Determination of Higgs coupling uncertainties in the THDMS

Bachelor thesis colloquium

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Heading Agenda

Subheading, optional

1. **Introduction**
2. **N2HDM**
3. **THDMS**
4. **Data generation**
5. **Evaluation**

Introduction

LEP and CMS excesses

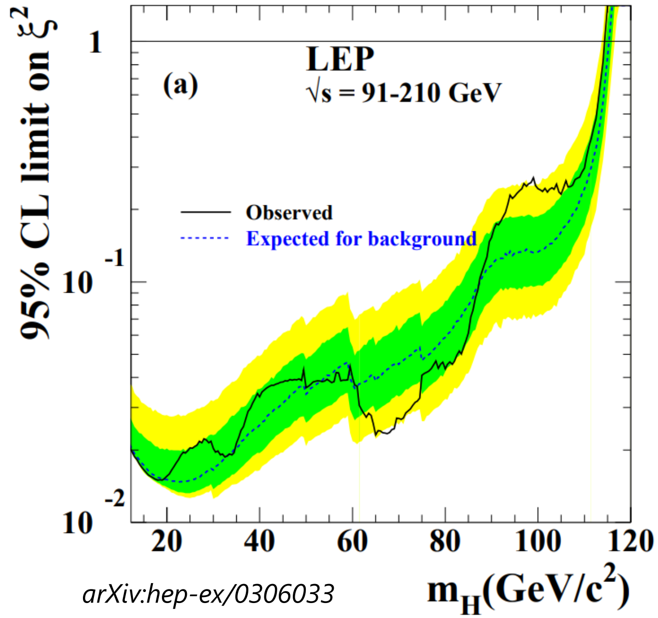
- 96 GeV excess at LEP and CMS

$$\mu_{LEP} = \frac{\sigma\left(e^+e^- \to Z\phi \to Zb\bar{b}\right)}{\sigma^{\rm SM}\left(e^+e^- \to ZH^{\phi}_{\rm SM} \to Zb\bar{b}\right)} = 0.117 \pm 0.057$$

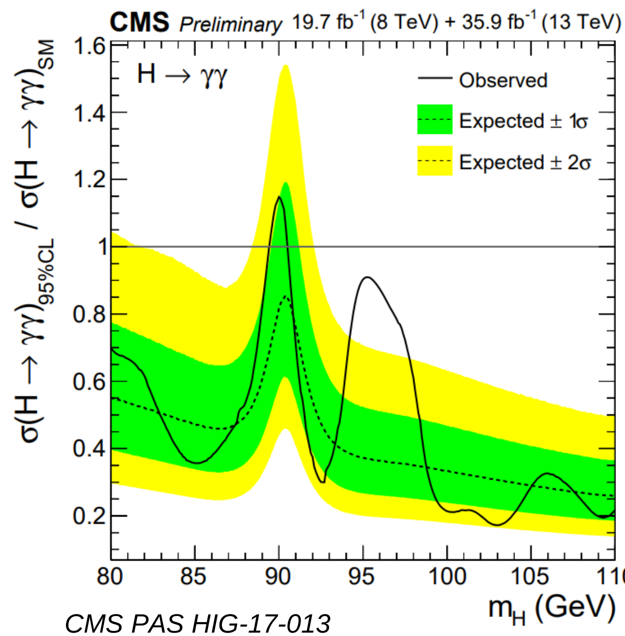
$$\mu_{CMS} = \frac{\sigma\left(gg \to \phi \to \gamma\gamma\right)}{\sigma^{\rm SM}\left(gg \to H^{\phi}_{\rm SM} \to \gamma\gamma\right)} = 0.6 \pm 0.2$$

- Idea: fit both excesses with a 96 GeV Higgs boson.

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



arXiv:hep-ex/0306033



CMS PAS HIG-17-013

Introduction

Data generation

Scan

- Parameter scan using SARAH
- Create spectra with SPheno

Constraints

- Theoretical constraints
  - Tree-Level Perturbativity → SARAH & SPheno checks
  - Boundedness from below → SARAH & SPheno checks
- Experimental constraints
  - LEP, Tevatron & LHC Higgs searches → HiggsBounds
  - SM Higgs couplings → HiggsSignals
  - Electroweak precision observables → Fit for *S,T,U* parameters
  - Flavour physics $B \to X_s \gamma$ limit → Lower bounds for $m_{H^\pm}$

