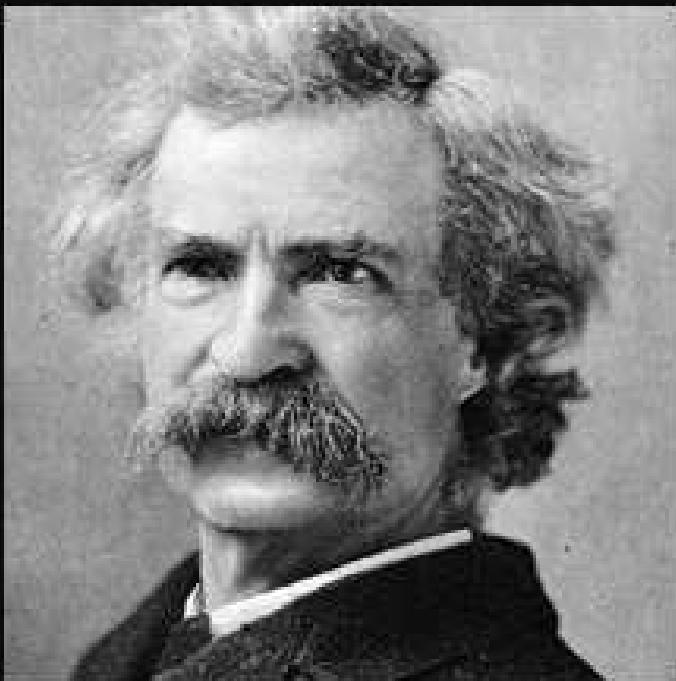


## Some original SUSY literature:



The reports of my death have  
been greatly exaggerated.

~ Mark Twain

# New SUSY Higgs Benchmarks for the LHC – HL-LHC and ILC implications

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

Corpus Cristi, 05/2019

- Motivation
- New MSSM Higgs Benchmarks for the LHC
- Implications for the HL-LHC and the ILC
- Conclusions

## 1. Motivation

Two facts:

We have a discovery!

The SM cannot be the ultimate theory!

**Conclusion: It cannot be “the SM Higgs” !**

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

**Q':** Which model?

## 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 additional 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?

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

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### Some “recent” measurements:

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

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### Simple SUSY models predicted correctly:

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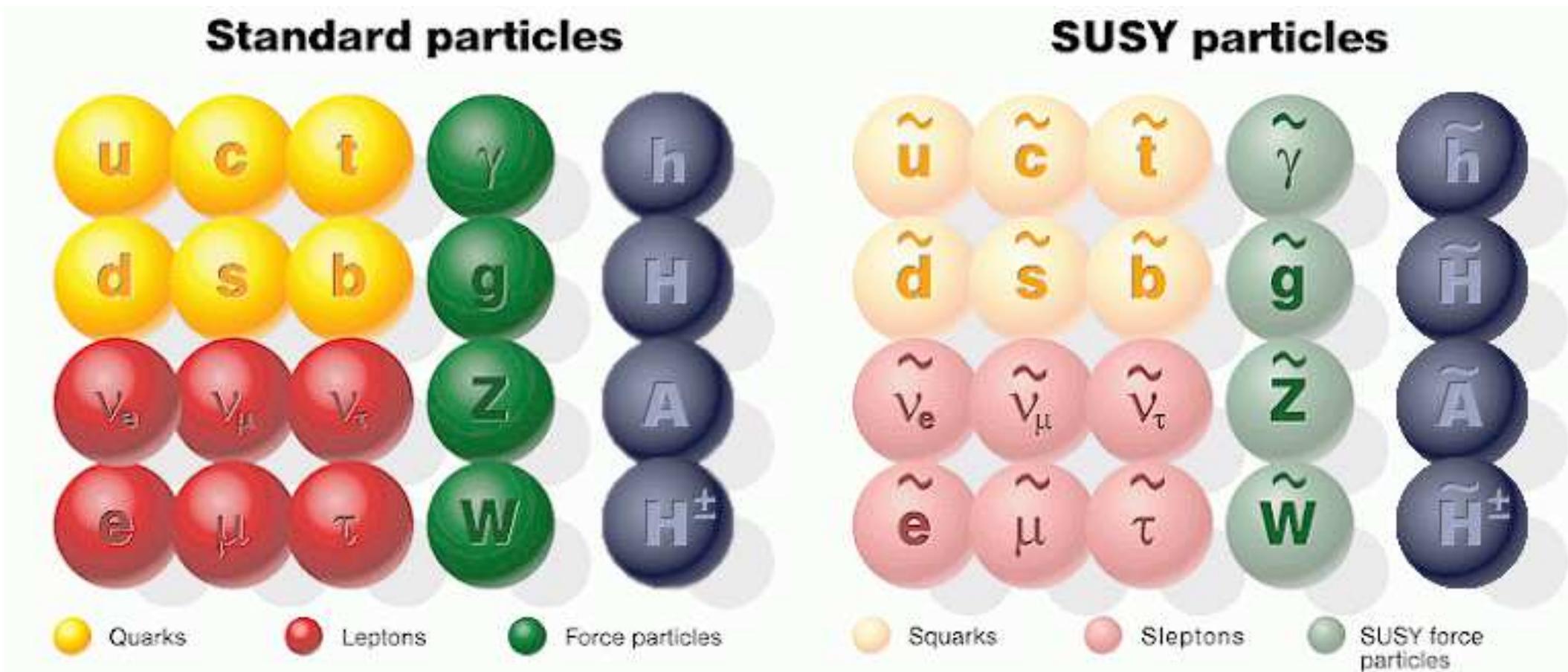
Simple SUSY models predicted correctly:

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

$\Rightarrow$  **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  
( $\Rightarrow$  many (close to) zero according to experimental data)  
 $\Rightarrow$  no model missed (within the MSSM)  
 $\Rightarrow \mathcal{O}(100)$  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  
 $\Rightarrow$  prediction for soft SUSY-breaking terms  
in terms of small set of parameters  
 $\Rightarrow$  easy to handle, but not all relevant phenomenology captured

## C. Benchmark scenarios:

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

## The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

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

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

$$\begin{aligned} V = & m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ & + \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2 \end{aligned}$$

physical states:  $h^0, H^0, A^0, H^\pm$       Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

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

Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

physical states:  $h^0, H^0, A^0, H^\pm$       Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

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

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

Complex parameters enter via loop corrections:

- $\mu$  : 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

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

Result:

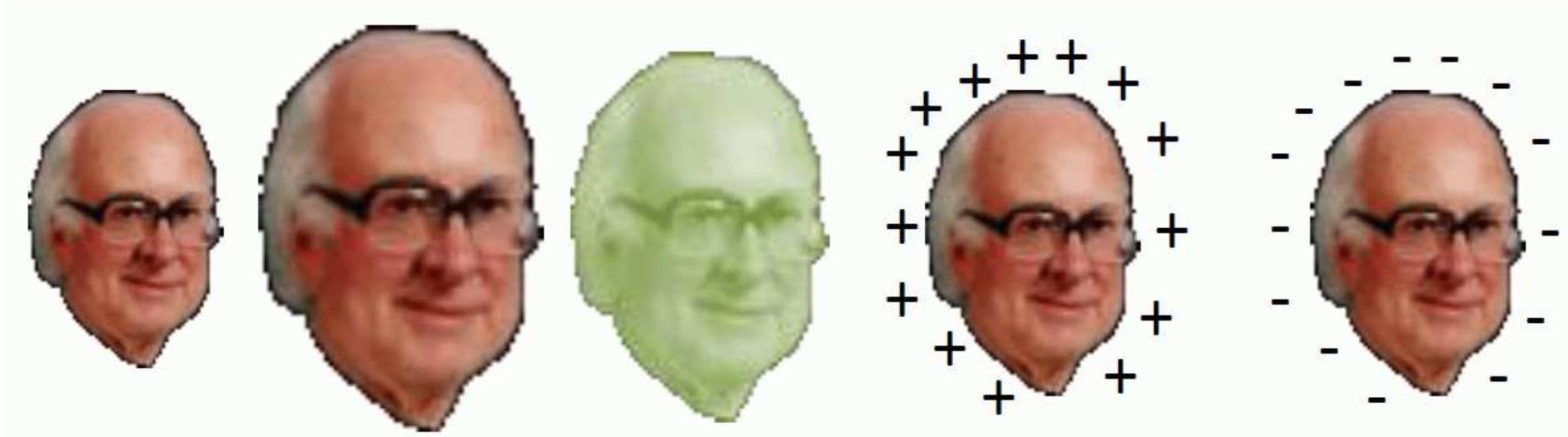
$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

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

⇒ 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?

→ investigate benchmark scenarios:

- Vary only  $M_A$  (or  $M_{H^\pm}$ ) 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:  $h \rightarrow \gamma\gamma$ ,  $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
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  $M_{\text{SUSY}}$
- 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

