"So, Edith, you didn't tell me?...Your son finished law school?"

Light Higgs Bosons at the ILC

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

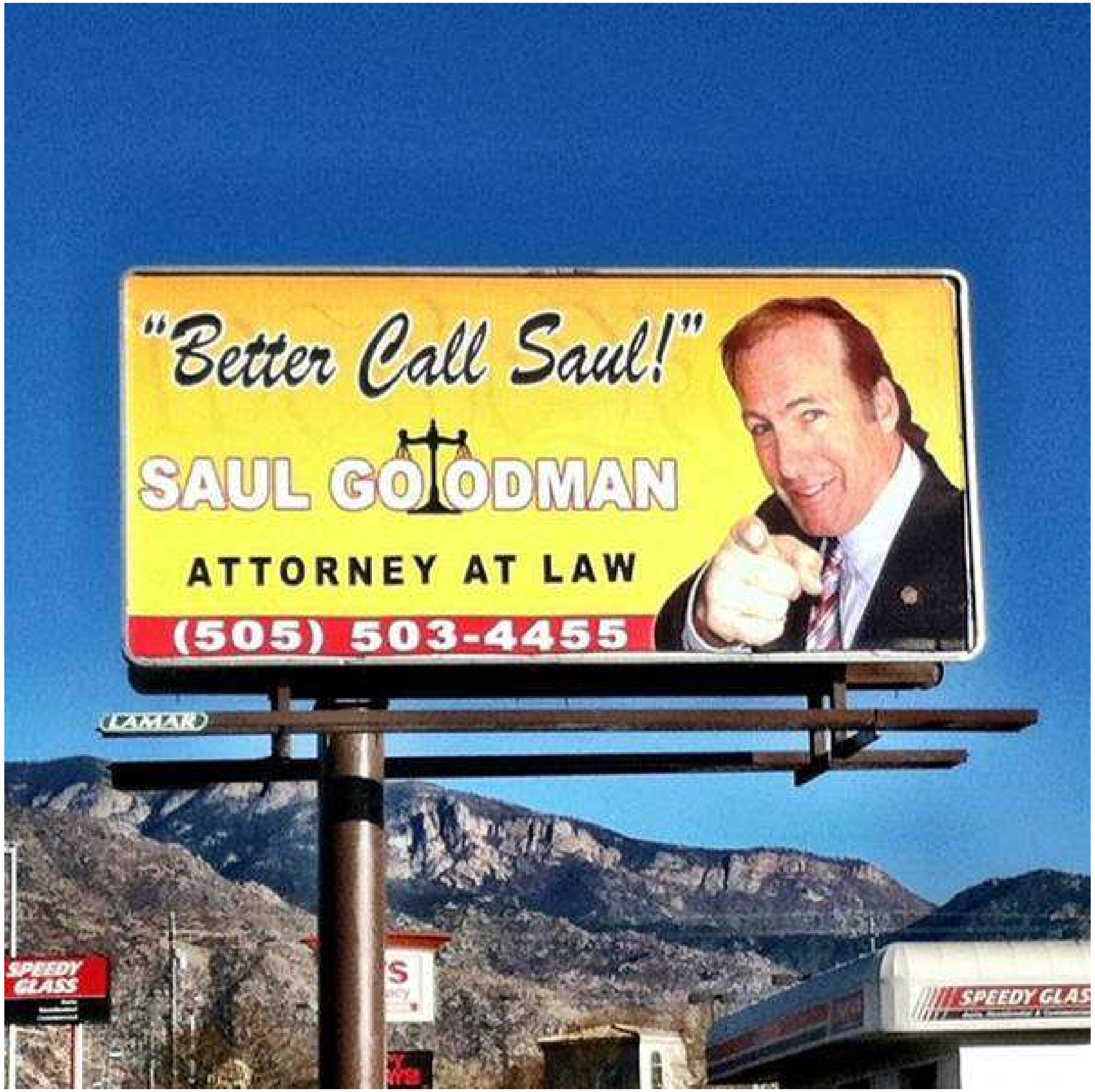
Osaka/zoom, 03/2021

(mainly) with *[M. Chakraborti,* $\{$*T. Biekötter], G. Weiglein*$\}$

- The Excesses
- General Analysis
- Probes of the 125 GeV Higgs at the ILC
- Probes of the 96 GeV Higgs at the ILC
- Conclusions

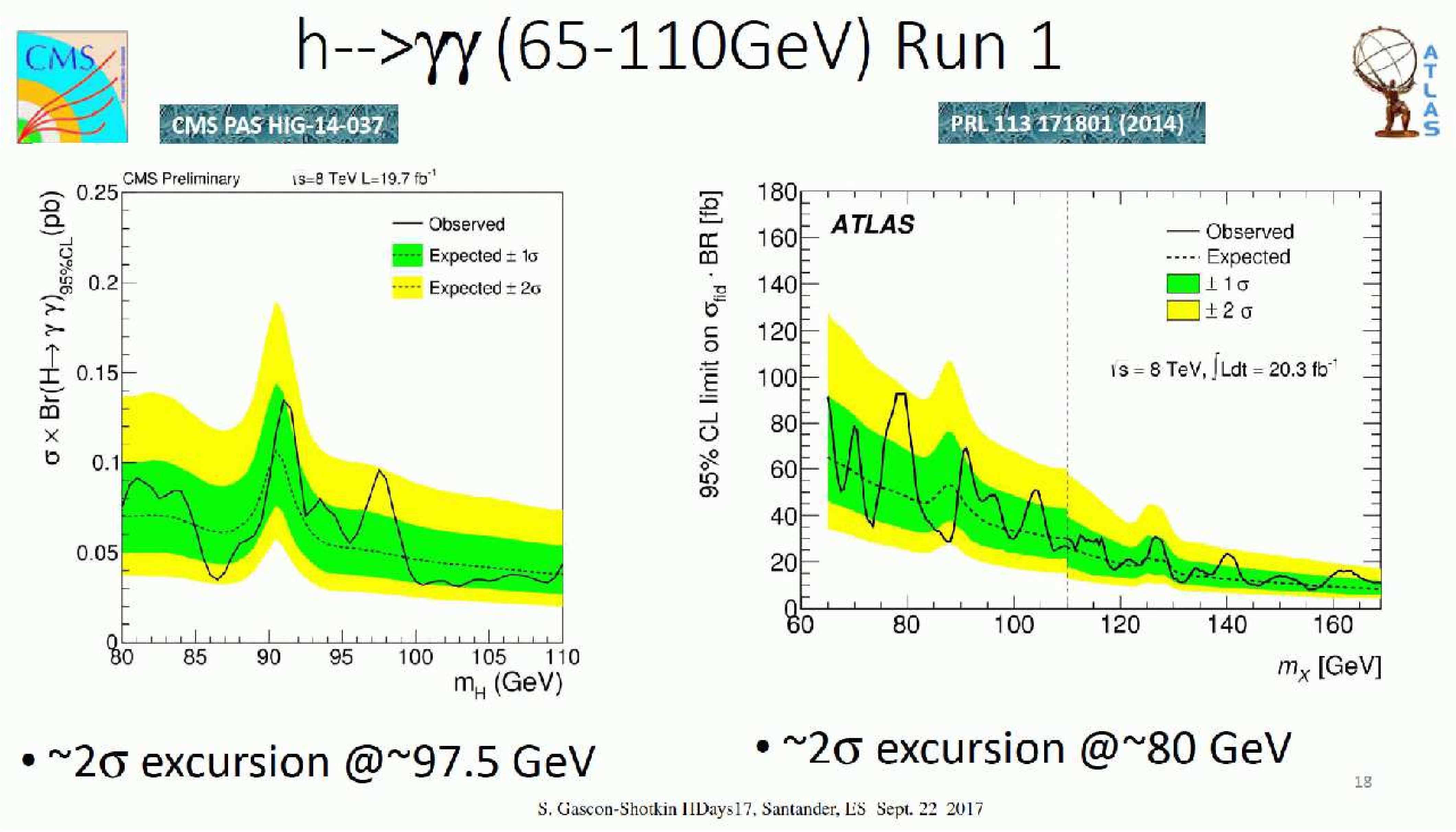
1. The excesses

- What was seen in Run I?
- What was seen in Run II?
- What was seen at LEP?
- Should we get excited?
- Which model fits?



What was seen at Run I?

[*S. Shotkin, talk at HDays17*]



h-->γγ (65-110GeV) Run 1

CMS PAS HIG-14-037

PRL 113 171801 (2014)

- ~2σ excursion @~97.5 GeV

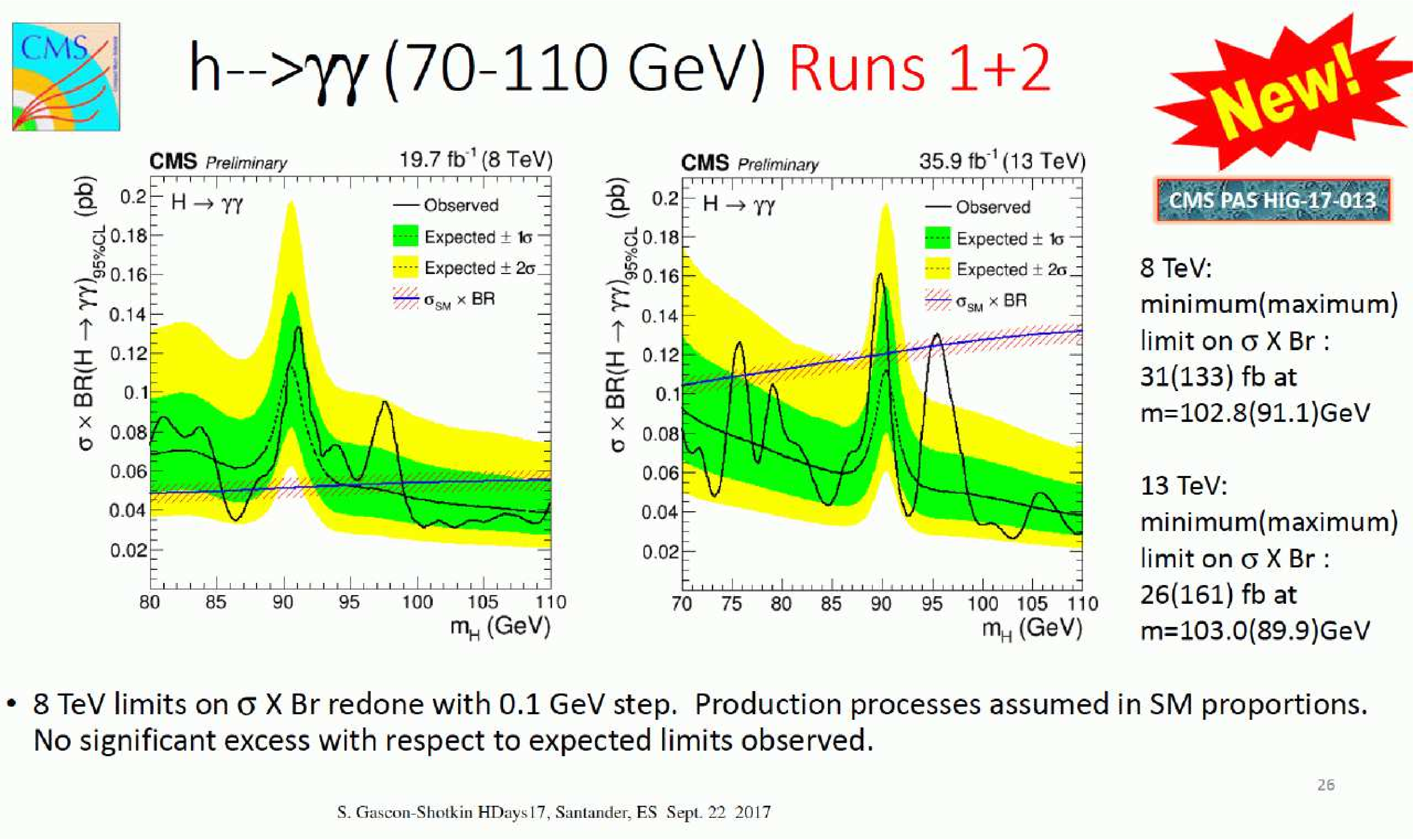
- ~2σ excursion @~80 GeV

18

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

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

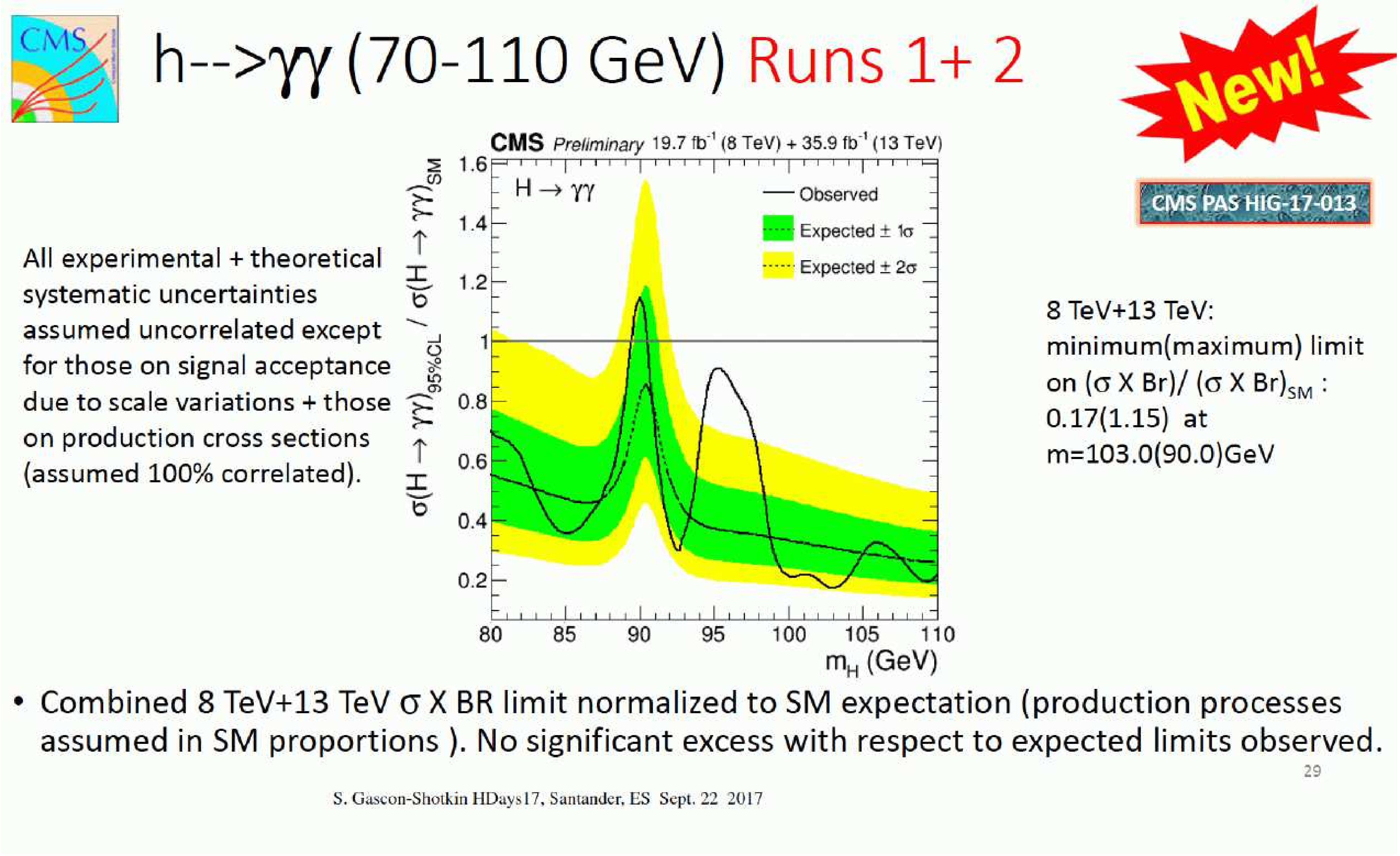
- 8 TeV limits on σ X Br redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