Introduction

Couplings

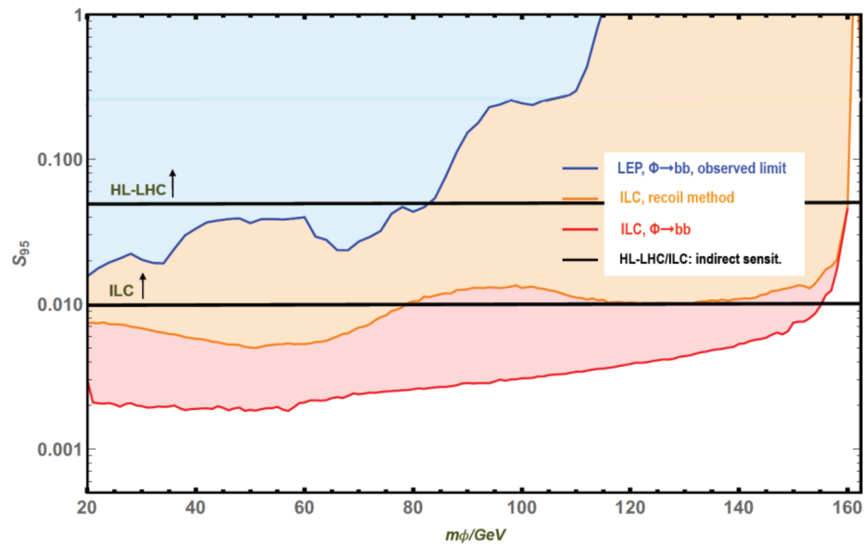
- S_{95} -method to calculate precisions at LEP, ILC and HL-LHC

$$S_{95} = \frac{\hat{\sigma}}{\sigma_{ref}} = \frac{\hat{n}}{n}$$

$$S_{95} \hat{=} \left| \frac{(g_{\phi ZZ})^2}{(g_{HZZ}^{\text{SM}})^2} \right|$$

- Upper bound for Higgs searches at HL-LHC

$$\frac{(g_{\phi ZZ})^2}{(g_{HZZ})^2} \leq 1 - (1 - |\Delta g_{HZZ}|)^2$$



arXiv:1801.09662 [hep-ph]

N2HDM

Potential and field conventions

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

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

$$\Phi_S = v_S + \rho_S$$

$\mathbb{Z}_2$-symmetry

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

N2HDM

Types of 2HDM

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
lepton-specific	Φ_2	Φ_2	Φ_1
flipped	Φ_2	Φ_1	Φ_2

	u-type$(c_{ht\bar{t}})$	d-type$(c_{hb\bar{b}})$	leptons$(c_{h\tau^+\tau^-})$
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
lepton-specific	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
flipped	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

$$R = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1}c_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ s_{\alpha_1}s_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} & -s_{\alpha_1}s_{\alpha_2}c_{\alpha_3} - c_{\alpha_1}s_{\alpha_3} & c_{\alpha_2}c_{\alpha_3} \end{pmatrix} \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

THDMS

Potential and field conventions

$$
\begin{aligned}
V =& m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
&+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + m_S^2(S^\dagger S) + \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2) \\
&+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \Big(- m_{12}^2\Phi_1^\dagger\Phi_2 + \frac{\mu_{s1}}{6}S^3 + \mu_{12}S\Phi_1^\dagger\Phi_2 + \text{h.c.}\Big)
\end{aligned}
$$

$$
\Phi_1 = \begin{pmatrix}\chi_1^+ \\ \phi_1\end{pmatrix} = \begin{pmatrix}\chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}}\end{pmatrix} \quad \Phi_2 = \begin{pmatrix}\chi_2^+ \\ \phi_2\end{pmatrix} = \begin{pmatrix}\chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}}\end{pmatrix}
$$

$$
S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}}
$$

$$
\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 174 \text{ GeV}
$$

$\mathbb{Z}_2$-symmetry

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

$\mathbb{Z}_3$-symmetry

$$
\begin{pmatrix}\Phi_1 \\ \Phi_2 \\ S\end{pmatrix} = \begin{pmatrix}1 & & \\ & e^{i2\pi/3} & \\ & & e^{-i2\pi/3}\end{pmatrix}\begin{pmatrix}\Phi_1 \\ \Phi_2 \\ S\end{pmatrix}
$$

THDMS

parameters

$$V = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + m_S^2(S^\dagger S) + \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2)$$
$$+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \left(- m_{12}^2\Phi_1^\dagger\Phi_2 + \frac{\mu_{s1}}{6}S^3 + \mu_{12}S\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)$$

12 free parameters

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_1',\ \lambda_2',\ \lambda_3'',\ m_{12},\ \mu_{S1},\ \mu_{12},\ v_S,\ \tan\beta$$

Mass input

$$m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4,\ v_S,\ \tan\beta$$

$\alpha_{1,2,3,4}$ → mixing angles
$m_{h_{1,2,3}}$ → scalar Higgs masses
$m_{a_{1,2}}$ → pseudo-scalar Higgs masses
$m_{H^\pm}$ → charged Higgs mass
$\tan\beta$ → ratio of doublet vevs
v_s → singlet vev

