



“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 and its Higgs Bosons at the LHC

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

Freiburg, 02/2017

- Motivation
- SUSY after LHC Run I/II
- SUSY Higgs mass and rate measurements
- MSSM Higgs results (CMSSM, NUHM1/2, pMSSM8)
- 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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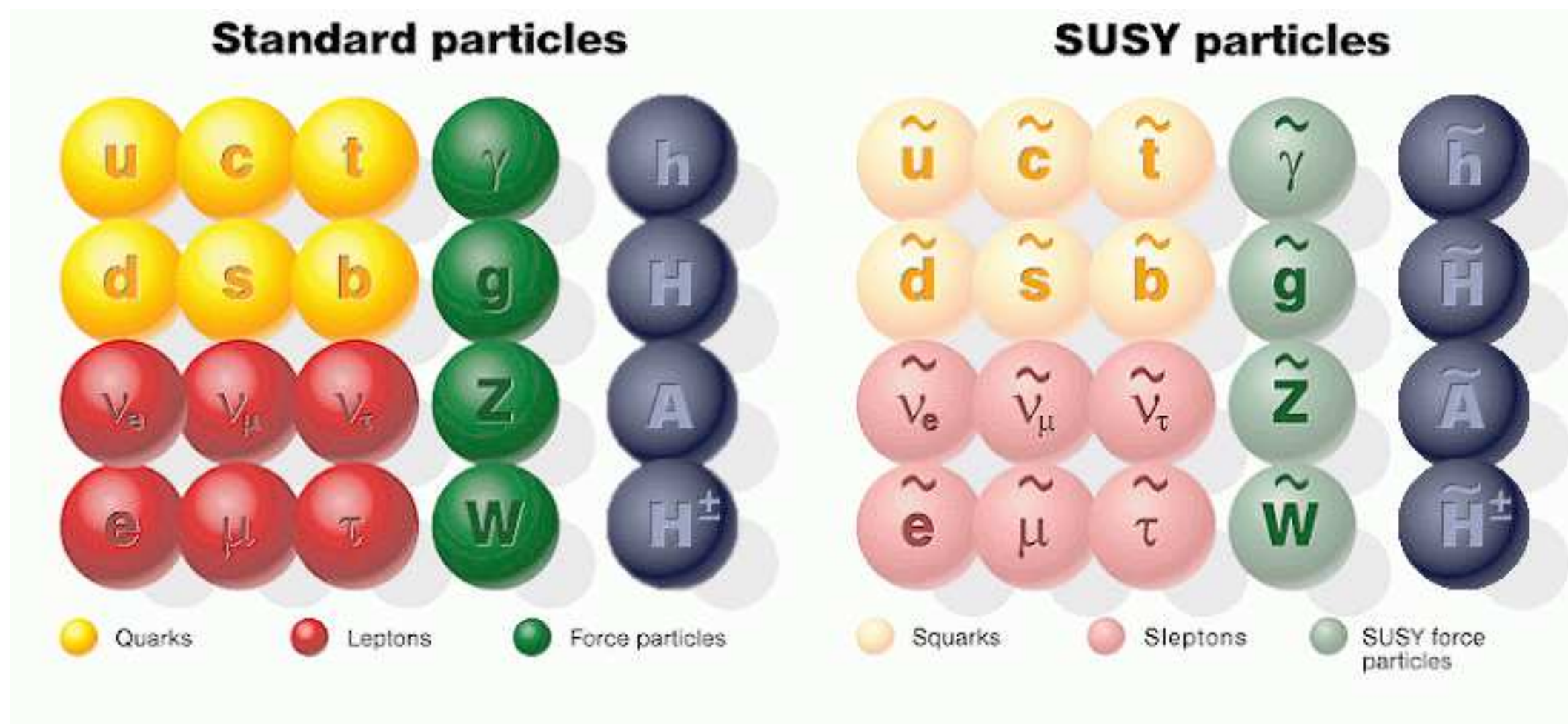
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⇒ **good motivation to look at SUSY! :-)**

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
 $\tan \beta$: ratio of Higgs vacuum expectation values
 $\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

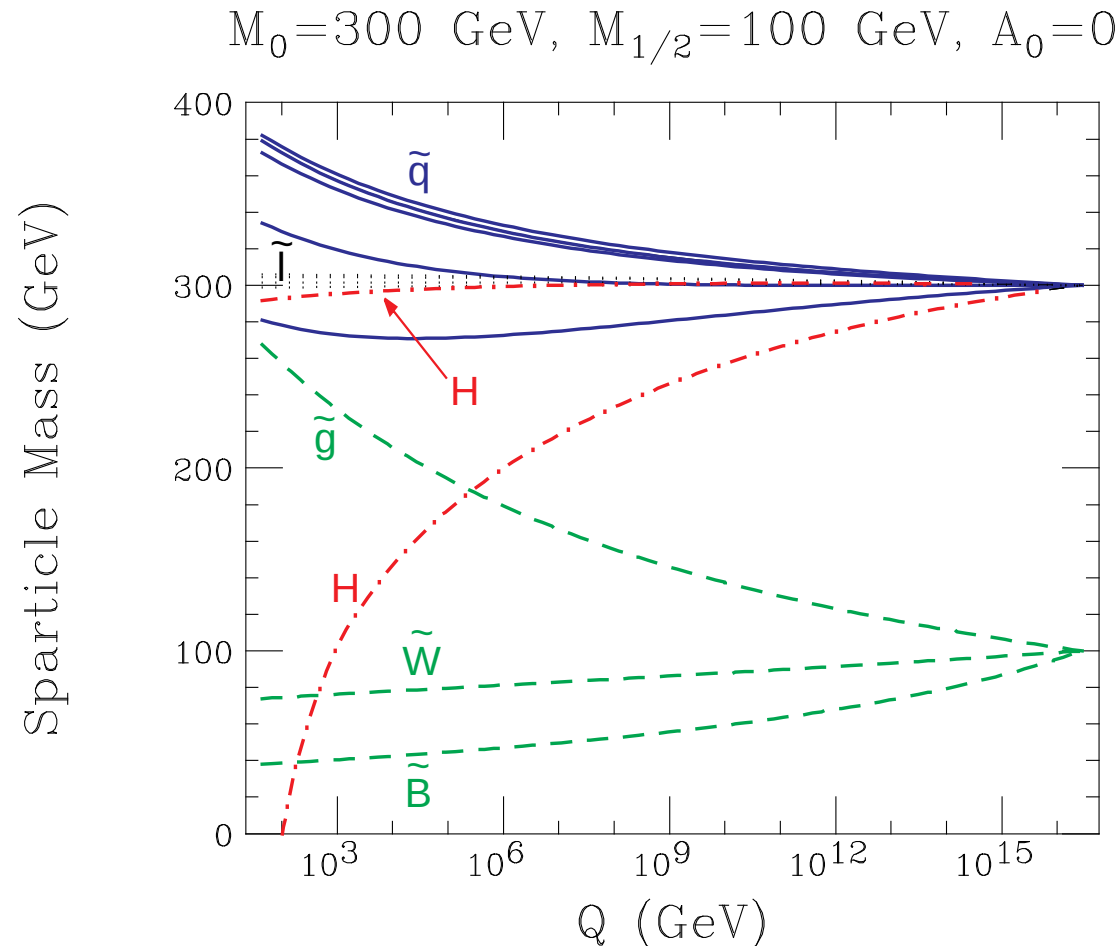
} at the GUT scale

⇒ particle spectra from renormalization group running to weak scale

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

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

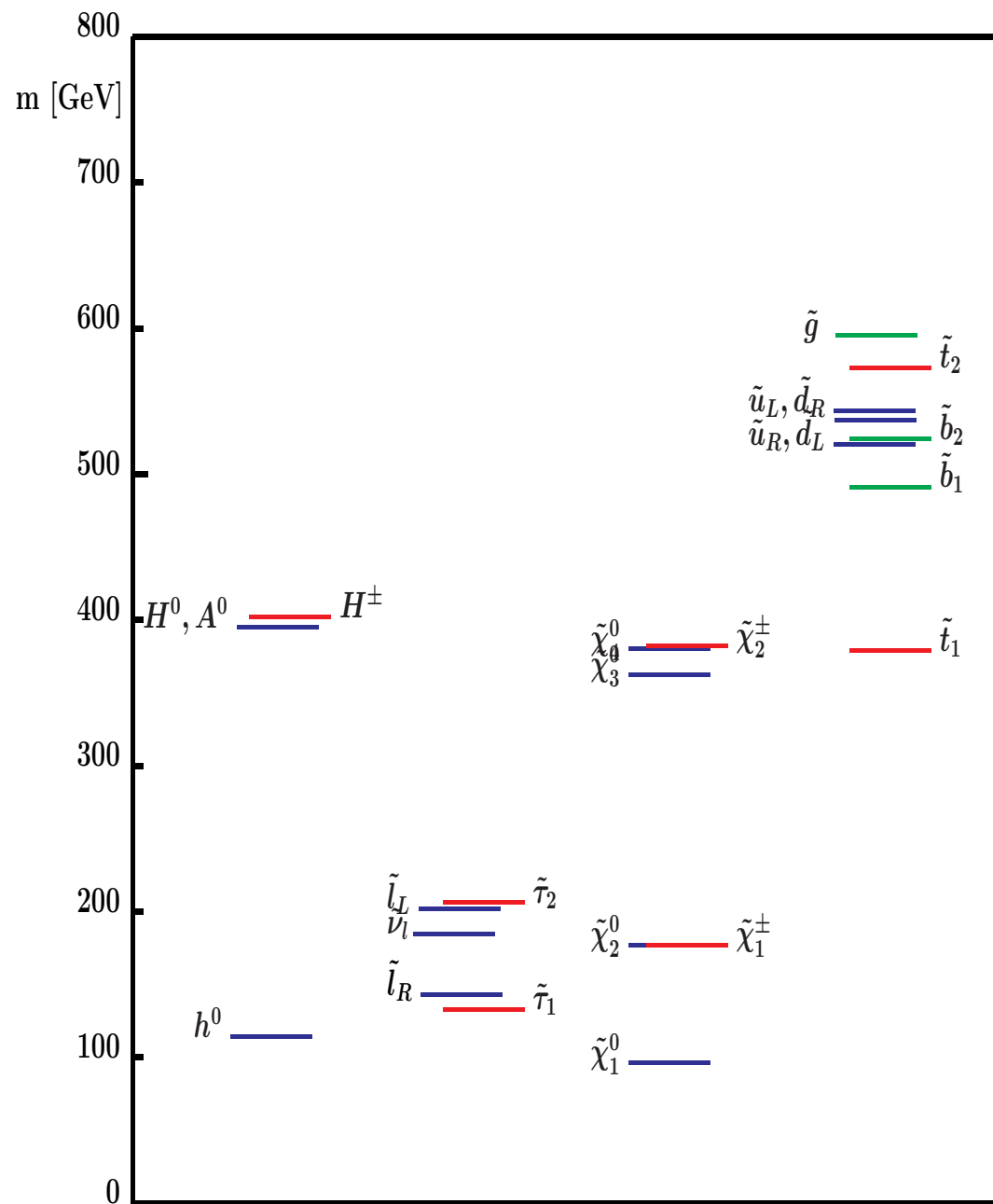
⇒ particle spectra from renormalization group running to weak scale



⇒ 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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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 parameter: μ

⇒ Note: other “8 parameter selections” possible

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Solution: investigate also the “general MSSM”

⇒ 10 parameters are manageable ⇒ pMSSM10

- squark mass parameters: $m_{\tilde{q}_{12}}, m_{\tilde{q}_3}$
- slepton mass parameter: $m_{\tilde{l}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: $M_A, \tan \beta$
- Higgs mixing parameter: μ

⇒ Note: other “10 parameter selections” possible

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- Higgs boson mass (LHC)

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- Higgs boson mass (LHC)
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- SUSY searches (LHC)
- electroweak precision data
- flavor data
- astrophysical data

2. SUSY after LHC Run I/II: 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/II) 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]

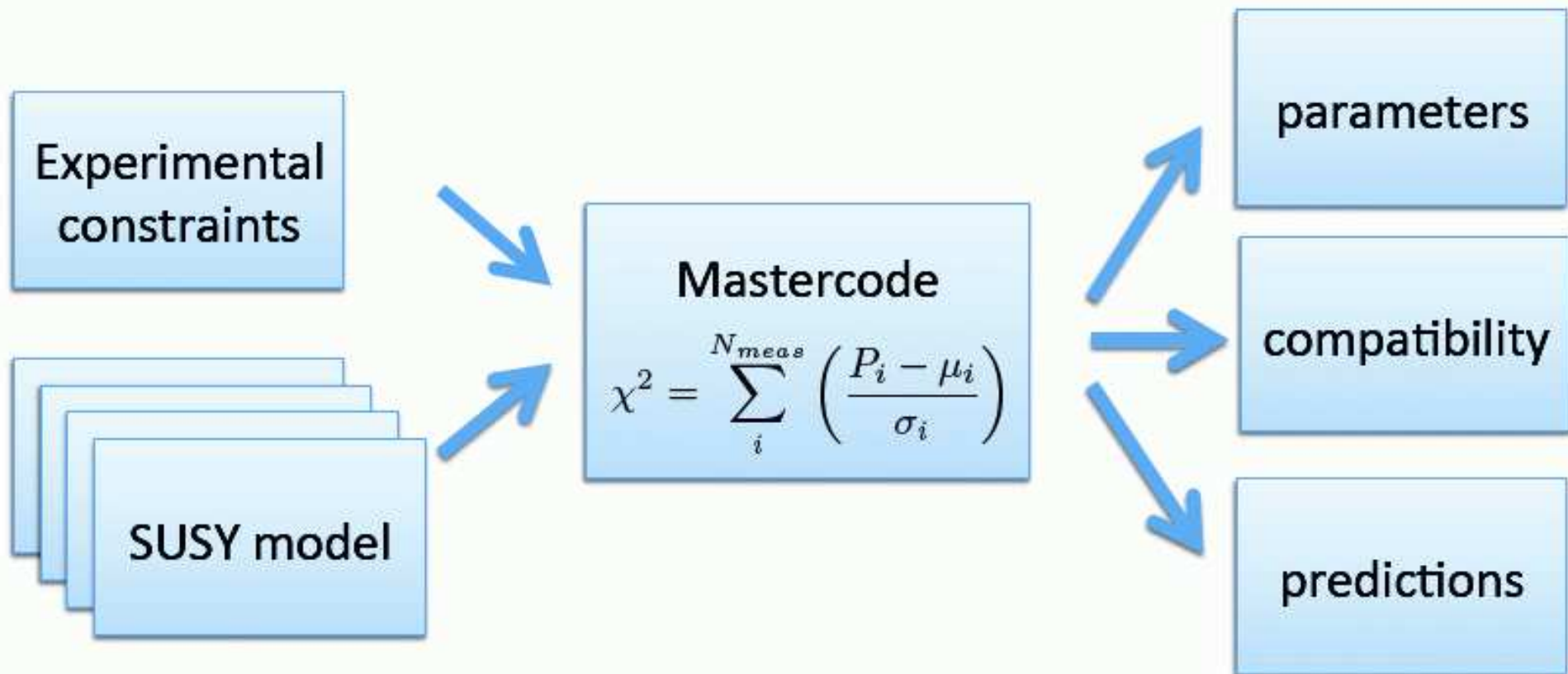
⇒ all most-up-to-date codes on the market!

⇒ crucial for precision!

The χ^2 evaluation:



Global fits of SUSY



Results in GUT based models

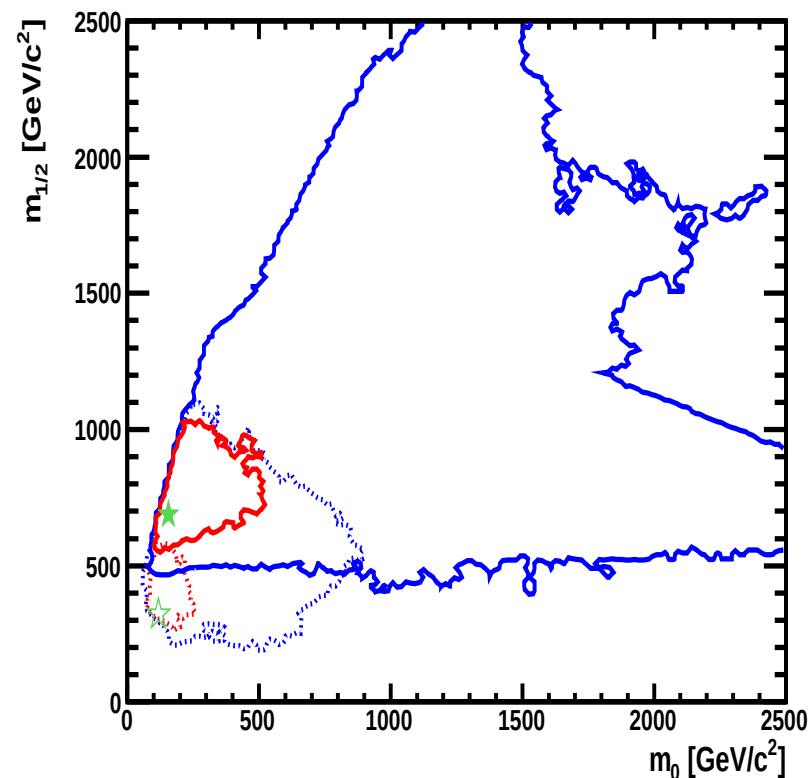
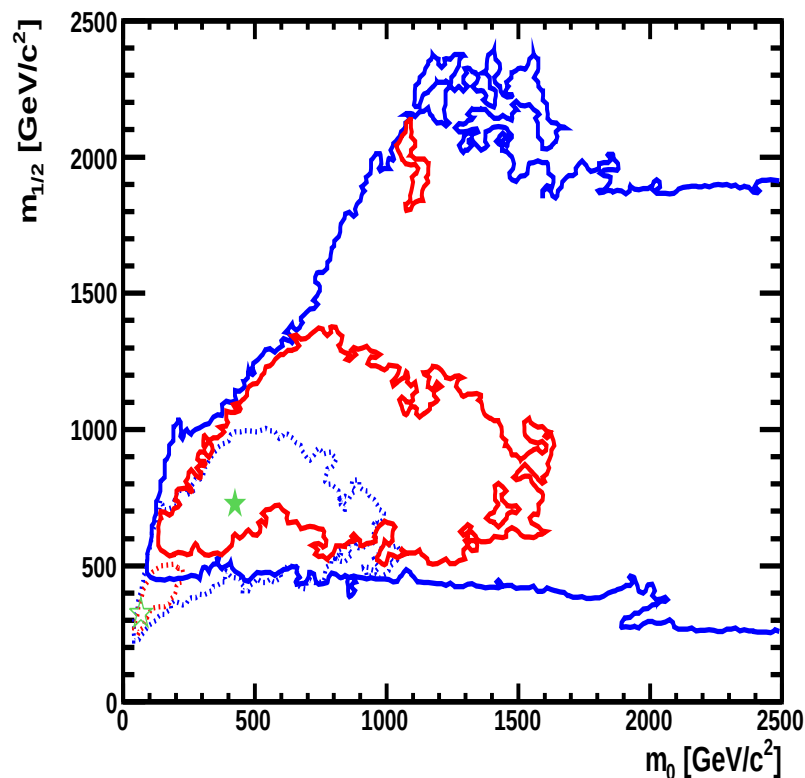


m_0 - $m_{1/2}$ plane including 1/fb of LHC data:

[2011]

CMSSM

NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

⇒ new best-fit point within old 95% CL area

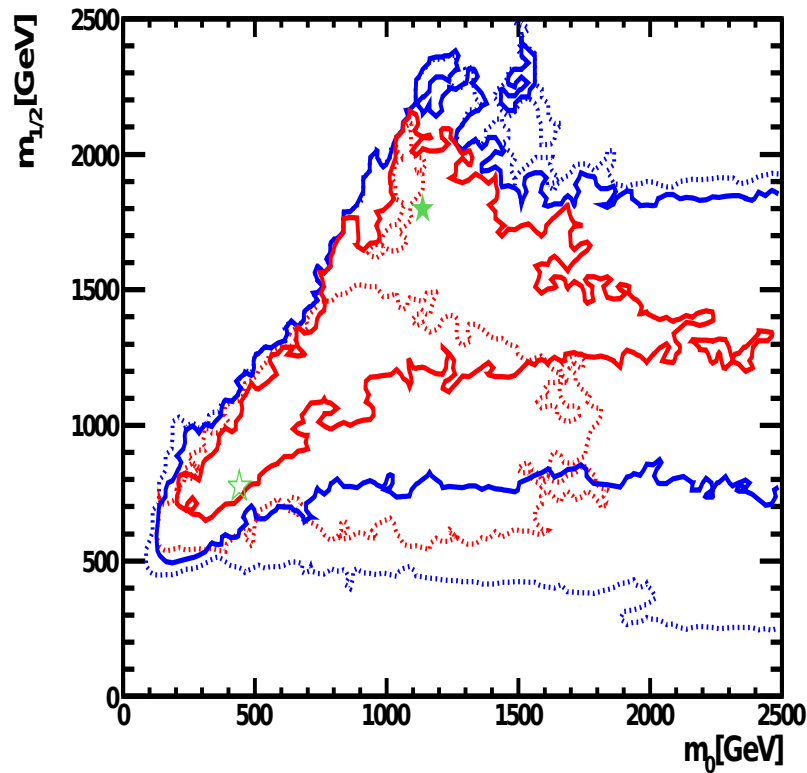
⇒ hardly any overlap between old and new 68% CL areas

⇒ shift to higher masses

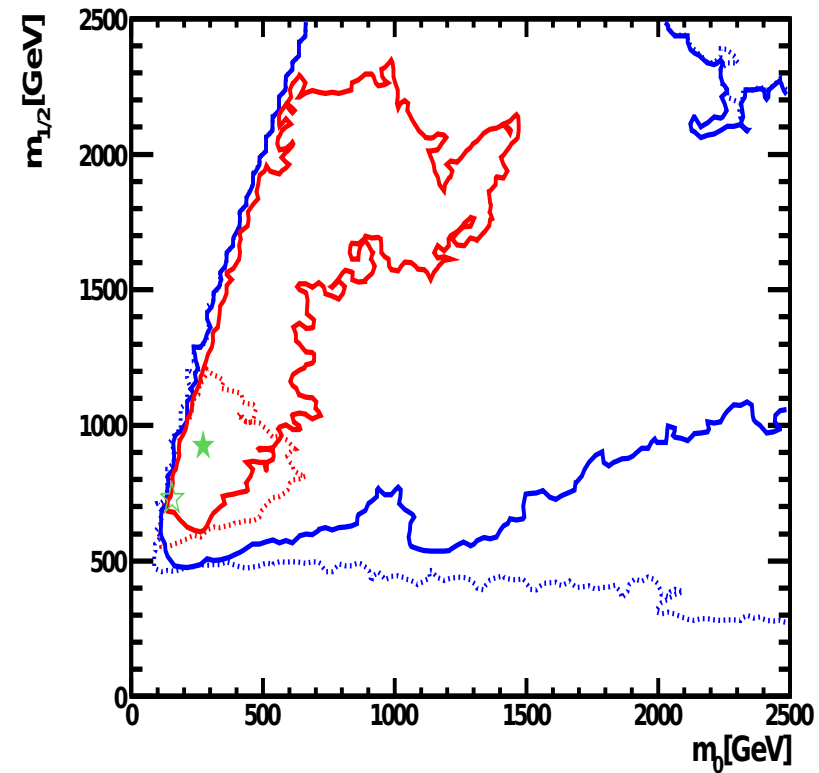
m_0 - $m_{1/2}$ plane including “Higgs measurement”:

[2011]

CMSSM



NUHM1

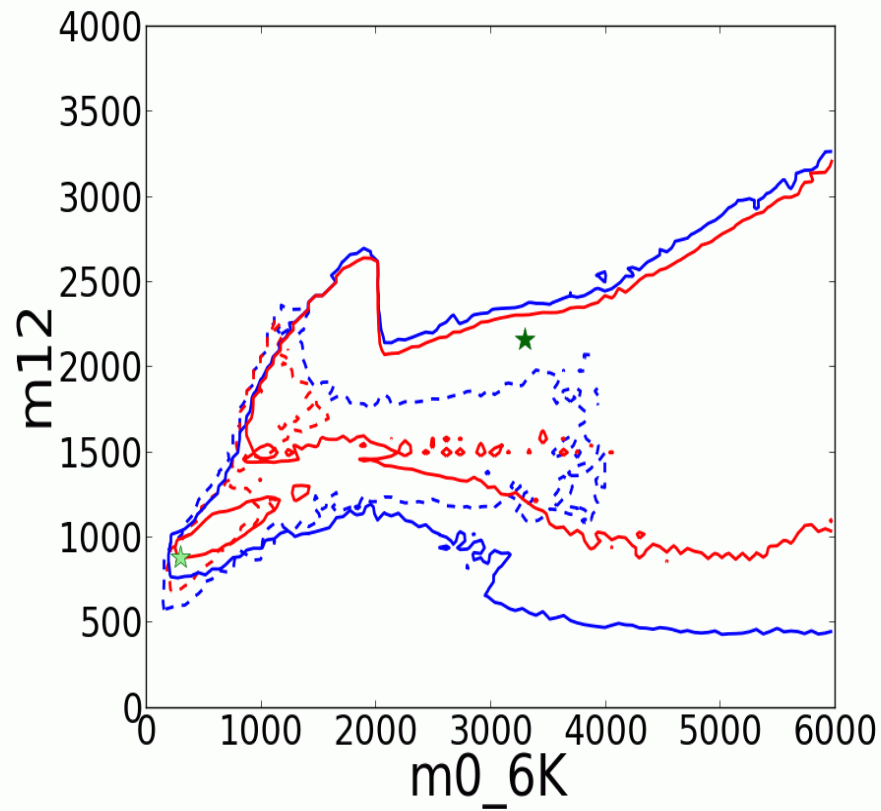


dotted: pre-Higgs, solid: post-Higgs
 $\Rightarrow$ shift to even higher masses
 even larger allowed ranges ...

