
HAVE YOU HEARD? THEY DISCOVERED THE GOD PARTI...
IT'S CALLED THE HIGGS BOSON!

Higgs Bosons below 125 GeV?!

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

Osaka, 02/2019

- Motivation
- What to expect from SUSY Higgs Bosons
- A Higgs Boson at 96 GeV?!
- 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. 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. ...

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

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

Which model should we focus on?

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

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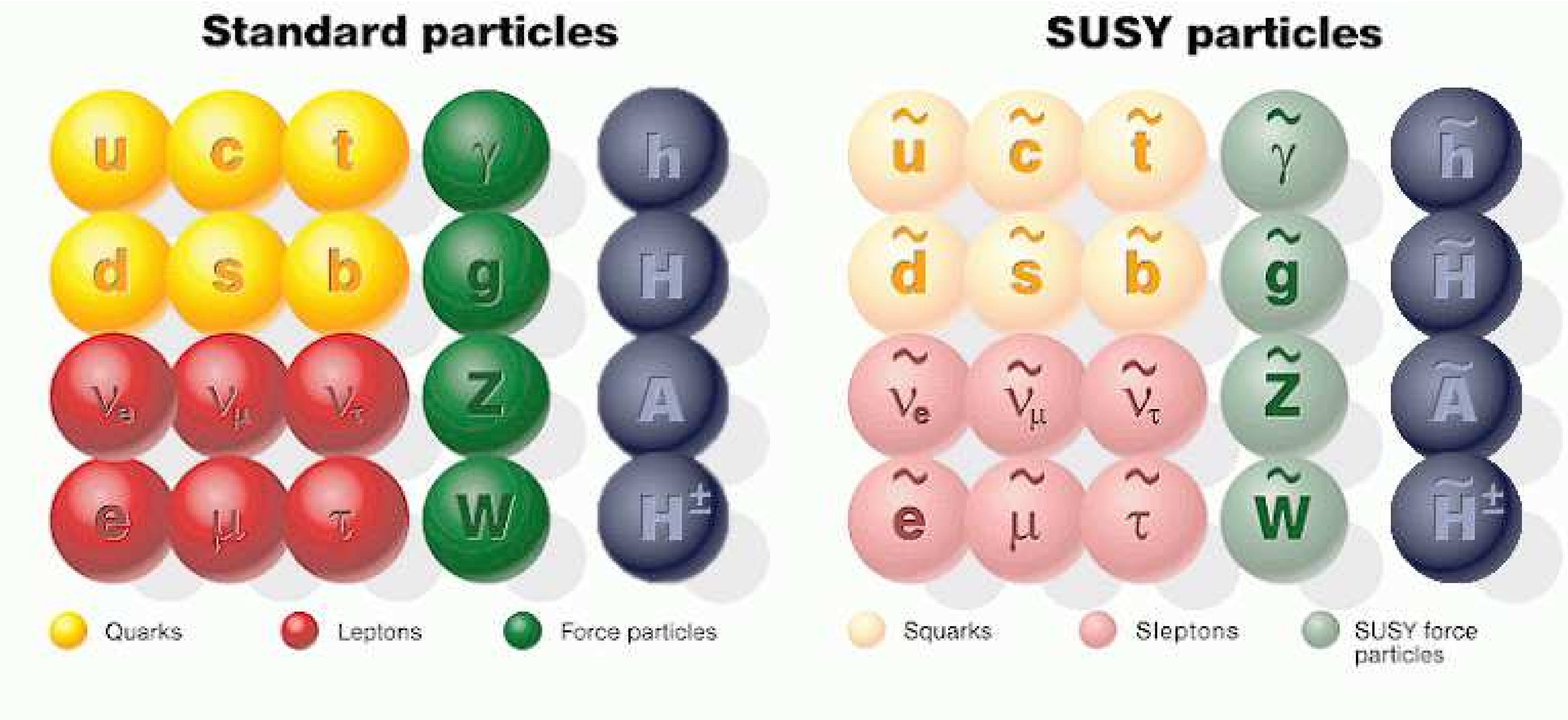
⇒ **good motivation to look at SUSY! :-)**

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

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

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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:

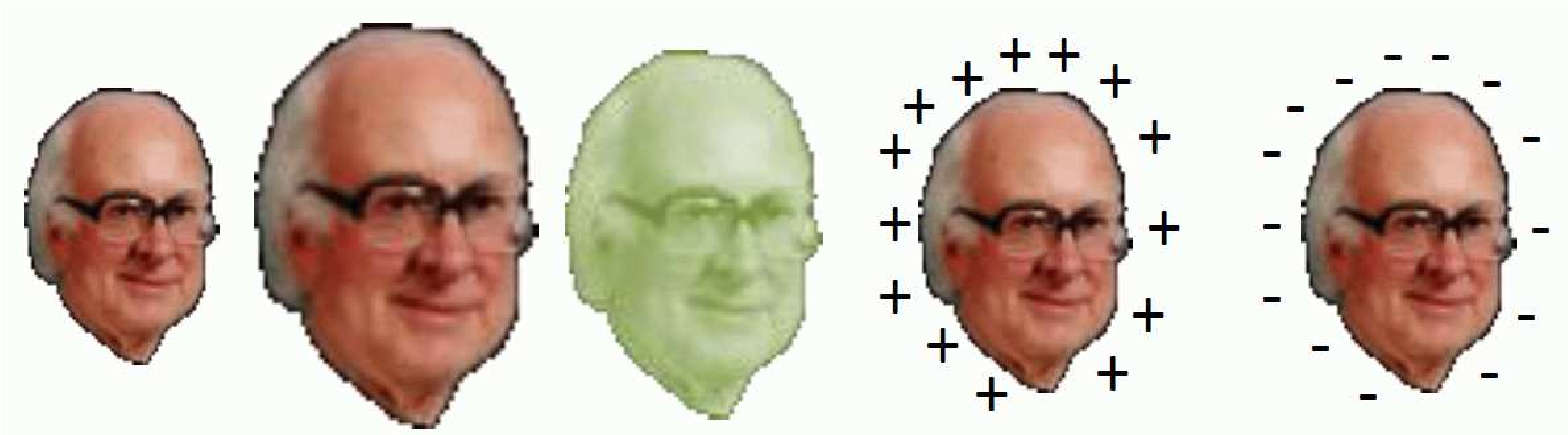
$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

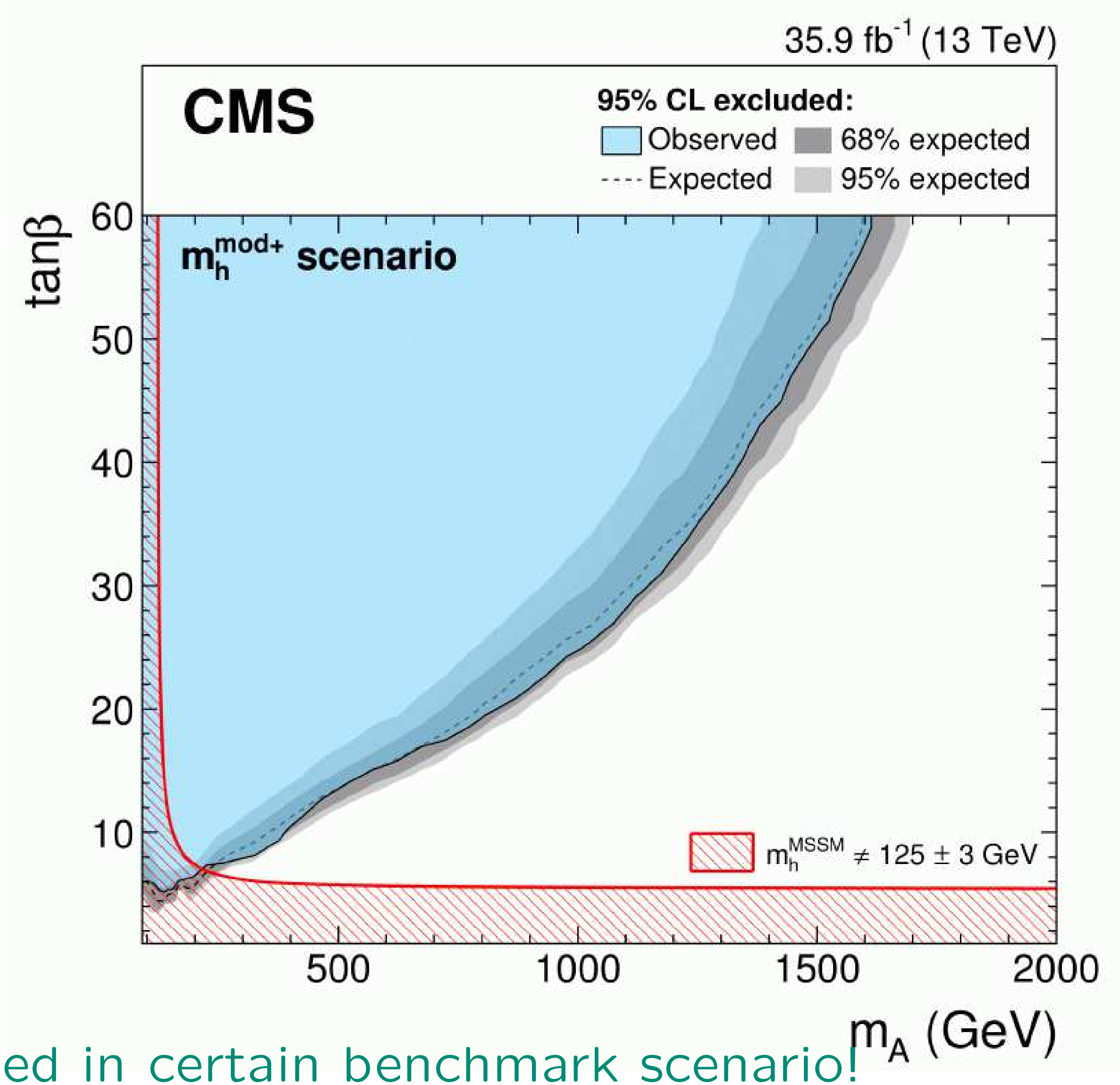
$$m_{h_3} > m_{h_2} > m_{h_1}$$

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

2. What to expect from SUSY Higgs Bosons



MSSM Higgs exclusion contours in M_A–$\tan\beta$ plane: $b\bar{b}, gg \to h, H, A \to \tau^+\tau^-$



⇒ limits obtained in certain benchmark scenario!

We have a ~ 125 GeV SM-like Higgs boson

⇒ What are the options?

1. Decoupling limit:
   $M_A \gg M_Z$ ⇒ the light Higgs becomes SM-like

2. Alignment without decoupling:
   ⇒ a $\mathcal{CP}$-even Higgs becomes SM-like due to an "accidental" cancellation

3. Heavy Higgs SM-like: (in the "alignment w/o decoupling" scen.)
   ⇒ is the case with the heavy $\mathcal{CP}$-even Higgs being SM-like
   ⇒ a case with a Higgs below 125 GeV!
   ⇒ (still) a viable solution?!

Obtaining a light Higgs with SM-like couplings

[*J. Gunion, H. Haber, hep-ph/0207010*]

$\to \mathcal{CP}$ conserving 2HDM in the Higgs basis ($\langle H_1 \rangle = v/\sqrt{2}$, $\langle H_2 \rangle = 0$)

$$\mathcal{V} = \ldots + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \ldots + \left[\tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.} \right] + \ldots$$

$\Rightarrow \mathcal{CP}$-even mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & M_A^2 + Z_5 v^2 \end{pmatrix}$$

with mixing angle $\cos(\beta - \alpha) \equiv c_{\beta-\alpha}$

Decoupling limit: $M_A^2 \gg Z_i v^2$
$\Rightarrow m_h^2 \sim Z_1 v^2$, $|c_{\beta-\alpha} \ll 1|$, h is SM-like

Alignment limit: $Z_6 = 0$ and $Z_1 < Z_5 + M_A^2/v^2$
$\Rightarrow h$ is identical to the SM Higgs, $c_{\beta-\alpha} = 0$
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$\Rightarrow H$ is identical to the SM Higgs, $c_{\beta-\alpha} = 1$

Alignment limit: see e.g.

[M. Carena, I. Low, N. Shah, C. Wagner '13][M. Carena, H. Haber, I. Low, N. Shah, C. Wagner '14]

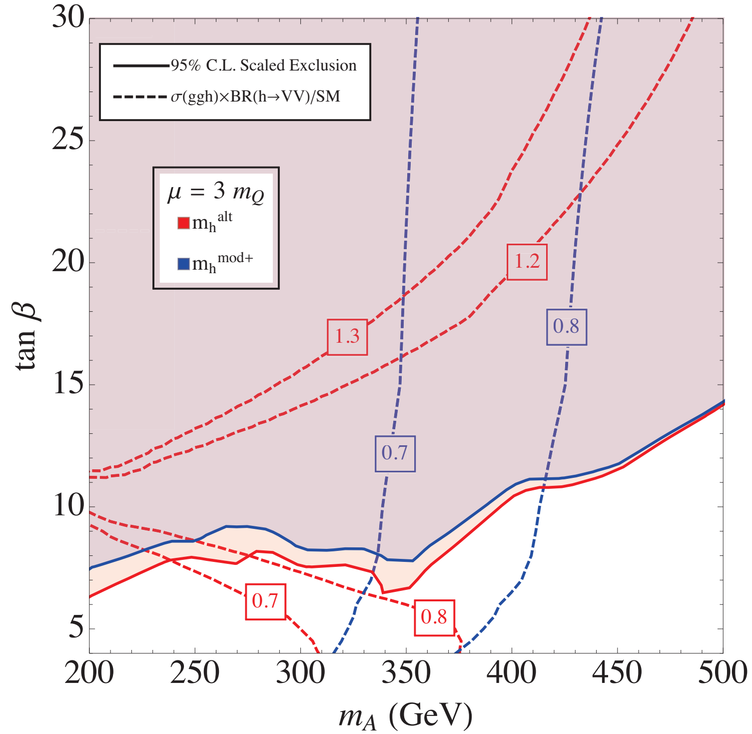
In the MSSM $Z_6 = 0$ can be obtained through an "accidental" cancellation between tree-level and loop contribution, roughly at:

$$\tan\beta \sim \left[M_h^2 + M_Z^2 + \frac{3m_t^2\mu^2}{4\pi^2 v^2 M_S^2}\left(\frac{A_t^2}{2M_S^2} - 1\right)\right] \Big/ \left[\frac{3m_t^2}{4\pi^2 v^2}\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)\right]$$

Compare: $m_h^{\rm mod+}$ and $m_h^{\rm alt}$:
$A_t/M_S = 2.45$, $A_t = A_f$,
$M_S = m_{\tilde f} \geq 1$ TeV, $m_{\tilde g} = 1.5$ TeV,
$M_2 = 2\,M_1 = 200$ GeV, μ adjustable

(low M_A and $\tan\beta$: tune $M_S \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

$\Rightarrow$ SM-like Higgs for all M_A



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m_h^{alt}: HiggsSignals [P. Bechtle et al. '15]

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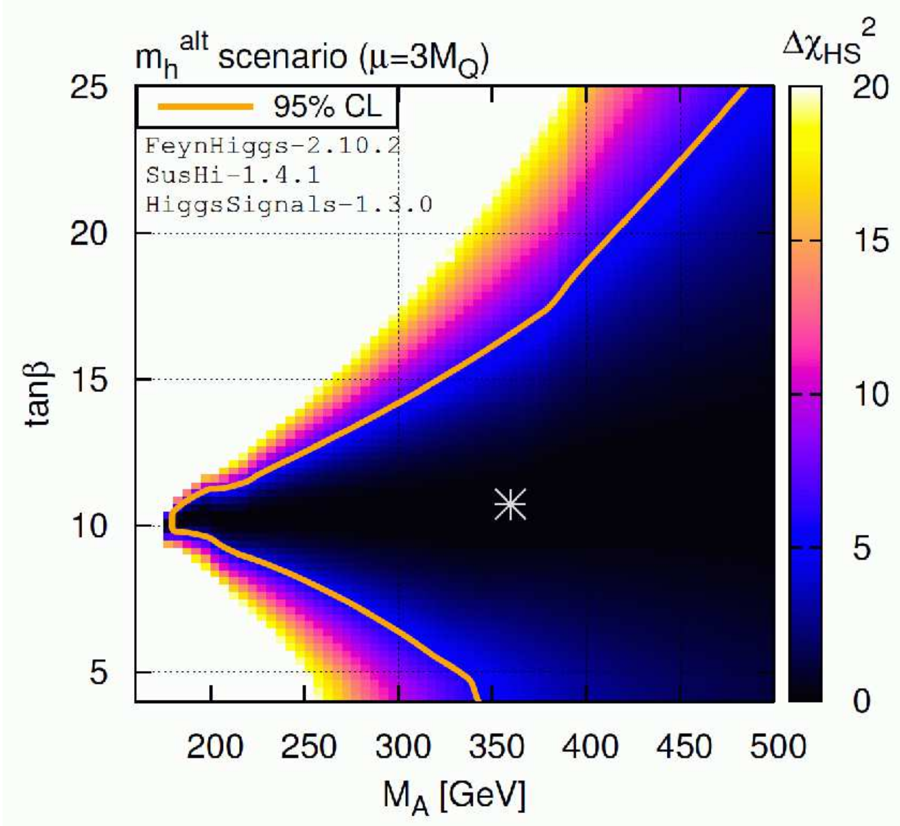


Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

$\to$ investigate benchmark scenarios:

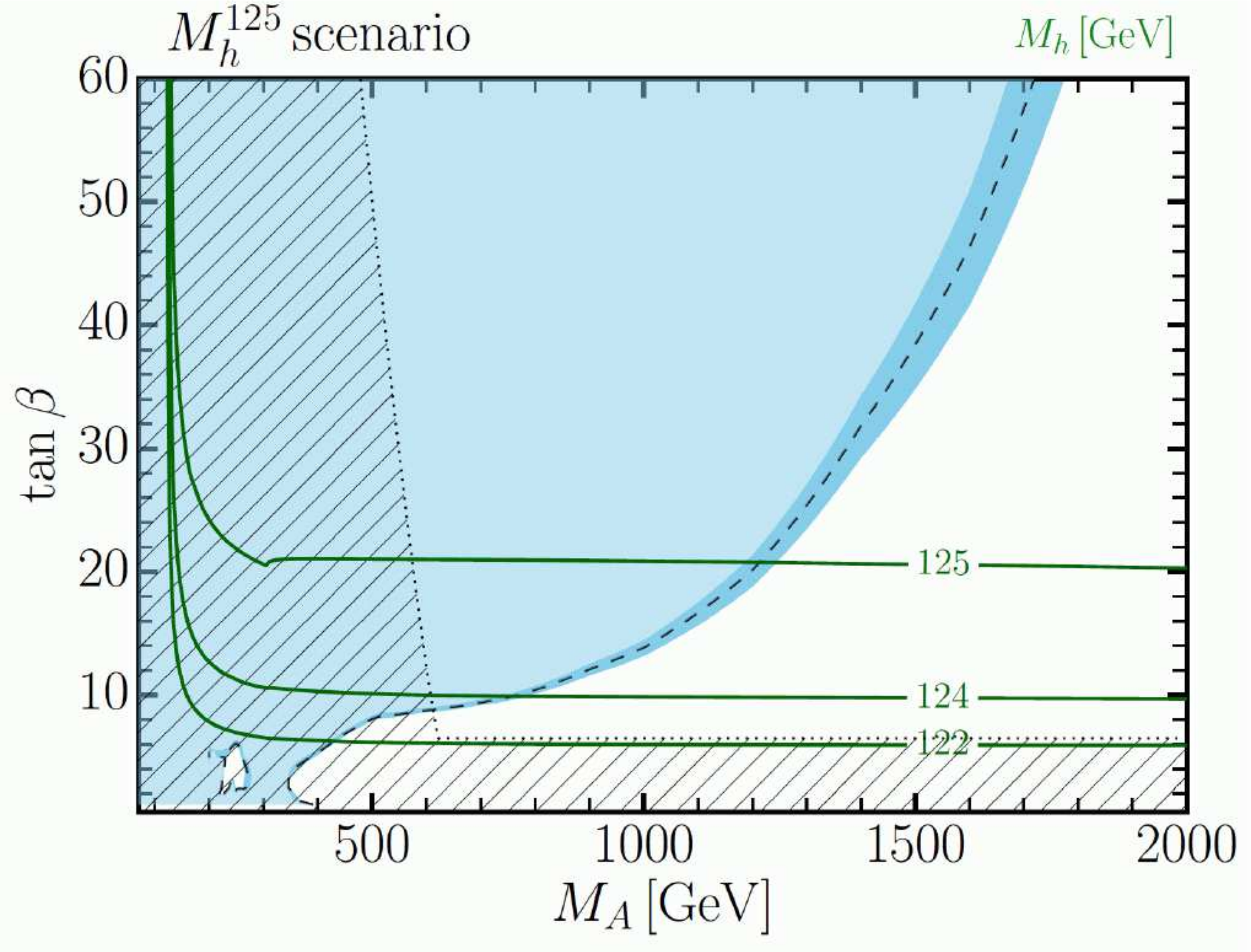
$\to$ Vary only M_A and $\tan\beta$
$\to$ Keep all other SUSY parameters fixed

[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

New benchmark: M_h^{125}

[H. Bahl et al., '18]



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

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

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

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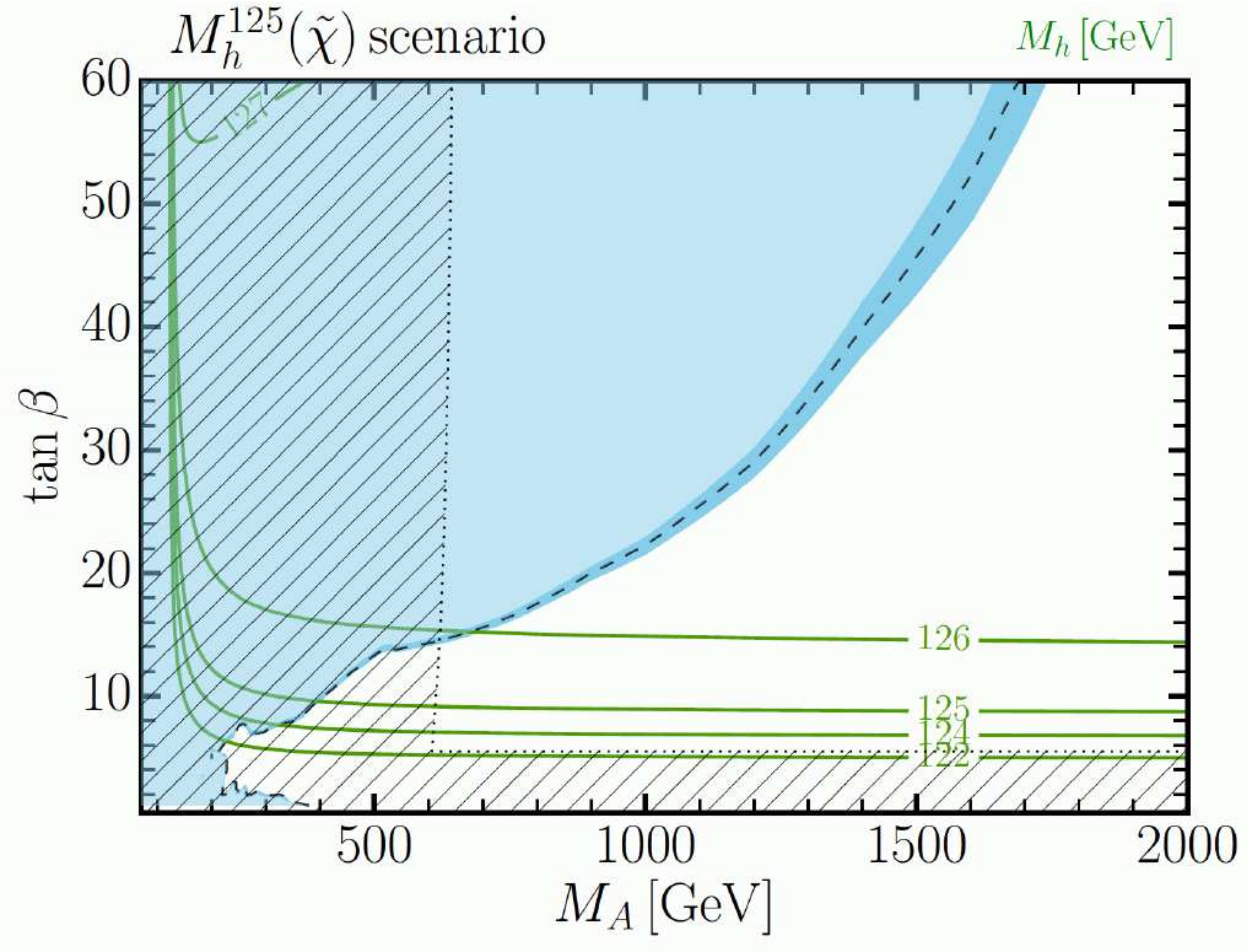
$$X_t = 2.8 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

⇒ new vanilla benchmark model

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



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⇒ strongly reduced heavy Higgs coverage

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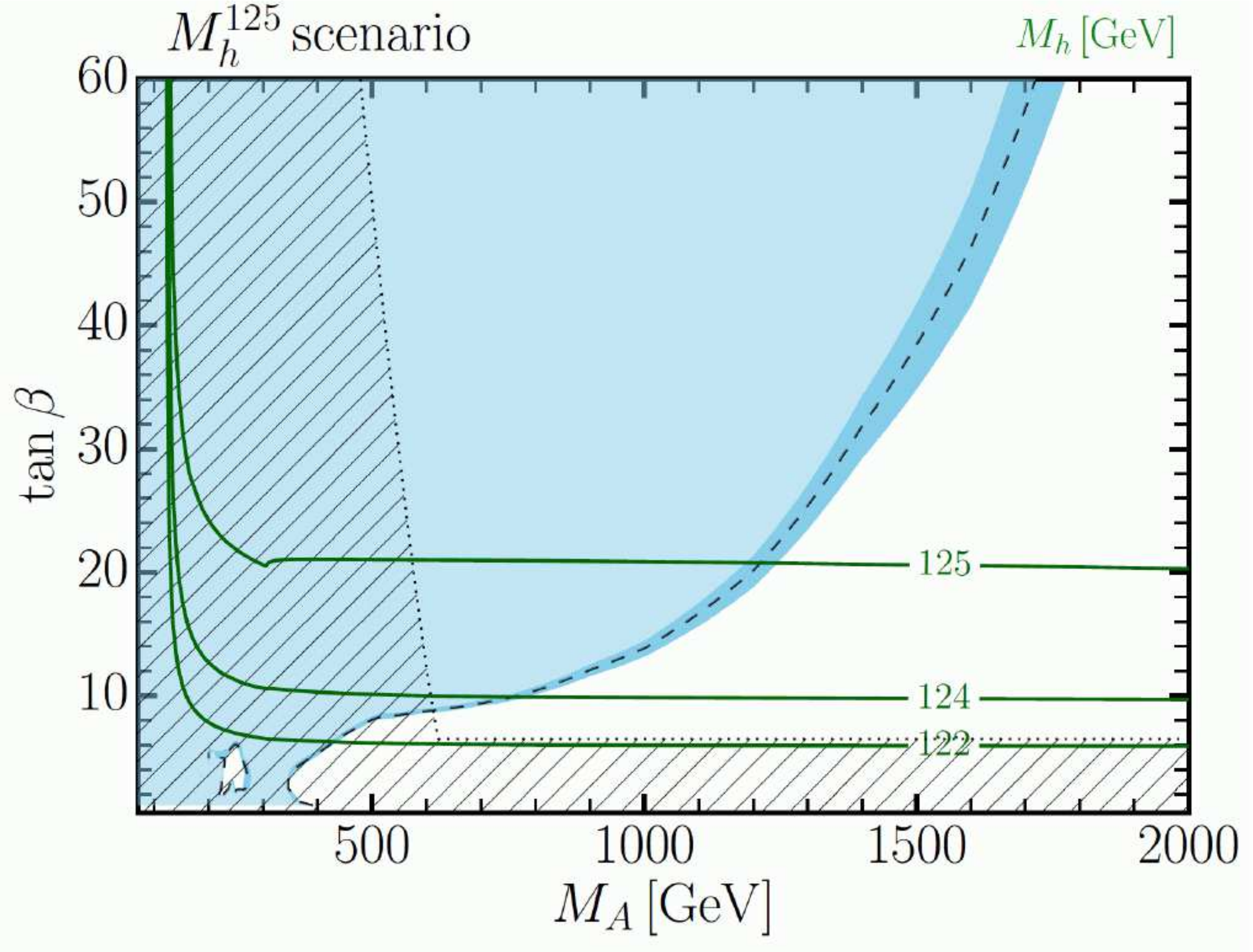

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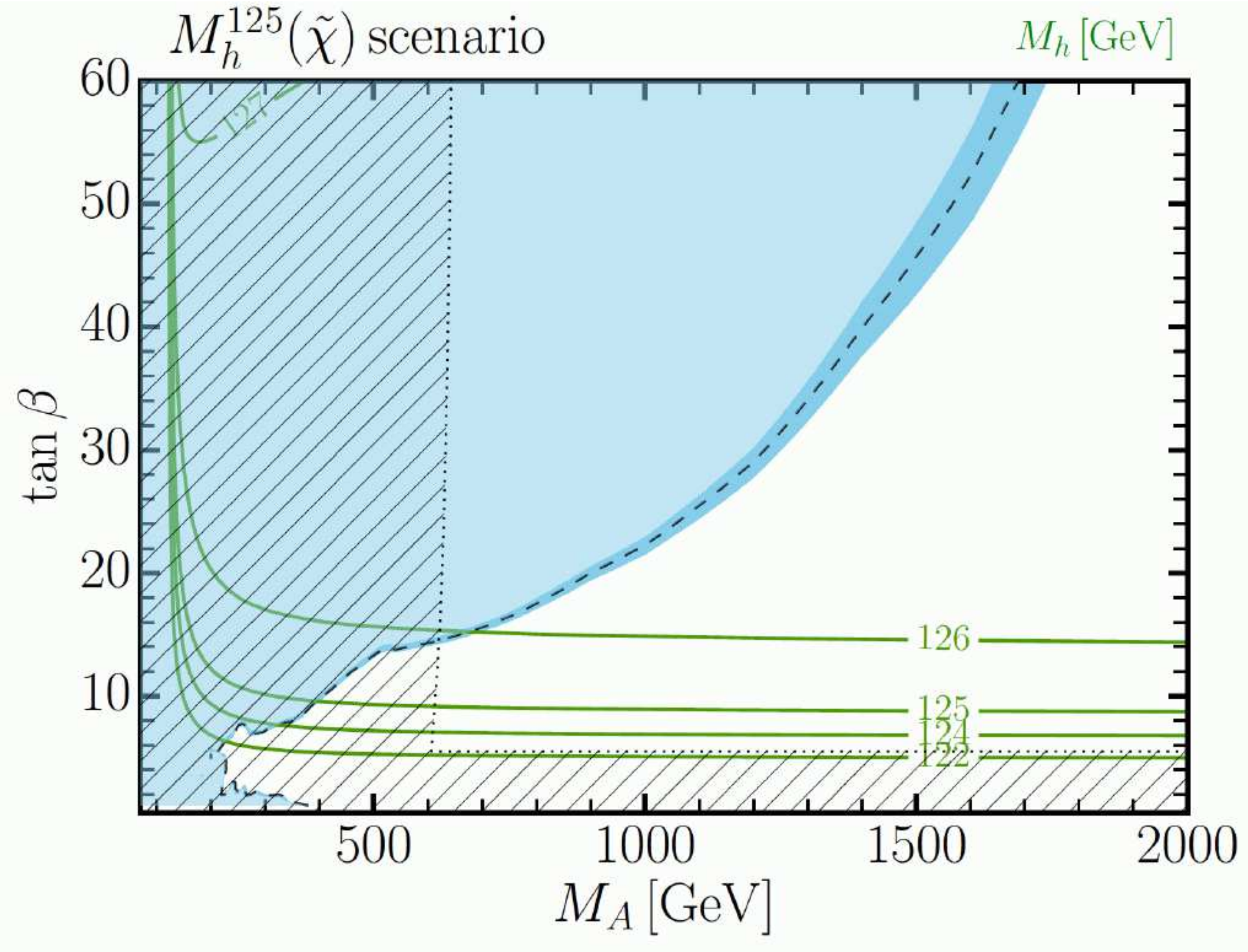

