"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!"

BSM Higgs Bosons at the HL/HE-LHC

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

CERN, 06/2018

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Theory Status I

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1. Why it is not the SM Higgs
2. BSM Higgs Bosons above 125 GeV
3. BSM Higgs Bosons below 125 GeV
4. BSM Higgs Boson at 125 GeV
5. Conclusions

BSM Higgs Bosons at the HL/HE-LHC

More Questions than Answers

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

CERN, 06/2018

1. Why it is not the SM Higgs

2. BSM Higgs Bosons above 125 GeV

3. BSM Higgs Bosons below 125 GeV

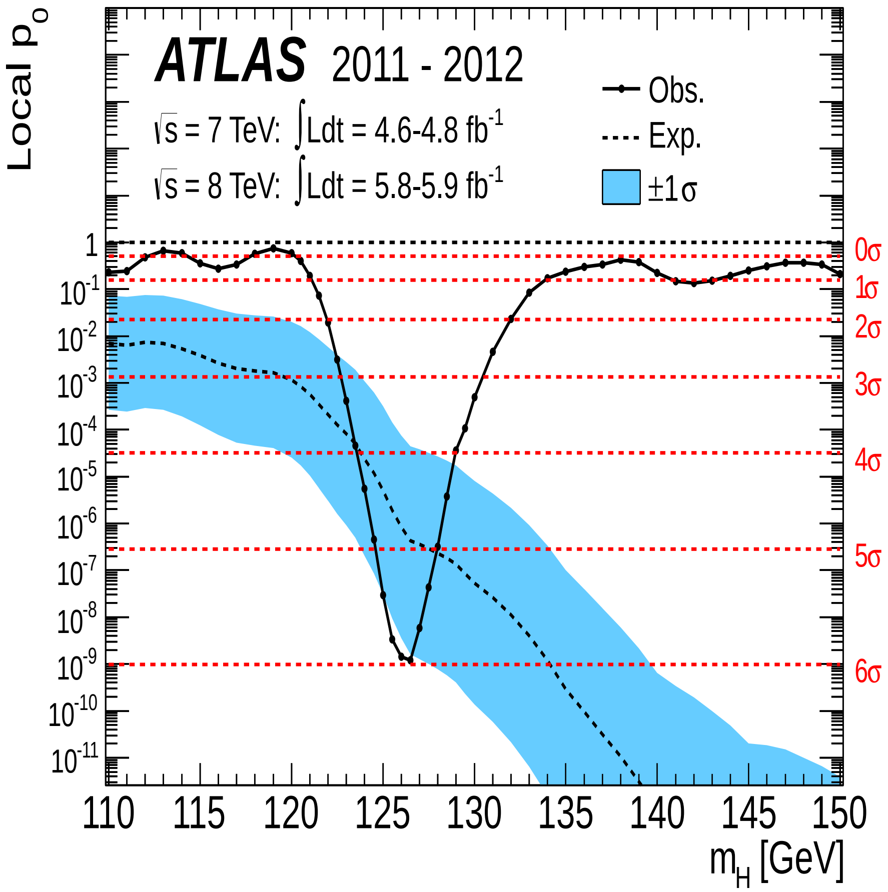
4. BSM Higgs Boson at 125 GeV

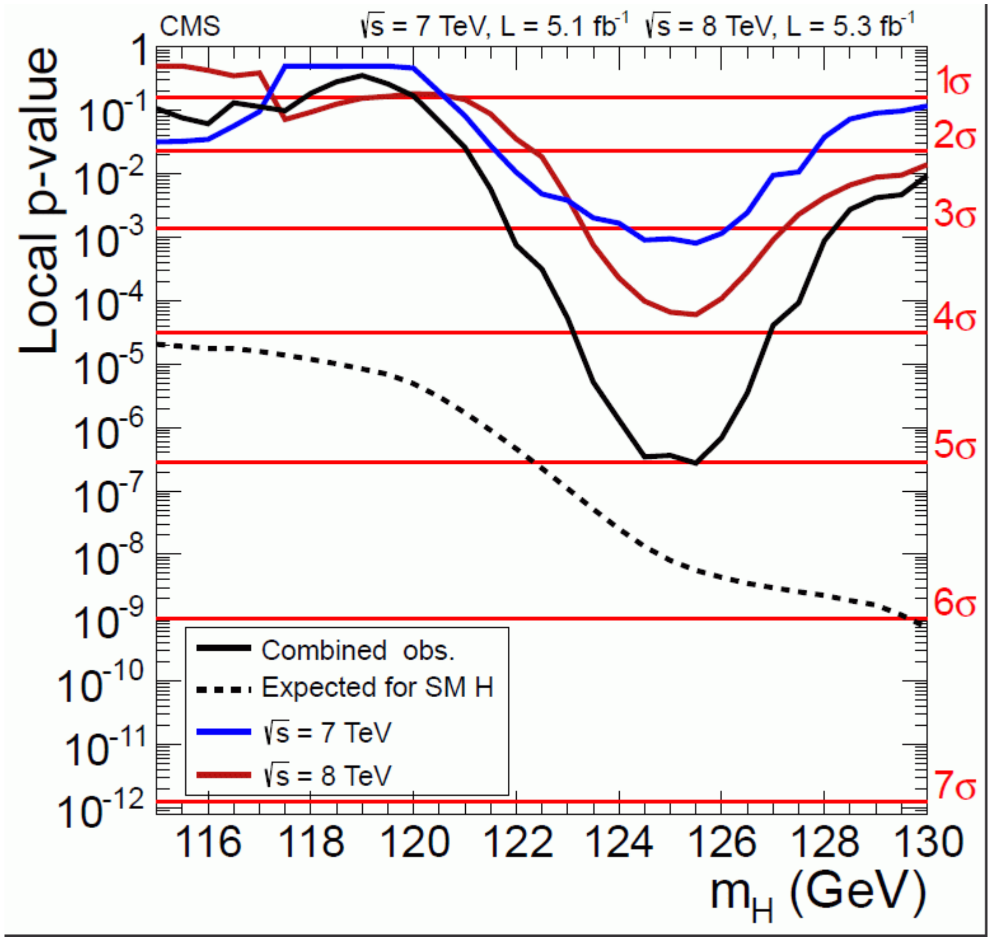
5. Conclusions

1. Why it is not the SM Higgs

Fact I:

We have a discovery!

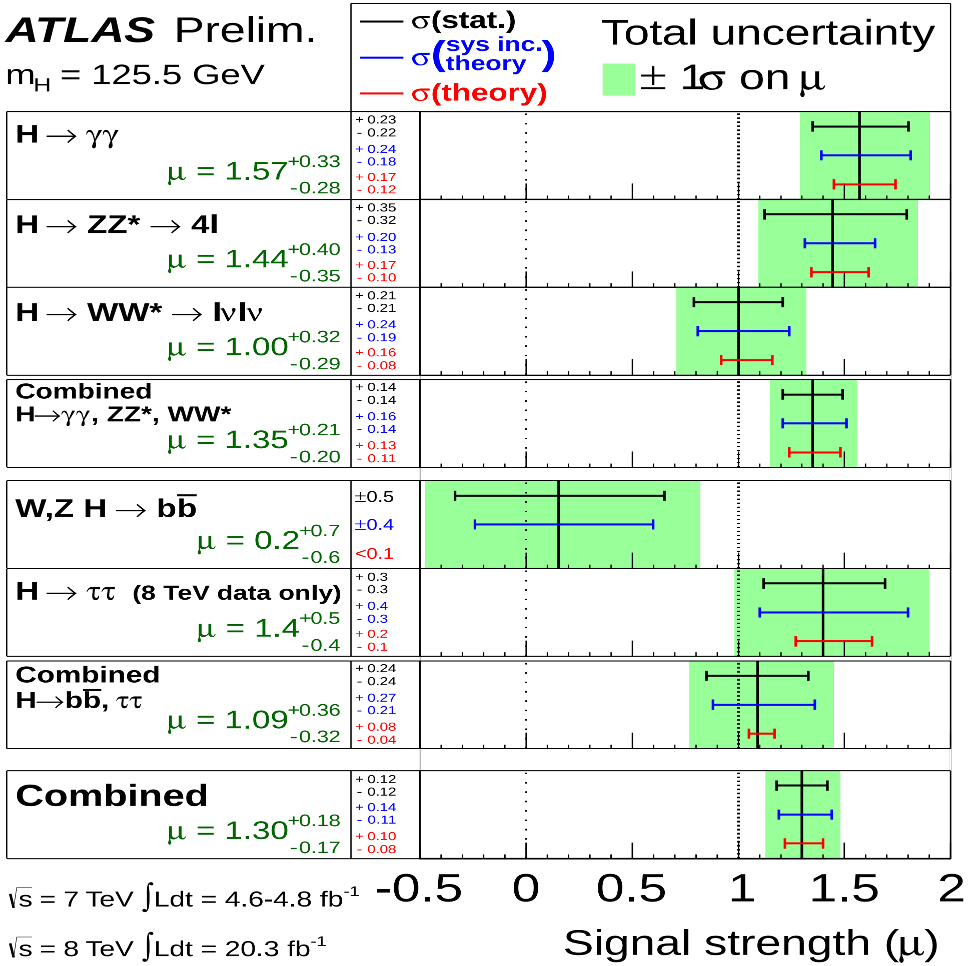


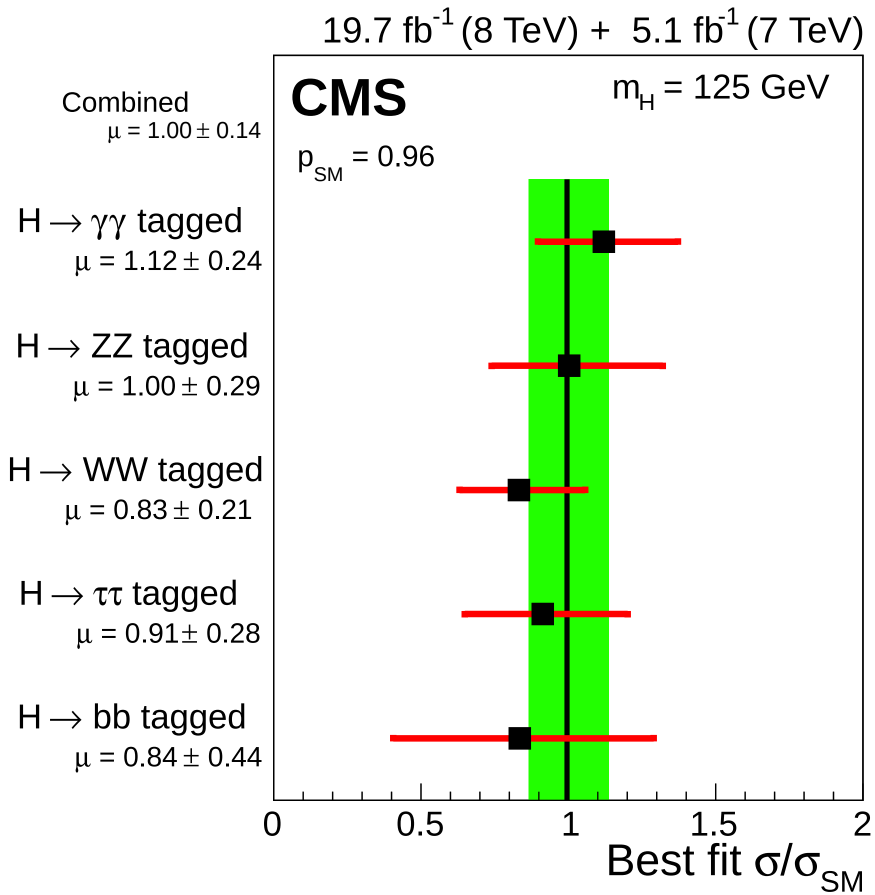


1. Why it is not the SM Higgs

Fact I:

We have an SM-like discovery!





Fact II:

The SM cannot be the ultimate theory!

Some facts:

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

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

A1: check changed properties

A2: check for additional Higgs bosons
A2': check for additional Higgs bosons above and below 125 GeV

The main questions:

- What are the couplings of this particle to other known elementary particles? Is its coupling to each particle proportional to that particles mass, as required by the BEH mechanism?

- What are the mass, total width, spin and $\mathcal{CP}$ properties of this particle? Are there additional sources of $\mathcal{CP}$ violation in the Higgs sector?

- What is the value of the particles self-coupling? Is this consistent with the expectation from the symmetry-breaking potential?

- Is this particle a single, fundamental scalar as in the SM, or is it part of a larger structure? Is it part of a model with additional scalar singlets/doublets/ldots?
  Or, could it be a composite state, bound by new interactions?

- Does this particle couple to new particles with no other couplings to the SM ("Higgs portal")? Is the particle mixed with new scalars of exotic origin, for example, the radion of extra-dimensional models?

$\Rightarrow$ What can be done at the LHC Run 3, at the HL-LHC, at the HE-LHC?

Models with extended Higgs sectors:

1. SM with addional Higgs singlet
2. Two Higgs Doublet Model (THDM): type I, II, III, IV
3. Minimal Supersymmetric Standard Model (MSSM)
4. MSSM with one extra singlet (NMSSM)
5. MSSM with more extra singlets
6. SM/MSSM with Higgs triplets
7. ...

$\Rightarrow$ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

$\Rightarrow$ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

Extended Higgs sectors

Compatibility with the experimental results requires:

- A SM-like Higgs at ~ 125 GeV
- Properties of the other Higgs bosons (masses, couplings,...) have to be such that they are in agreement with the present bounds

Prediction for the mass of the SM-like Higgs vs. exp. result:

- Important constraints on parameter space of the model
- Limited by remaining theoretical uncertainties
- Very accurate Higgs-mass predictions needed

The "sum rule":

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a ``sum rule":

$$\sum_i g^2_{H_i VV} = \left(g^{\mathrm{SM}}_{HVV}\right)^2$$

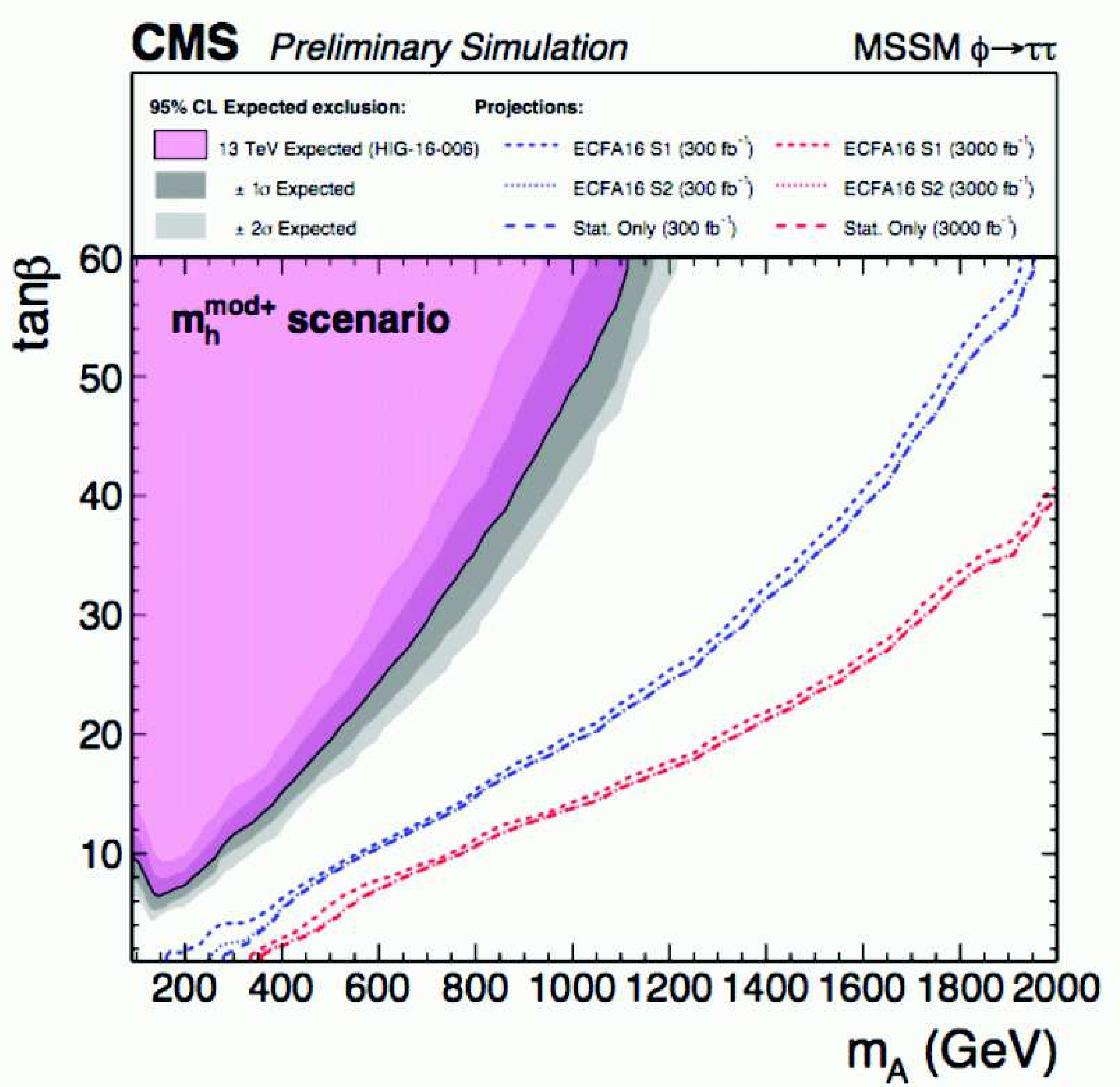
⇒ •The SM coupling strength is ``shared" between the Higgses of an extended Higgs sector, $\varkappa_V \leqq 1$

•The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons; heavy Higgses usually have a much smaller width than a SM-like Higgs of the same mass

• Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!

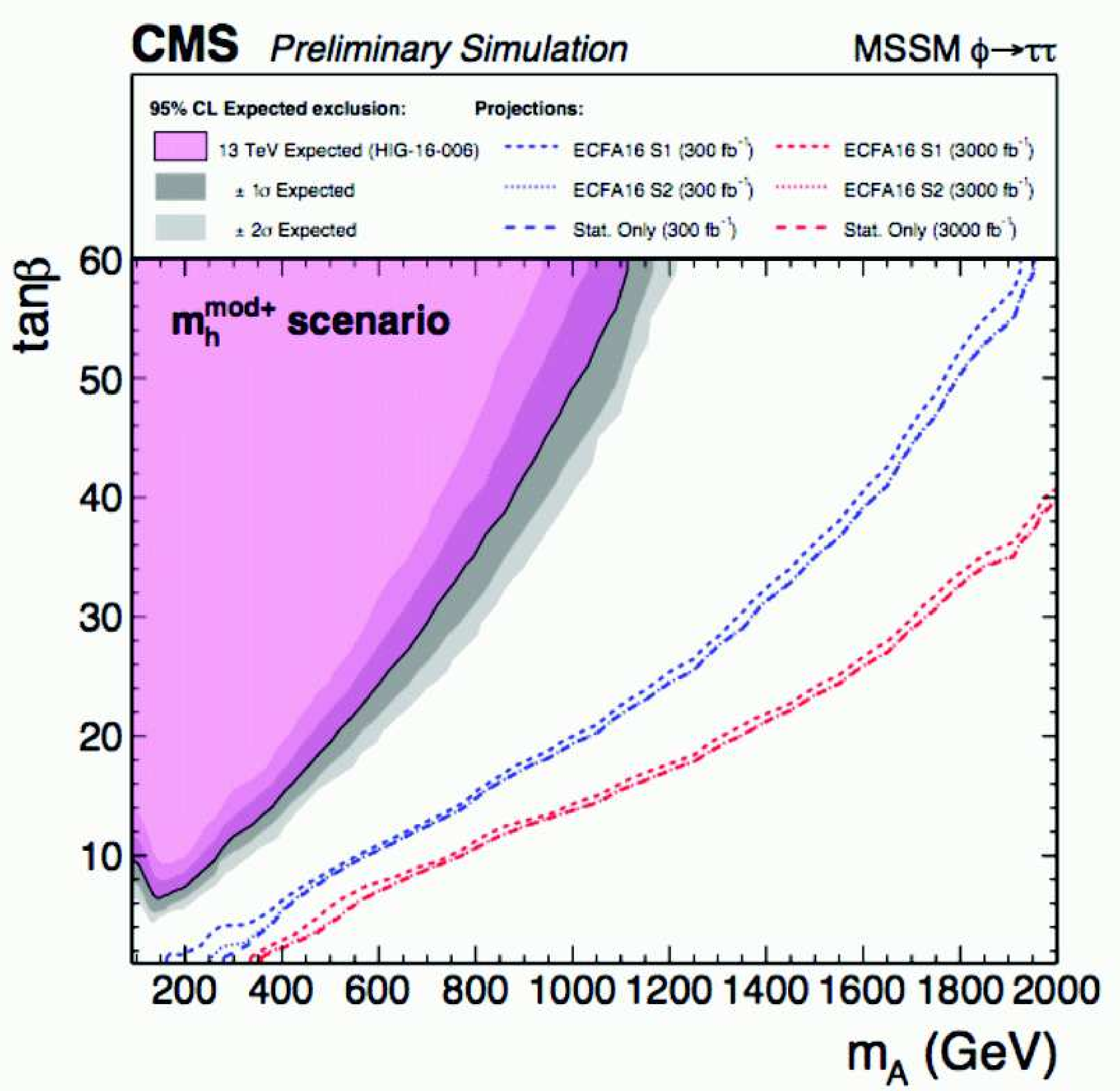
[*Taken from G. Weiglein '18*]

2. BSM Higgs Bosons above 125 GeV



$\Rightarrow$ strong (HL-)LHC limits

2. BSM Higgs Bosons above 125 GeV



⇒ strong (HL-)LHC limits

Do we know the HE-LHC limits?