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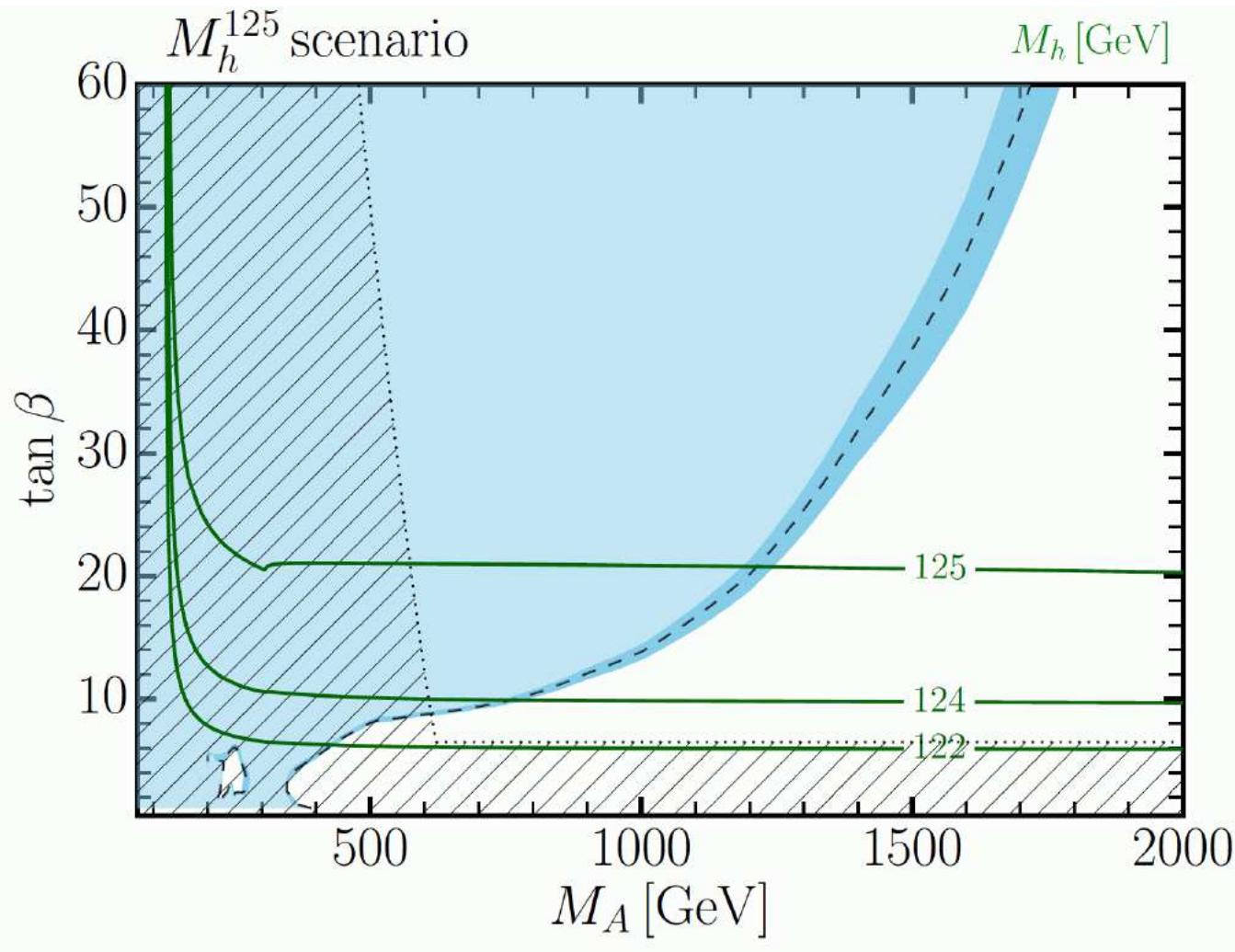
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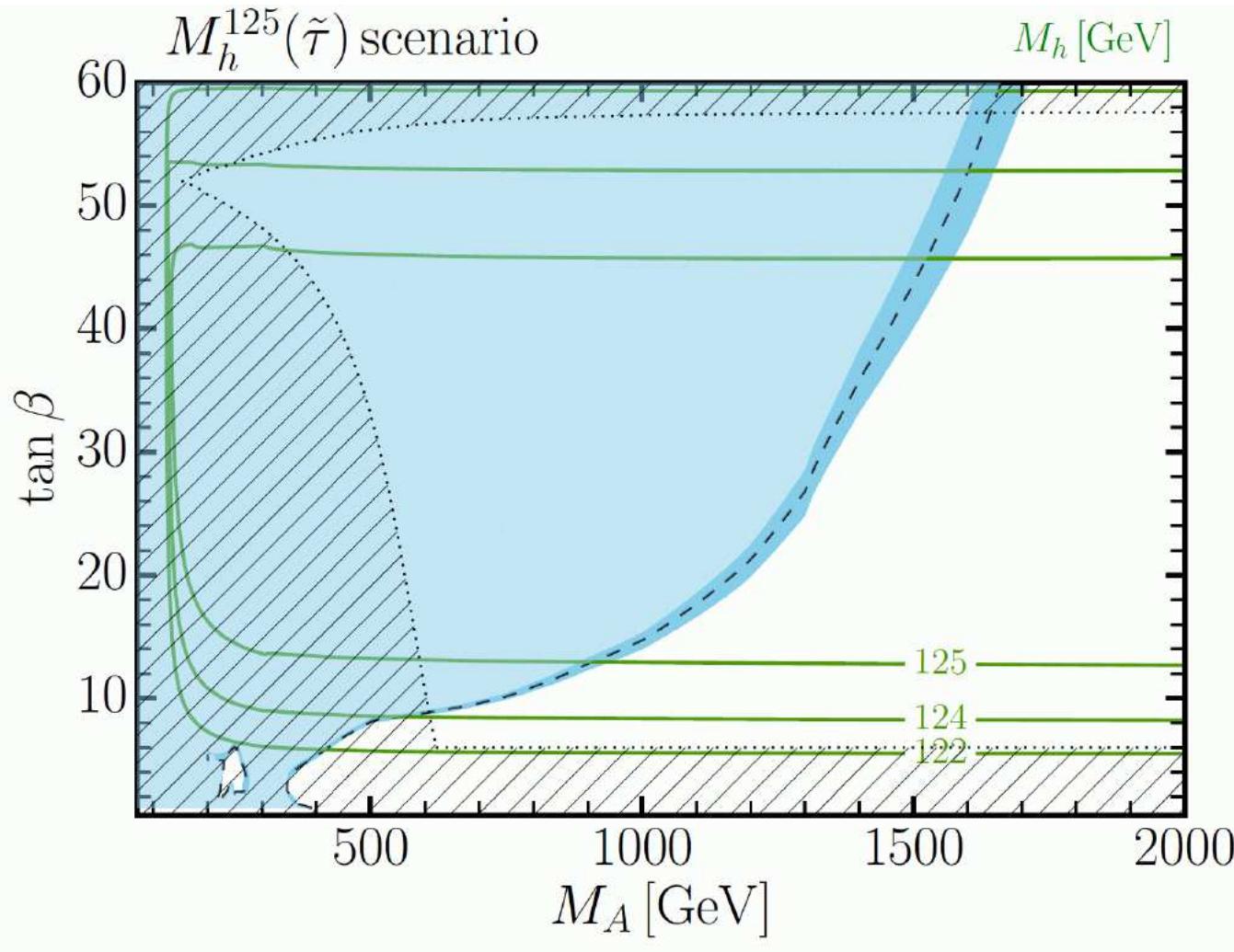
## Data on purpose not to be taken into account:

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



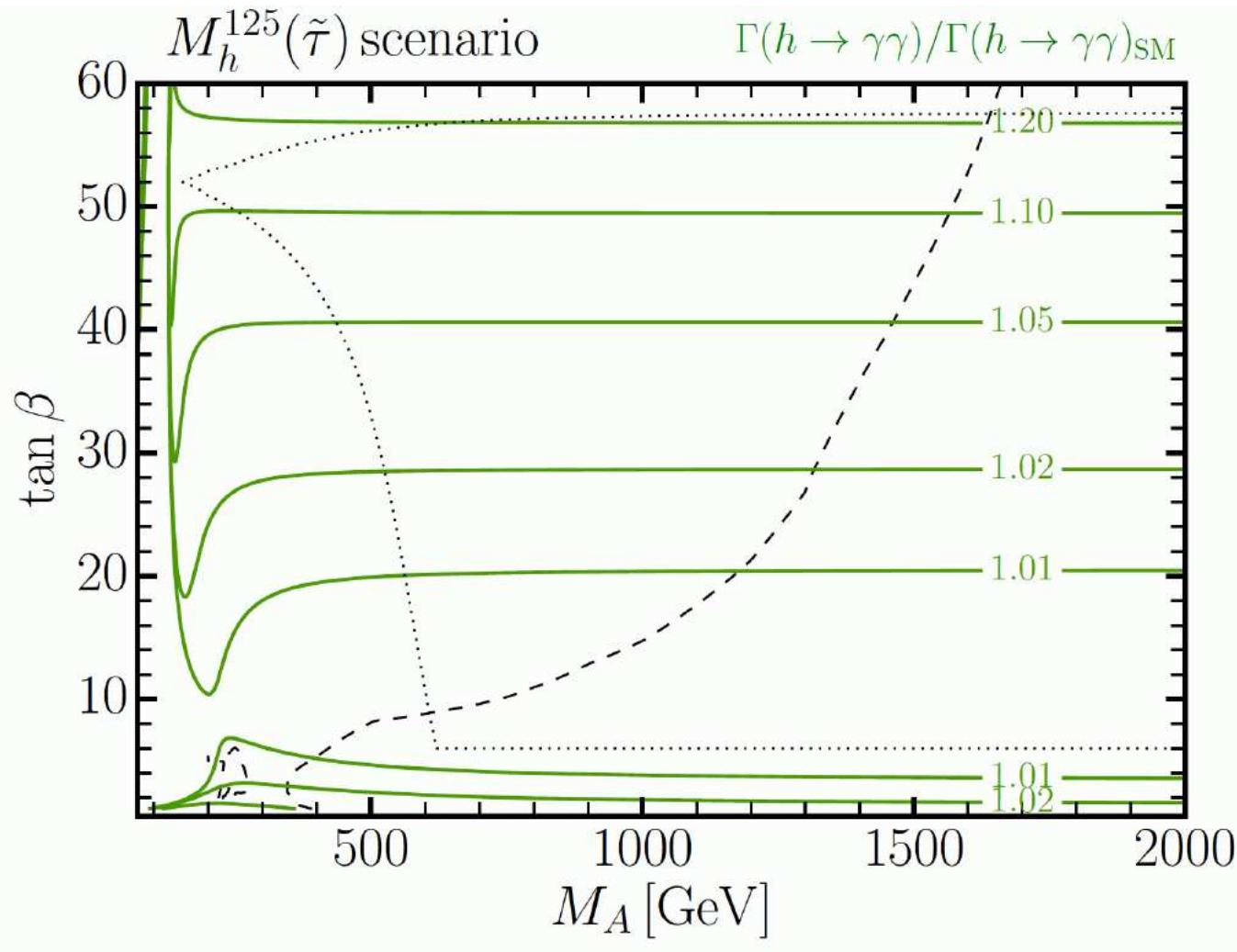
$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$  TeV  
 $M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$  TeV  
 $\mu = 1$  TeV,  $M_1 = 1$  TeV  
 $M_2 = 1$  TeV,  $M_3 = 2.5$  TeV  
 $X_t = 2.8$  TeV  
 $A_t = A_b = A_\tau$

