"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!"

SUSY Higgs Bosons in the Light of LHC Data

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

Taipei, 09/2017

- Motivation
- SUSY Higgs mass and rate measurements
- MSSM Higgs results (CMSSM, NUHM1/2, pMSSM8)
- $\phi_{95} \to \gamma\gamma$
- Conclusions

1. Motivation

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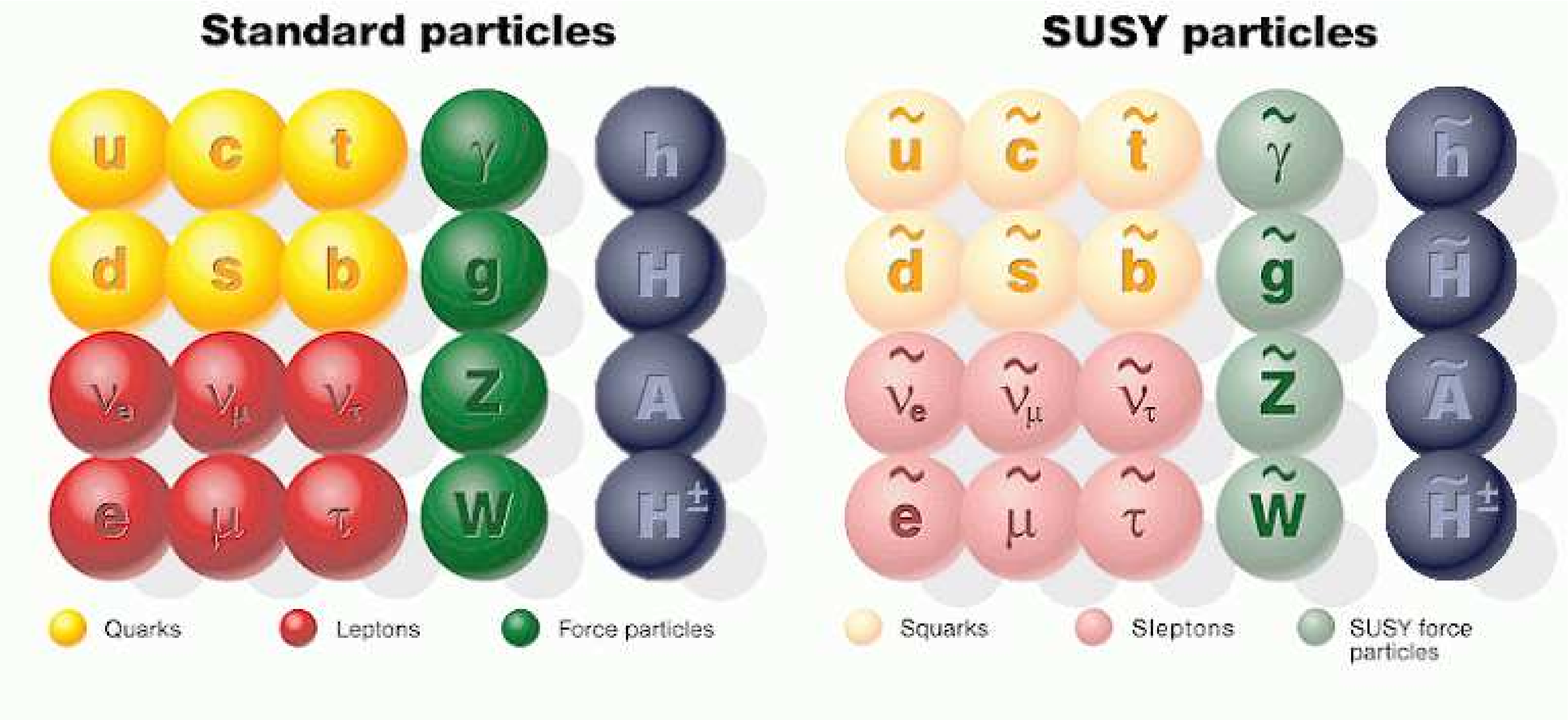
⇒ **good motivation to look at SUSY! :-)**

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

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

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!

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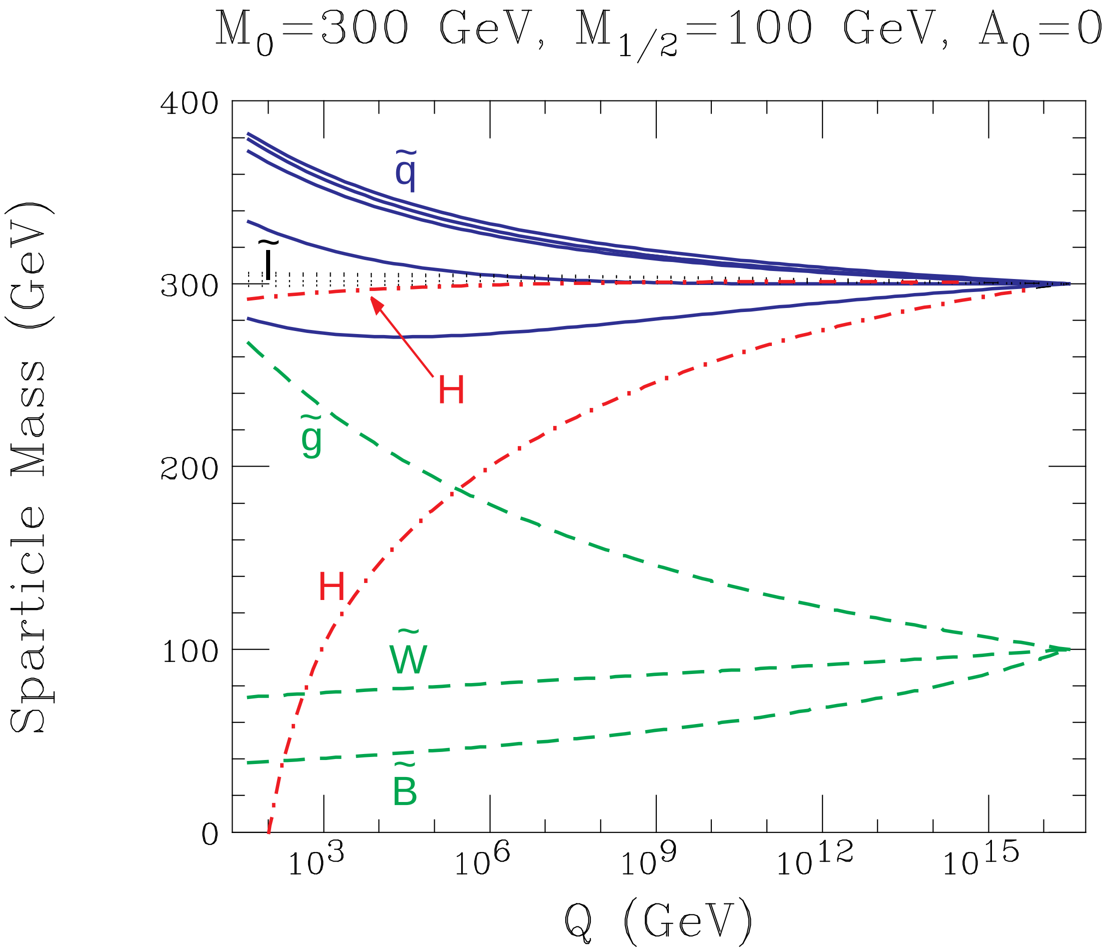
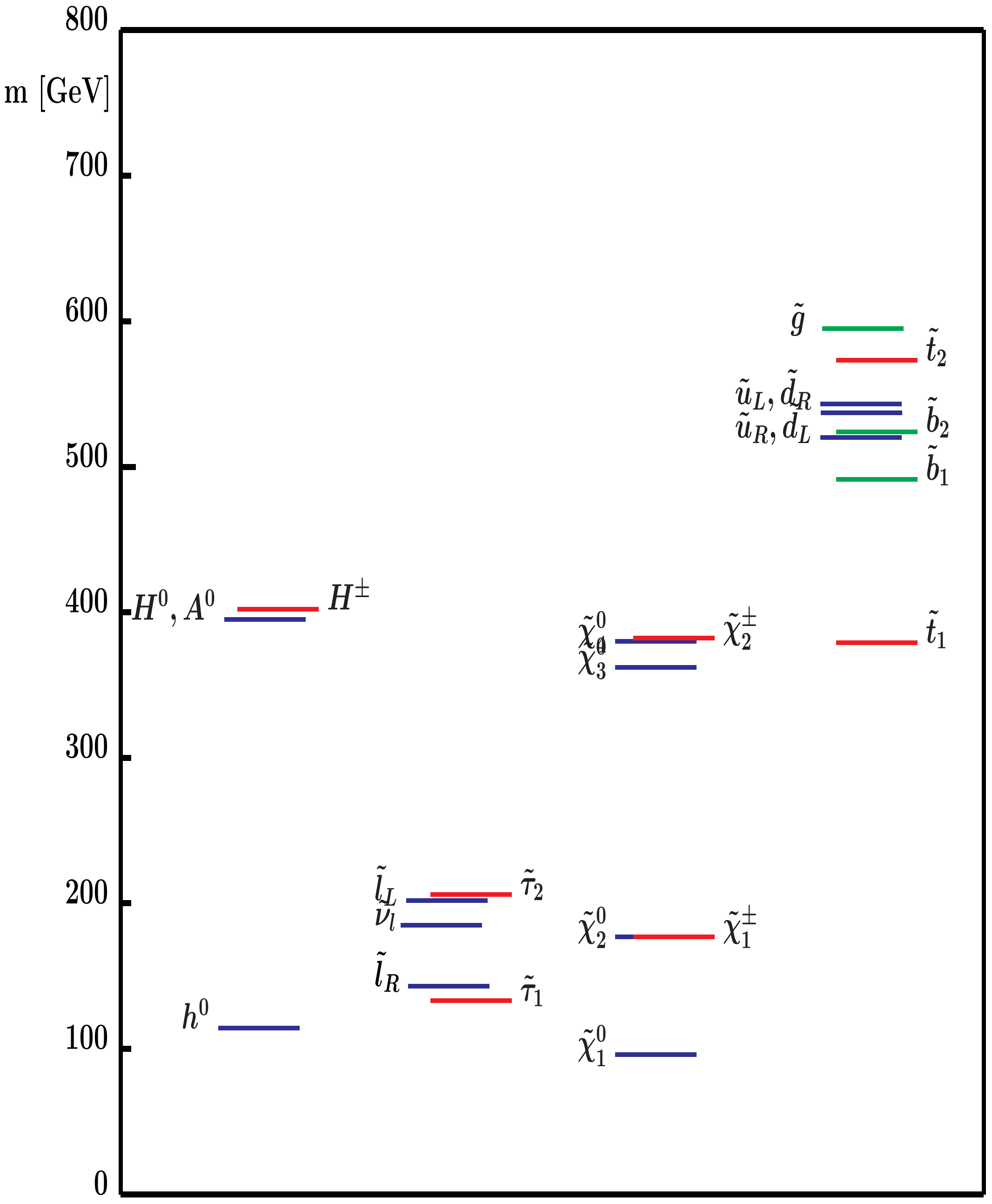
⇒ particle spectra from renormalization group running to weak scale



⇒ one parameter turns negative ⇒ Higgs mechanism for free

“Typical” CMSSM scenario (SPS 1a benchmark scenario):

Strong connection between all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

⇒ effectively M_A as free parameters at the EW scale

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu \text{ and } M_A$$

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

⇒ effectively M_A and μ as free parameters at the EW scale

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } M_A$$

Problem: We cannot be sure about the SUSY-breaking mechanism

⇒ it is possible that with the CMSSM, NUHM1, NUHM2, . . . we missed the "correct" mechanism

⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

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tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

⇒ 8 parameters are manageable ⇒ pMSSM8

- 3rd gen. squark mass parameters: $m_{\tilde{q}_3}$
- slepton mass parameter: $m_{\tilde{l}_3}$, $m_{\tilde{l}_{1,2}}$
- gaugino masses: M_2
- trilinear coupling: A_t
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing paramter: μ

⇒ Note: other "8 parameter selections" possible

Data we have:

- Higgs boson mass (LHC) ⇒ FeynHiggs

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- electroweak precision data ⇒ FeynWZ, FeynHiggs
- flavor data ⇒ SuperIso, SuFla
- astrophysical data (DM properties) ⇒ MicrOMEGAs, SSARD

2. SUSY Higgs mass and rate measurements

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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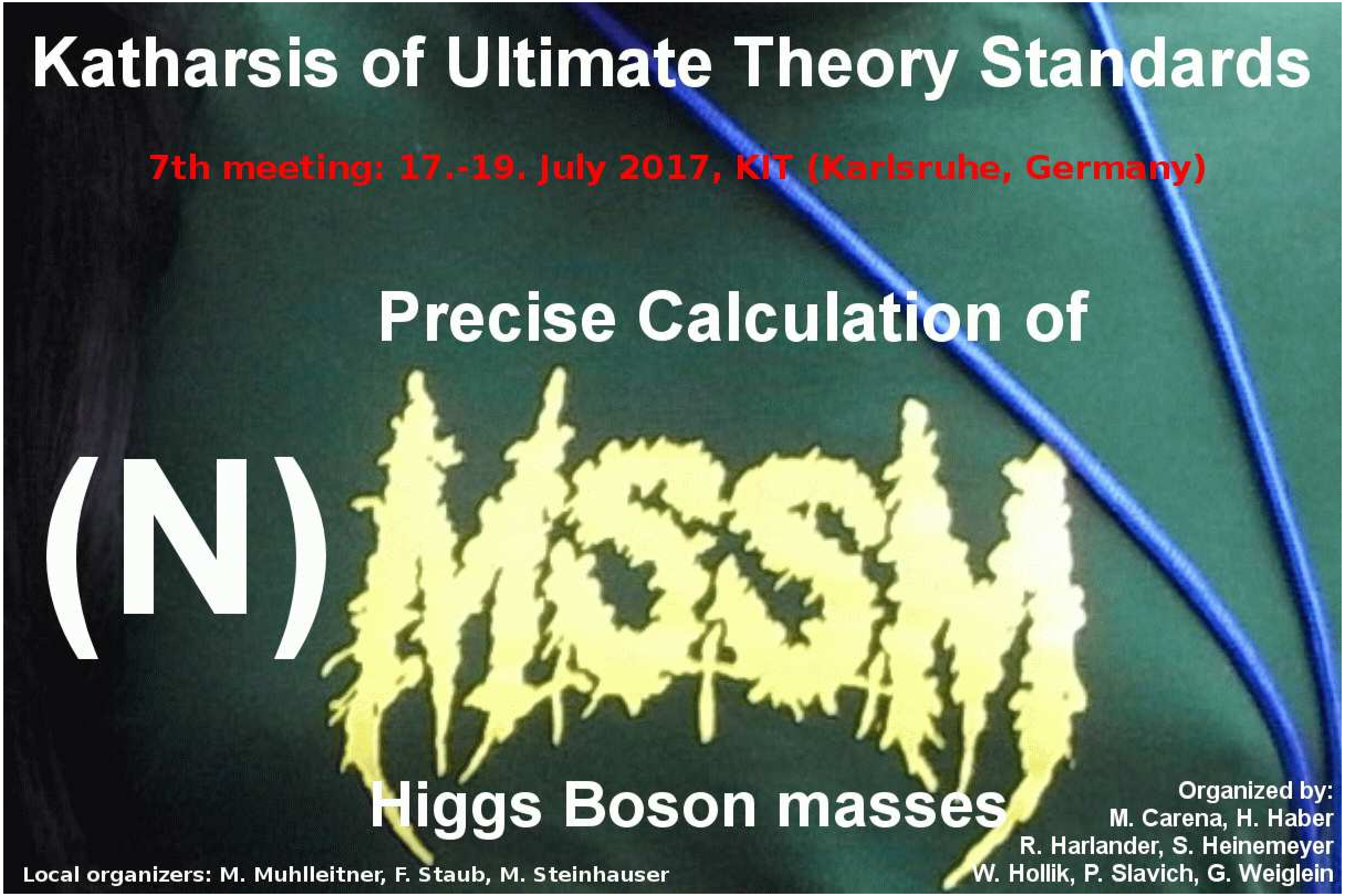
MSSM theory:

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 (maybe 2 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

7th meeting: 17.-19. July 2017, KIT (Karlsruhe, 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

Local organizers: M. Muhlleitner, F. Staub, M. Steinhauser

⇒ next meeting: 01/2018 in Paris

Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

$\Rightarrow$ mixing important in stop sector!

