"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Impact of LC measurements on SUSY Higgs Sectors

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

Sendai, 10/2019

- Motivation
- Examples for additional Higgs Bosons
- Implications from the ILC
- The ILC and the 96 GeV "excess"
- Conclusions

1. Motivation: Two Facts:

1: We have a discovery!

2: The SM cannot be the ultimate theory!

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Q': Which model?

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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. N2HDM: 2HDM with one extra singlet: type I, II, III, IV
4. Minimal Supersymmetric Standard Model (MSSM)
5. MSSM with one extra singlet (NMSSM)
6. MSSM with more extra singlets (e.g. $\mu\nu$SSM)
7. SM/MSSM with Higgs triplets
8. ...

⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

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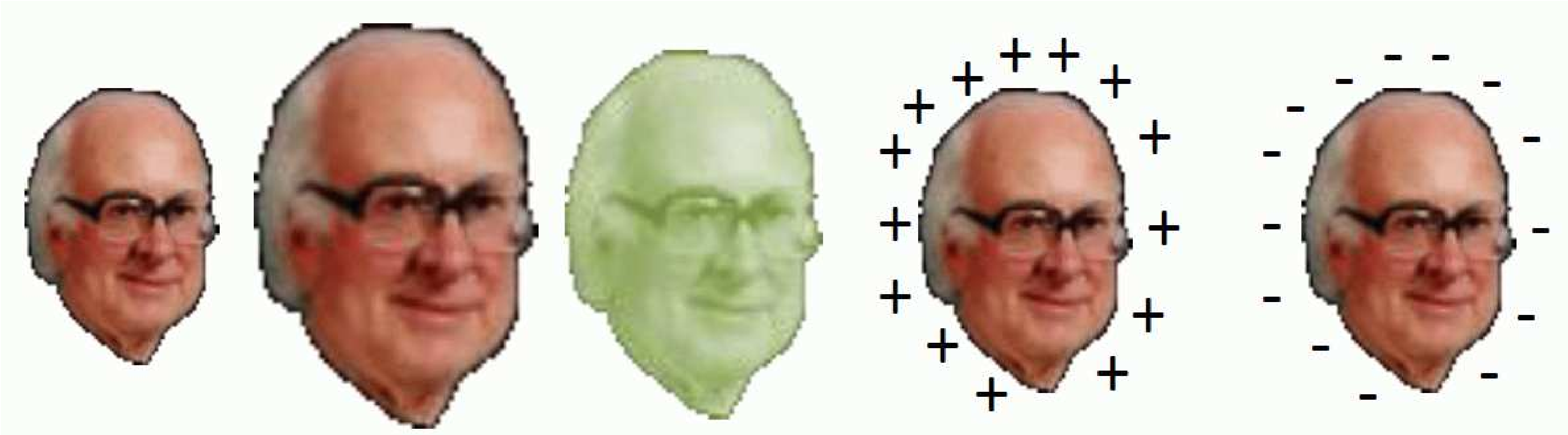
2. Examples for additional Higgs Bosons



Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

→ investigate benchmark scenarios:

→ Vary only M_A and $\tan\beta$
→ 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 model
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \to \gamma\gamma$, $H/A \to \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^{\pm}\tilde{\chi}_l^{\mp}$
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 in detail:

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) ⇒ FeynHiggs

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– SUSY searches (LHC)

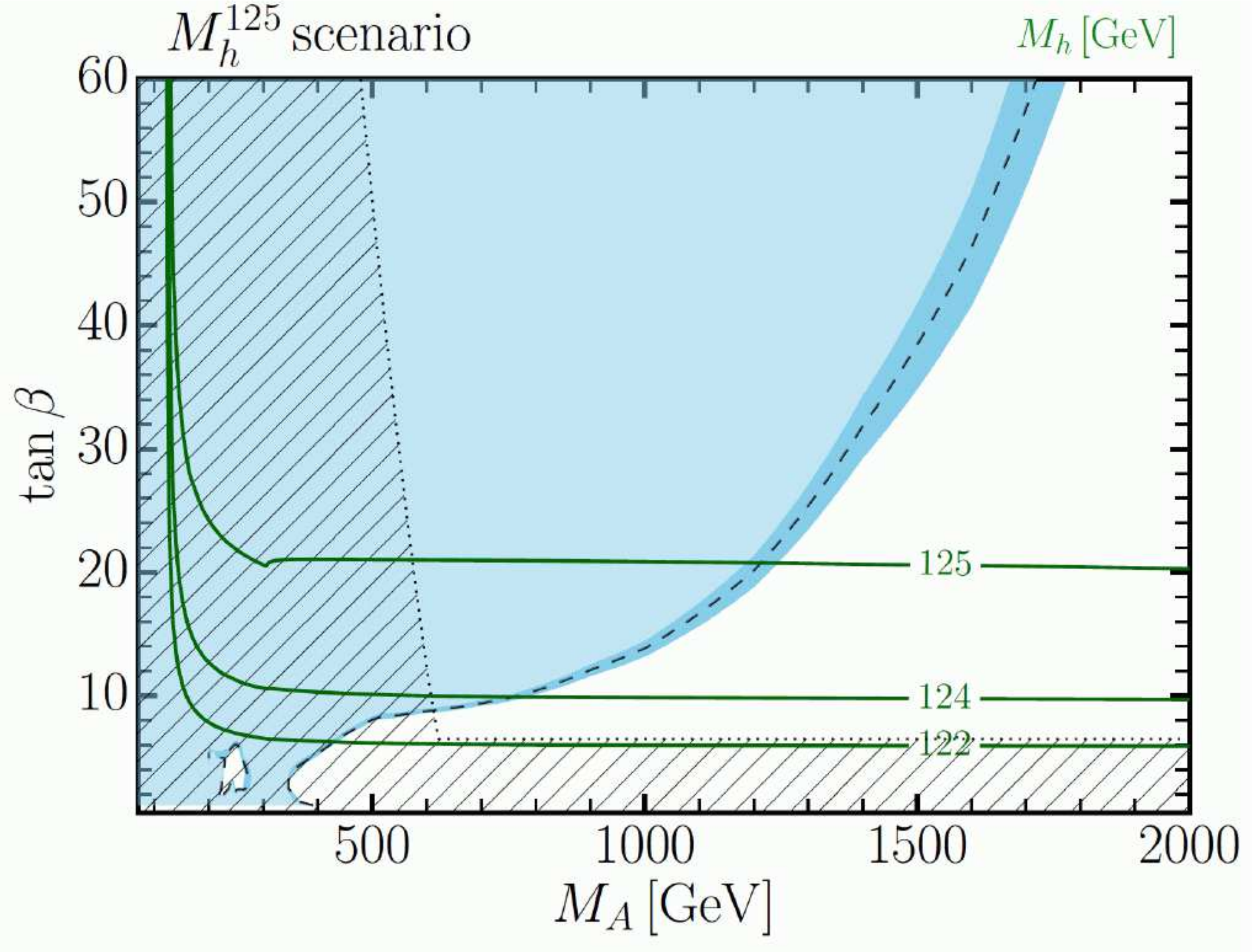
Data on purpose not to be taken into account:

– electroweak precision data

– flavor data

– astrophysical data (DM properties)

New benchmark: M_h^{125}



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

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

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

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

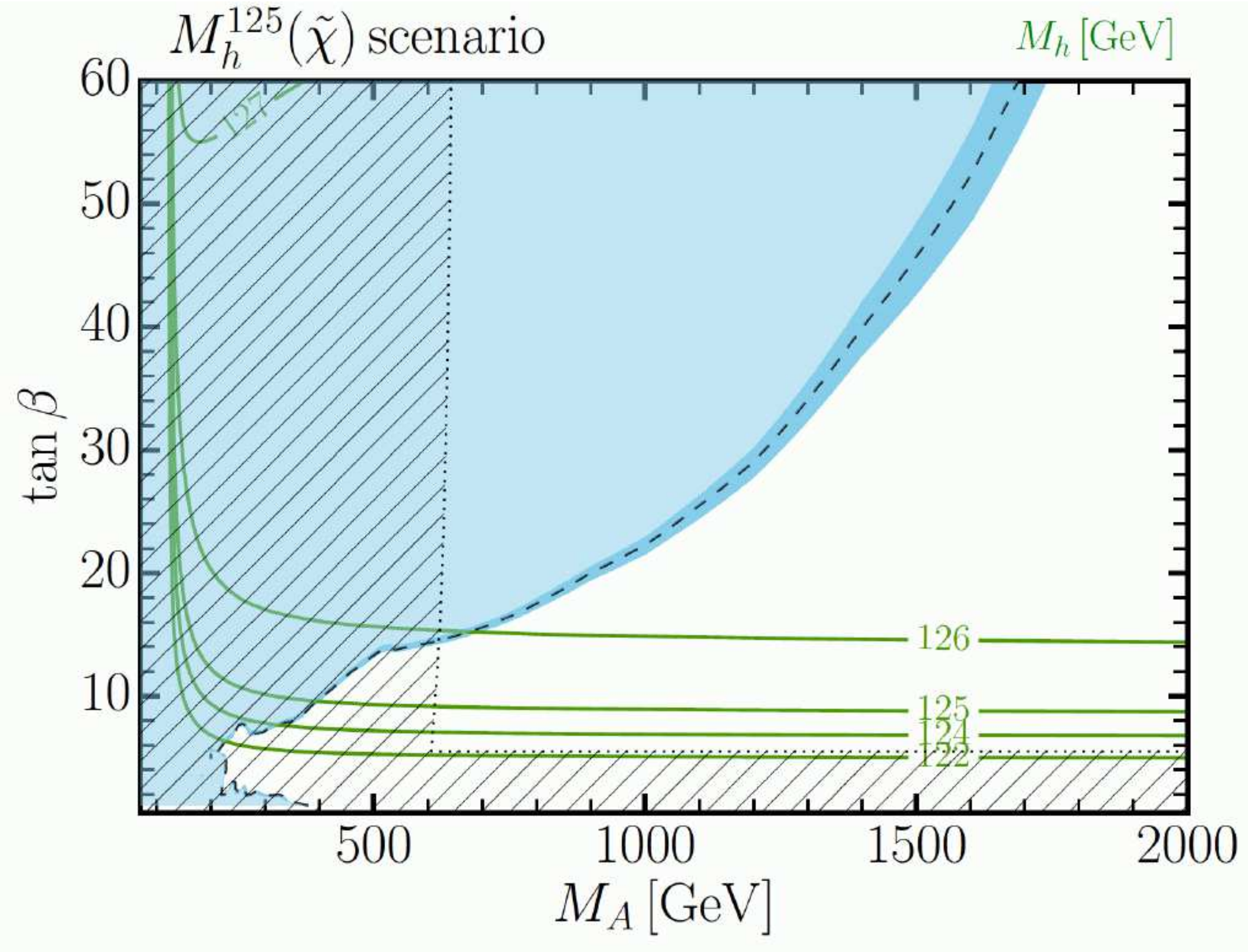
$X_t = 2.8$ TeV

$A_t = A_b = A_\tau$

⇒ new vanilla benchmark model

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

[*E. Bagnaschi 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 ⇒ LC needed?!

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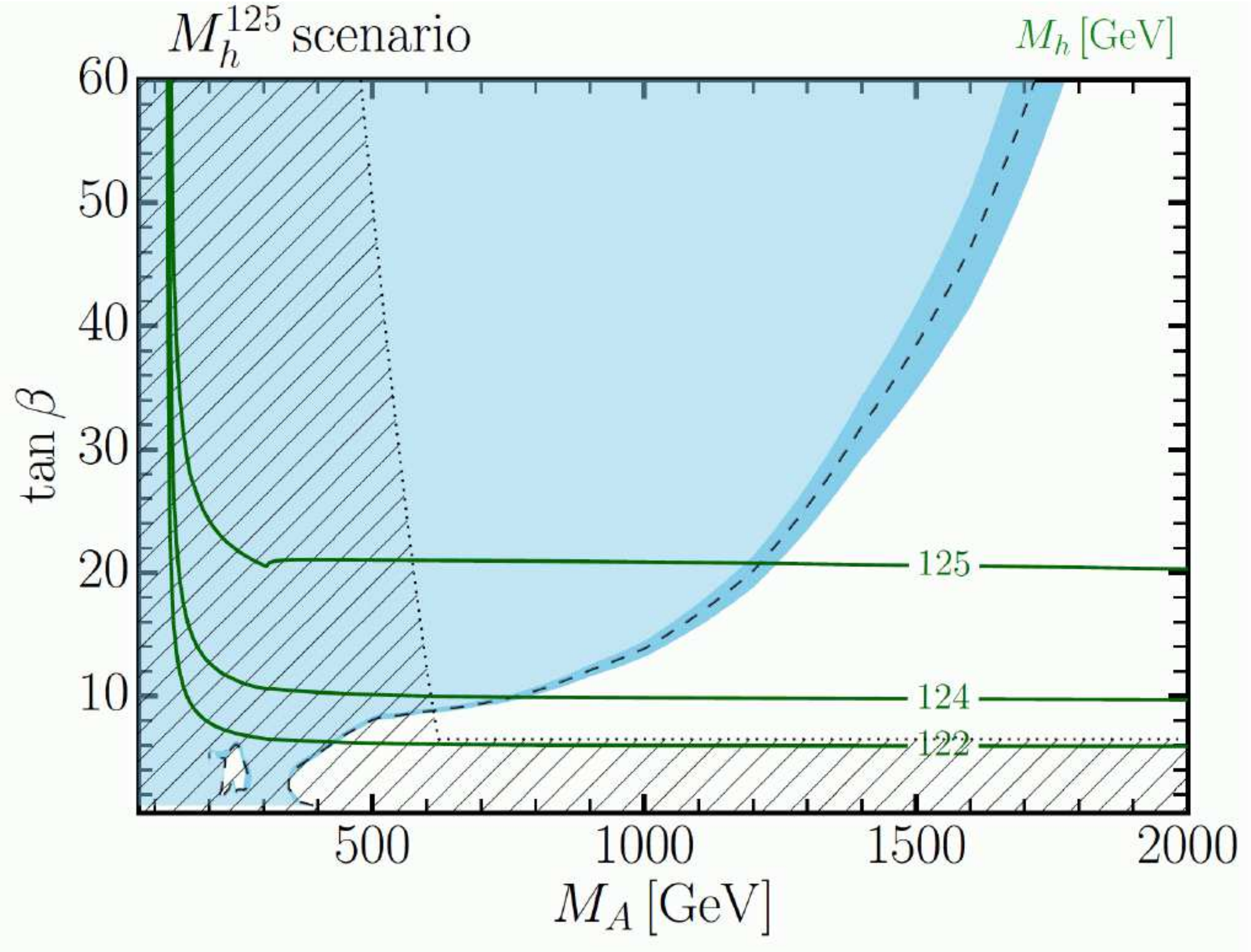

