"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!"

The 96 GeV Excess at the ILC

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

Hamburg/zoom, 06/2020

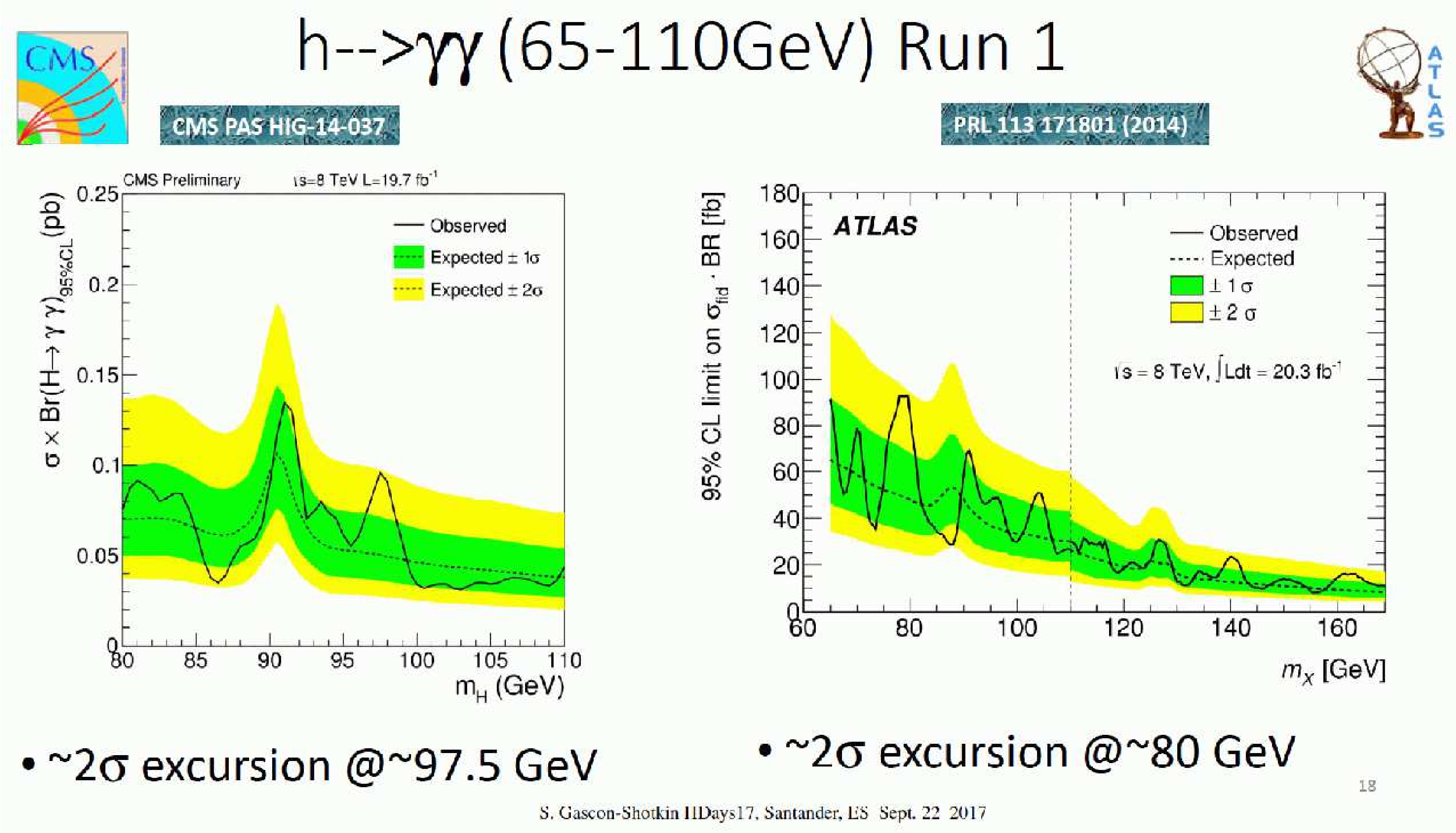
- The Excesses
- General Analysis
- Probes of the 125 GeV Higgs
- Probes of the 96 GeV Higgs at the ILC
- Conclusions

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*]

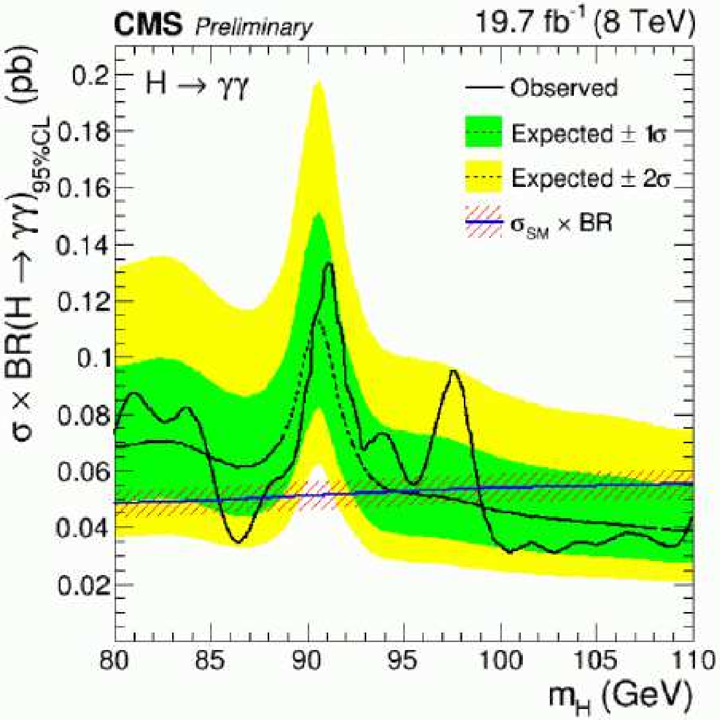


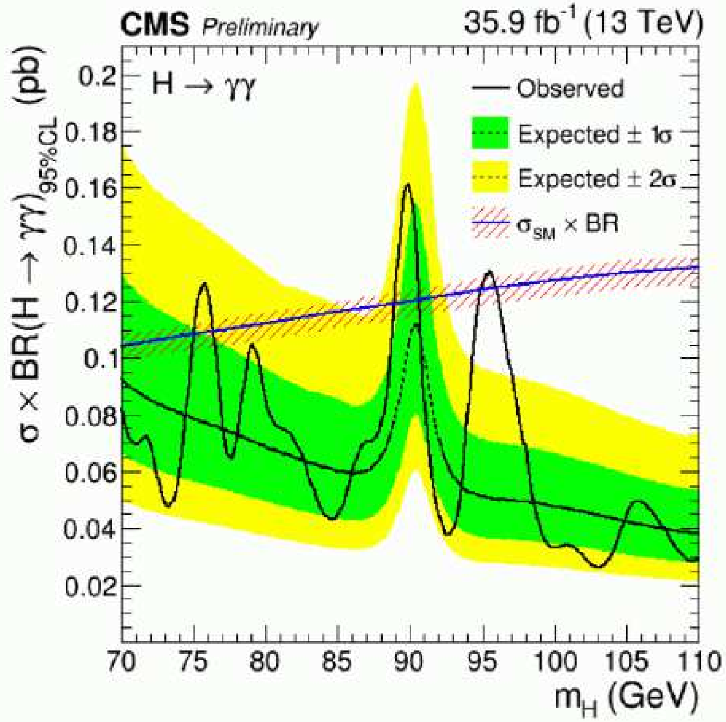
 [S. Shotkin, talk at HDays17]

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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What was seen at Run II?

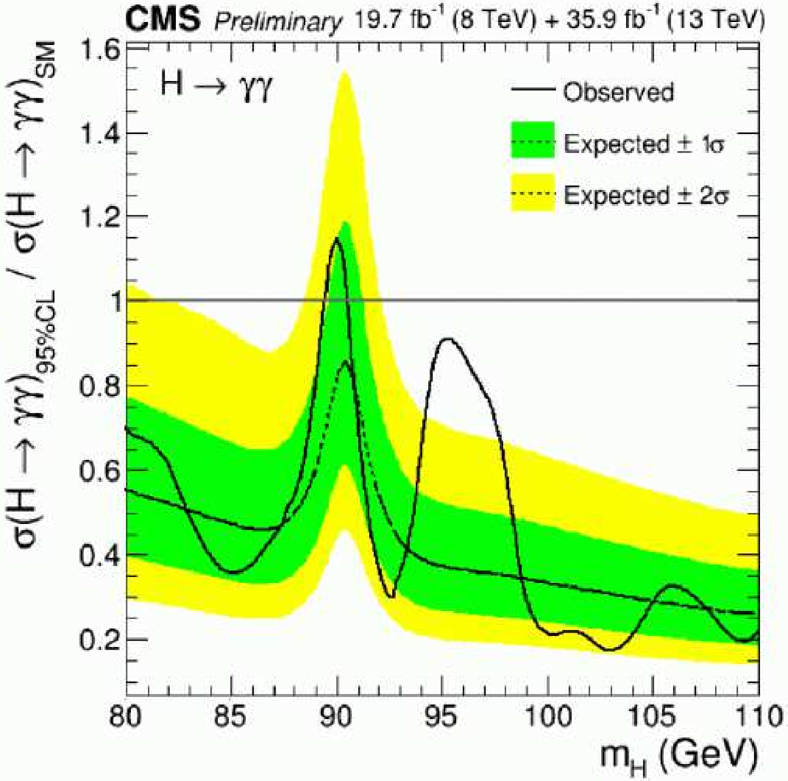
[*S. Shotkin, talk at HDays17*]

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 (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.

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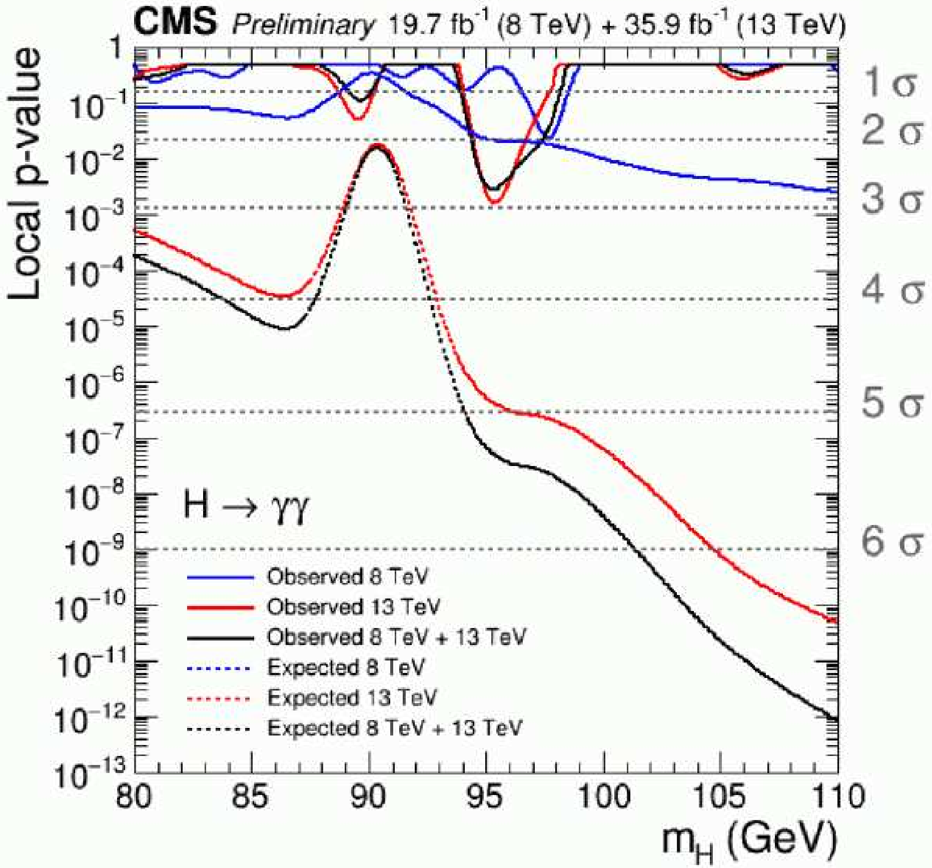
h-->γγ (70-110 GeV) Runs 1+ 2

