
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD
HM

LHC result interpretation in multi-Higgs SUSY models:
MSSM, NMSSM, hMSSM, . . .

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

Uppsala, 10/2016

- Introduction
- Relevance of SUSY Higgs Mass Calculations
- Higgs boson mass scales from rate measuements?
- MSSM results (CMSSM, NUHM1/2, hMSSM, pMSSM)
- NMSSM results
- Conclusions

1. Introduction

Fact:

The SM cannot be the ultimate theory!

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

⇒ Time to get ready for BSM physics

Which model should we focus on?

Some “recent” measurements:

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

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⇒ good motivation to look at SUSY! :-)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^\pm_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets ⇐ focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Data we have:

- Higgs boson mass (LHC)

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- Higgs boson signal strengths (LHC) $\Rightarrow$ HiggsSignals

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- electroweak precision data
- flavor data
- astrophysical data

2. Relevance of SUSY Higgs Mass Calculations

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS: $M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV

CMS: $M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV

combined: $M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

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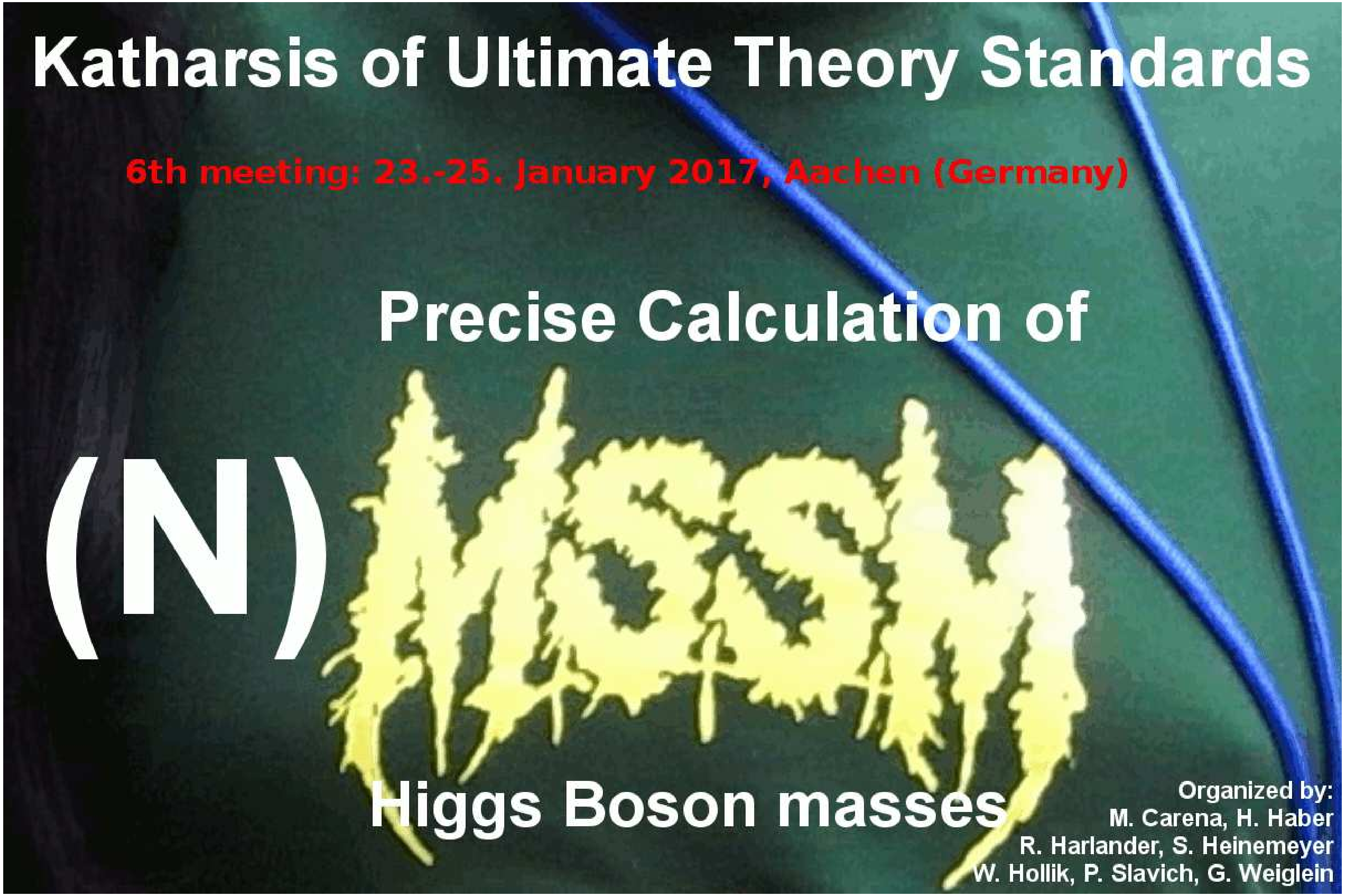
MSSM theory:

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV

→ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

Working group on M_h predictions: sites.google.com/site/kutsmh



Katharsis of Ultimate Theory Standards

6th meeting: 23.-25. January 2017, Aachen (Germany)

Precise Calculation of

(N)MSSM

Higgs Boson masses

Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

Enlarged Higgs sector: Two Higgs doublets

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

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

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)

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

$\tilde{t}$ sector of the MSSM:

Stop mass matrices

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

with

$$X_t = A_t - \mu / \tan\beta$$

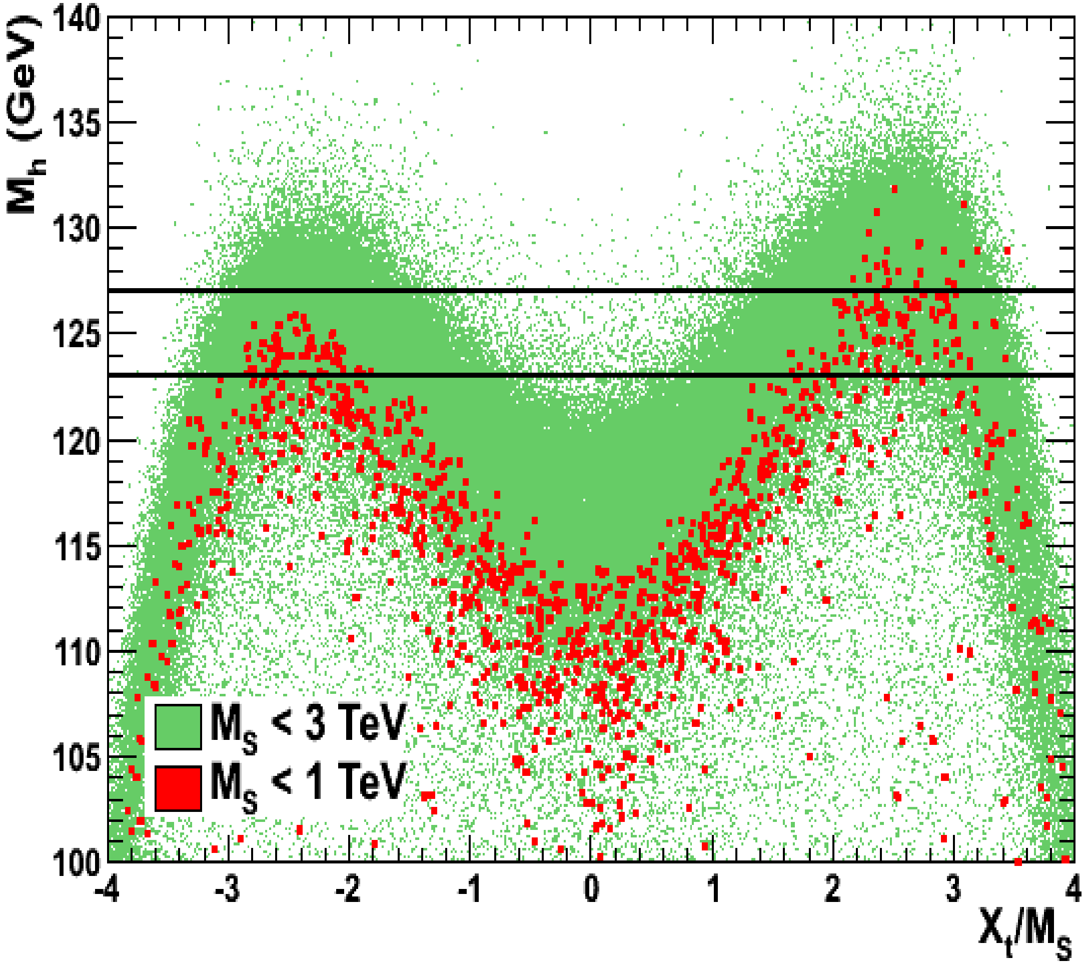
⇒ mixing important in stop sector!

Simplifying abbreviation:

$$M_{\text{SUSY}} := M_{\tilde{t}_L} = M_{\tilde{t}_R}$$

Stop masses vs. $M_h = 125$ GeV

[A. Arbey et al., '11]



$\Rightarrow$ $M_h \sim 125$ GeV requires large X_t and/or large M_{SUSY}

$\Rightarrow$ results depend strongly on your M_h calculation/precision!

Tree-level result for m_h, m_H:

$$m_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

For this workshop:

$$\boxed{m_{\mathrm{H}^\pm}^2 = M_A^2 + M_W^2}$$

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

Method I:

Higher-order corrections in the Feynman diagrammatic method:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
(→ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

$\Rightarrow$ complex roots of det$(M_{hH}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

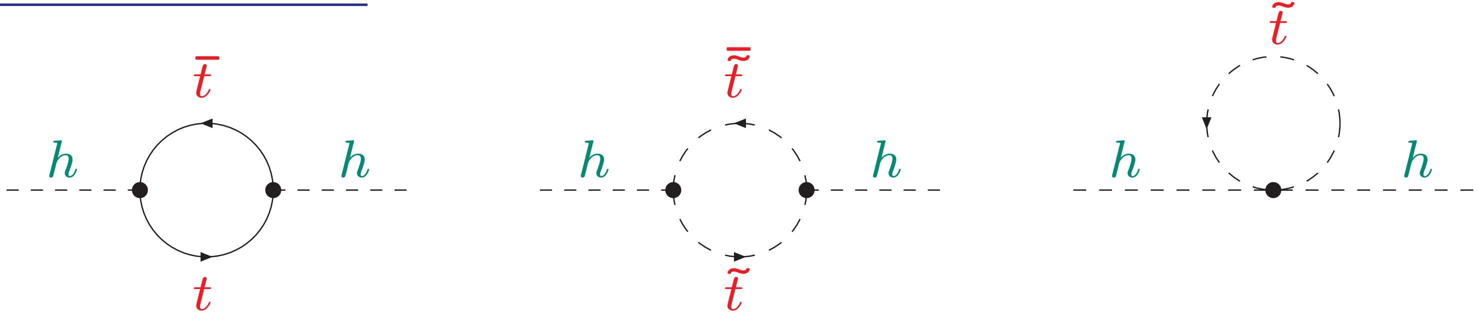
Calculation of renormalized Higgs boson self-energies:

$\hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots$ ⇒ Heidi's talk

all MSSM particles contribute

main contribution: $t/\tilde{t}$ sector ($\tilde{t}$: scalar top, SUSY partner of the t)

Very leading 1-Loop:



2-Loop:

To avoid large corrections:

On-shell renormalization of the scalar top sector ⇒ X_t^{OS}

$$\sim m_t^4 \left[\log^2 \left(\frac{m_{\tilde{t}}}{m_t} \right) + \log \left(\frac{m_{\tilde{t}}}{m_t} \right) \right]$$

Structure of higher-order corrections:

One-loop:

$$\Delta M_h^2 \sim m_t^2 \alpha_t \left[L + L^0\right] \ , \quad L := \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$$

Two-loop: $\Delta M_h^2 \sim m_t^2 \left\{\alpha_t \alpha_s \left[L^2 + L + L^0\right] + \alpha_t^2 \left[L^2 + L + L^0\right]\right\}$

Three-loop:

$$\begin{aligned}\Delta M_h^2 \sim m_t^2 \{ \quad & \alpha_t \alpha_s^2 \left[L^3 + L^2 + L + L^0\right] \\ & + \alpha_t^2 \alpha_s \left[L^3 + L^2 + L + L^0\right] \\ & + \alpha_t^3 \left[L^3 + L^2 + L + L^0\right] \}\end{aligned}$$

Partial results: [S. Martin '07]

[R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08] ⇒ *H3m*

H3m adds $\mathcal{O}\left(\alpha_t \alpha_s^2\right)$ corrections to *FeynHiggs*

Large $m_{\tilde{t}}$ ⇒ large L ⇒ resummation of logs necessary ⇒ Method **II**

Method II: EFT approach: Log resummation via RGE's:

Excellent overview paper: [*P. Draper, G. Lee, C. Wagner, arXiv:1312.5743*]

Simple example for log resummation:

SUSY mass scale: $M_{\mathrm{SUSY}} = M_{\mathrm{S}} \sim m_{\tilde{t}}$

Above M_{SUSY}: MSSM
Below M_{SUSY}: SM

Relevant SM parameters:
- quartic coupling λ
- top Yukawa coupling h_t ($\alpha_t = h_t^2/(4\,\pi)$)
- strong coupling constant g_s ($\alpha_s = g_s^2/(4\,\pi)$)

1. Take: $h_t(m_t), g_s(m_t)$

   SM RGEs for h_t, g_s: $h_t, g_s(m_t) \to h_t, g_s(M_{\mathrm{S}})$

2. Take $\lambda(M_{\mathrm{S}}), h_t(M_{\mathrm{S}}), g_s(M_{\mathrm{S}})$

   SM RGEs for λ, h_t, g_s: $\lambda, h_t, g_s(M_{\mathrm{S}}) \to \lambda, h_t, g_s(m_t)$

3. Evaluate M_h^2

$$M_h^2 \sim 2\lambda(m_t)v^2$$

Method I ⊕ II: Combination of FD and RGE result

$$\Delta M_h^2 = (\Delta M_h^2)^{\mathsf{RGE}}(X_t^{\overline{\mathsf{MS}}}, M_S^{\overline{\mathsf{MS}}}, \overline{m}_t) - (\Delta M_h^2)^{\mathsf{FD,LL1,LL2}}(X_t^{\mathsf{OS}}, M_S^{\mathsf{OS}}, \overline{m}_t)$$

$$M_h^2 = (M_h^2)^{\mathsf{FD}} + \Delta M_h^2$$

Technical aspect:

$$(\Delta M_h^2)^{\mathsf{FD,LL1,LL2}}(X_t^{\mathsf{OS}}, M_S^{\mathsf{OS}}, \overline{m}_t)$$

$$:= (\Delta M_h^2)^{\mathsf{FD,LL1,LL2}}(X_t^{\overline{\mathsf{MS}}}, M_S^{\overline{\mathsf{MS}}}, \overline{m}_t)\Big|_{X_t^{\overline{\mathsf{MS}}} \to X_t^{\mathsf{OS}}, M_S^{\overline{\mathsf{MS}}} = M_S^{\mathsf{OS}}}$$

⇒ combination of best FD result with
resummed LL, NLL corrections for large $m_{\tilde{t}}$

⇒ most precise M_h prediction for large $m_{\tilde{t}}$ ⇒ FeynHiggs 2.10.0

[T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '13][H. Bahl, W. Hollik '16]

Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's
- Inclusion of gluino mass scale in RGE's
- Inclusion of EW effects in RGE's
- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
- "Two Higgs Doublet Model" below M_S
- Splitting in the scalar top sector
- ...