Data generation

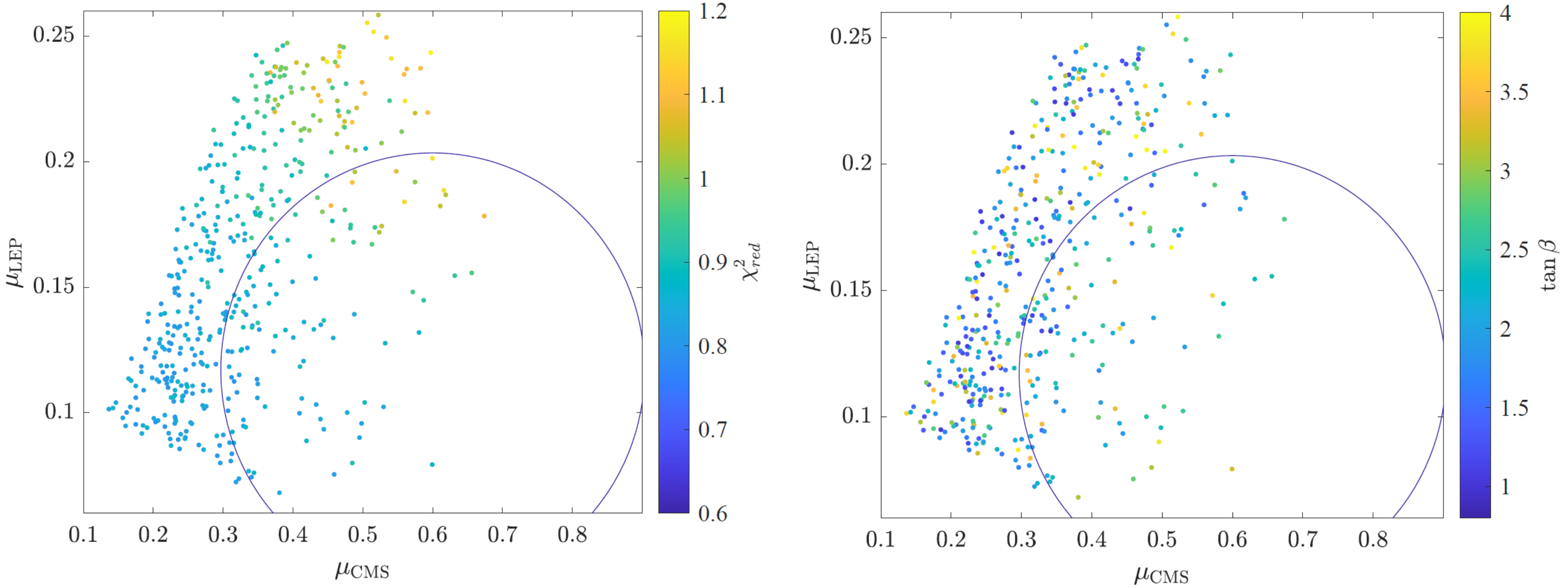
Scan using SARAH

Parameter	Scanning range	Parameter	Scanning range
α_1	$(0.8,\ 1.45)$	m_{h_3}	$(650,\ 1000)$
α_2	$(0.93,\ 1.25)$	m_a	$(200,\ 500)$
α_3	$(0.93,\ \frac{\pi}{2})$	m_A	$(650,\ 1000)$
α_4	$(1.565,\ \frac{\pi}{2})$	$m_{H^\pm}$	$(650,\ 1000)$
m_{h_1}	$(80,\ 93)$	$\tan\beta$	$(1,\ 4)$
m_{h_2}	$(122,\ 126)$	v_S	$(100,\ 2000)$