26

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

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)/ (σ X Br)$_{SM}$: 0.17(1.15) at m=103.0(90.0)GeV

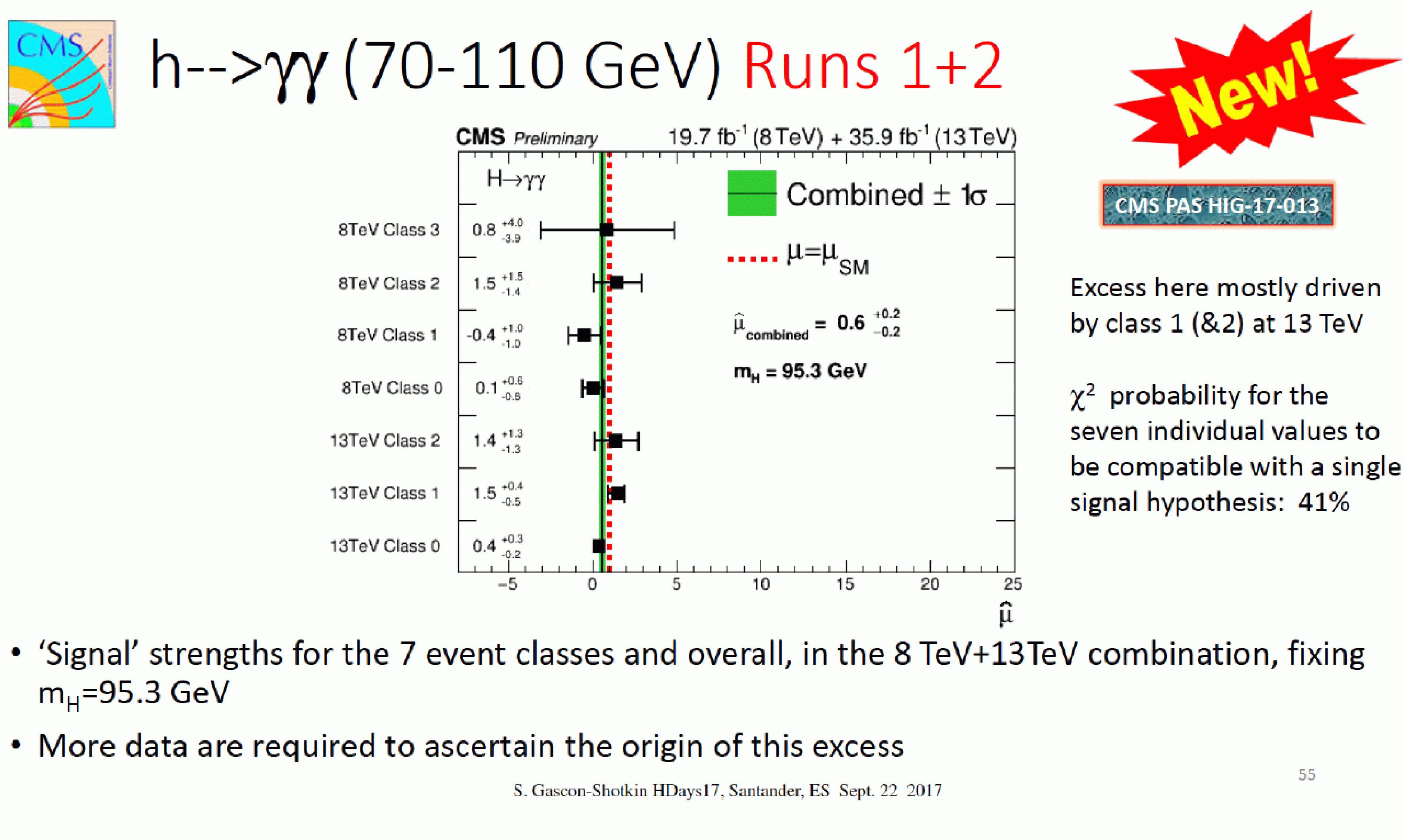
- Combined 8 TeV+13 TeV σ X BR limit normalized to SM expectation (production processes assumed in SM proportions). No significant excess with respect to expected limits observed.

29

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

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%

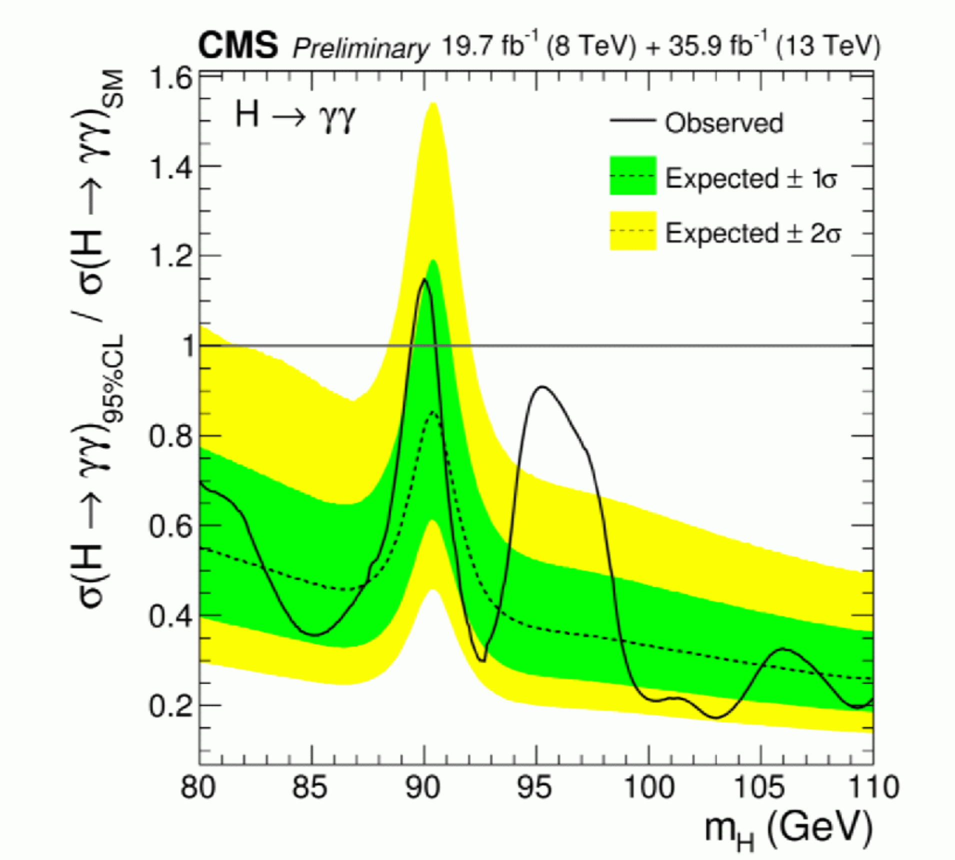
- ‘Signal’ strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing m_H=95.3 GeV
- More data are required to ascertain the origin of this excess

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

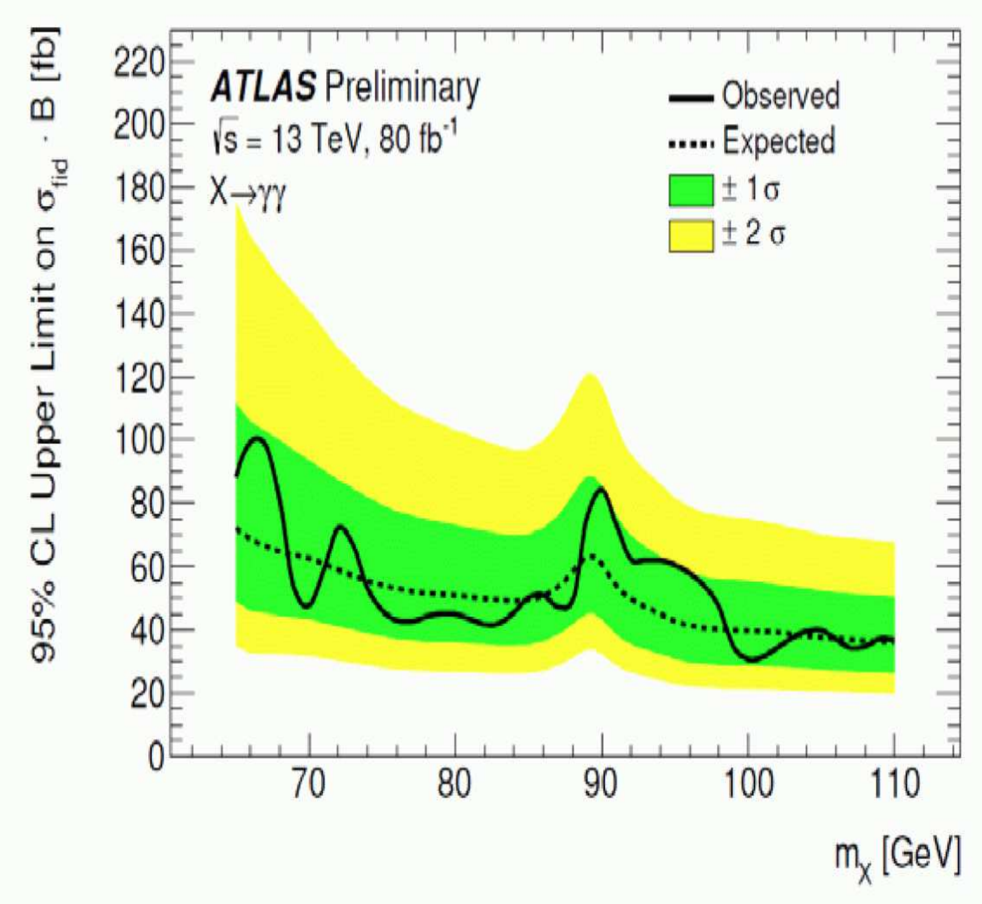
55

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

What about ATLAS?



CMS PAS HIG-17-013



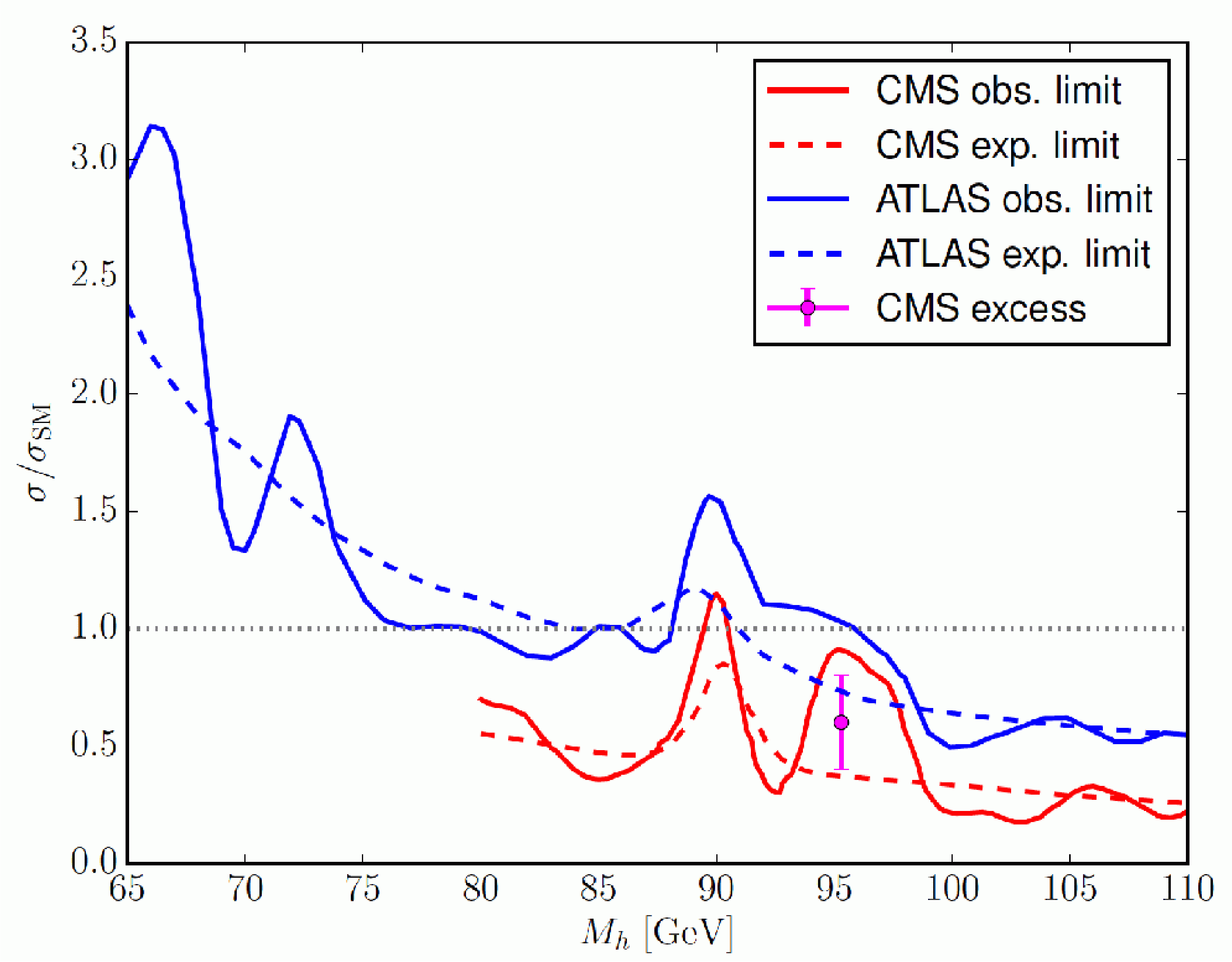
Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

⇒ ATLAS limit is even weaker than CMS exclusion limit (120 fb)

