
We still believe in supersymmetry
You must be joking

SUSY Higgs Boson Phenomenology

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Tangier, 09/2019

- Motivation
- New MSSM Higgs Benchmarks for the LHC
- Implications for the HL-LHC and the ILC
- SUSY and the 96 GeV "excess"
- Conclusions

1. Motivation

Two facts:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be “the SM Higgs”!

1. Motivation

Two facts:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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

1. Motivation

Two facts:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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

Models with extended Higgs sectors:

1. SM with addional Higgs singlet
2. Two Higgs Doublet Model (THDM): type I, II, III, IV
3. Minimal Supersymmetric Standard Model (MSSM)
4. MSSM with one extra singlet (NMSSM)
5. MSSM with more extra singlets
6. SM/MSSM with Higgs triplets
7. . . .

$\Rightarrow$ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

$\Rightarrow$ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, . . .

Which model should we focus on?

Which model should we focus on? $\Rightarrow$ experimental data as guidance!

Which model should we focus on? $\Rightarrow$ experimental data as guidance!

Some "recent" measurements:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

Which model should we focus on? $\Rightarrow$ experimental data as guidance!

Some "recent" measurements:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

Simple SUSY models predicted correctly:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

Which model should we focus on? ⇒ experimental data as guidance!

Some "recent" measurements:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

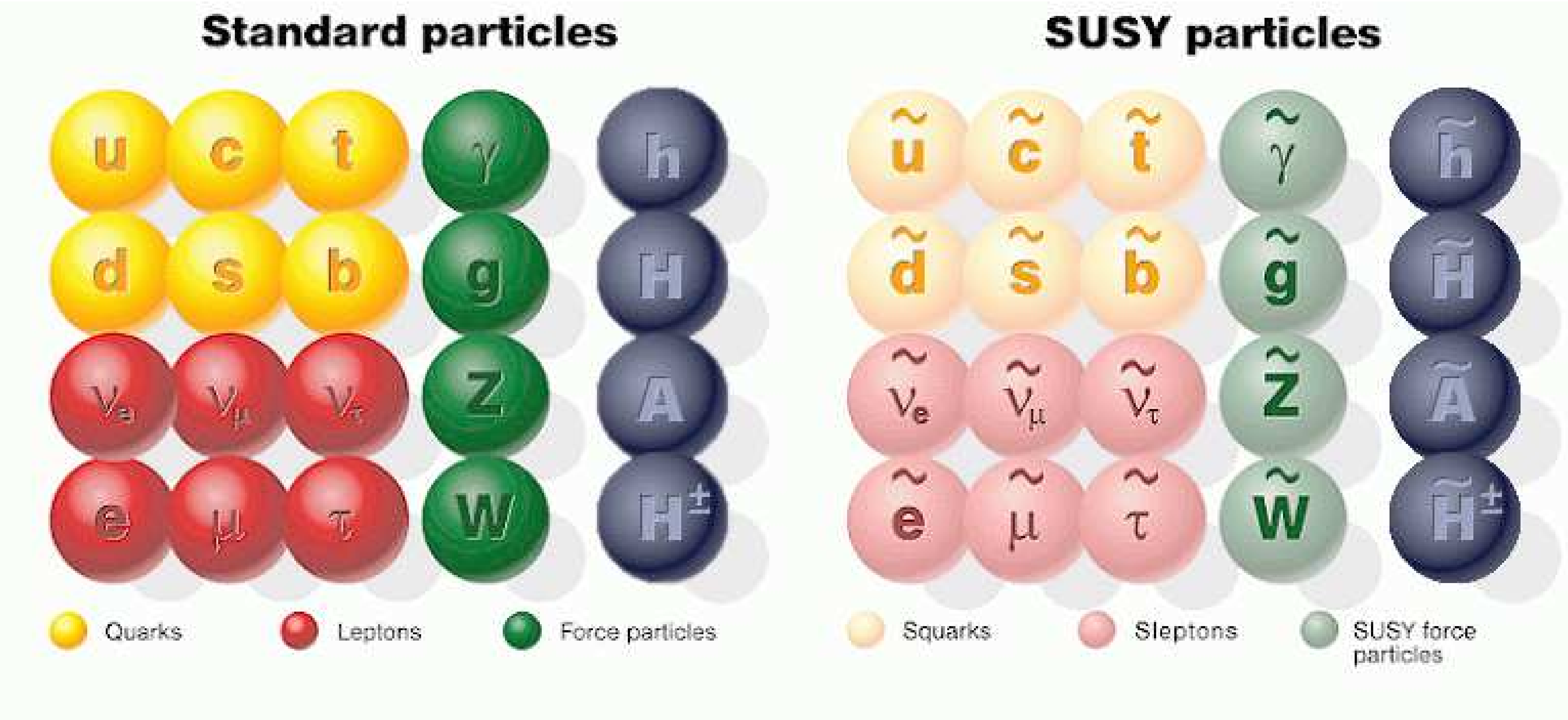
Simple SUSY models predicted correctly:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

⇒ good motivation to look at SUSY! :-)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved
no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case: 105 new parameters: masses, mixing angles, phases

(⇒ many (close to) zero according to experimental data)

⇒ no model missed (within the MSSM)

⇒ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, FUTs, . . . :

assumption on the scenario that achieves spontaneous SUSY breaking
⇒ prediction for soft SUSY-breaking terms
in terms of small set of parameters

⇒ easy to handle, but not all relevant phenomenology captured

C. Benchmark scenrios:

fix all-2 MSSM parameters in a smart way, explore benchmark planes
⇒ easy to handle, interesting phenomenology captured!

The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

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)

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

The MSSM Higgs sector: with $\mathcal{CP}$ violation

Enlarged Higgs sector: Two Higgs doublets

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}|H_1\bar{H}_2|^2$$

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)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot\beta, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

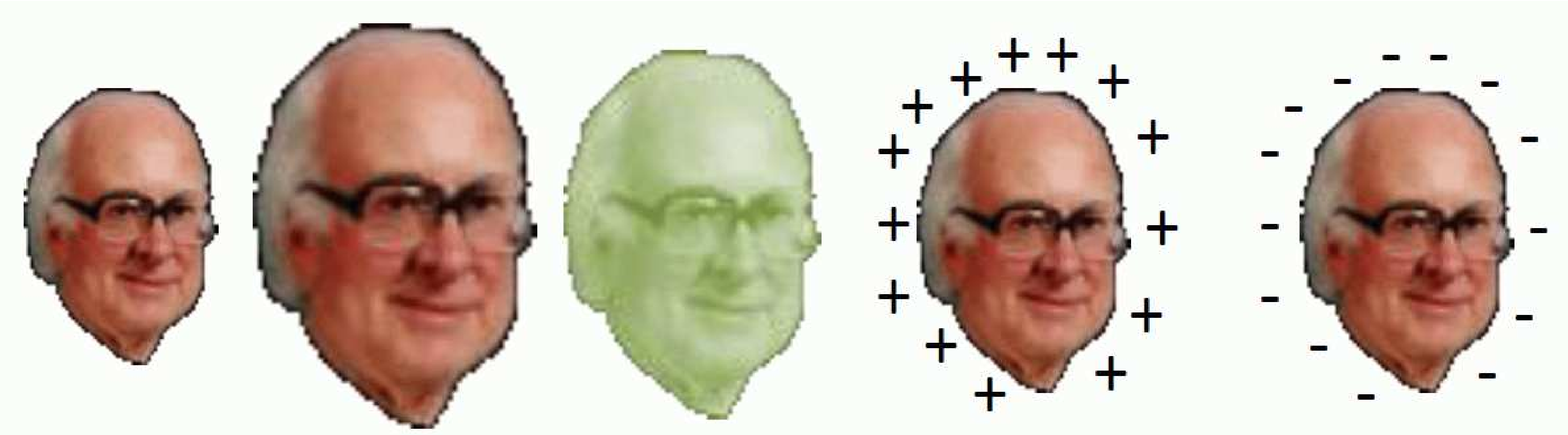
$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

2. New MSSM Higgs Benchmarks for the LHC



Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

$\rightarrow$ investigate benchmark scenarios:

$\rightarrow$ Vary only M_A (or $M_{H^\pm}$) and $\tan\beta$
$\rightarrow$ Keep all other SUSY parameters fixed

[*E. Bagnaschi, H. Bahl, E. Fuchs, T. Hahn, S.H., S. Liebler, S. Patel, P. Slavich, T. Stefaniak, C. Wagner, G. Weiglein '18*]

1. M_h^{125} scenario: 2HDM-like (similar to the hMSSM, but a true SUSY model)
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \rightarrow \gamma\gamma$, $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \rightarrow \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^\pm\tilde{\chi}_l^\mp$
4. M_h^{125} (alignment) scenario: h SM-like for very low M_A
5. M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2-h_3 interference

Not covered:

Set of benchmarks for low $\tan\beta$

[*H. Bahl, S. Liebler, T. Stefaniak '19*]

– use 2HDM as low-energy model

– (mainly) EFT calculation, RGE running to M_{SUSY}

– implemented in FeynHiggs (so far priv.)

Heavy SUSY particles: $M_{h,\text{EFT}}^{125}$

light EW-inos: $M_{h,\text{EFT}}^{125}(\tilde{\chi})$

Data to be taken into account:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

Data to be taken into account:

– Higgs boson mass (LHC) ⇒ FeynHiggs

– Higgs boson signal strengths (LHC) ⇒ HiggsSignals/SusHi

Data to be taken into account:

– Higgs boson mass (LHC) ⇒ FeynHiggs

– Higgs boson signal strengths (LHC) ⇒ HiggsSignals/SusHi

– Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds

Data to be taken into account:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

– Higgs boson signal strengths (LHC) $\Rightarrow$ HiggsSignals/SusHi

– Higgs boson exclusion bounds (LHC, Tevatron, LEP) $\Rightarrow$ HiggsBounds

– SUSY searches (LHC)

Data to be taken into account:

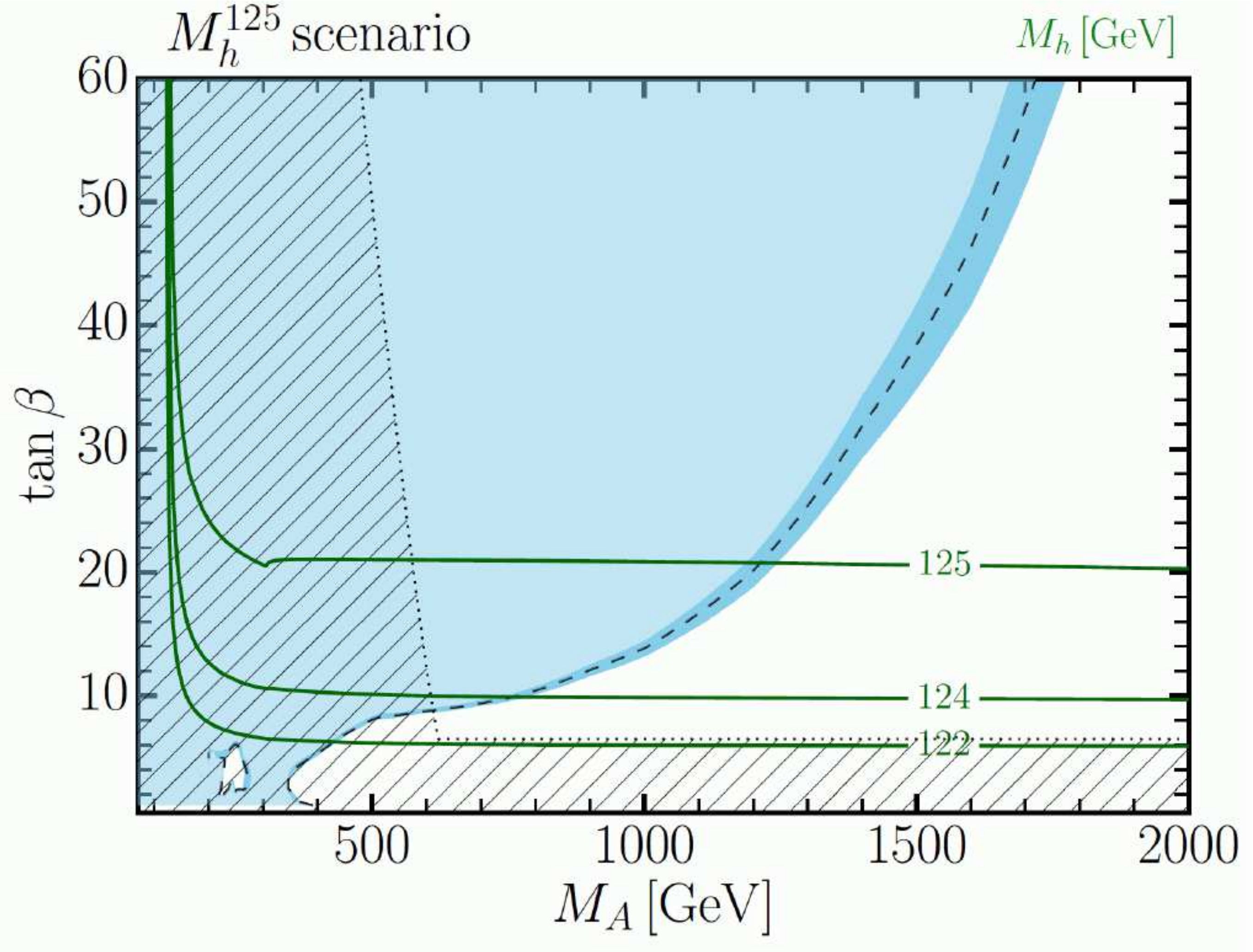
- Higgs boson mass (LHC) ⇒ FeynHiggs
- Higgs boson signal strengths (LHC) ⇒ HiggsSignals/SusHi
- Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds
- SUSY searches (LHC)

Data on purpose not to be taken into account:

- electroweak precision data
- flavor data
- astrophysical data (DM properties)

New benchmark: M_h^{125}

[H. Bahl et al., '18]



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

$$\mu = 1 \text{ TeV}, \; M_1 = 1 \text{ TeV}$$

$$M_2 = 1 \text{ TeV}, \; M_3 = 2.5 \text{ TeV}$$

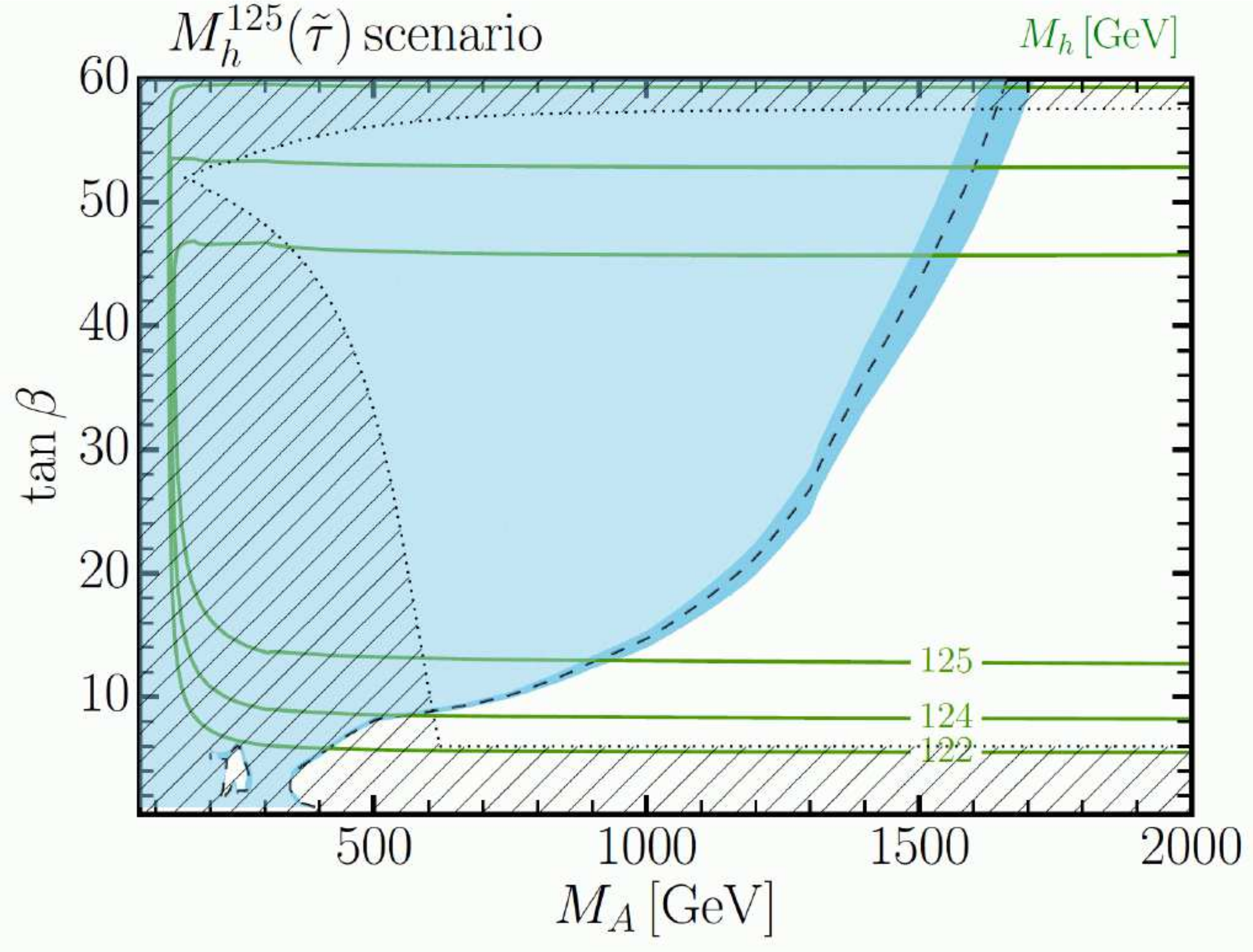
$$X_t = 2.8 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

⇒ new vanilla benchmark model

New benchmark: $M_h^{125}(\tilde{\tau})$

[H. Bahl et al., '18]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 350$ GeV

$\mu = 1$ TeV, $M_1 = 180$ GeV

$M_2 = 300$ GeV, $M_3 = 2.5$ TeV

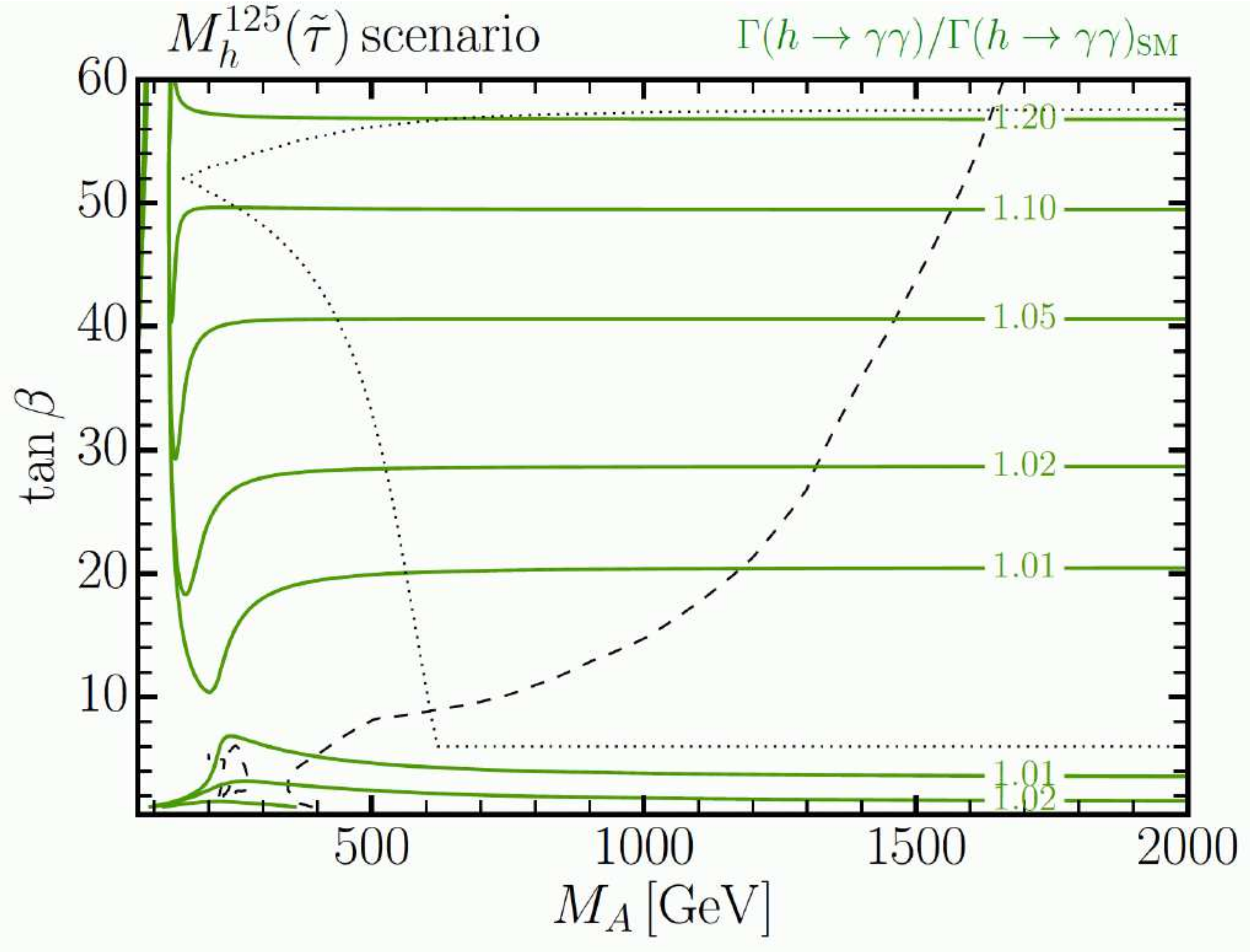
$X_t = 2.8$ TeV

$A_t = A_b, A_\tau = 800$ GeV

⇒ slightly reduced heavy Higgs coverage

New benchmark: $M_h^{125}(\tilde{\tau})$

[H. Bahl et al., '18]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 350$ GeV