Values taken in $\overline{DR}$-scheme and converted to on-shell scheme

Data generation

Scan using Sarah

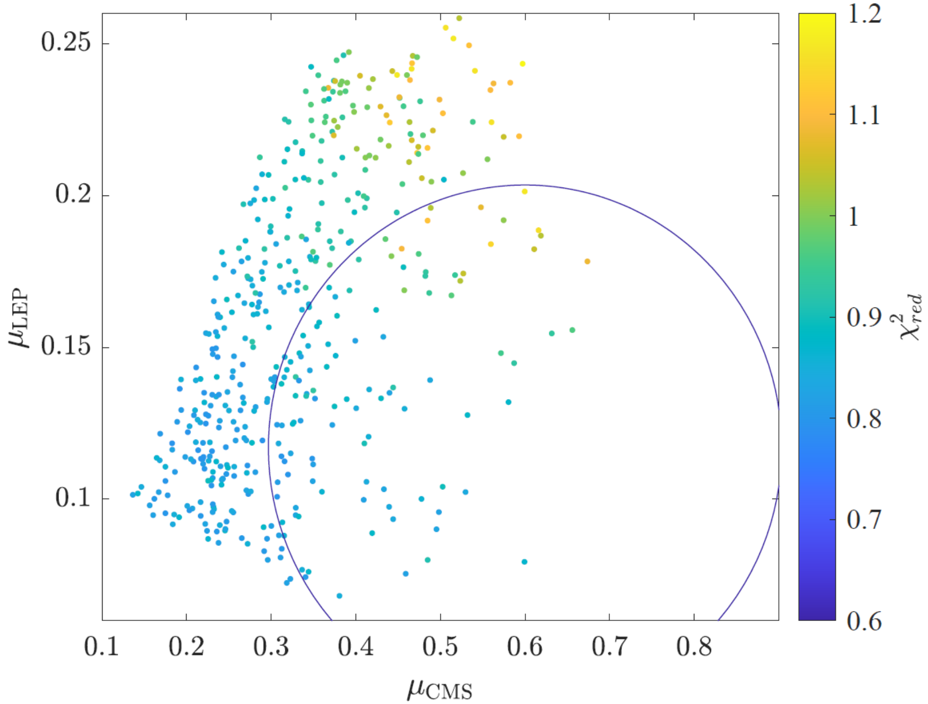


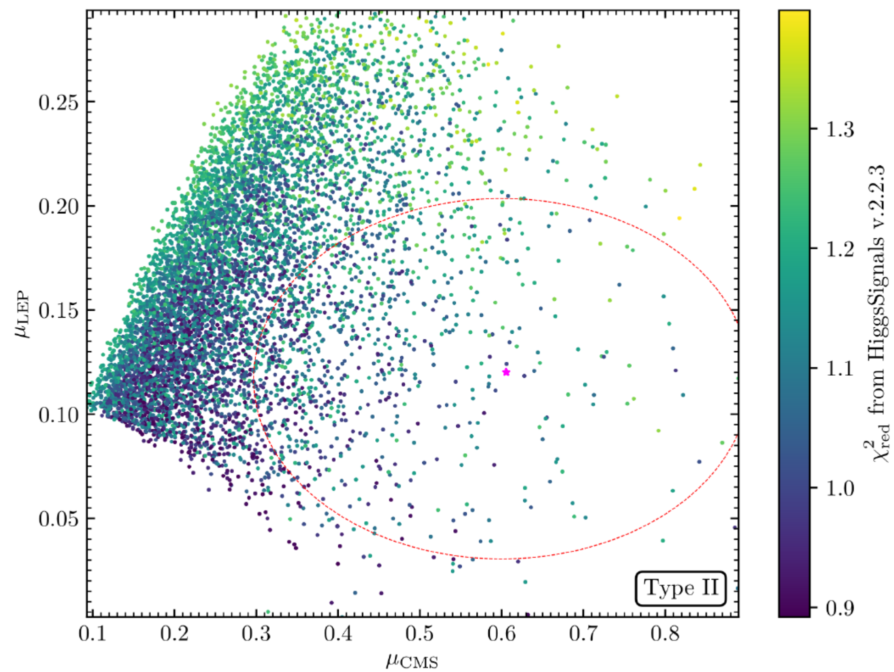
$$\chi^2_{red} = \frac{\chi^2}{n_{obs}}$$