Simplifying abbreviation:

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

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, $c_{\beta-\alpha} = 0$

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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]

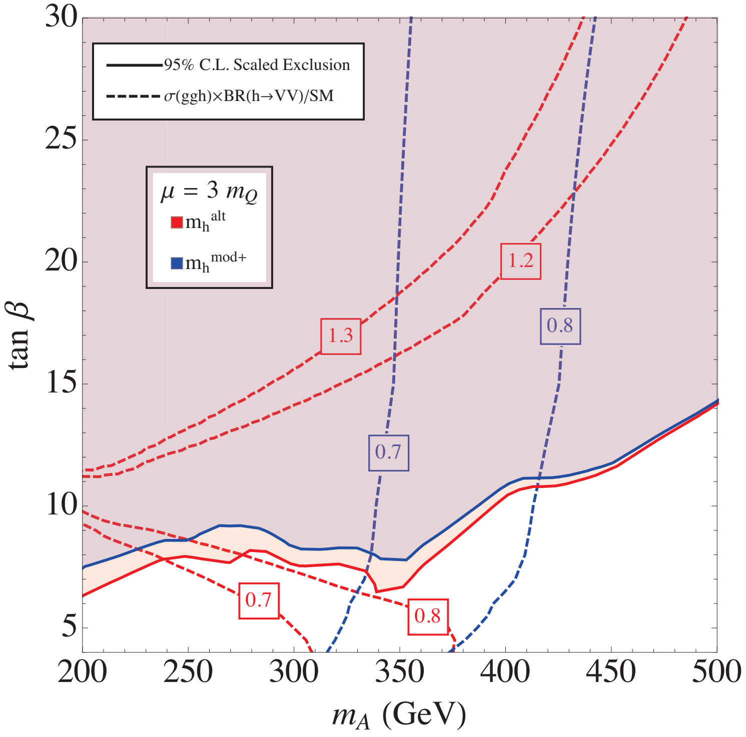
In the MSSM $Z_6 = 0$ can be obtained through an "accidental" cancellation between tree-level and loop contribution, roughly at:

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

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

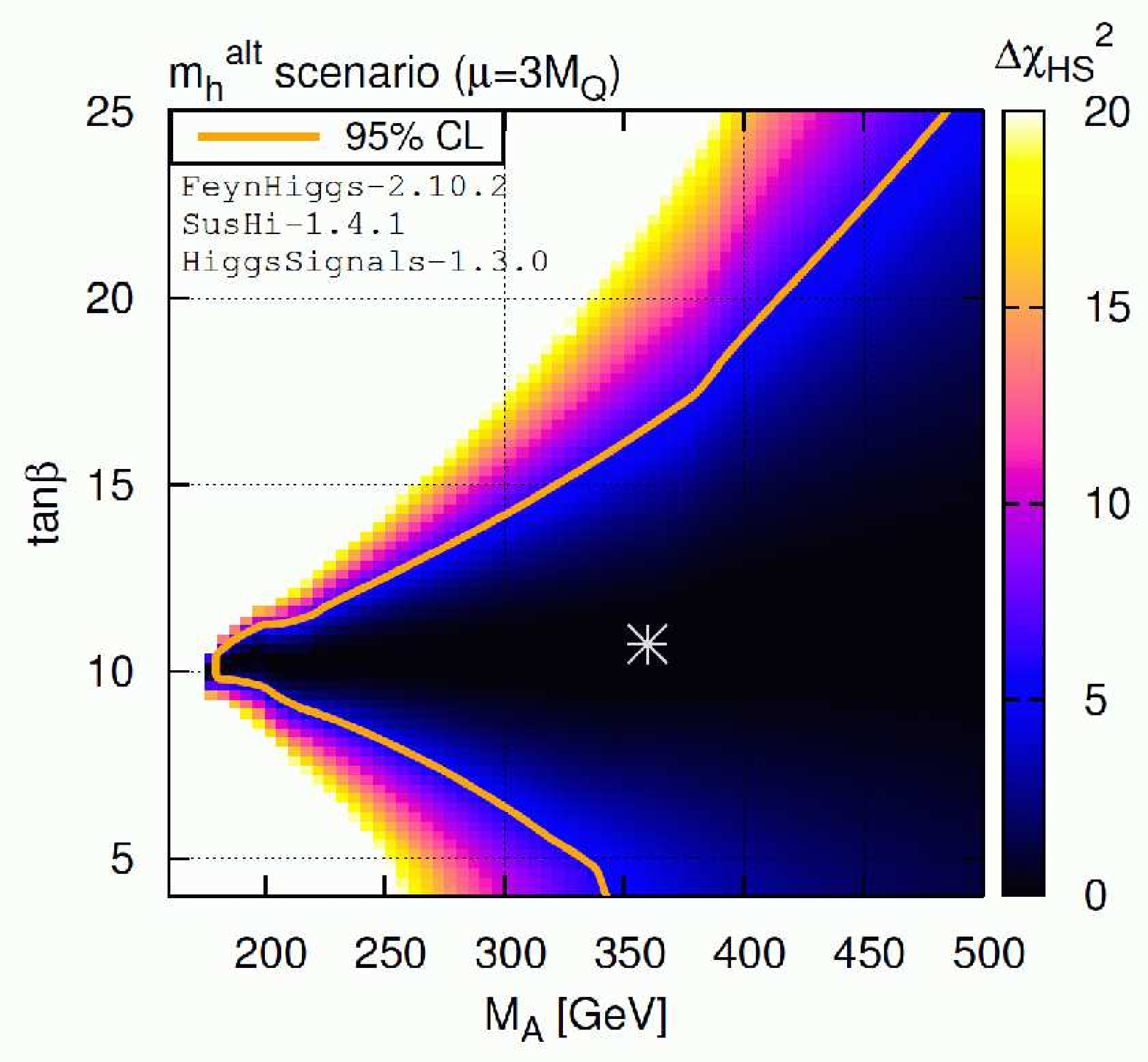
(low M_A and $\tan\beta$: tune $M_\mathrm{S} \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

$\Rightarrow$ SM-like Higgs for all M_A



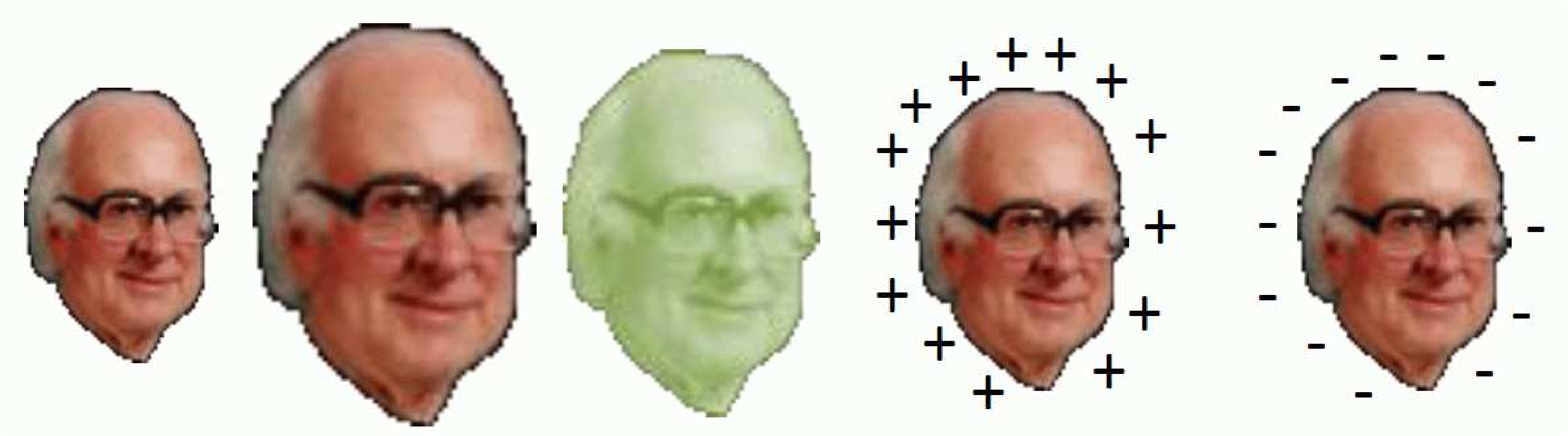
Preferred $m_h^{\rm alt}$ parameter space from HiggsSignals:

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



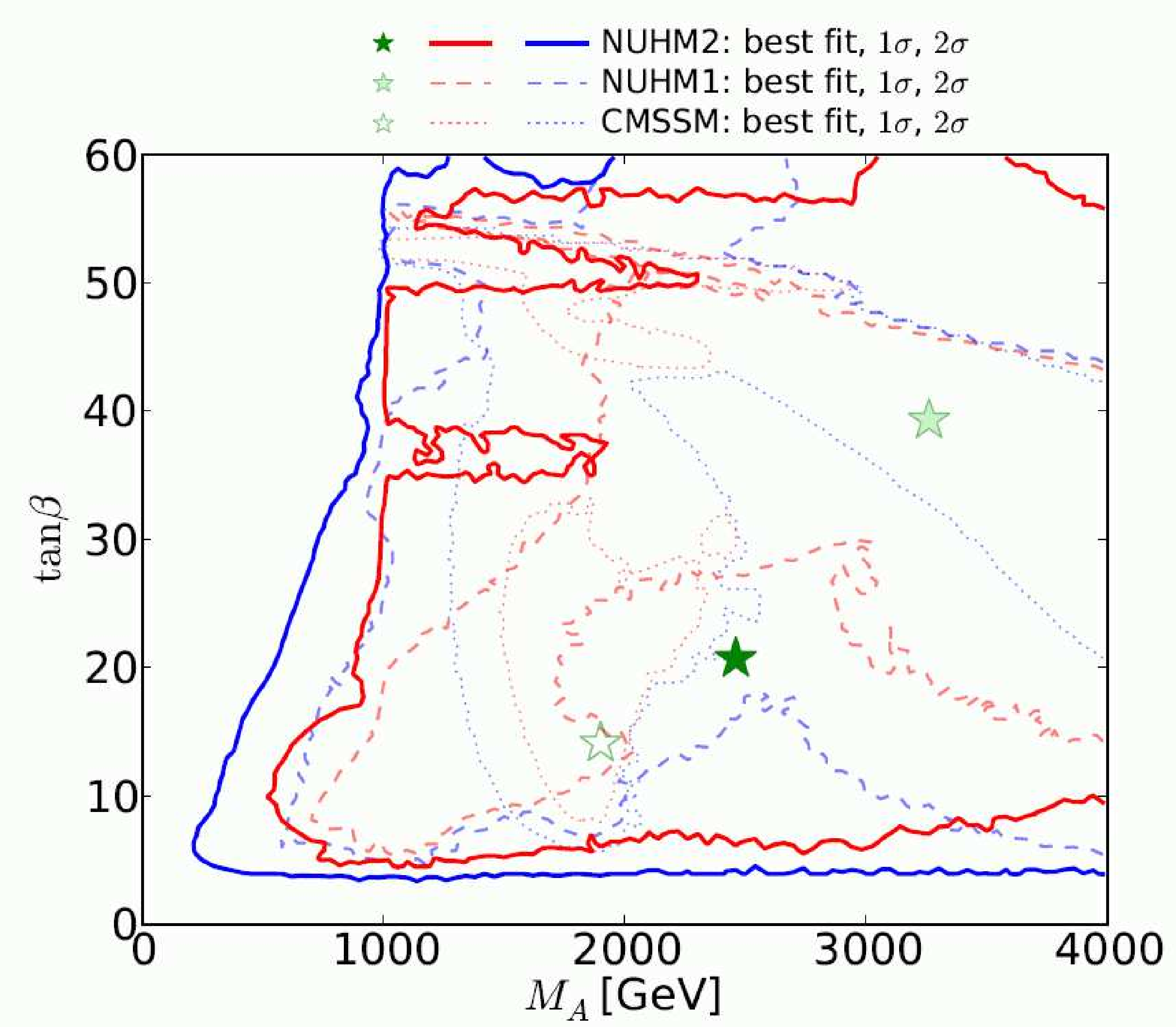
⇒ no Higgs mass scale restrictions from rates (in general)

3. MSSM Higgs results (CMSSM, NUHM1/2, pMSSM8)



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

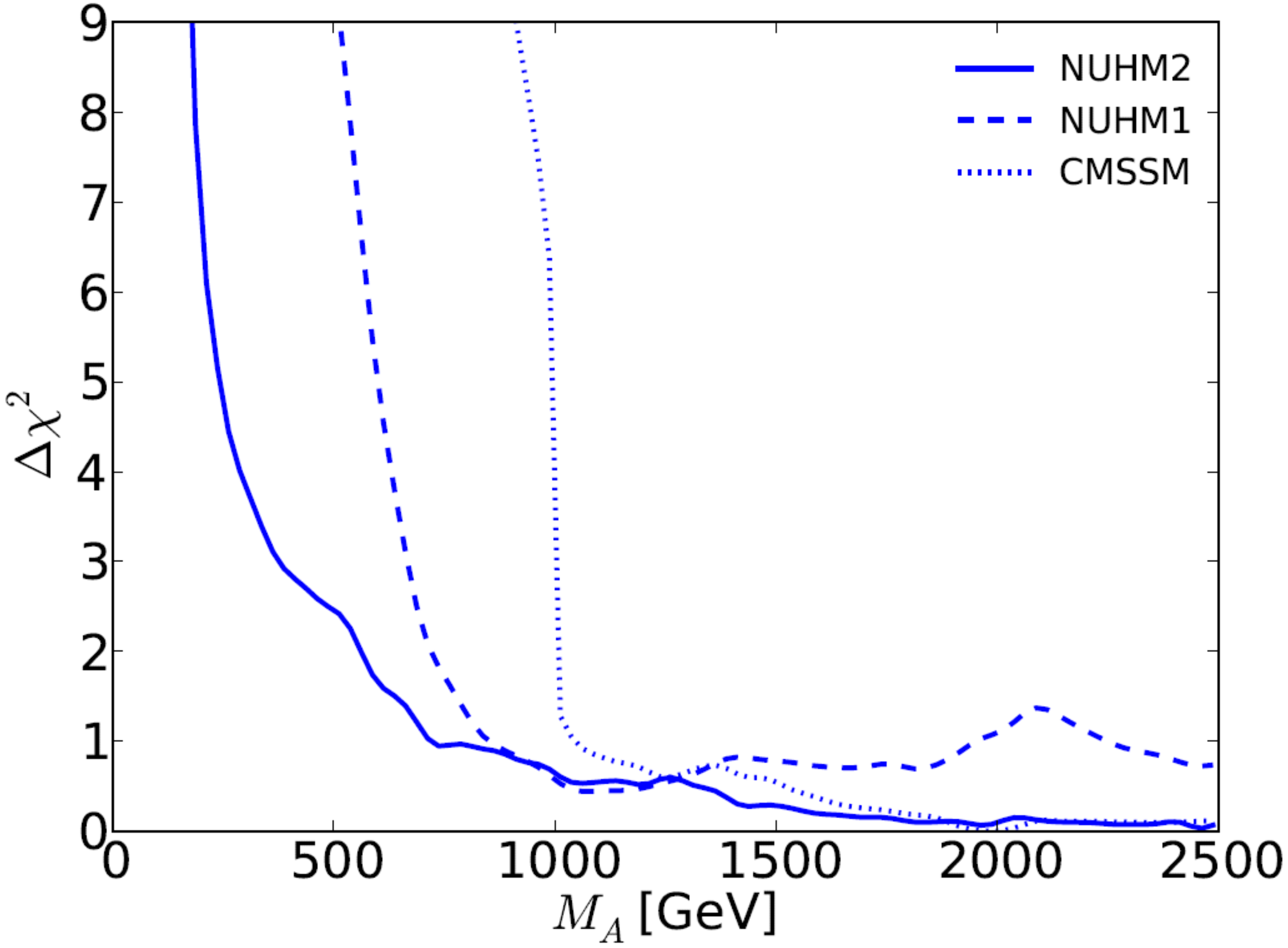
[2015]



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

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

[2015]



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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