⇒ new vanilla benchmark model



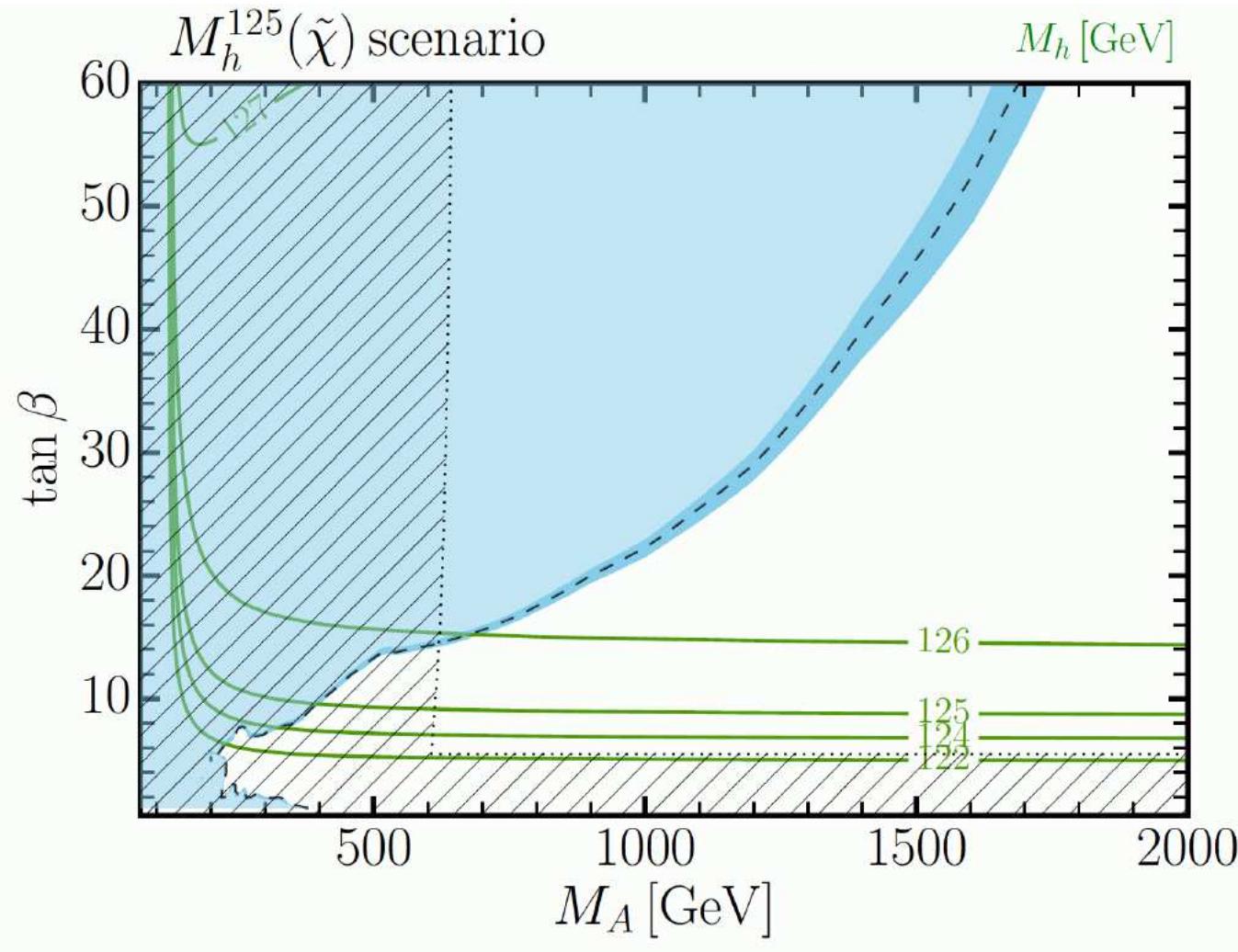
$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$   
 $M_{\tilde{L}_3} = M_{\tilde{E}_3} = 350 \text{ GeV}$   
 $\mu = 1 \text{ TeV}, M_1 = 180 \text{ GeV}$   
 $M_2 = 300 \text{ GeV}, M_3 = 2.5 \text{ TeV}$   
 $X_t = 2.8 \text{ TeV}$   
 $A_t = A_b, A_\tau = 800 \text{ GeV}$

⇒ slightly reduced heavy Higgs coverage



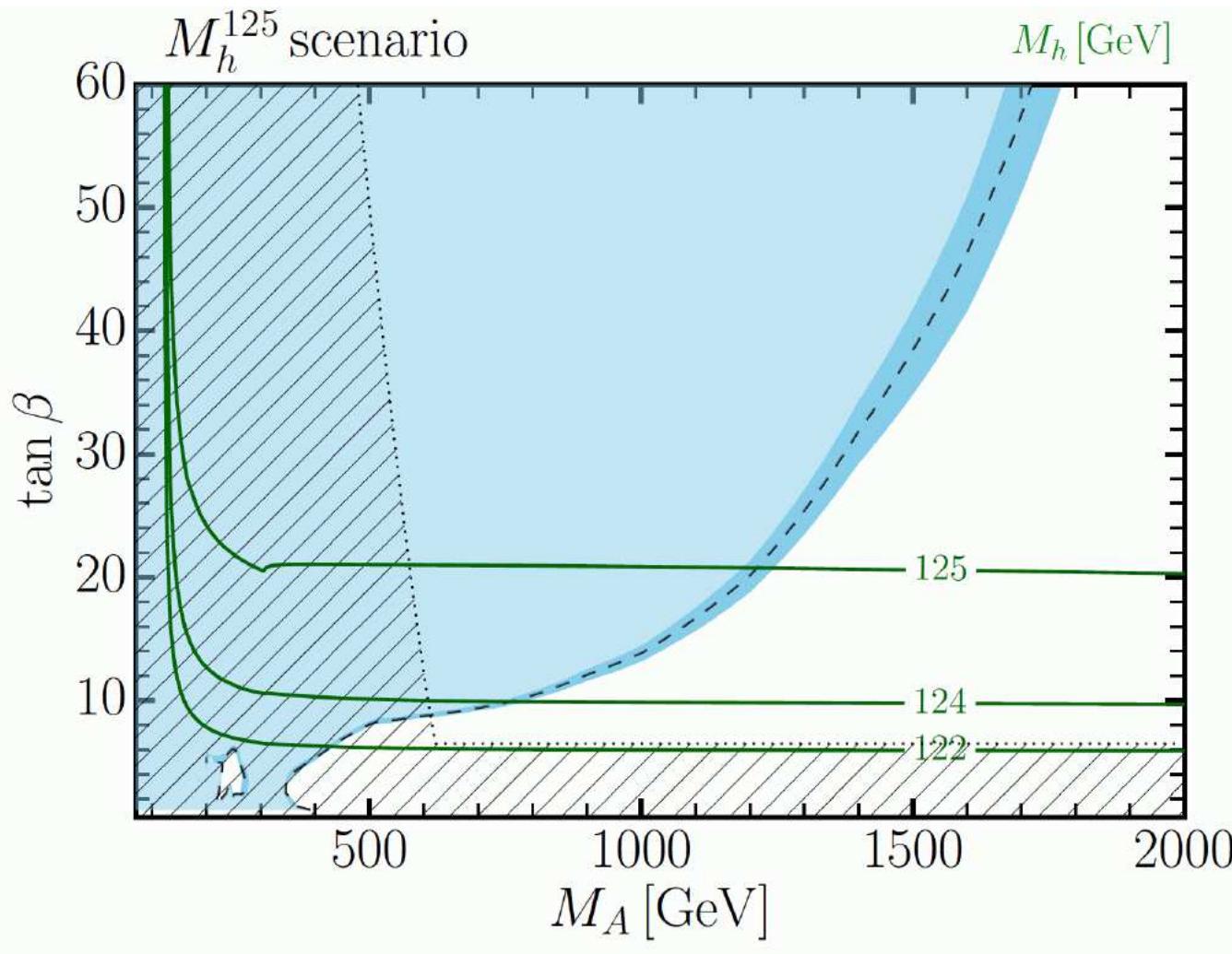
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⇒ strong impact on  $\Gamma(h \rightarrow \gamma\gamma)$



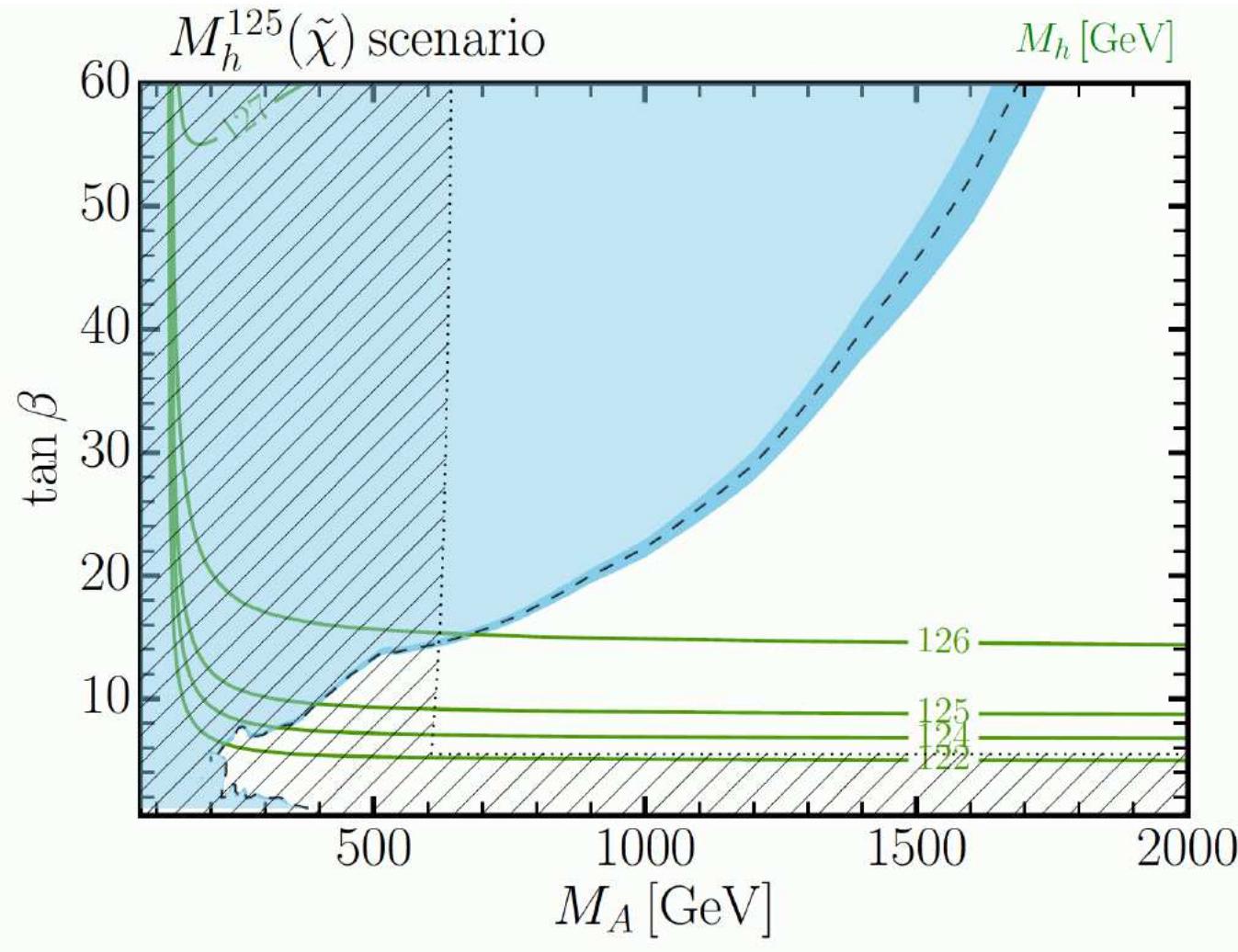
$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$  TeV  
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 $\mu = 180$  GeV,  $M_1 = 160$  GeV  
 $M_2 = 180$  GeV,  $M_3 = 2.5$  TeV  
 $X_t = 2.5$  TeV  
 $A_t = A_b = A_\tau$