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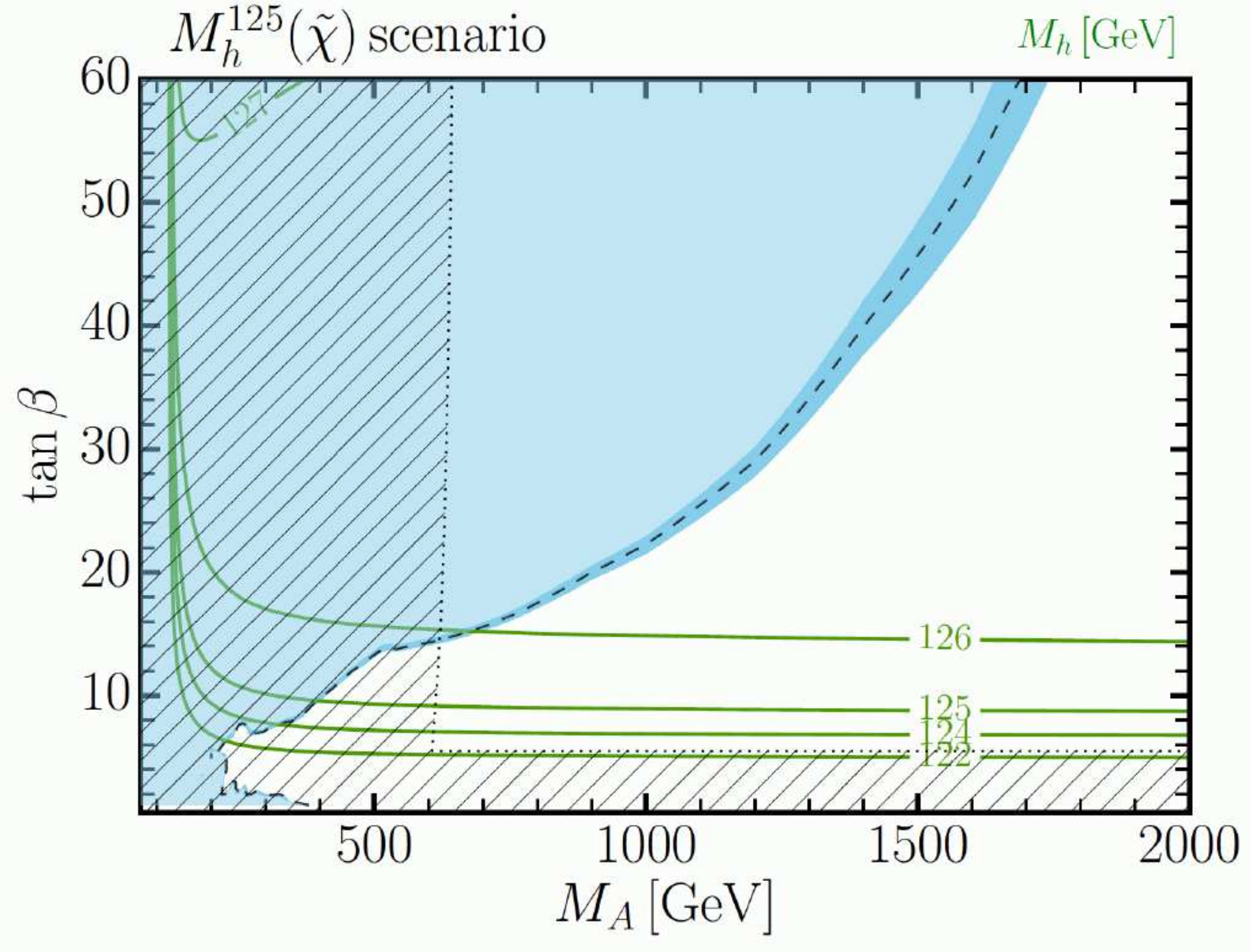

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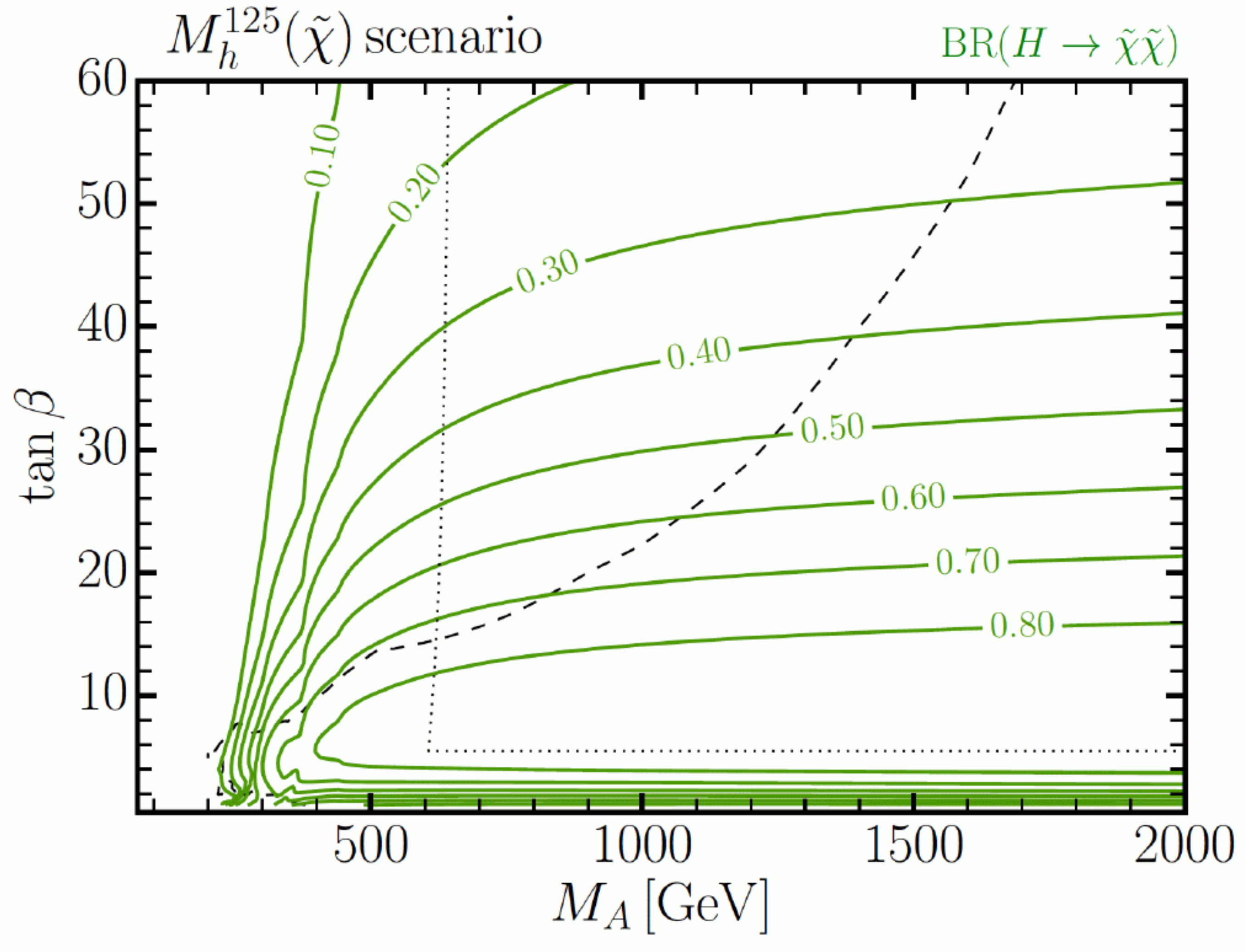

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$X_t = 2.5$ TeV

$A_t = A_b = A_\tau$

$\Rightarrow$ Huge BR of heavy Higgses to EW-inos $\Rightarrow$ LC opportunities?!

New benchmark: M_H^{125}

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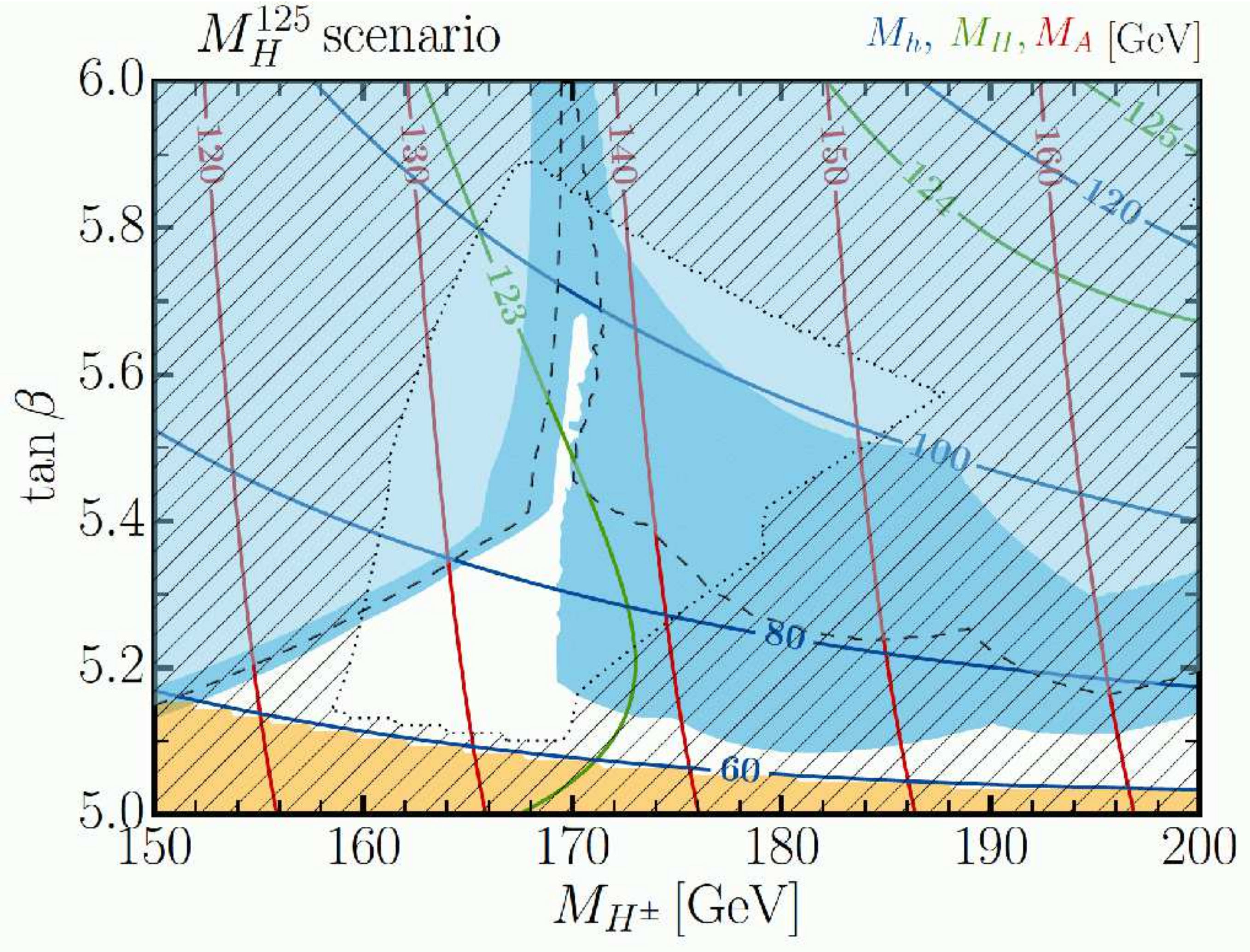


$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = 750 \text{ GeV} - 2(M_{H^\pm} - 150 \text{ GeV})$$

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

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

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

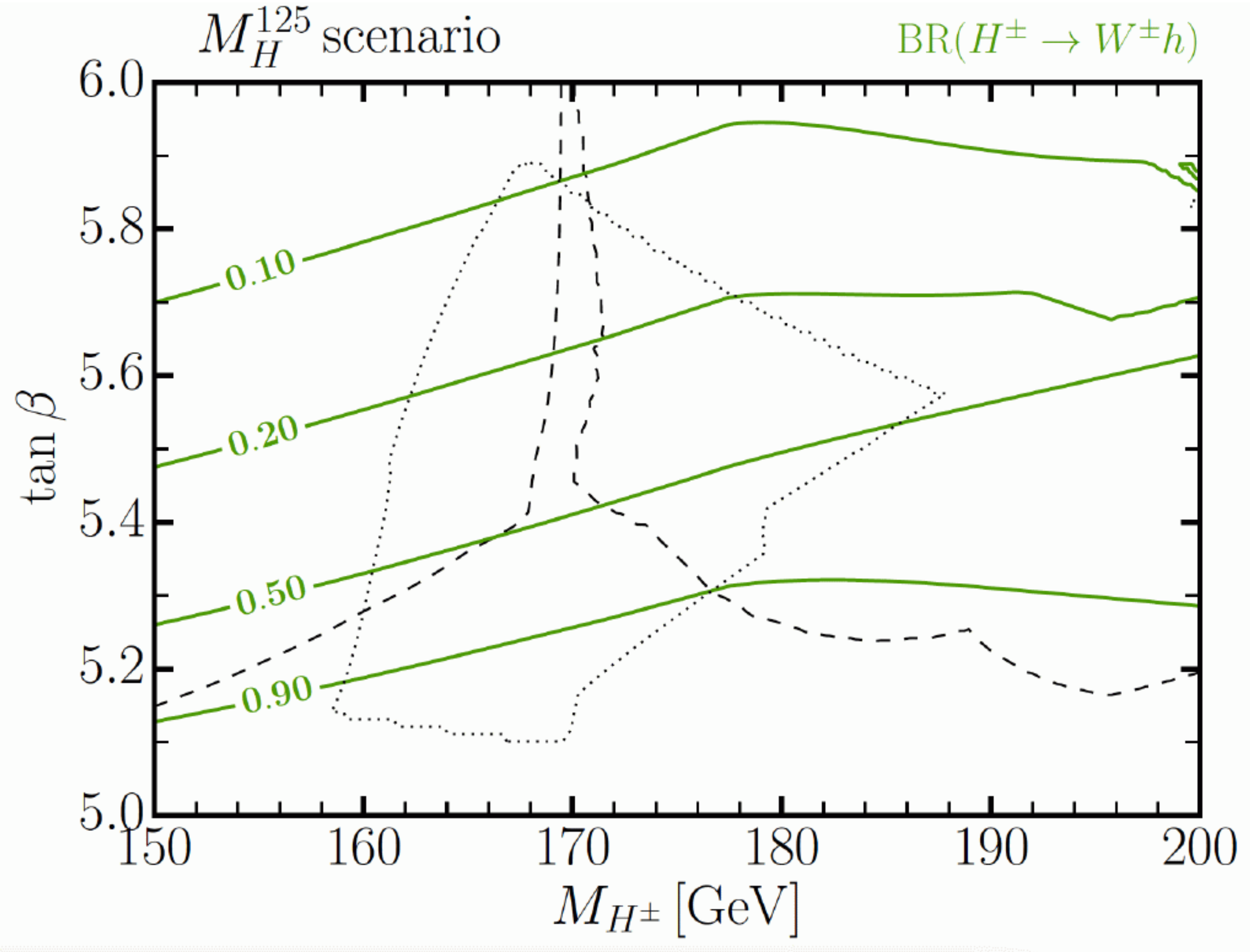
$$M_2 = 1 \text{ TeV}, \; M_3 = 2.5 \text{ TeV}$$

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

⇒ exotic solution still viable!

New benchmark: M_H^{125}

[*E. Bagnaschi et al., '18*]



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

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

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

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

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

3. Implications from 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]

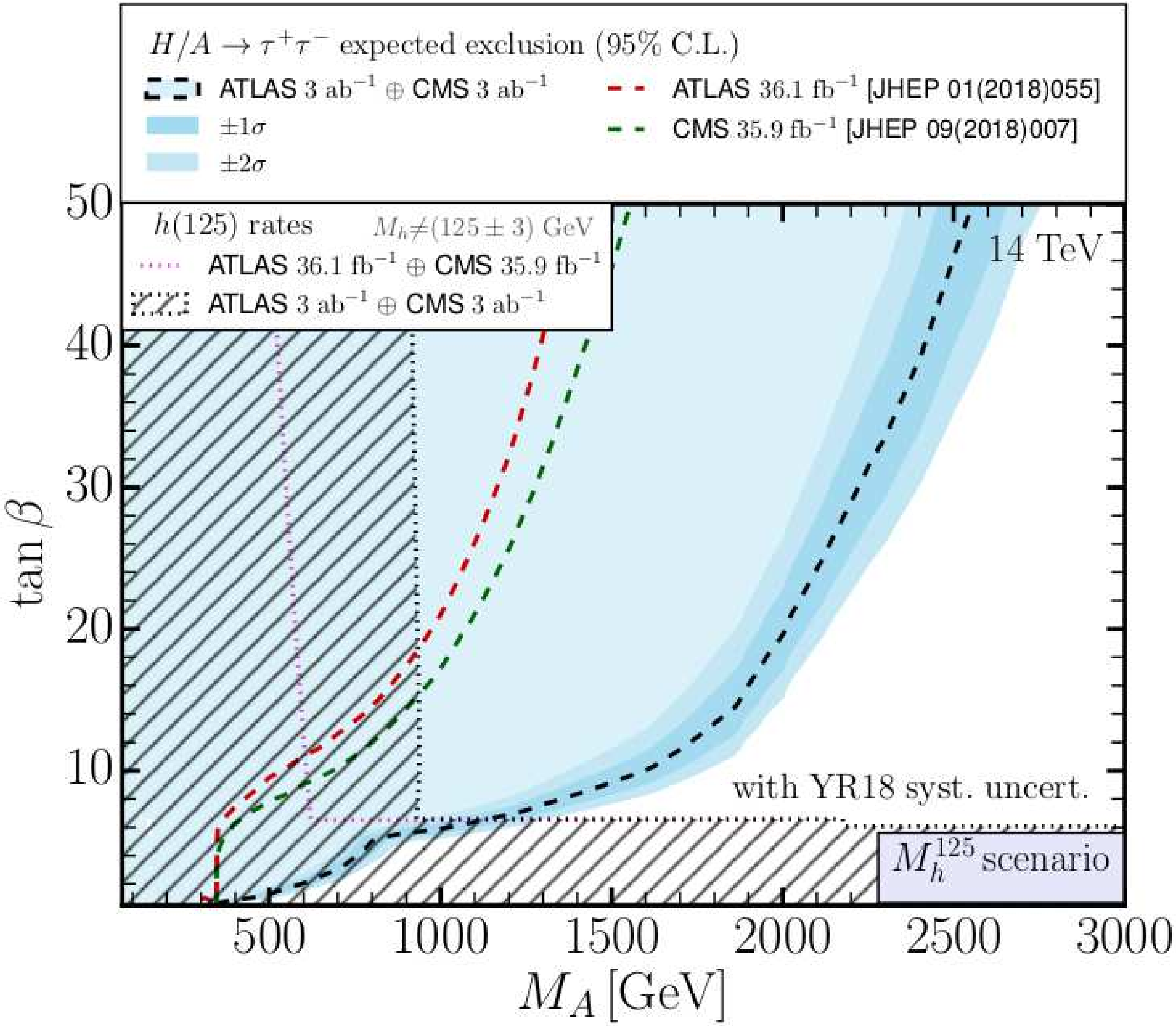
ILC:

– 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

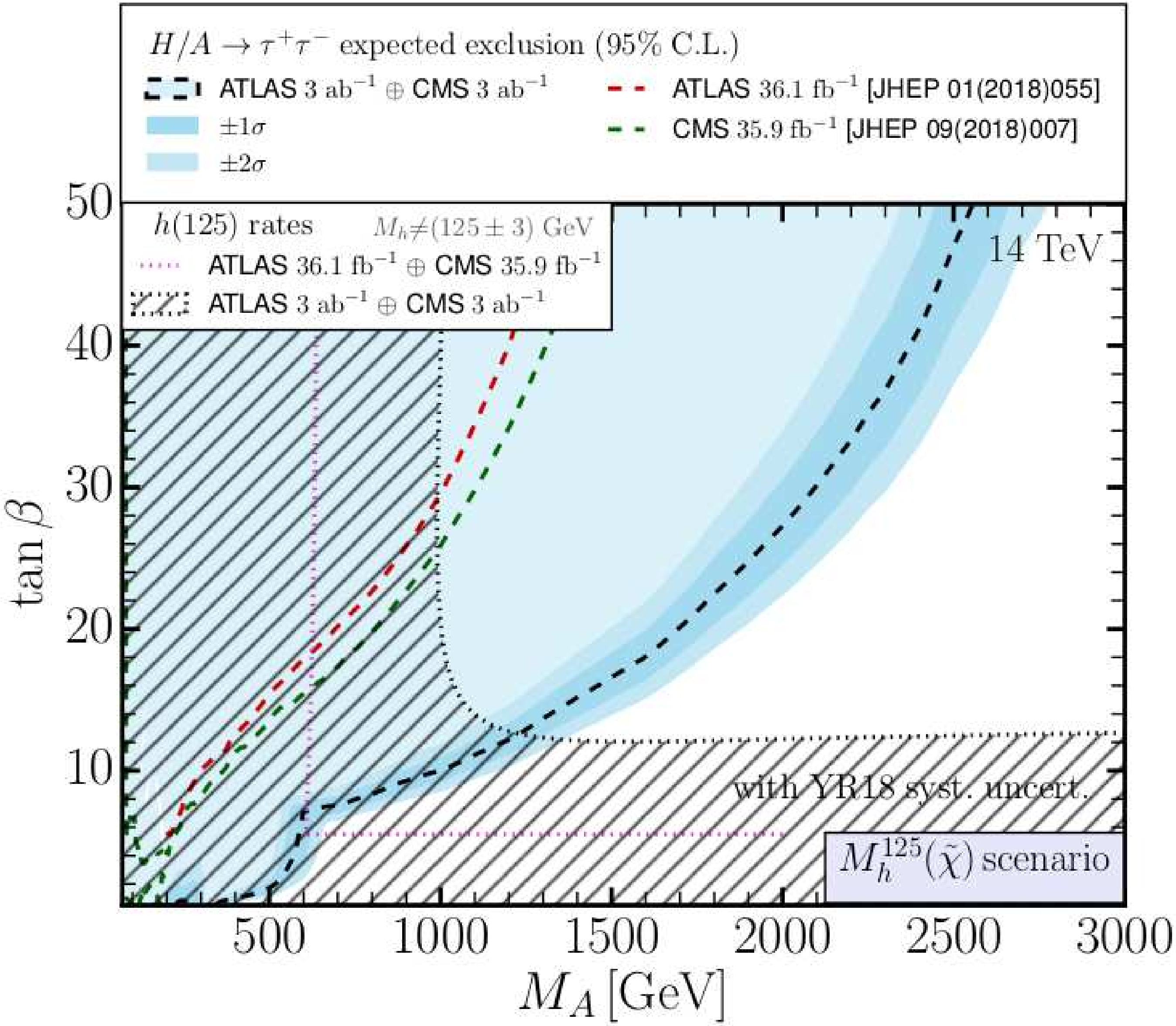
[H. Bahl et al., PRELIMINARY]



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

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

[H. Bahl et al., PRELIMINARY]

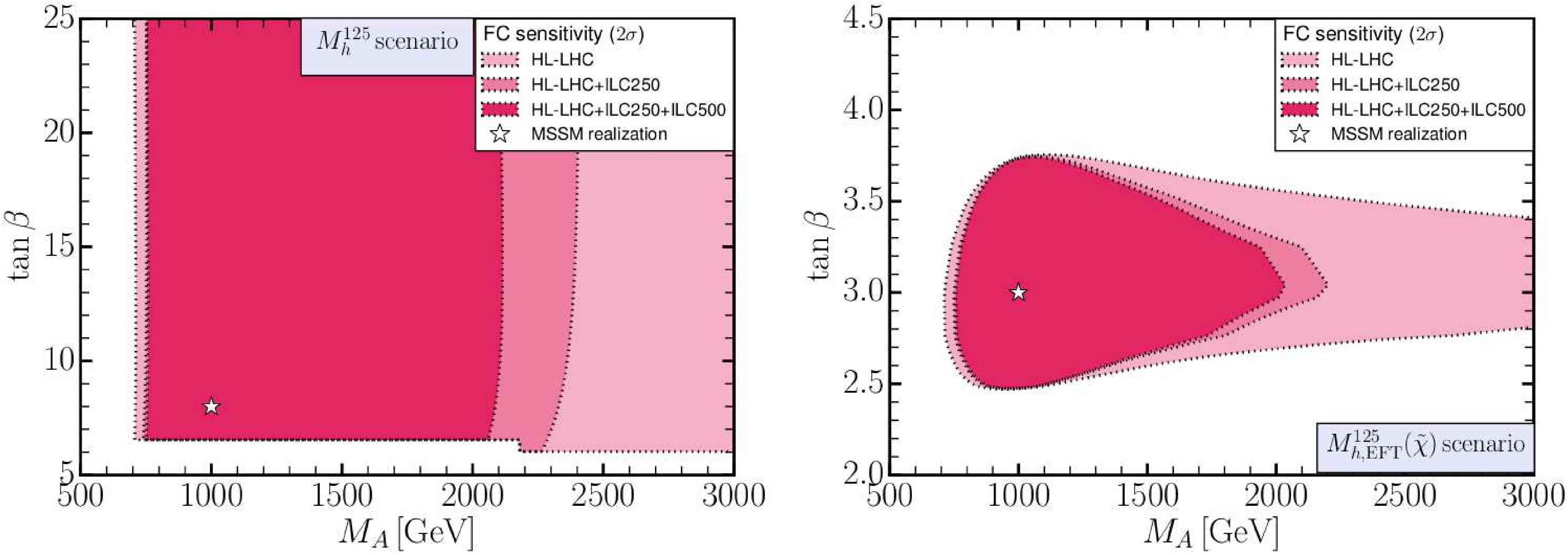


⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV

Relevance of ILC improvement:

[H. Bahl et al., PRELIMINARY]

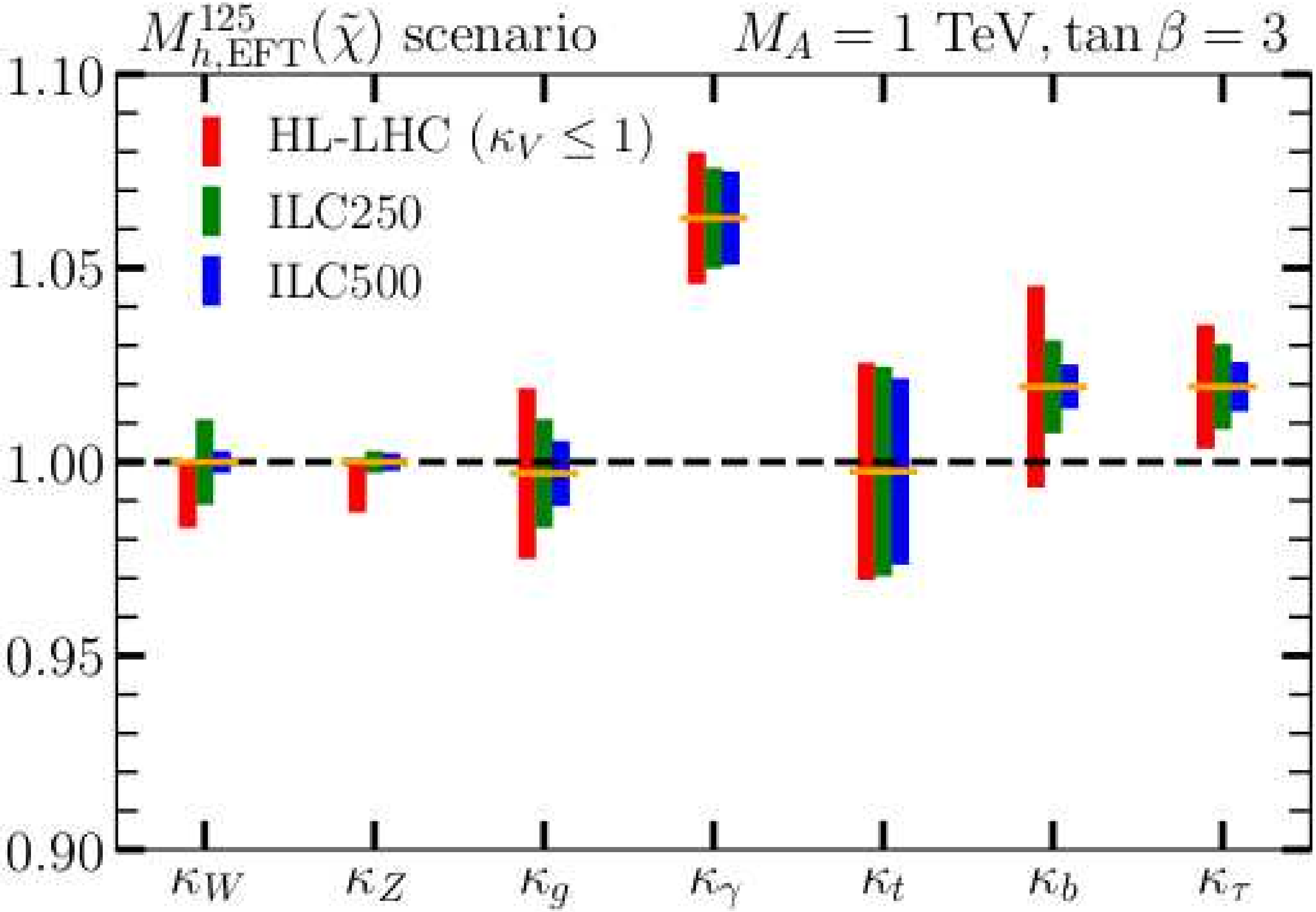
- Assume a realization of an MSSM point: $M_A = 1$ TeV, $\tan\beta = 7/3$
- What limits can be set from rate/coupling measurements?



$\Rightarrow$ 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. The ILC and the 96 GeV "excess"

- What was seen in Run I?
- What was seen in Run II?
- What was seen at LEP?
- Which model fits?
- indirect ILC opportunities
- direct ILC opportunities

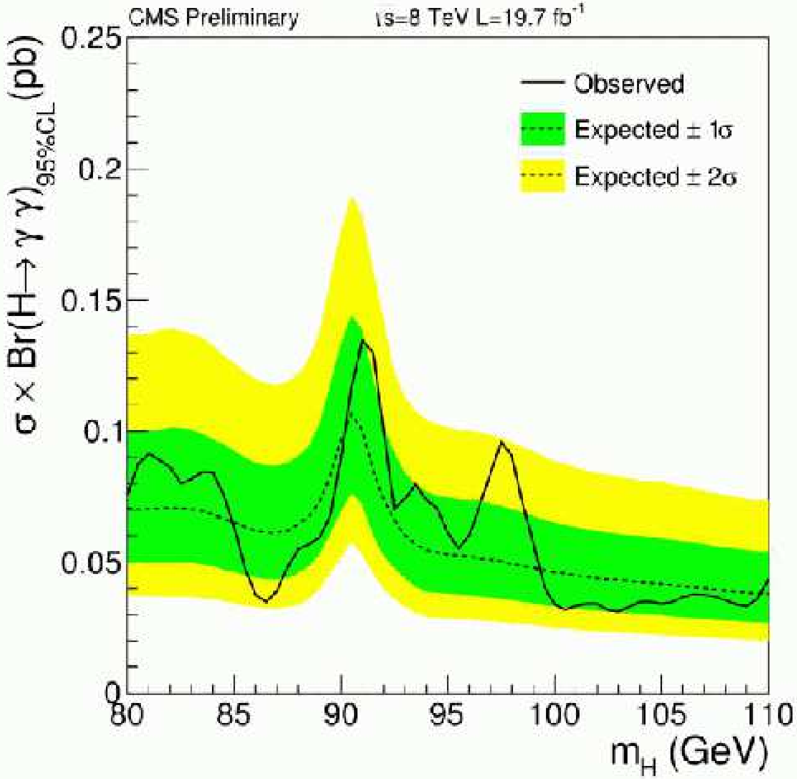
What was seen at Run I?

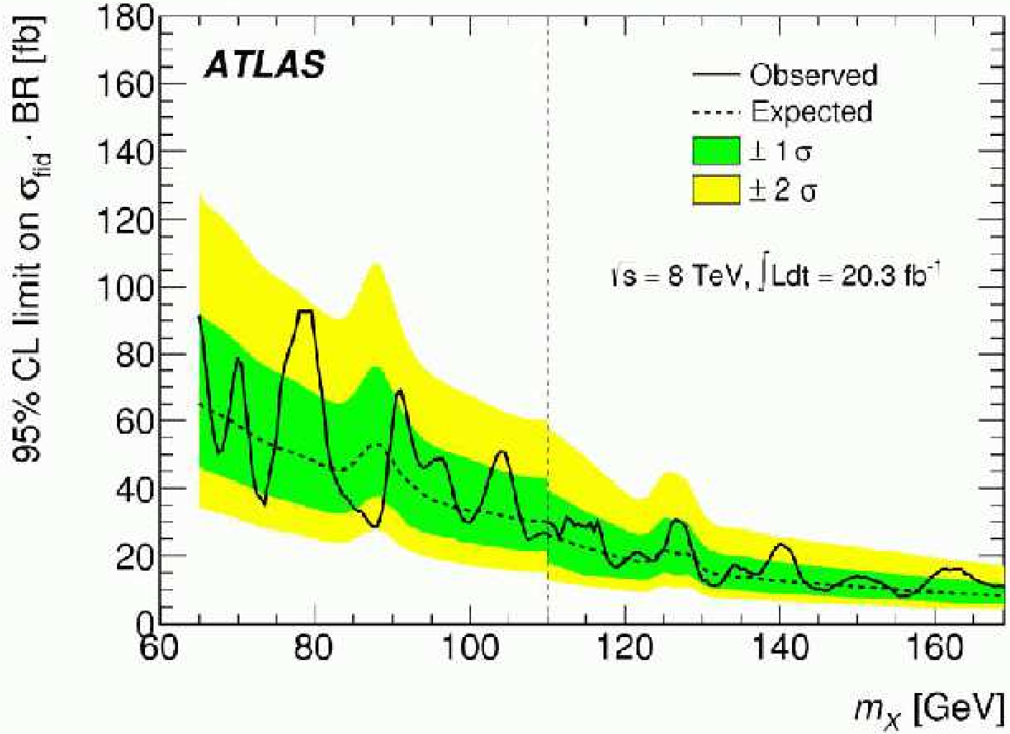
[*S. Shotkin, talk at HDays17*]

h-->γγ (65-110GeV) Run 1

CMS PAS HIG-14-037

PRL 113 171801 (2014)