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

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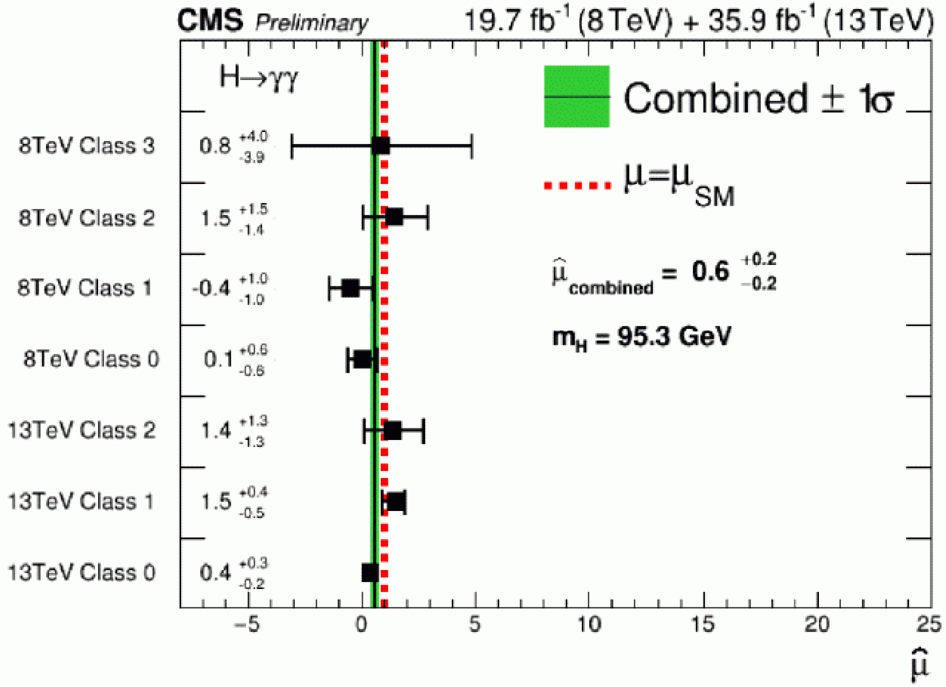
 [S. Shotkin, talk at HDays17]

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

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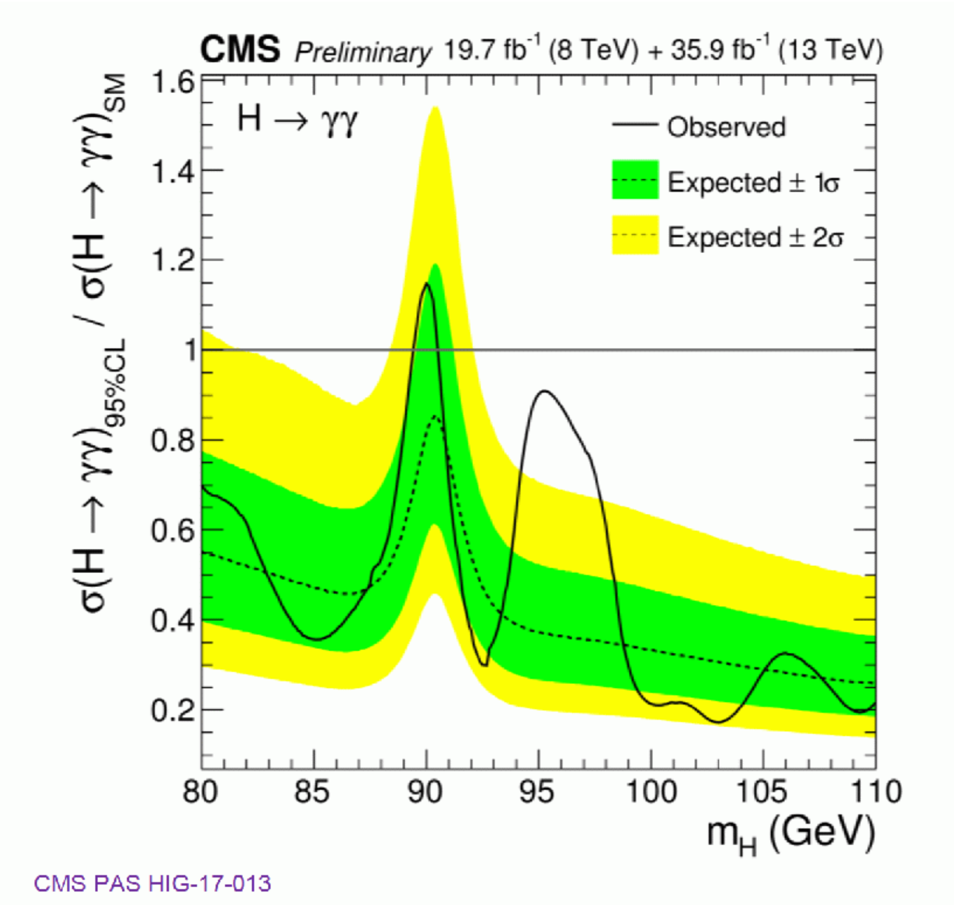
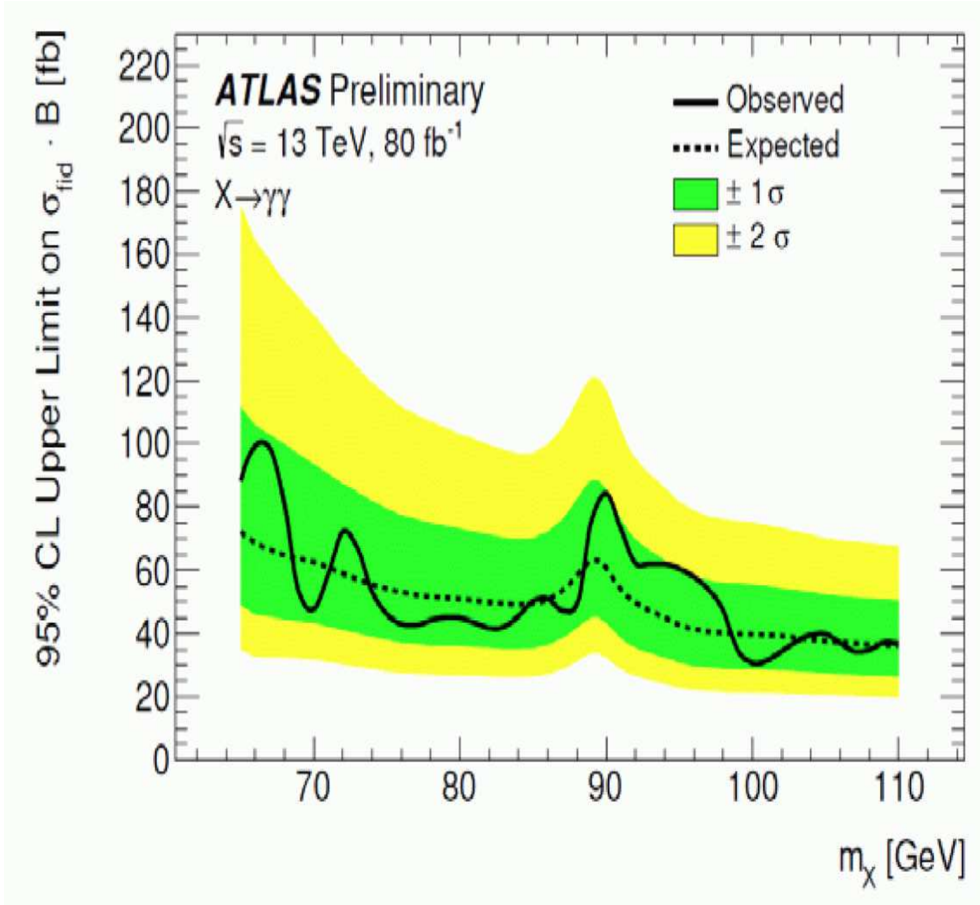
$$\mu_{\rm CMS}(96\ {\rm GeV}) = [\sigma(pp \to h_1) \times {\rm BR}(h_1 \to \gamma\gamma)]_{\rm exp/SM} = 0.6 \pm 0.2$$

What about ATLAS?





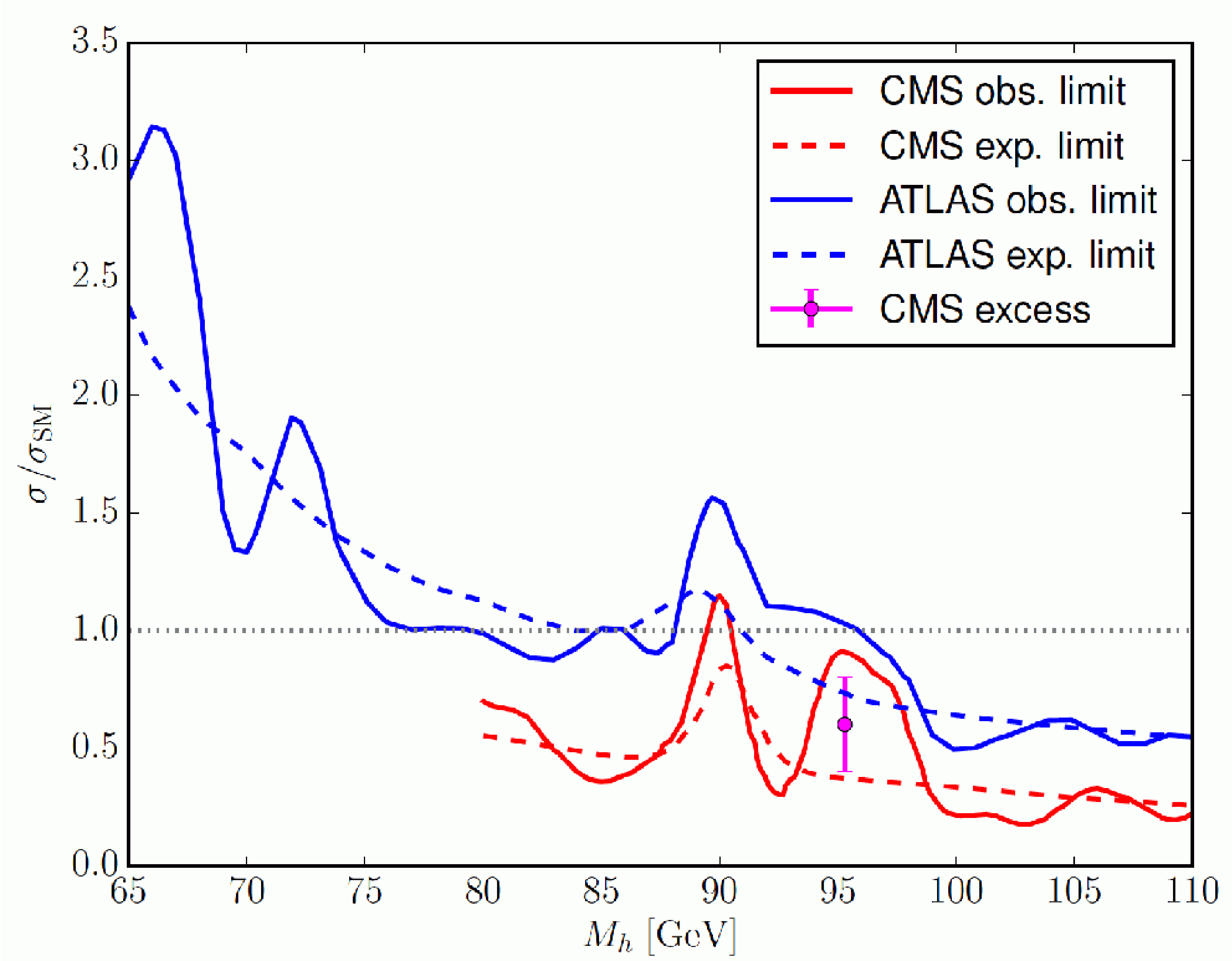
Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