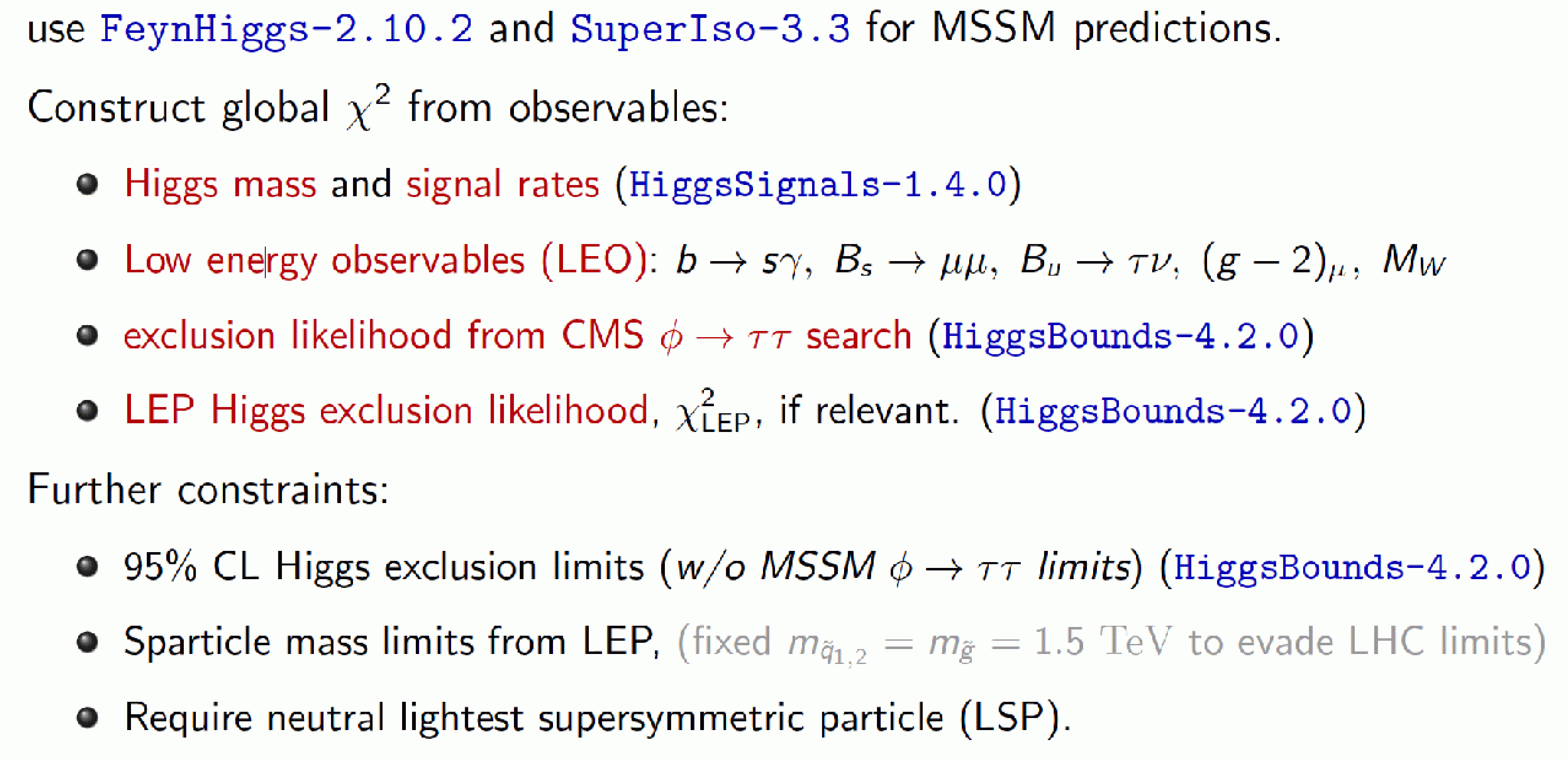
M_1 fixed by GUT relation

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)

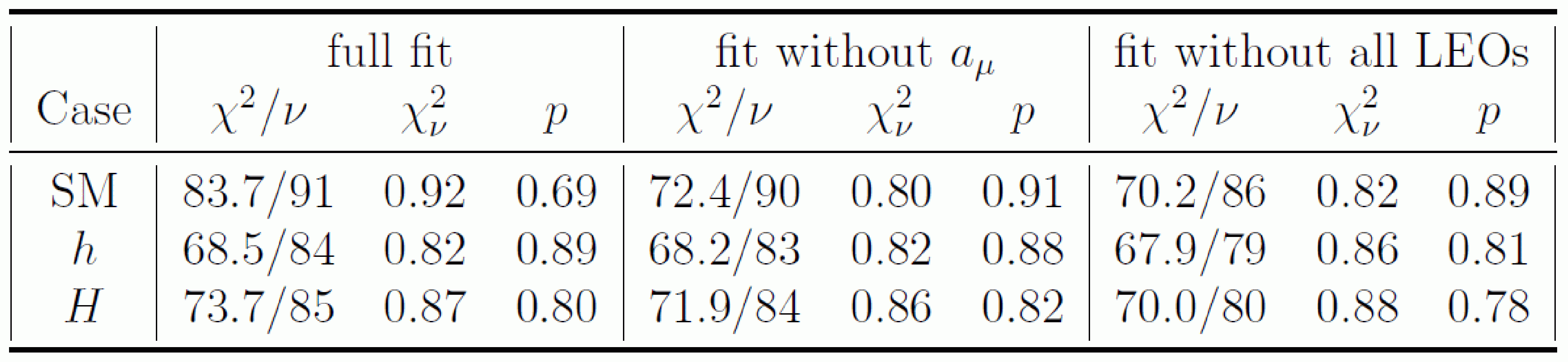
Further constraints:

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

Newly included: CheckMate to check SUSY exclusion limits

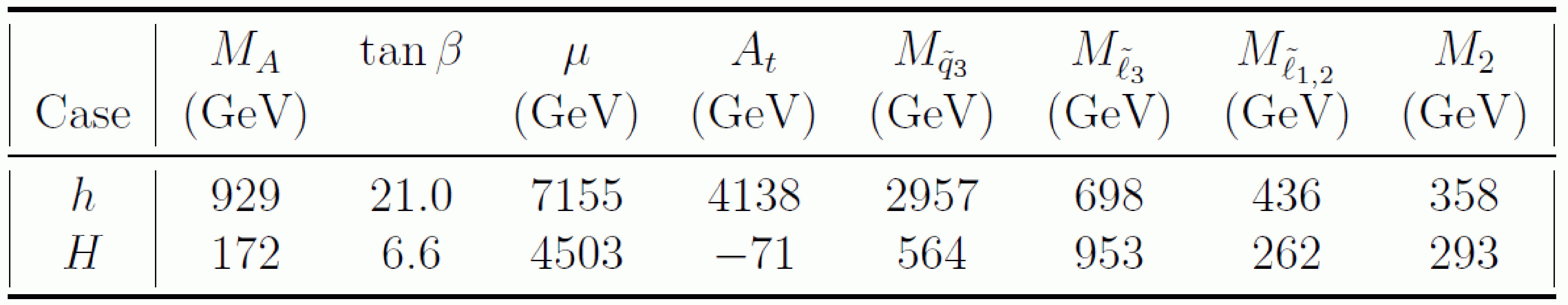
⇒ "naive" χ^2 calculation (heavily relying on HiggsSignals)

The best-fit points:



Case	full fit			fit without a_μ			fit without all LEOs		
	χ^2/ν	χ^2_ν	p	χ^2/ν	χ^2_ν	p	χ^2/ν	χ^2_ν	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

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:

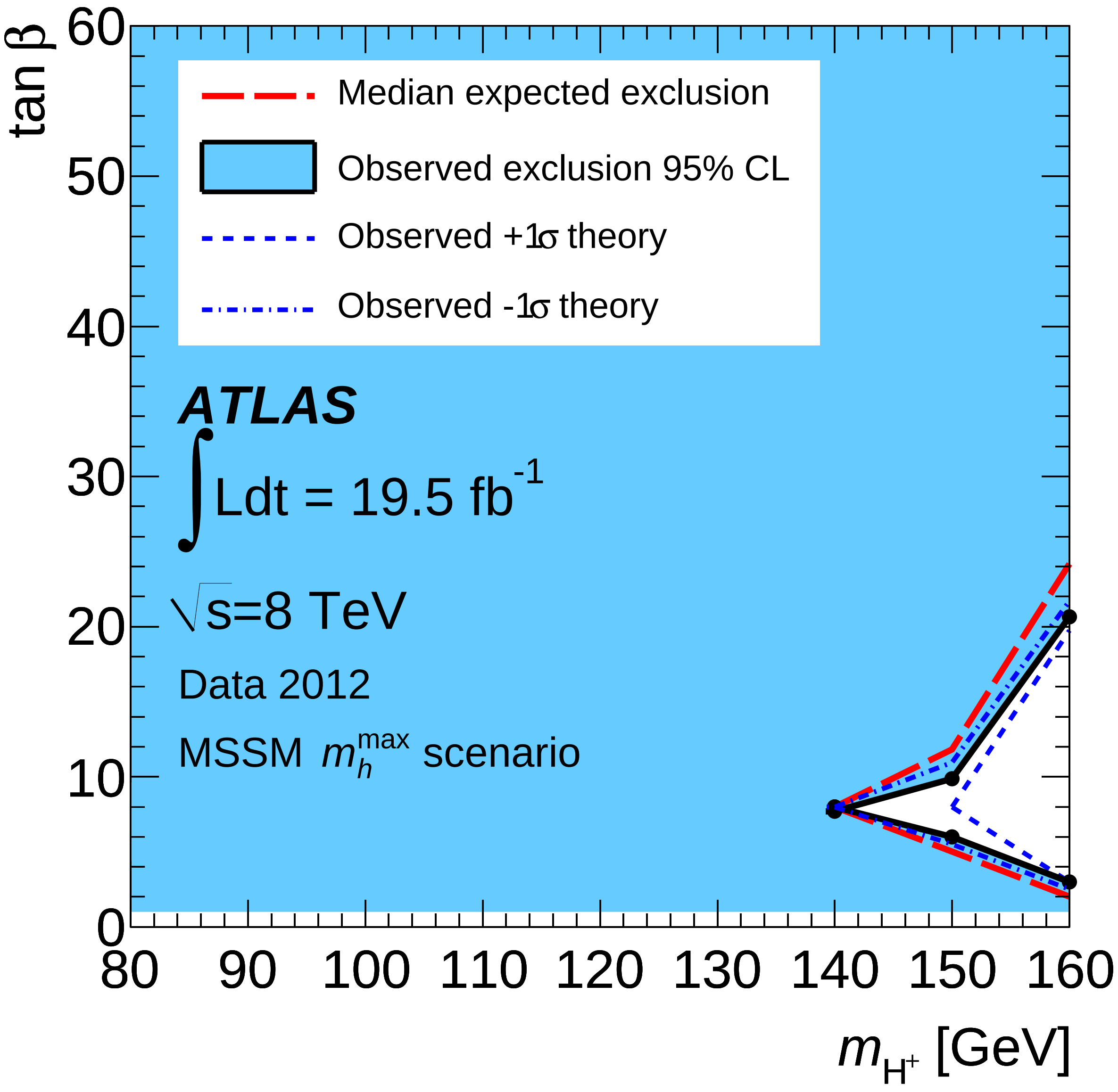
– direct searches for the lightest $\mathcal{CP}$-even Higgs
– direct searches for the heavy neutral Higgses
– direct searches for the charged Higgses
– flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

⇒ original scenario: low-M_H

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

ATLAS results for charged Higgs searches:

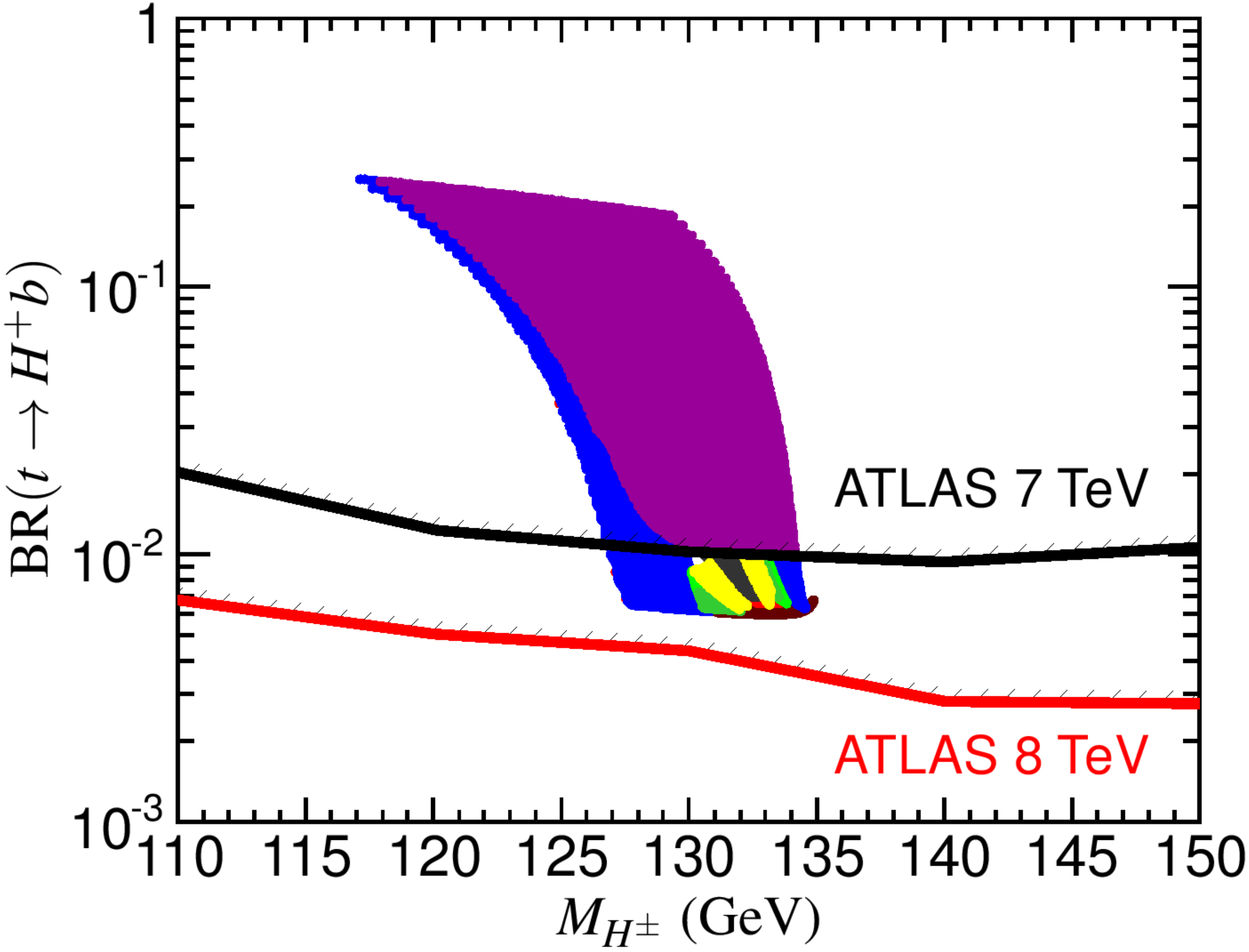
[ATLAS '15]