$\mu = 1$ TeV, $M_1 = 180$ GeV

$M_2 = 300$ GeV, $M_3 = 2.5$ TeV

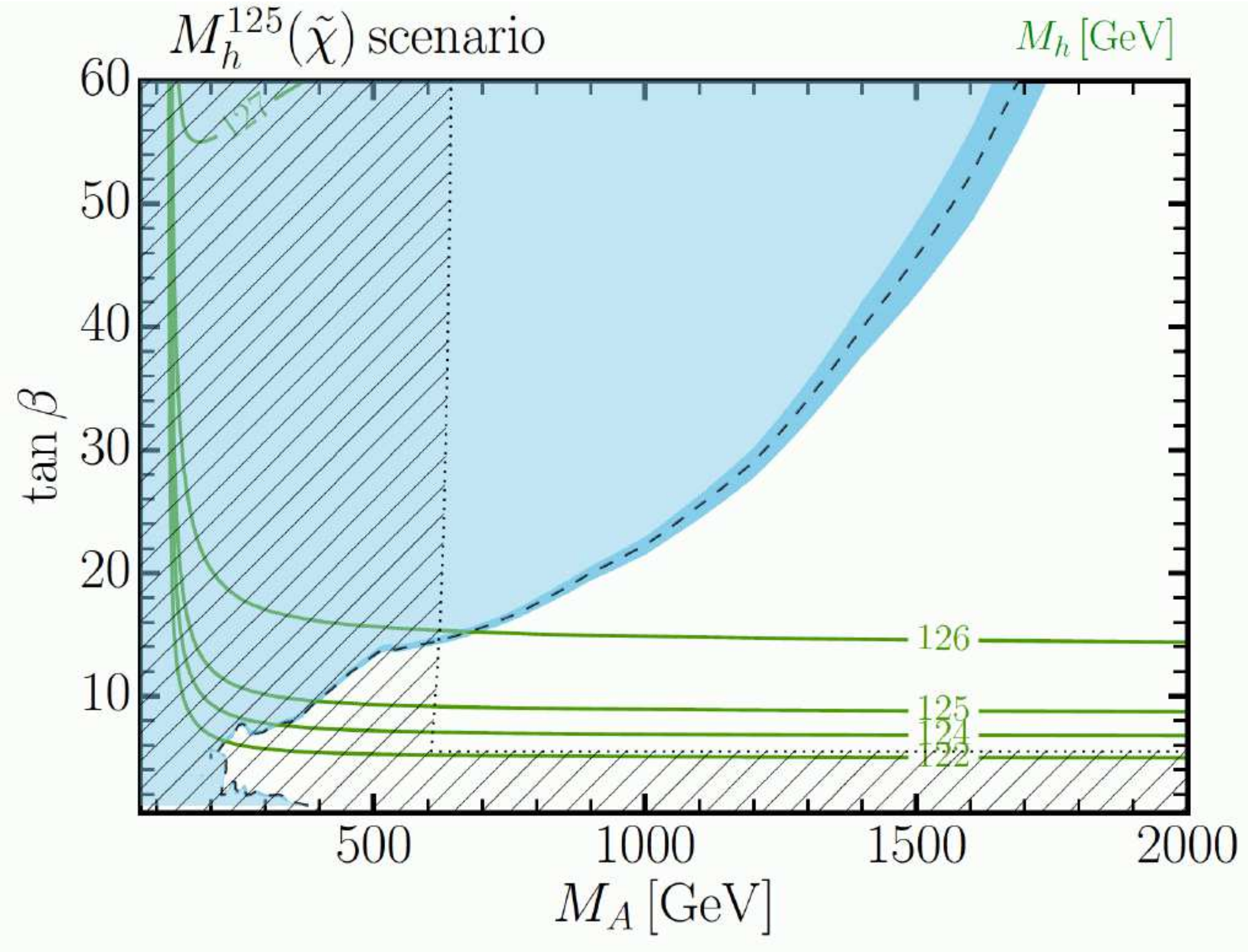
$X_t = 2.8$ TeV

$A_t = A_b, A_\tau = 800$ GeV

$\Rightarrow$ strong impact on $\Gamma(h \to \gamma\gamma)$

New benchmark: $M_h^{125}(\tilde{\chi})$

[H. Bahl et al., '18]



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

$$\mu = 180 \text{ GeV}, \; M_1 = 160 \text{ GeV}$$

$$M_2 = 180 \text{ GeV}, \; M_3 = 2.5 \text{ TeV}$$

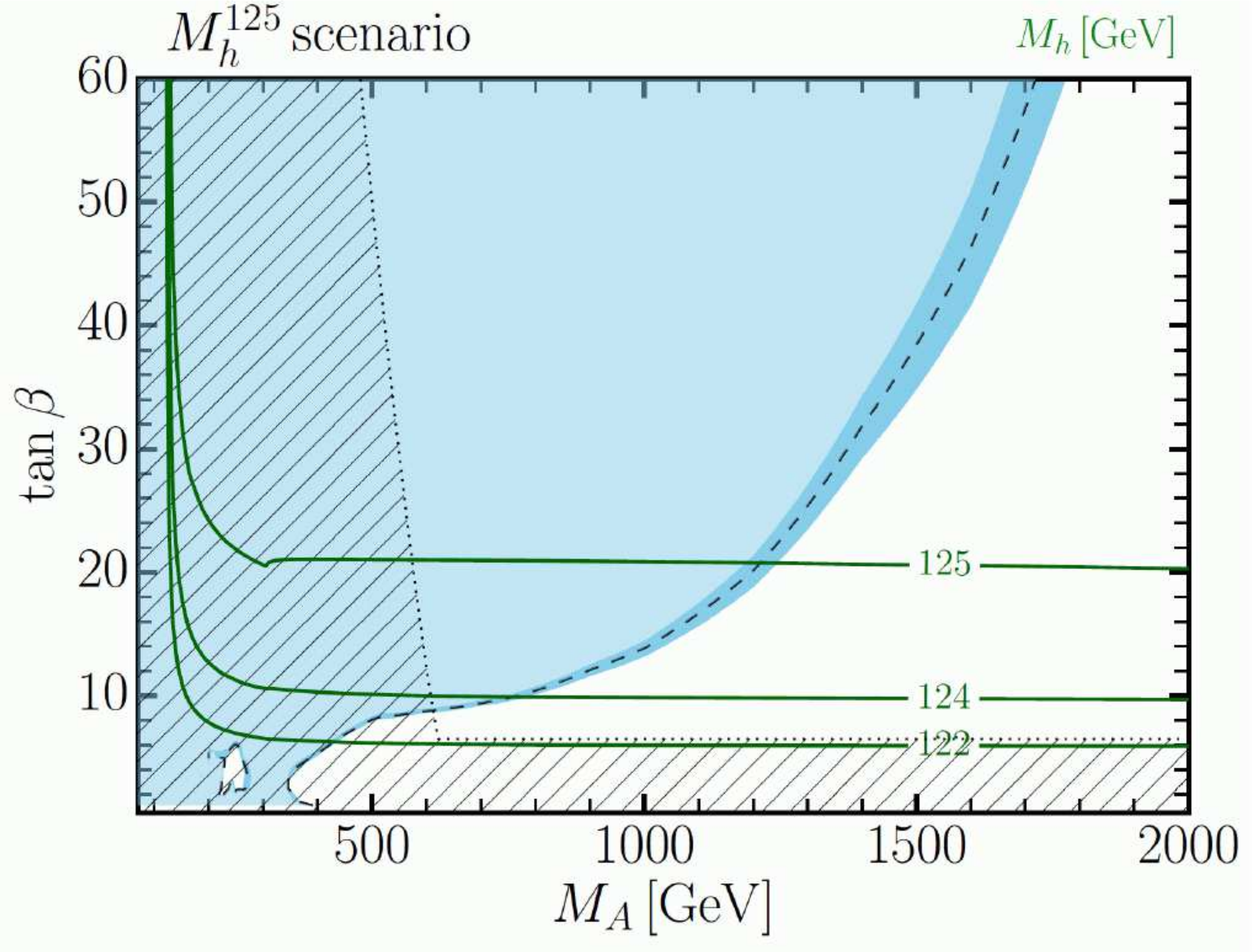
$$X_t = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

⇒ strongly reduced heavy Higgs coverage

New benchmark: M_h^{125}

[*H. Bahl et al., '18*]



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

$$\mu = 1 \text{ TeV}, \; M_1 = 1 \text{ TeV}$$

$$M_2 = 1 \text{ TeV}, \; M_3 = 2.5 \text{ TeV}$$

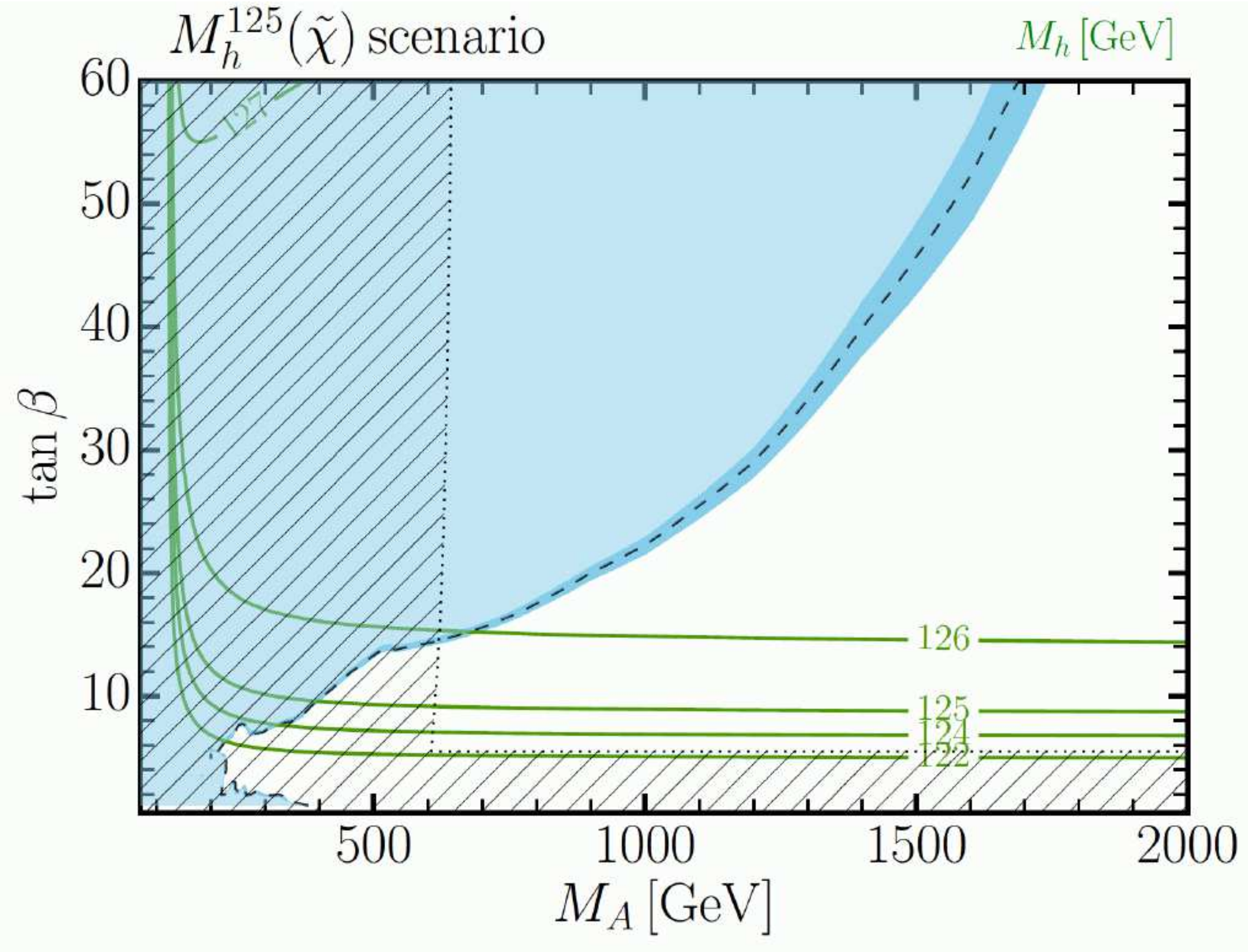
$$X_t = 2.8 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

⇒ new vanilla benchmark model

New benchmark: $M_h^{125}(\tilde{\chi})$

[*H. Bahl et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 180$ GeV, $M_1 = 160$ GeV

$M_2 = 180$ GeV, $M_3 = 2.5$ TeV

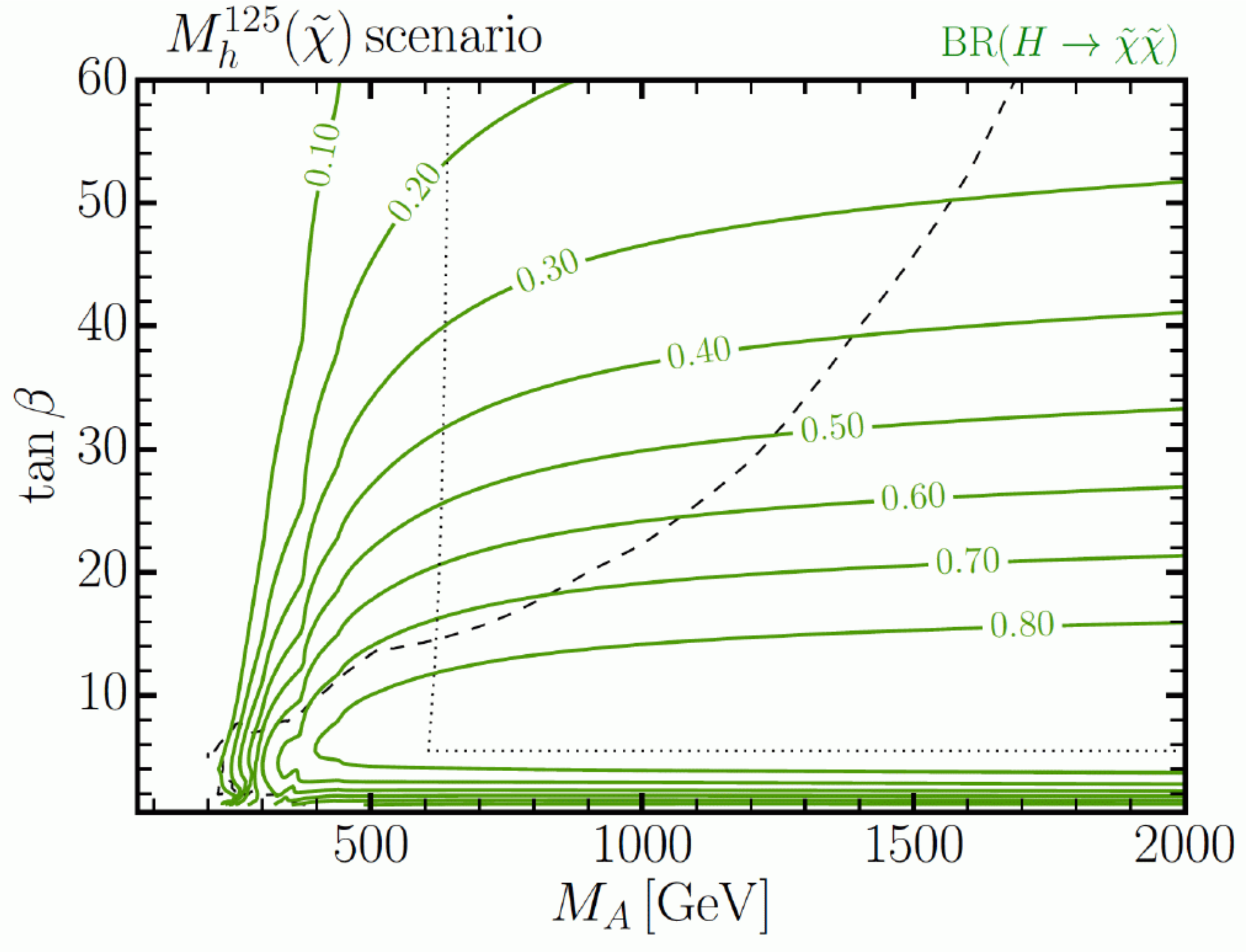
$X_t = 2.5$ TeV

$A_t = A_b = A_\tau$

$\Rightarrow$ strongly reduced heavy Higgs coverage

New benchmark: $M_h^{125}(\tilde{\chi})$

[*H. Bahl et al., '18*]

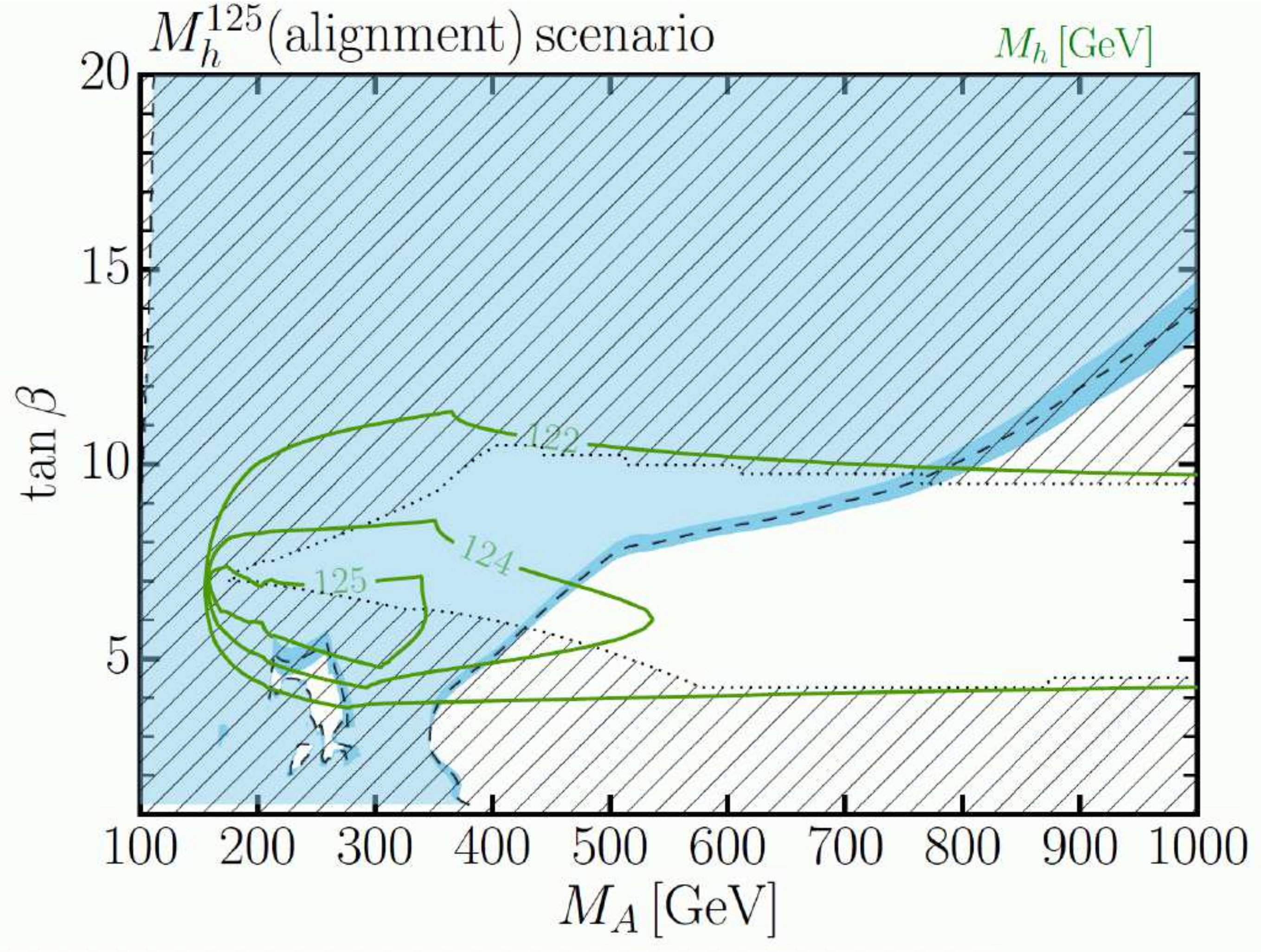


$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$
$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$
$$\mu = 180 \text{ GeV}, \; M_1 = 160 \text{ GeV}$$
$$M_2 = 180 \text{ GeV}, \; M_3 = 2.5 \text{ TeV}$$
$$X_t = 2.5 \text{ TeV}$$
$$A_t = A_b = A_\tau$$