⇒ strongly reduced heavy Higgs coverage



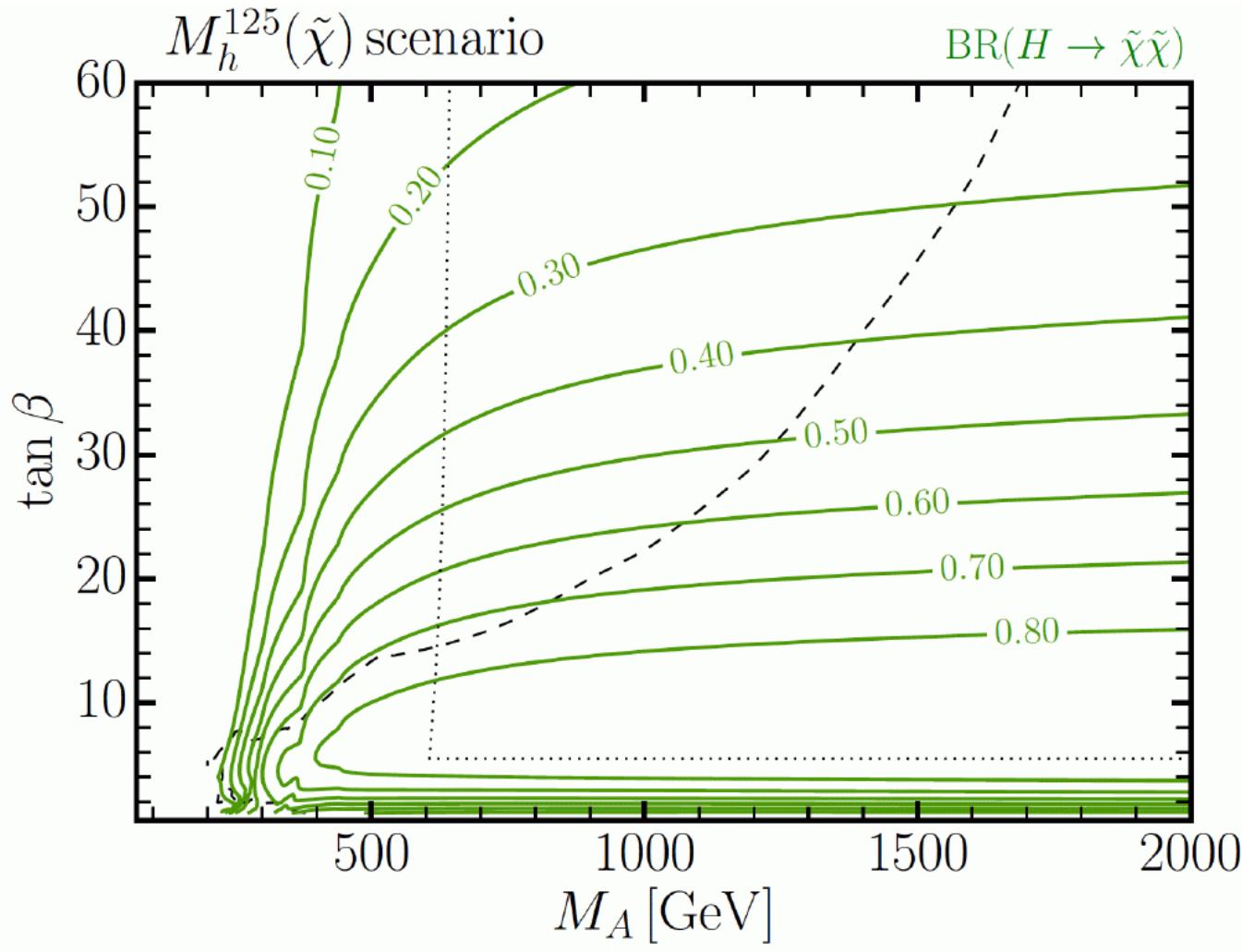
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⇒ new vanilla benchmark model



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

⇒ strongly reduced heavy Higgs coverage



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

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

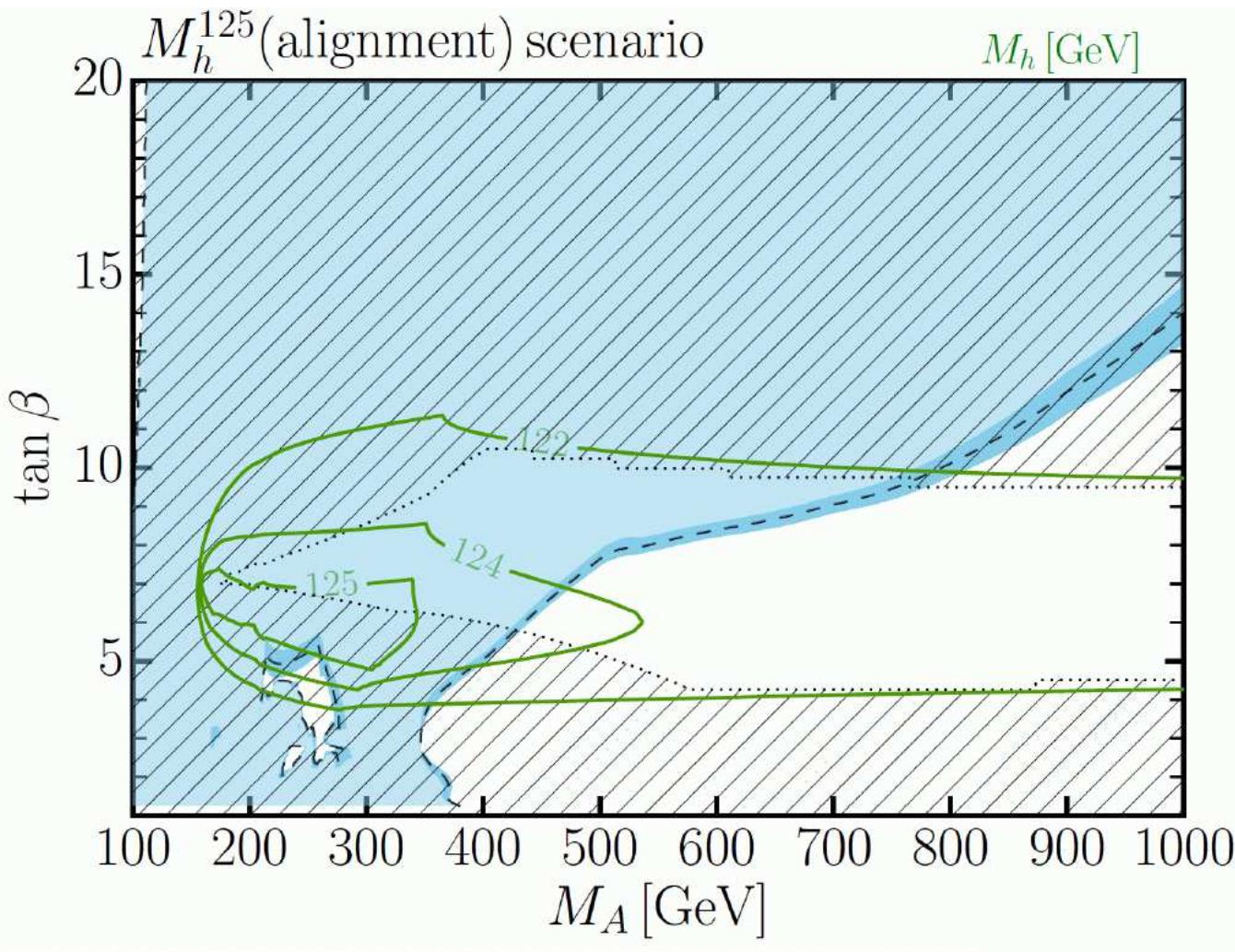
$$\mu = 180 \text{ GeV}, M_1 = 160 \text{ GeV}$$

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

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

$$A_t = A_b = A_\tau$$

→ Huge BR of heavy Higgses to EW-inos



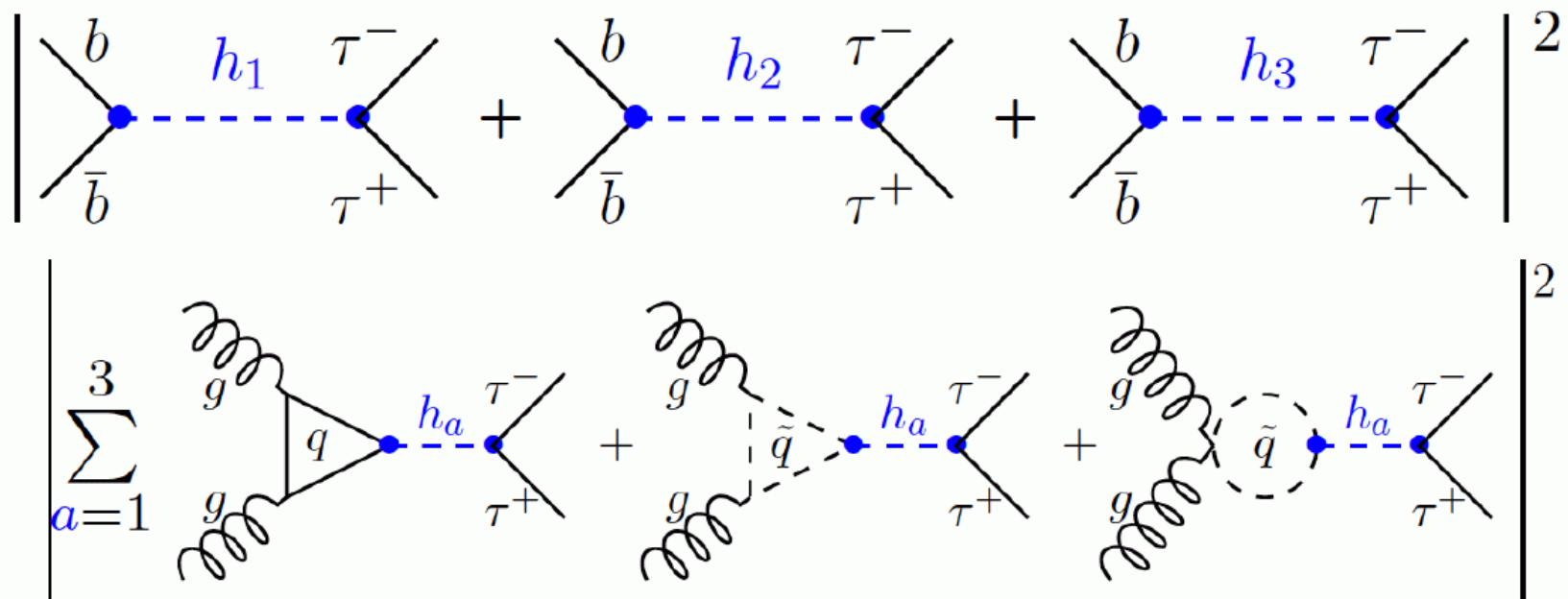
$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2.5$  TeV  
 $M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$  TeV  
 $\mu = 7.5$  TeV,  $M_1 = 500$  GeV  
 $M_2 = 1$  TeV,  $M_3 = 2.5$  TeV  
 $A_t = A_b = A_\tau = 6.25$  TeV