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

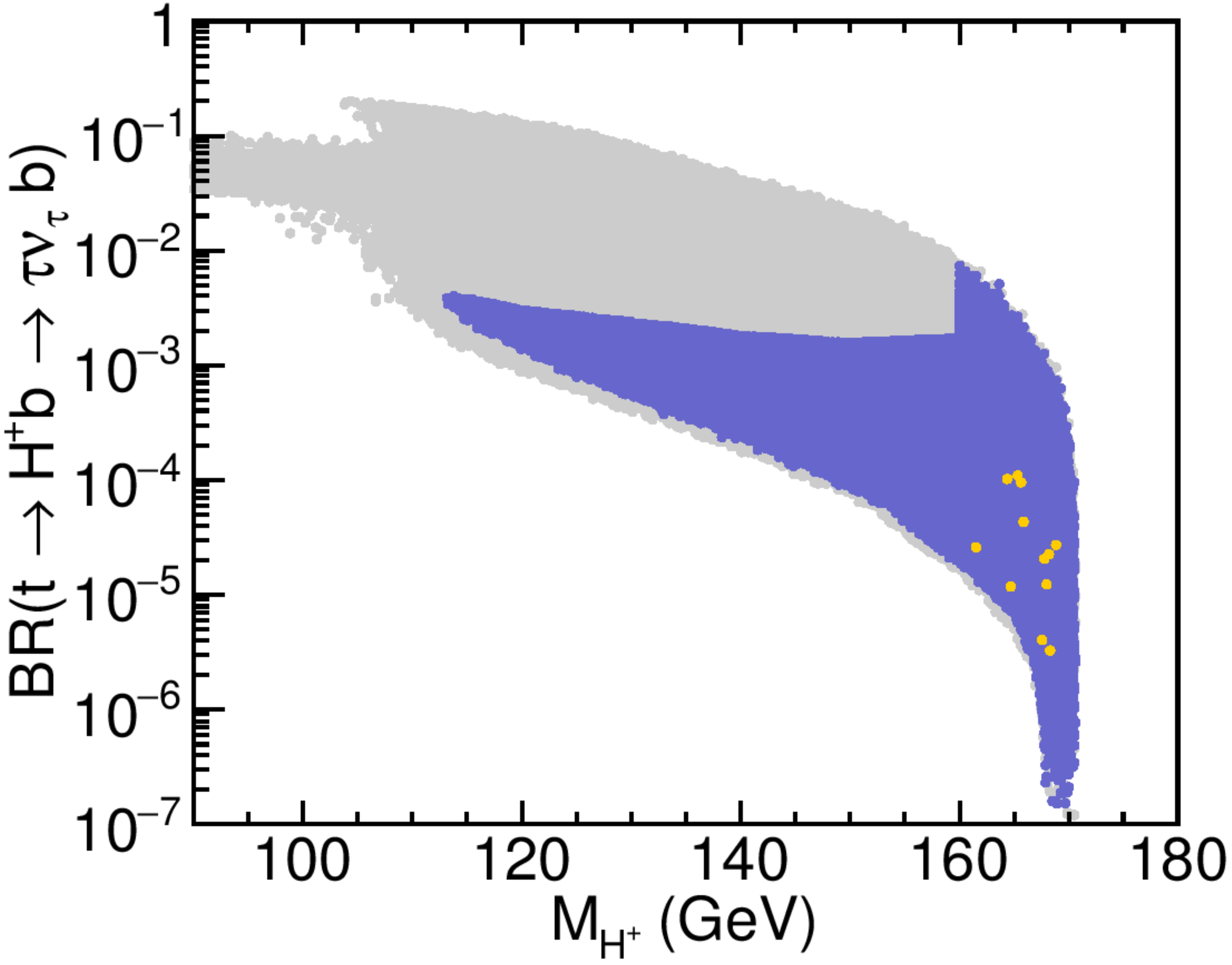
Application of charged Higgs limits on low-M_H scenario:

[*HiggsBounds 4.1*]



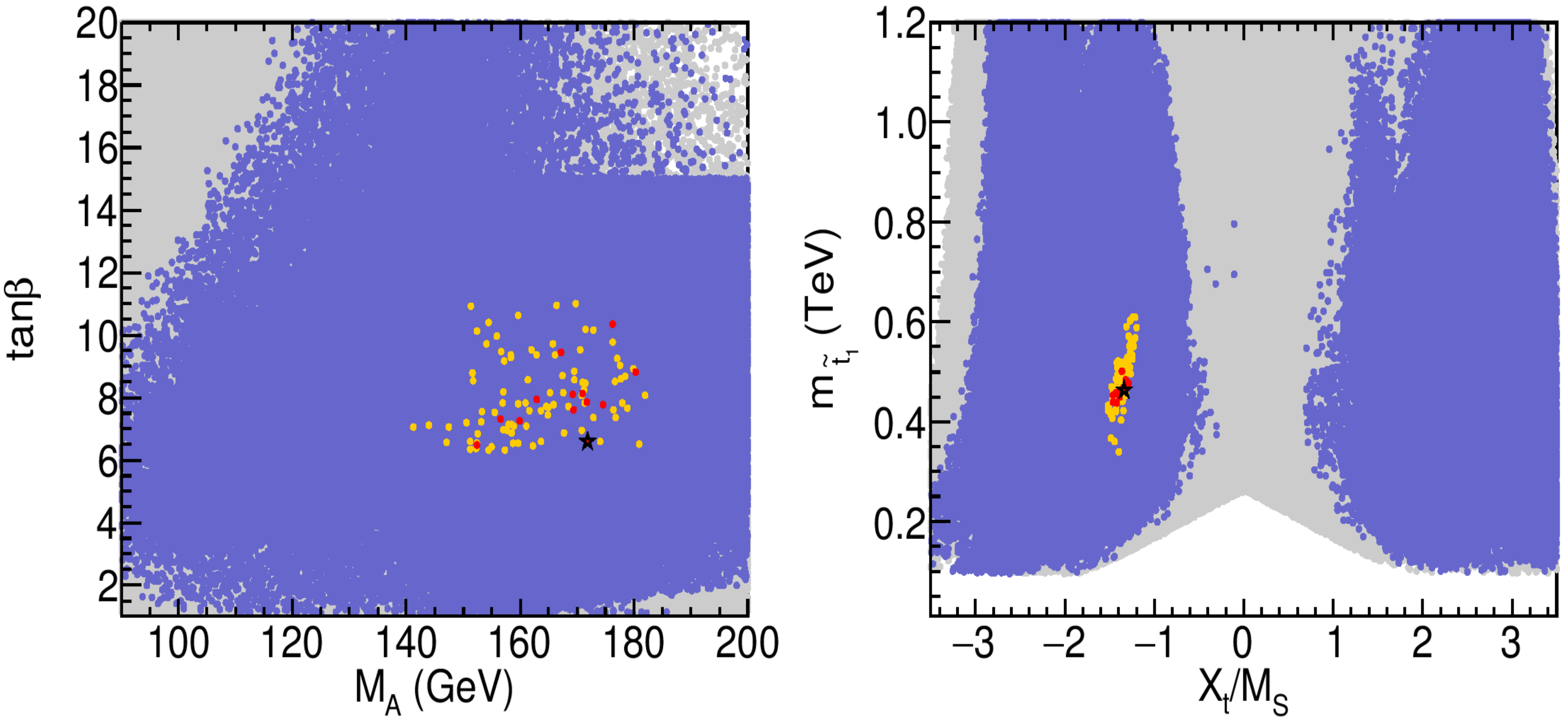
$\Rightarrow$ that (particular incarnation of the) low-M_H scenario is excluded!

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



$\Rightarrow$ “tricky” region below and beyond the top threshold!

Heavy-Higgs case: preferred parameters

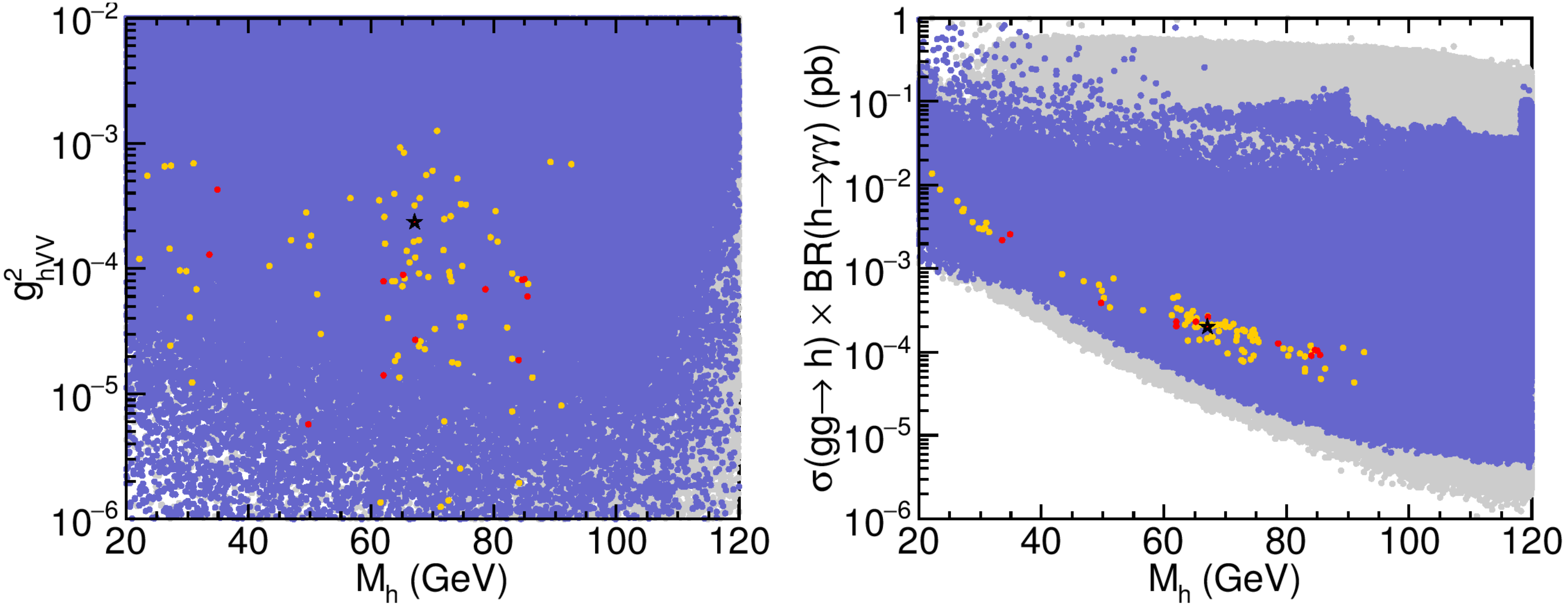


$\Rightarrow M_A \sim 140 \ldots 180$ GeV $\Rightarrow m_{\tilde{t}_1} \sim 350 \ldots 650$ GeV

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

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

Where is the light Higgs?



$\Rightarrow$ strongly reduced couplings to gauge bosons $\Rightarrow$ beyond LEP reach!

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

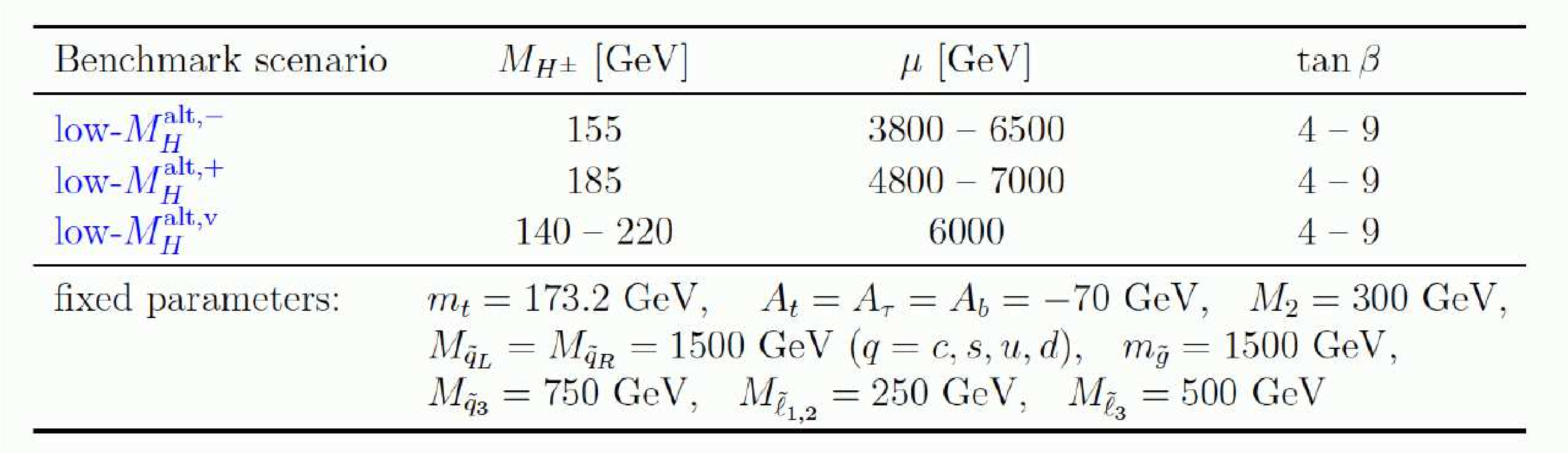
$\Rightarrow$ visible in $gg \to h \to \gamma\gamma$?

$\Rightarrow M_h \sim$ 95 GeV possible?!

New low-M_H benchmark scenarios

$\Rightarrow$ currently investigated by the LHCHXSWG!

Based on our best-fit region:



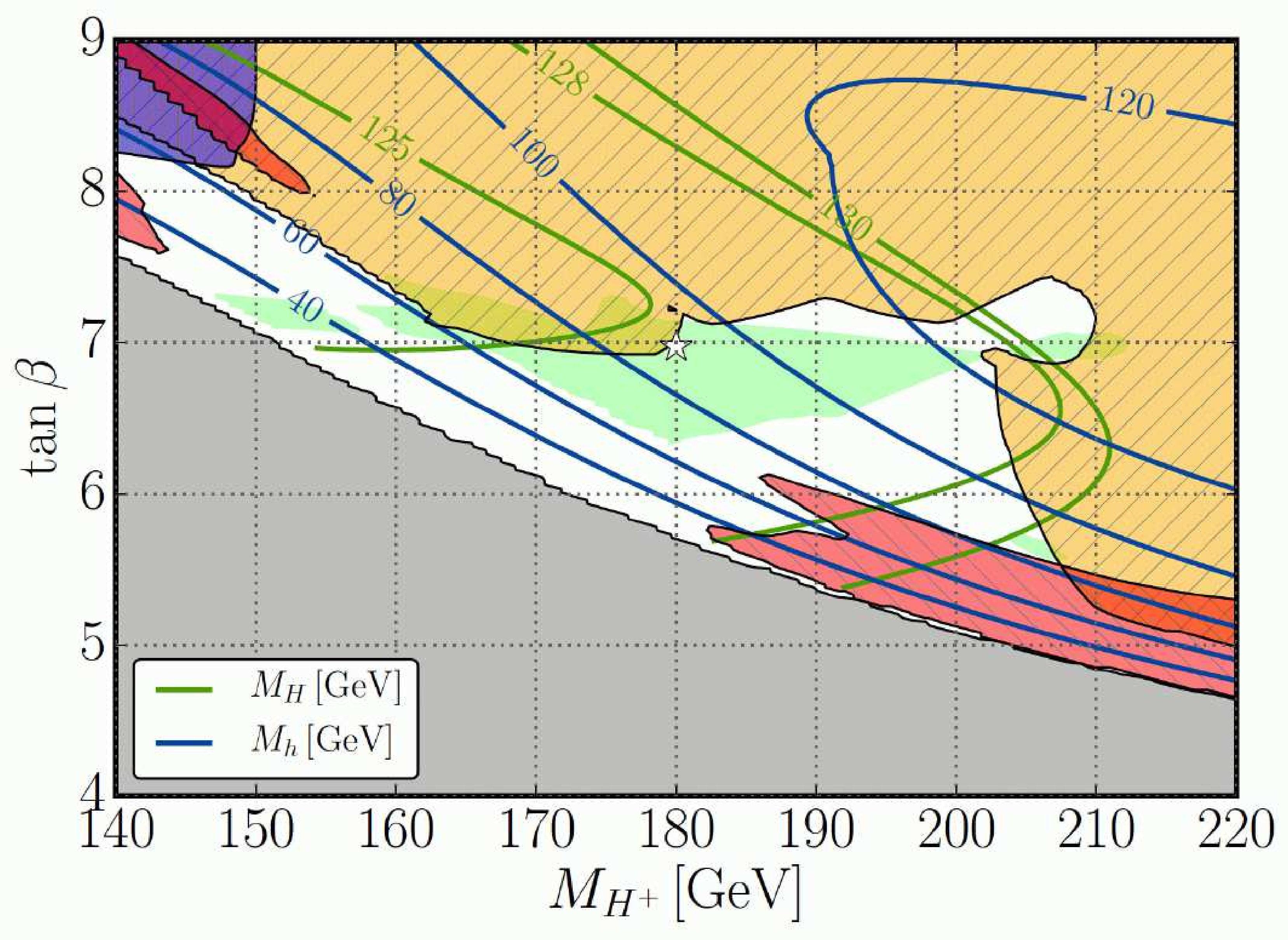
Benchmark scenario	$M_{H^\pm}$ [GeV]	μ [GeV]	$\tan\beta$
low-$M_H^{\text{alt},-}$	155	3800 – 6500	4 – 9
low-$M_H^{\text{alt},+}$	185	4800 – 7000	4 – 9
low-$M_H^{\text{alt,v}}$	140 – 220	6000	4 – 9
fixed parameters:	$m_t = 173.2$ GeV, $A_t = A_\tau = A_b = -70$ GeV, $M_2 = 300$ GeV, $M_{\tilde{q}_L} = M_{\tilde{q}_R} = 1500$ 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 $M_{H^\pm} > m_t$