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

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

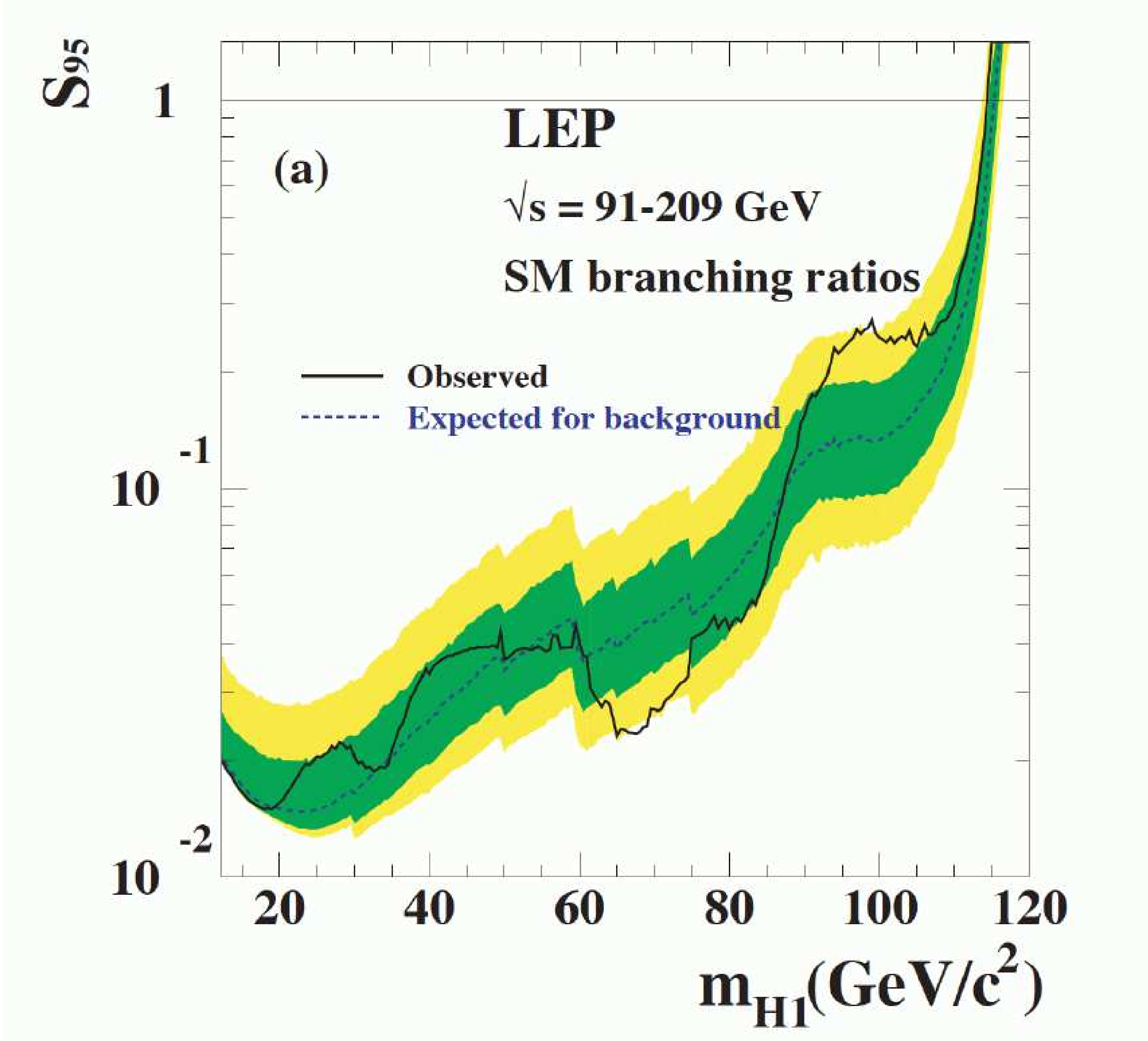
CMS and ATLAS in direct comparison:

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



⇒ everything well compatible with the excess!

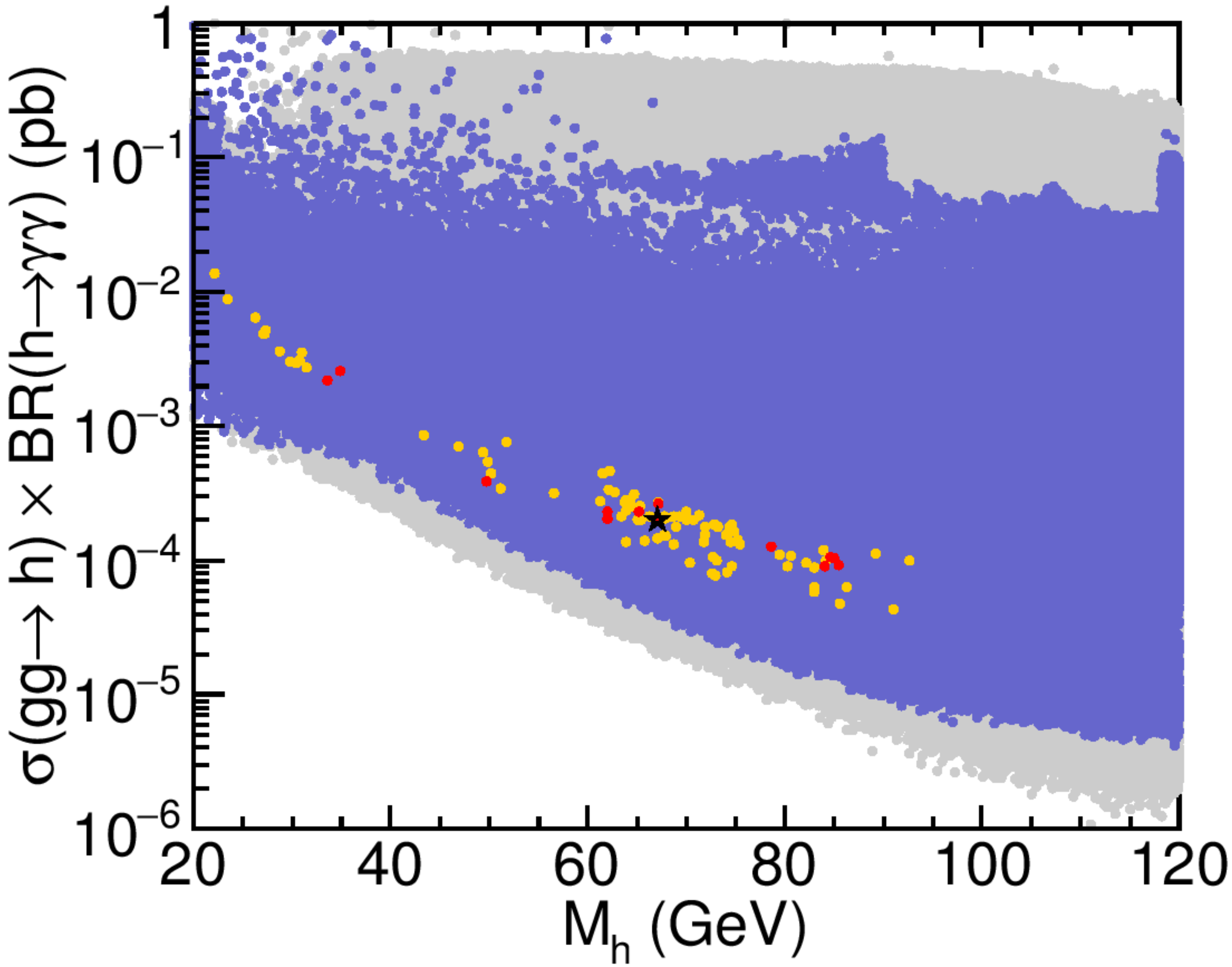
What was seen at LEP?



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

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!

$\Rightarrow$ 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 $\Rightarrow$ back-up

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 $\text{BR}(h_1 \to \gamma\gamma)$
- c_{h_1tt} not reduced for μ_{CMS}
- $c_{h_1\tau\tau}$ possibly reduced to enhance $\text{BR}(h_1 \to \gamma\gamma)$

	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)
  $\chi^2_{\rm red} := \chi^2/n_{\rm obs}$
- 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:

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

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

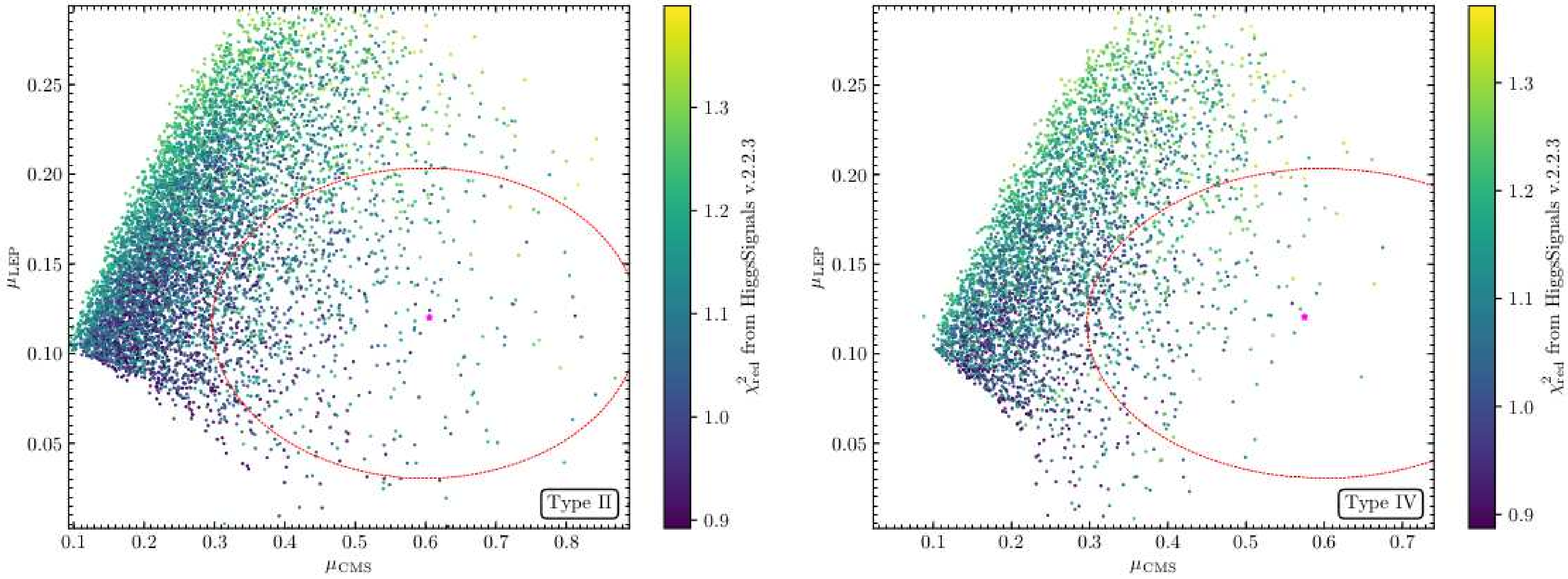
$$\mu_{\text{CMS}} = \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$
$$= \left|c_{h_1tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H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

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

⇒ "best-fit point"

Fitting the excesses:

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



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

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

What can we learn from future measurements?

