
We still believe in supersymmetry
You must be joking

A Higgs Boson at 96 GeV?!

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Hong Kong, 01/2020

- Motivation & the "excesses"
- General analysis
- SUSY realizations
- Conclusions

1. Motivation & the “excesses”

Two Facts:

We have an SM-like Higgs 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?

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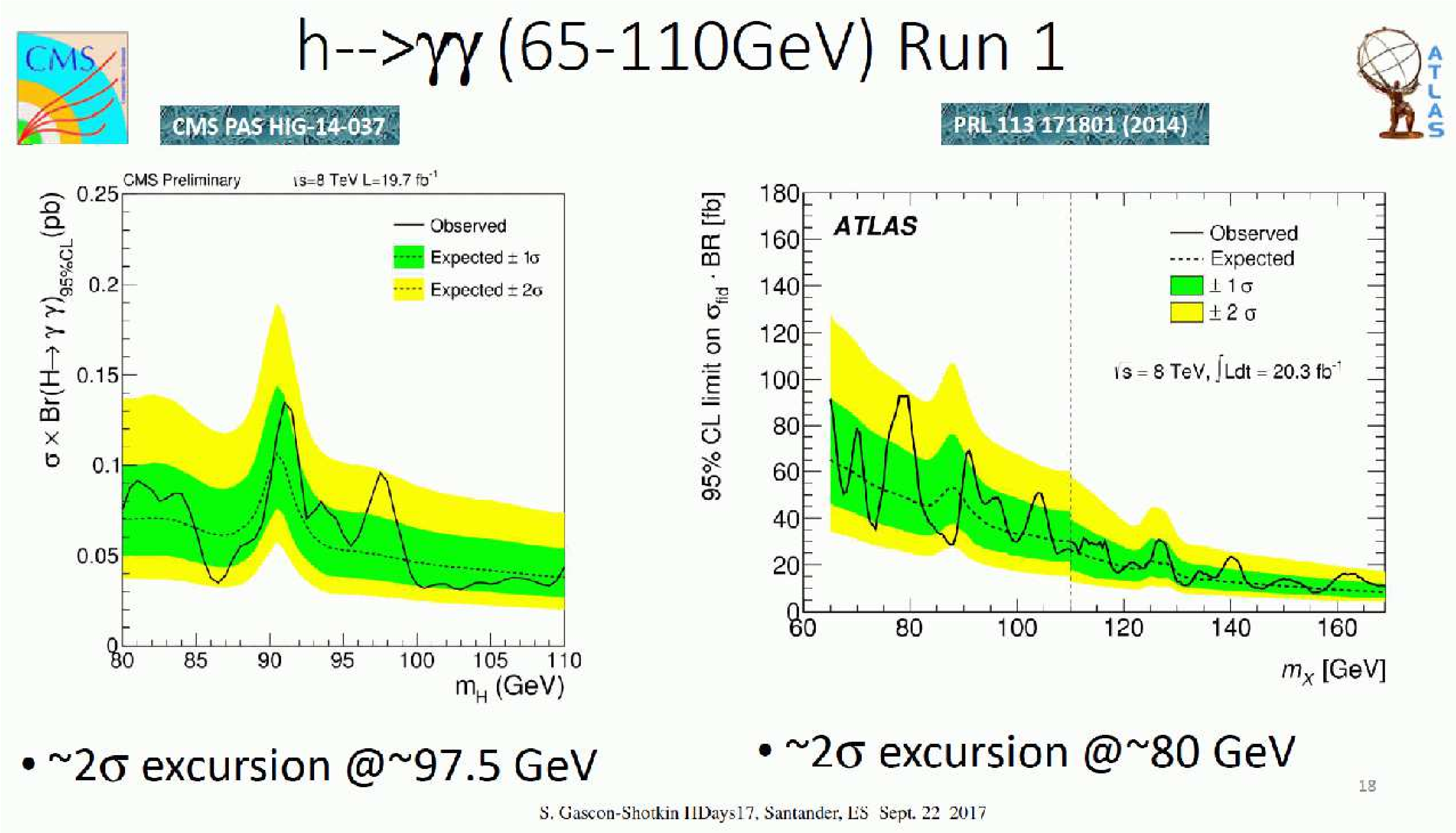
Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

A1: check changed properties

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

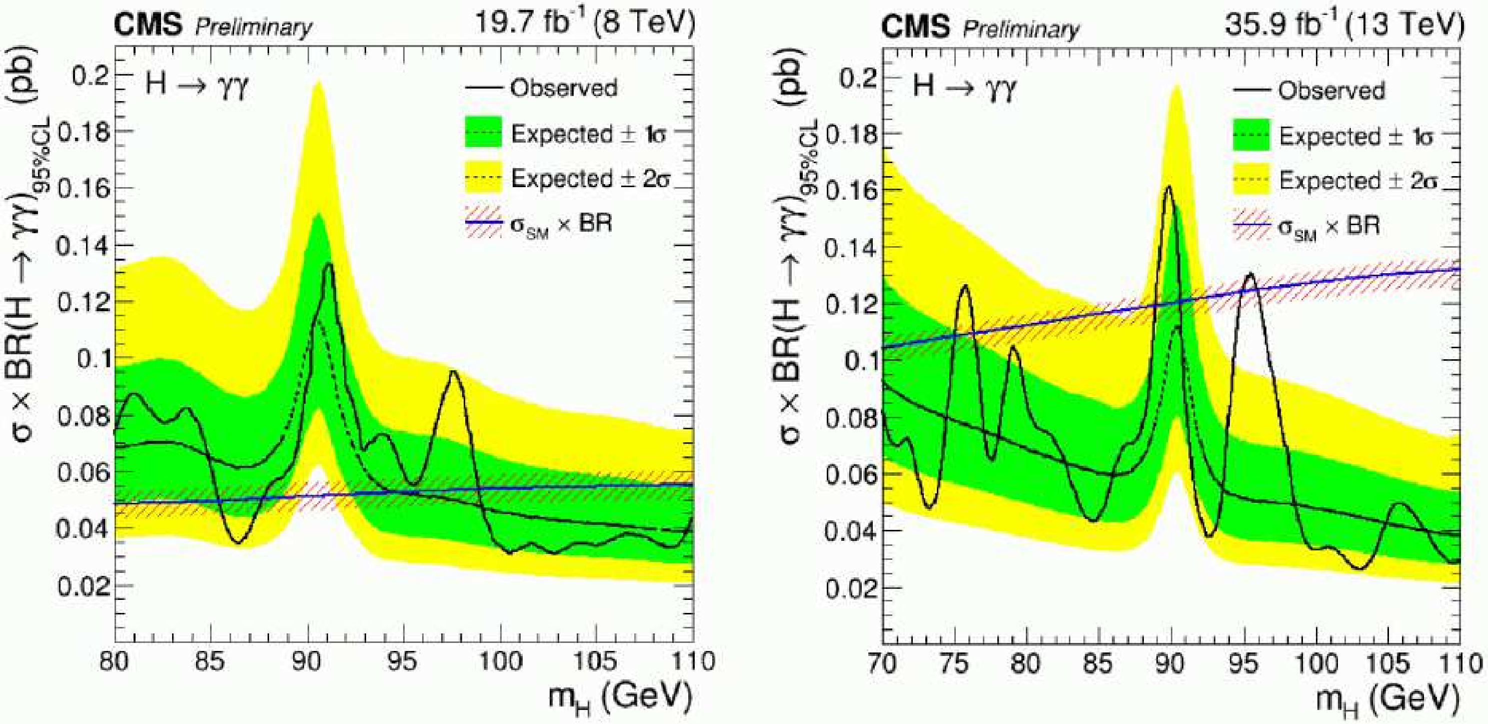
$\Rightarrow$ some results of searches below 125 GeV

[*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

What was seen at Run II?