⇒ Huge BR of heavy Higgses to EW-inos

New benchmark: M_h^{125}(align)

[*H. Bahl et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 7.5$ TeV, $M_1 = 500$ GeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

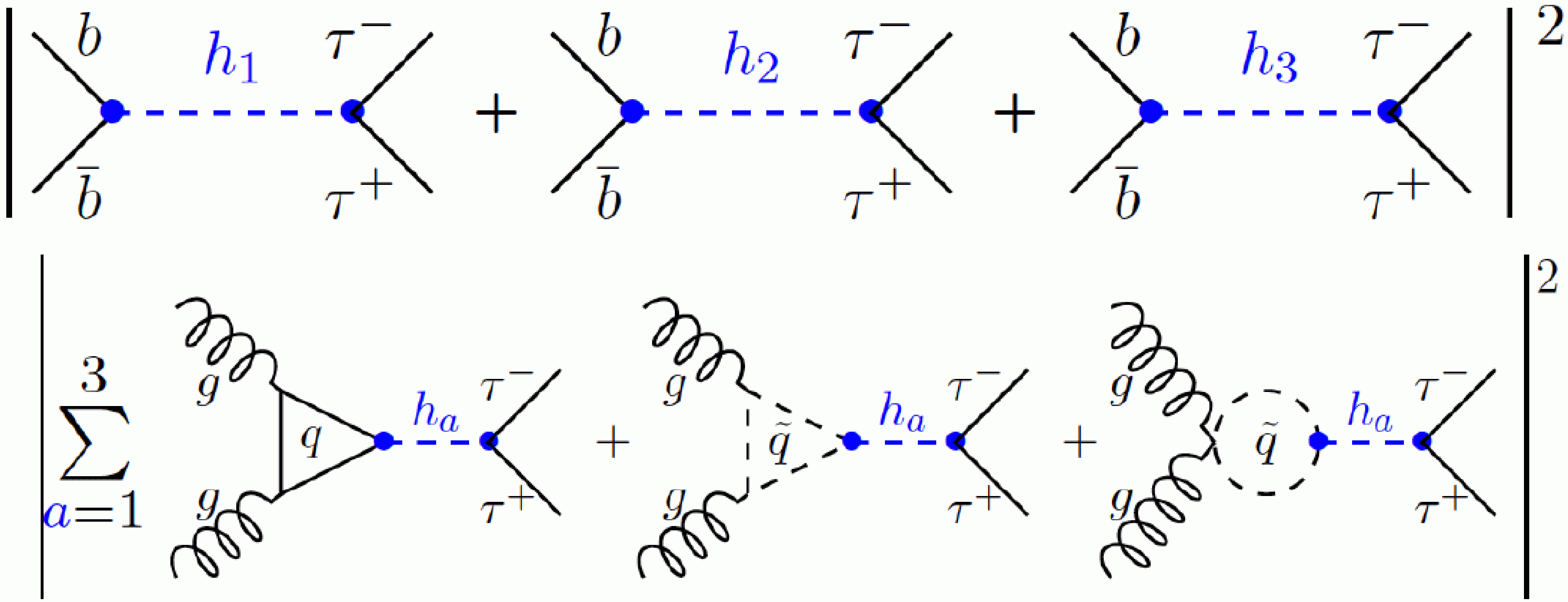
$A_t = A_b = A_\tau = 6.25$ TeV

$\Rightarrow h$ SM-like for very low M_A

LHC Higgs searches for complex parameters:

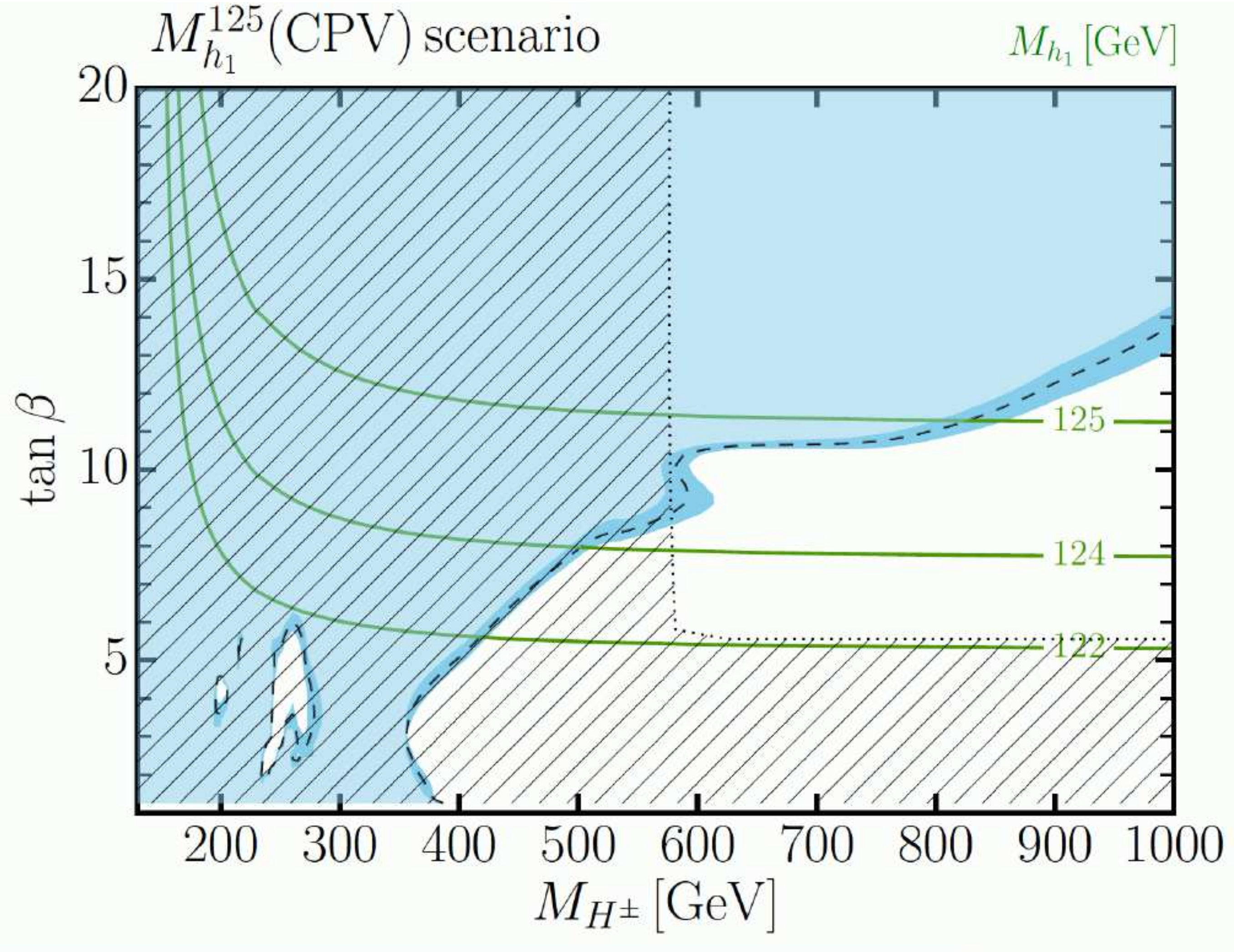
$h_1 \sim H_{125}$, $M_{h_2} \approx M_{h_3}$, CPV: large h_2-h_3 mixing possible:

Higgs bosons as intermediate states in $\{b\bar{b}, gg\} \to h_a \to \tau\tau$



New benchmark: $M_{h_1}^{125}$(CPV)

[H. Bahl et al., '18]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 1.65$ TeV, $M_1 = 1$ TeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$|A_t| = \mu/\tan\beta + 2.8$ TeV

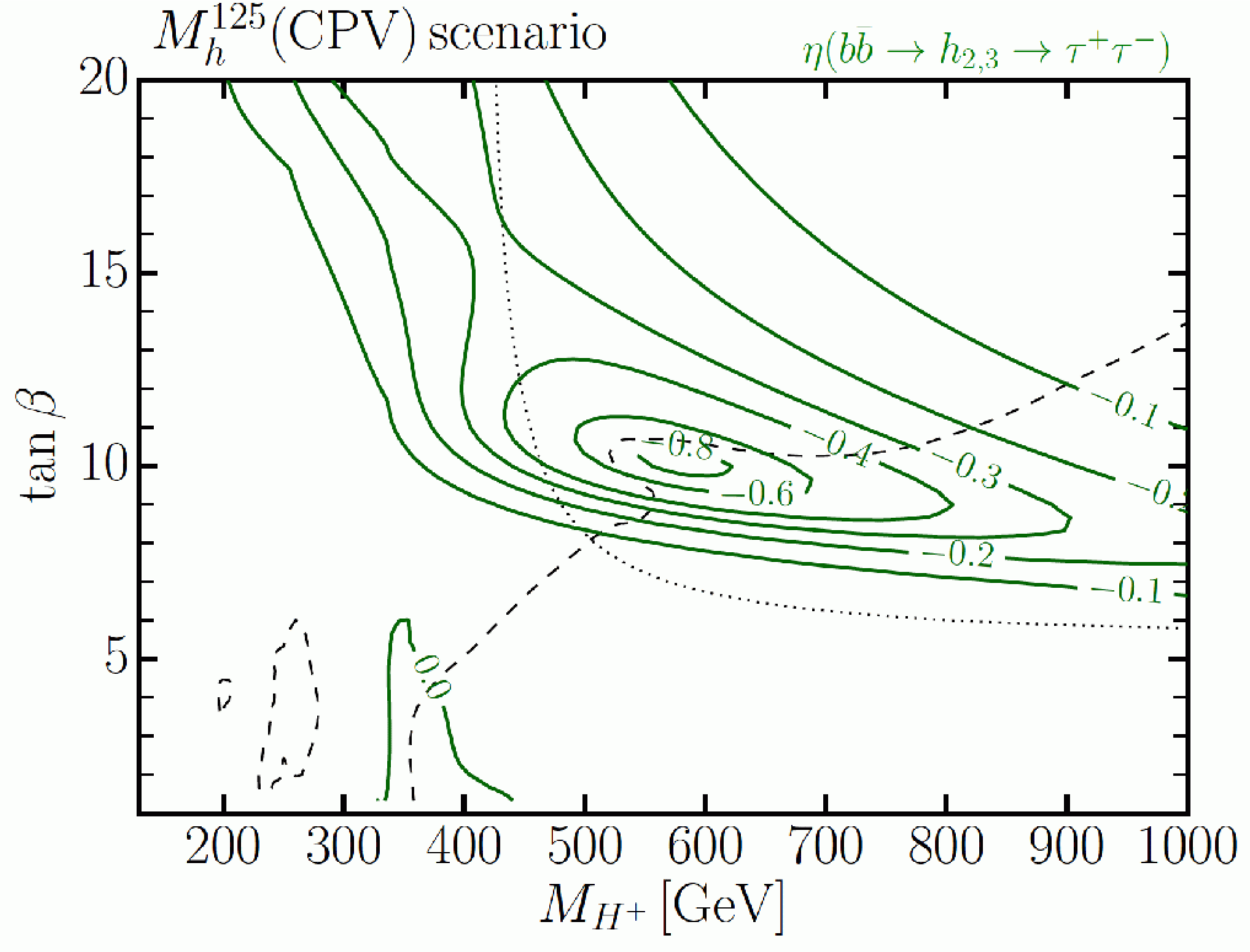
$\phi_{A_t} = 2/15\,\pi$

$|A_t| = A_b = A_\tau$

⇒ reduced coverage due to h_2-h_3 interference

New benchmark: $M_{h_1}^{125}$(CPV)

[*H. Bahl et al., '18*]

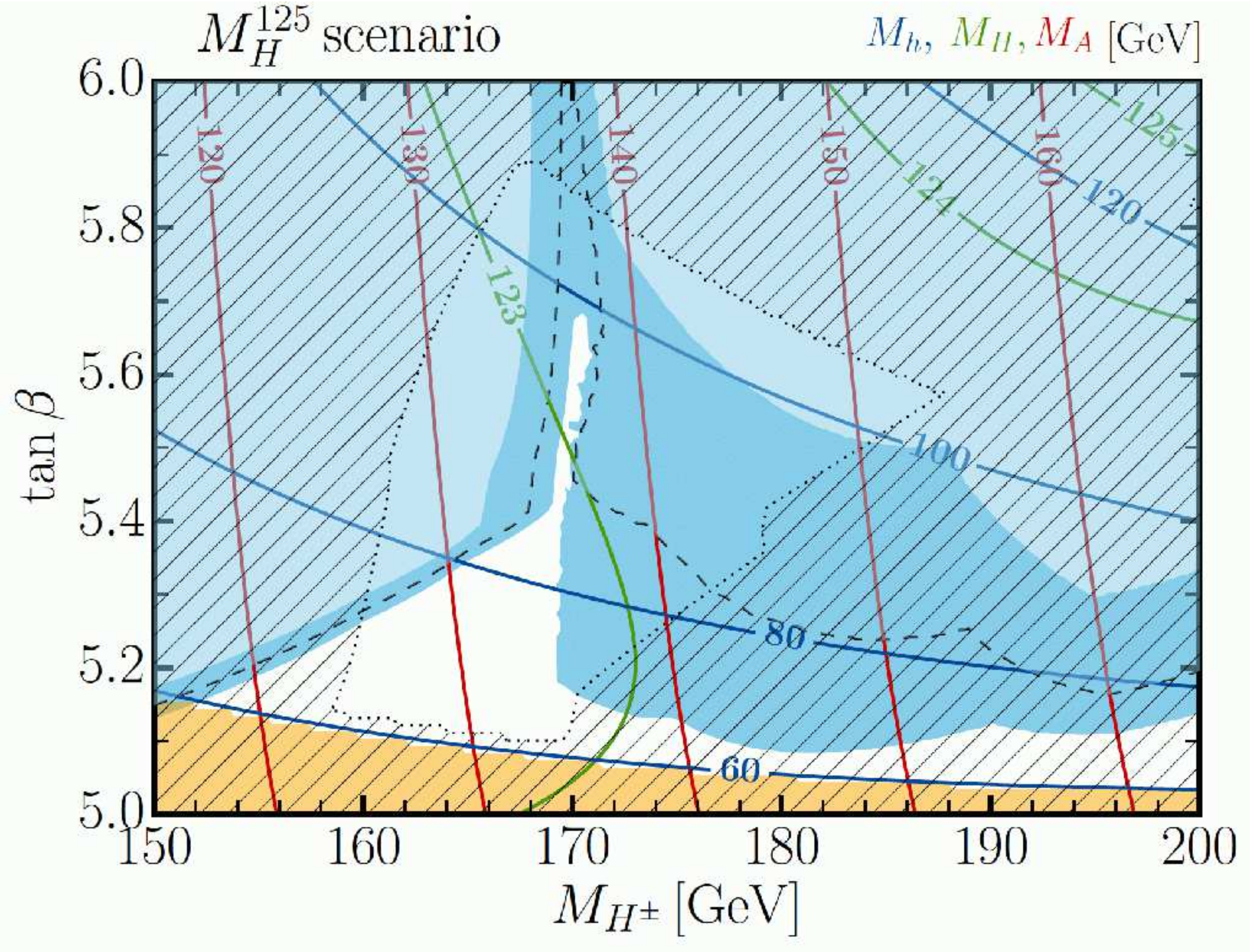


$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2 \text{ TeV}$$
$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$
$$\mu = 1.65 \text{ TeV}, \; M_1 = 1 \text{ TeV}$$
$$M_2 = 1 \text{ TeV}, \; M_3 = 2.5 \text{ TeV}$$
$$|A_t| = \mu/\tan\beta + 2.8 \text{ TeV}$$
$$\phi_{A_t} = 2/15\,\pi$$
$$|A_t| = A_b = A_\tau$$

⇒ reduced coverage due to h_2-h_3 interference

New benchmark: M_H^{125}

[H. Bahl et al., '18]



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = 750 \text{ GeV} - 2(M_{H^\pm} - 150 \text{ GeV})$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2 \text{ TeV}$$

$$\mu = [5.8 \text{ TeV} + 20(M_{H^\pm} - 150 \text{ GeV})] \times M_{\tilde{Q}_3}/750 \text{ GeV}$$

$$M_1 = M_{\tilde{Q}_3} - 75 \text{ GeV}$$

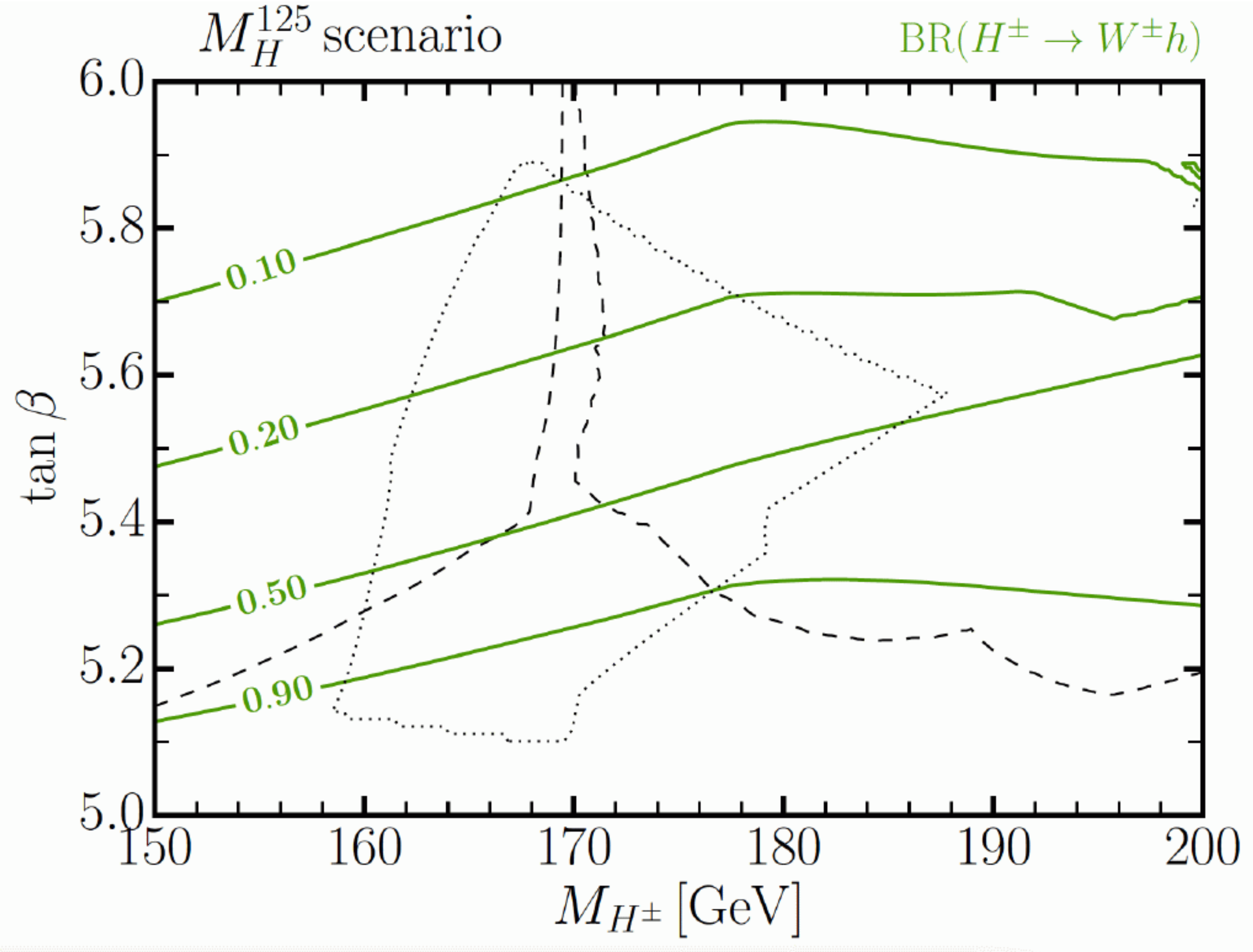
$$M_2 = 1 \text{ TeV}, \; M_3 = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau = 0.65 M_{\tilde{Q}_3}$$

$\Rightarrow$ exotic solution still viable!