- LHC h_{125} coupling measurements

- HL-LHC h_{125} coupling measurements

- ILC (or other e^+e^- coll.) h_{125} coupling measurements

- NEW: ILC (or other e^+e^- coll.) ϕ_{96} coupling measurements
  [*S.H., P. Toledo '20*]

- 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 (or other e^+e^- coll.)

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

What can we learn from future measurements?

- LHC h_{125} coupling measurements $\Leftarrow$ focus
- HL-LHC h_{125} coupling measurements $\Leftarrow$ focus
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- direct production of ϕ_{96} at the HL-LHC
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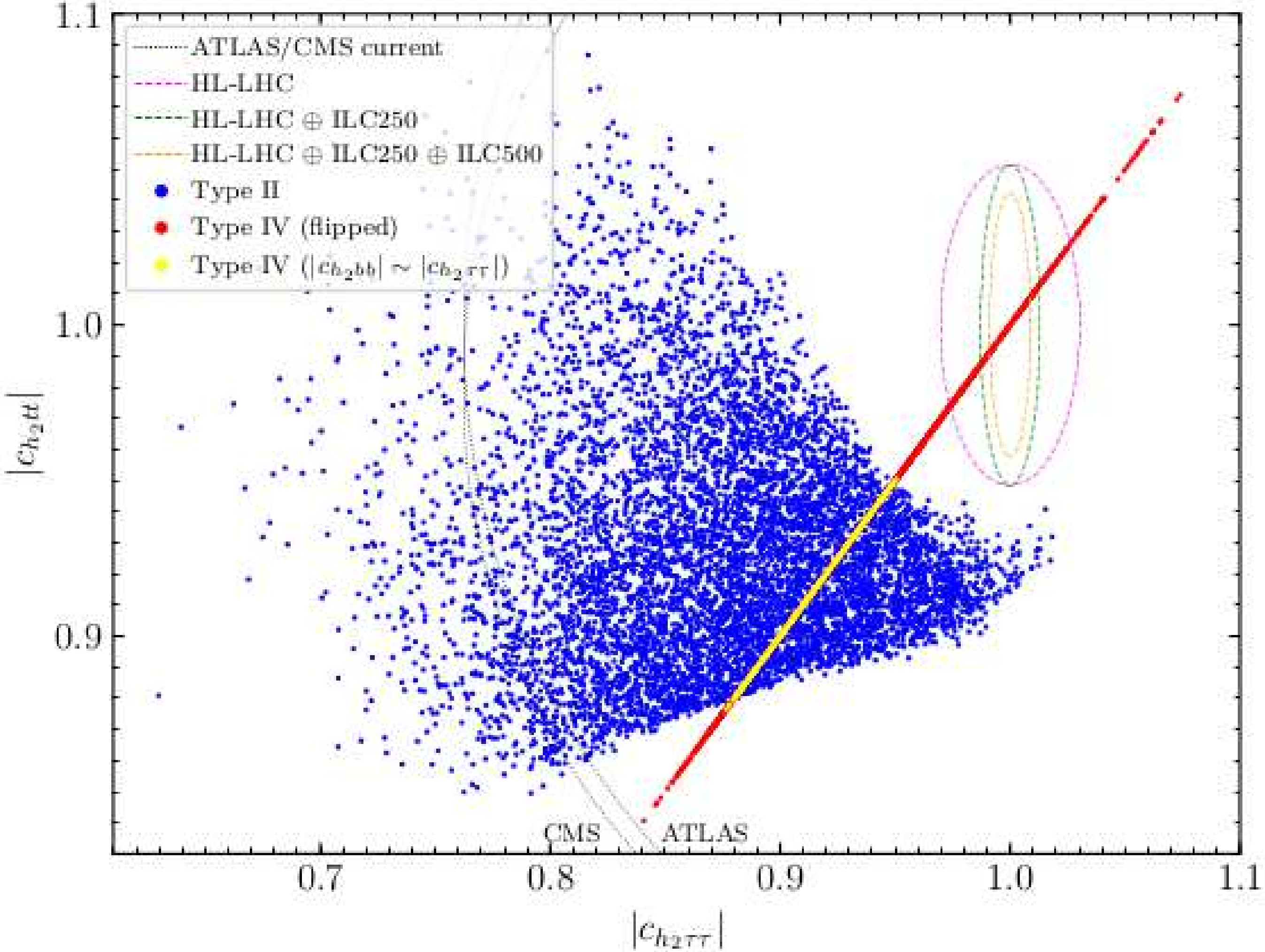
- production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/. . .

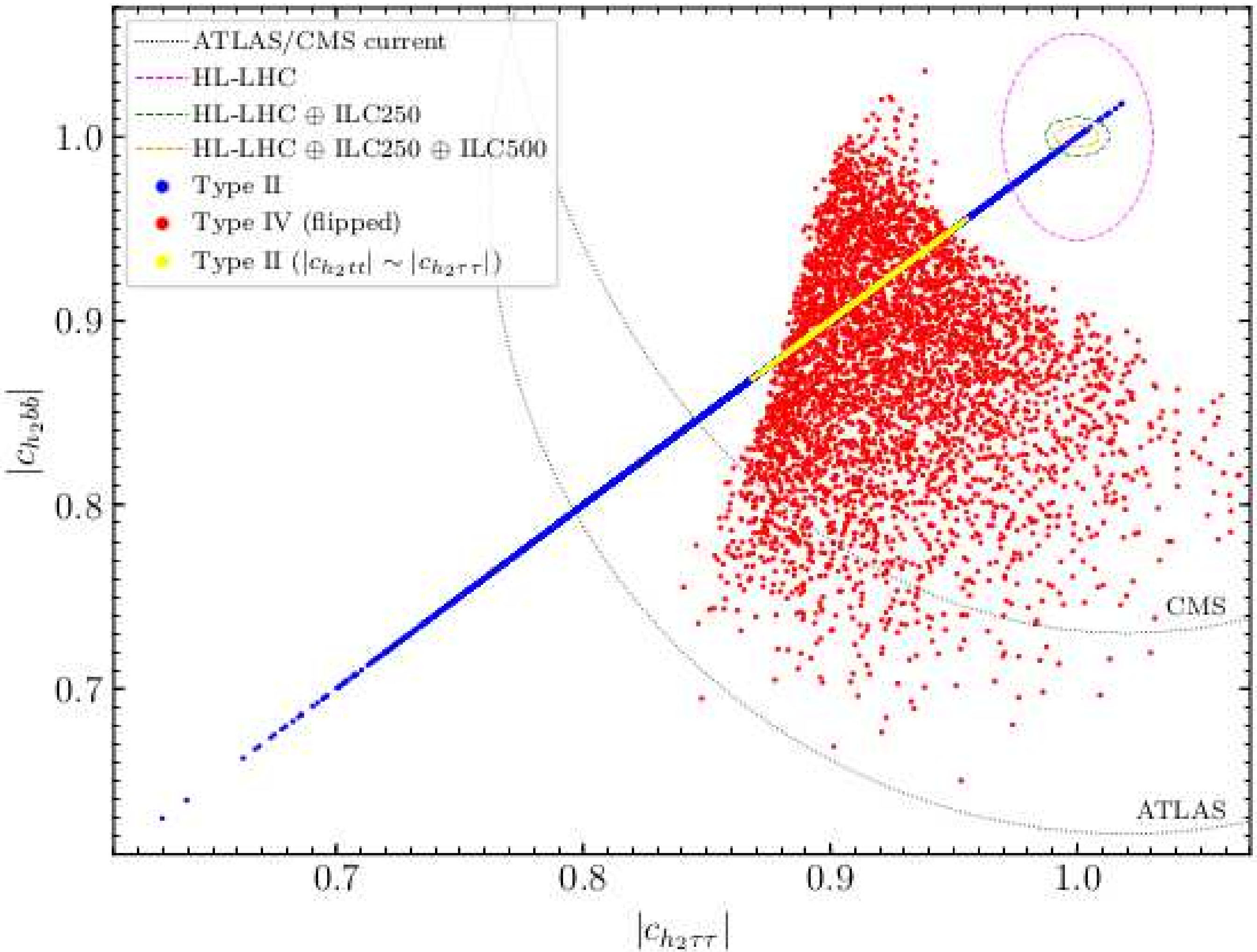
3. Probes of the 125 GeV Higgs

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



⇒ type II shows deviation from SM

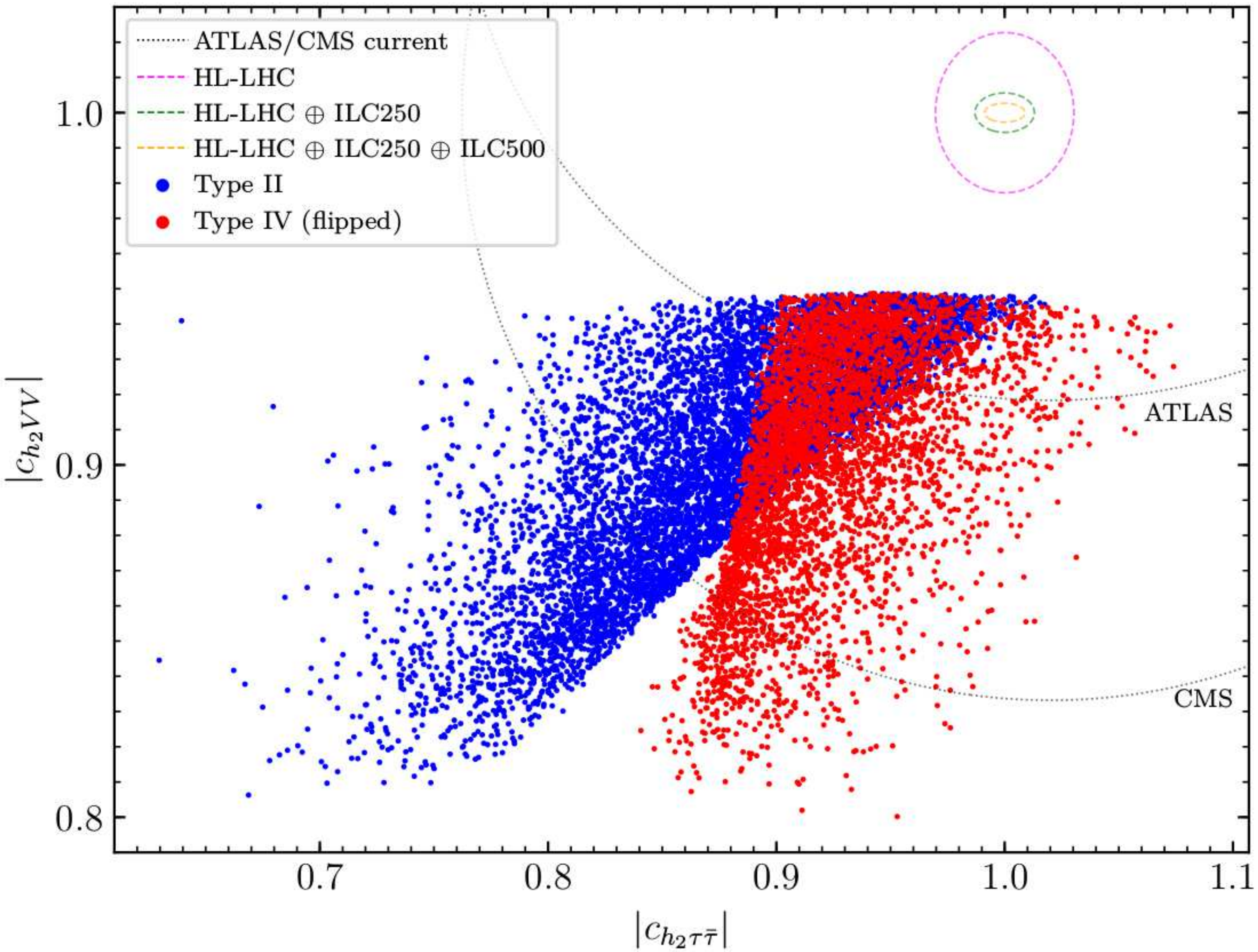
Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ 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!