χ^2 calculated by HiggsSignals with $n_{obs} = 107$

Evaluation

Comparison of N2HDM to THDMS data sets





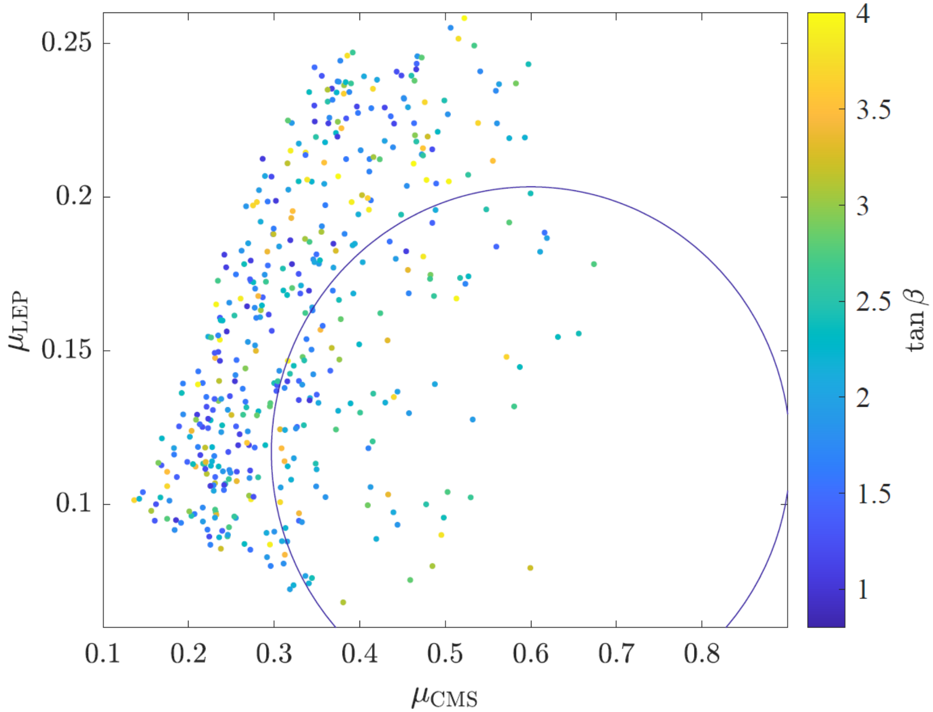
$n_{obs} = 107$

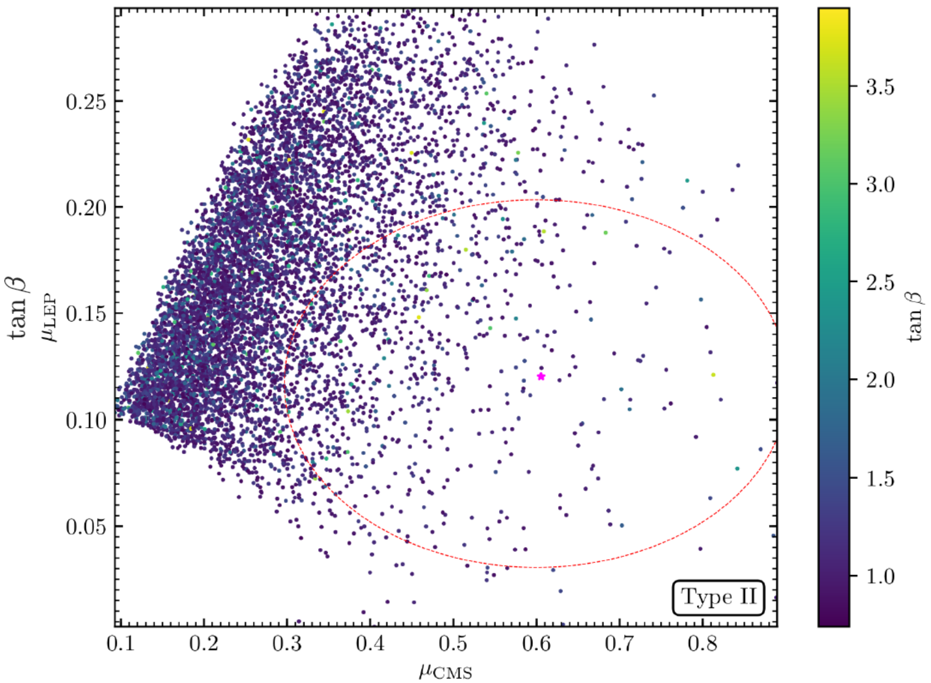
$$\chi^2_{red} = \frac{\chi^2}{n_{obs}}$$