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

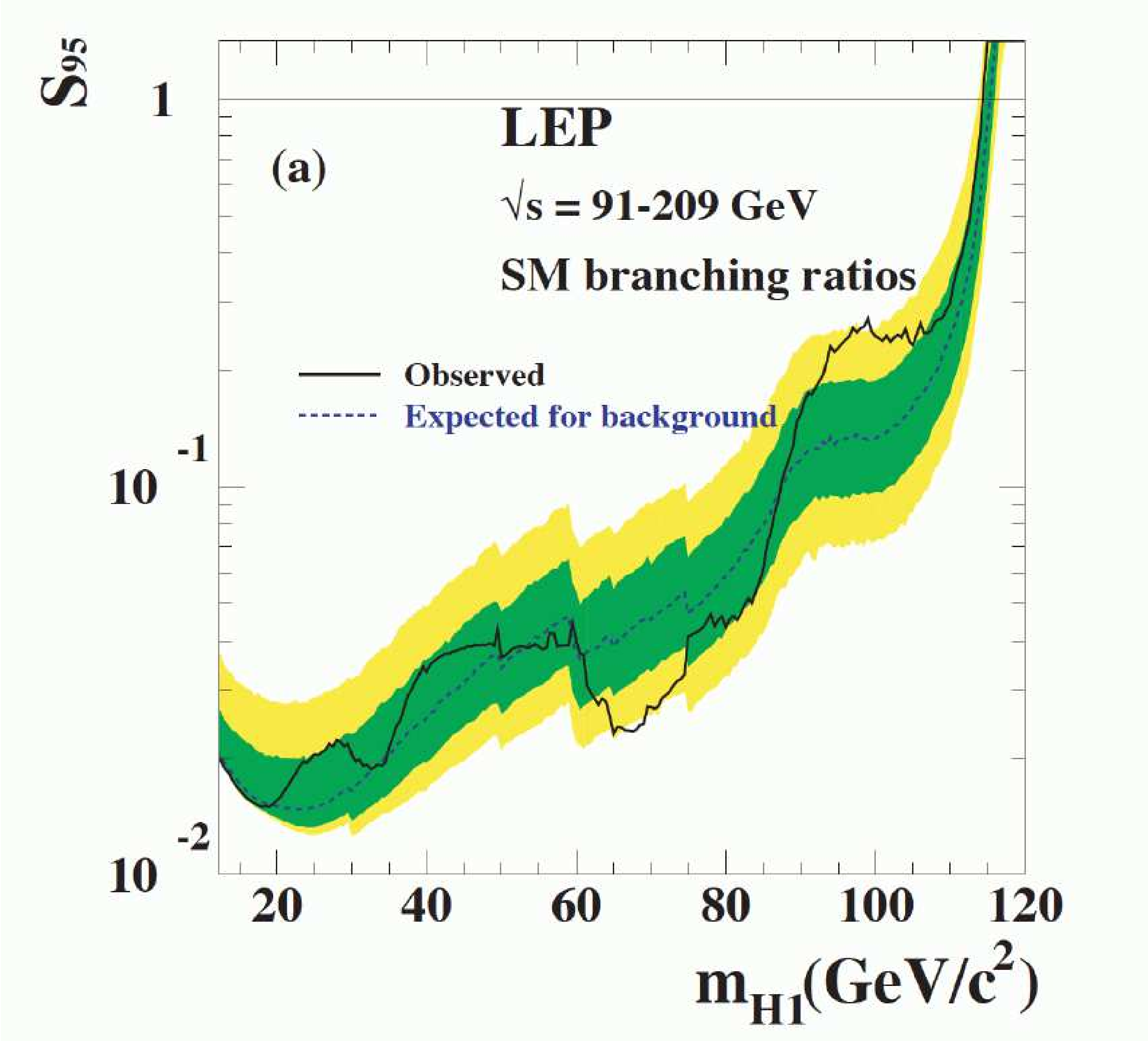
CMS and ATLAS in direct comparison:

[*T. Stefaniak et al. '18*]



⇒ everything well compatible with the excess!

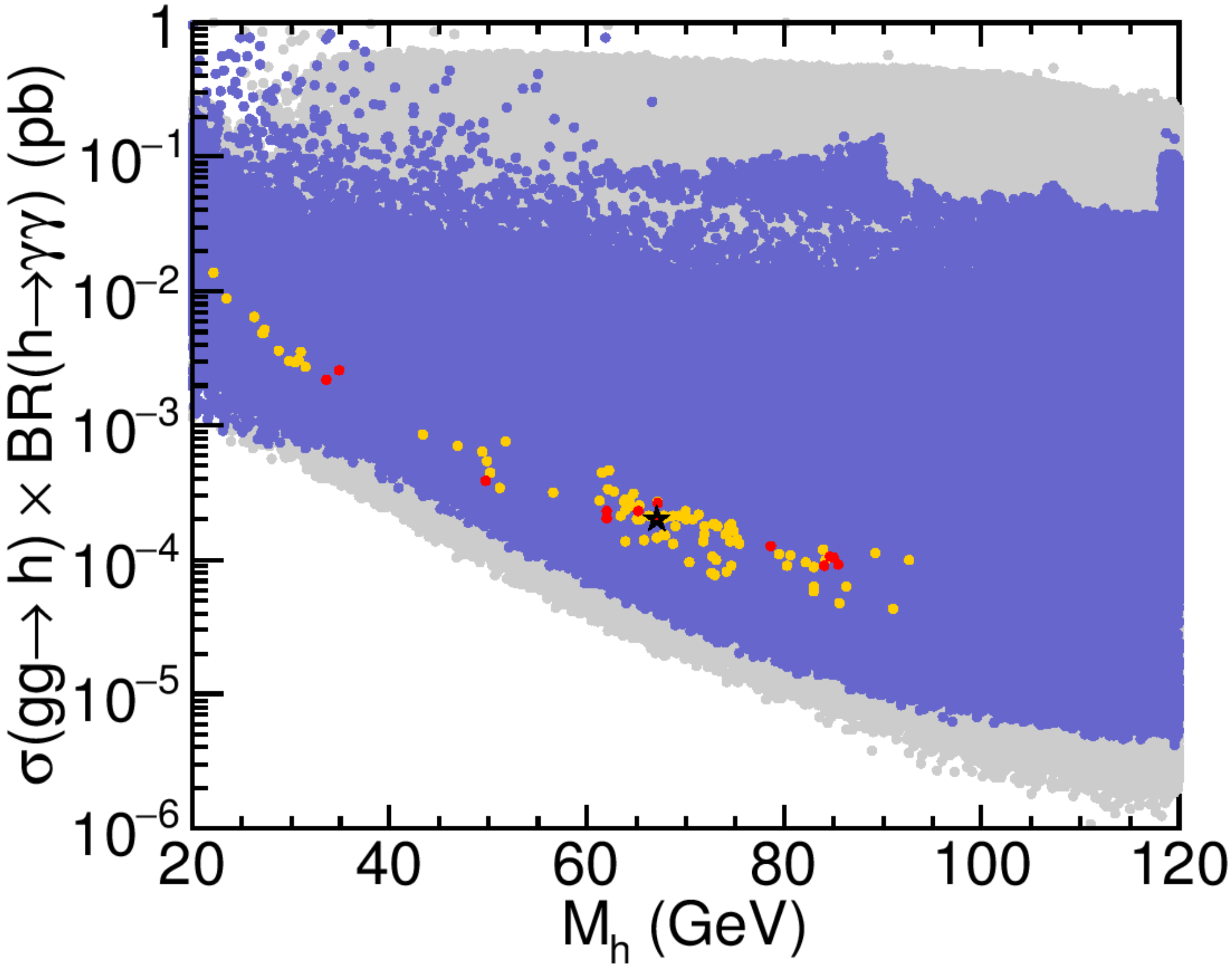
What was seen at LEP?



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

What about the MSSM?

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



⇒ too small rates! ⇒ 2HDM structure to "rigid"

2. General analysis

MSSM: too small rates!

⇒ problem: 2HDM structure to “rigid”

More general Ansatz:

- richer Higgs structure
  ⇒ add (at least) another Higgs singlet
- drop SUSY for now
  ⇒ allow for more flexibility
  ⇒ but check for hints towards SUSY
- check explicit SUSY scenarios later ⇒ back-up

More general Ansatz: **N2HDM**

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

Fields: ⇒ talk by Pedro Ferreira on the N2HDM (session 8, 10.00h CET)

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

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: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_S \to \Phi_S$

Z_2' symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to \Phi_2$, $\Phi_S \to -\Phi_S$ (broken by v_S ⇒ no DM)

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})

⇒ only type II and IV can fit CMS and LEP excesses

⇒ Parameter scan ⇒ ScannerS

Constraints:

- Tree-level perturbativity ⇒ ScannerS
- Minimum of potential is global minimum ⇒ ScannerS
  . . . or sufficiently long-lived ⇒ Evade
- Higgs searches at LEP, Tevatron, LHC ⇒ HiggsBounds
- SM-like Higgs properties ⇒ HiggsSignals (N2HDECAY, SusHi)
  ⇒ χ^2_{125} (with $\chi^2_{\text{SM},125} = 84.4$)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) ⇒ SuperIso bounds
- Electroweak precision data (T and S) ⇒ ScannerS

⇒ talk by Jonas Wittbrodt on HiggsBounds/HiggsSignals
(session 4B, 11.30h CET)

Fitting the excesses:

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

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

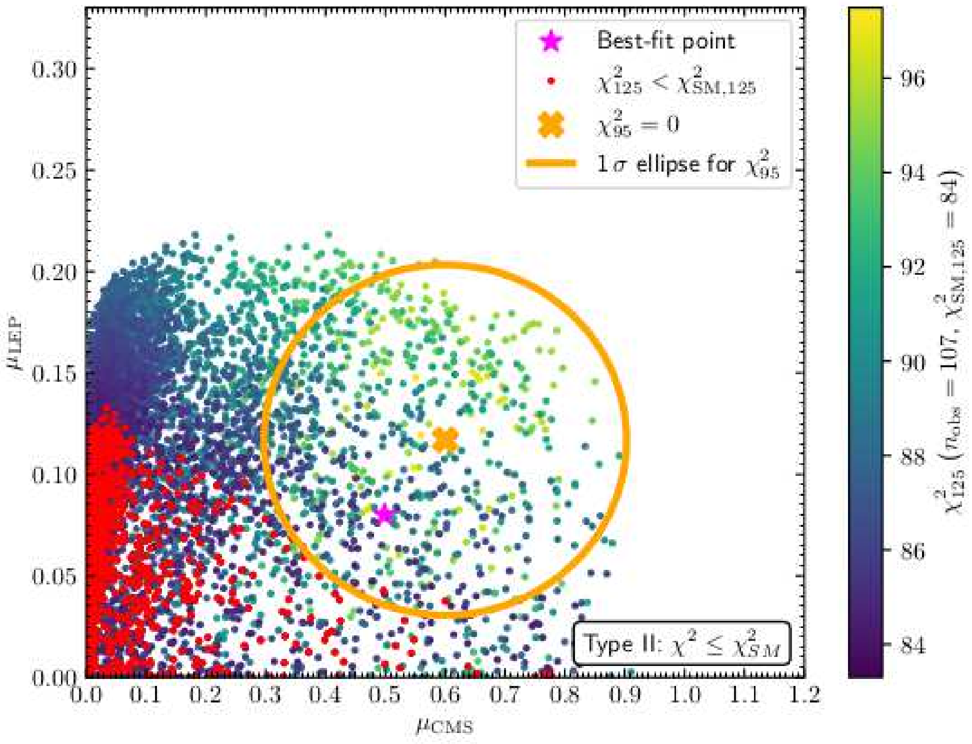
$$\begin{aligned}\mu_{\text{CMS}} &= \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)} \\ &= \left|c_{h_1 tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H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

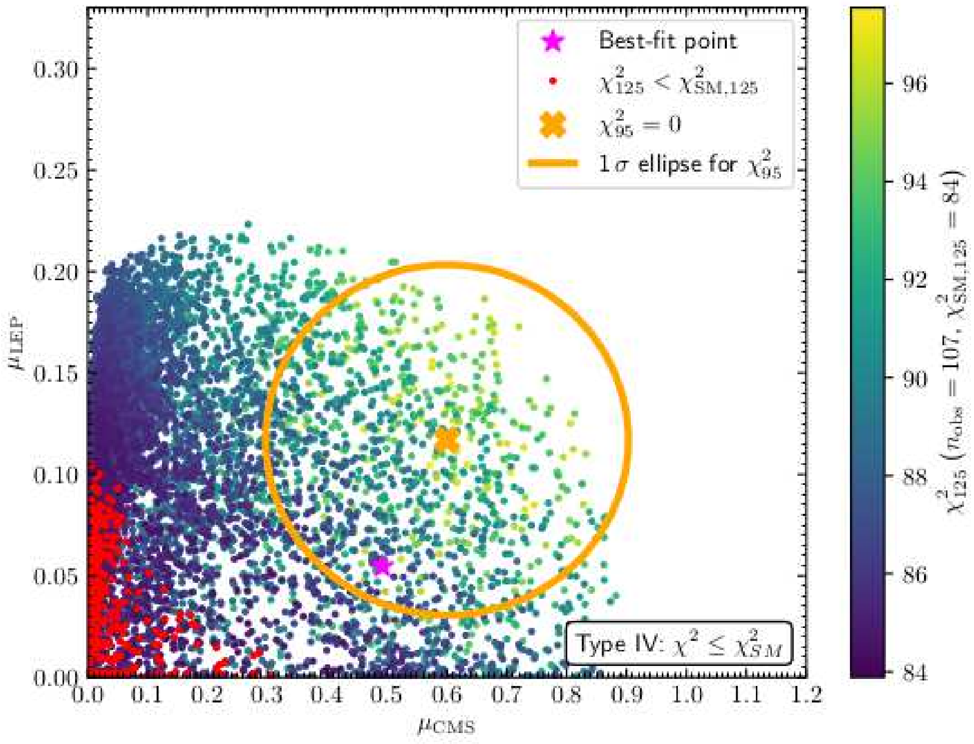
$$\chi^2_{\text{CMS}-\text{LEP}} = \frac{(\mu_{\text{LEP}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\text{CMS}} - 0.6)^2}{(0.2)^2}$$

⇒ "best-fit point"

Fitting the excesses:

[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



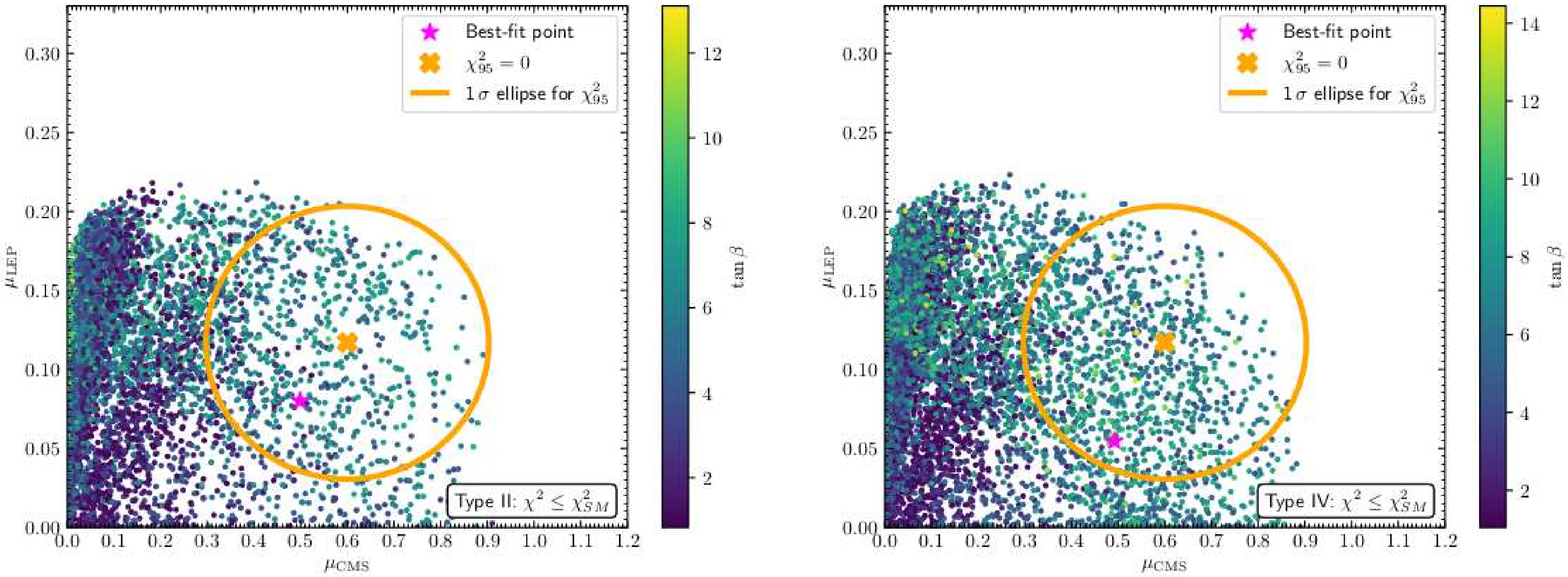


⇒ excesses well fitted, with good χ^2_{125}

red points have $\chi^2_{125} < \chi^2_{\mathrm{SM},125}$

Fitting the excesses:

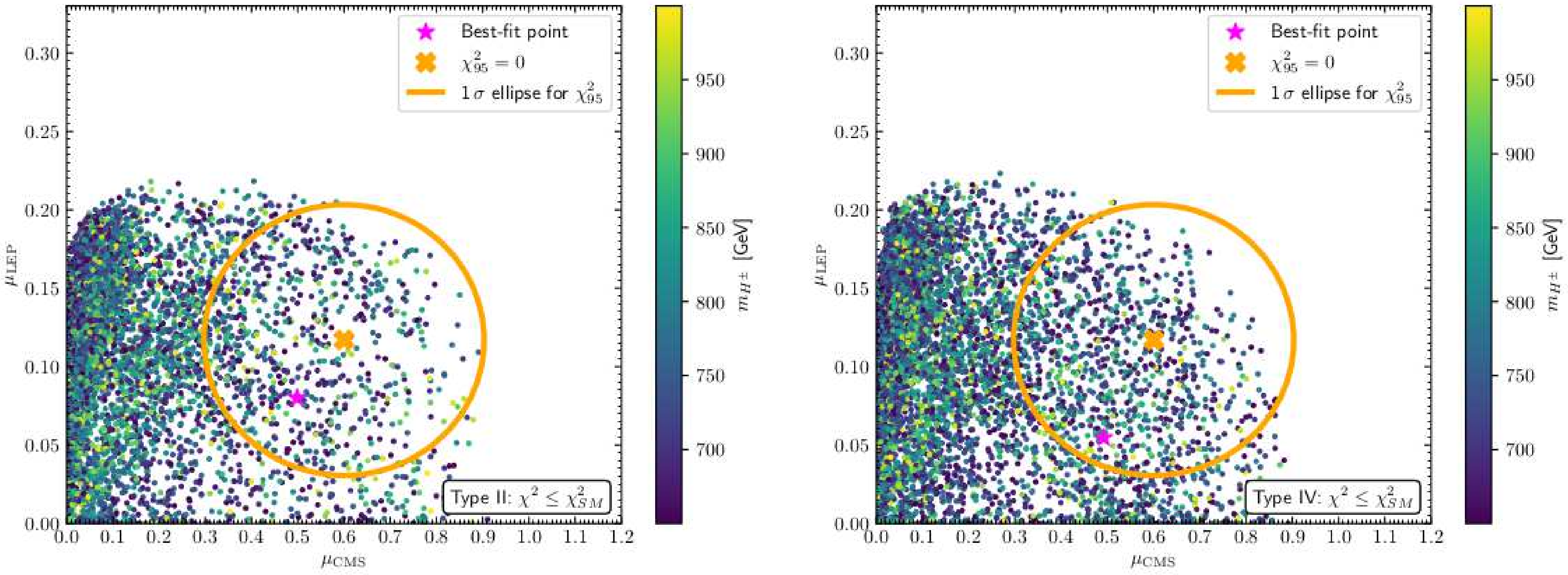
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



$\Rightarrow$ preferred $\tan\beta$: 0.9 – 10.3 (type II) and 1.2 - 14.5 (type IV)

Fitting the excesses:

[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ preferred $M_{H^\pm}$: 650 GeV – 1000 GeV (lower limit: flavor constr.)

⇒ scanned mass range covered ⇒ higher $M_{H^\pm}$ values possible . . .

Best-fit point in type II:

[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{h^\pm}$		
95.45	125.09	771.08	738.71	714.94		

$\tan\beta$	α_1	α_2	α_3	m_{12}	v_S	
5.19	1.50	1.20	1.48	330.00	1002.79	

$\mathrm{BR}_{h_1}^{bb}$	$\mathrm{BR}_{h_1}^{gg}$	$\mathrm{BR}_{h_1}^{cc}$	$\mathrm{BR}_{h_1}^{\tau\tau}$	$\mathrm{BR}_{h_1}^{\gamma\gamma}$	$\mathrm{BR}_{h_1}^{WW}$	$\mathrm{BR}_{h_1}^{ZZ}$
0.493	0.268	0.162	0.050	$5.318 \cdot 10^{-3}$	0.019	$2.628 \cdot 10^{-3}$

$\mathrm{BR}_{h_2}^{bb}$	$\mathrm{BR}_{h_2}^{gg}$	$\mathrm{BR}_{h_2}^{cc}$	$\mathrm{BR}_{h_2}^{\tau\tau}$	$\mathrm{BR}_{h_2}^{\gamma\gamma}$	$\mathrm{BR}_{h_2}^{WW}$	$\mathrm{BR}_{h_2}^{ZZ}$
0.554	0.087	0.032	0.060	$2.596 \cdot 10^{-3}$	0.233	0.029

$\mathrm{BR}_{h_3}^{tt}$	$\mathrm{BR}_{h_3}^{bb}$	$\mathrm{BR}_{h_3}^{\tau\tau}$	$\mathrm{BR}_{h_3}^{h_1h_1}$	$\mathrm{BR}_{h_3}^{h_1h_2}$	$\mathrm{BR}_{h_3}^{h_2h_2}$	$\mathrm{BR}_{h_3}^{WW}$
0.450	0.160	0.024	0.021	0.146	0.102	0.064

BR_{A}^{tt}	BR_{A}^{bb}	$\mathrm{BR}_{A}^{\tau\tau}$	$\mathrm{BR}_{A}^{Zh_1}$	$\mathrm{BR}_{A}^{Zh_2}$		
0.696	0.150	0.022	0.116	0.014		

$\mathrm{BR}_{H^\pm}^{tb}$	$\mathrm{BR}_{H^\pm}^{\tau\nu}$	$\mathrm{BR}_{H^\pm}^{Wh_1}$	$\mathrm{BR}_{H^\pm}^{Wh_2}$			
0.846	0.024	0.115	0.013			

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

Best-fit point in type IV:

[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{h^\pm}$
95.67	125.09	746.91	866.93	723.20

$\tan\beta$	α_1	α_2	α_3	m_{12}	v_S
5.57	1.51	1.18	1.48	310.59	732.02

$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{cc}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.299	0.239	0.142	0.295	$4.685 \cdot 10^{-3}$	0.017	$2.360 \cdot 10^{-3}$

$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{cc}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.538	0.088	0.033	0.072	$2.597 \cdot 10^{-3}$	0.235	0.029

$\text{BR}_{h_3}^{tt}$	$\text{BR}_{h_3}^{bb}$	$\text{BR}_{h_3}^{\tau\tau}$	$\text{BR}_{h_3}^{h_1h_1}$	$\text{BR}_{h_3}^{h_1h_2}$	$\text{BR}_{h_3}^{h_2h_2}$	$\text{BR}_{h_3}^{WW}$
0.368	0.193	$1.975 \cdot 10^{-5}$	0.029	0.164	0.125	0.081

BR_{A}^{tt}	BR_{A}^{bb}	$\text{BR}_{A}^{\tau\tau}$	$\text{BR}_{A}^{Zh_1}$	$\text{BR}_{A}^{Zh_2}$	$\text{BR}_{A}^{Zh_3}$	$\text{BR}_{A}^{WH^\pm}$
0.130	0.037	$0.580 \cdot 10^{-5}$	0.043	0.005	0.100	0.685

$\text{BR}_{H^\pm}^{tb}$	$\text{BR}_{H^\pm}^{\tau\nu}$	$\text{BR}_{H^\pm}^{Wh_1}$	$\text{BR}_{H^\pm}^{Wh_2}$
0.828	$3.024 \cdot 10^{-5}$	0.152	0.018

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

Mini excursion: 2HDMS (instead of N2HDM) - type II only

[S.H., C. Li, F. Lika, G. Moortgat-Pick, S. Paasch – VERY PRELIMINARY]

N2HDM: 2 complex Higgs doublets, 1 real Higgs singlet
Z_2 and Z'_2 symmetry

2HDMS: 2 complex Higgs doublets, 1 complex Higgs singlet
Z_2 and Z_3 symmetry
⇒ resembles the NMSSM Higgs sector (but without SUSY)

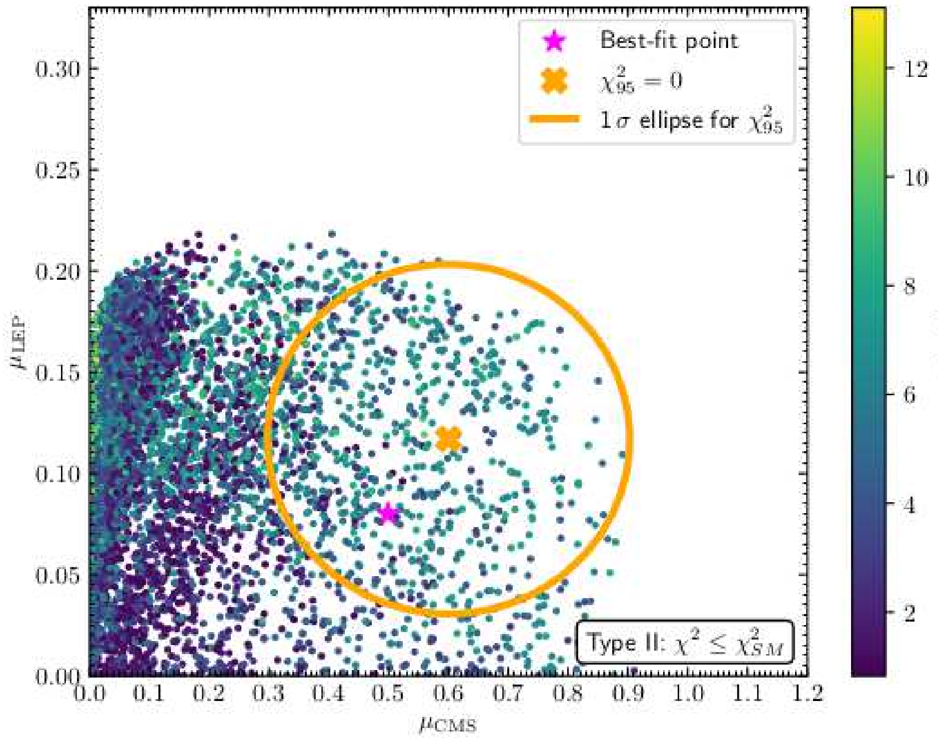
Constraints: as for the N2HDM:
⇒ ScannerS, Evade, HiggsBounds, HiggsSignals, SuSHi, SuperIso

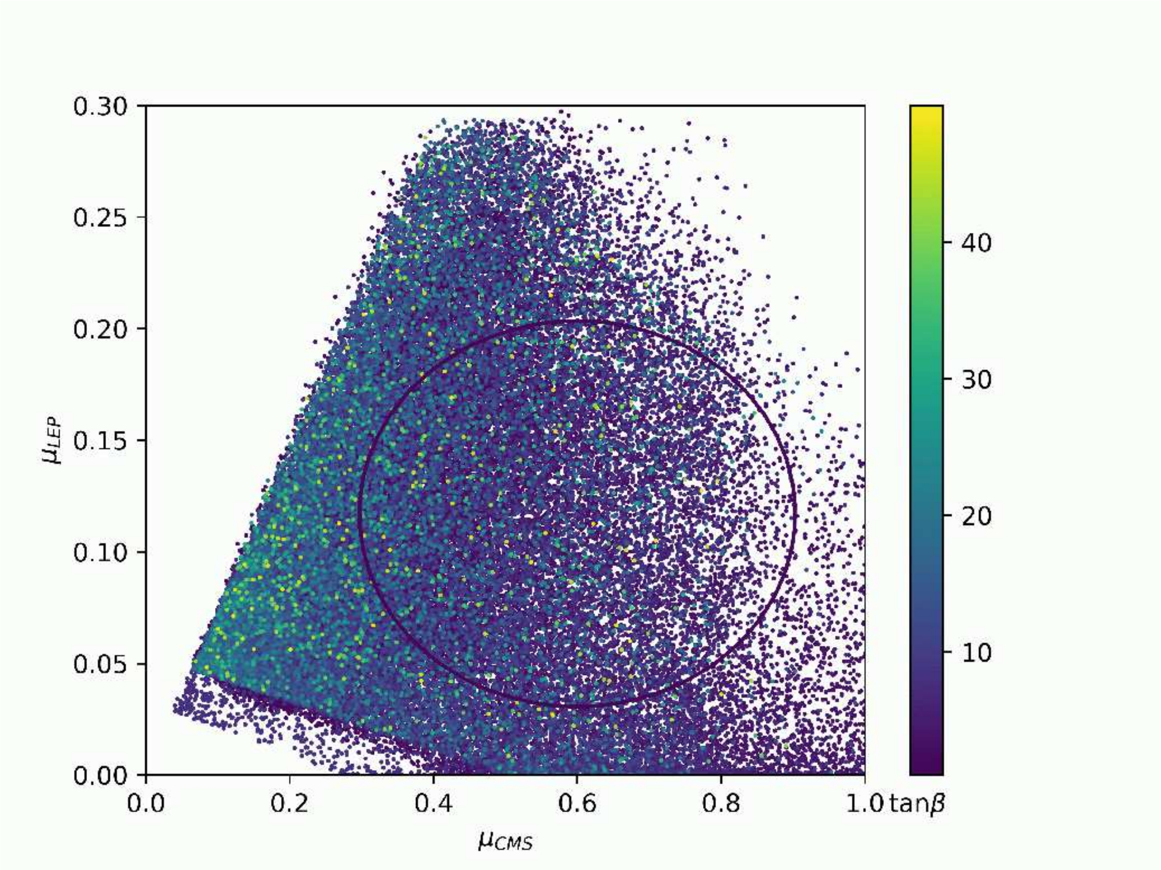
⇒ 2HDMS can “obviously” also fit the excesses at ~ 96 GeV

Q: Are there relevant differences?
(apart from the extra $\mathcal{CP}$-odd Higgs?)

