"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!**"

Insights/Updates in the MSSM:
Impact on Higgs Boson Searches

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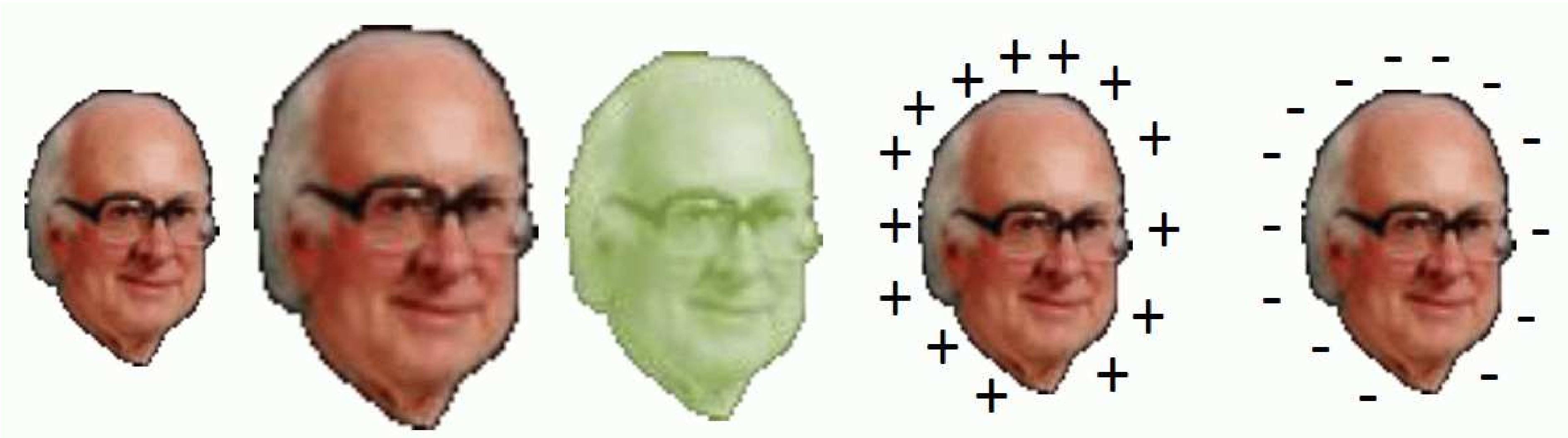
CERN, 10/2016

- Introduction
- SUSY Higgs Mass Calculations
- Higgs boson mass scales from rate measuements?
- pMSSM8 results
- Complex parameters
- Conclusions

1. Introduction



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)

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

$\tilde{t}$ 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:

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

Data we have:

– Higgs boson mass (LHC)

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- SUSY searches (LHC)

- 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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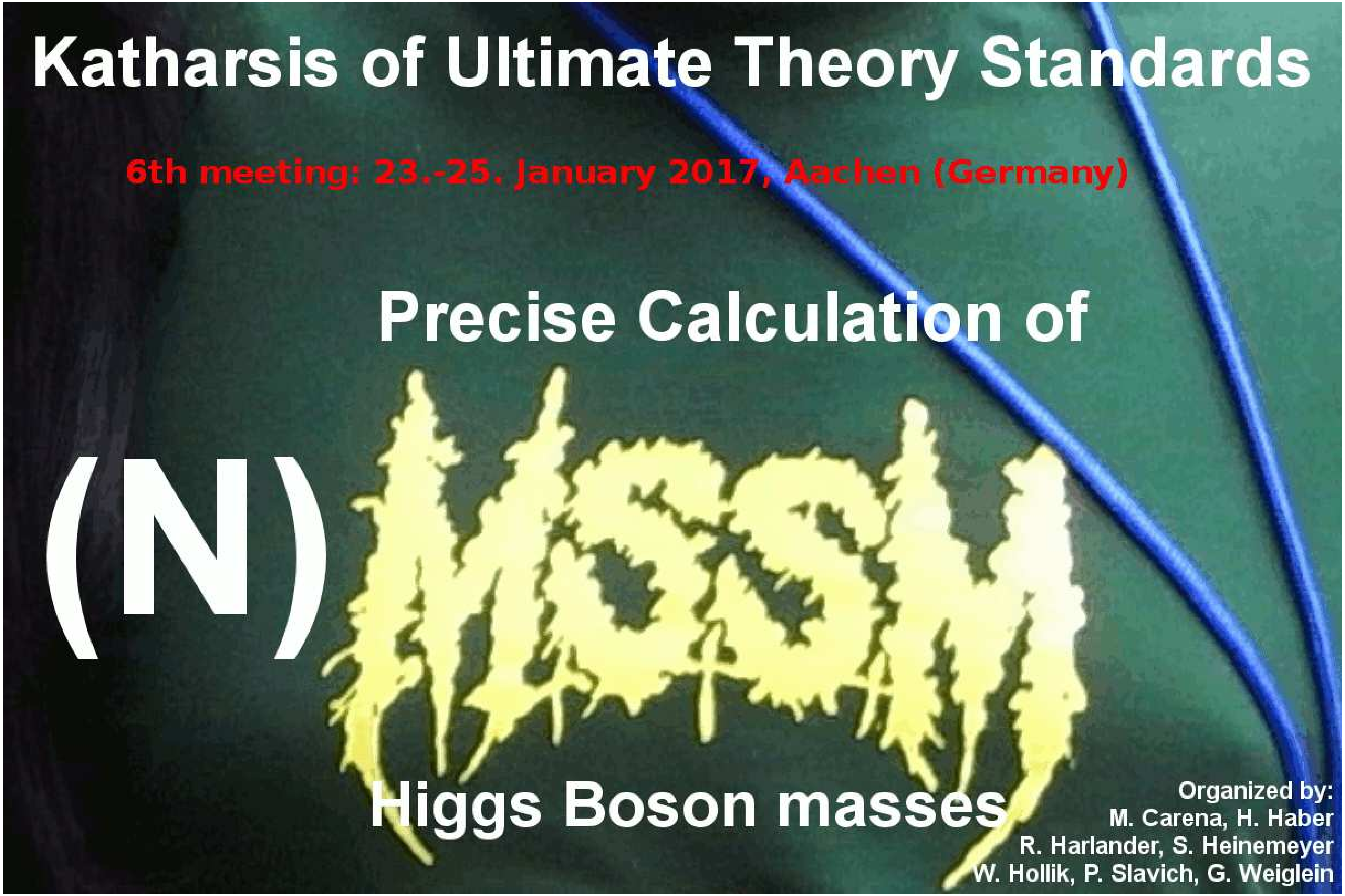
MSSM theory:

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

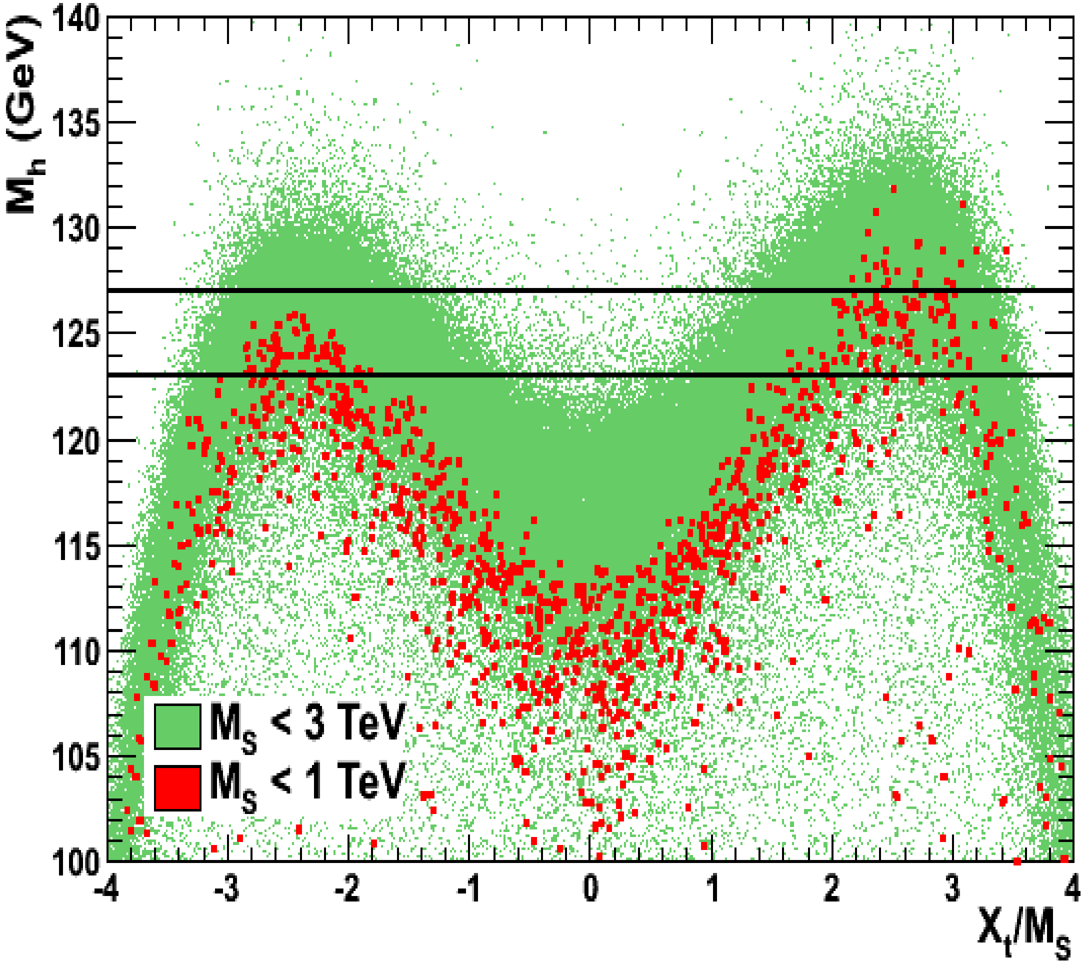
$\to$ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

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



Stop masses vs. $M_h = 125$ GeV

[*A. Arbey et al., '11*]



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

⇒ results depend strongly on your M_h calculation/precision!

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

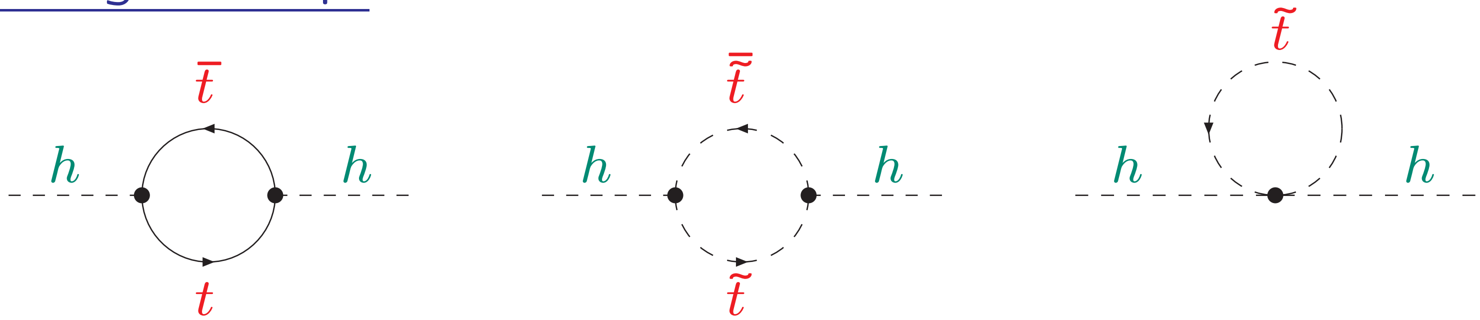
Calculation of renormalized Higgs boson self-energies:

$$\hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots$$

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 $\Rightarrow X_t^{\mathrm{OS}}$

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

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: $$\Delta M_h^2 \sim m_t^2 \Big\{ \quad \alpha_t \alpha_s^2 \left[L^3 + L^2 + L + L^0\right] \\ + \alpha_t^2 \alpha_s \left[L^3 + L^2 + L + L^0\right] \\ + \alpha_t^3 \left[L^3 + L^2 + L + L^0\right] \Big\}$$

Partial results: [*S. Martin '07*]

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

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

Large $m_{\tilde{t}}$ $\Rightarrow$ large L $\Rightarrow$ resummation of logs necessary $\Rightarrow$ 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: $M_{\mathsf{SUSY}} = M_{\mathsf{S}} \sim m_{\tilde{t}}$

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: $h_t, g_s(m_t) \to h_t, g_s(M_{\mathsf{S}})$

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

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

3. Evaluate M_h^2

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

Method I ⊕ II: Combination of FD and RGE result

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

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

Technical aspect:

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

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

⇒ 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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  $\Rightarrow$ included into FeynHiggs

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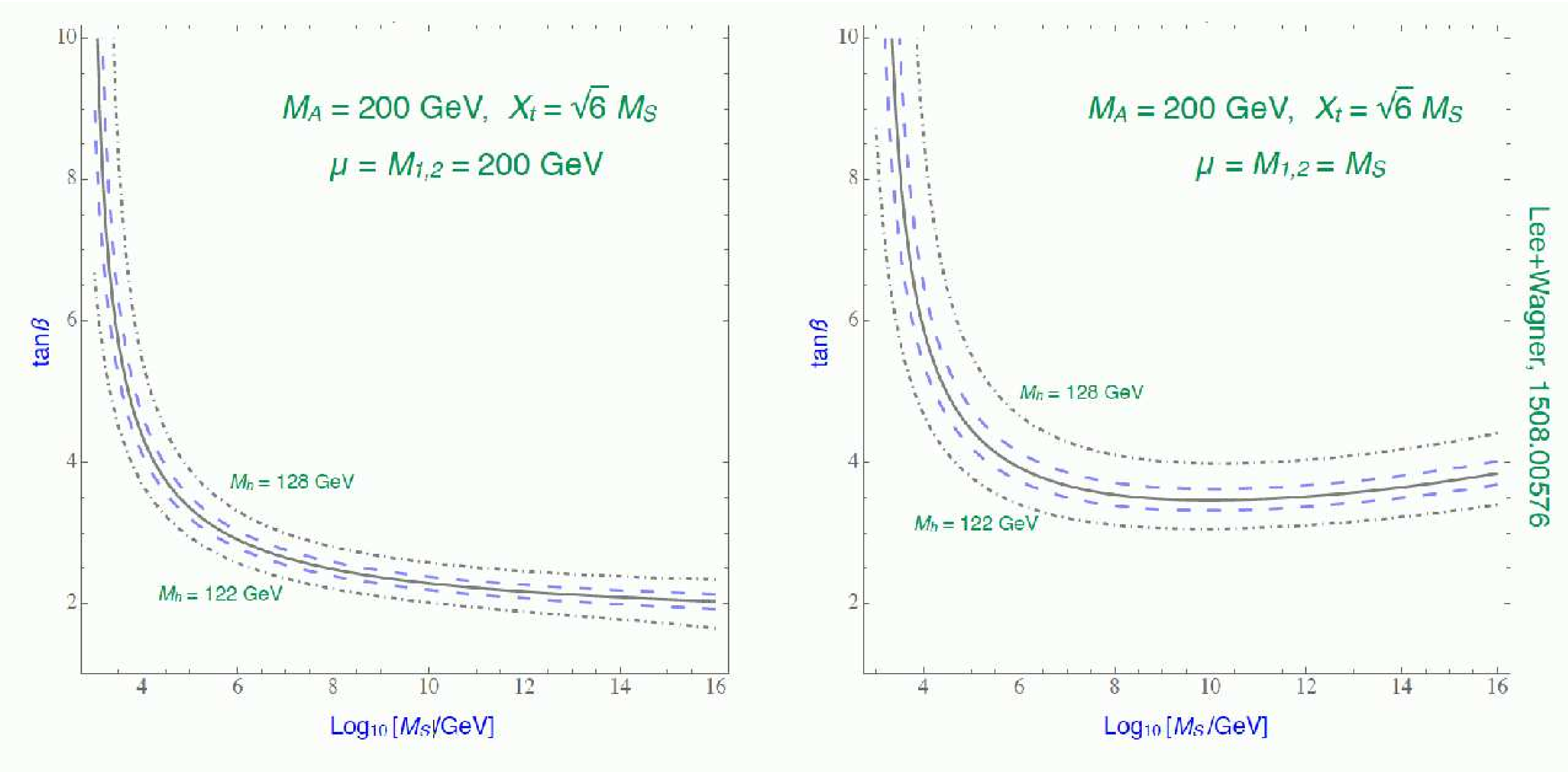
- "Two Higgs Doublet Model" below M_S
  $\Rightarrow$ work in progress for FeynHiggs , only code so far: MhEFT

- Splitting in the scalar top sector
  $\Rightarrow$ future work

- . . .

2HDM as low-energy theory: MhEFT



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

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

Example for M_h calculations: [P. Slavich, HDays16]

NOTE: the updates in FeynHiggs affect also the “standard” scenarios

Simplified benchmark point: $\tan\beta = 20$, all SUSY masses = 1 TeV, X_t varied to maximize M_h

Public code	M_h [GeV]
SPheno 3.3.8	126.3
SuSpect 2.43	125.8
SoftSUSY 3.7.0	124.3
NMSSMTools 4.9.1	124.6
FeynHiggs 2.11.3	128.1
FeynHiggs 2.12.0	126.3

Same $\overline{DR}$ calculation of the Higgs mass, differences in determination of top Yukawa (SPheno, SuSpect, SoftSUSY, NMSSMTools)

OS calculation of Higgs mass (using running m_t at NNLO in loops) (FeynHiggs 2.11.3)

Including resummation plus EW effects in m_t (FeynHiggs 2.12.0)

All of these codes include full 1-loop + dominant (strong+Yukawa) 2-loop corrections to M_h

Relevance for the LHCHXSWG?!

Classical benchmark scenarios

- m_h^{max}
- $m_h^{\text{mod}+}$
- $m_h^{\text{mod}-}$
- light-stop
- light-stau
- tau-phobic

⇒ change in M_h calculation?!

low-tan β scenarios: low-tb-high, hMSSM

Proper EFT code(s) for light 2HDM / heavy SUSY now available

⇒ Time to update our benchmark scenarios?

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 later!)
   $\Rightarrow$ 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*]

$\to$ $\mathcal{CP}$ 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, $c_{\beta-\alpha} = 0$
$Z_6 = 0$ 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]

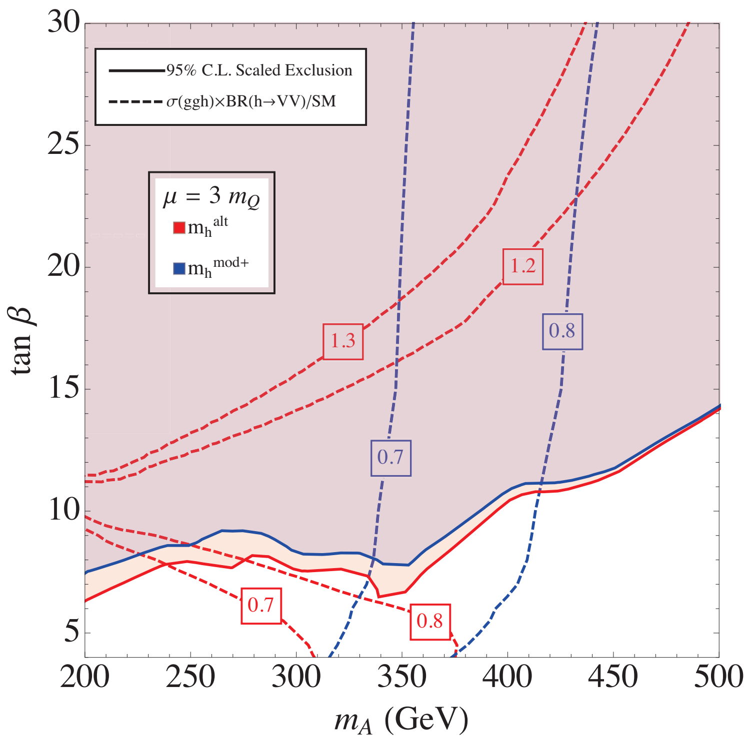
In the MSSM $Z_6 = 0$ can be obtained through an "accidental" cancellation between tree-level and loop contribution, roughly at:

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

Compare: $m_h^{\text{mod}+}$ and m_h^{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

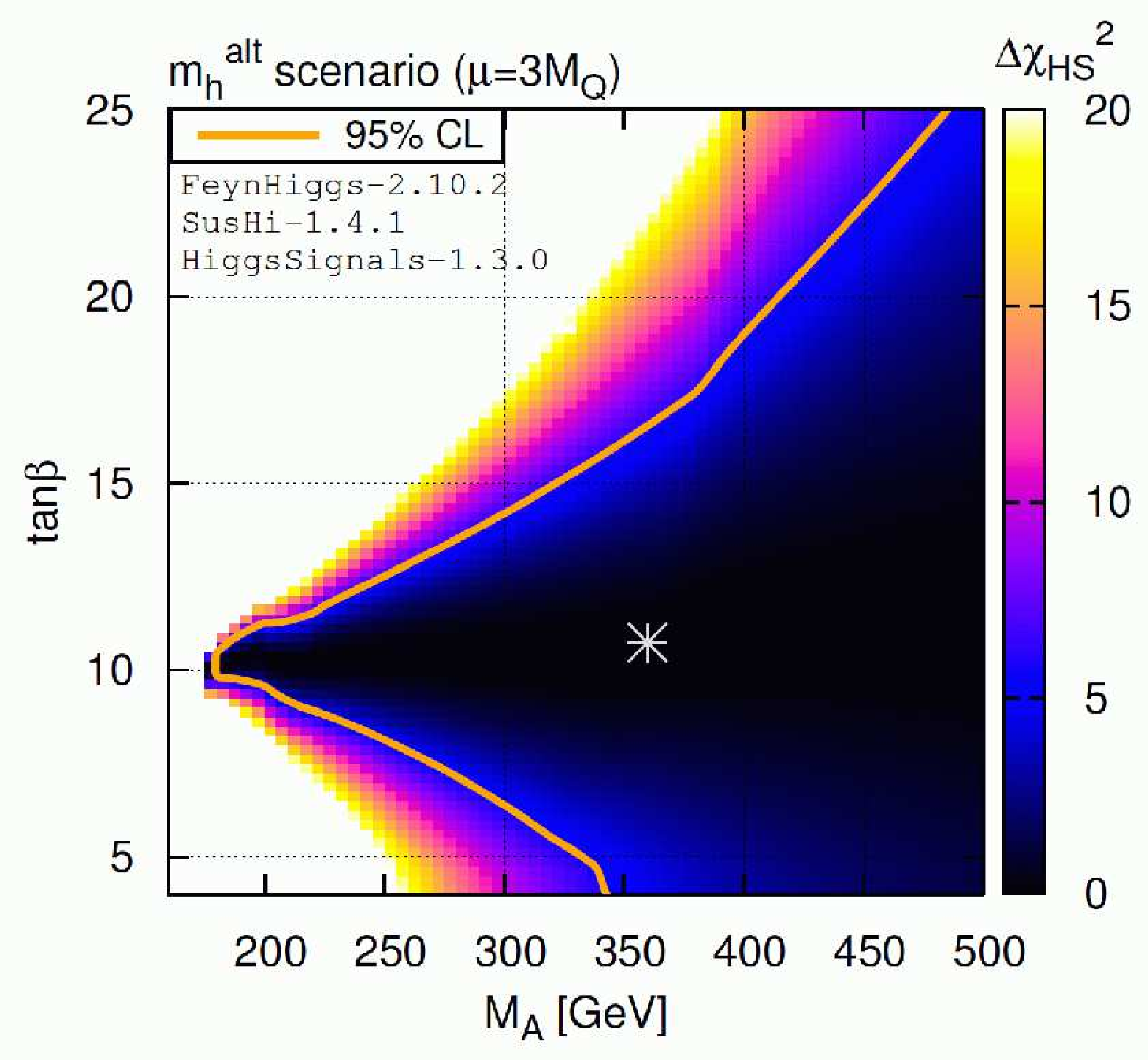
(low M_A and $\tan\beta$: tune $M_S \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