There is more . . . (I)

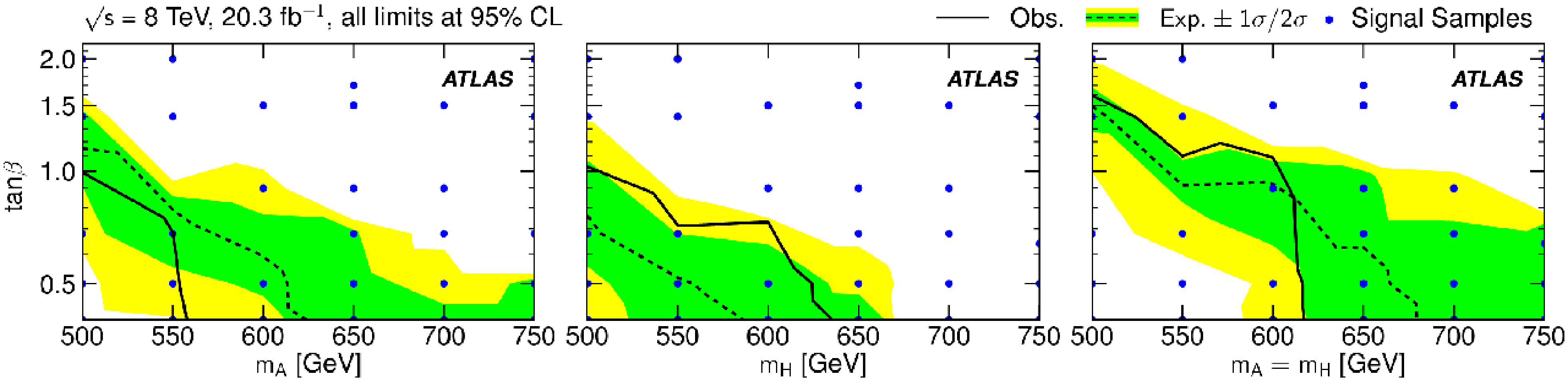
We need the HL-LHC and HE-LHC limits in:

1. SM with addional Higgs singlet
2. Two Higgs Doublet Model (THDM): type I, II, III, IV
3. Minimal Supersymmetric Standard Model (MSSM)
4. MSSM with one extra singlet (NMSSM)
5. MSSM with more extra singlets
6. SM/MSSM with Higgs triplets
7. . . .

⇒ covered? After this workshop (series)? ToDo?!

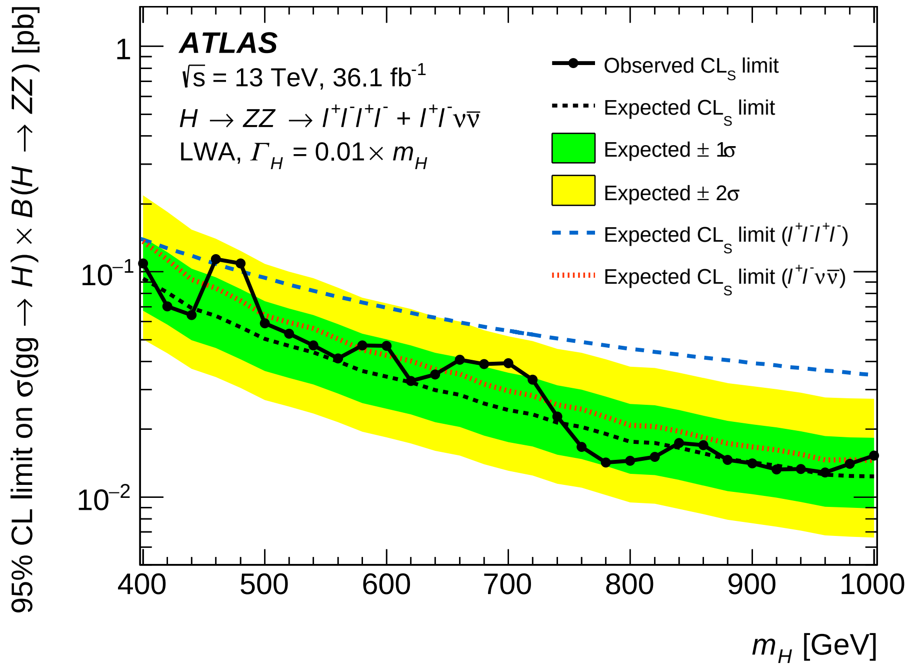
There is more . . . (II)

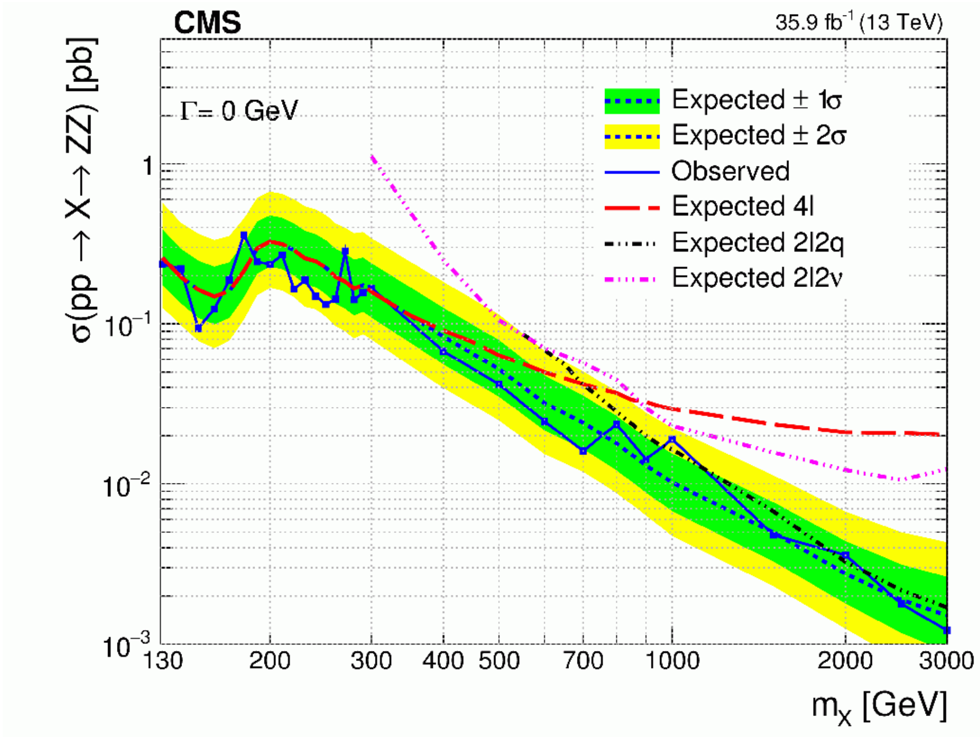
What about the $t\bar{t}$ mode/limits?



We need the HL-LHC and HE-LHC limits! ToDo?!

$gg \to \Phi \to ZZ/WW?$





Remember the sum rule: $\sum_i g^2_{H_iVV} = (g^{\rm SM}_{HVV})^2$

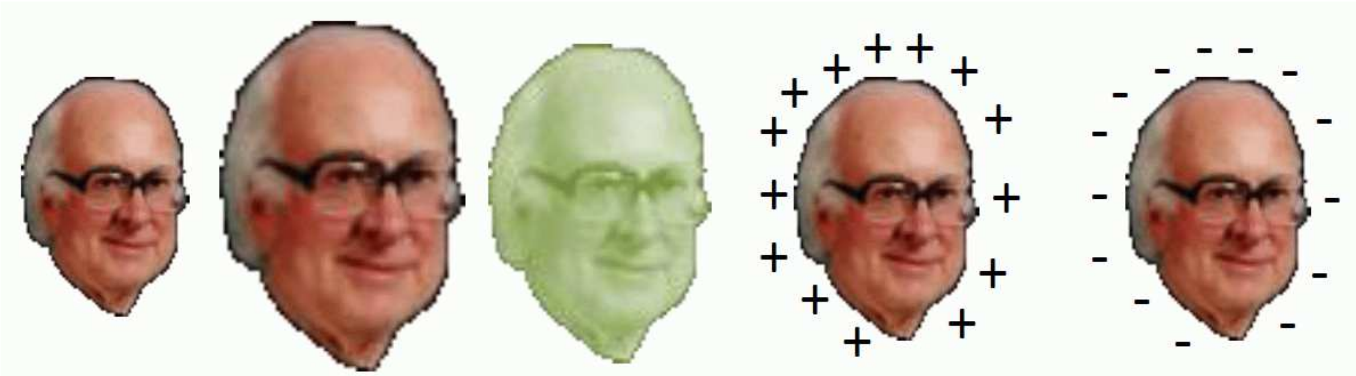
How far down in $g^2_{H_iVV}$ can the HL-LHC or HE-LHC go? ToDo?!

Are there any realistic models with such a high M_Φ?

"Such a high" = beyond Run 3
but possibly in the reach of HL-LHC or HE-LHC ?

A couple of examples:

– CMSSM, NUHM1, NUHM2
– mAMSB
– SU(5) MSSM
– sub-GUT
– pMSSM11
– Finite Unified Theory (FUT)
– . . .



Tool for combined SUSY/Higgs analysis: MasterCode

⇒ collaborative effort of theorists and experimentalists

[Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Liu, Lucio, Martinez Santos, Olive, Richards, Sakurai, Weiglein]

Über-code for the combination of different tools:

– Über-code original in Fortran, now re-written in C++

– tools are included as subroutines

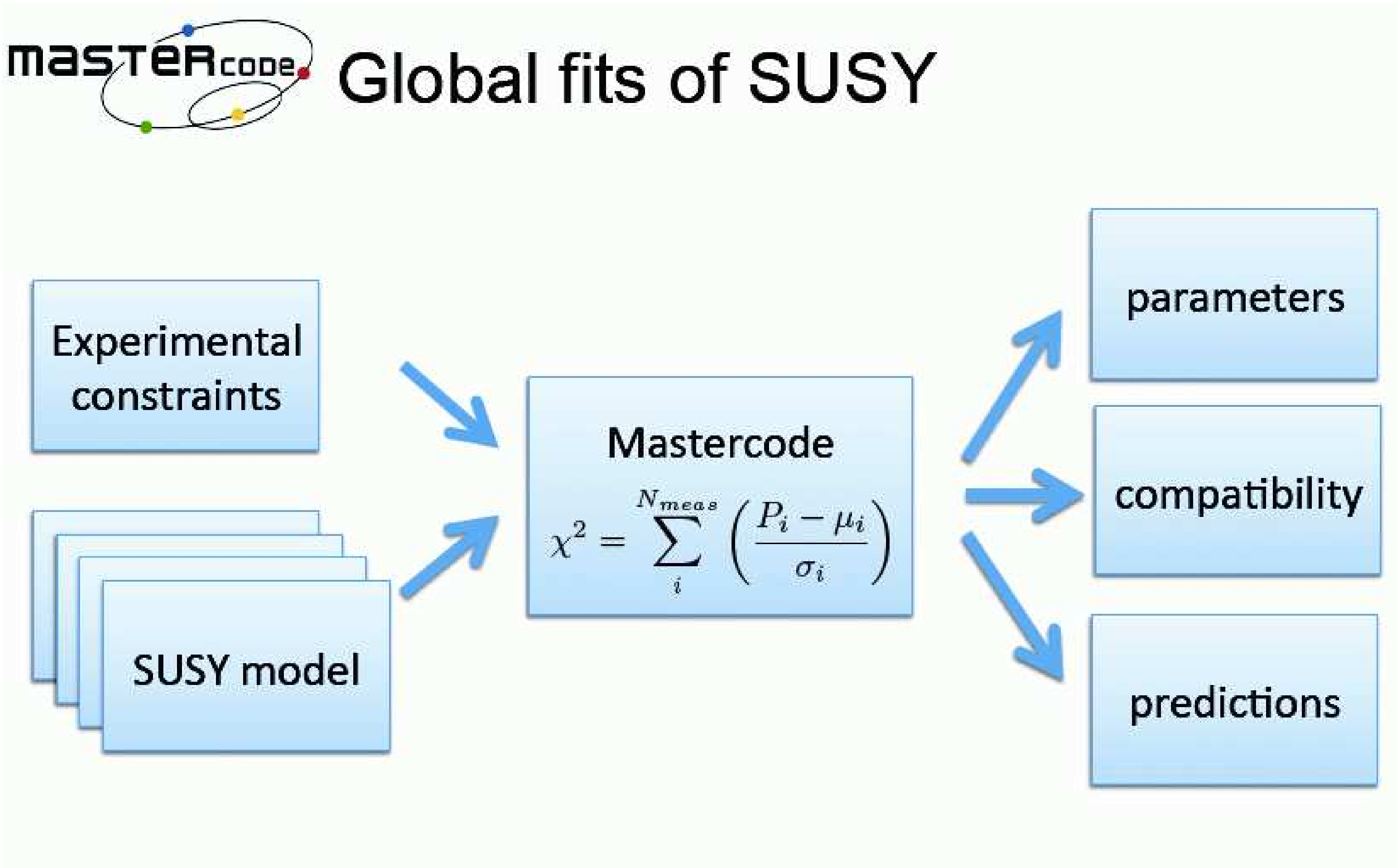
– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)

– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

The χ^2 evaluation:



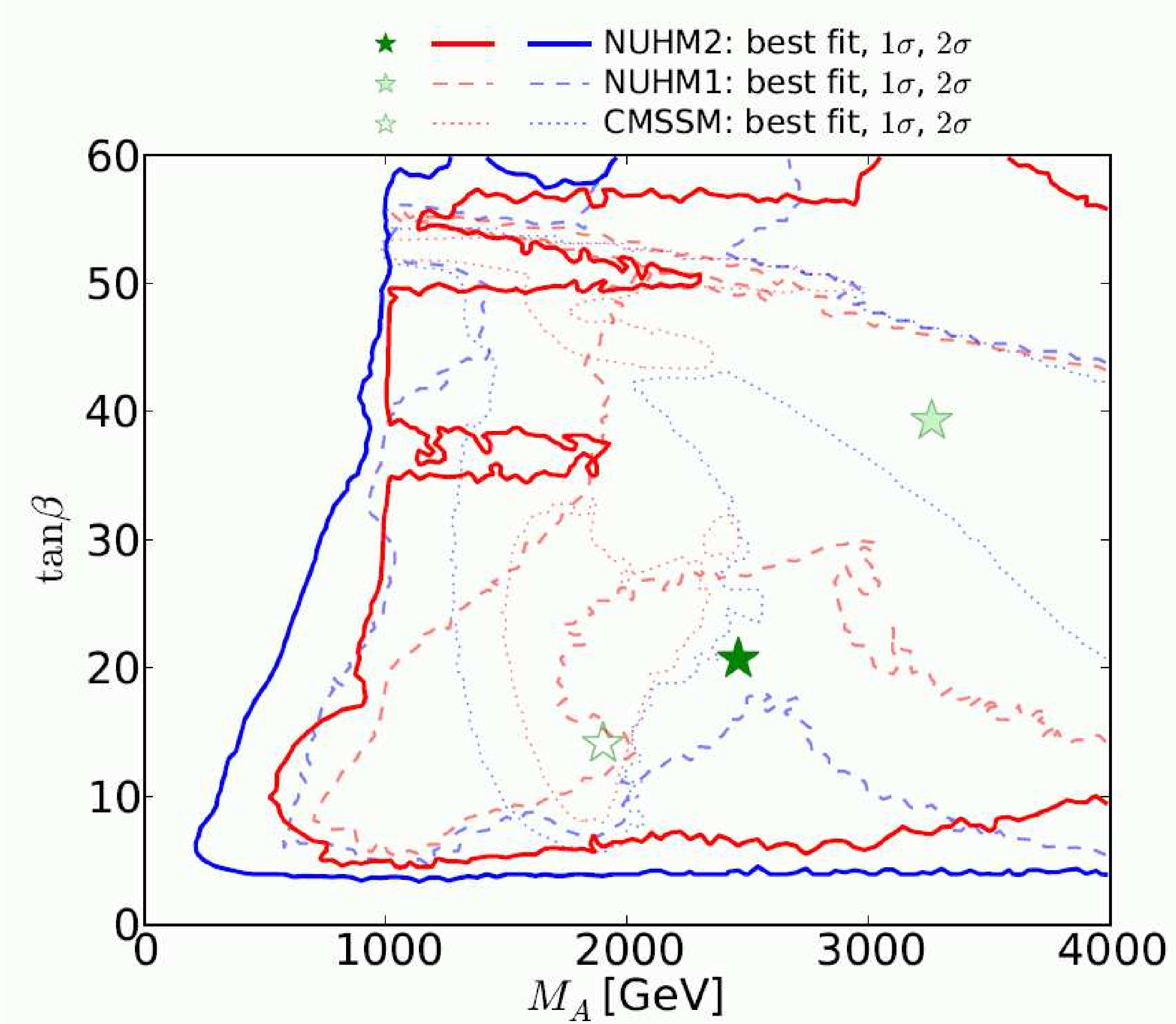
Data we have:

- Higgs boson mass (LHC) ⇒ FeynHiggs
- Higgs boson signal strengths (LHC) ⇒ HiggsSignals
- Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds
- SUSY searches (LHC) ⇒ own re-cast (Fastlim approach)

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

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

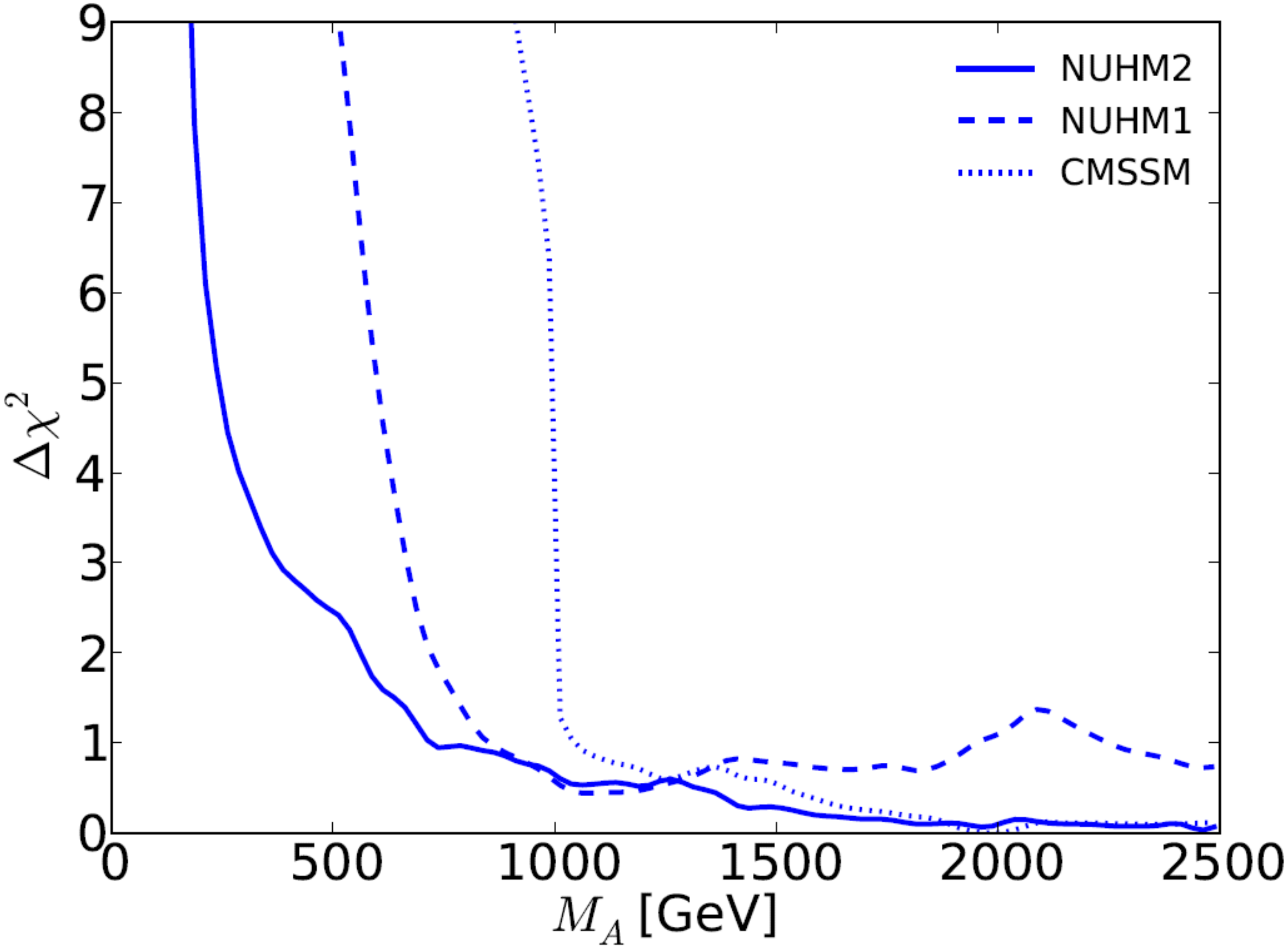
[2015]