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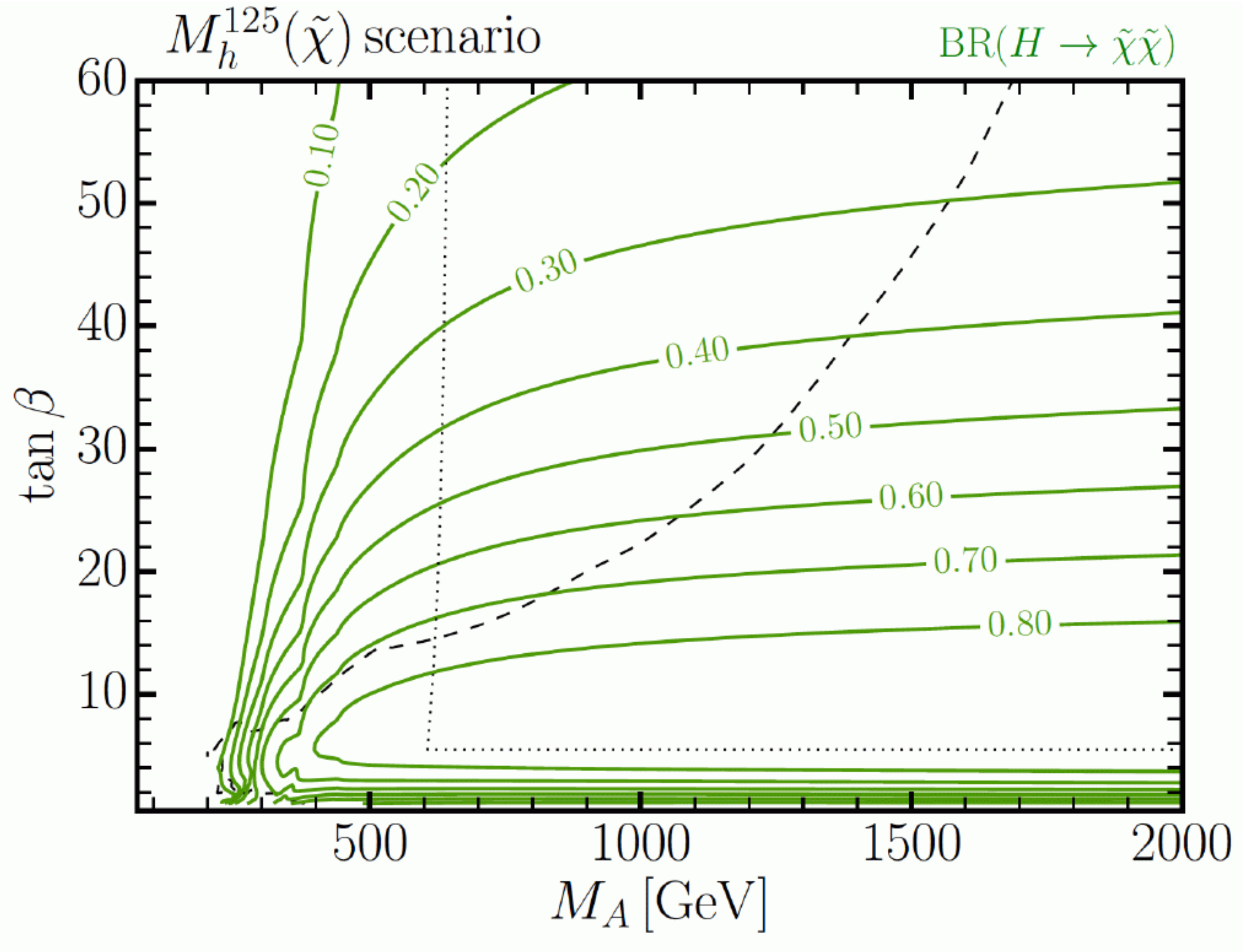

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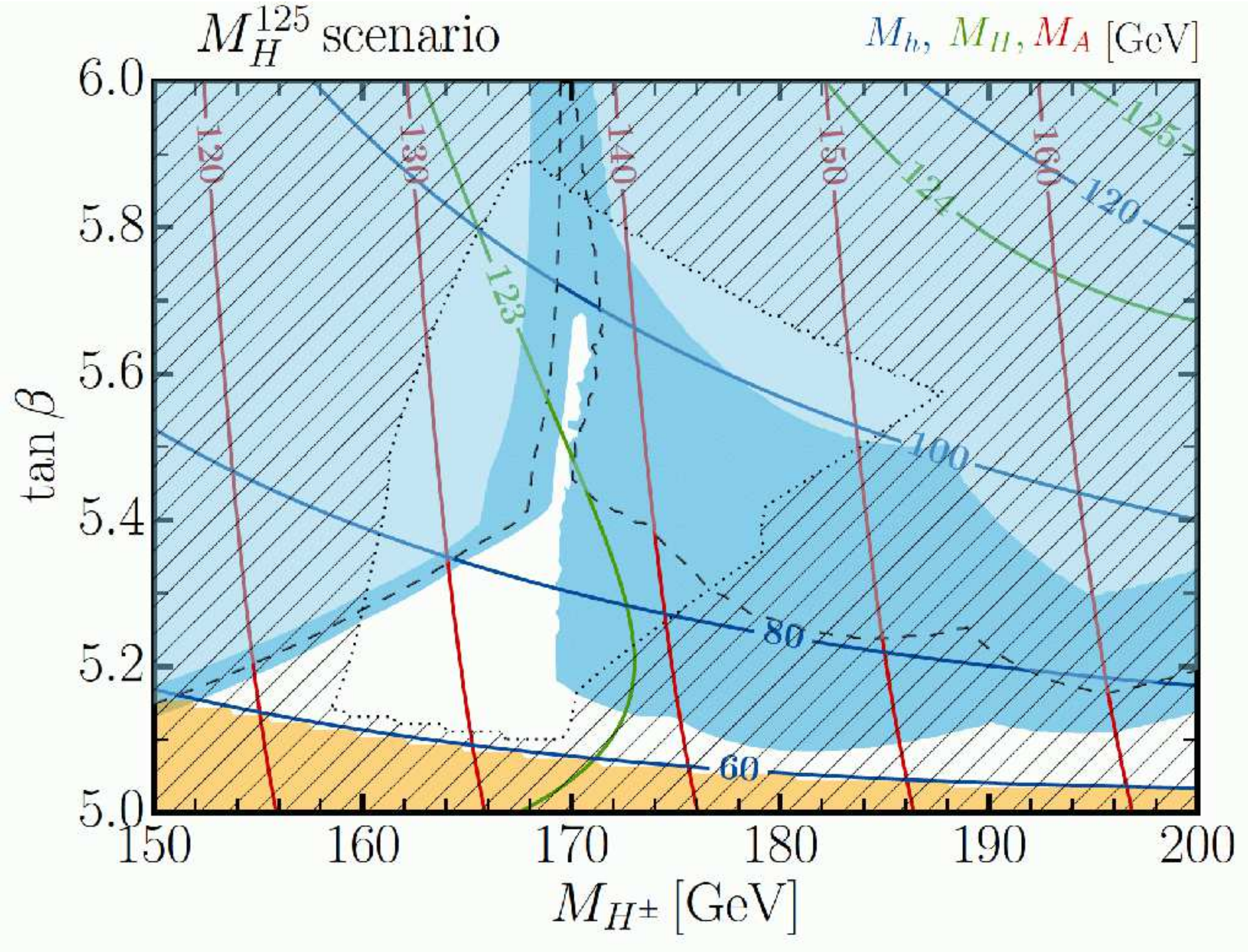
$X_t = 2.5$ TeV

$A_t = A_b = A_\tau$

⇒ Huge BR of heavy Higgses to EW-inos

New benchmark: M_H^{125}

[H. Bahl et al., '18]



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

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

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

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

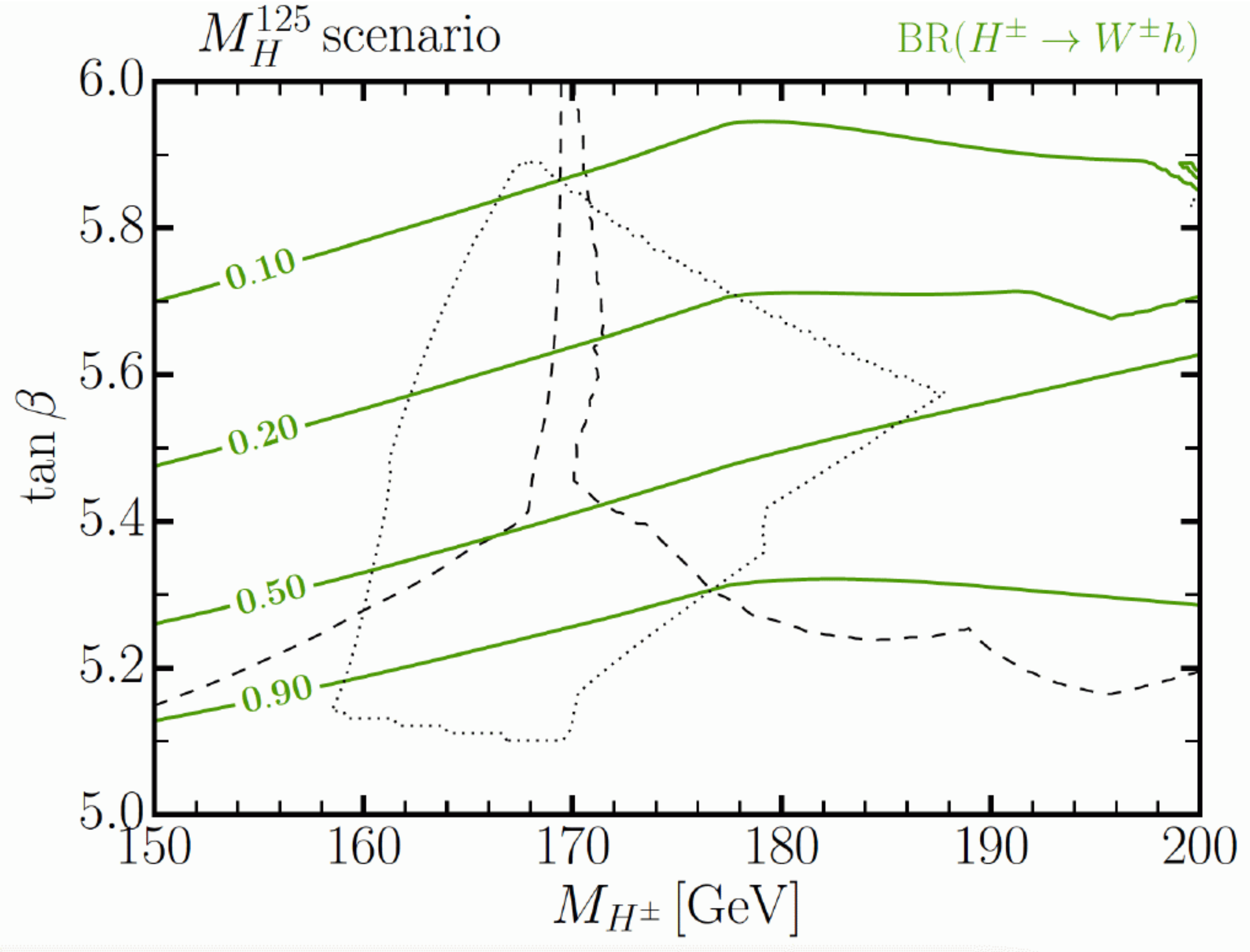
$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

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

⇒ exotic solution still viable! ⇒ scenario with a Higgs below 125 GeV!

New benchmark: M_H^{125}

[*H. Bahl 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 $\mathrm{BR}(H^\pm \to W^\pm h)$

Interesting case: light singlet

Singlet does not couple to SM particles!

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"Non-interacting particles are hard to detect."  [*F. Klinkhamer*]

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"Easily" possible in the NMSSM:

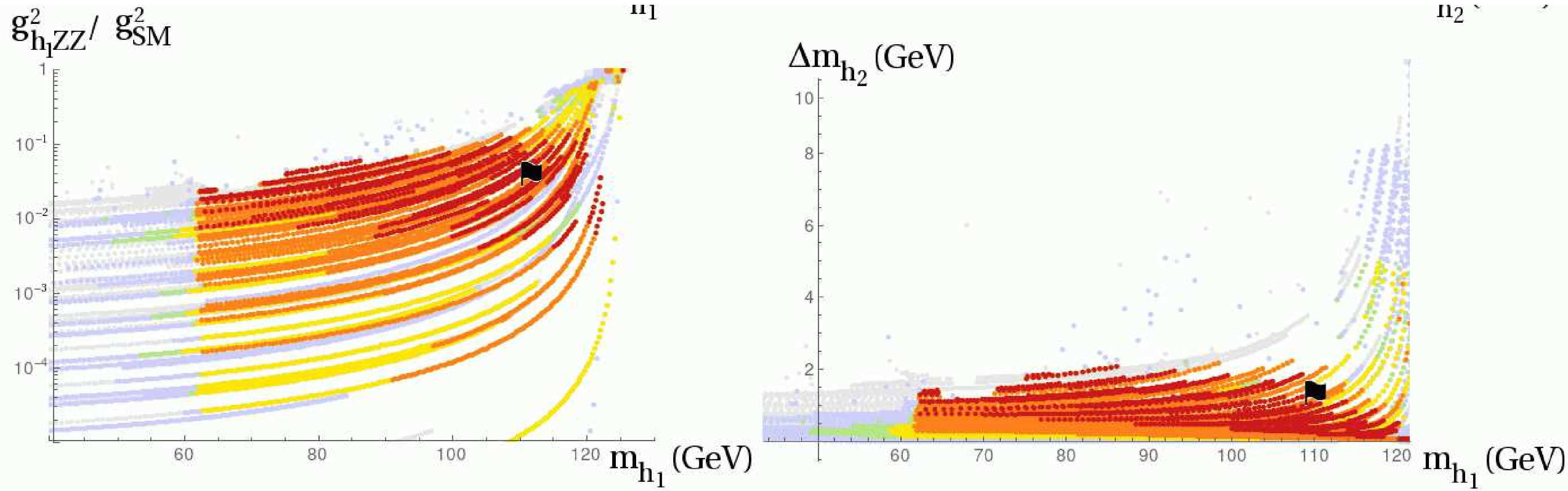
Light, singlet-like Higgs below 125 GeV

Which collider can find them?

NMSSM parameter scan: [F. Domingo, G. Weiglein '15]

Parameters:

$\tan\beta = 8$, $M_A = 1$ TeV, $A_\kappa = -2...0$ TeV, $\mu = 120...2000$ GeV,
$2M_1 = M_2 = 500$ GeV, $M_3 = 1.5$ TeV, $m_{\tilde{Q}_3} = 1$ TeV, $m_{\tilde{Q}_{1,2}} = 1.5$ TeV,
$A_t = -2$ TeV, $A_{b,\tau} = -1.5$ TeV



⇒ light Higgs below 125 GeV

⇒ strongly reduced couplings to gauge bosons!

⇒ possibly within ILC reach!

3. A Higgs Boson at 96 GeV?!

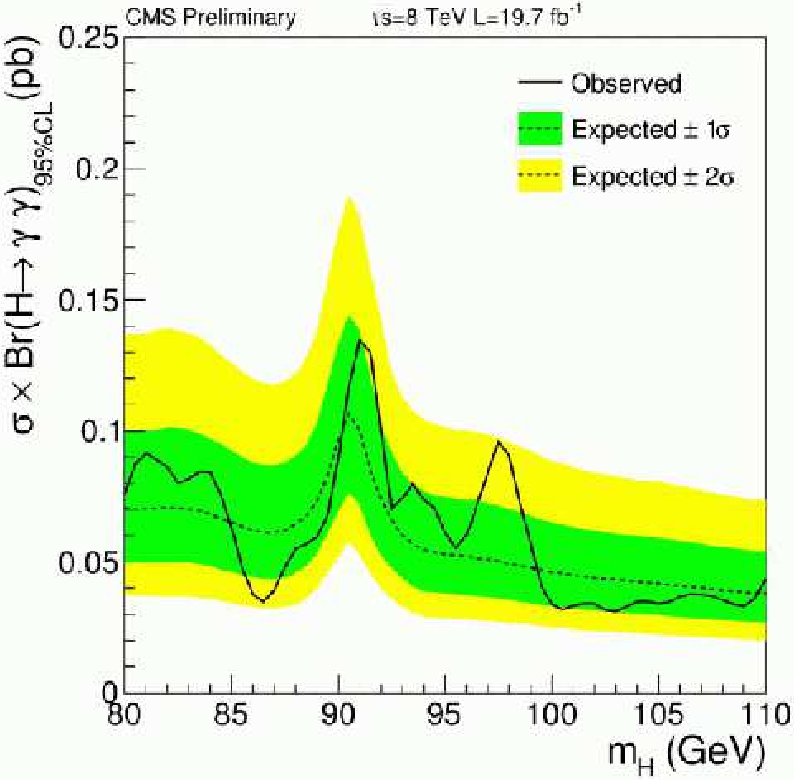
- What was seen in Run I?
- What was seen in Run II?
- What was seen at LEP?
- Should we get excited?
- Which model fits?
- Implications for the ILC250

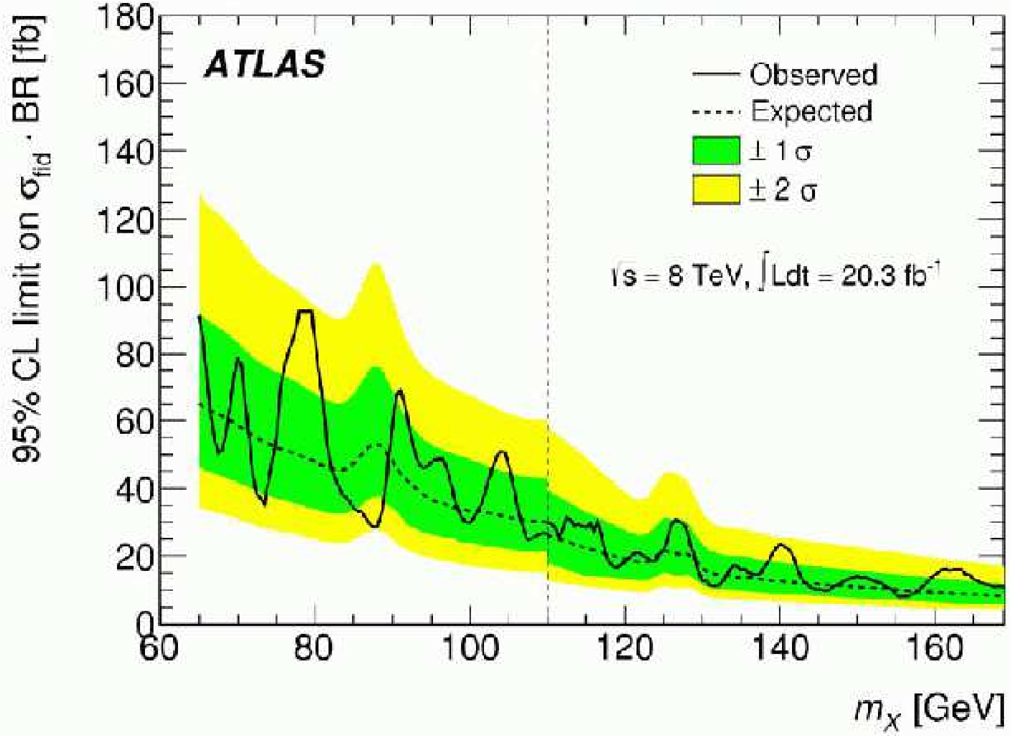
 [S. Shotkin, talk at HDays17]