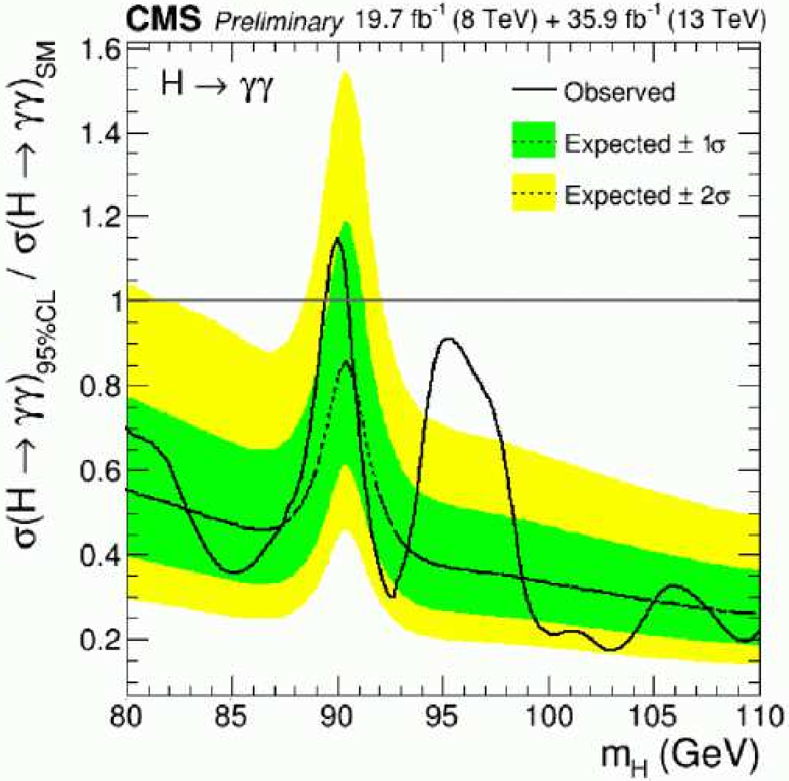
[*S. Shotkin, talk at HDays17*]

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013

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



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

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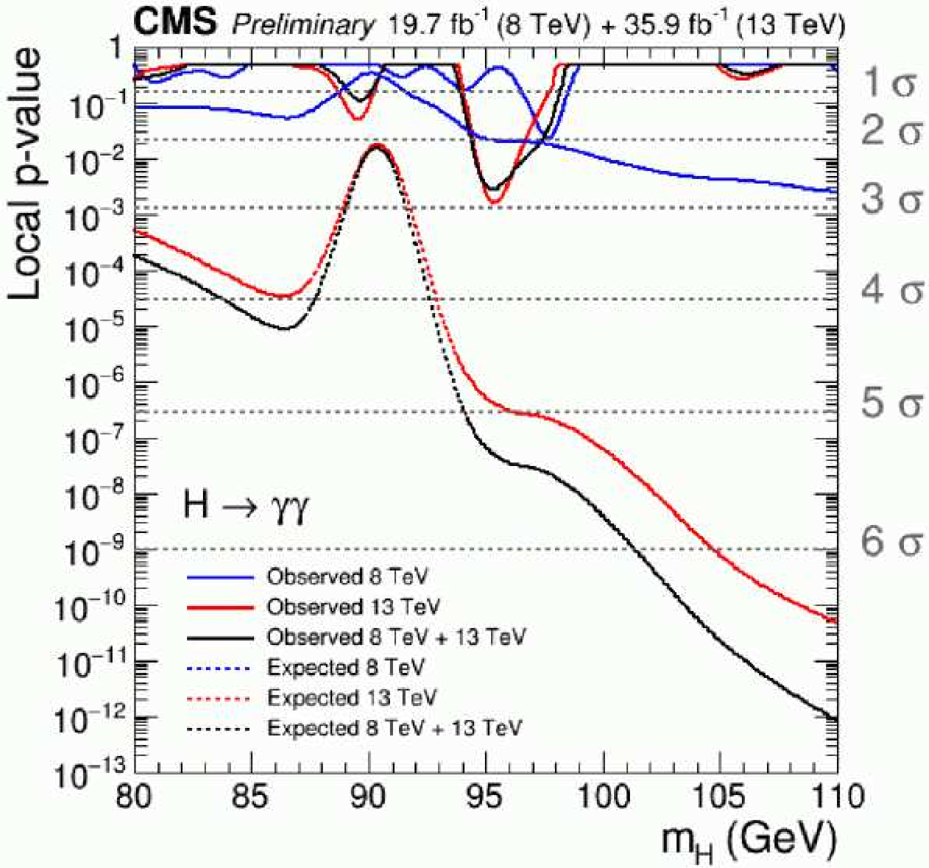

- Expected and observed local p-values for 8 TeV, 13 TeV and their combination S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

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

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h-->γγ (70-110 GeV) Runs 1+2

New!

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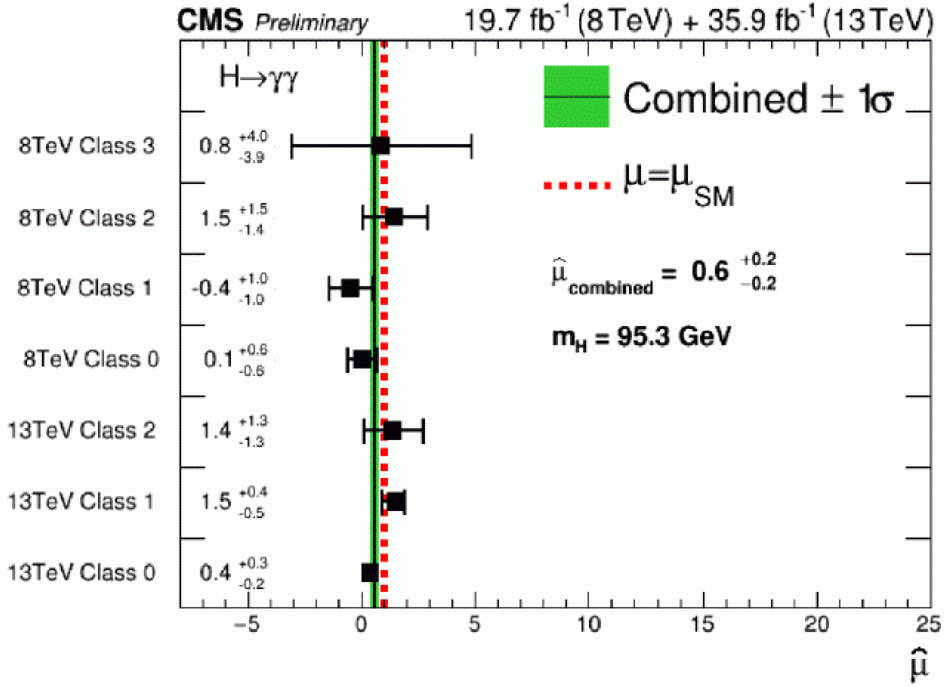