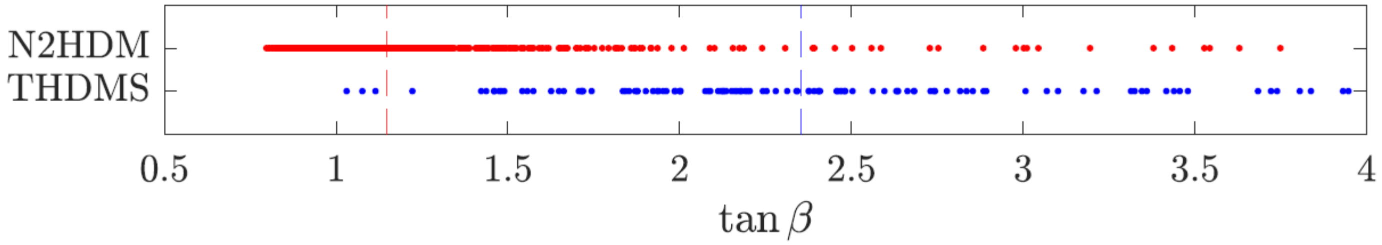
$n_{obs} = 101$

Evaluation

Comparison of N2HDM to THDMS data sets



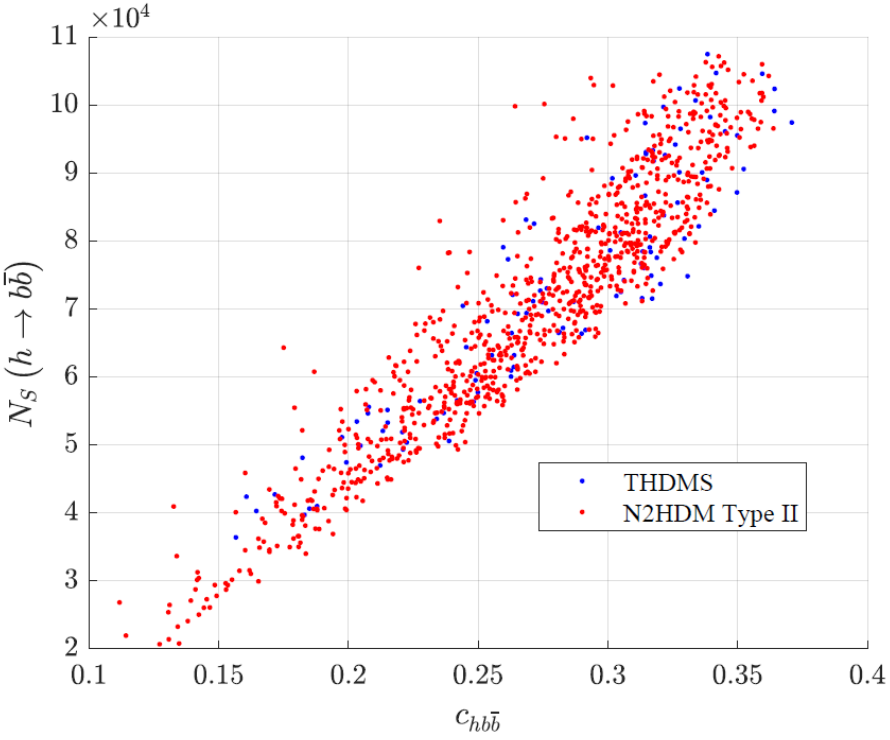


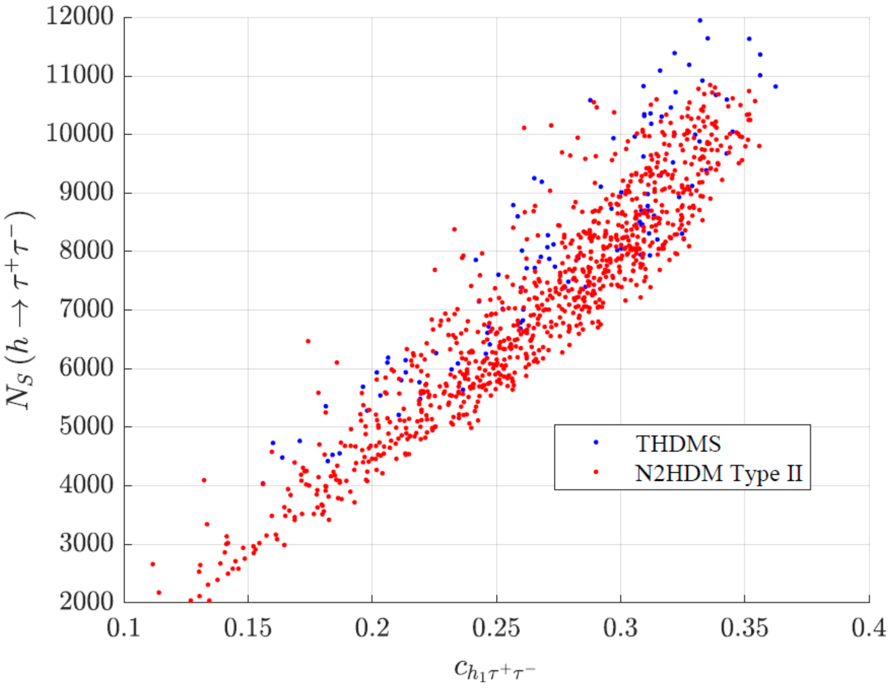


Evaluation

Reproduction of N2HDM signal events

$$N_S(h \to xx) = \mathcal{L}_{int} \cdot \sigma\left(e^+e^- \to hZ\right) \cdot \mathrm{BR}\left(h \to xx\right)$$





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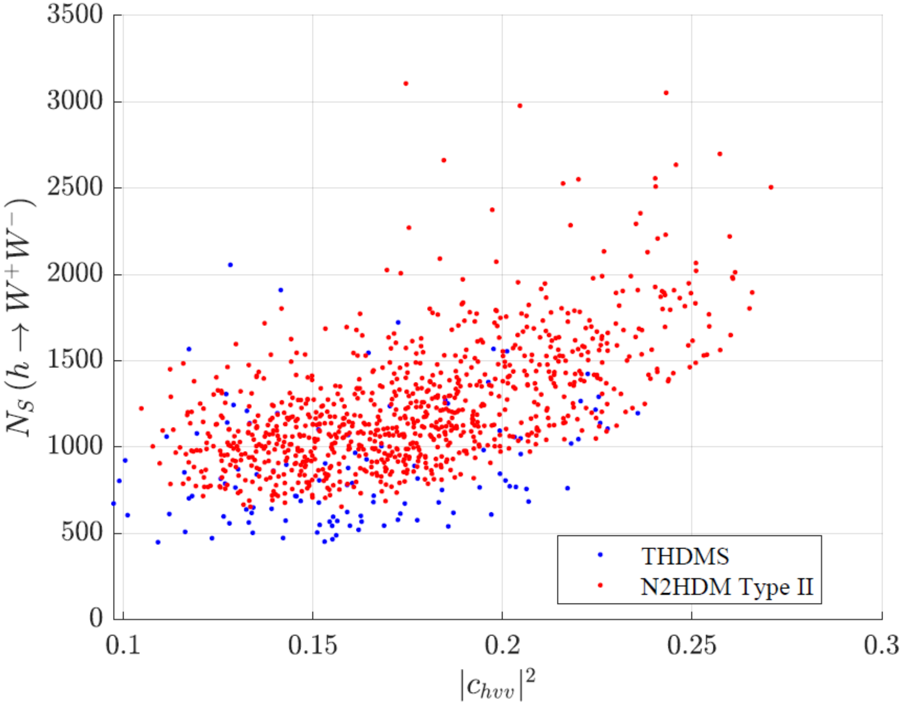
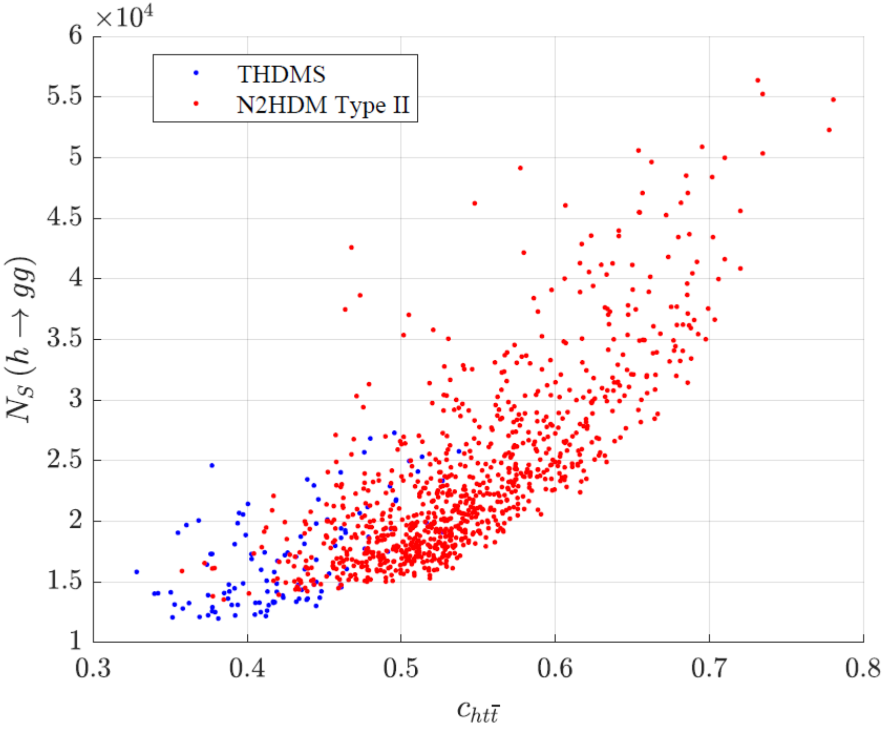