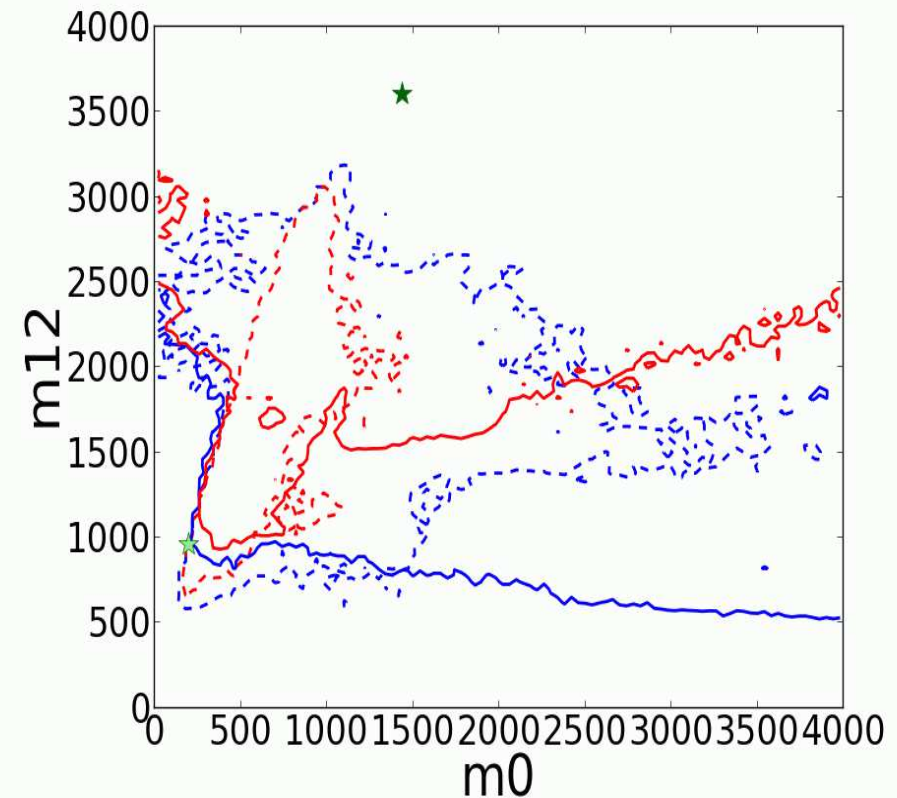
m_0 - $m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



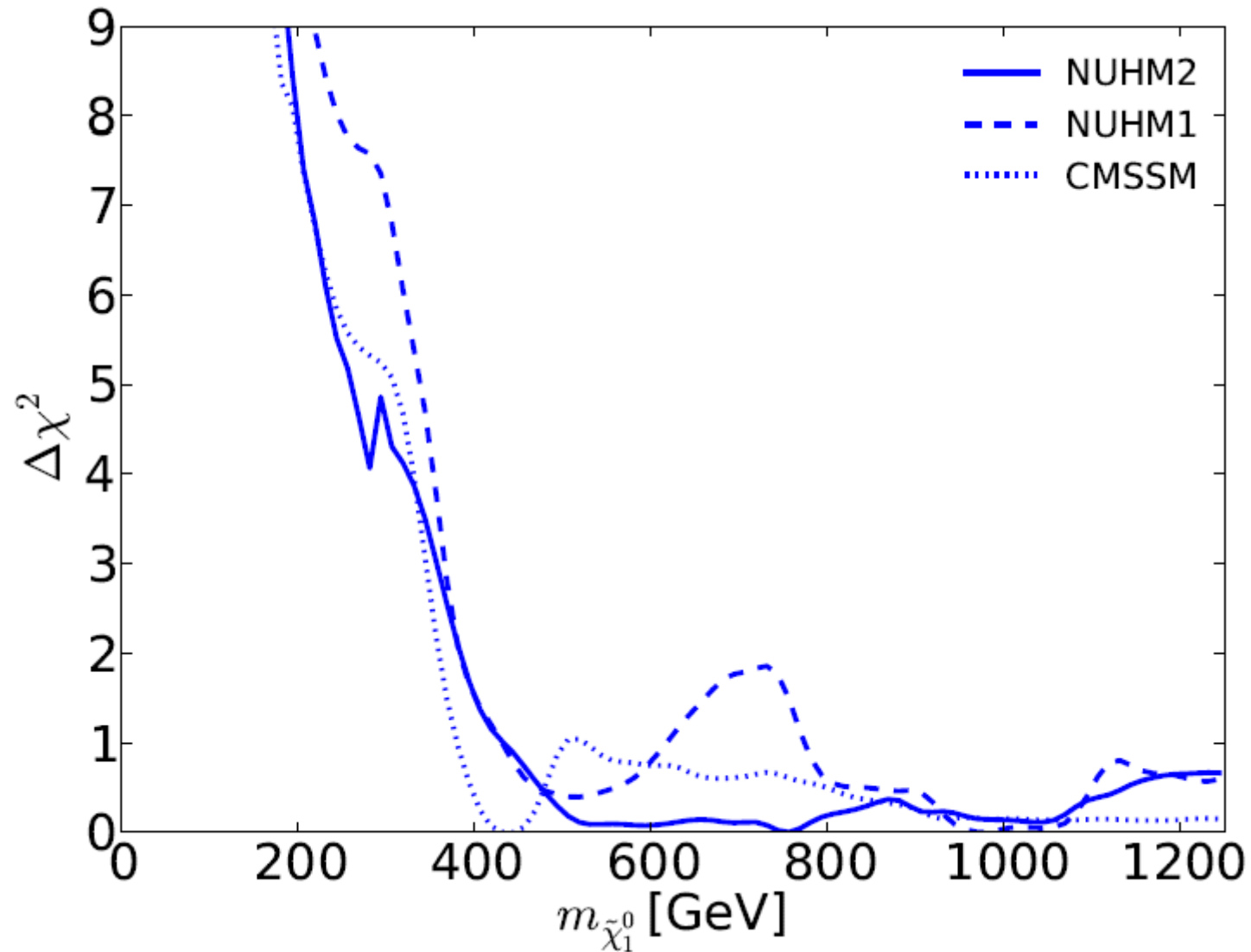
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ shift to even higher masses

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LSP mass incl. 20/fb of LHC data

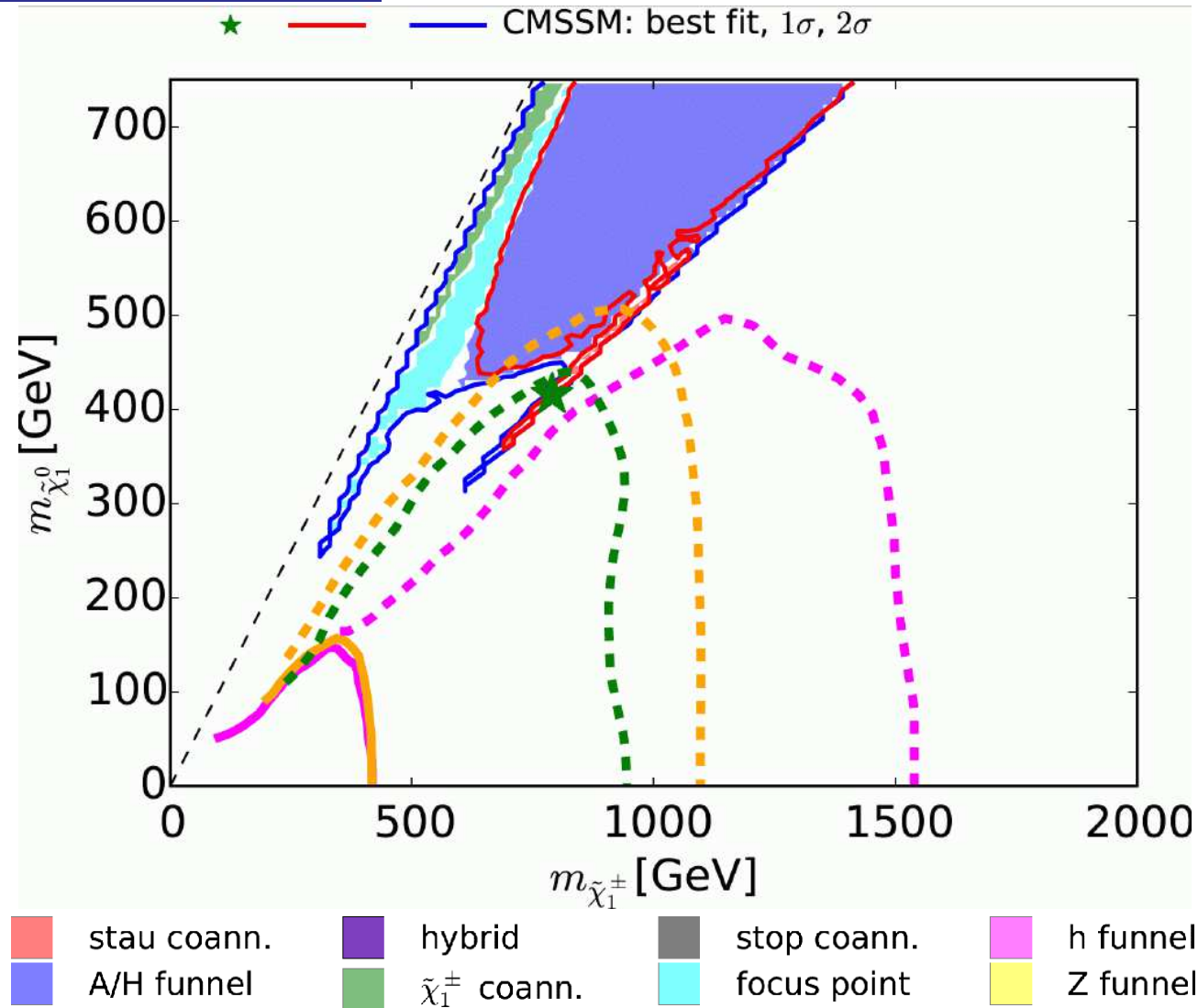
[2014]



⇒ only very large values are favored

LHC prospects for CMSSM:

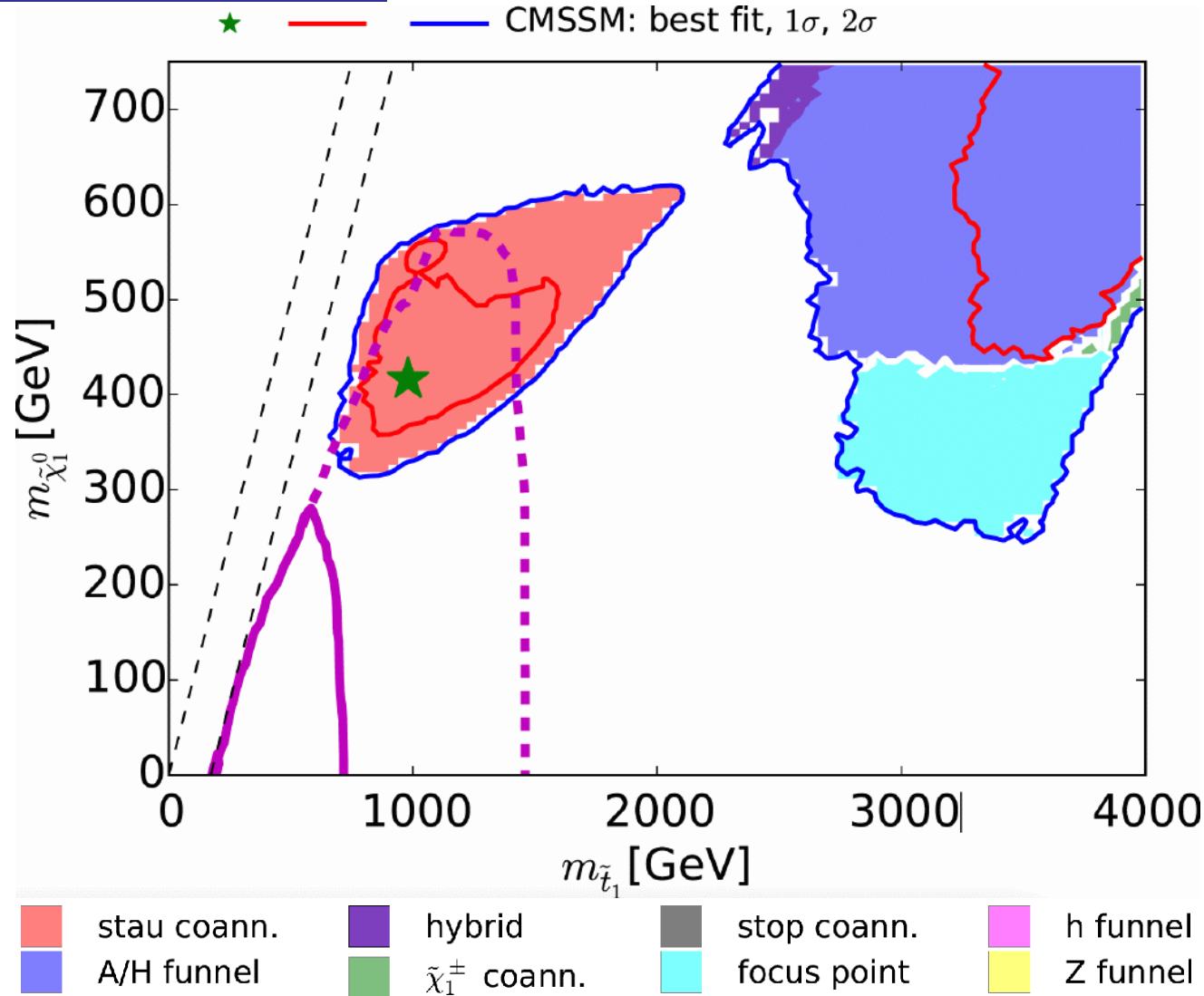
[2015]



solid: current LHC limits, dashed: HL-LHC prospects
 $\Rightarrow$ best-fit point, but not much more can be covered! (in EW searches)

LHC prospects for CMSSM:

[2015]



solid: current LHC limits, dashed: HL-LHC prospects
 ⇒ best-fit regions can partially be covered! (in colored searches)

What is happening to the χ^2 ?

Low energy data (mostly $(g-2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

M_h “measurement” moves the fit to even higher scales

$\Rightarrow$ tension, reflected in rising χ^2 : (note: HiggsSignals **not** included!)

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan \beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC $1\text{ fb}^{-1} \oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC $20\text{ fb}^{-1} \oplus M_h$	32.8/24	11%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
LHC $1\text{ fb}^{-1} \oplus M_h$	29.7/22	13%	830	290	660	33
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Probabilities still “so so”, but this might change with LHC run II data.

Not finding SUSY now **does not make SUSY prospects look bad,**
makes some very constrained models look bad!

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An MSSM **Higgs at 125 GeV** **makes CMSSM/NUHM1 less likely**

And requires SUSY realizations that are in agreement with

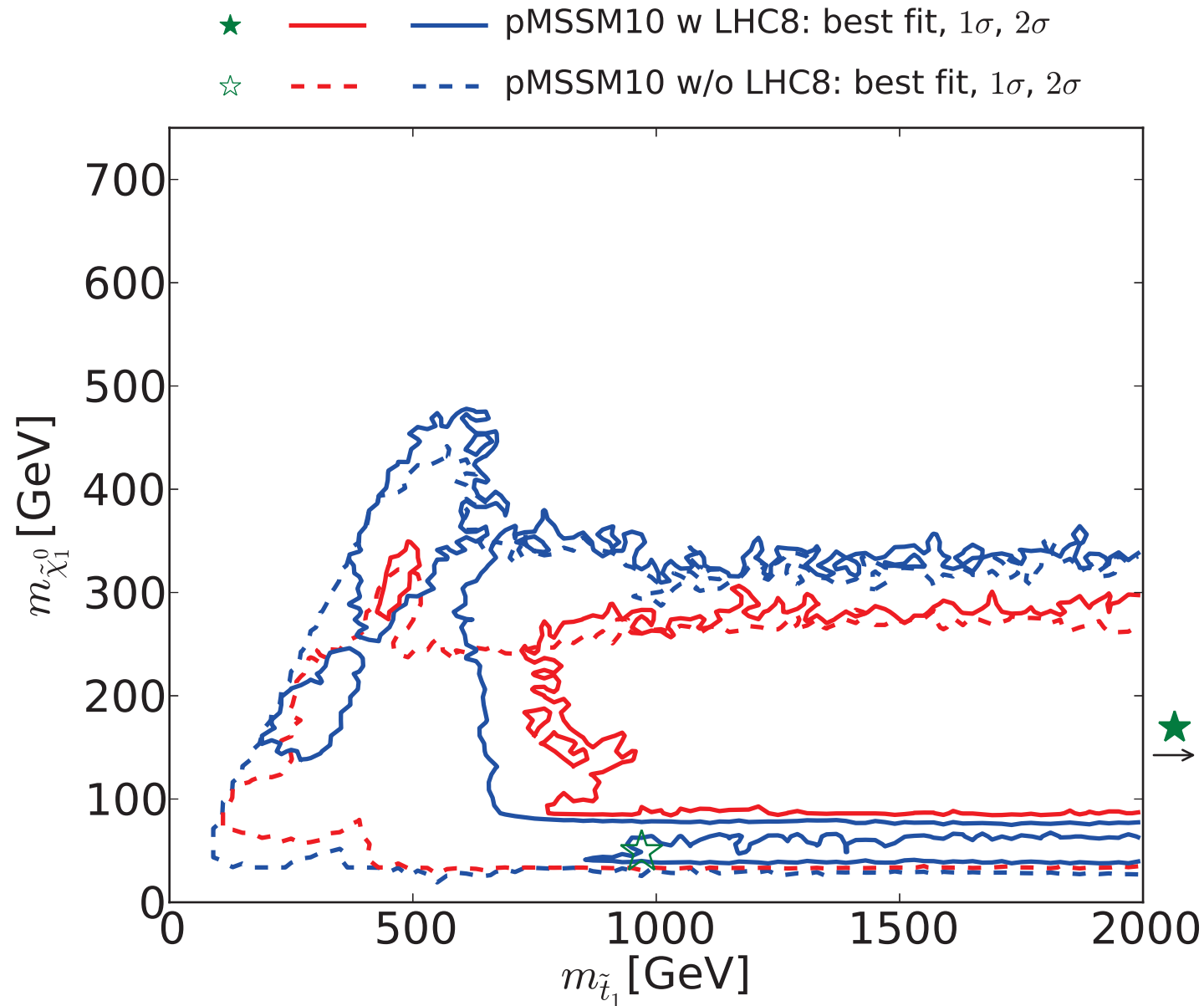
- **higher colored mass scales** (LHC limits)
- **lower uncolored mass scales** (EWPO; $(g-2)_\mu$) $\Rightarrow$ **check pMSSM10!**

Results in the pMSSM10

Parameter	Range	Number of segments
M_1	(-1 , 1) TeV	2
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde{q}}$	(0 , 4) TeV	2
$m_{\tilde{q}_3}$	(0 , 4) TeV	2
$m_{\tilde{l}}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan \beta$	(1 , 60)	1
Total number of boxes		128