Excess here mostly driven by class 1 (&2) at 13 TeV

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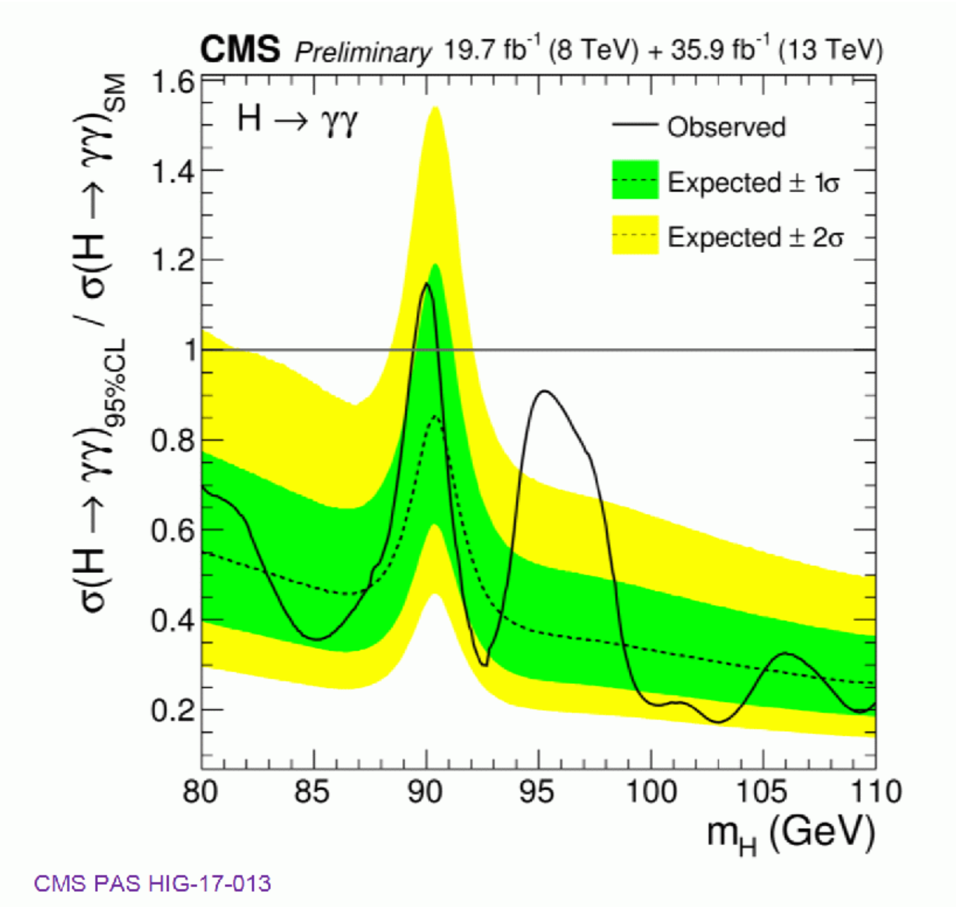
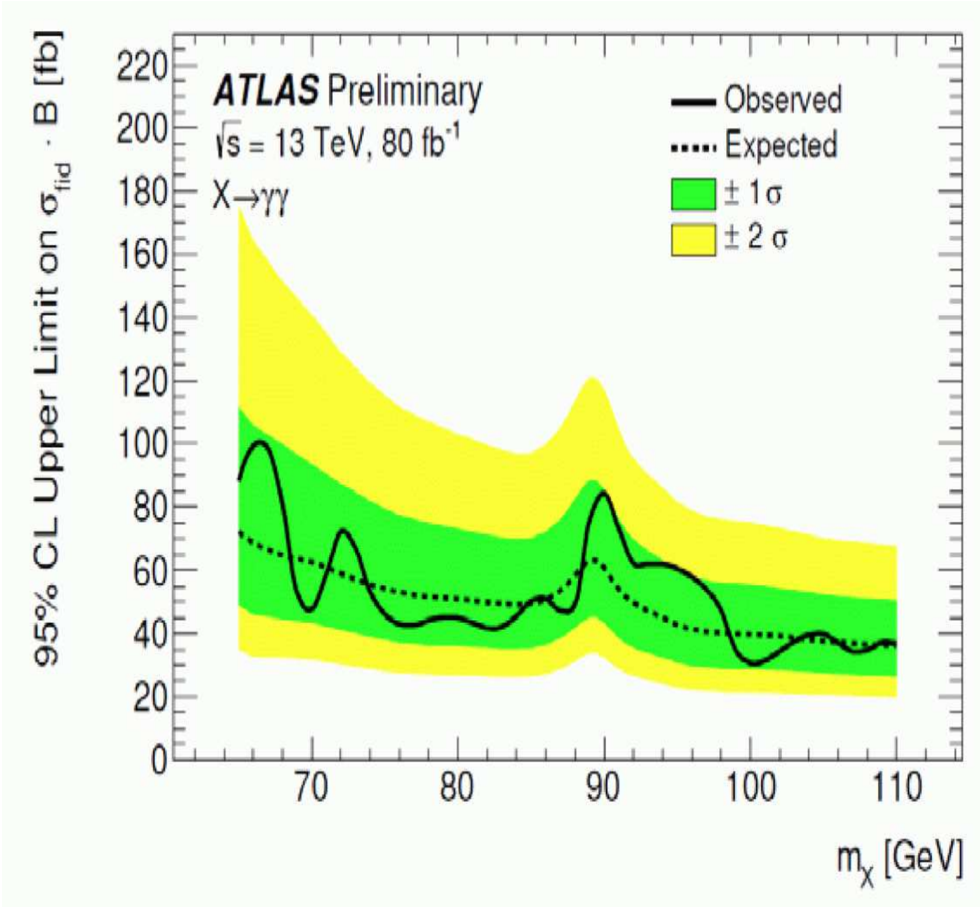
$$\mu_{\rm CMS}(96\ {\rm GeV}) = [\sigma(pp \to h_1) \times {\rm BR}(h_1 \to \gamma\gamma)]_{\rm exp/SM} = 0.6 \pm 0.2$$

What about ATLAS?





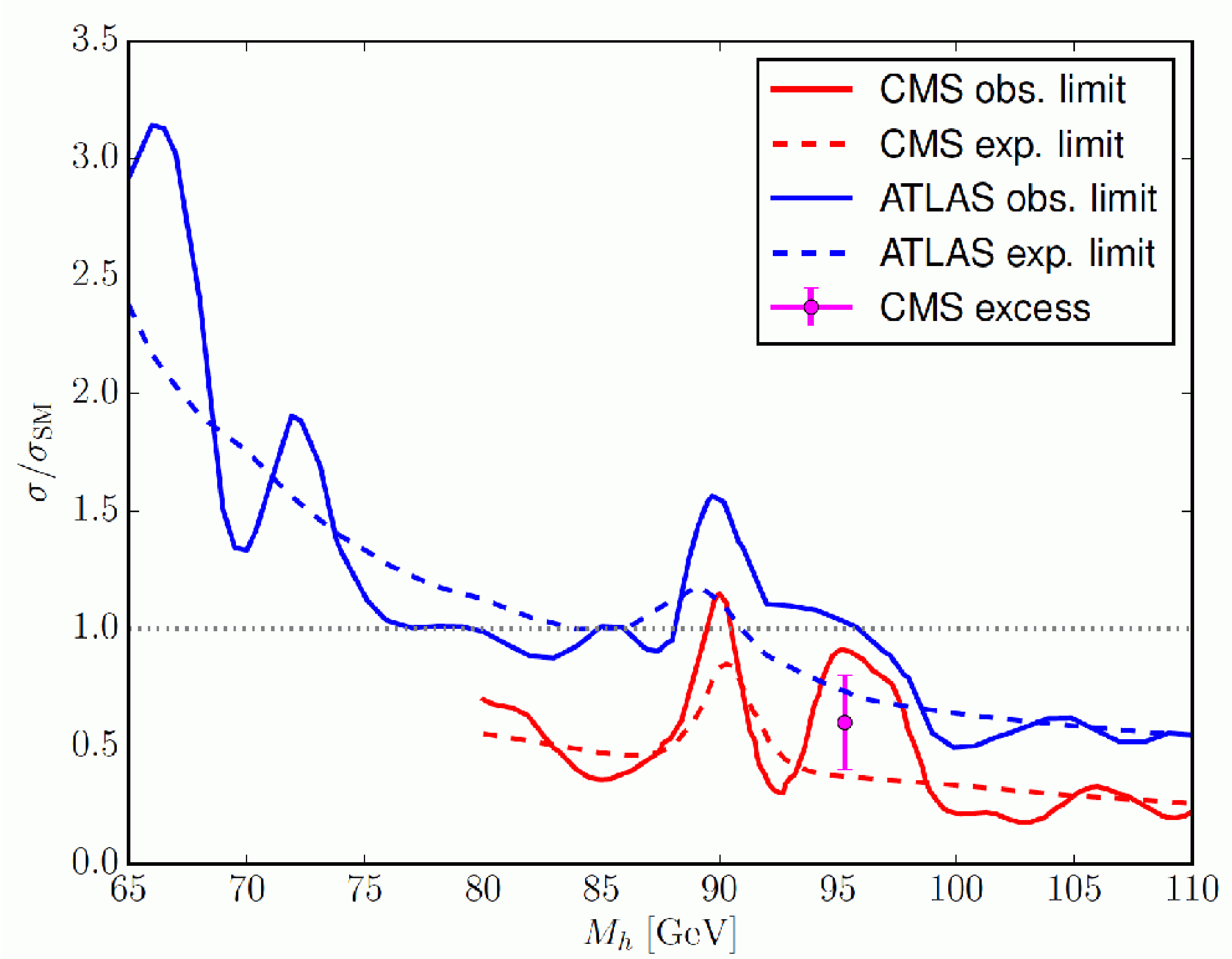
Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

⇒ ATLAS exclusion limit even weaker than CMS!

Q: why does ATLAS has same sensitivity with twice amount of data?