New benchmark: M_H^{125}

[H. Bahl et al., '18]



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = 750 \text{ GeV} - 2(M_{H^\pm} - 150 \text{ GeV})$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2 \text{ TeV}$$

$$\mu = [5.8 \text{ TeV} + 20(M_{H^\pm} - 150 \text{ GeV})]\times M_{\tilde{Q}_3}/750 \text{ GeV}$$

$$M_1 = M_{\tilde{Q}_3} - 75 \text{ GeV}$$

$$M_2 = 1 \text{ TeV}, \; M_3 = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau = 0.65 M_{\tilde{Q}_3}$$

$\Rightarrow$ large BR($H^\pm \to W^\pm h$)

3. Implications for the HL-LHC and the ILC

[H. Bahl, P. Bechtle, S.H., S. Liebler, T. Stefaniak, G. Weiglein '19 – PRELIMINARY]

HL-LHC:

– will improve direct search limits
– will improve rate measurements (production $\times$ decay)
  systematic/theory uncertainties: S2 scenario

[M. Cepeda et al. '19 – YR18]

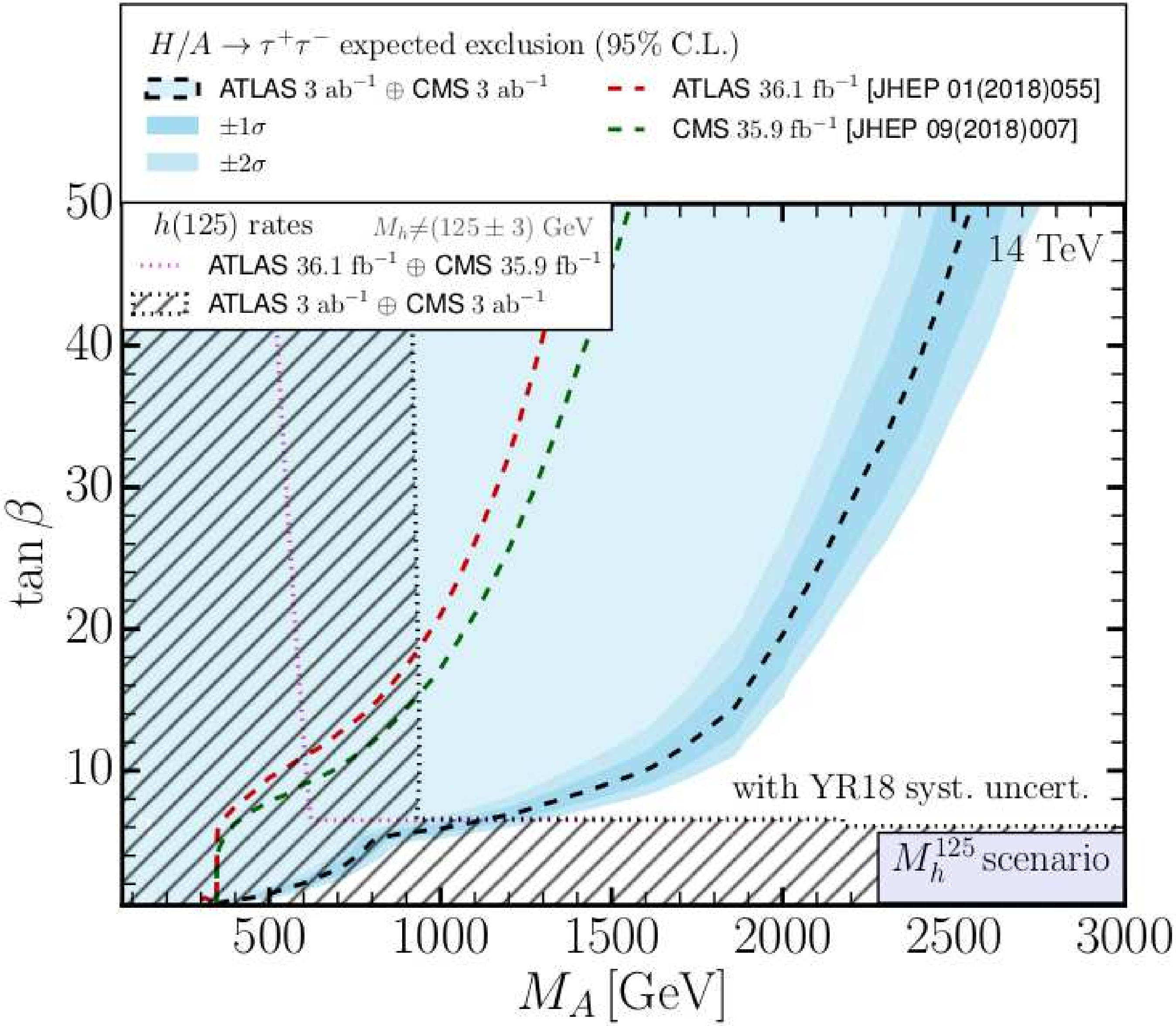
ILC:

– will improve rate measurements (no theory assumptions!)
  – $250\,\text{fb}^{-1}$ at ILC250 $\oplus$ $500\,\text{fb}^{-1}$ at ILC500
  – polarization: $P(e^-, e^+) = (-80\%, +30\%)$

[T. Barklow et al. '17, '19]

HL-LHC reach in M_h^{125} scenario

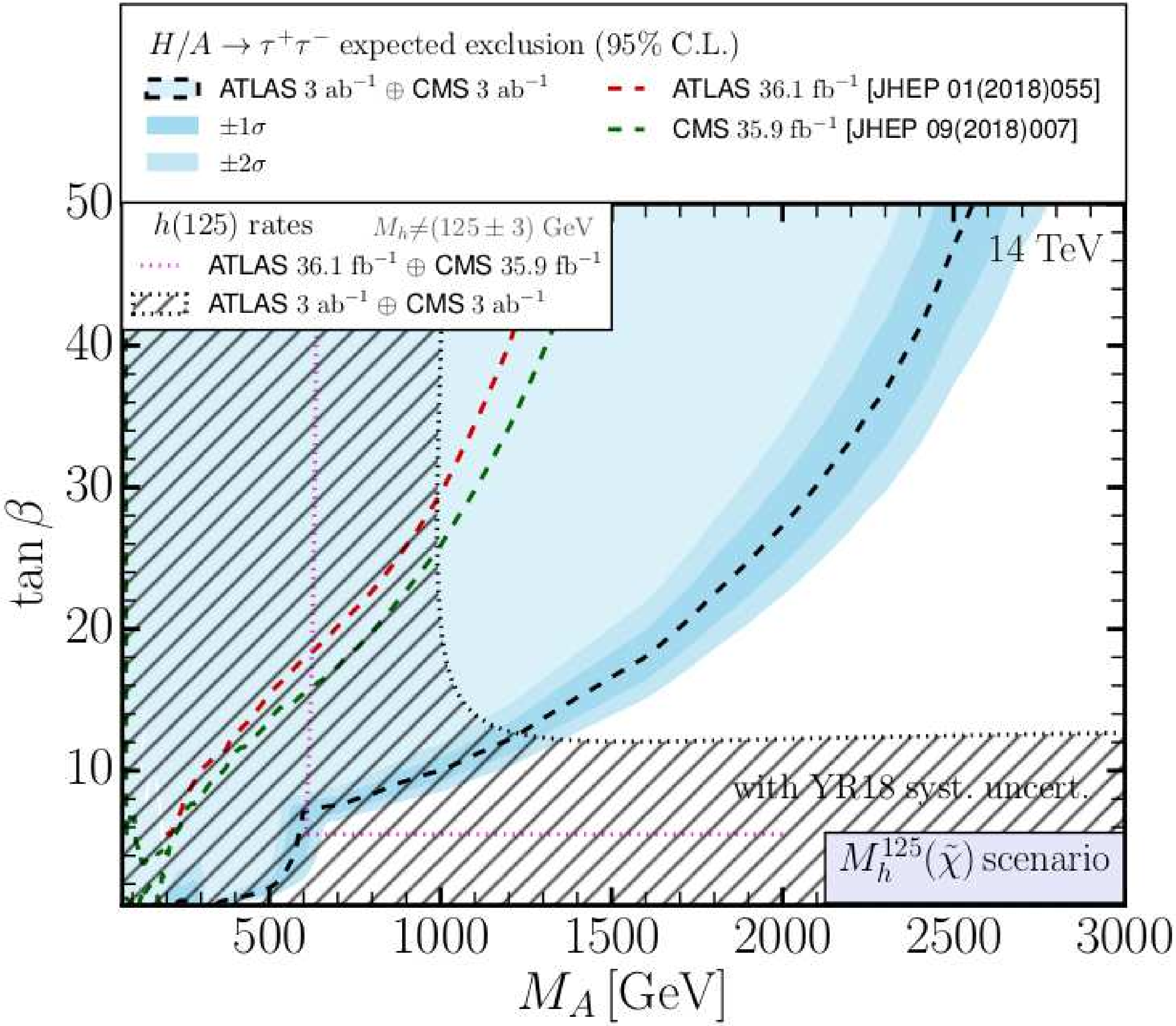
[*H. Bahl et al., PRELIMINARY*]



⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV

HL-LHC reach in $M_h^{125}(\tilde{\chi})$ scenario

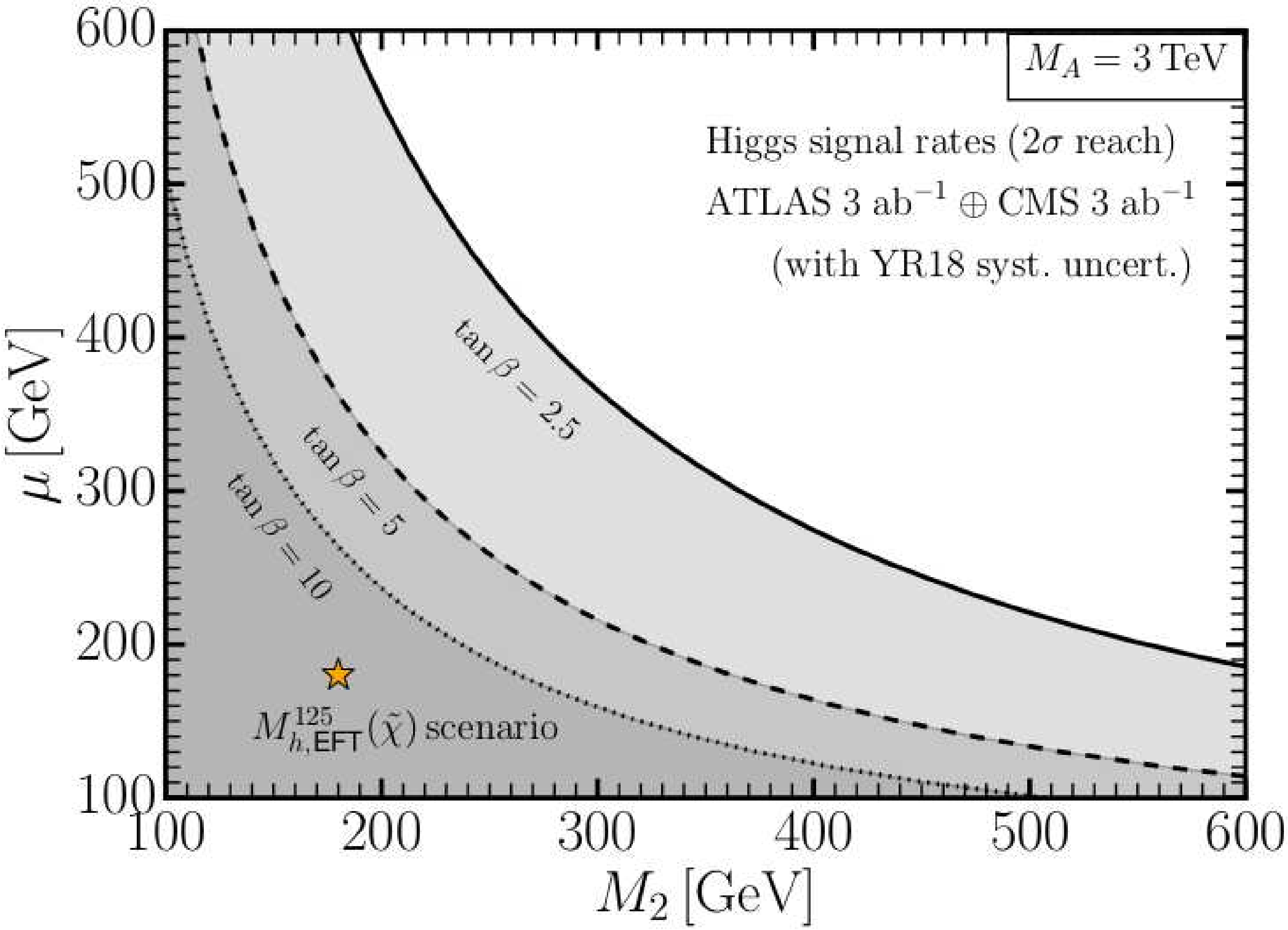
[*H. Bahl et al., PRELIMINARY*]



⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV

Indirect HL-LHC reach in $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario [*H. Bahl et al., PRELIMINARY*]

$\Rightarrow$ reach for charginos (mainly) via $h \to \gamma\gamma$:

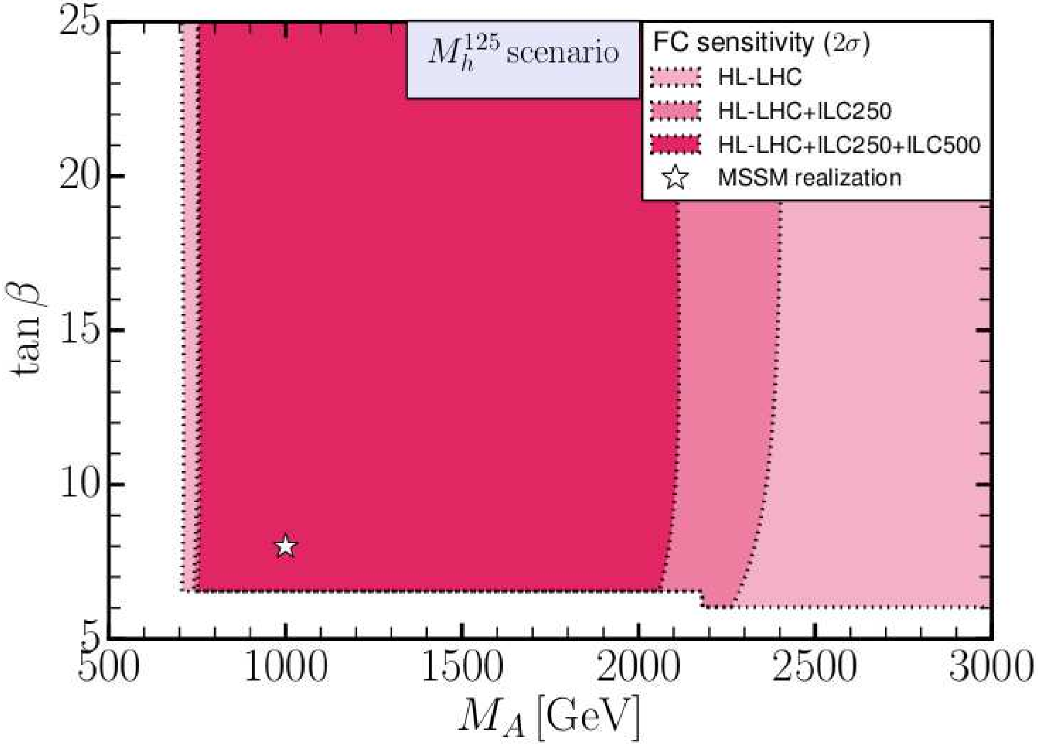


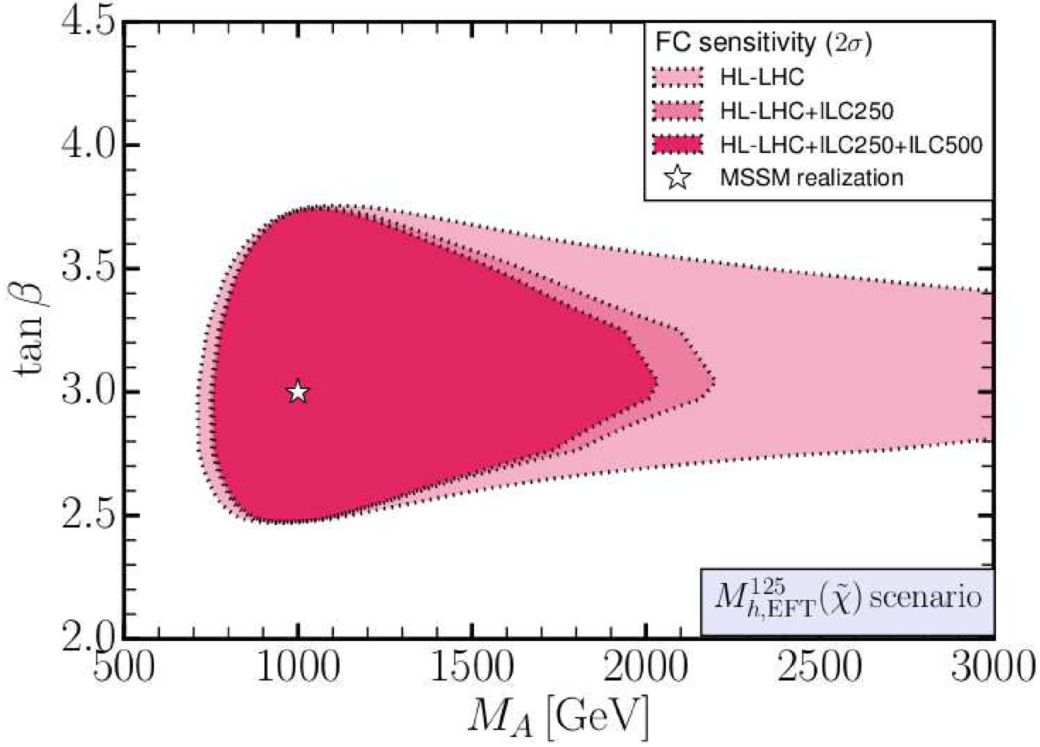
$\Rightarrow$ strong reach for low $\tan\beta$

Relevance of ILC improvement:

[*H. Bahl et al., PRELIMINARY*]

– Assume a realization of an MSSM point: $M_A = 1$ TeV, $\tan\beta = 7/3$
– What limits can be set from rate/coupling measurements?