⇒ high masses natural - partially covered by HL/HE-LHC

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

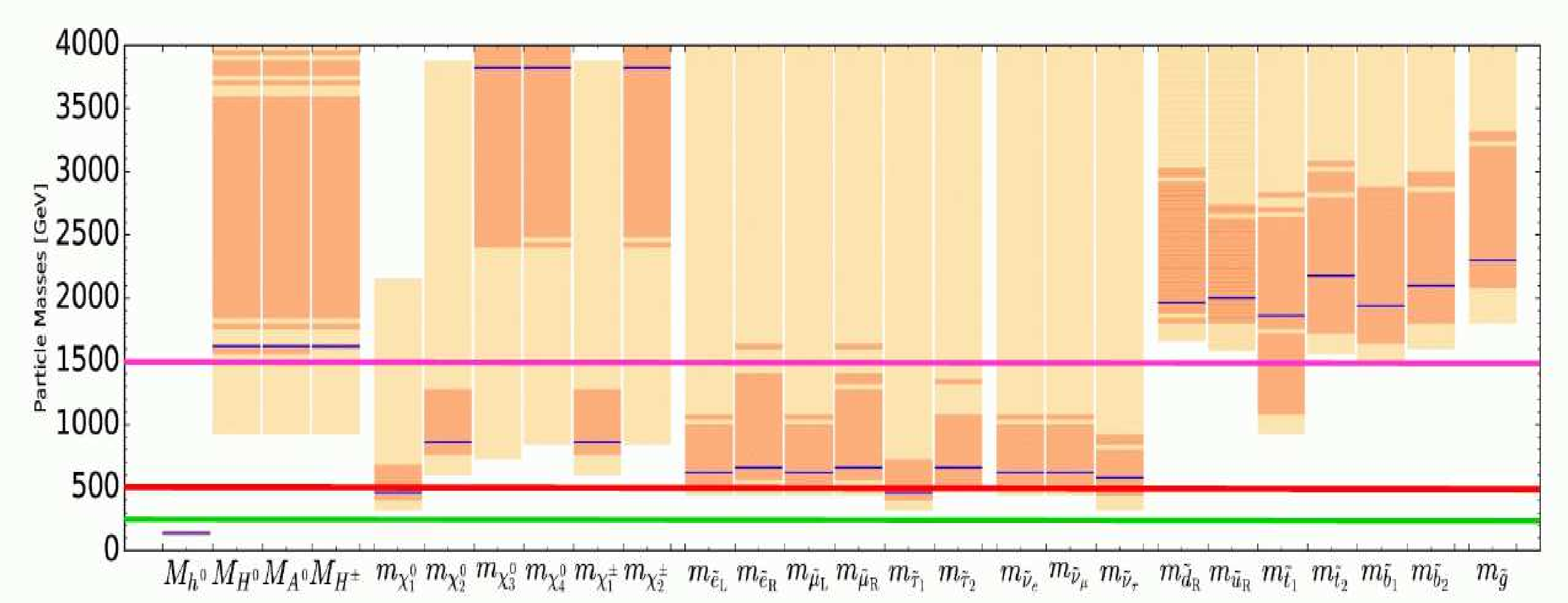
[2015]



$\Rightarrow$ high masses natural - partially covered by HL/HE-LHC

SU(5) prediction: best-fit masses

[2016]

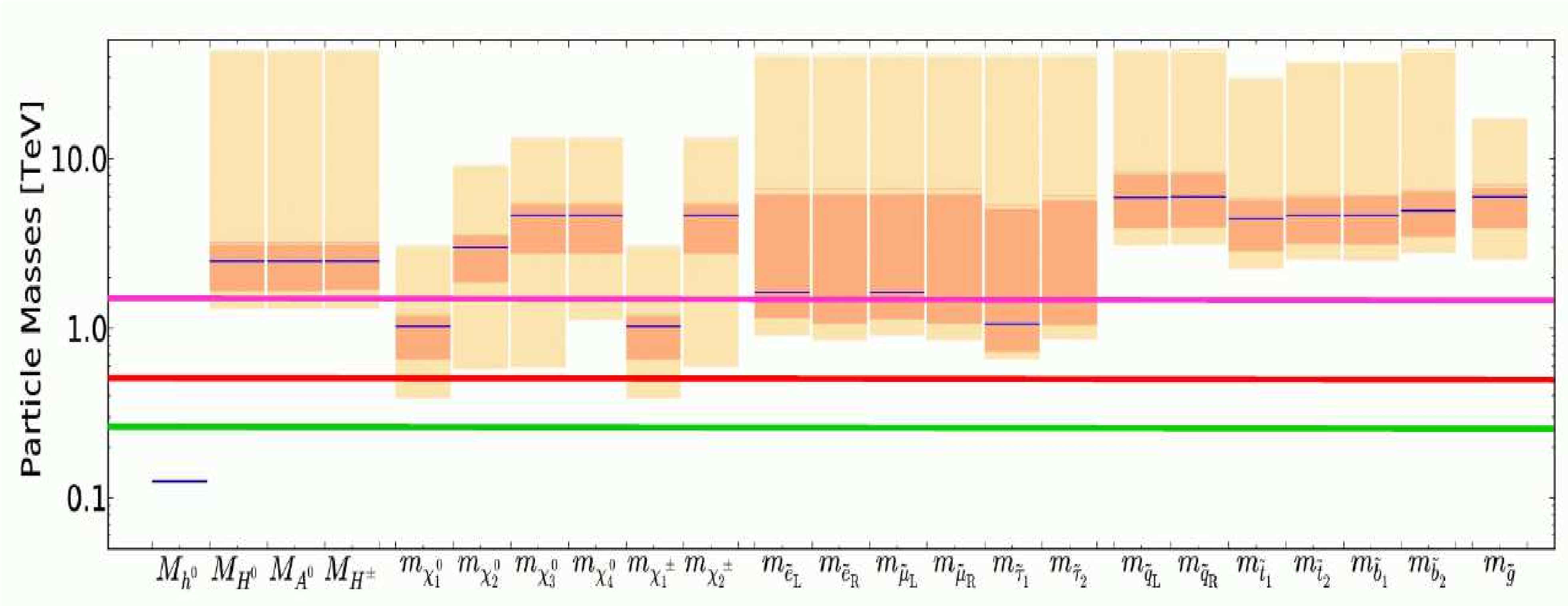


⇒ high masses natural - partially covered by HL/HE-LHC

⇒ $1\,\sigma$ ranges covered by HE-LHC?

mAMSB prediction: best-fit masses (wino)

[2016]

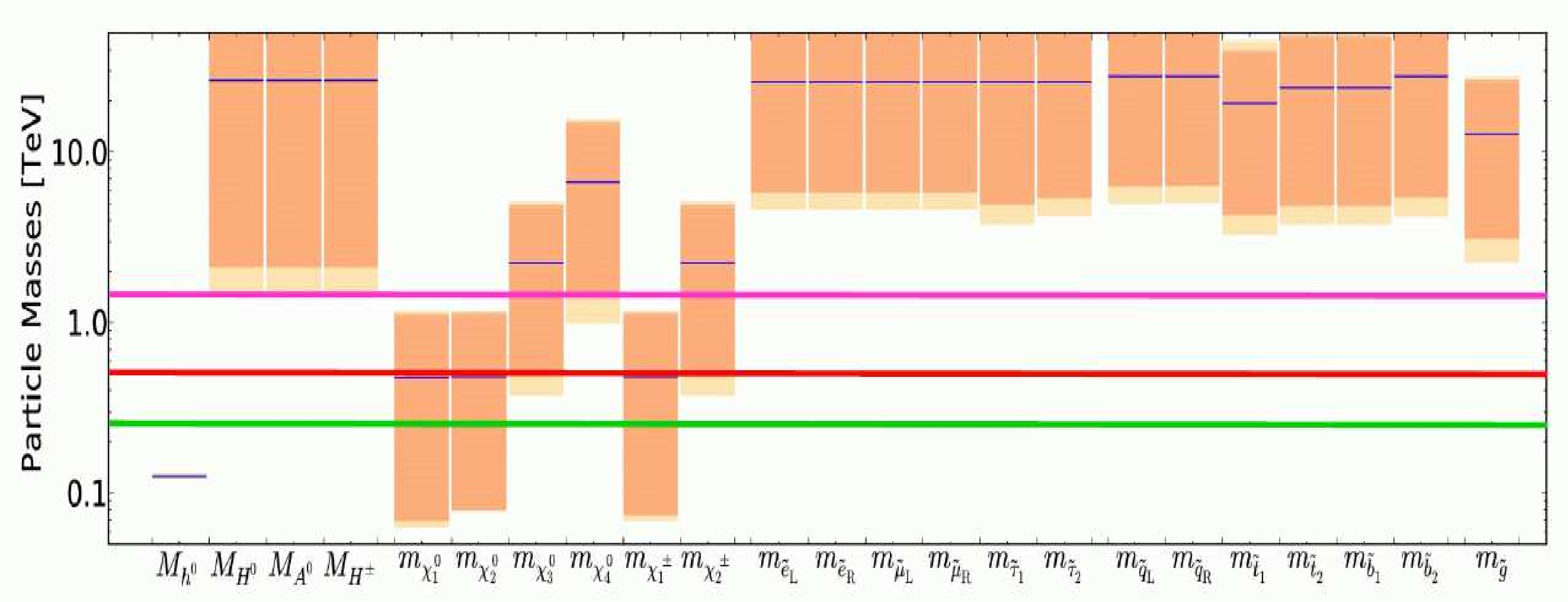


⇒ high masses natural - partially covered by HL/HE-LHC

⇒ $1\,\sigma$ ranges covered by HE-LHC?

mAMSB prediction: best-fit masses (higgsino)

[2016]

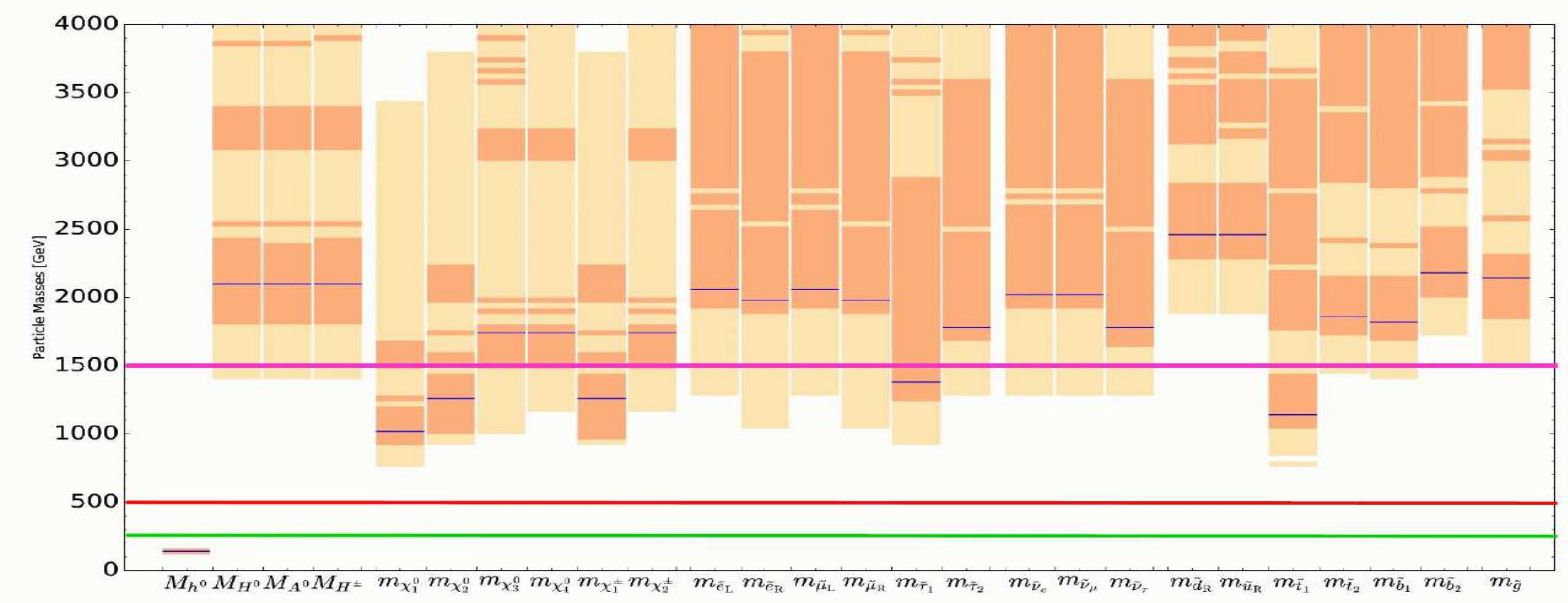


$\Rightarrow$ high masses natural - partially covered by HL/HE-LHC

$\Rightarrow$ $1\,\sigma$ ranges not covered by HE-LHC! $\rightarrow$ FCC-hh?

sub-GUT prediction: best-fit masses

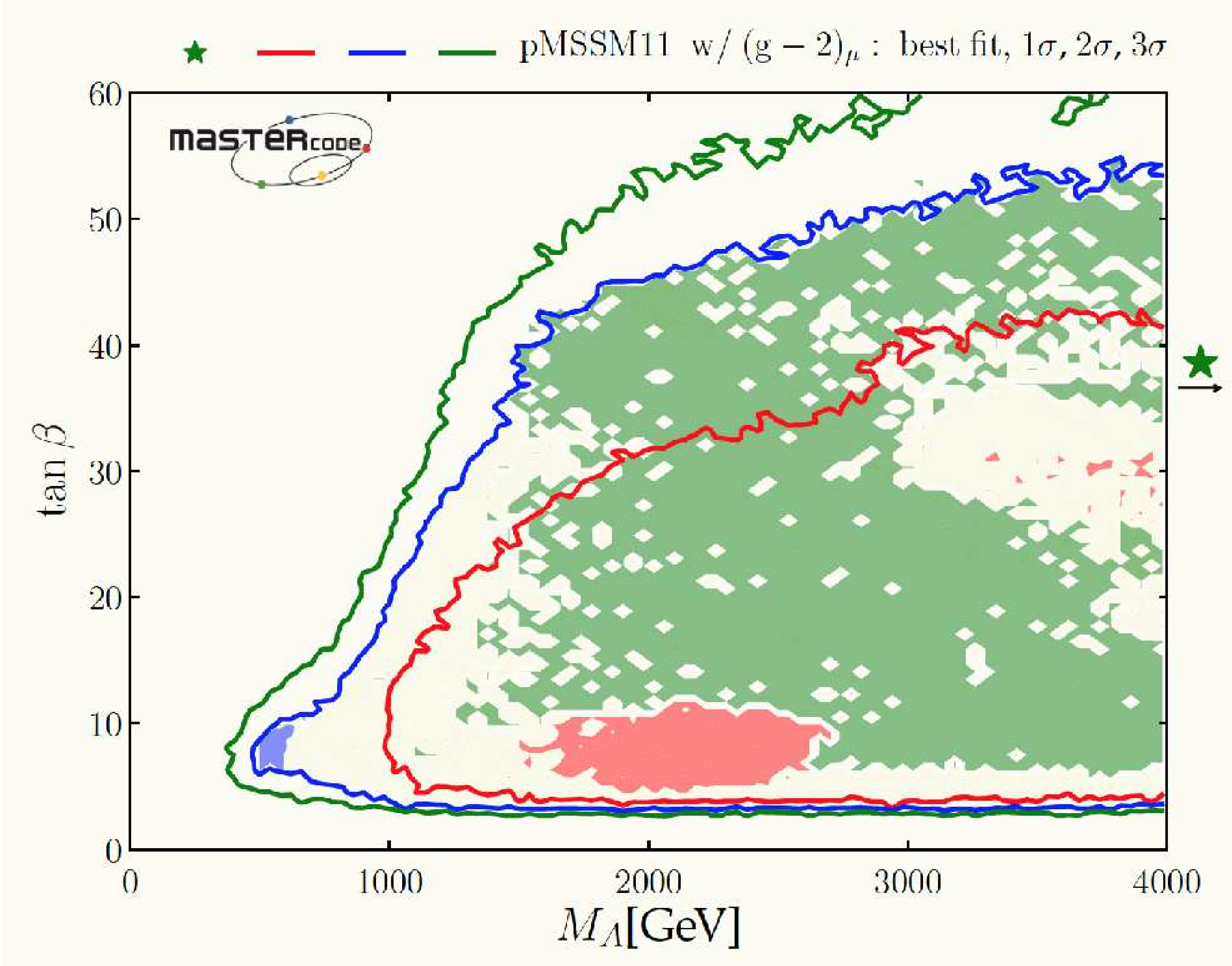
[2017]



$\Rightarrow$ high masses natural - partially covered by HL/HE-LHC

$\Rightarrow$ $1\,\sigma$ ranges covered by HE-LHC?

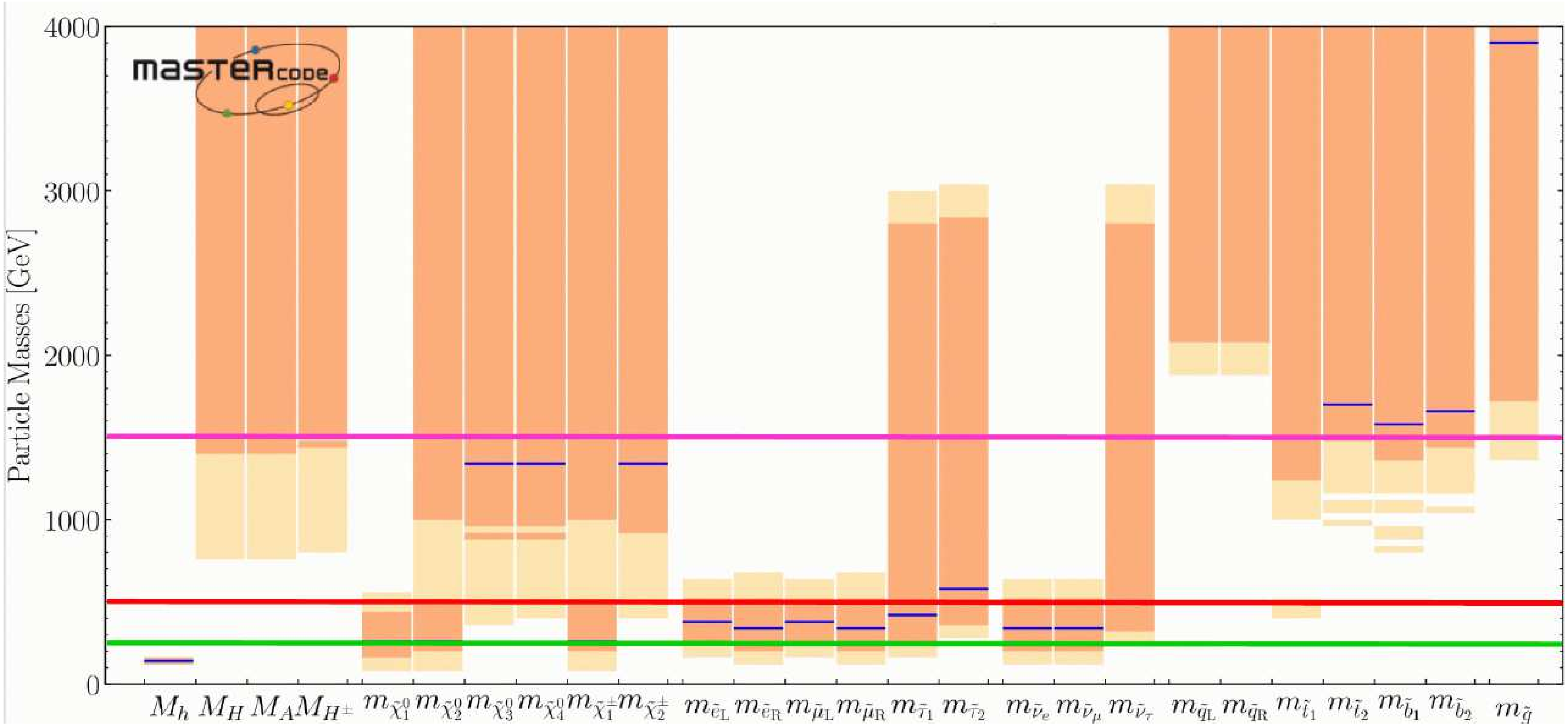
pMSSM11 prediction: M_A-$\tan\beta$ plane



$\Rightarrow$ low mass scales allowed, high mass scales favored
what can be covered by HE-LHC?

pMSSM11 prediction: best-fit masses

[2017]



⇒ high masses natural - partially covered by HL/HE-LHC

⇒ $1\,\sigma$ ranges not covered by HE-LHC

Finite Unified Theories (FUT)

[S.H., M. Mondragon, N. Tracas, G. Zoupanos '17]

Main idea of FUT:

– search for renormalization group invariant relations among parameters
– first for dimensionless parameters
– then also for dimension full (soft SUSY breaking) parameters
– leads to "required" relations among the parameters
– so far restricted for (s)fermions to 3rd generation

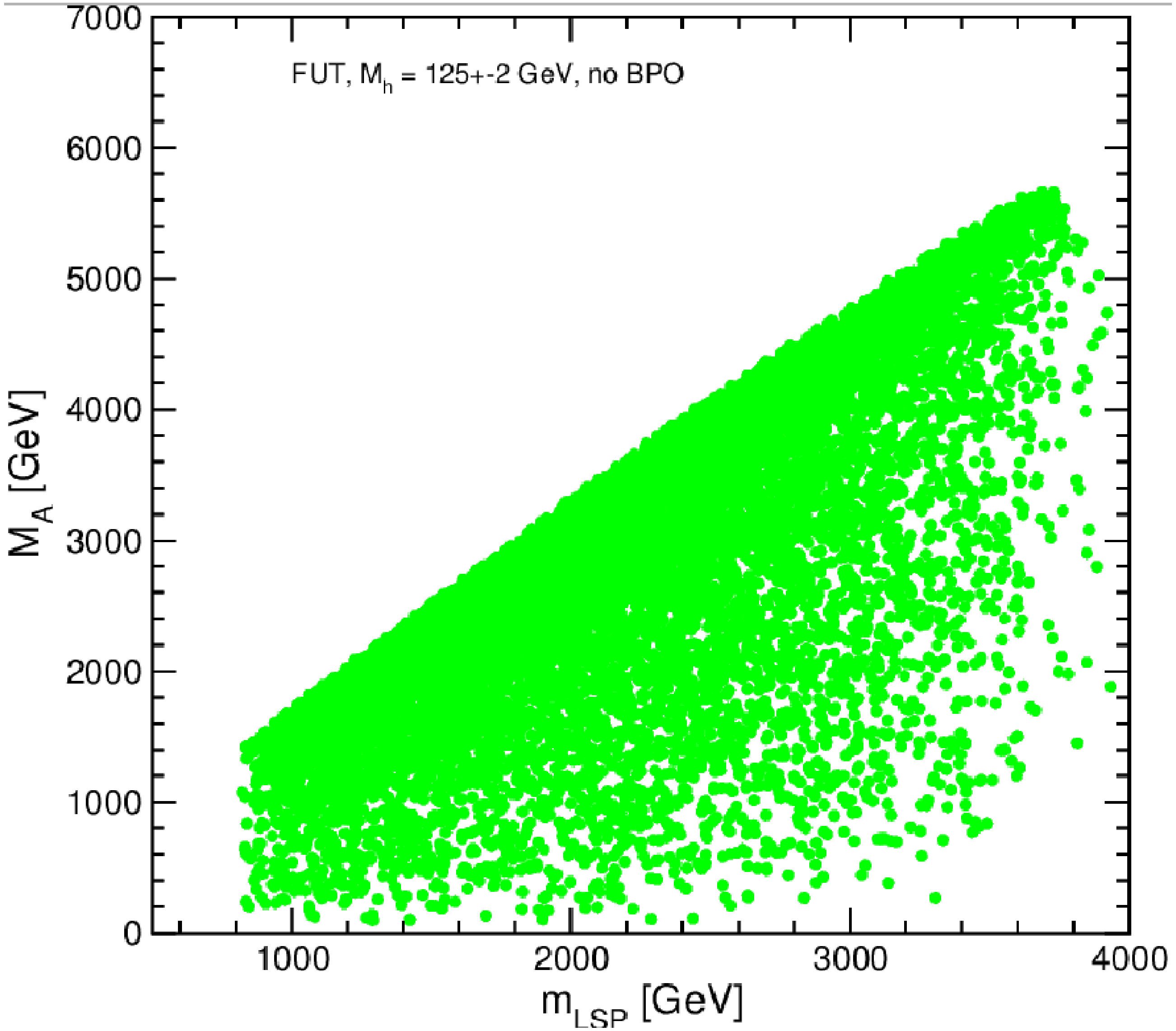
$\Rightarrow$ correct prediction of m_t, m_b, M_h, Higgs couplings, . . .