Comparing $\tan\beta$:

(Remember: point density has no physical meaning!)





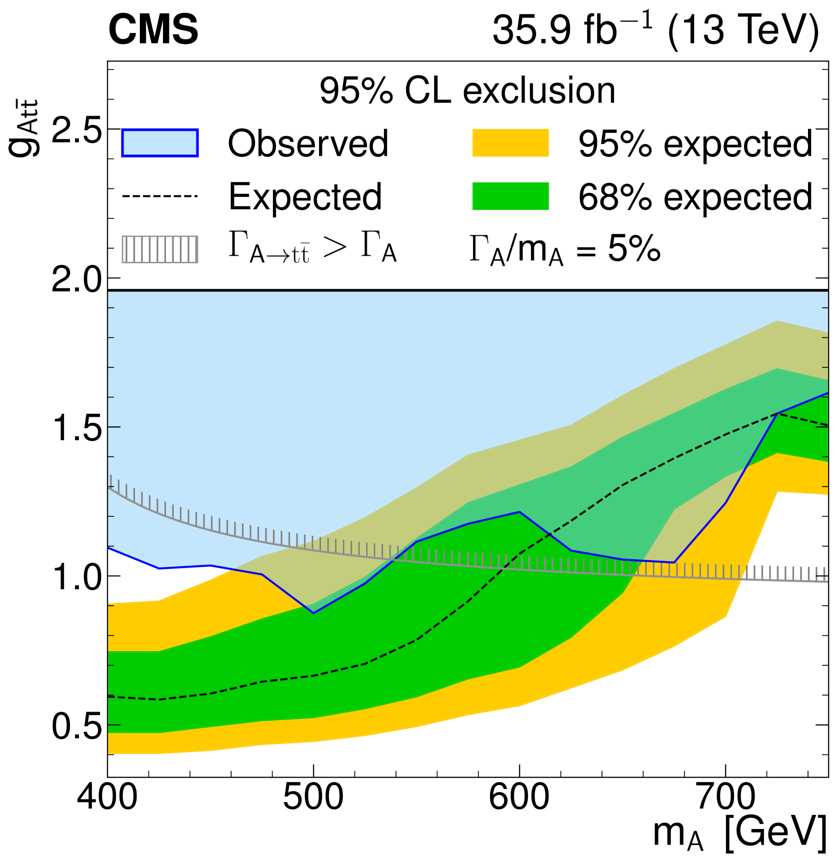
N2HDM: $\tan\beta \lesssim 10$

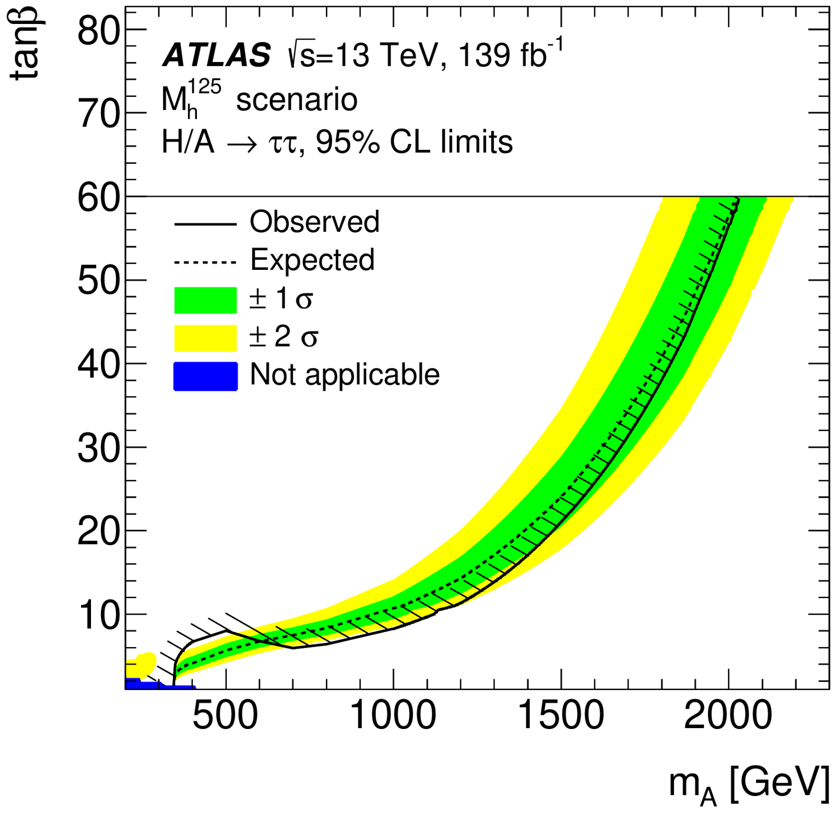
2HDMS: no $\tan\beta$ limits

singlet component of h_1: $M^2_{13} = v(2\lambda'_1 v_S \cos\beta + \mu_{12} \sin\beta)$

$V = \ldots + \lambda'_1 (S^\dagger S)(\Phi_1^\dagger \Phi_1) + \mu_{12} S \Phi_1^\dagger \Phi_2$ in the 2HDMS, forbidden by Z'_2

Mini excursion II: other excesses





CMS: excess for $A \to t\bar{t}$ at $M_A \sim$ 400 GeV

ATLAS: excess for $H/A \to \tau^+\tau^-$ at $M_{H/A} \sim$ 400 GeV

Connection to excesses at 96 GeV?

⇒ talk by Thomas Biekötter (session 4A, 11.30h CET)

What can we learn from future measurements?

- LHC h_{125} coupling measurements
- HL-LHC h_{125} coupling measurements
- ILC h_{125} coupling measurements

- direct production of ϕ_{96} at the LHC
- direct production of ϕ_{96} at the HL-LHC
- direct production of ϕ_{96} at the ILC
- ILC ϕ_{96} coupling measurements

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

ILC = ILC (or other e^+e^- collider)

What can we learn from future measurements?

- LHC h_{125} coupling measurements
- HL-LHC h_{125} coupling measurements $\Leftarrow$ focus
- ILC h_{125} coupling measurements $\Leftarrow$ focus

- direct production of ϕ_{96} at the LHC
- direct production of ϕ_{96} at the HL-LHC
- direct production of ϕ_{96} at the ILC $\Leftarrow$ focus
- ILC ϕ_{96} coupling measurements $\Leftarrow$ focus

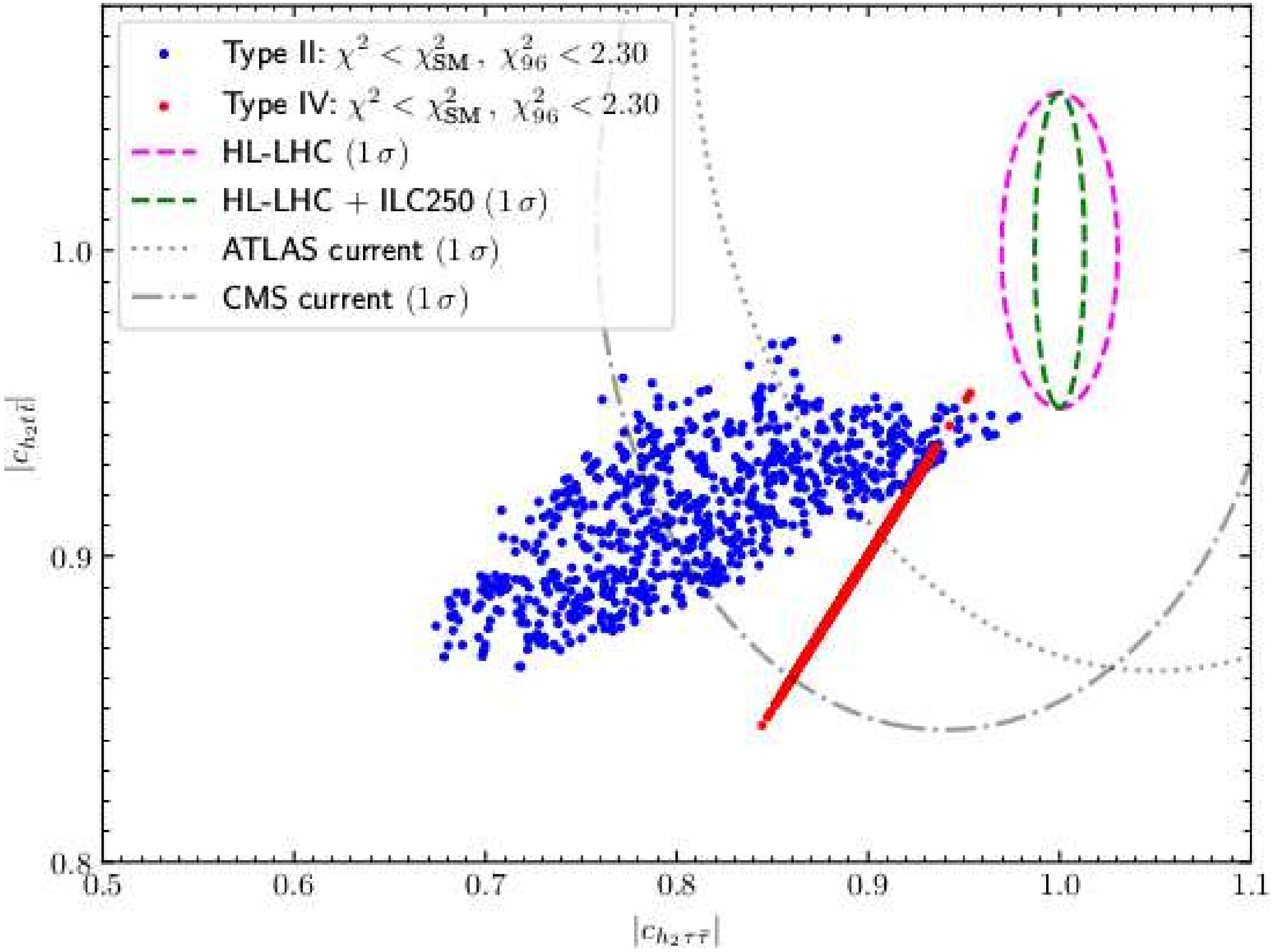
- production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/...

ILC = ILC (or other e^+e^- collider)

3. Probes of the 125 GeV Higgs at the ILC

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

[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ both types show some deviation from SM

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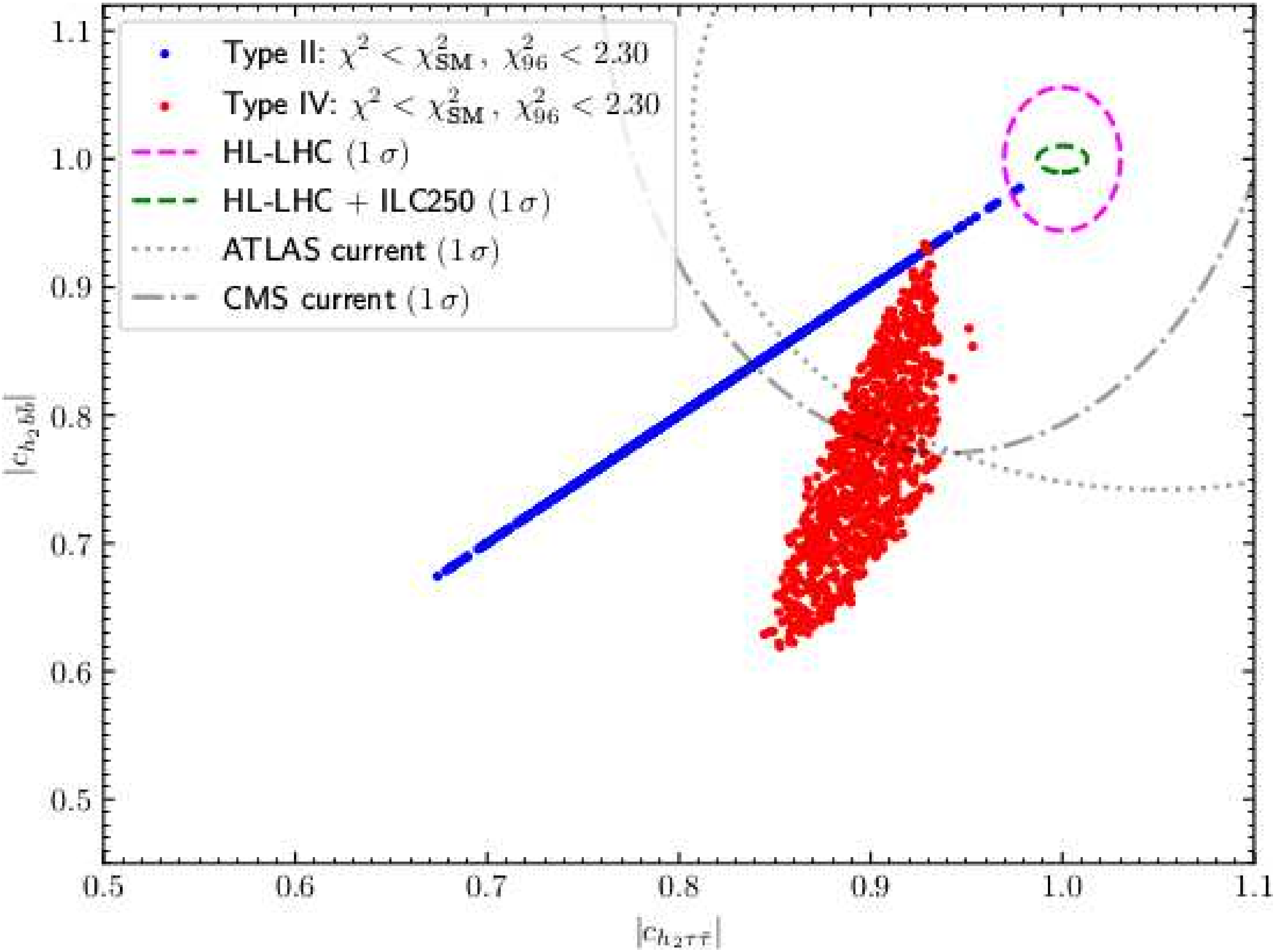