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- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
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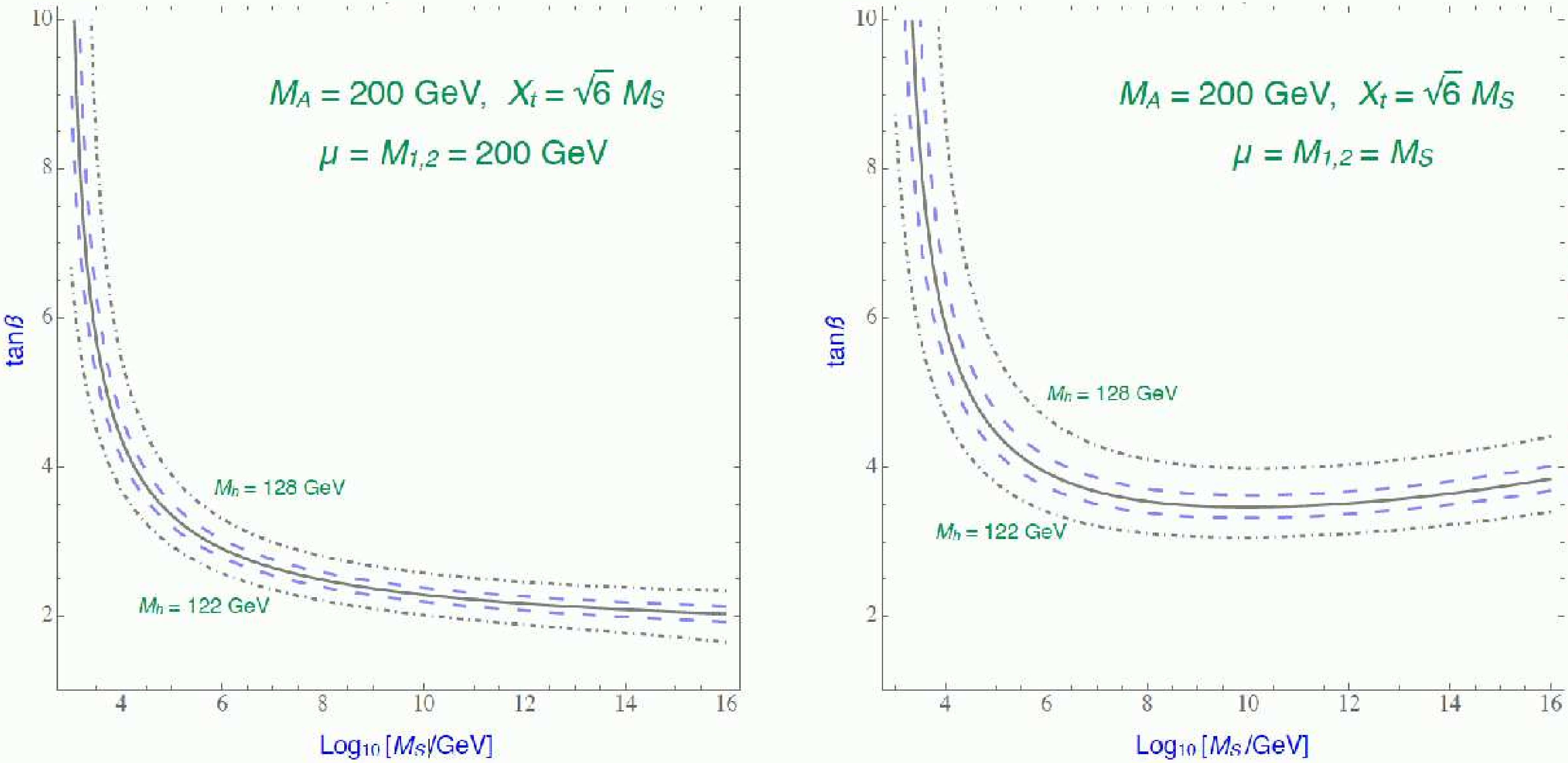
- "Two Higgs Doublet Model" below M_S
  ⇒ work in progress for FeynHiggs , only code so far: MhEFT

- Splitting in the scalar top sector
  ⇒ future work

- . . . ⇒ Heidi's talk

2HDM as low-energy theory: MhEFT



Lee+Wagner, 1508.00576

$\Rightarrow$ $M_h = 125$ GeV and low M_A, $\tan\beta$ cannot "everywhere" be realized!

$\Rightarrow$ impact for charged Higgses?!

Codes on the market:

1.) Fixed order codes: good for all scales low
- SuSpect
- SPheno/SARAH
- SoftSUSY/FlexibleSUSY
- H3m

2.) EFT codes: good for all scales high
- SusyHD
- MhEFT
- HSSUSY

3.) Hybrid codes: good always?!
- FeynHiggs
- FlexibleEFTHiggs

Obviously: quality depends on the details implemented

3. Higgs boson mass scales from rate measuements?

We have a $\sim$ 125 GeV SM-like Higgs boson

$\Rightarrow$ What are the options?

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

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

3. Heavy Higgs SM-like: (see above!)
   $\Rightarrow$ is the case with the heavy $\mathcal{CP}$-even Higgs being SM-like still a viable solution?

Obtaining a light Higgs with SM-like couplings

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

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

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

⇒ $\mathcal{CP}$-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, $c_{\beta-\alpha} = 0$
$Z_6 = 0$ and $Z_1 > Z_5 + M_A^2/v^2$
$\Rightarrow$ 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 $m_h^{\rm alt}$:

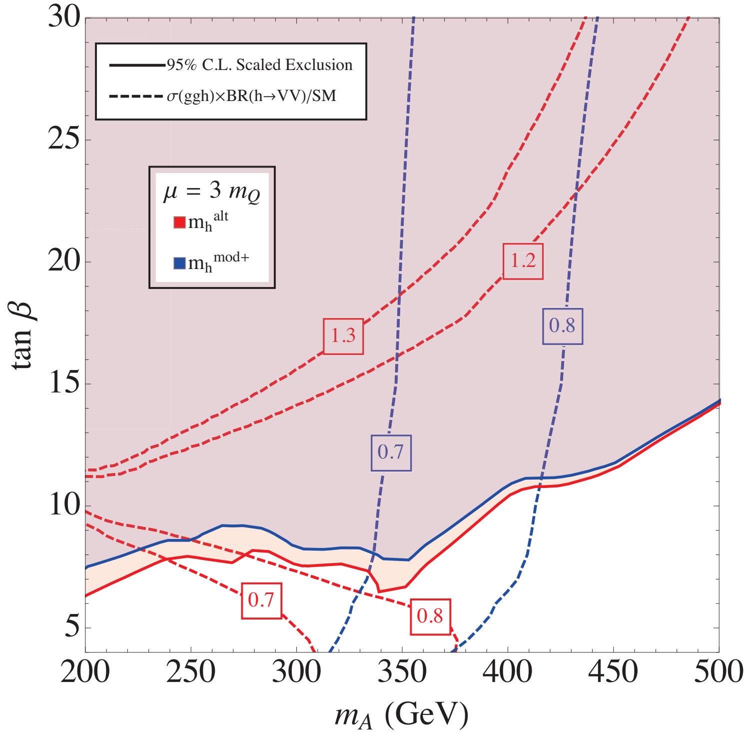
$A_t/M_S = 2.45,\ A_t = A_f$,

$M_S = m_{\tilde f} \geq 1$ TeV, $m_{\tilde g} = 1.5$ TeV,

$M_2 = 2\,M_1 = 200$ GeV, μ adjustable

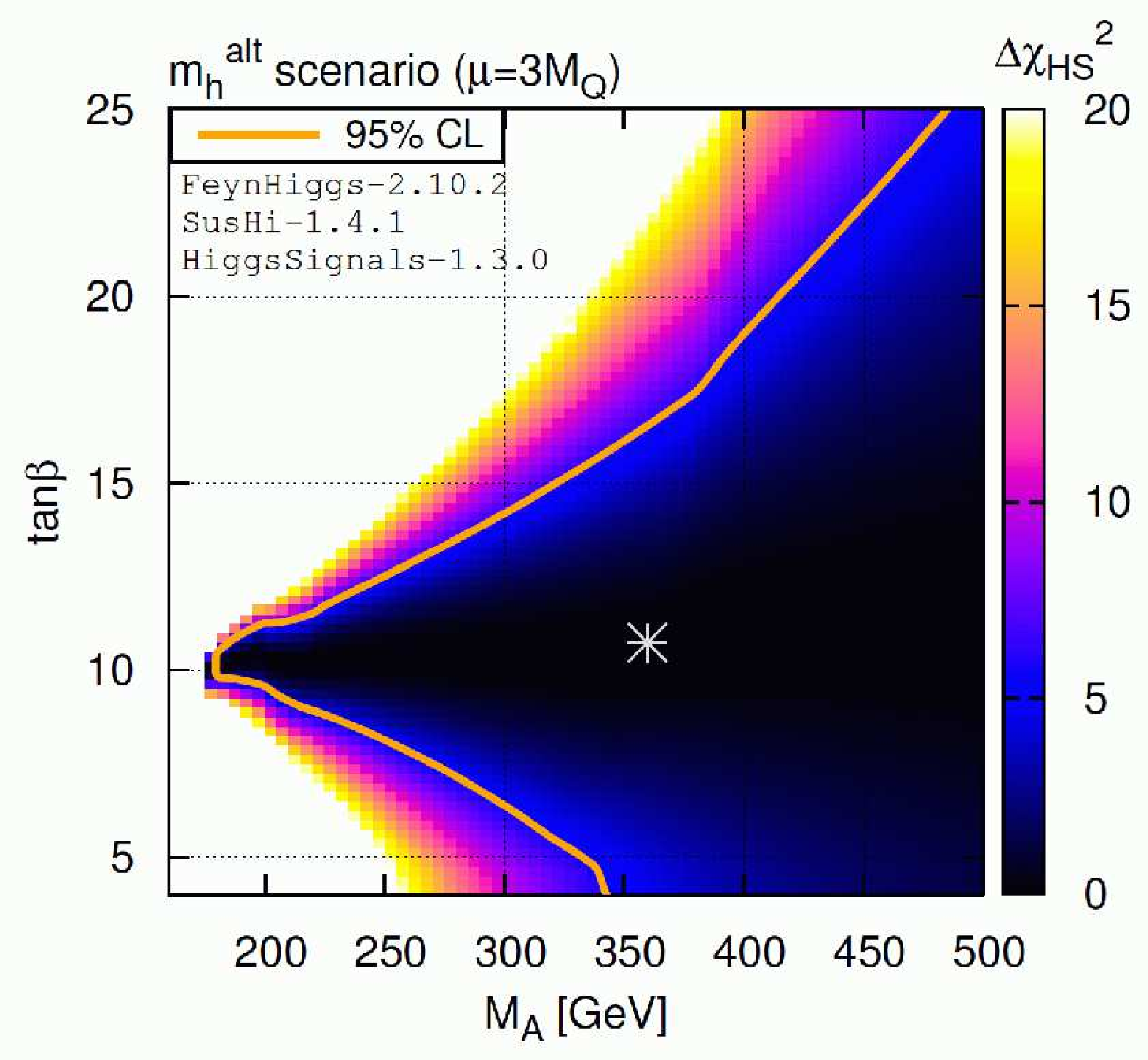
(low M_A and $\tan\beta$: tune $M_S \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

⇒ SM-like Higgs for all M_A



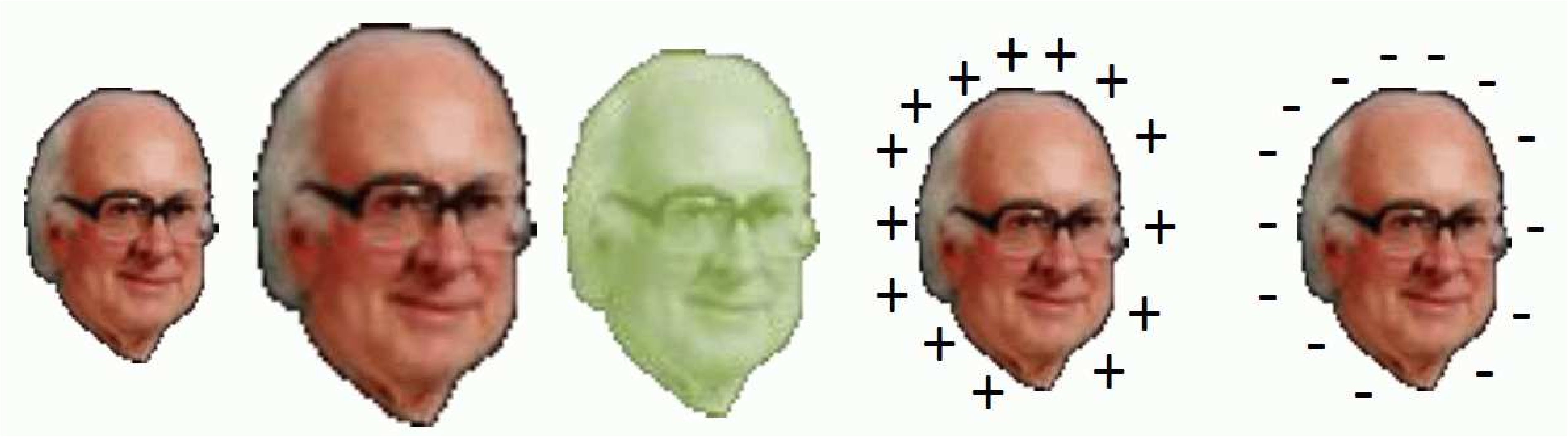
Preferred $m_h^{\rm alt}$ parameter space from HiggsSignals:

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '15]



⇒ no Higgs mass scale restrictions from rates (in general)

4. Results in the MSSM



MSSM versions:

CMSSM: m_0, $m_{1/2}$, A_0, $\tan\beta$ (+sign μ)

NUHM1: m_0, $m_{1/2}$, A_0, $\tan\beta$, M_A or μ (+sign μ)

NUHM2: m_0, $m_{1/2}$, A_0, $\tan\beta$, M_A and μ (+sign μ)

hMSSM: $M_h = 125$ GeV, everything very heavy, except M_A

pMSSM8: 8 free parameters . . .

CMSSM, NUHM1, NUHM2 analysis: **MasterCode**

⇒ collaborative effort of theorists and experimentalists
[Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Lucio, Mallik, Marouche, Martinez Santos, Olive, Richards, Sakurai, Weiglein]

- (so far) one model: (MFV) MSSM

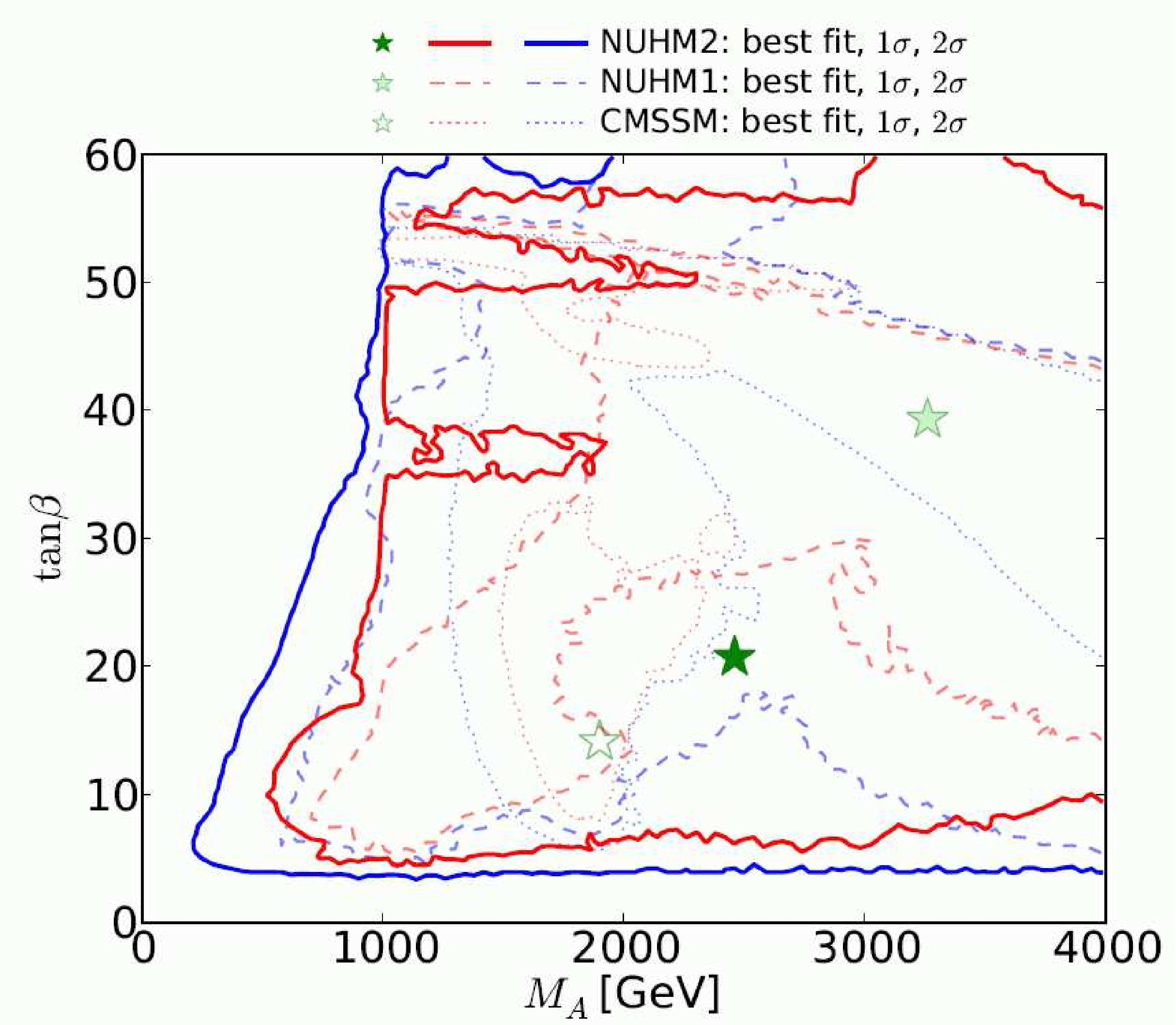
- tools included:
  - our own LHC SUSY search (Run I) implementation ⇒ NEW
    (3 search categories: colored, electroweak, compressed stop)
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Higgs signal strengths [*HiggsSignals*] ⇒ NEW
  - Higgs exclusion bounds [*HiggsBounds*] ⇒ NEW
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Electroweak precision observables [*FeynWZ*]
  - Dark Matter observables [*MicrOMEGAs, SSARD*]
  - for GUT scale models: RGE running [*SoftSusy*]

⇒ all most-up-to-date codes on the market!