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

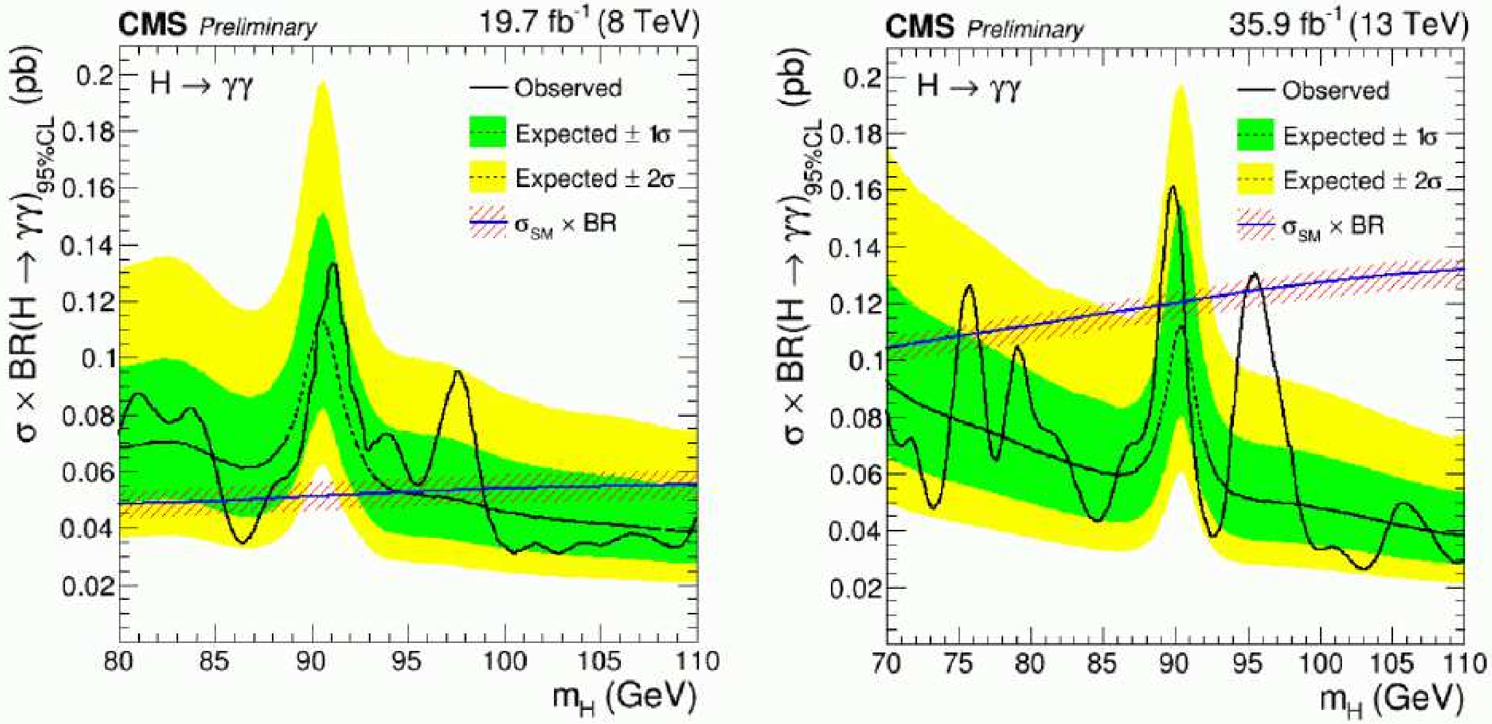
What was seen at Run II?

[*S. Shotkin, talk at HDays17*]

h-->γγ (70-110 GeV) Runs 1+2

New!

CMS PAS HIG-17-013



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

What was seen at Run II?

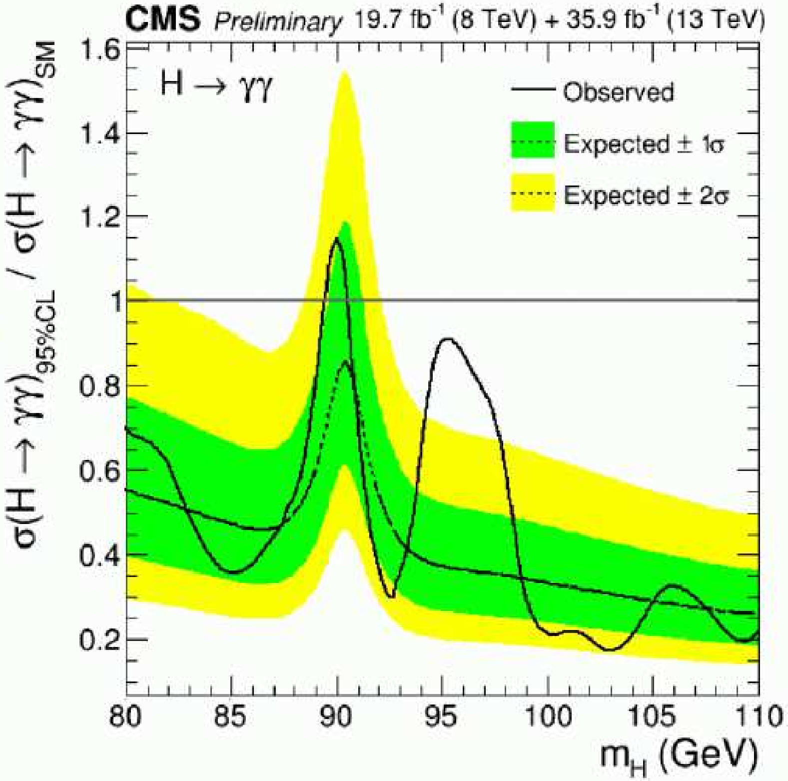
[*S. Shotkin, talk at HDays17*]

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.

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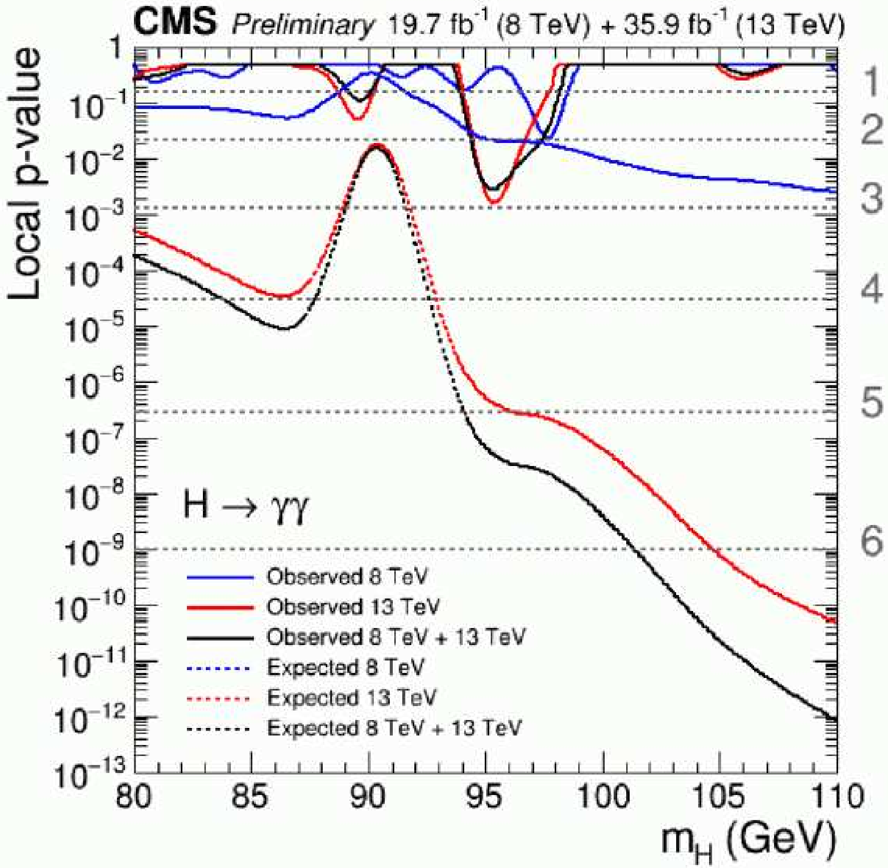
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

h-->γγ (70-110 GeV) Runs 1+ 2

New!



CMS PAS HIG-17-013

8 TeV: 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

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

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017 30

h-->γγ (70-110 GeV) Runs 1+2

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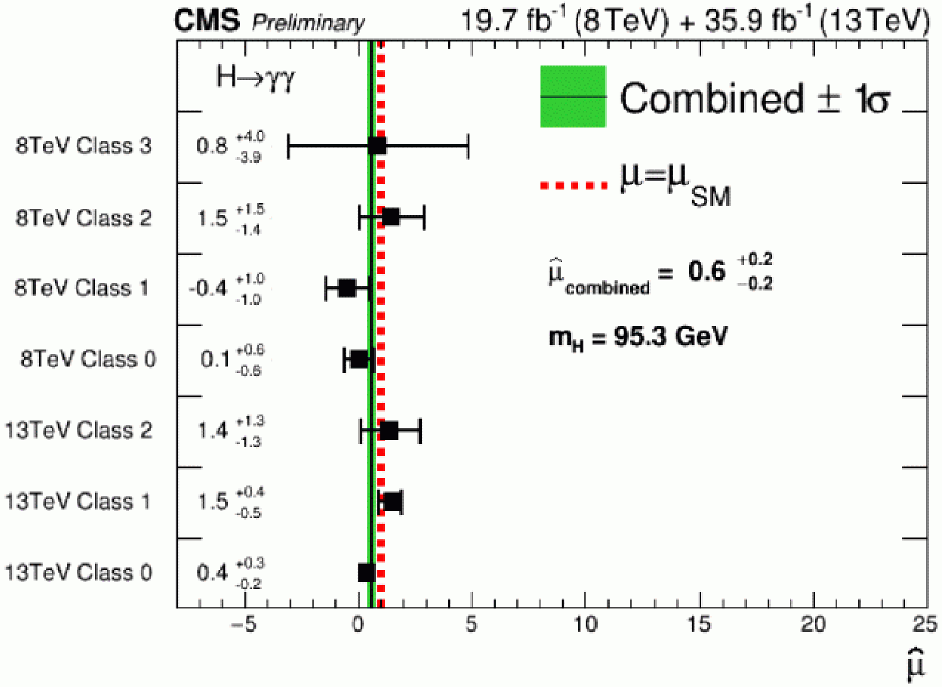
CMS PAS HIG-17-013



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

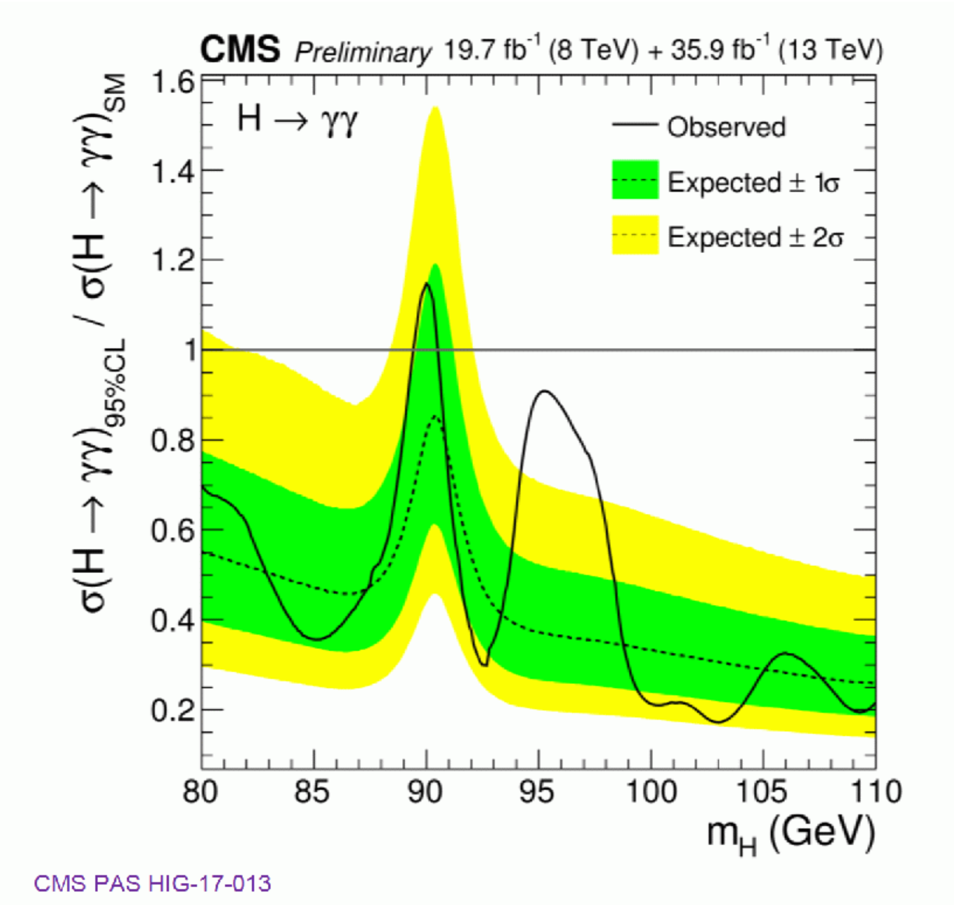
χ^2 probability for the seven individual values to be compatible with a single signal hypothesis: 41%

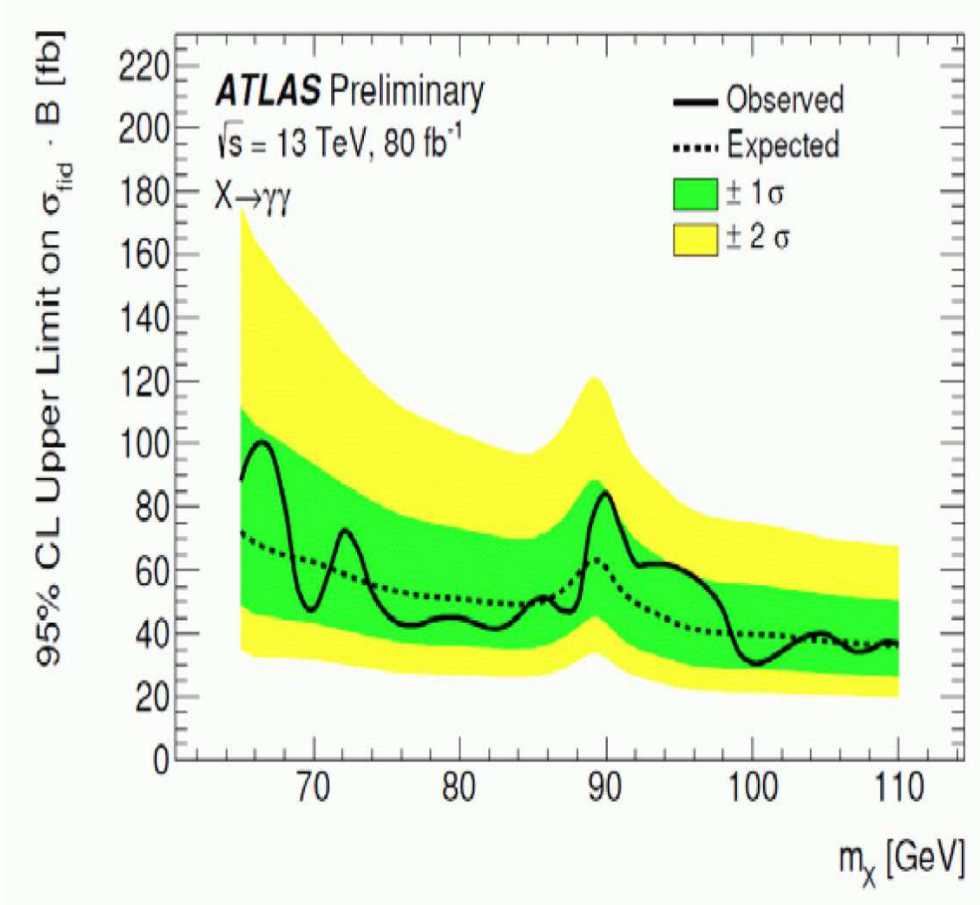
- 'Signal' strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing m_H=95.3 GeV
- More data are required to ascertain the origin of this excess

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?

