
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

SUSY and its Higgs Bosons at the LHC

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

Hamburg, 03/2017

- Motivation
- SUSY after LHC Run I/II
- SUSY Higgs mass and rate measurements
- MSSM Higgs results (CMSSM, NUHM1/2, pMSSM8)
- Conclusions

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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

$\Rightarrow$ 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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Simple SUSY models predicted correctly:

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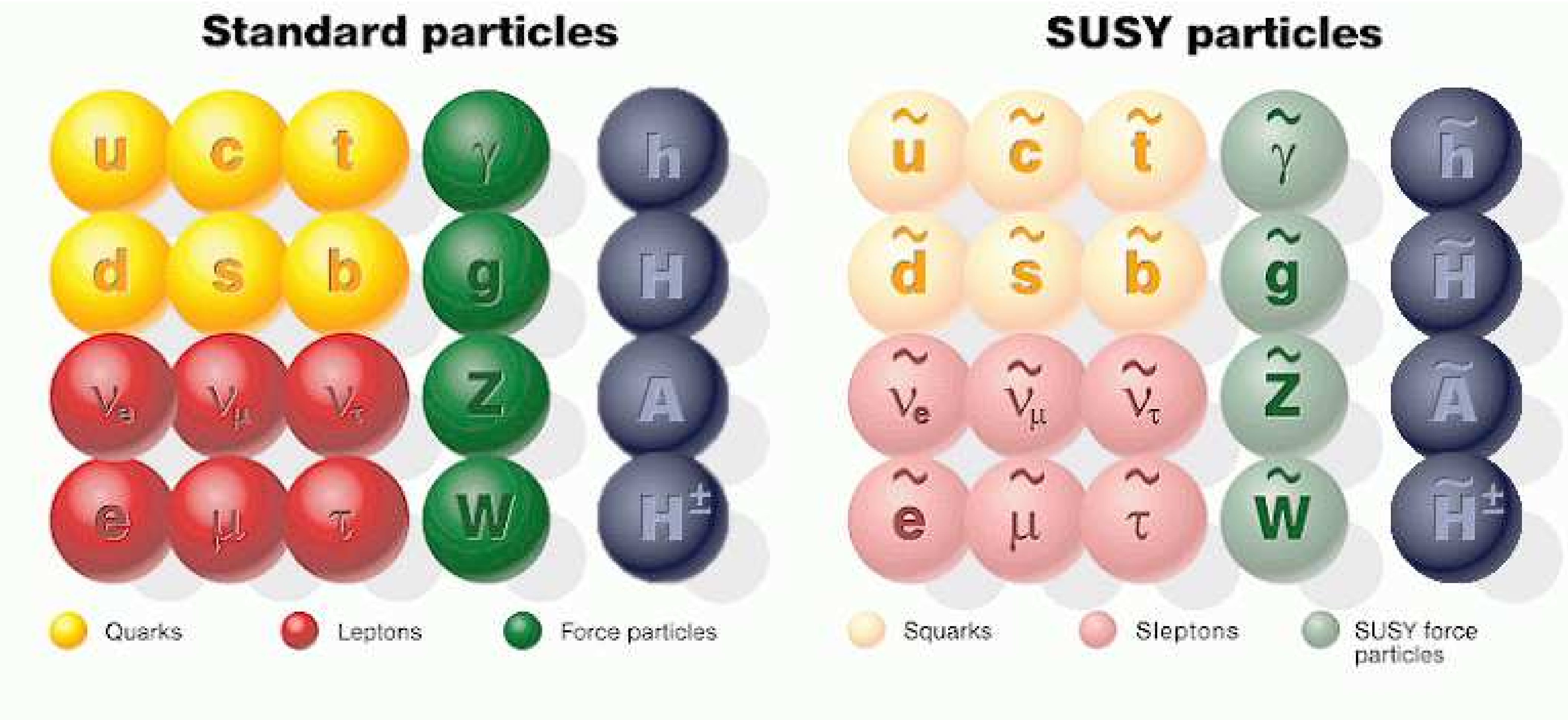
⇒ good motivation to look at SUSY! :-)

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

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

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

$\mathrm{sign}(\mu)$: 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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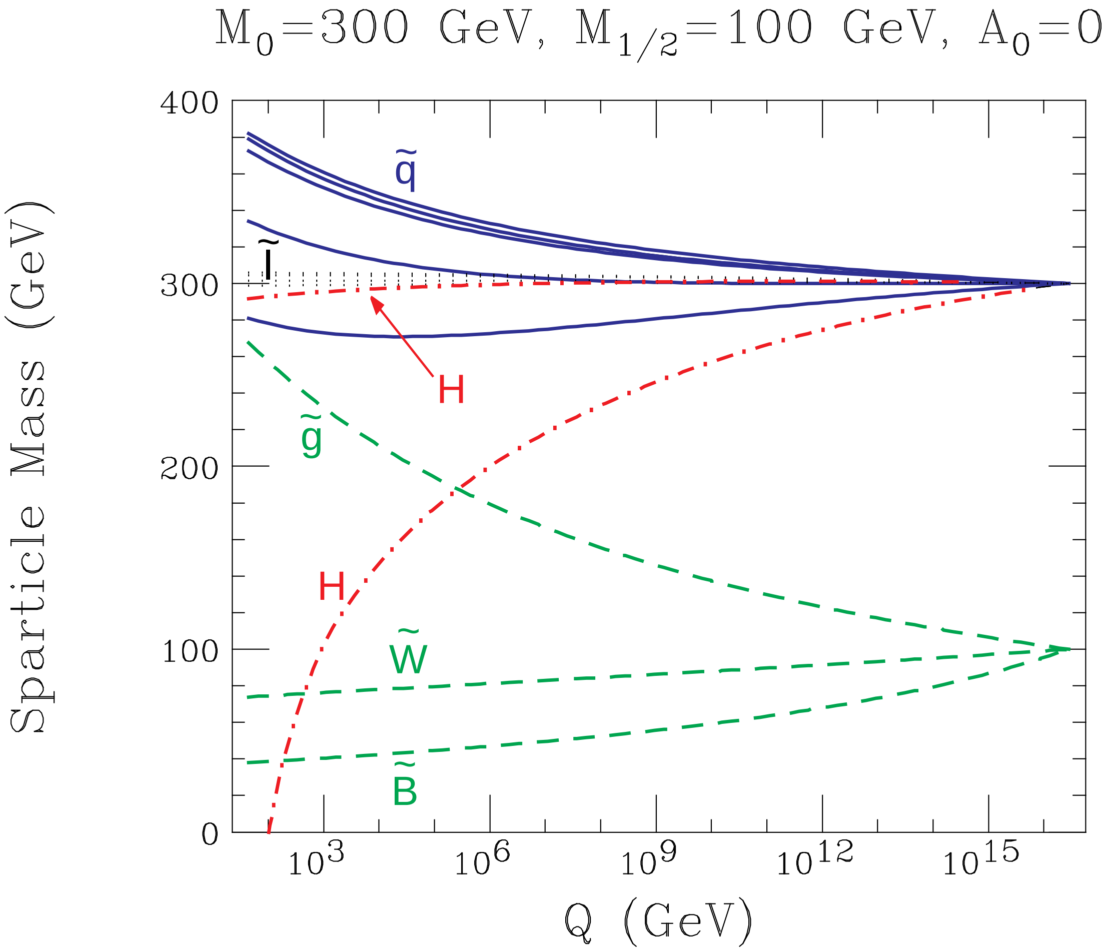


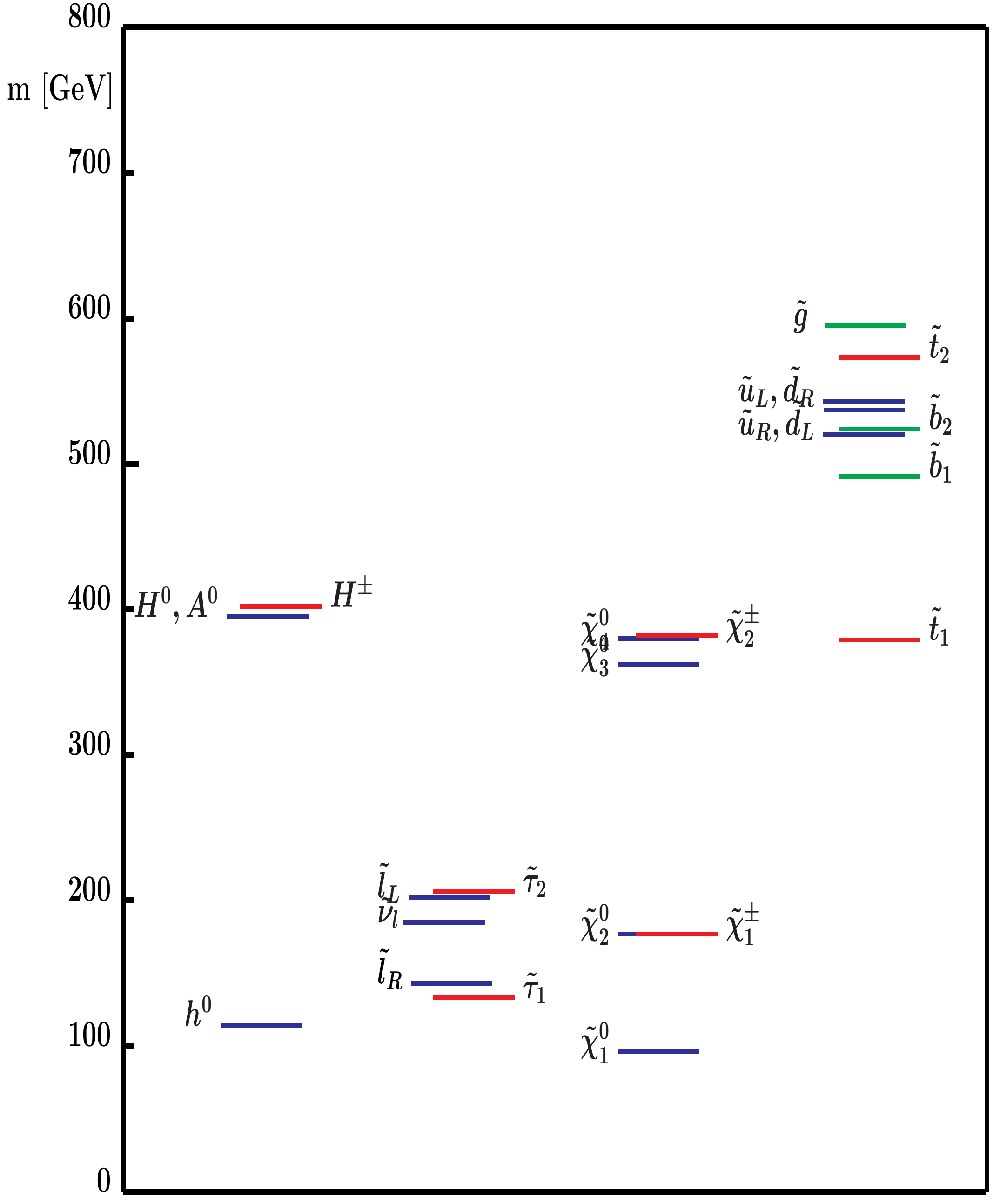
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Close 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

$\Rightarrow$ effectively M_A as free parameters at the EW scale

> $\Rightarrow$ 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

$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

> $\Rightarrow$ 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: close 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

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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 paramter: μ

⇒ Note: other "10 parameter selections" possible

Data we have:

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- SUSY searches (LHC)

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

2. SUSY after LHC Run I/II: MasterCode

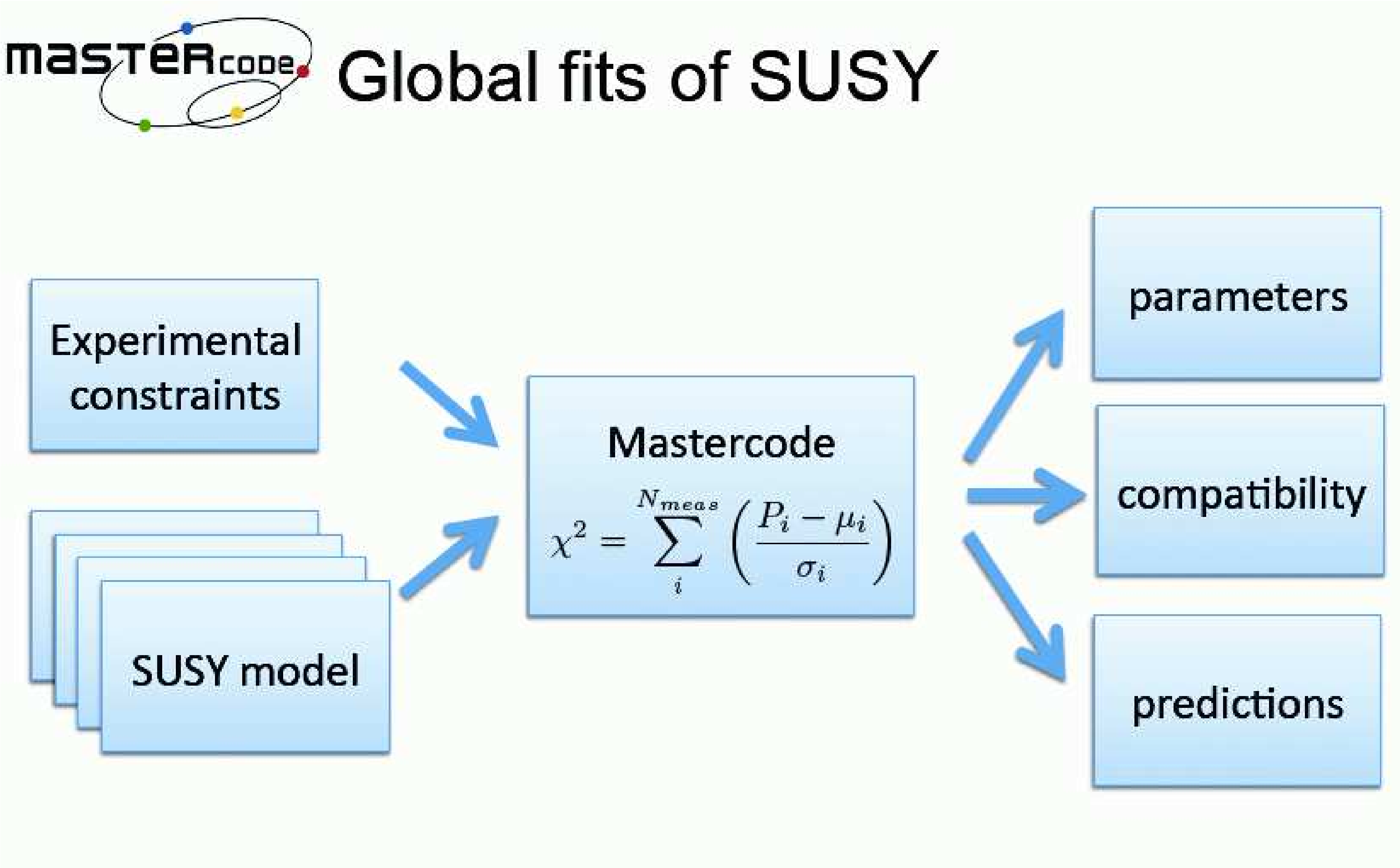
⇒ collaborative effort of theorists and experimentalists
[Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Lucio, Martinez Santos, Olive, Richards, Sakurai, Suarez Fernandez, Weiglein]

– (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:

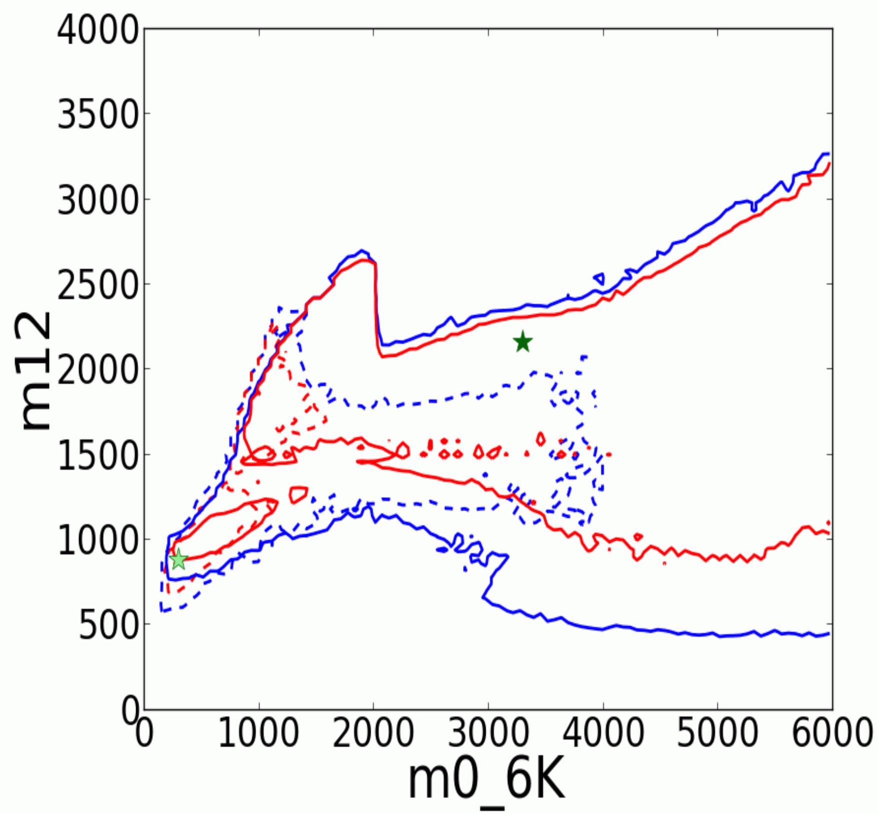


Results in GUT based models

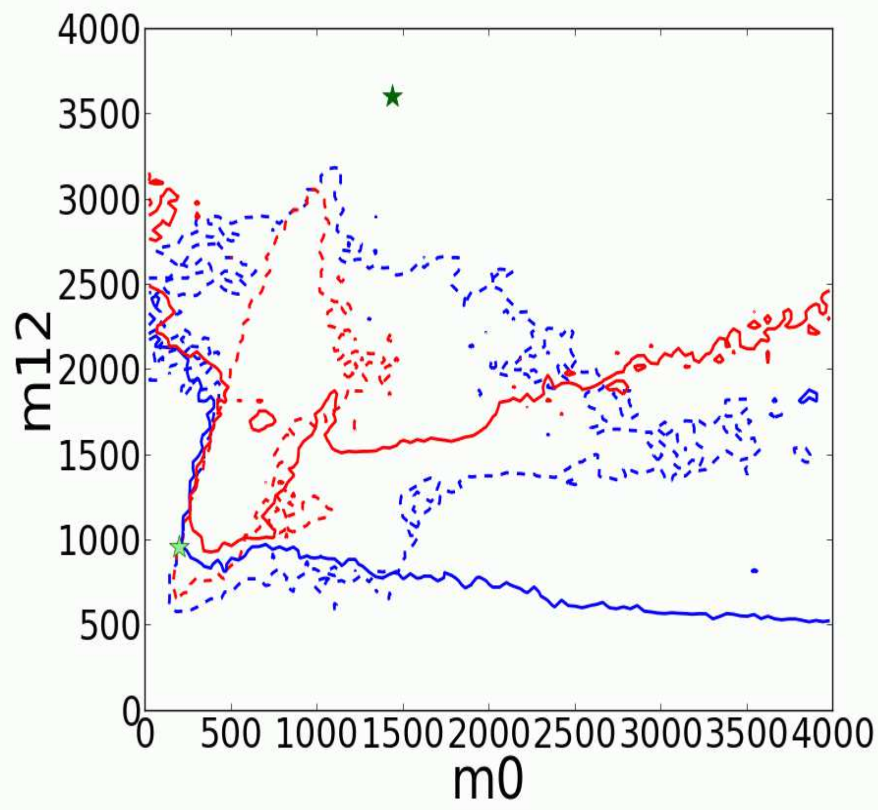
m_0-$m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



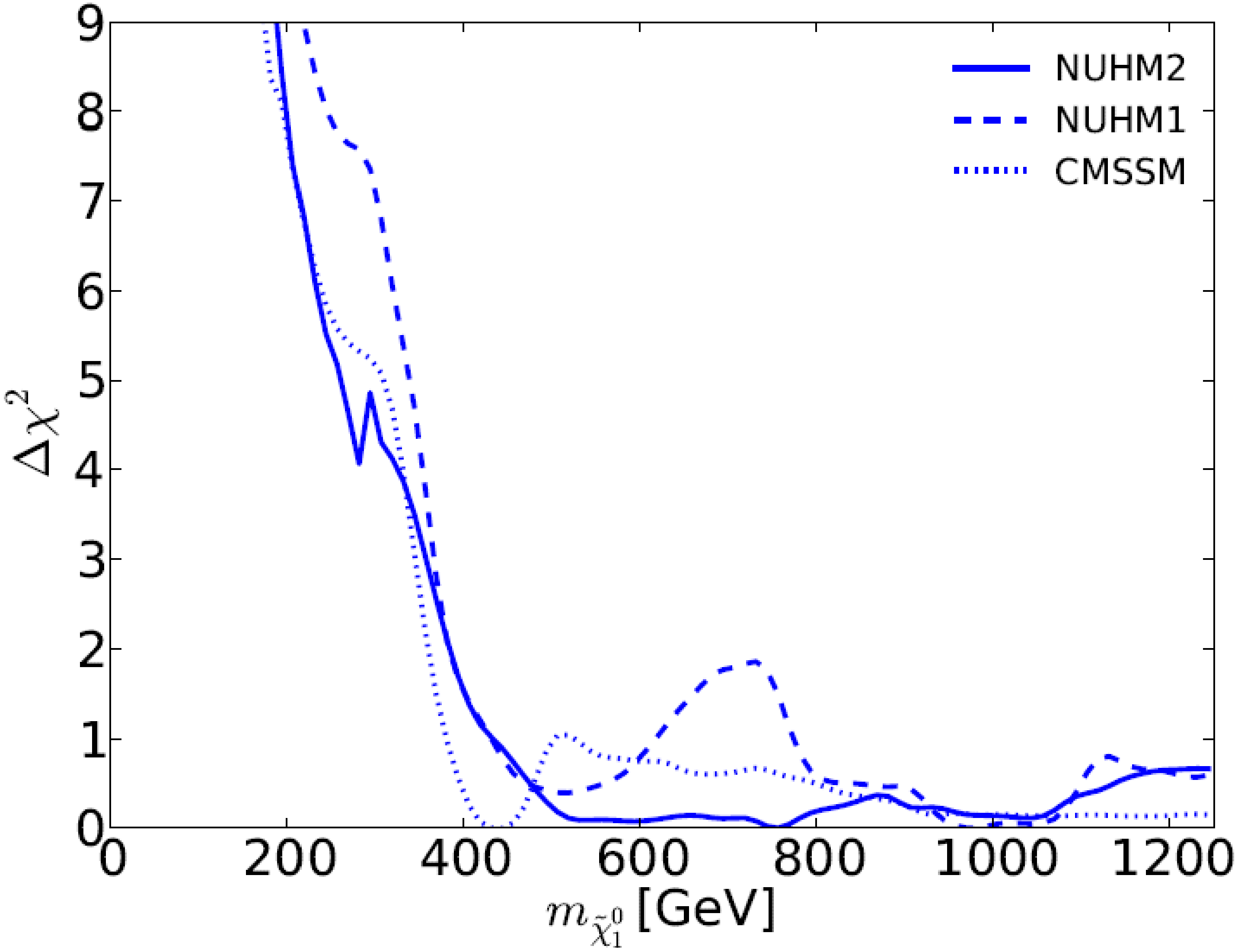
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

$\Rightarrow$ shift to even higher masses

even larger allowed ranges . . .