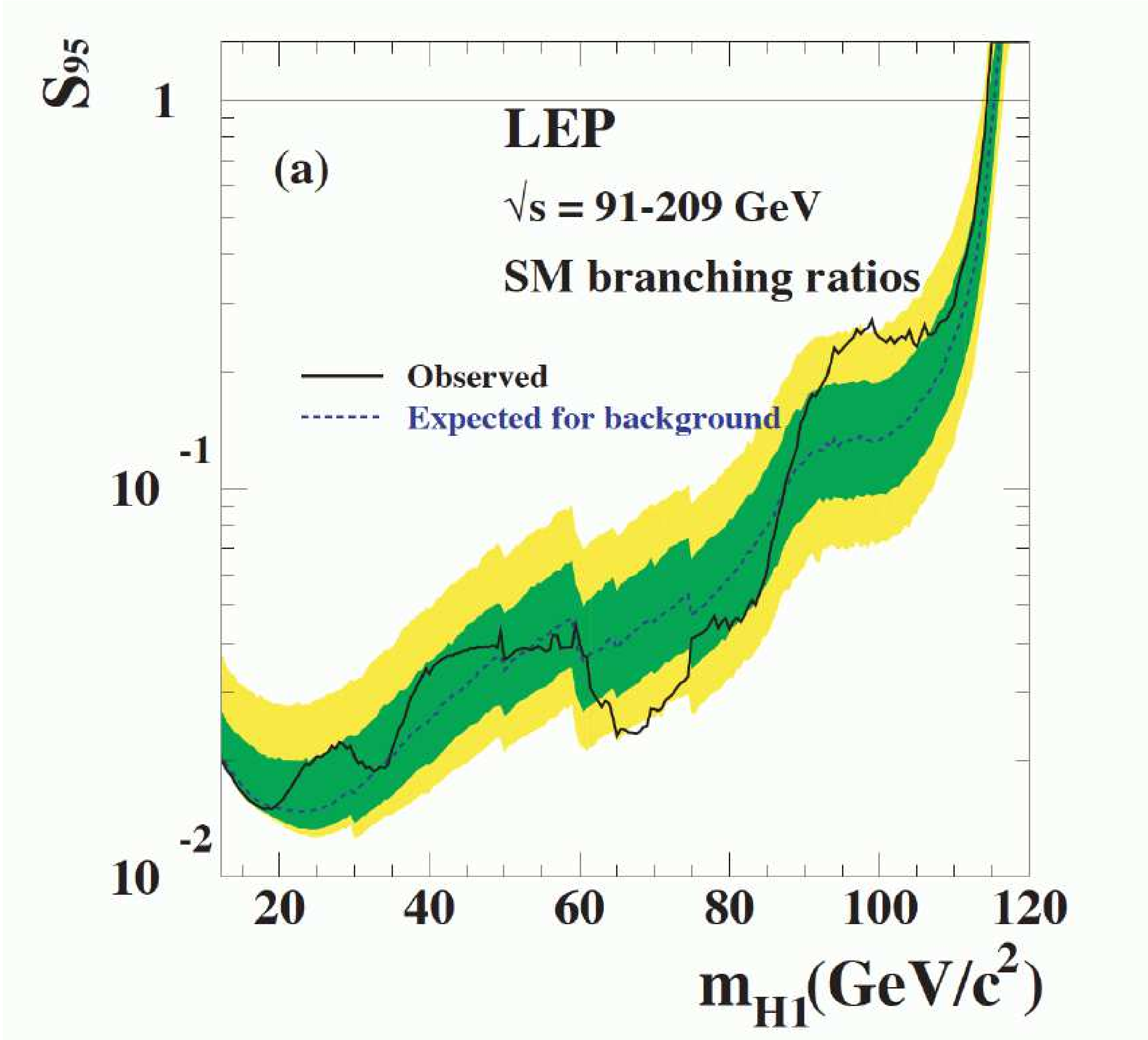
CMS and ATLAS in direct comparison:

[S.H., T. Stefaniak '18]



⇒ if there is something, it would look exactly like this!

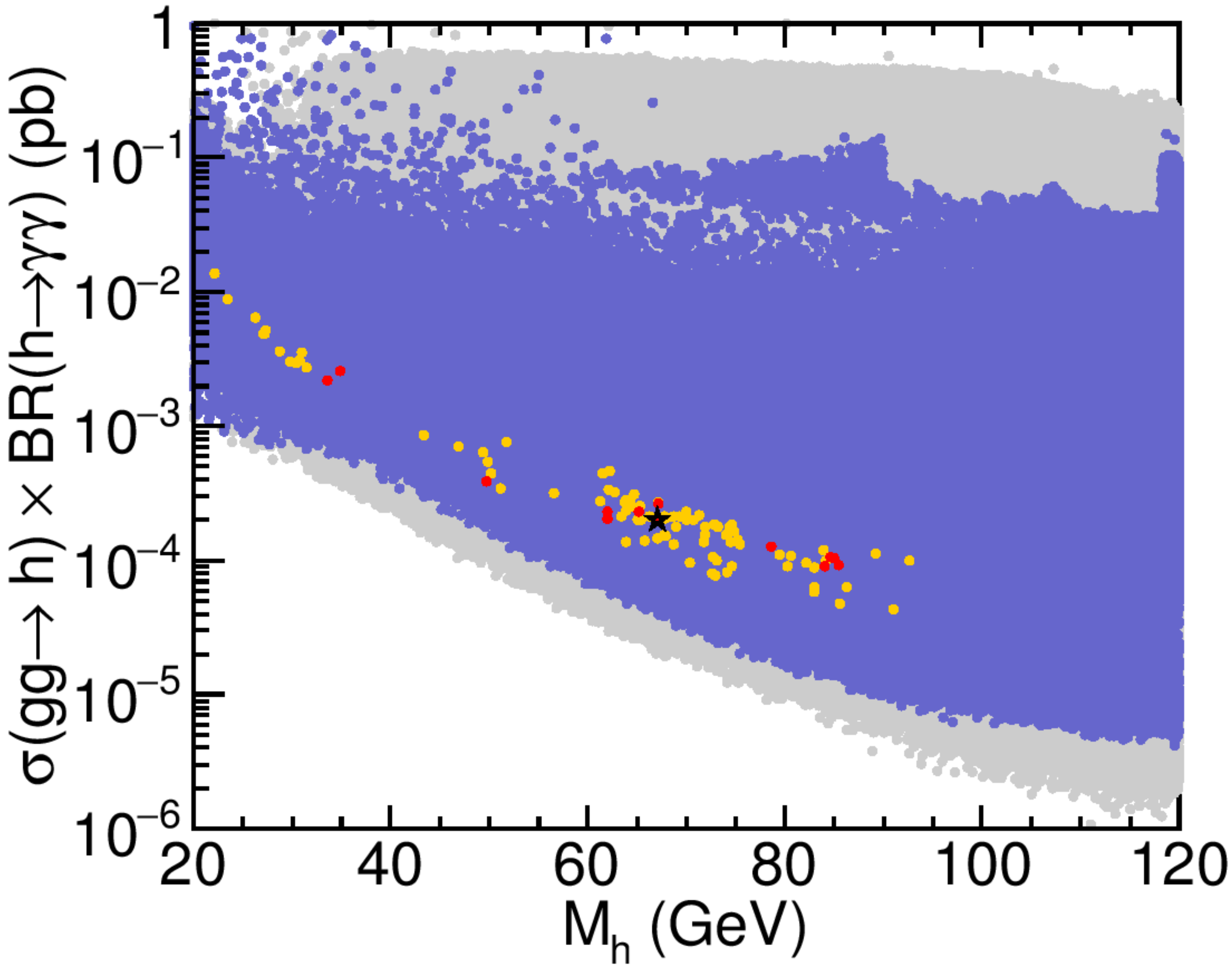
What was seen at LEP?



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

What about the MSSM?

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



$\Rightarrow$ too small rates! $\Rightarrow$ problem: 2HDM structure to "rigid"

2. General analysis

MSSM: too small rates!

$\Rightarrow$ problem: 2HDM structure to “rigid”

More general Ansatz:

– richer Higgs structure
  $\Rightarrow$ add (at least) another Higgs singlet

– drop SUSY for now
  $\Rightarrow$ allow for more flexibility
  $\Rightarrow$ but check for hints towards SUSY

– check explicit SUSY scenarios later

More general Ansatz: **N2HDM**

[T. Biekötter, M. Chakraborti, S.H. '19]

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S$$

Potential:

$$\begin{aligned} V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

Z_2 symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to \Phi_S$

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

$\Rightarrow$ exactly as in 2HDM

Three neutral $\mathcal{CP}$-even Higgses:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}, \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

Coupling to massive gauge bosons: (identical for all four types)

	$c_{h_iVV} = c_\beta R_{i1} + s_\beta R_{i2}$
h_1	$c_{\alpha_2} c_{\beta-\alpha_1}$
h_2	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta-\alpha_1}$
h_3	$-c_{\alpha_3} c_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta-\alpha_1}$

Coupling to fermions: (same pattern as in 2HDM)

	u-type (c_{h_itt})	d-type (c_{h_ibb})	leptons ($c_{h_i\tau\tau}$)
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton-specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

“Physical” input parameters:

$$\alpha_{1,2,3}\,, \quad \tan\beta\,, \quad v\,, \quad v_S\,, \quad m_{h_{1,2,3}}\,, \quad m_A\,, \quad M_{H^\pm}\,, \quad m_{12}^2$$

Needed to fit the two excesses: $m_{h_1} \sim 96$ GeV, $m_{h_2} \sim 125$ GeV

- $c^2_{h_1VV}$ strongly reduced for μ_{LEP}
- c_{h_1bb} reduced to enhance BR($h_1 \to \gamma\gamma$)
- c_{h_1tt} not reduced for μ_{CMS}
- $c_{h_1\tau\tau}$ possibly reduced to enhance BR($h_1 \to \gamma\gamma$)

	Decrease $c_{h_1b\bar{b}}$	No decrease $c_{h_1t\bar{t}}$	No enhancement $c_{h_1\tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{12}}{s_\beta})$:-)
type II	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{11}}{c_\beta})$:-)
type III	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{11}}{c_\beta})$:-(
type IV	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(