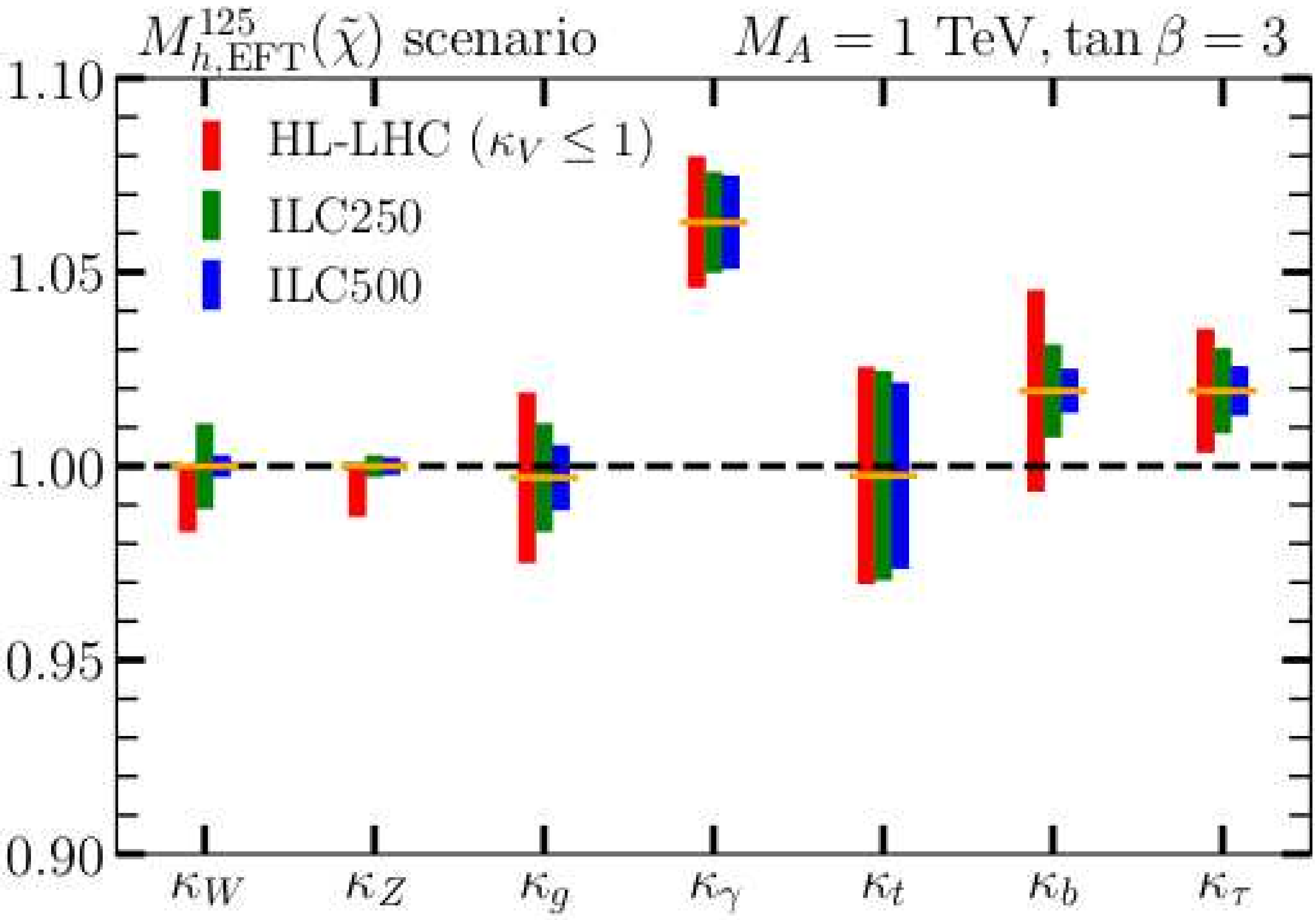




$\Rightarrow$ only ILC measurements give upper limit on M_A

$\Rightarrow$ limits on $\tan\beta$ only for small(er) $\tan\beta$

Individual improvements from ILC in the κ's: [*H. Bahl et al., PRELIMINARY*]



$\Rightarrow \geq 2\,\sigma$ deviation are observed, but upper bound only via ILC

4. SUSY and the 96 GeV "excess"

– What was seen in Run I?

– What was seen in Run II?

– What was seen at LEP?

– Should we get excited?

– Which model fits?

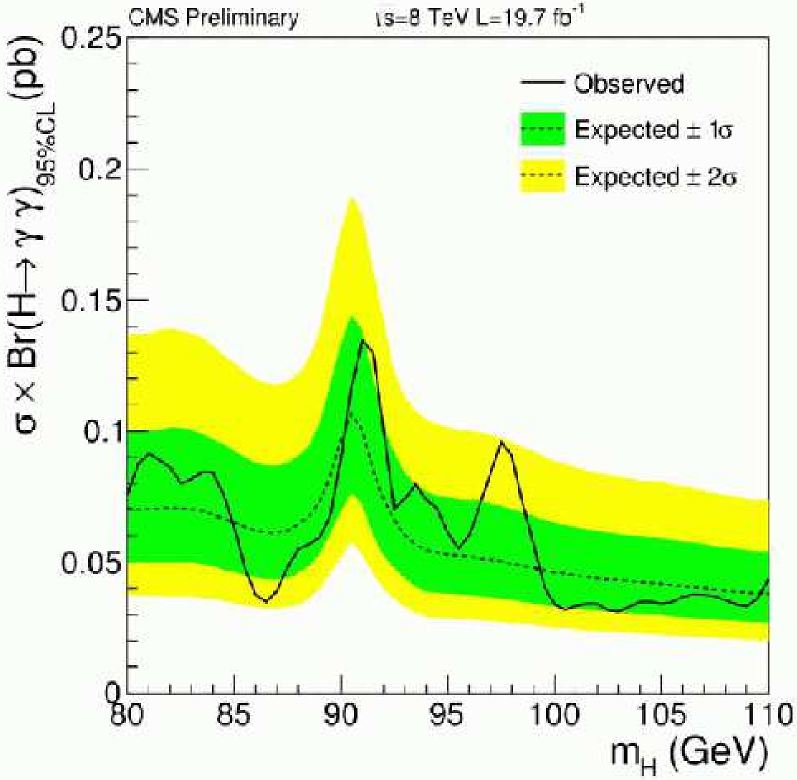
– Future projects

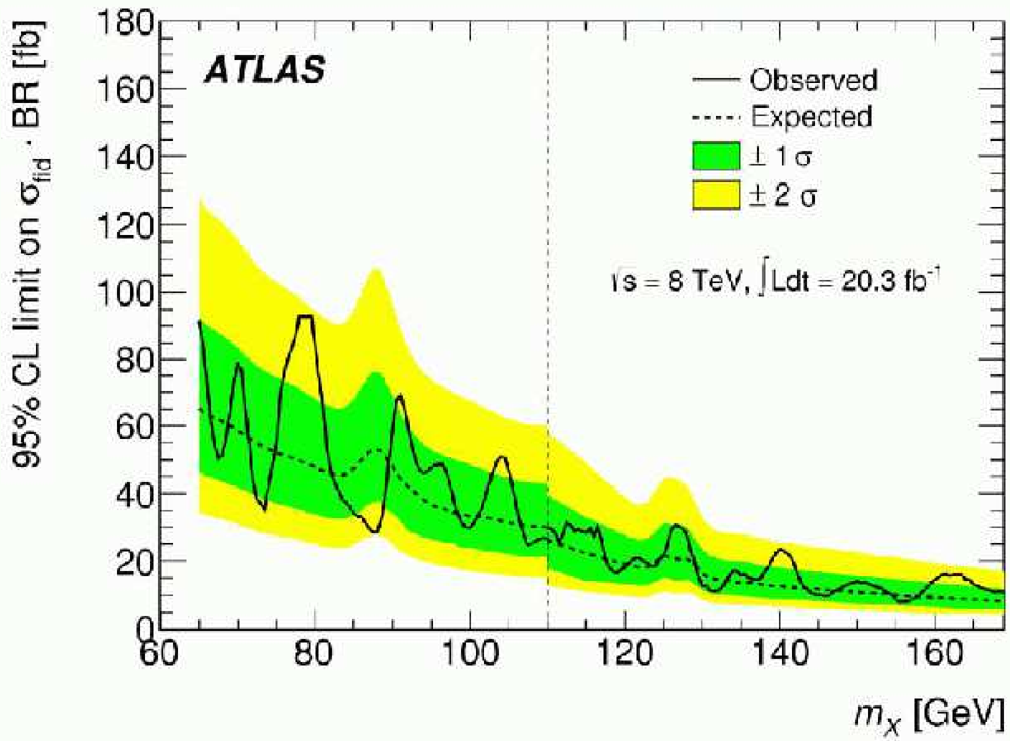
 [*S. Shotkin, talk at HDays17*]

h-->γγ (65-110GeV) Run 1

CMS PAS HIG-14-037

PRL 113 171801 (2014)





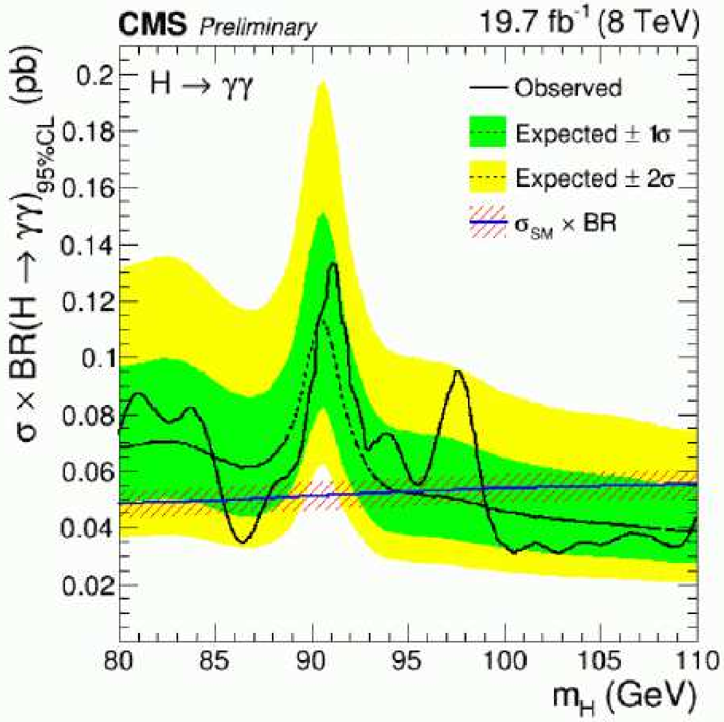
- ~2σ excursion @~97.5 GeV
- ~2σ excursion @~80 GeV

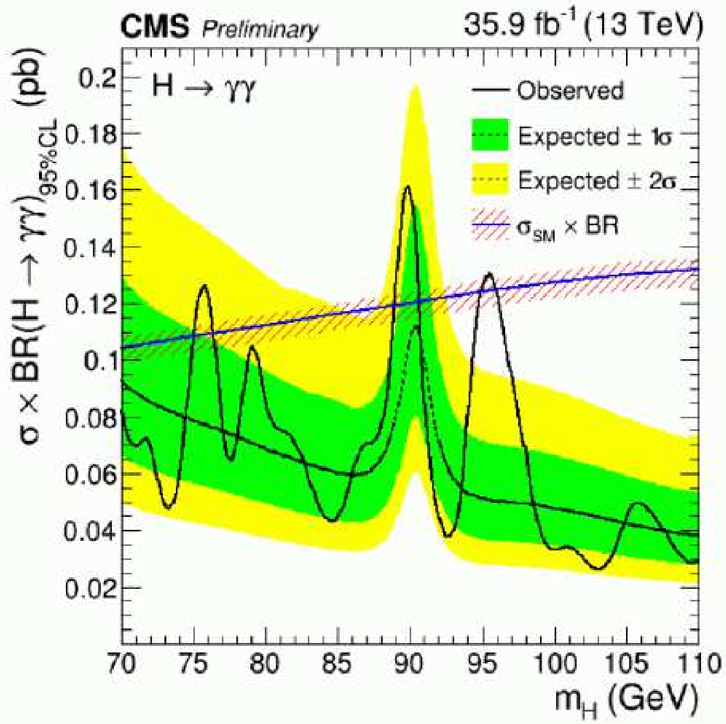
18

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

h-->γγ (70-110 GeV) Runs 1+2

New!





CMS PAS HIG-17-013

8 TeV: minimum(maximum) limit on σ X Br : 31(133) fb at m=102.8(91.1)GeV

13 TeV: minimum(maximum) limit on σ X Br : 26(161) fb at m=103.0(89.9)GeV

- 8 TeV limits on σ X Br redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

26

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

What was seen at Run II?

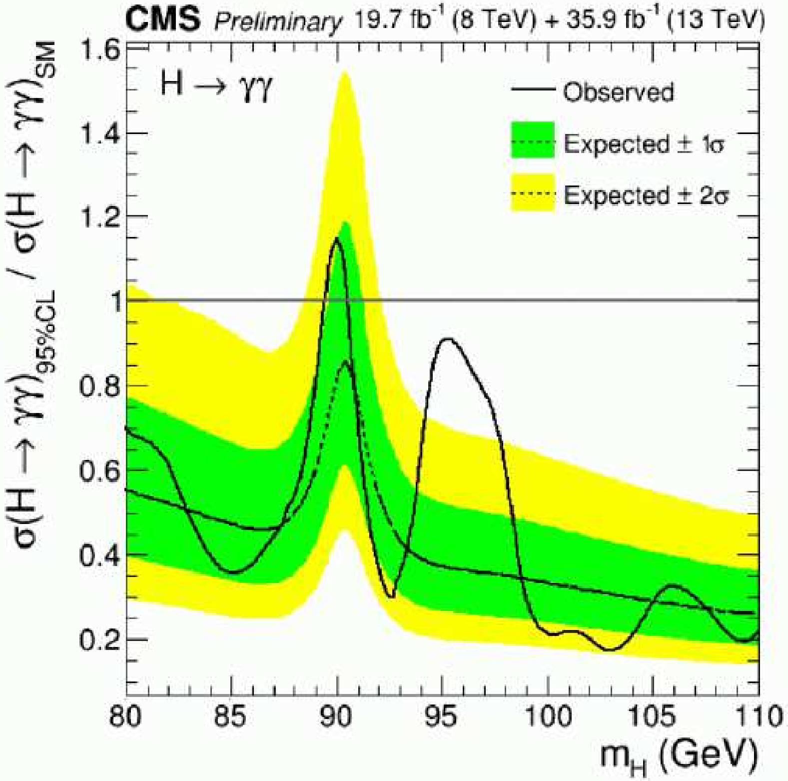
[*S. Shotkin, talk at HDays17*]

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013

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).



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

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

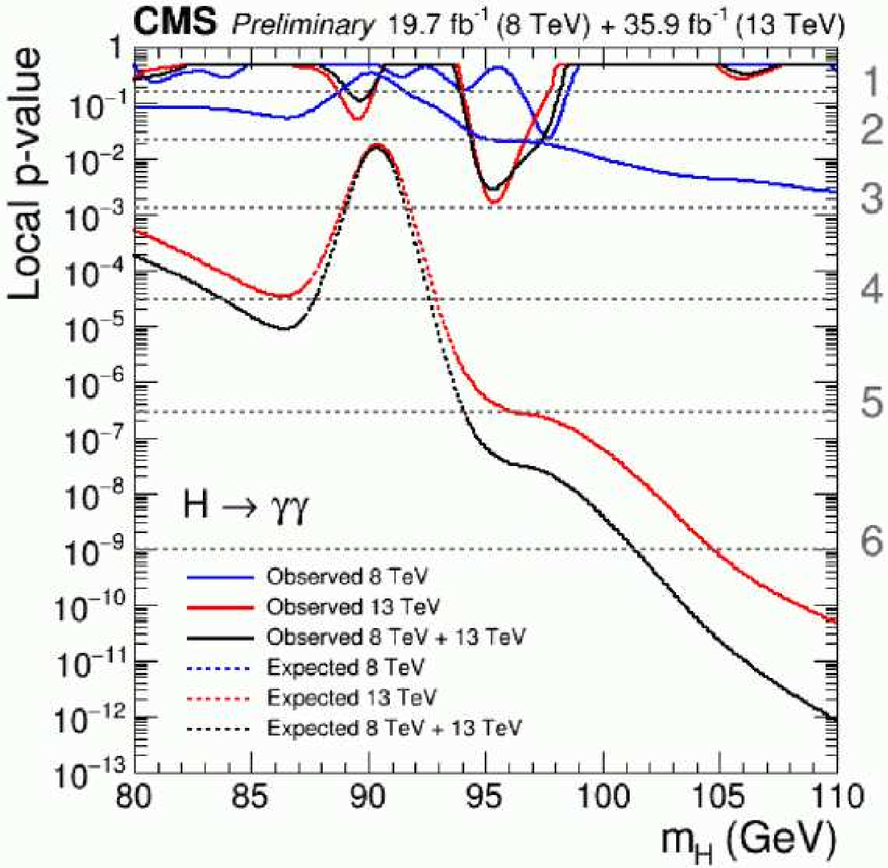
29

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013



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

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

8 TeV: Excess with ~2.0 σ local significance at m=97.6 GeV

13 TeV: Excess with ~2.9 σ local (1.47 σ global) significance at m=95.3 GeV

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

More data are required to ascertain the origin of this excess

30

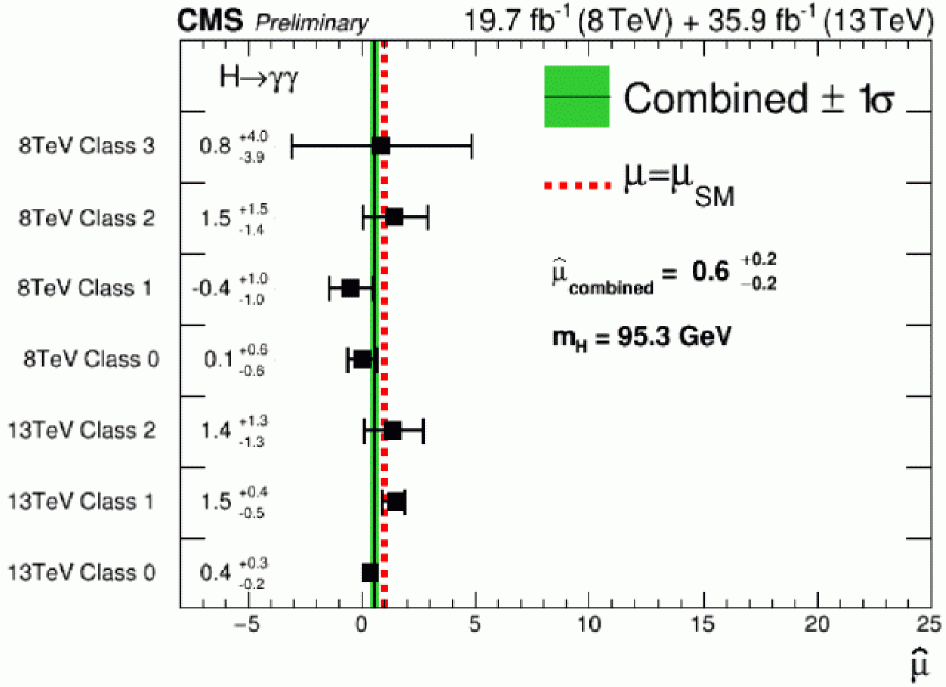
What was seen at Run II?

[S. Shotkin, talk at HDays17]

h-->γγ (70-110 GeV) Runs 1+2

New!