LSP mass incl. 20/fb of LHC data

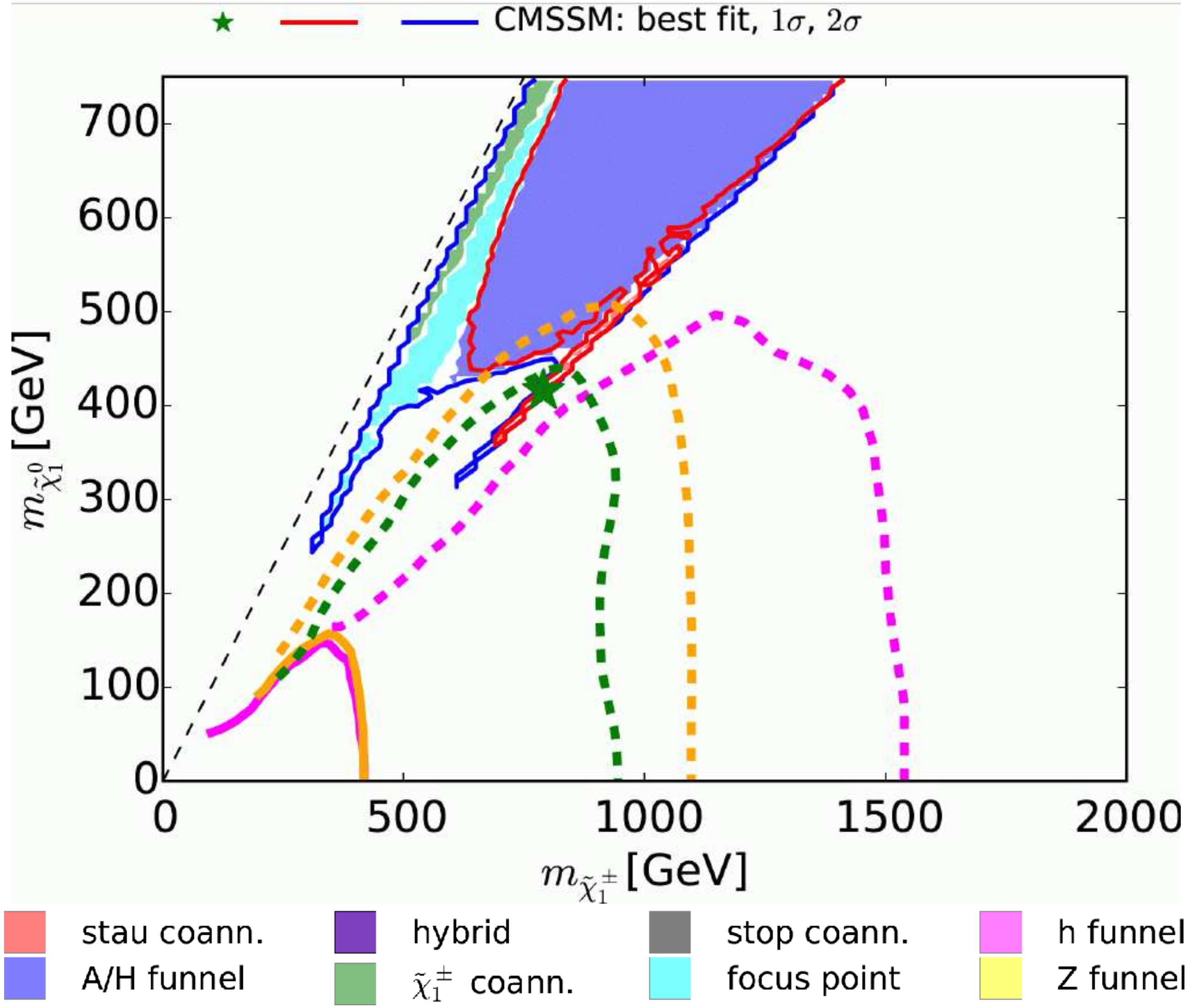
[2014]



⇒ 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)

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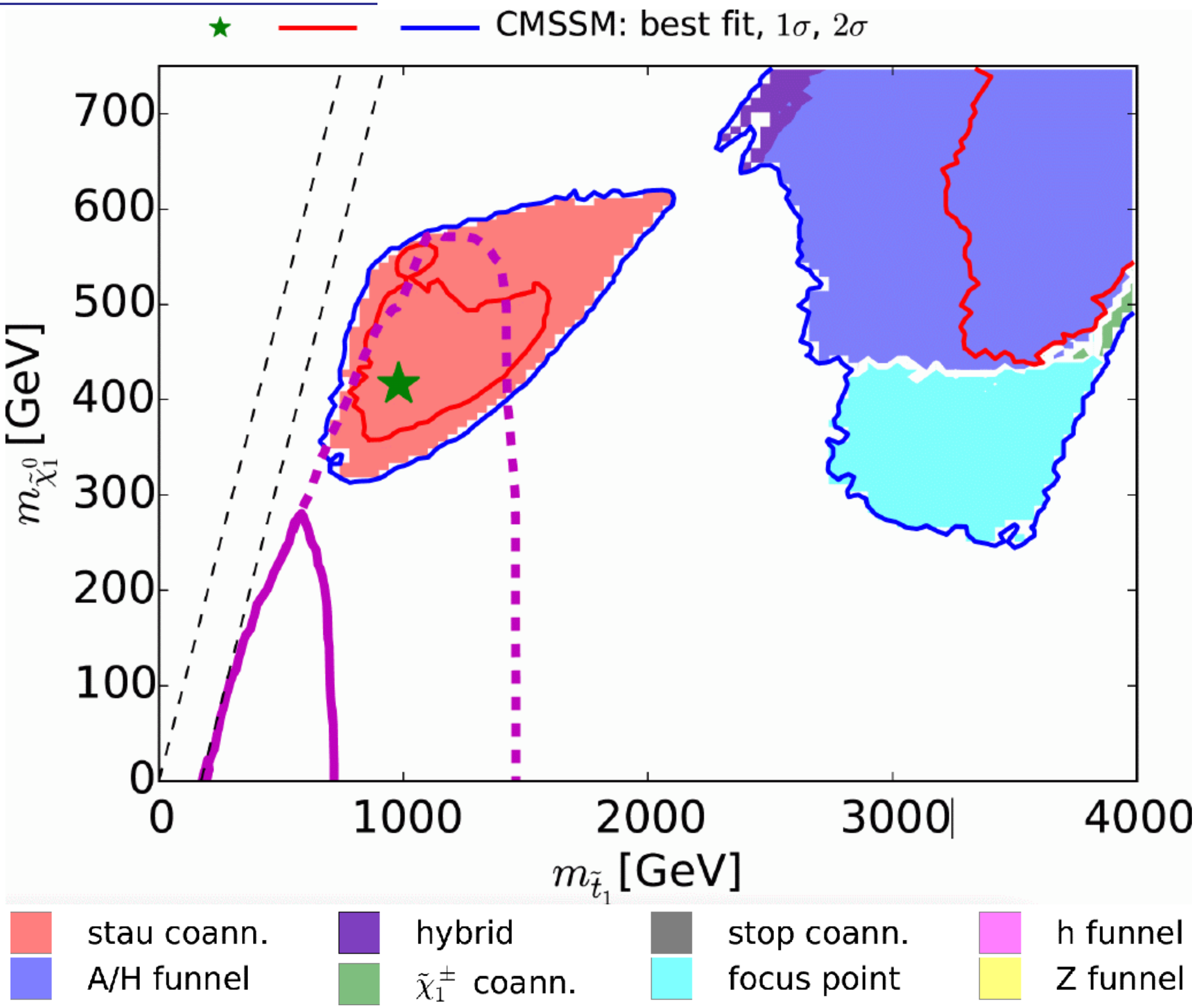

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⇒ best-fit regions can partially be covered! (in colored searches)

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

$\Rightarrow$ 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 fb^{-1} $\oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC 20 fb^{-1} $\oplus M_h$	32.8/24	11%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
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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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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!

And requires SUSY realizations that are in agreement with

– higher colored mass scales (LHC limits)

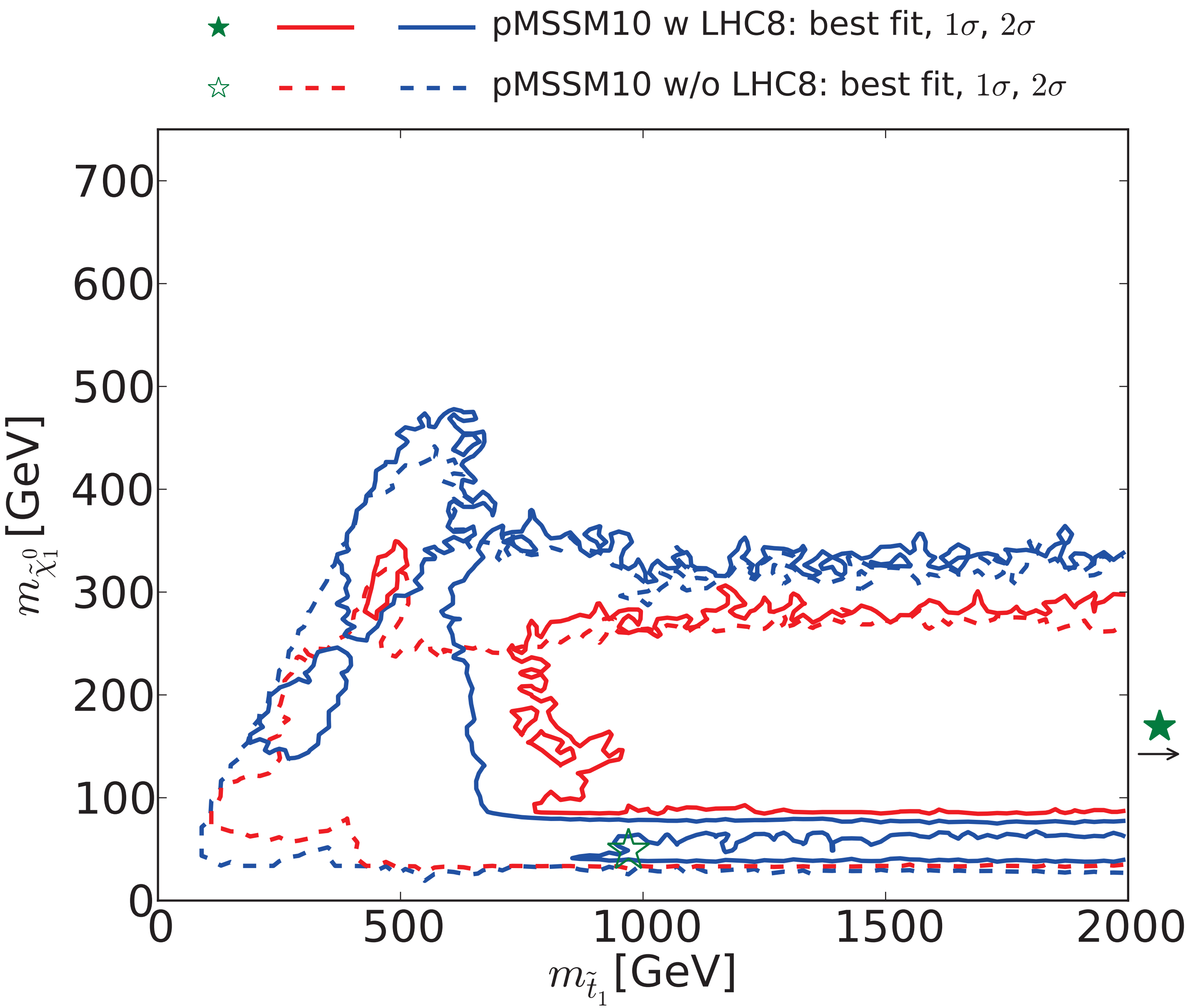
– lower uncolored mass scales (EWPO; $(g-2)_\mu$) $\Rightarrow$ check pMSSM10!

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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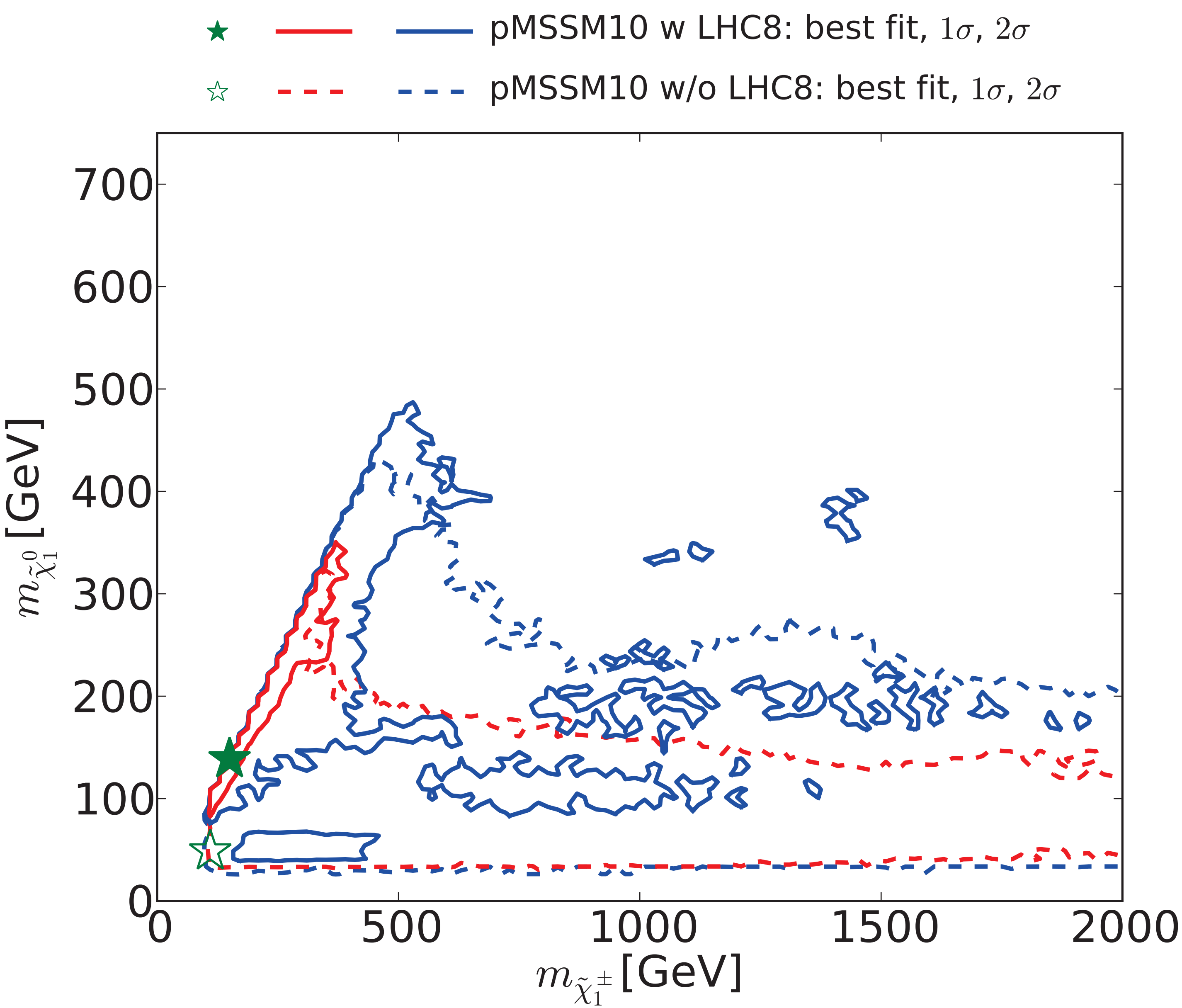

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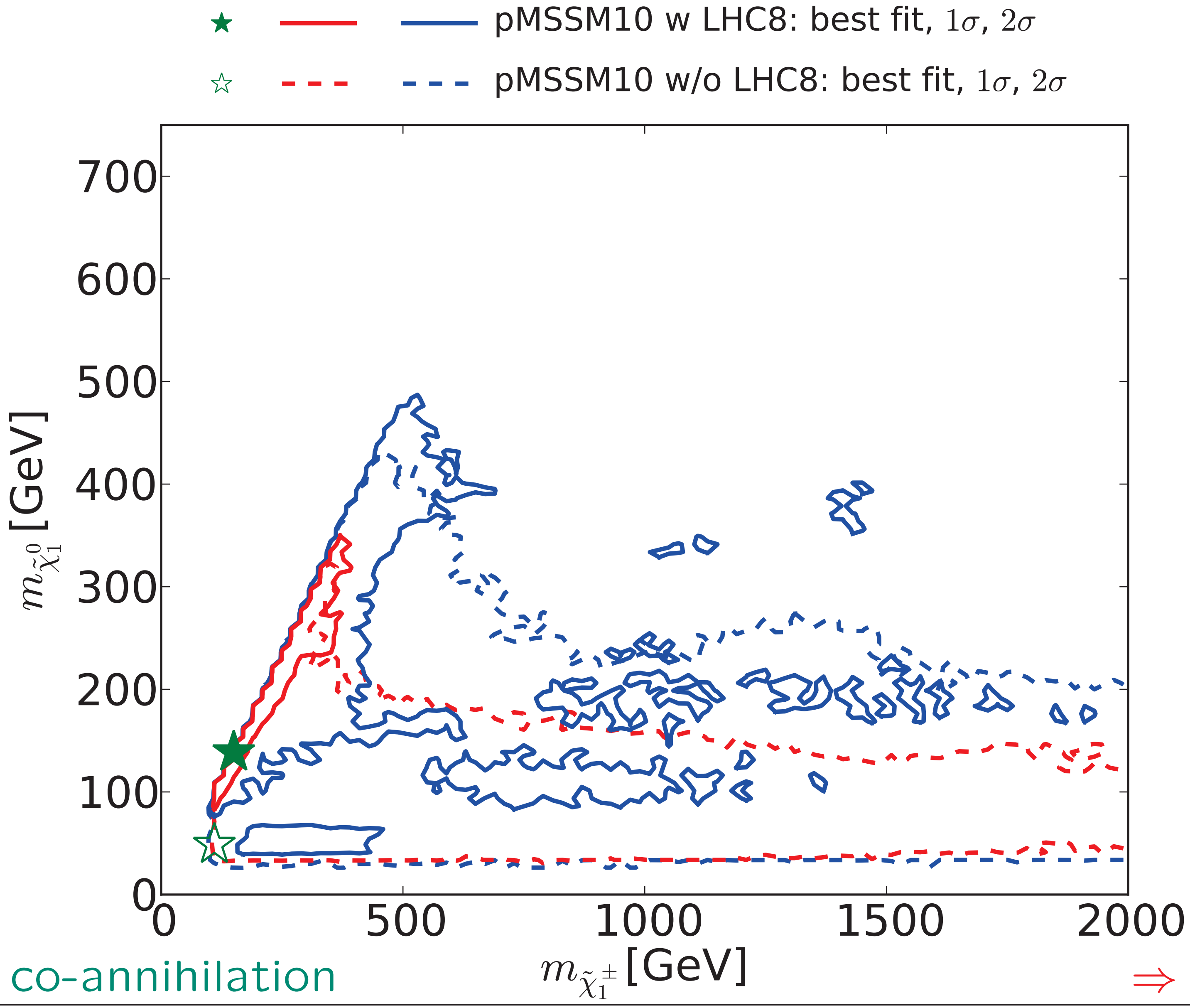
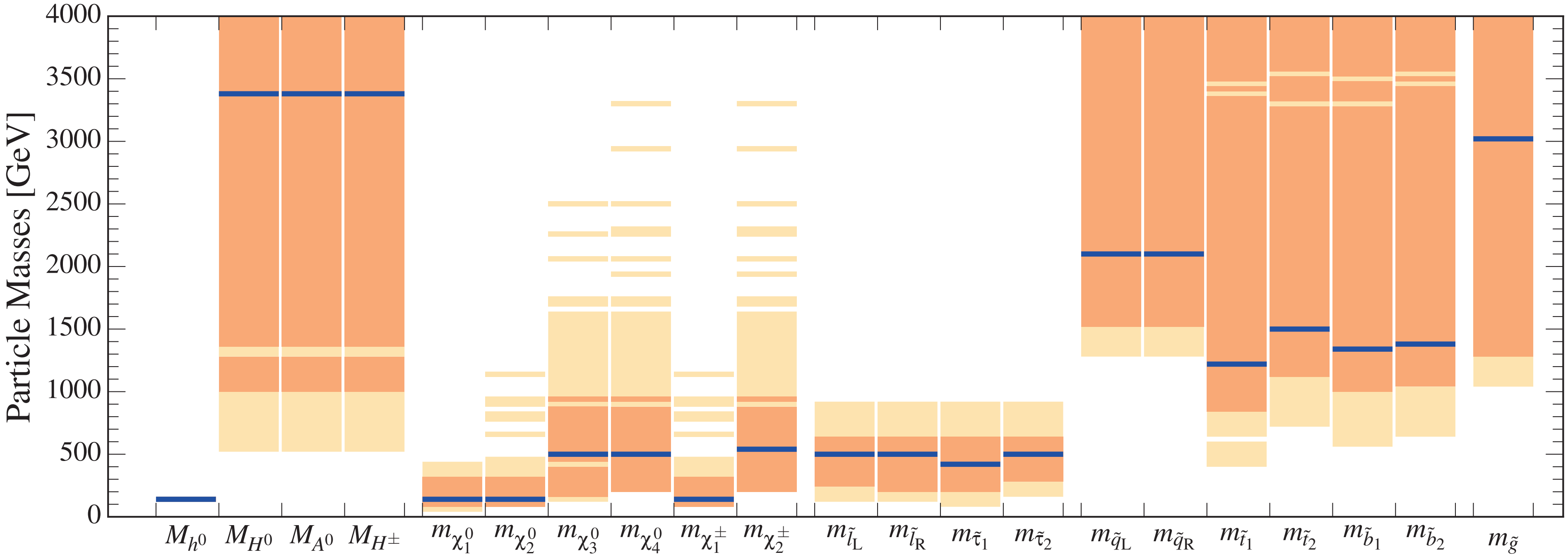