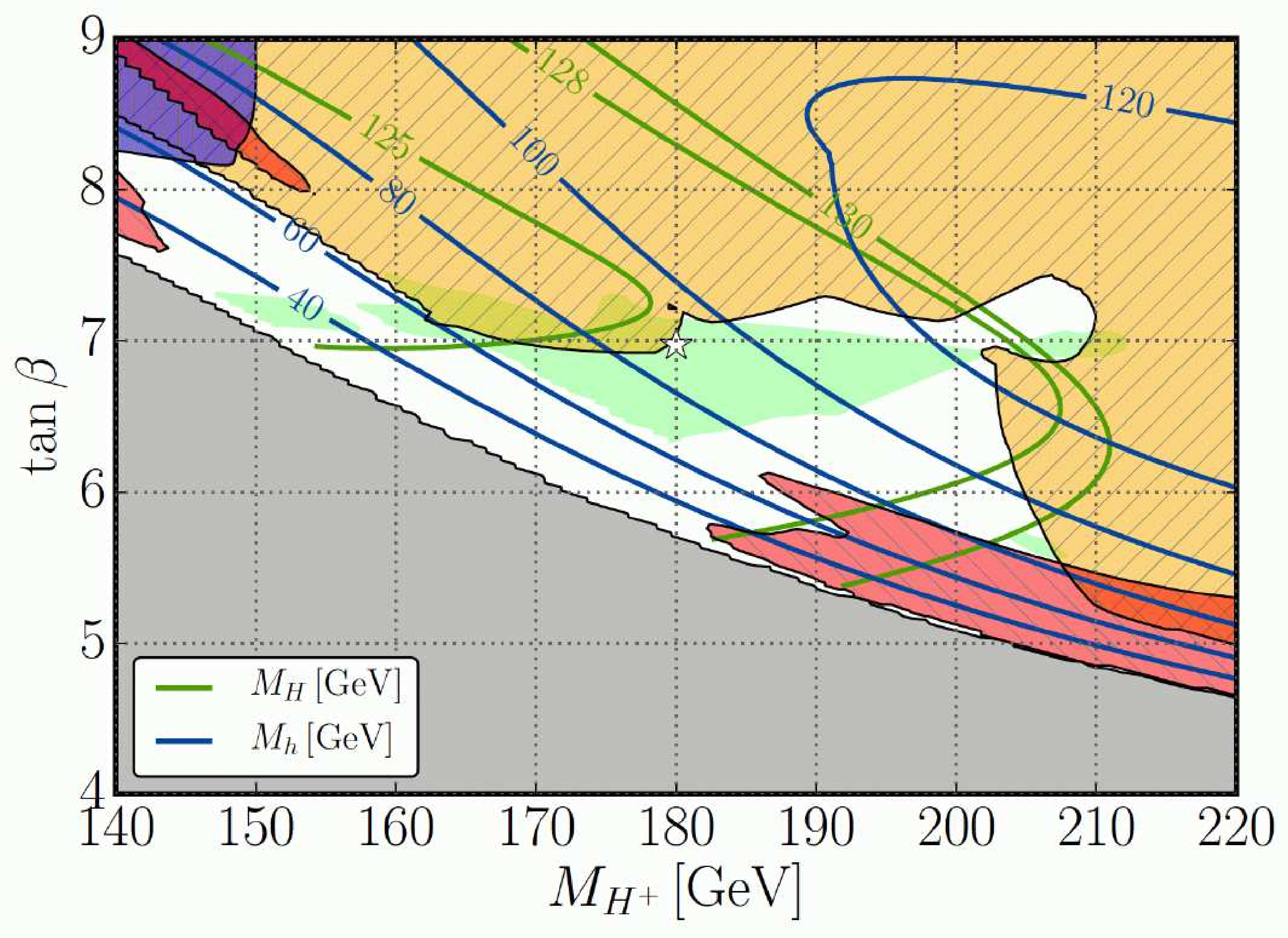
low-$M_H^{\text{alt v}}$: varied $M_{H^\pm}$ (μ fixed)

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

4. $\phi_{95} \to \gamma\gamma$

- What was seen in Run I?

- What was seen in Run II?

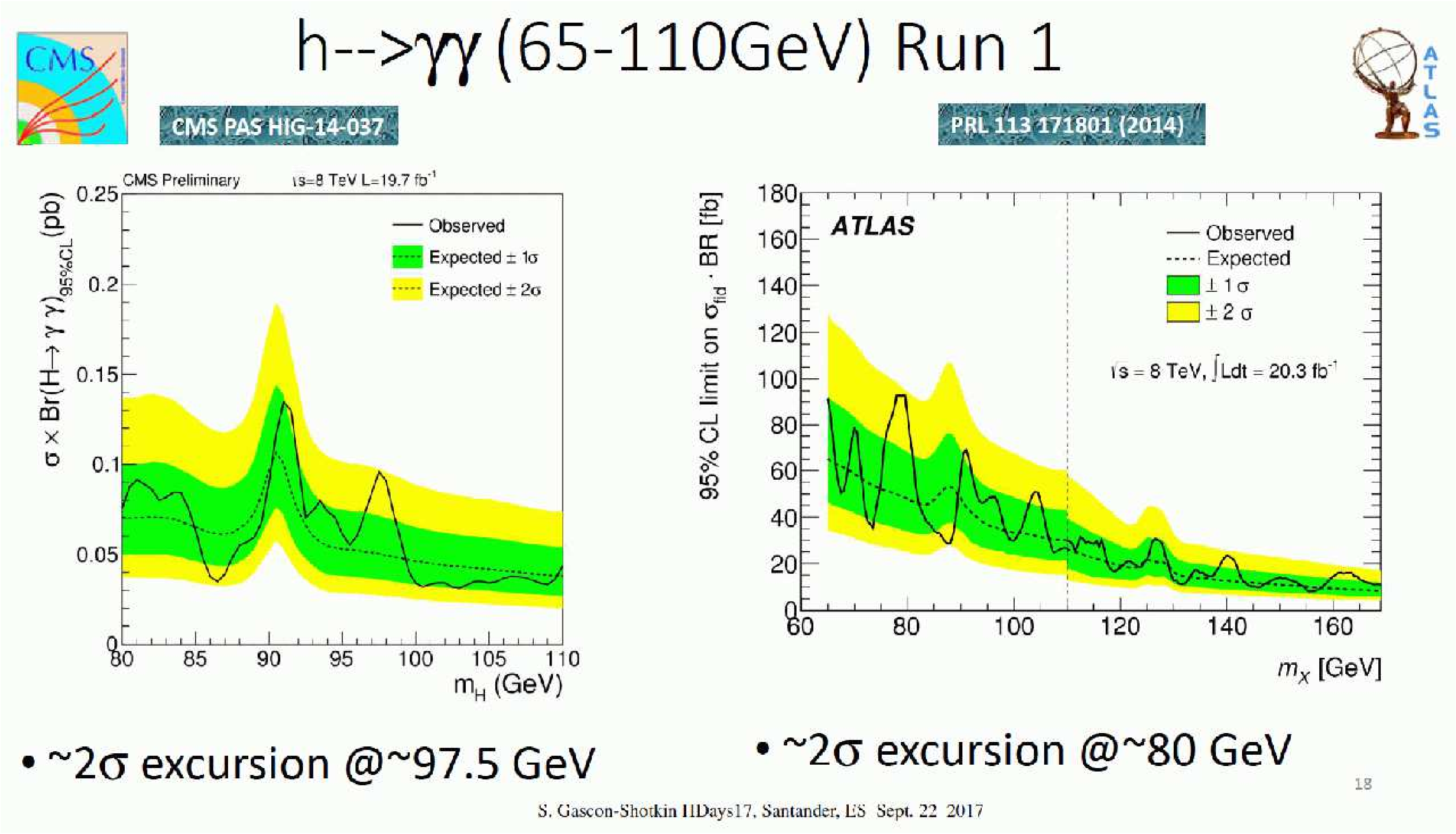
- What was seen at LEP?

- Should we get excited?

- Which model fits?

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

18

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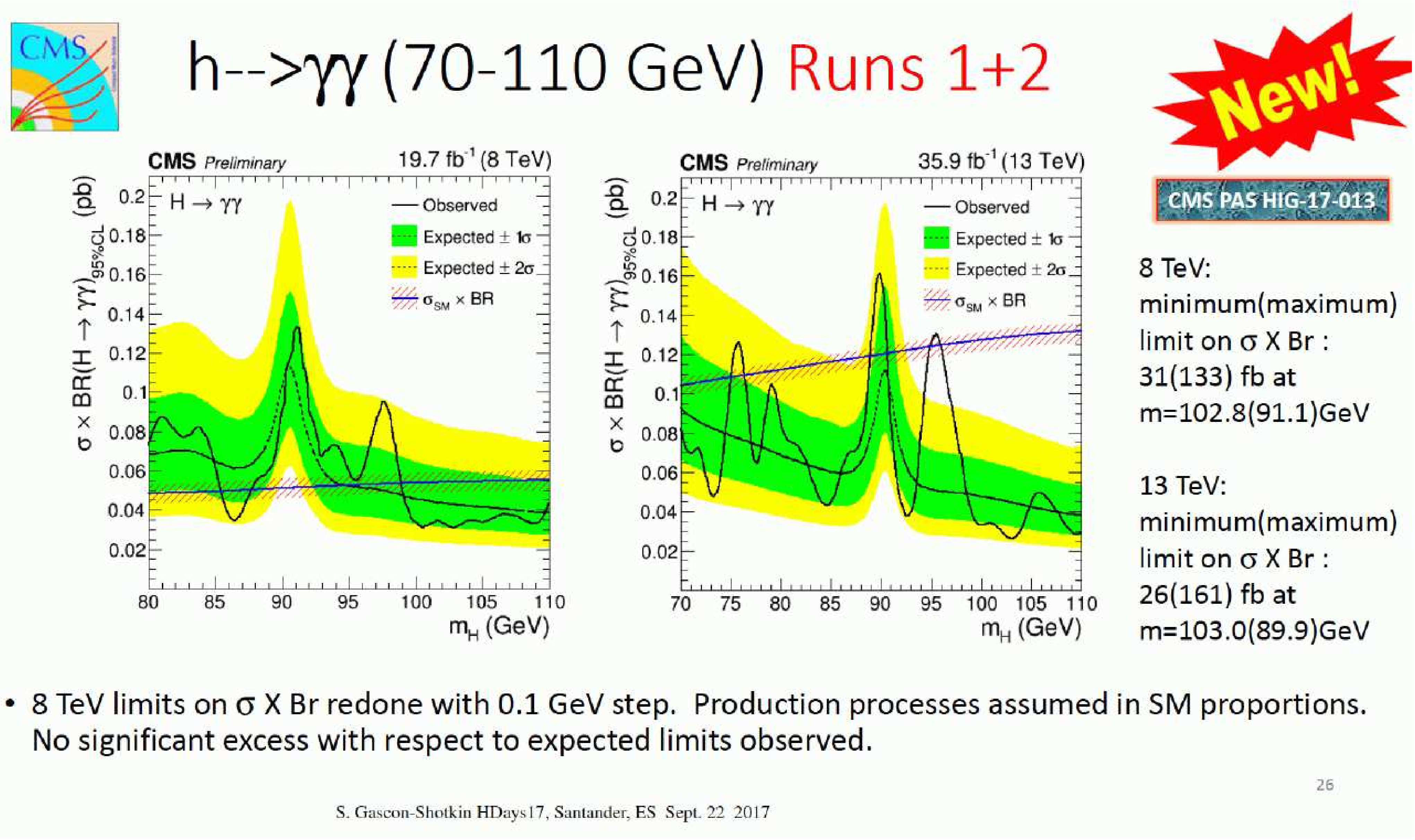
What was seen at Run II?

[*S. Shotkin, talk at HDays17*]



h-->γγ (70-110 GeV) Runs 1+2

CMS PAS HIG-17-013

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

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

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

26

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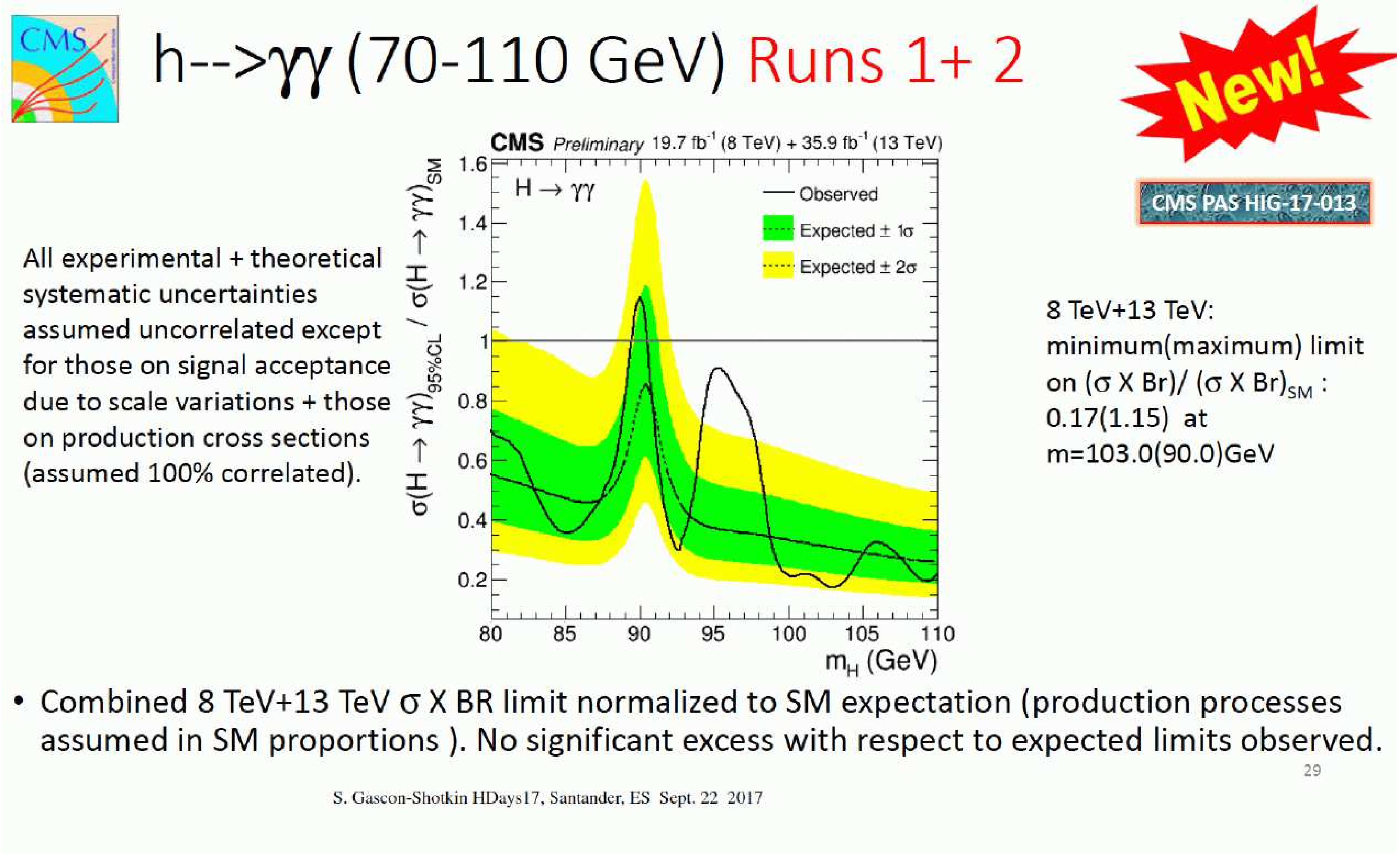
What was seen at Run II?