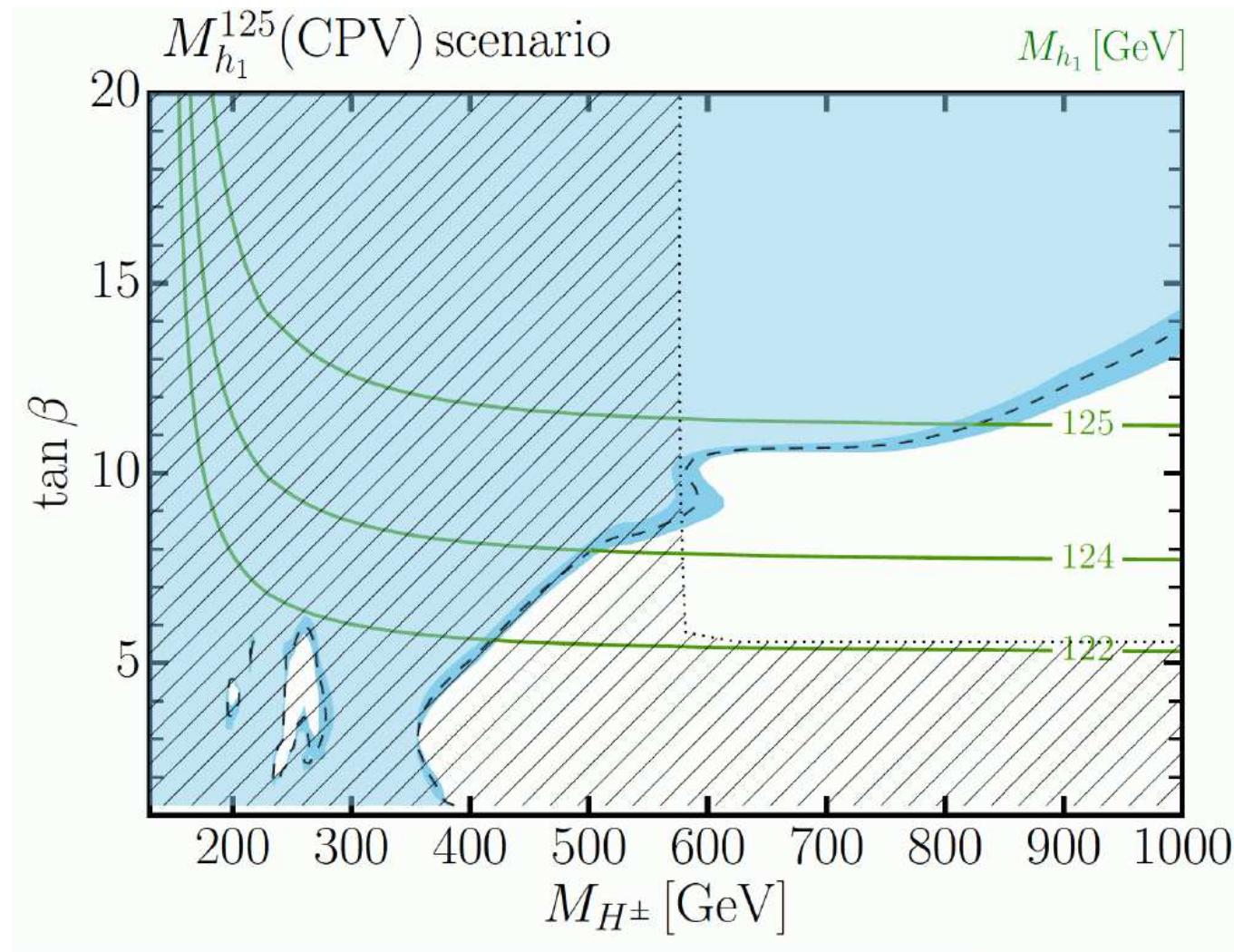
$\Rightarrow h$  SM-like for very low  $M_A$

## 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:

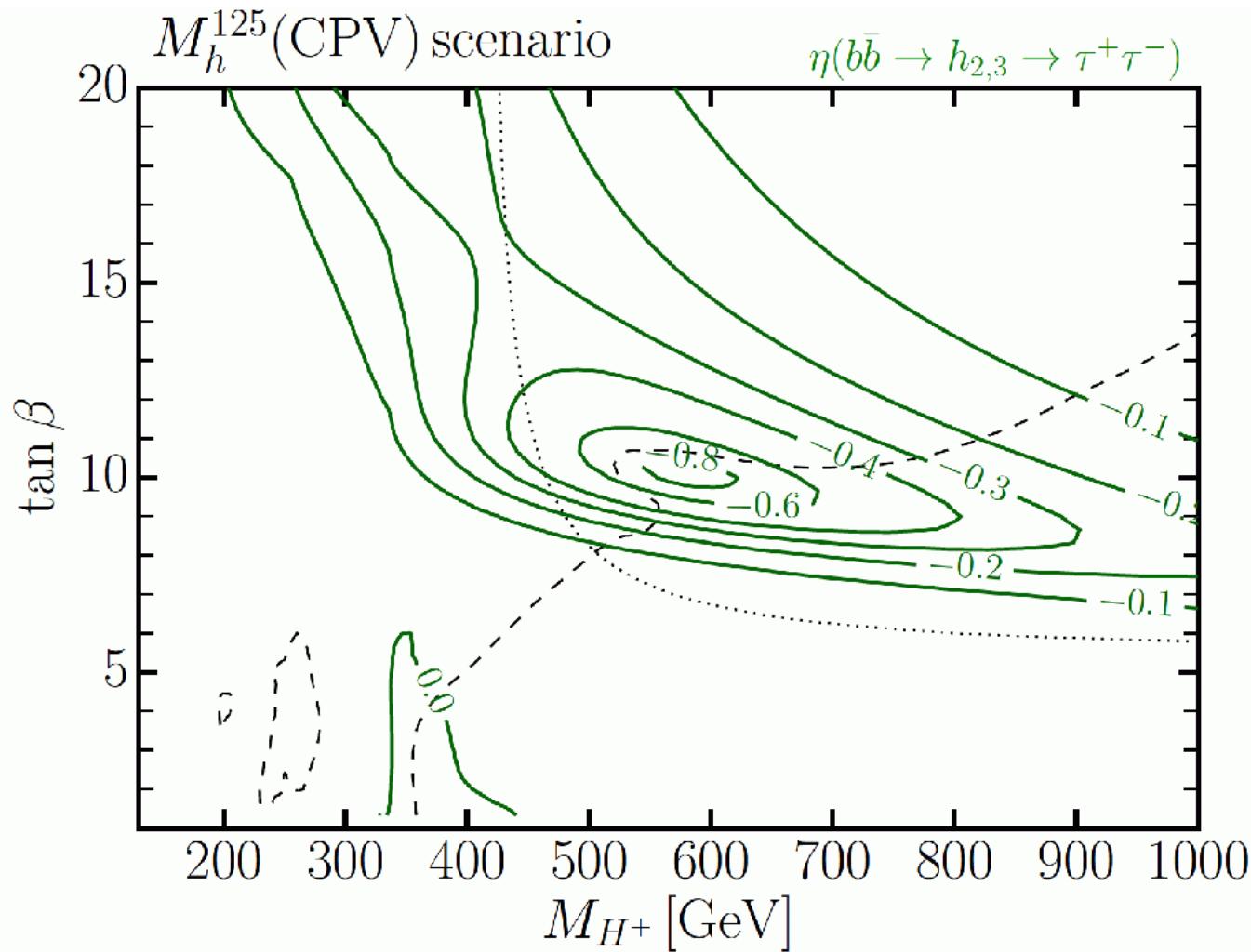
Higgs bosons as intermediate states in  $\{b\bar{b}, gg\} \rightarrow h_a \rightarrow \tau\tau$





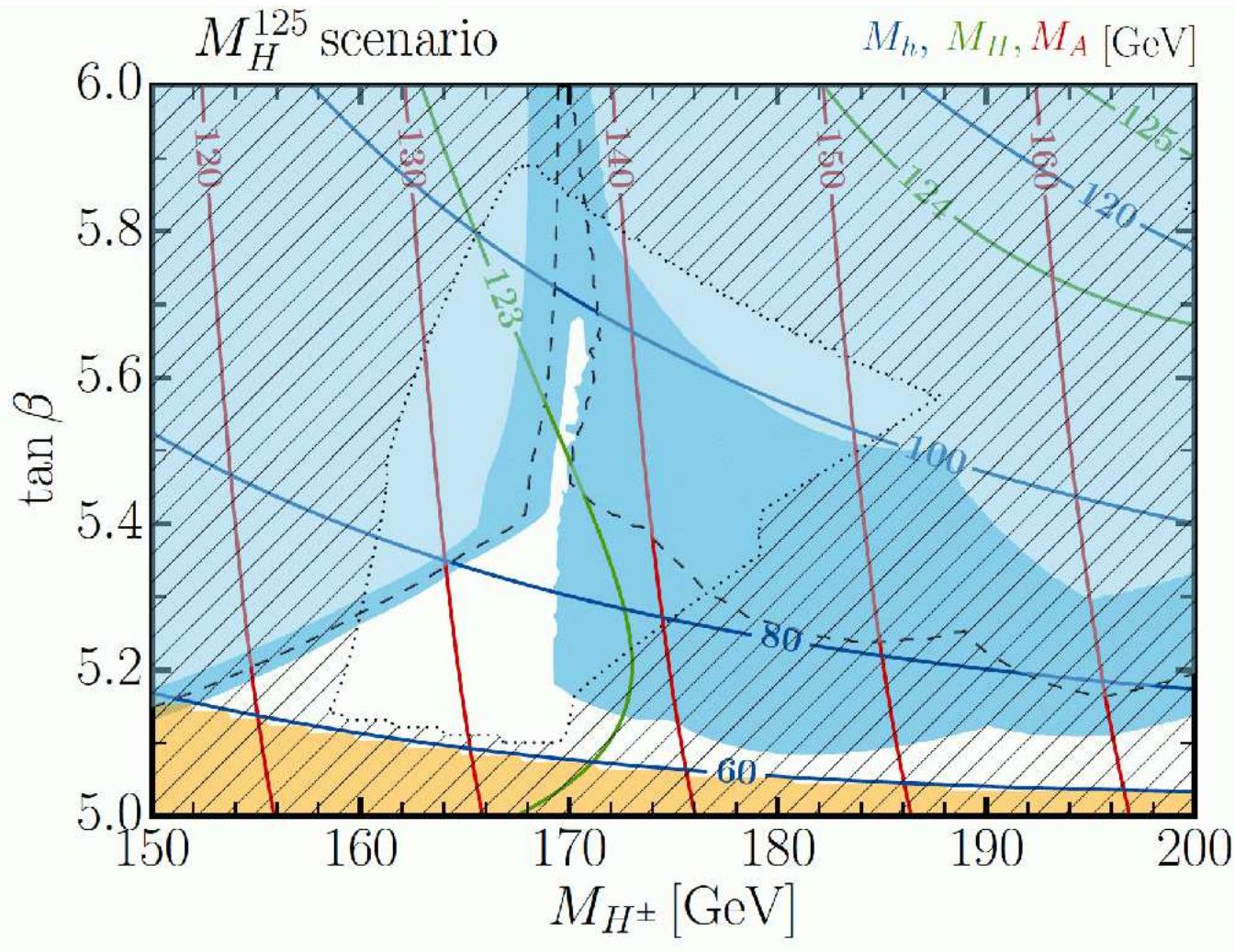
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 $|A_t| = \mu / \tan \beta + 2.8$  TeV  
 $\phi_{A_t} = 2/15 \pi$   
 $|A_t| = A_b = A_\tau$