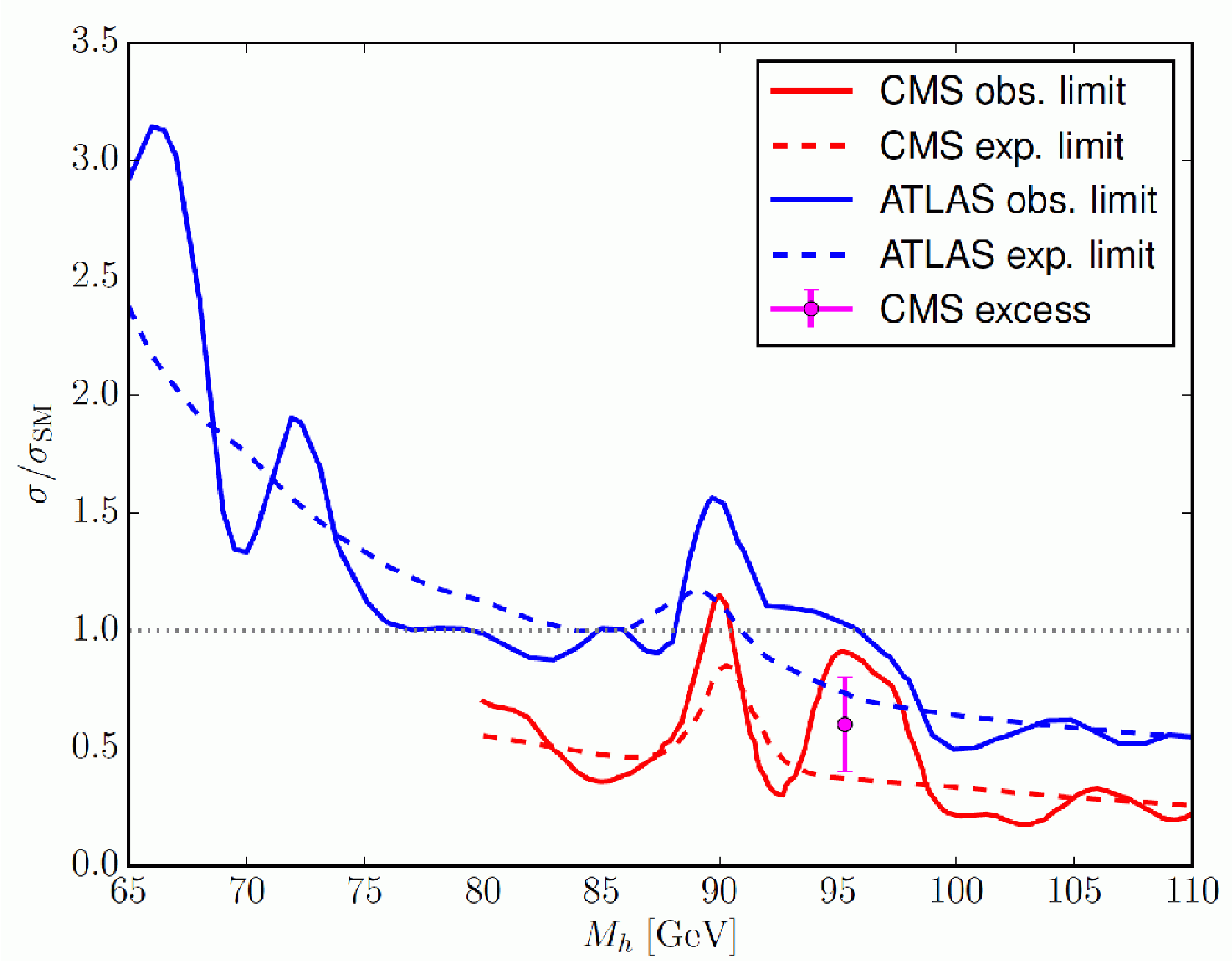




Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

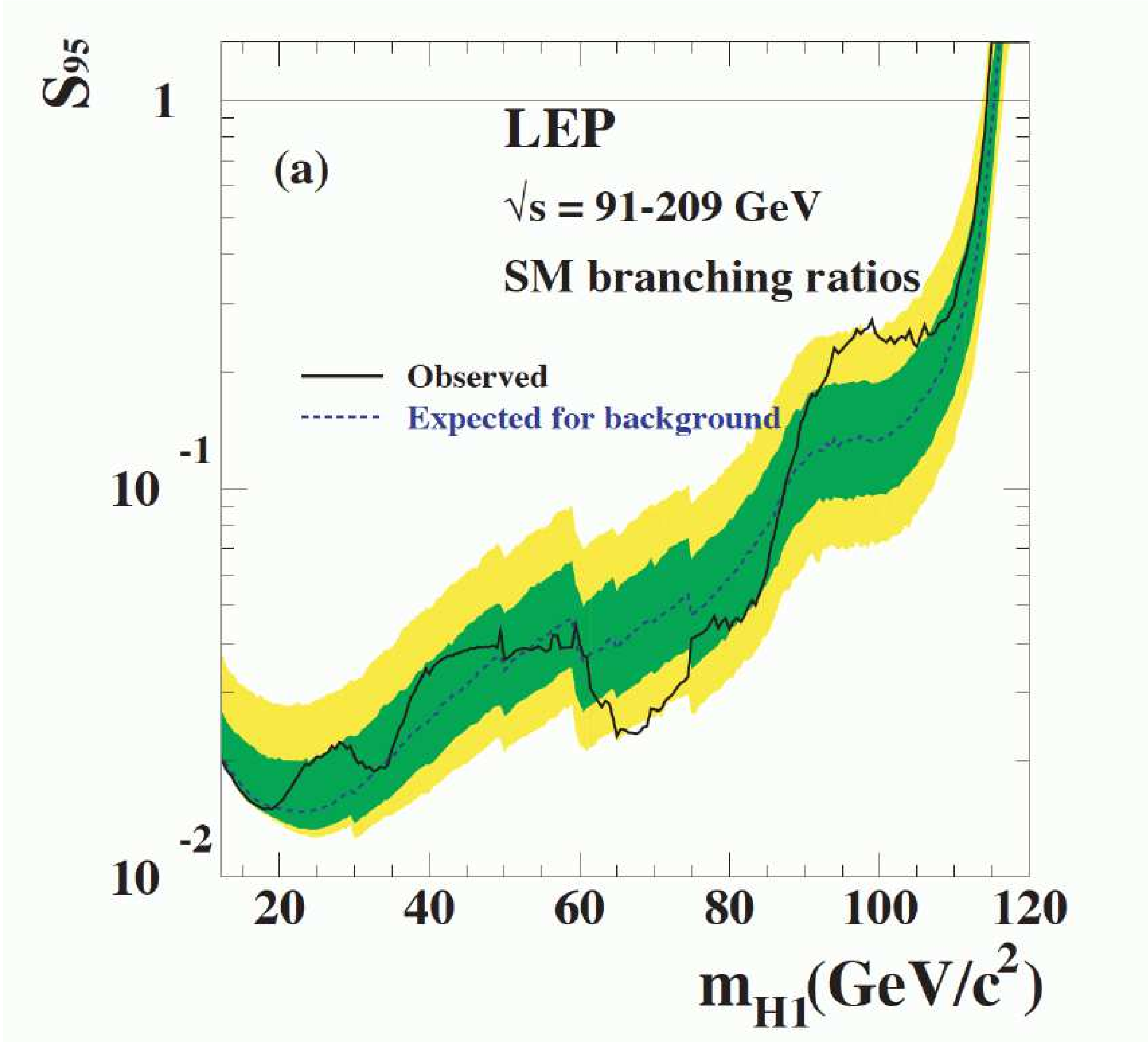
⇒ ATLAS exclusion limit even weaker than CMS!

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



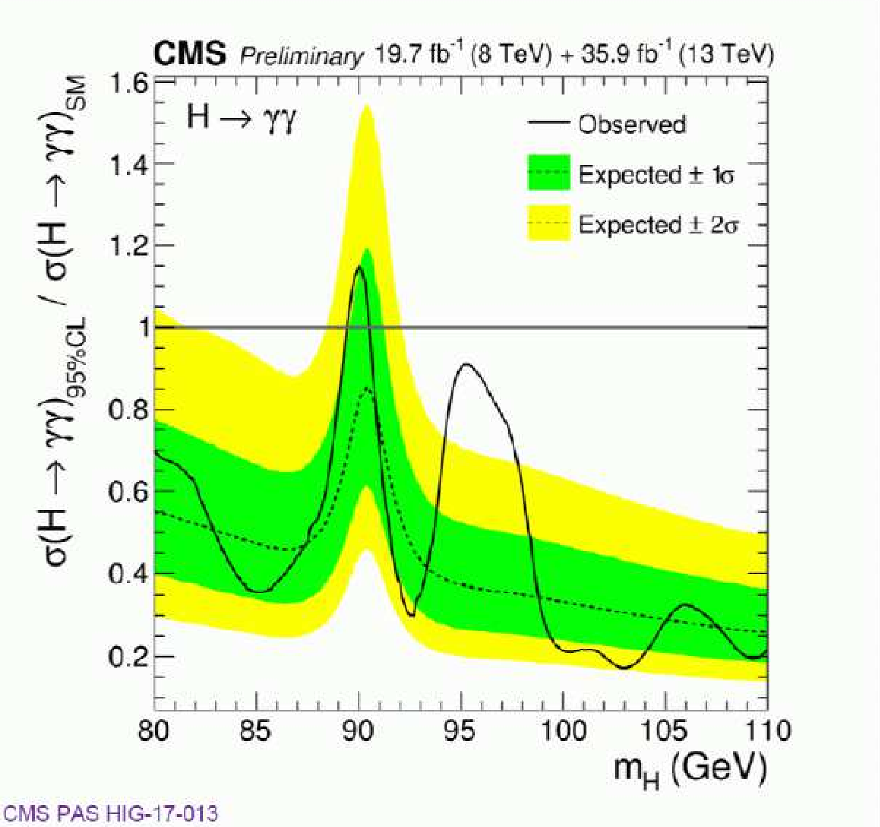
⇒ everything well compatible with the excess!

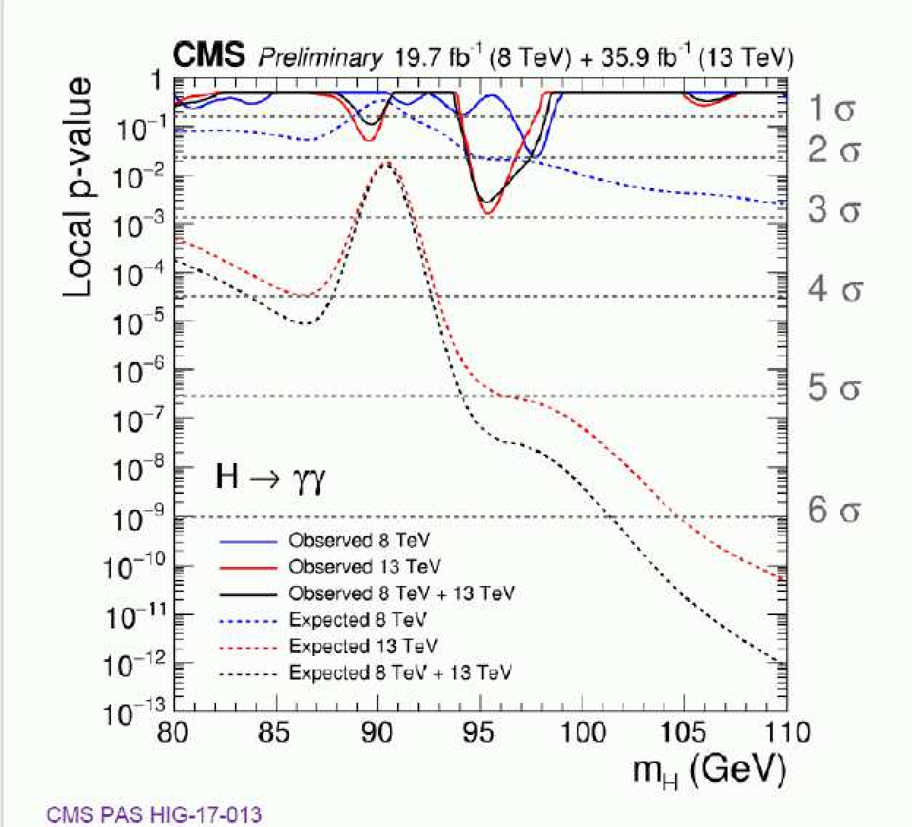
What was seen at LEP?



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

- **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**

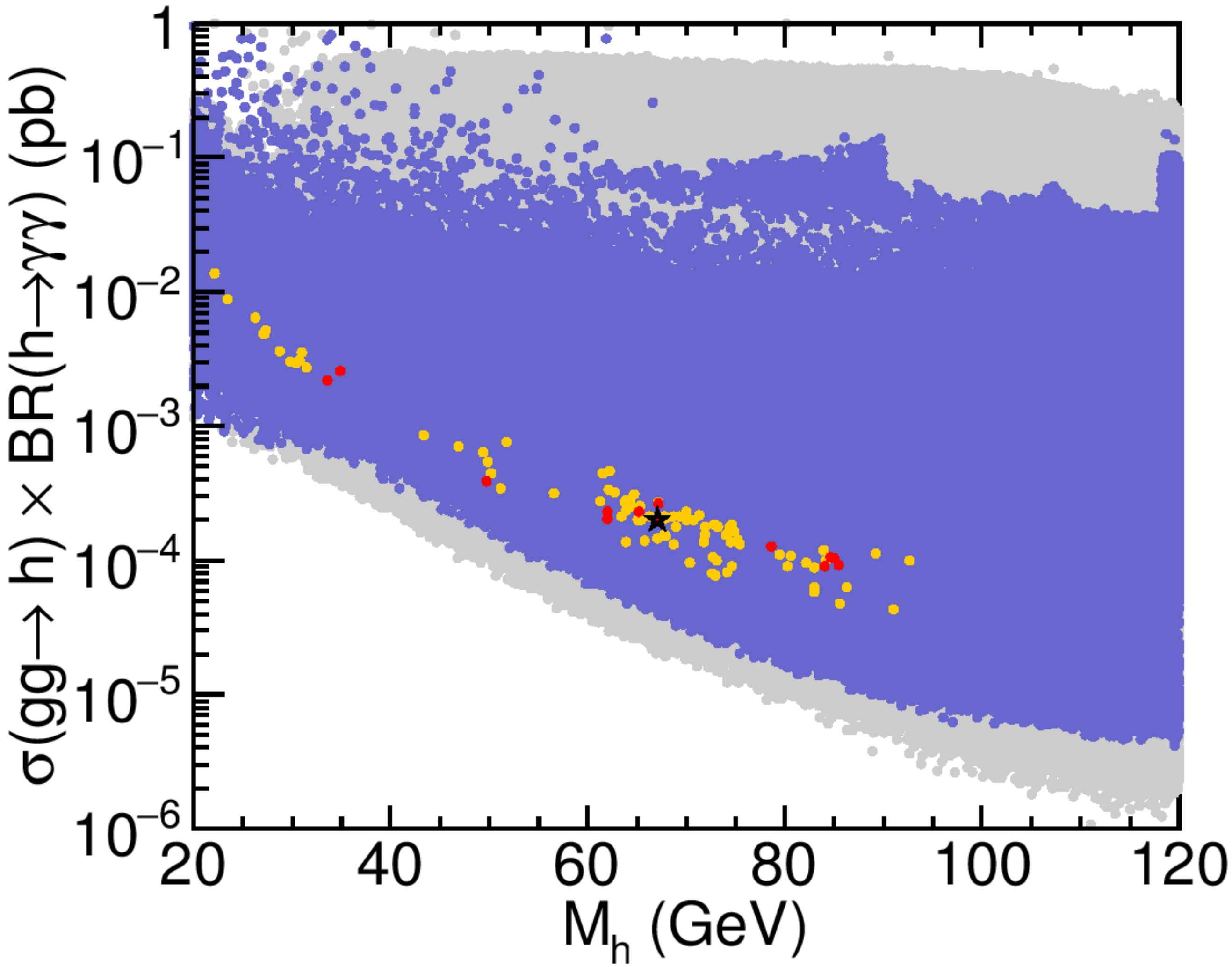




Q: When do you dare to something “significant”?

What about the MSSM?

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



⇒ too small rates!