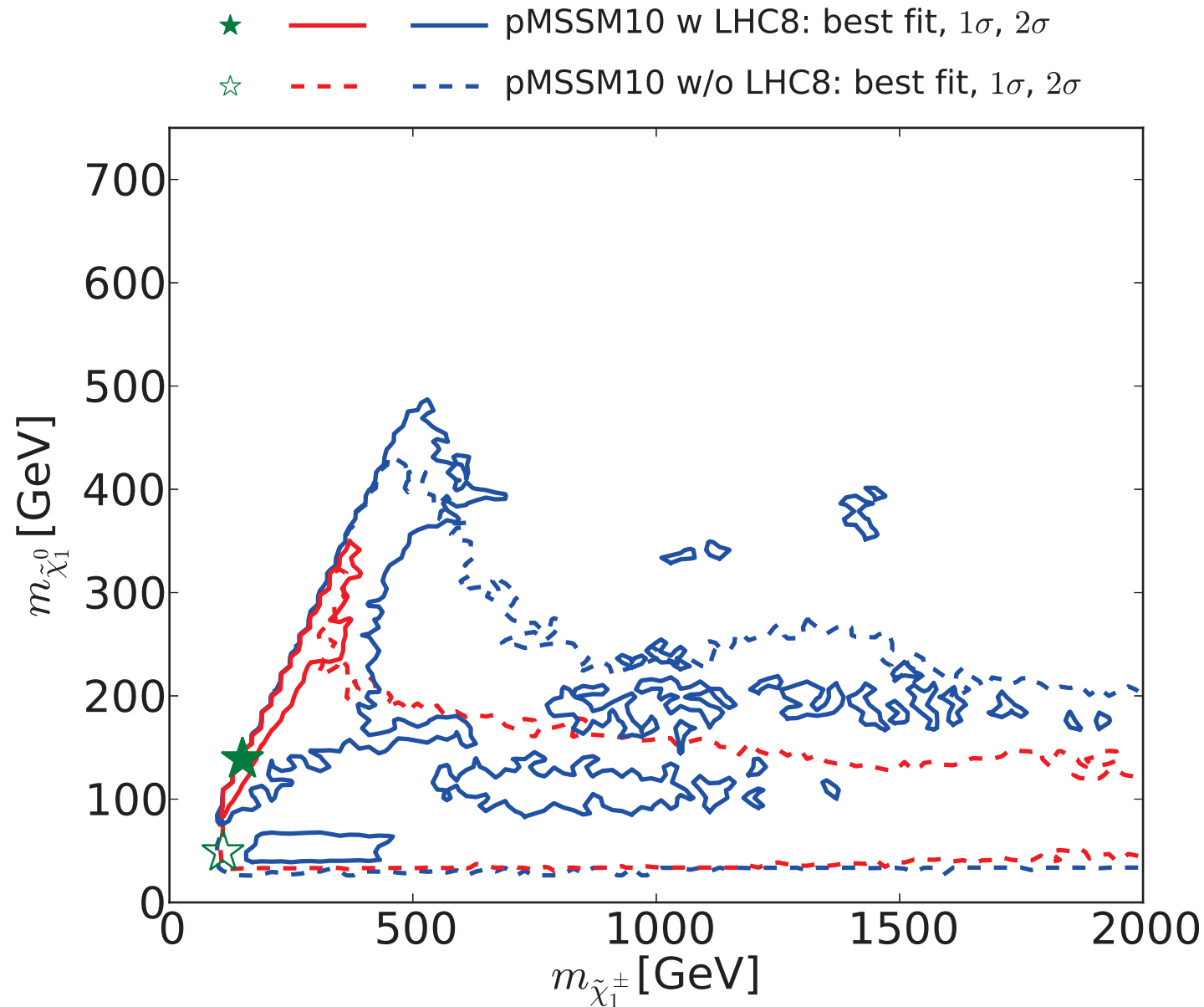
pMSSM10 prediction: DM mass vs. light stop mass:

[2015]



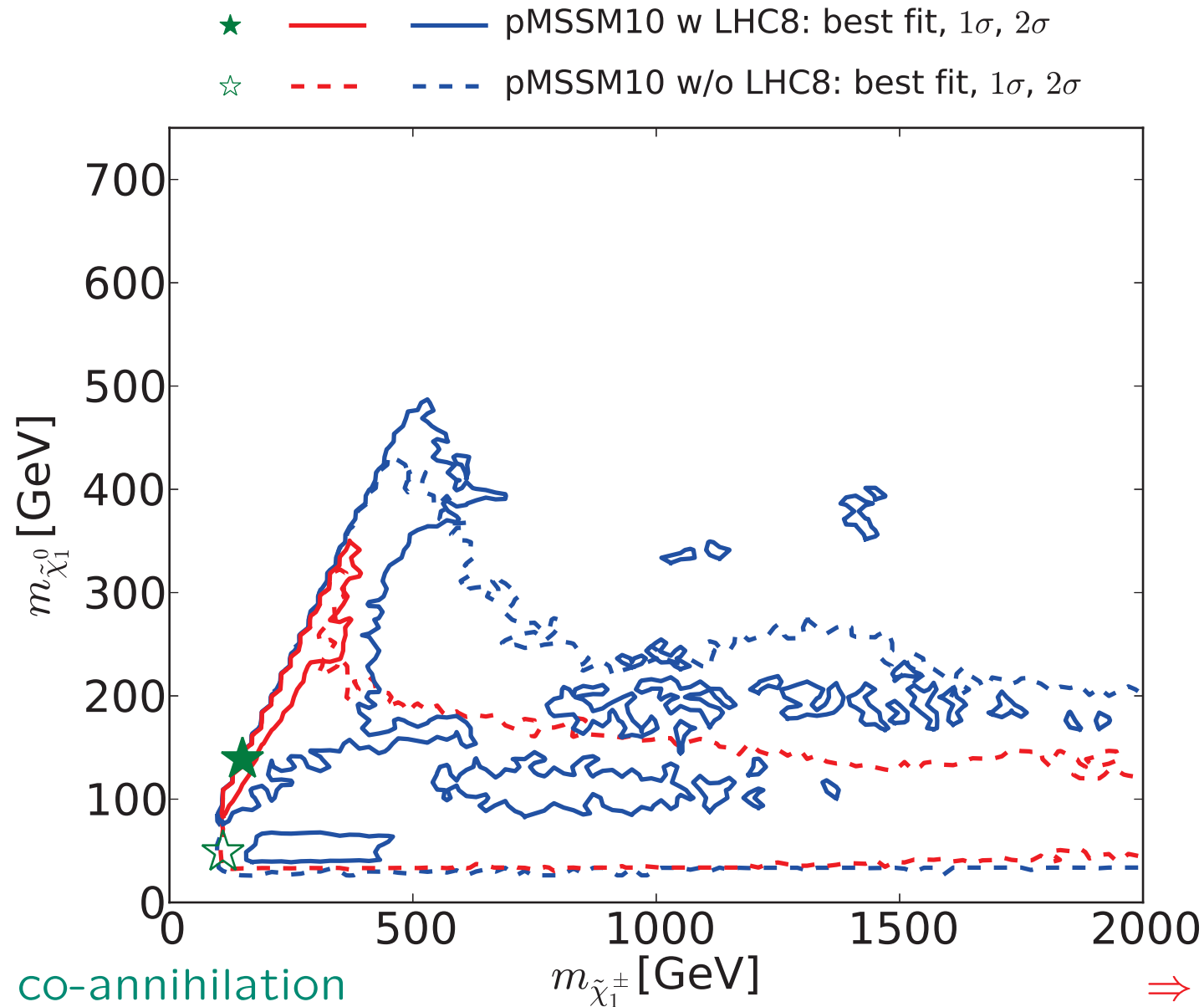
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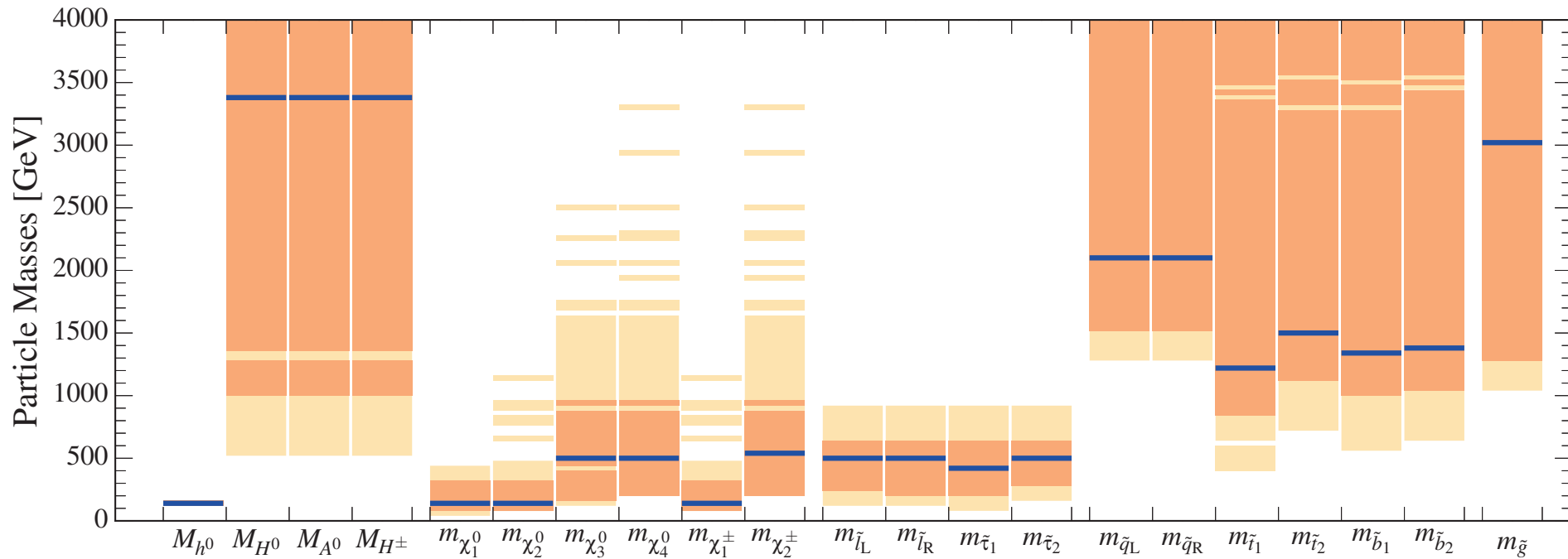
pMSSM10 prediction: DM mass vs. light stop mass:

[2015]



pMSSM10 prediction: best-fit masses

[2015]



⇒ high colored masses

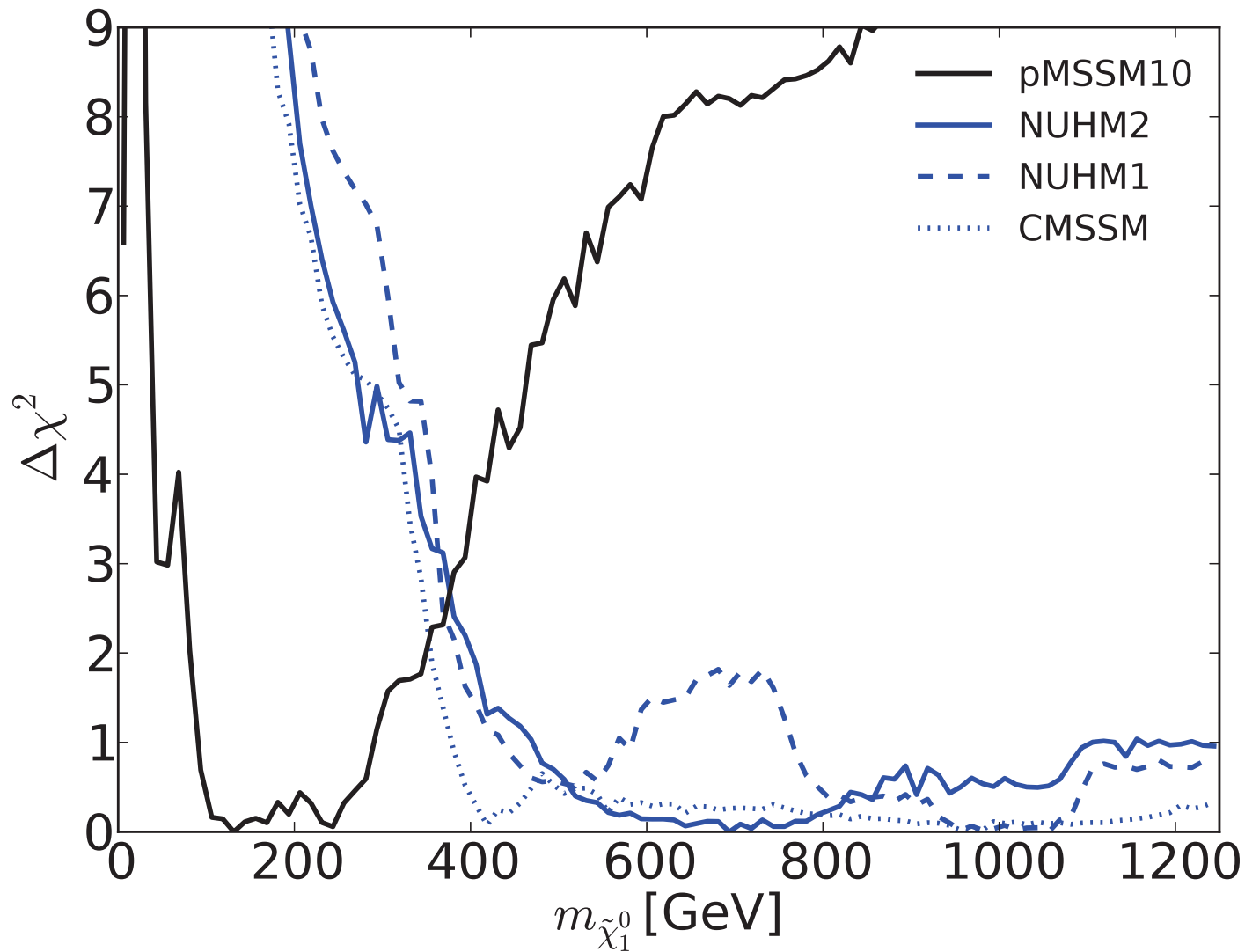
⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for $m_{\tilde{\chi}_1^0}$ (DM) and EW spectrum

pMSSM10 prediction: DM mass

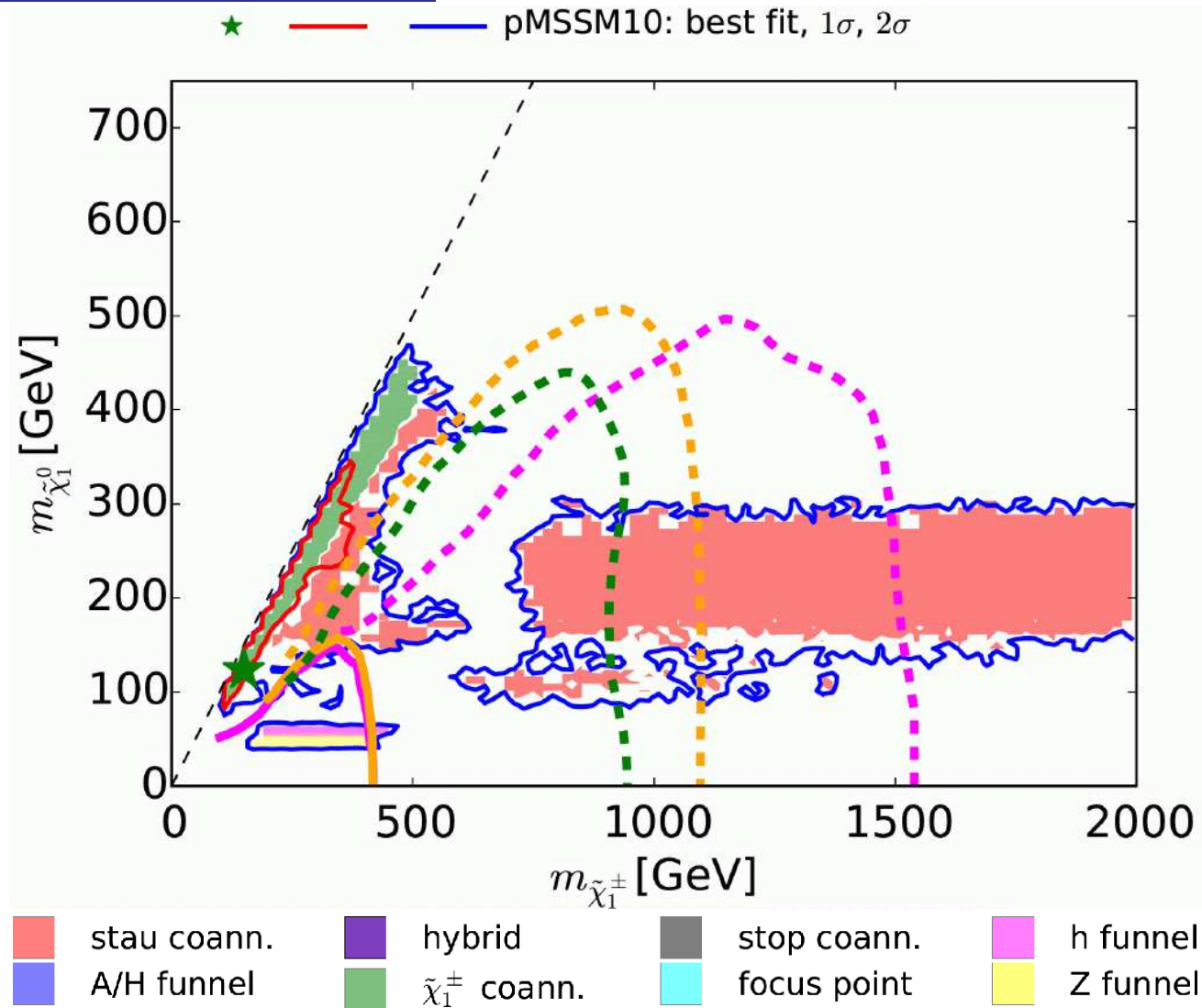
[2015]



⇒ pMSSM10 predicts much lower DM mass than GUT-based models

LHC prospects for pMSSM10:

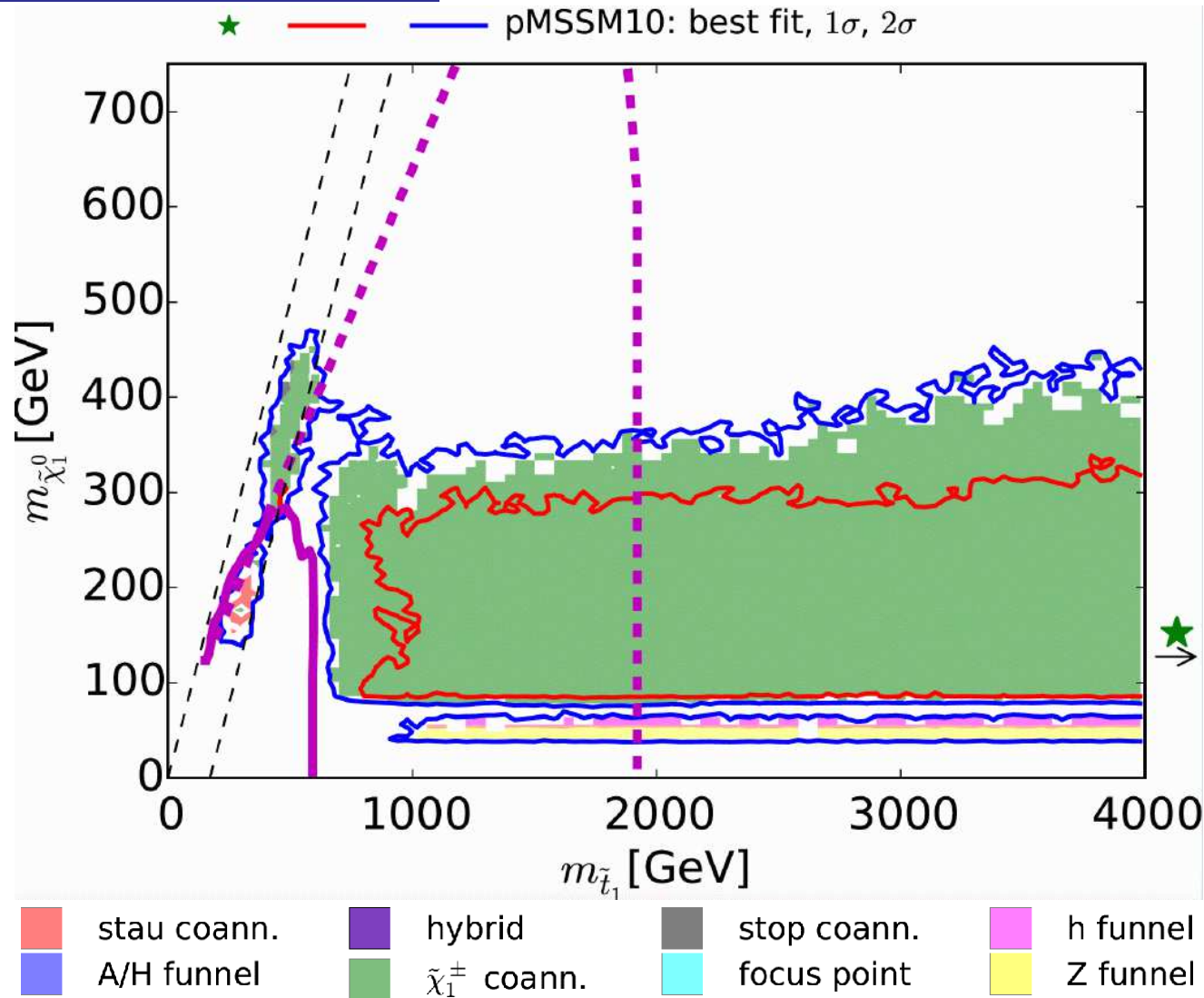
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LHC prospects for pMSSM10:

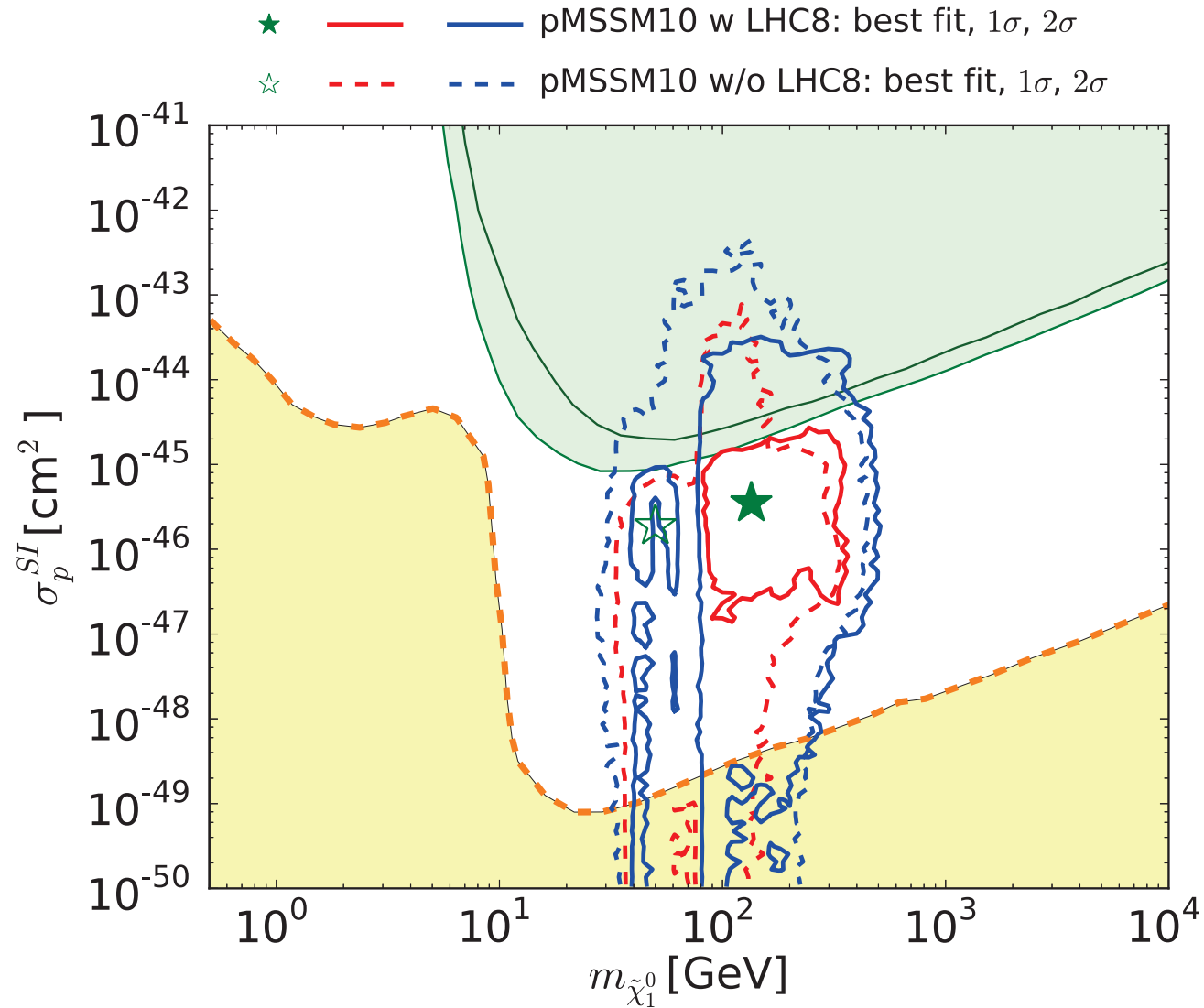
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solid: current LHC limits, dashed: HL-LHC prospects
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pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. σ_p^{SI} :