⇒ crucial for precision!

M_A-tan β plane in CMSSM, NUHM1, NUHM2:

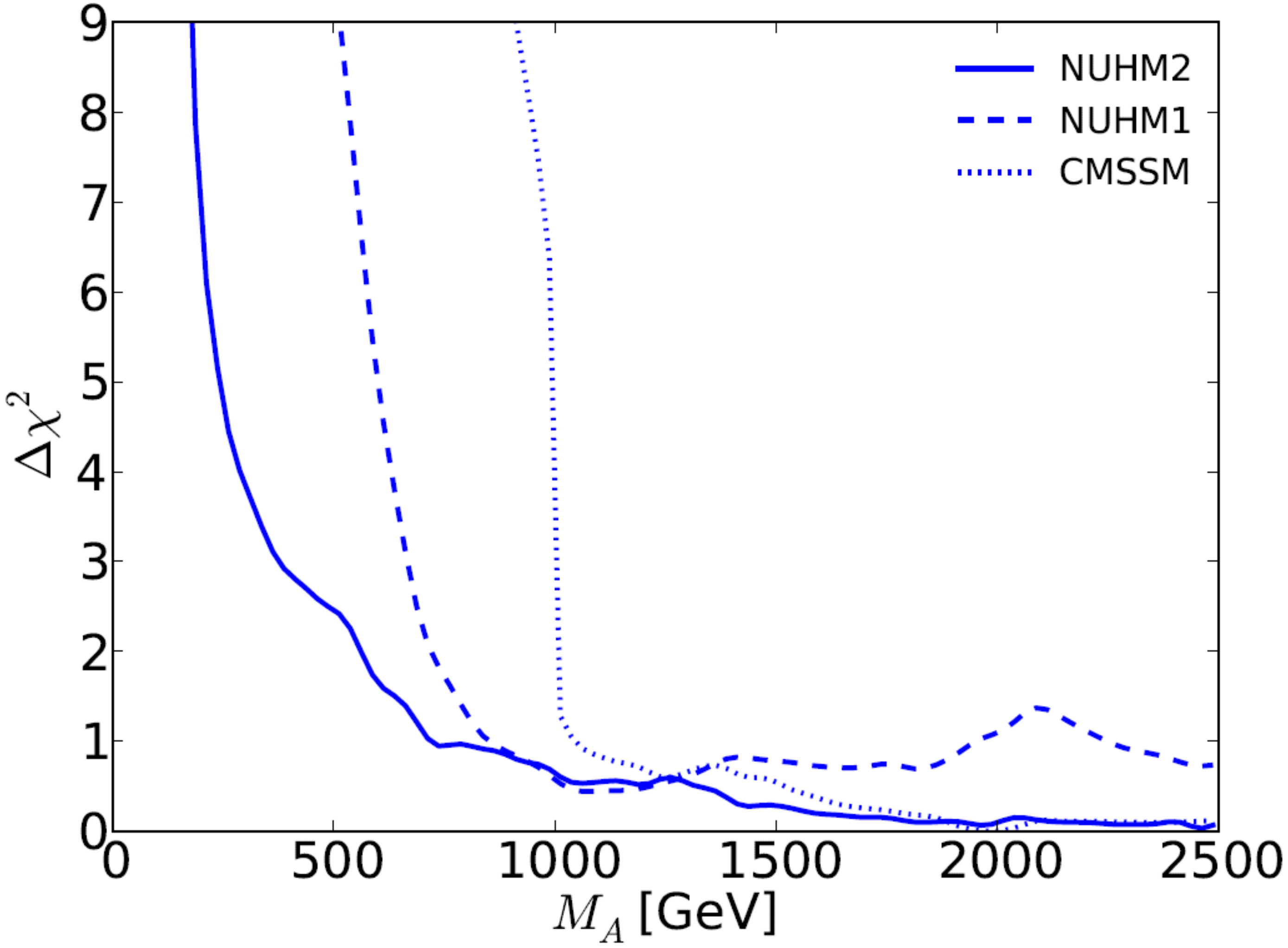
[2015]



⇒ high mass scales, only in NUHM2 lighter Higgs bosons . . .

M_A-$\Delta\chi^2$ in CMSSM, NUHM1, NUHM2:

[2015]



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hMSSM [A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevellion, V. Riquer '13]

Assumptions:

- MSSM
- $M_h = 125$ GeV
- only Higgs sector could be light, all SUSY particles heavy
  $\Rightarrow$ no SUSY effects in loops

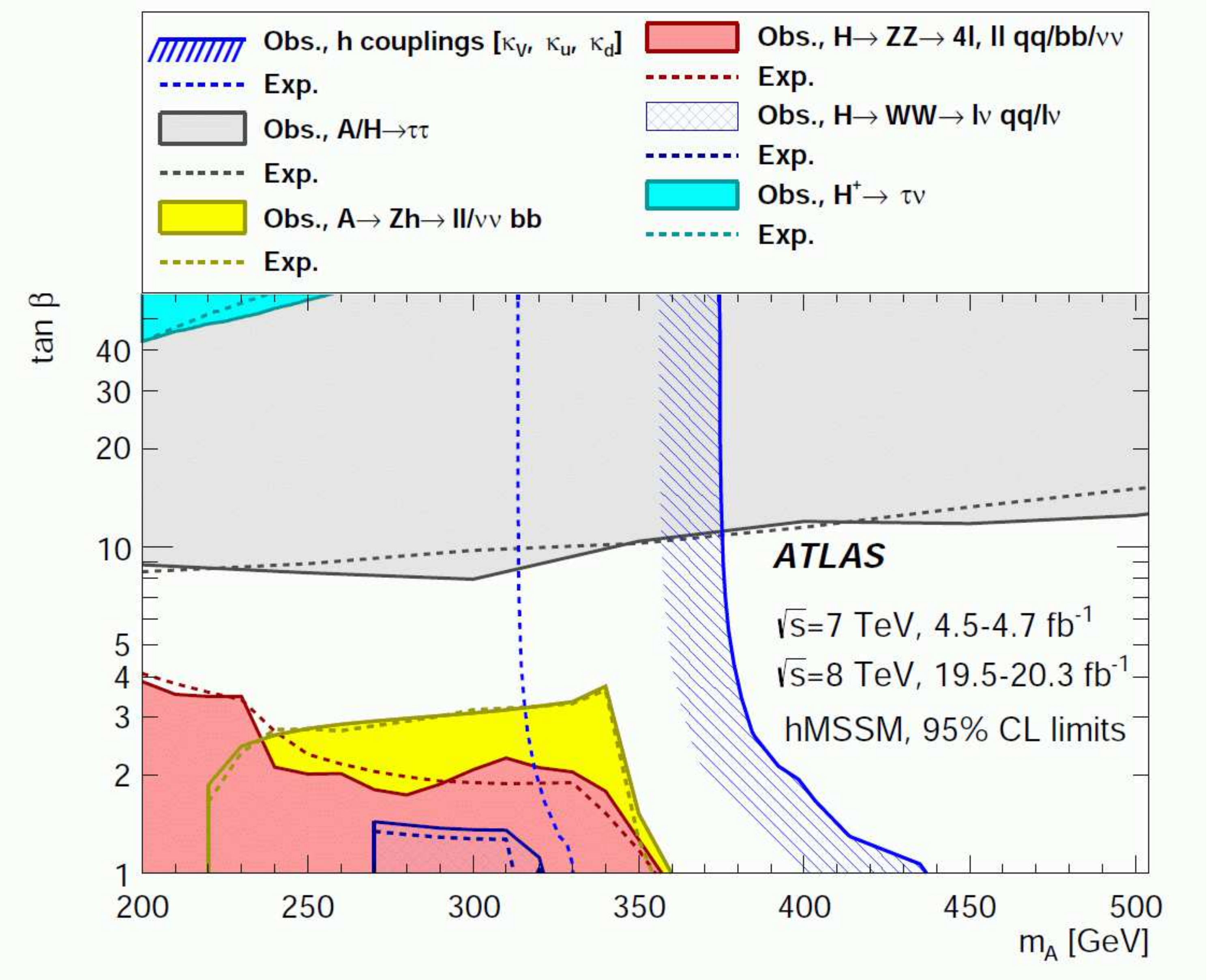
$\Rightarrow$ trade M_h for ΔM^2_{hH}
$\Rightarrow$ calculate M_H and α
$\Rightarrow$ calculate M_A and $M_{H^\pm}$ via tree-level formulas

What to expect?

- deviations in g_{hVV}, g_{htt} and g_{hbb}
- decoupling with M_A, nearly independent of $\tan\beta$

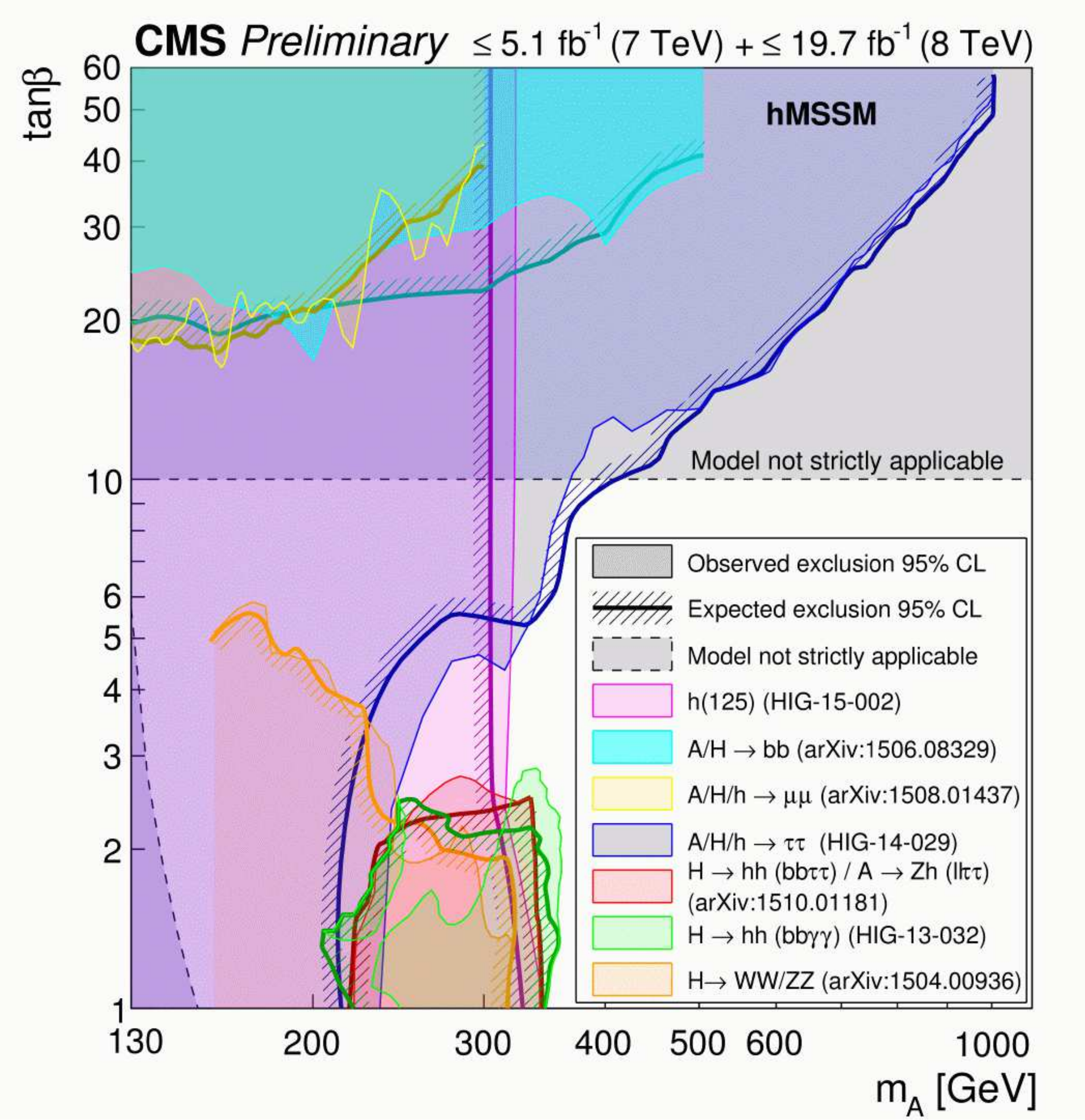
Personal opinion: a particularly boring scenario
$\Rightarrow$ hMSSM cannot be realized for low M_A and $\tan\beta$ (MhEFT)
$\Rightarrow$ Alignment without decoupling cannot be realized!

ATLAS results for the hMSSM



⇒ as expected...

CMS results for the hMSSM



⇒ as expected. . .

Results in the pMSSM8

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

- decoupling, $M_h = 125$ GeV
- alignment without decoupling, $M_h = 125$ GeV
- "heavy Higgs" case, $M_H = 125$ GeV, h lighter

	Min	Max
M_A	90 GeV	1000 GeV
$\tan\beta$	1	60
M_{Q_3}	200 GeV	5000 GeV
A_t	$-3M_{Q_3}$	$+3M_{Q_3}$
μ	$-3M_{Q_3}$	$+3M_{Q_3}$
M_{L_3}	200 GeV	1000 GeV
$M_{L_{1,2}}$	200 GeV	1000 GeV
M_2	200 GeV	500 GeV

$M_{Q_{1,2}} = M_{U_{1,2}} = M_{D_{1,2}} = 1.5$ TeV

$M_{D_3} = M_{U_3} = M_{Q_3}$

$M_{L_{1,2}} = M_{E_{1,2}}$

$A_b = A_\tau = A_t$

$M_3 = 1.5$ TeV

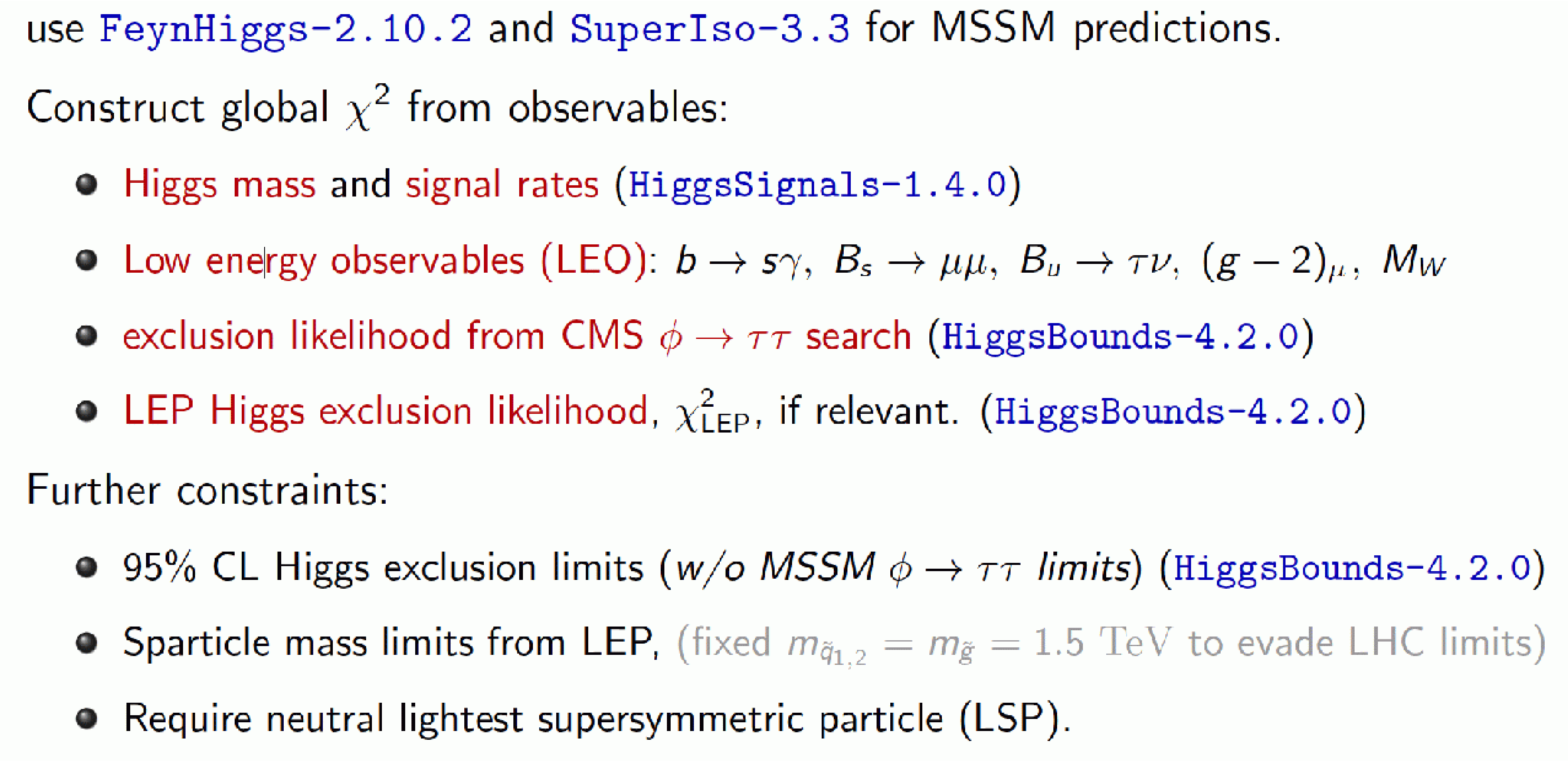
M_1 fixed by GUT relation

10^7 random points

$$R^{\phi}_{XX} := \frac{\Sigma_i[\sigma_i(\phi)\times \mathrm{BR}(\phi\to XX)]_{\mathrm{MSSM}}}{\Sigma_i[\sigma_i(\phi)\times \mathrm{BR}(\phi\to XX)]_{\mathrm{SM}}}$$

Our tools:

taken from [*T. Stefaniak*]



use FeynHiggs-2.10.2 and SuperIso-3.3 for MSSM predictions.