[S. Shotkin, talk at HDays17]



h-->$\gamma\gamma$ (70-110 GeV) Runs 1+ 2

CMS PAS HIG-17-013

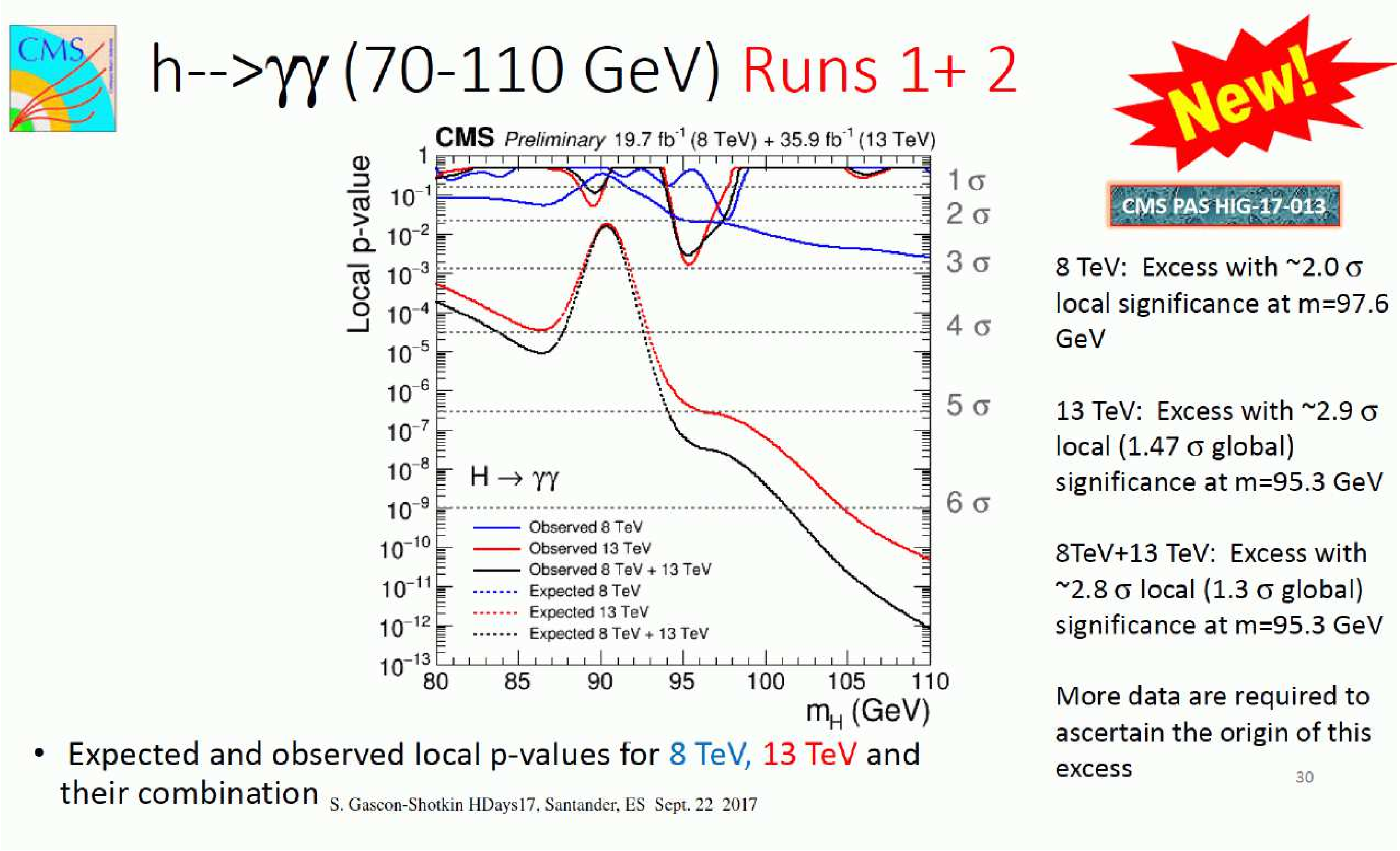
All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).

8 TeV+13 TeV: minimum(maximum) limit on $(\sigma \text{ X Br})/ (\sigma \text{ X Br})_{SM}$: 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.

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: 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

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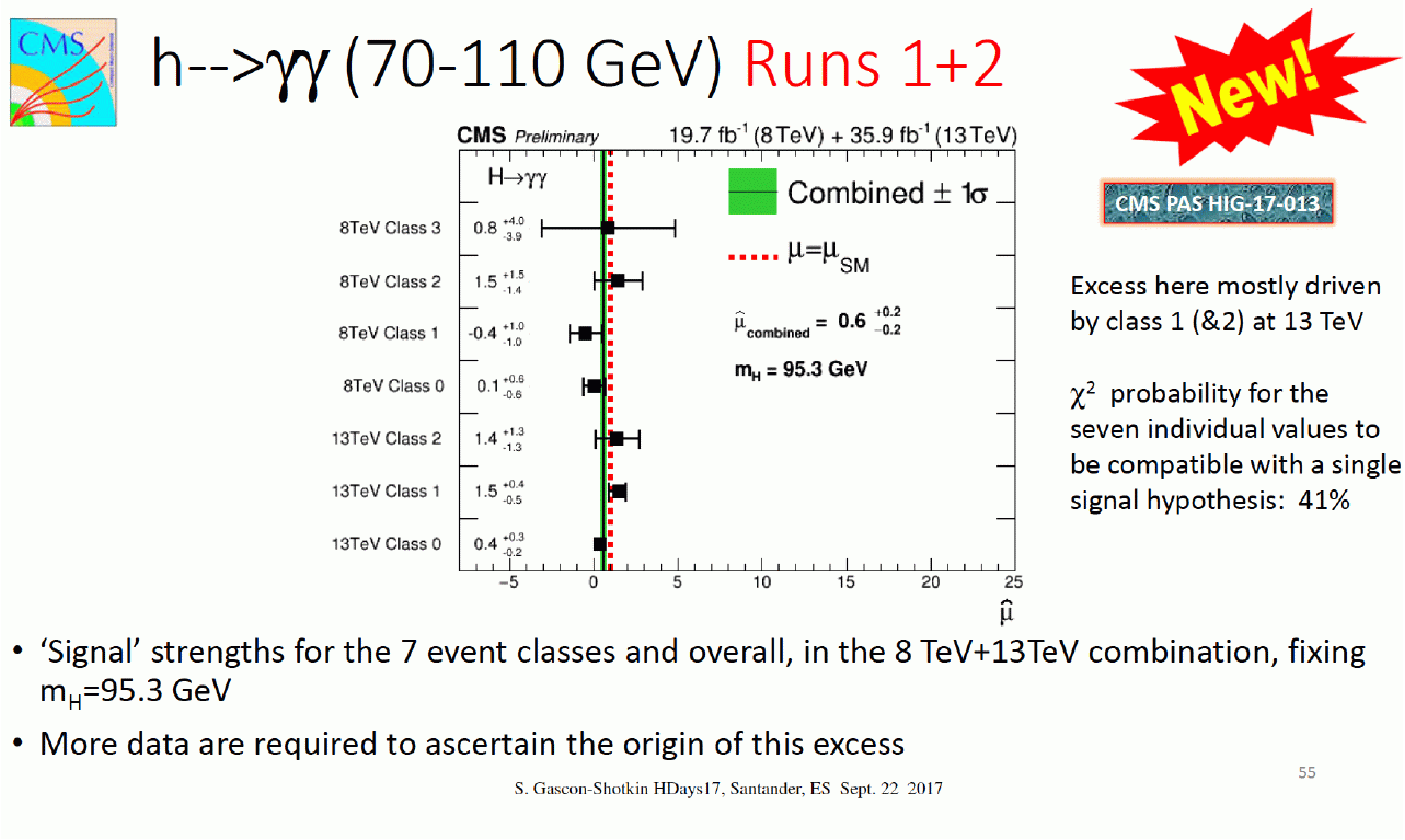
30

What was seen at Run II?

[S. Shotkin, talk at HDays17]



h-->γγ (70-110 GeV) Runs 1+2

New!

CMS PAS HIG-17-013

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

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

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

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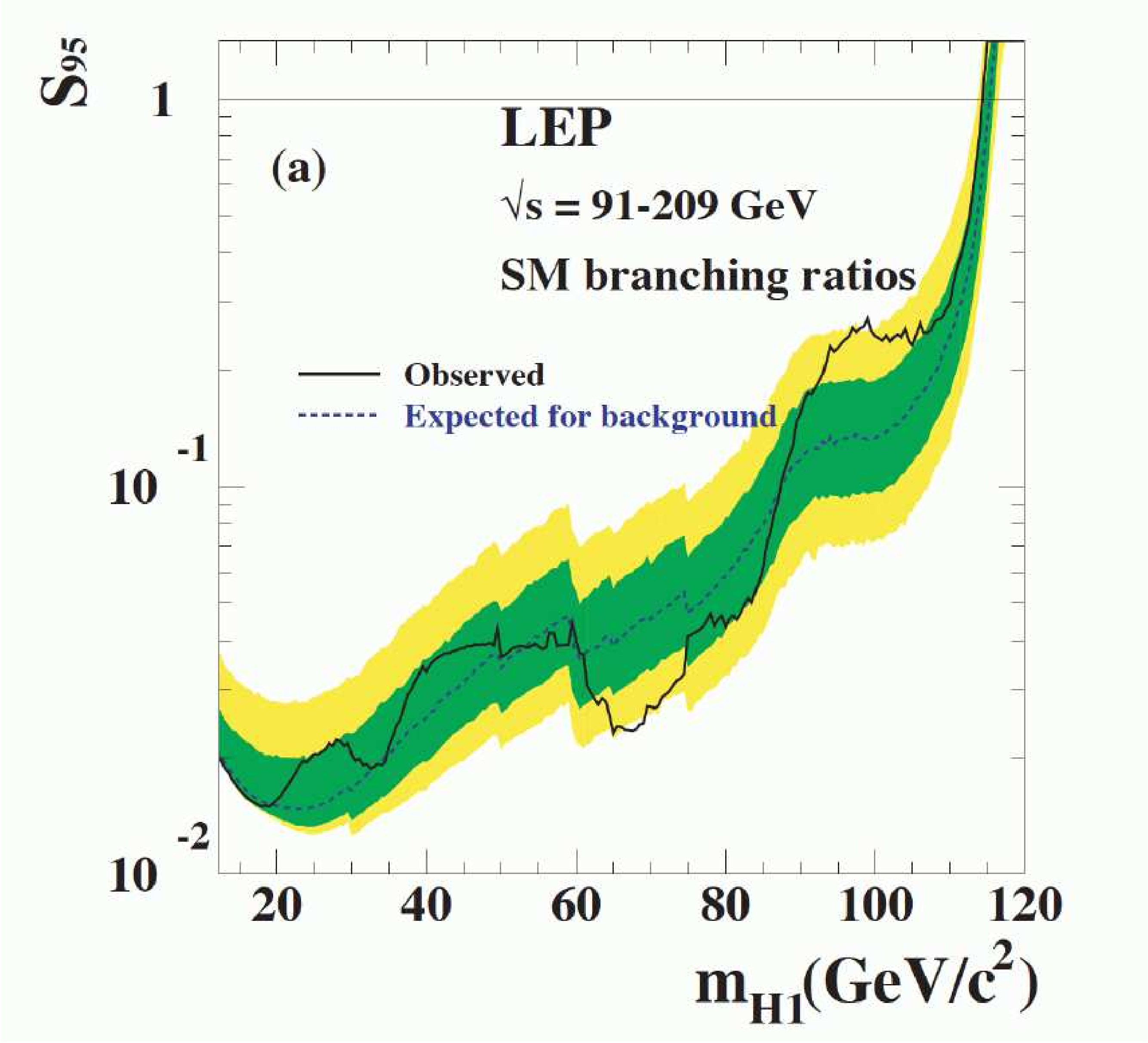
What was seen at LEP?

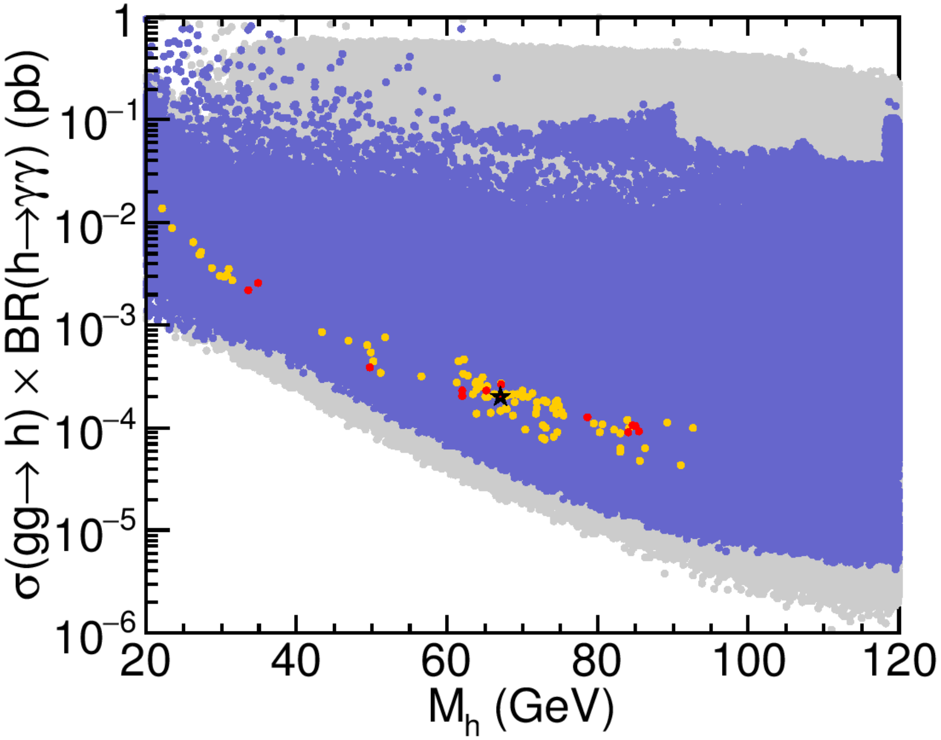


Should we get excited?

⇒ according to CMS no!

⇒ let's wait for ATLAS, ETA summer '18

Which model fits?



⇒ not the MSSM

⇒ 2HDM? NMSSM? . . . ?   HAVE FUN!

5. Conclusinos

- SUSY is (still) the best motivated BSM theory

- 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

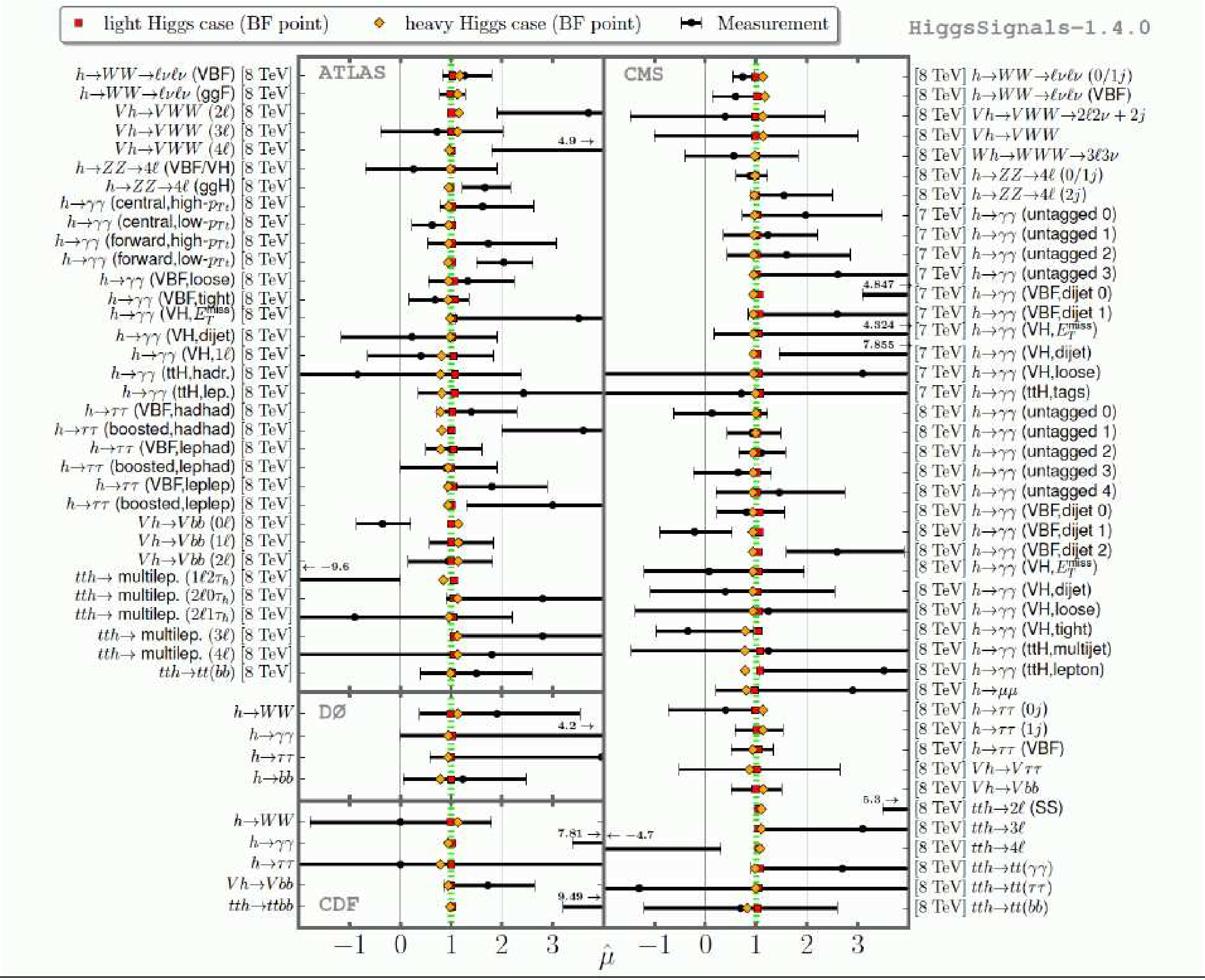
- MSSM results in GUT based models:
  - CMSSM, NUHM1: relatively high Higgs mass scales favored
  - NUHM2: somewhat lower values possible, but still high . . .