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

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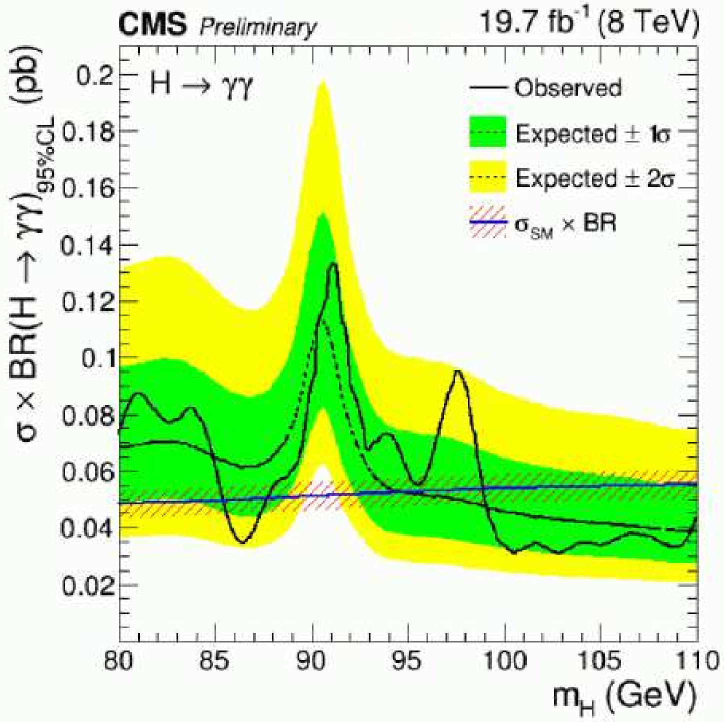
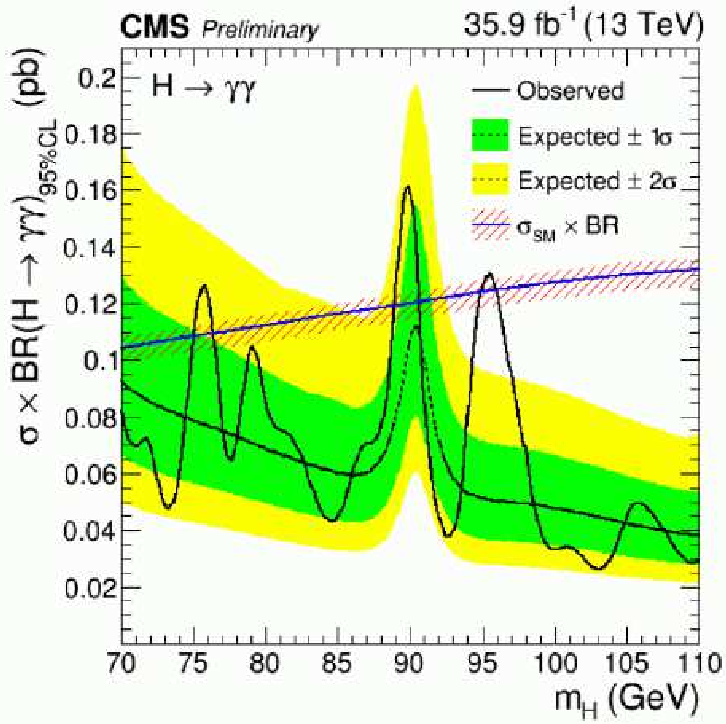
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

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.

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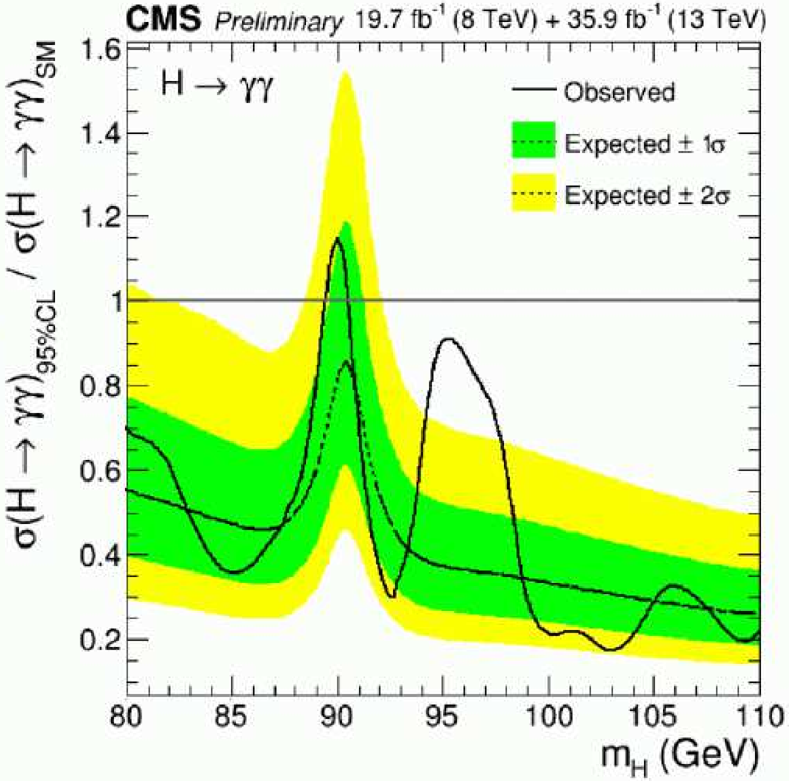
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

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 (σ X Br)/ (σ X 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.

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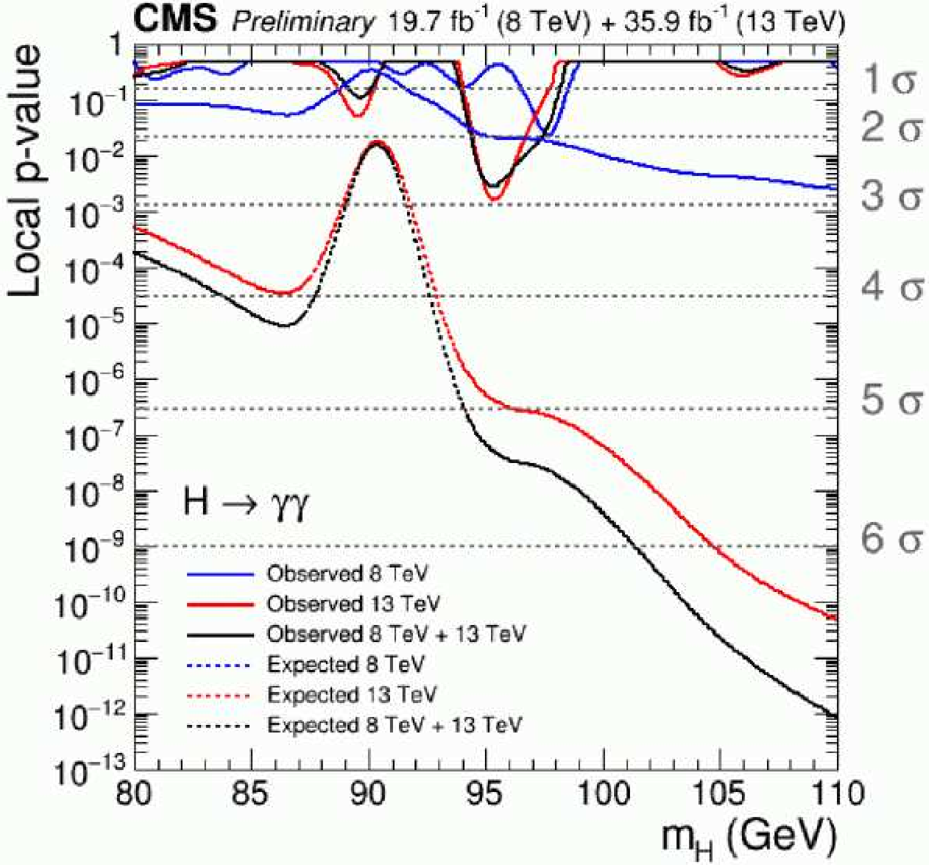
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

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

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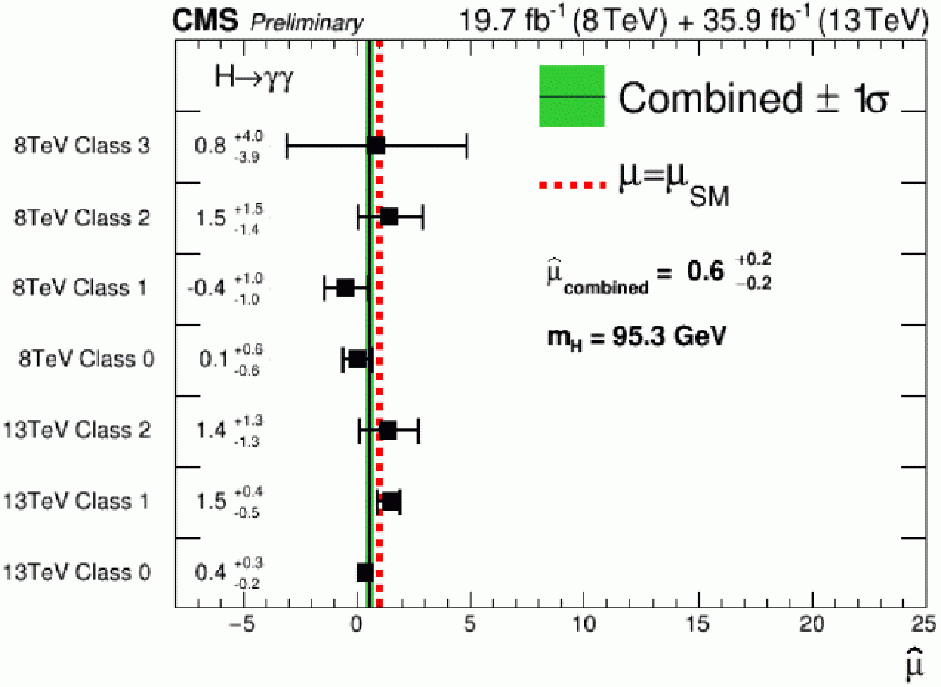
 [S. Shotkin, talk at HDays17]

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

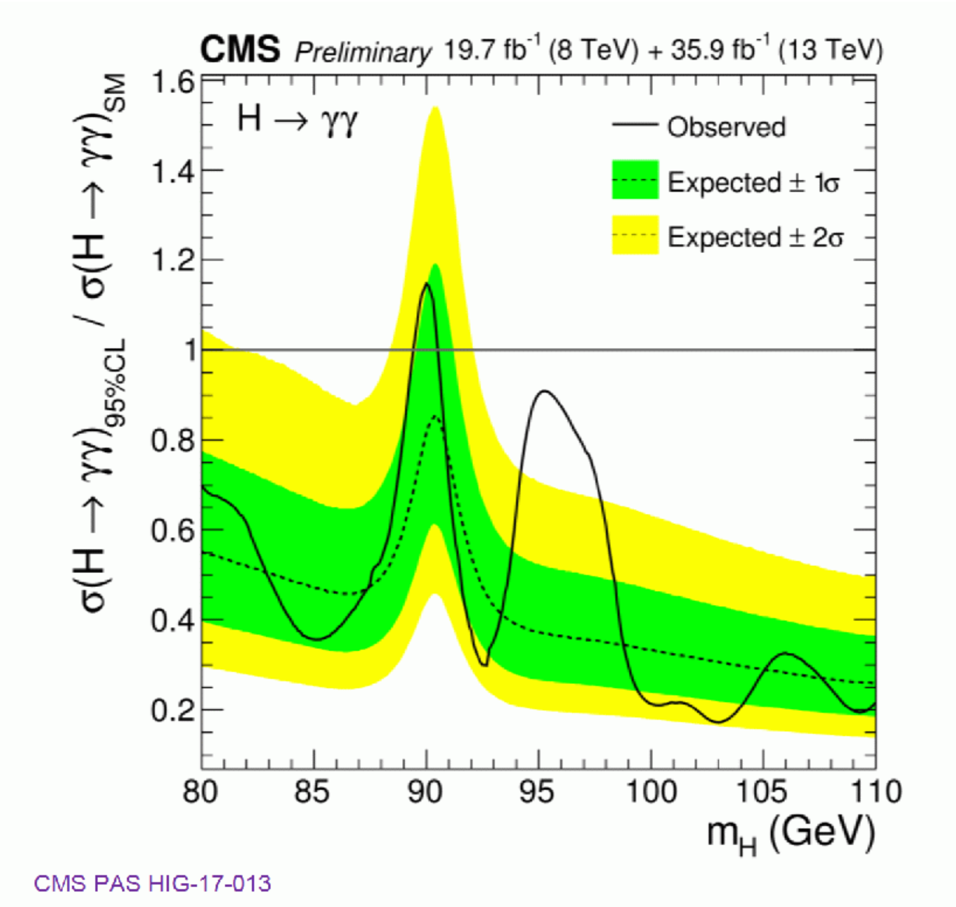
χ^2 probability for the seven individual values to be compatible with a single signal hypothesis: 41%

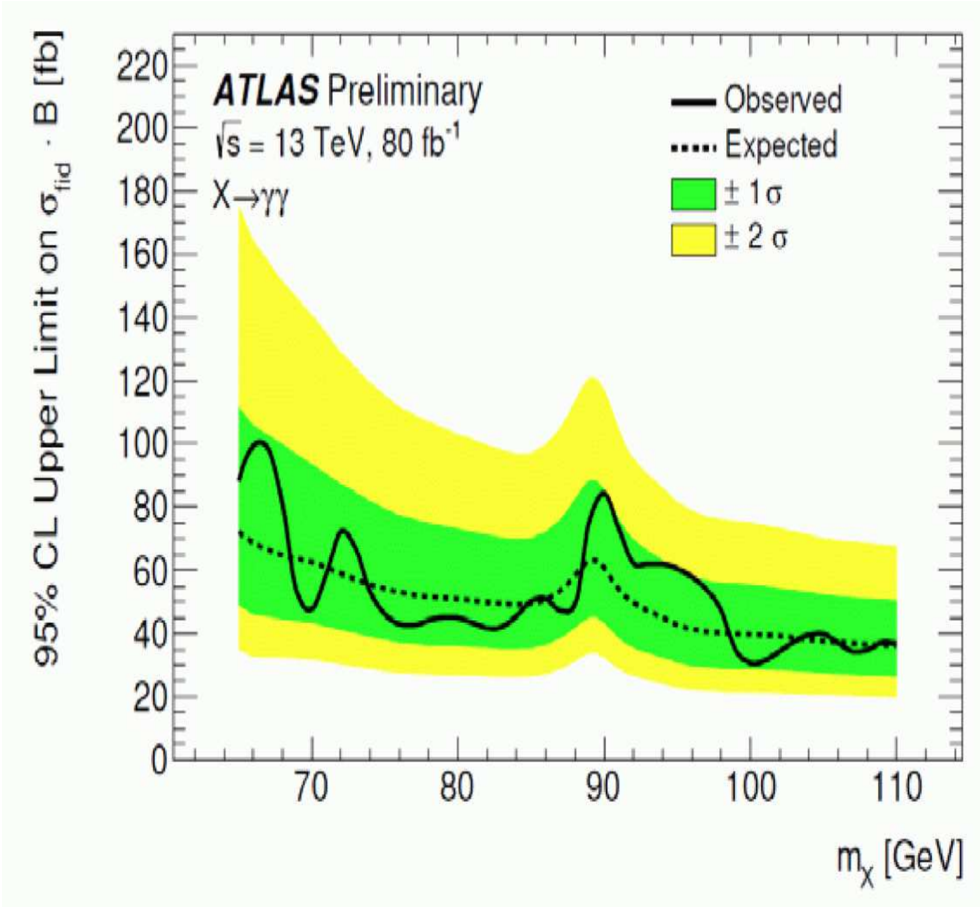
- 'Signal' strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing m_H=95.3 GeV
- More data are required to ascertain the origin of this excess

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

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

What about ATLAS?