$\Rightarrow$ chargino co-annihilation

$\Rightarrow M_1 \approx M_2$

pMSSM10 prediction: best-fit masses

[2015]



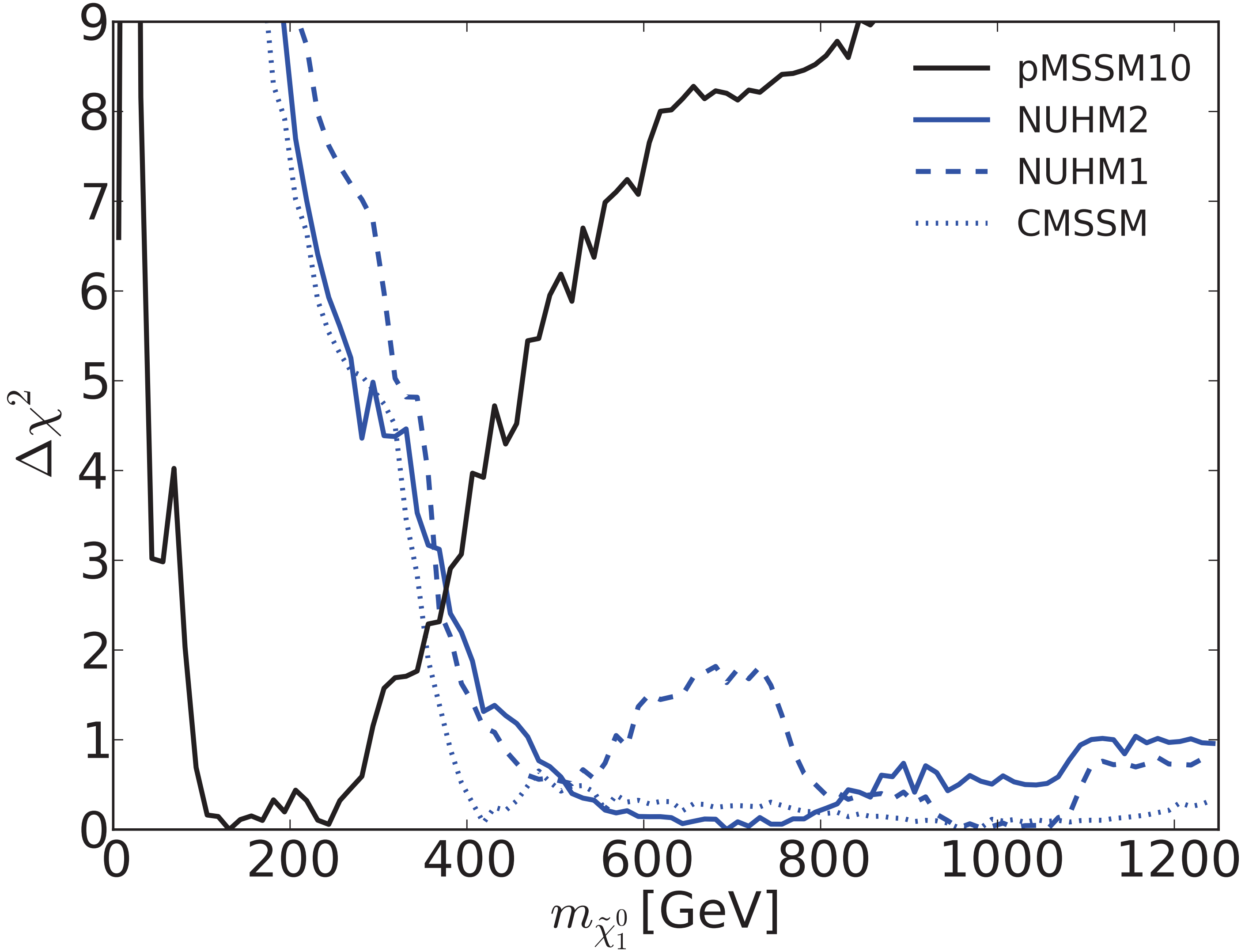
⇒ high colored masses

⇒ 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

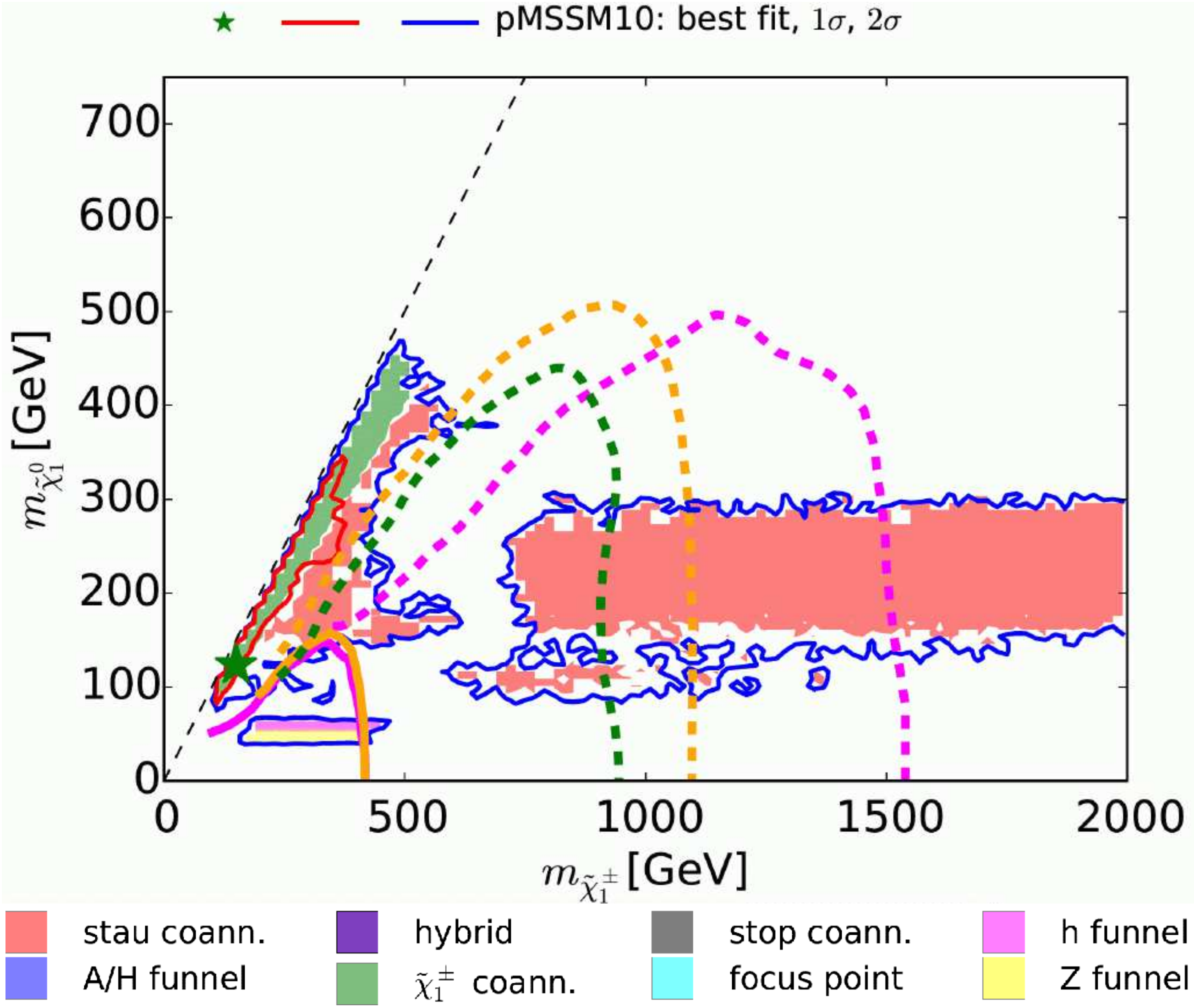
[2015]



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

LHC prospects for pMSSM10:

[2015]



solid: current LHC limits, dashed: HL-LHC prospects

⇒ best-fit regions not covered! (in EW searches)

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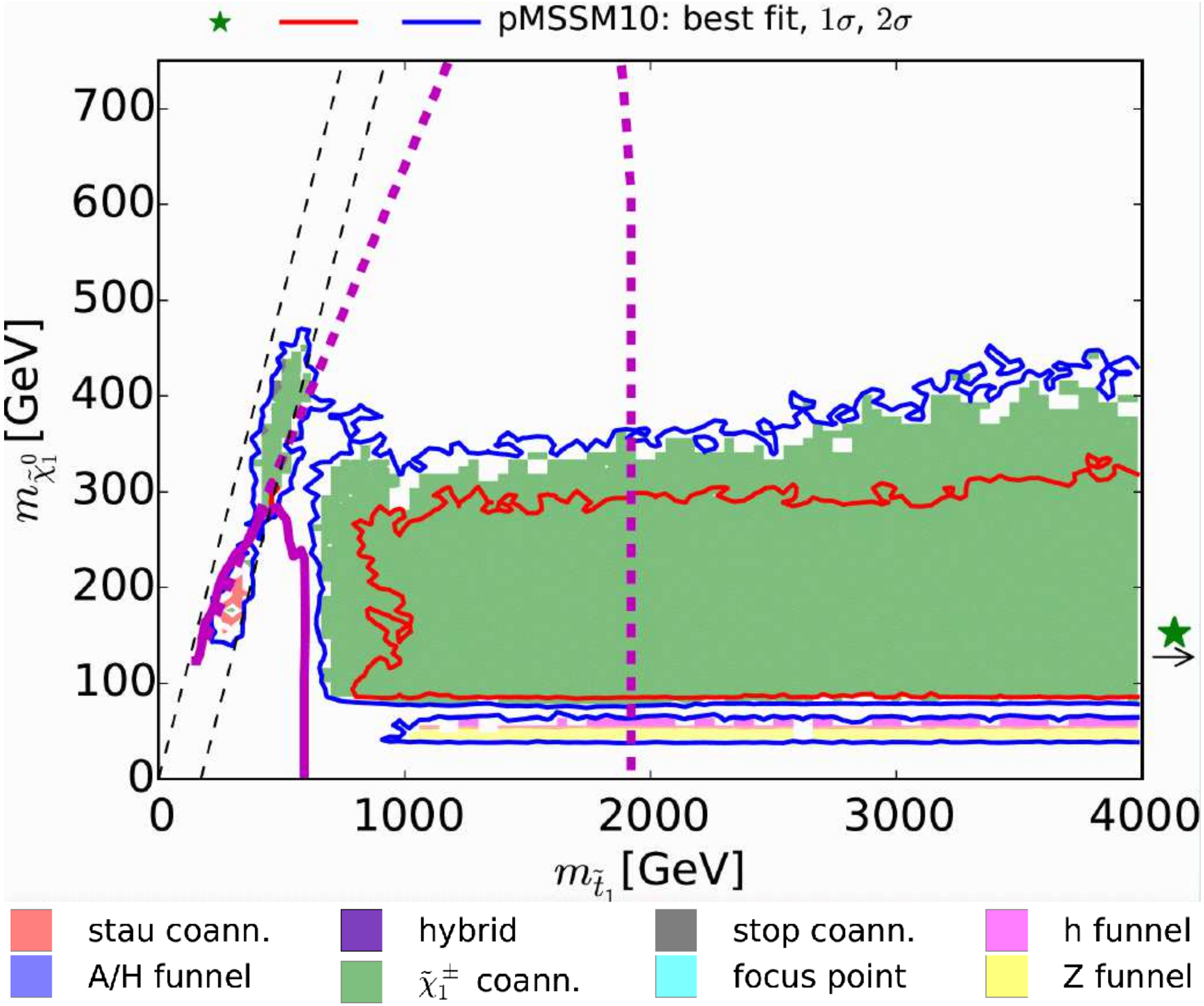

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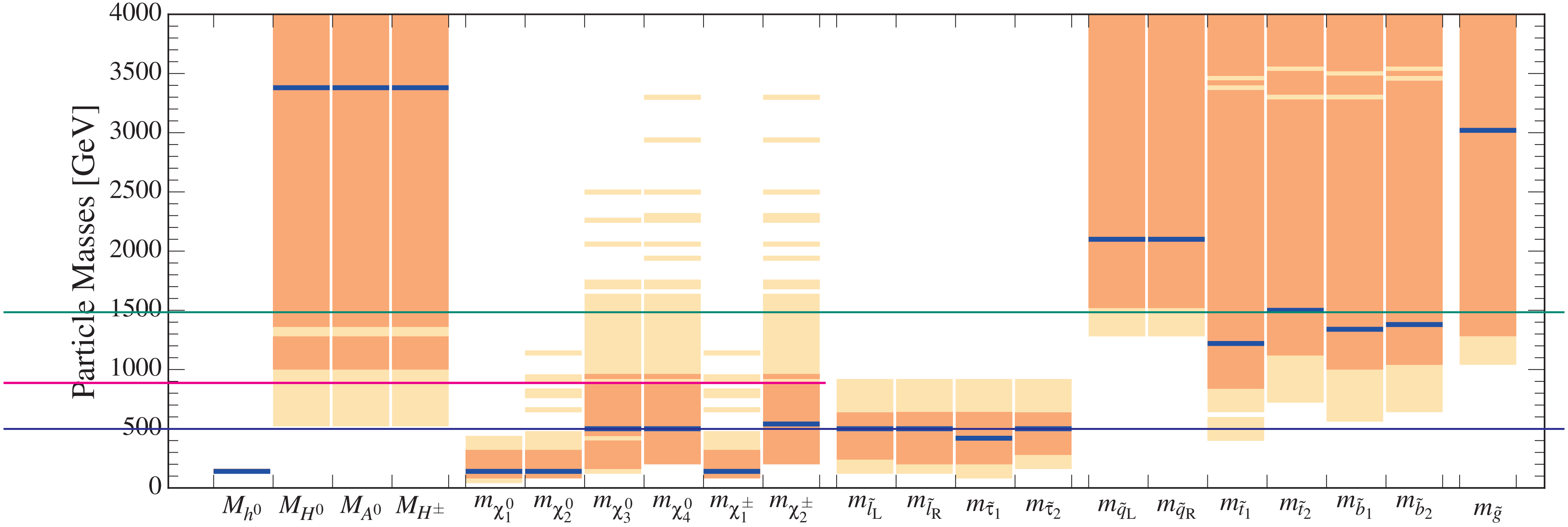
e^+e^- prospects for pMSSM10:

[2015]



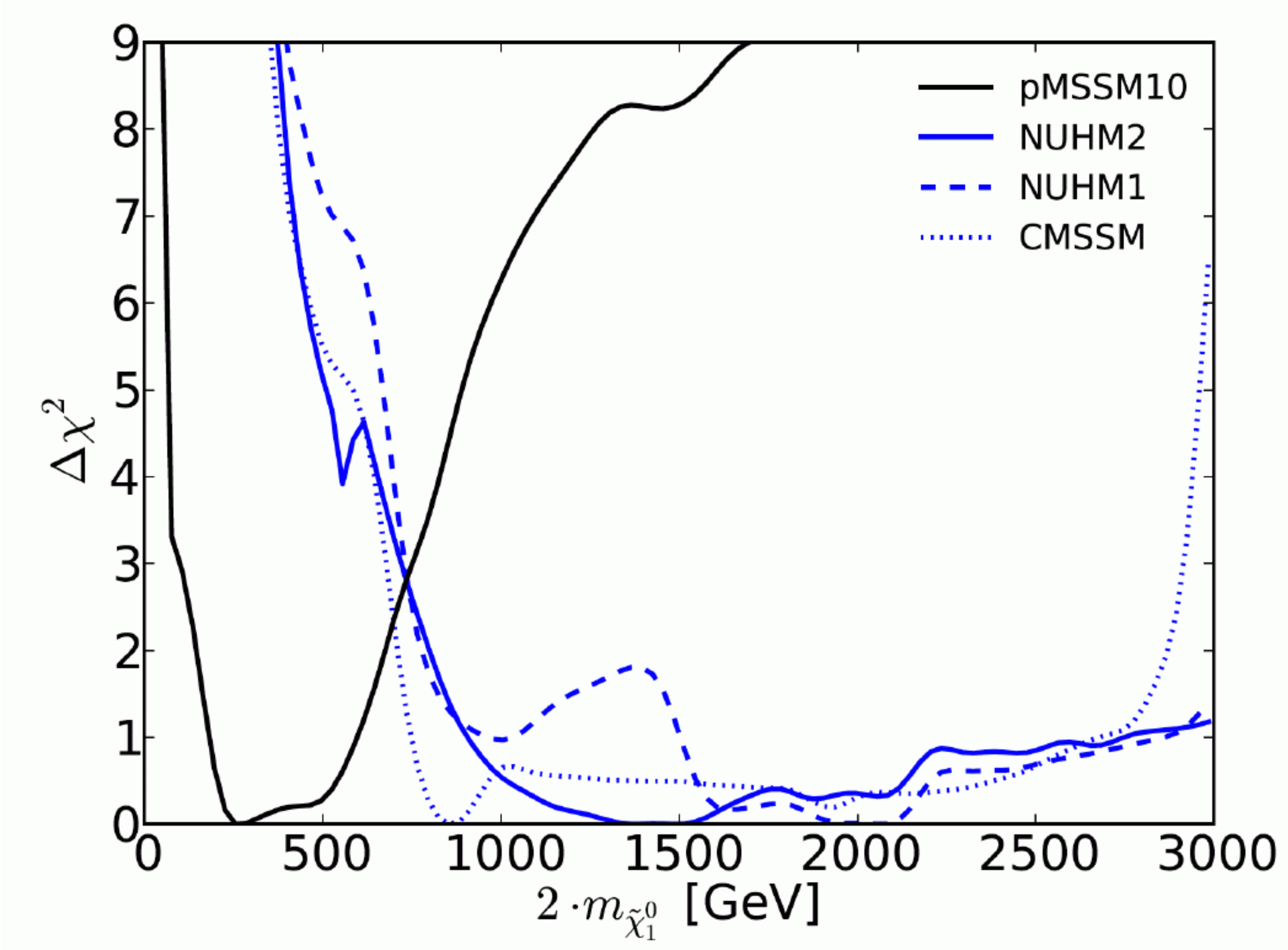
ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of EW particle and DM easy!

ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ higher reach for non-diagonal production!