Construct global χ^2 from observables:

- Higgs mass and signal rates (`HiggsSignals-1.4.0`)
- Low energy observables (LEO): $b \to s\gamma$, $B_s \to \mu\mu$, $B_u \to \tau\nu$, $(g-2)_\mu$, M_W
- exclusion likelihood from CMS $\phi \to \tau\tau$ search (`HiggsBounds-4.2.0`)
- LEP Higgs exclusion likelihood, χ^2_{LEP}, if relevant. (`HiggsBounds-4.2.0`)

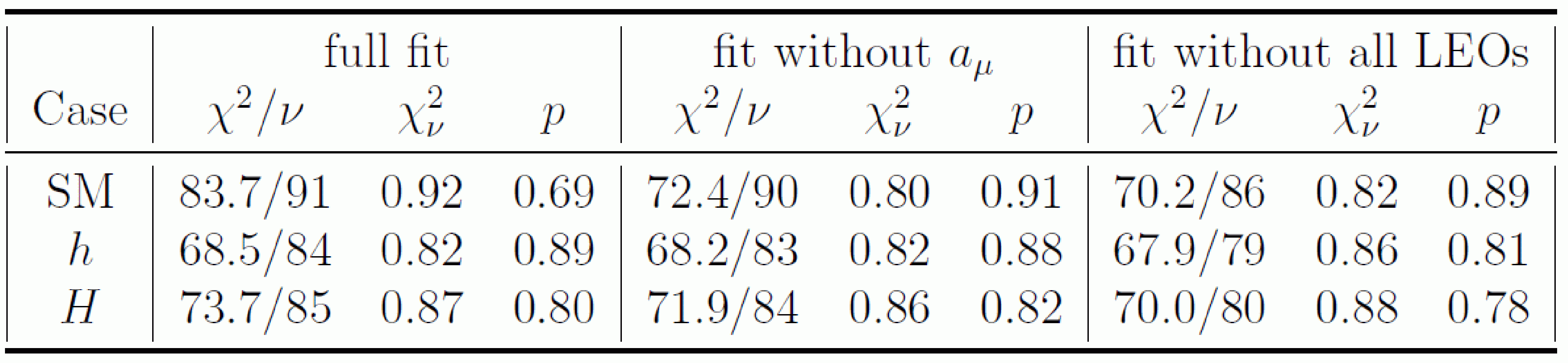
Further constraints:

- 95% CL Higgs exclusion limits (*w/o MSSM* $\phi \to \tau\tau$ *limits*) (`HiggsBounds-4.2.0`)
- Sparticle mass limits from LEP, (fixed $m_{\tilde{q}_{1,2}} = m_{\tilde{g}} = 1.5\ \mathrm{TeV}$ to evade LHC limits)
- Require neutral lightest supersymmetric particle (LSP).

Newly included: CheckMate to check SUSY exclusion limits

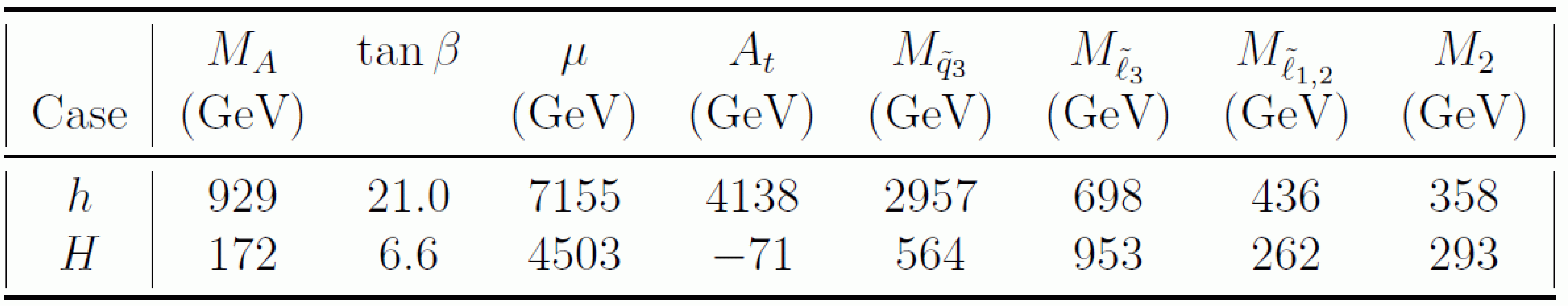
$\Rightarrow$ “naive” χ^2 calculation (heavily relying on HiggsSignals)

The best-fit points:



Case	full fit χ^2/ν	full fit χ^2_ν	full fit p	fit without a_μ χ^2/ν	fit without a_μ χ^2_ν	fit without a_μ p	fit without all LEOs χ^2/ν	fit without all LEOs χ^2_ν	fit without all LEOs p
SM	83.7/91	0.92	0.69	72.4/90	0.80	0.91	70.2/86	0.82	0.89
h	68.5/84	0.82	0.89	68.2/83	0.82	0.88	67.9/79	0.86	0.81
H	73.7/85	0.87	0.80	71.9/84	0.86	0.82	70.0/80	0.88	0.78

Best-fit points parameters:

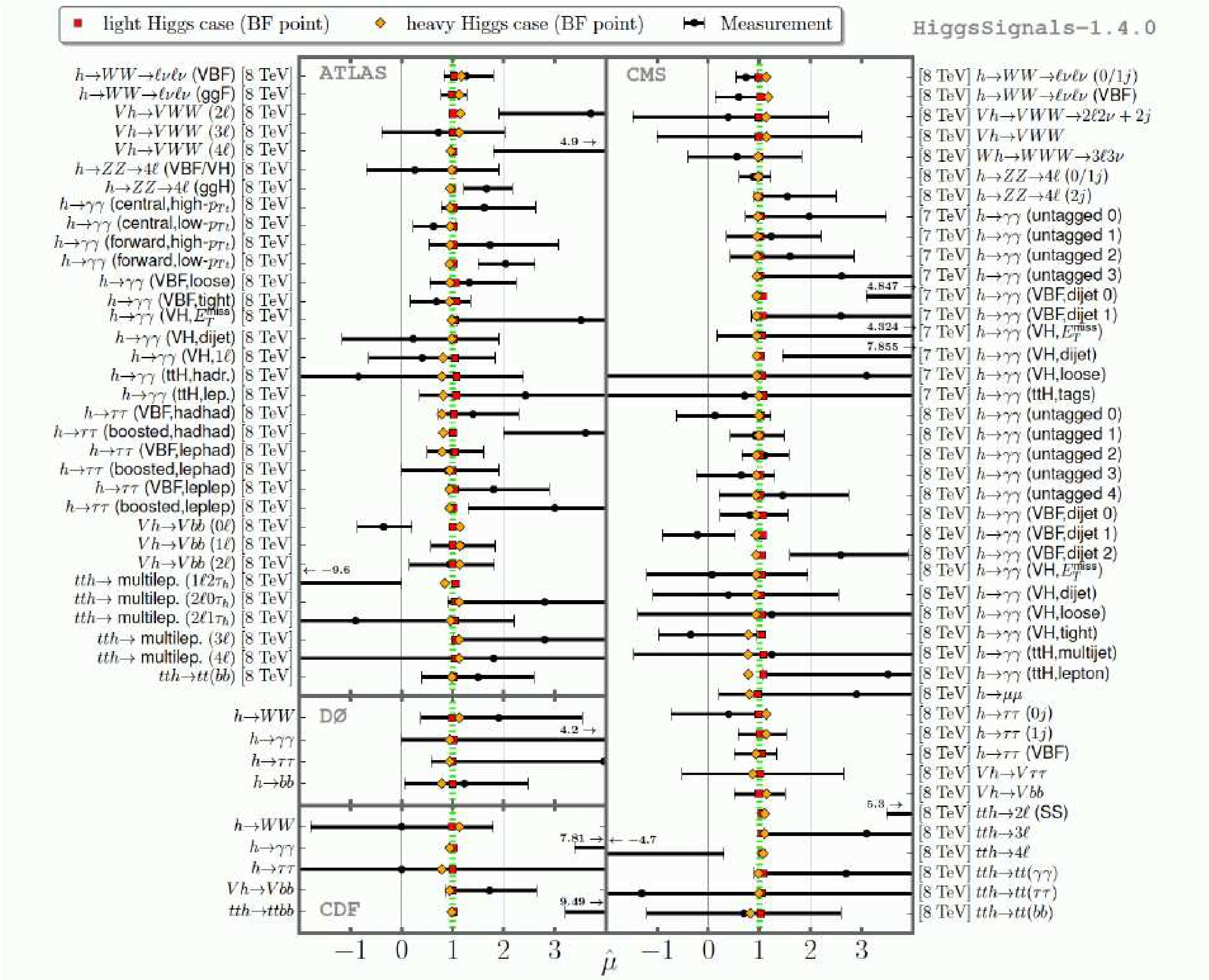


Case	M_A (GeV)	$\tan\beta$	μ (GeV)	A_t (GeV)	$M_{\tilde{q}3}$ (GeV)	$M_{\tilde{\ell}_3}$ (GeV)	$M_{\tilde{\ell}_{1,2}}$ (GeV)	M_2 (GeV)
h	929	21.0	7155	4138	2957	698	436	358
H	172	6.6	4503	−71	564	953	262	293

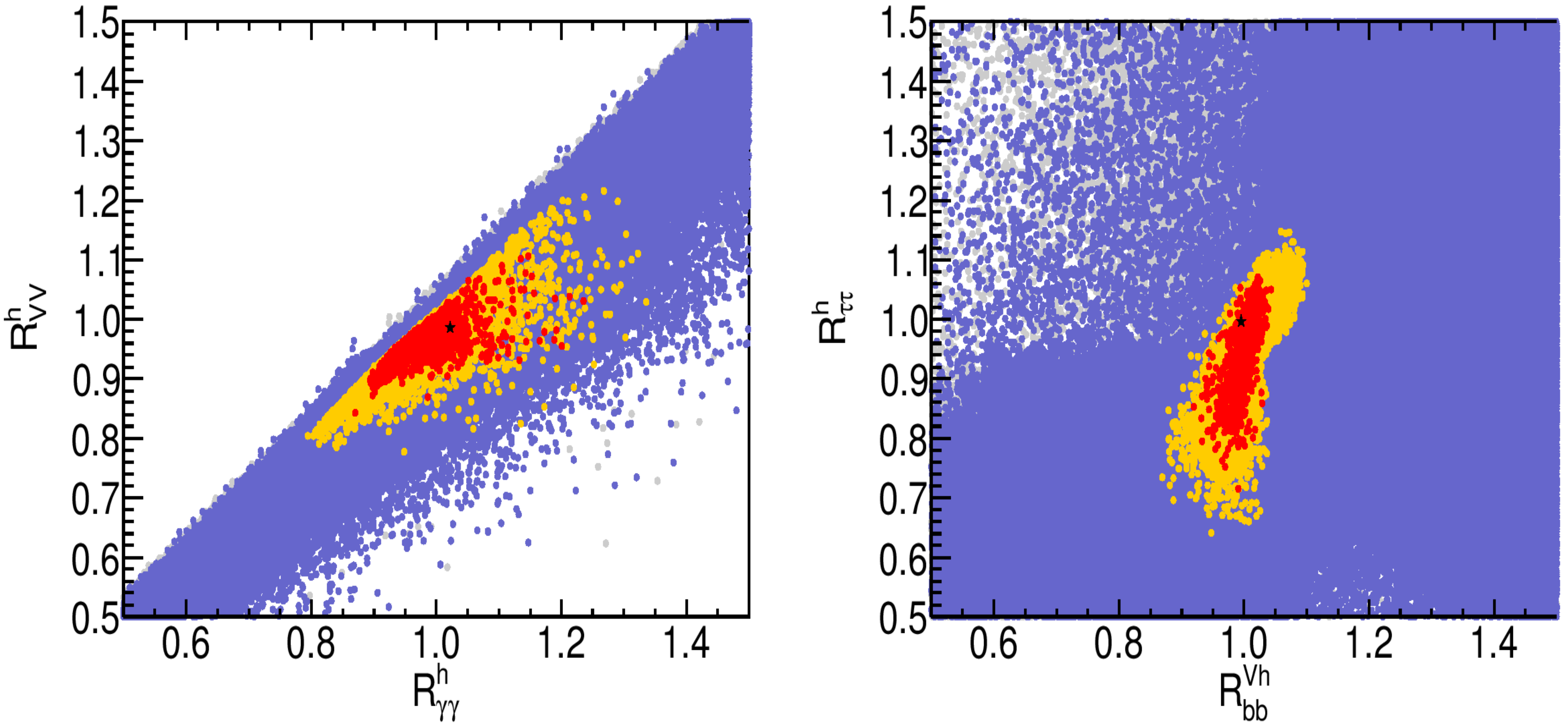
⇒ SM and both MSSM cases provide similar fit to the Higgs data

⇒ Including LEOs, SM fit becomes worse

Best-fit point rates in the two Higgs cases:



Light-Higgs case: preferred rates

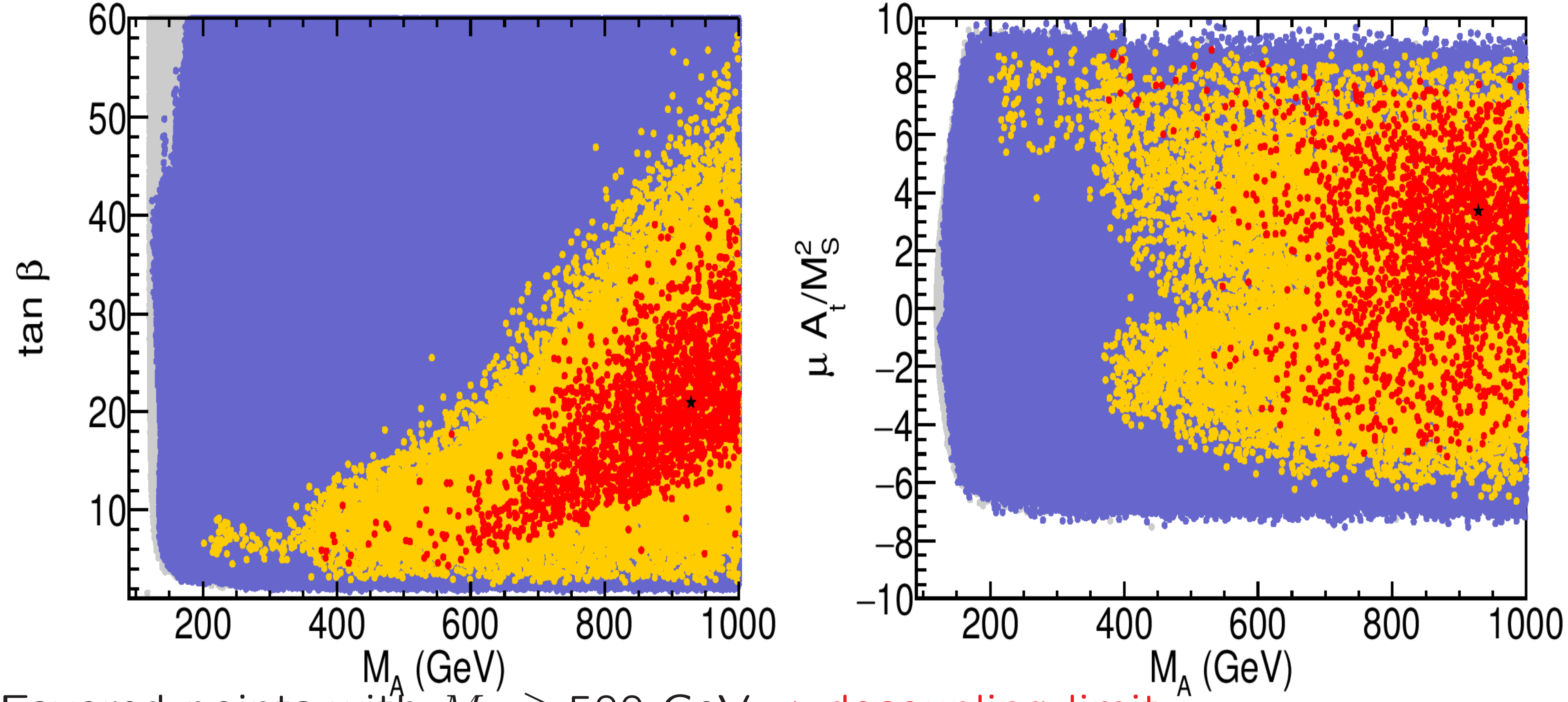


$$R^h_{VV} = 0.99^{+0.09}_{-0.08}, \quad R^h_{\gamma\gamma} = 1.02^{+0.16}_{-0.10}, \quad R^{Vh}_{bb} = 1.00^{+0.02}_{-0.05}, \quad R^h_{\tau\tau} = 1.00^{+0.06}_{-0.20}$$

⇒ all very SM-like (no surprise . . .)