Demanding $M_h = 125.1 \pm 2$ GeV:

– general spectrum $\Rightarrow$ BSM working group
$\Rightarrow$ (naturally) not touched by LHC so far
– Higgs predictions with HL/HE-LHC prospects

Finite Unified Theories (FUT) predictions:

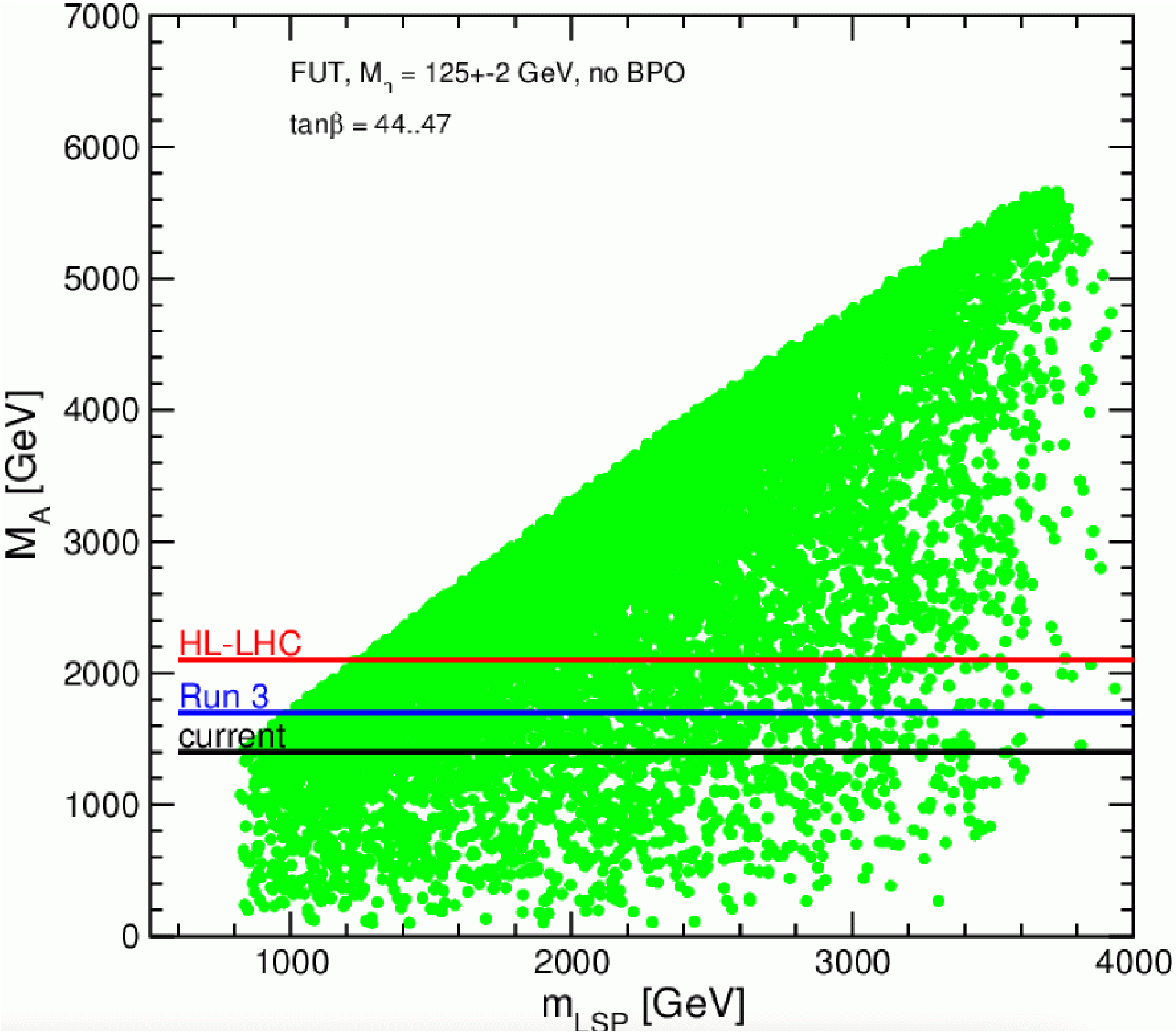
[*S.H., J. Kalinowski, M. Mondragon, N. Tracas, G. Zoupanos '18*]



$\Rightarrow$ naturally high M_A predicted

Finite Unified Theories (FUT) predictions:

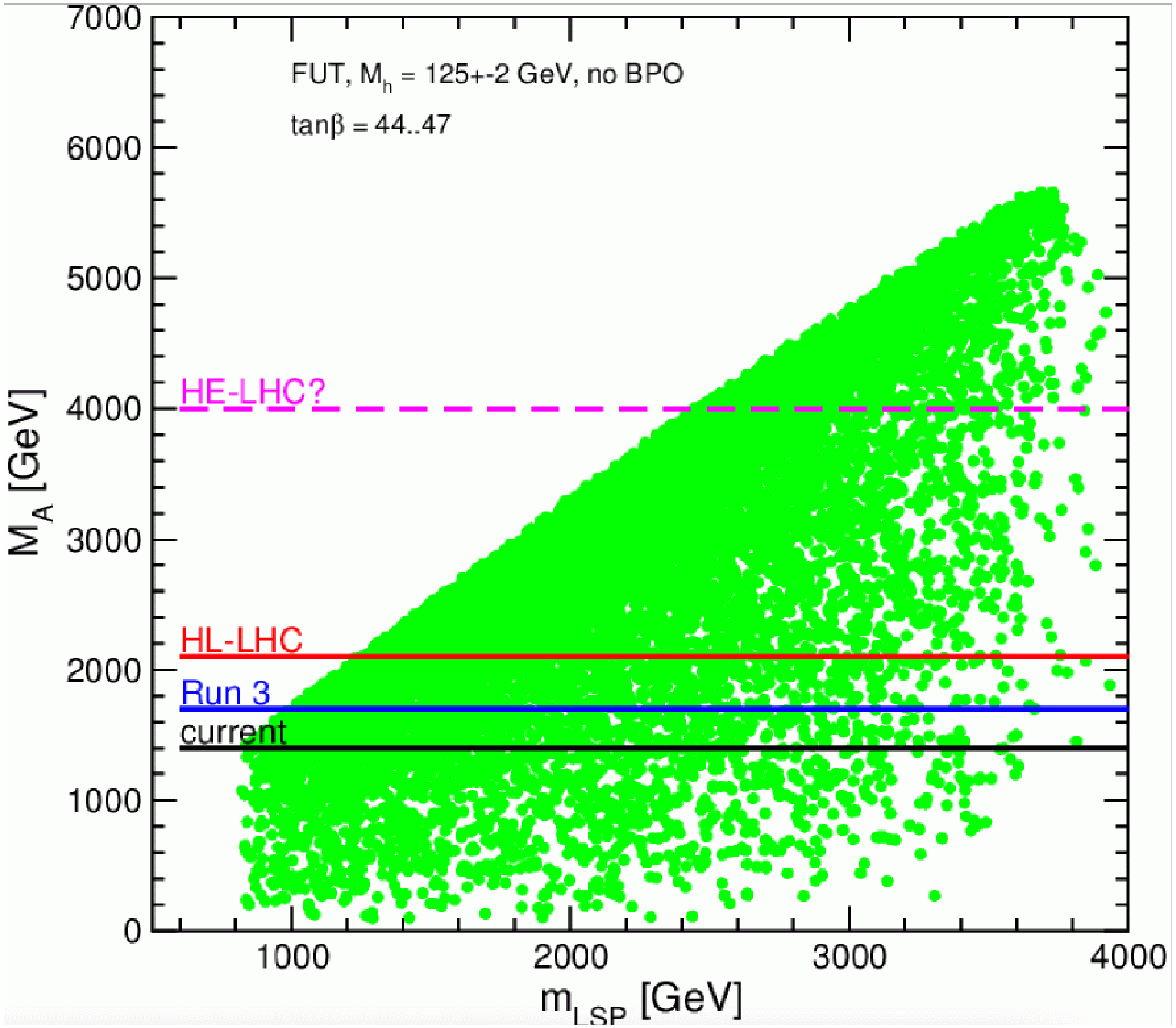
[*S.H., J. Kalinowski, M. Mondragon, N. Tracas, G. Zoupanos '18*]



⇒ tan β prediction ⇒ experimental limits on M_A

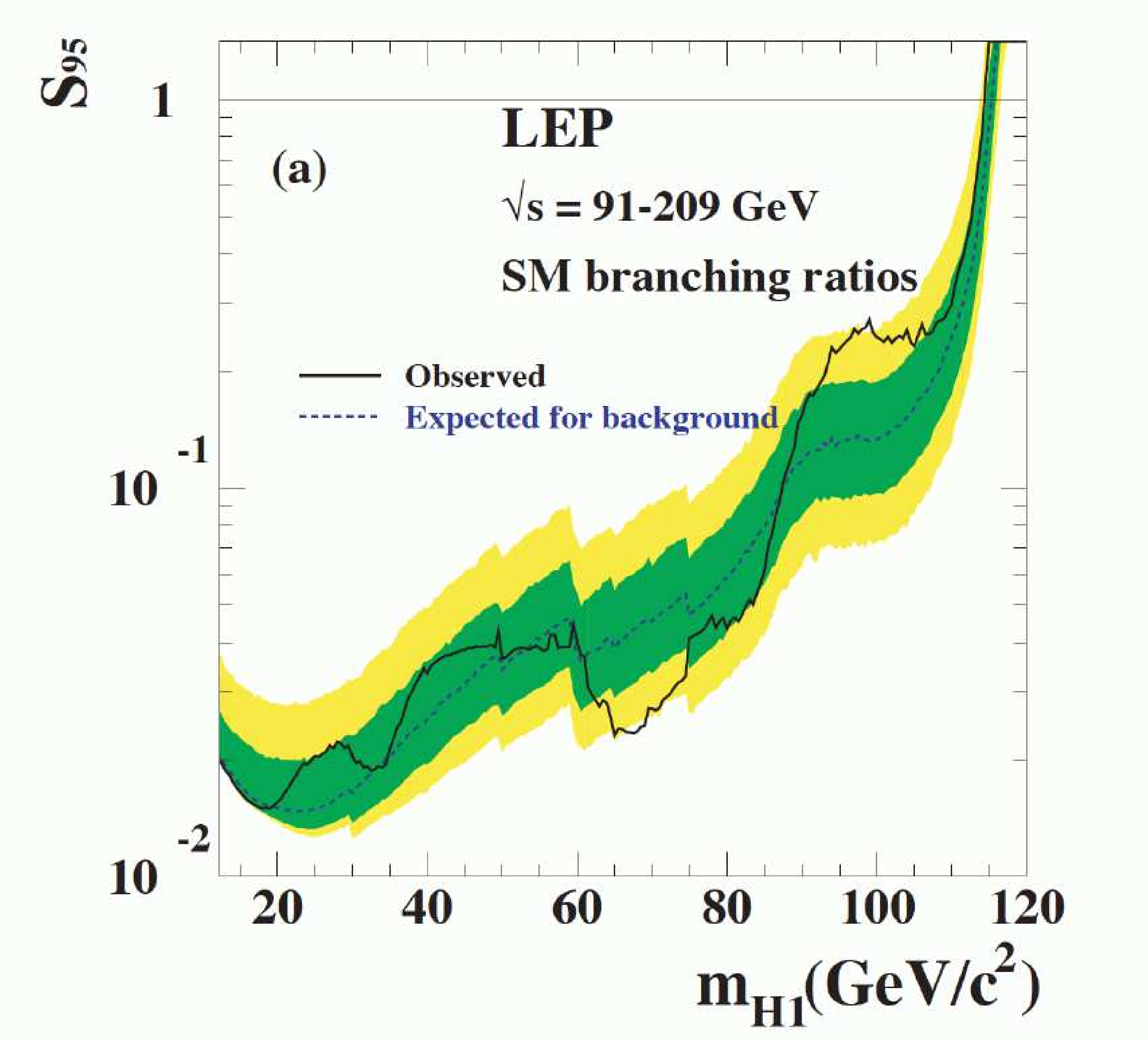
Finite Unified Theories (FUT) predictions:

[*S.H., J. Kalinowski, M. Mondragon, N. Tracas, G. Zoupanos '18*]



⇒ how far can the HE-LHC test (or rule out) this scenario ToDo?!

3. BSM Higgs Bosons below 125 GeV

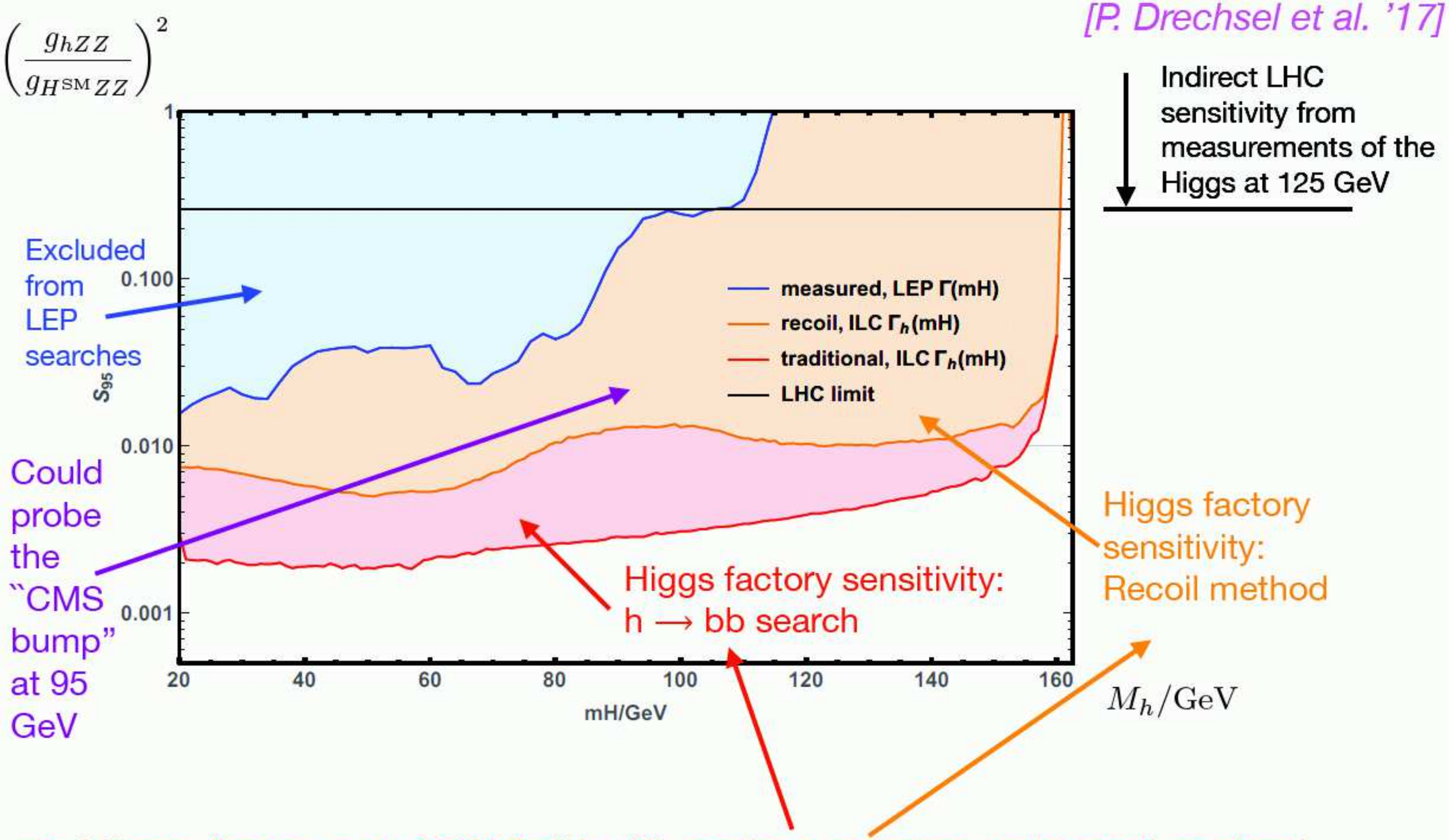


⇒ LEP limits!

⇒ HL/HE-LHC limits?

ILC reach for light Higgs bosons:

Example for discovery potential for new light states:
Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs



⇒ Higgs factory at 250 GeV will explore a large untested region!

[*Talk by G. Weiglein '18*] What can the HL/HE-LHC do here? ToDo?!

Three physics examples for light Higgs bosons:

1. MSSM with heavy $\mathcal{CP}$-even Higgs at 125 GeV

2. NMSSM with second lightest $\mathcal{CP}$-even Higgs at 125 GeV

3. Experimental "evidence" for a light state below 125 GeV

$\Rightarrow$ what can the HL-LHC see?

$\Rightarrow$ what can the HE-LHC see?