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

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

[2014]

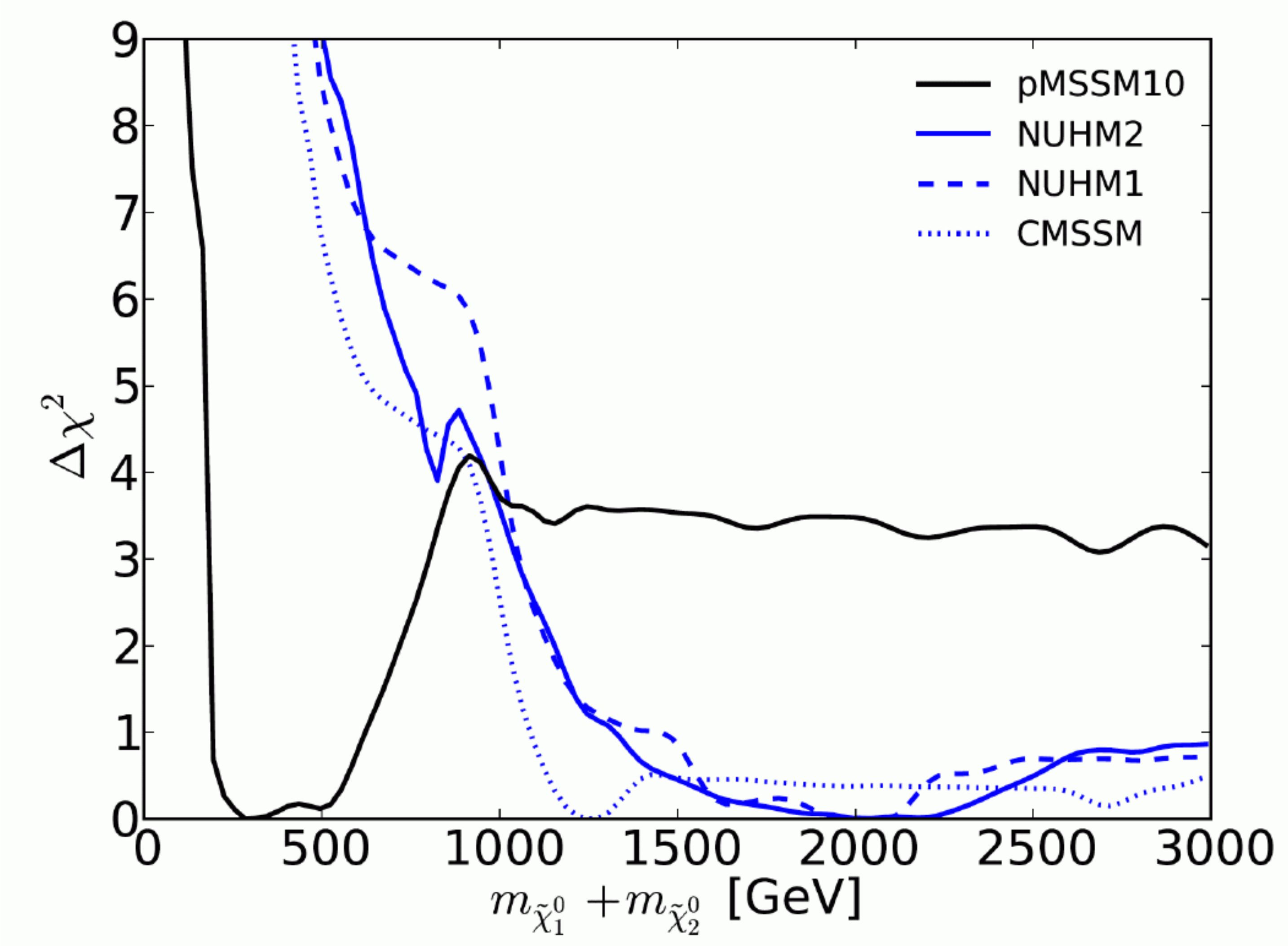


⇒ GUT based models: ILC :-(, CLIC possible

⇒ pMSSM10: easy at the ILC

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

[2014]



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

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

3. SUSY Higgs mass and rate measurements

The Higgs mass accuracy: experiment vs. theory:

Experiment:

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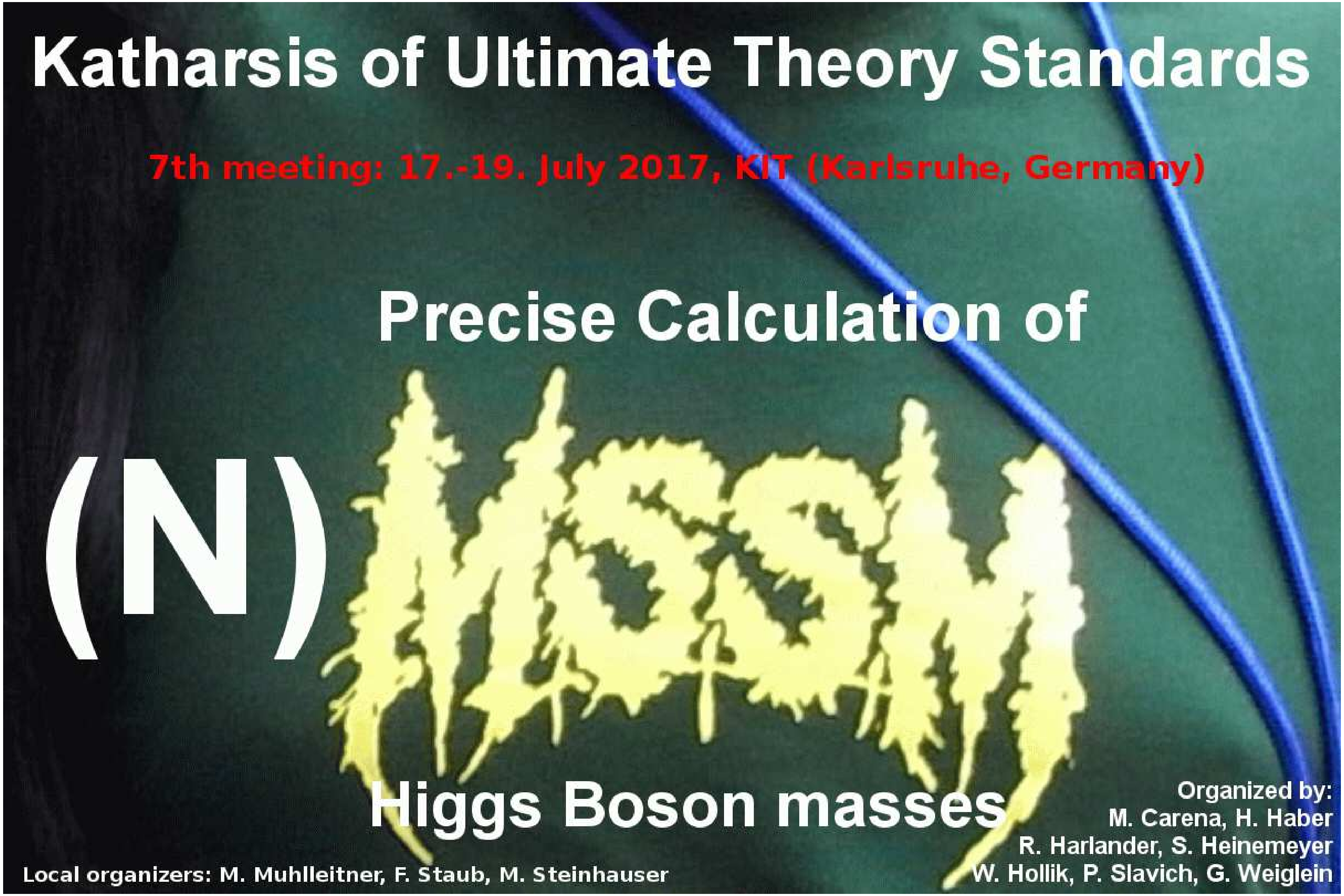
MSSM theory:

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

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

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



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:

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

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: (in the "alignment w/o decoupling" scen.)
   $\Rightarrow$ 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

Example: $m_h^{\text{mod}+}$ scenario:

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

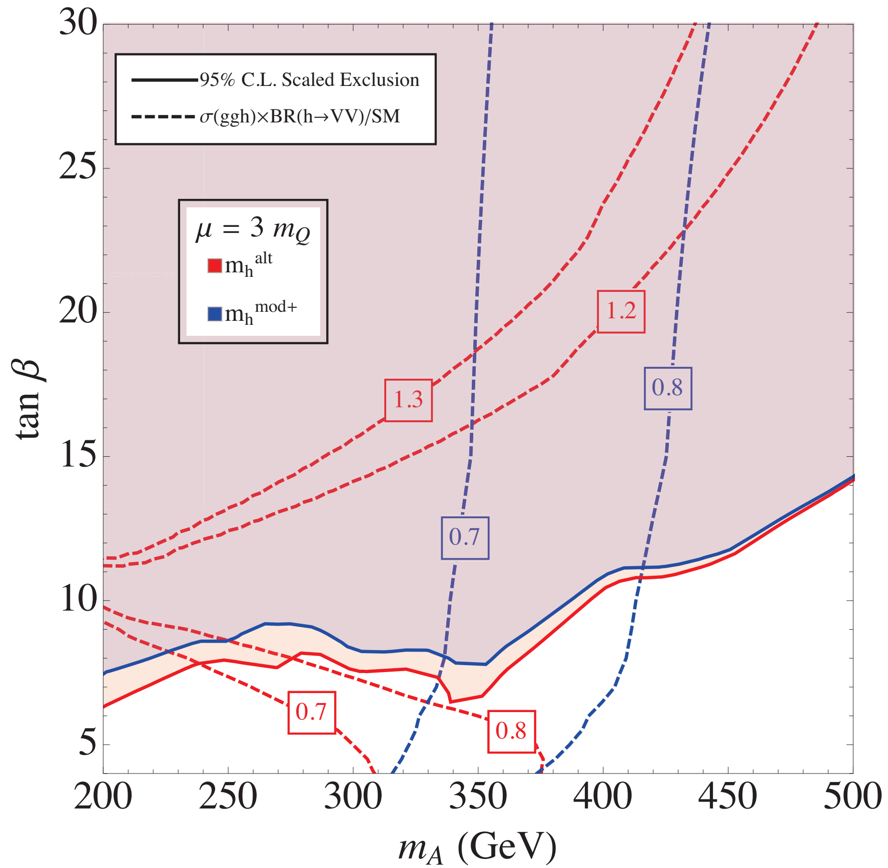
$M_S = m_{\tilde f} \geq 1$ TeV, $m_{\tilde g} = 1.5$ TeV,

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

$\Rightarrow$ SM-like Higgs for all M_A

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

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



Alignment limit: see e.g.
[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '15]

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

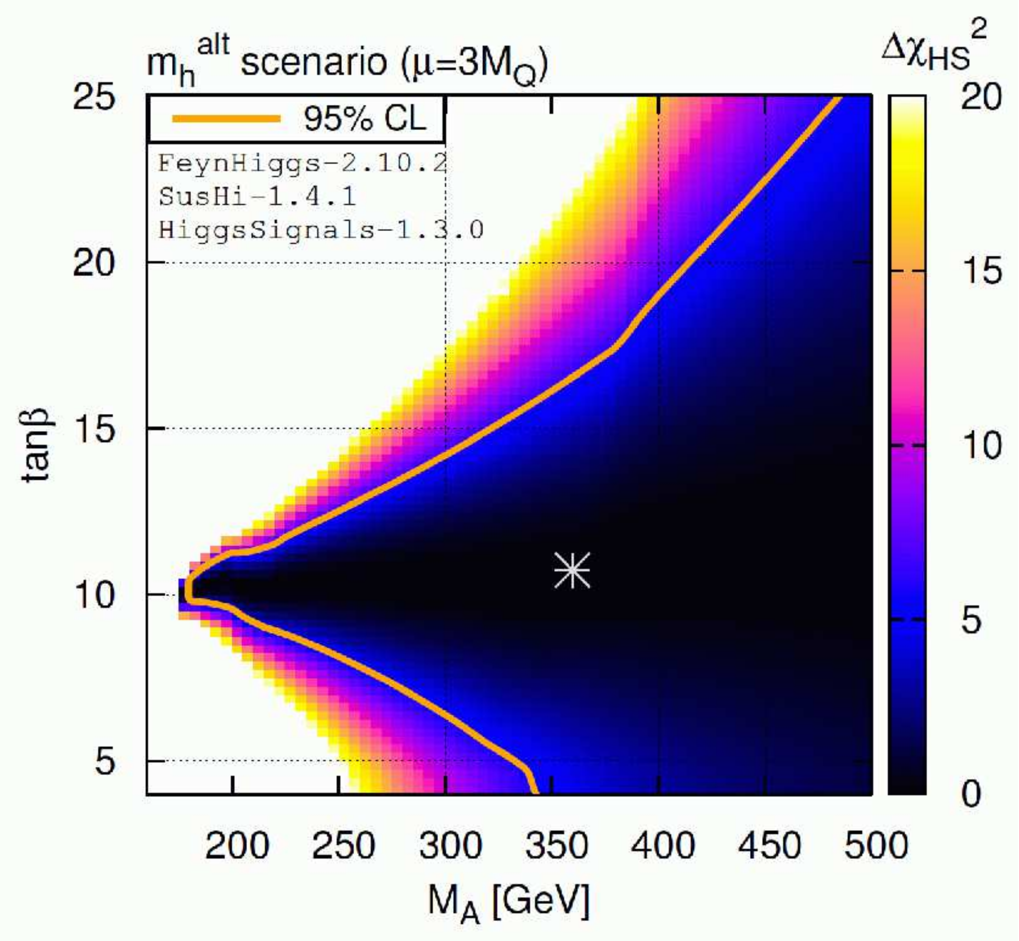
Example: $m_h^{\rm mod+}$ scenario:
$A_t/M_S = 2.45,\ A_t = A_f,$
$M_S = m_{\tilde f} \geq 1$ TeV, $m_{\tilde g} = 1.5$ TeV,
$M_2 = 2\,M_1 = 200$ GeV, μ adjustable

$\Rightarrow$ SM-like Higgs for all M_A

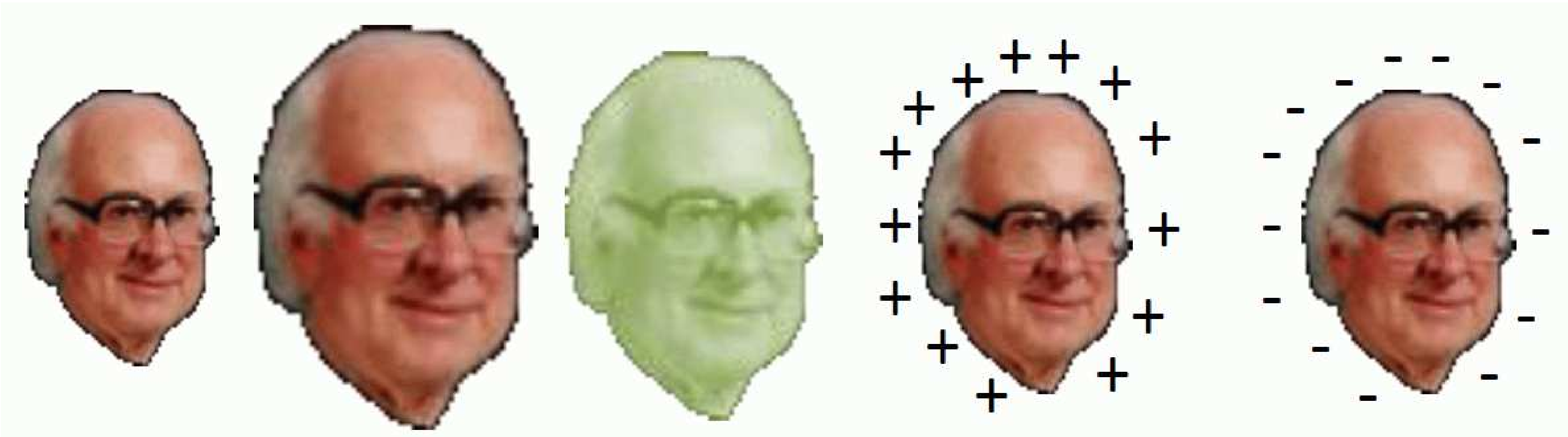
$\tan\beta \sim$

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

$m_h^{\rm mod+}$ scenario with HiggsSignals :

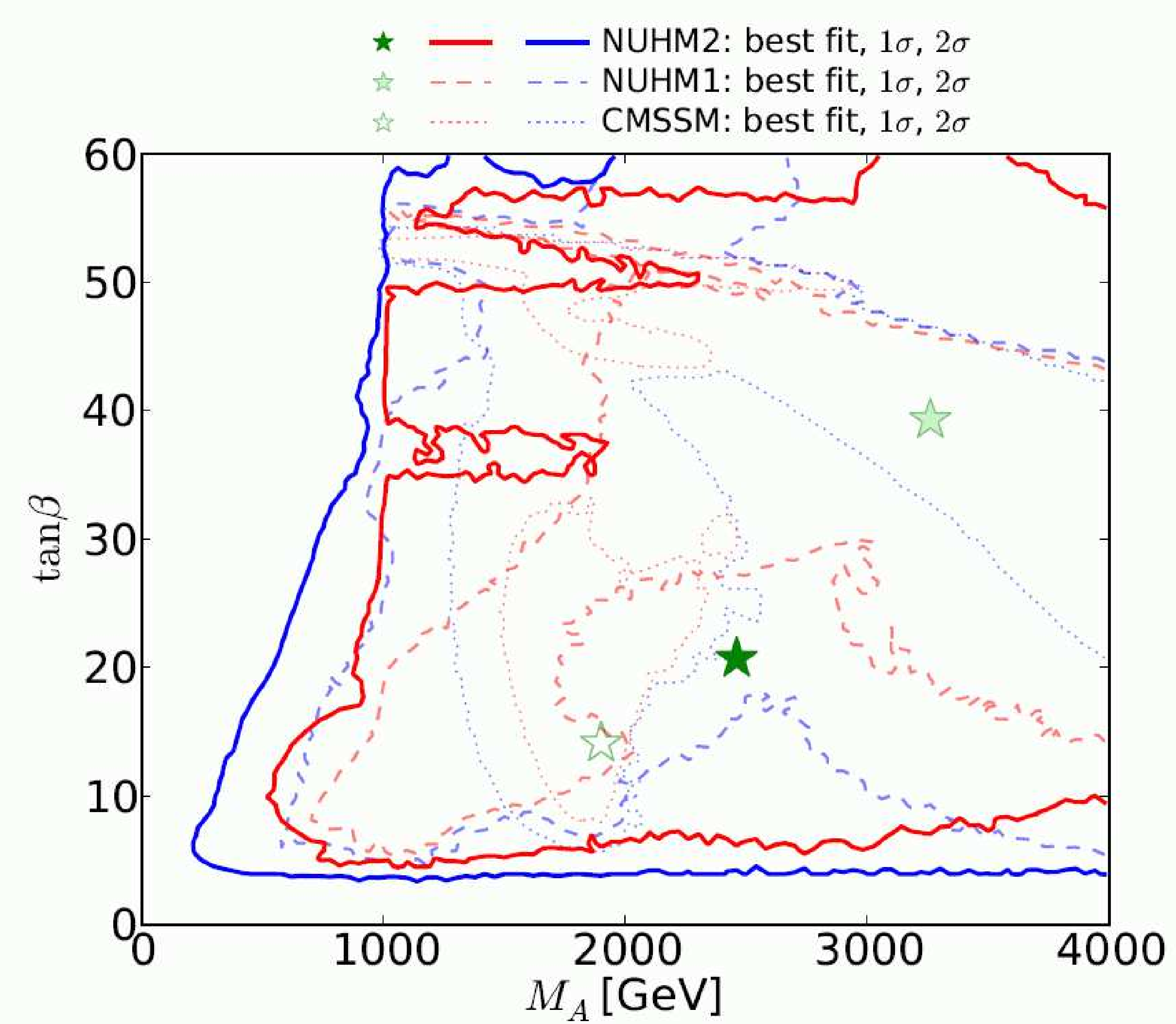


4. MSSM Higgs results (CMSSM, NUHM1/2, pMSSM8)



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

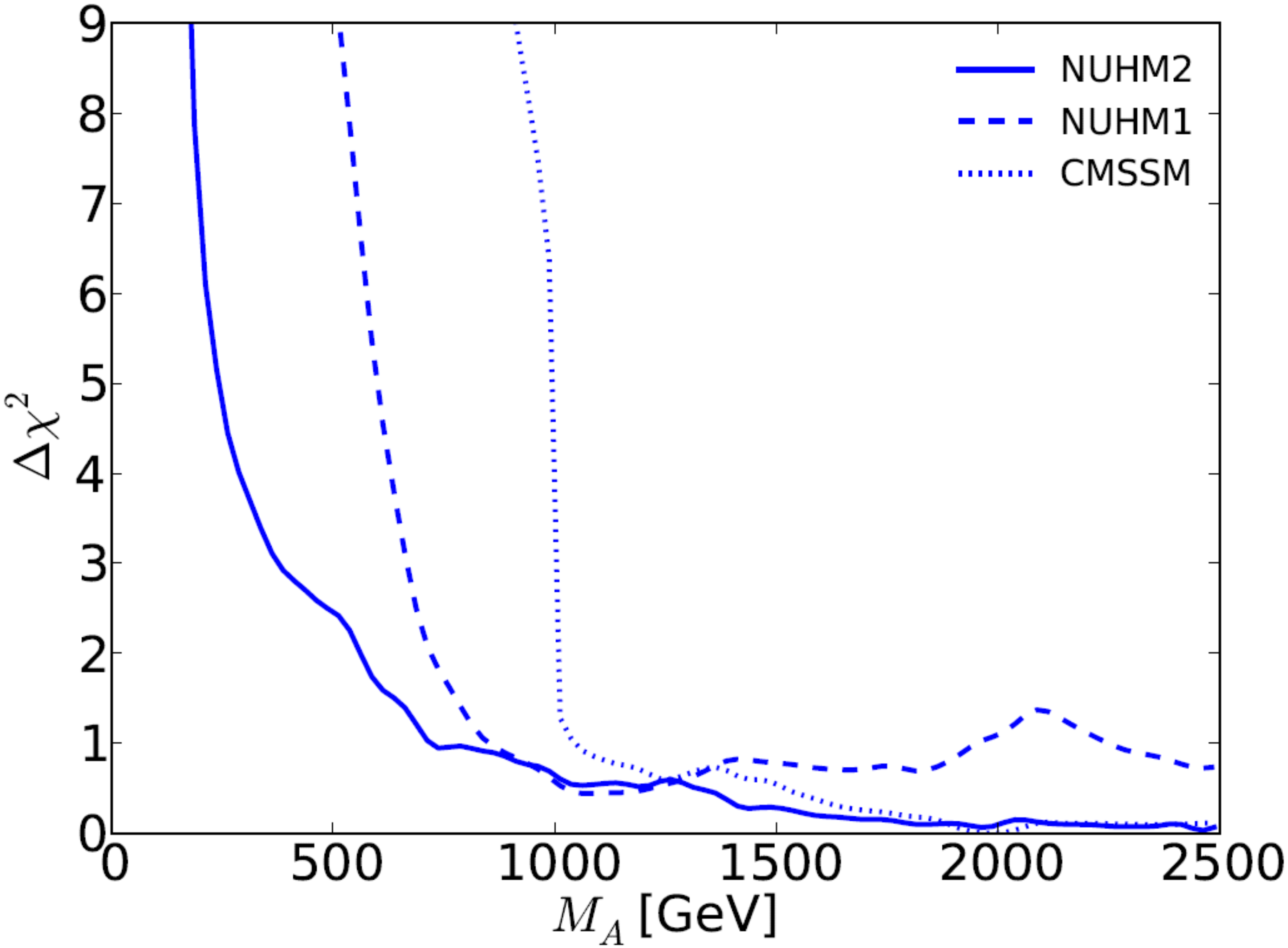
[2015]