⇒ but some (BSM) spread is allowed!

Light-Higgs case: preferred parameters



Favored points with $M_A \gtrsim 500$ GeV $\Rightarrow$ decoupling limit

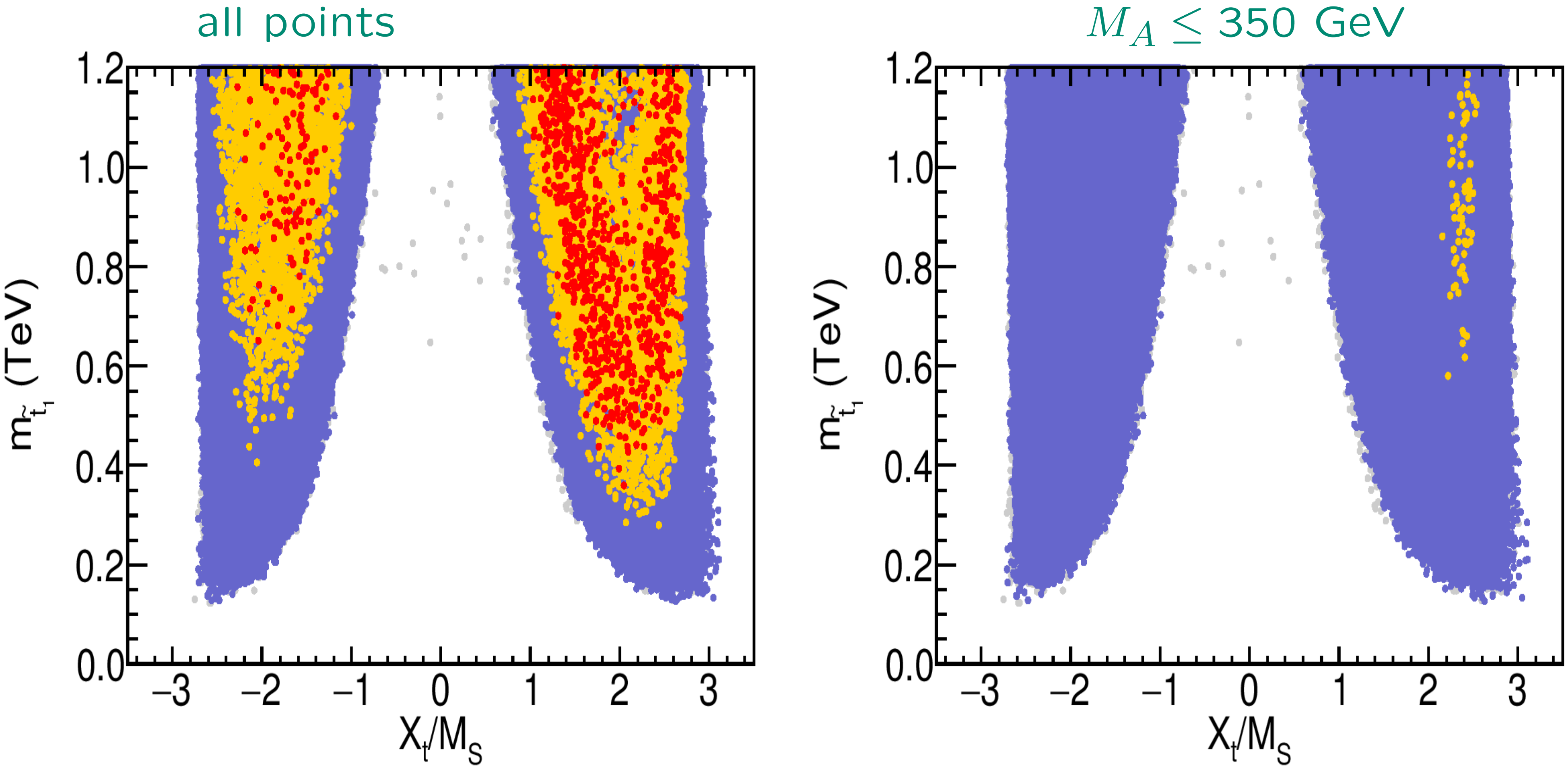
$M_A \gtrsim 200$ GeV $\Rightarrow$ alignment limit

Alignment: $\tan\beta \sim 1/\left[\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)\right]$

$\Rightarrow$ small(er) $\tan\beta$ needed to avoid $\tau\tau$ limits $\Rightarrow \mu A_t/M_S^2$ larger

$\Rightarrow$ positive A_t preferred (for $\mu > 0$)

Light-Higgs case: preferred parameters in the $\tilde{t}$ sector



⇒ light stops down to $m_{\tilde{t}_1} \sim 300$ GeV possible

(even lighter stops possible with $M_{\tilde{t}_L} \neq M_{\tilde{t}_R}$)

The "exotic" solution:
the discovery is interpreted as the heavy $\mathcal{CP}$-even Higgs

In principle also possilbe:

$$M_h < 125 \text{ GeV}$$
$$M_H \approx 125 \text{ GeV}$$

Consequences:

– all Higgs bosons very light
– easy(?) discovery of additional Higgs bosons at the LHC

Constraints:

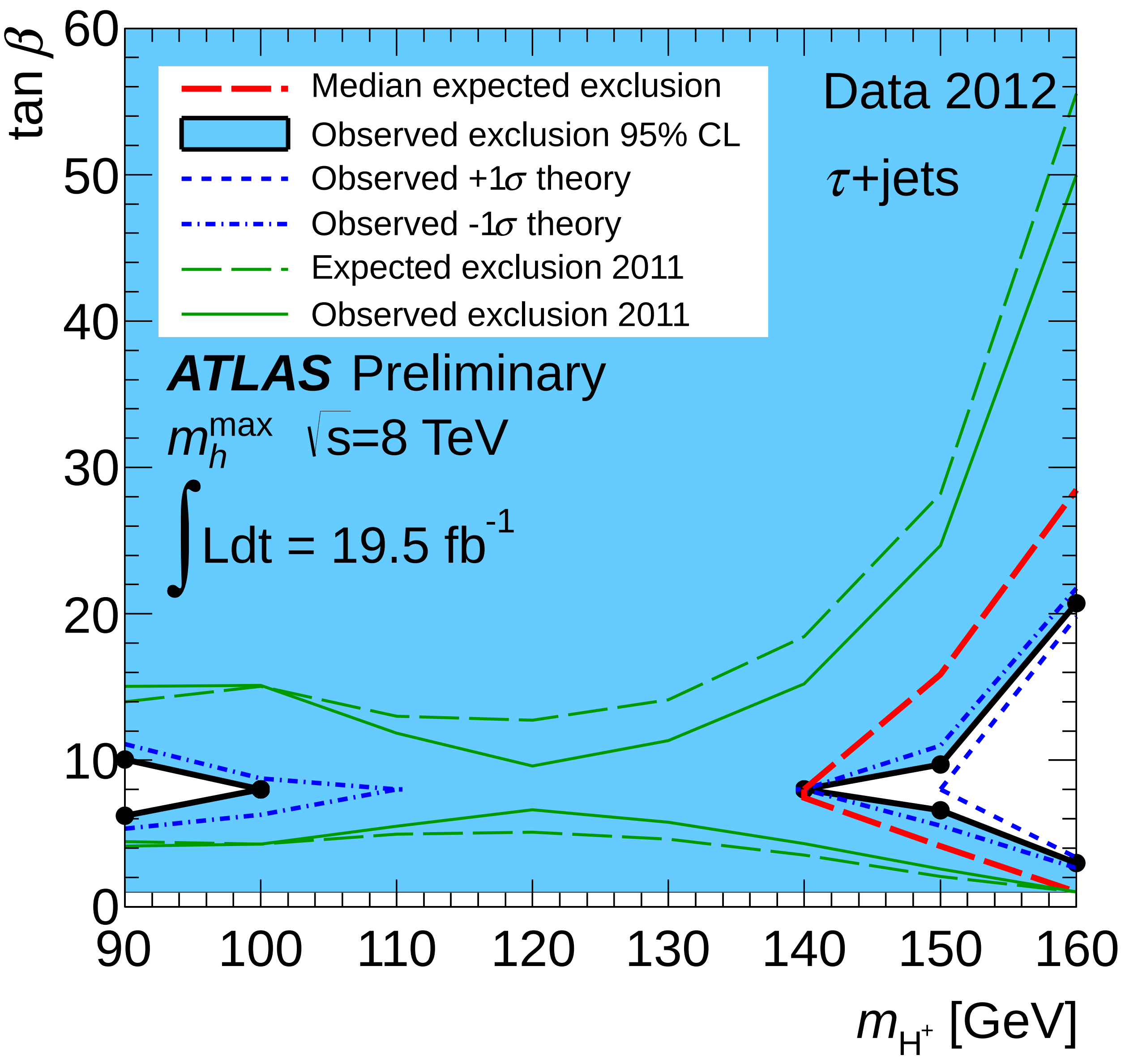
– direct searches for the lightest $\mathcal{CP}$-even Higgs
– direct searches for the heavy neutral Higgses
– direct searches for the charged Higgses
– flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

$\Rightarrow$ original scenario: low-M_H

[M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein '13]

ATLAS results for charged Higgs searches:

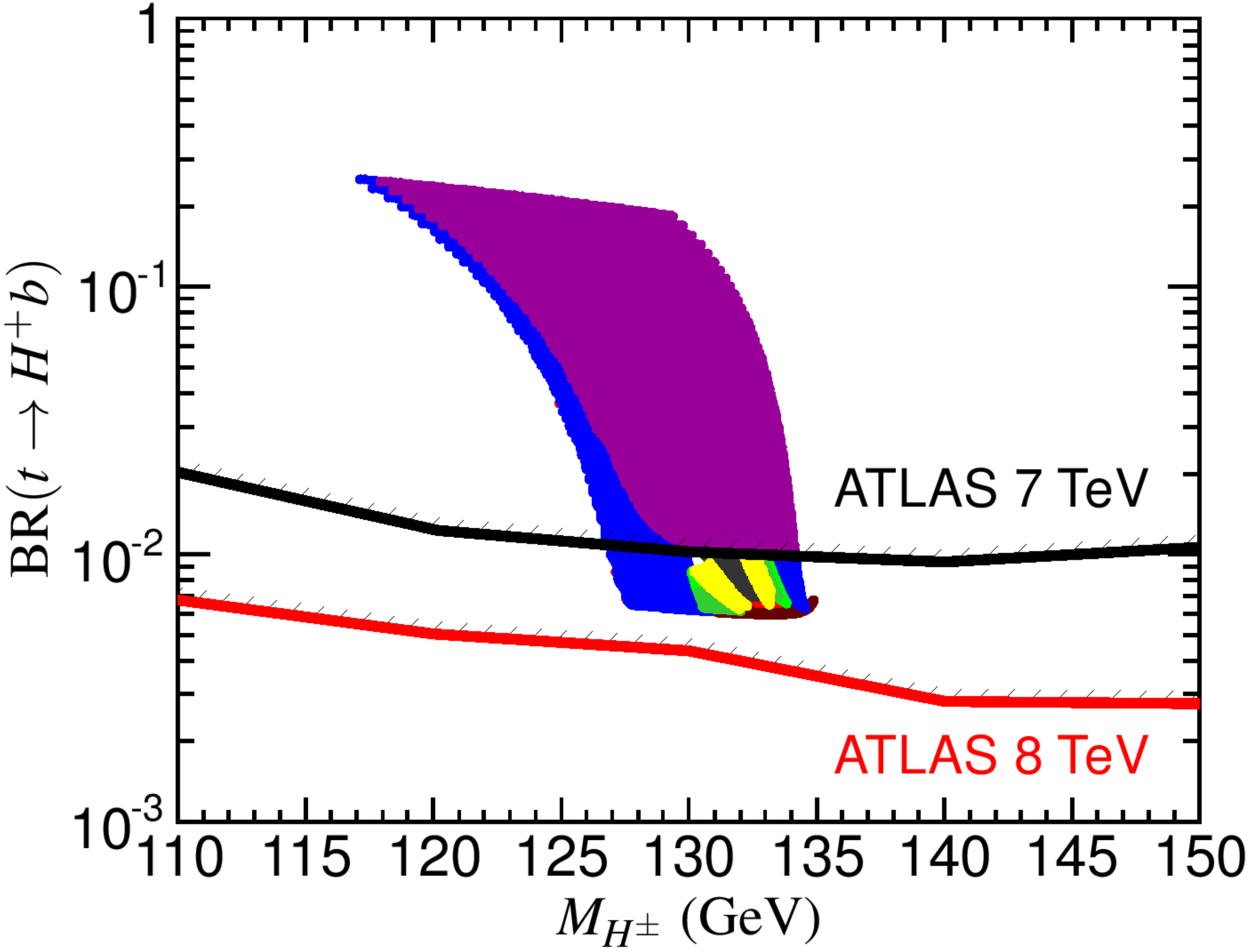
[ATLAS '13]



⇒ exclusion of light $M_{H^\pm}$ in the m_h^{max} scenario! . . . low-M_H?