$\Rightarrow$ SM-like Higgs for all M_A



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

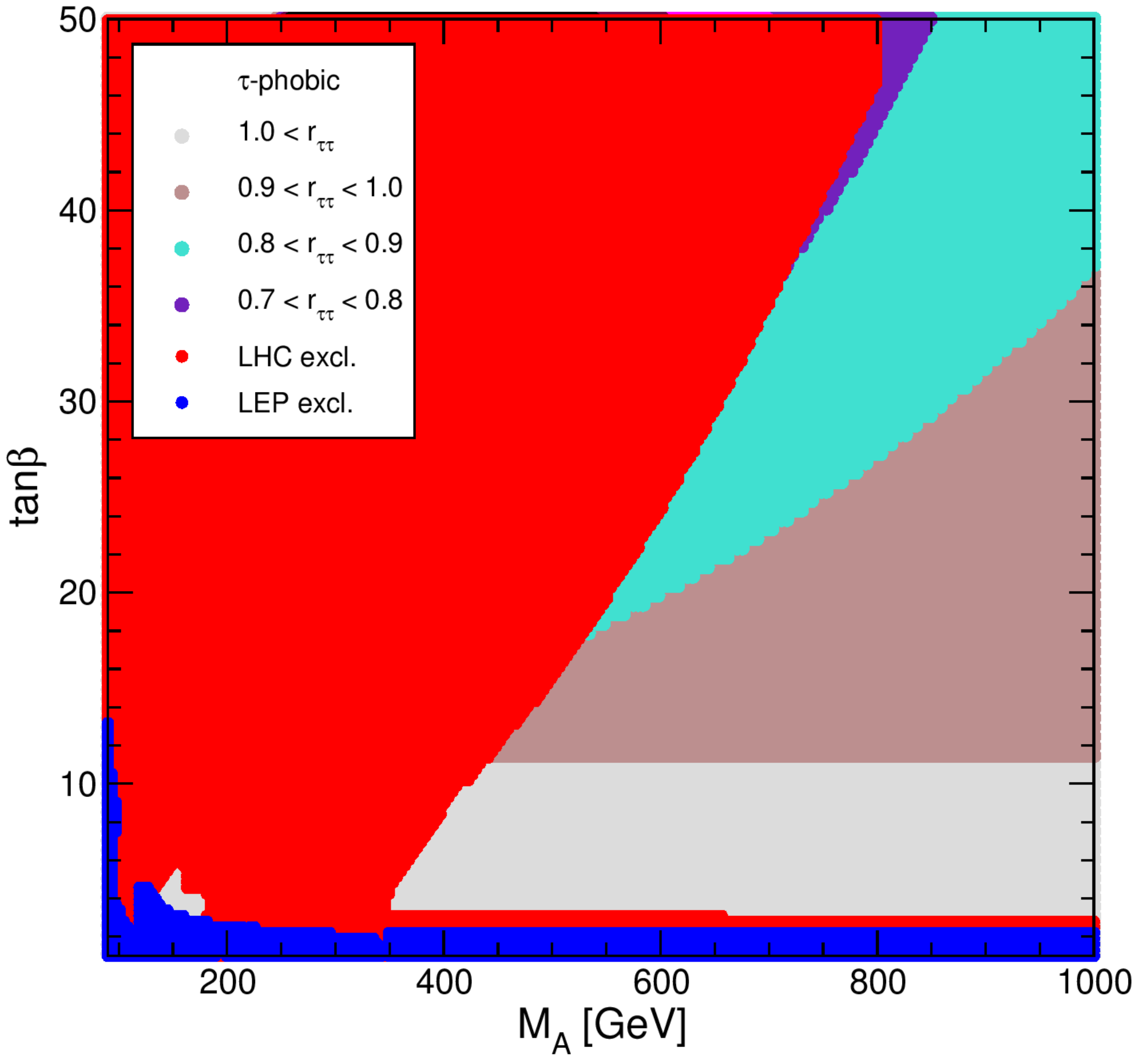
[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '15*]



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

"Old" τ-phobic Higgs scenario:

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



$$m_t = 173.2 \text{ GeV},$$
$$M_{\text{SUSY}} = 1500 \text{ GeV},$$
$$\mu = 2000 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{\text{OS}} = 2.45\, M_{\text{SUSY}},$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$m_{\tilde{l}_3} = 500 \text{ GeV} .$$

$\Rightarrow$ horizontal line indicates alignment limit

Relevance for the LHCHXSWG?!

Classical benchmark scenarios

– m_h^{max}

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– light-stop

– light-stau

– tau-phobic

⇒ change in M_h calculation?!

⇒ improved limits in M_A-$\tan\beta$ plane!

⇒ new SUSY search limits!

⇒ Time to devise a new "alignment scenario"?!

4. 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

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

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

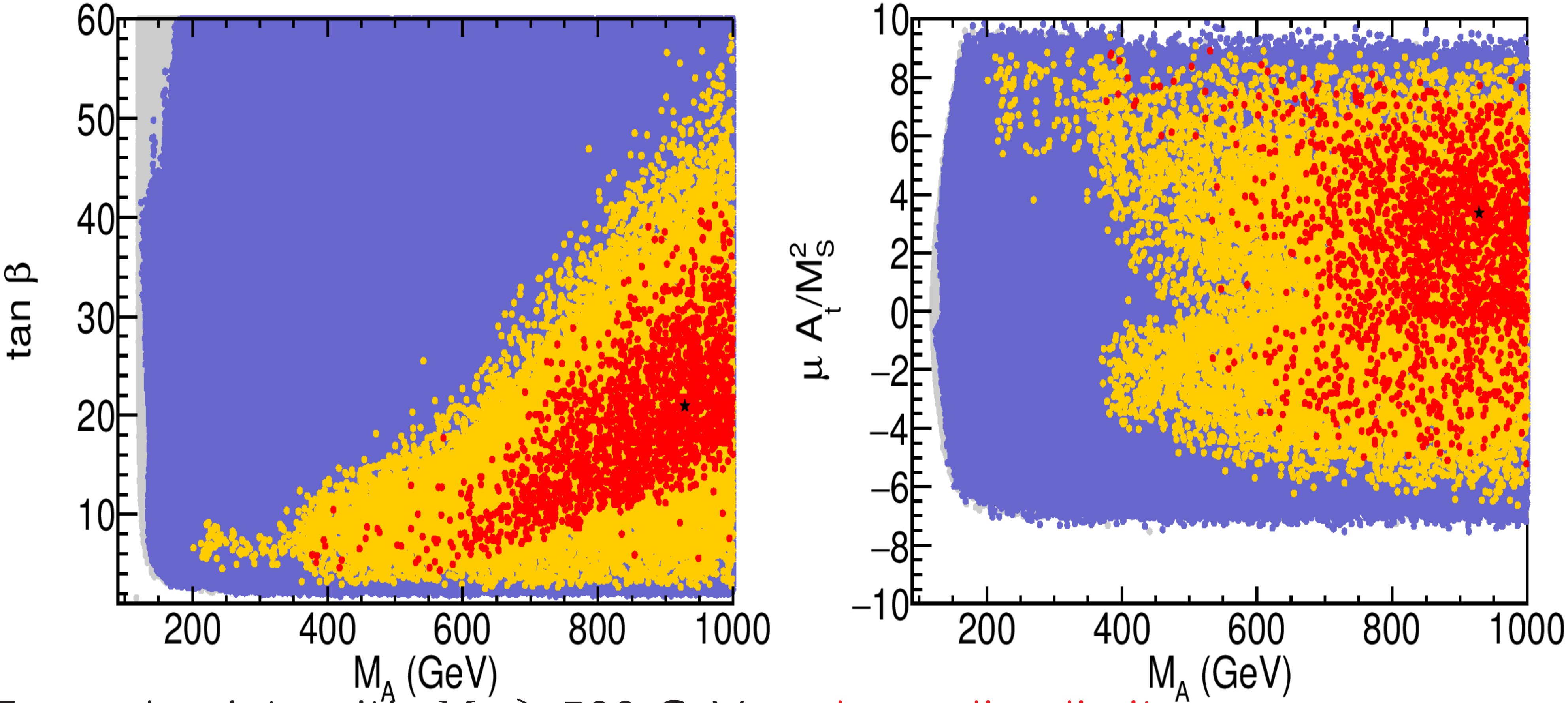
Best-fit points parameters:

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

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 $\mu > 0$)

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

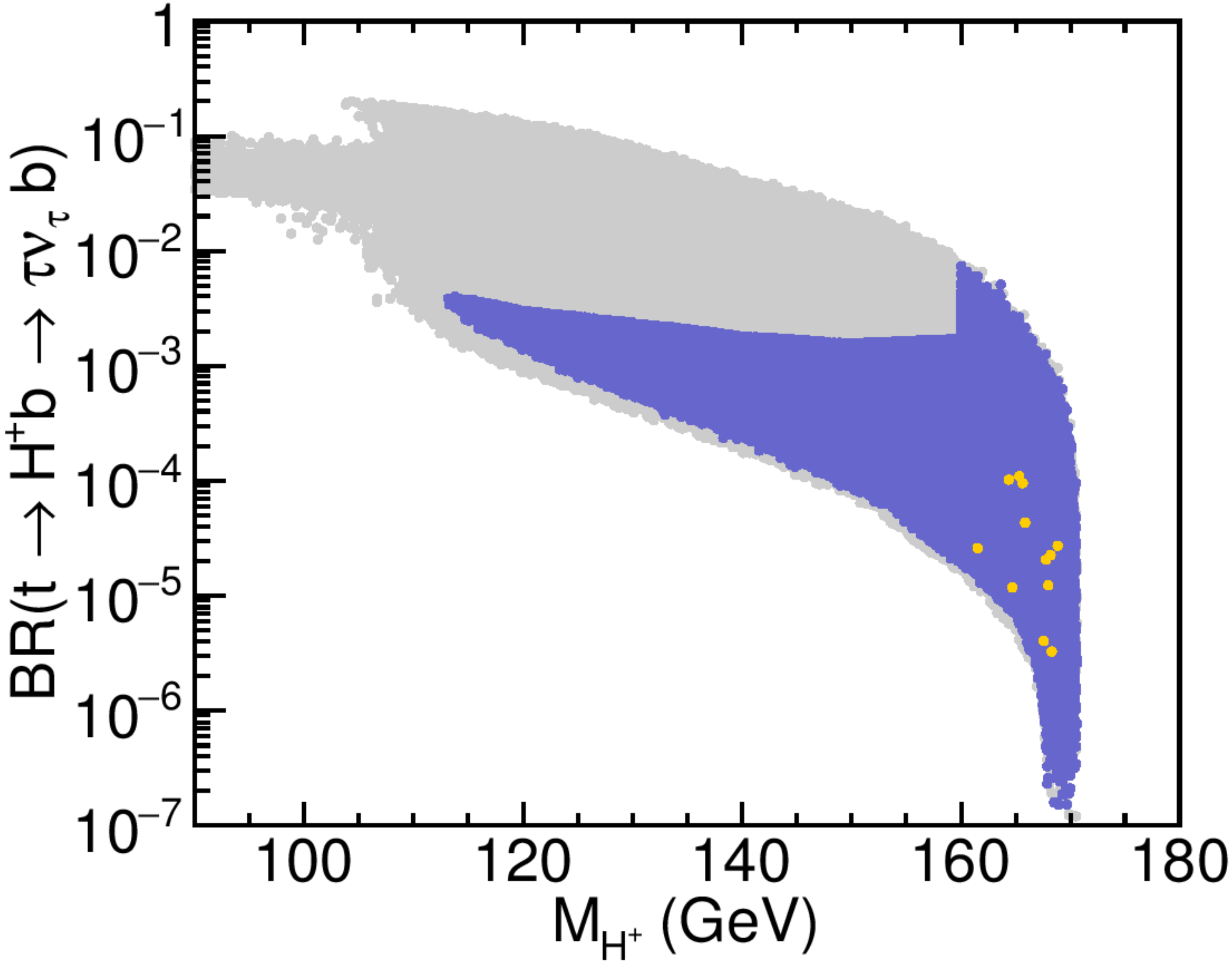
Constraints:

– 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*]