⇒ 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

$M_{Q_{1,2}} = M_{U_{1,2}} = M_{D_{1,2}} = 1.5$ 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, $\chi^2_{\rm LEP}$, 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

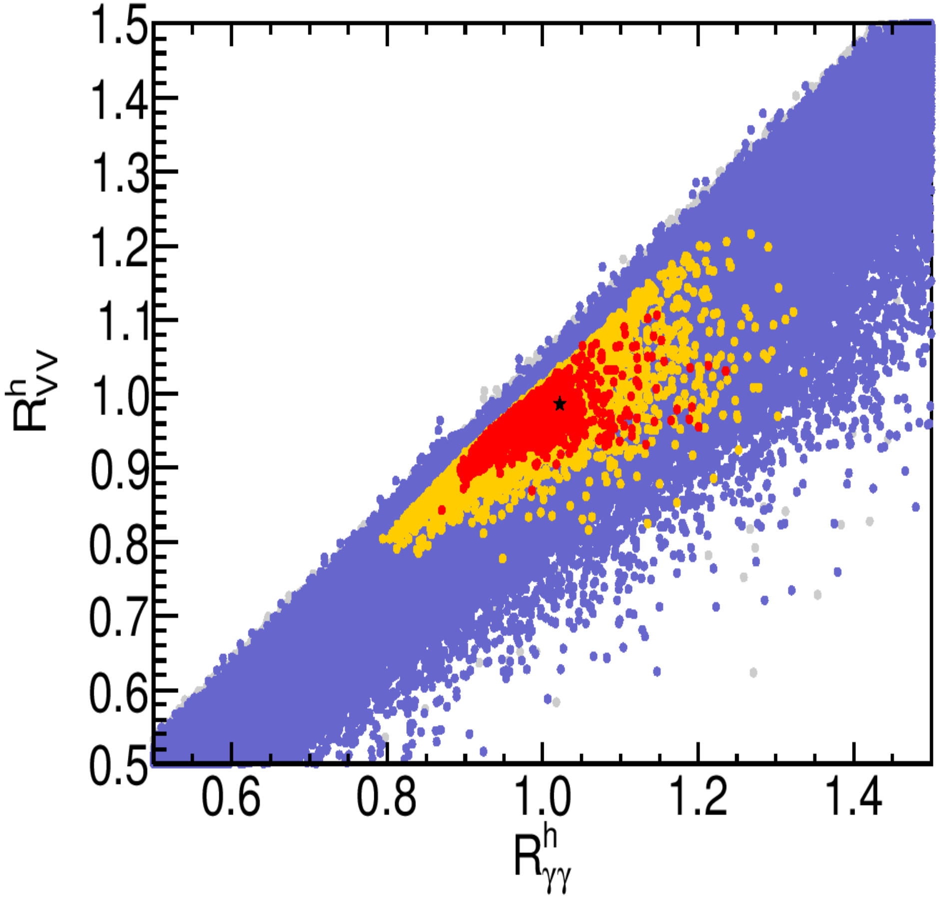
Best-fit points parameters:

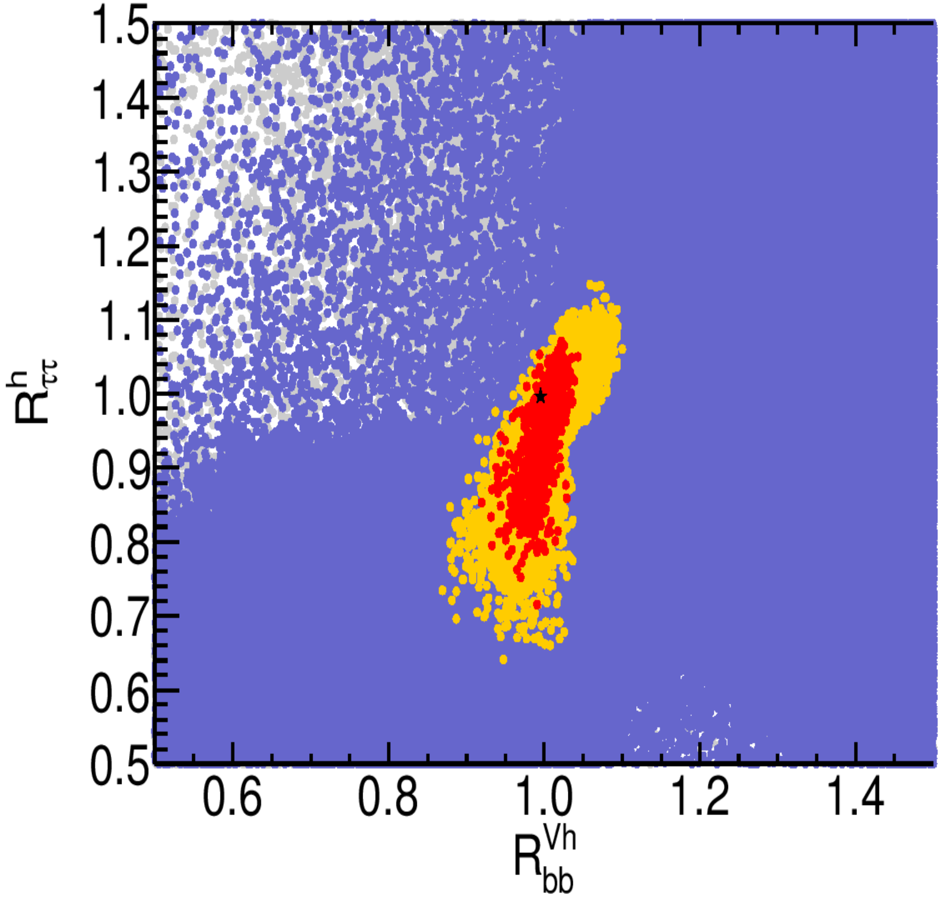
Case	M_A (GeV)	$\tan\beta$	μ (GeV)	A_t (GeV)	$M_{\tilde{q}3}$ (GeV)	$M_{\tilde{\ell}_3}$ (GeV)	$M_{\tilde{\ell}_{1,2}}$ (GeV)	M_2 (GeV)
h	929	21.0	7155	4138	2957	698	436	358
H	172	6.6	4503	−71	564	953	262	293

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

⇒ Including LEOs, SM fit becomes worse

1) Light-Higgs case: preferred rates



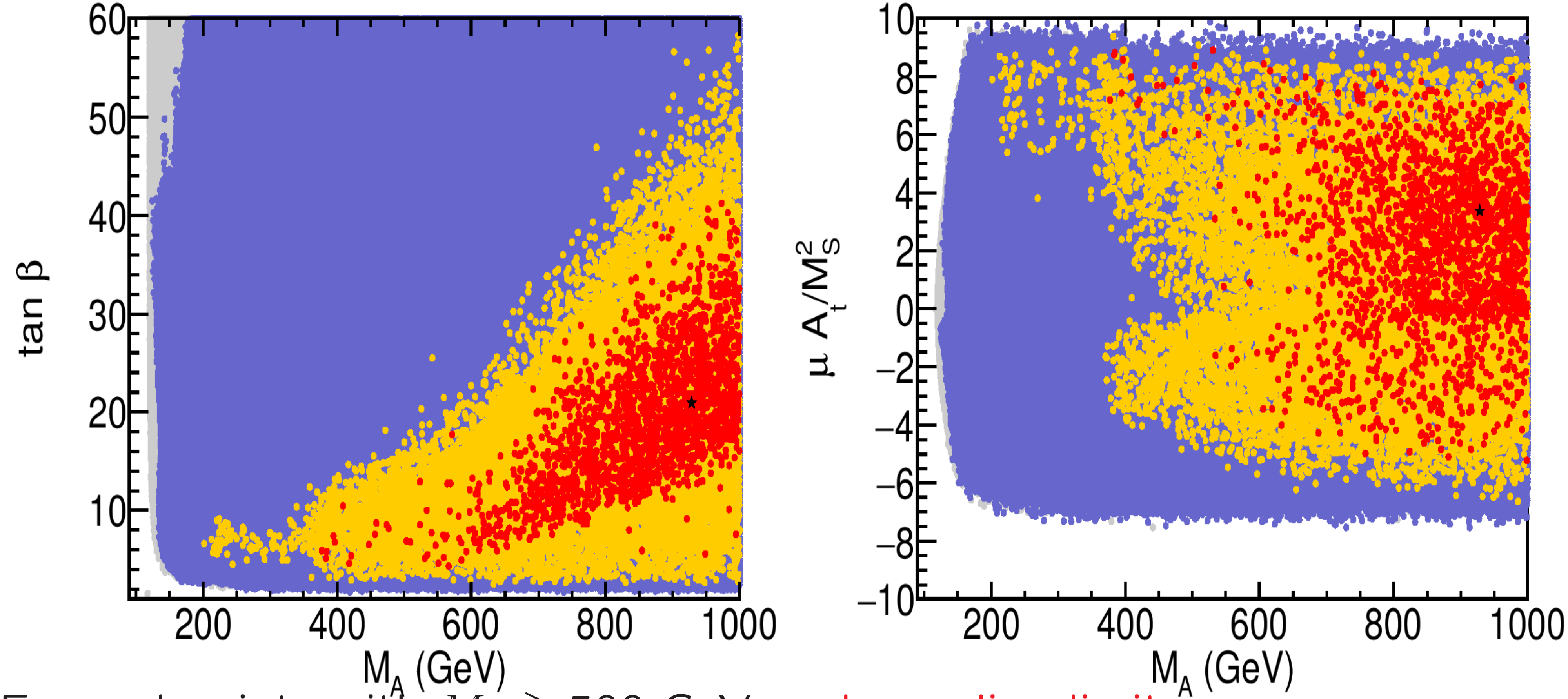


$R^h_{VV} = 0.99^{+0.09}_{-0.08}$, $R^h_{\gamma\gamma} = 1.02^{+0.16}_{-0.10}$, $R^{Vh}_{bb} = 1.00^{+0.02}_{-0.05}$, $R^h_{\tau\tau} = 1.00^{+0.06}_{-0.20}$

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

⇒ but some (BSM) spread is allowed!

1) Light-Higgs case: preferred parameters



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

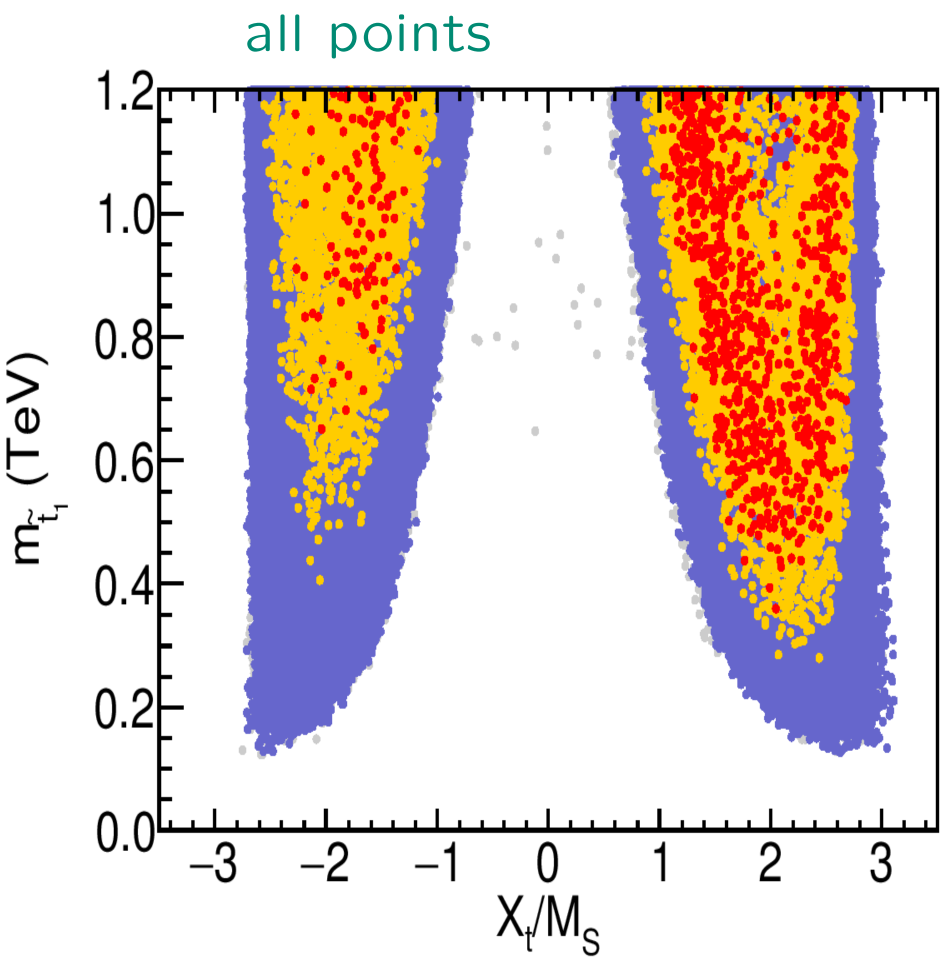
$M_A \gtrsim 200$ GeV $\Rightarrow$ alignment limit

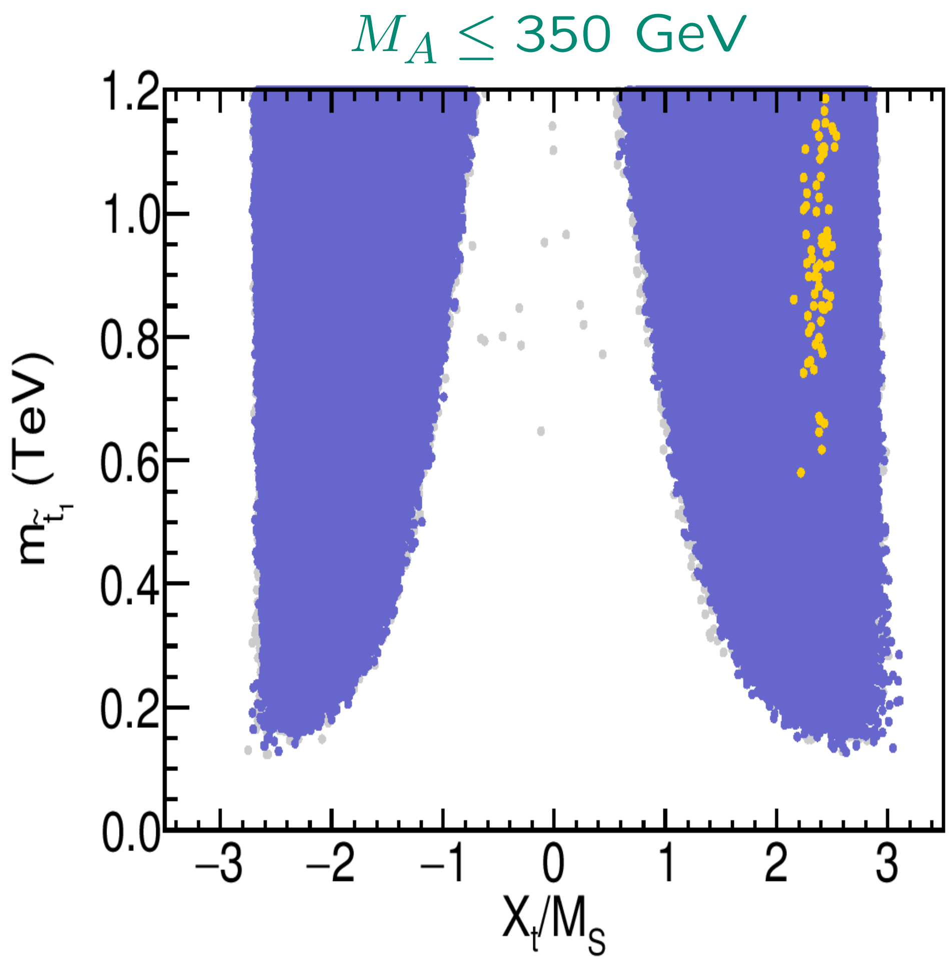
Alignment: $\tan\beta \sim 1/\left[\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)\right]$

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

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

1) 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 possilbe:

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

Consequences:

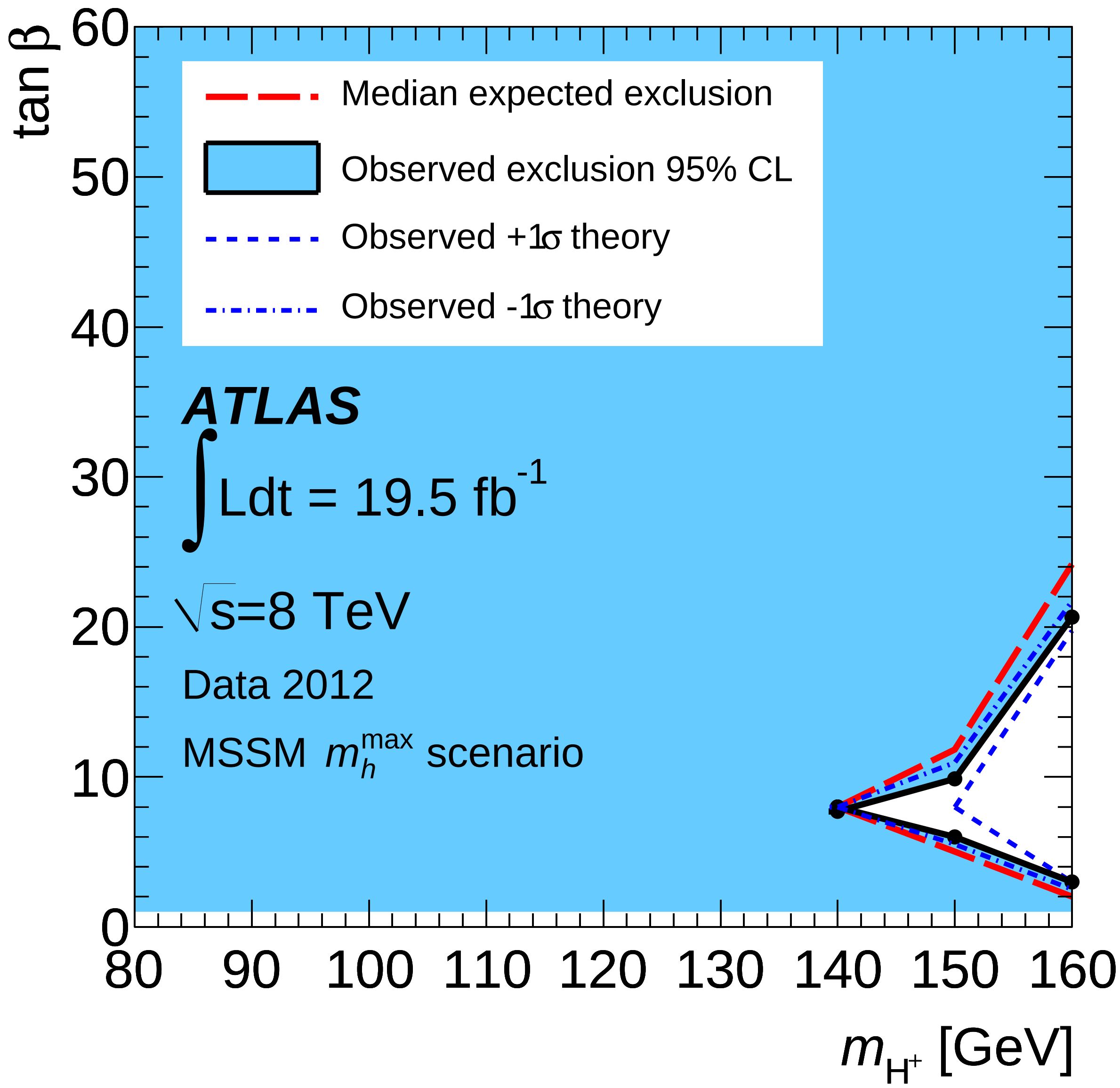
– all Higgs bosons very light
– easy(?) discovery of additional Higgs bosons at the LHC

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*]