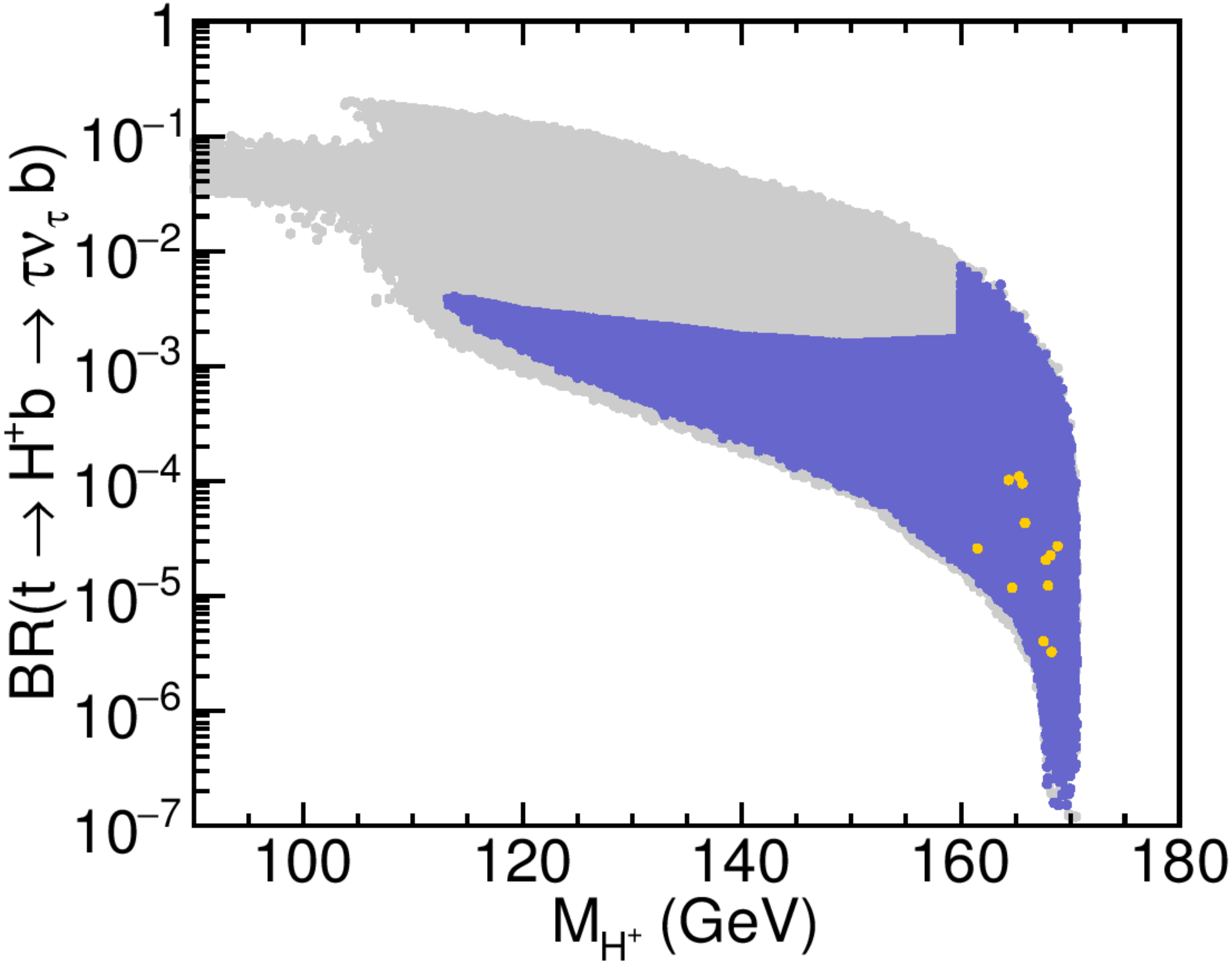
Application of charged Higgs limits on low-M_H scenario:

[*HiggsBounds 4.1*]



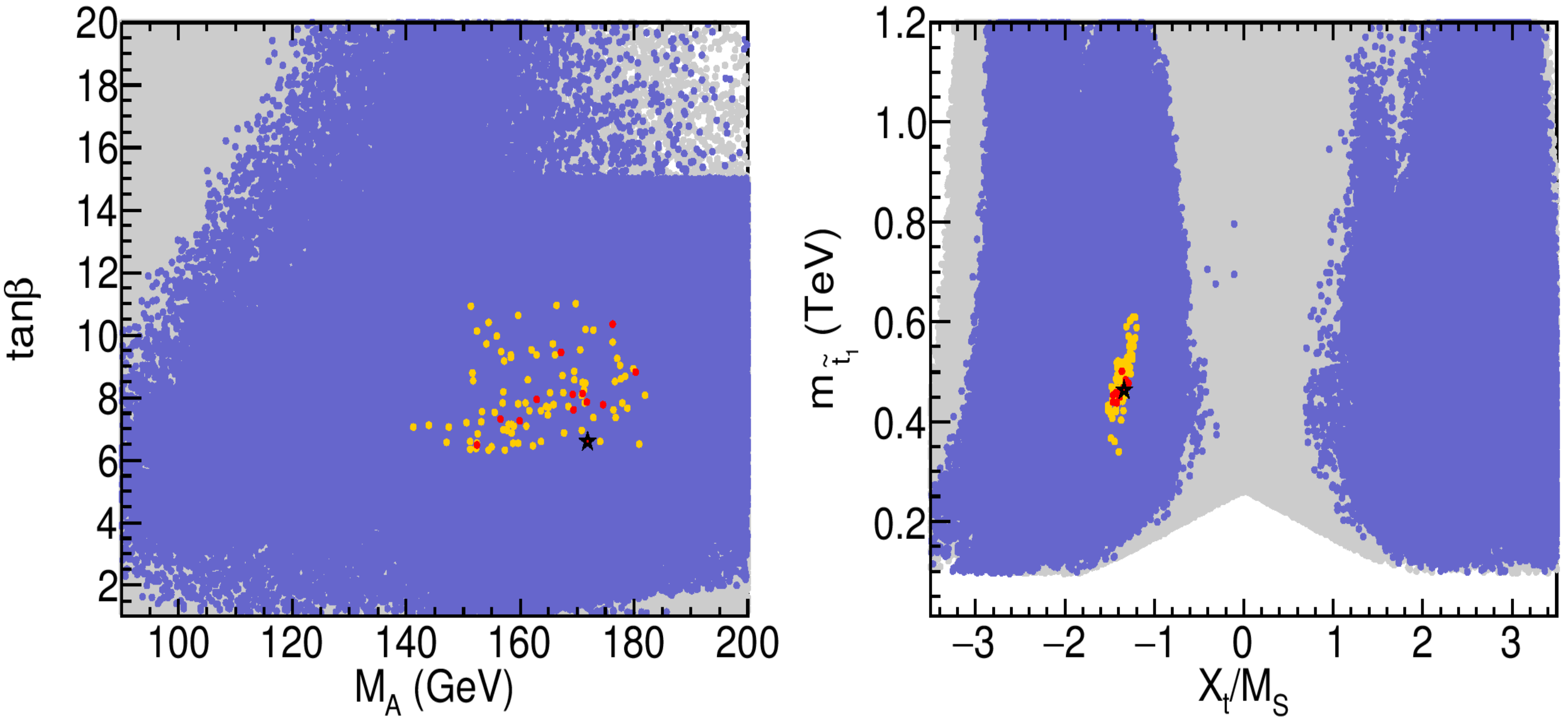
⇒ that (particular incarnation of the) low-M_H scenario is excluded!

How to avoid BR($t \to H^{\pm}b$) bounds: ⇒ higher $M_{H^{\pm}}$!



⇒ "tricky" region below and beyond the top threshold!

Heavy-Higgs case: preferred parameters



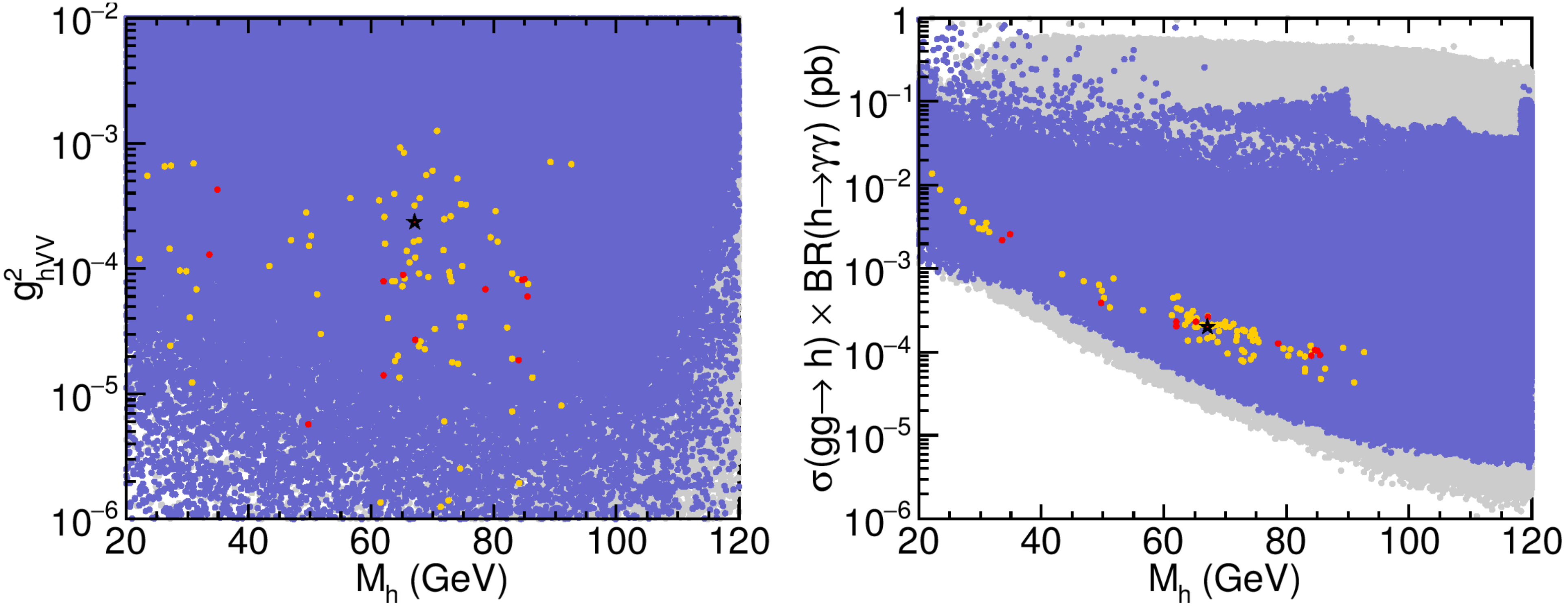
$\Rightarrow M_A \sim 140 \ldots 180$ GeV

$\Rightarrow m_{\tilde{t}_1} \sim 350 \ldots 650$ GeV

$R^h_{VV} = [0.95, 1.13]$, $R^h_{\gamma\gamma} = [0.81, 0.94]$, $R^{Vh}_{bb} = [0.94, 1.03]$, $R^h_{\tau\tau} = [0.78, 0.90]$

$\Rightarrow$ not fully SM-like . . .

Where is the light Higgs?

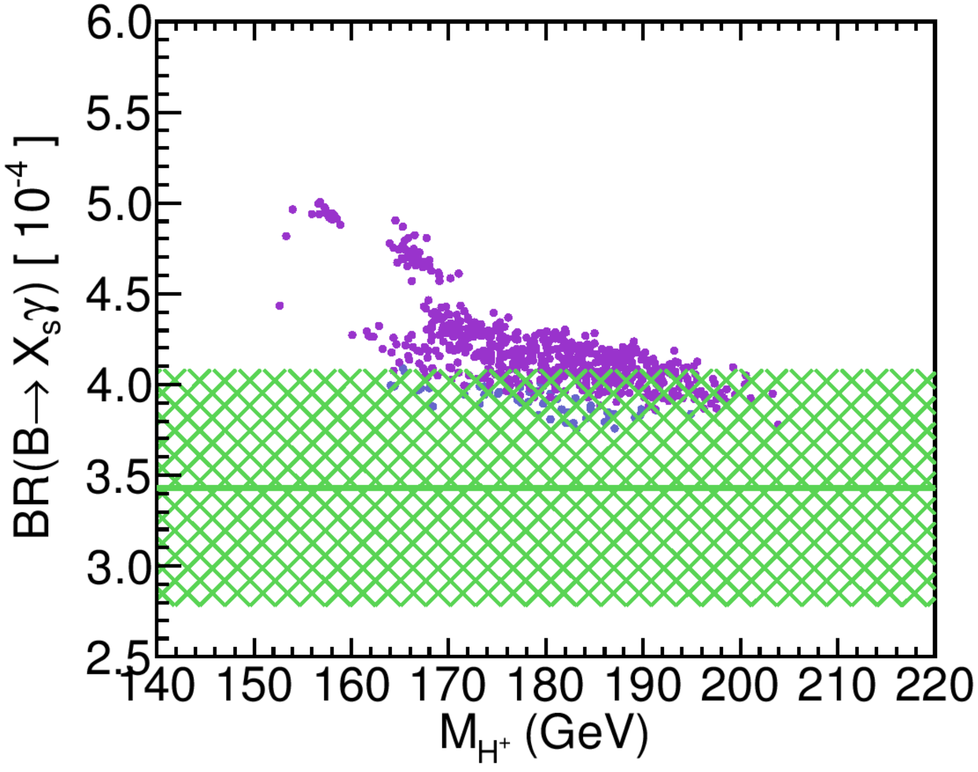


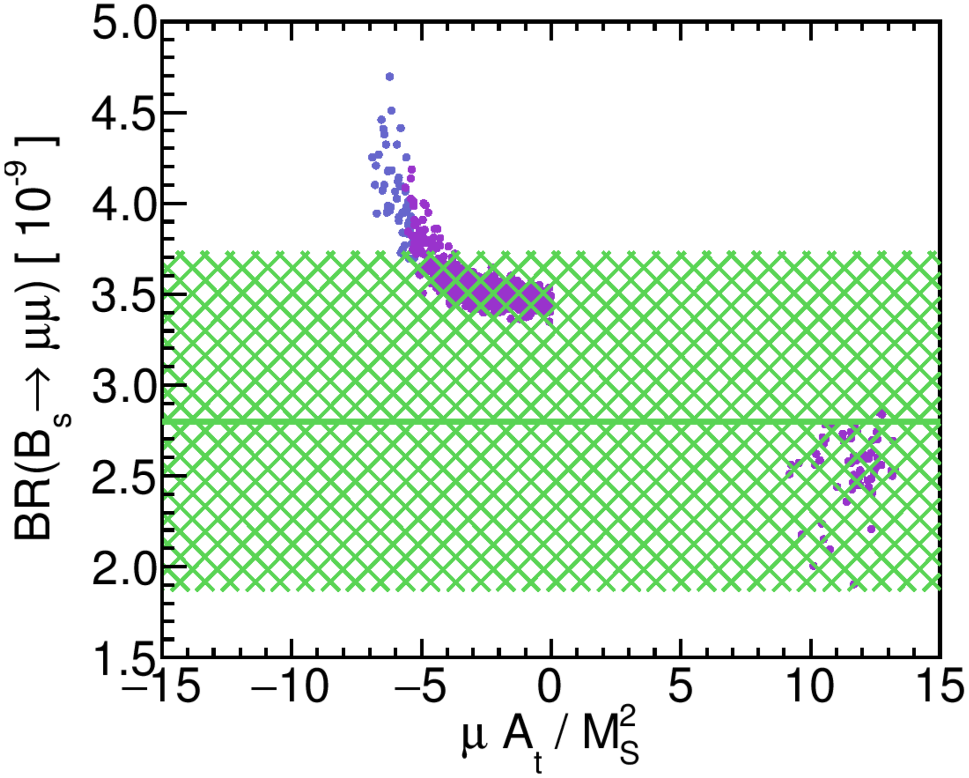
⇒ strongly reduced couplings to gauge bosons ⇒ beyond LEP reach!

⇒ $M_h > M_H/2$ (mostly) to avoid $H \to hh$ (or BR$(H \to hh) \lesssim 10\%$)

⇒ visible in $gg \to h \to \gamma\gamma$?

B-physics constraints?

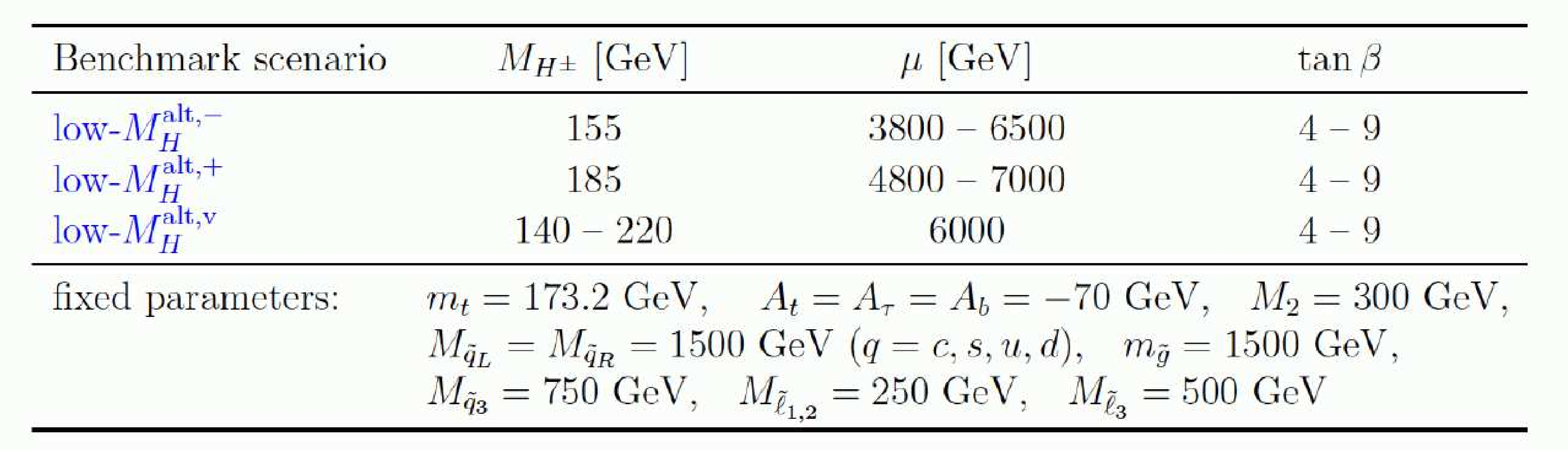




⇒ flavor constraints fulfilled!