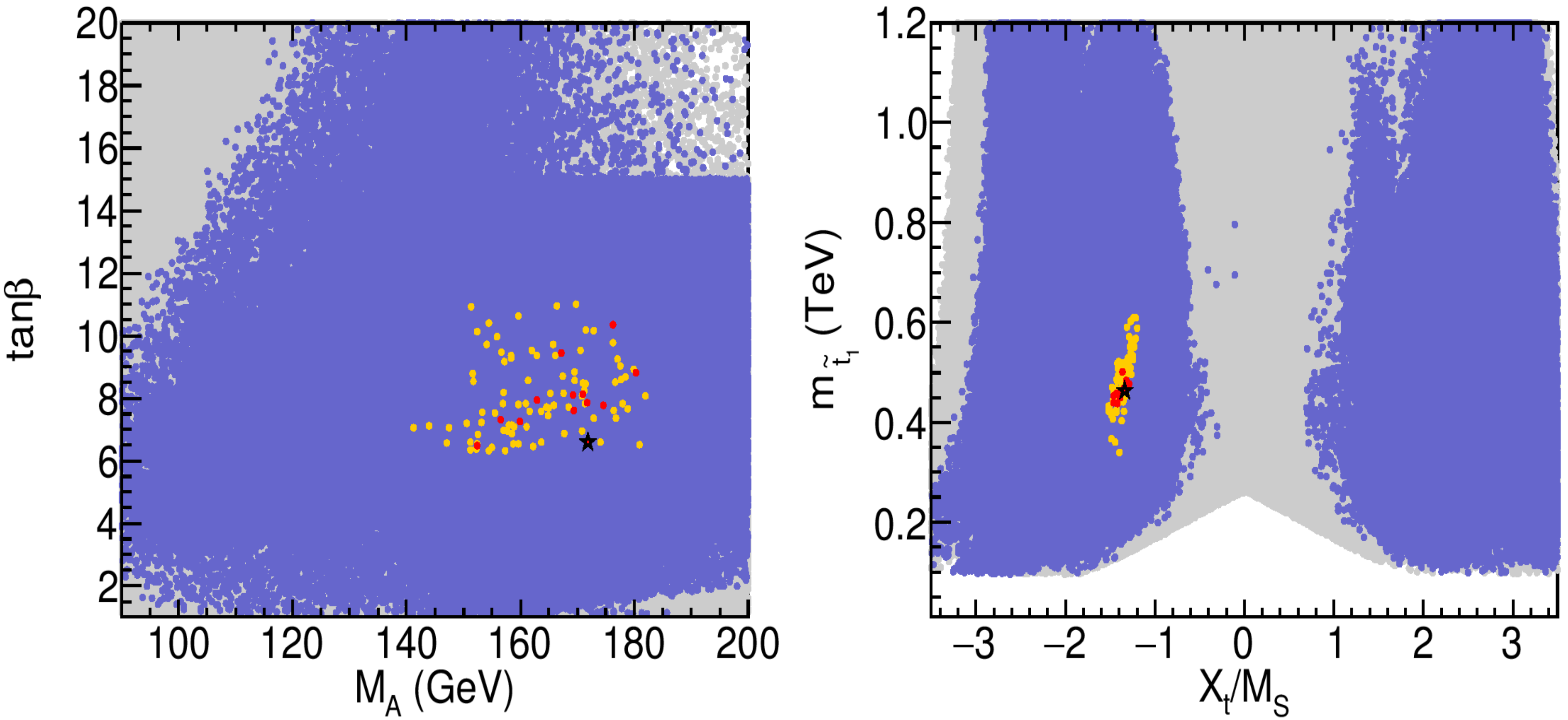
$\Rightarrow$ ruled out by charged Higgs searches (limits on BR($t \to H^\pm b$))

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

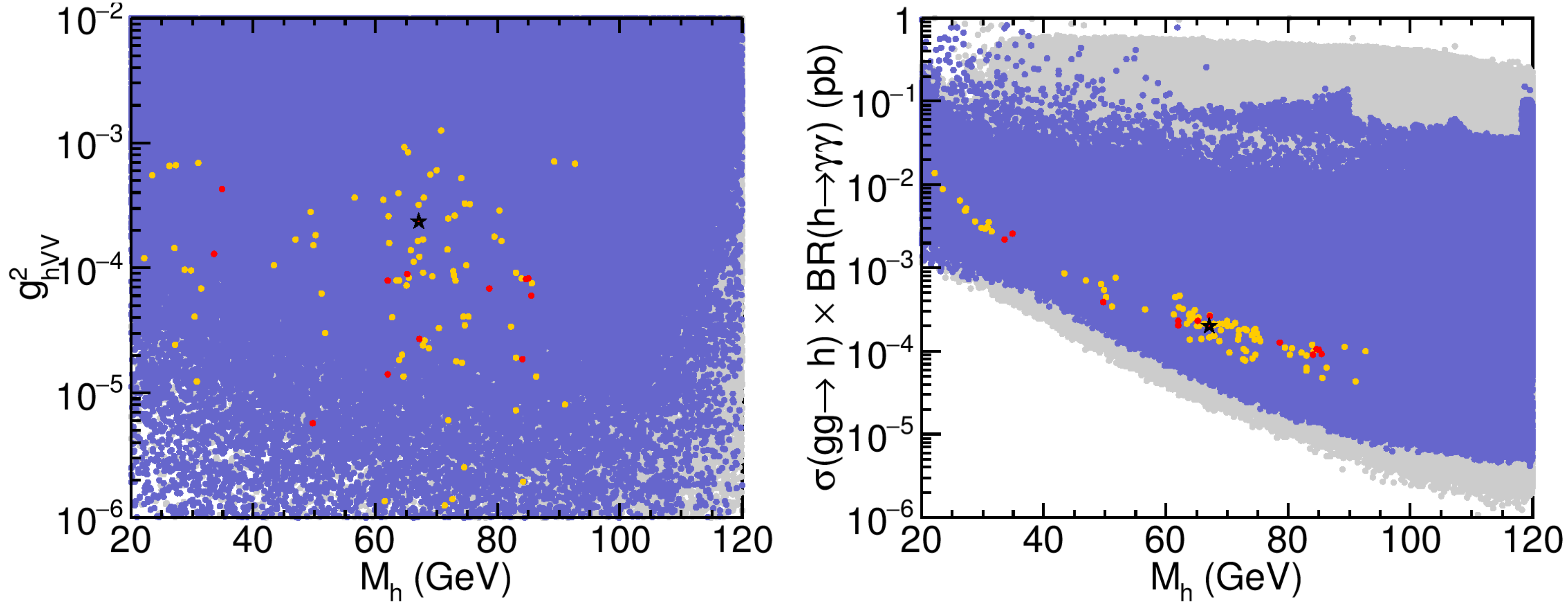


$\Rightarrow M_A \sim 140 \ldots 180$ GeV $\qquad \Rightarrow m_{\tilde{t}_1} \sim 350 \ldots 650$ GeV

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

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

New low-M_H benchmark scenarios

Based on our best-fit region:

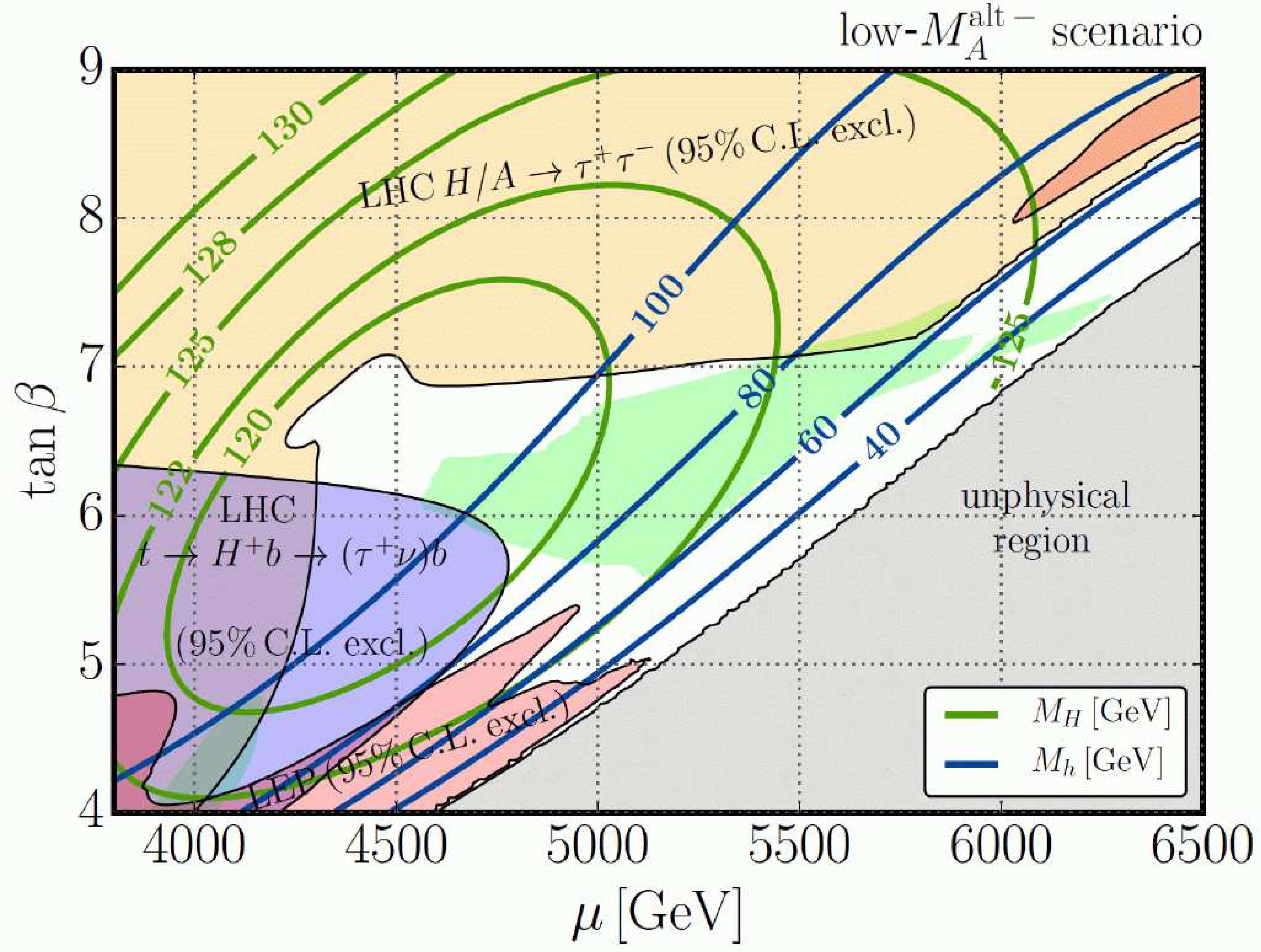
Benchmark scenario	$M_{H^\pm}$ [GeV]	μ [GeV]	$\tan\beta$
low-$M_H^{\text{alt},-}$	155	3800 – 6500	4 – 9
low-$M_H^{\text{alt},+}$	185	4800 – 7000	4 – 9
low-$M_H^{\text{alt,v}}$	140 – 220	6000	4 – 9
fixed parameters:	$m_t = 173.2$ GeV, $A_t = A_\tau = A_b = -70$ GeV, $M_2 = 300$ GeV, $M_{\tilde{q}_L} =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

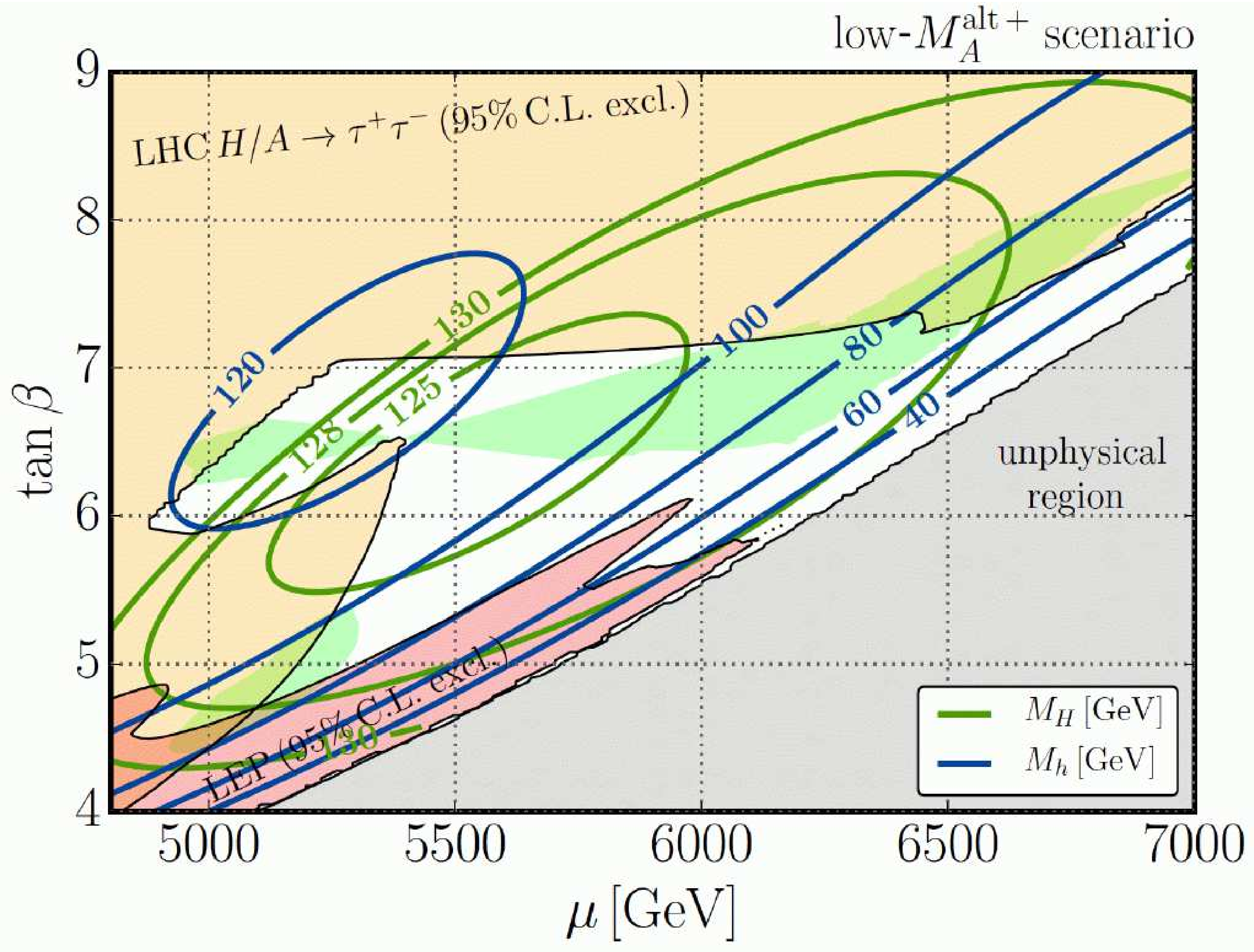
low-$M_H^{\text{alt v}}$: varied $M_{H^\pm}$ (μ fixed)