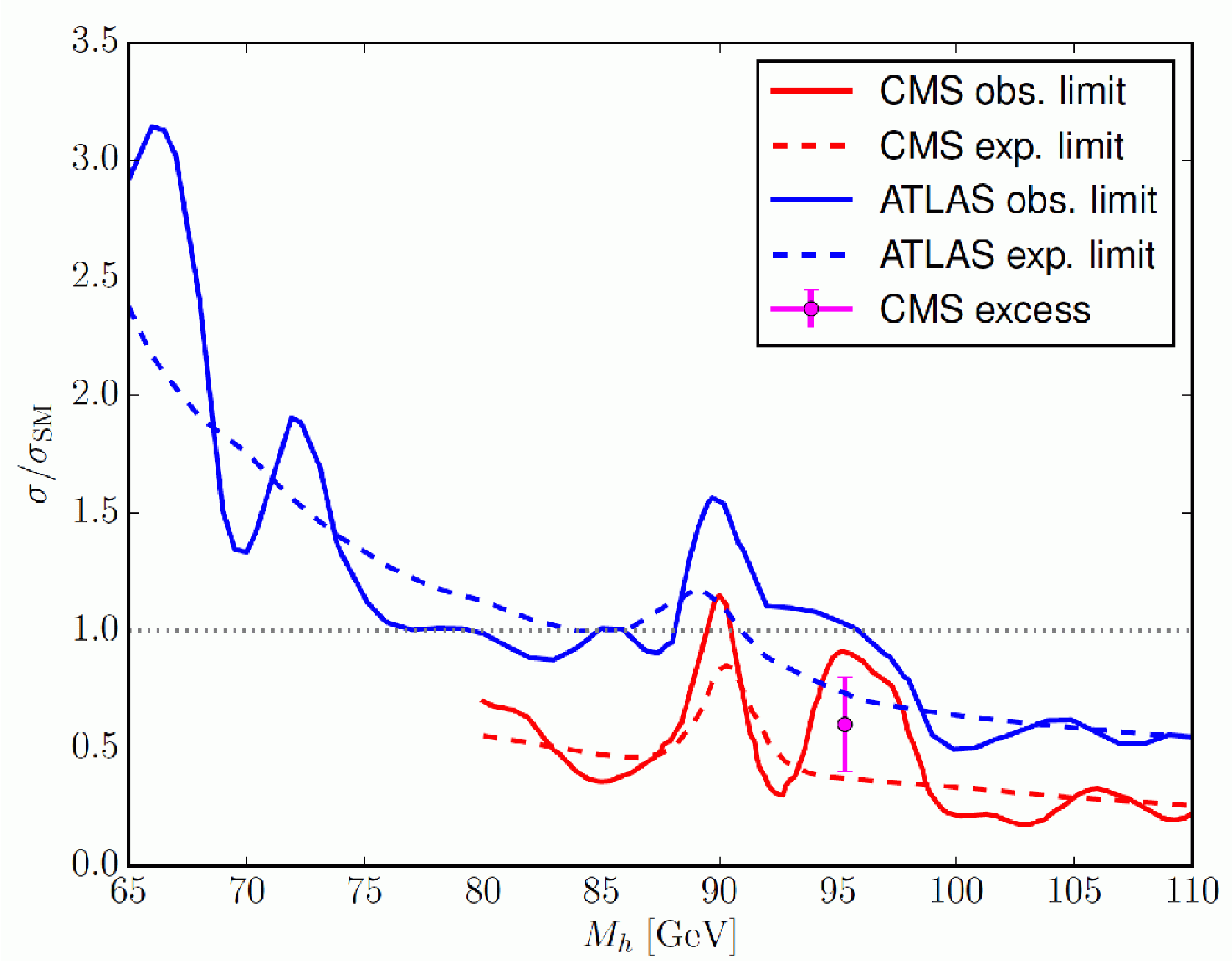
Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

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

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

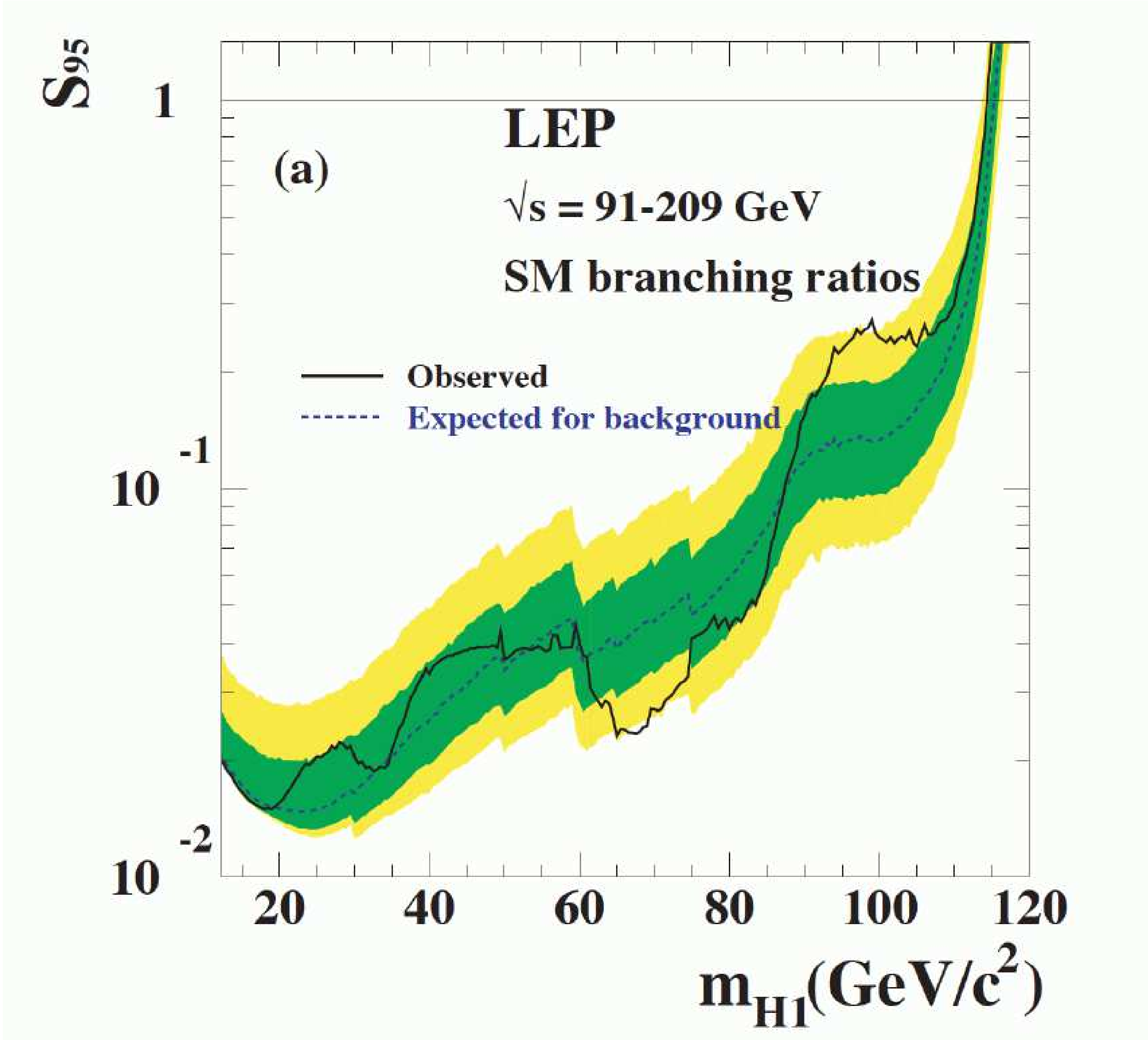
CMS and ATLAS in direct comparison:

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



⇒ everything well compatible with the excess!

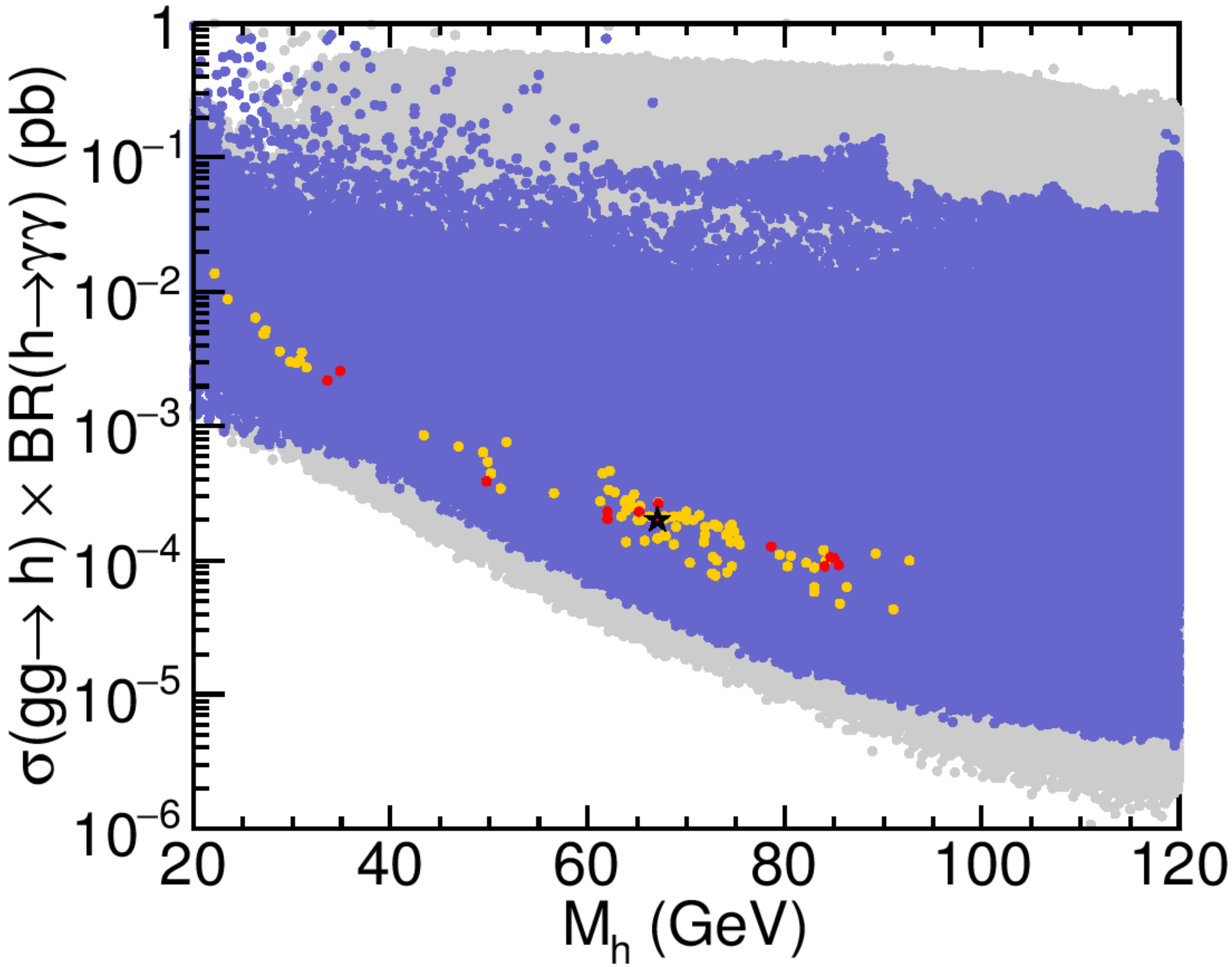
What was seen at LEP?



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

What about the MSSM?

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



⇒ too small rates! ⇒ 2HDM structure to "rigid"

More general Ansatz: **N2HDM**

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

Fields:

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

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:

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

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 μ_{LEP}
- c_{h_1bb} reduced to enhance BR($h_1 \to \gamma\gamma$)
- c_{h_1tt} not reduced for μ_{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

⇒ Parameter scan ⇒ ScannerS

Constraints:

- Tree-level perturbativity ⇒ ScannerS
- Minimum of potential is global minimum ⇒ ScannerS
- Higgs searches at LEP, Tevatron, LHC ⇒ HiggsBounds
- SM-like Higgs properties ⇒ 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}) ⇒ SuperIso bounds
- Electroweak precision data (T and S) ⇒ ScannerS

Fitting the excesses:

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

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

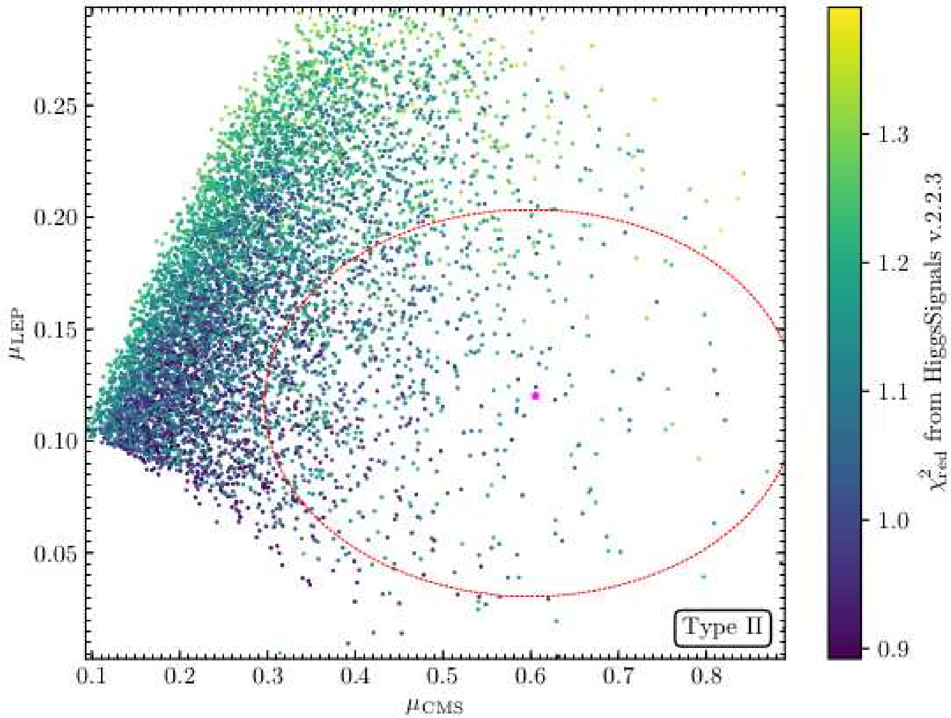
$$\mu_{\text{CMS}} = \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$
$$= \left|c_{h_1tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H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

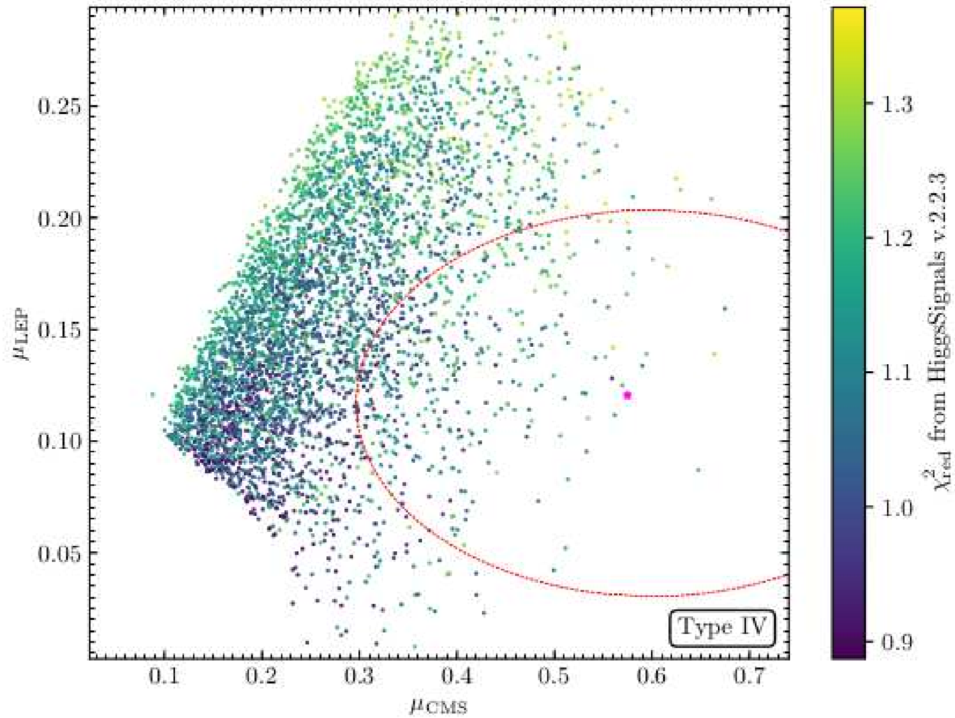
$$\chi^2_{\text{CMS-LEP}} = \frac{(\mu_{\text{LEP}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\text{CMS}} - 0.6)^2}{(0.2)^2}$$

$\Rightarrow$ “best-fit point”

Fitting the excesses:

[*T. Biekötter, M. Chakraborti, S.H. '19*]





$\Rightarrow$ excesses well fitted, with good χ^2_{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