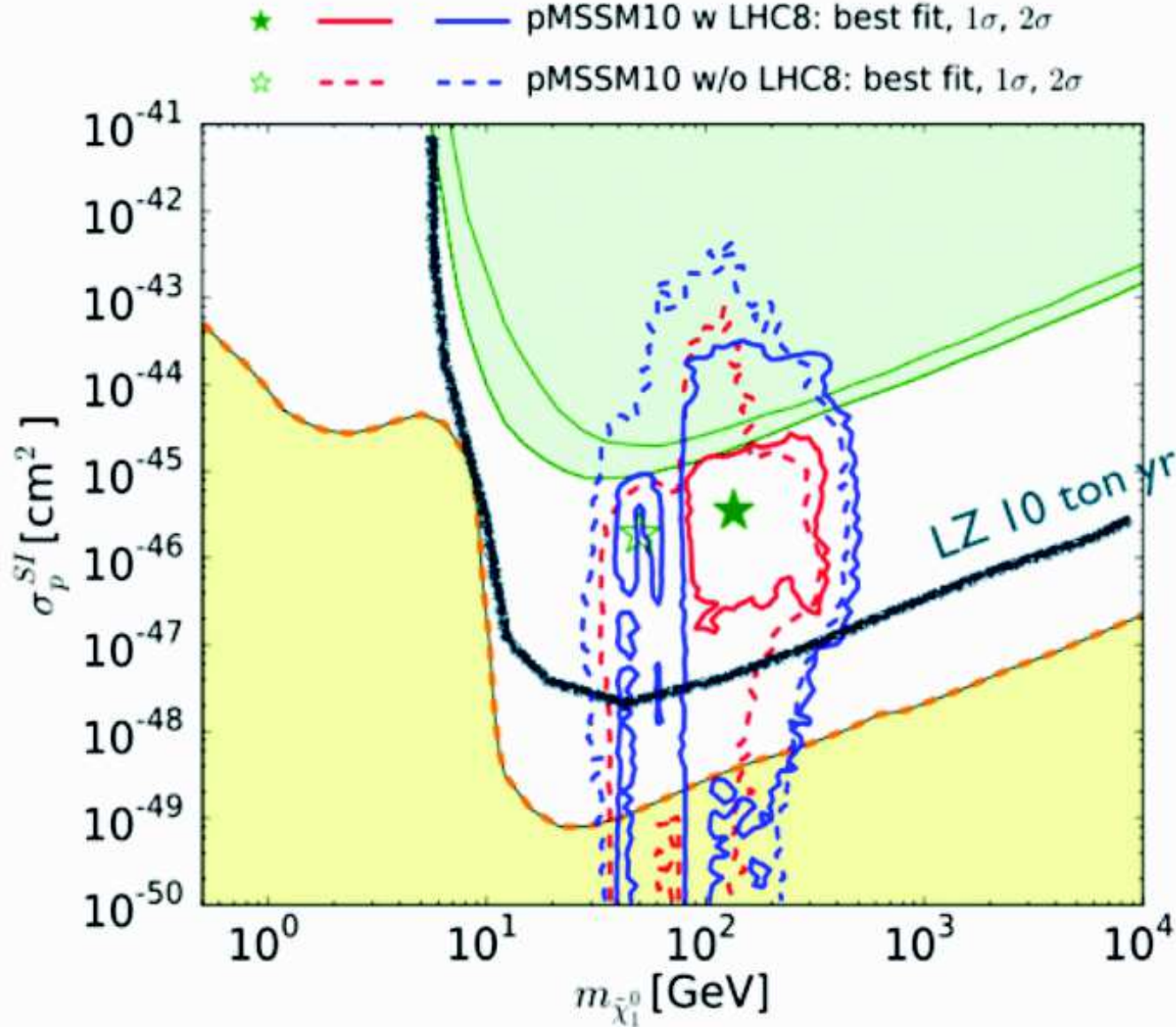
[2015]



⇒ LHC bounds try to “rescue” DD experiments!

pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. σ_p^{SI} : future expectations

[2015]



⇒ 68% CL areas covered by next round of DD experiments

3. SUSY Higgs mass and rate measurements



The Higgs mass accuracy: experiment vs. theory:

Experiment:

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

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

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

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MSSM theory:

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

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

Katharsis of Ultimate Theory Standards

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

Precise Calculation of

(N)

Higgs Boson masses

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

⇒ next meeting: 07/2017 in Karlsruhe

Enlarged Higgs sector: Two Higgs doublets

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

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

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

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

Stop mass matrices

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

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 measurements?

We have a ~ 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 ($\langle H_1 \rangle = v/\sqrt{2}$, $\langle H_2 \rangle = 0$)

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

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

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

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

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

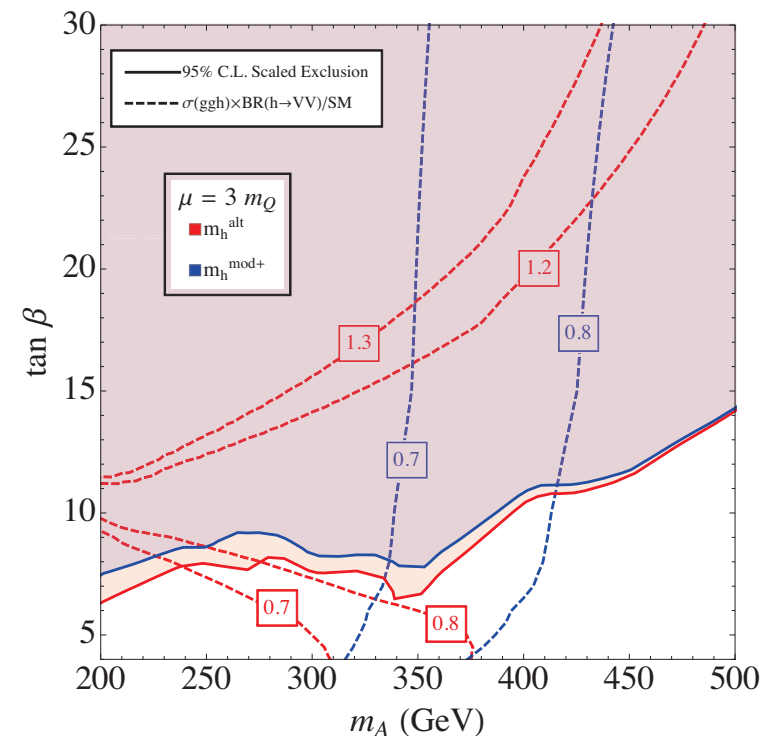
$$A_t/M_S = 2.45, \quad A_t = A_f,$$

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

$$M_2 = 2 M_1 = 200 \text{ GeV}, \quad \mu \text{ adjustable}$$

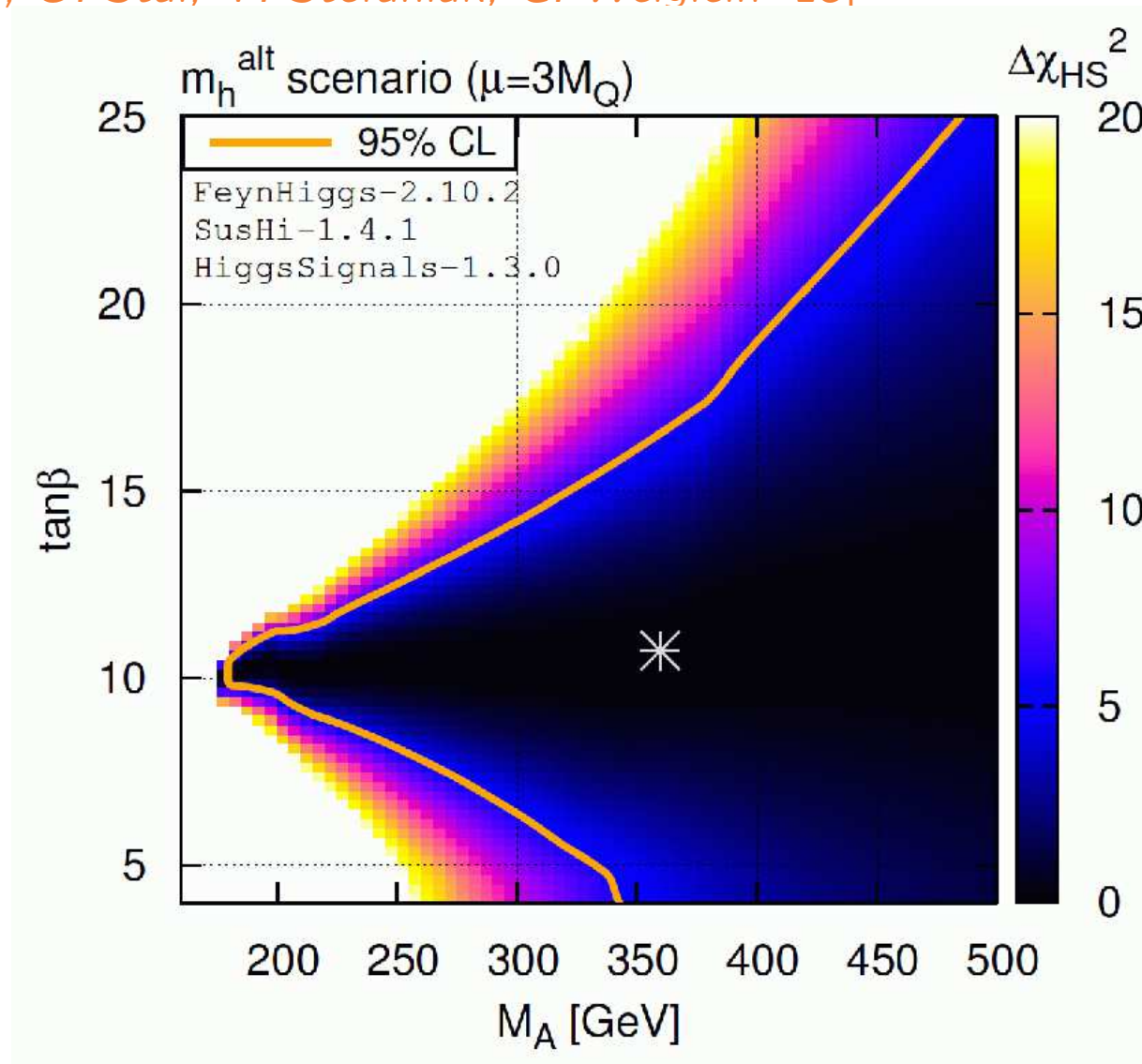
(low M_A and $\tan \beta$: tune $M_S \geq 1 \text{ TeV}$
to obtain $M_h \geq 122 \text{ GeV}$)

$\Rightarrow$ SM-like Higgs for all M_A



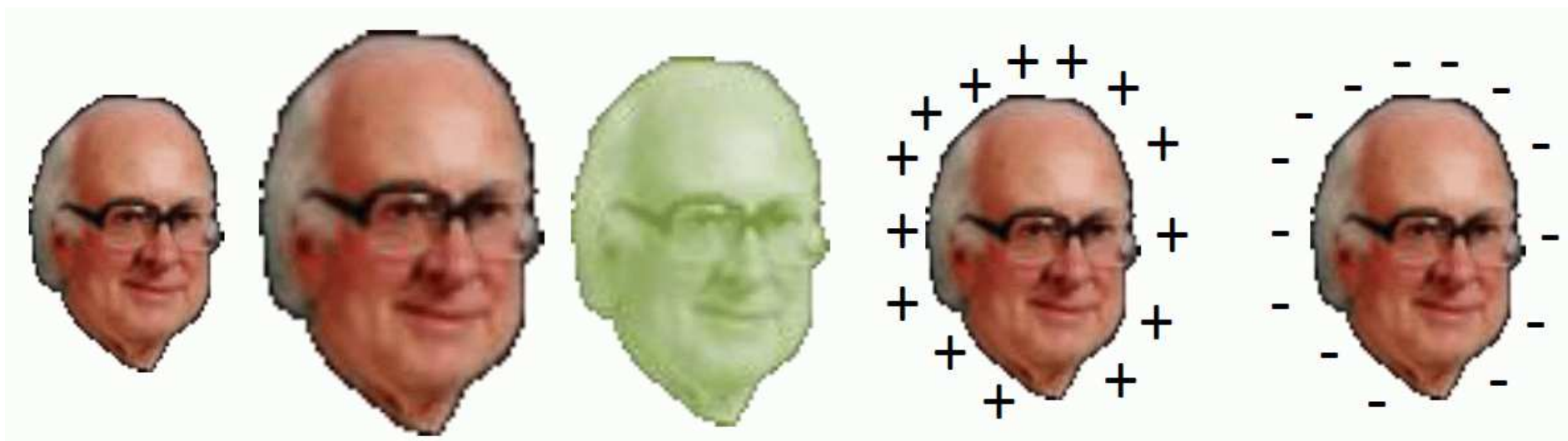
Preferred m_h^{alt} parameter space from HiggsSignals:

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



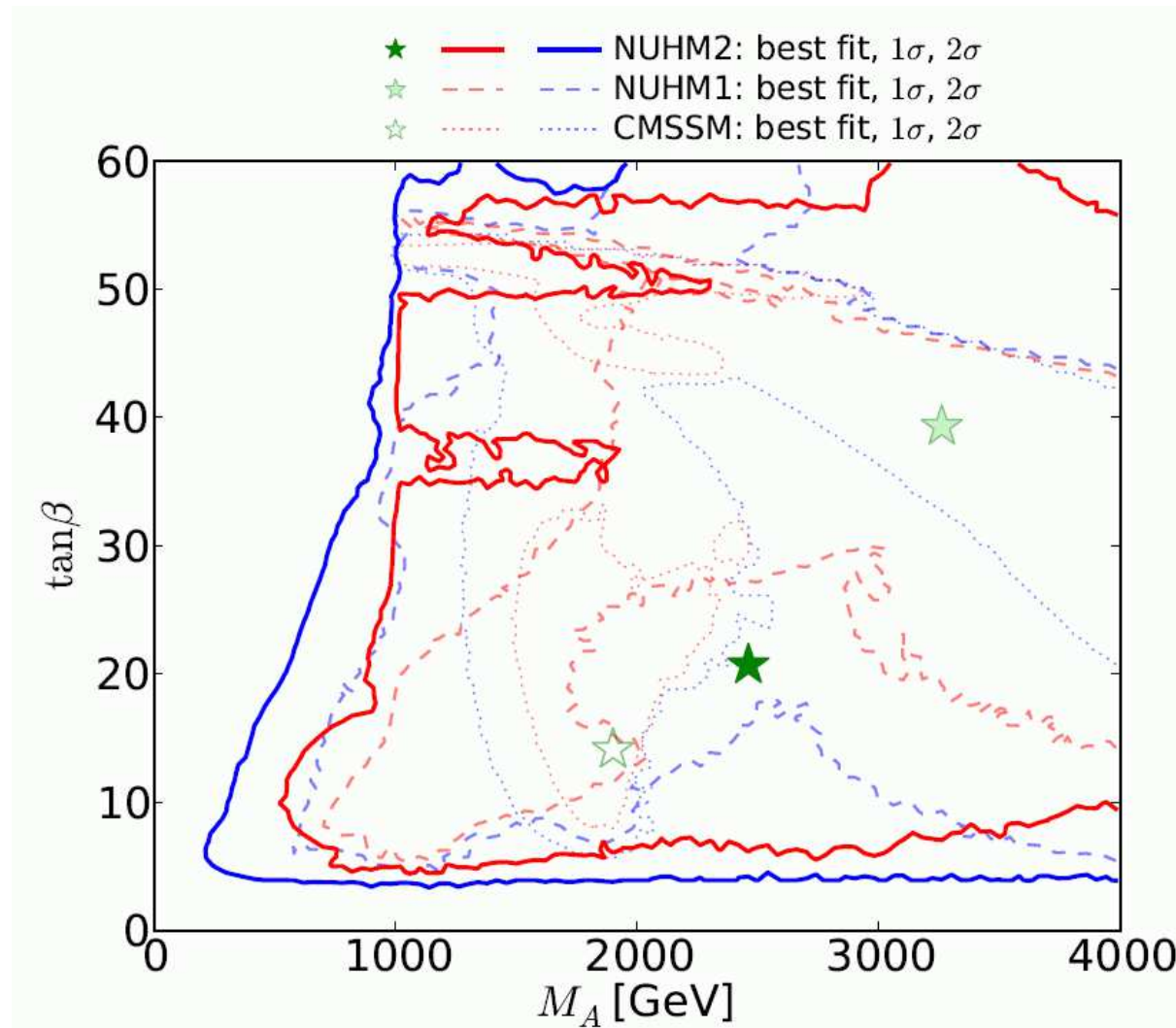
⇒ no Higgs mass scale restrictions from rates (in general)

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



M_A - $\tan\beta$ plane in CMSSM, NUHM1, NUHM2:

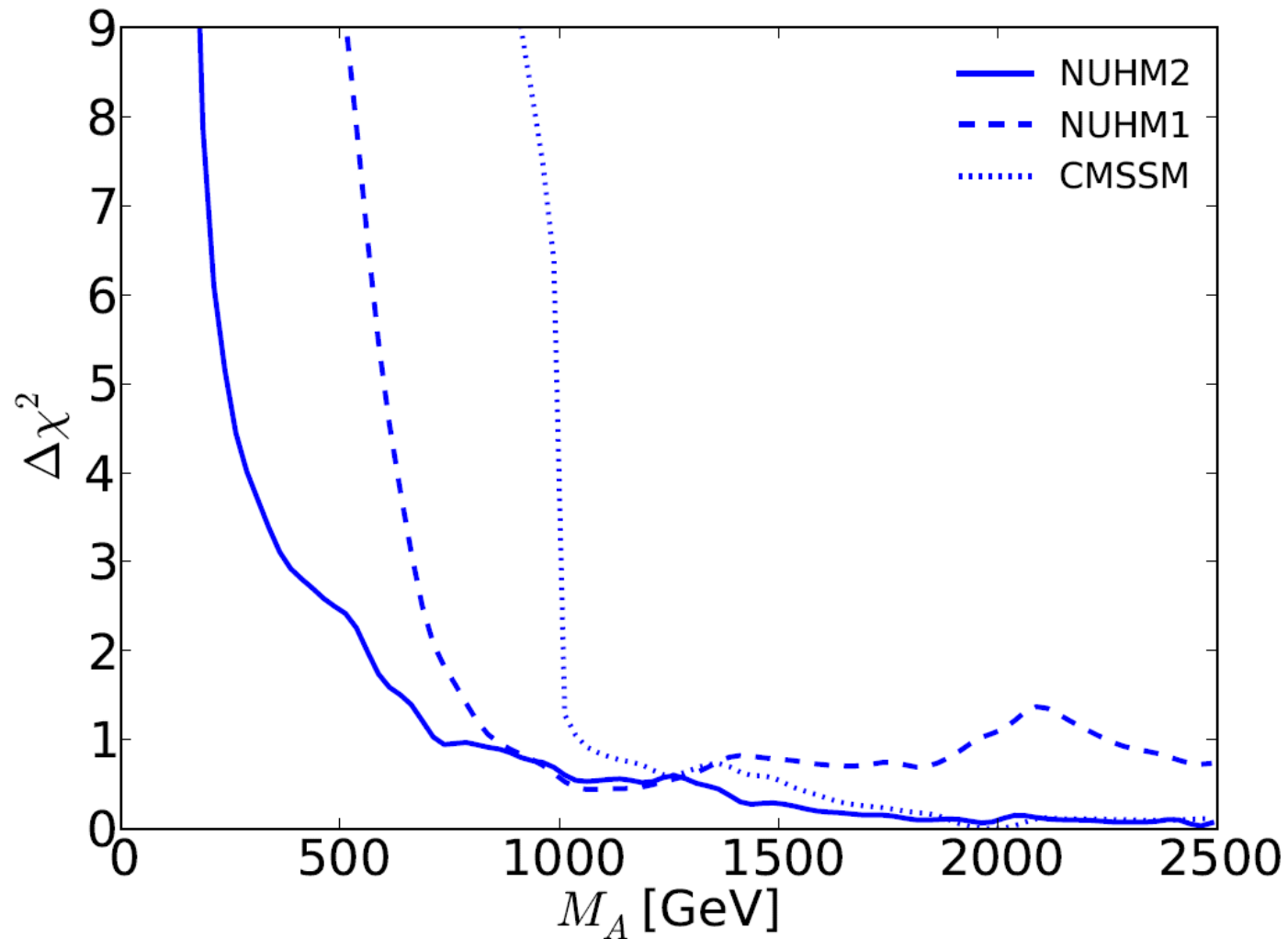
[2015]



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

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

[2015]



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

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

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

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

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

$$A_b = A_\tau = A_t$$

$$M_3 = 1.5 \text{ TeV}$$

M_1 fixed by GUT relation

10^7 random points

$$R_{XX}^\phi := \frac{\sum_i [\sigma_i(\phi) \times \text{BR}(\phi \rightarrow XX)]_{\text{MSSM}}}{\sum_i [\sigma_i(\phi) \times \text{BR}(\phi \rightarrow XX)]_{\text{SM}}}$$

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): $b \rightarrow s\gamma$, $B_s \rightarrow \mu\mu$, $B_u \rightarrow \tau\nu$, $(g-2)_\mu$, M_W
- exclusion likelihood from CMS $\phi \rightarrow \tau\tau$ 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 $\phi \rightarrow \tau\tau$ 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

$\Rightarrow$ “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_ν^2	p	χ^2/ν	χ_ν^2	p	χ^2/ν	χ_ν^2	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