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



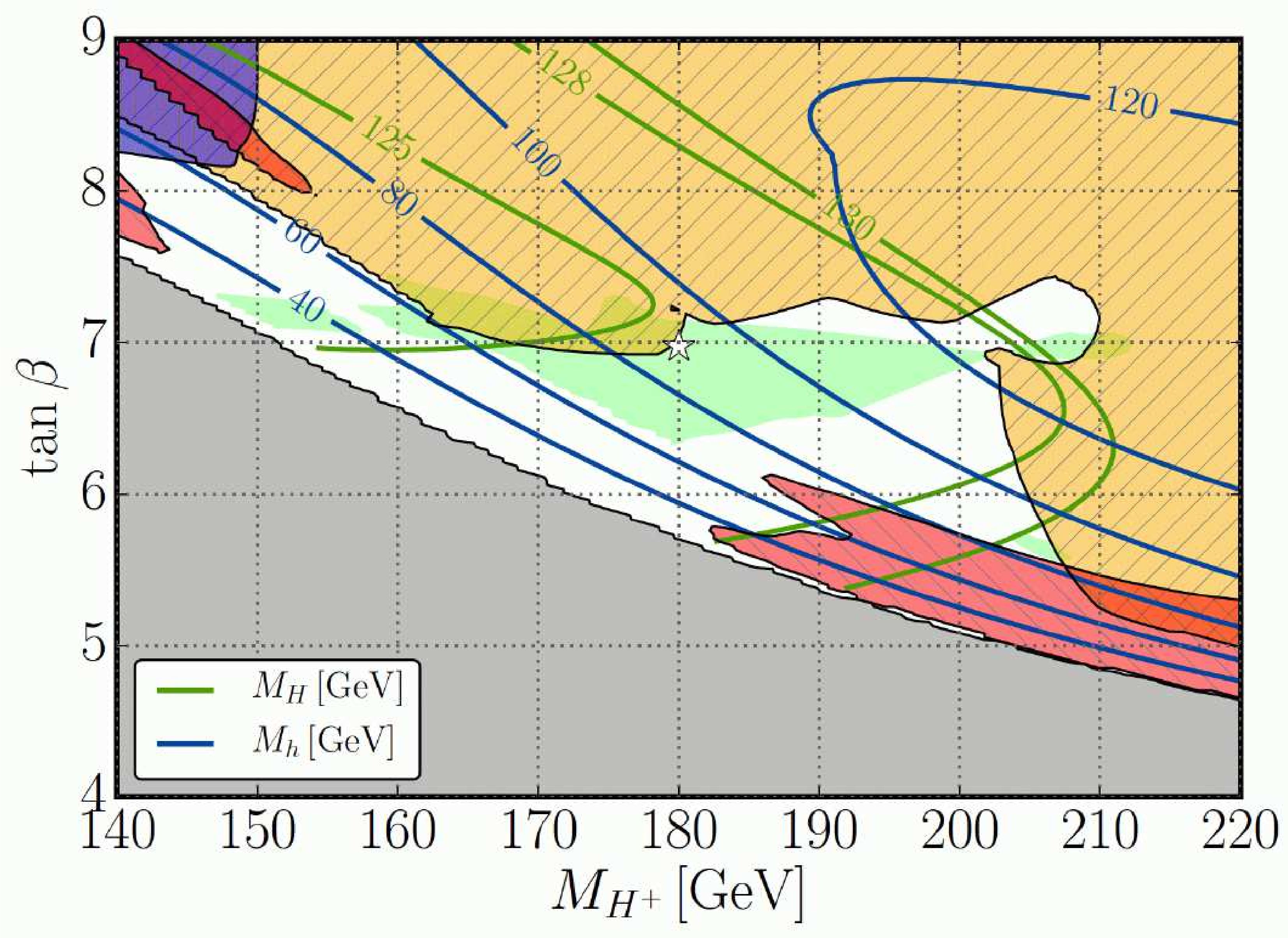
⇒ green area in agreement with all data!

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



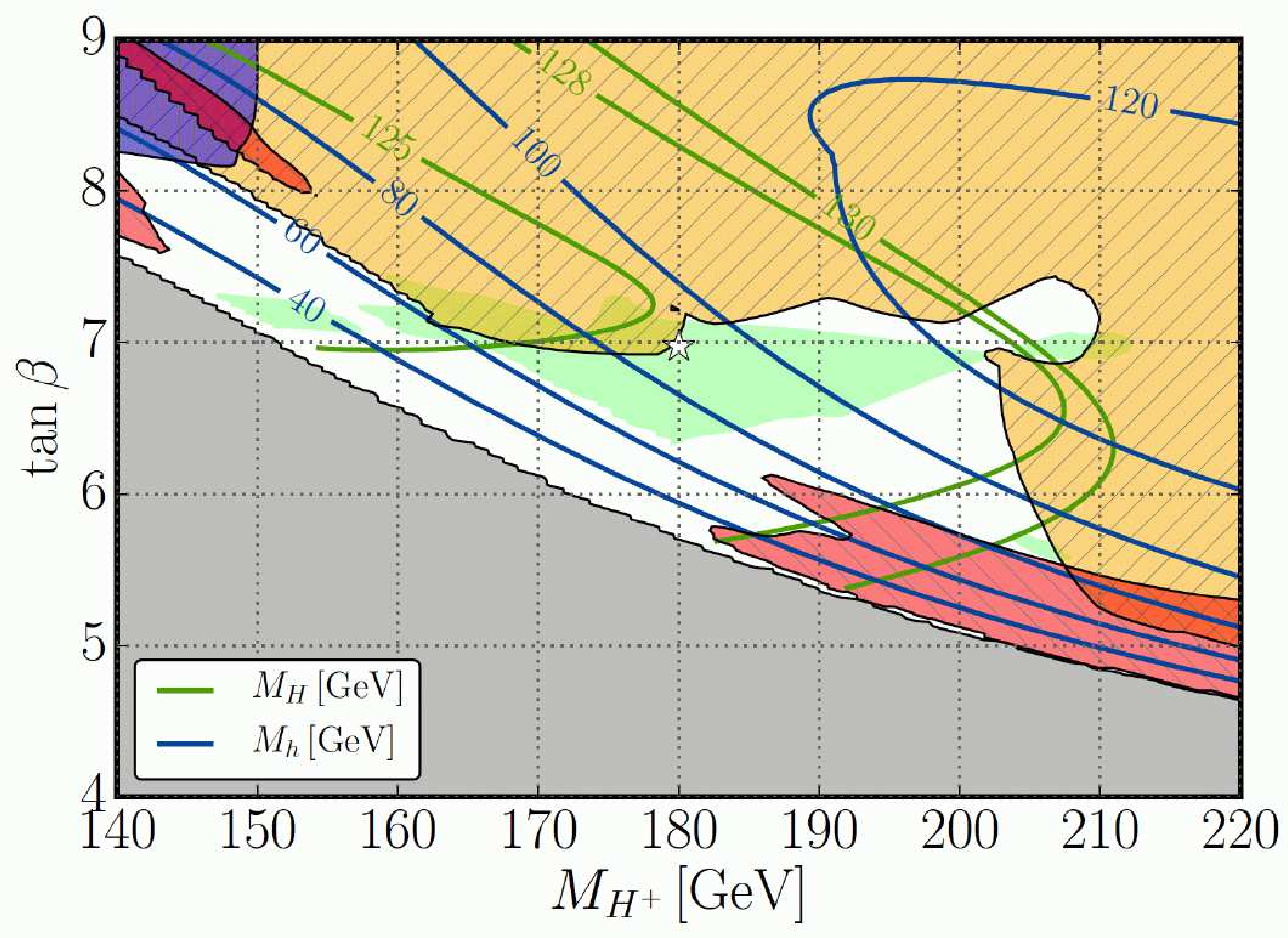
⇒ green area in agreement with all data! $M_H \sim M_h \sim 125$ GeV possible!

low-$M_H^{\text{alt v}}$(140 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!**

5. Complex parameters

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1\bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

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

Input parameters: (to be determined experimentally)

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

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:

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

with

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

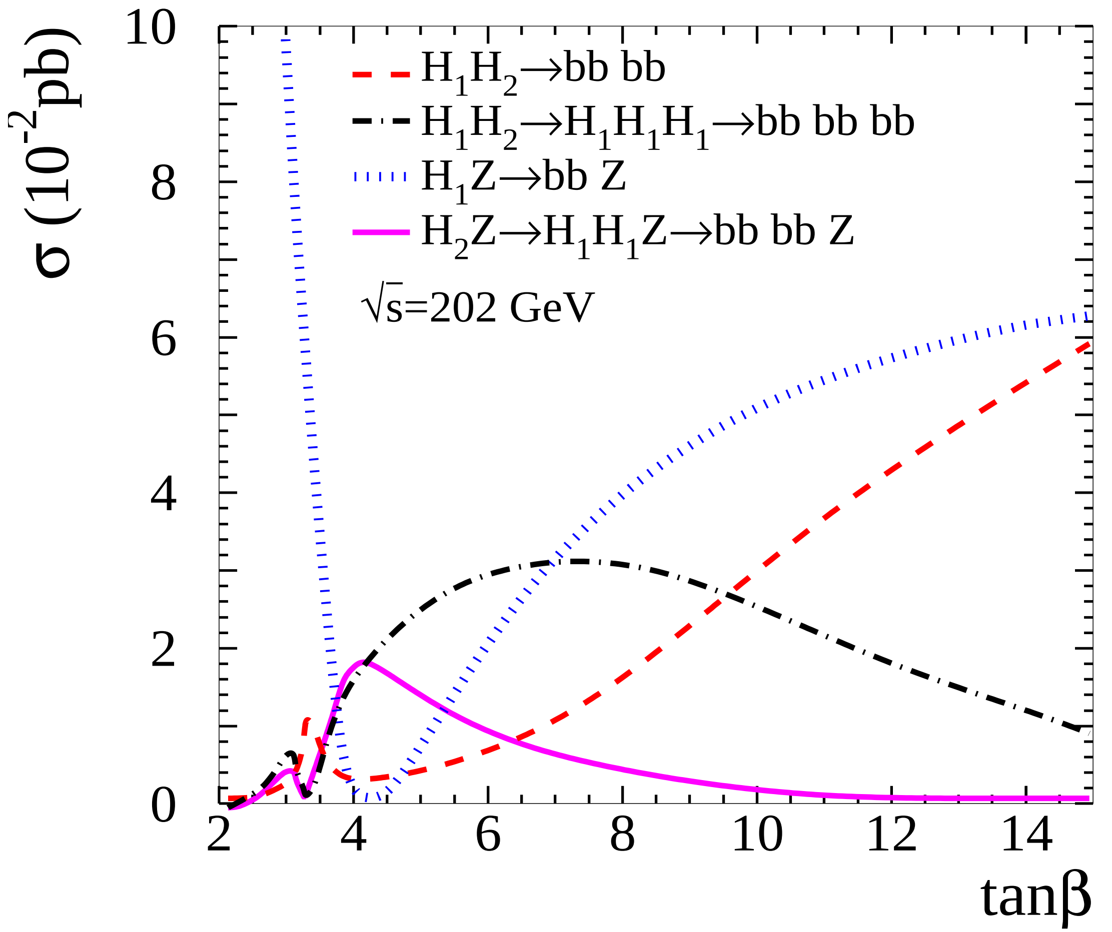
$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