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
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- direct production of ϕ_{96} at the LHC
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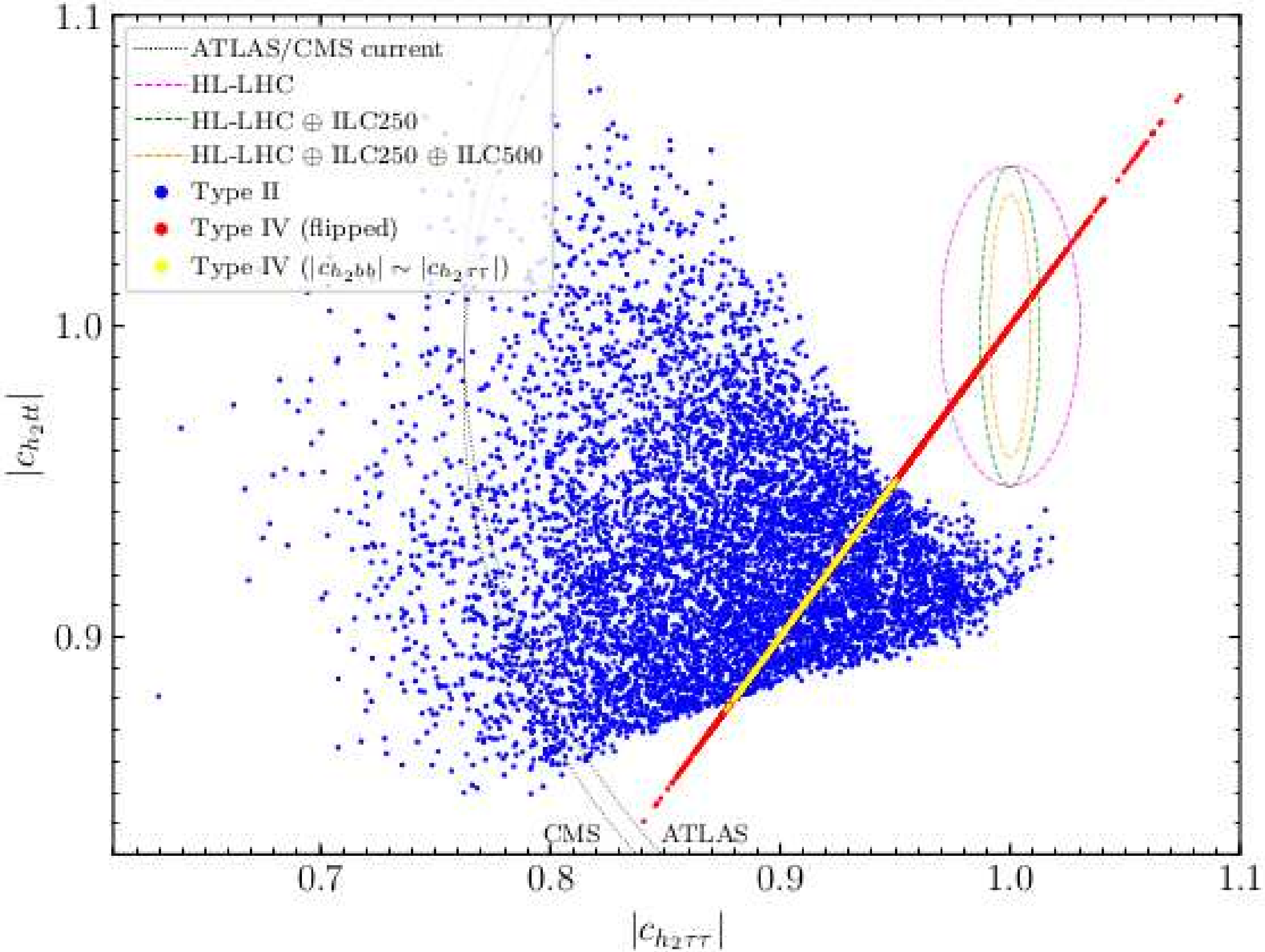
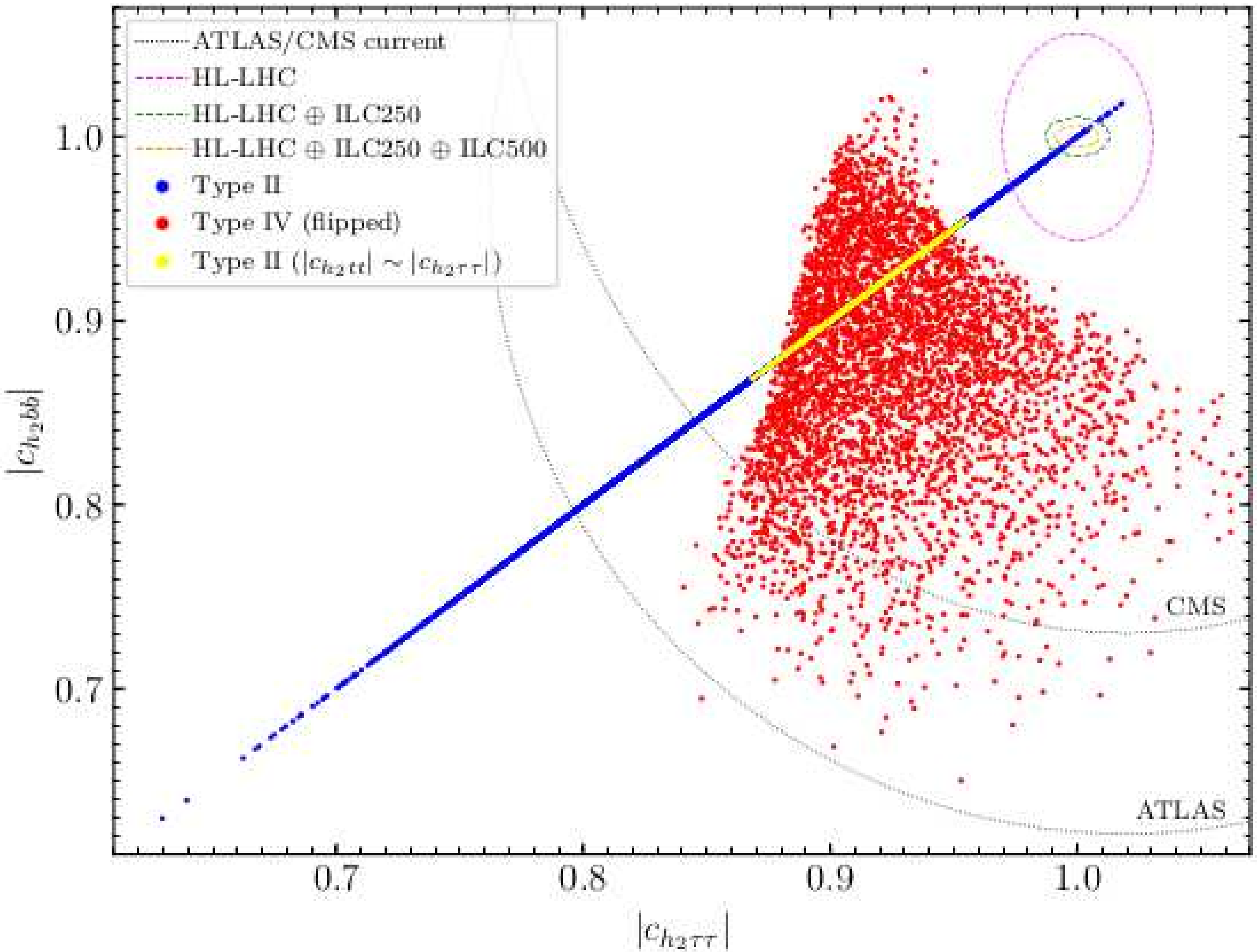
- production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/...

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



⇒ type II shows deviation from SM

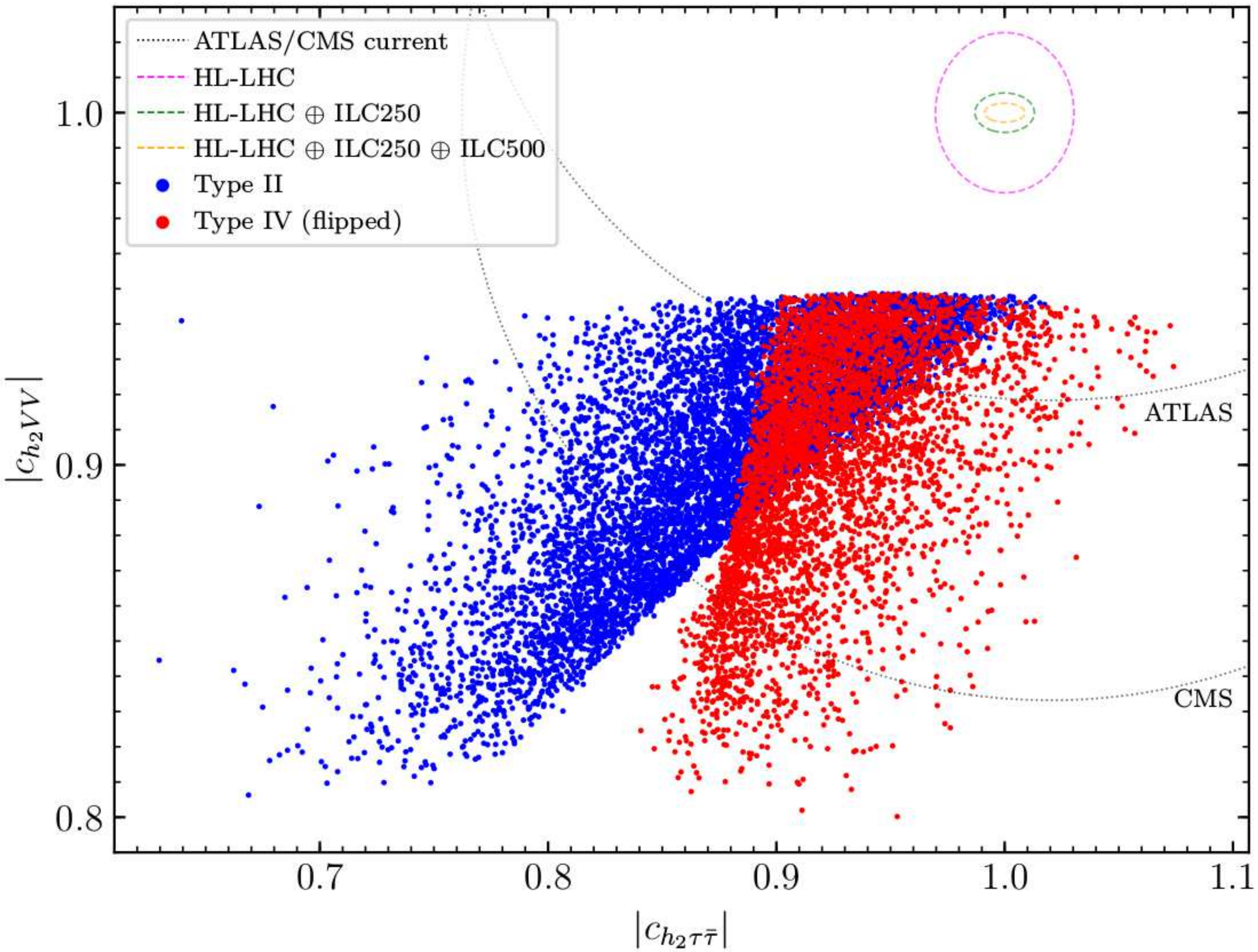
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type IV shows deviations from SM

⇒ N2HDM can always be distinguished from SM!

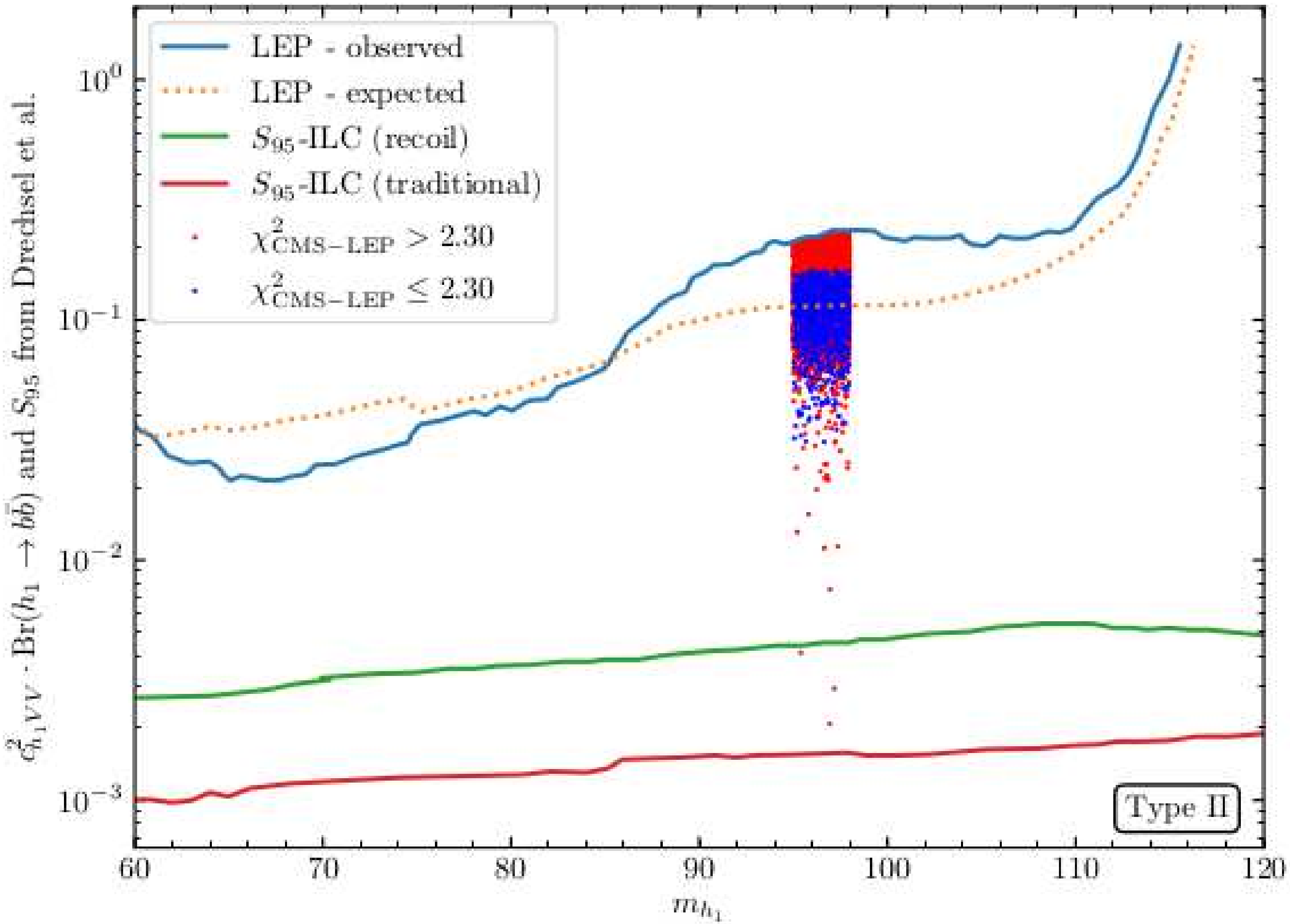
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ 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

5. Conclusinos

- There are many models out there with extended Higgs sectors
  SUSY is (still / of course) the best-motivated BSM scenario

- Benchmark scenarios/searches: Data taken into account: Higgs/SUSY
  Data on purpose not taken into account: EW/Flavor/DM
  - 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