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

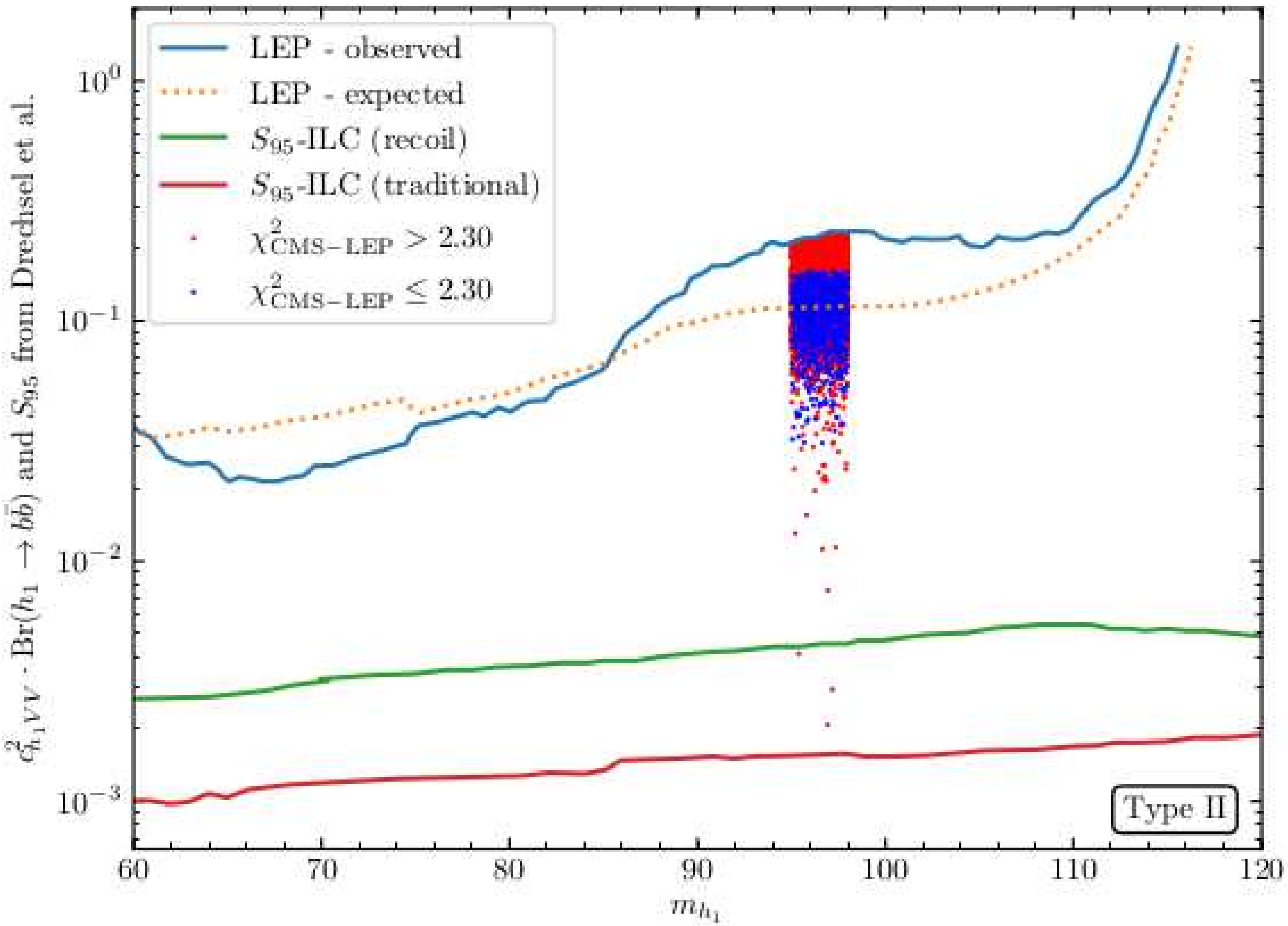
  Thanks go to:

  – T. Biekötter (for the data and discussions)
  – 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)

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

Next project? ⇒ ILC production of the light scalar

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



⇒ new state easily in the reach of the ILC ⇒ 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'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 $D = 2$ as starting point

Evaluating uncertainties of ϕ_{96}:

- Coupling is measured via decay

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

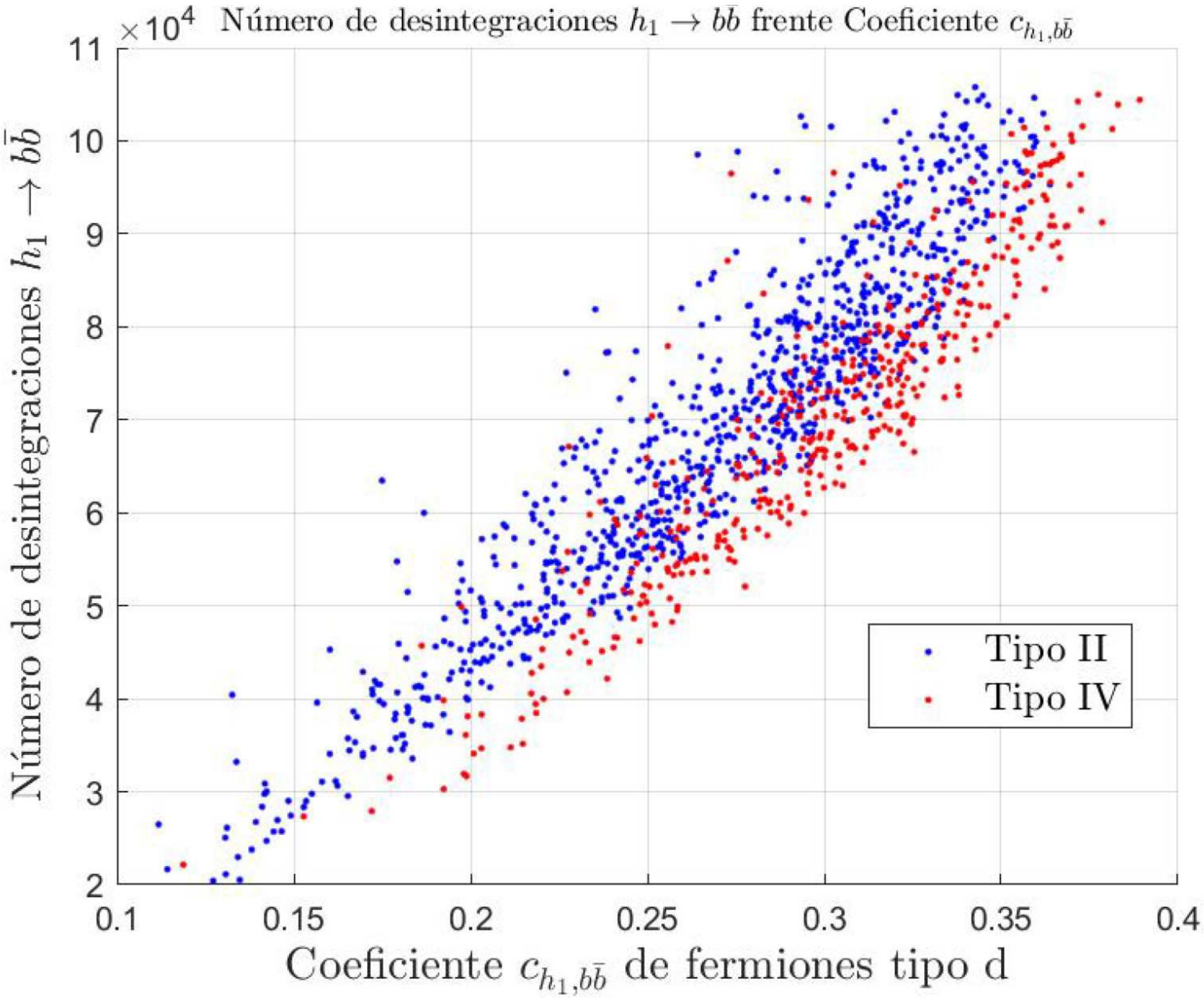
$$\to \sqrt{\frac{D + f_H}{1 + f_H}} \times \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}} \times \sqrt{\frac{\mathrm{BR}(H \to xx)}{\mathrm{BR}(\phi \to xx)}} \times \frac{(1 - \mathrm{BR}(H \to xx))}{(1 - \mathrm{BR}(\phi \to xx))}$$