Example I: Results in the pMSSM8

[P. Bechtle et al. '16]

The best-fit points:

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

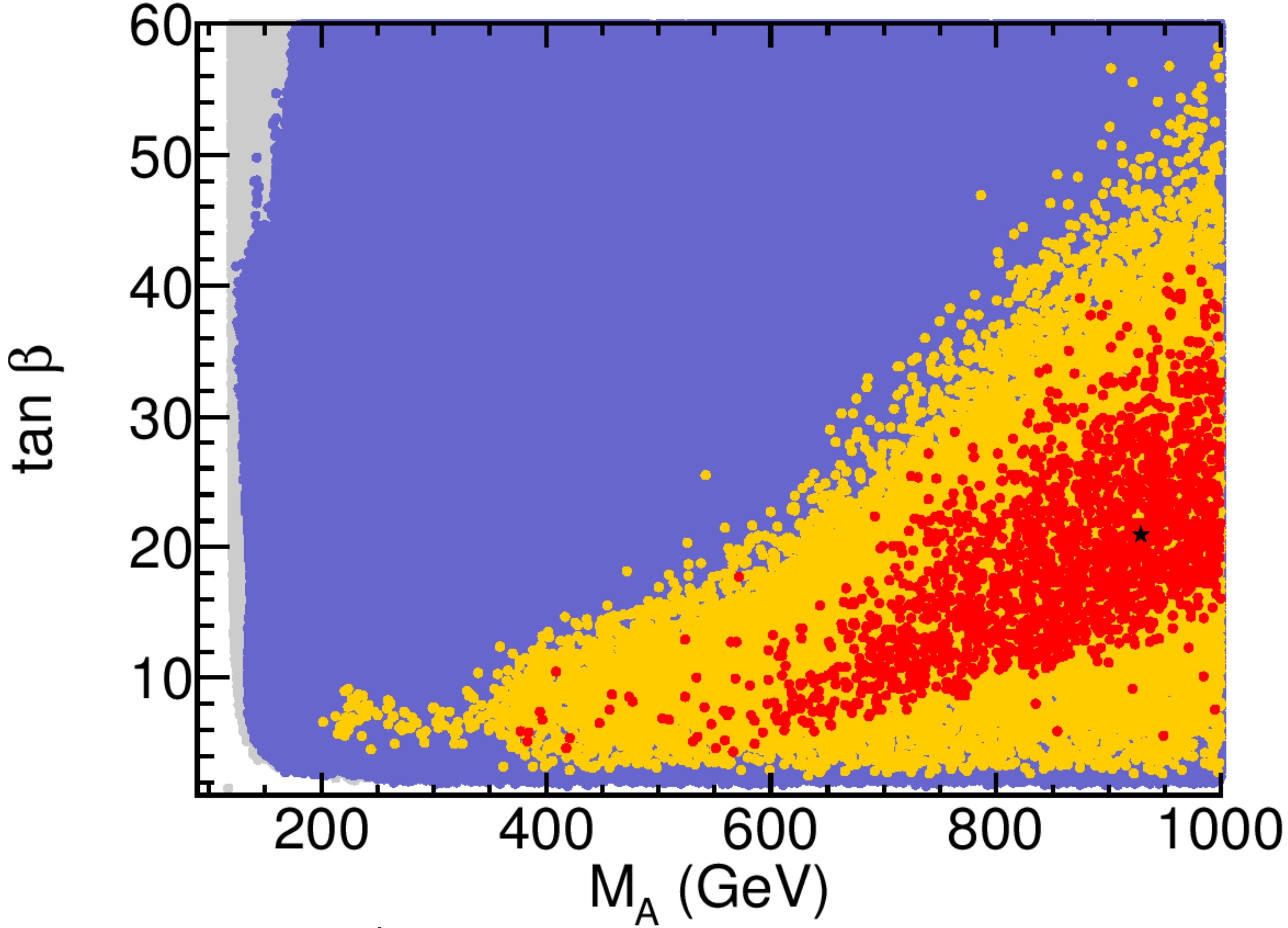
Best-fit points parameters:

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

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

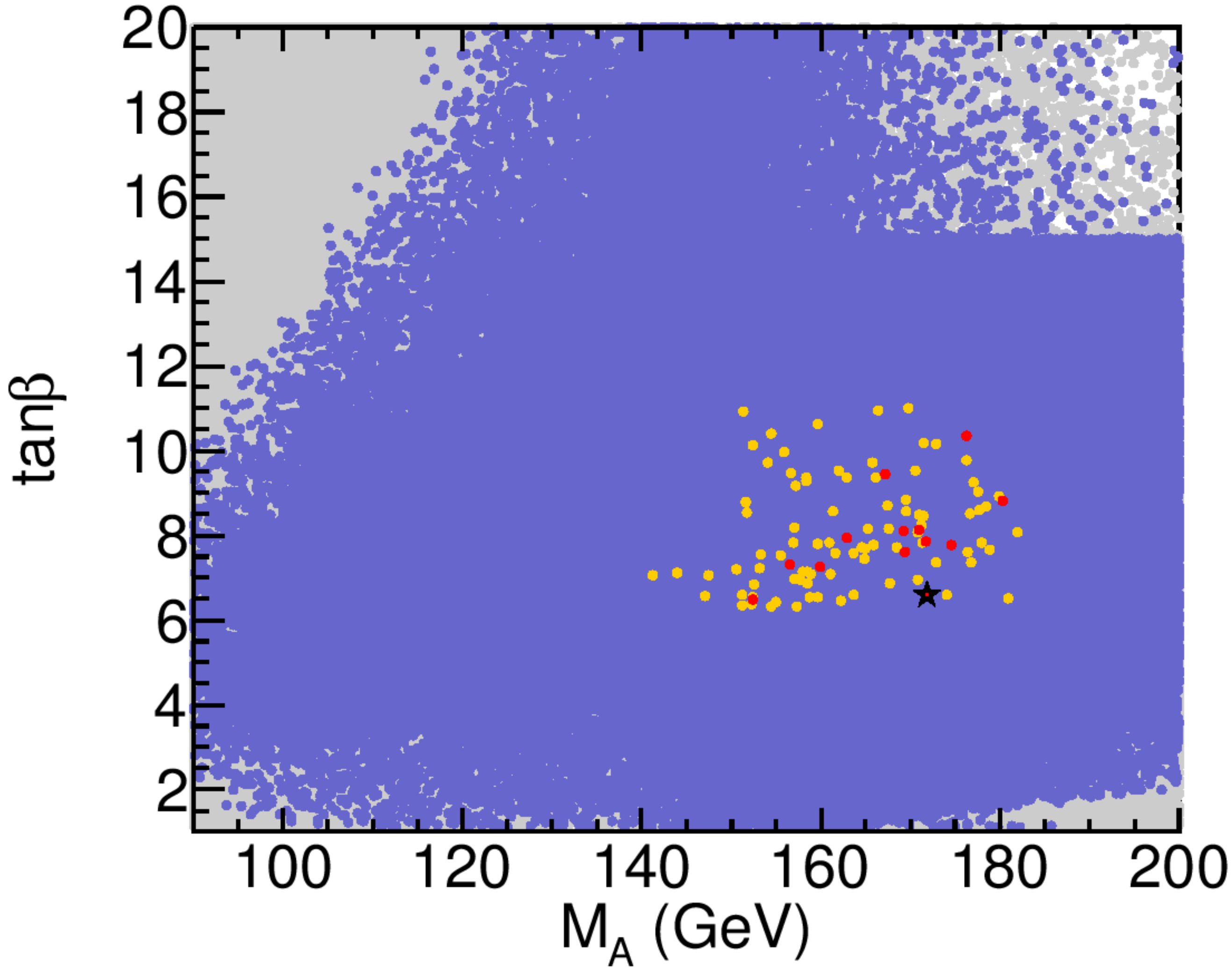
⇒ Including LEOs, SM fit becomes worse

1) Light-Higgs case: preferred parameters [*P. Bechtle et al. '16*]



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

2) Heavy-Higgs case: preferred parameters [*P. Bechtle et al. '16*]

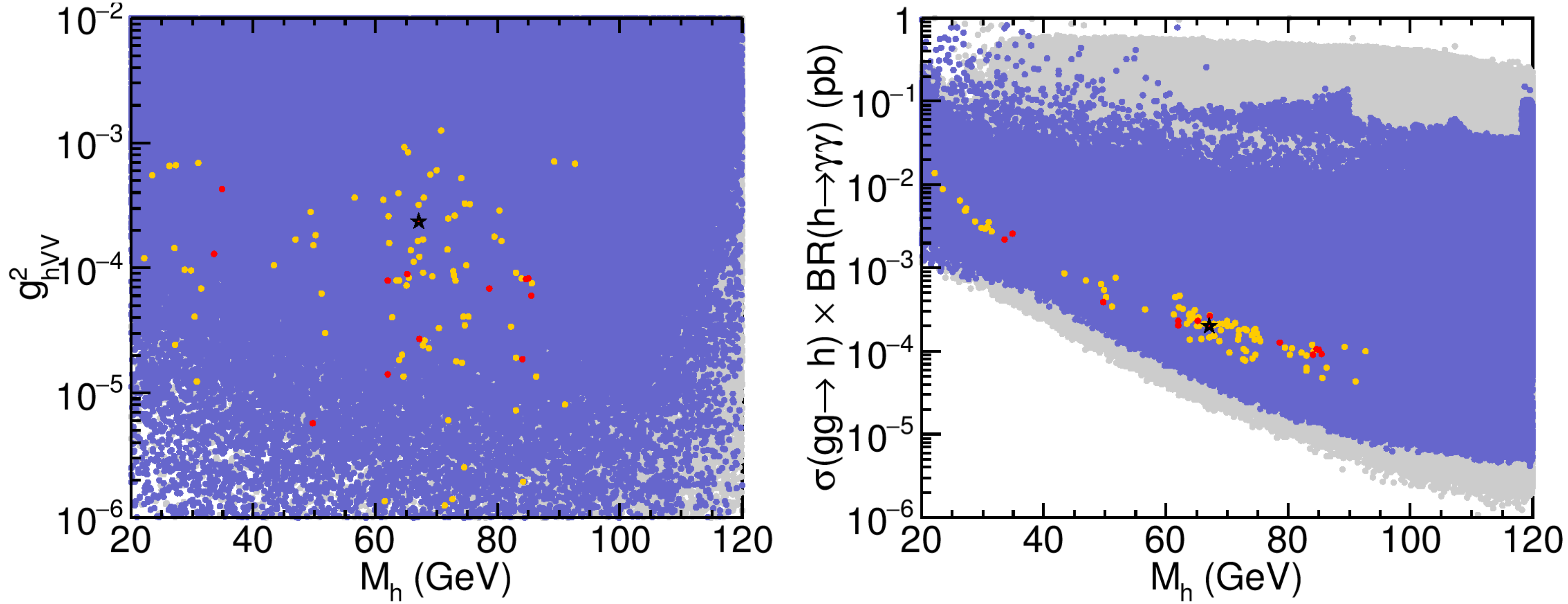


$\Rightarrow M_A \sim 140 \ldots 180$ GeV

$R^H_{VV} = [0.95, 1.13]$, $R^H_{\gamma\gamma} = [0.81, 0.94]$, $R^{VH}_{bb} = [0.94, 1.03]$, $R^H_{\tau\tau} = [0.78, 0.90]$
$\Rightarrow$ not fully SM-like . . .

Where is the light Higgs?

[*P. Bechtle et al. '16*]



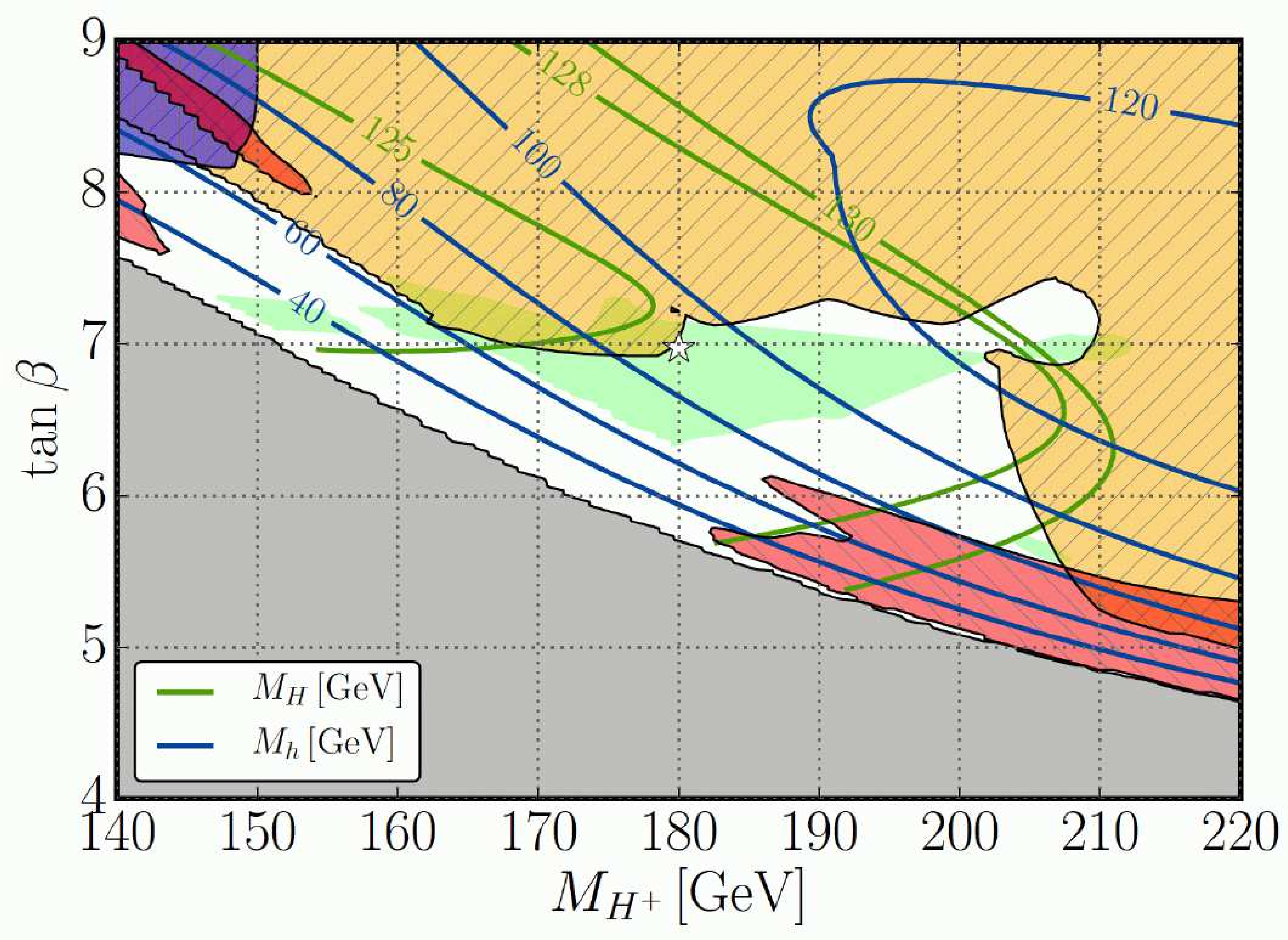
⇒ strongly reduced couplings to gauge bosons ⇒ beyond LEP reach!

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

⇒ visible in $gg \to h \to \gamma\gamma$? What can the HE-LHC do?

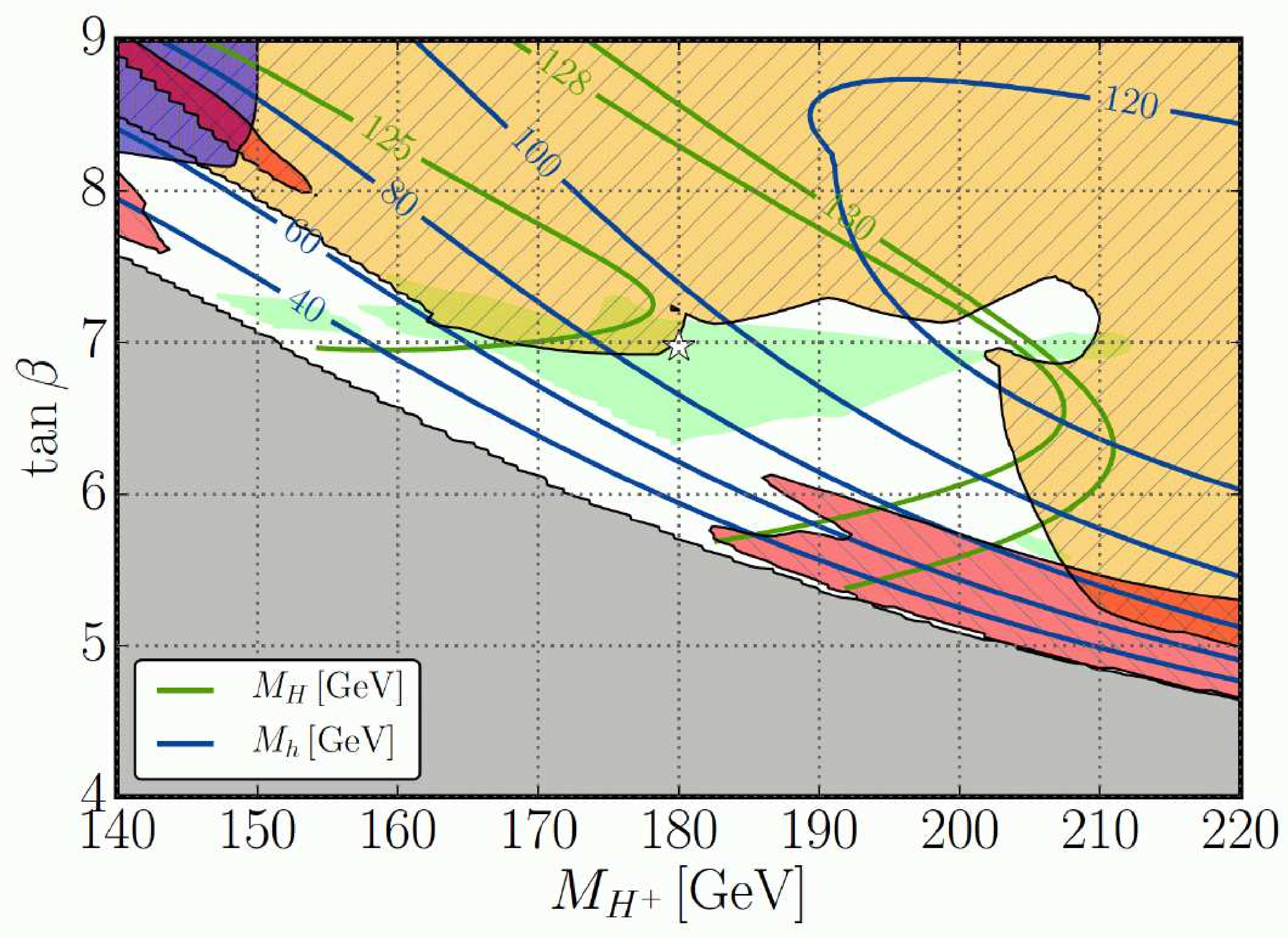
low-$M_H^{\text{alt v}}$(140 GeV $\leq M_{H^\pm} \leq$ 220 GeV):

[*P. Bechtle et al. '16*]



⇒ green area in agreement with all data!

low-$M_H^{\rm alt\,v}$(140 GeV $\leq M_{H^\pm} \leq$ 220 GeV): [P. Bechtle et al. '16]



⇒ green area in agreement with all data! Update WIP [P. Slavich et al. '18]

Example II: light singlet

Singlet does not couple to SM particles!

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

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Singlet does not couple to SM particles!

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

"Easily" possible in the NMSSM:

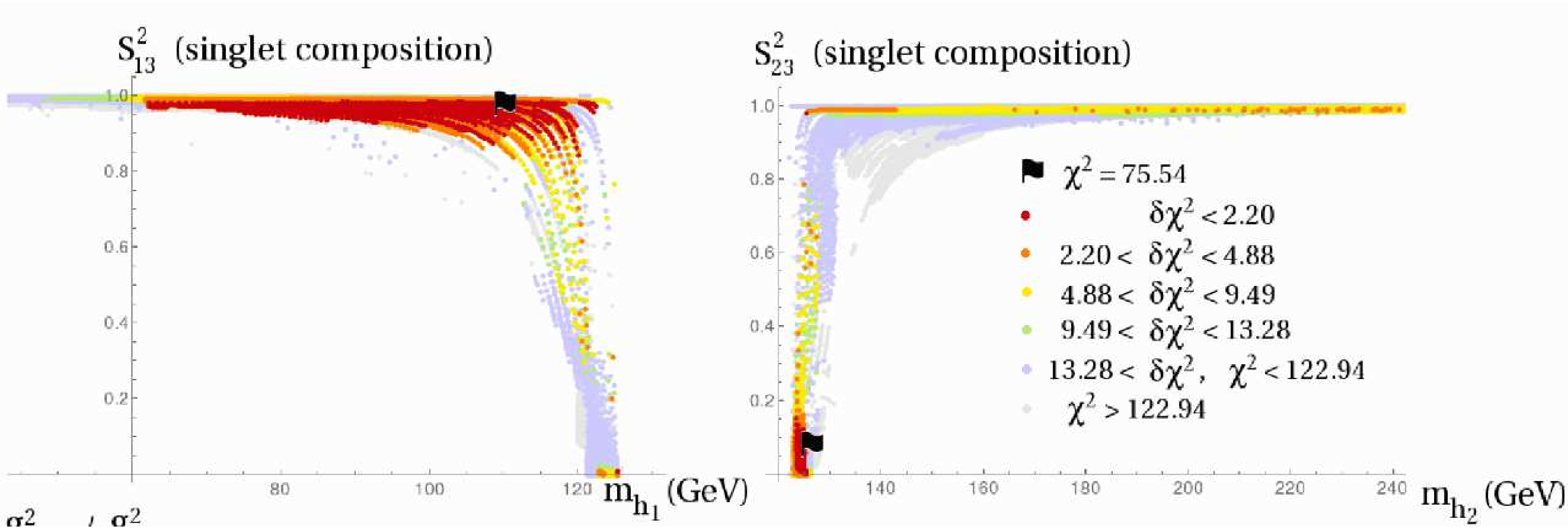
Light, singlet-like Higgs below 125 GeV

Can the HL/HE-LHC find them? ToDo?!