Type II and IV: c_{h_1bb} and c_{h_1tt} independent

Type II bonus: $c_{h_1\tau\tau}$ can be suppressed (together with c_{h_1bb})

$\Rightarrow$ only type II and IV can fit CMS and LEP excesses

$\Rightarrow$ Parameter scan $\Rightarrow$ ScannerS

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS

- Minimum of potential is global minimum $\Rightarrow$ ScannerS

- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds

- SM-like Higgs properties $\Rightarrow$ HiggsSignals (N2HDECAY, SusHi)
  $\chi^2_{\text{red}} := \chi^2 / n_{\text{obs}}$

- Flavor physics (mainly BR($B_s \to X_s \gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds

- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

Fitting the excesses:

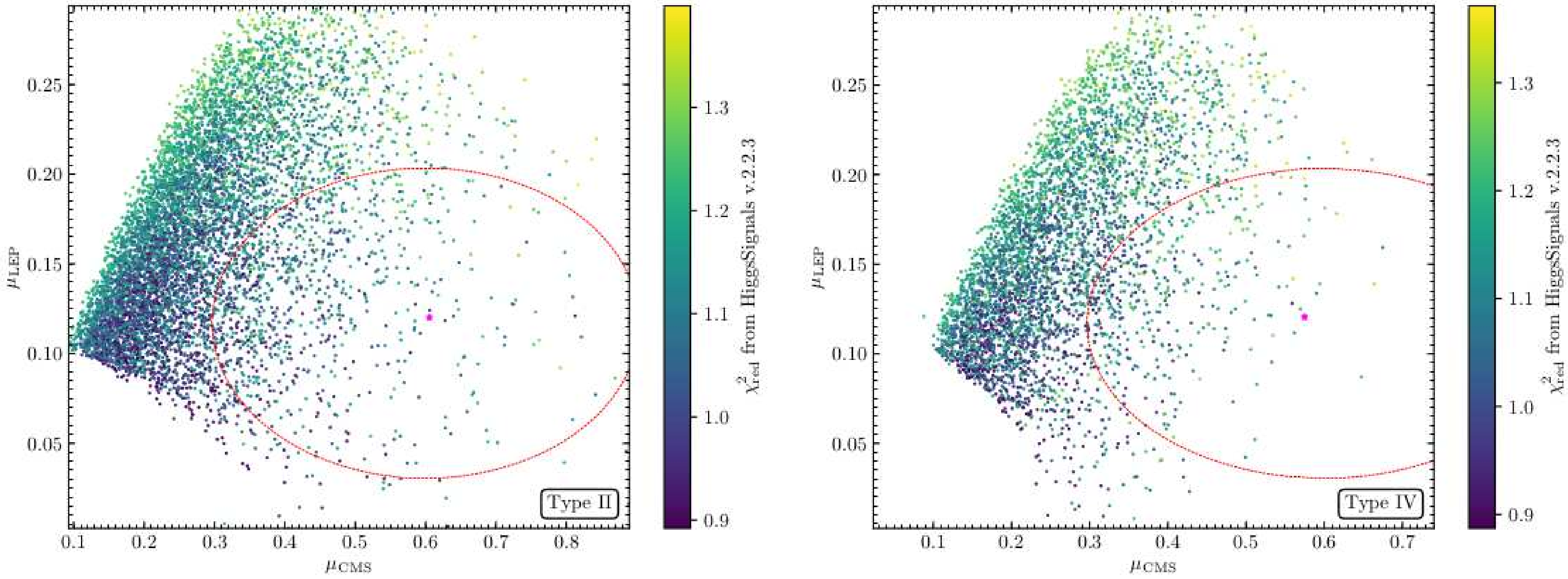
$$\mu_{\text{LEP}} = 0.117 \pm 0.057, \qquad \mu_{\text{CMS}} = 0.6 \pm 0.2$$

$$\mu_{\text{LEP}} = \frac{\sigma_{\text{N2HDM}}(e^+e^- \to Zh_1)}{\sigma_{\text{SM}}(e^+e^- \to ZH)} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}$$
$$= \left|c_{h_1VV}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}$$

$$\mu_{\text{CMS}} = \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$
$$= \left|c_{h_1tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$

$$\chi^2_{\text{CMS-LEP}} = \frac{(\mu_{\text{LEP}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\text{CMS}} - 0.6)^2}{(0.2)^2}$$

$\Rightarrow$ “best-fit point”



⇒ excesses well fitted, with good $\chi^2_{\rm red}$: 0.9 – 1.3

⇒ preferred $M_{H^\pm}$: 650 GeV – 950 GeV (lower limit: flavor constr.)
⇒ preferred $\tan\beta$: 0.8 – 3.8

Best-fit point in type II:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
96.5263	125.09	535.86	712.578	737.829	
$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.26287	1.26878	-1.08484	-1.24108	80644.3	272.72
$\mathrm{BR}_{h_1}^{bb}$	$\mathrm{BR}_{h_1}^{gg}$	$\mathrm{BR}_{h_1}^{\tau\tau}$	$\mathrm{BR}_{h_1}^{\gamma\gamma}$	$\mathrm{BR}_{h_1}^{WW}$	$\mathrm{BR}_{h_1}^{ZZ}$
0.5048	0.2682	$5.09 \cdot 10^{-2}$	$2.582 \cdot 10^{-3}$	$1.37 \cdot 10^{-2}$	$1.753 \cdot 10^{-3}$
$\mathrm{BR}_{h_2}^{bb}$	$\mathrm{BR}_{h_2}^{gg}$	$\mathrm{BR}_{h_2}^{\tau\tau}$	$\mathrm{BR}_{h_2}^{\gamma\gamma}$	$\mathrm{BR}_{h_2}^{WW}$	$\mathrm{BR}_{h_2}^{ZZ}$
0.5916	0.0771	$6.36 \cdot 10^{-2}$	$2.153 \cdot 10^{-3}$	0.2087	$2.610 \cdot 10^{-3}$

$\Rightarrow$ surprizingly large $\mathrm{BR}_{h_1}^{\gamma\gamma}$

Best-fit point in type IV:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
97.8128	125.09	485.998	651.502	651.26	

$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.3147	1.27039	-1.02829	-1.32496	41034.1	647.886

$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.4074	0.20714	0.248324	$2.139 \cdot 10^{-3}$	$1.347 \cdot 10^{-2}$	$1.579 \cdot 10^{-3}$

$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.5363	0.09388	$7.58 \cdot 10^{-2}$	$2.247 \cdot 10^{-3}$	0.2267	$2.836 \cdot 10^{-2}$

$\Rightarrow$ substantially larger $\text{BR}_{h_1}^{\tau\tau}$ than in type II

What can we learn from future measurements?

– LHC h_{125} coupling measurements

– HL-LHC h_{125} coupling measurements

– ILC (or other e^+e^- collider) h_{125} coupling measurements

– direct production of ϕ_{96} at the LHC

– direct production of ϕ_{96} at the HL-LHC

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– production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/. . .