New low-M_H benchmark scenarios

Based on our best-fit region:



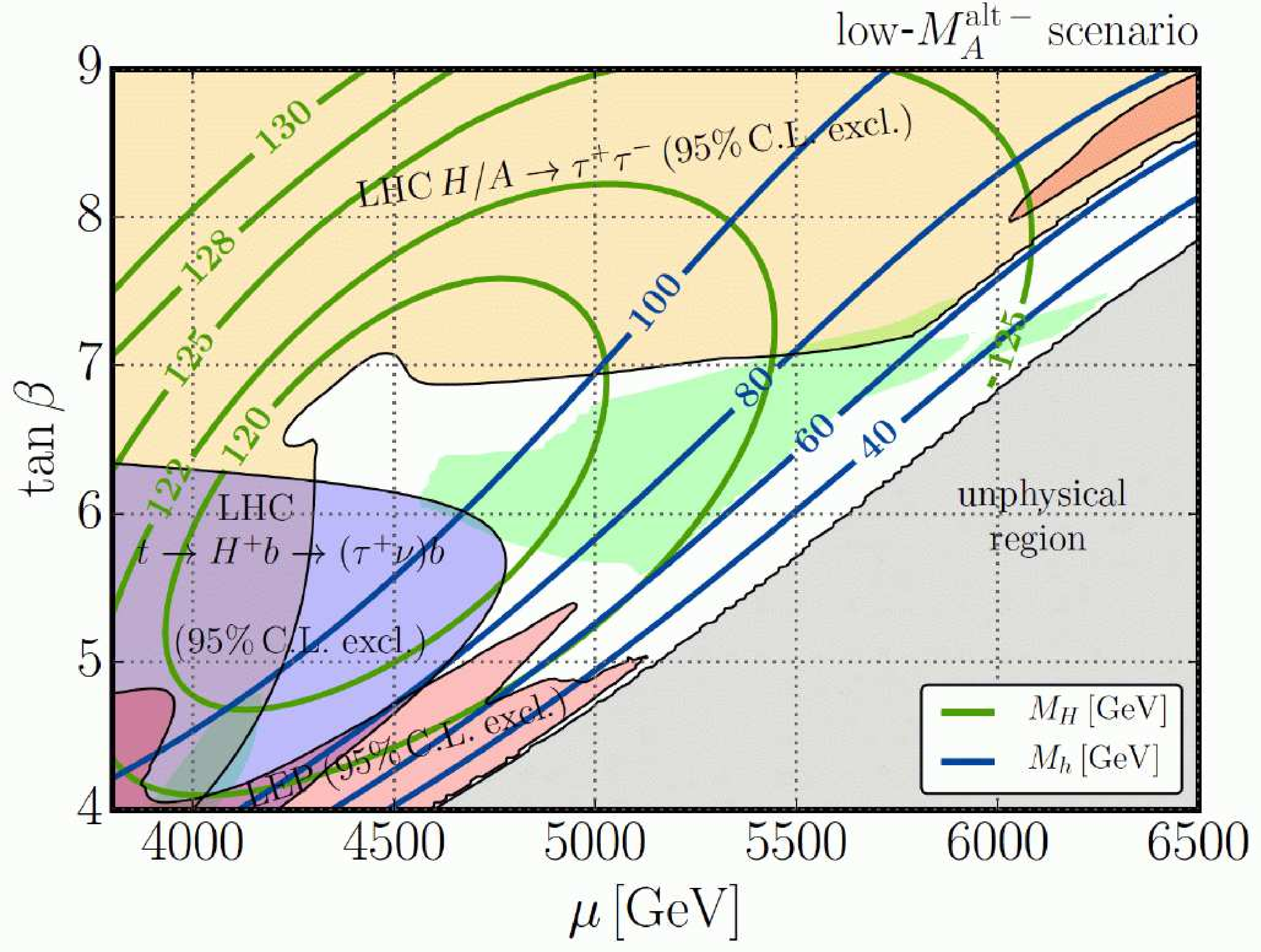
Benchmark scenario	$M_{H^\pm}$ [GeV]	μ [GeV]	$\tan\beta$
low-$M_H^{\text{alt},-}$	155	3800 – 6500	4 – 9
low-$M_H^{\text{alt},+}$	185	4800 – 7000	4 – 9
low-$M_H^{\text{alt},\text{v}}$	140 – 220	6000	4 – 9
fixed parameters:	$m_t = 173.2$ GeV, $A_t = A_\tau = A_b = -70$ GeV, $M_2 = 300$ GeV, $M_{\tilde{q}_L} = M_{\tilde{q}_R} = 1500$ GeV $(q = c, s, u, d)$, $m_{\tilde{g}} = 1500$ GeV, $M_{\tilde{q}_3} = 750$ GeV, $M_{\tilde{\ell}_{1,2}} = 250$ GeV, $M_{\tilde{\ell}_3} = 500$ GeV		

low-$M_H^{\text{alt}-}$: fixed $M_{H^\pm} < m_t$

low-$M_H^{\text{alt}+}$: fixed $M_{H^\pm} > m_t$

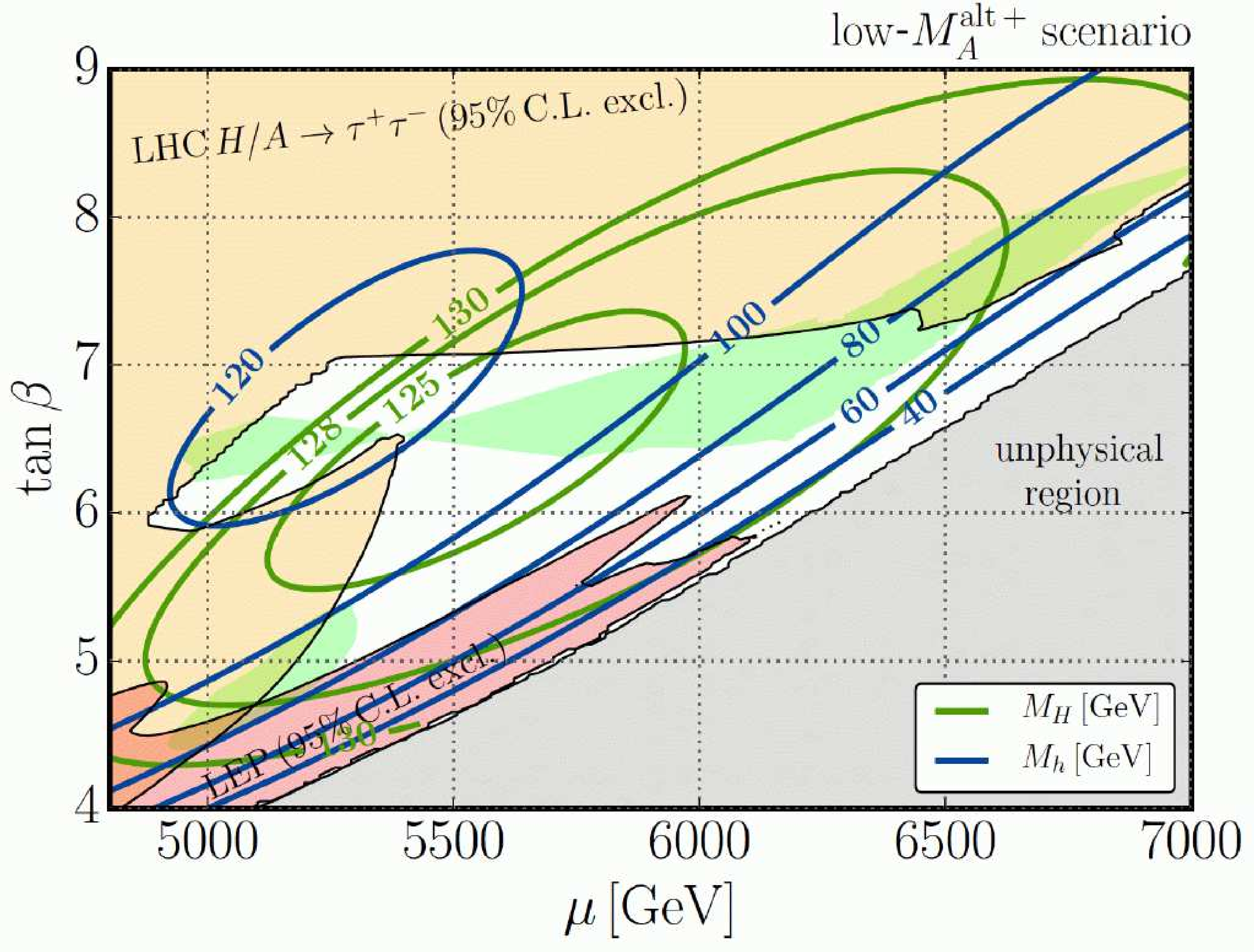
low-$M_H^{\text{alt v}}$: varied $M_{H^\pm}$ (μ fixed)

low-$M_H^{\text{alt}-}$(155 GeV $= M_{H^\pm} < m_t$):



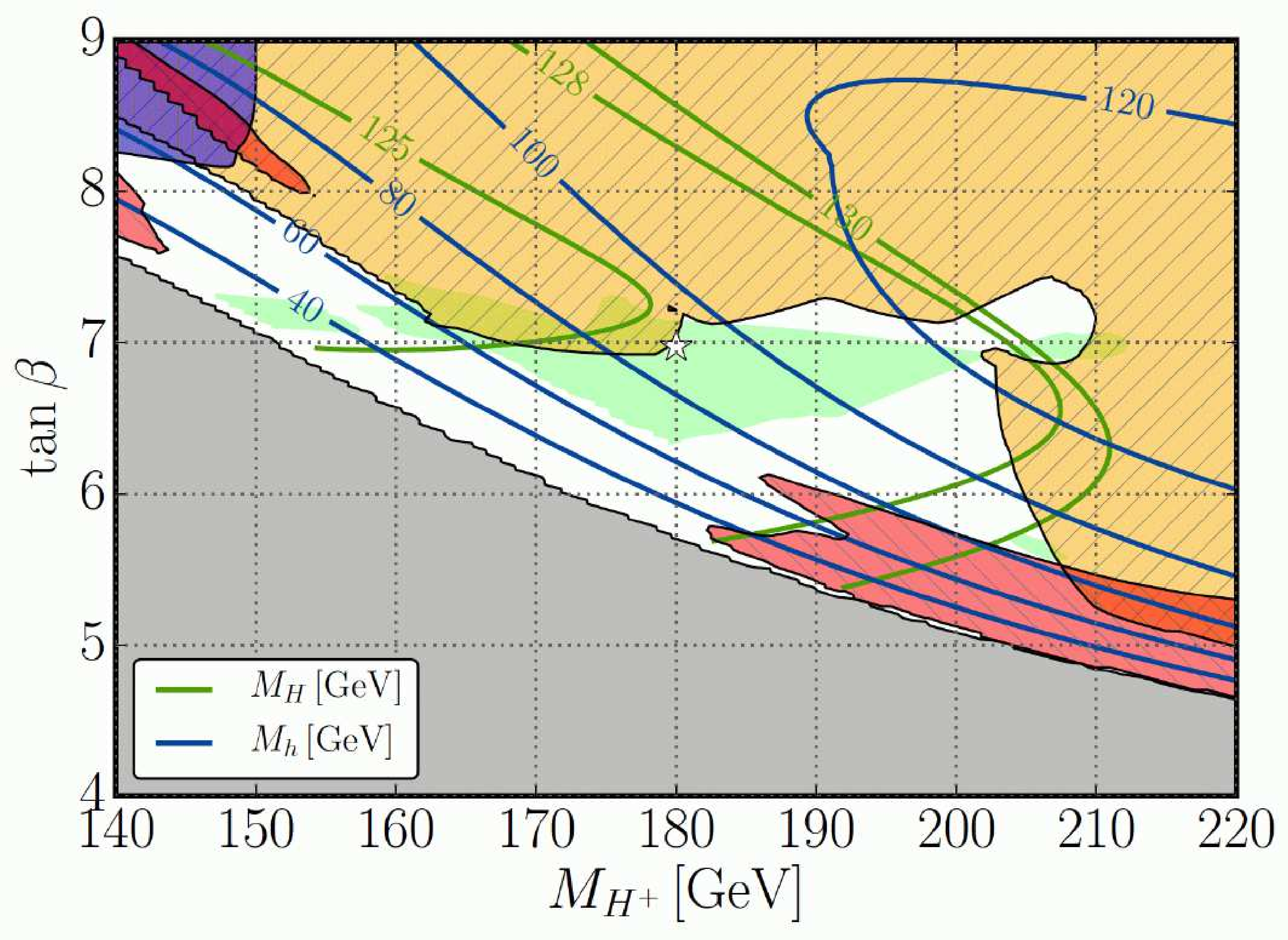
⇒ green area in agreement with all data!

low-$M_H^{\text{alt}+}$(180 GeV $= M_{H^\pm} > m_t$):



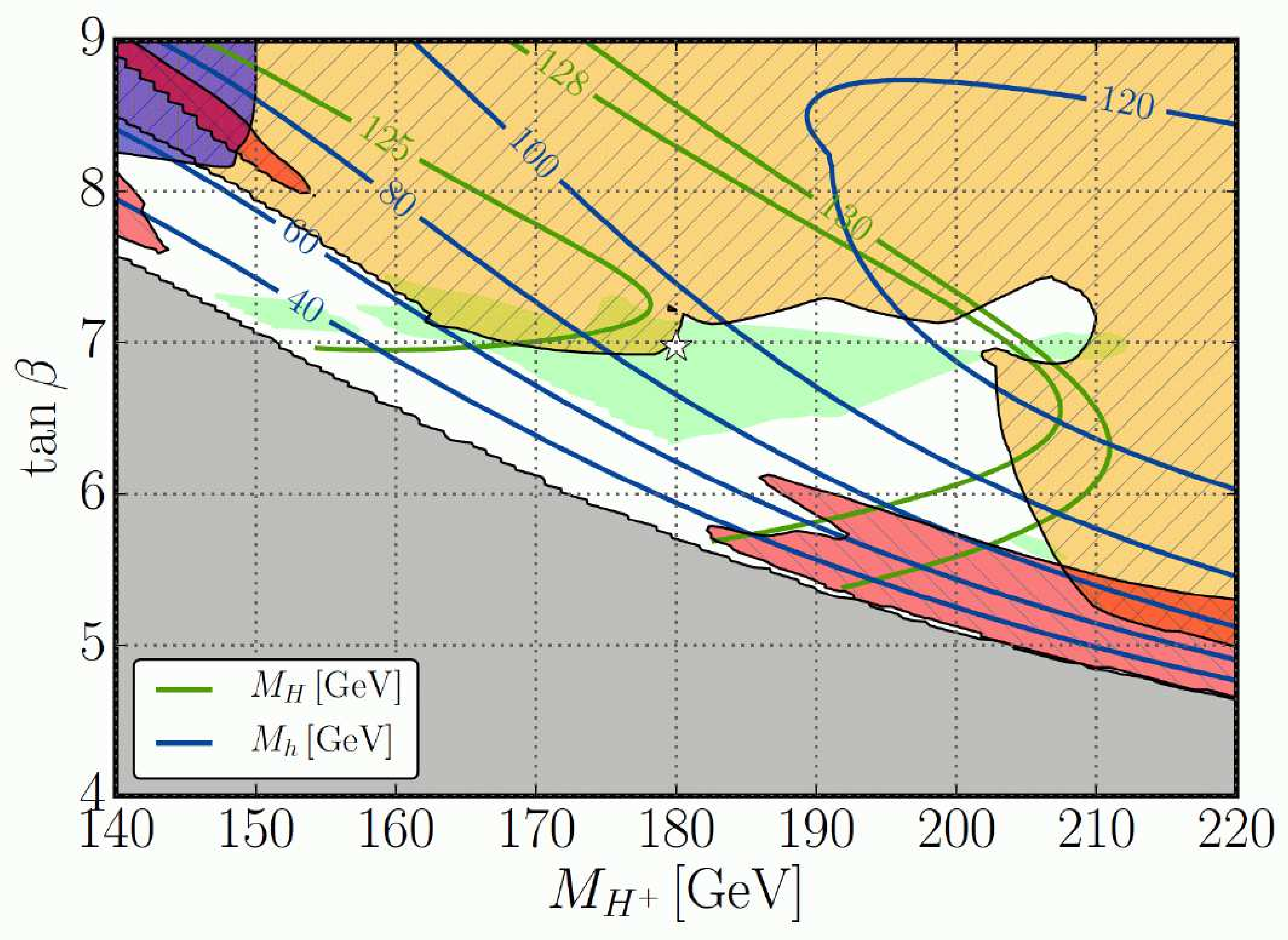
⇒ green area in agreement with all data! $M_H \sim M_h \sim 125$ GeV possible!