CMS PAS HIG-17-013



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

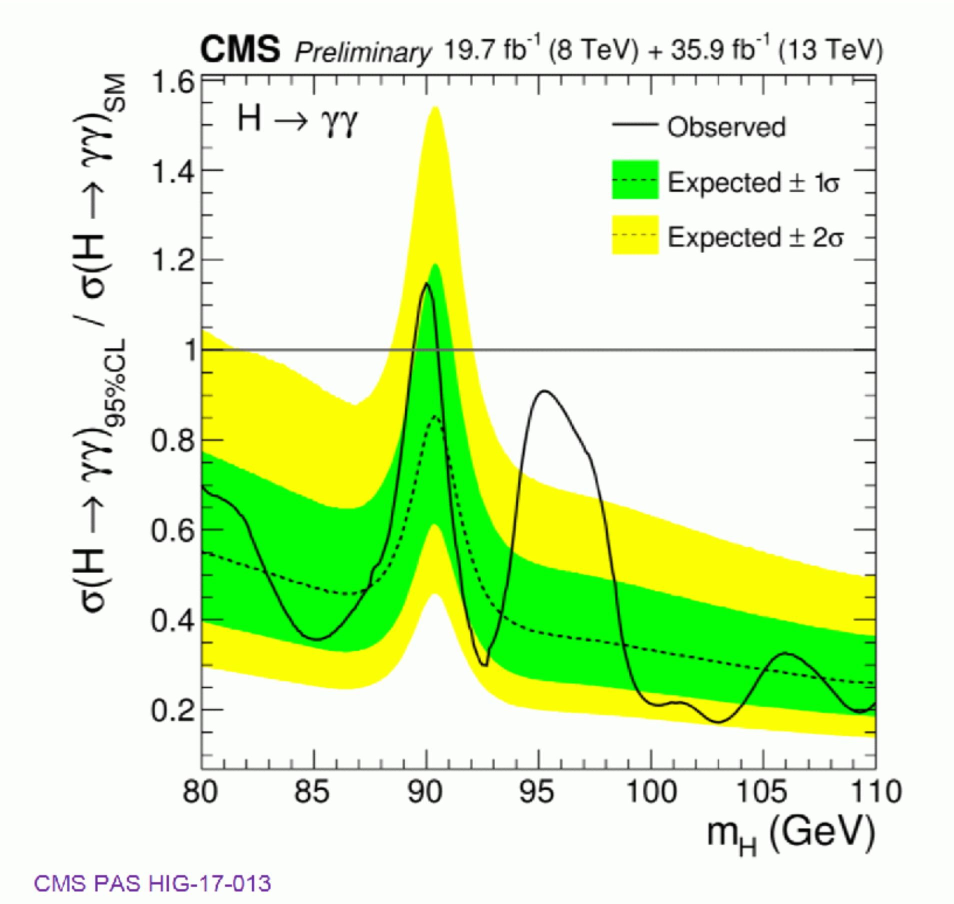
χ^2 probability for the seven individual values to be compatible with a single signal hypothesis: 41%

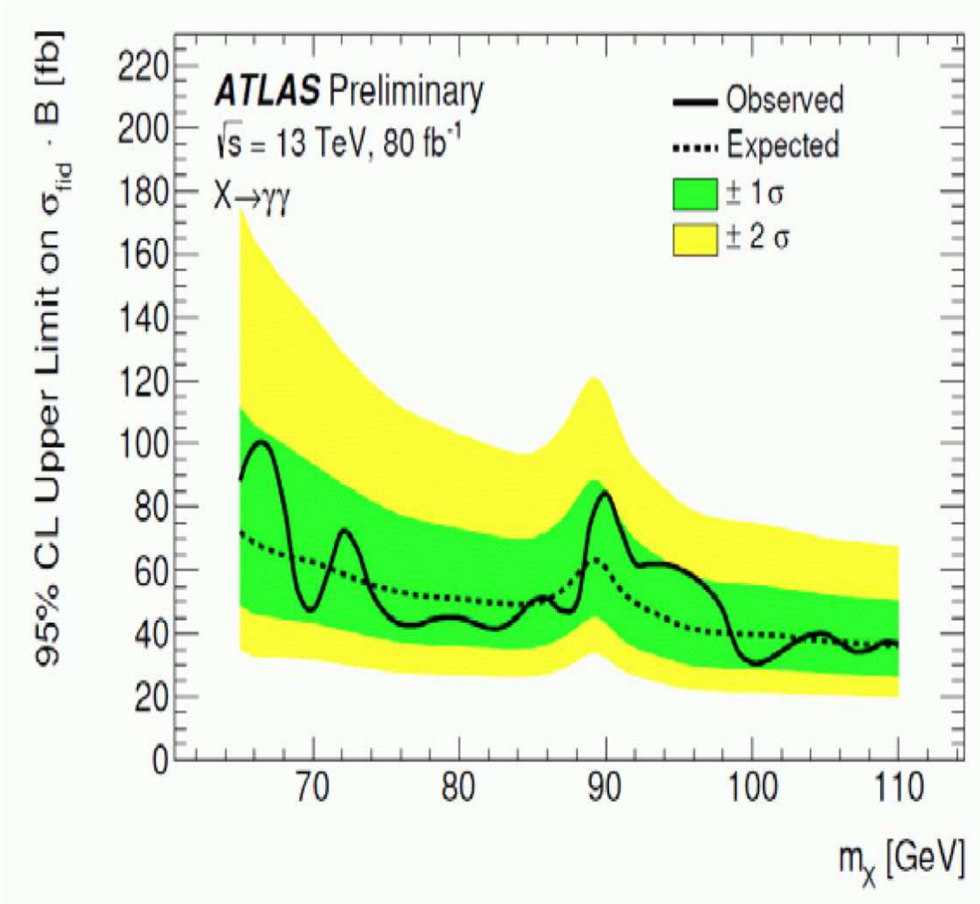
- 'Signal' strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing m_H=95.3 GeV
- More data are required to ascertain the origin of this excess

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017 55

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

What about ATLAS?





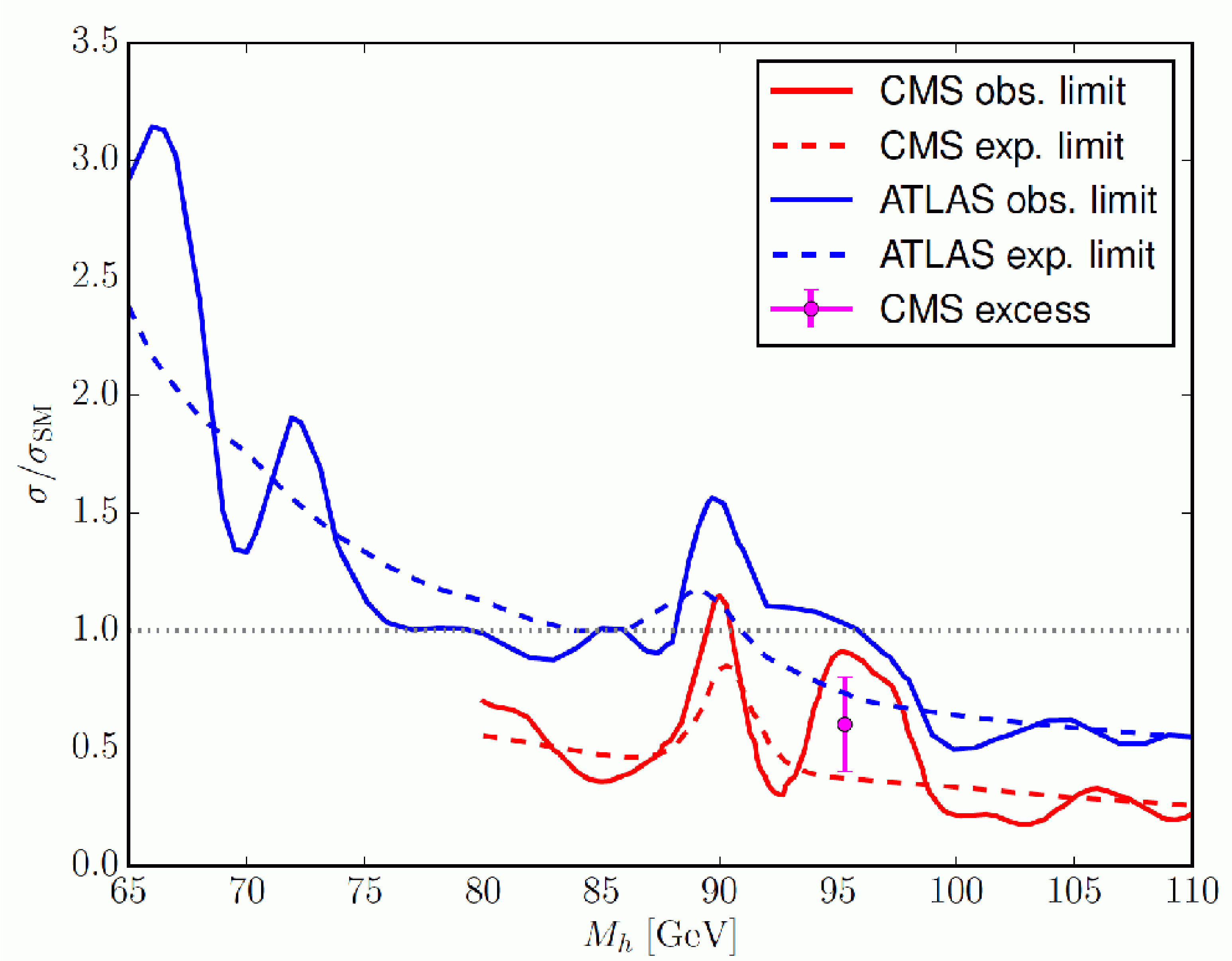
Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

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

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

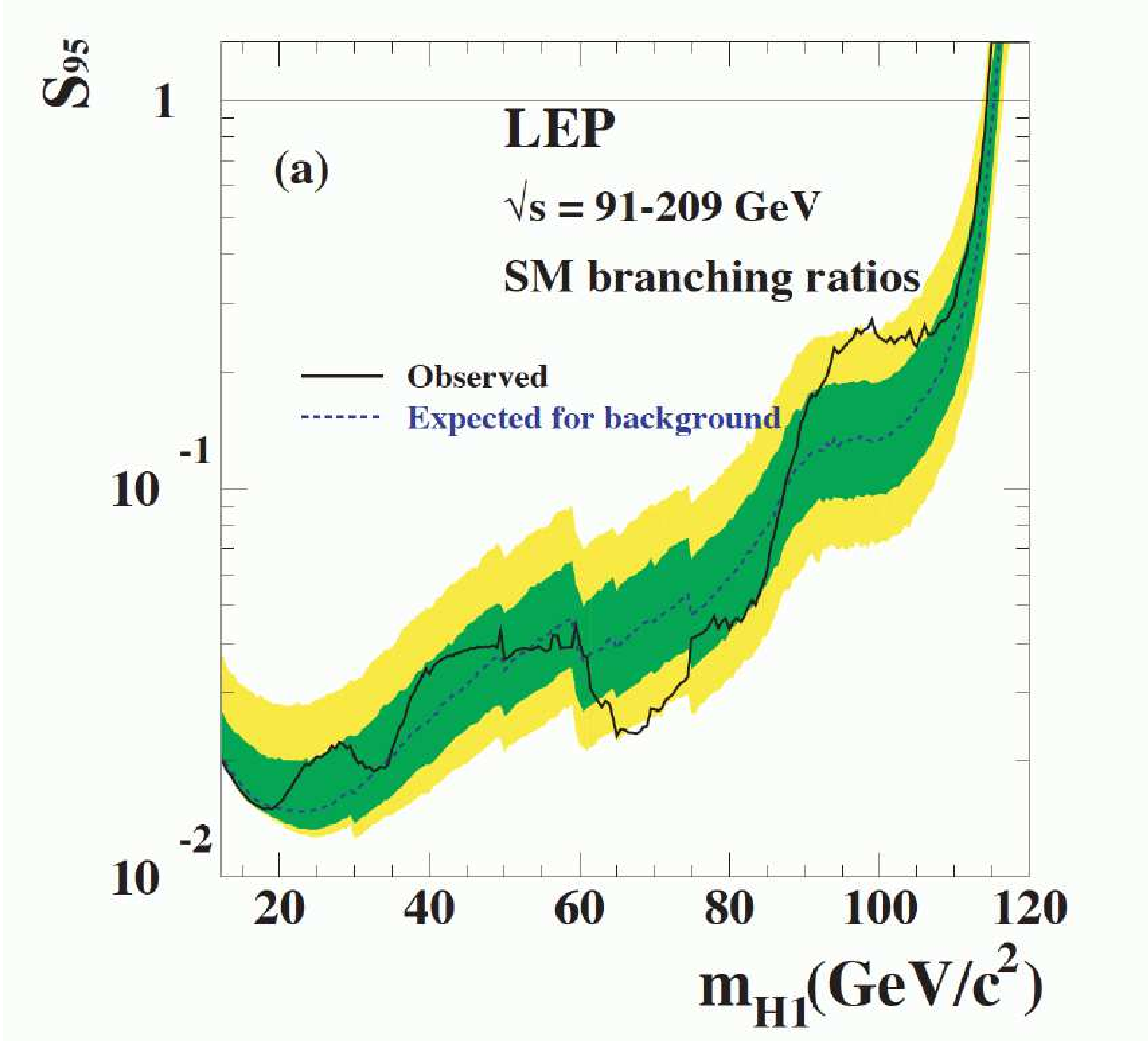
CMS and ATLAS in direct comparison:

[*T. Stefaniak et al. '18*]



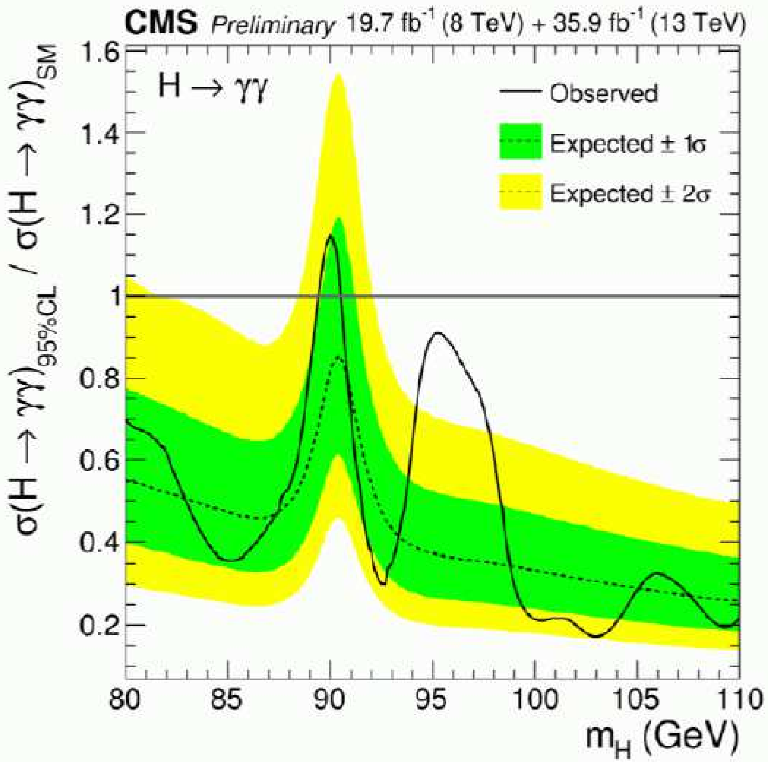
$\Rightarrow$ everything well compatible with the excess!

What was seen at LEP?

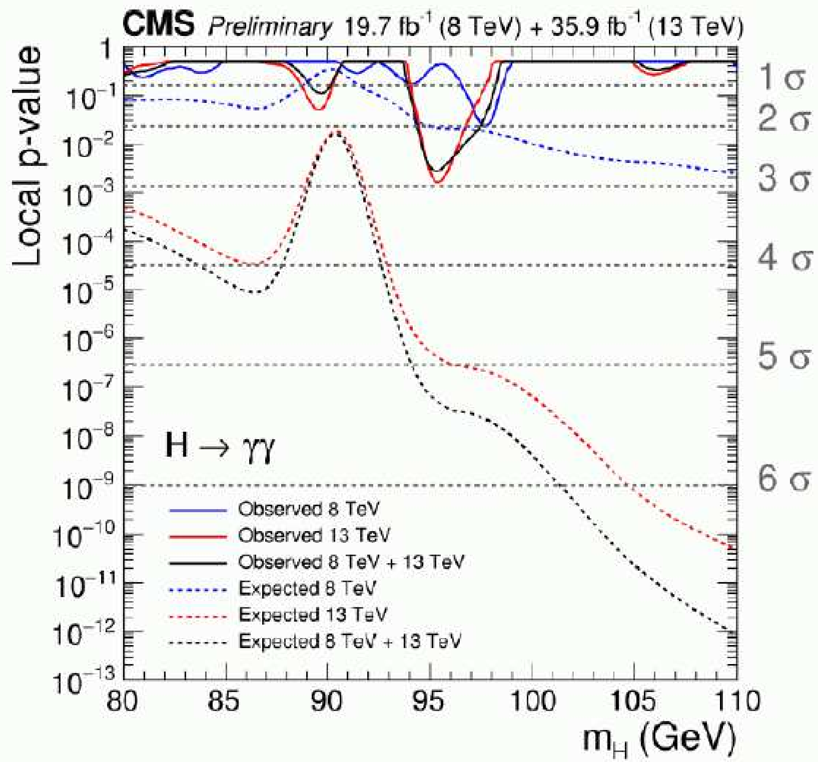


$$\mu_{\text{LEP}}(98\text{ GeV}) = \left[\sigma(e^+e^- \to Zh_1) \times \text{BR}(h_1 \to b\bar{b})\right]_{\text{exp/SM}} = 0.117 \pm 0.057$$

- **Combined 8 TeV + 13 TeV** σ×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**



CMS PAS HIG-17-013

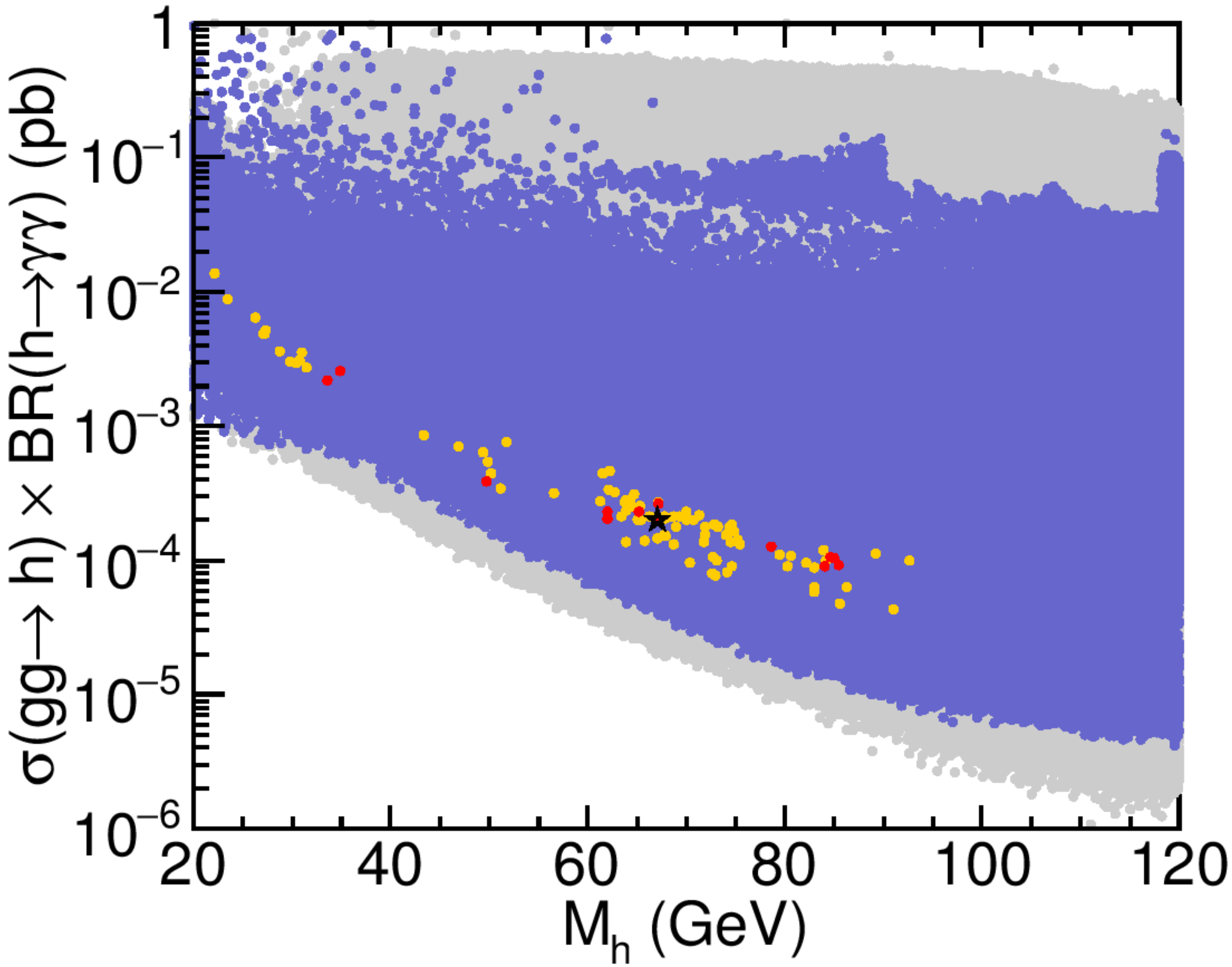


CMS PAS HIG-17-013

Q: When do you dare to call something "significant"?

What about the MSSM?

[*P. Bechtle, H. Haber, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '16*]



⇒ too small rates!

What about the NMSSM?