Codes: Cross sections: SusHiMi (in preparation)
Branching ratios: FeynHiggs, CPsuperH

$\mathcal{CP}$V effects on Higgs boson searches:

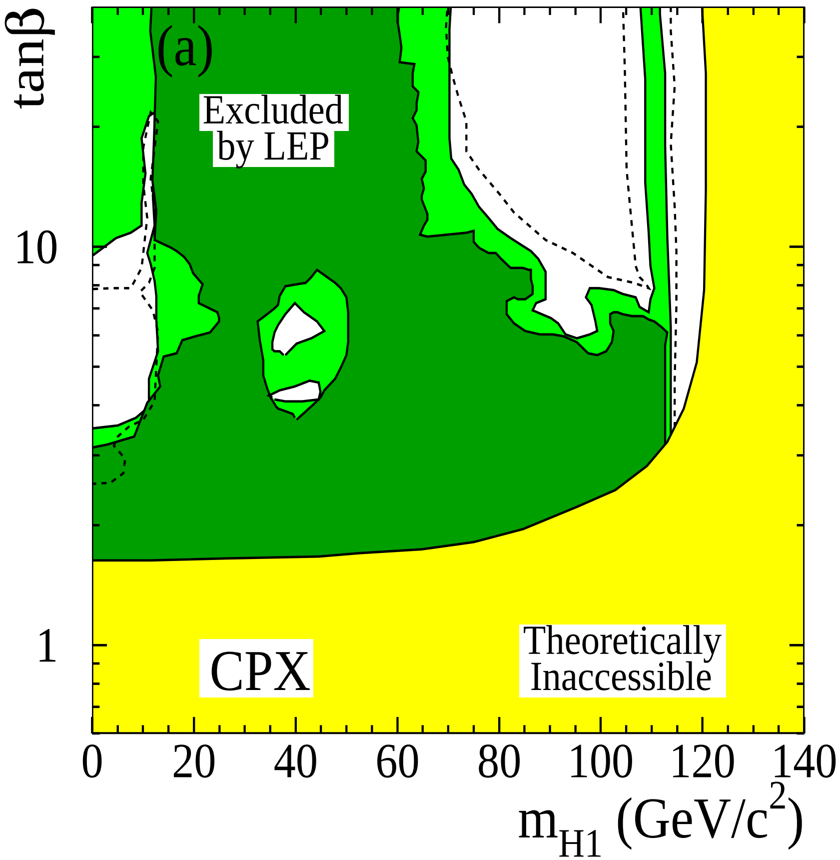
CPX: benchmark scenario in the cMSSM
[*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00*]

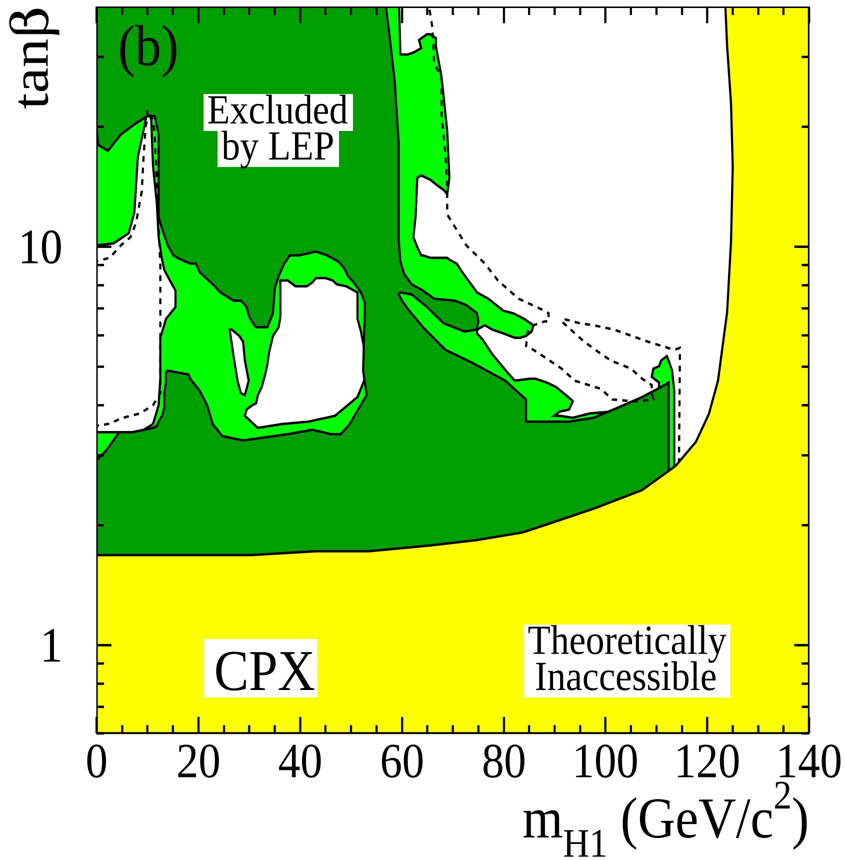
LEP Higgs production cross sections: [*LEPHiggsWG '06*]



Results of LEP searches in CPX scenario: [LEPHiggsWG '06]

$m_t = 169.3$ GeV $m_t = 174.3$ GeV





The LEP analysis showed unexcluded holes in the m_{h_1}–$\tan\beta$ plane

$\Rightarrow$ masses below ~ 62 GeV contrained, but above . . . ?

“H-A” mixing with ϕ_{A_t}:

[*E. Fuchs, G. Weiglein ’15*]

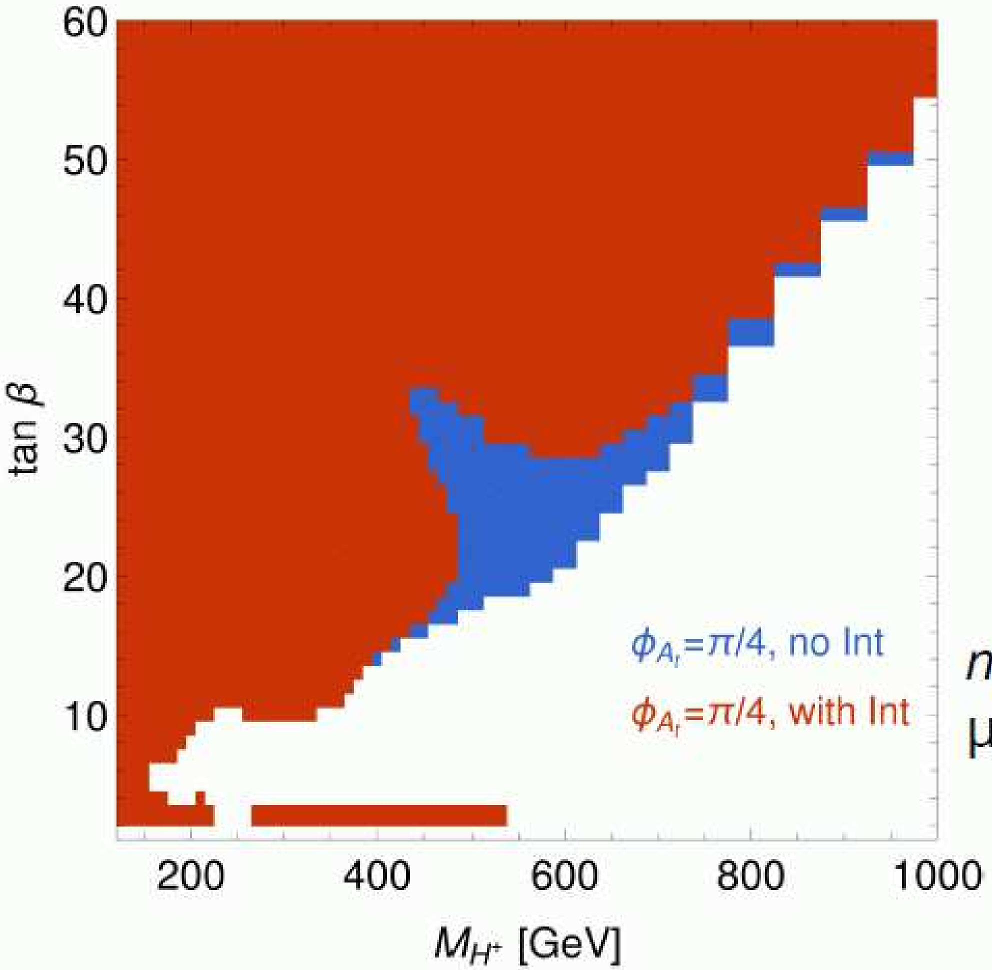
[E. Fuchs, G. W. ’15]

Exclusion limits from neutral Higgs searches in the MSSM with and without interference effects:

CP-violating case,
$\phi_{At} = \pi / 4$

H, A are nearly mass degenerate: large mixing possible in CP-violating case!

Incoherent sum is not sufficient!



m_h^{mod+} scenario,
μ = 1000 GeV

⇒ Large CP-violating interference effects between H, A possible

Relevance for the LHCHXSWG?!

Classical benchmark scenarios in the rMSSM!

- m_h^{max}
- $m_h^{\text{mod+}}$
- $m_h^{\text{mod}-}$
- light-stop
- light-stau
- tau-phobic

⇒ inclusion of complex phases?!

⇒ Time to devise scenarios for the cMSSM?!

- "H-A" interference
- $M_{h_1} < 125$ GeV

Conclusinos

- Recent "MSSM updates" (or neglected issues):
  - improved mass calculations
  - improved Higgs/SUSY limits
  - complex phases

- SUSY Higgs mass predictios are far behind experimental accuracy

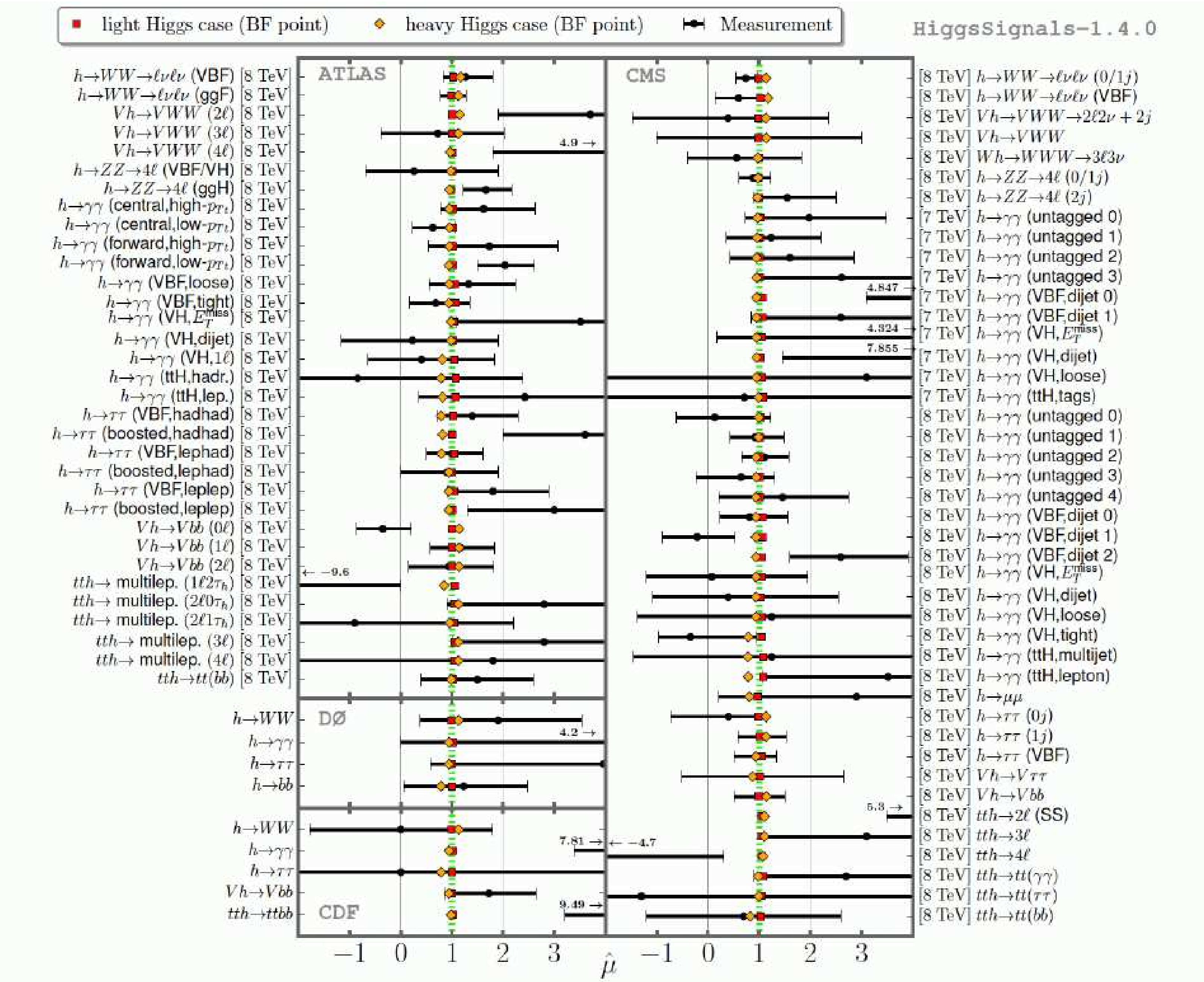
- Higgs rate measurements can be fulfilled by
  - the light $\mathcal{CP}$-even Higgs in the decoupling regime
  - the light $\mathcal{CP}$-even Higgs in the alignment w/o decoupling regime
  - the heavy $\mathcal{CP}$-even Higgs with $M_h < 125$ GeV