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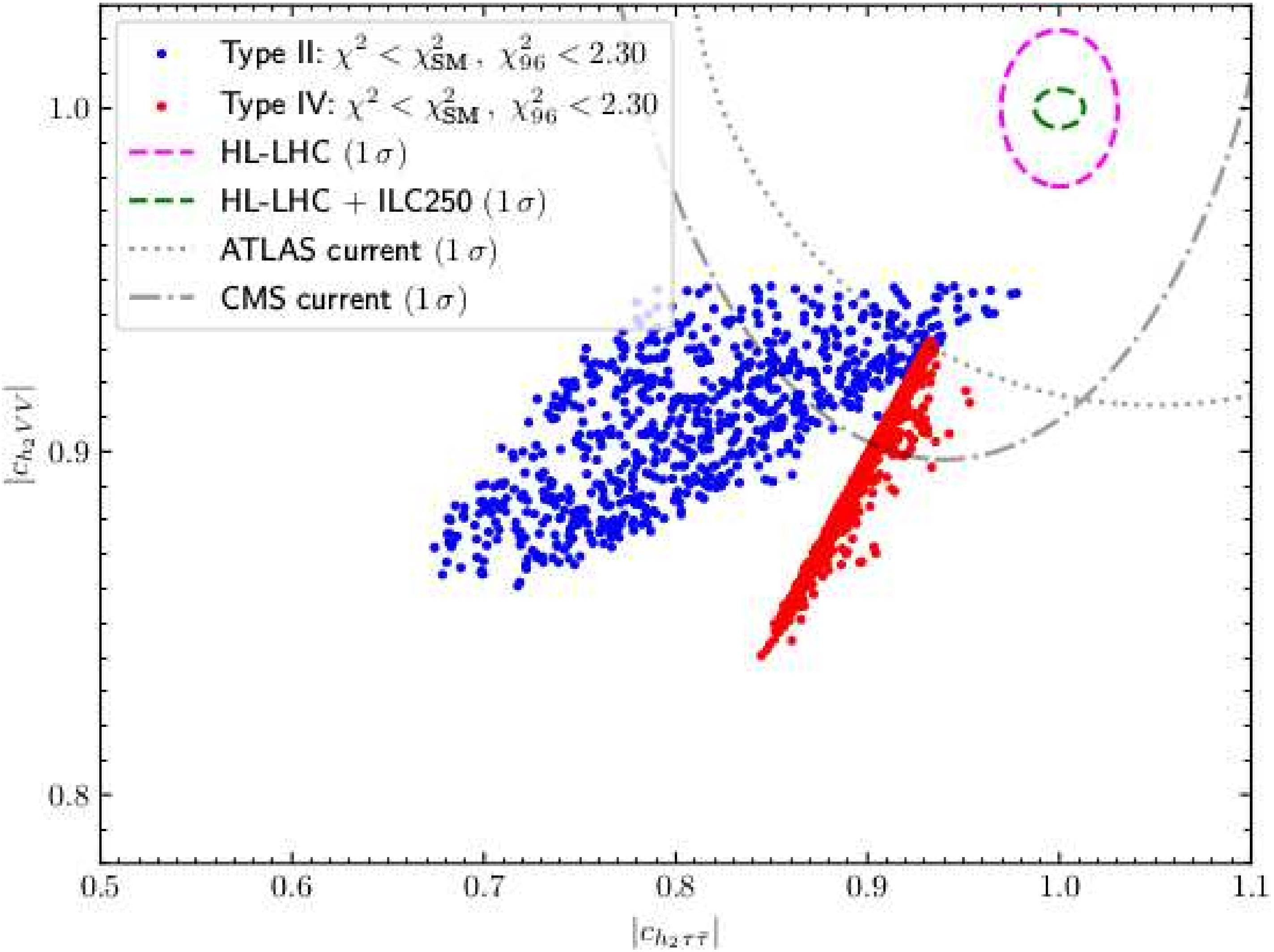


⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM!

4. Probes of the 96 GeV Higgs at the ILC

- Direct production at the ILC

  Uses work by:

  [*P. Drechsel, G. Moortgat-Pick, G. Weiglein '18*]

  [*Y. Wang, M. Berggren, J. List '20*]

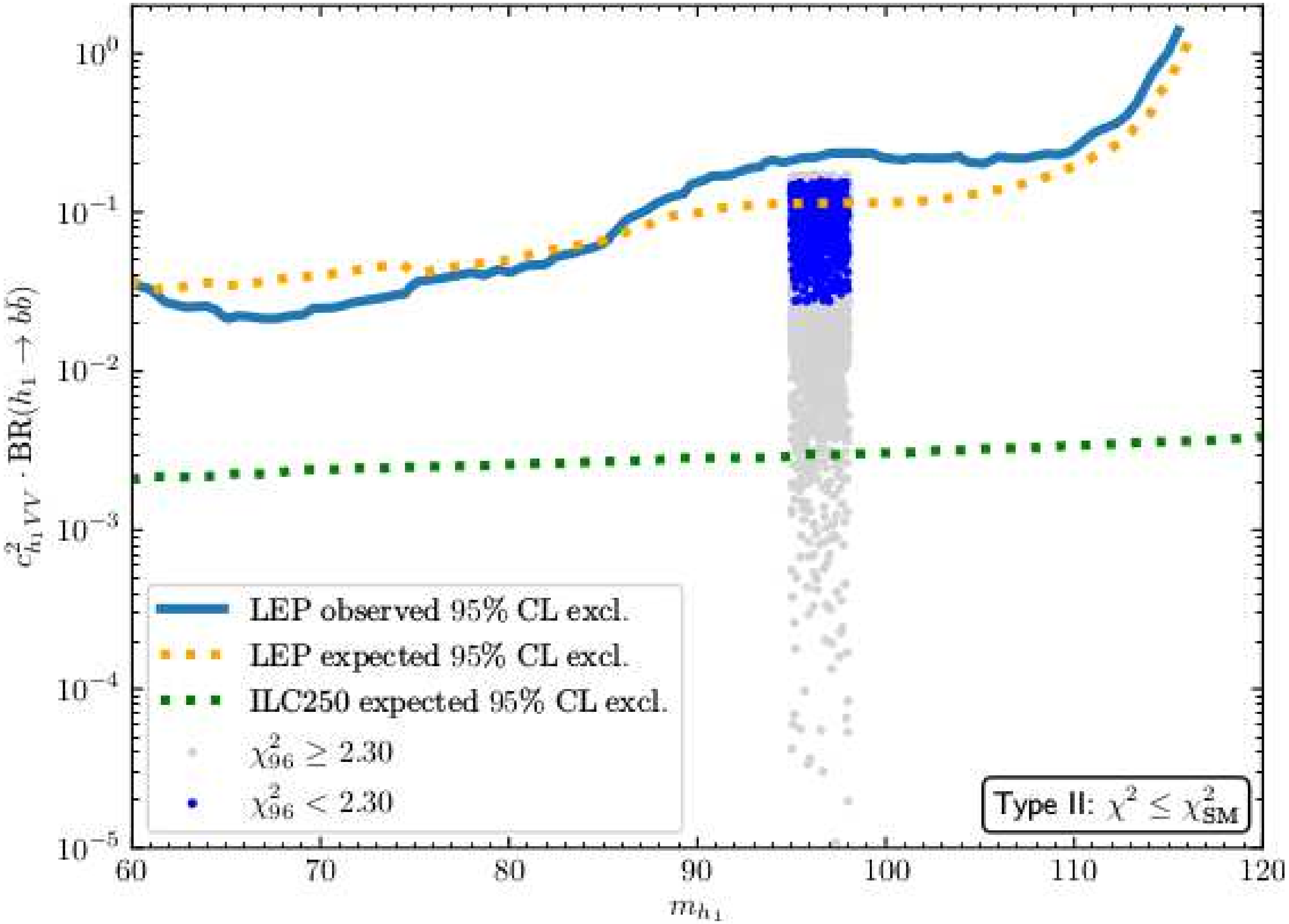
- Coupling measurements at the ILC

  Thanks go to:
  - M. Cepeda (for her help with the formulas)
  - J. List (for help on S/B in BSM models)
  - J. Tian (for help on S/B in the SM)
  - C. Schappacher (for some production cross sections)

$\Rightarrow$ focus on "good" points with $\chi^2_{\text{CMS}-\text{LEP}} < 2.3$

ILC production of the light scalar in the N2HDM type II:

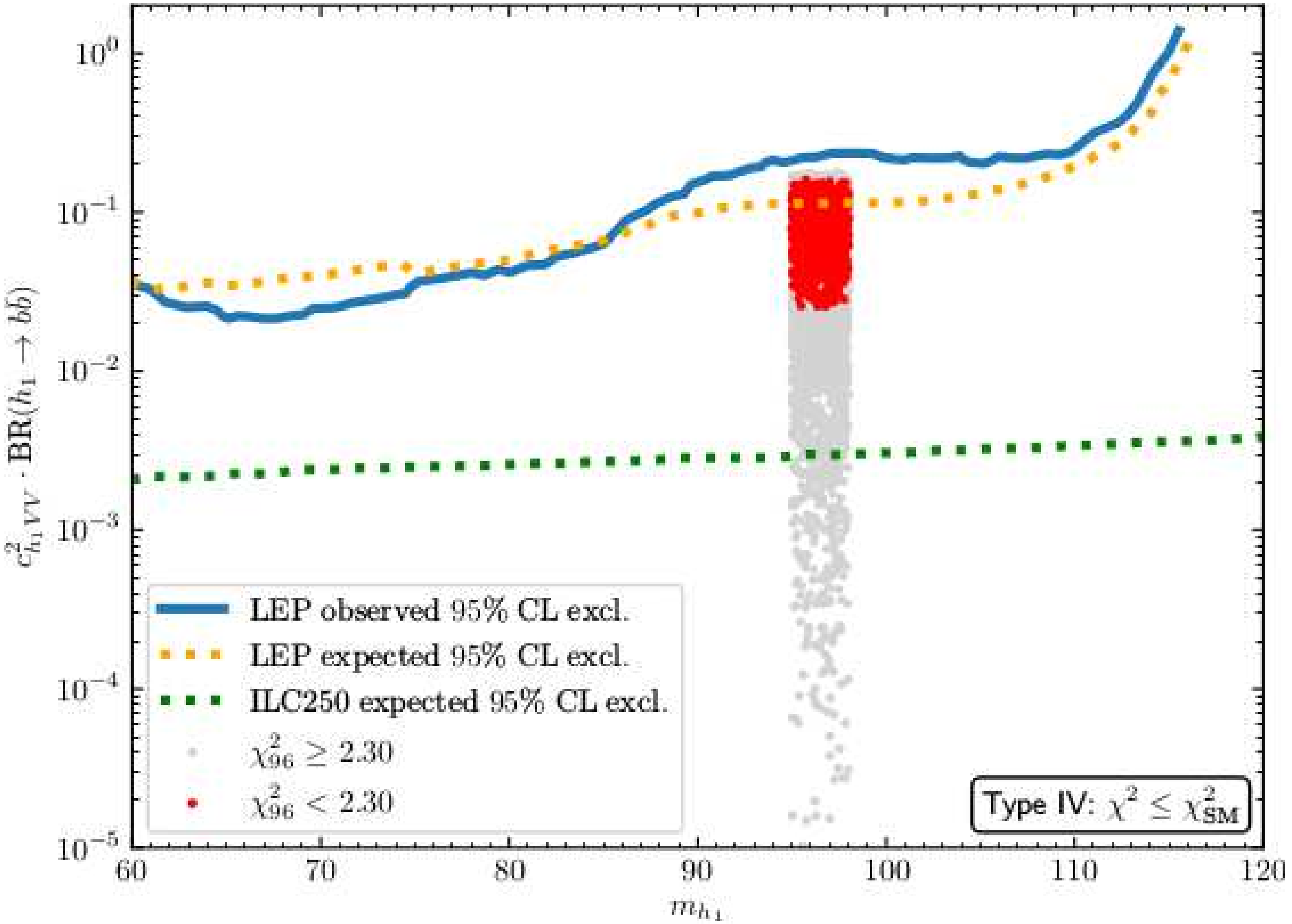
[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



⇒ new state easily in the reach of the ILC ⇒ coupling measurements

ILC production of the light scalar in the N2HDM type IV:

[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



$\Rightarrow$ new state easily in the reach of the ILC $\Rightarrow$ coupling measurements

How to evaluate the precision of ϕ_{96} coupling measurements?