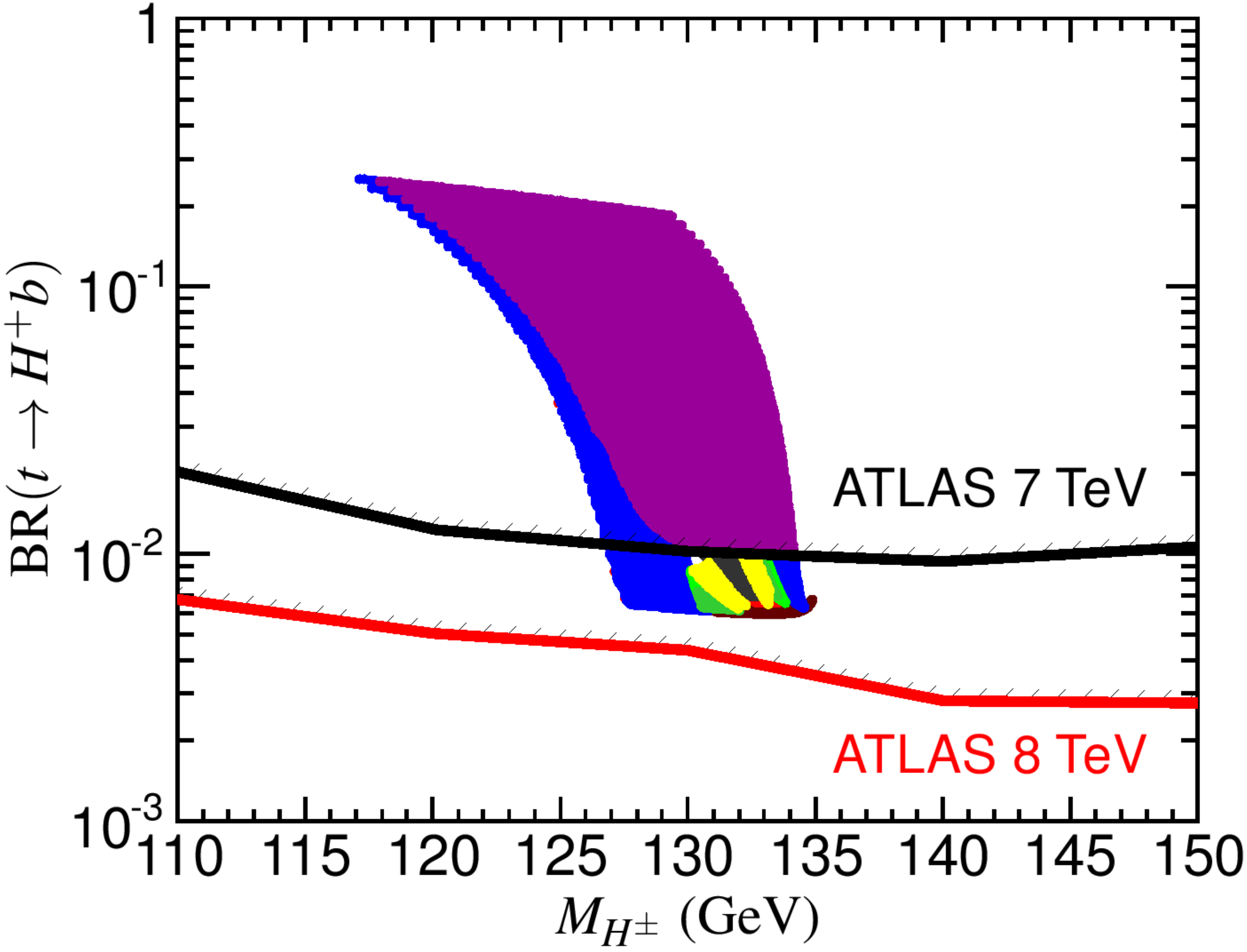
ATLAS results for charged Higgs searches: [ATLAS '15]



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

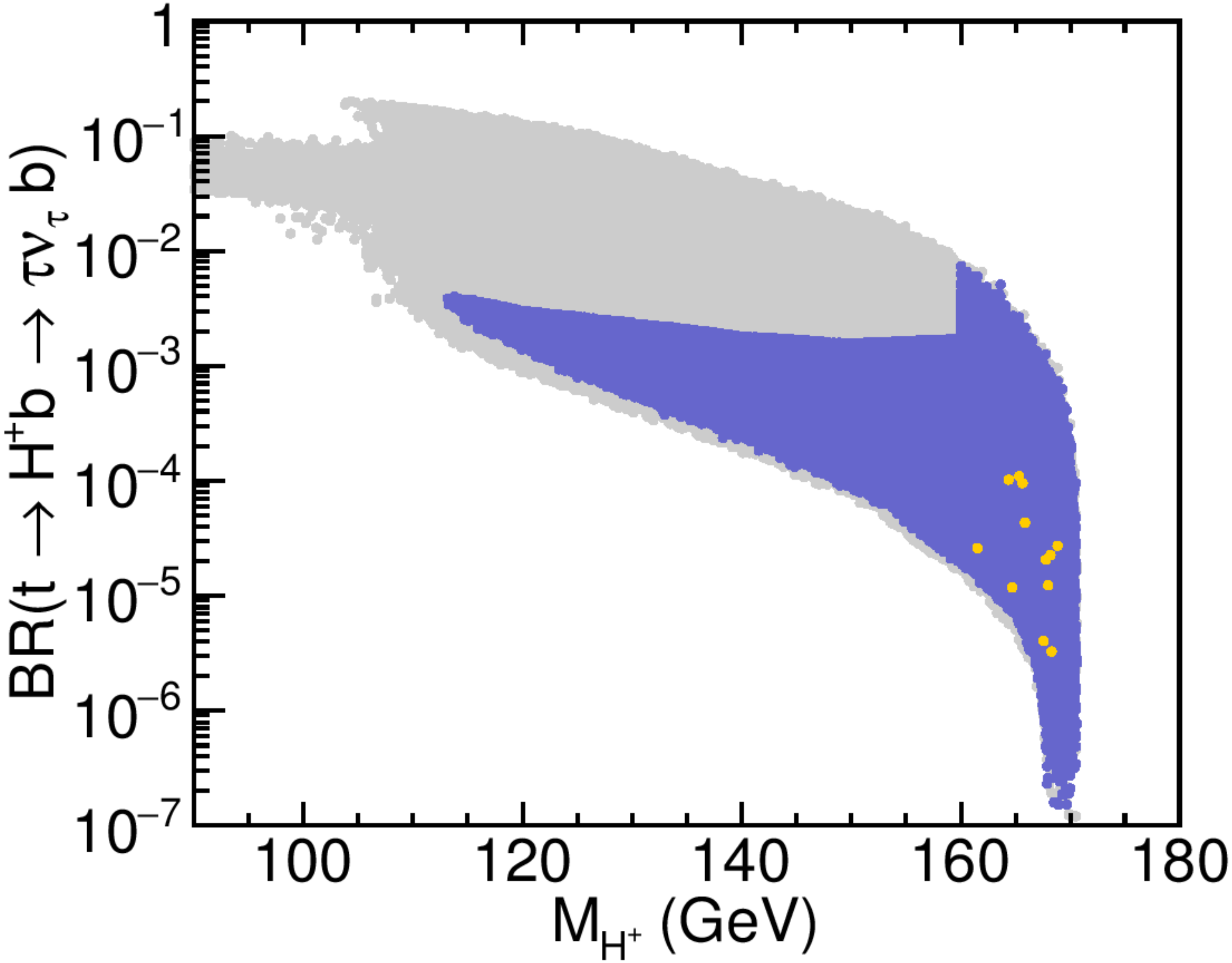
Application of charged Higgs limits on low-M_H scenario:

[*HiggsBounds 4.1*]



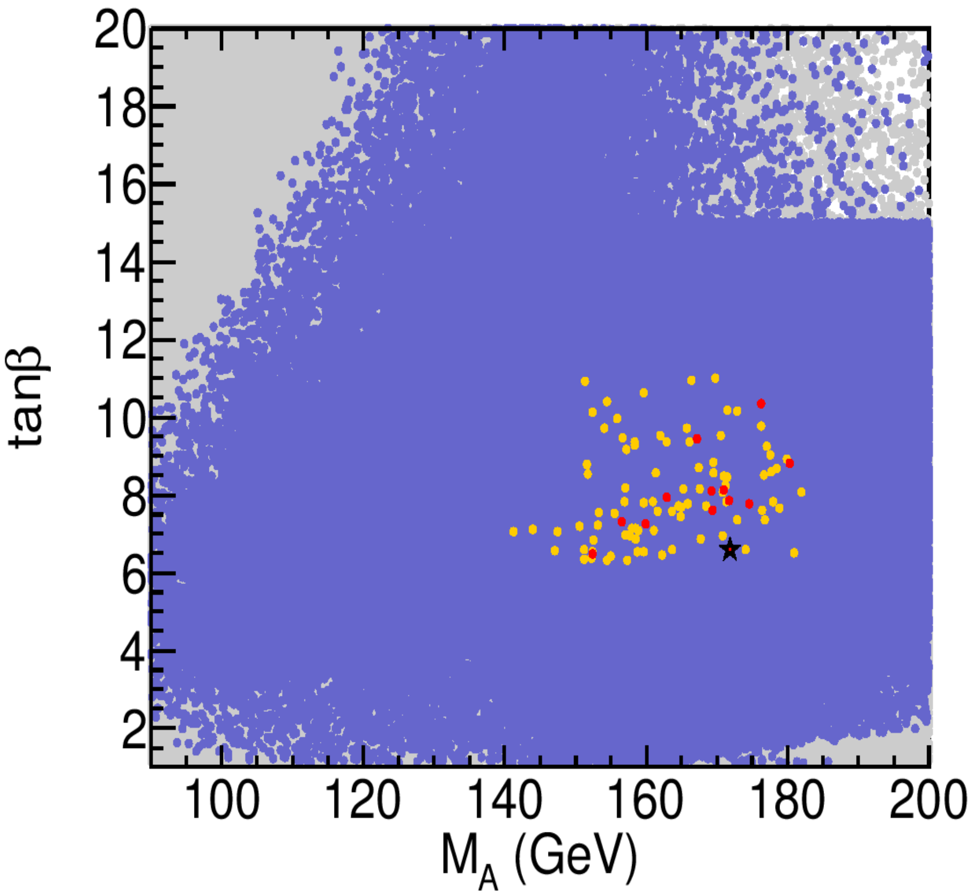
$\Rightarrow$ that (particular incarnation of the) low-M_H scenario is excluded!

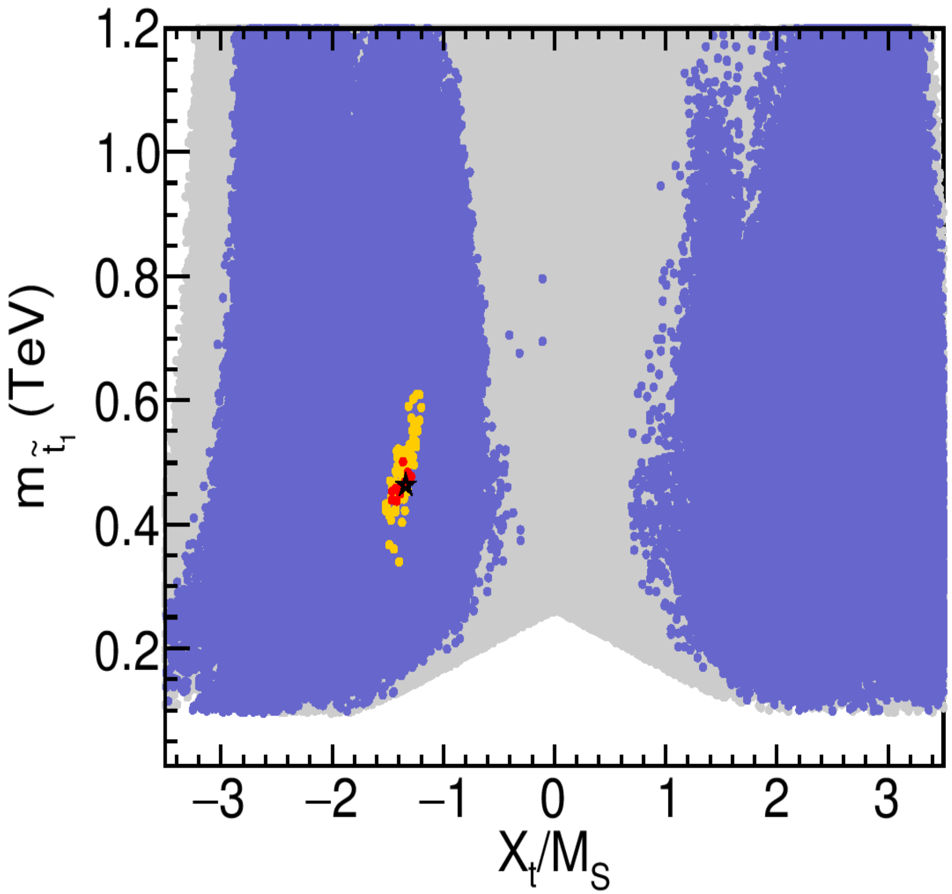
How to avoid BR($t \to H^{\pm}b$) bounds: $\Rightarrow$ higher $M_{H^{\pm}}$!



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

2) Heavy-Higgs case: preferred parameters



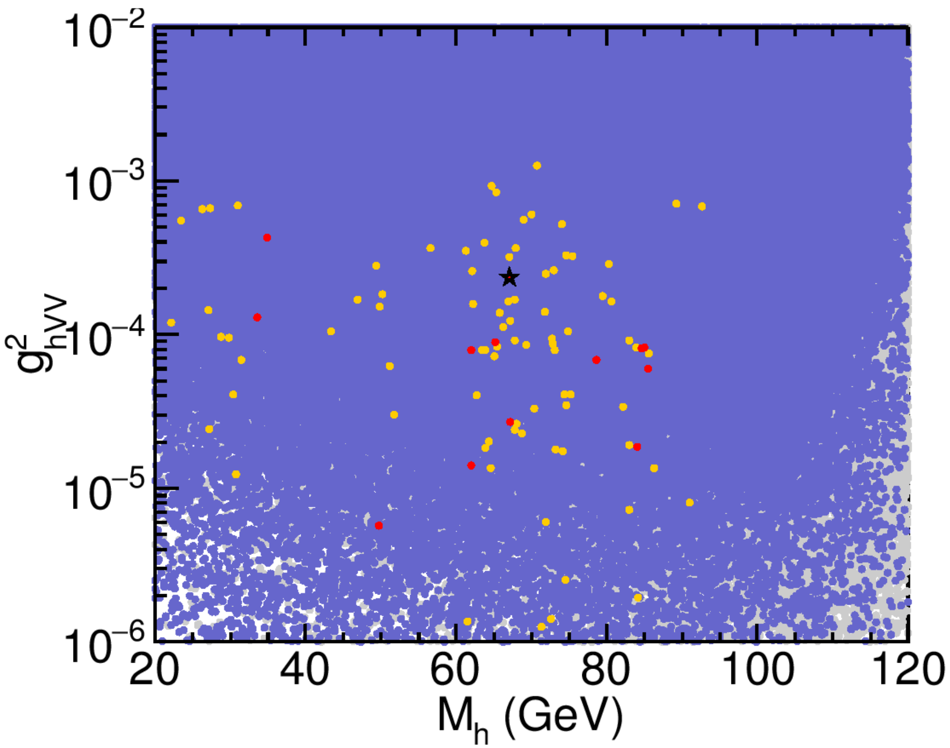


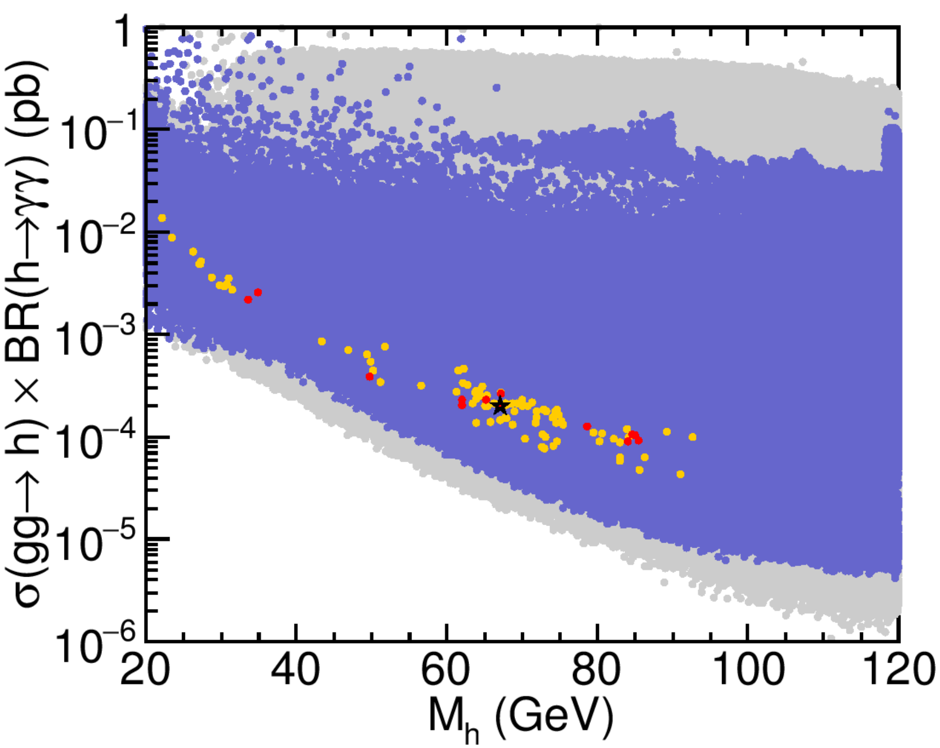
$\Rightarrow M_A \sim 140 \ldots 180$ GeV $\Rightarrow m_{\tilde{t}_1} \sim 350 \ldots 650$ GeV

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

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

New low-M_H benchmark scenarios

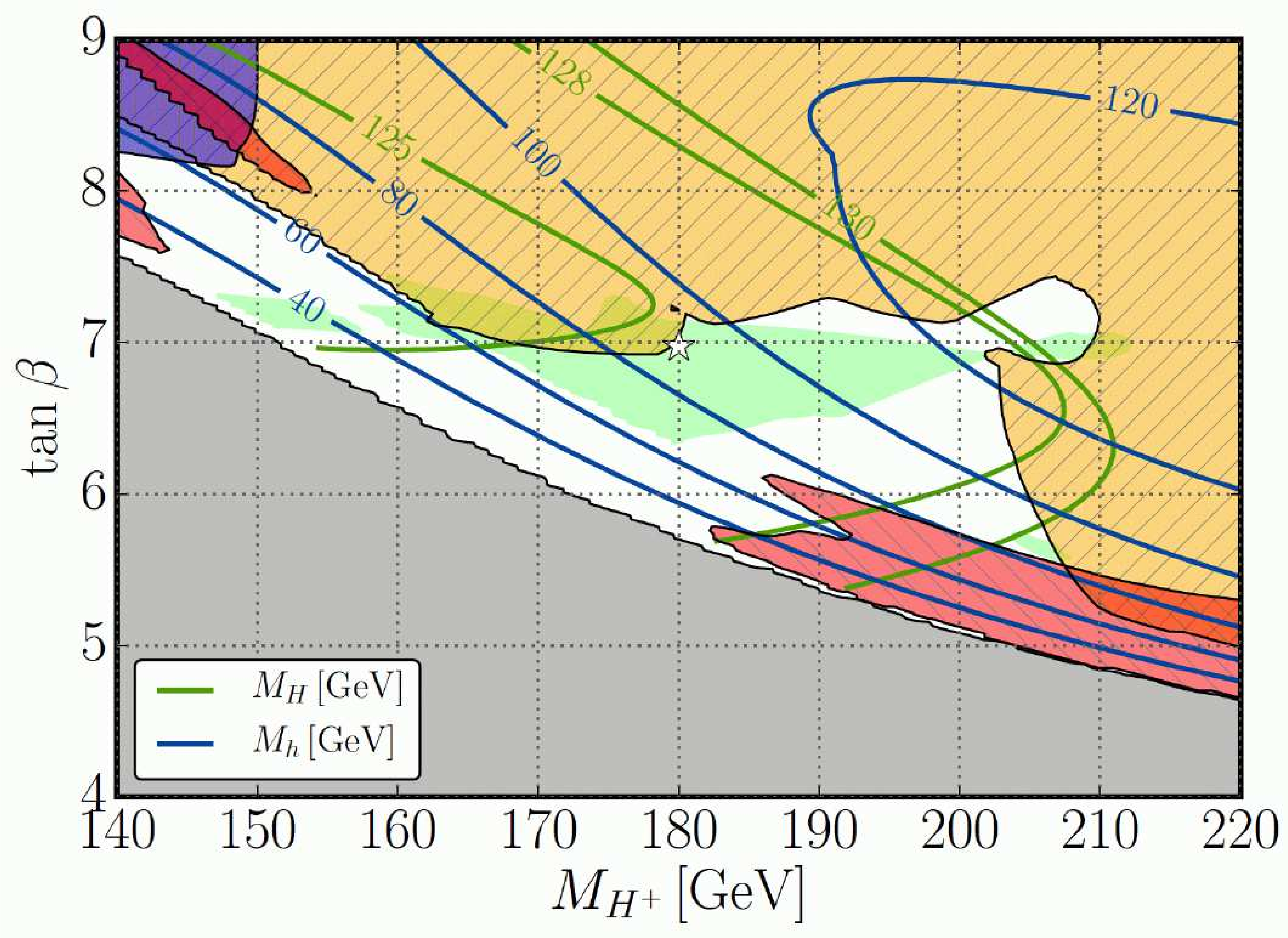
Based on our best-fit region:

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 $M_{H^\pm} < m_t$

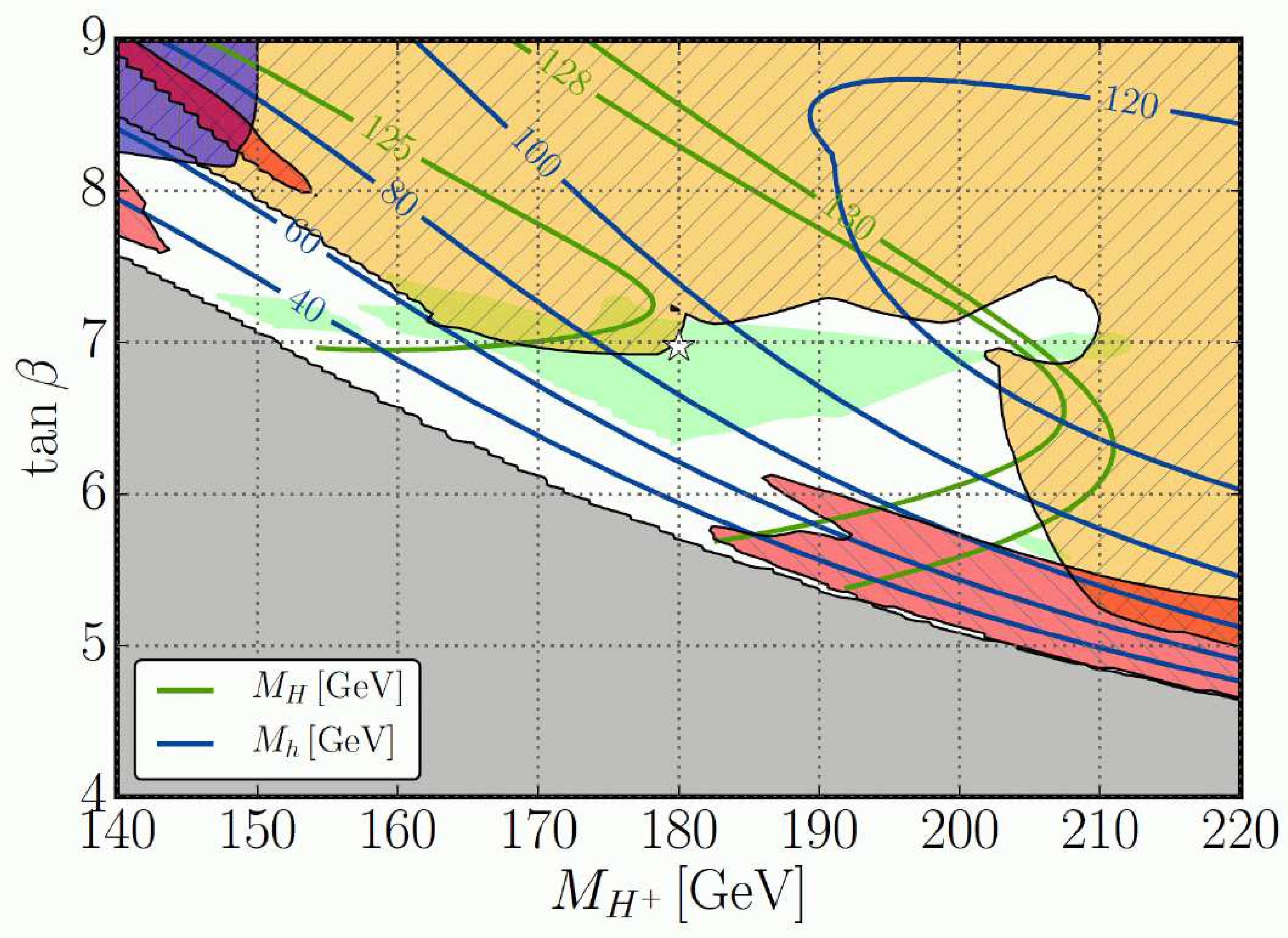
low-$M_H^{\text{alt}+}$: fixed $M_{H^\pm} > m_t$

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



$\Rightarrow$ 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. 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!