- Update for benchmark scenarios necessary?
  - classical scenarios updated?!
  - new low-M_H scenarios $\Rightarrow$ exist already!
  - new alignment scenario
  - scenario with complex phases: "H-A" mixing, $M_{h_1} < 125$ GeV

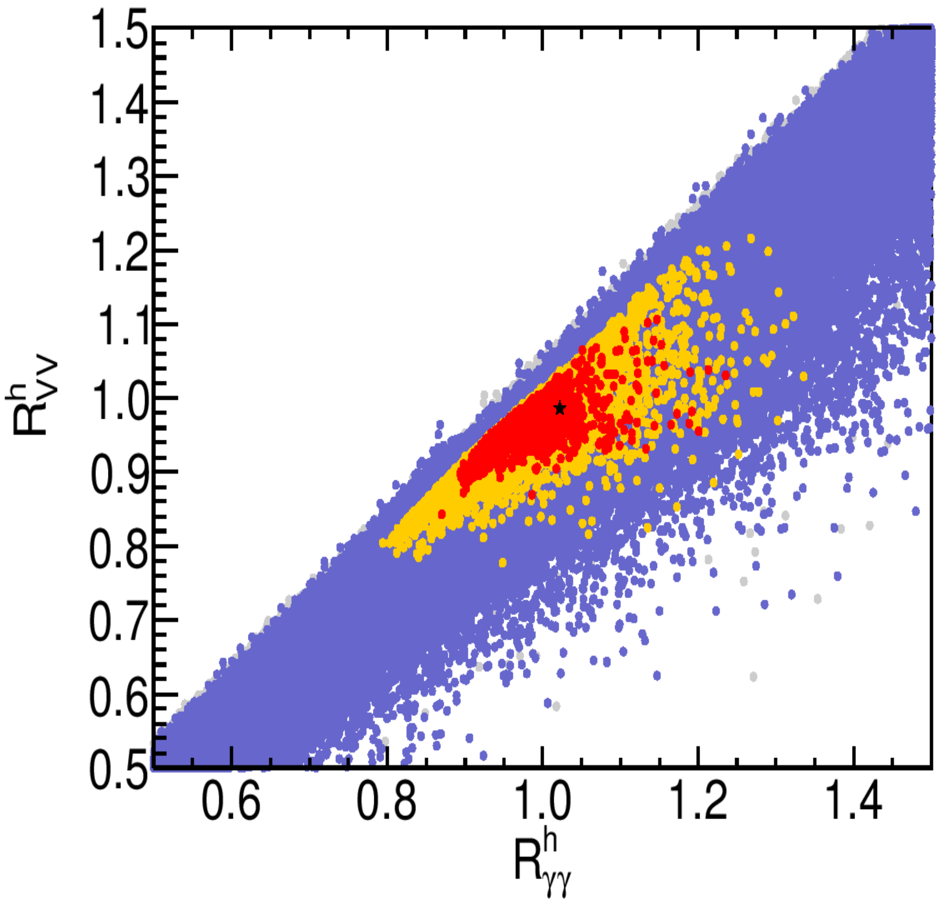
For Reisaburo: HiggsCouplings 2017: 6.-10. Nov. (Heidelberg)

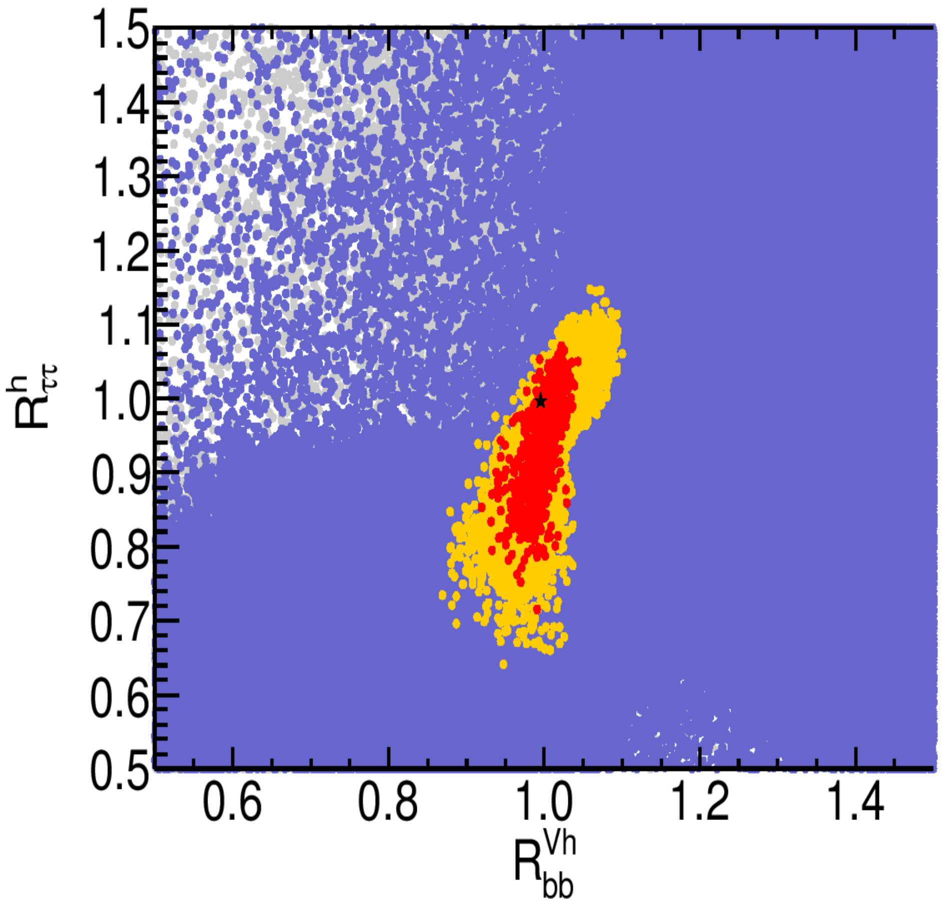

Further Questions?

Best-fit point rates in the two Higgs cases:



Light-Higgs case: preferred rates



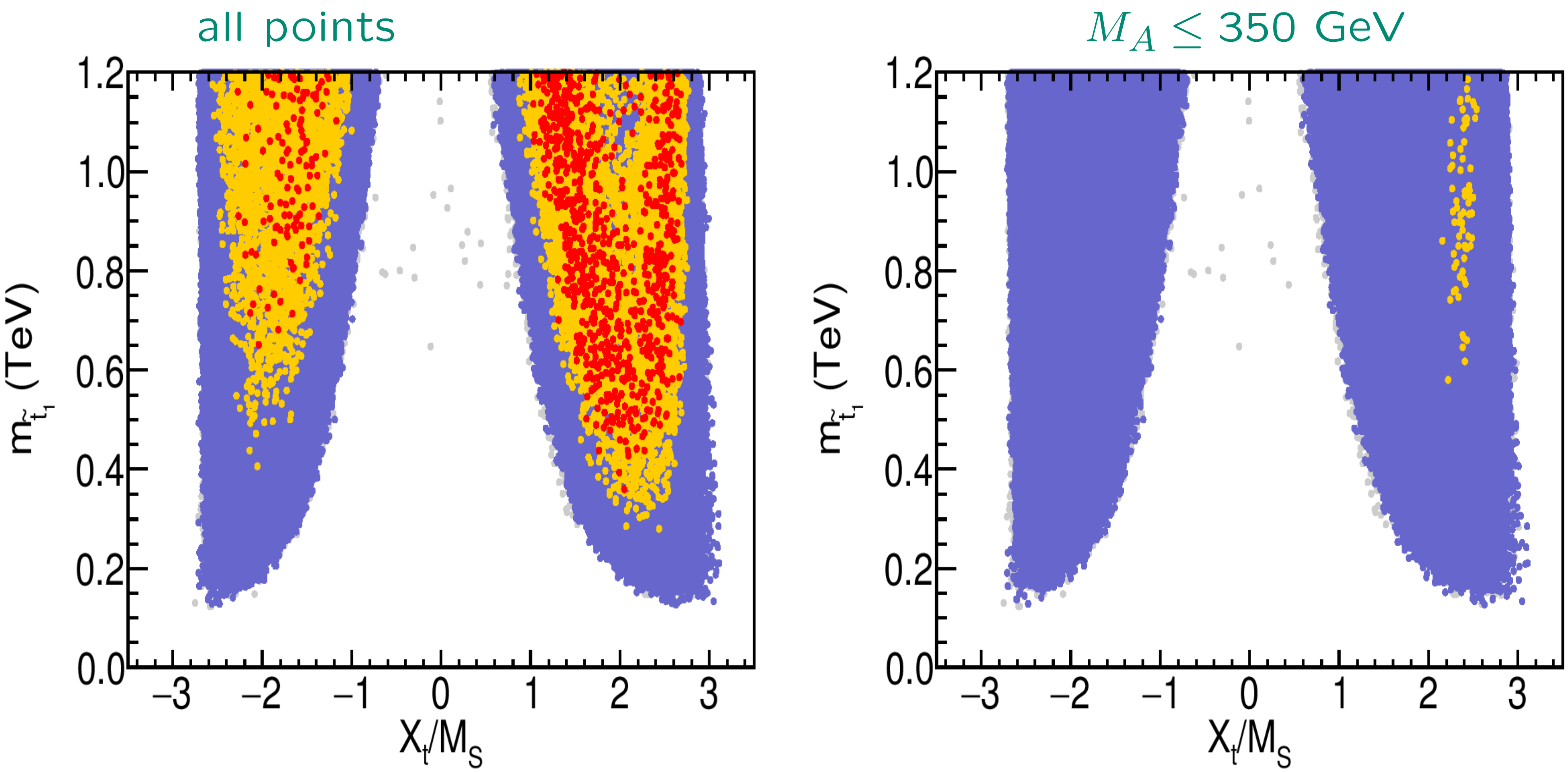


$R^h_{VV} = 0.99^{+0.09}_{-0.08}$, $\quad R^h_{\gamma\gamma} = 1.02^{+0.16}_{-0.10}$, $\quad R^{Vh}_{bb} = 1.00^{+0.02}_{-0.05}$, $\quad R^h_{\tau\tau} = 1.00^{+0.06}_{-0.20}$

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

⇒ but some (BSM) spread is allowed!