Start with data of the SM Higgs:

SM Higgs BRs: [YR4 LHCHXSWG]

final state	$b\bar{b}$	gg	$\tau^+\tau^-$	WW^*	σ_{ZH}
BR	0.582	0.082	0.063	0.214	206 fb

SM Higgs coupling uncertainties:
ILC, $\mathcal{L}_{\text{int}} = 2\,\text{ab}^{-1}$ at $\sqrt{s} = 250$ GeV [T. Barklow et al. '17]

coupling	$b\bar{b}$	gg	$\tau^+\tau^-$	WW	ZZ
rel. unc. [%]	1.04	1.60	1.16	0.65	0.66

SM Higgs S/B: [S. Dawson et al. '13] [J. Tian, priv. commun.]

coupling	$H \to b\bar{b}$	$H \to gg$	$H \to \tau^+\tau^-$	$H \to WW$	σ_{ZH}
S/B	1/0.89	1/13	1/0.44	1/0.96	1/1.65

Some more basics:

$$f := S/B \equiv N_S/N_B$$

$$\frac{\Delta N_S}{N_S} = \frac{1}{\sqrt{N_S}} \sqrt{1 + 1/f}$$

Holds is background is known perfectly and the overall uncertainty is dominated by statistical precision

Uncertainty improves with $1/\sqrt{N_S}$ for $f = S/B \gg 1$

Cross section for ϕ_{96}:

$$\sigma(e^+e^- \to \phi Z) = \sigma_{\text{SM}}(e^+e^- \to Z\, H_{\text{SM}}^{\phi 96}) \times |c_{\phi VV}|^2$$

$$\sigma_{\text{SM}}(e^+e^- \to Z\, H_{\text{SM}}^{\phi 96}) = 0.332\,\text{pb}$$

$\Rightarrow \mathcal{O}\left(10^5\right)$ ϕ_{96}'s can be produced at $\sqrt{s} = 250$ GeV and $\mathcal{L}_{\text{int}} = 2\,\text{ab}^{-1}$

Evaluating uncertainties:

- Coupling is measured via decay
  A new Higgs boson ϕ couples with g_x to xx

$$\Gamma(\phi \to xx) \propto g_x^2$$

$$\mathrm{BR}(\phi \to xx) =: 1/p$$

$$\frac{\Delta N_S}{N_S} = 2\,\frac{\Delta g_x}{g_x}\left(1 - \frac{1}{p}\right)$$

- Coupling is measured via production: g_Z

$$\sigma(e^+e^- \to Z\phi) \propto g_Z^2$$

$$\frac{\Delta N_S}{N_S} = 2\,\frac{\Delta g_x}{g_x}$$

- Final assumption: $$\left(\frac{N_S}{N_B}\right)_H \Big/ \left(\frac{N_S}{N_B}\right)_\phi = f_H/f_\phi =: D$$
  with $D = 3$ as starting point

Evaluating uncertainties of ϕ_{96}:

- Coupling is measured via decay

$$\left(\frac{\Delta g_x}{g_x}\right)_\phi = \left(\frac{\Delta g_x}{g_x}\right)_H \times \frac{\left(\frac{\Delta N_S}{N_S}\right)_\phi}{\left(\frac{\Delta N_S}{N_S}\right)_H} \times \frac{\left(1-\frac{1}{p_H}\right)}{\left(1-\frac{1}{p_\phi}\right)}$$

$$\to \sqrt{\frac{D+f_H}{1+f_H}} \times \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}} \times \sqrt{\frac{\mathrm{BR}(H \to xx)}{\mathrm{BR}(\phi \to xx)}} \times \frac{(1-\mathrm{BR}(H \to xx))}{(1-\mathrm{BR}(\phi \to xx))}$$

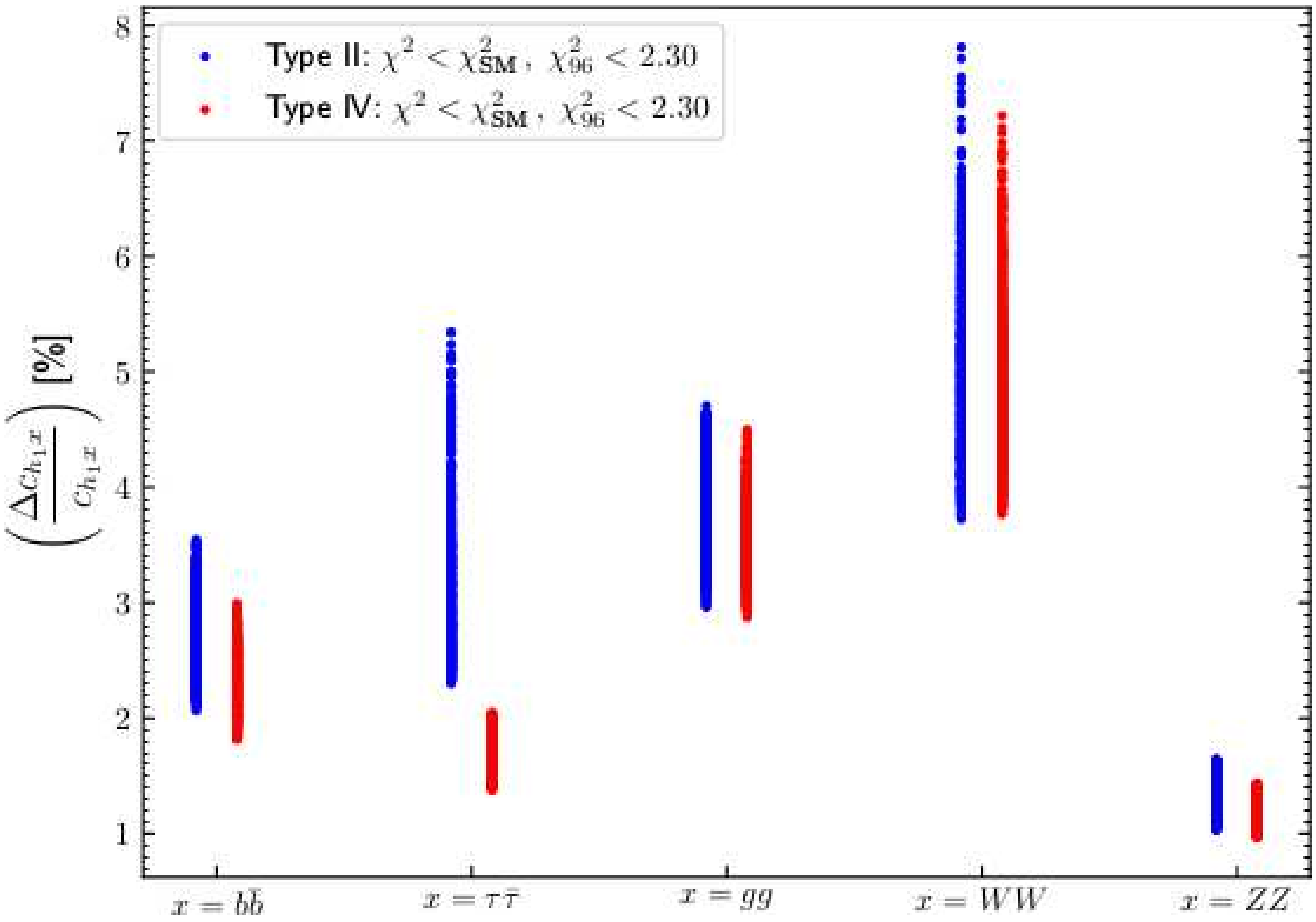
- Coupling is measured via production: g_Z (S/B does not change)

$$\left(\frac{\Delta g_Z}{g_Z}\right)_\phi = \left(\frac{\Delta g_Z}{g_Z}\right)_H \times \frac{\left(\frac{\Delta N_S}{N_S}\right)_\phi}{\left(\frac{\Delta N_S}{N_S}\right)_H}$$

$$\to \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}}$$

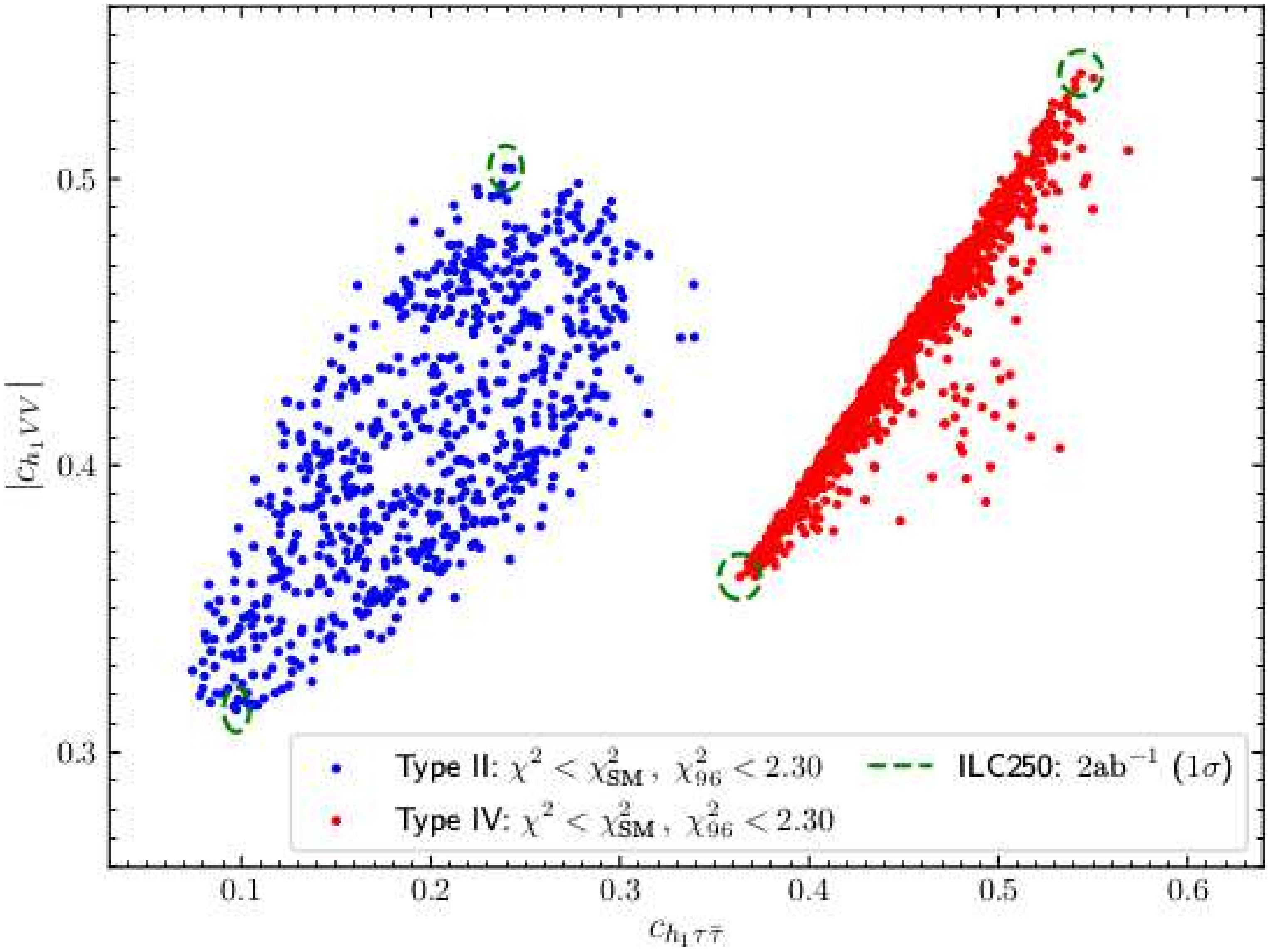
N2HDM: ILC coupling measurements of ϕ_{96}:

[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



⇒ clear difference in $g_{h_1\tau\tau}$ as expected

N2HDM: $\tau\tau$ vs. WW/ZZ: [*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ model distinction possible via coupling measurements

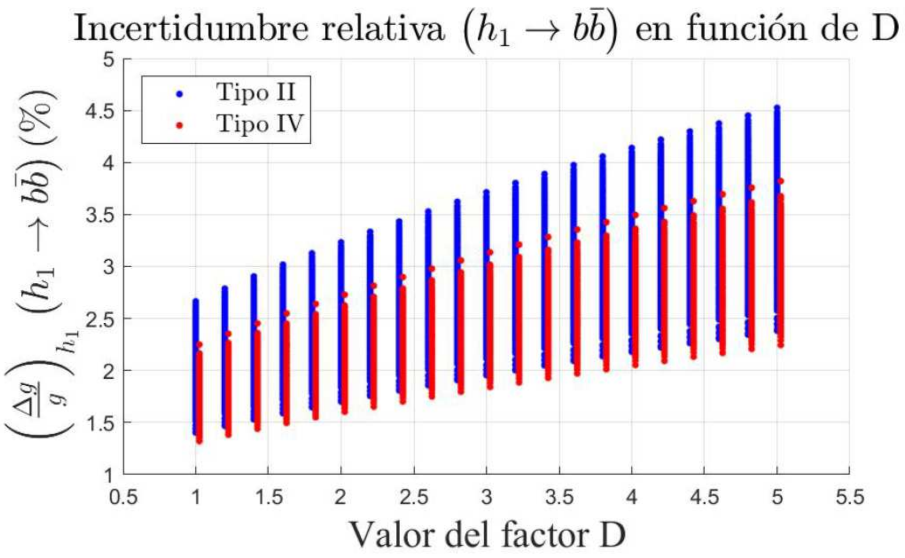
5. Conclusinos

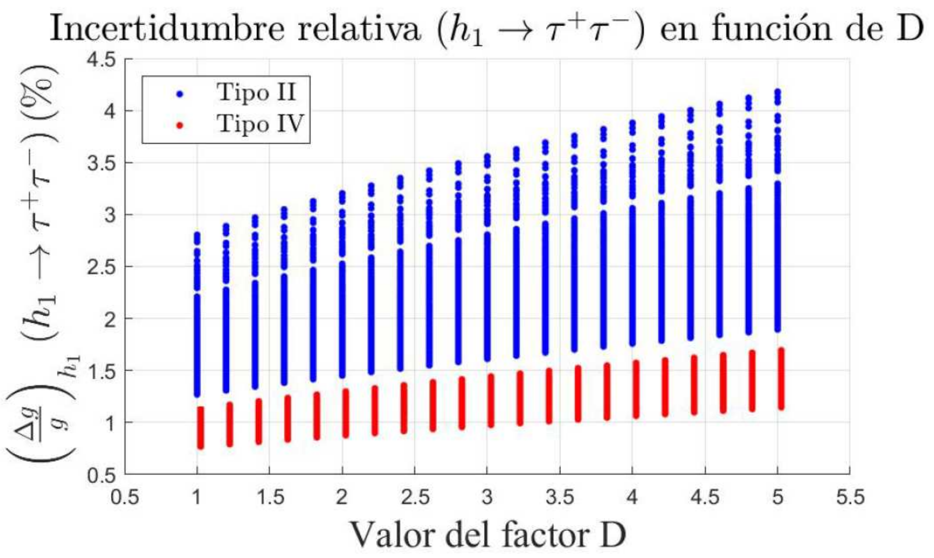
- Interesting excesses at ~ 96 GeV:
  CMS: $pp \to \phi \to \gamma\gamma$ ($3\,\sigma$ local) ATLAS: no sensitivity (yet)
  LEP: $e^+e^- \to Z\,\phi \to Z\,b\bar{b}$ ($2\,\sigma$ local)
- MSSM cannot explain the CMS excess $\Rightarrow$ to rigid 2HDM structure
  More general ansatz: $\Rightarrow$ N2HDM analysis (also 2HDMS)
- Only type II and IV can fit both excesses simultaneously
  $\Rightarrow$ type II "most easily" (as predicted by SUSY :-)
- Analysis with ScannerS, HiggsBounds, HiggsSignals, N2HDecay,
  Evade, SusHi, SuperIso
  $\Rightarrow$ many good fit points ($\chi^2_{\text{CMS}-\text{LEP}} < 2.3$) found
- ILC250: analysis of $h_2(125)$:
  - precision measurements of couplings can distinguish N2HDM vs. SM
  - possible distinction between type II and IV
- ILC250: analysis of h_1:
  - h_1 can be produced abundantly
  - number of $\tau\tau$ events clearly distinguishes type II and IV
  - precision in couplings: 1-8%: g_Z best from production
  - coupling measurements ($\tau\tau$, ZZ) clearly distinguishes type II and IV

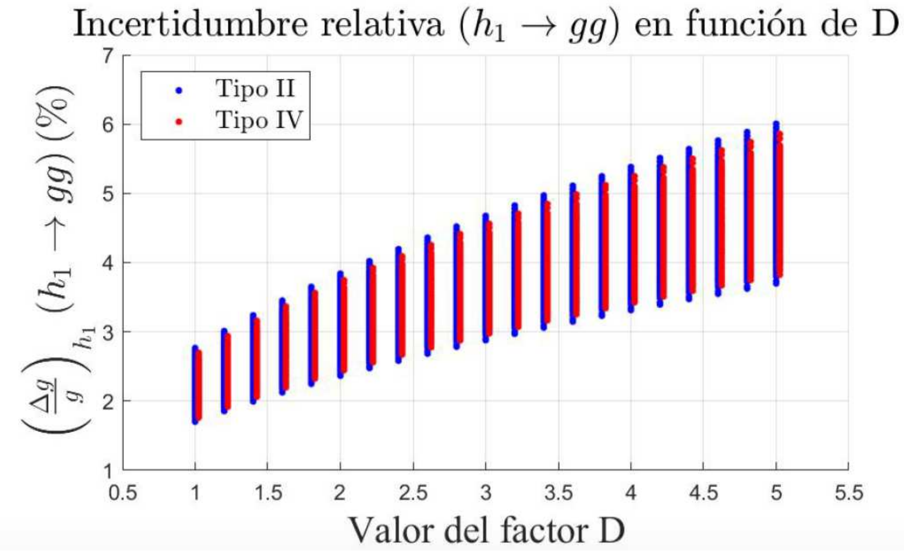
Further Questions?