Evaluation

Calculation of coupling uncertainties

Main equations:

$$\frac{\left(\frac{\Delta g_x}{g_x}\right)_h}{\left(\frac{\Delta g_x}{g_x}\right)_H} = \sqrt{\left(\frac{D+f_H}{1+f_H}\right)\left(\frac{\sigma\left(e^+e^- \to ZH\right)}{\sigma\left(e^+e^- \to Zh\right)}\right)\left(\frac{\mathrm{BR}\left(H \to xx\right)}{\mathrm{BR}\left(h \to xx\right)}\right)} \cdot \frac{\left(1-\mathrm{BR}\left(H \to xx\right)\right)}{\left(1-\mathrm{BR}\left(h \to xx\right)\right)}$$

Evaluation via decay

$$D := \frac{f_H}{f_h} \qquad f_\phi := \left(\frac{S}{B}\right)_\phi = \left(\frac{N_S}{N_B}\right)_\phi$$

Evaluation via production

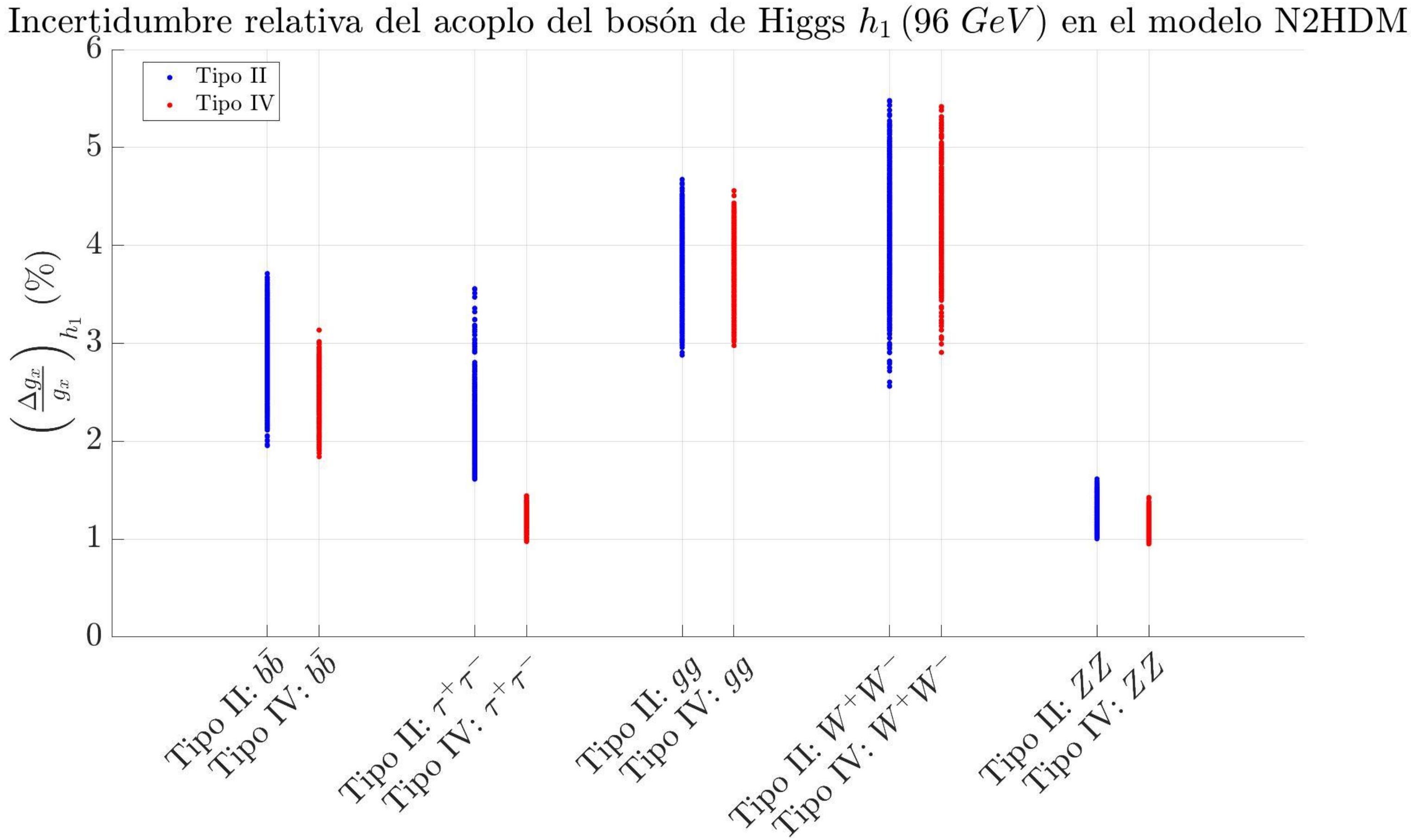
$$\frac{\left(\frac{\Delta g_Z}{g_Z}\right)_h}{\left(\frac{\Delta g_Z}{g_Z}\right)_H} = \sqrt{\frac{\sigma\left(e^+e^- \to ZH\right)}{\sigma\left(e^+e^- \to Zh\right)}}$$

