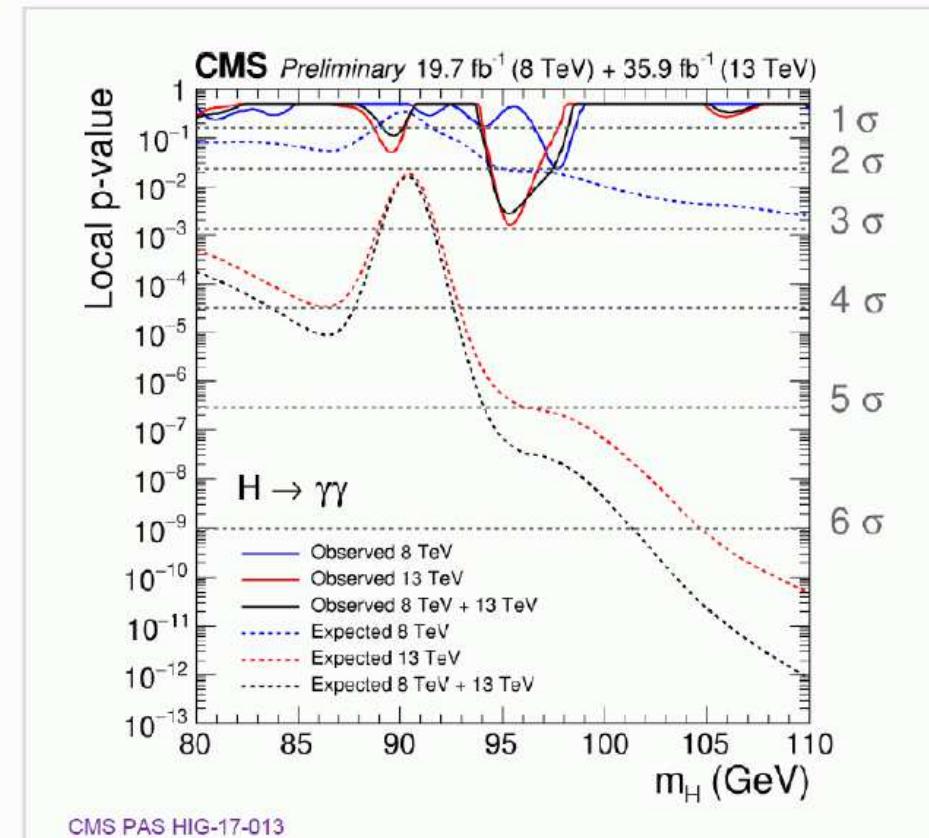
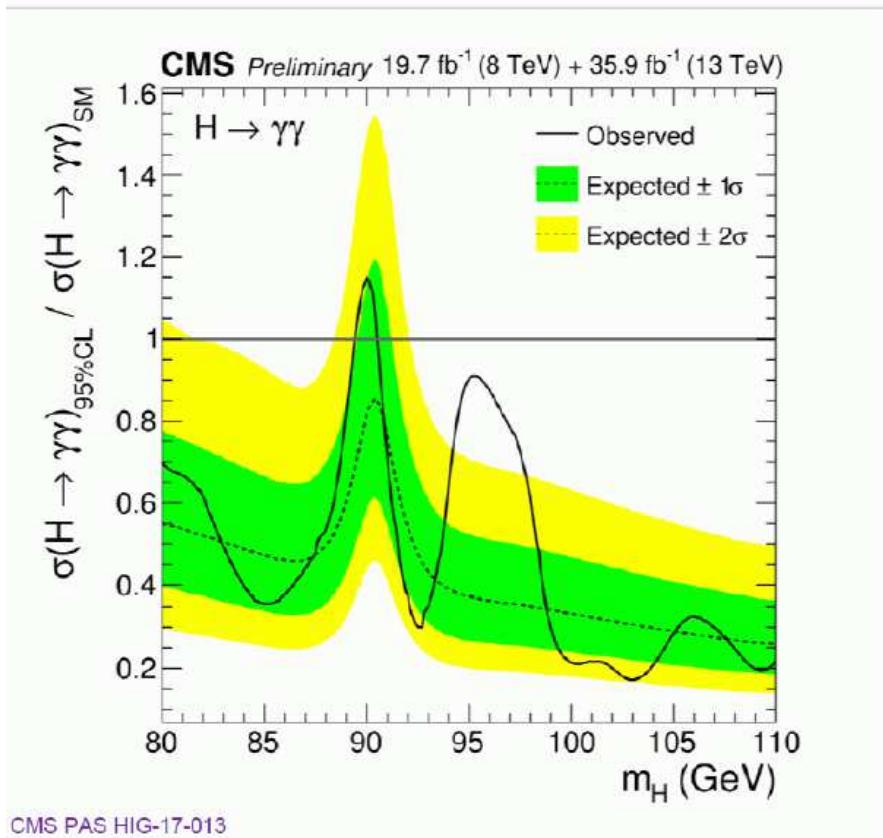
Q: why does ATLAS has same sensitivity with twice amount of data?