NMSSM parameter scan: [F. Domingo, G. Weiglein '15]

Parameters:

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



⇒ light Higgs below 125 GeV has large singlet component

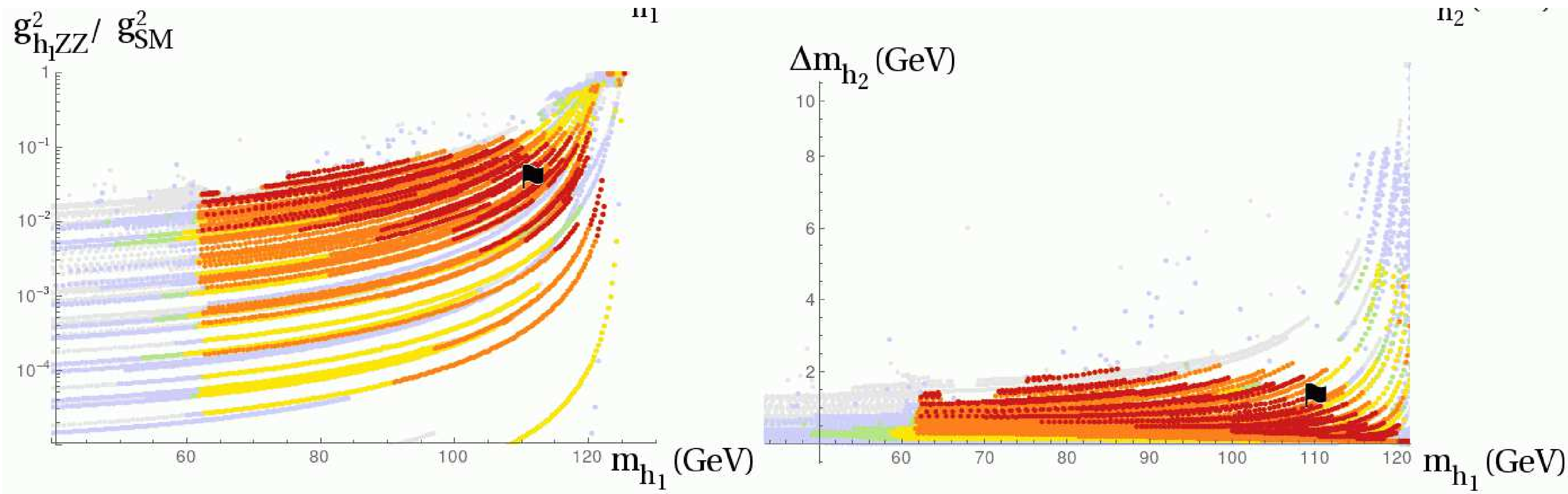
⇒ second Higgs is SM-like

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

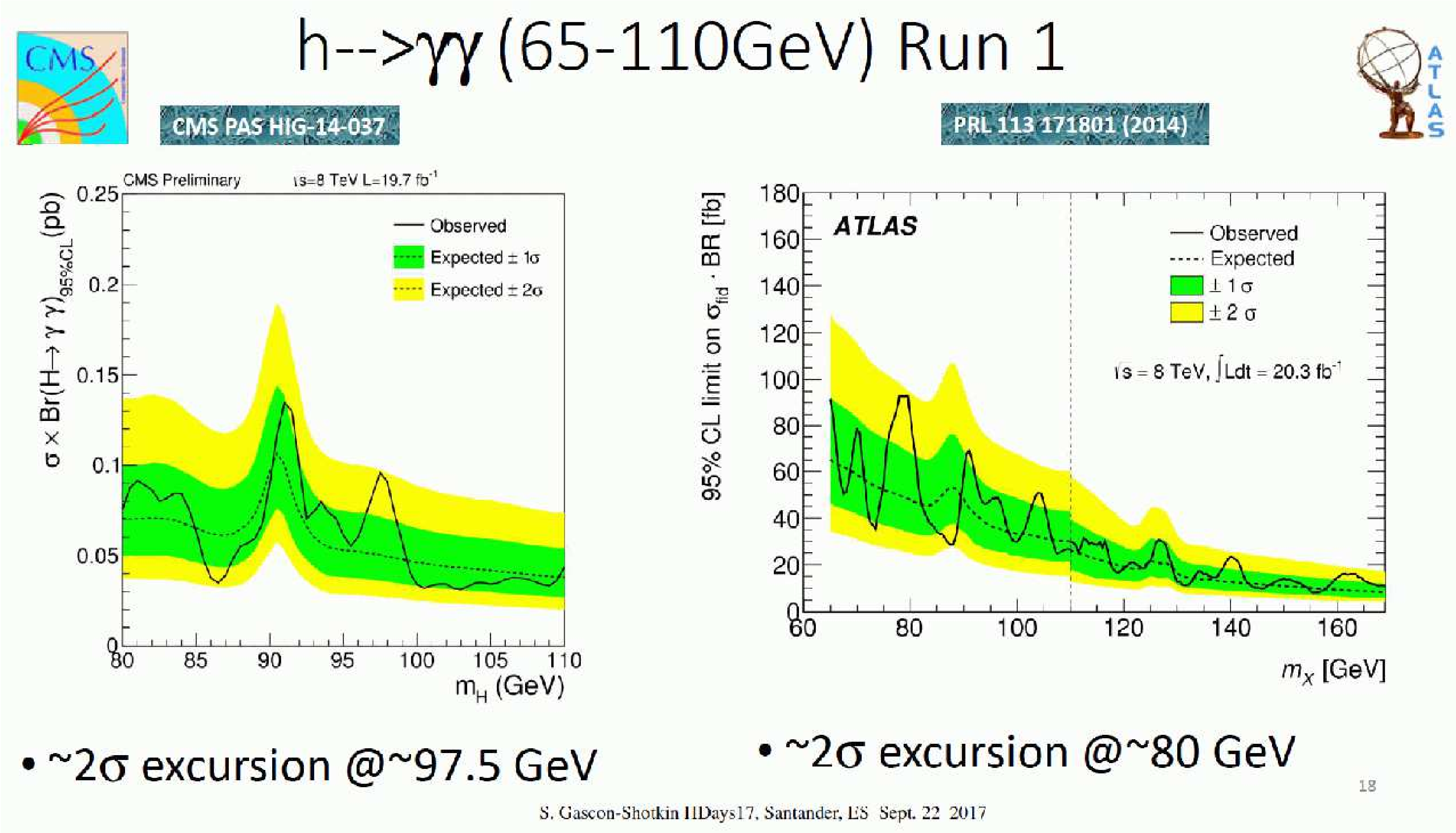


⇒ light Higgs below 125 GeV

⇒ strongly reduced couplings to gauge bosons!

⇒ HL/HE-LHC reach? ToDo?!

Example III: "96 GeV excess" : [*S. Shotkin, talk at HDays17*]

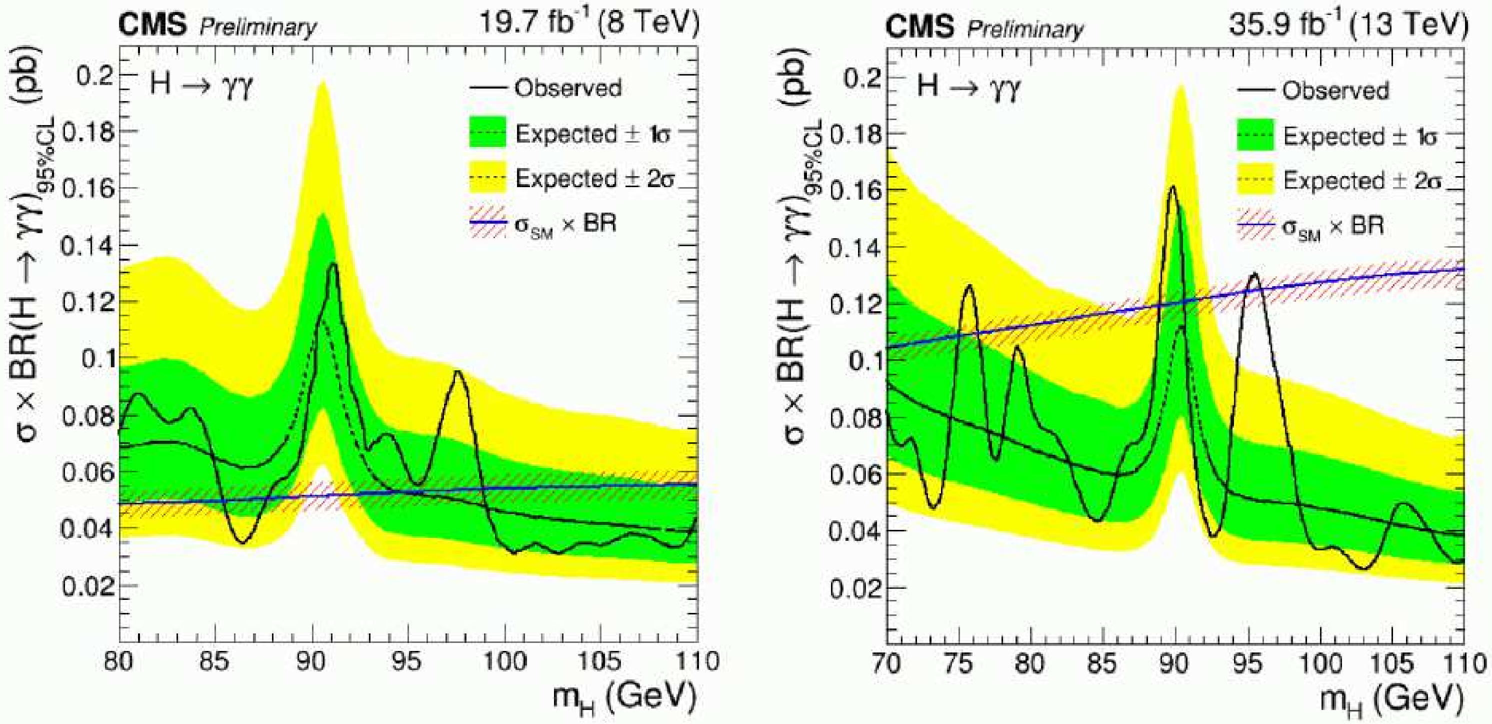


"96 GeV excess": what was seen at Run II? *[S. Shotkin, talk at HDays17]*

h-->γγ (70-110 GeV) Runs 1+2

New!

CMS PAS HIG-17-013



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

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

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

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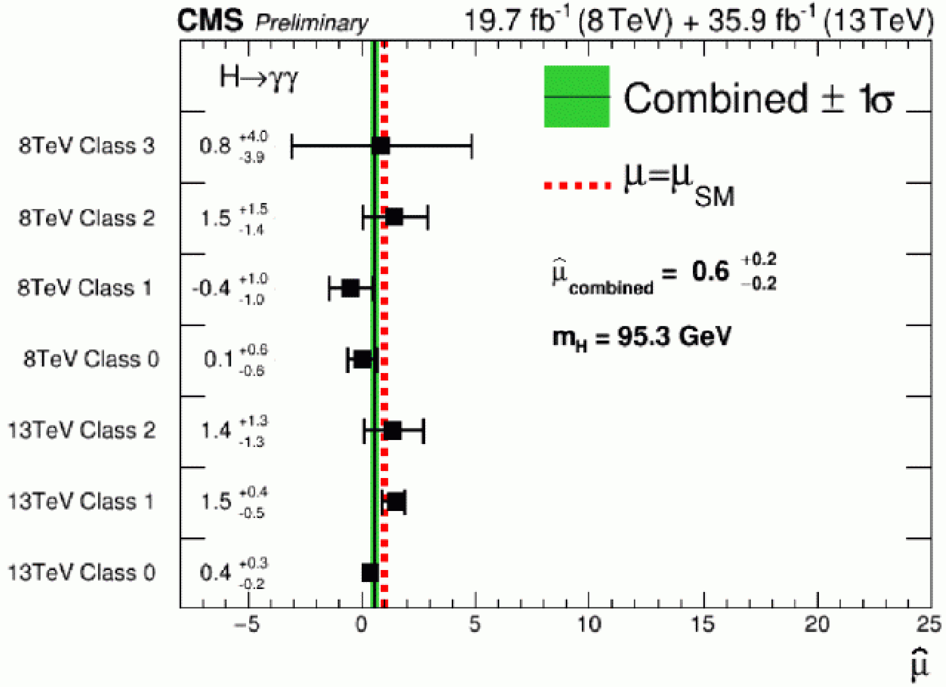
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

h-->γγ (70-110 GeV) Runs 1+2

New!



CMS PAS HIG-17-013

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

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

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

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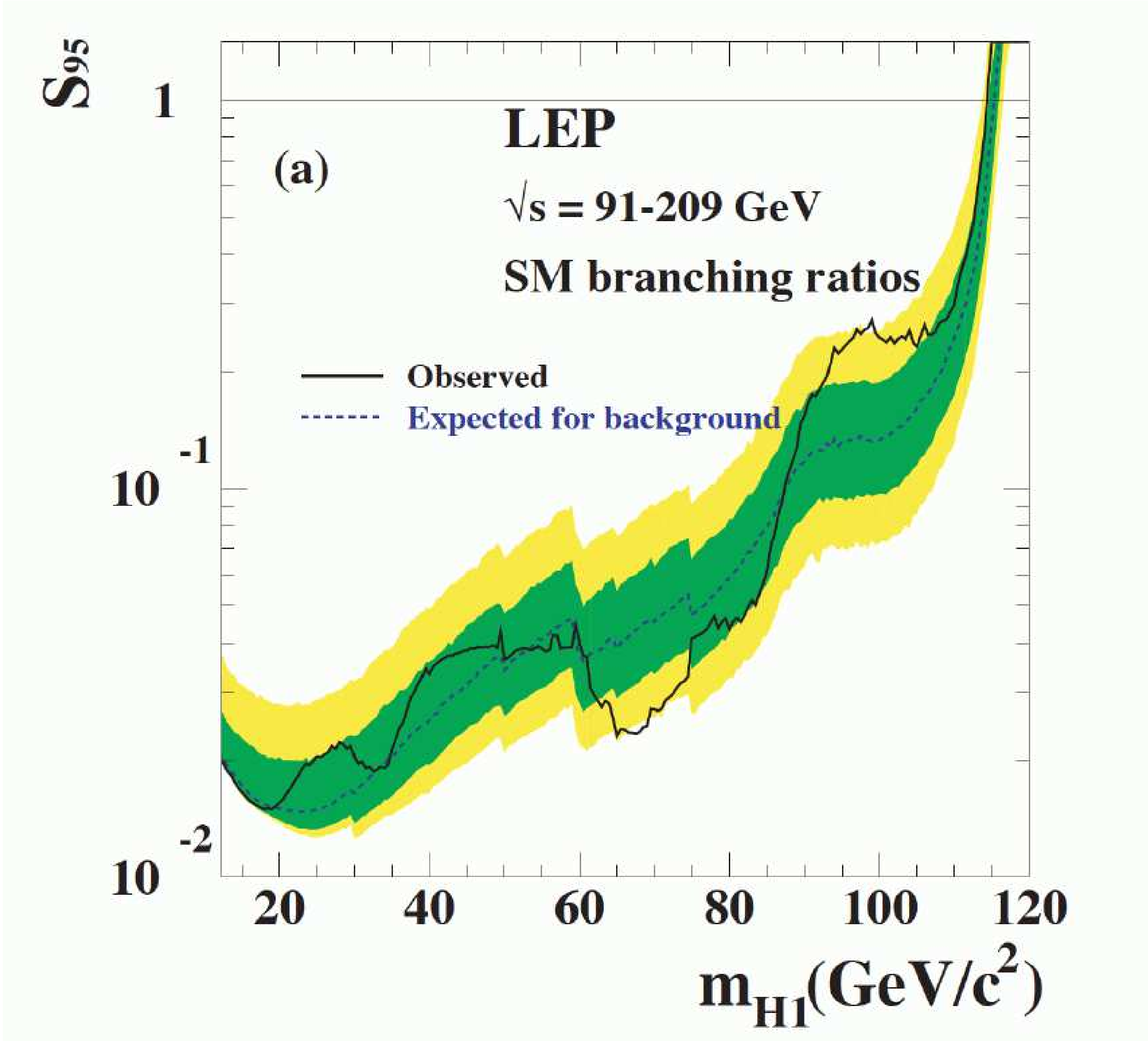
$$\mu_{\mathrm{CMS}}(96\ \mathrm{GeV}) = [\sigma(pp \to h_1) \times \mathrm{BR}(h_1 \to \gamma\gamma)]_{\mathrm{exp/SM}} = 0.6 \pm 0.2$$

"96 GeV excess": what was seen at LEP?



$$\mu_{\mathrm{LEP}}(98\ \mathrm{GeV}) = \left[\sigma(e^+e^- \to Zh_1) \times \mathrm{BR}(h_1 \to b\bar{b})\right]_{\mathrm{exp/SM}} = 0.117 \pm 0.057$$

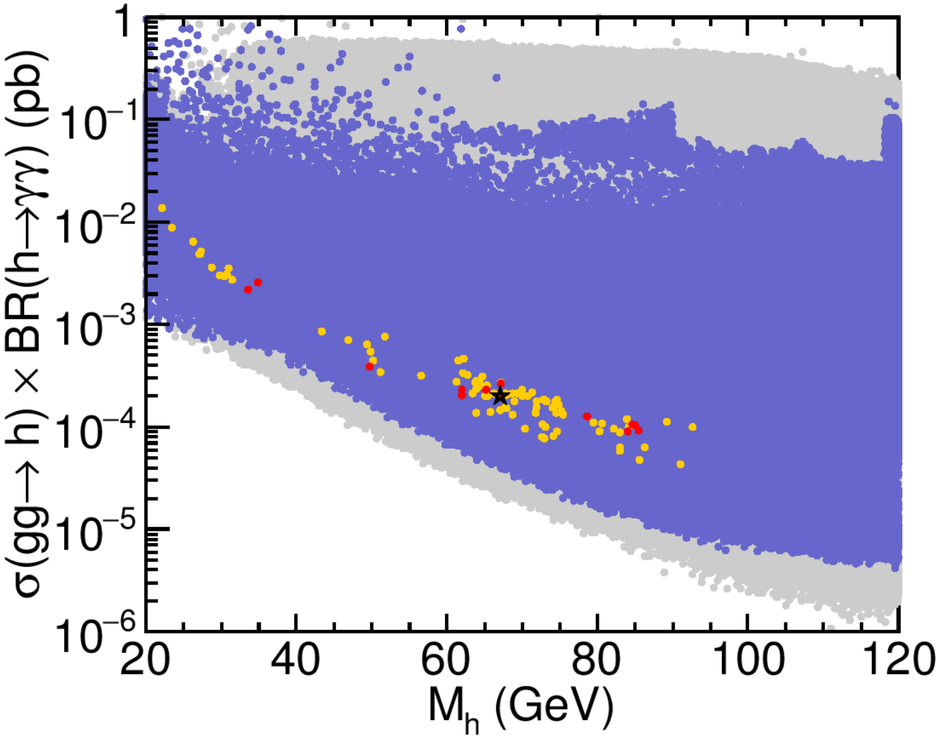
Should we get excited?

⇒ according to CMS no!

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

Which model fits?

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



⇒ not the MSSM

⇒ 2HDM? NMSSM?

Check the $\mu\nu$SSM

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)
$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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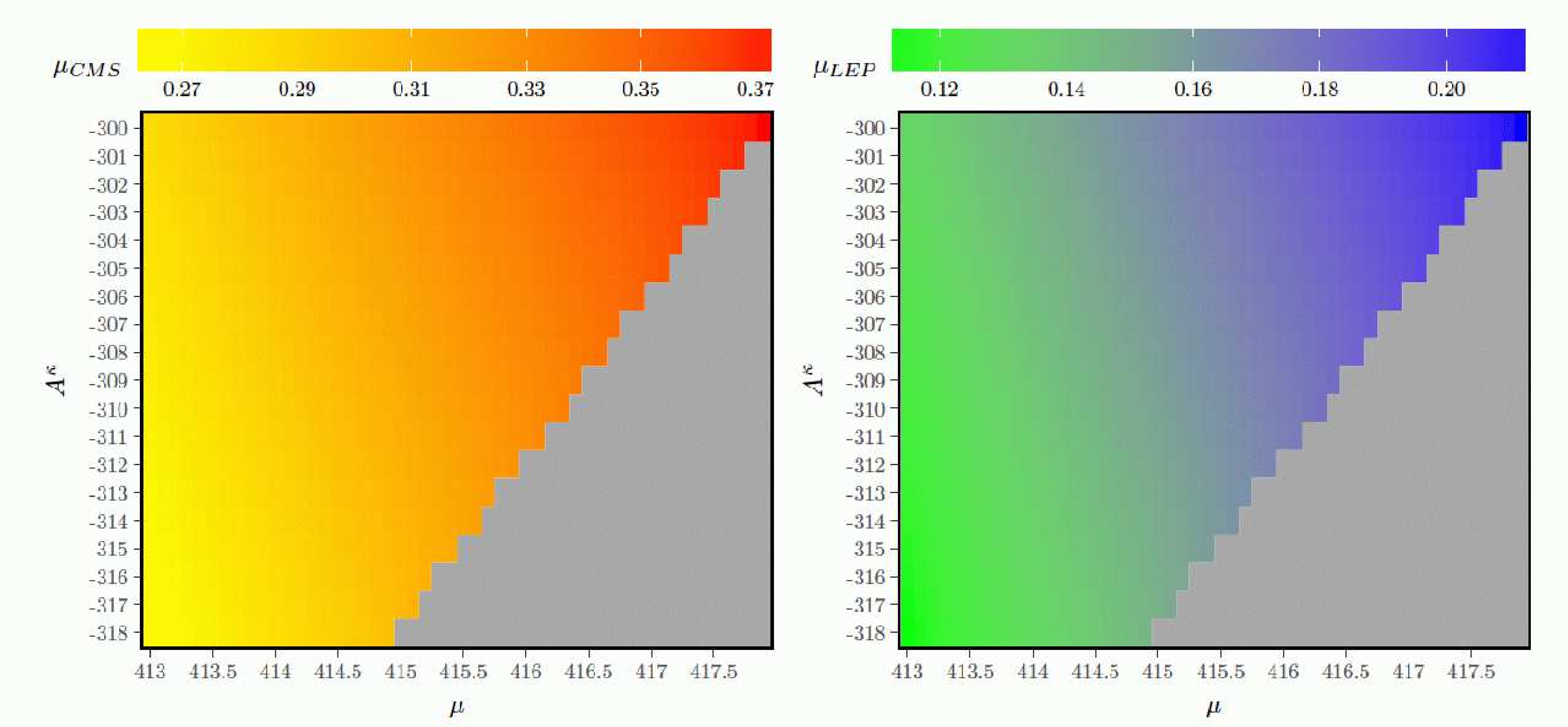
Can the $\mu\nu$SSM explain the two "excesses"?