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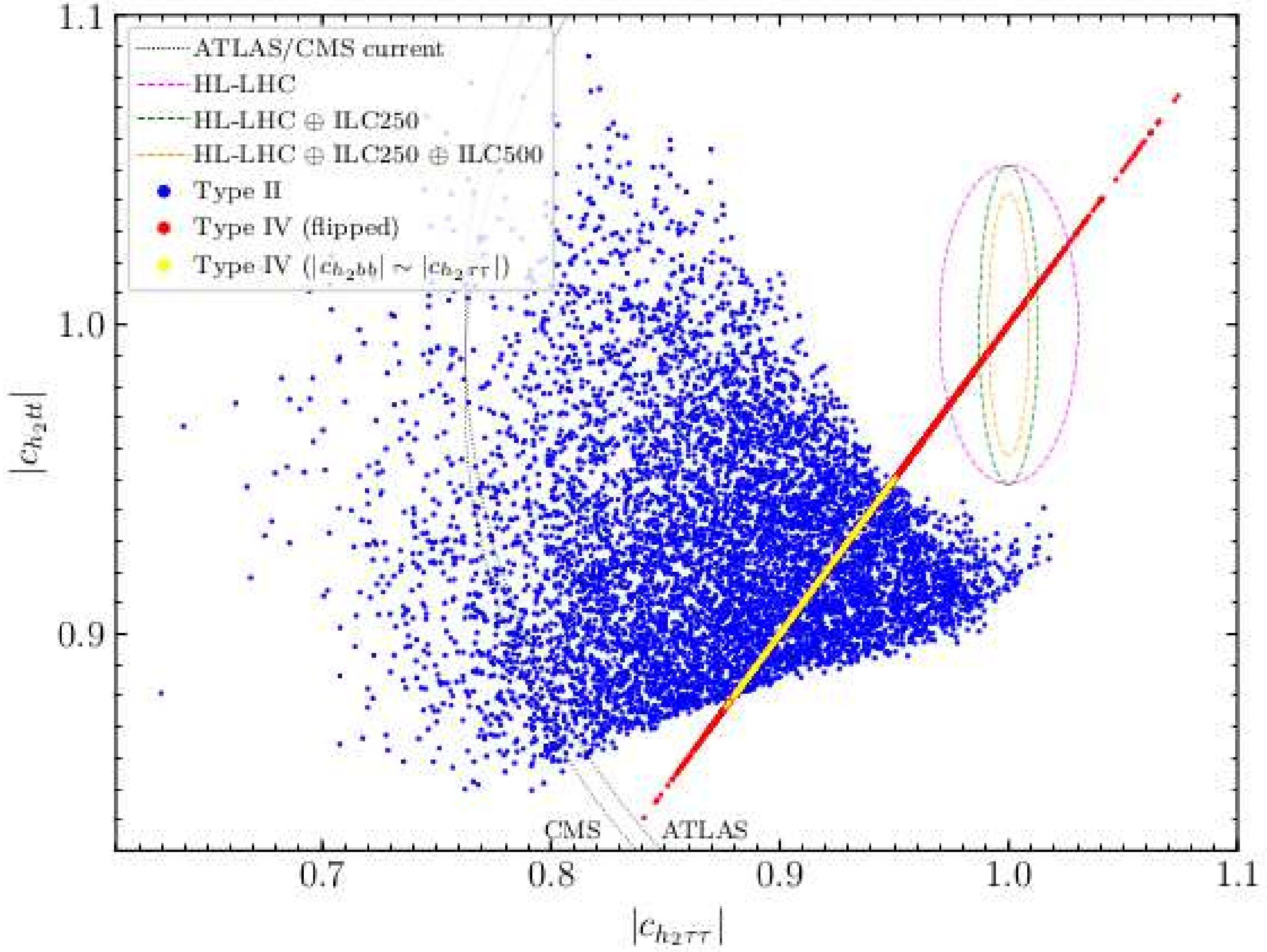
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type II shows deviation from SM

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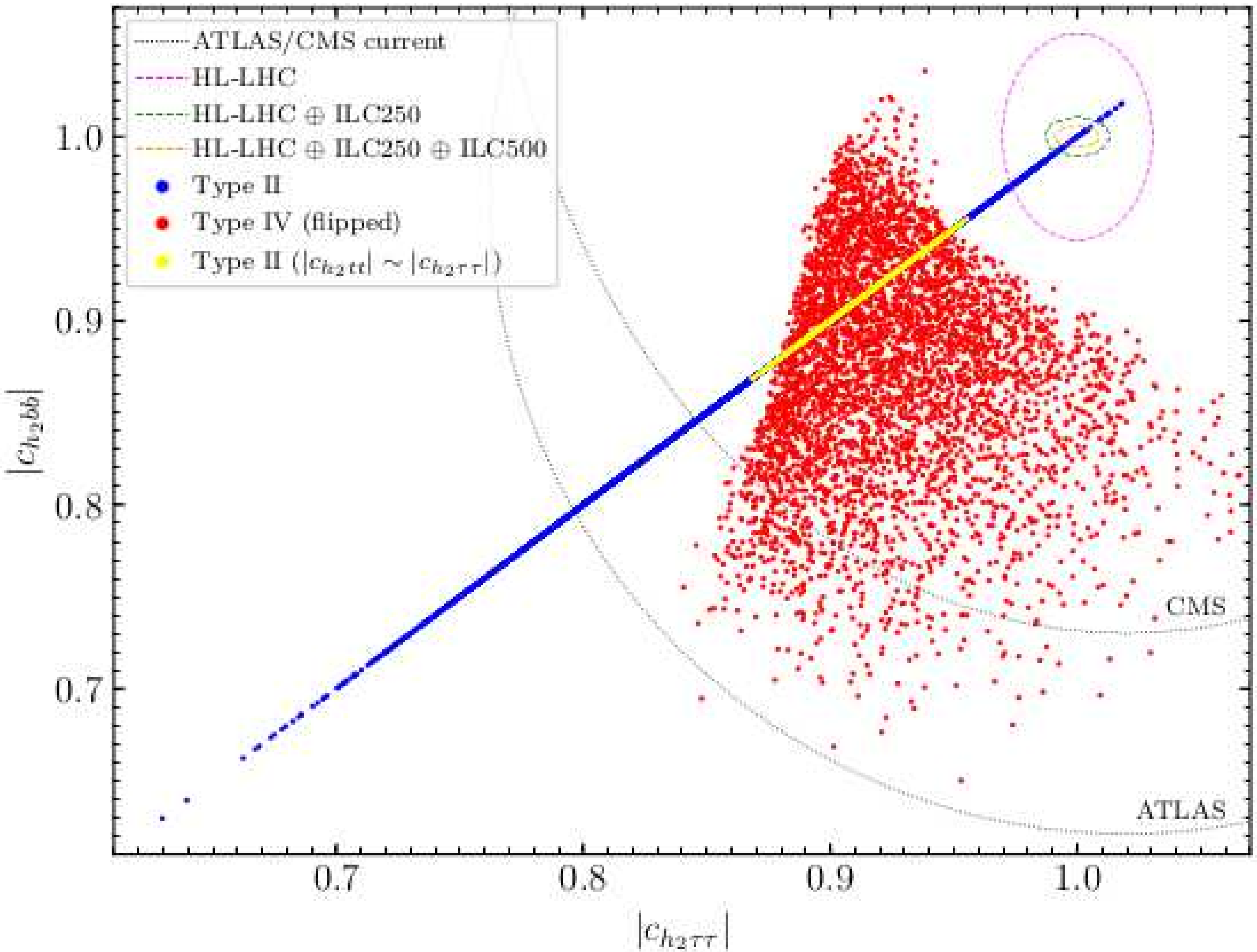
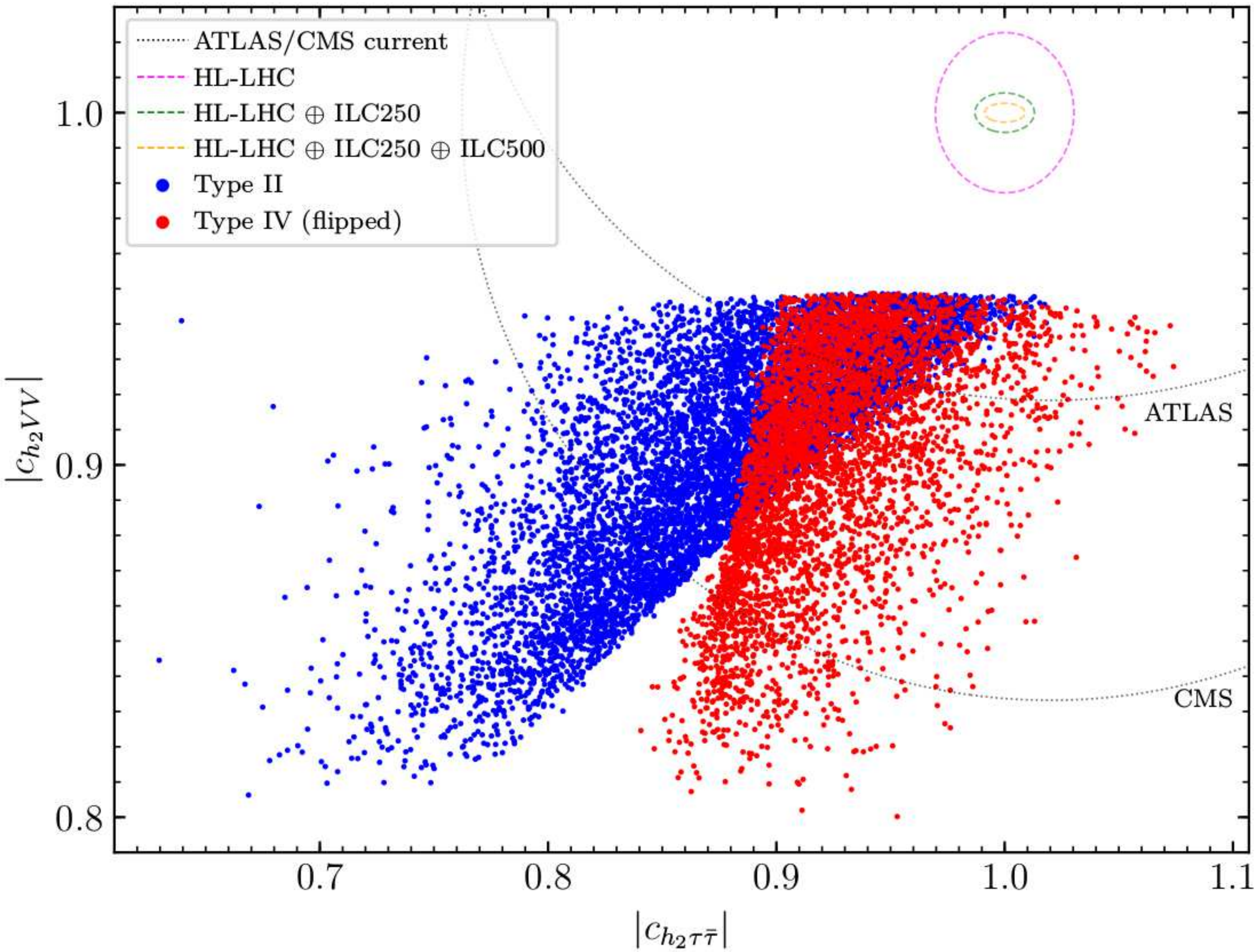


⇒ type IV shows deviations from SM

⇒ N2HDM can always be distinguished from SM!