  ⇒ pMSSM8/10 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

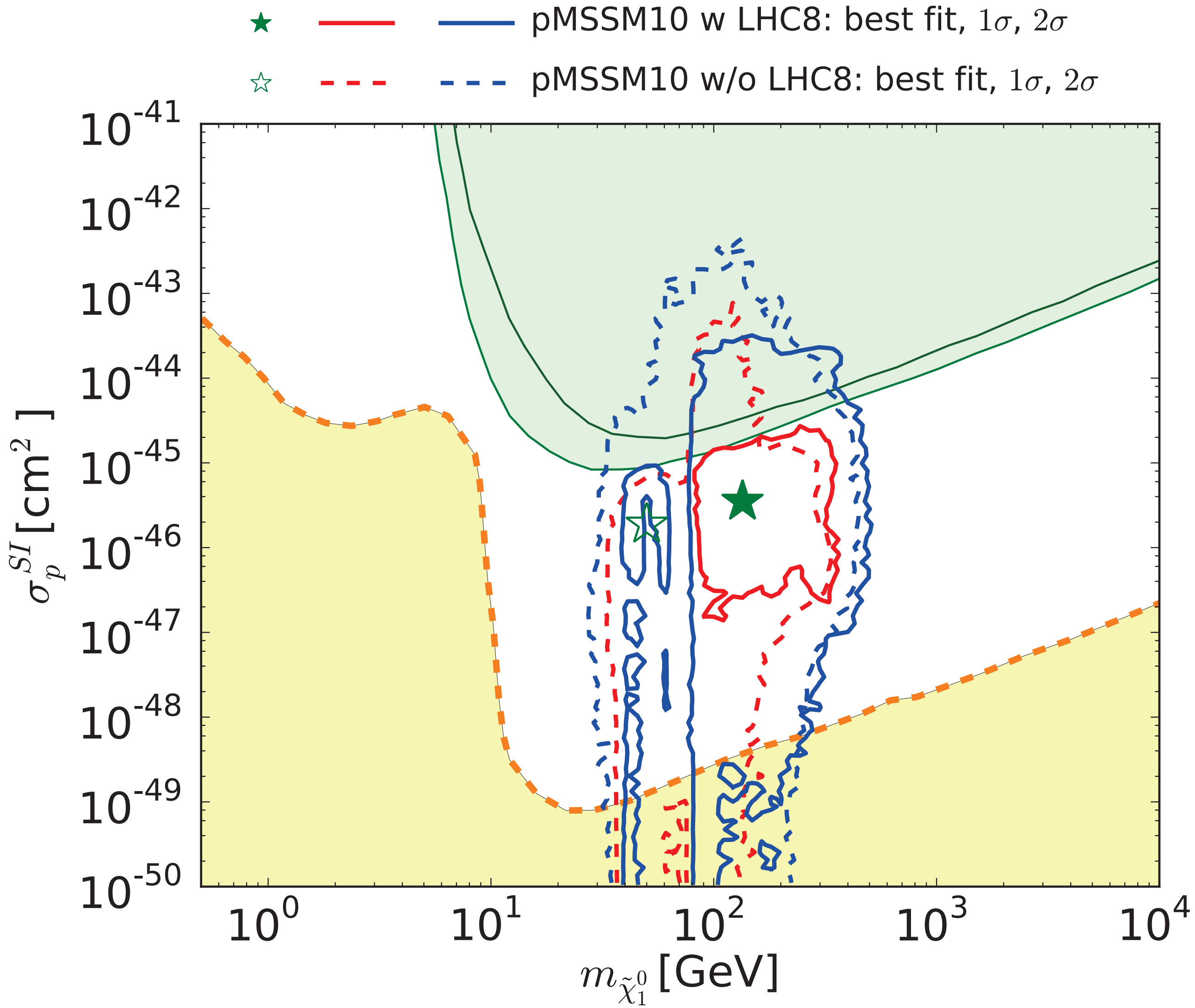
- MSSM results:
  – CMSSM, NUHM1: relatively high Higgs mass scales favored
  – NUHM2: somewhat lower values possible, but still high . . .
  – pMSSM8: light $\mathcal{CP}$-even Higgs for "all" M_A
  heavy $\mathcal{CP}$-even Higgs
  ⇒ new benchmark scenarios


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

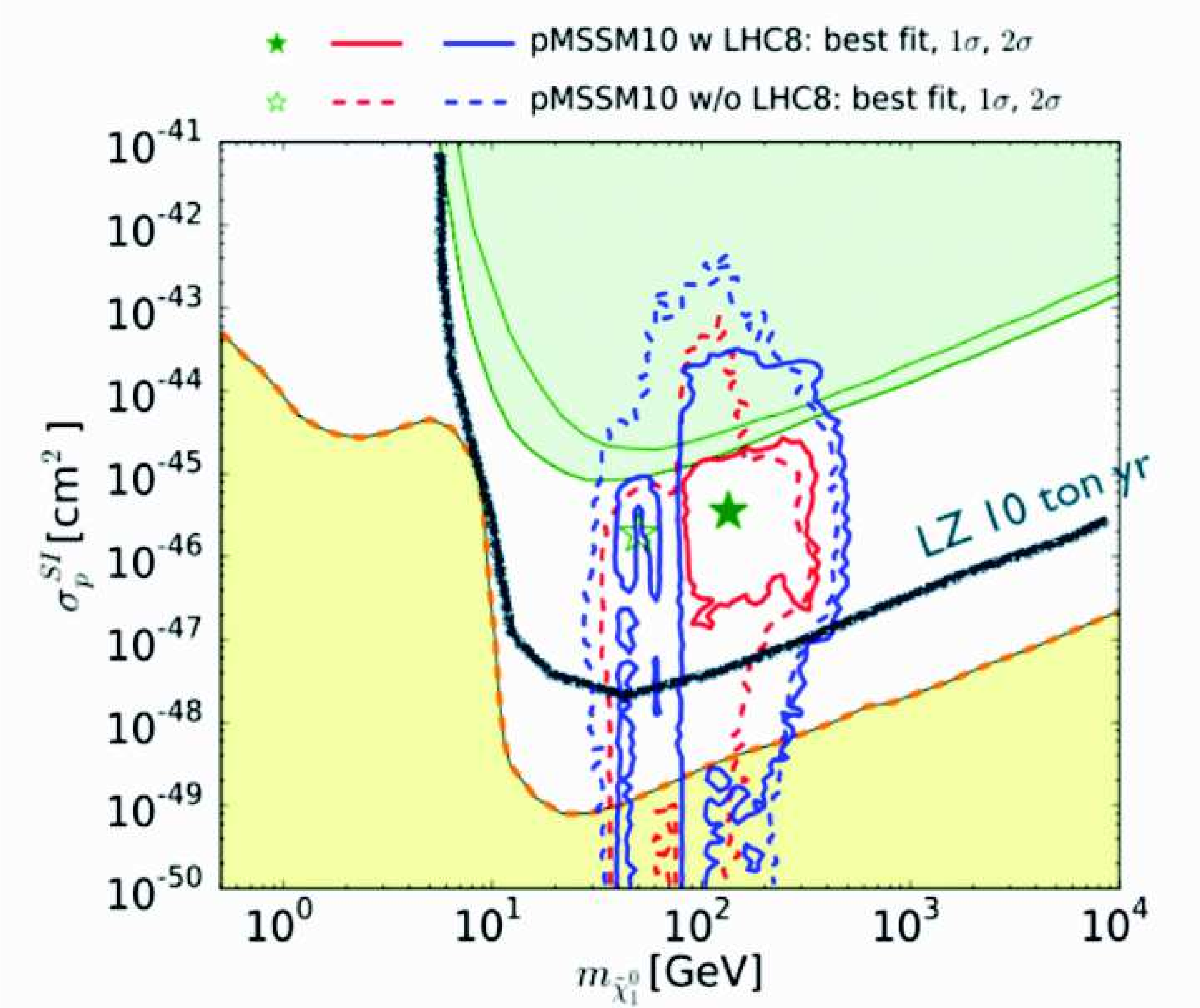
[2015]



⇒ 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

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

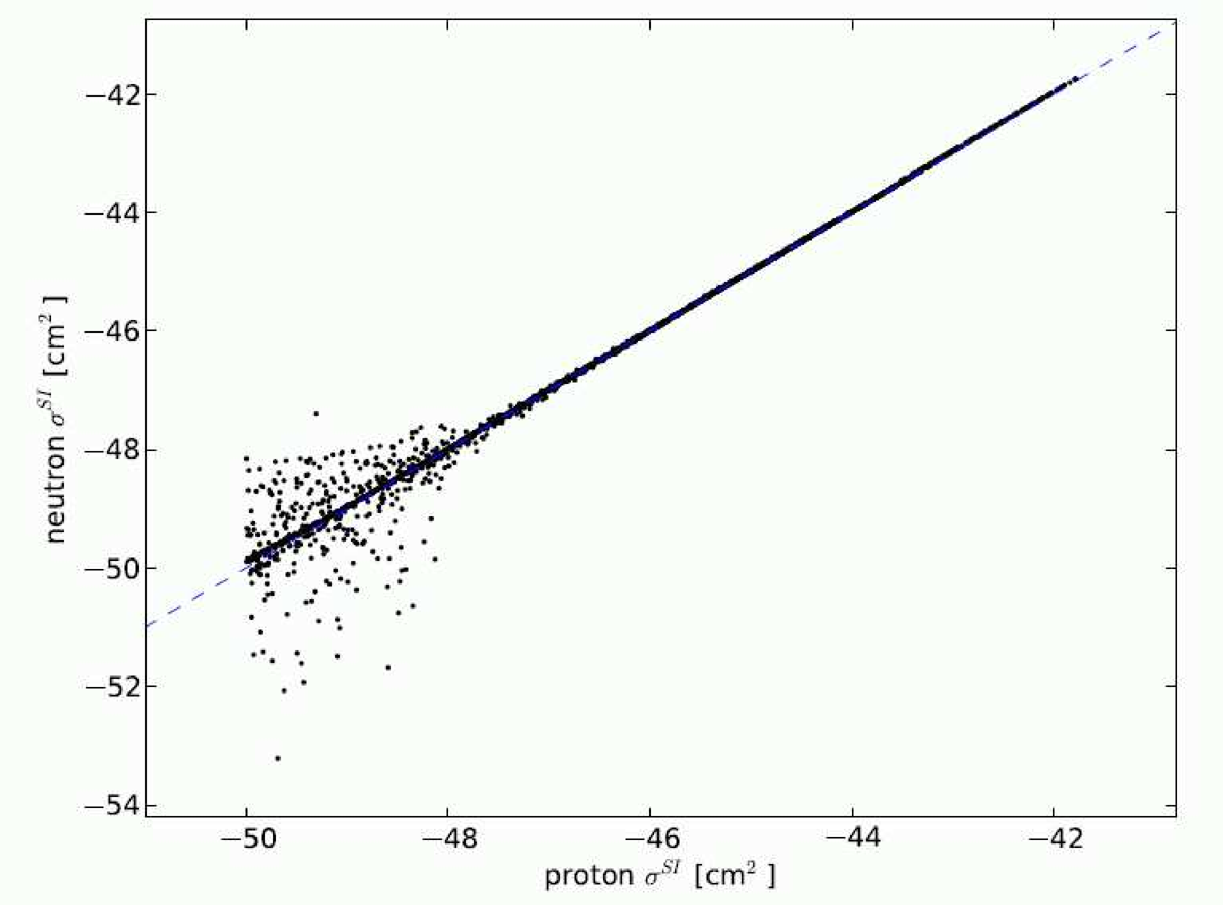
[2015]

σ_p^{SI} is evaluated for p-scattering

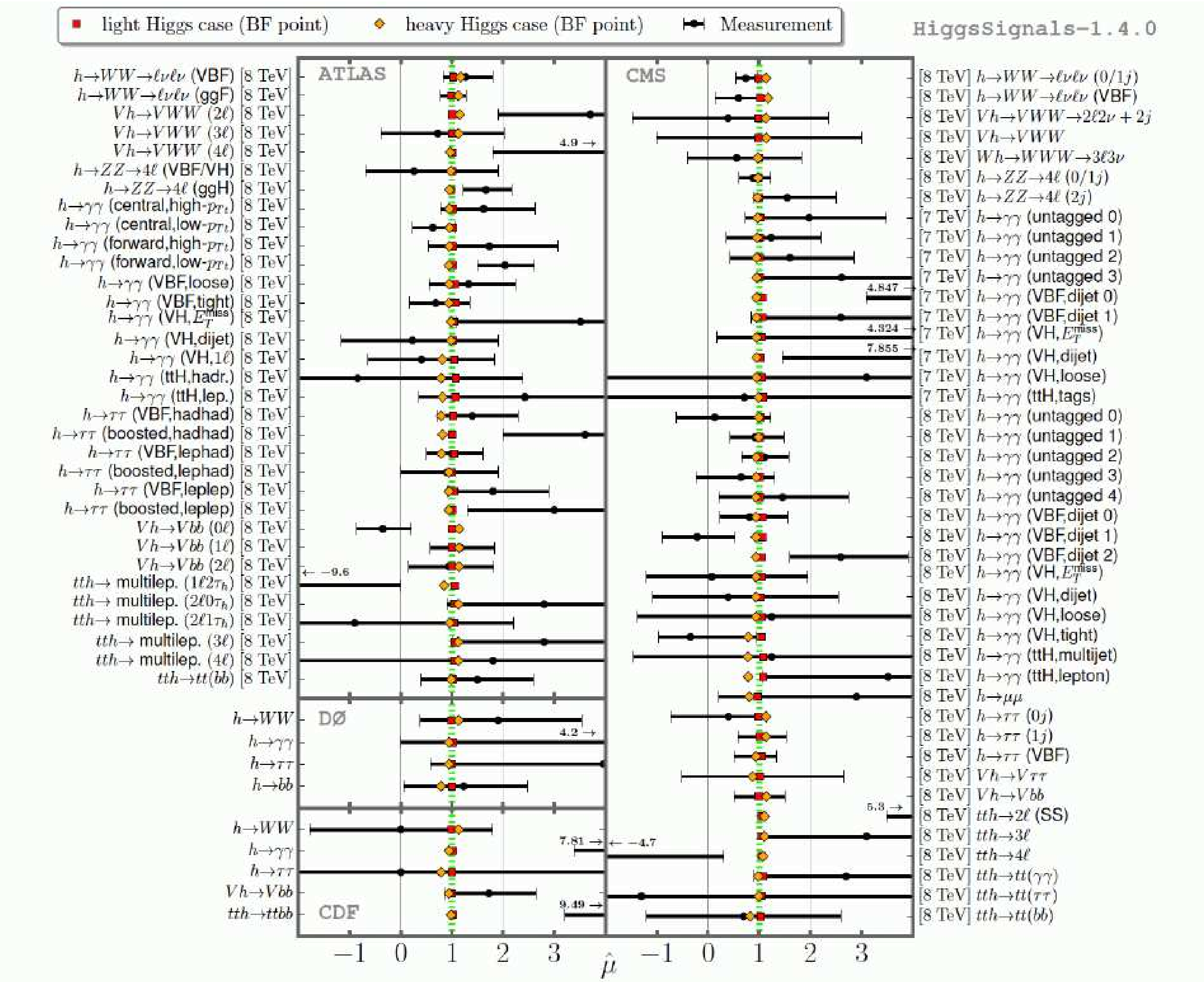
Can n-scattering come to rescue?

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

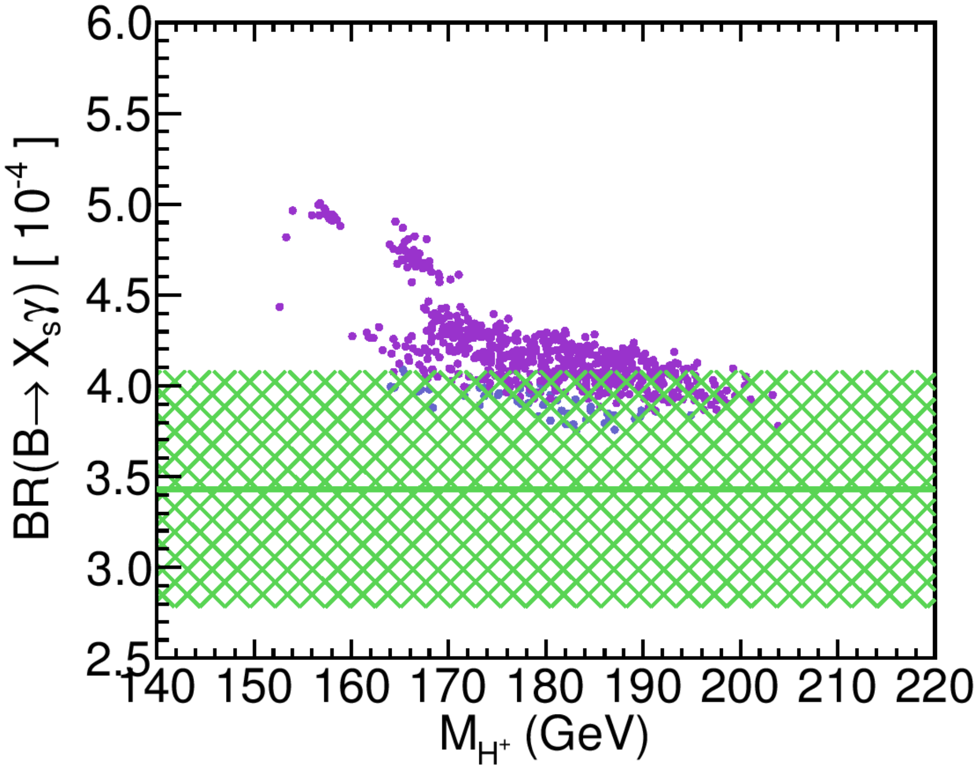
$\Rightarrow$ no "no-lose theorem" for DD experiments!