low-$M_H^{\text{alt v}}$($140\text{ GeV} \leq M_{H^\pm} \leq 220\text{ GeV}$):



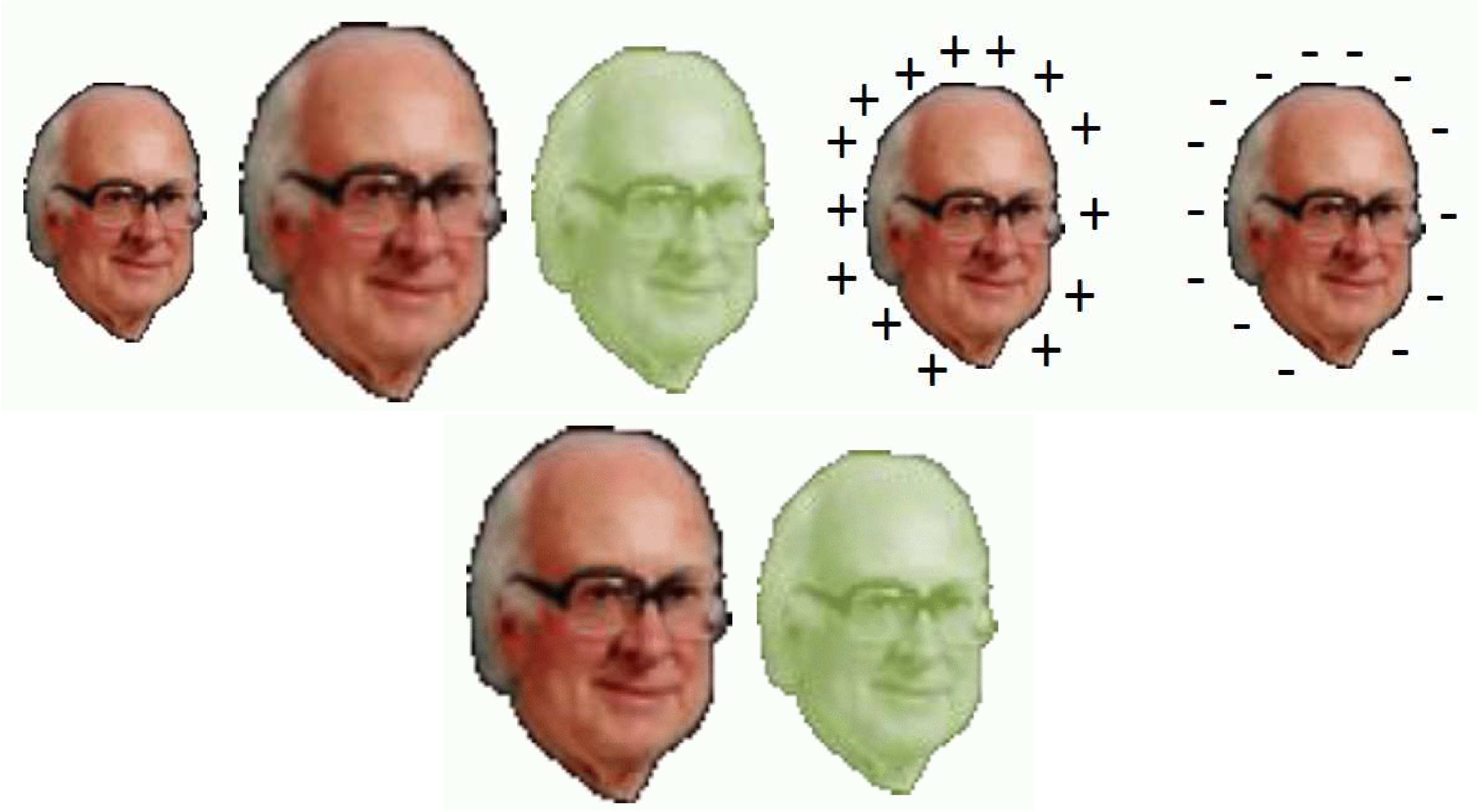
⇒ green area in agreement with all data!

low-$M_H^{\text{alt v}}$(140 GeV $\leq M_{H^\pm} \leq$ 220 GeV):



⇒ green area in agreement with all data! **Go and exclude it!**

5. Results in the NMSSM



Some NMSSM Higgs theory   (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

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

Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} \\
S &= v_s + S_R + IS_I
\end{aligned}
$$

$$
\begin{aligned}
V = {} & (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
& + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

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

Higgs spectrum:

$$\begin{aligned} \mathcal{CP}\text{−even} &: h_1, h_2, h_3 \\ \mathcal{CP}\text{−odd} &: a_1, a_2 \\ \text{charged} &: H^+, H^- \\ \text{Goldstones} &: G^0, G^+, G^- \end{aligned}$$

Neutralinos:

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

compared to the MSSM: one singlino more

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

Mass of the lightest $\mathcal{CP}$-even Higgs: (no singlet mixing)

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

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

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

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

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

Mass of the charged Higgs:

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

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

Mass of the lightest $\mathcal{CP}$-even Higgs: (no singlet mixing)

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

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

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

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

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

Mass of the charged Higgs:

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

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

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

Interesting case: light singlet

Singlet does not couple to SM particles!

Interesting case: light singlet

Singlet does not couple to SM particles!

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

Interesting case: light singlet

Singlet does not couple to SM particles!

“Non-interacting particles are hard to detect.”

[*F. Klinkhamer*]

“Easily” possible in the NMSSM:

Light, singlet-like Higgs below 125 GeV

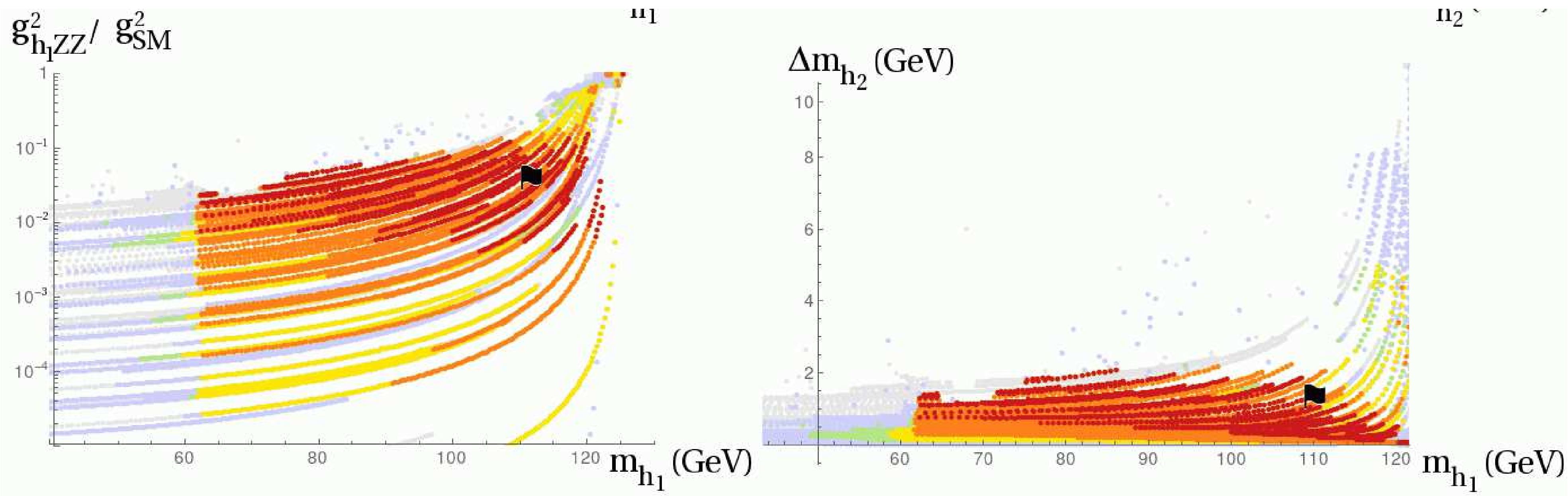
Can the LHC find them?

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



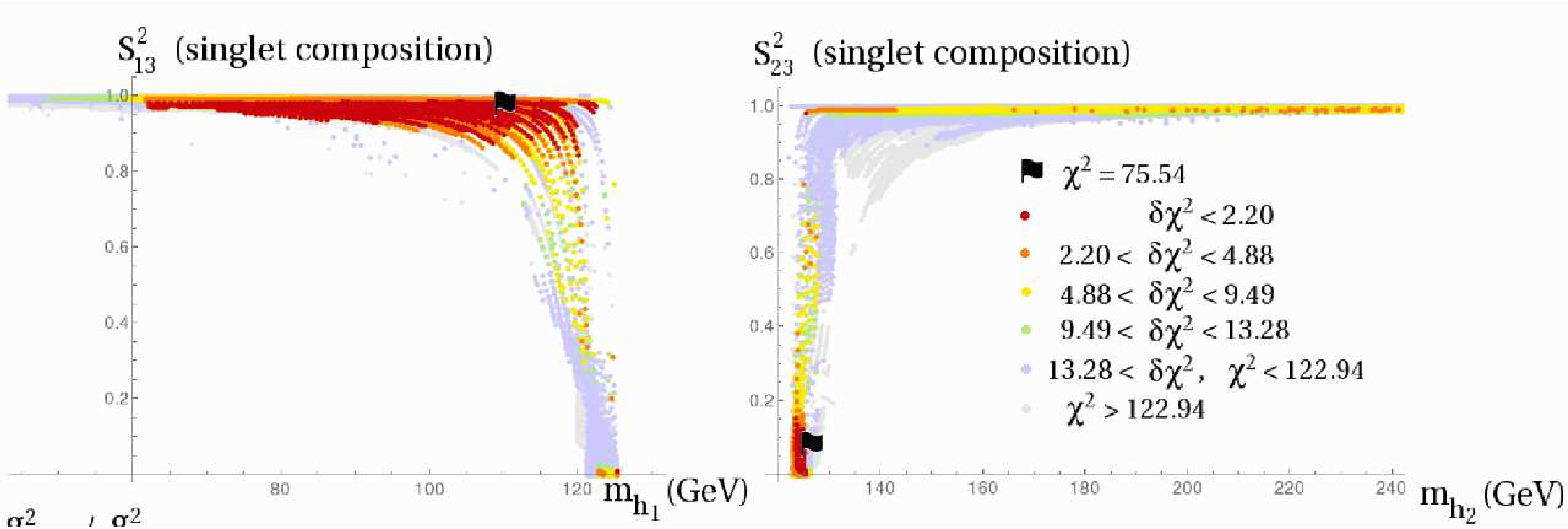
⇒ light Higgs below 125 GeV
⇒ strongly reduced couplings to gauge bosons!

NMSSM parameter scan:

[F. Domingo, G. Weiglein '15]

Parameters:

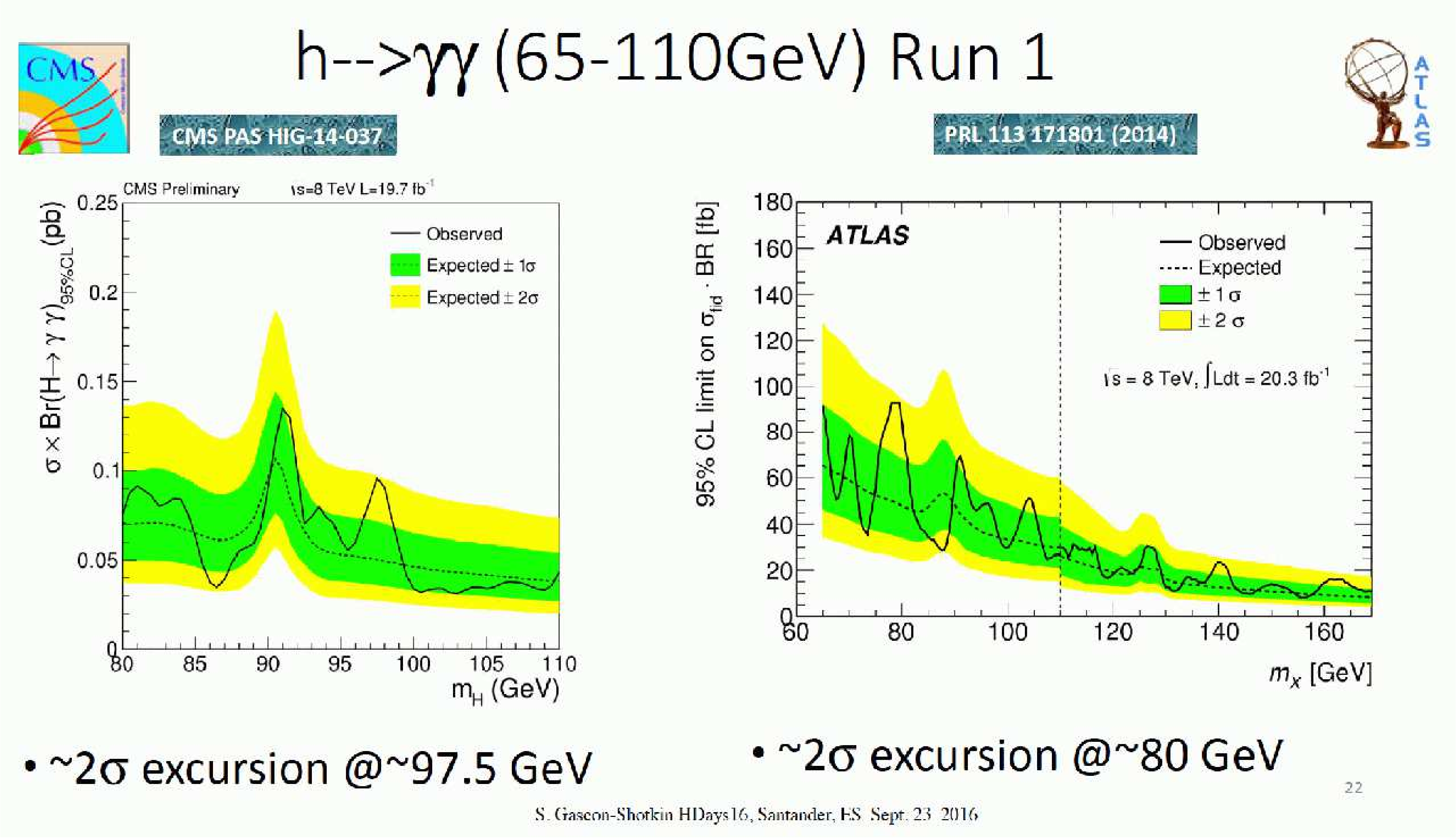
$\tan\beta = 8$, $M_A = 1$ TeV, $A_\kappa = -2...0$ TeV, $\mu = 120...2000$ GeV,
$2M_1 = M_2 = 500$ GeV, $M_3 = 1.5$ TeV, $m_{\tilde{Q}_3} = 1$ TeV, $m_{\tilde{Q}_{1,2}} = 1.5$ TeV,
$A_t = -2$ TeV, $A_{b,\tau} = -1.5$ TeV



⇒ light Higgs below 125 GeV has large singlet component

⇒ second Higgs is SM-like

(Only?) possible search channel: $h_1 \to \gamma\gamma$



h-->γγ (65-110GeV) Run 1

CMS PAS HIG-14-037

PRL 113 171801 (2014)

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

22

S. Gascon-Shotkin HDays16, Santander, ES Sept. 23 2016

⇒ no sensitivity yet!

Conclusinos

- SUSY is (still) the best motivated BSM theory

- SUSY Higgs mass predictios are far behind experimental accuracy

- Higgs rate measurements can be fulfilled by
  - the light $\mathcal{CP}$-even Higgs in the decoupling regime
  - the light $\mathcal{CP}$-even Higgs in the alignment w/o decoupling regime
  - the heavy $\mathcal{CP}$-even Higgs with $M_h < 125$ GeV

- MSSM results:
  - CMSSM, NUHM1, NUHM2: relatively high Higgs mass scales favored
  - hMSSM: simple decoupling with large M_A
  - pMSSM8: light $\mathcal{CP}$-even Higgs for "all" M_A
    heavy $\mathcal{CP}$-even Higgs
    ⇒ new benchmark scenarios

- NMSSM results:
  Interesting possiblity: light singlet-like state below 125 GeV
  ⇒ LHC searches via $\gamma\gamma$, no sensitivity (yet)


Further Questions?