⇒ reduced coverage due to  $h_2$ - $h_3$  interference



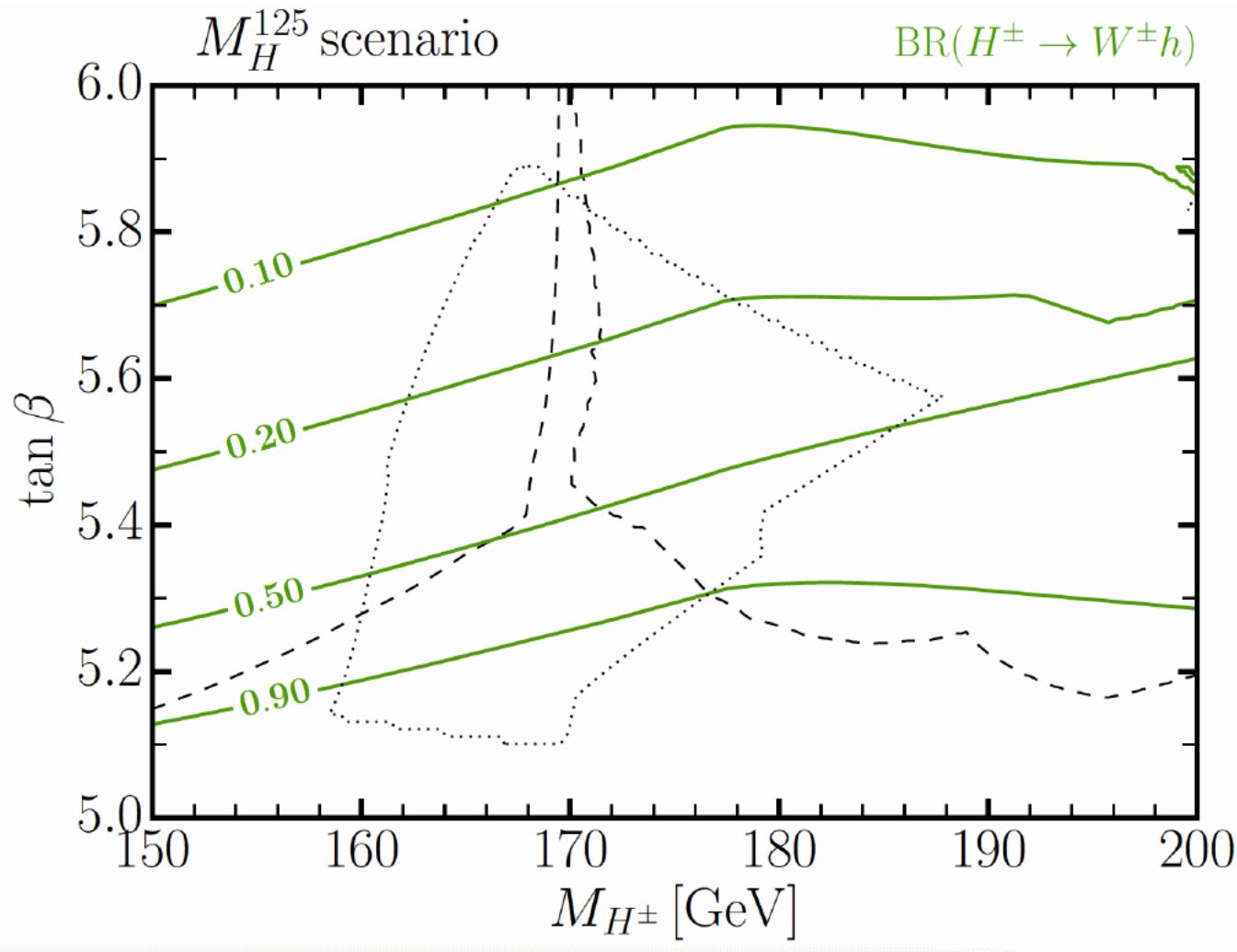
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 \end{aligned}$$

⇒ reduced coverage due to  $h_2$ - $h_3$  interference



$$\begin{aligned}
 M_{\tilde{Q}_3} &= M_{\tilde{U}_3} = 750 \text{ GeV} \\
 &- 2(M_{H^\pm} - 150 \text{ GeV}) \\
 M_{\tilde{L}_3} &= M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2 \text{ TeV} \\
 \mu &= [5.8 \text{ TeV} \\
 &+ 20(M_{H^\pm} - 150 \text{ GeV})] \times \\
 &M_{\tilde{Q}_3}/750 \text{ GeV} \\
 M_1 &= M_{\tilde{Q}_3} - 75 \text{ GeV} \\
 M_2 &= 1 \text{ TeV}, M_3 = 2.5 \text{ TeV} \\
 A_t &= A_b = A_\tau = 0.65 M_{\tilde{Q}_3}
 \end{aligned}$$

⇒ exotic solution still viable!



$$\begin{aligned}
 M_{\tilde{Q}_3} &= M_{\tilde{U}_3} = 750 \text{ GeV} \\
 &\quad - 2(M_{H^\pm} - 150 \text{ GeV}) \\
 M_{\tilde{L}_3} &= M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2 \text{ TeV} \\
 \mu &= [5.8 \text{ TeV} \\
 &\quad + 20(M_{H^\pm} - 150 \text{ GeV})] \times \\
 &\quad M_{\tilde{Q}_3}/750 \text{ GeV} \\
 M_1 &= M_{\tilde{Q}_3} - 75 \text{ GeV} \\
 M_2 &= 1 \text{ TeV}, M_3 = 2.5 \text{ TeV} \\
 A_t = A_b = A_\tau &= 0.65 M_{\tilde{Q}_3}
 \end{aligned}$$

⇒ large  $\text{BR}(H^\pm \rightarrow W^\pm h)$

### 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:

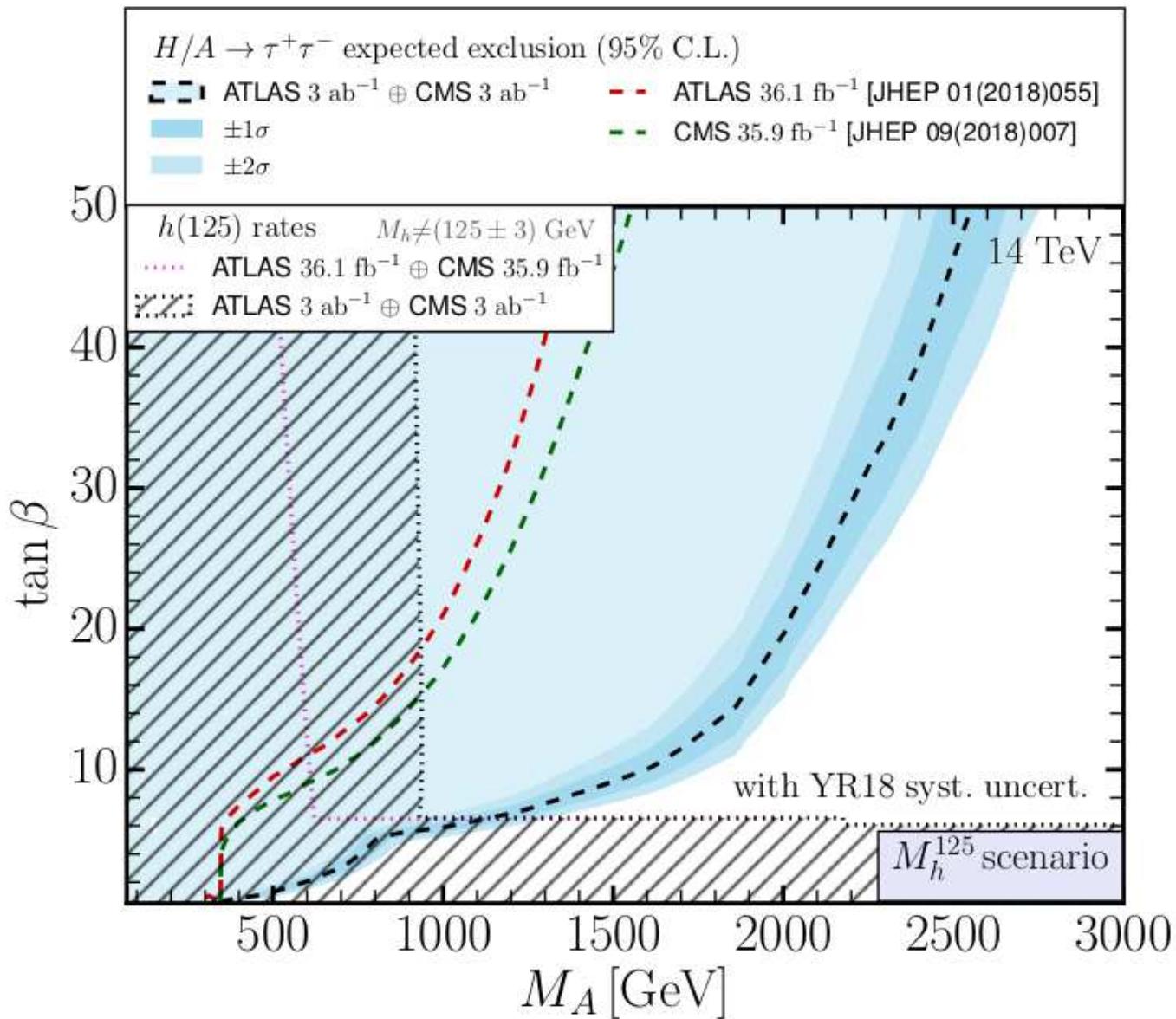
- will improve direct search limits
- will improve rate measurements (production  $\times$  decay)  
systematic/theory uncertainties: S2 scenario

[*M. Cepeda et al. '19 – YR18*]