What was seen at LEP?



$$\mu_{\text{LEP}}(98 \text{ GeV}) = [\sigma(e^+e^- \rightarrow Z h_1) \times \text{BR}(h_1 \rightarrow b\bar{b})]_{\text{exp/SM}} = 0.117 \pm 0.057$$

- **Combined 8 TeV + 13 TeV** $\sigma \times \text{BR}$ limit normalized to SM expectation:
 - Production processes assumed in SM proportions
 - **No significant excess** with respect to background expectations
- Expected and observed local p-values for **8 TeV**, **13 TeV** and their **combination**



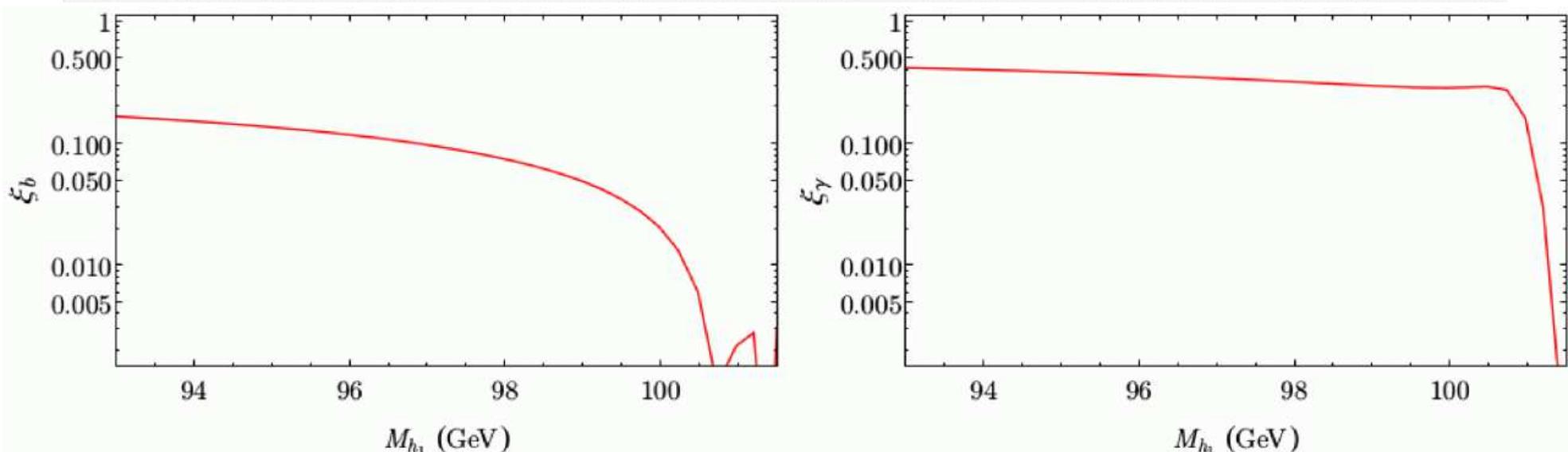
Q: When do you dare to something “significant” ?

What about the NMSSM?

Parameters:

$$\lambda = 0.6, \kappa = 0.035, \tan\beta = 2, \mu_{\text{eff}} = (397 + 15x) \text{ GeV}, M_{H^\pm} = 1 \text{ TeV}, A_\kappa = -325 \text{ GeV}, M_{\text{SUSY}} = 1 \text{ TeV}, A_t = A_b = 0$$

$$\xi_b \equiv \frac{\Gamma[h_1 \rightarrow ZZ] \cdot \text{BR}[h_1 \rightarrow b\bar{b}]}{\Gamma[H_{\text{SM}}(M_{h_1}) \rightarrow ZZ] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \rightarrow b\bar{b}]} \sim \frac{\sigma[e^+e^- \rightarrow Z(h_1 \rightarrow b\bar{b})]}{\sigma[e^+e^- \rightarrow Z(H_{\text{SM}}(M_{h_1}) \rightarrow b\bar{b})]}$$
$$\xi_\gamma \equiv \frac{\Gamma[h_1 \rightarrow gg] \cdot \text{BR}[h_1 \rightarrow \gamma\gamma]}{\Gamma[H_{\text{SM}}(M_{h_1}) \rightarrow gg] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \rightarrow \gamma\gamma]} \sim \frac{\sigma[gg \rightarrow h_1 \rightarrow \gamma\gamma]}{\sigma[gg \rightarrow H_{\text{SM}}(M_{h_1}) \rightarrow \gamma\gamma]}.$$



⇒ both “excesses” can be fitted simultaneously!

4. Conclusions

- High precision predictions in BSM models for Higgs physics are needed!
→ to match experimental accuracy at the LHC and ILC/CLIC
- FeynHiggs provides these predictions for the MSSM
(⇒ code adopted by the LHCHXSWG)
- It is high time for MSSM → NMSSM
... with the same workflow!
FeynHiggs Ansatz: combine genuine NMSSM calculations
with higher-order MSSM corrections
- Re-vamp the Higgs decay calculations:
 - check/improve MSSM
 - NMSSM in exactly the same way
 - numerical examples to show the size of the effects
- $\phi_{96} \rightarrow \gamma\gamma$:
 - CMS sees interesting “excess”, ATLAS has the same limits
 - LEP saw $\phi_{98} \rightarrow b\bar{b}$

⇒ NMSSM can explain both excesses simultaneously

Higgs Days at Santander 2018

Theory meets Experiment

10.-14. September



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Further Questions?