[*T. Biekötter, S.H., C. Muñoz, arXiv:1712.07475*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	M_1
$\sqrt{2}\cdot 10^{-5}$	10^{-7}	-1000	2	$[413; 418]$	0.6	956.035	0.035	$[-300; -318]$	100
M_2	M_3	$m^2_{\tilde{Q}_{iL}}$	$m^2_{\tilde{u}_{iR}}$	$m^2_{\tilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\tilde{e}})_{ii}$	A_{33}^e	$A_{11,22}^e$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

Can the $\mu\nu$SSM explain the two "excesses"?

[*T. Biekötter, S.H., C. Muñoz, arXiv:1712.07475*]



⇒ YES, WE CAN! :-)

(at the $1 - 1.5\,\sigma$ level)

⇒ what can the HL/HE-LHC see? ToDo?!

4. BSM Higgs Boson at 125 GeV

- Higgs coupling measurements
  - old HL-LHC numbers, still correct?
    $\Rightarrow$ contrast with concrete model predictions!
  - no HE-LHC numbers ($\to$ discussion yesterday)

  $\Rightarrow$ where are the priorities?

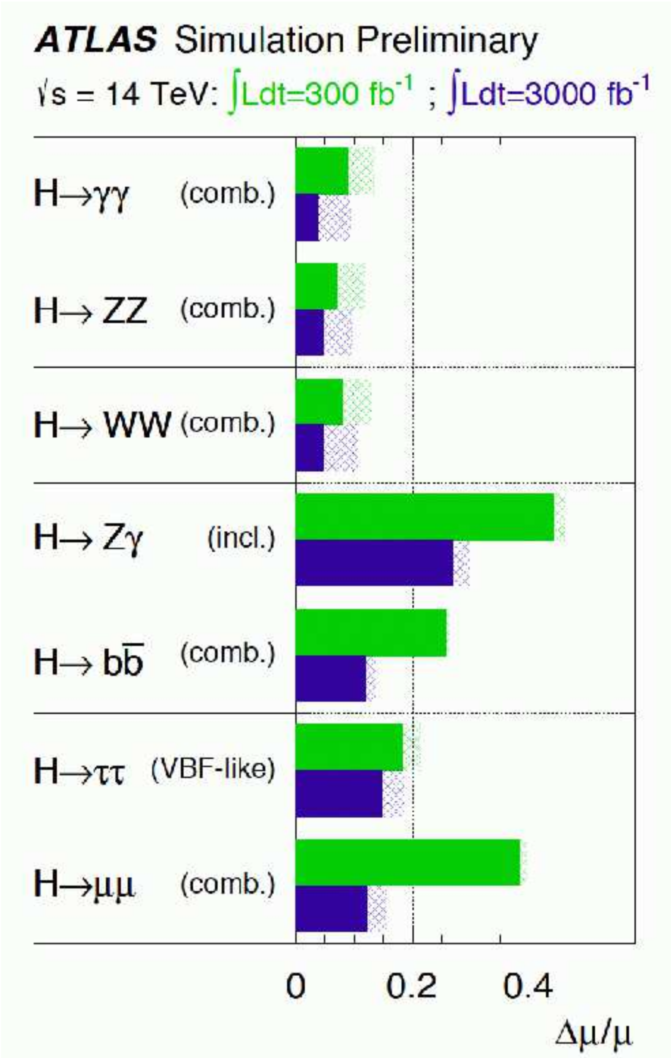
- Higgs self-coupling measurements
  - depressing HL-LHC prospects
  - HE-LHC estimates?

- $\mathcal{CP}$-admixture of the 125 GeV Higgs
  - depressing HL-LHC prospects
  - HE-LHC estimates?

- Exotic Higgs decays at 125 GeV
  - depressing(?) HL-LHC prospects
  - HE-LHC estimates?

- ...

Higgs coupling measurements:



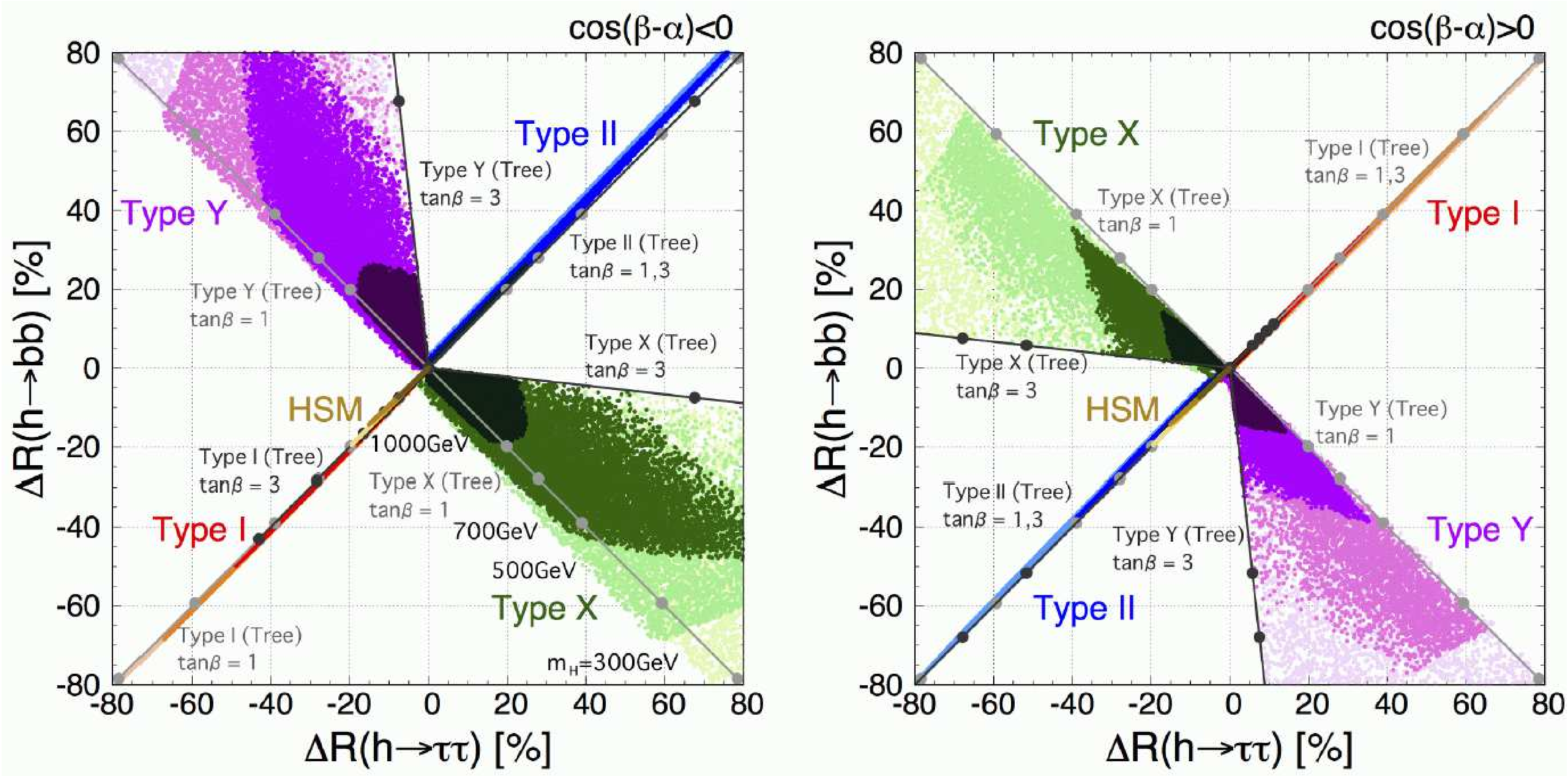
⇒ what can be done with this precision?

⇒ updates!

⇒ HE-LHC prospects?! ToDo?!

Higgs couplings: 2HDM example (I):

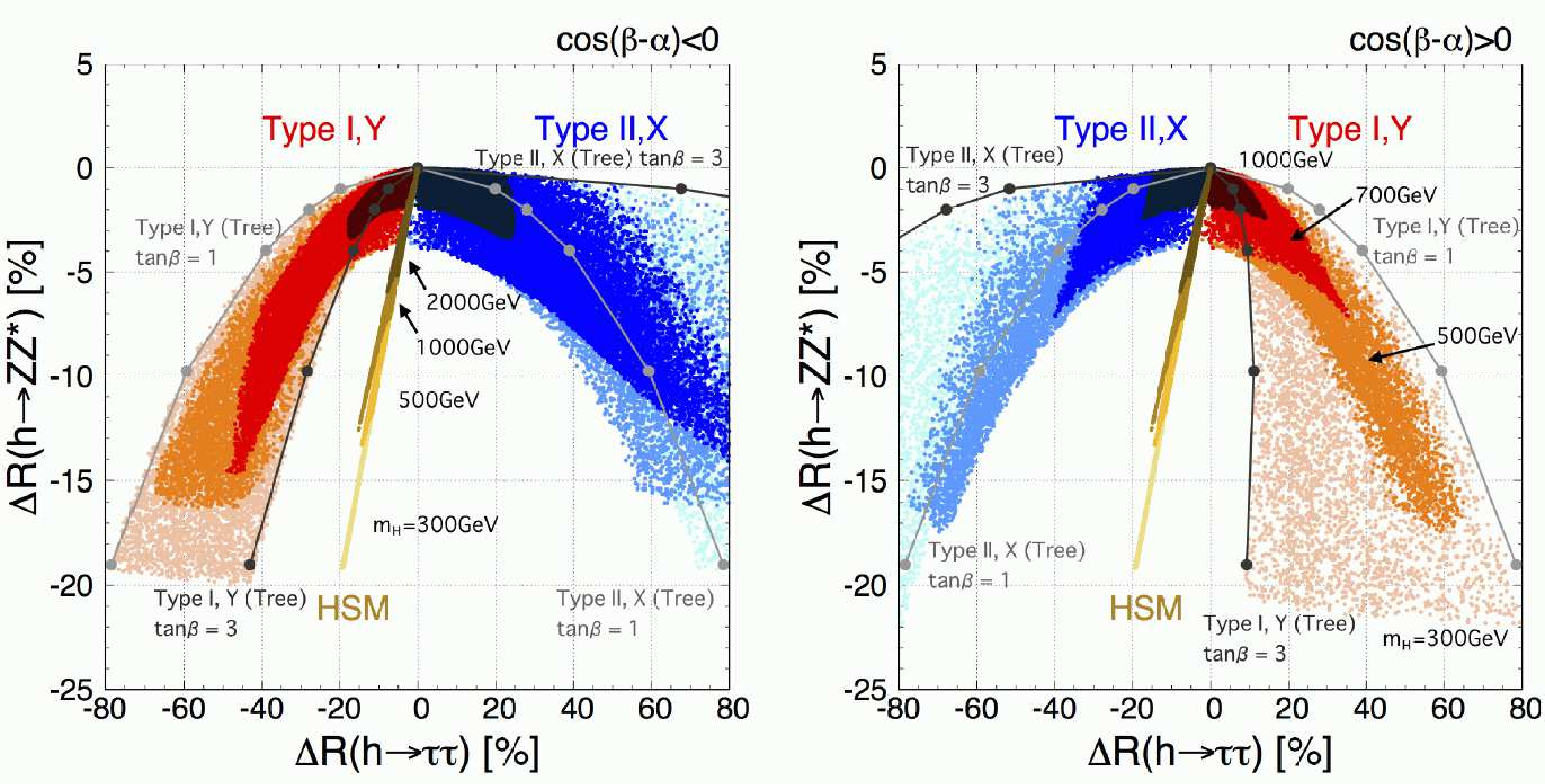
[*S. Kanemura et al. '18*]



⇒ HE-LHC precision has the potential to discriminate the models?!

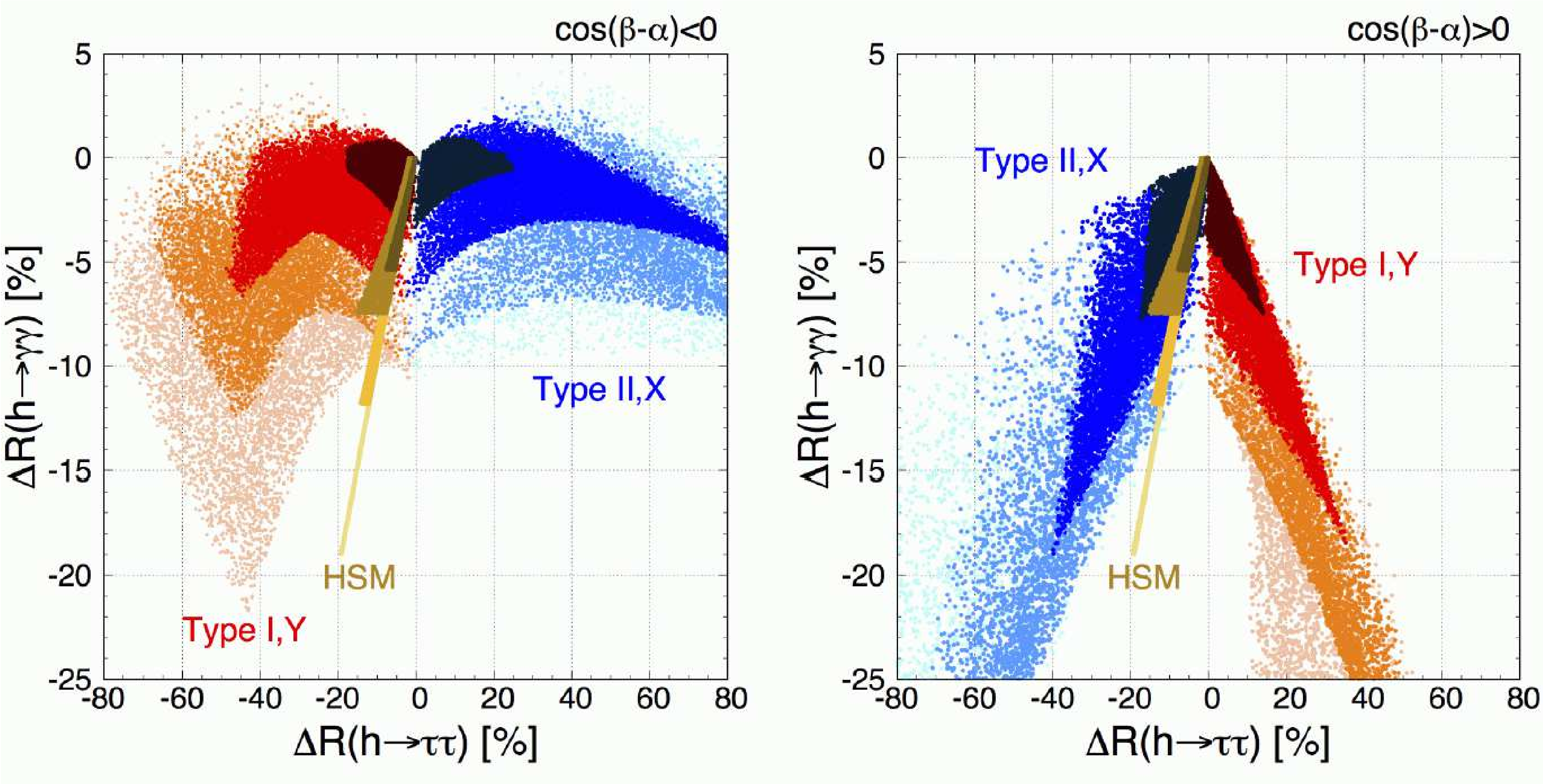
Higgs couplings: 2HDM example (II):

[*S. Kanemura et al. '18*]



⇒ HE-LHC precision has the potential to discriminate the models?!

Higgs couplings: 2HDM example (III): [*S. Kanemura et al. '18*]



⇒ HE-LHC precision has the potential to discriminate the models?!

Particularly challenging: Higgs self-coupling

Desired precision in λ?

$\Rightarrow$ highly model dependent

Examples: [R. Gupta, H. Rzehak, J. Wells '13]

- Higgs singlet extension: $(\Delta\lambda/\lambda)^{\rm max} \sim -18\%$
- Composite Higgs models: $(\Delta\lambda/\lambda)^{\rm max} \sim +20\%$
- MSSM: $(\Delta\lambda/\lambda)^{\rm max} \lesssim -15\%$
- NMSSM: $(\Delta\lambda/\lambda)^{\rm max} \lesssim -25\%$

Current HL-LHC "precision" does not help

$\Rightarrow$ reliable updates?!

$\Rightarrow$ HE-LHC precision? ToDo?!

Required precision for $\mathcal{CP}$-admixture?

$$\boxed{H = \cos\alpha\ \mathcal{CP}\text{-even} + \sin\alpha\ \mathcal{CP}\text{-odd}}$$

$$\mathcal{A}(X \to VV) = \frac{1}{v}\left(a_1 m_V^2 \varepsilon_1^* \varepsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$\mathcal{A}(X \to f\bar{f}) = \frac{m_f}{v}\bar{u}_2\,(b_1 + i b_2 \gamma_5)\,u_1$$

$$f_{\mathcal{CP}} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$

Desired precision:

gauge bosons: $f_{\mathcal{CP}} \lesssim 10^{-5}$ (loop suppressed)

fermions: $f_{\mathcal{CP}} \lesssim 10^{-2}$

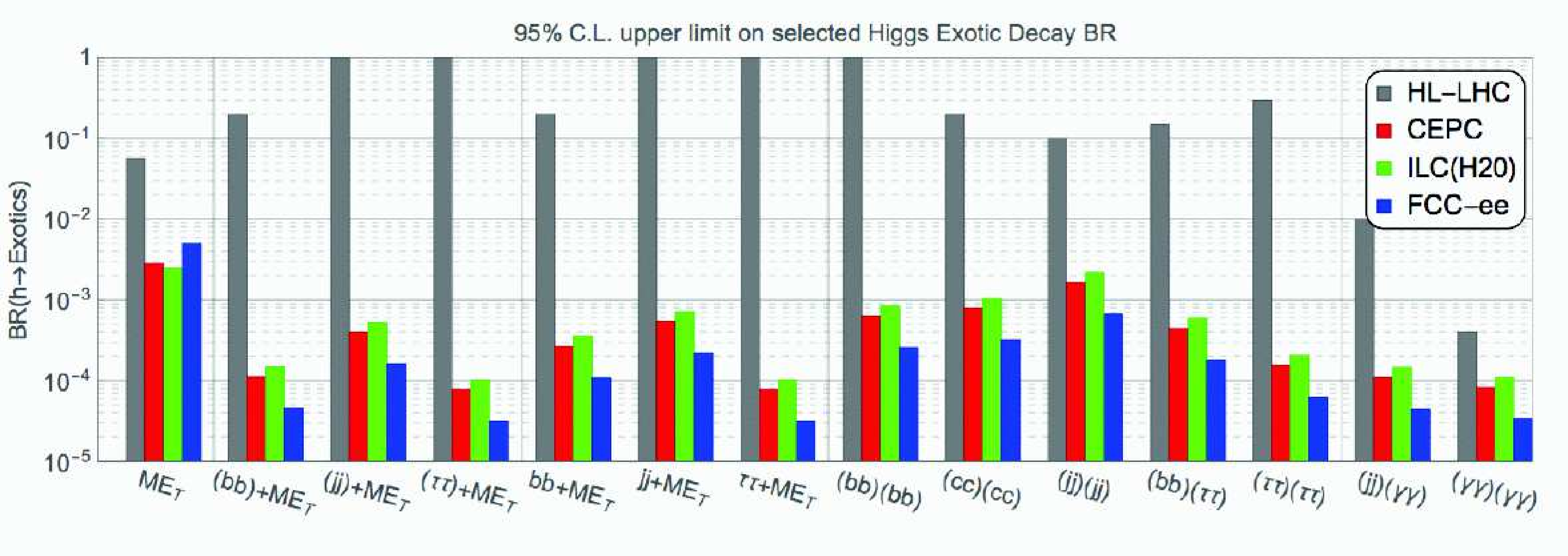
Current HL-LHC “precision” does not help

$\Rightarrow$ reliable updates?!

$\Rightarrow$ HE-LHC precision? ToDo?!

Exotic Higgs decays:

[*Z. Liu, L.-T. Wang, H. Zhang '17*]



Current HL-LHC "precision" does not help

⇒ reliable updates?!

⇒ HE-LHC precision? ToDo?!

5. Conclusions

- The discovered Higgs boson is not the SM Higgs boson
- Test for changed properties
  Test for additional Higgs bosons above and below 125 GeV
- BSM Higgs bosons above 125 GeV:
  HL-LHC and HE-LHC limits needed for a variety of BSM models
  $\Rightarrow$ Covered after this workshop (series)? ToDo?!
  There are (SUSY) models naturally beyond Run 3/HL-LHC,
  but with interesting HE-LHC prospects ToDo?!
- BSM Higgs bosons below 125 GeV:
  $\Rightarrow$ characterized by reduced hVV coupling
  $\Rightarrow$ What can the HL-LHC or HE-LHC see? ToDo?!
- BSM Higgs boson at 125 GeV:
  precise Higgs coupling measurement can distinguish models
  $\Rightarrow$ possibly interesting prospects for HL/HE-LHC?!
  Higgs self-coupling, $\mathcal{CP}$-admixture, exotic decays:
  $\Rightarrow$ so far "depressing" HL-LHC prospects
  $\Rightarrow$ HE-LHC prospects? ToDo?!


Higgs Days at Santander 2018
Theory meets Experiment
10.-14. September
Contact: Sven.Heinemeyer@cern.ch
Local: Gervasio.Gomez@cern.ch
http://hdays.csic.es


Further Questions?