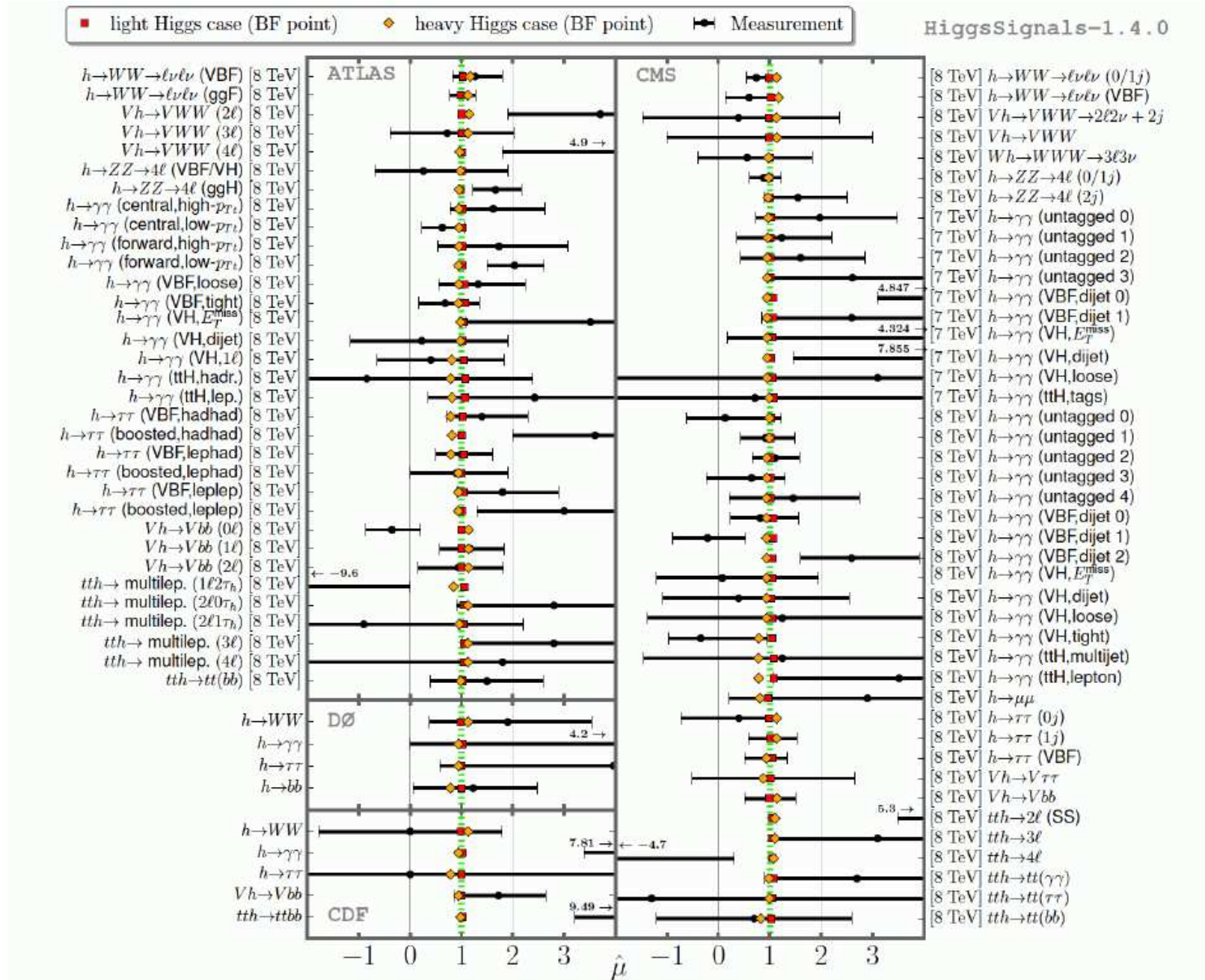
Best-fit points parameters:

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

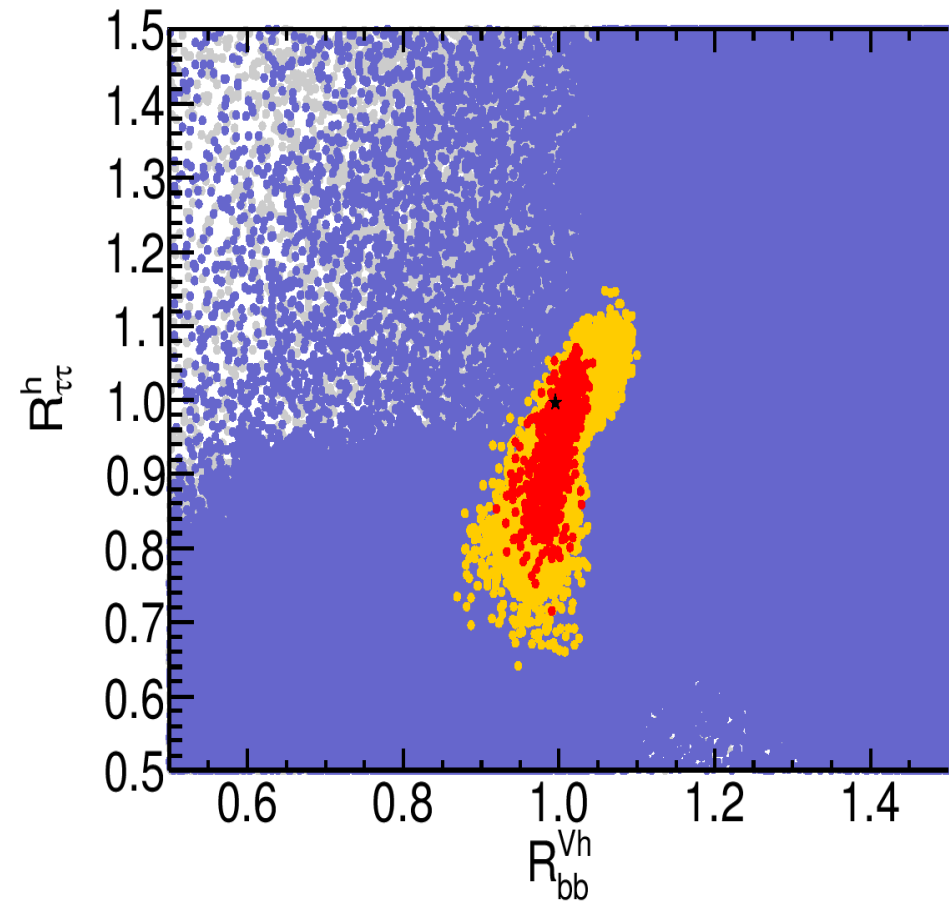
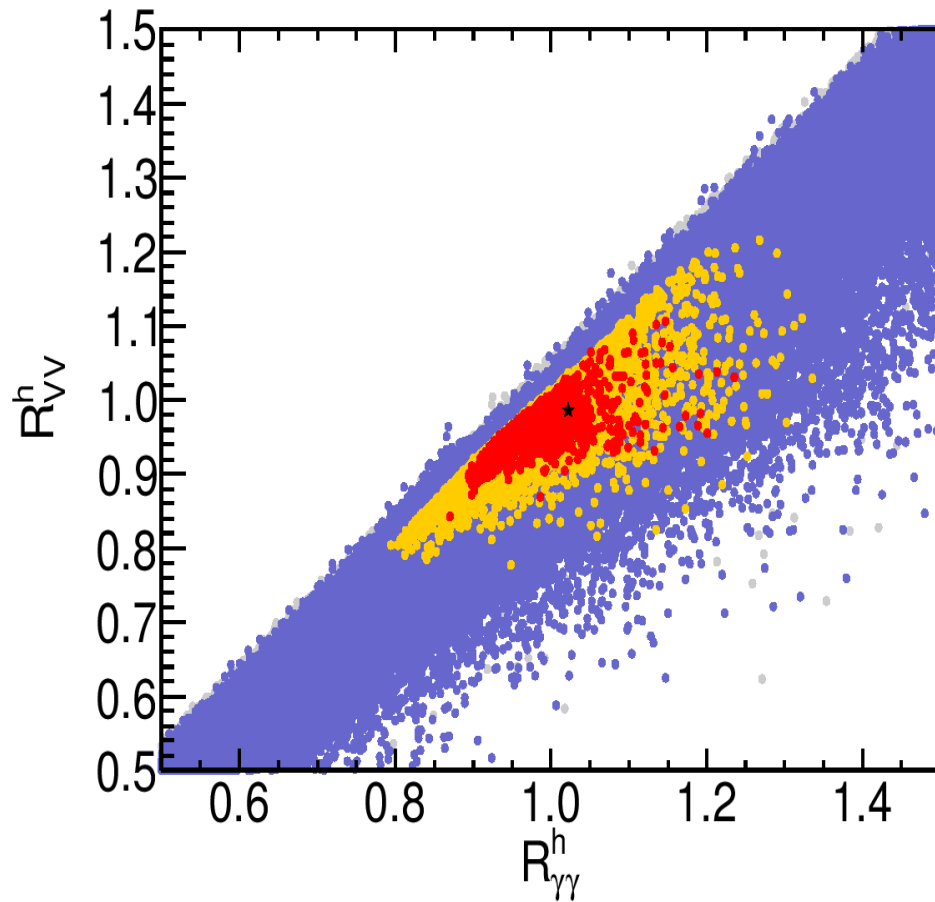
⇒ SM and both MSSM cases provide similar fit to the Higgs data

⇒ Including LEOs, SM fit becomes worse

Best-fit point rates in the two Higgs cases:



Light-Higgs case: preferred rates

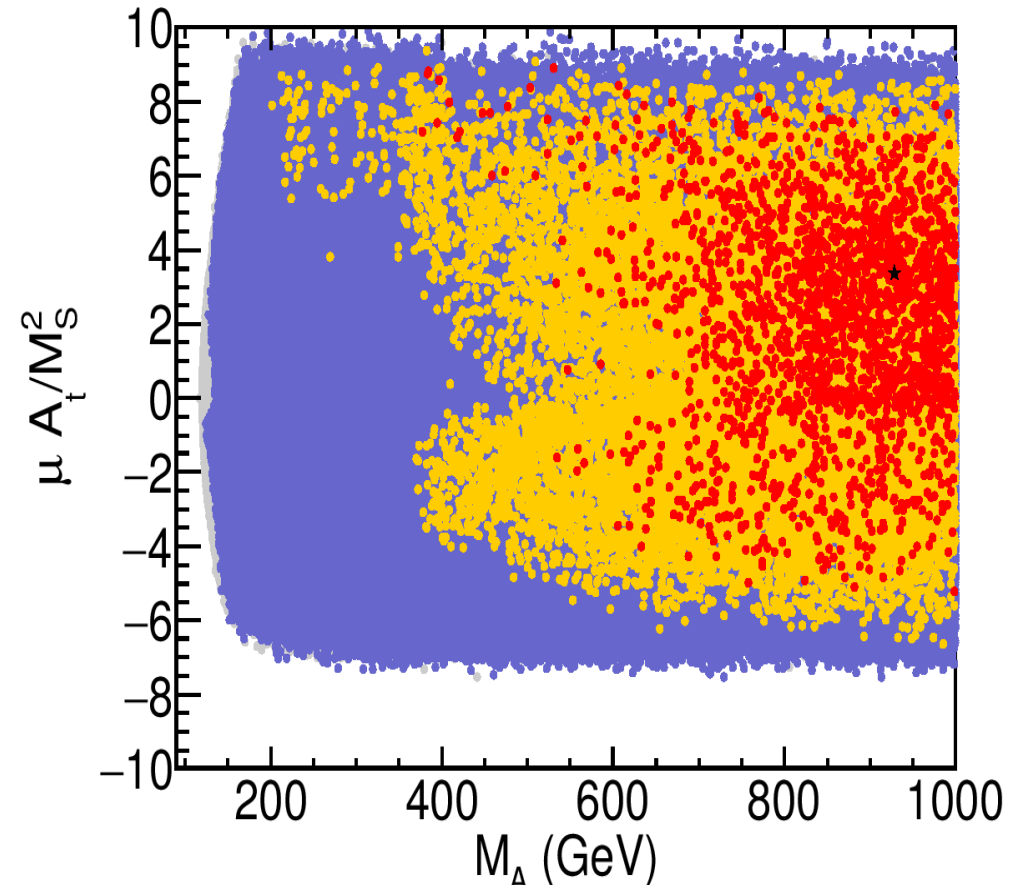
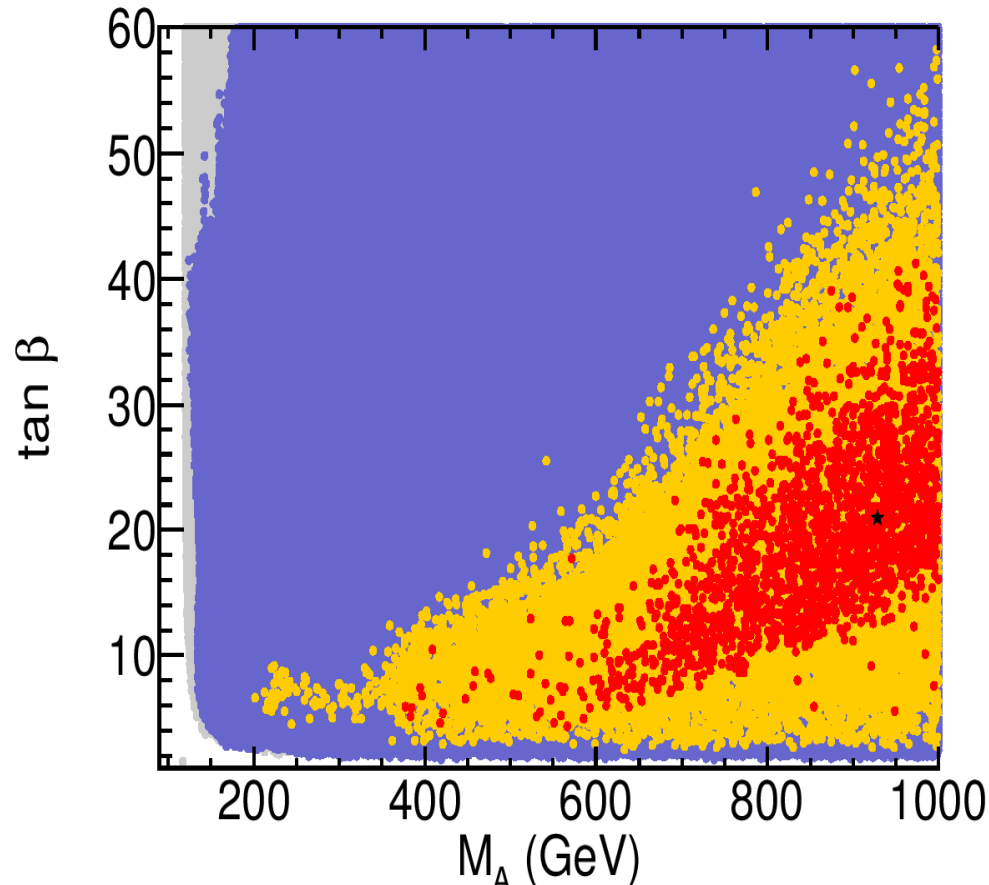


$$R_{VV}^h = 0.99^{+0.09}_{-0.08}, \quad R_{\gamma\gamma}^h = 1.02^{+0.16}_{-0.10}, \quad R_{bb}^{Vh} = 1.00^{+0.02}_{-0.05}, \quad R_{\tau\tau}^h = 1.00^{+0.06}_{-0.20}$$

⇒ 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

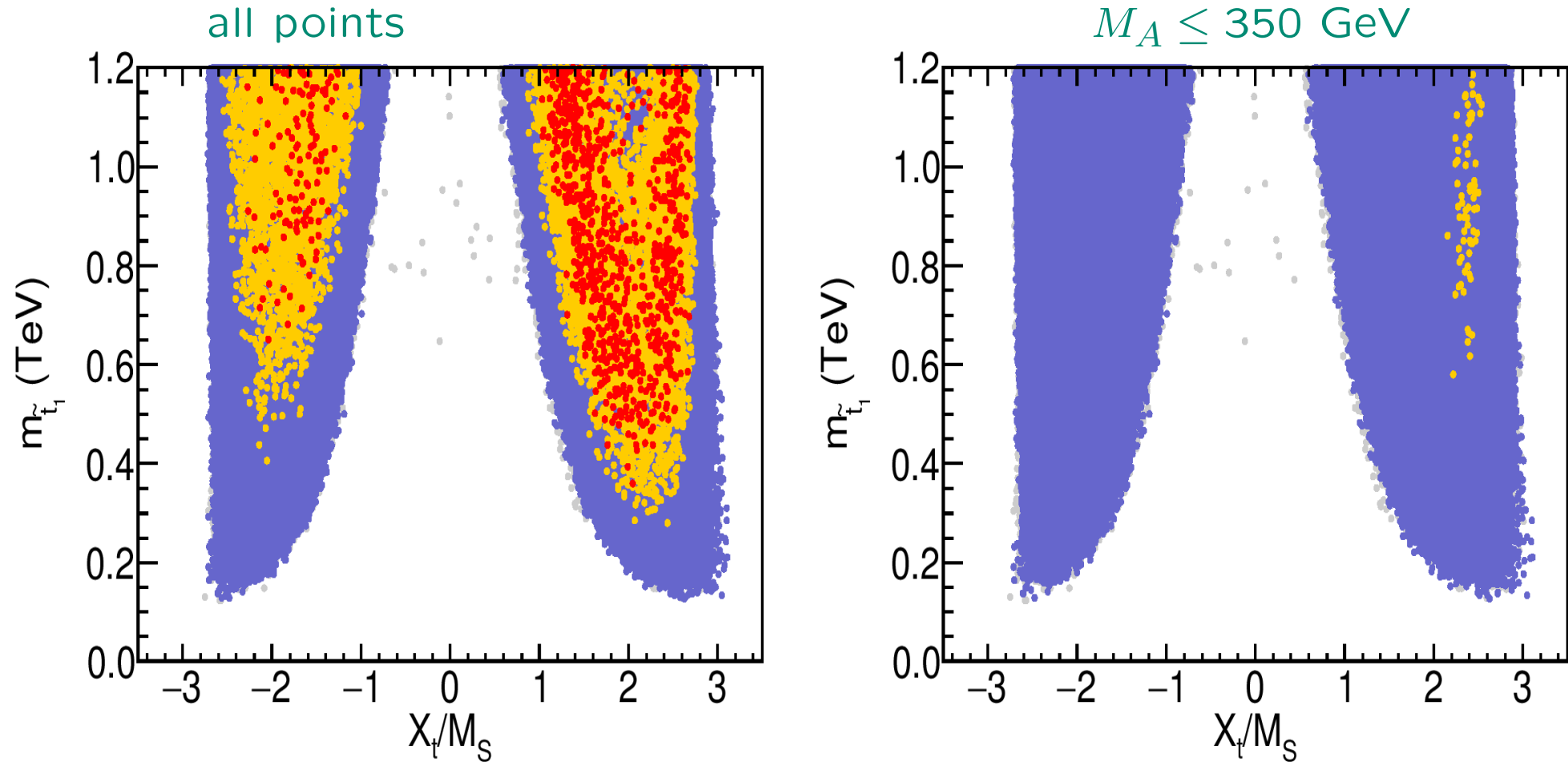
$M_A \gtrsim 200$ GeV $\Rightarrow$ alignment limit

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

$\Rightarrow$ 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 $M_{\tilde{t}_L} \neq M_{\tilde{t}_R}$)

The “exotic” solution:

the discovery is interpreted as the heavy $\mathcal{CP}$ -even Higgs

In principle also possible:

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

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

Consequences:

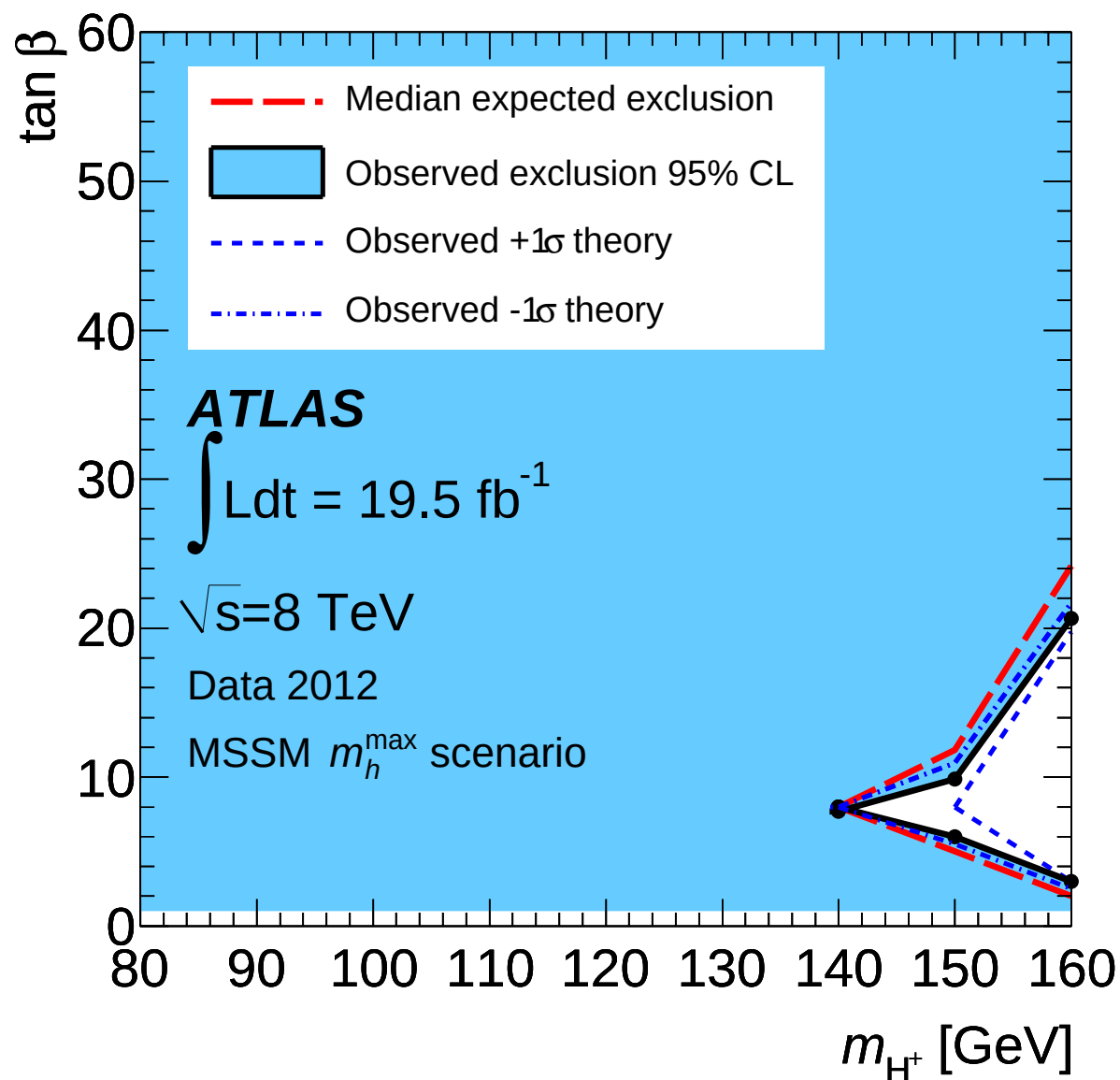
- all Higgs bosons very light
- easy(?) discovery of additional Higgs bosons at the LHC

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 ($\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ etc.)