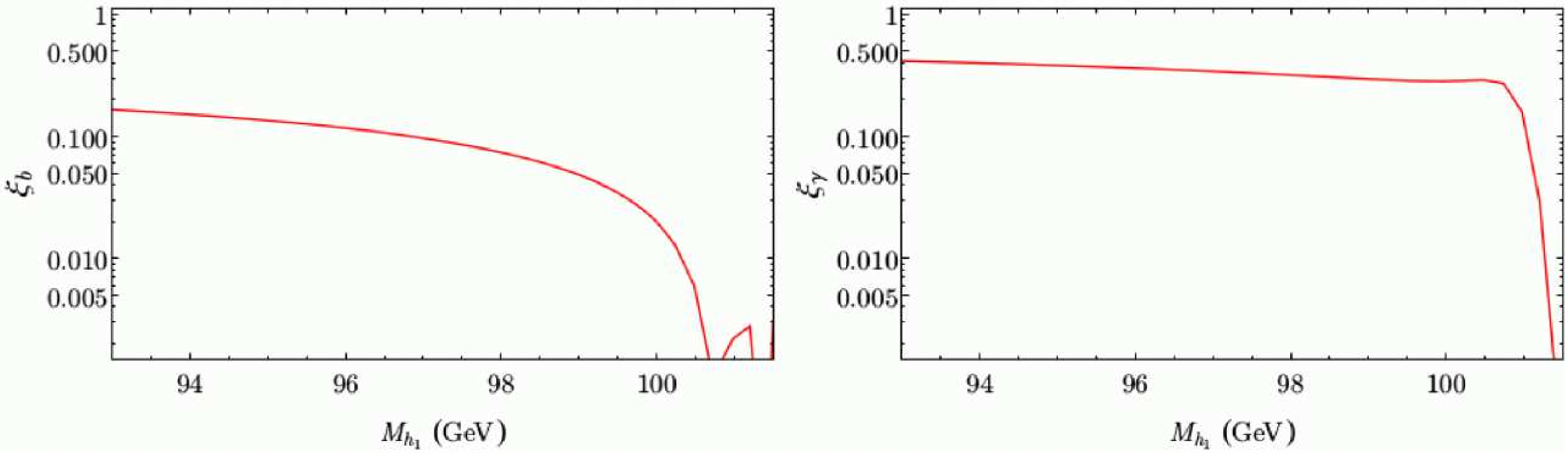
[F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

$$\xi_b \equiv \frac{\Gamma[h_1 \to ZZ] \cdot {\rm BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\rm SM}(M_{h_1}) \to ZZ] \cdot {\rm BR}[H_{\rm SM}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+e^- \to Z(H_{\rm SM}(M_{h_1}) \to b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot {\rm BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\rm SM}(M_{h_1}) \to gg] \cdot {\rm BR}[H_{\rm SM}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\rm SM}(M_{h_1}) \to \gamma\gamma]} .$$



⇒ both "excesses" can be fitted simultaneously!

What about the $\mu\nu$SSM?

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)
$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

What about the $\mu\nu$SSM?

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)

$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

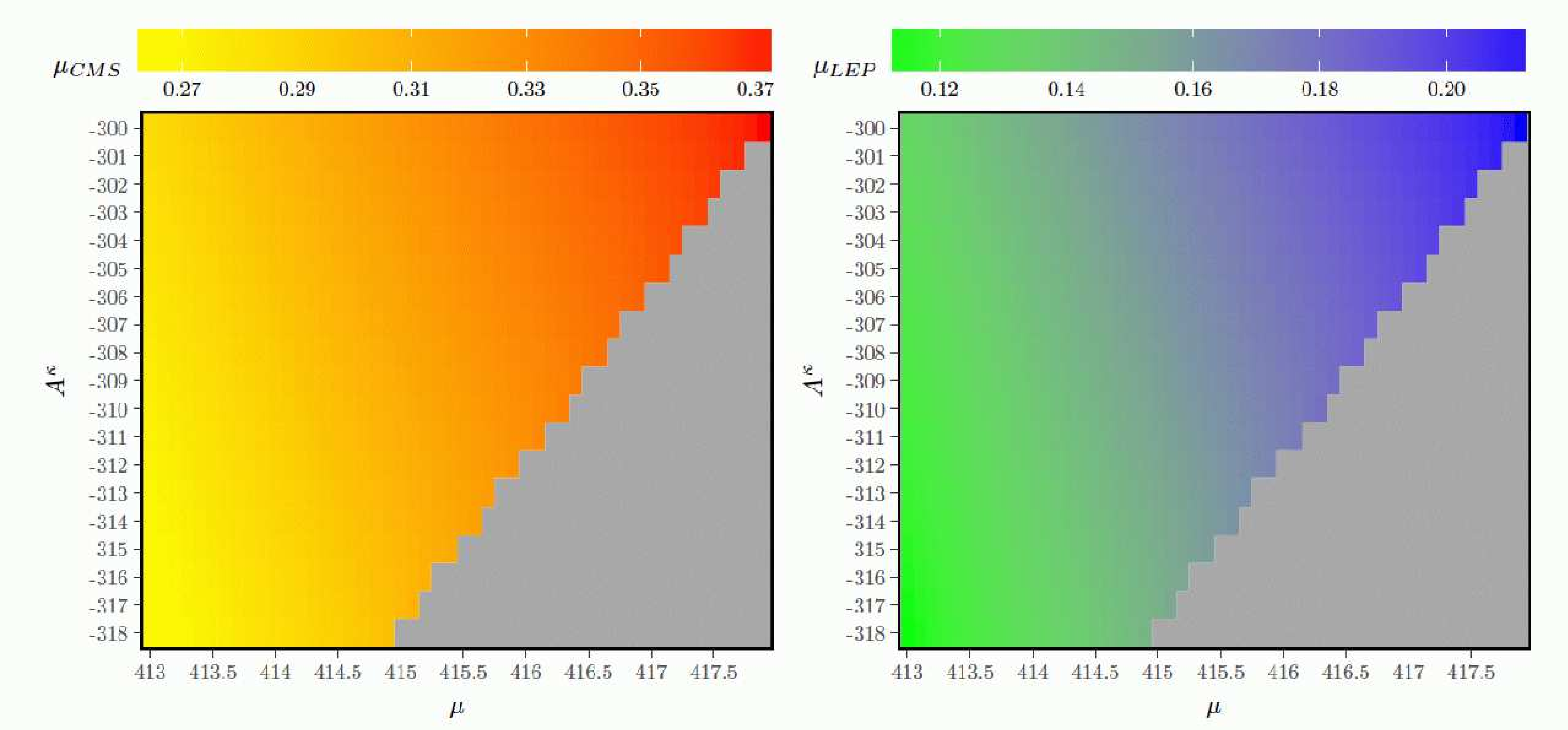
Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	M_1
$\sqrt{2}\cdot 10^{-5}$	10^{-7}	-1000	2	$[413; 418]$	0.6	956.035	0.035	$[-300; -318]$	100
M_2	M_3	$m^2_{\tilde{Q}_{iL}}$	$m^2_{\tilde{u}_{iR}}$	$m^2_{\tilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\tilde{e}})_{ii}$	A_{33}^e	$A_{11,22}^e$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]

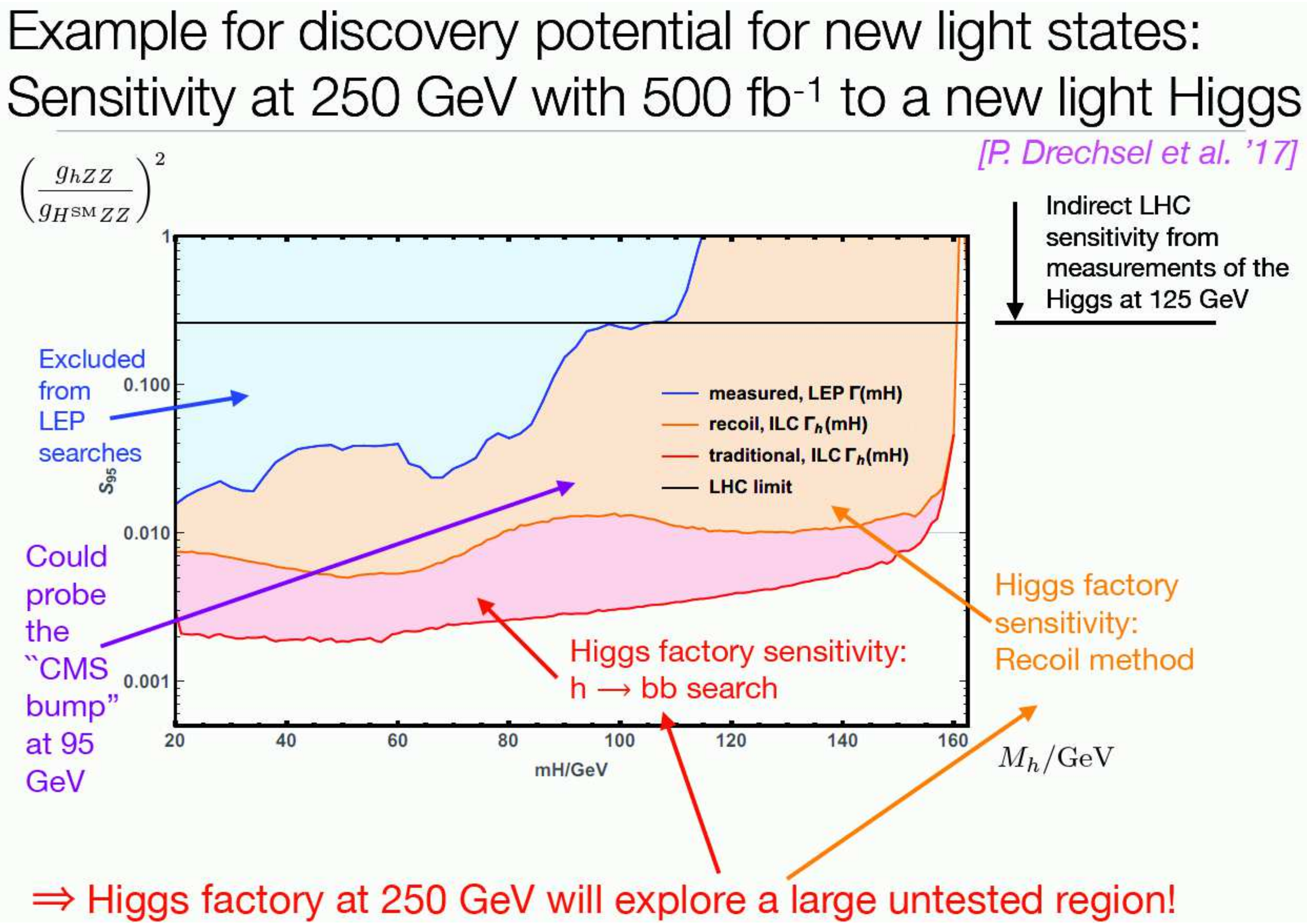


$\Rightarrow$ YES, WE CAN! :-)

(at the $1 - 1.5\,\sigma$ level)

Next project?

Next project? ILC reach for light Higgs bosons:



[*Taken from G. Weiglein '18*]

5. Conclusinos

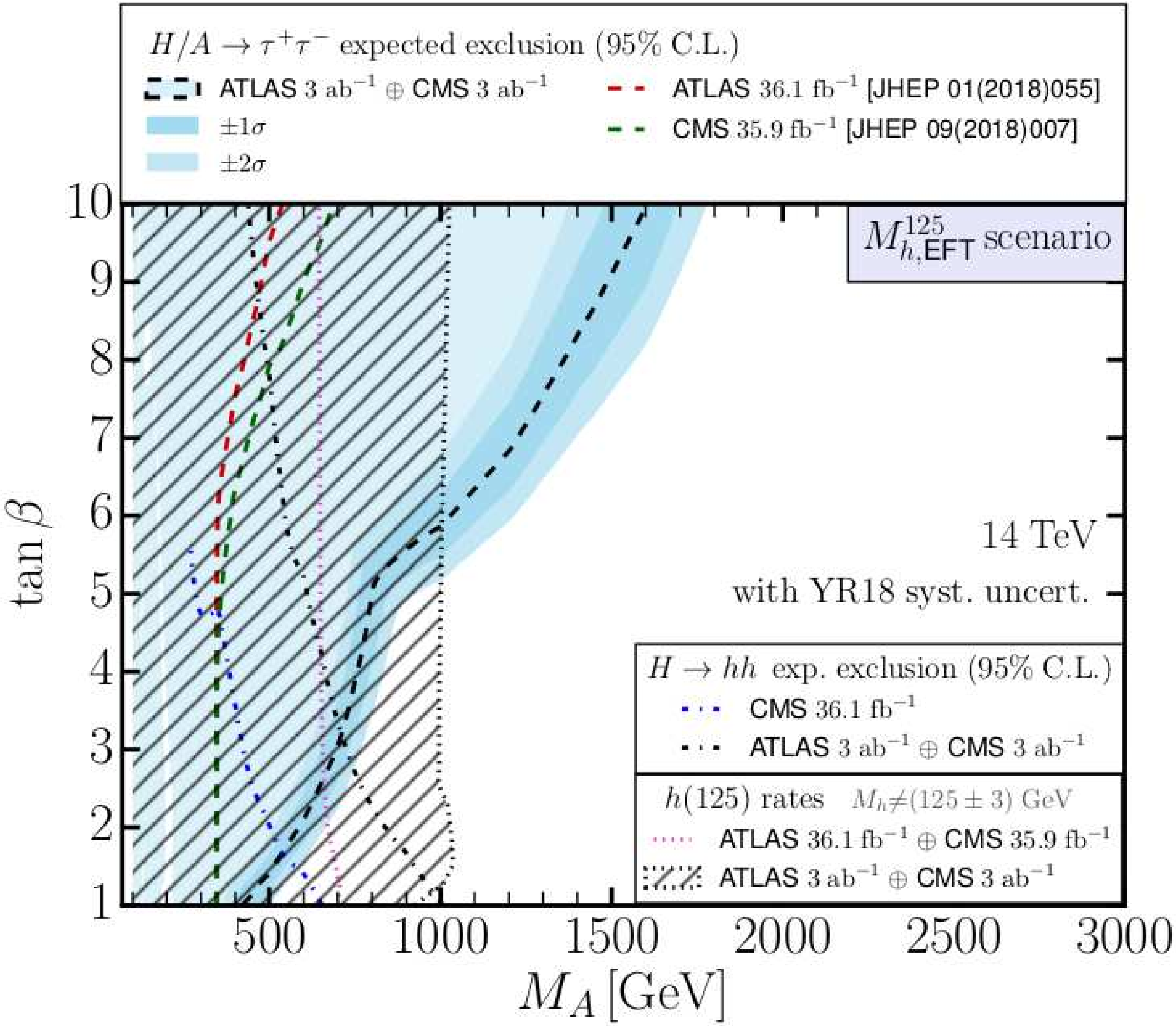
- SUSY is (still) the best-motivated BSM scenario
  - unconstrained MSSM: 105 new parametes
  - constrained: CMSSM, NUHM, SU(5), mAMSB, sub-GUT, FUT, . . .
  - benchmark models: parameter planes
- Benchmark scenarios/searches: Data taken into account: Higgs/SUSY
  Data on purpose not taken into account: EW/Flavor/DM
- New benchmark proposal (selection):
  - M_h^{125} scenario: 2HDM-like model
  - $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^\pm\tilde{\chi}_l^\mp$
  - M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
- Implications for HL-LHC and ILC:
  - direct $\oplus$ indirect HL-LHC reach: $M_A \gtrsim 1200$ GeV
  - interesting reach for charginos via $h \to \gamma\gamma$
  - ILC measurements can be crucial to set upper limits on M_A
- A light Higgs at 96 GeV?
  new CMS/ATLAS result (and old LEP result) possibly interesting!
  - MSSN cannot explain the excesses
  - NMSSM/$\mu\nu$SSM can explain CMS(/ATLAS) and LEP excesses

  $\Rightarrow$ perfect physics case for the ILC: 96 GeV direct $\oplus$ 125 GeV coupl.


Further Questions?

HL-LHC reach in $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario

[*H. Bahl et al., PRELIMINARY*]



$\Rightarrow$ indirect measurements stronger at low $\tan\beta$: $M_A \gtrsim$ 1000 GeV

More general Ansatz: **N2HDM**

[*T. Biekötter, M. Chakraborti, S.H. – arXiv:1903.11661*]

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \; \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \; \Phi_S = v_S + \rho_S$$

Potential:

$$\begin{aligned} V = \; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

Z_2 symmetry: $\Phi_1 \to \Phi_1 , \quad \Phi_2 \to -\Phi_2 , \quad \Phi_S \to \Phi_S$

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

$\Rightarrow$ exactly as in 2HDM

Three neutral $\mathcal{CP}$-even Higgses:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}, \qquad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

Coupling to massive gauge bosons: (identical for all four types)

	$c_{h_i VV} = c_\beta R_{i1} + s_\beta R_{i2}$
h_1	$c_{\alpha_2} c_{\beta-\alpha_1}$
h_2	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta-\alpha_1}$
h_3	$-c_{\alpha_3} c_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta-\alpha_1}$

Coupling to fermions: (same pattern as in 2HDM)

	u-type ($c_{h_i tt}$)	d-type ($c_{h_i bb}$)	leptons ($c_{h_i \tau\tau}$)
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton-specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

"Physical" input parameters:

$$\alpha_{1,2,3}\,,\quad \tan\beta\,,\quad v\,,\quad v_S\,,\quad m_{h_{1,2,3}}\,,\quad m_A\,,\quad M_{H^\pm}\,,\quad m_{12}^2$$

Needed to fit the two excesses: $m_{h_1} \sim 96$ GeV, $m_{h_2} \sim 125$ GeV

– $c^2_{h_1VV}$ strongly reduced for $\mu_{\rm LEP}$
– c_{h_1bb} reduced to enhance BR($h_1 \to \gamma\gamma$)
– c_{h_1tt} not reduced for $\mu_{\rm CMS}$
– $c_{h_1\tau\tau}$ possibly reduced to enhance BR($h_1 \to \gamma\gamma$)

	Decrease $c_{h_1b\bar{b}}$	No decrease $c_{h_1t\bar{t}}$	No enhancement $c_{h_1\tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{12}}{s_\beta})$:-)
type II	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{11}}{c_\beta})$:-)
type III	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{11}}{c_\beta})$:-(
type IV	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(

Type II and IV: c_{h_1bb} and c_{h_1tt} independent

Type II bonus: $c_{h_1\tau\tau}$ can be suppressed (together with c_{h_1bb})

$\Rightarrow$ only type II and IV can fit CMS and LEP excesses

$\Rightarrow$ Parameter scan $\Rightarrow$ ScannerS

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS
- Minimum of potential is global minimum $\Rightarrow$ ScannerS
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (N2HDECAY, SusHi)
  $\chi^2_{\text{red}} := \chi^2/n_{\text{obs}}$
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

Fitting the excesses:

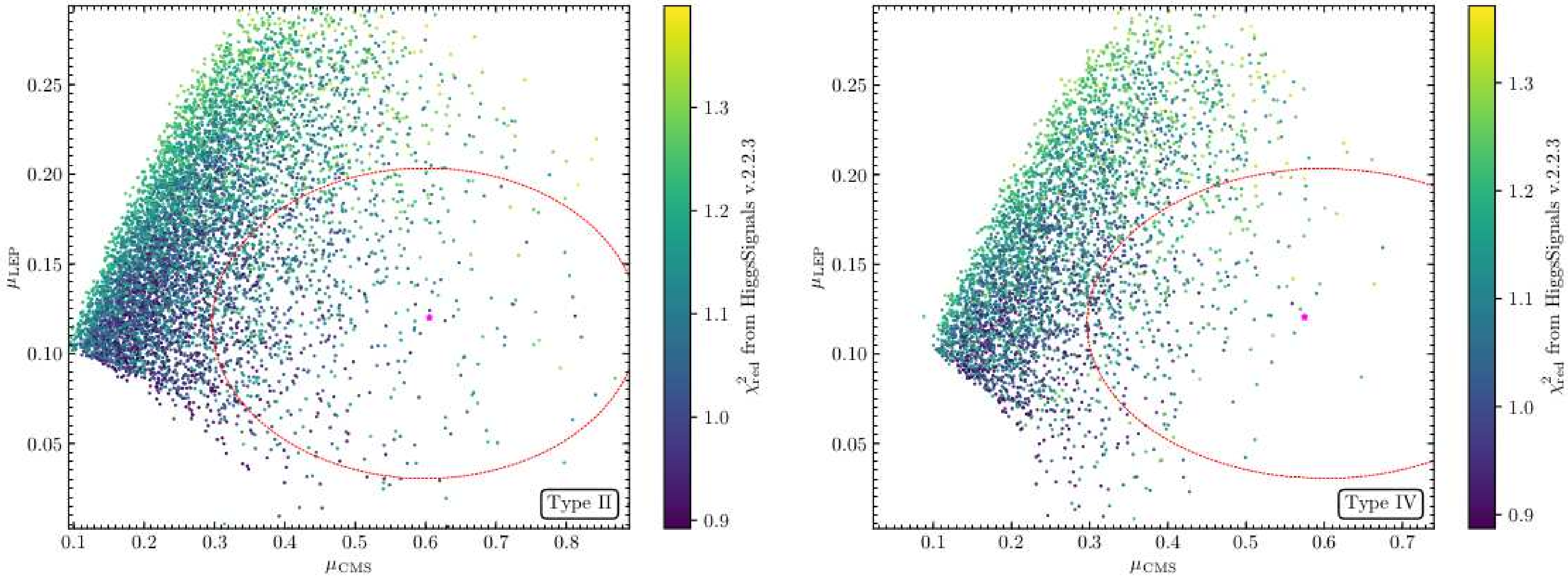
$$\mu_{\text{LEP}} = 0.117 \pm 0.057, \qquad \mu_{\text{CMS}} = 0.6 \pm 0.2$$

$$\mu_{\text{LEP}} = \frac{\sigma_{\text{N2HDM}}(e^+e^- \to Zh_1)}{\sigma_{\text{SM}}(e^+e^- \to ZH)} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}$$
$$= \left|c_{h_1VV}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}$$

$$\mu_{\text{CMS}} = \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$
$$= \left|c_{h_1tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$

$$\chi^2_{\text{CMS-LEP}} = \frac{(\mu_{\text{LEP}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\text{CMS}} - 0.6)^2}{(0.2)^2}$$

$\Rightarrow$ “best-fit point”



$\Rightarrow$ excesses well fitted, with good $\chi^2_{\rm red}$: 0.9 – 1.3

$\Rightarrow$ preferred $M_{H^\pm}$: 650 GeV – 950 GeV (lower limit: flavor constr.)