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

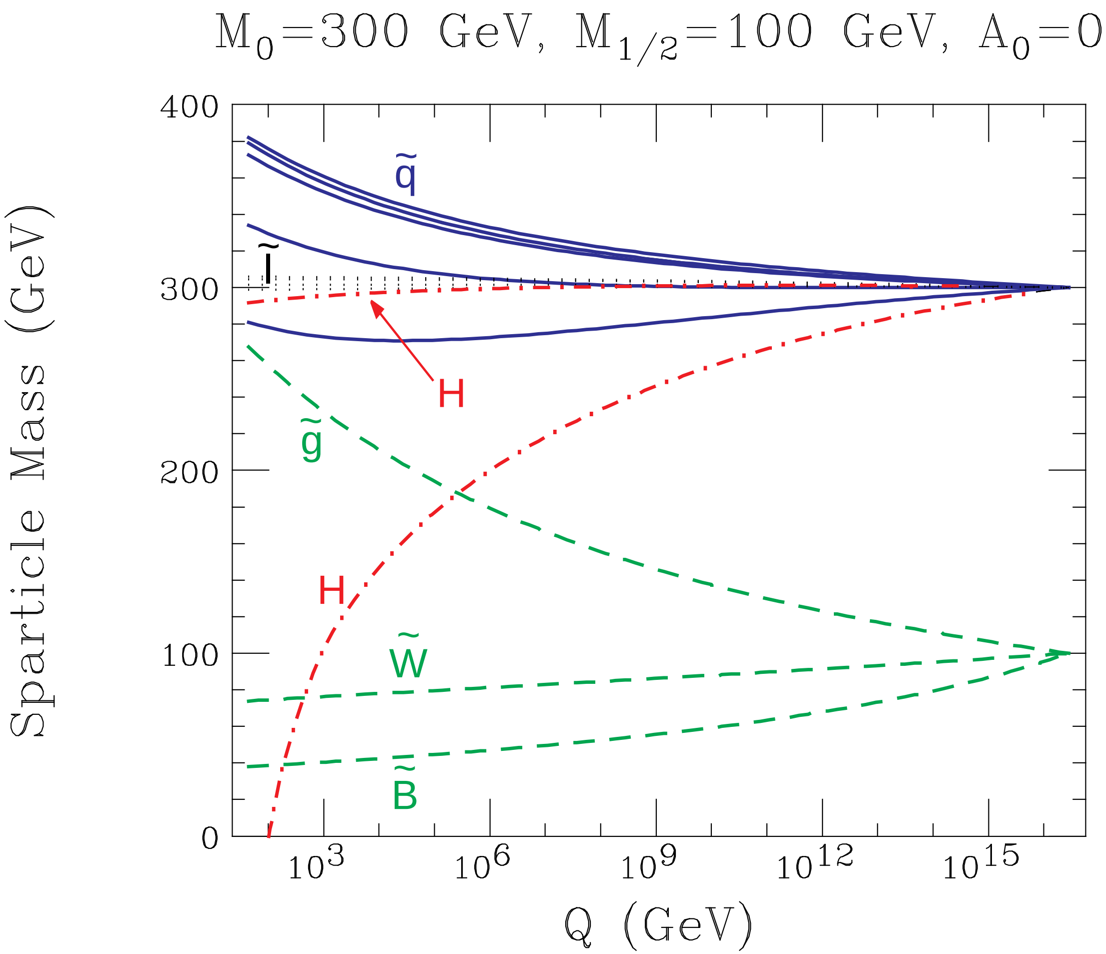
sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

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

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

⇒ particle spectra from renormalization group running to weak scale



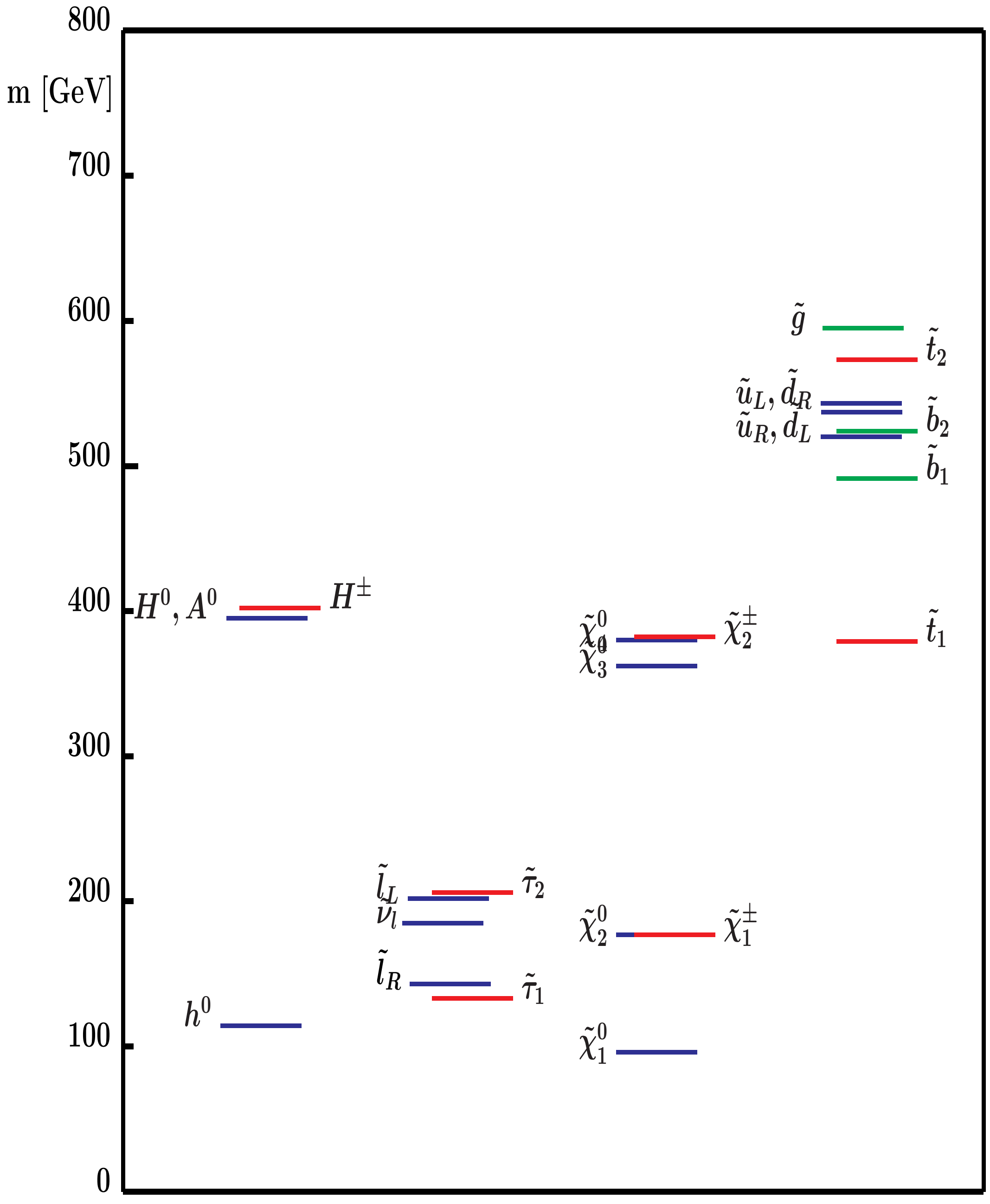
⇒ one parameter turns negative ⇒ Higgs mechanism for free

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

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

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

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

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

GUT based models: 4.) SU(5) GUT:

Assumption I:

no unification of scalar Higgs parameter at the GUT scale

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

Assumption II:

$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, \quad (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$$

$\Rightarrow$ Scenario characterized by

$$m_5,\ m_{10},\ m_{1/2},\ A_0,\ \tan\beta,\ m_{H_u},\ m_{H_d}$$

GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan\beta, \mathrm{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\mathrm{Planck}}$: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term
introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference
$\Rightarrow \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 + \pi^{\pm}$ with very soft pions

GUt based models: 6.) sub-GUT:

Based on CMSSM with unification at $M_{\text{GUT}} \sim 2 \cdot 10^{16}$ GeV:

> $\Rightarrow$ Scenario characterized by
>
> $$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

Unification is assumed at $M_{\text{in}} \leq M_{\text{GUT}}$:

> $\Rightarrow$ Scenario characterized by
>
> $$M_{\text{in}},\ m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

Possible realization in "mirage unification"
warped extra dimensions
...

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

$\Rightarrow$ it is possible that with the CMSSM, NUHM, SU(5), mAMSB, sub-GUT
we missed the "correct" mechanism

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

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

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

Solution: investigate also the “general MSSM”

⇒ 11 parameters are manageable ⇒ pMSSM11

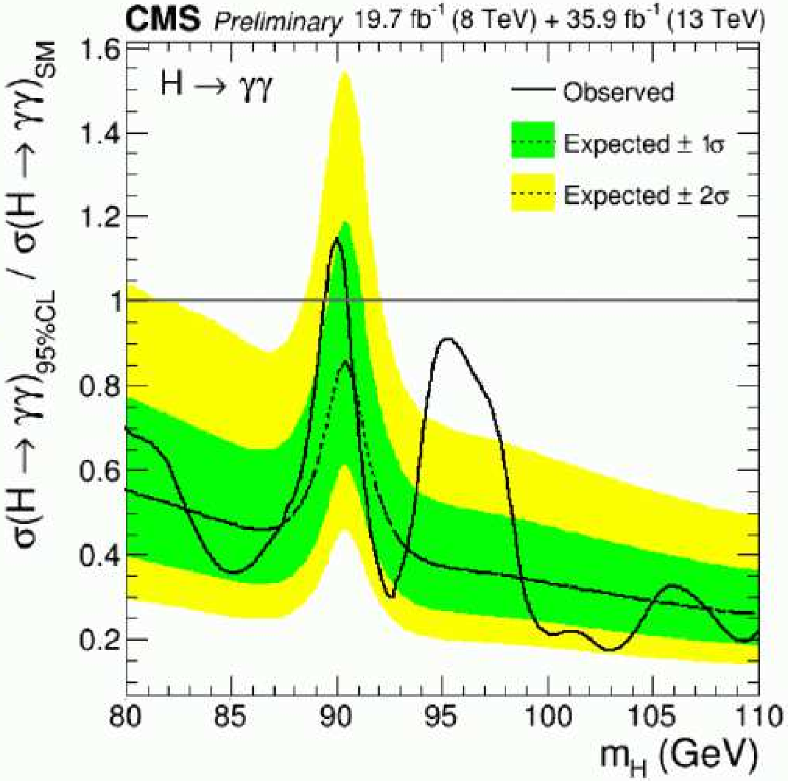
- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
- slepton mass parameter(s): $m_{\tilde{l}}$, $m_{\tilde{\tau}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing paramter: μ

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013

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



8 TeV+13 TeV: minimum(maximum) limit on (σ X Br)/ $(\sigma \text{ X Br})_{SM}$: 0.17(1.15) at m=103.0(90.0)GeV

- Combined 8 TeV+13 TeV σ X BR limit normalized to SM expectation (production processes assumed in SM proportions). No significant excess with respect to expected limits observed.

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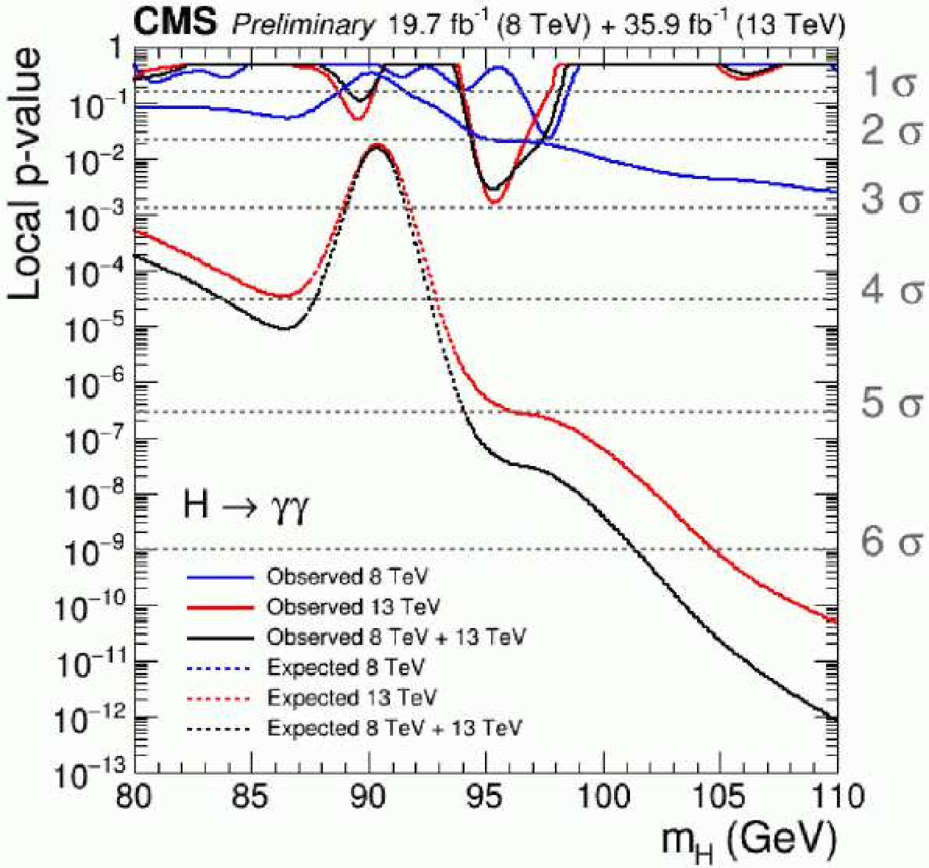
h-->γγ (70-110 GeV) Runs 1+ 2

New!



CMS PAS HIG-17-013

8 TeV: Excess with ~2.0 σ local significance at m=97.6 GeV

13 TeV: Excess with ~2.9 σ local (1.47 σ global) significance at m=95.3 GeV

8TeV+13 TeV: Excess with ~2.8 σ local (1.3 σ global) significance at m=95.3 GeV

More data are required to ascertain the origin of this excess

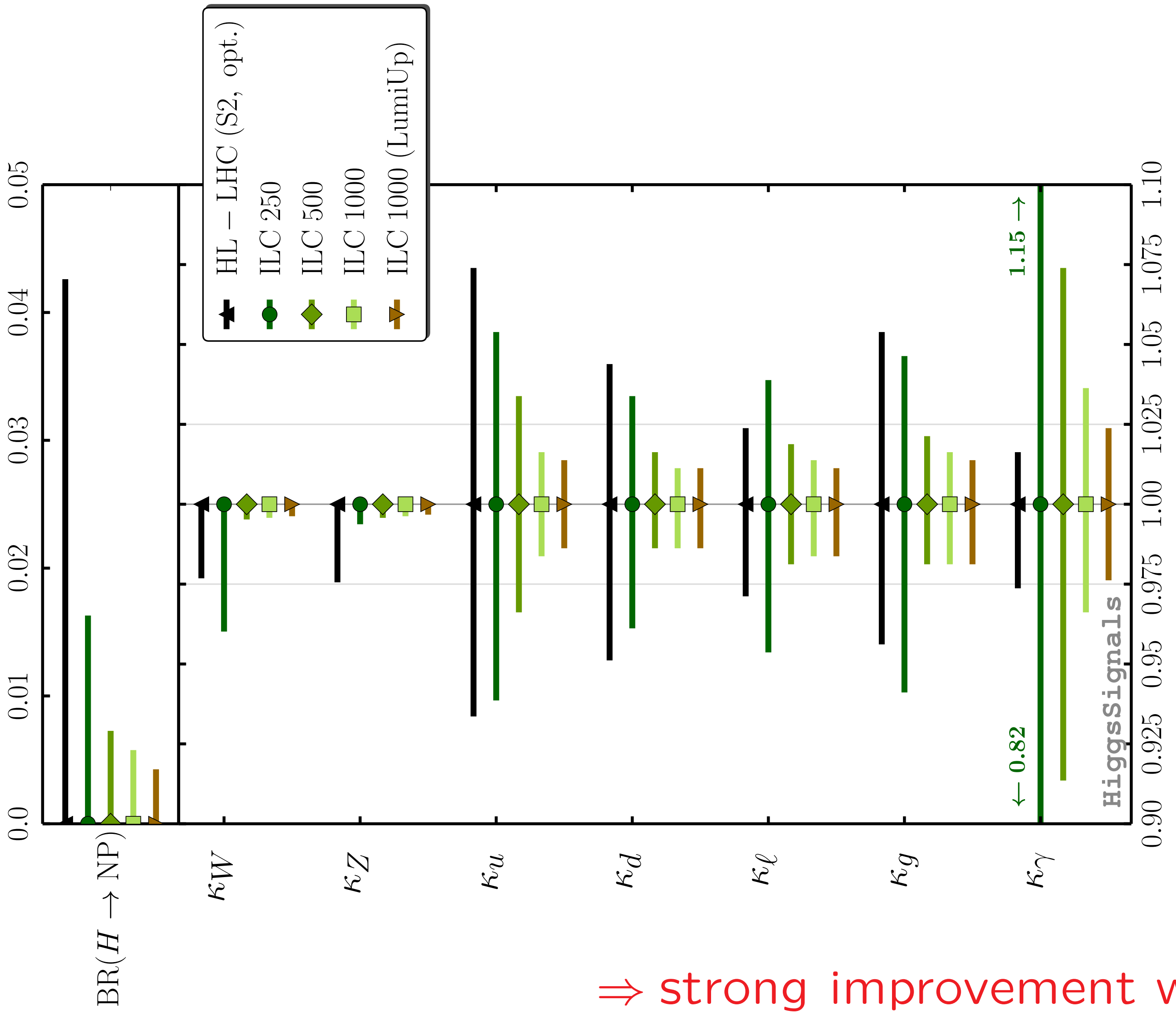
- Expected and observed local p-values for 8 TeV, 13 TeV and their combination

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017 30

HL-LHC vs. ILC in the most general κ framework:

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

assumption: $\kappa_V \leq 1$

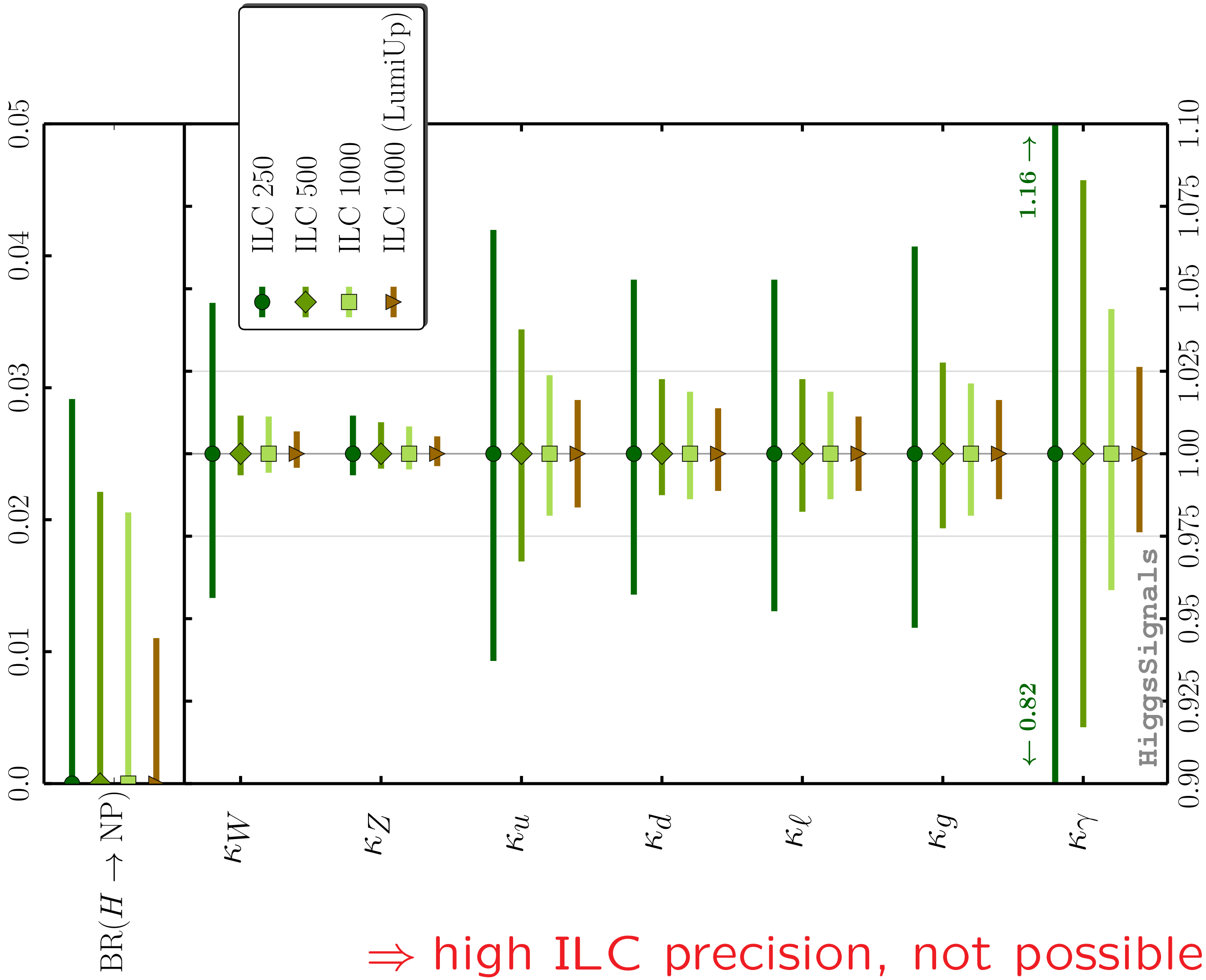


⇒ strong improvement with the ILC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit



⇒ high ILC precision, not possible at the LHC