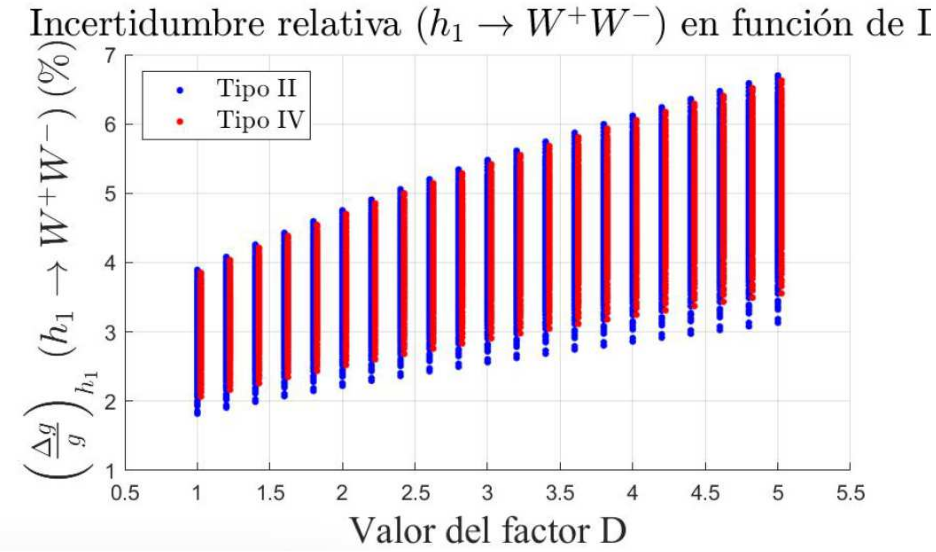
N2HDM: dependence on $D = f_H/f_\phi$:

[S.H., P. Toledo '20]









⇒ non-negligible, but small ⇒ "robust" result

SUSY realizations

What about SUSY??

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⇒ type II fits best, type II is needed for SUSY ⇒ no surprize! ;-)

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- NMSSM
- $\mu\nu$SSM
- ...

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⇒ type II fits best, type II is needed for SUSY ⇒ no surprize! ;-)

⇒ 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?

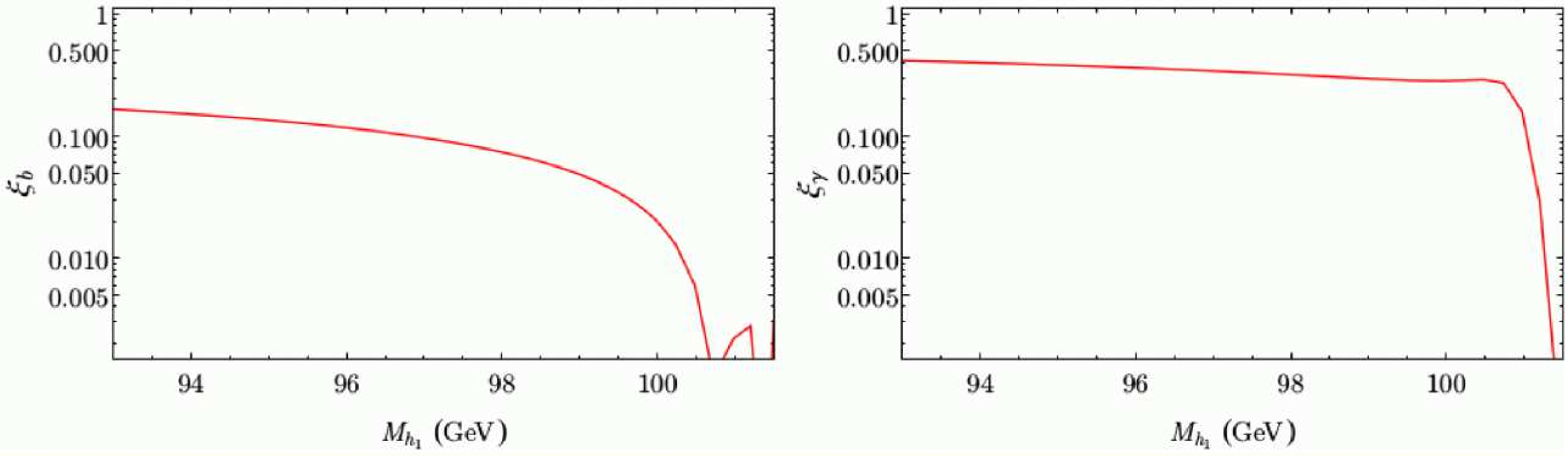
[F. Domingo, S.H., S. Passehr, G. Weiglein '18]

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, $A_t = A_b = 0$

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

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



⇒ 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)
⇒ EW scale seesaw to reproduce the neutrino data

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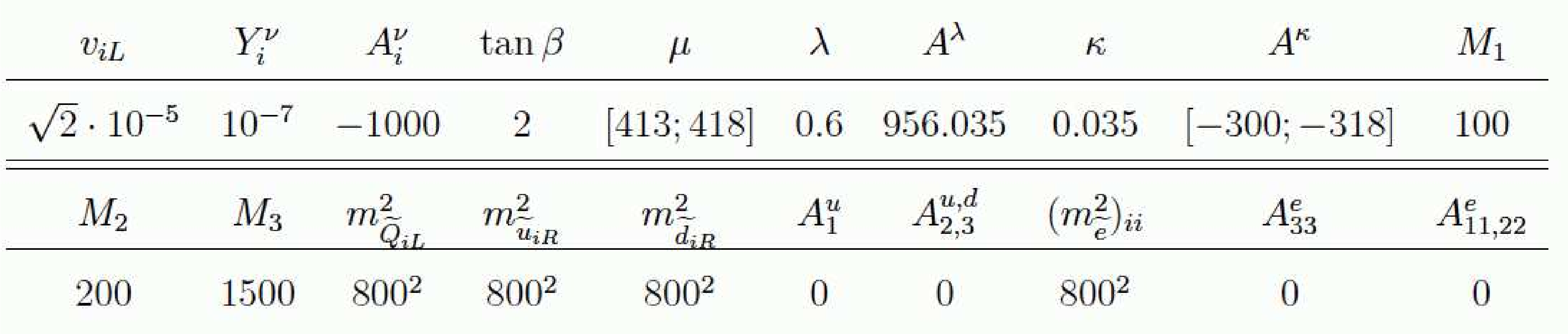
Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '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	$m^2_{\widetilde{Q}_{iL}}$	$m^2_{\widetilde{u}_{iR}}$	$m^2_{\widetilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\widetilde{e}})_{ii}$	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?

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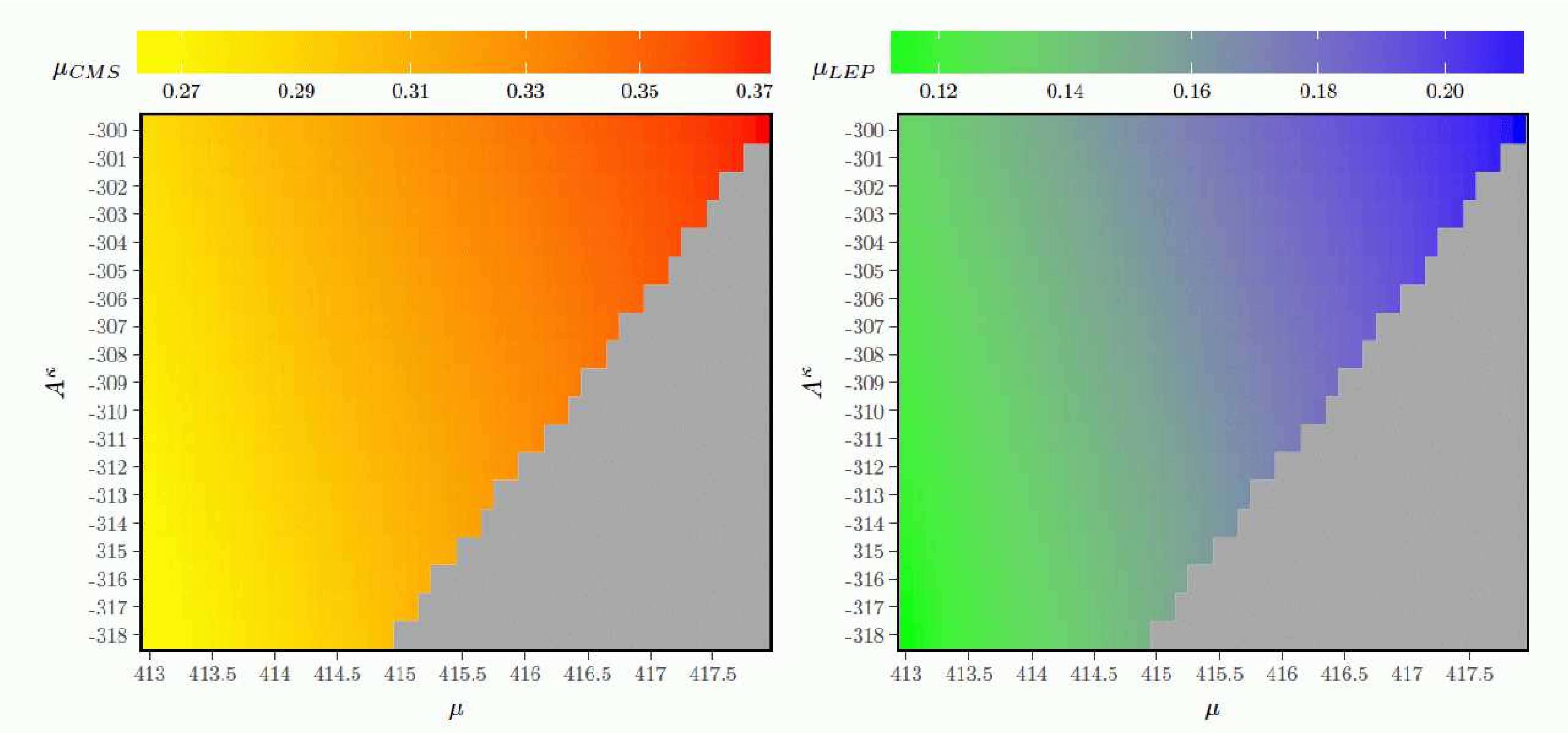
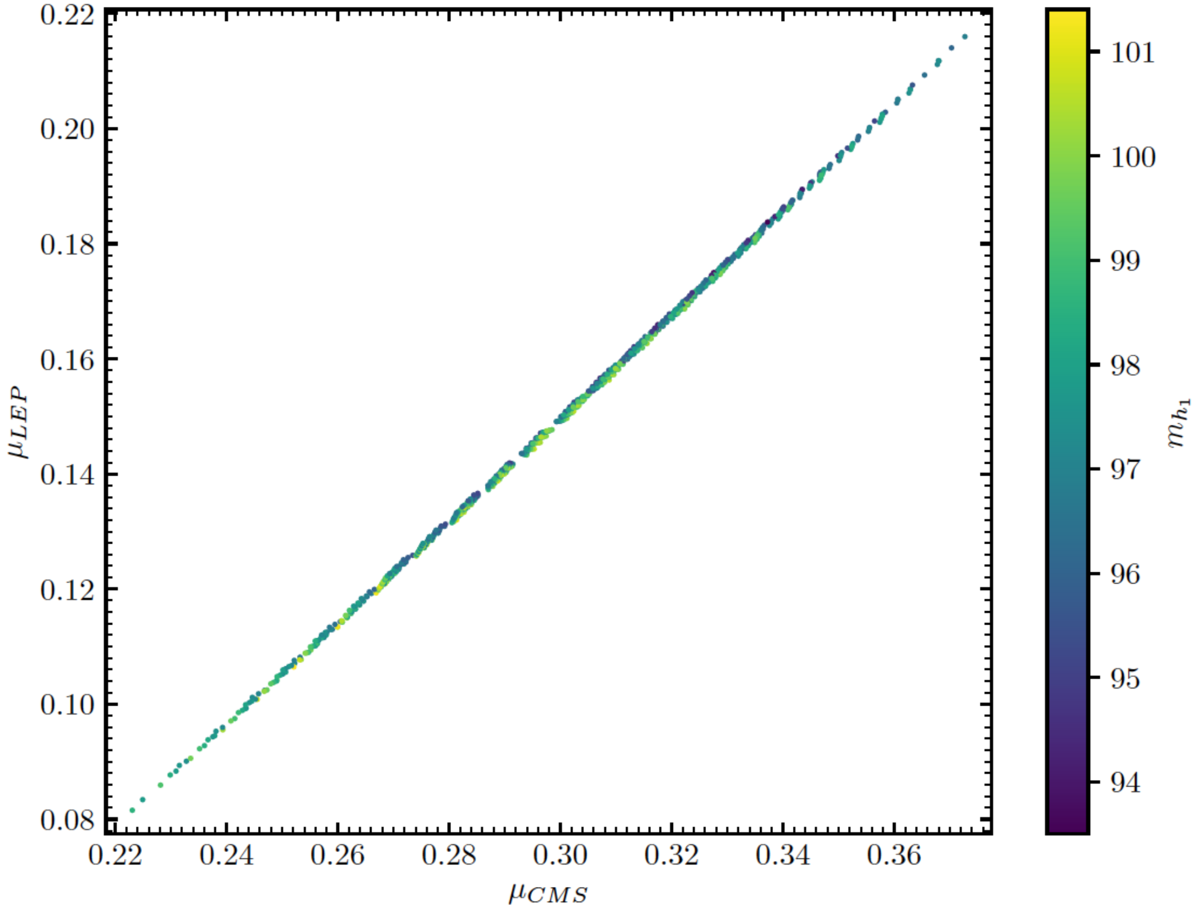


⇒ YES, WE CAN! :-)

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]



$\Rightarrow$ SUSY enforces strong correlation!

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