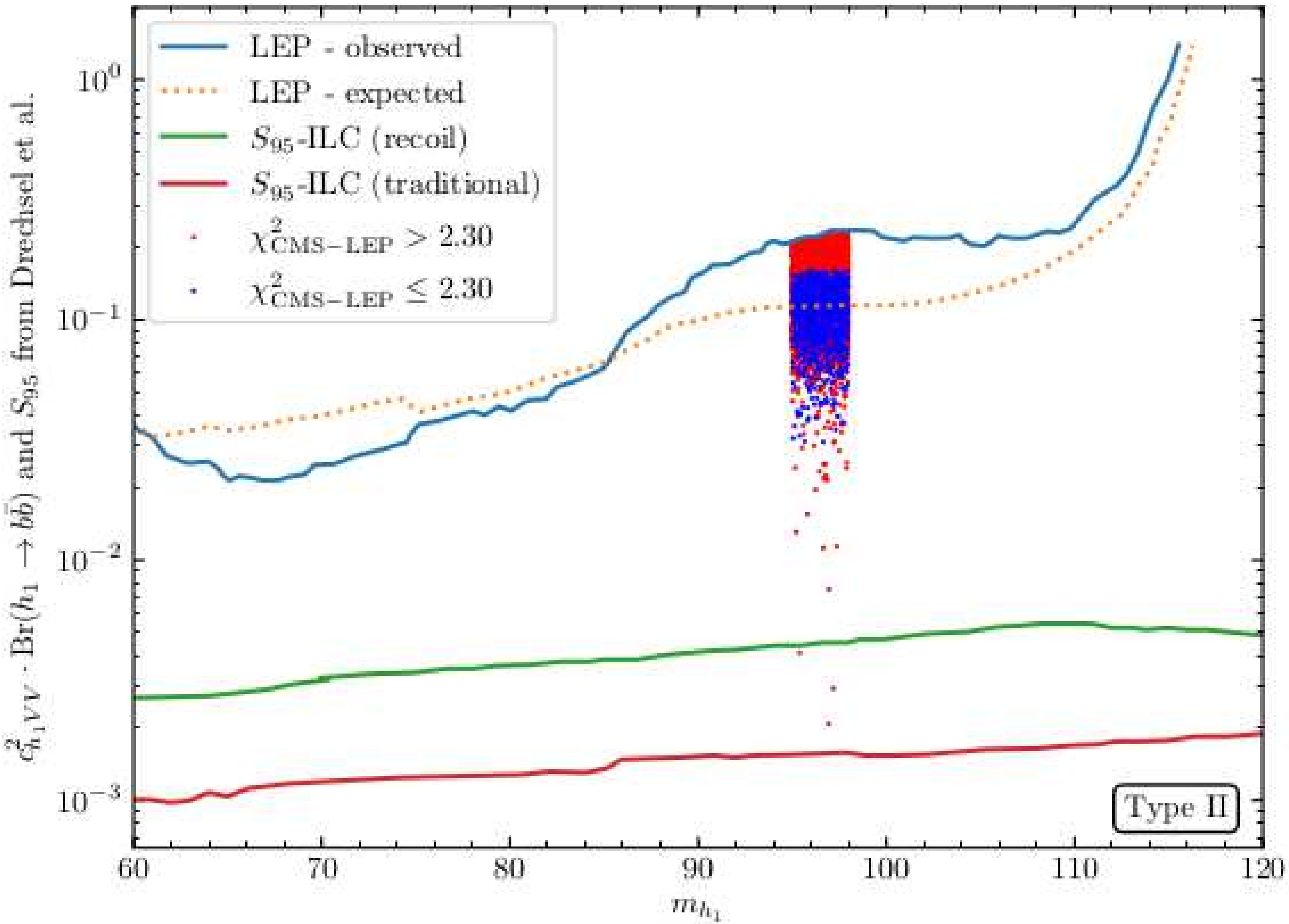
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM!

Next project? $\Rightarrow$ ILC production of the light scalar



$\Rightarrow$ new state easily in the reach of the ILC (or other e^+e^- collider)

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– NMSSM
– $\mu\nu$SSM
– . . .

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$\Rightarrow$ models with an additional singlet??

– NMSSM
– $\mu\nu$SSM
– ...

Q: Can the models fit the excesses despite the additional SUSY constraints on the Higgs sector **???**

What about the NMSSM?

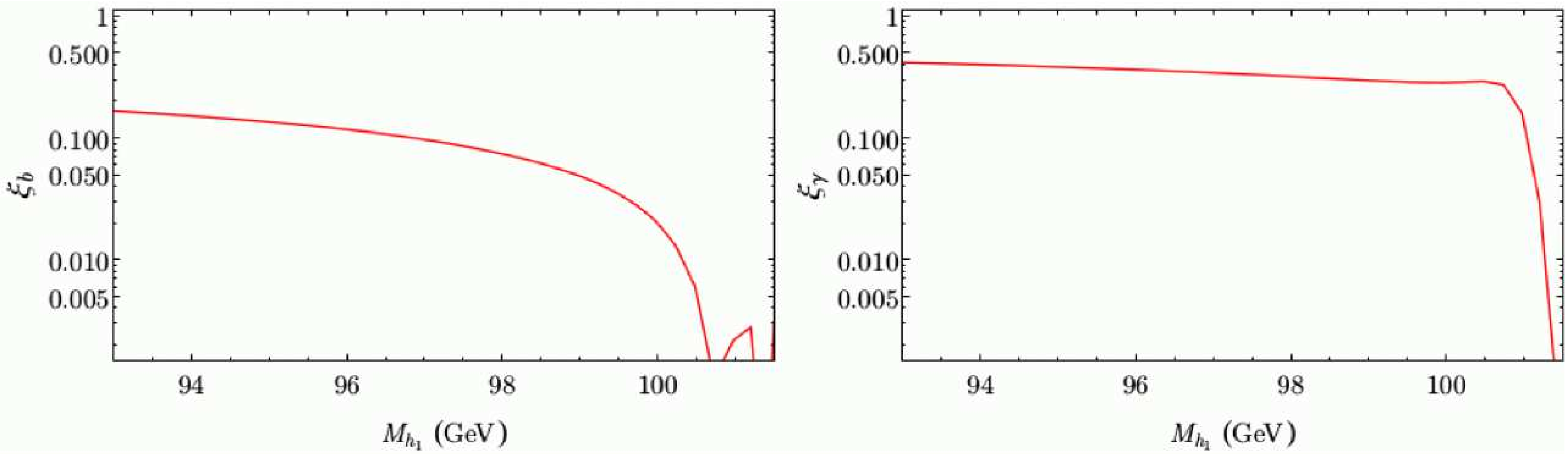
[F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

$\lambda = 0.6,\ \kappa = 0.035,\ \tan\beta = 2,\ \mu_{\text{eff}} = (397 + 15x)$ GeV, $M_{H^\pm} = 1$ TeV, $A_\kappa = -325$ GeV, $M_{\text{SUSY}} = 1$ TeV, $A_t = A_b = 0$

$$\xi_b \equiv \frac{\Gamma[h_1 \to ZZ] \cdot \text{BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to ZZ] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+e^- \to Z(H_{\text{SM}}(M_{h_1}) \to b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot \text{BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to gg] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} \,.$$



$\Rightarrow$ both excesses can be fitted simultaneously (at $1 - 1.5\,\sigma$)!

What about 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

What about the $\mu\nu$SSM?