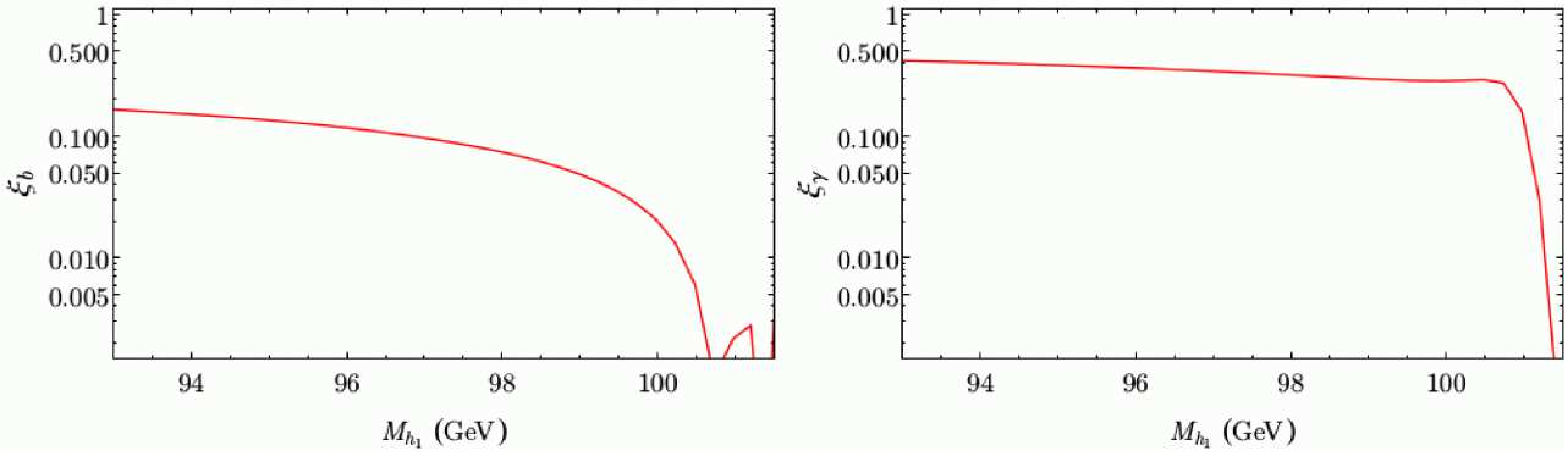
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

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



$\Rightarrow$ 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

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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

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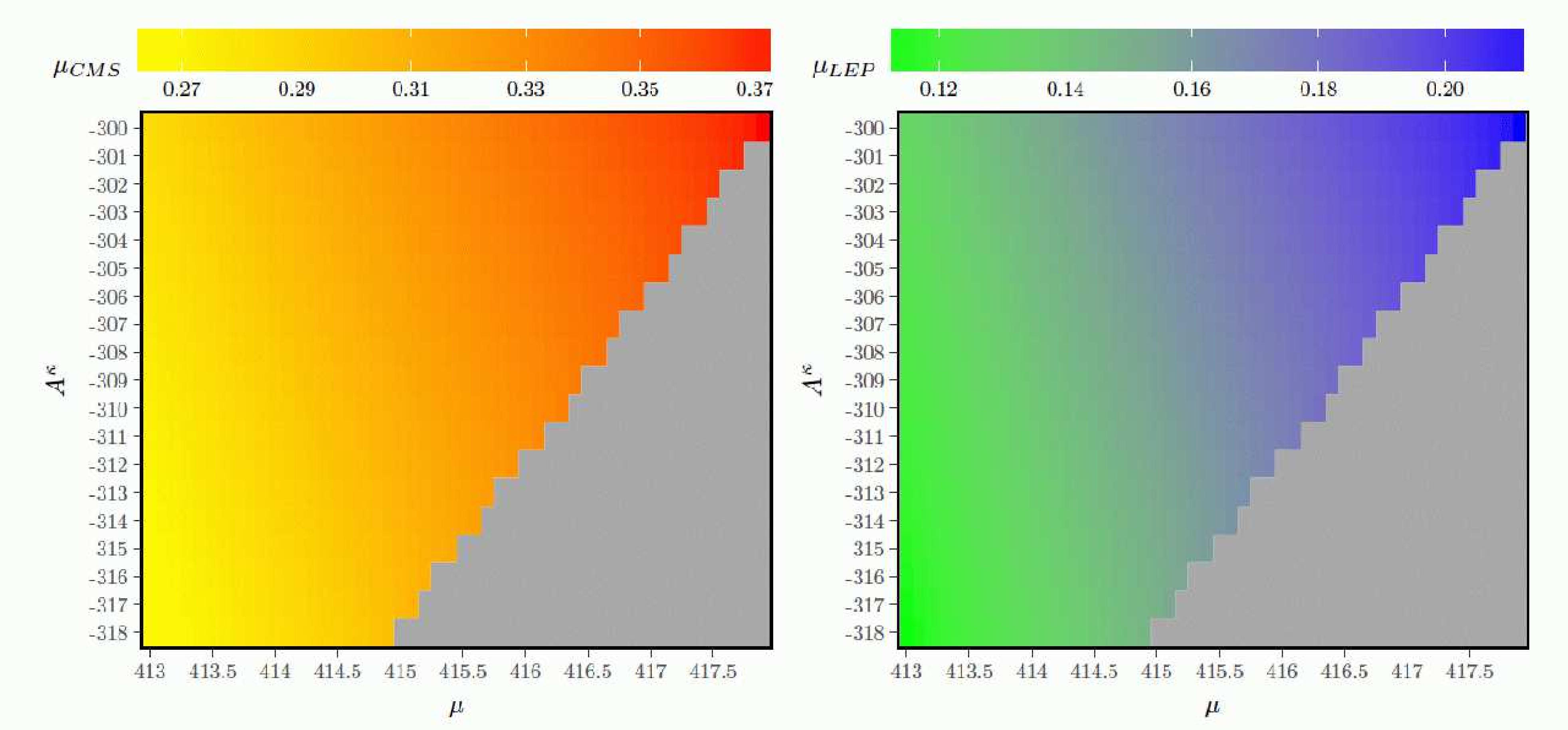


$\Rightarrow$ Yes, it can! :-)

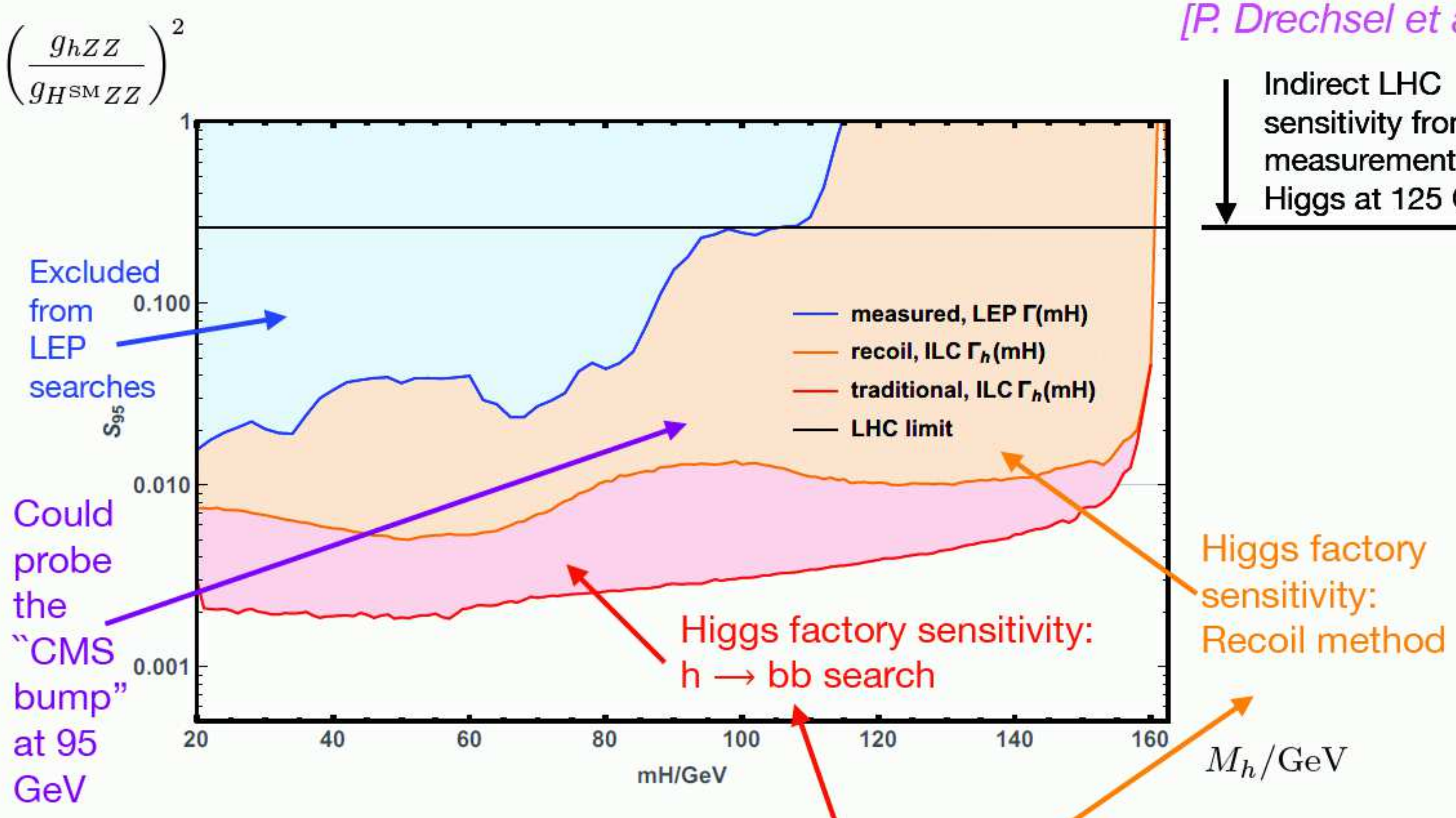
(at the $1 - 1.5\,\sigma$ level)

Implications for the ILC250:

Implications for the ILC250: reach for light Higgs bosons:

Example for discovery potential for new light states:
Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs

[P. Drechsel et al. '17]



⇒ Higgs factory at 250 GeV will explore a large untested region!

[*Taken from G. Weiglein '18*]

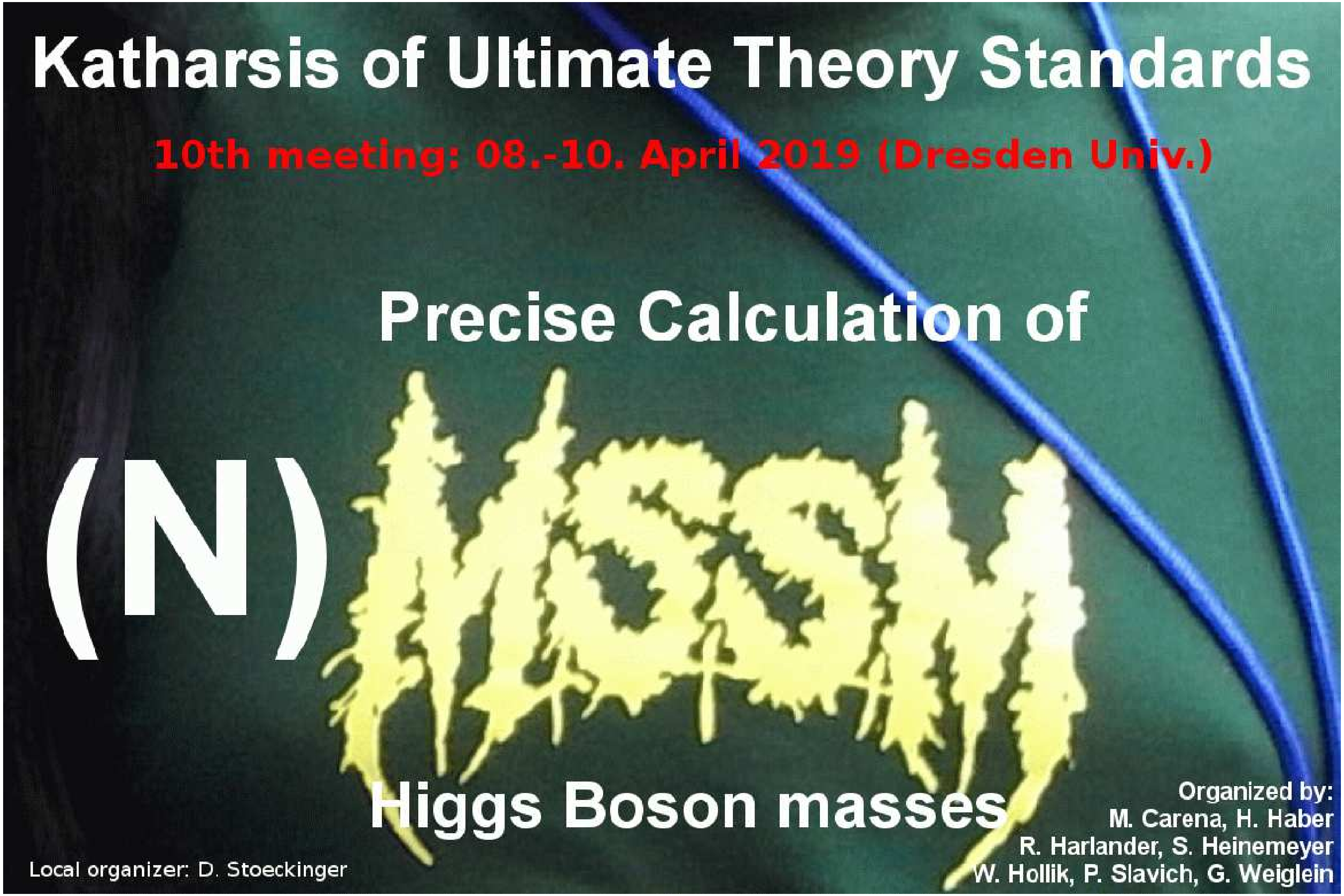
4. Conclusinos

- 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 not necessarily taken into account: EW/Flavor/DM

- New benchmark proposal:
  - M_h^{125} scenario: 2HDM-like model
  - $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \to \gamma\gamma$, $H/A \to \tilde{\tau}\tilde{\tau}$
  - $M_h^{125}(\tilde{\chi})$ 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} (alignment) scenario: h SM-like for very low M_A
  - M_H^{125} scenario: $M_H \sim 125$ GeV $\Rightarrow$ scenario with Higgs below 125 GeV
  - $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2-h_3 interference

- A light Higgs at 96 GeV? $\Rightarrow$ perfect case for the ILC250
  new CMS/ATLAS result $\oplus$ old LEP result possibly interesting!
  - NMSSM can explain CMS(/ATLAS) and LEP "excesses"
  - $\mu\nu$SSM can explain CMS(/ATLAS) and LEP "excesses"


Katharsis of Ultimate Theory Standards
10th meeting: 08.-10. April 2019 (Dresden Univ.)
Precise Calculation of
(N)MSSM
Higgs Boson masses
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein
Local organizer: D. Stoeckinger

Workshop announcement:

https://workshops.ift.uam-csic.es/FC2019

Search

Opportunities at Future High Energy Colliders

Workshop dates: June 11 - July 05 2019 (IFT, Madrid, Spain)

The workshop will bring together key theorists and experimentalists to address these questions, aiming at a more coherent, global view of the opportunities and rationale for the next generation of high energy colliders.

Program of the workshop:

- first week: dark matter and implications from cosmology
- second week: origin of lepton and quark flavour structure; fundamental symmetry tests
- third week: electroweak symmetry breaking; naturalness
- final week: discussion of complementary of the different collider opportunities as pertains to the physics themes.


Higgs Days at Santander 2019
Theory meets Experiment
16.-20. September
Contact: Sven.Heinemeyer@cern.ch
Local: Alicia.Calderon@cern.ch
Gervasio.Gomez@cern.ch
http://hdays.csic.es


Further Questions?