⇒ original scenario: low- M_H

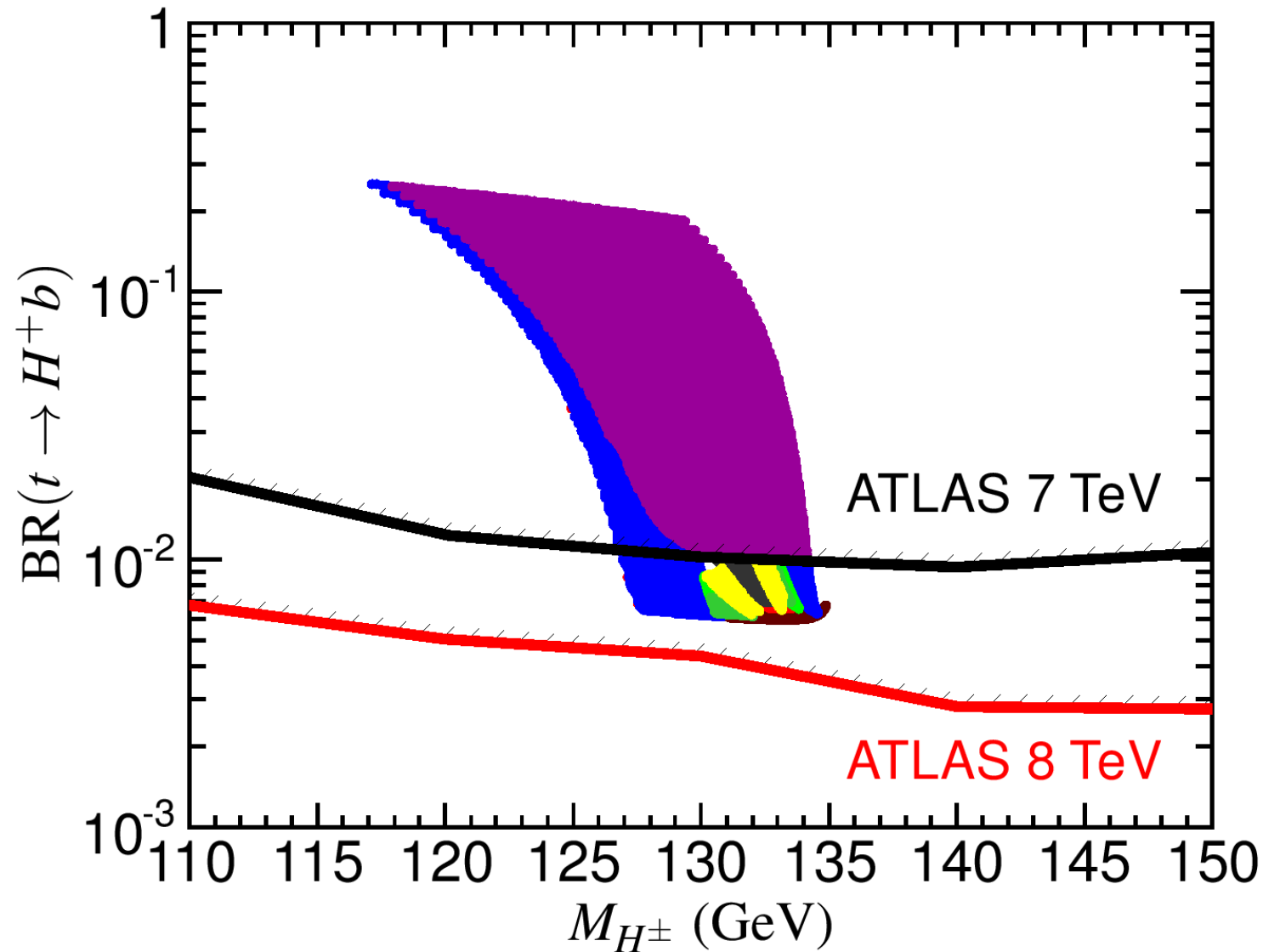
[M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein '13]



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

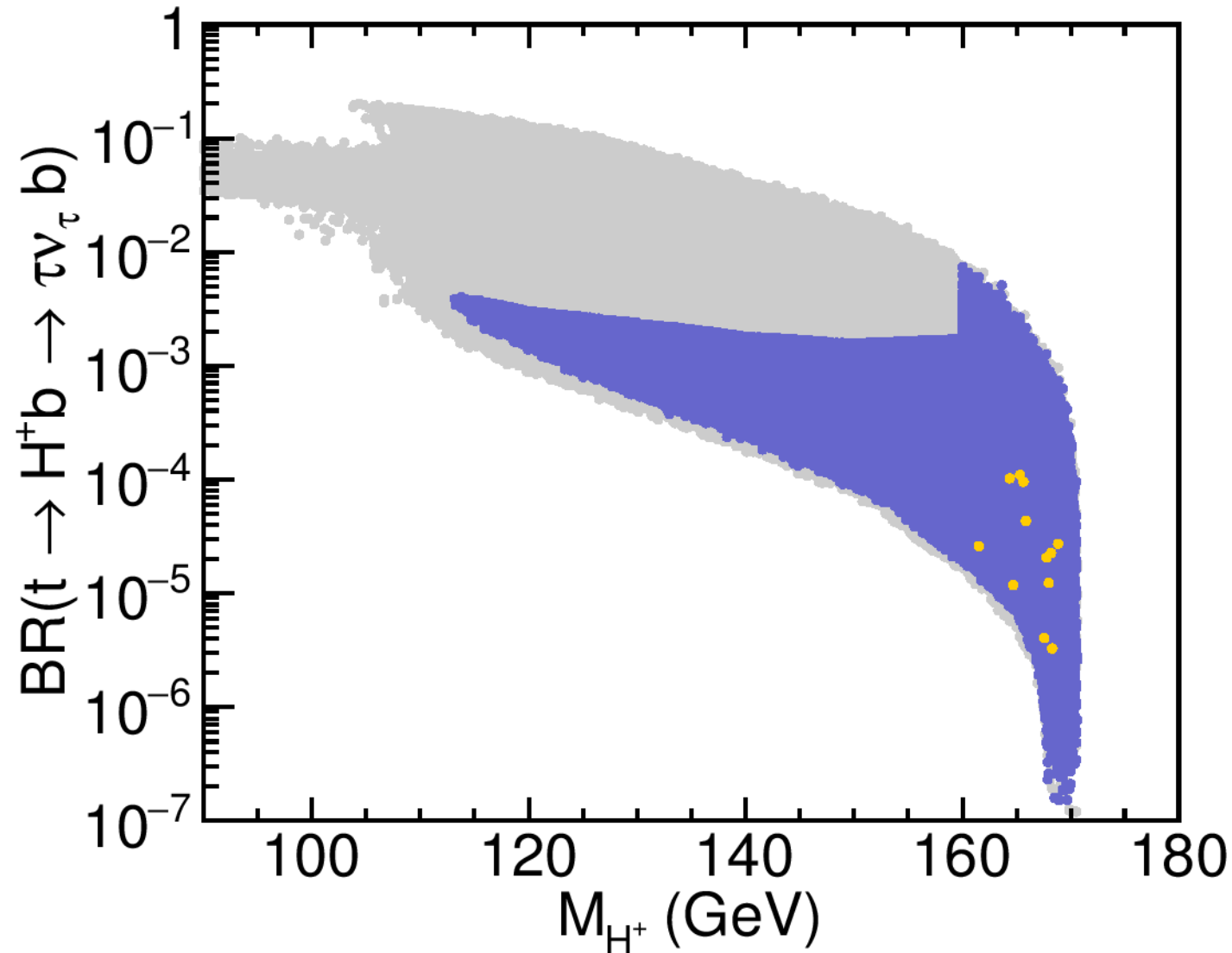
Application of charged Higgs limits on low- M_H scenario:

[*HiggsBounds* 4.1]



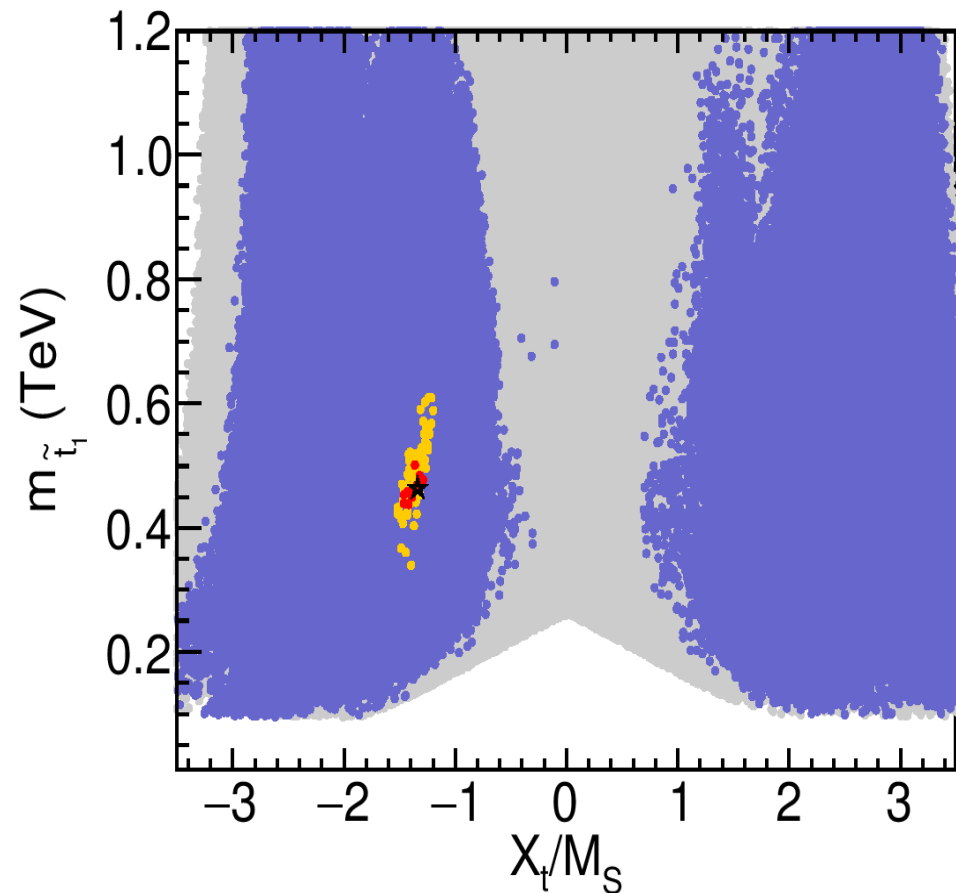
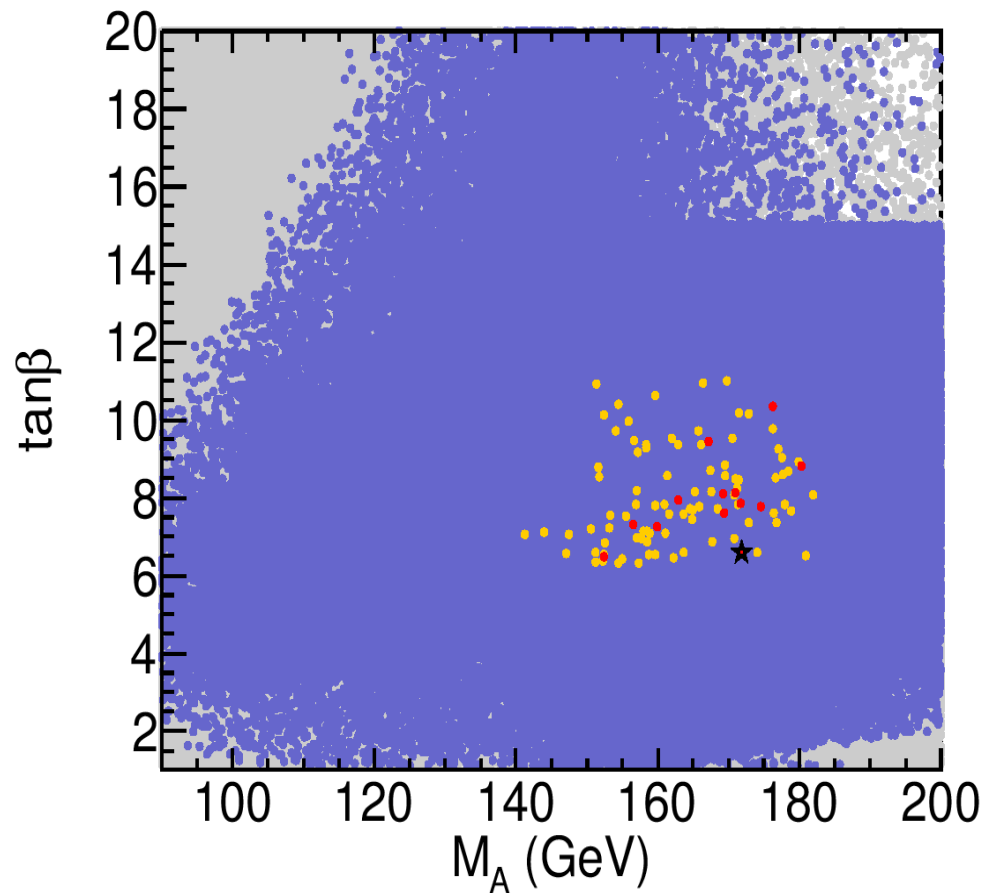
$\Rightarrow$ that (particular incarnation of the) low- M_H scenario is excluded!

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



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

Heavy-Higgs case: preferred parameters



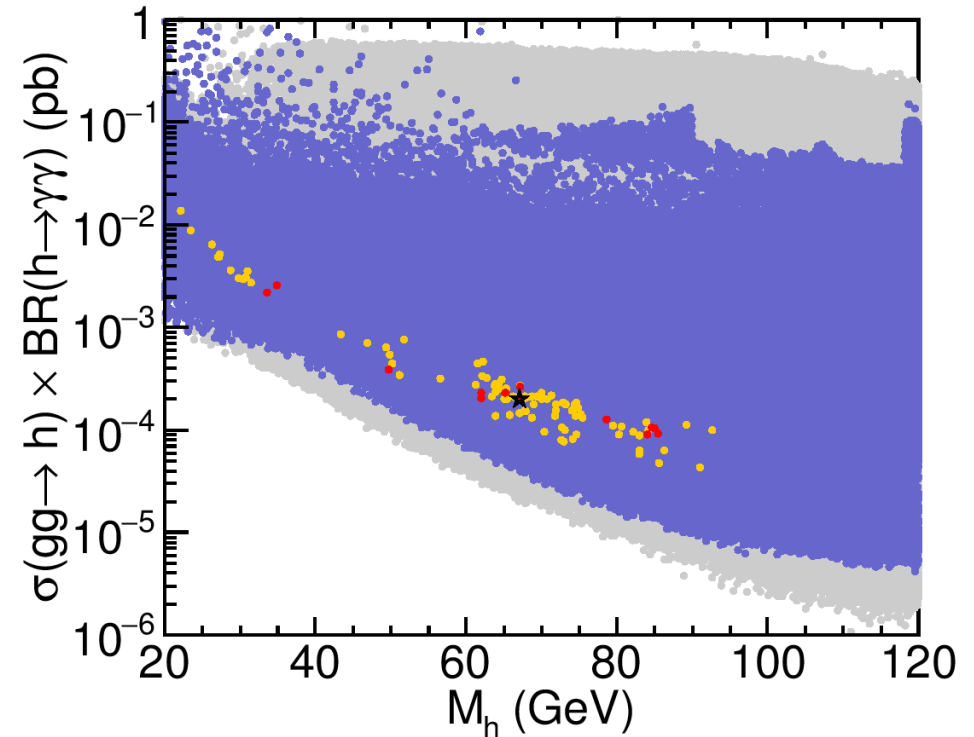
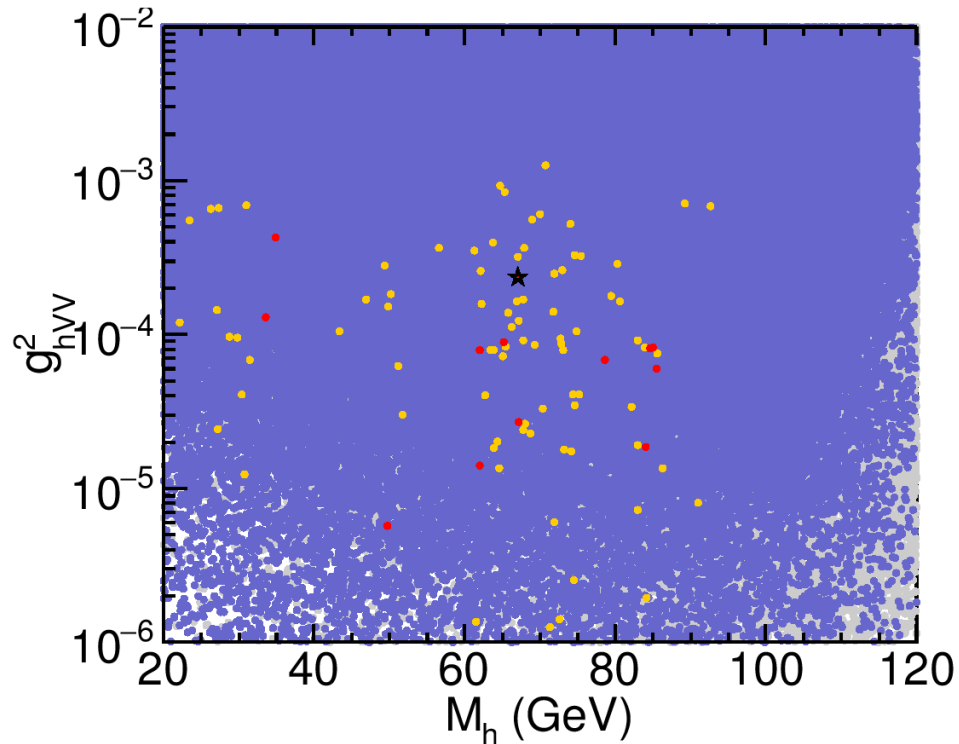
$\Rightarrow M_A \sim 140 \dots 180$ GeV

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

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

$\Rightarrow$ 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 $H \rightarrow hh$ (or $\text{BR}(H \rightarrow hh) \lesssim 10\%$)

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

New low- M_H benchmark scenarios

Based on our best-fit region:

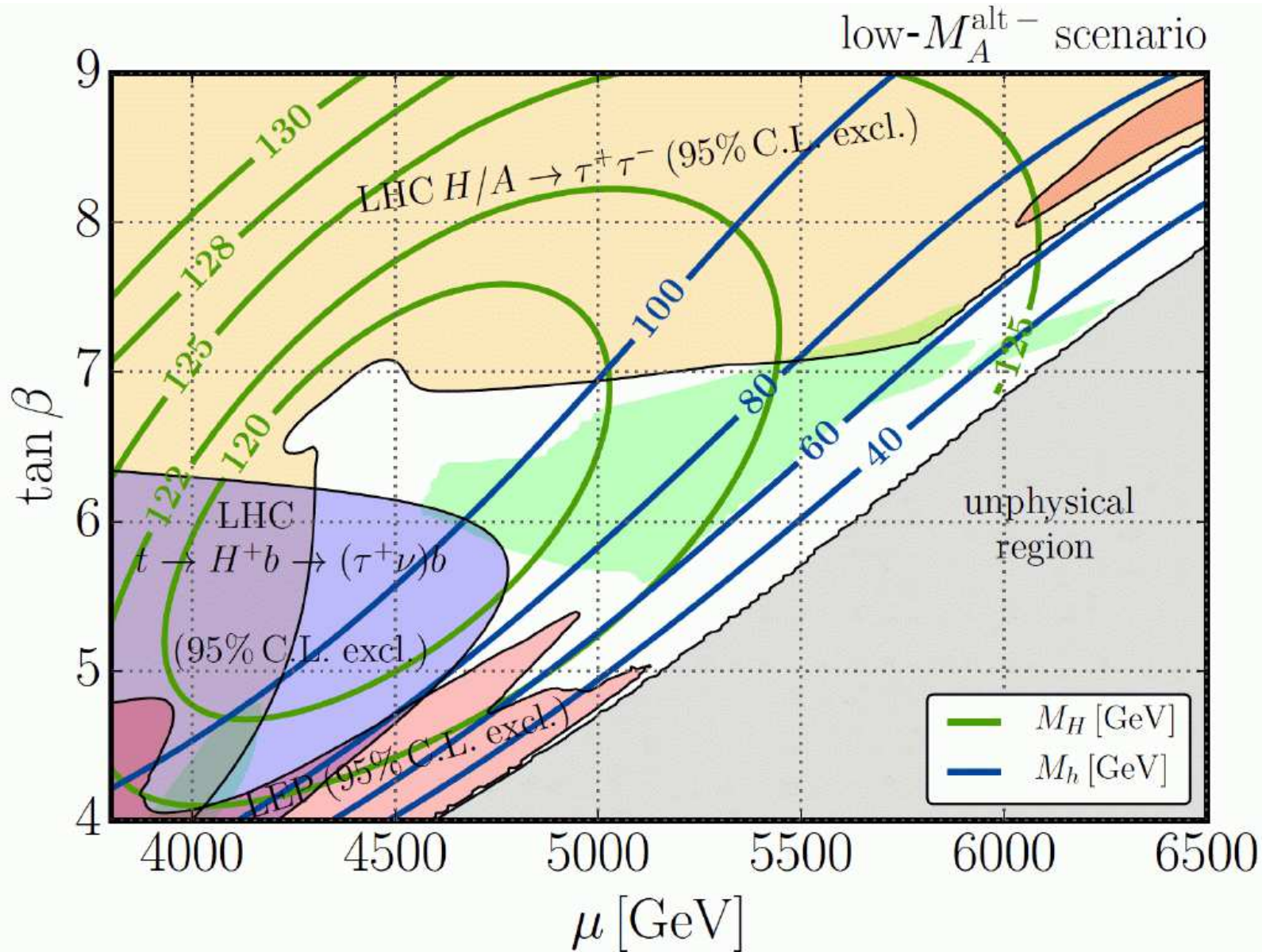
Benchmark scenario	$M_{H^\pm}$ [GeV]	μ [GeV]	$\tan \beta$
low- $M_H^{\text{alt},-}$	155	3800 – 6500	4 – 9
low- $M_H^{\text{alt},+}$	185	4800 – 7000	4 – 9
low- $M_H^{\text{alt},v}$	140 – 220	6000	4 – 9
fixed parameters:	$m_t = 173.2 \text{ GeV}, \quad A_t = A_\tau = A_b = -70 \text{ GeV}, \quad M_2 =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