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$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)

$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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

[*T. Biekötter, S.H., C. Muñoz '17*]

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

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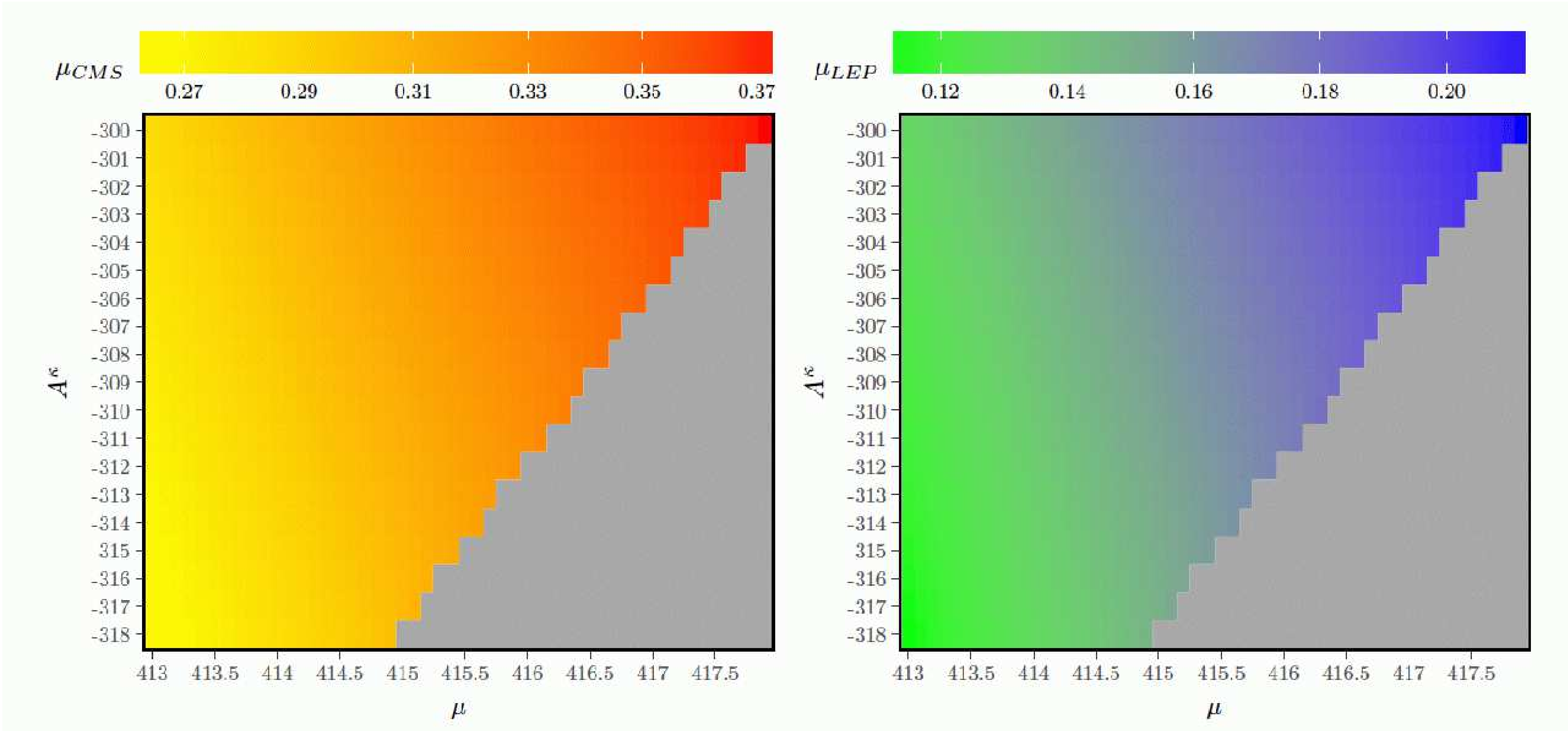
[*T. Biekötter, S.H., C. Muñoz '17*]

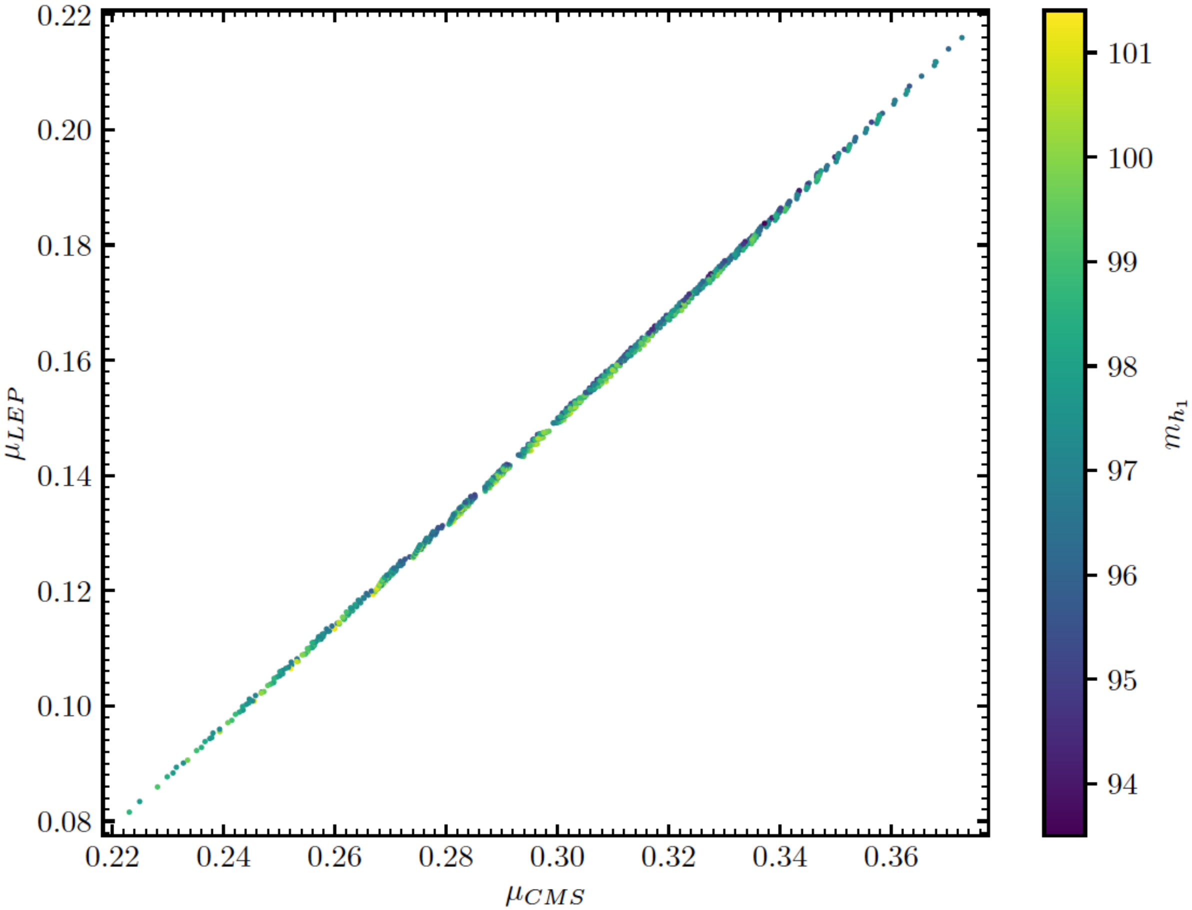


$\Rightarrow$ YES, WE CAN! :-)

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

Why can SUSY explain the excesses only at $1 - 1.5\,\sigma$?

[T. Biekötter, S.H., C. Muñoz '19]



⇒ SUSY enforces strong correlation!

⇒ note: ATLAS limits and CMS "observation"
will likely result in a lower $\mu_{\rm LHC}$!

4. Conclusinos

- Interesting excess in $\phi \to \gamma\gamma$ at 96 GeV at CMS
  Compatible with $\phi \to b\bar{b}$ at 98 GeV at LEP
  Compatible with ATLAS limits

- MSSM cannot explain the $\gamma\gamma$ excess $\Rightarrow$ 2HDM Higgs structure too rigid

- More general Ansatz: N2DHM
  - type II and IV can fit the excesses
  - type II fits best (as predicted by SUSY)

- Measurements of h_{125} couplings at e^+e^- colliders
  - can firmly establish a difference w.r.t. the SM
  - can distinguish between type II and IV

- Direct production of ϕ_{96} at e^+e^- colliders
  - production easily possible
  - detailed study of ϕ_{96} possible

- SUSY realizations:
  - NMSSM can explain both excesses at $1 - 1.5\,\sigma$
  - $\mu\nu$SSM can explain both excesses at $1 - 1.5\,\sigma$
  - SUSY enforces strong correlation between μ_{CMS} and μ_{LEP}
  - better agreement with μ_{LHC}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Theory meets Experiment
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Further Questions?