Data to be taken into account:

– Higgs boson mass (LHC) ⇒ FeynHiggs

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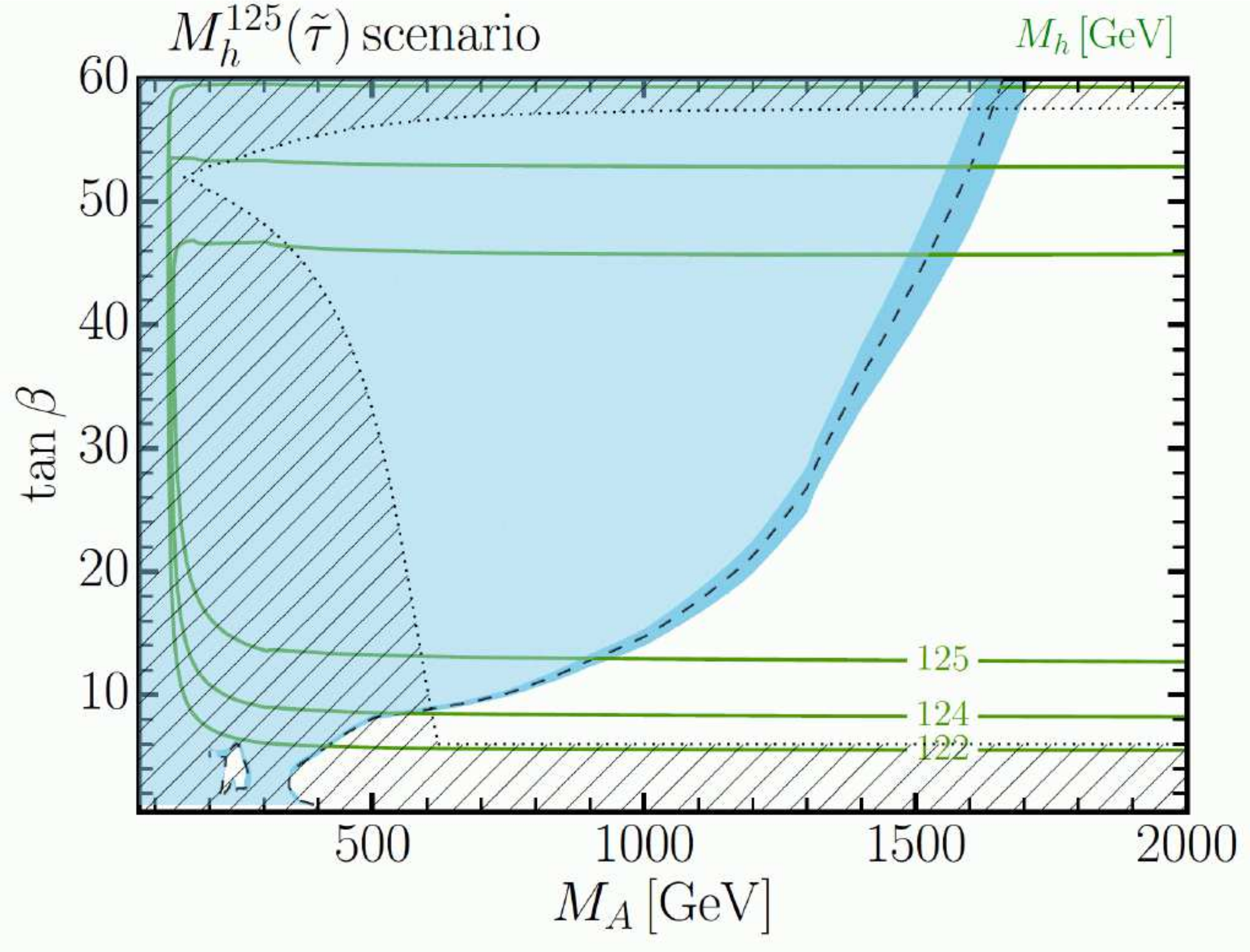
- Higgs boson exclusion bounds (LHC, Tevatron, LEP) $\Rightarrow$ HiggsBounds
- SUSY searches (LHC)

Data not necessarily to be taken into account:

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

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

$\Rightarrow$ slightly reduced heavy Higgs coverage

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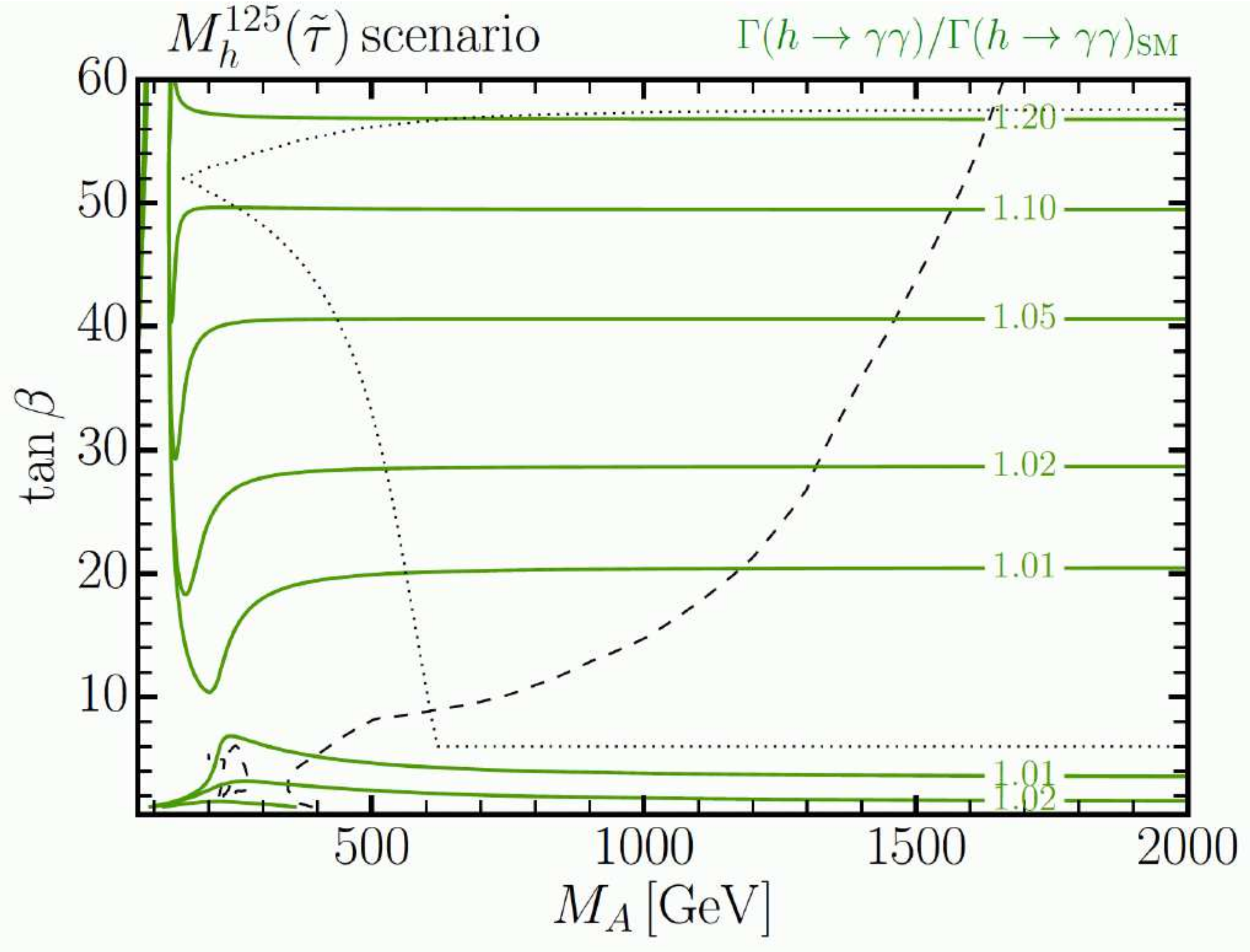

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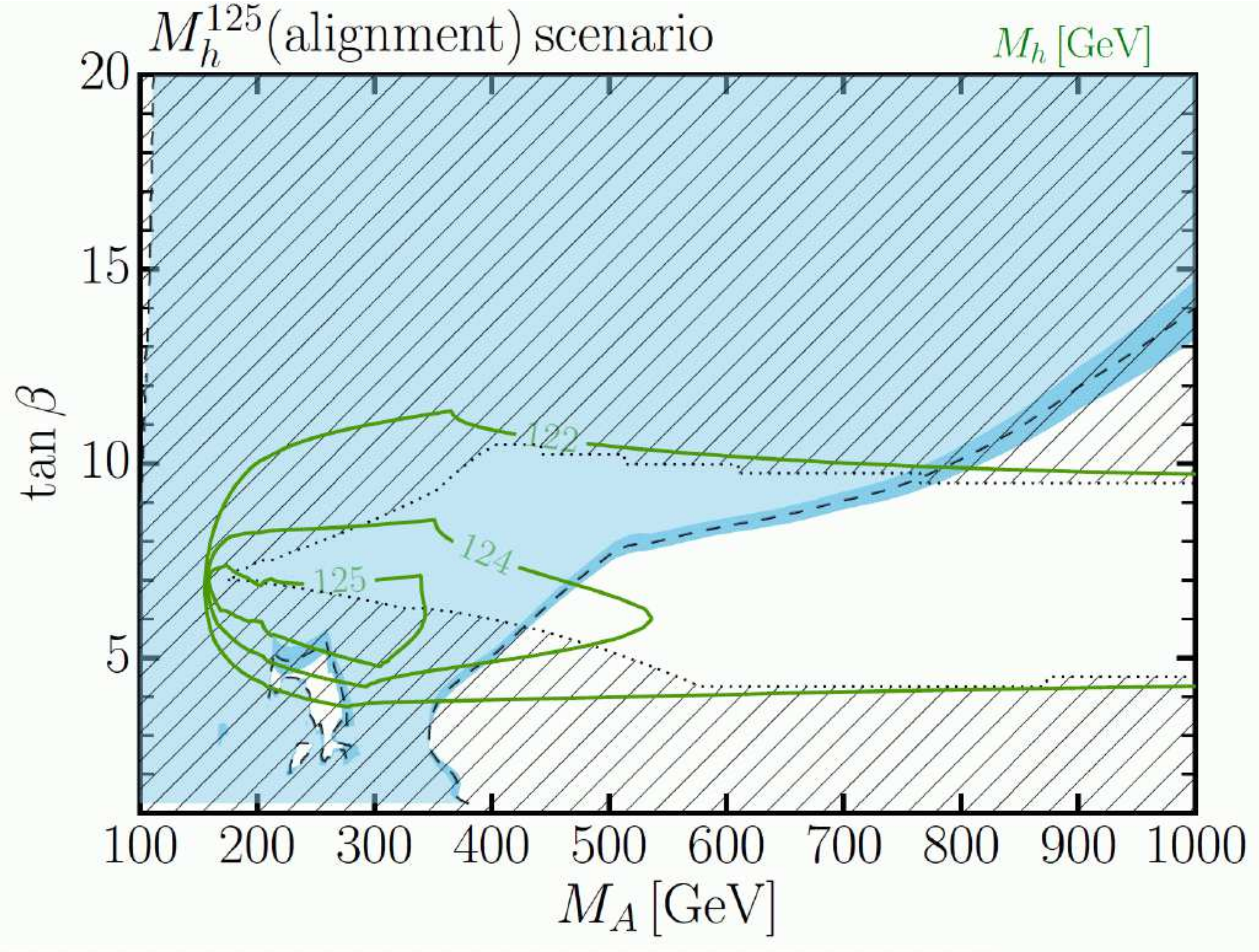
$\Rightarrow$ strong impact on $\Gamma(h \to \gamma\gamma)$



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

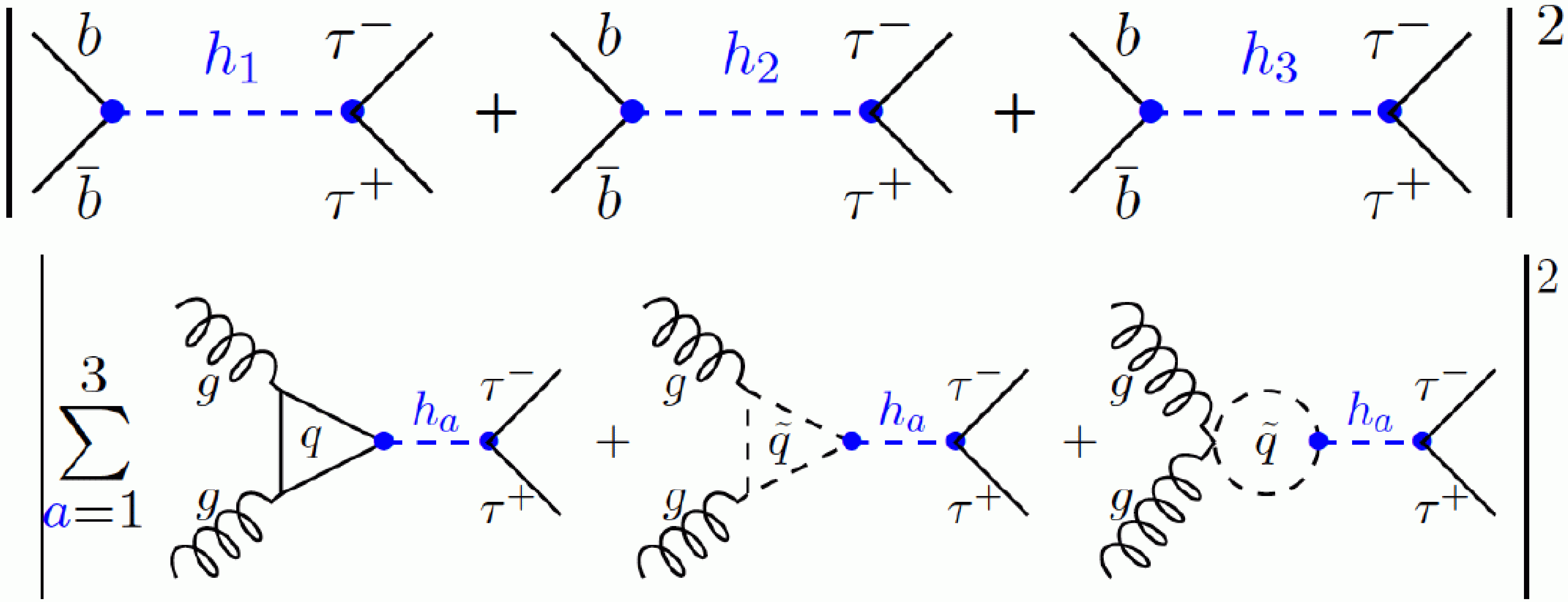
$A_t = A_b = A_\tau = 6.25$ TeV

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

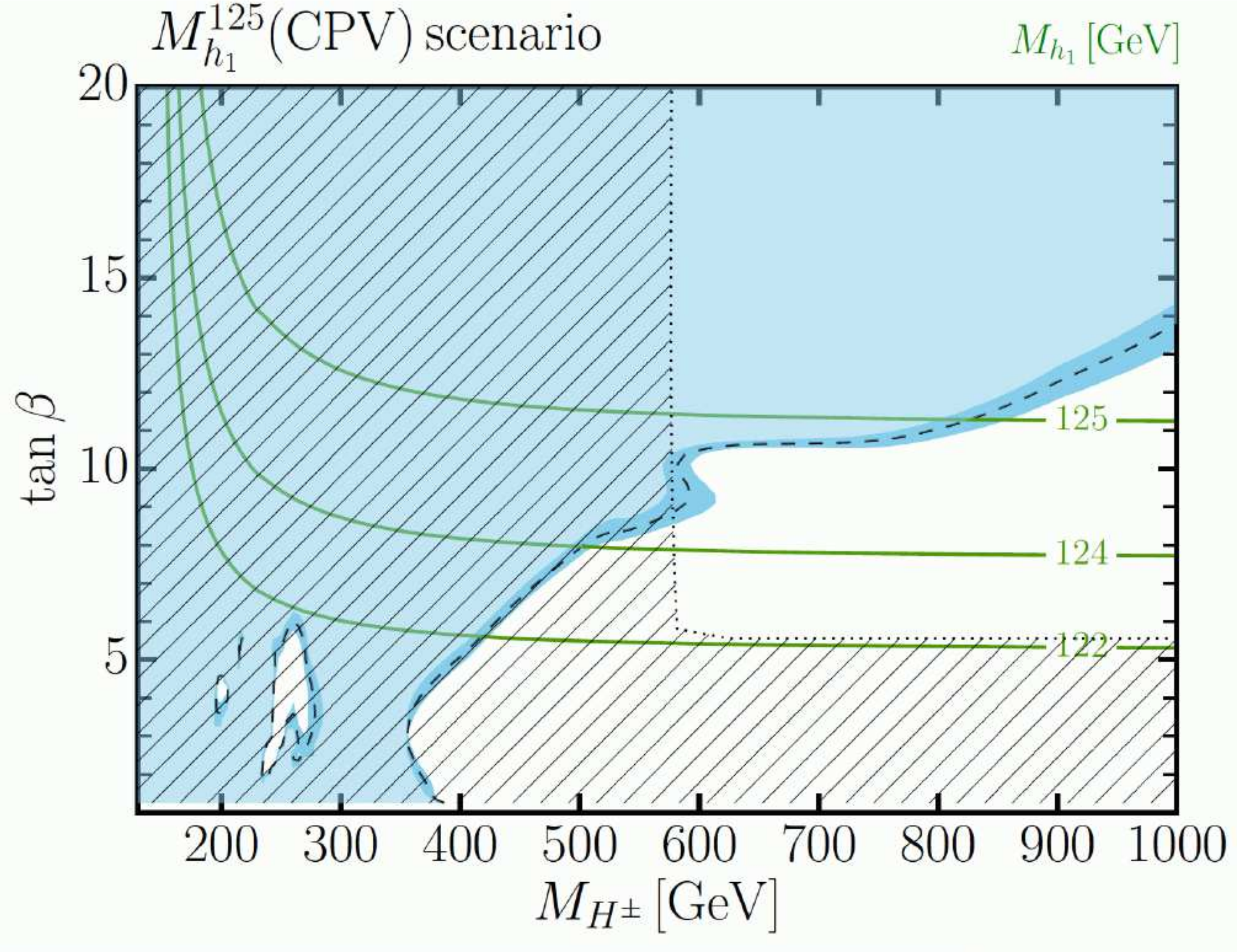
LHC Higgs searches for complex parameters:

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

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



[H. Bahl et al., '18]