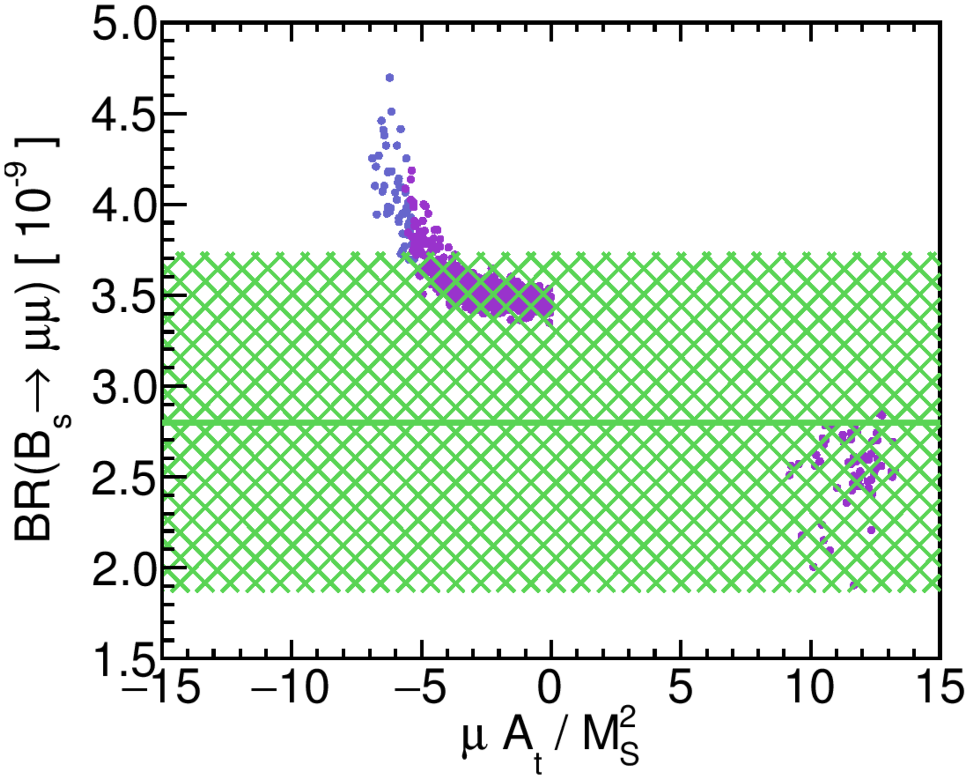


Best-fit point rates in the two Higgs cases:



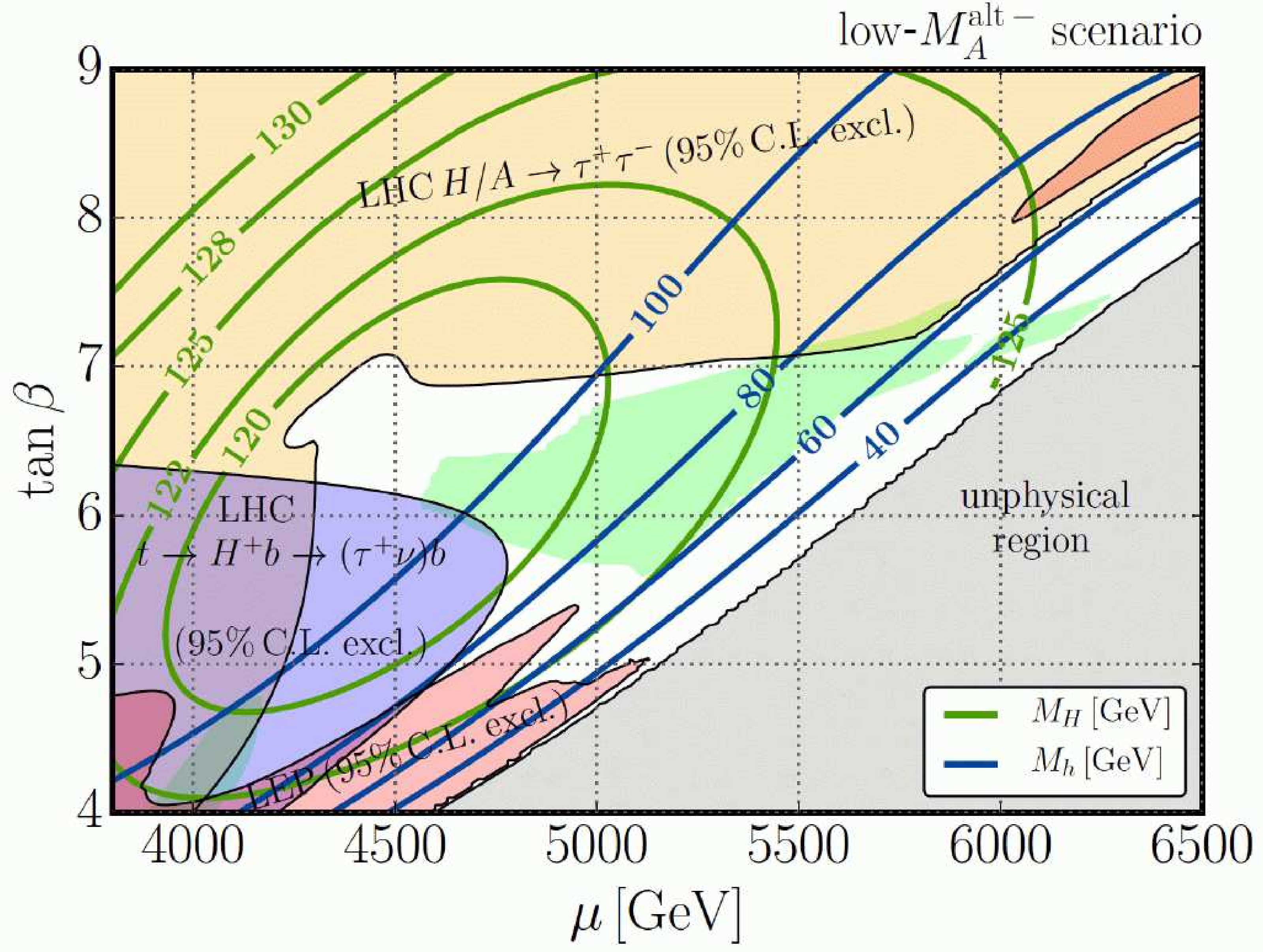
B-physics constraints?





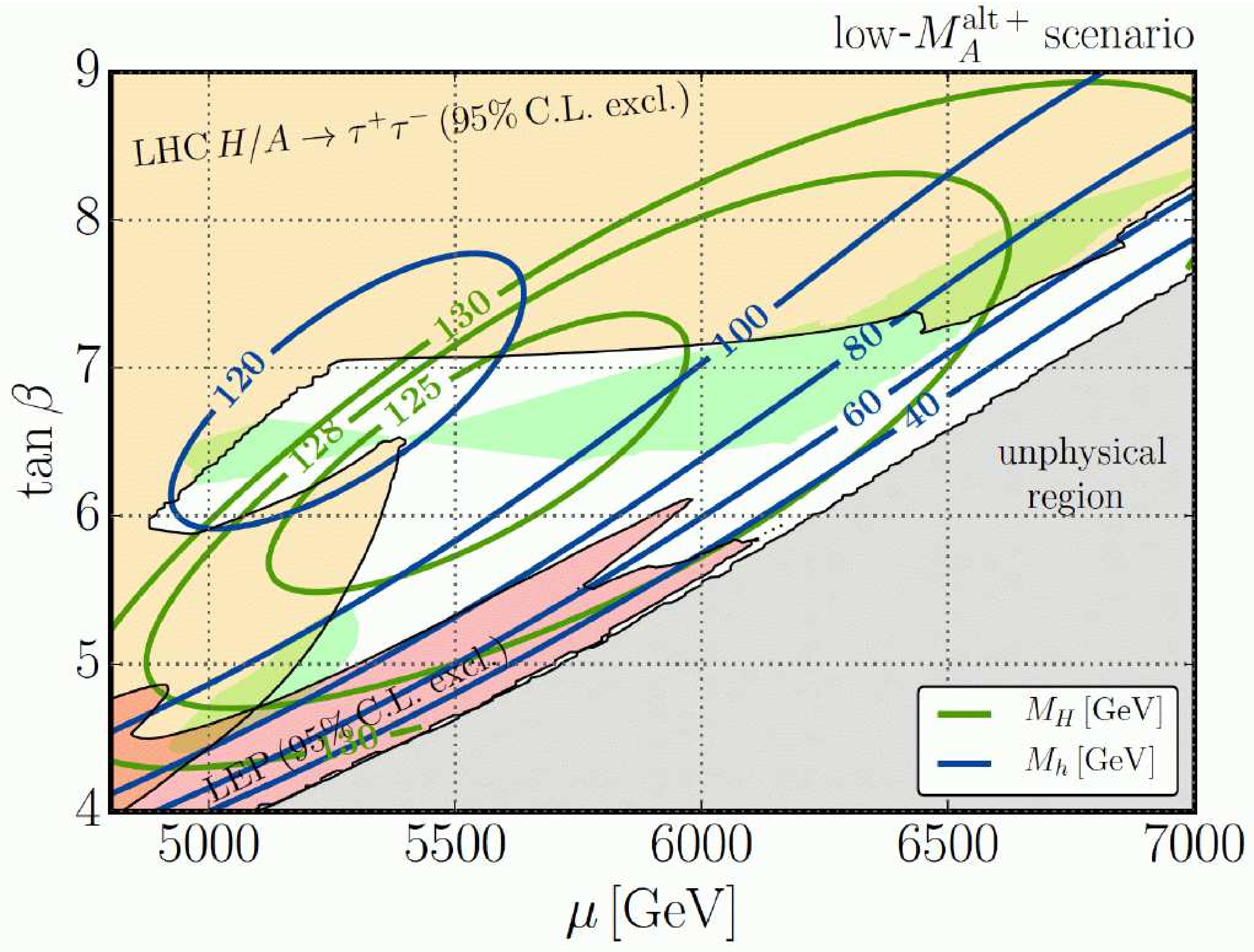
⇒ flavor constraints fulfilled!

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



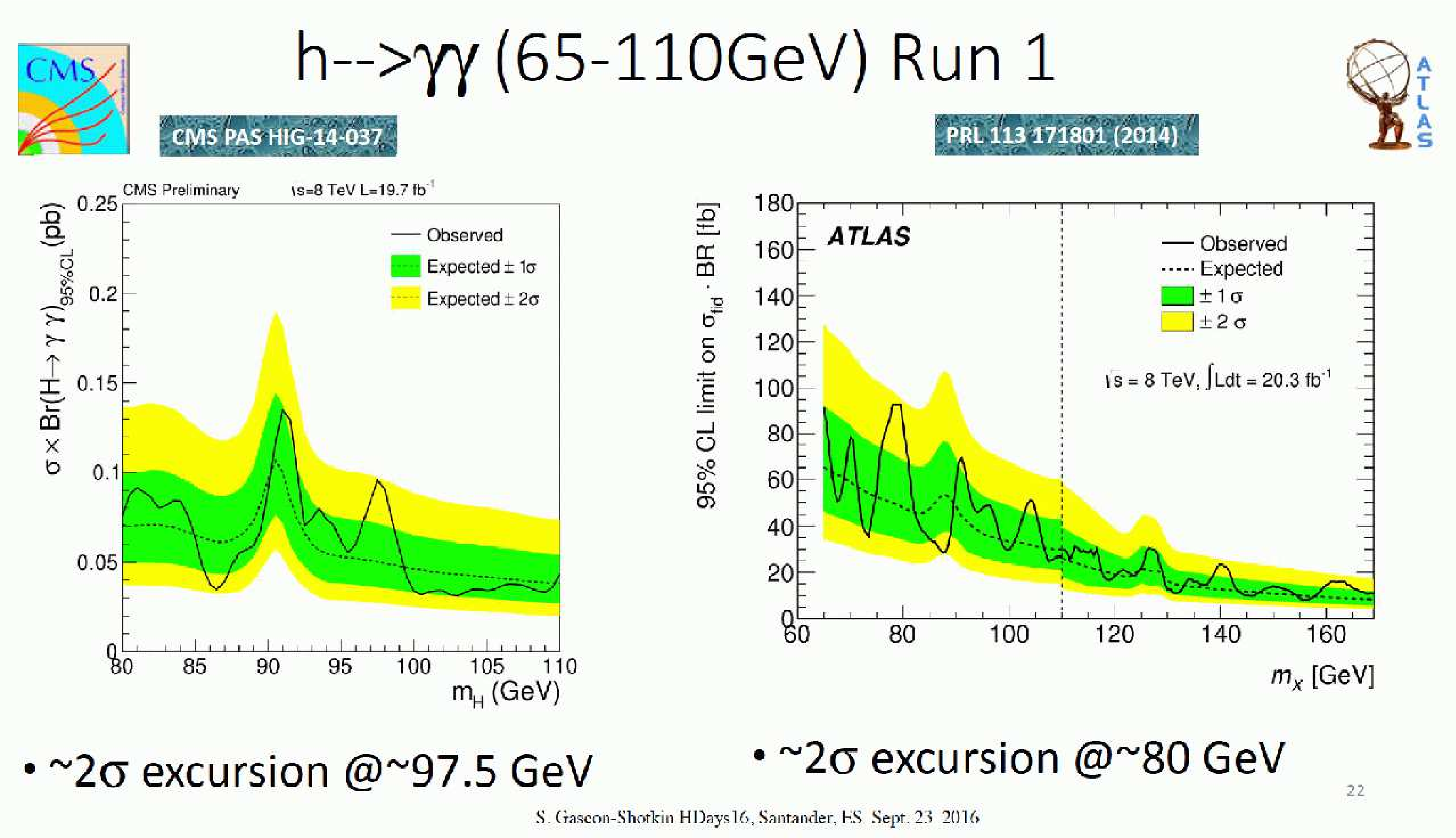
⇒ green area in agreement with all data!

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



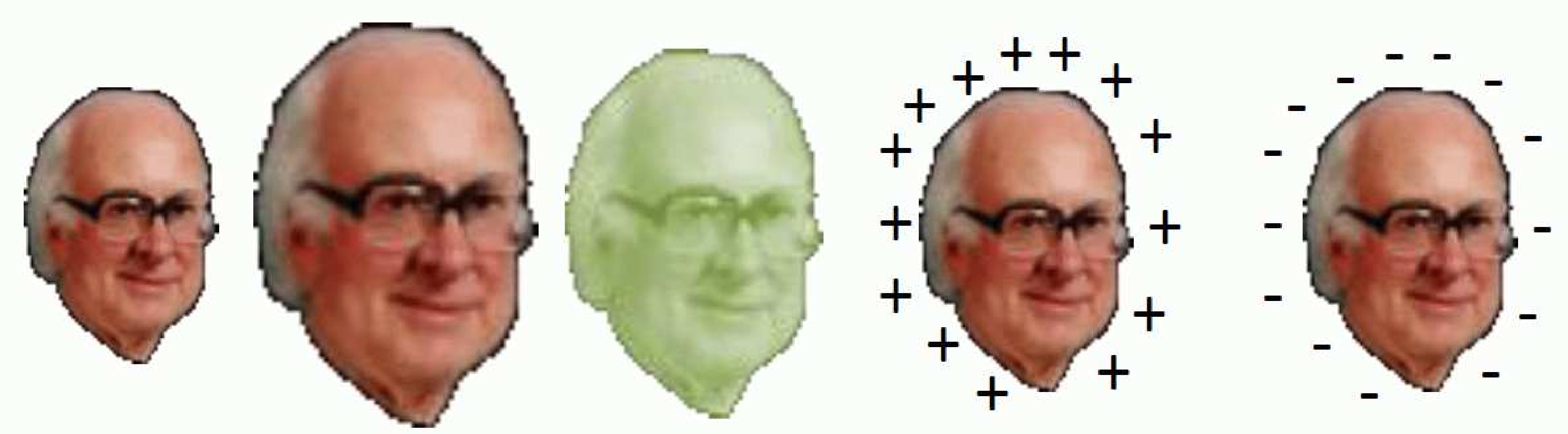
$\Rightarrow$ green area in agreement with all data! $M_H \sim M_h \sim 125$ GeV possible!

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



$\Rightarrow$ no sensitivity yet!

Results in the NMSSM



Some NMSSM Higgs theory (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

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

Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

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

Free parameters:

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

Higgs spectrum:

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

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)

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

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 $B_\text{eff} = A_\lambda + \kappa\, v_s,\ \mu_\text{eff} = \lambda\, v_s$ $\Rightarrow$ 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)

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

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

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

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

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

Mass of the charged Higgs:

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

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

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

Interesting case: light singlet

Singlet does not couple to SM particles!

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"Easily" possible in the NMSSM:

Light, singlet-like Higgs below 125 GeV

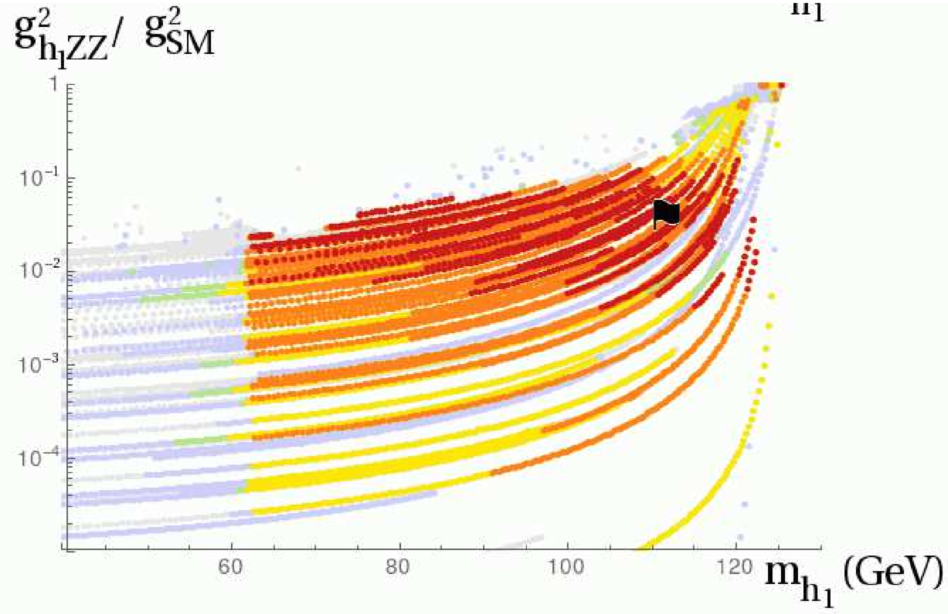
Can the LHC find them?

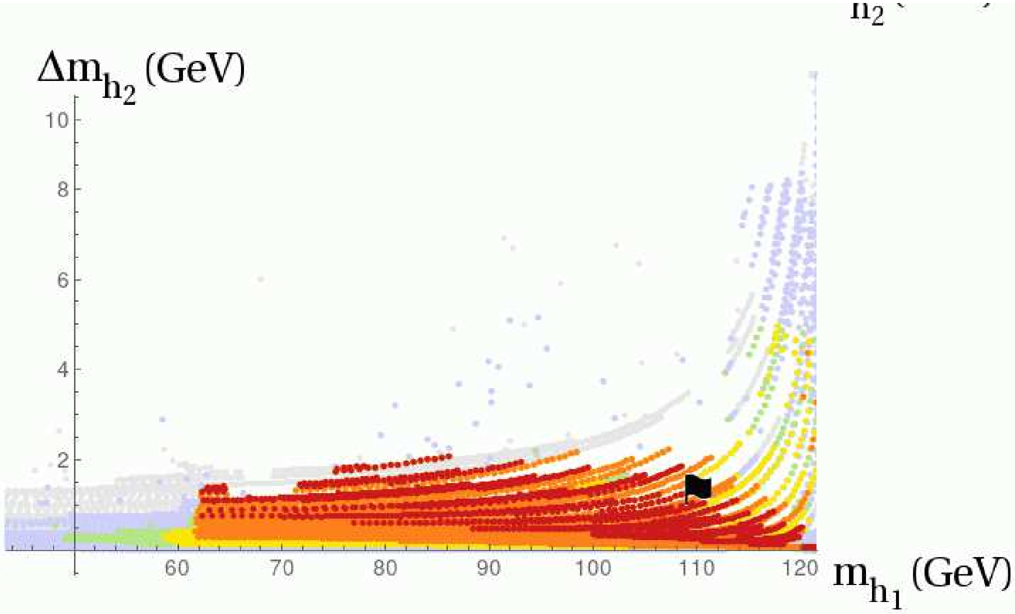
NMSSM parameter scan:

[*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!

Parameters:

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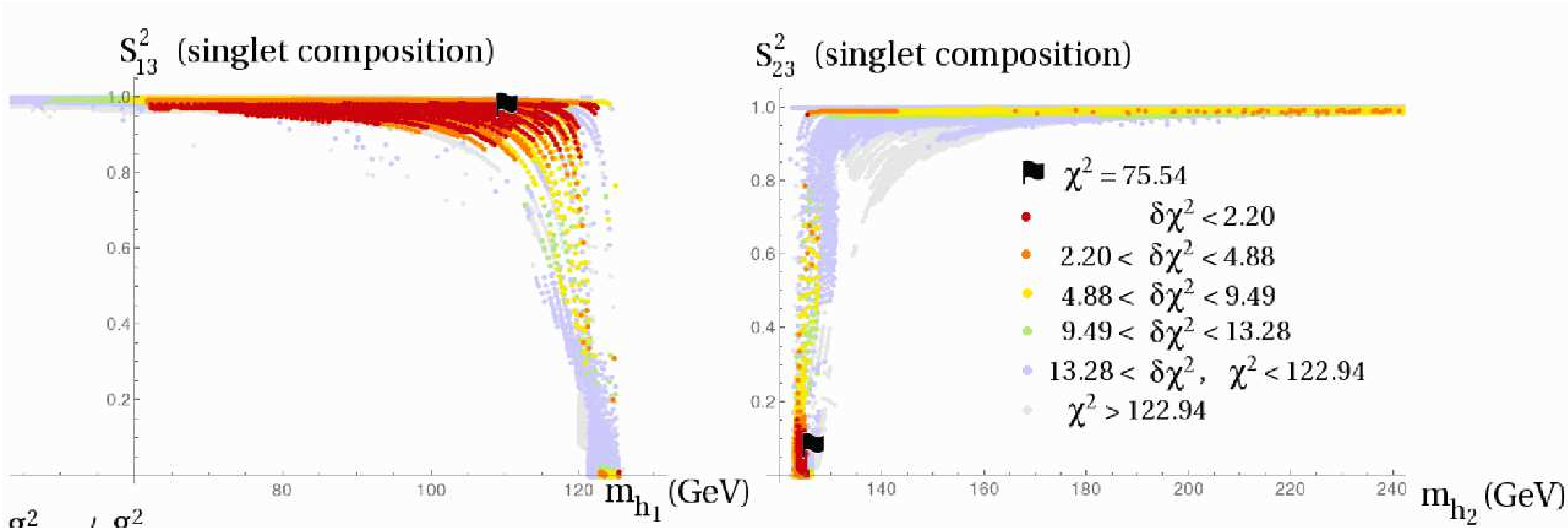

⇒ light Higgs below 125 GeV has large singlet component

⇒ second Higgs is SM-like