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

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

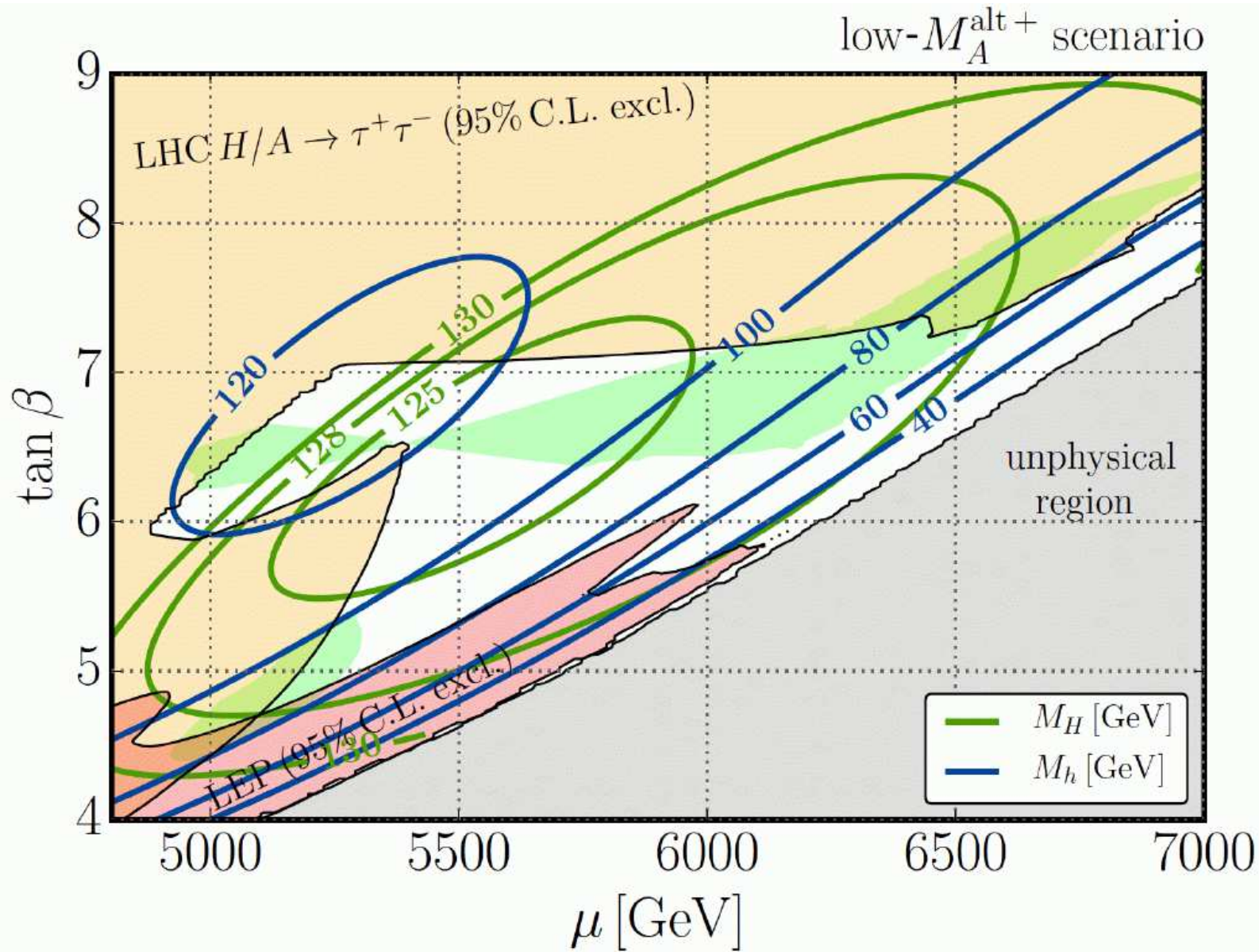
low- $M_H^{\text{alt},v}$: varied $M_{H^\pm}$ (μ fixed)

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



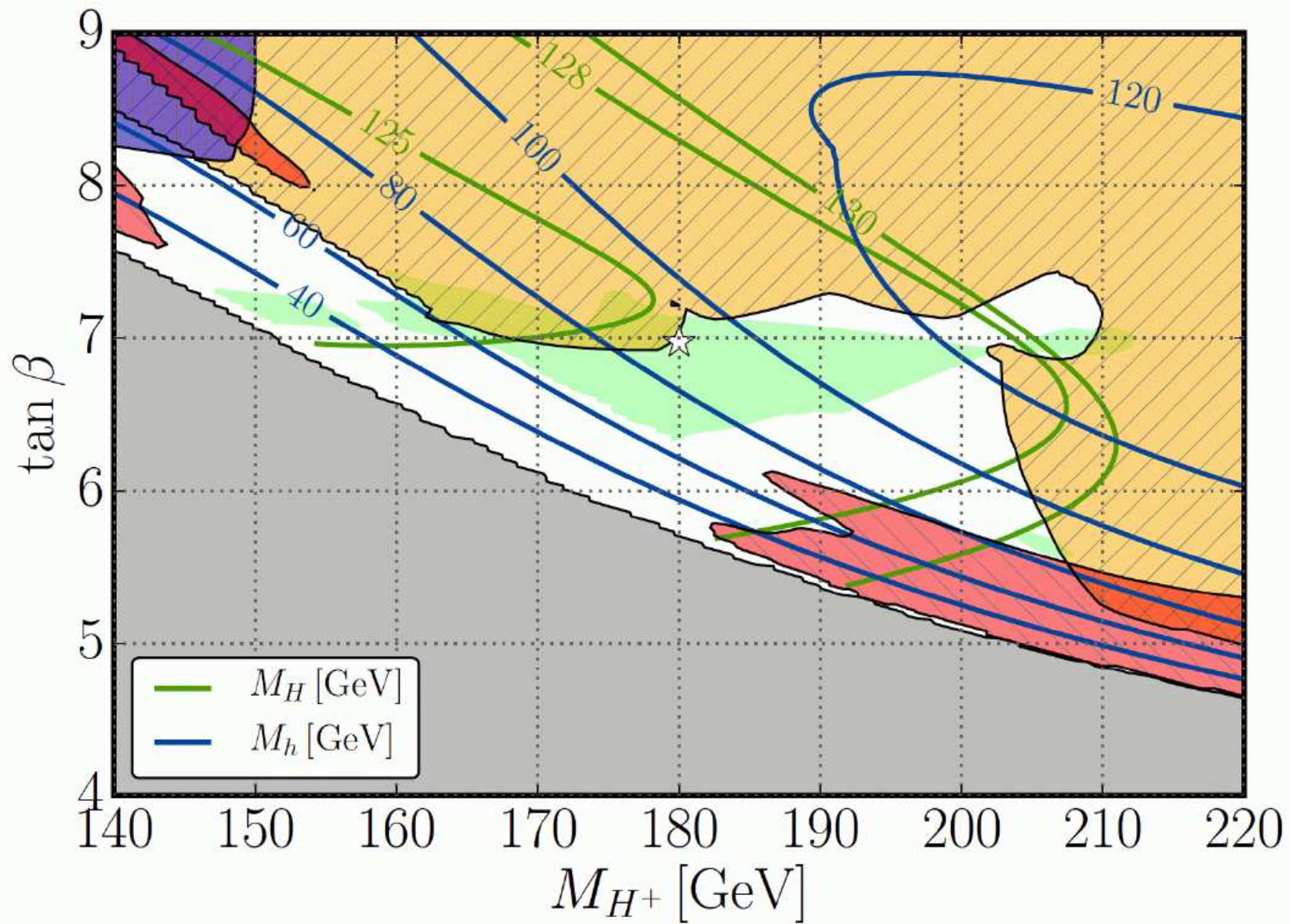
$\Rightarrow$ green area in agreement with all data!

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



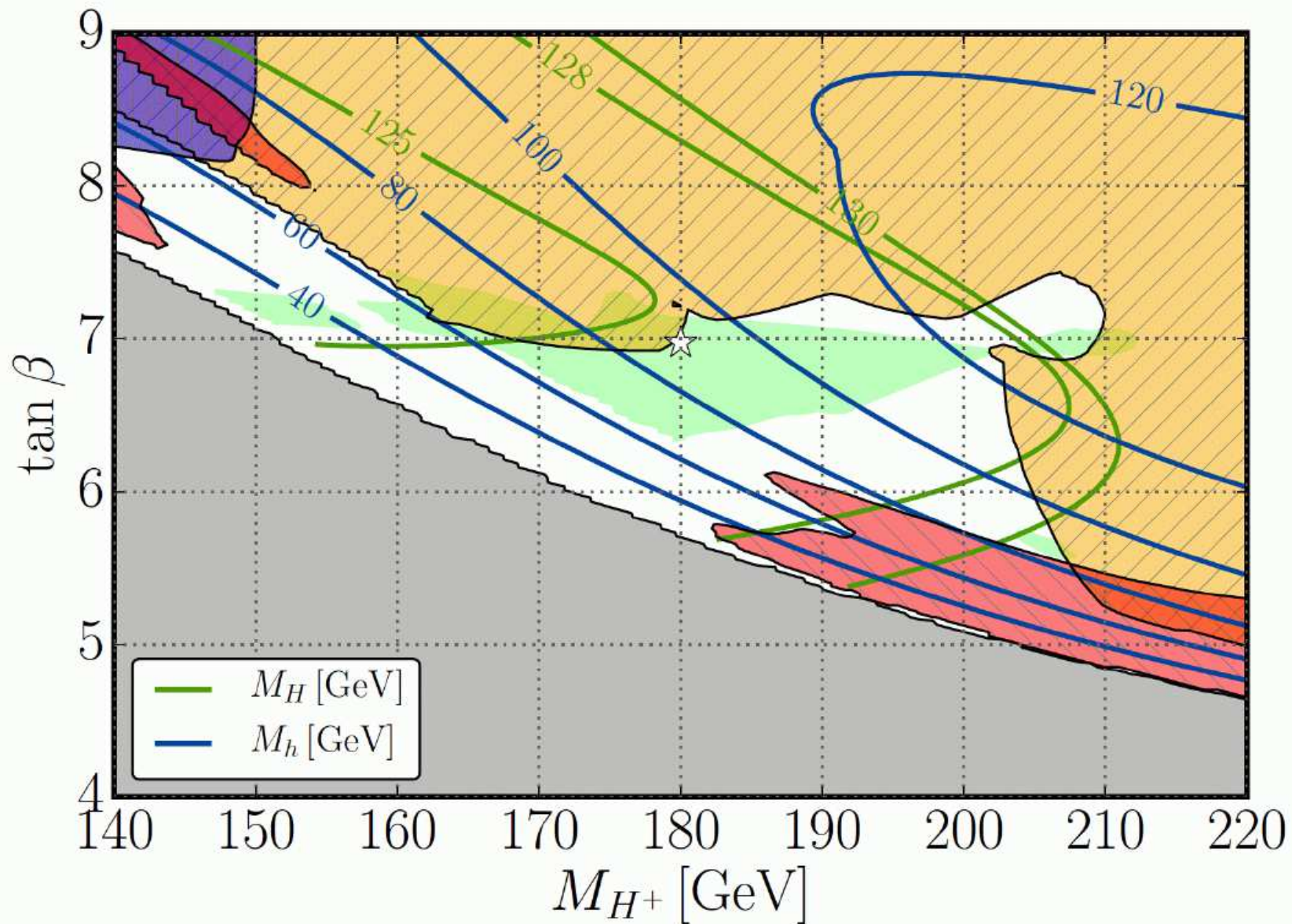
$\Rightarrow$ green area in agreement with all data! $M_H \sim M_h \sim 125$ GeV possible!

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



⇒ green area in agreement with all data!

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



⇒ green area in agreement with all data!

Go and exclude it!

5. Conclusinos

- SUSY is (still) the best motivated BSM theory
- LHC SUSY searches put pressure on CMSSM, NUHM1, NUHM2, ...
 - ⇒ tension between low-energy and LHC data!
 - ⇒ pMSSM10 provides excellent fit to all data
- 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: relatively high Higgs mass scales favored
 - NUHM2: somewhat lower values possible, but still high ...
 - pMSSM8: light $\mathcal{CP}$ -even Higgs for “all” M_A
 - heavy $\mathcal{CP}$ -even Higgs
 - ⇒ new benchmark scenarios

Higgs Days at Santander 2017

Theory meets Experiment

18.-22. September



contact: Sven.Heinemeyer@cern.ch
hdays.csic.es local: Gervasio.Gomez@cern.ch

Further Questions?



pMSSM10 analysis: DD experiments: p - vs. n -scattering

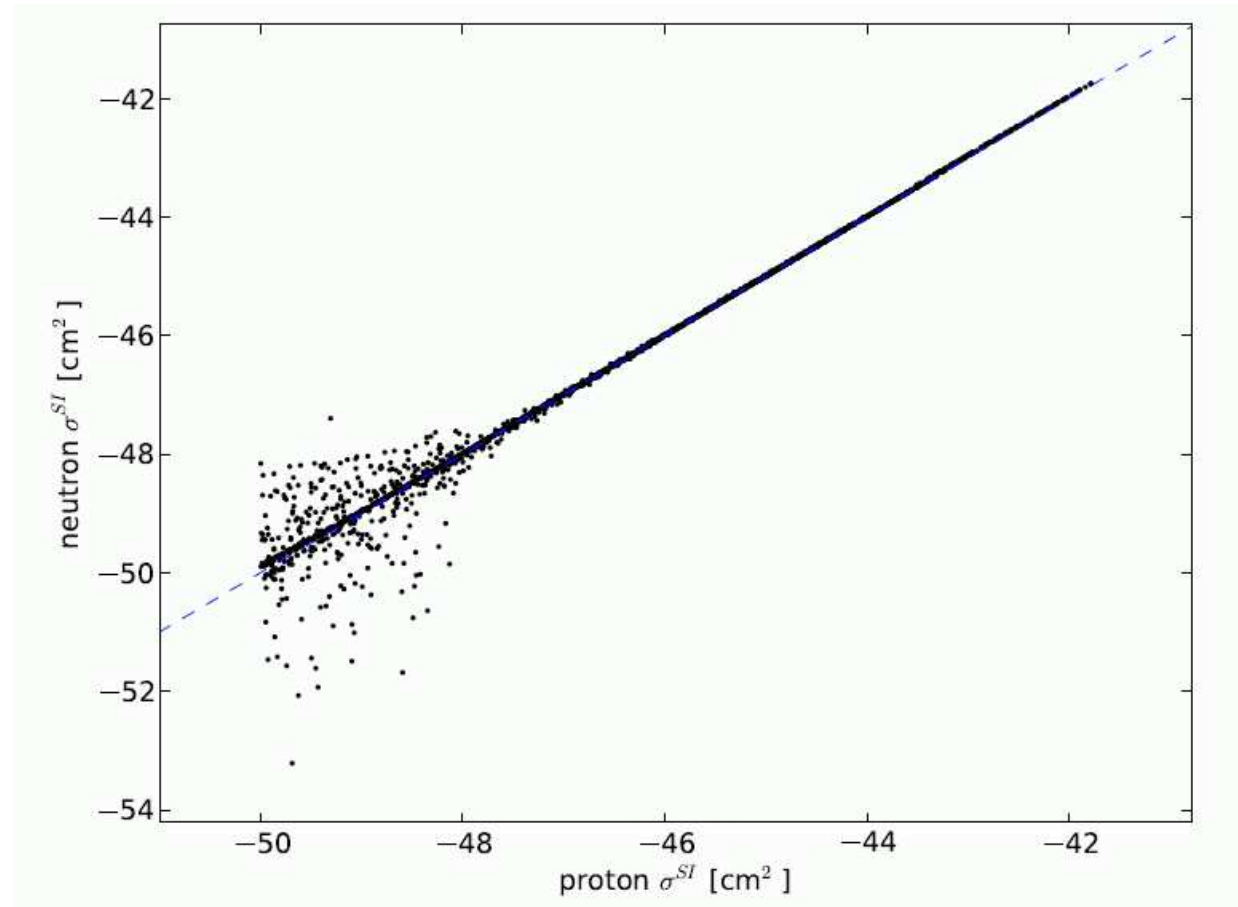
[2015]

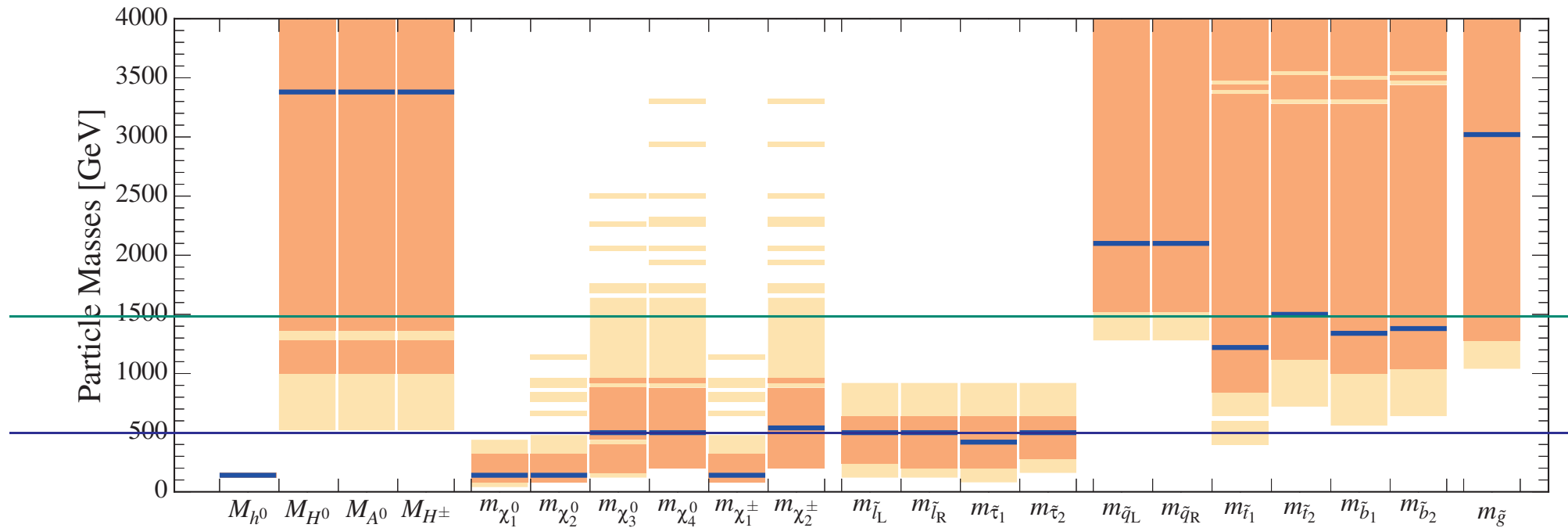
σ_p^{SI} is evaluated for
 p -scattering

Can n -scattering come
to rescue?

Some points with low σ_p^{SI}
have even lower σ_n^{SI}

$\Rightarrow$ no “no-lose theorem”
for DD experiments!



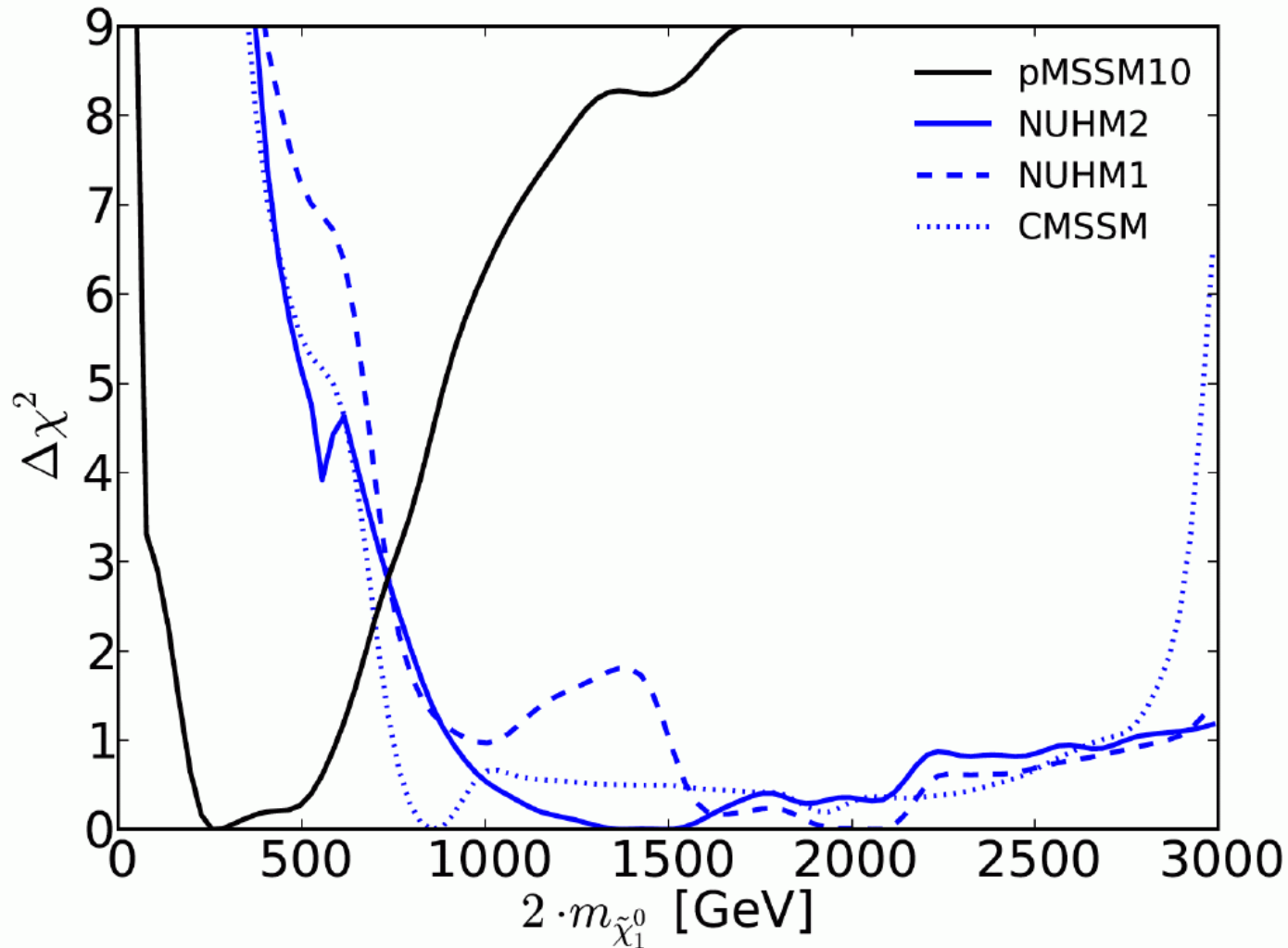


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of EW particle and DM easy!

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of EW particles and DM easy!