- pMSSM8:
  - light $\mathcal{CP}$-even Higgs for "all" M_A
    $\Rightarrow$ alignment without decoupling possible
  - heavy $\mathcal{CP}$-even Higgs at 125 GeV
    $\Rightarrow$ new benchmark scenarios

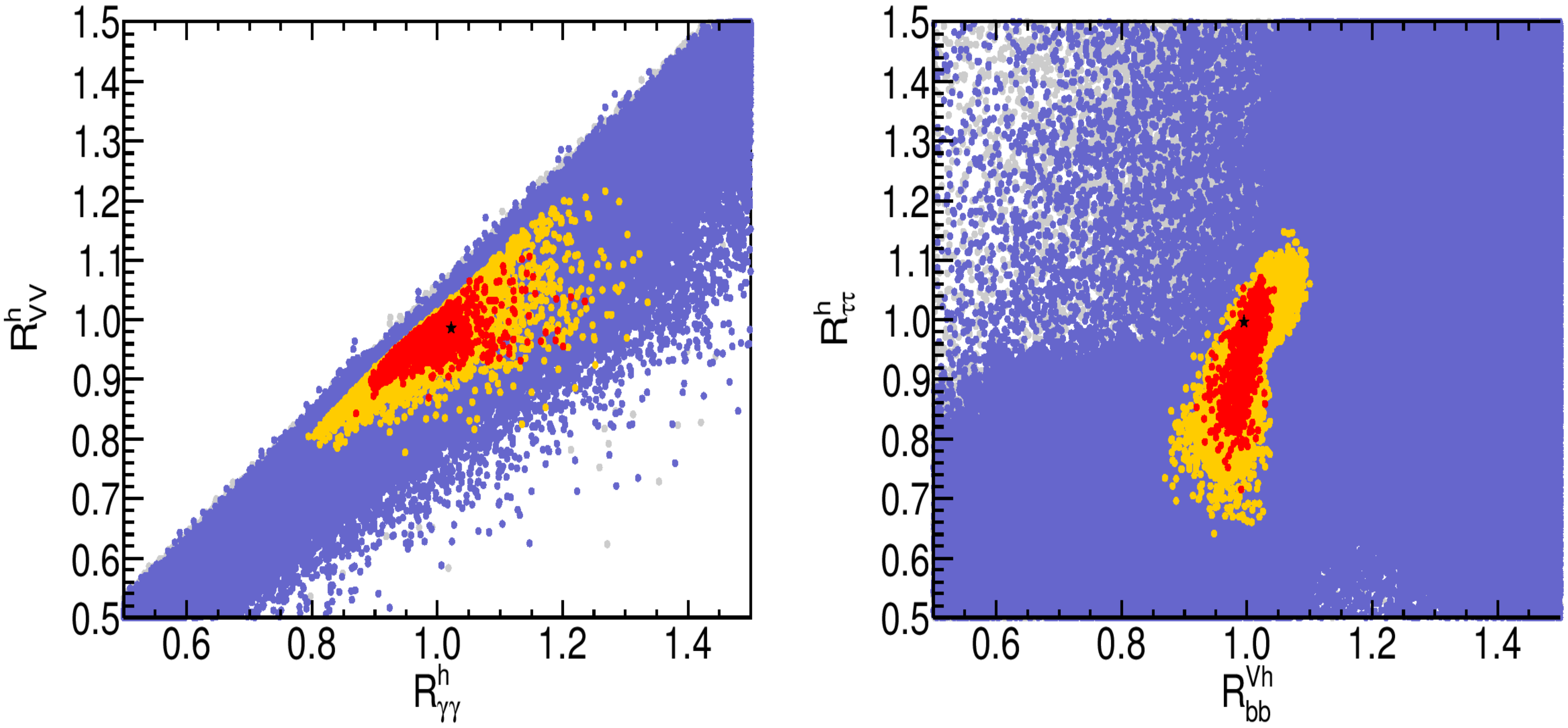
- $\phi_{95} \to \gamma\gamma$: new CMS result possibly interesting!


Further Questions?

Best-fit point rates in the two Higgs cases:



Light-Higgs case: preferred rates

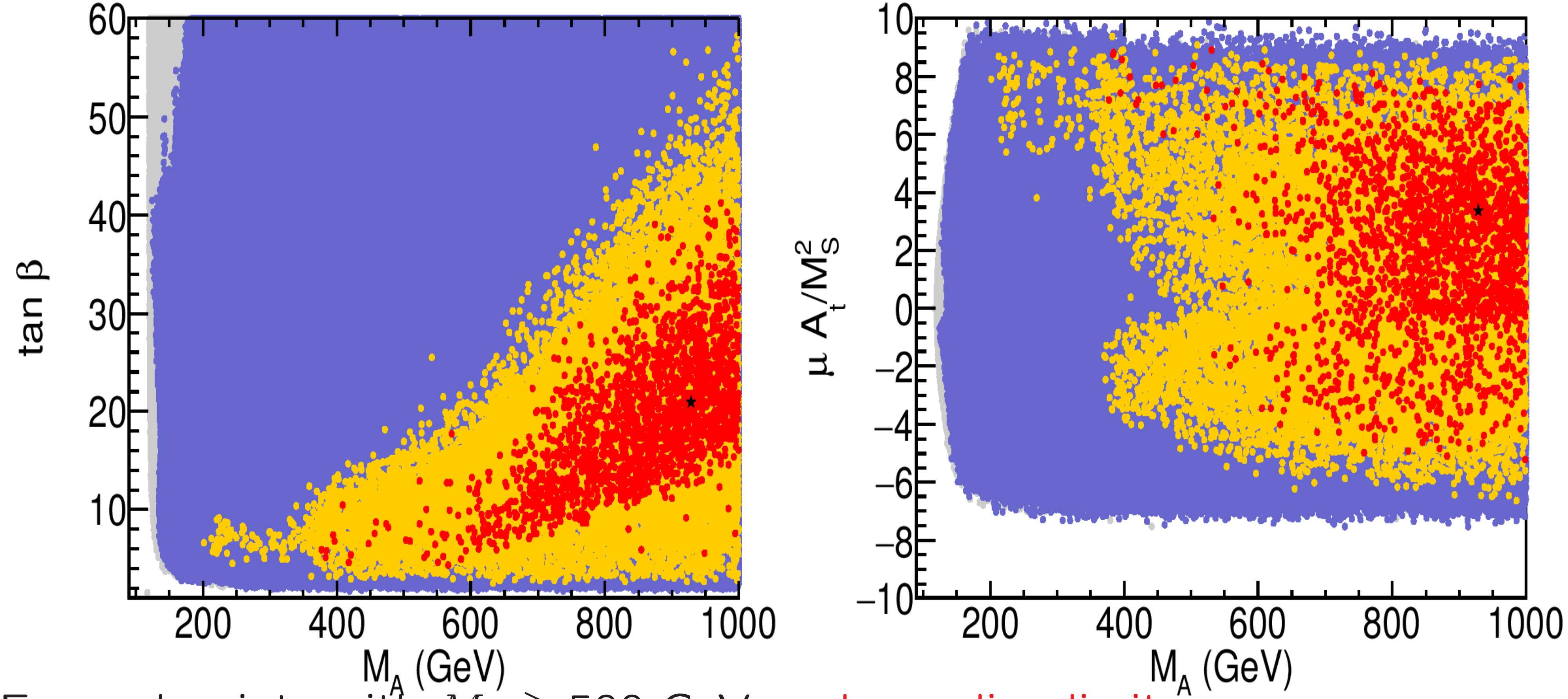


$R^h_{VV} = 0.99^{+0.09}_{-0.08}$, $R^h_{\gamma\gamma} = 1.02^{+0.16}_{-0.10}$, $R^{Vh}_{bb} = 1.00^{+0.02}_{-0.05}$, $R^h_{\tau\tau} = 1.00^{+0.06}_{-0.20}$

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

⇒ but some (BSM) spread is allowed!

Light-Higgs case: preferred parameters



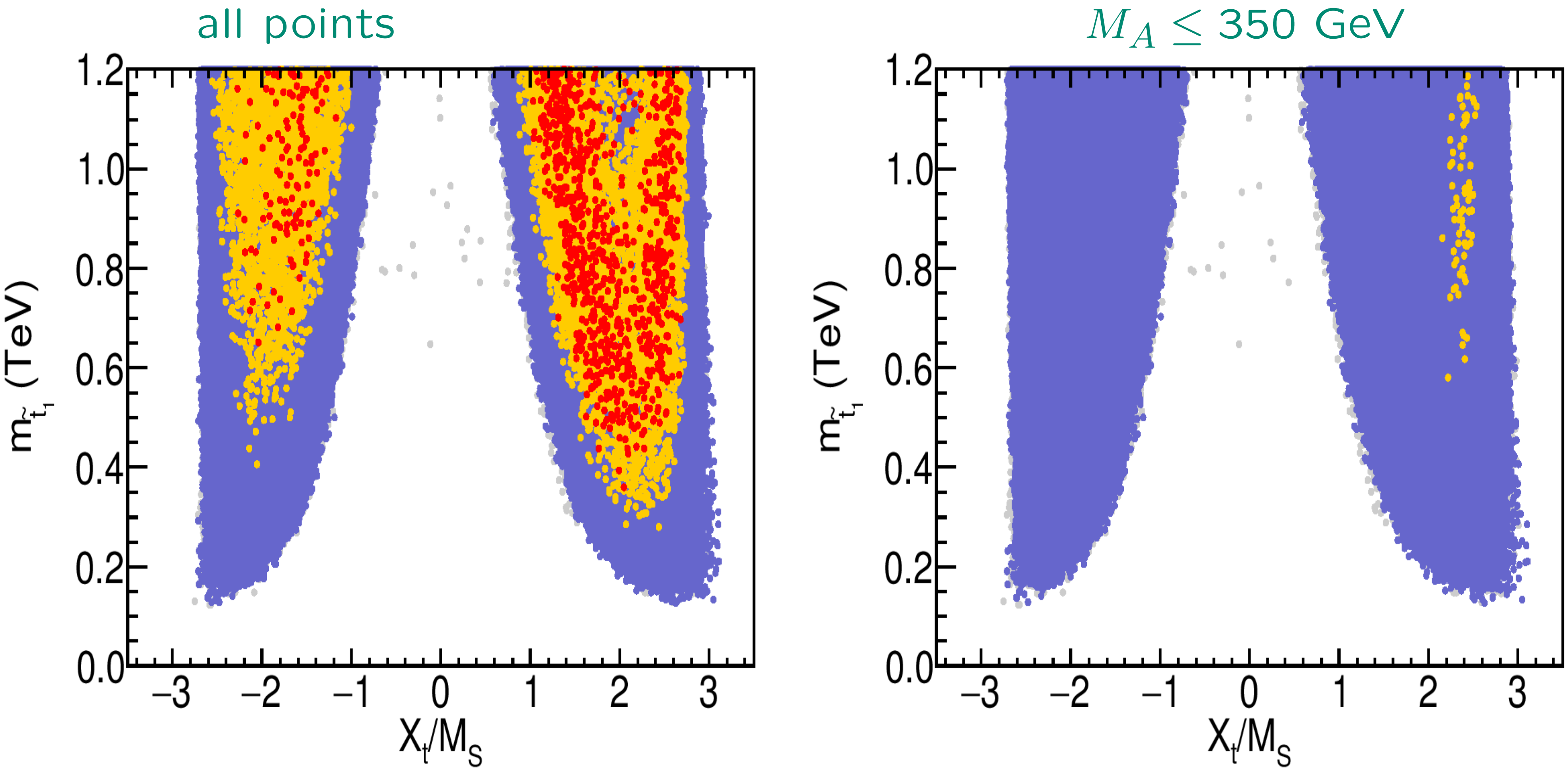
Favored points with $M_A \gtrsim$ 500 GeV $\Rightarrow$ decoupling limit
$M_A \gtrsim$ 200 GeV $\Rightarrow$ alignment limit

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 $\mu > 0$)

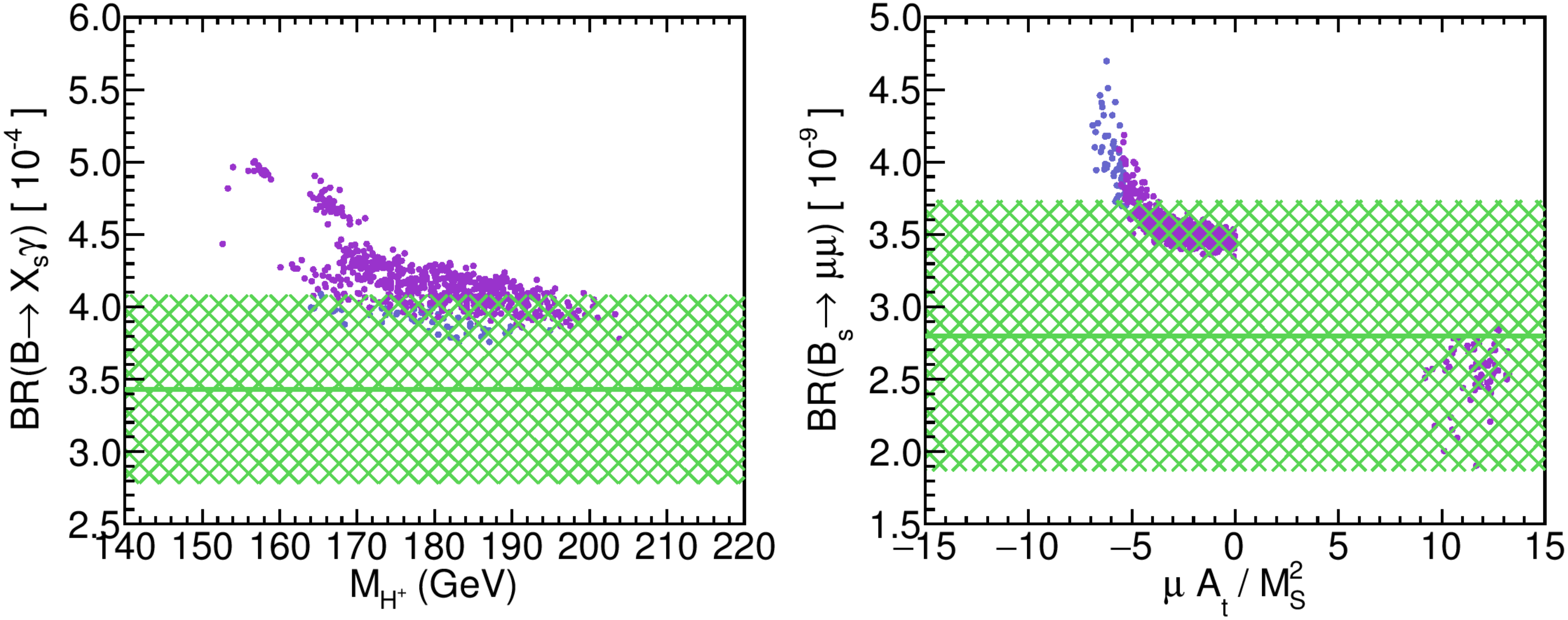
Light-Higgs case: preferred parameters in the $\tilde{t}$ sector