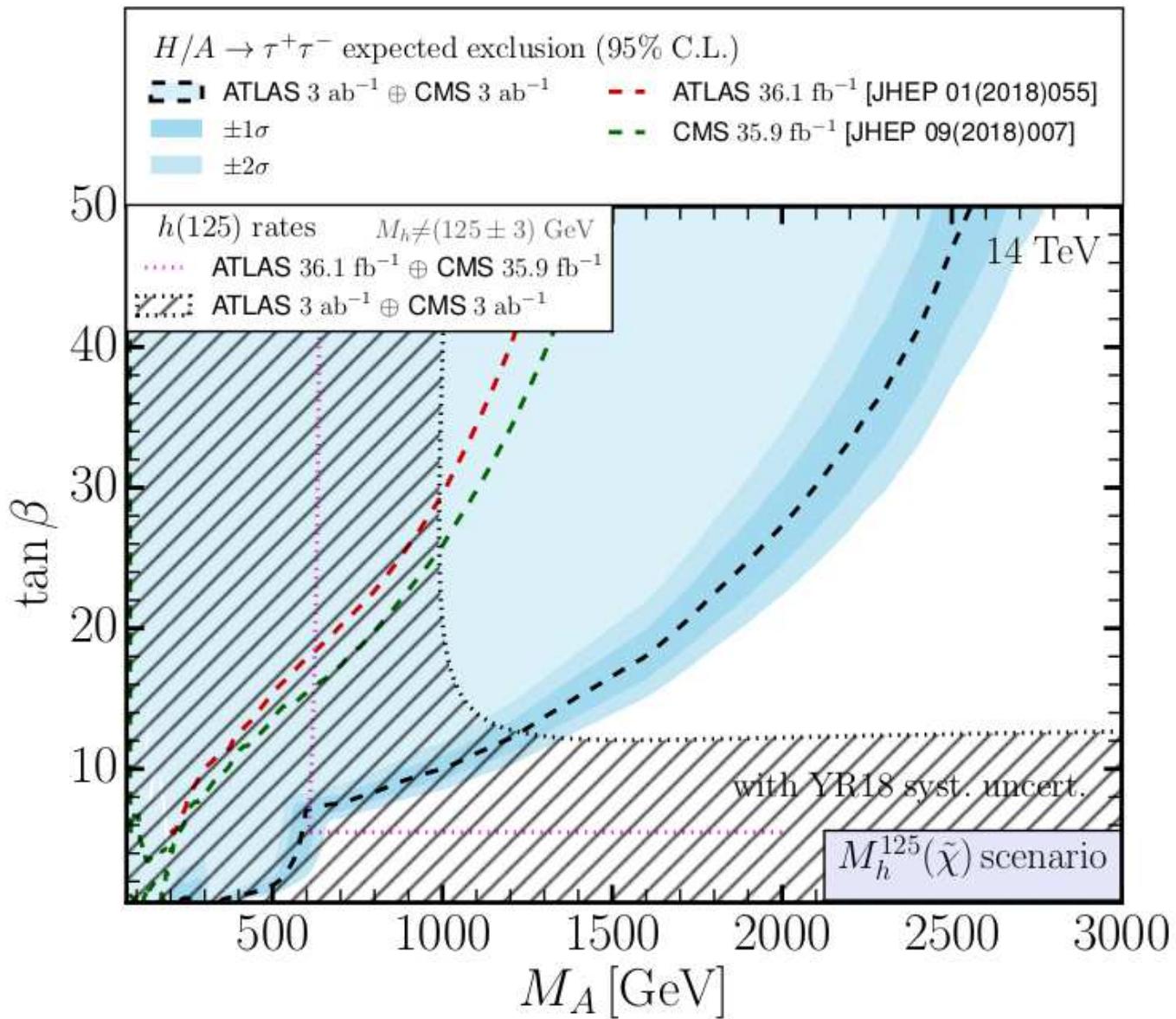
#### ILC:

- 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, K. Fujii, S. Jung, R. Karl, J. List, T. Ogawa, M. Peskin, J. Tian '17*]

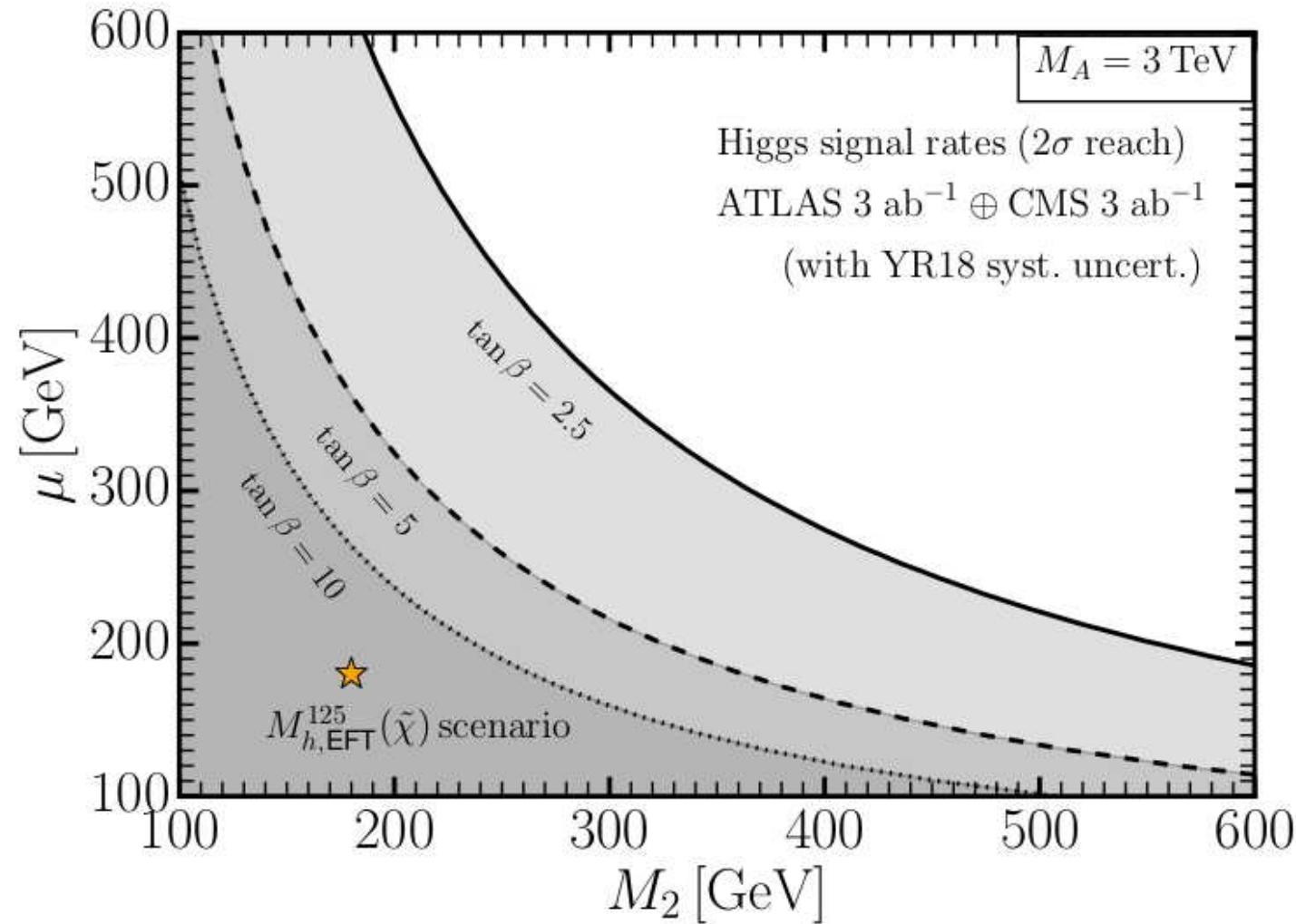


⇒ direct and indirect measurements:  $M_A \gtrsim 1200$  GeV



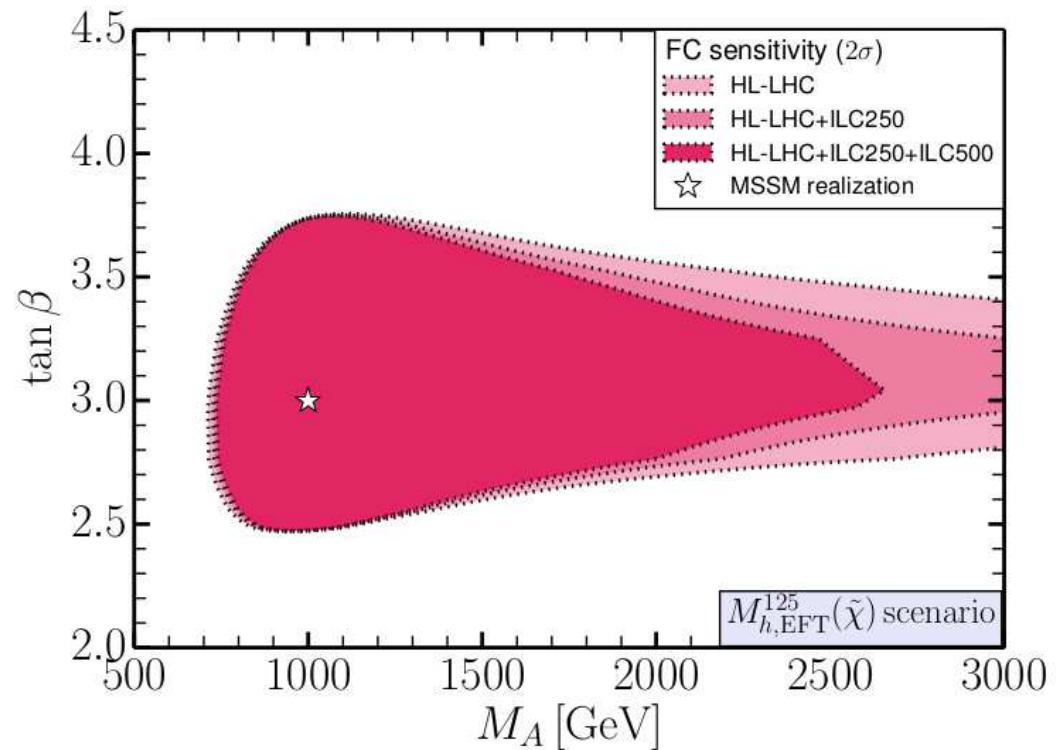
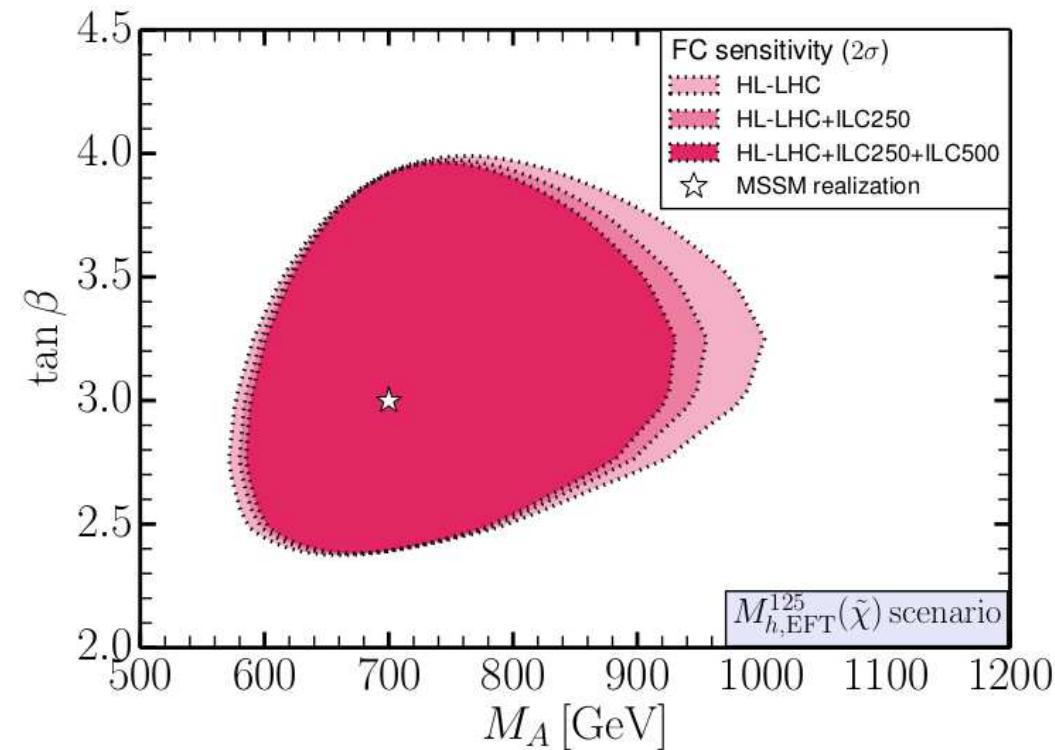
⇒ direct and indirect measurements:  $M_A \gtrsim 1200$  GeV