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

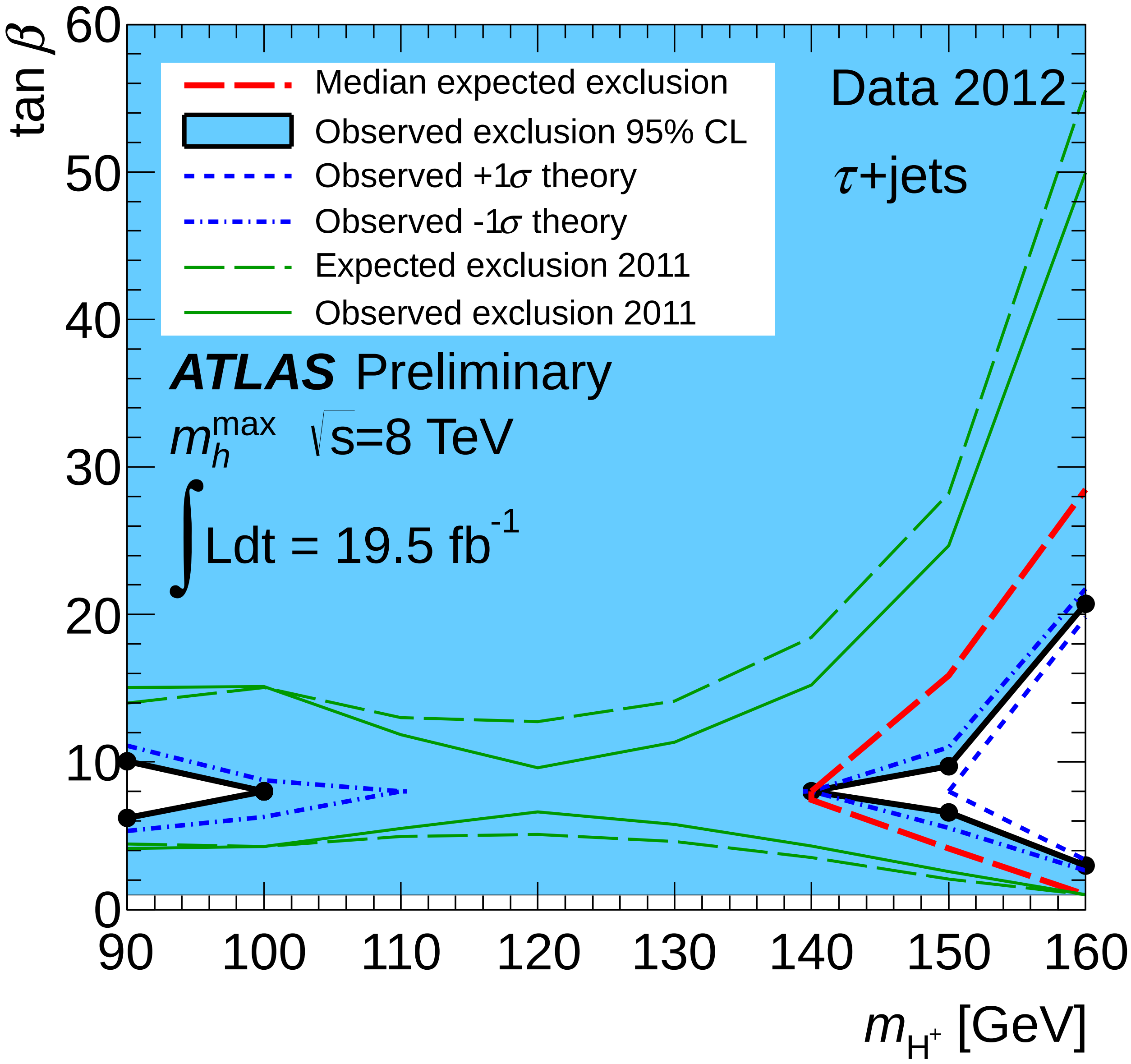


$\Rightarrow$ light stops down to $m_{\tilde{t}_1} \sim 300$ GeV possible

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

ATLAS results for charged Higgs searches:

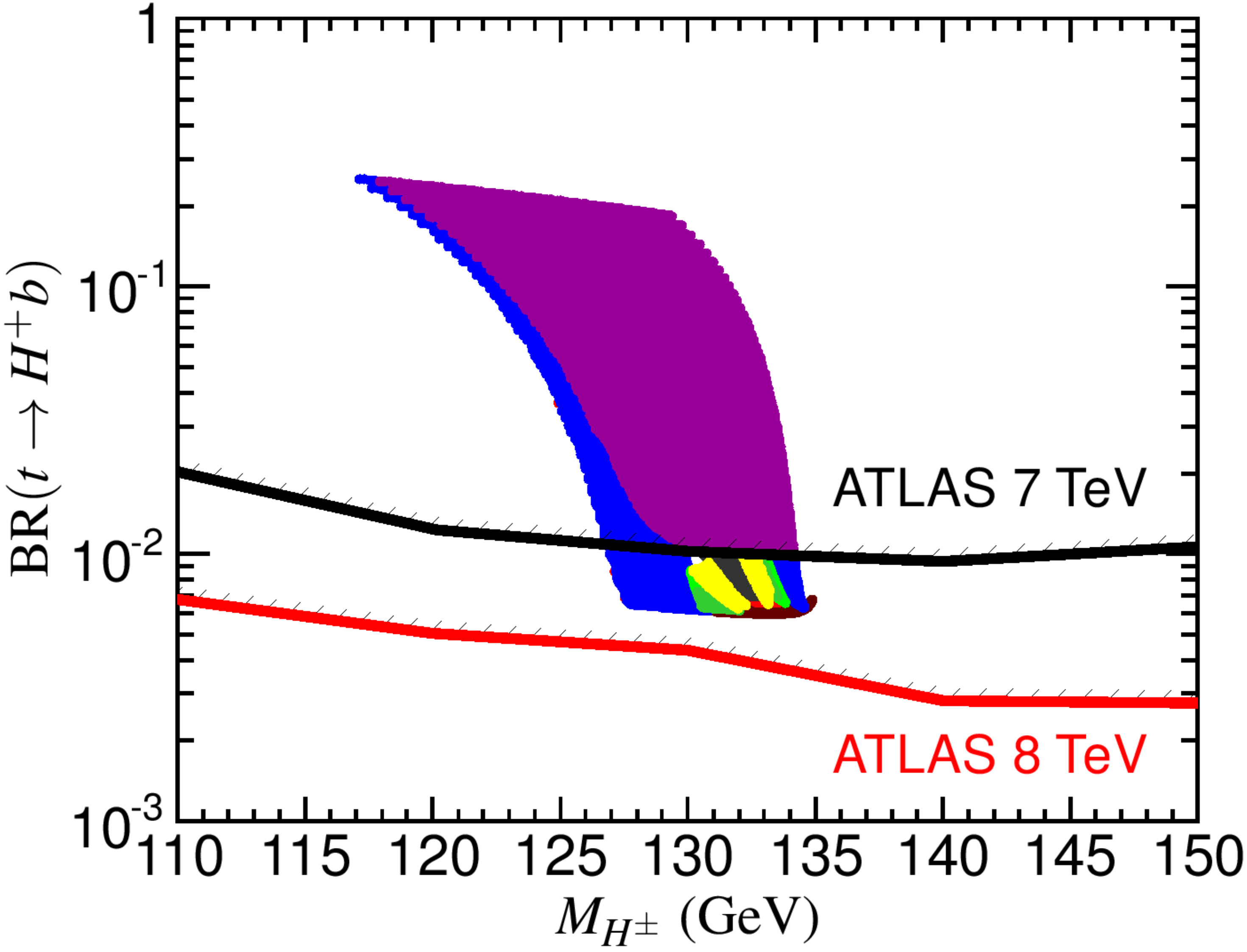
[*ATLAS '13*]



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

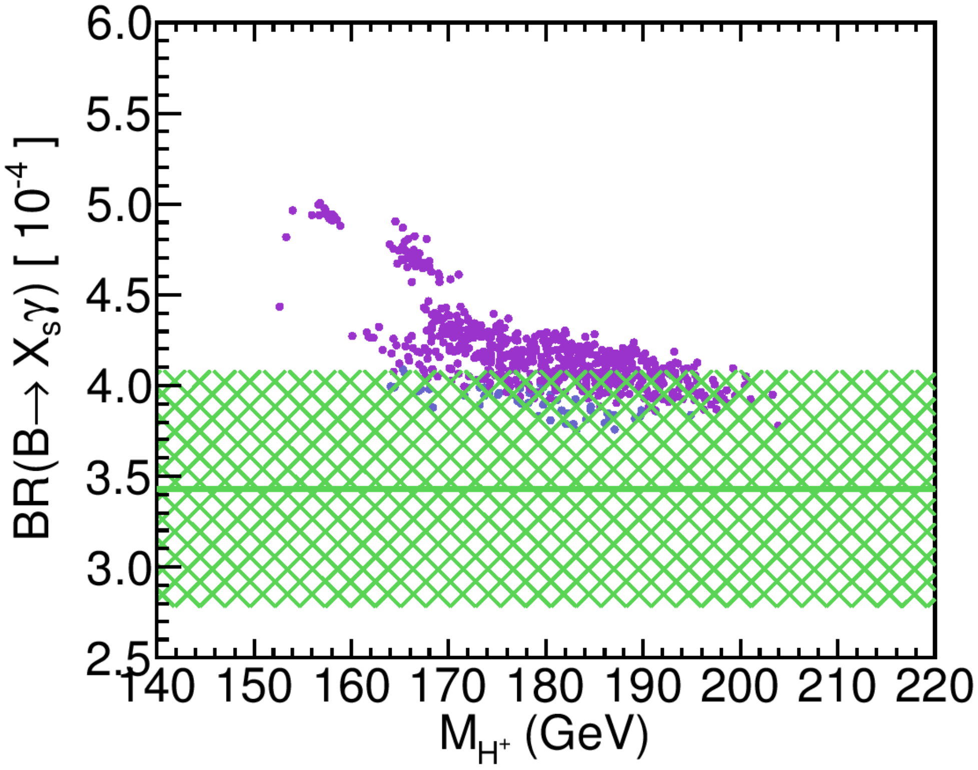
Application of charged Higgs limits on low-M_H scenario:

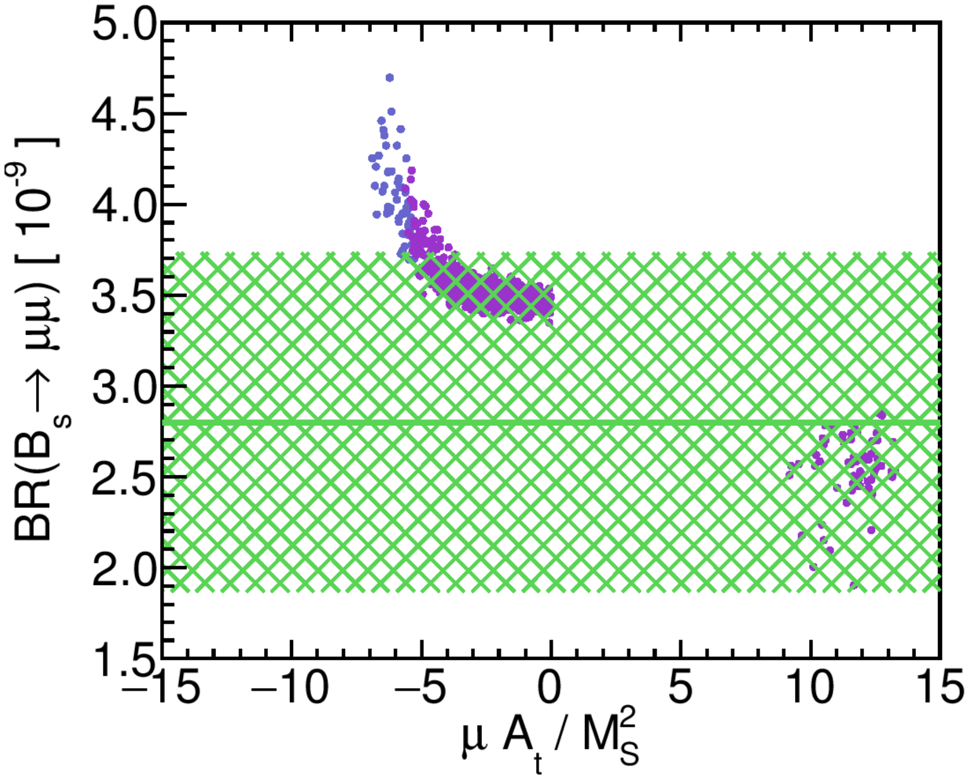
[*HiggsBounds 4.1*]



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

B-physics constraints?





$\Rightarrow$ flavor constraints fulfilled!

The Higgs sector of the cMSSM at tree-level:

- phase of m_{12} :

  $m_{12} = 0$ and $\mu = 0 \Rightarrow$ additional $U(1)$ (PQ) symmetry

  reality: $m_{12} \neq 0$, $\mu \neq 0$

  $\Rightarrow$ perform PQ transformation with ϕ_{PQ}

$$\begin{aligned} m_{12}^{2\prime} &= |m_{12}^2| e^{i(\phi_{m_{12}} - \phi_{\text{PQ}})} \\ \mu' &= |\mu| e^{i(\phi_\mu - \phi_{\text{PQ}})} \end{aligned}$$

  $\Rightarrow$ m_{12} can always be chosen real

- phase of H_2: ξ :

  mixing between $\mathcal{CP}$-even and $\mathcal{CP}$-odd states:

$$\mathcal{M}_{\mathcal{CP}-\text{even},\mathcal{CP}-\text{odd}} = \begin{pmatrix} 0 & m_{12}^2 \sin\xi \\ -m_{12}^2 \sin\xi & 0 \end{pmatrix}$$

  Tadpoles have to vanish: $T_A^{\text{tree}} \propto \sin\xi\, m_{12}^2 \stackrel{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ no $\mathcal{CP}$V at tree-level