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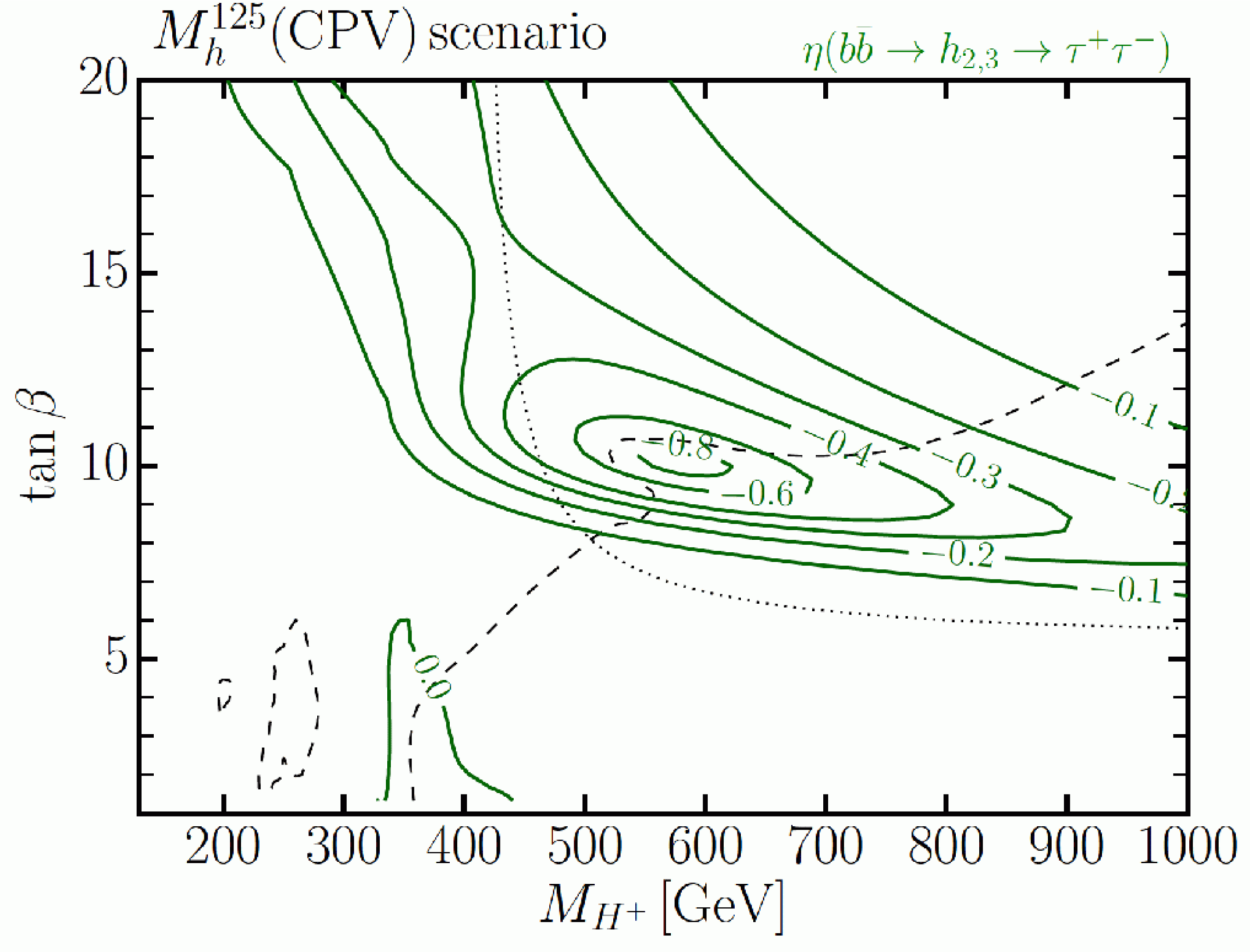
$|A_t| = \mu/\tan\beta + 2.8$ TeV

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

$|A_t| = A_b = A_\tau$

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

New benchmark: $M_{h_1}^{125}$(CPV) [H. Bahl et al., '18]



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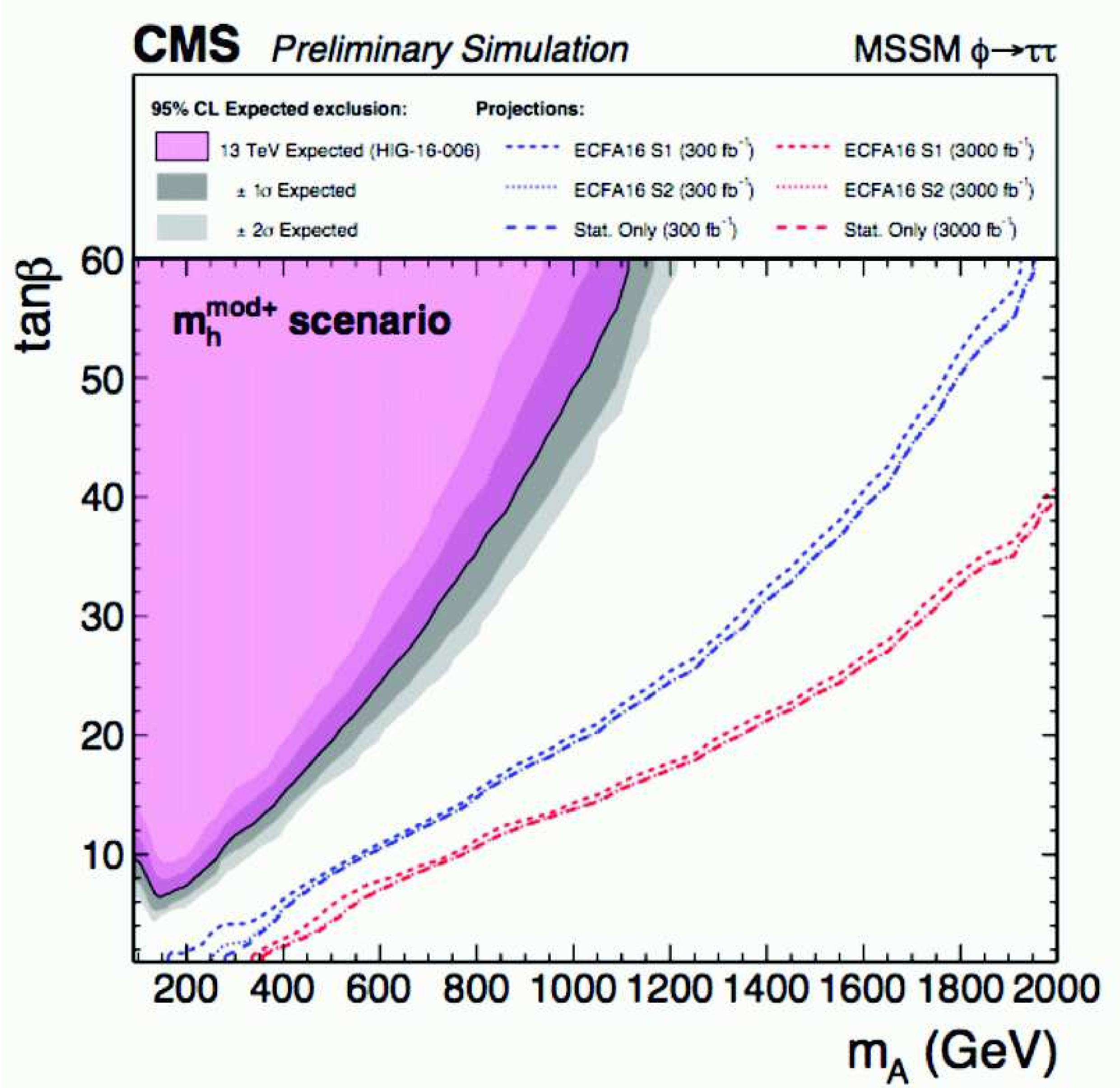
Future (HL-)LHC projections:

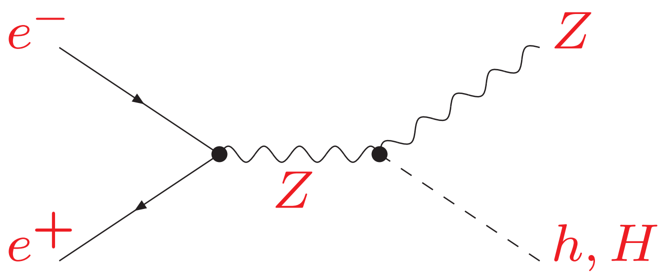


⇒ strong (HL-)LHC limits

Sum rule in the MSSM with h SM-like: $\sin(\beta-\alpha) \approx 1$, $\cos(\beta-\alpha) \approx 0$

Search for neutral SUSY Higgs bosons:

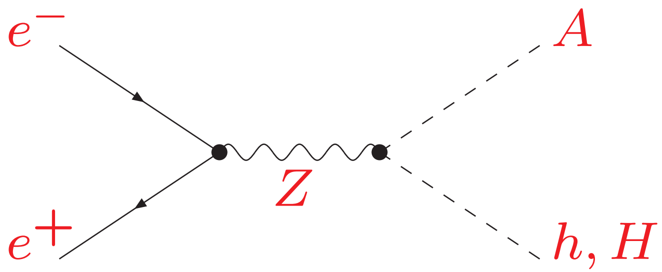
$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$$\sigma_{HZ} \approx \cos^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$e^+e^- \to Ah, AH$



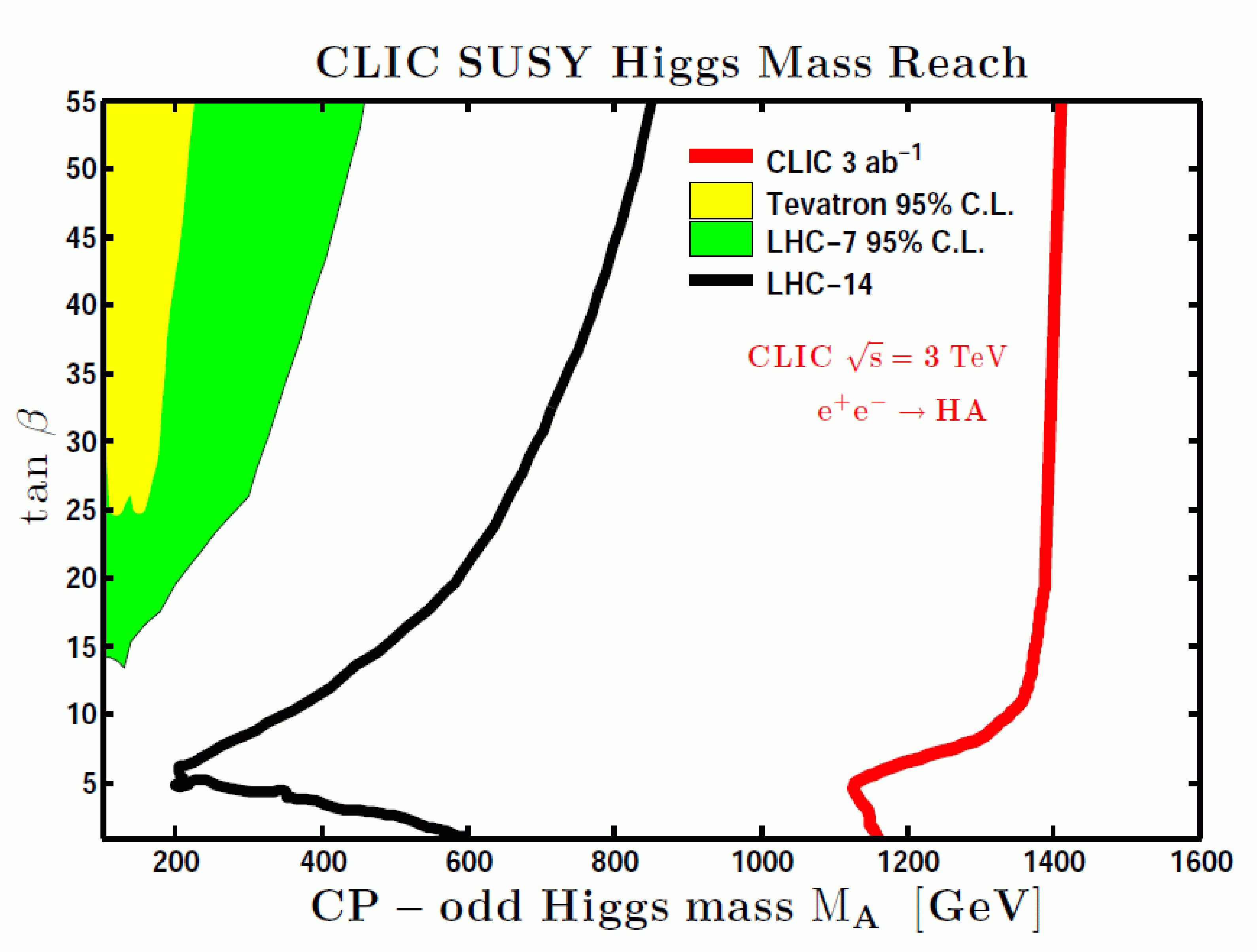
$$\sigma_{hA} \propto \cos^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$$\sigma_{HA} \propto \sin^2(\beta-\alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$\Rightarrow$ only pair production of heavy Higgs bosons! reach: $M_A \lesssim \sqrt{s}/2$

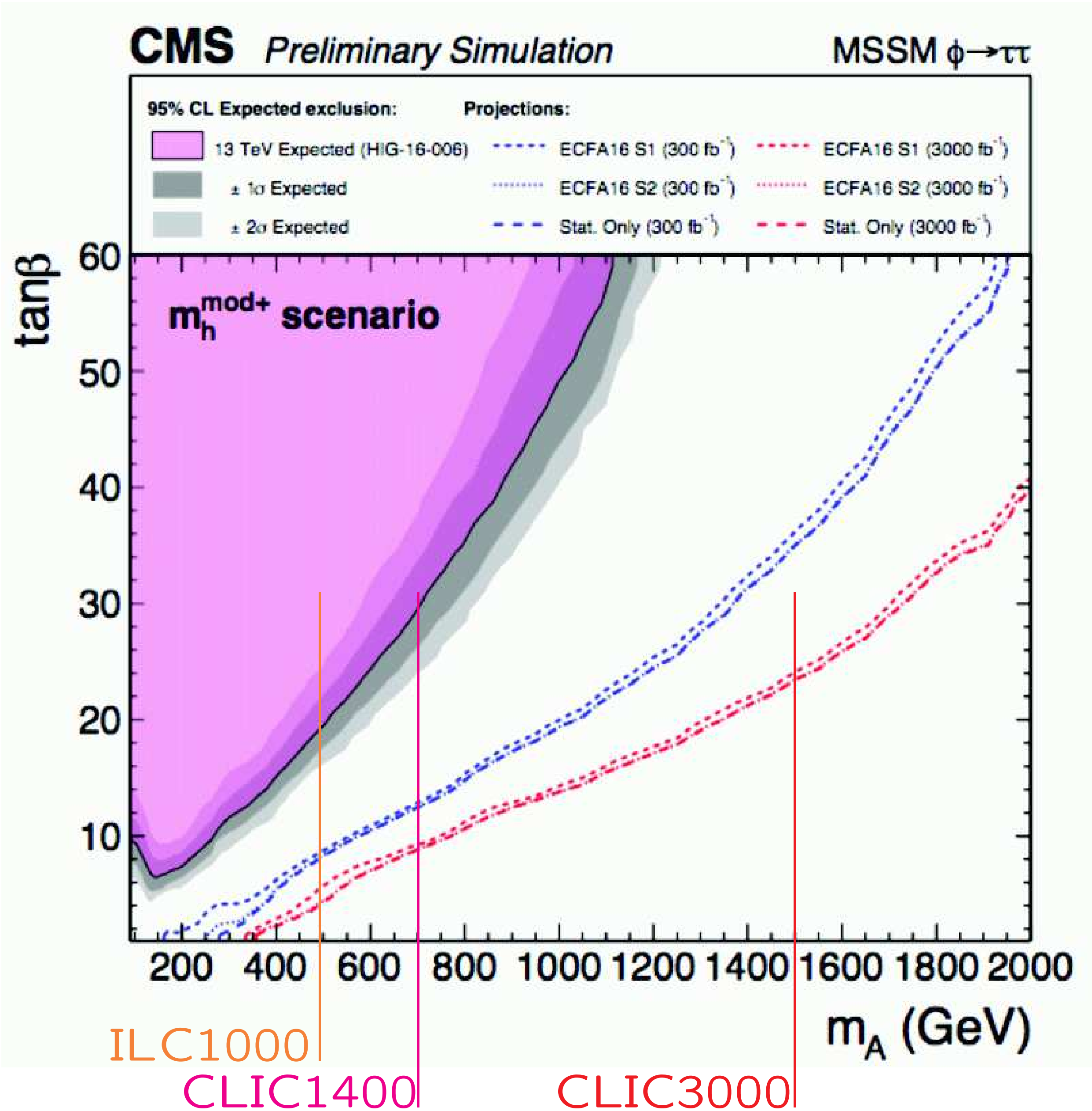
CLIC reach:

[*L. Linssen et al. '12*]



$\Rightarrow$ close to kinematic limit

“Simple” LC reach in the MSSM (neglecting $t\bar{t}$ final states)



⇒ unique opportunities!