⇒ reach for charginos (mainly) via  $h \rightarrow \gamma\gamma$ :



⇒ strong reach for low  $\tan \beta$

- Assume a realization of an MSSM point
- What limits can be set from rate/coupling measurements?



⇒ small improvements for  $M_A = 700$  GeV

⇒ only ILC measurements give upper limit for  $M_A = 1000$  GeV

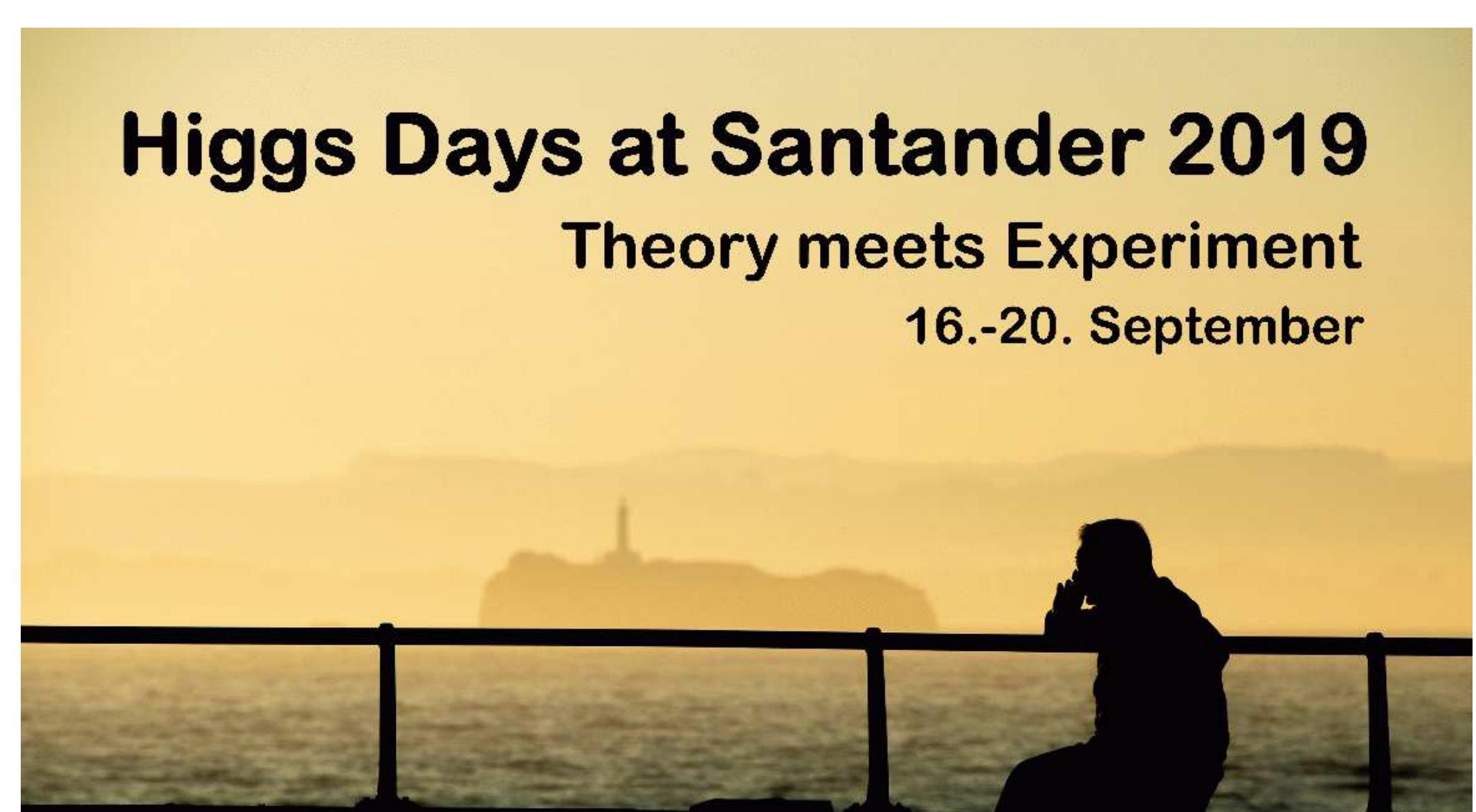
## 4. Conclusions

- SUSY is (still) the best-motivated BSM scenario
  - unconstrained MSSM: 105 new parameters
  - 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:
  - $M_h^{125}$  scenario: 2HDM-like model
  - $M_h^{125}(\tilde{\tau})$  scenario: light staus:  $h \rightarrow \gamma\gamma$ ,  $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
  - $M_h^{125}(\tilde{\chi})$  scenario: light EW-inos:  $H/A \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$
  - $M_h^{125}$  (alignment) scenario:  $h$  SM-like for very low  $M_A$
  - $M_H^{125}$  scenario:  $M_H \sim 125$  GeV, all Higgses light
  - $M_{h_1}^{125}$  (CPV) scenario: complex phases,  $h_2-h_3$  interference
- Implications for HL-LHC and ILC:
  - direct  $\oplus$  indirect HL-LHC reach:  $M_A \gtrsim 1200$  GeV
  - interesting reach for charginos via  $h \rightarrow \gamma\gamma$
  - **ILC measurements** can be crucial to set **upper limits** on  $M_A$

# Higgs Days at Santander 2019

## Theory meets Experiment

16.-20. September



EXCELENCIA  
SEVERO  
OCIOA



EXCELENCIA  
MARÍA  
DE MAEZTU



European  
Commission

Horizon 2020  
European Union funding  
for Research & Innovation



Instituto de  
Física  
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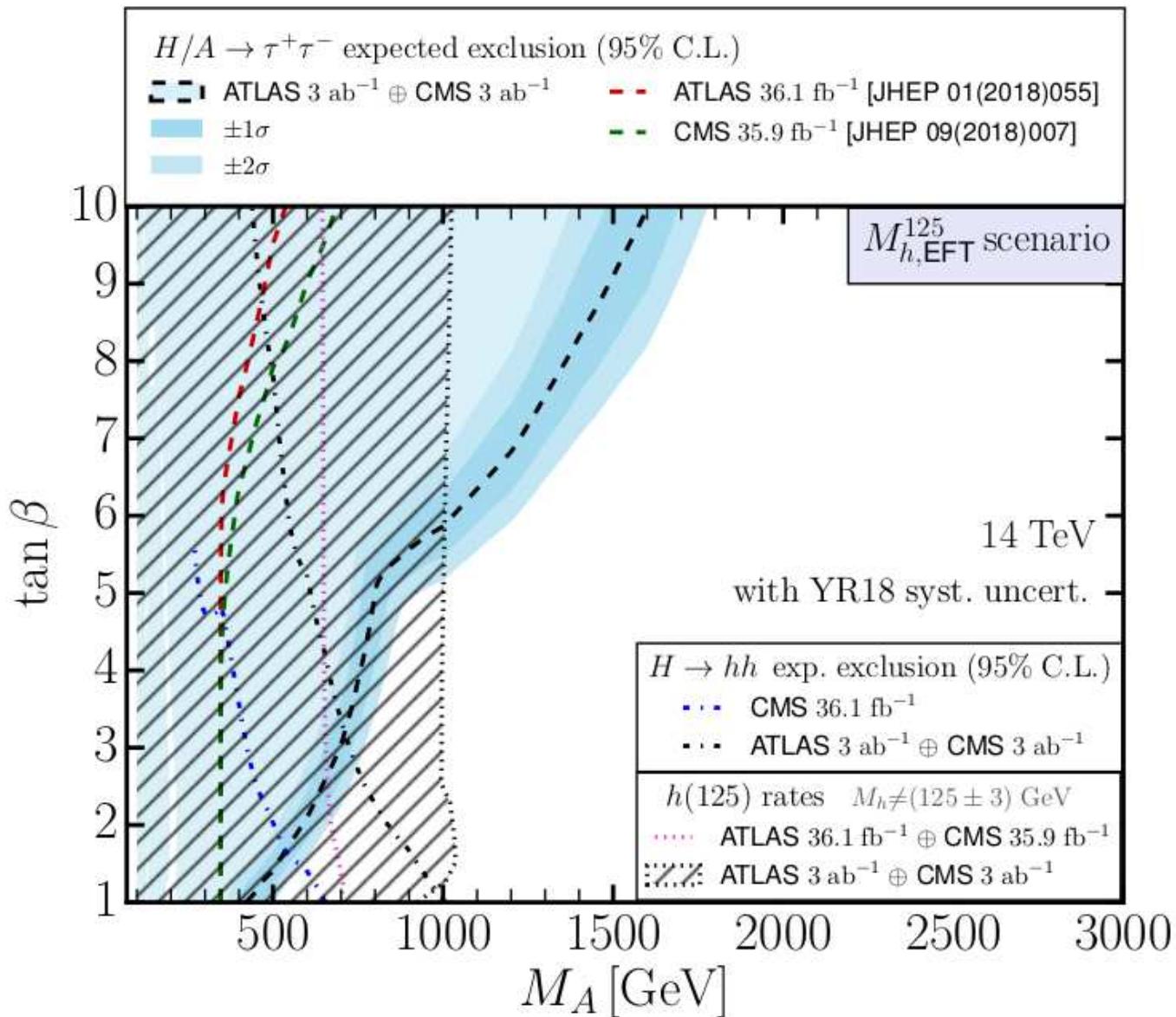
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Further Questions?



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