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

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

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

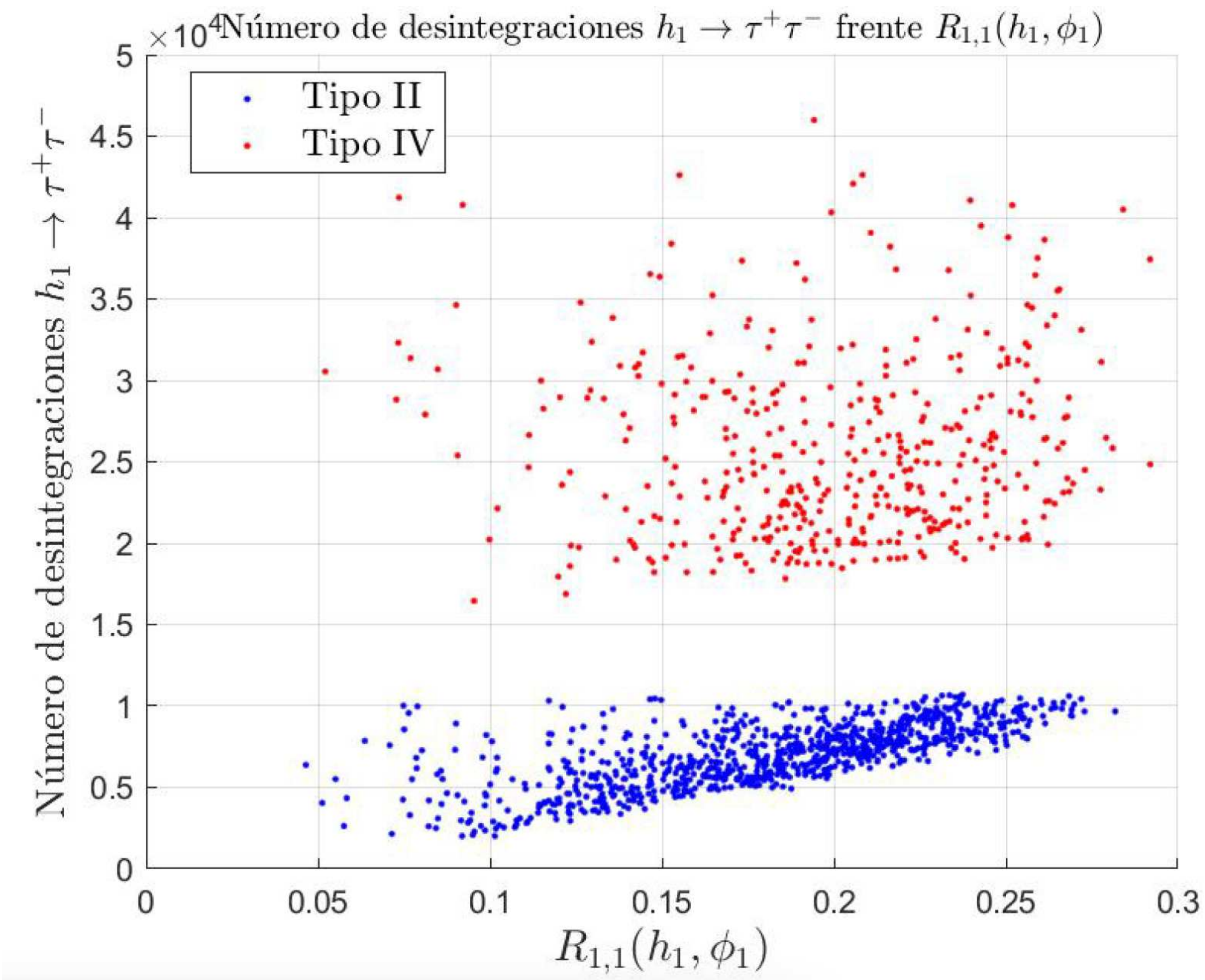
N2HDM: Number of $b\bar{b}$ events: [S.H., P. Toledo '20]



$\Rightarrow$ no difference between type II and IV

N2HDM: Number of $\tau^+\tau^-$ events:

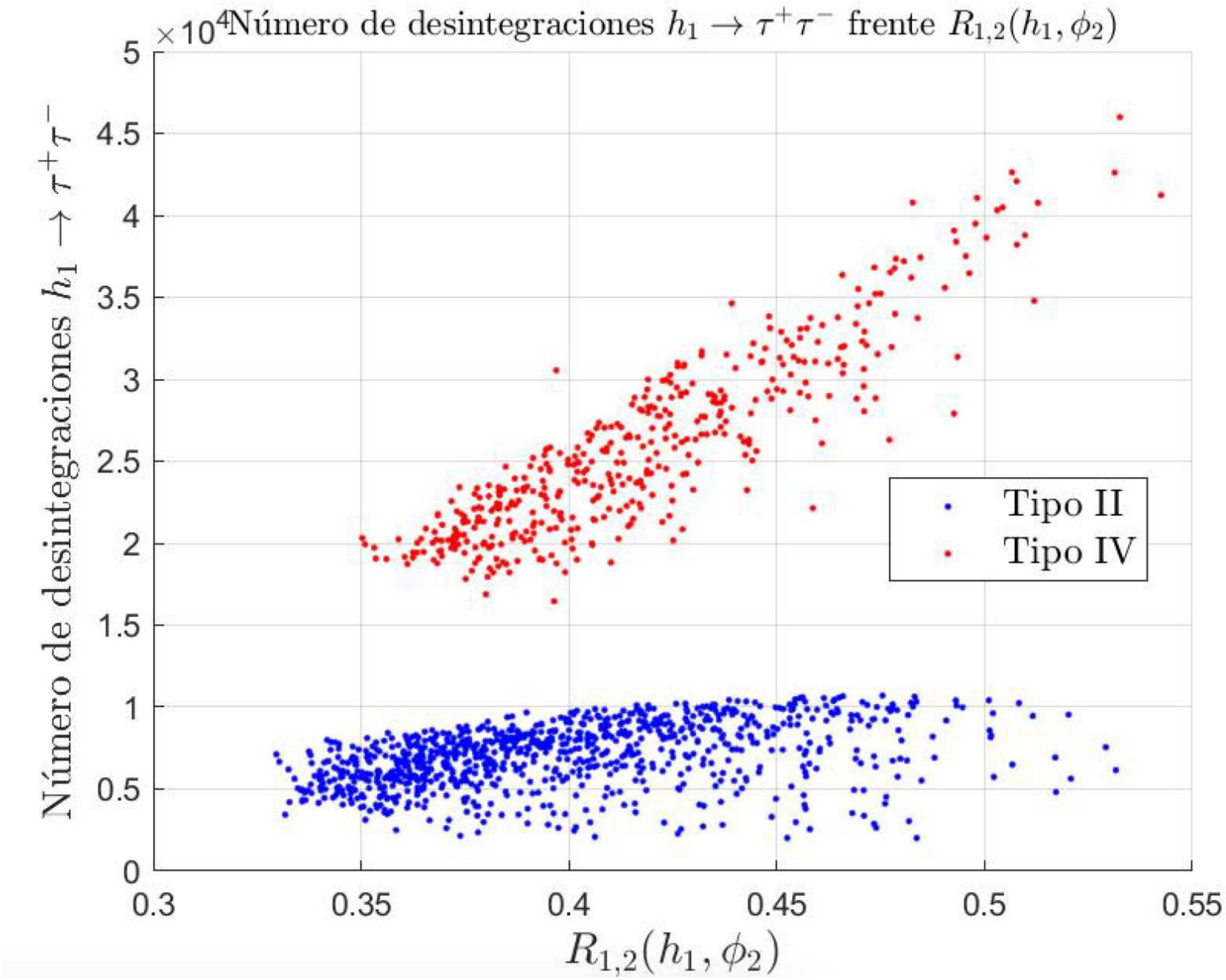
[S.H., P. Toledo '20]



⇒ clear distinction between type II and IV

⇒ linear dependence for type II

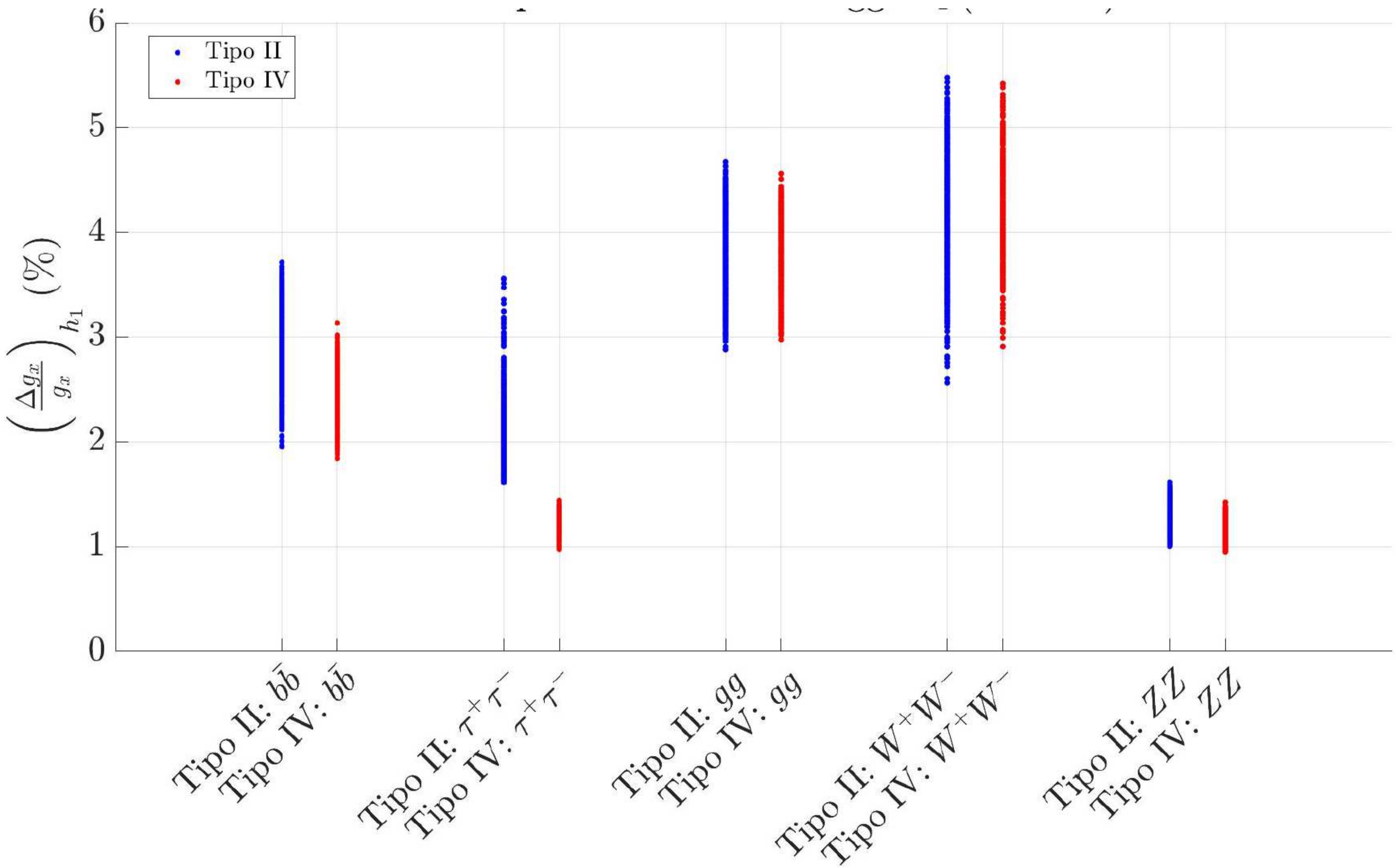
N2HDM: Number of $\tau^+\tau^-$ events: [S.H., P. Toledo '20]