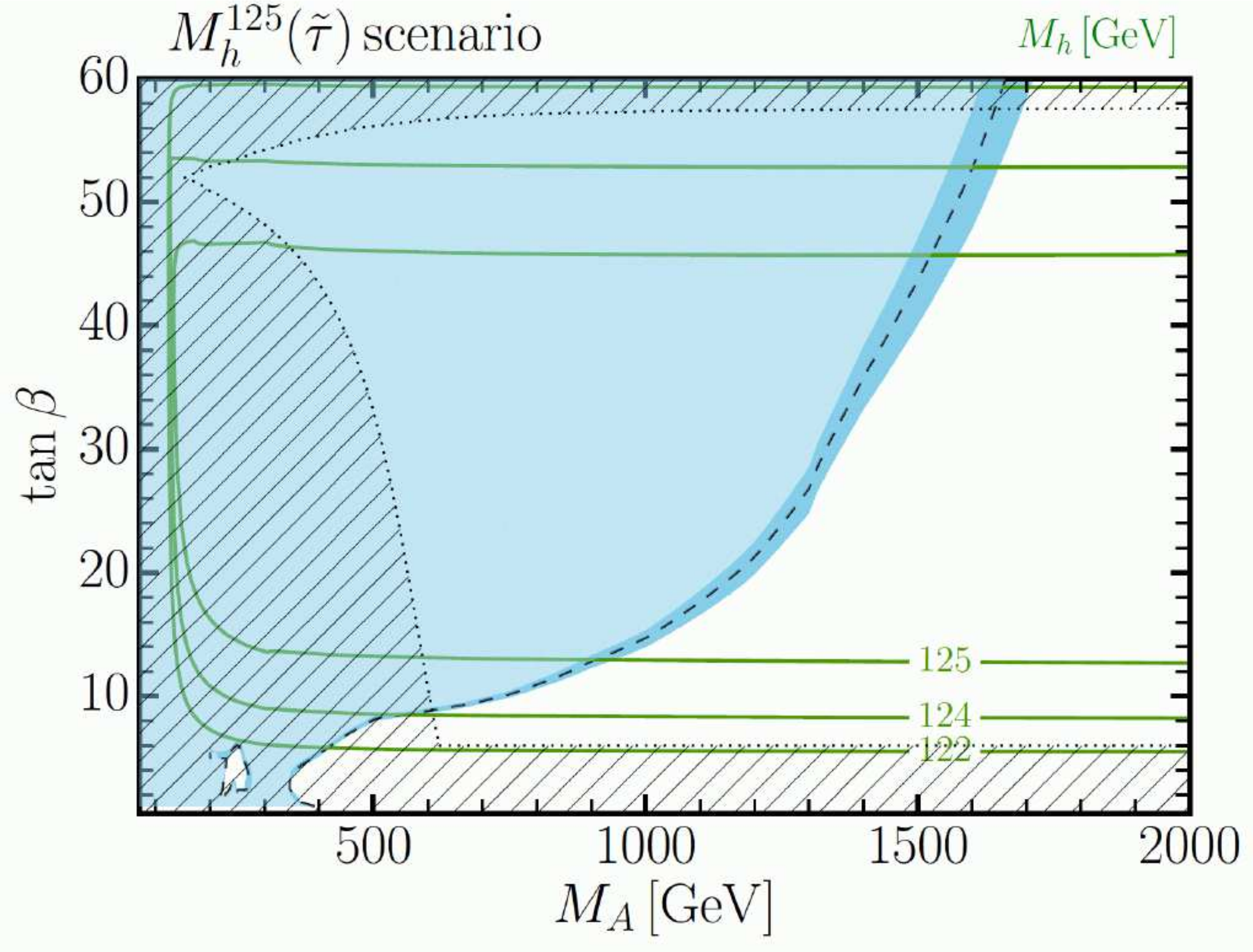
- A light Higgs at 96 GeV?
  new CMS/ATLAS result (and old LEP result) possibly interesting!
  - MSSN cannot explain the excesses
  - NMSSM/$\mu\nu$SSM can explain CMS(/ATLAS) and LEP excesses

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


Further Questions?

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

[*E. Bagnaschi et al., '18*]

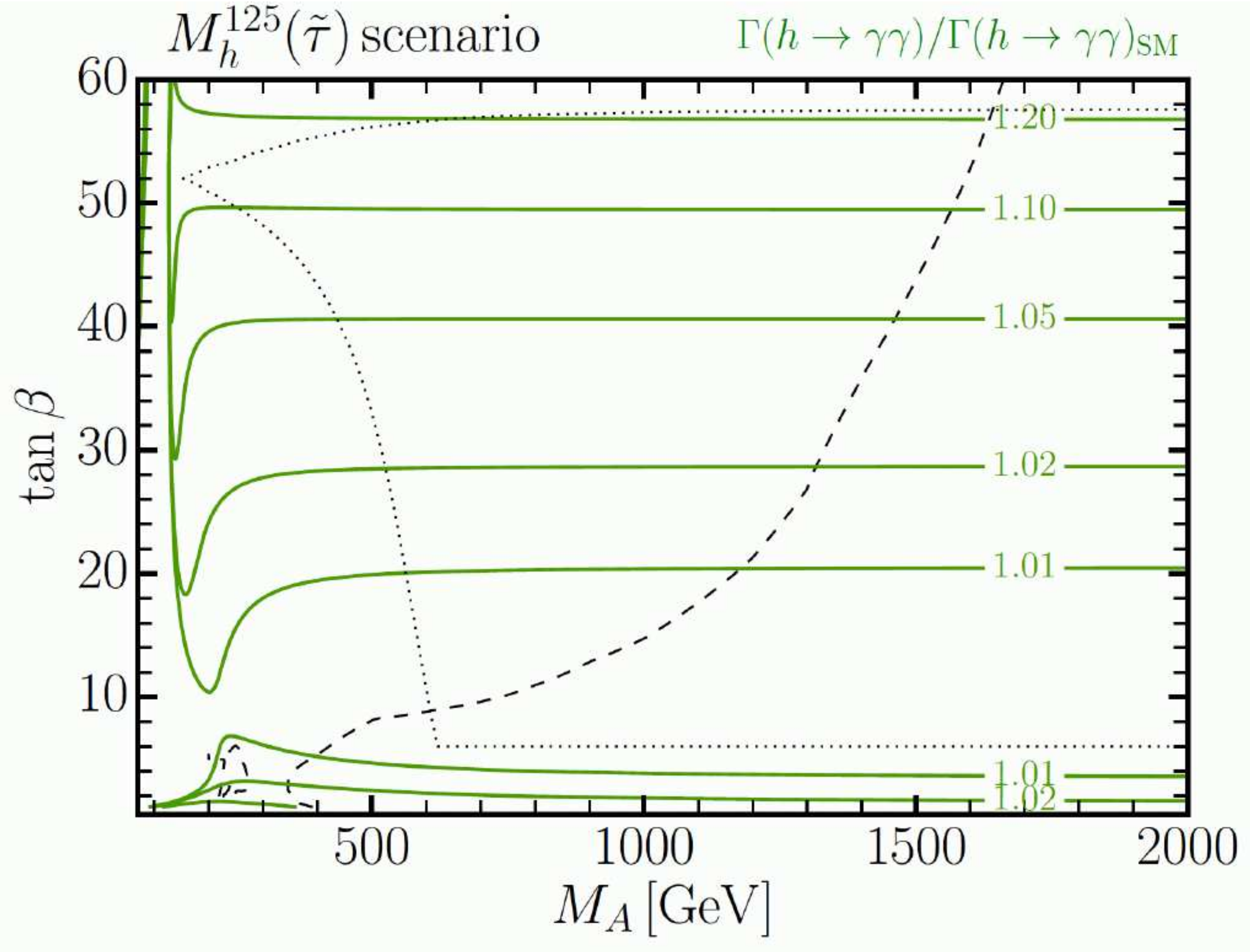


$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$
$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 350 \text{ GeV}$$
$$\mu = 1 \text{ TeV}, \; M_1 = 180 \text{ GeV}$$
$$M_2 = 300 \text{ GeV}, \; M_3 = 2.5 \text{ TeV}$$
$$X_t = 2.8 \text{ TeV}$$
$$A_t = A_b, A_\tau = 800 \text{ GeV}$$

⇒ slightly reduced heavy Higgs coverage

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

[*E. Bagnaschi et al., '18*]



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

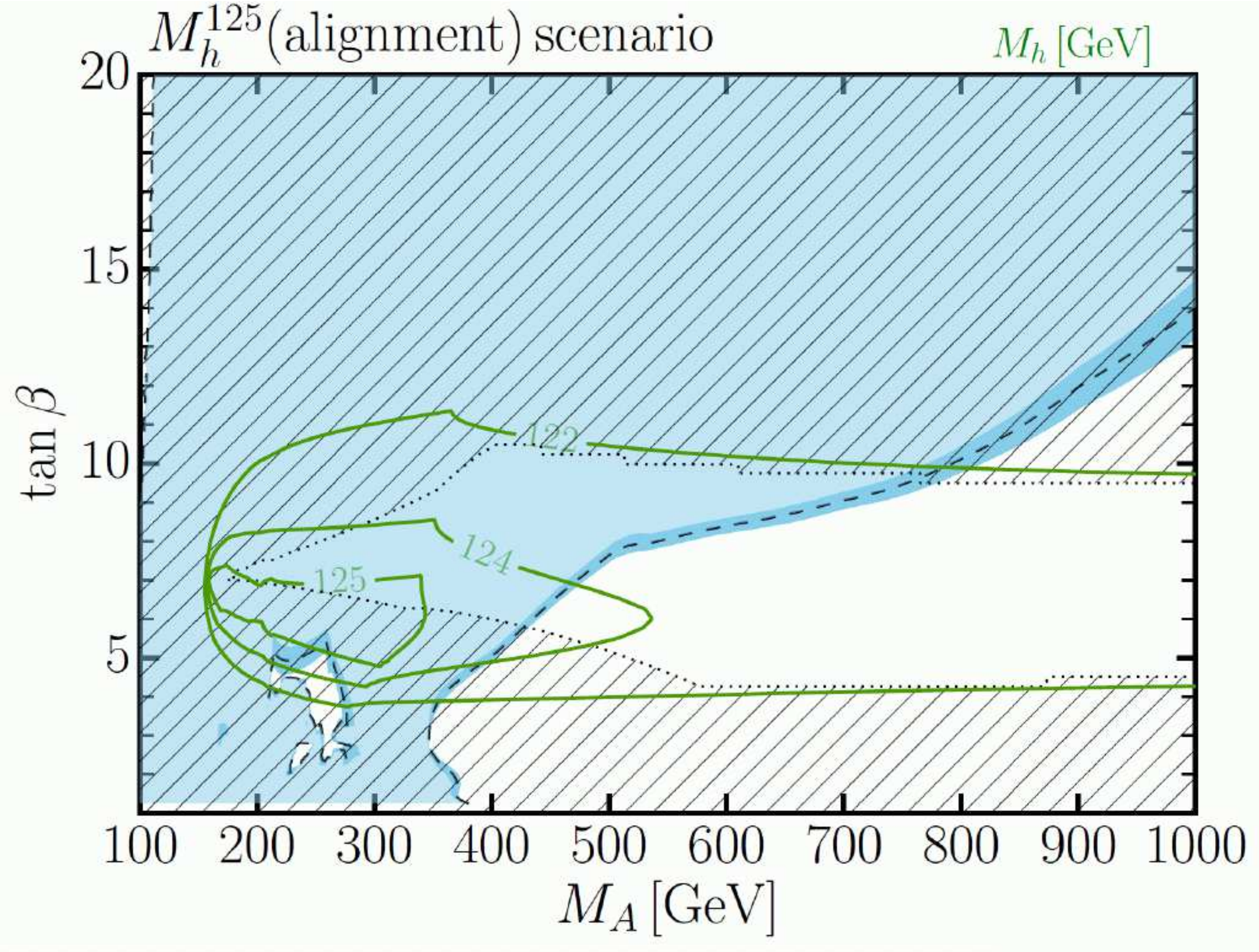
$X_t = 2.8$ TeV

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

$\Rightarrow$ strong impact on $\Gamma(h \to \gamma\gamma)$ $\Rightarrow$ measurable at the LC

New benchmark: M_h^{125}(align)

[*E. Bagnaschi 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

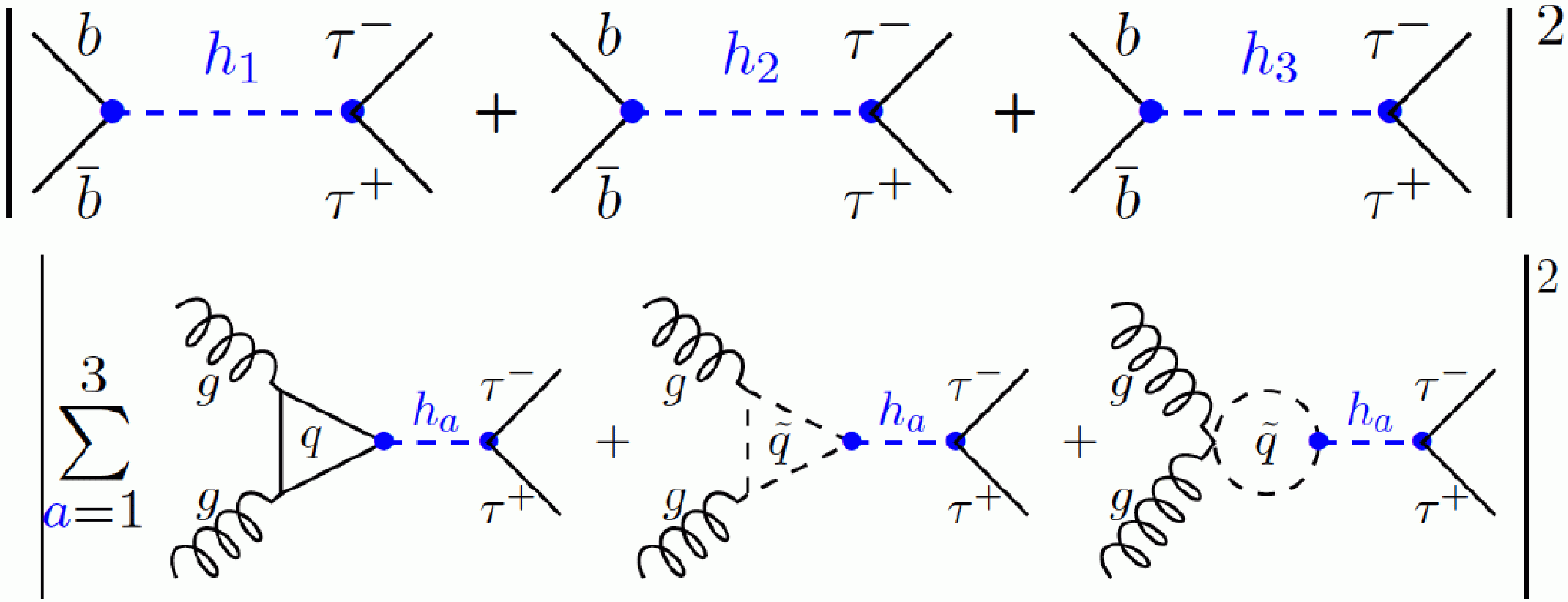
$A_t = A_b = A_\tau = 6.25$ TeV

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

LHC Higgs searches for complex parameters:

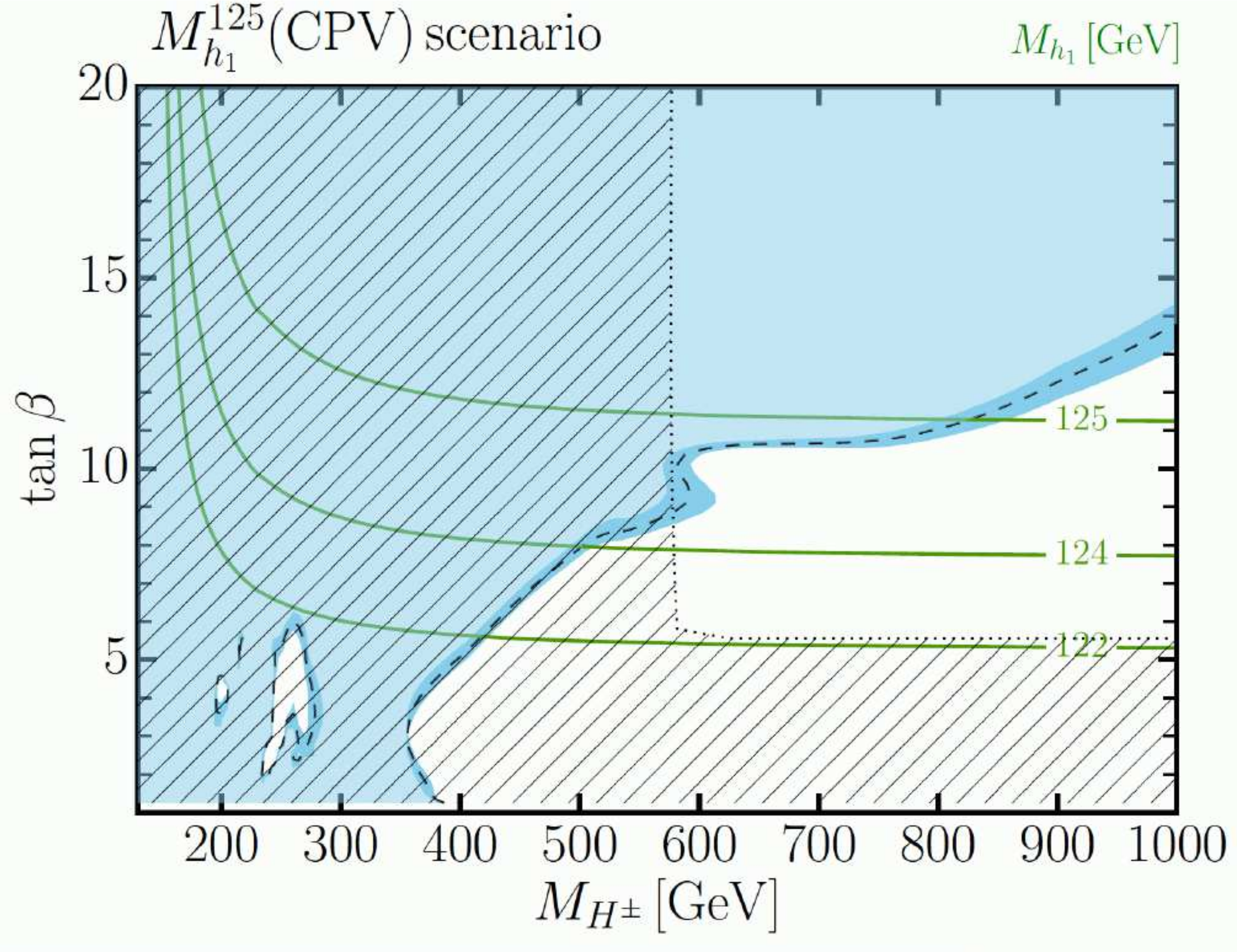
$h_1 \sim H_{125}$, $M_{h_2} \approx M_{h_3}$, CPV: large h_2-h_3 mixing possible:

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



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

[*E. Bagnaschi et al., '18*]



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$\mu = 1.65$ 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)

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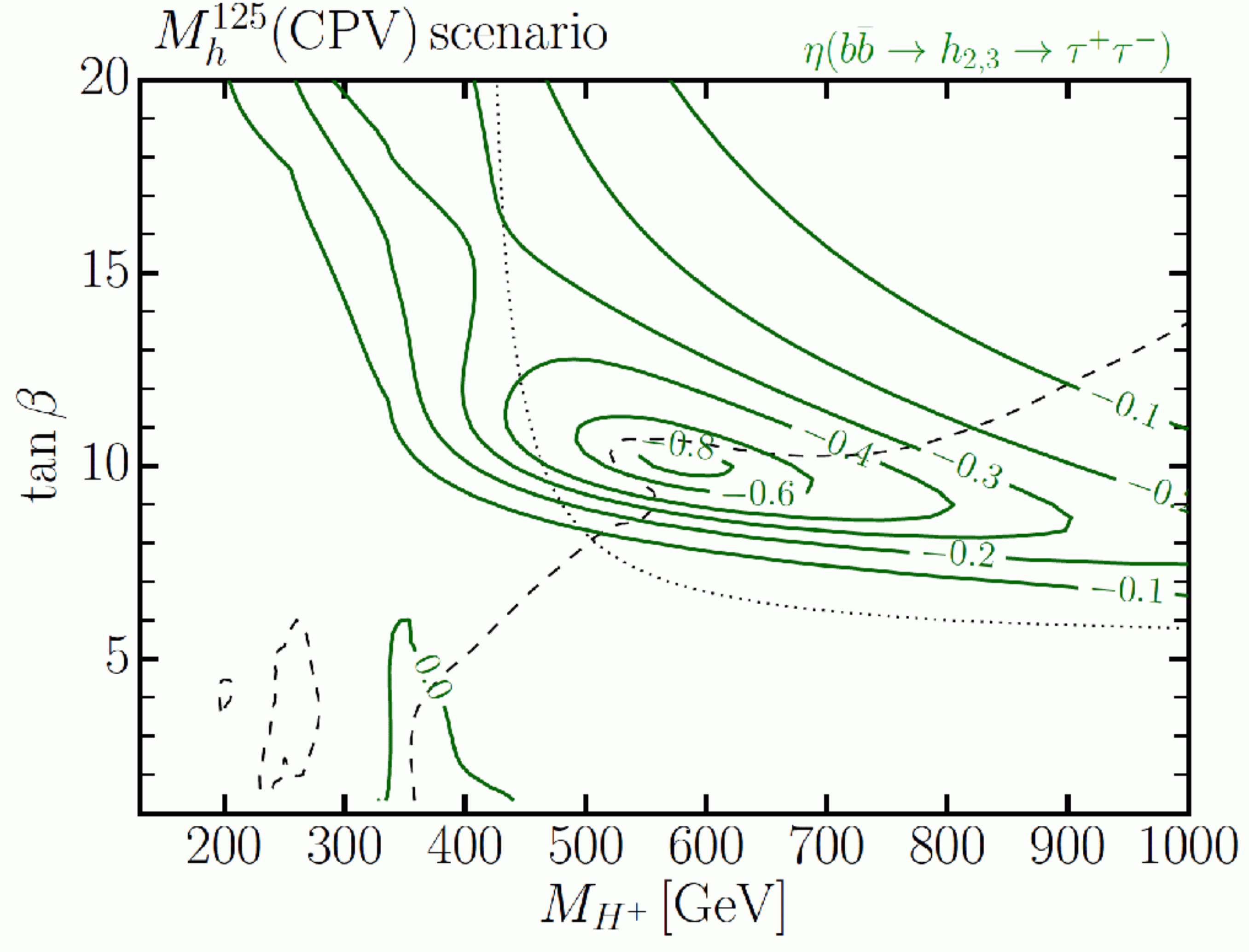

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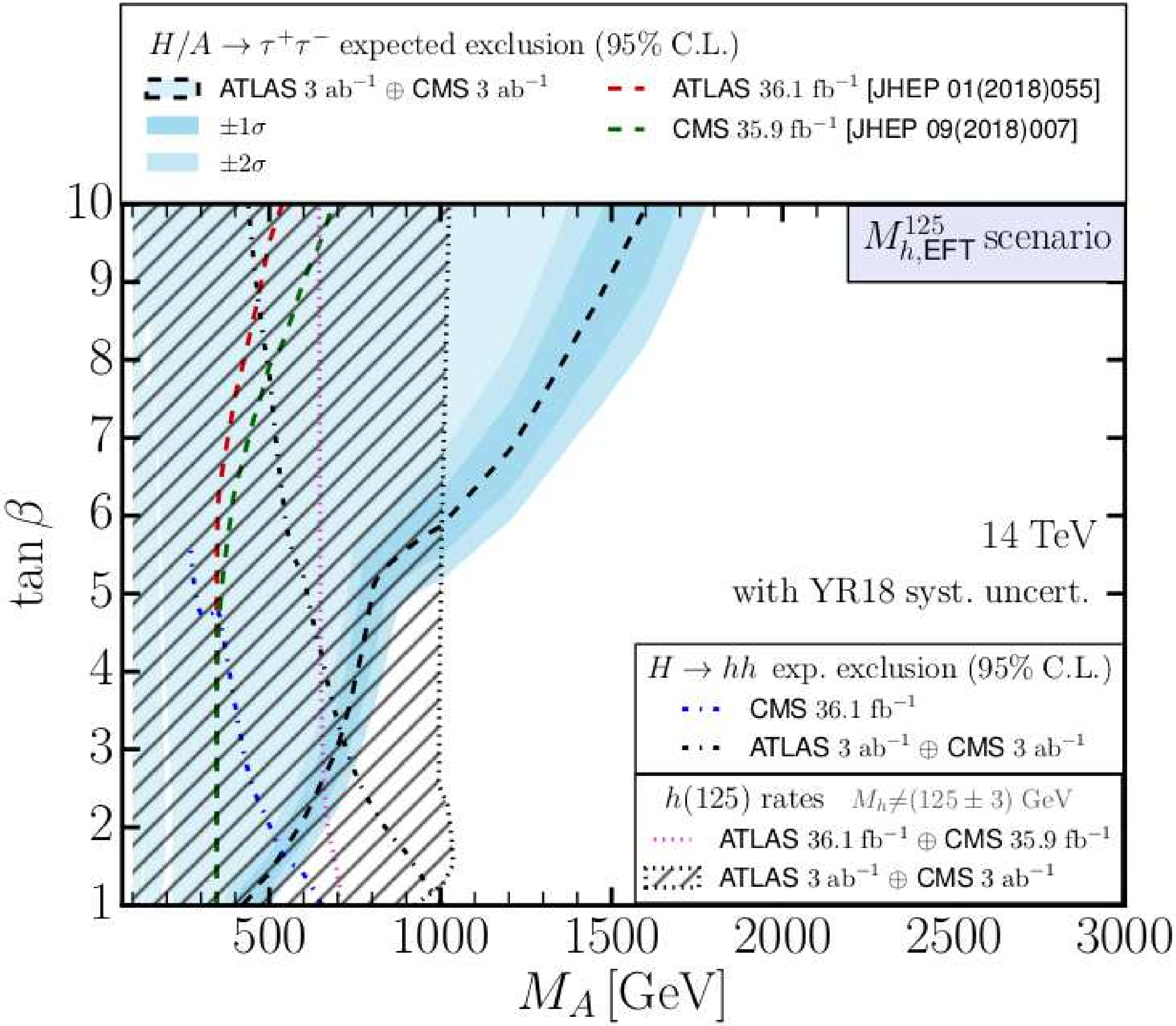
$|A_t| = A_b = A_\tau$

$\Rightarrow$ reduced coverage due to h_2-h_3 interference

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

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



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

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

	$c_{h_iVV} = c_\beta R_{i1} + s_\beta R_{i2}$
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_itt})	d-type (c_{h_ibb})	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:

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

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

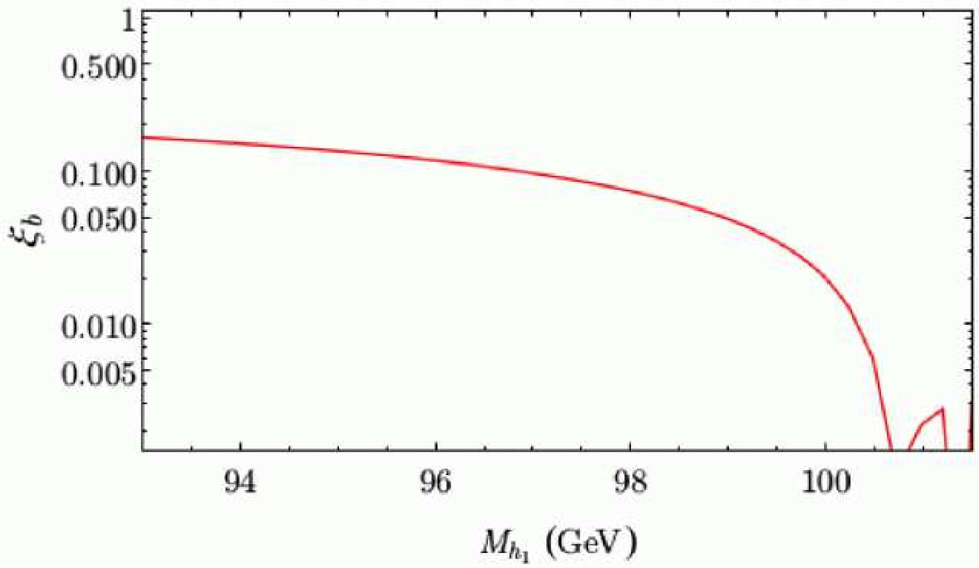
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

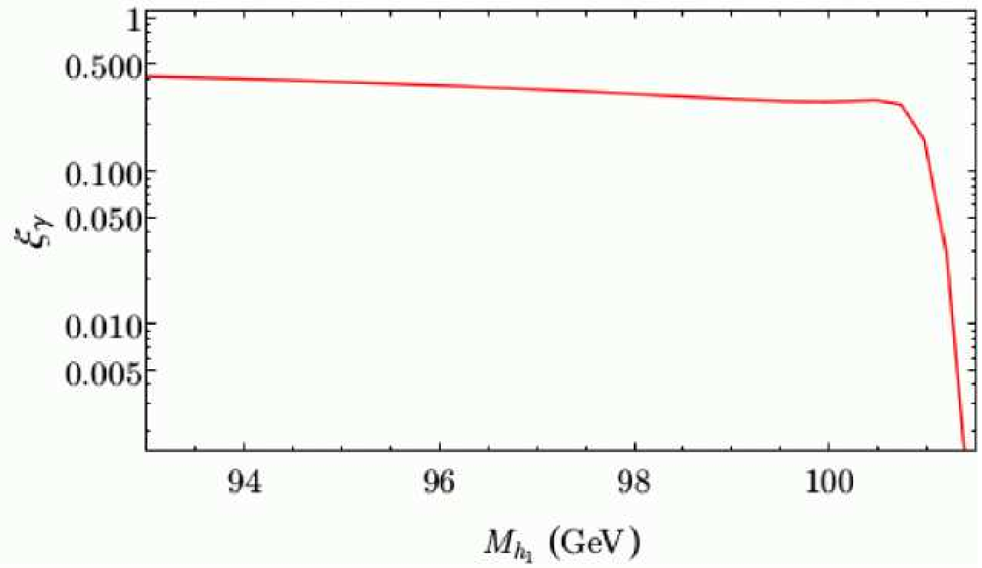
Parameters:

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

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

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





$\Rightarrow$ 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?

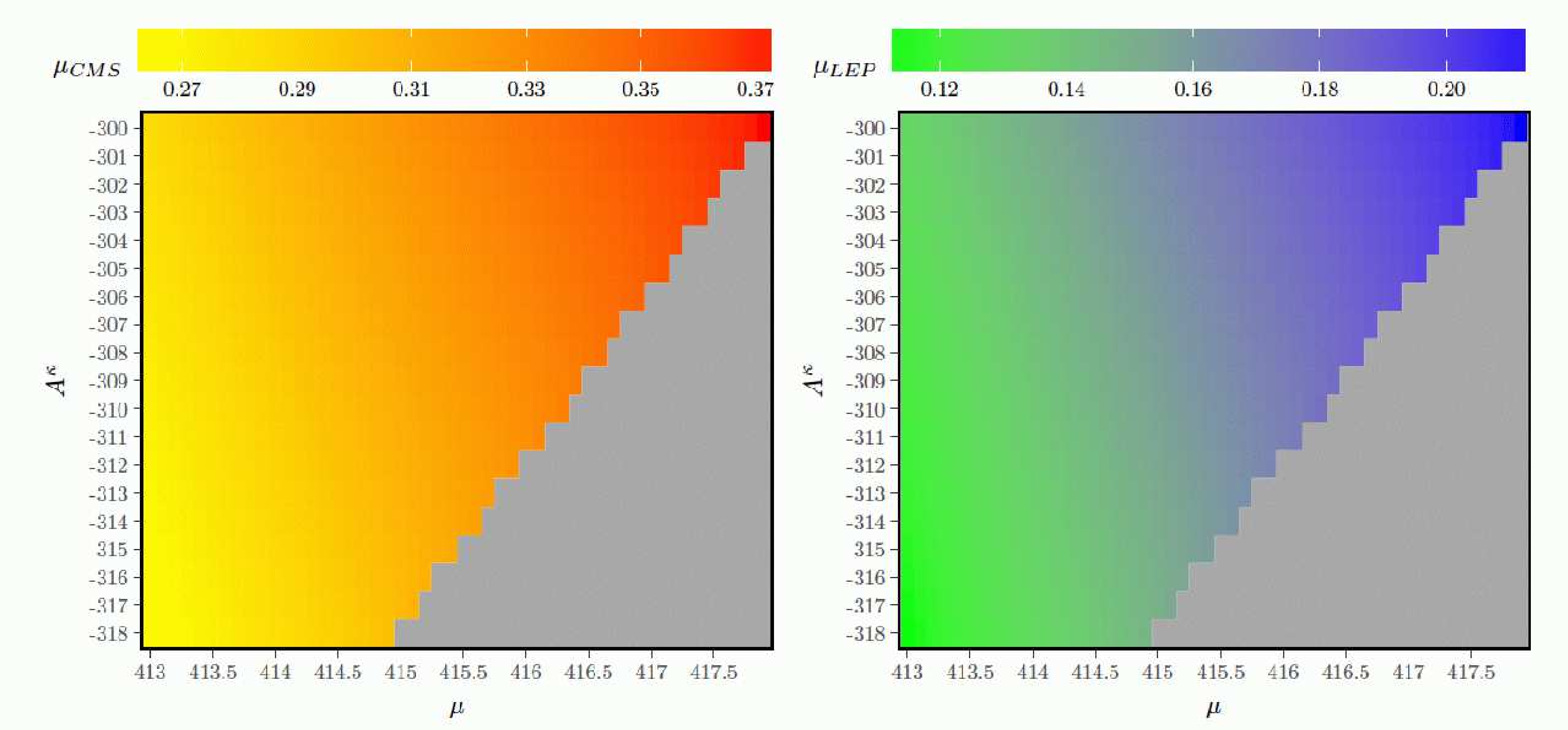
[*T. Biekötter, S.H., C. Muñoz '17*]

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)