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

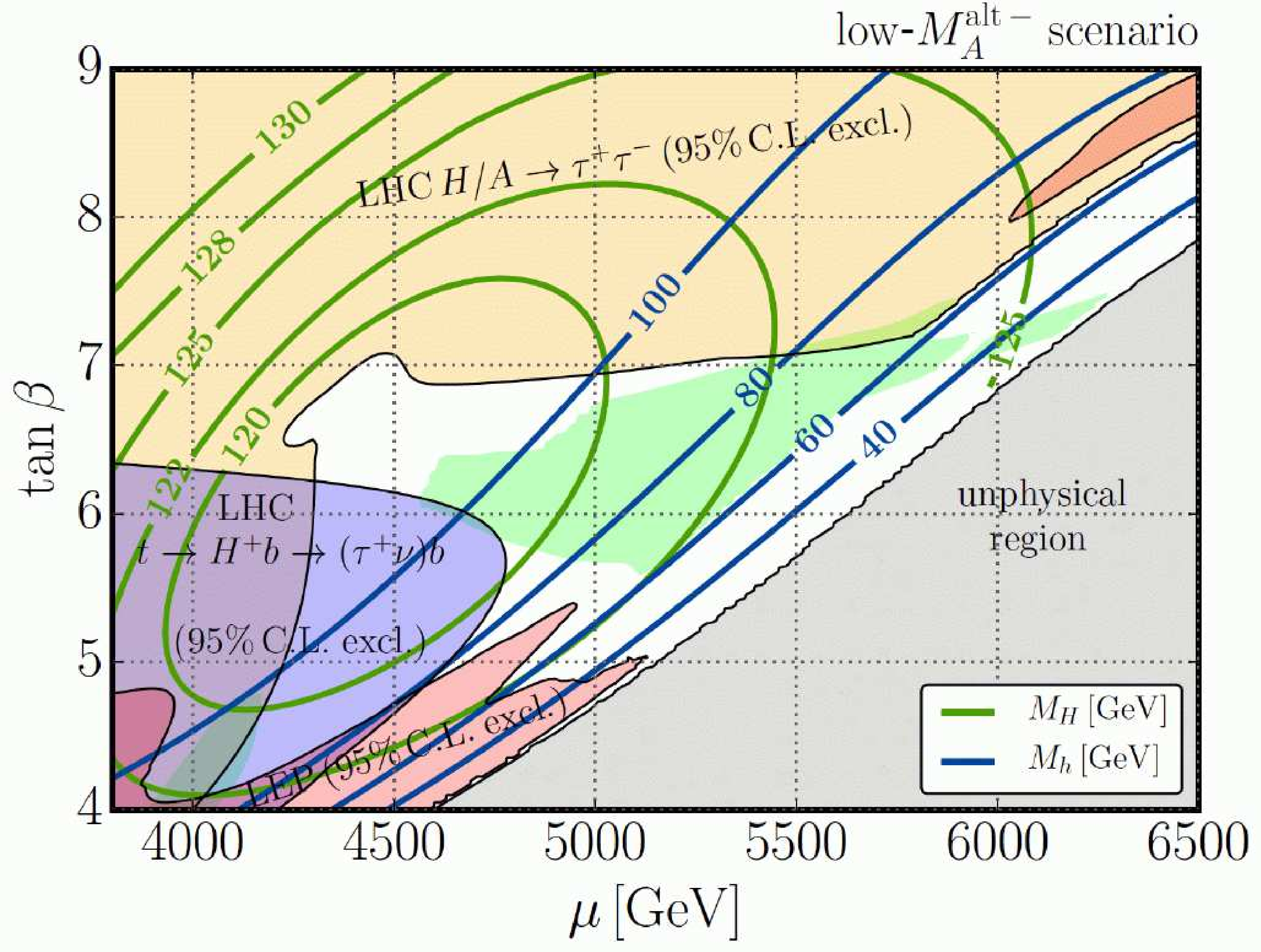
(even lighter stops possible with $M_{\tilde{t}_L} \neq M_{\tilde{t}_R}$)

B-physics constraints?



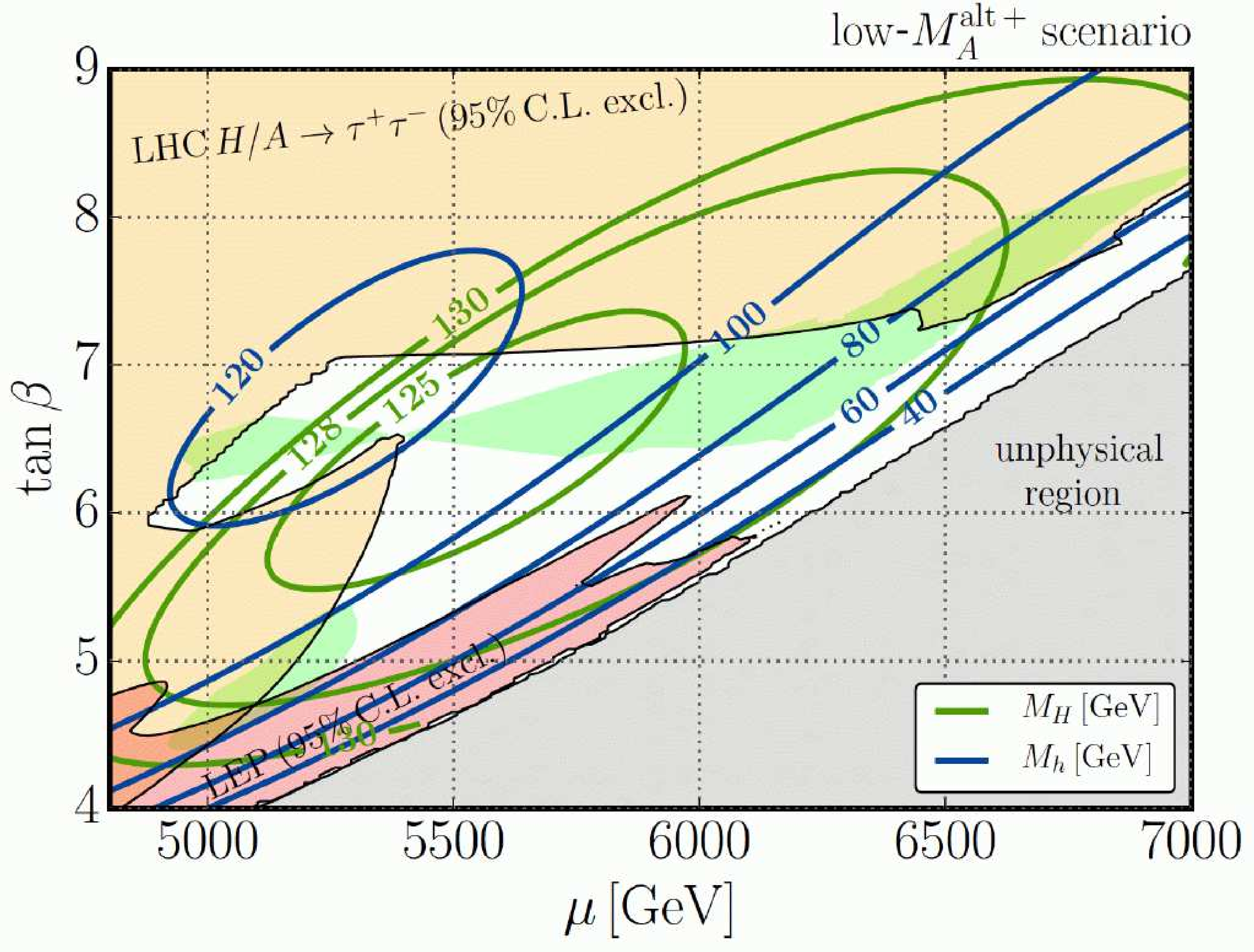
⇒ flavor constraints fulfilled!

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



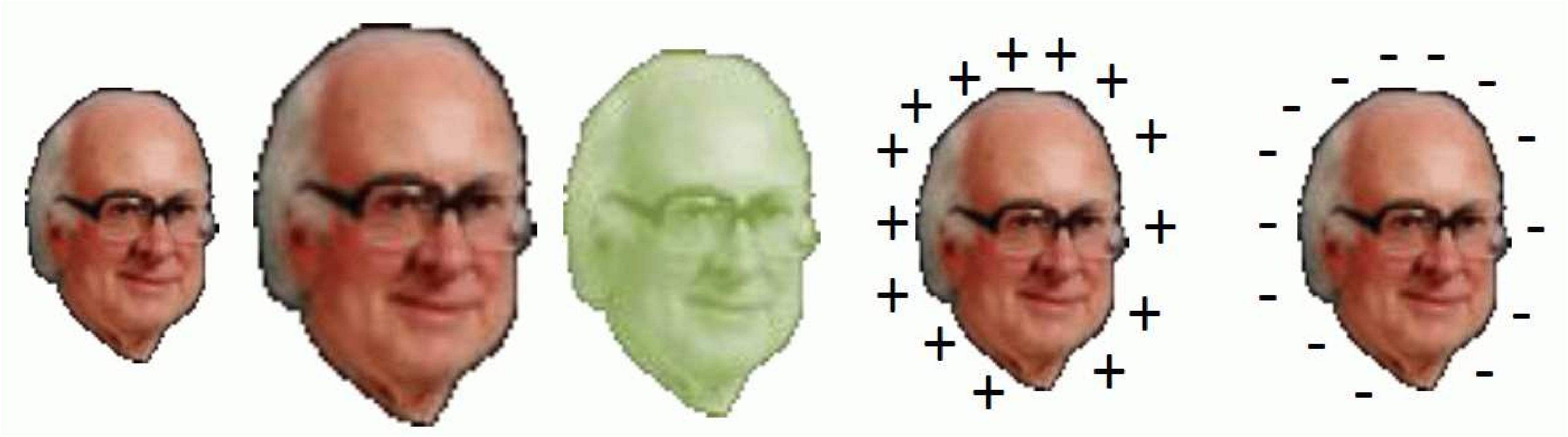
⇒ green area in agreement with all data!

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!

Results in the NMSSM



Some NMSSM Higgs theory (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

$$
\begin{aligned}
V = \; & (\tilde{m}_1^2 + |\cancel{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\cancel{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
& + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

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

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

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:

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

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

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

Mass of the charged Higgs:

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

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

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:

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

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

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

Mass of the charged Higgs:

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

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

⇒ $M_{h_1}^\text{MSSM,tree} \le M_{h_1}^\text{NMSSM,tree}$, 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!

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“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:

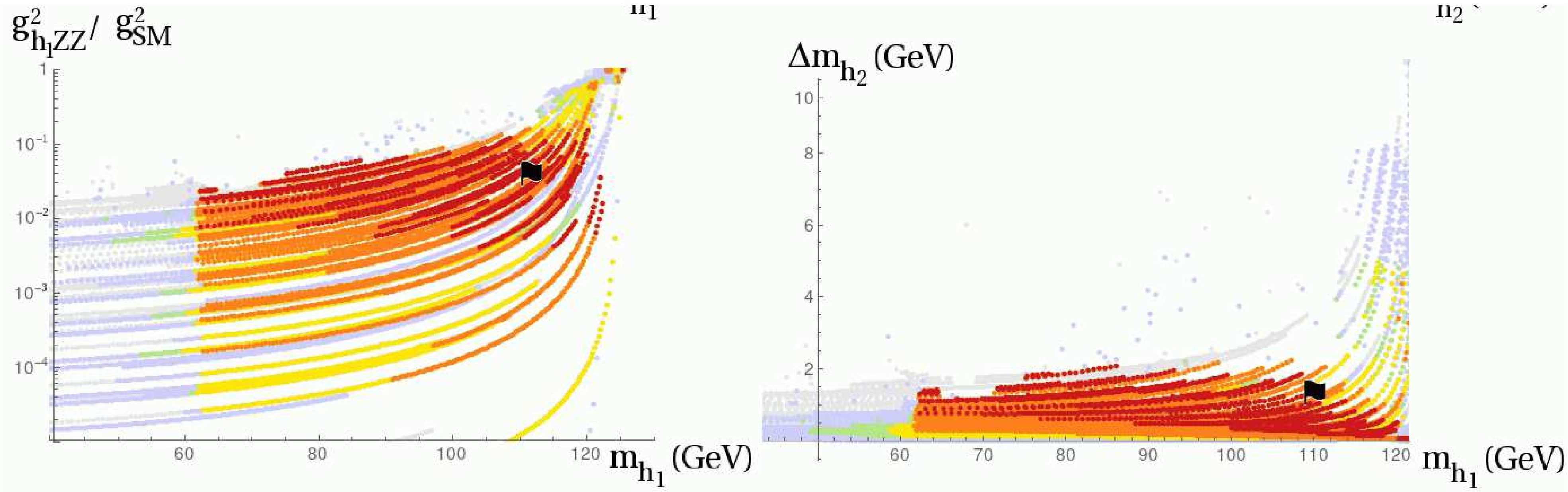
Light, singlet-like Higgs below 125 GeV

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

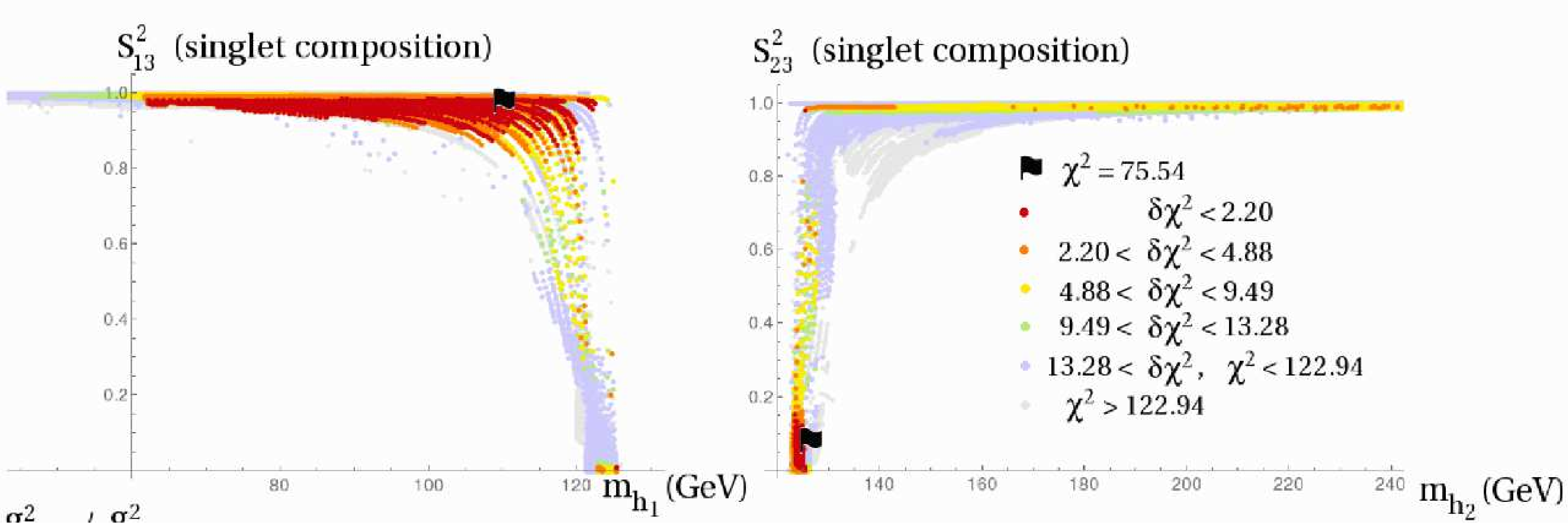
⇒ strongly reduced couplings to gauge bosons!

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