⇒ clear distinction between type II and IV

⇒ linear dependence for type IV

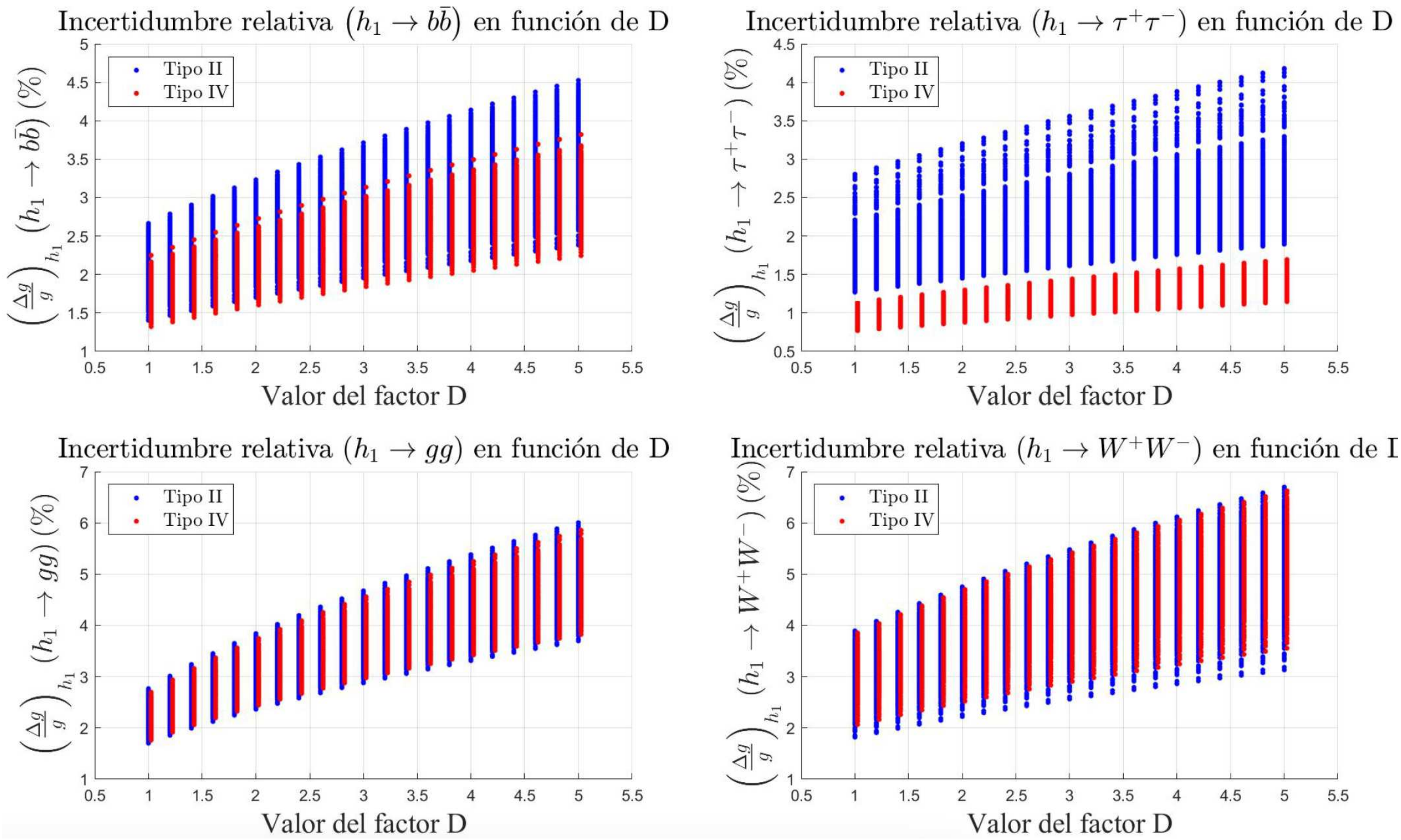
N2HDM: precision of ILC coupling measuements [S.H., P. Toledo '20]



$\Rightarrow \mathcal{O}(1-5\%)$: g_Z best from production, g_τ very precise in type IV

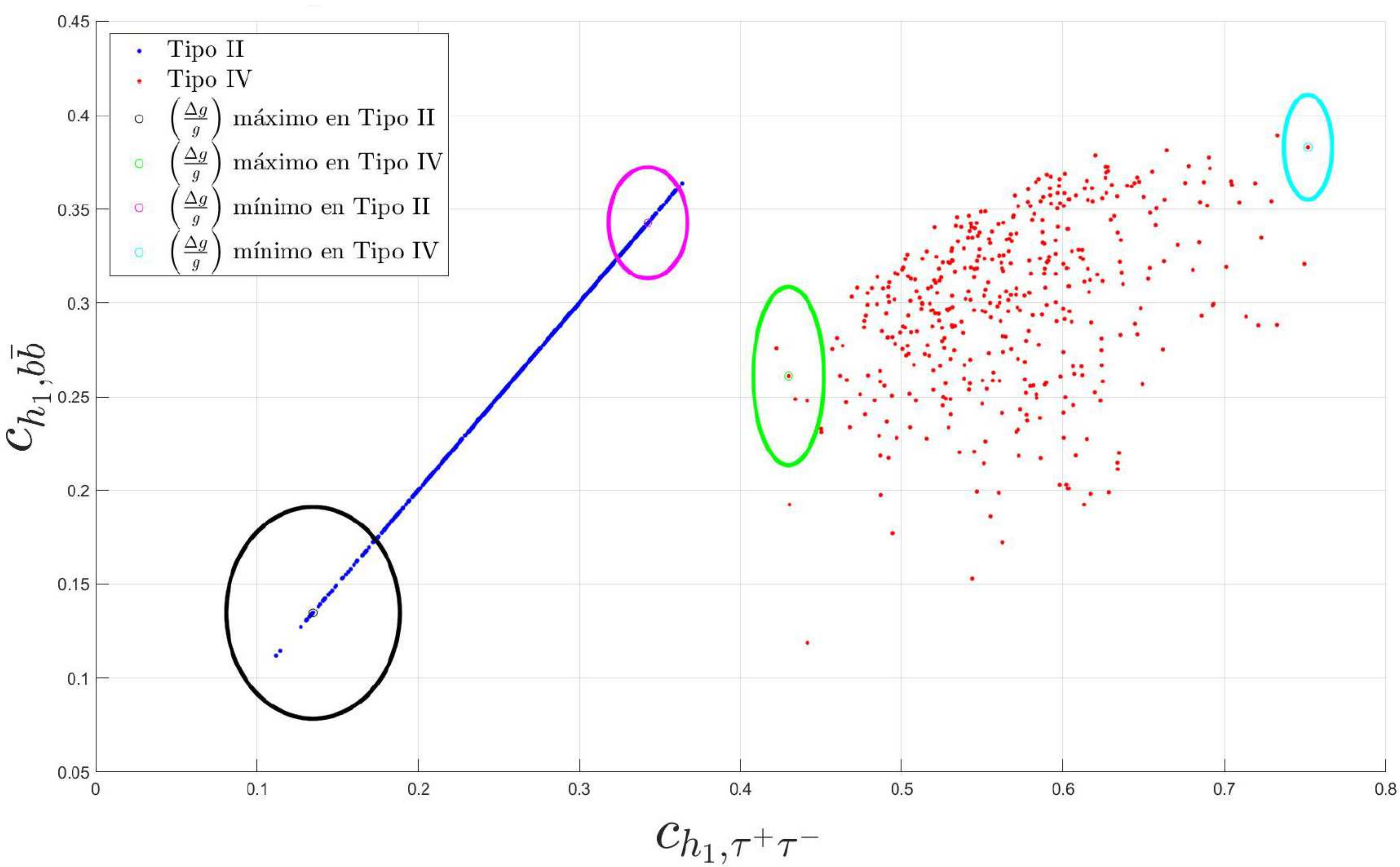
N2HDM: dependence on $D = f_H/f_\phi$:

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

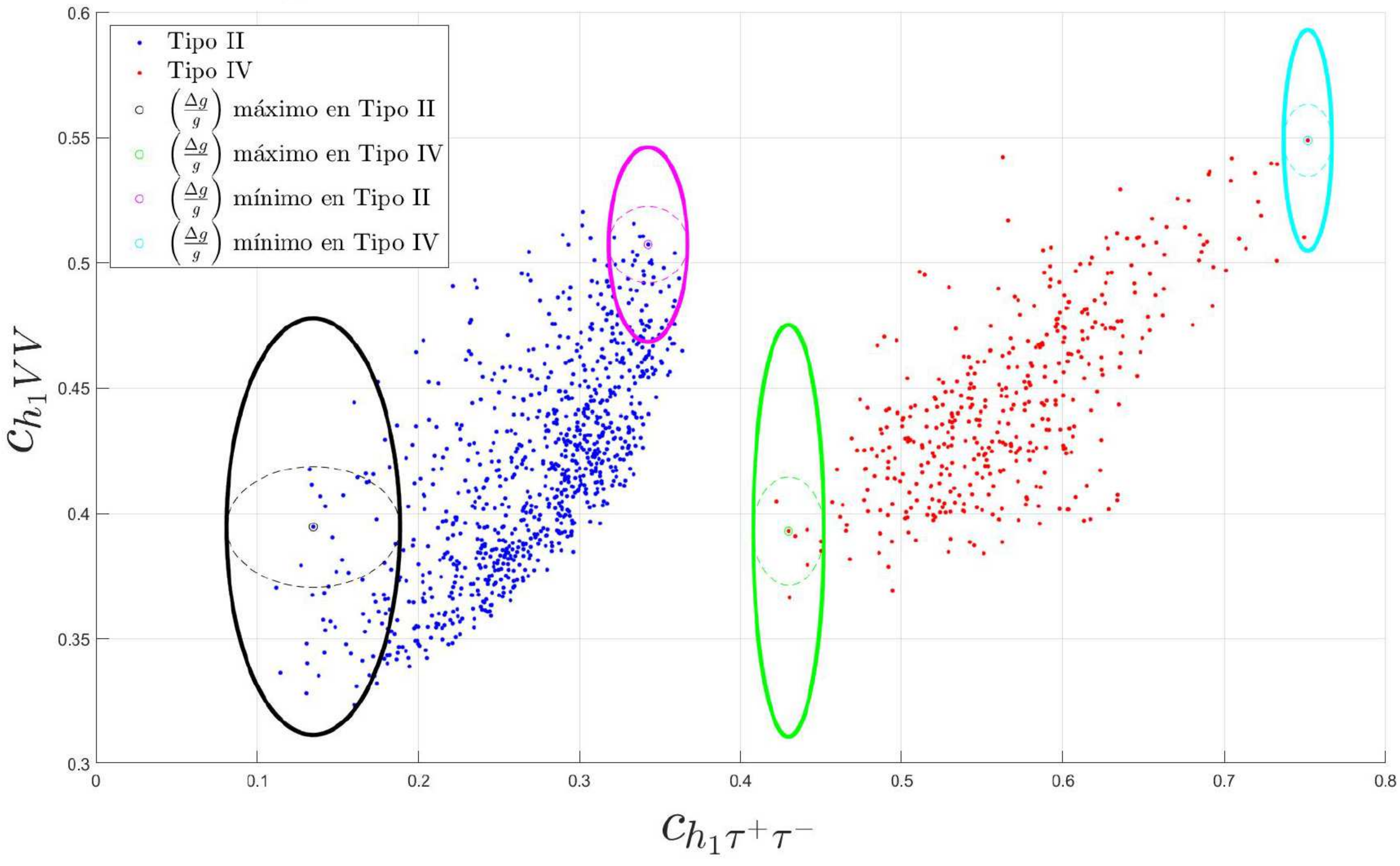


$\Rightarrow$ non-negligible, but small $\Rightarrow$ "robust" result

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



$\Rightarrow$ model distinction possible via coupling measurements



$\Rightarrow$ 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

- Only type II and IV can fit both excesses simultaneously
  $\Rightarrow$ type II fits best (as predicted by SUSY :-)

- Analysis with ScannerS, HiggsBounds, HiggsSignals, N2HDMDecay, SusHi, SuperIso
  $\Rightarrow$ many good fit points ($\chi^2_{\text{CMS}-\text{LEP}} < 2.3$) found

- Couplings of $h_2(125)$ can distinguish N2HDM vs. SM and type II and IV

- Coupling analysis of h_1:
  - number of $\tau\tau$ events clearly distinguishes type II and IV
  - $\Rightarrow \mathcal{O}\,(1-5\%)$: g_Z best from production, g_τ very precise in type IV
  - no strong dependence on $D = f_H/f_\phi$
  - coupling measurements ($\tau\tau$, $b\bar{b}$, ZZ) distinguishes type II and IV


Further Questions?