$\Rightarrow$ preferred $\tan\beta$: 0.8 – 3.8

Best-fit point in type II:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
96.5263	125.09	535.86	712.578	737.829	
$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.26287	1.26878	-1.08484	-1.24108	80644.3	272.72
$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.5048	0.2682	$5.09 \cdot 10^{-2}$	$2.582 \cdot 10^{-3}$	$1.37 \cdot 10^{-2}$	$1.753 \cdot 10^{-3}$
$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.5916	0.0771	$6.36 \cdot 10^{-2}$	$2.153 \cdot 10^{-3}$	0.2087	$2.610 \cdot 10^{-3}$

$\Rightarrow$ surprizingly large $\text{BR}_{h_1}^{\gamma\gamma}$

Best-fit point in type IV:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
97.8128	125.09	485.998	651.502	651.26	
$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.3147	1.27039	-1.02829	-1.32496	41034.1	647.886
$\mathrm{BR}_{h_1}^{bb}$	$\mathrm{BR}_{h_1}^{gg}$	$\mathrm{BR}_{h_1}^{\tau\tau}$	$\mathrm{BR}_{h_1}^{\gamma\gamma}$	$\mathrm{BR}_{h_1}^{WW}$	$\mathrm{BR}_{h_1}^{ZZ}$
0.4074	0.20714	0.248324	$2.139 \cdot 10^{-3}$	$1.347 \cdot 10^{-2}$	$1.579 \cdot 10^{-3}$
$\mathrm{BR}_{h_2}^{bb}$	$\mathrm{BR}_{h_2}^{gg}$	$\mathrm{BR}_{h_2}^{\tau\tau}$	$\mathrm{BR}_{h_2}^{\gamma\gamma}$	$\mathrm{BR}_{h_2}^{WW}$	$\mathrm{BR}_{h_2}^{ZZ}$
0.5363	0.09388	$7.58 \cdot 10^{-2}$	$2.247 \cdot 10^{-3}$	0.2267	$2.836 \cdot 10^{-2}$

$\Rightarrow$ substantially larger $\mathrm{BR}_{h_1}^{\tau\tau}$ than in type II

What can we learn from future measurements?

- LHC h_{125} coupling measurements
- HL-LHC h_{125} coupling measurements
- ILC (or other e^+e^- collider) h_{125} coupling measurements

- direct production of ϕ_{96} at the LHC
- direct production of ϕ_{96} at the HL-LHC
- direct production of ϕ_{96} at the ILC (or other e^+e^- coll.)

- production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/...

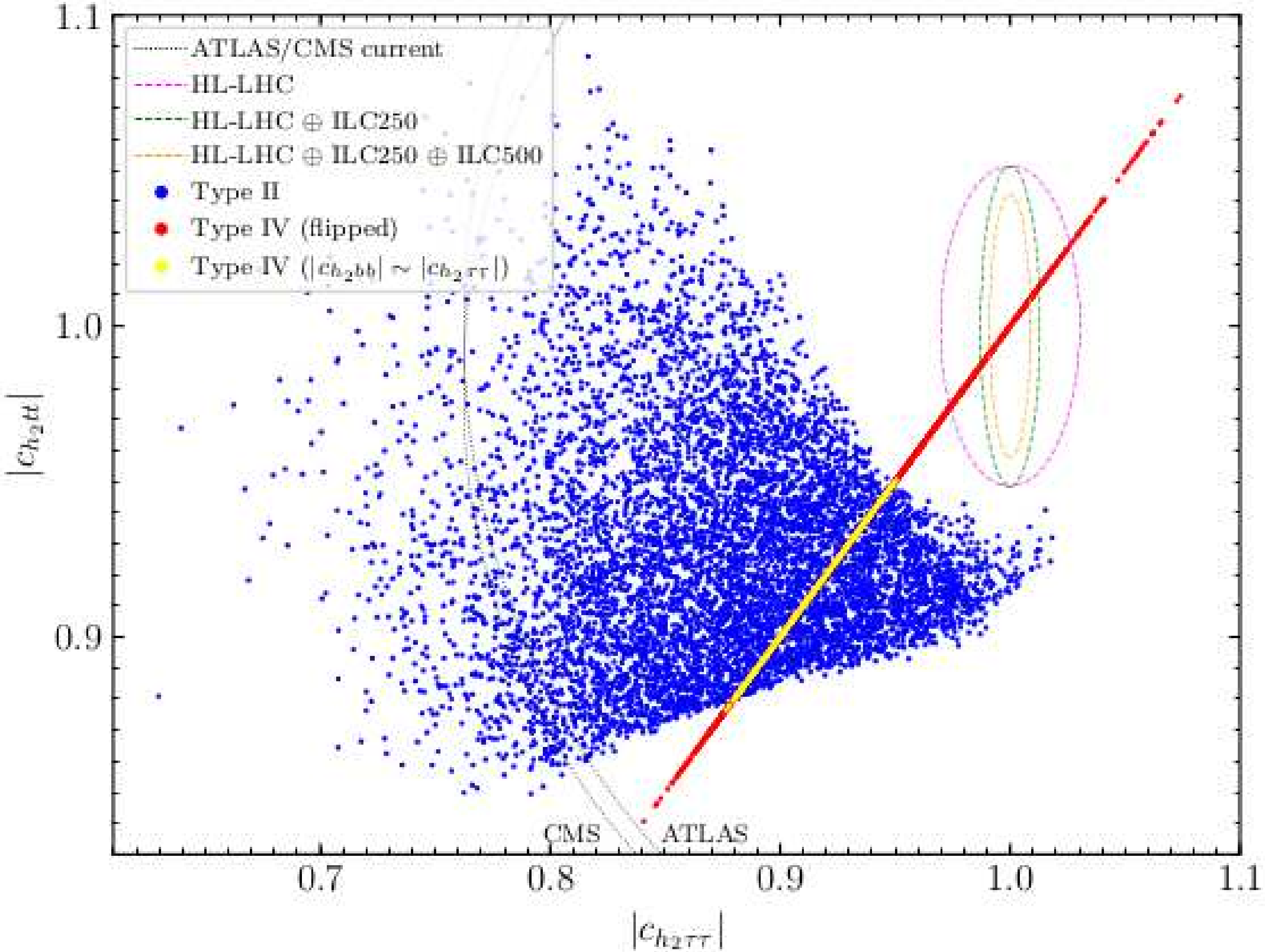
What can we learn from future measurements?

- LHC h_{125} coupling measurements ⇐ focus
- HL-LHC h_{125} coupling measurements ⇐ focus
- ILC (or other e^+e^- collider) h_{125} coupling measurements ⇐ focus

- direct production of ϕ_{96} at the LHC
- direct production of ϕ_{96} at the HL-LHC
- direct production of ϕ_{96} at the ILC (or other e^+e^- coll.) ⇐ focus

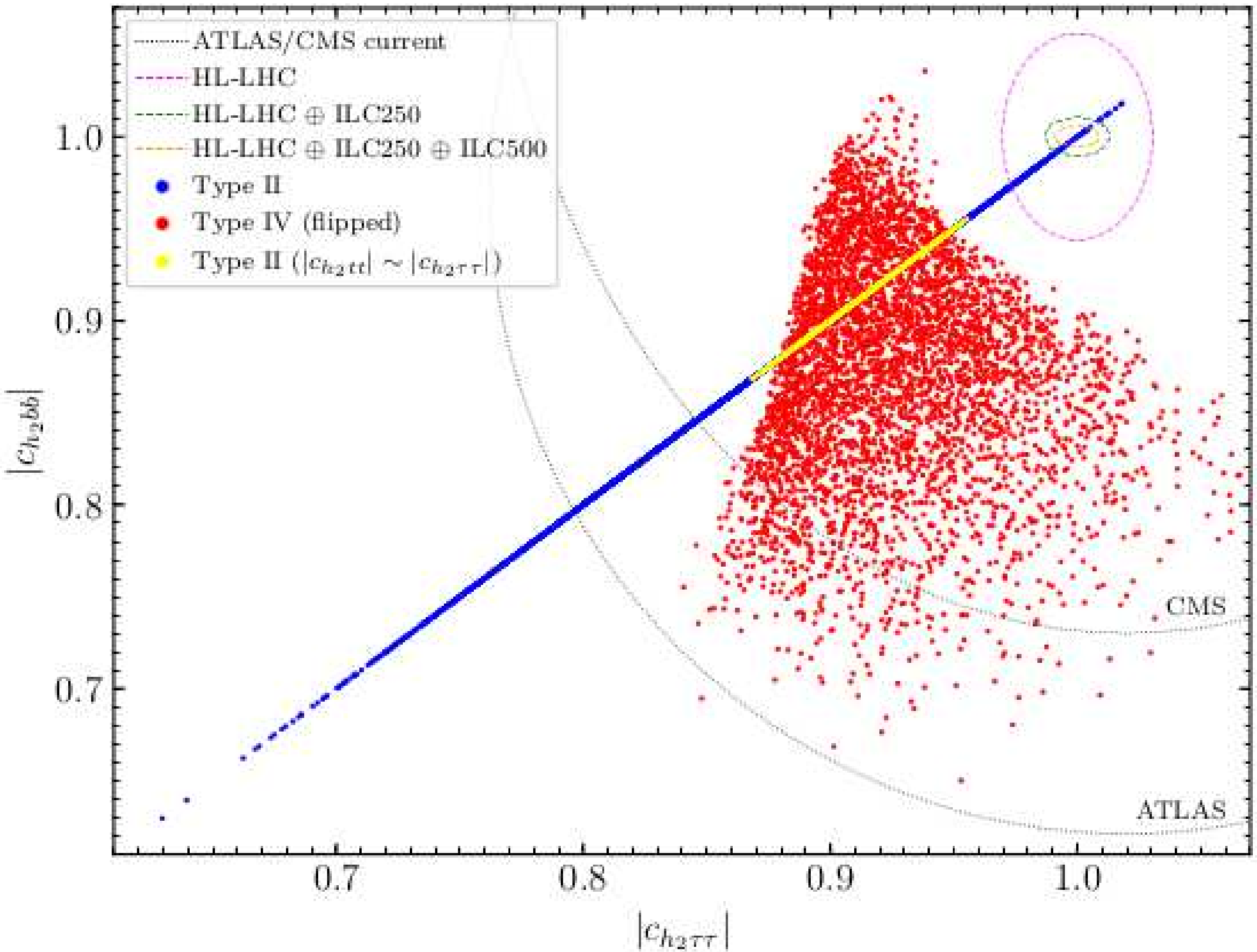
- production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/...

Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type II shows deviation from SM

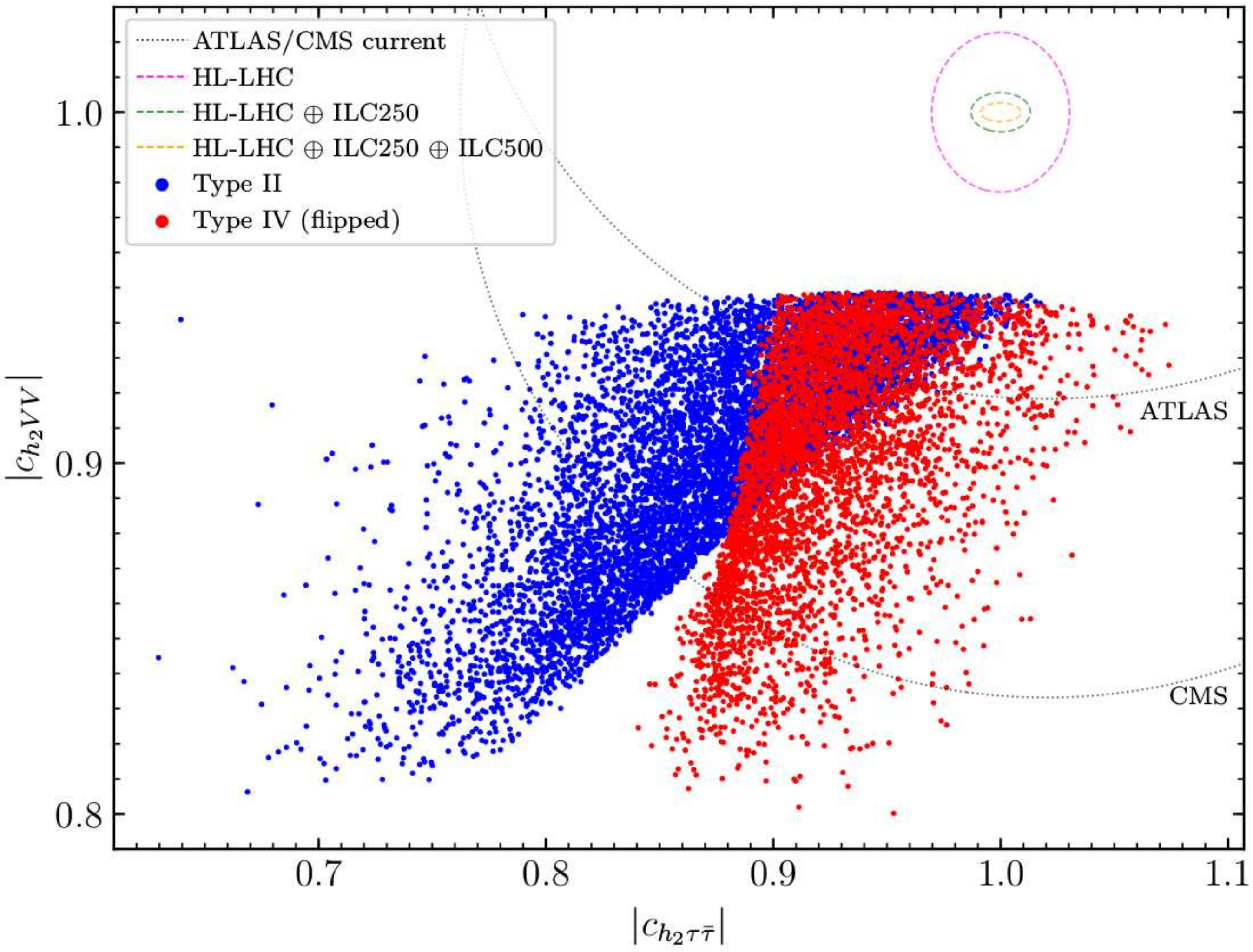
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type IV shows deviations from SM

⇒ N2HDM can always be distinguished from SM!

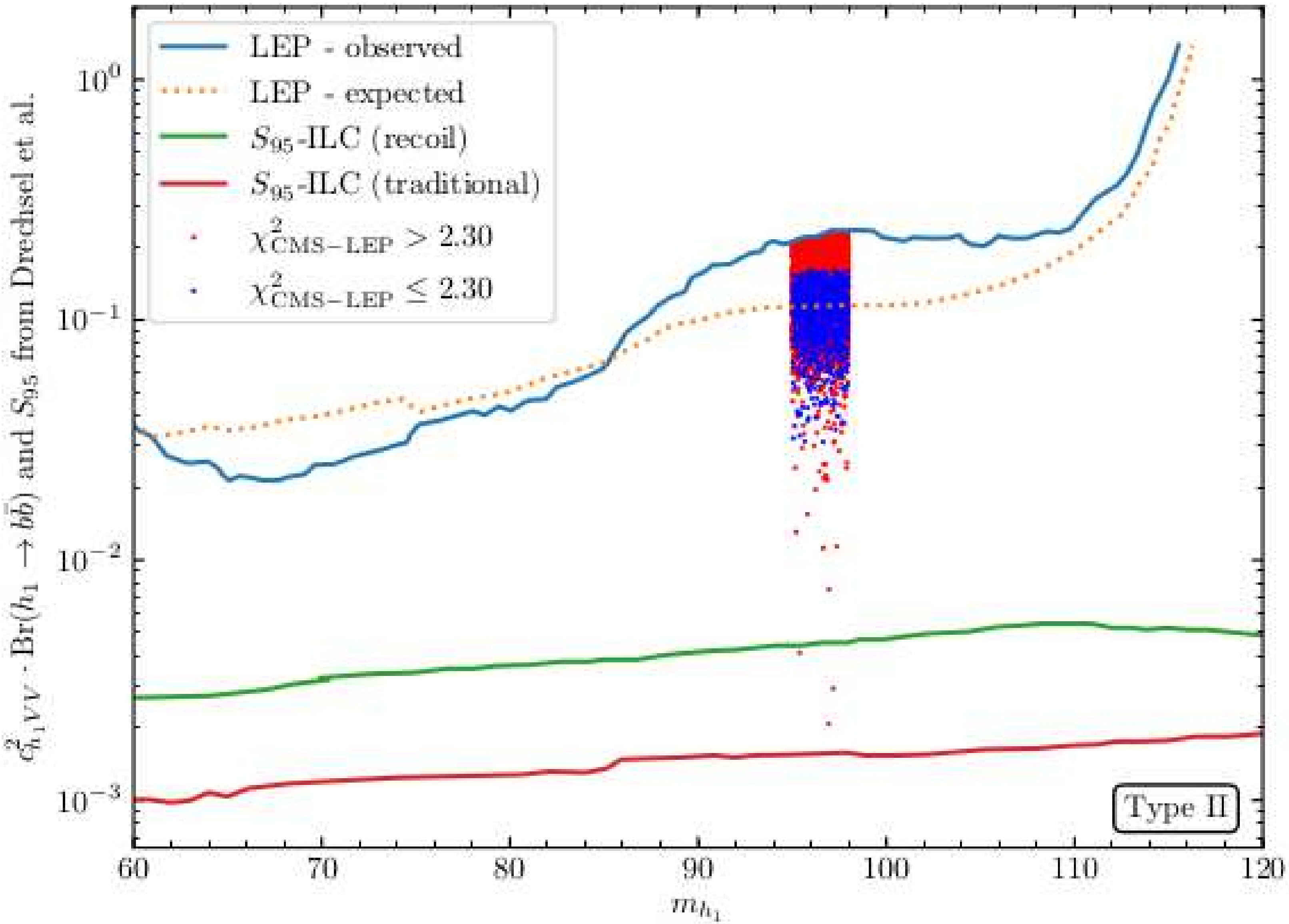
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM!

Next project? ⇒ ILC production of the light scalar



⇒ new state easily in the reach of the ILC