DM production cross sections: $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 (+\gamma)$

[2014]

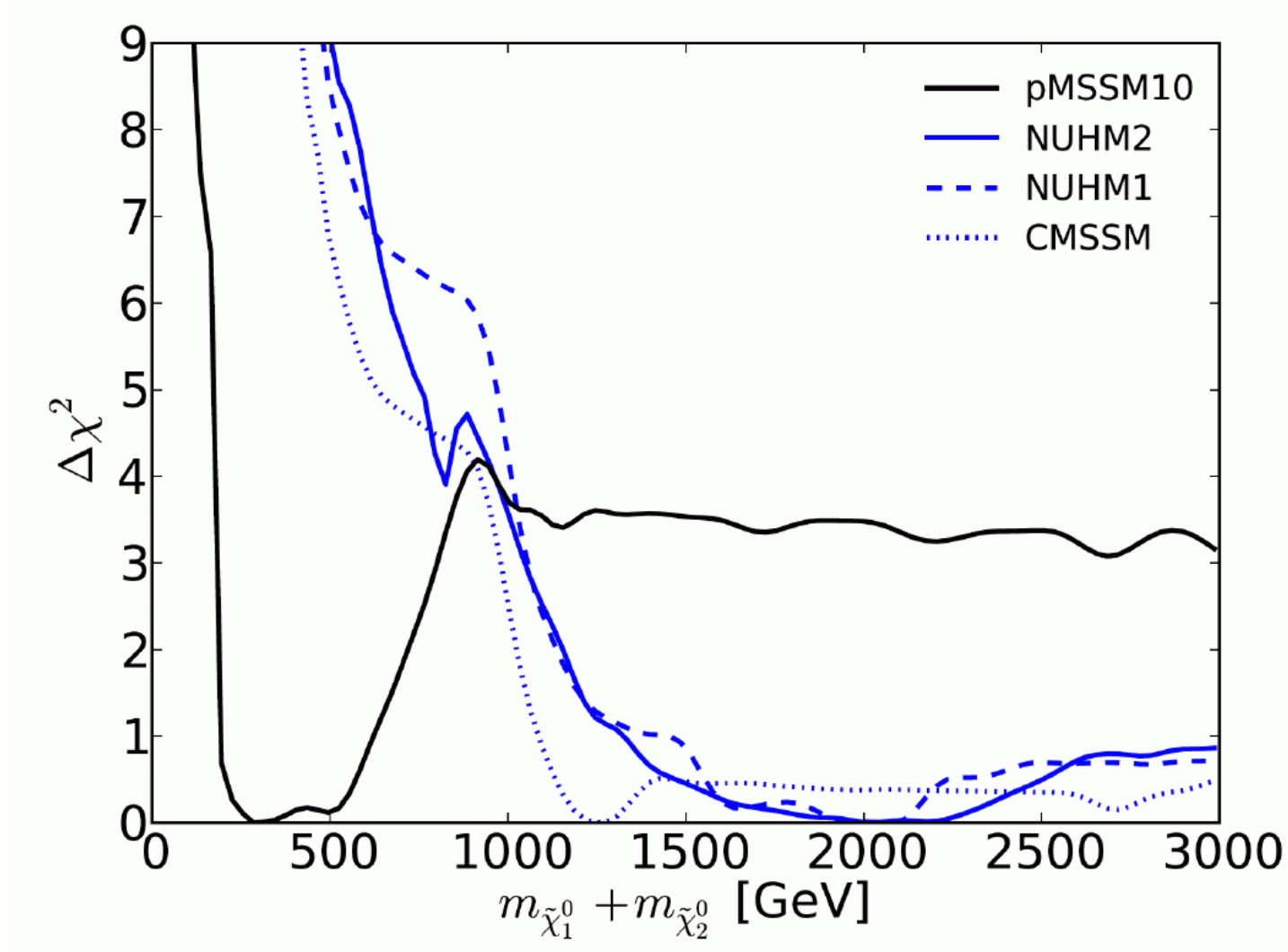


⇒ GUT based models: ILC :-(, CLIC possible

⇒ pMSSM10: easy at the ILC

DM production cross sections: $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$

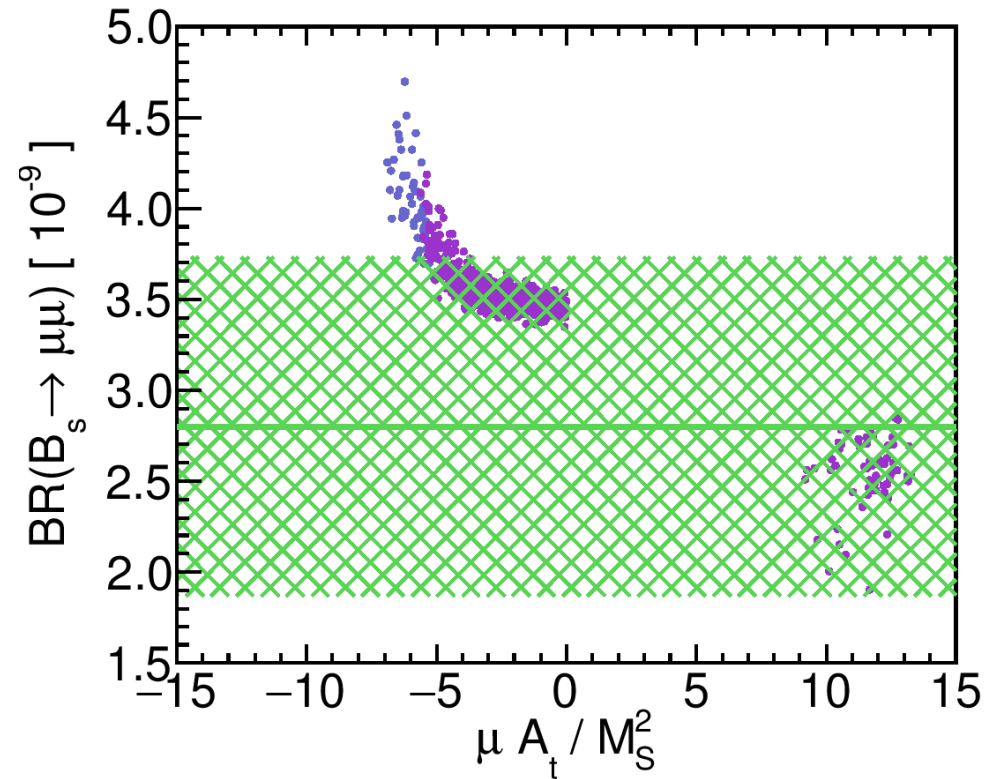
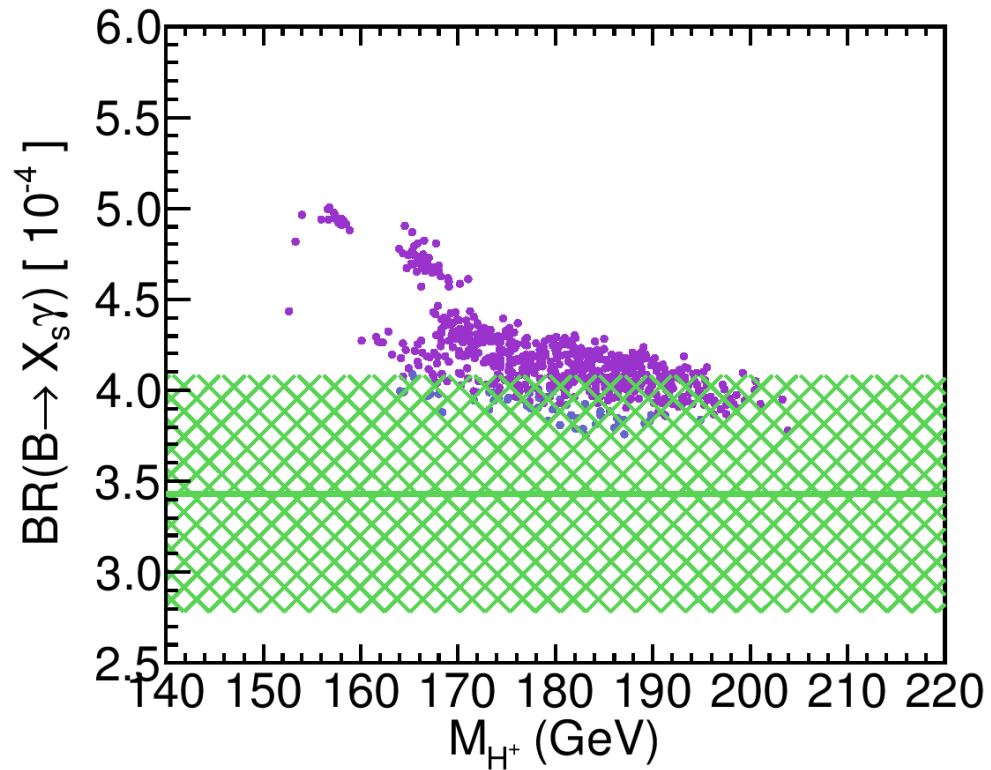
[2014]



⇒ GUT based models: ILC :-(, CLIC possible

⇒ pMSSM10: easy at the ILC - but no real upper limit

B-physics constraints?



⇒ flavor constraints fulfilled!

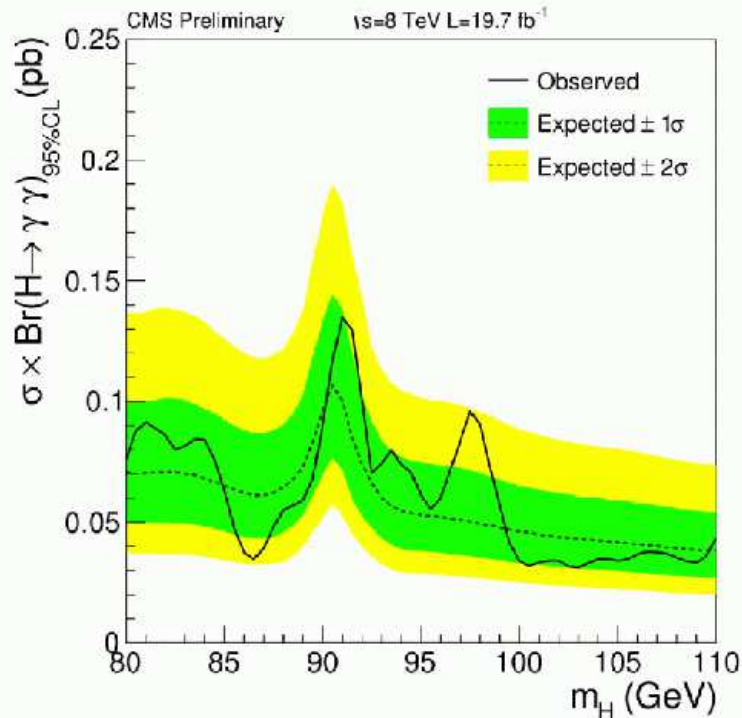
(Only?) possible search channel: $h_1 \rightarrow \gamma\gamma$



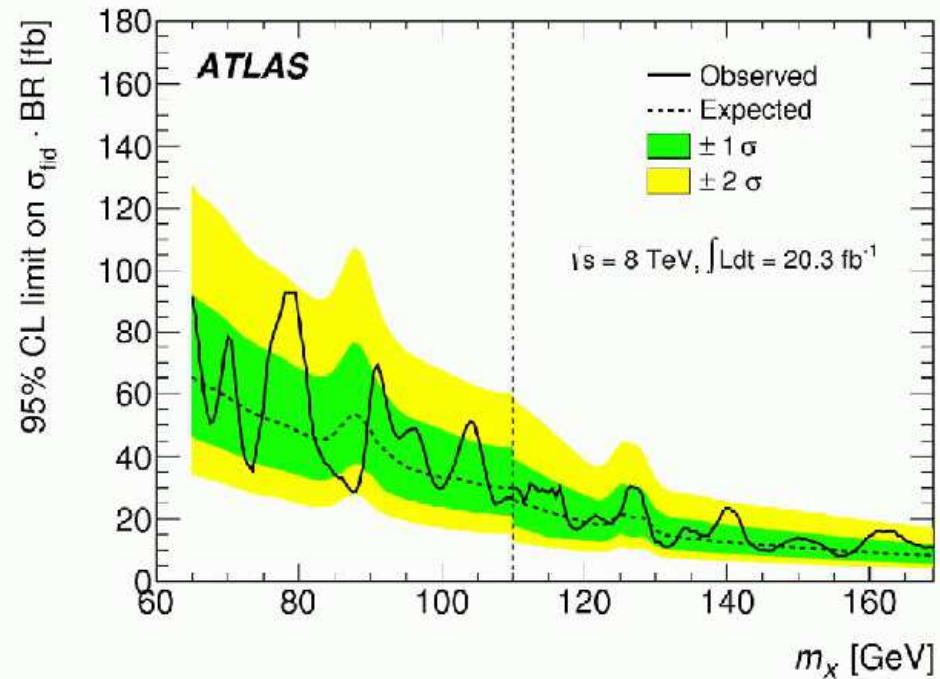
CMS PAS HIG-14-037

$h \rightarrow \gamma\gamma$ (65-110 GeV) Run 1

PRL 113 171801 (2014)



• $\sim 2\sigma$ excursion @ $\sim 97.5 \text{ GeV}$



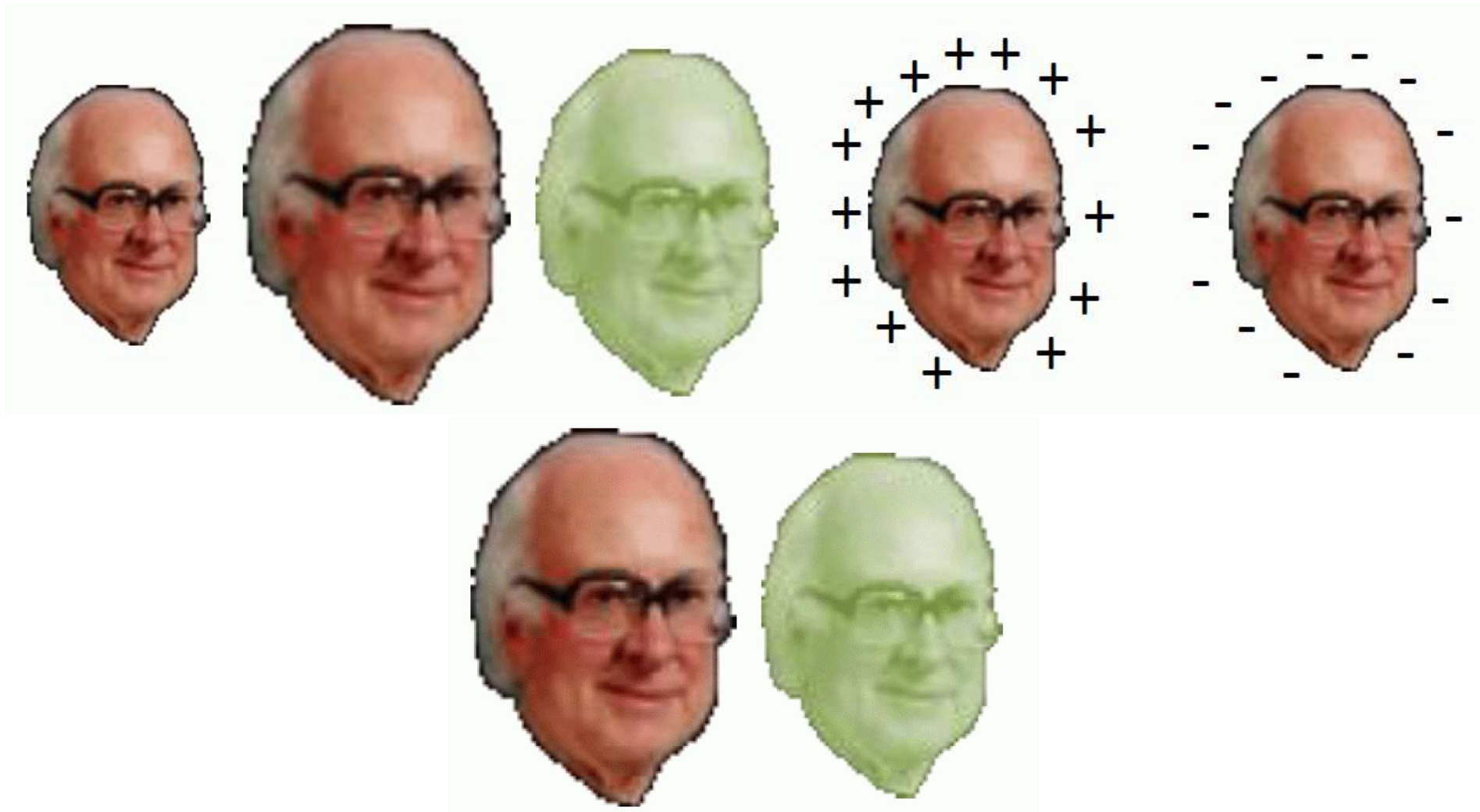
• $\sim 2\sigma$ excursion @ $\sim 80 \text{ GeV}$

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

22

$\Rightarrow$ no sensitivity yet!

Results in the NMSSM



Some NMSSM Higgs theory (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

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

$$S = v_s + S_R + IS_I$$

$$\begin{aligned} V = & (\tilde{m}_1^2 + |\mu\lambda S|^2)H_1\bar{H}_1 + (\tilde{m}_2^2 + |\mu\lambda S|^2)H_2\bar{H}_2 - m_{12}^2(\epsilon_{ab}H_1^aH_2^b + \text{h.c.}) \\ & + \frac{g'^2 + g^2}{8}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \frac{g^2}{2}|H_1\bar{H}_2|^2 \\ & + |\lambda(\epsilon_{ab}H_1^aH_2^b) + \kappa S^2|^2 + m_S^2|S|^2 + (\lambda A_\lambda(\epsilon_{ab}H_1^aH_2^b)S + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.}) \end{aligned}$$

Free parameters:

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

Higgs spectrum:

$\mathcal{CP}$ –even : h_1, h_2, h_3

$\mathcal{CP}$ –odd : a_1, a_2

charged : H^+, H^-

Goldstones : G^0, G^+, G^-

Neutralinos:

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

compared to the MSSM: one singlino more

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

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

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

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

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

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

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

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)

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

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

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

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

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

Mass of the charged Higgs:

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

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

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

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]

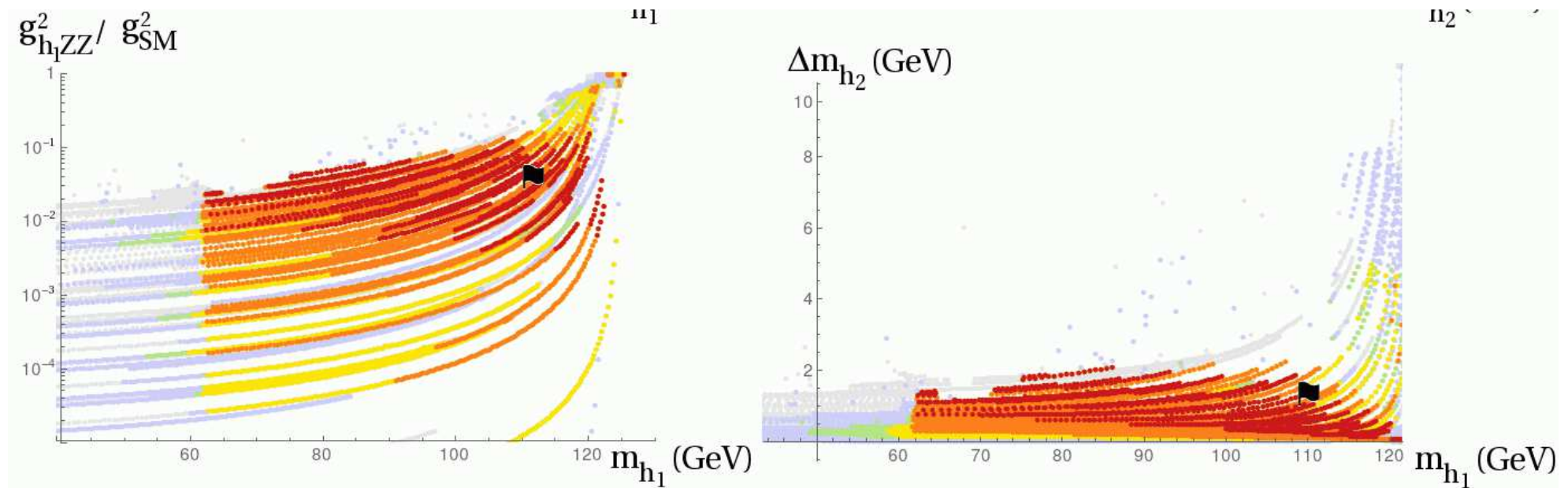
“Easily” possible in the NMSSM:

Light, singlet-like Higgs below 125 GeV

Can the LHC find them?

Parameters:

$\tan \beta = 8$, $M_A = 1$ TeV, $A_\kappa = -2 \dots 0$ TeV, $\mu = 120 \dots 2000$ 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

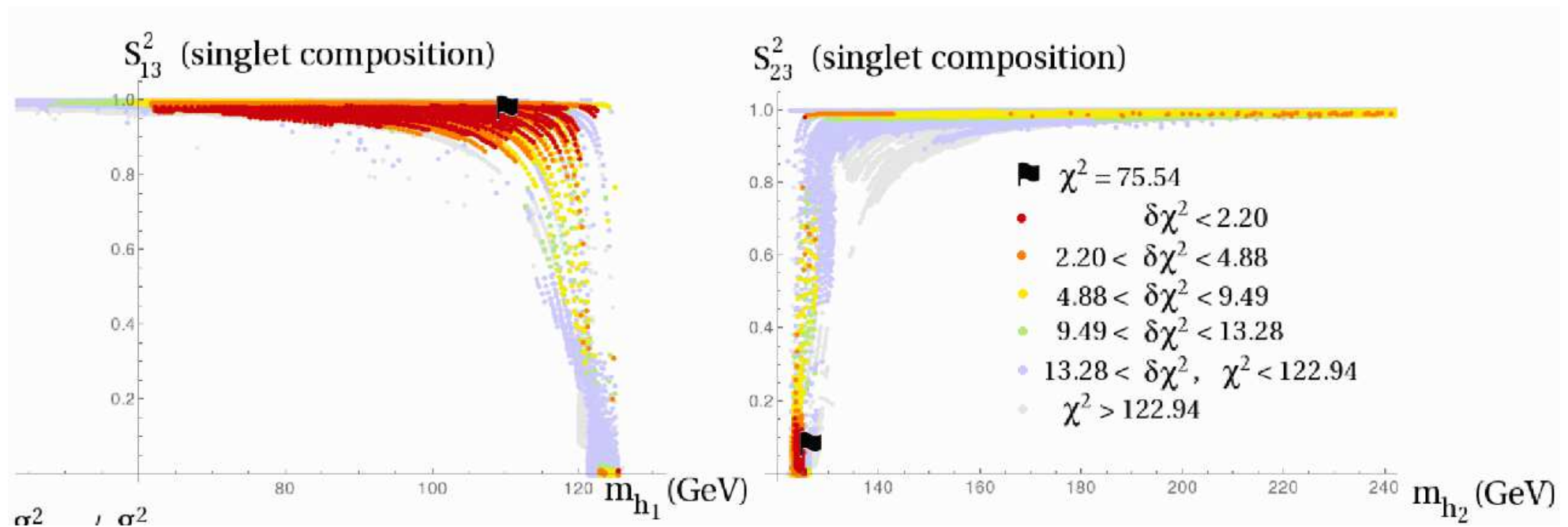


⇒ light Higgs below 125 GeV

⇒ strongly reduced couplings to gauge bosons!

Parameters:

$\tan \beta = 8$, $M_A = 1$ TeV, $A_\kappa = -2 \dots 0$ TeV, $\mu = 120 \dots 2000$ 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