SUSY realizations

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- NMSSM
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- ...

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

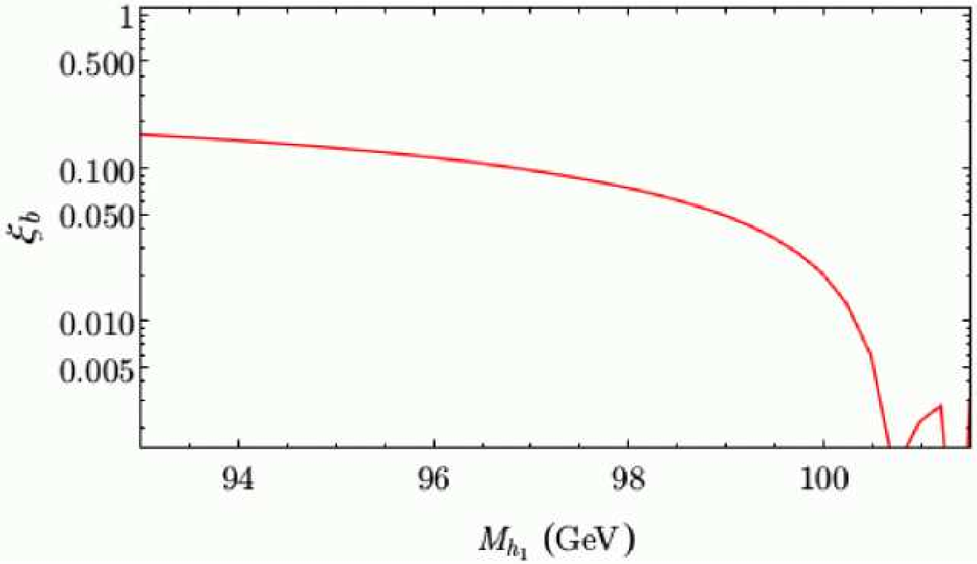
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

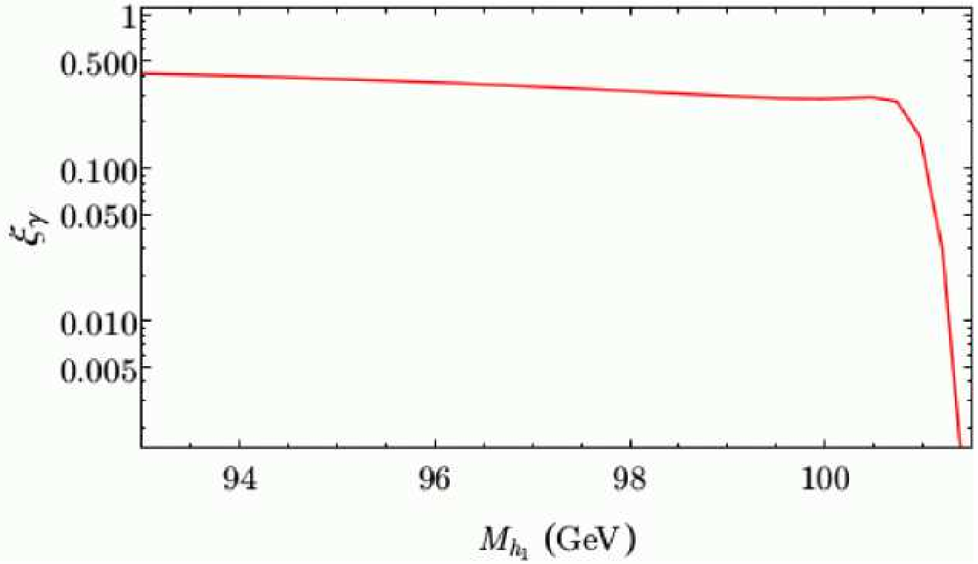
Parameters:

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

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

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





$\Rightarrow$ 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

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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

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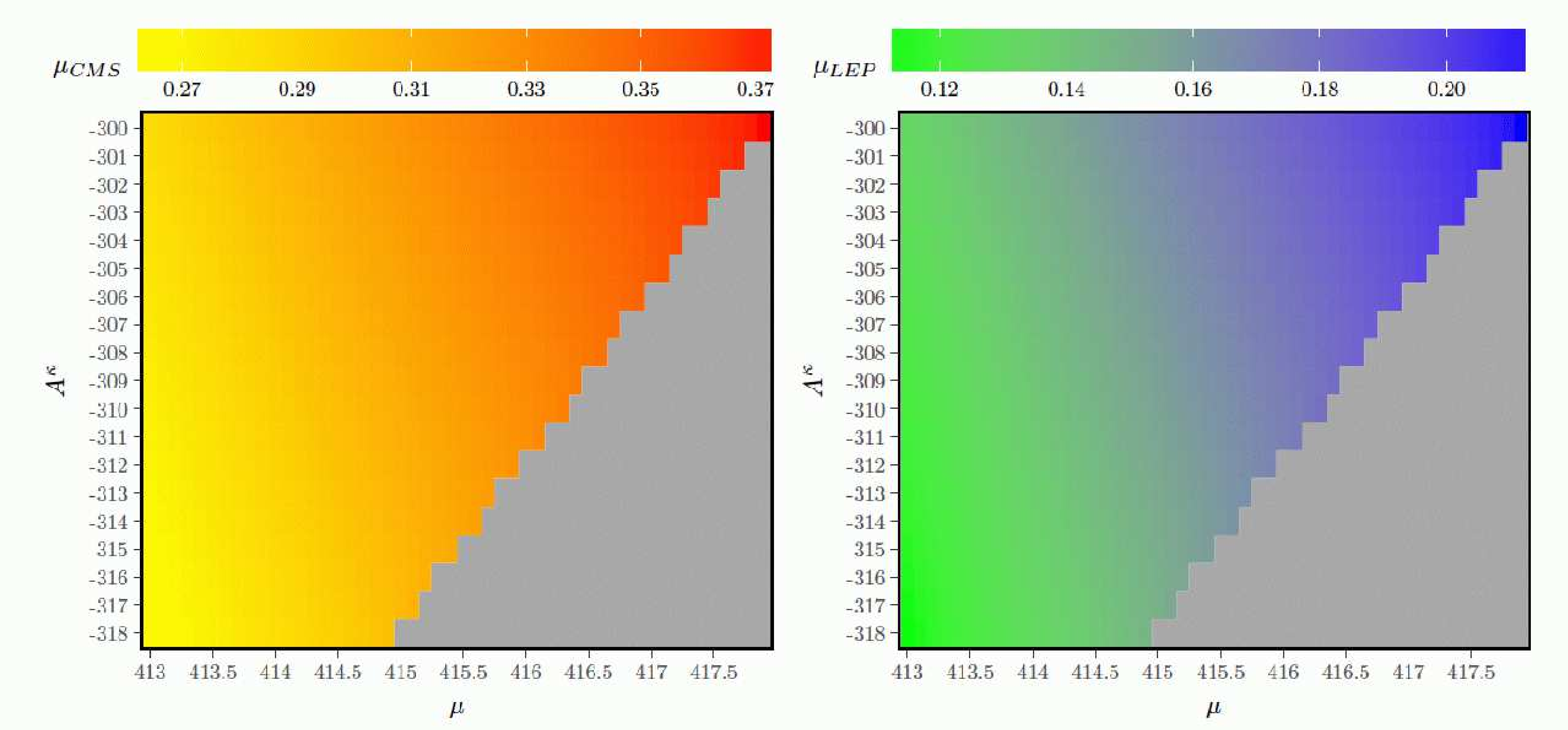
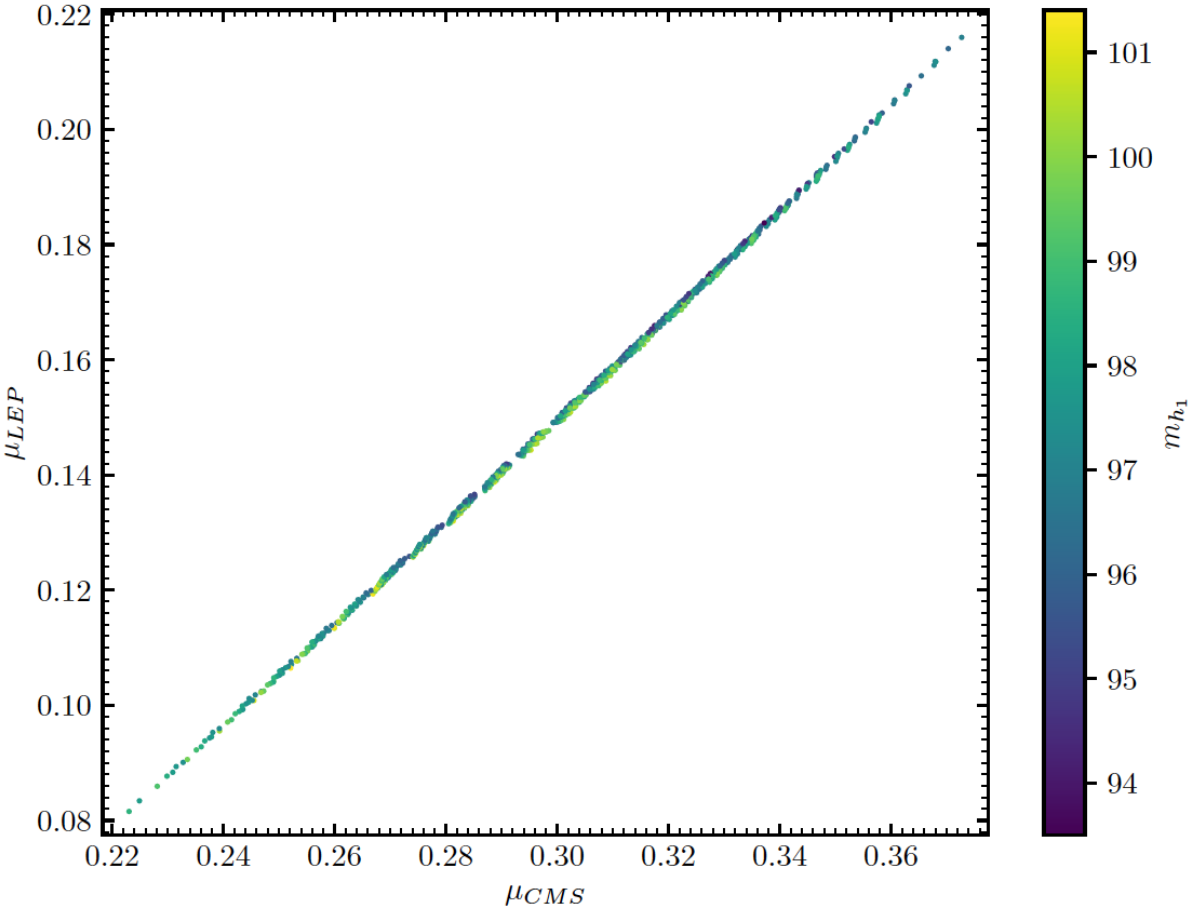


$\Rightarrow$ YES, WE CAN! :-)

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 $\mu_{\rm LHC}$!

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