- D parameter is the only unknown value

  Previous studies of Higgs between 20 and 100 GeV suggest $D \sim 2-3$

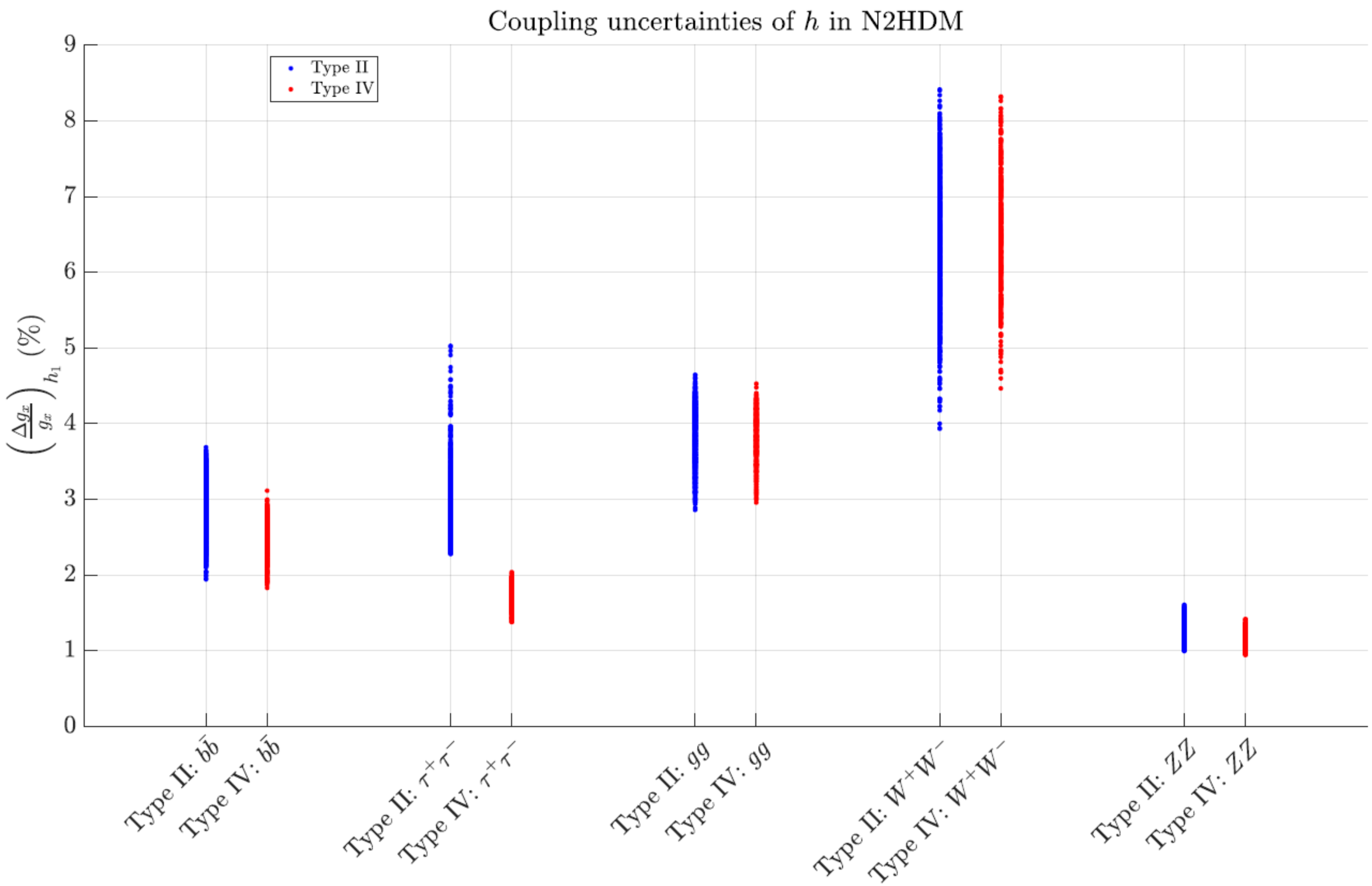
Evaluation

Reproduction



Evaluation

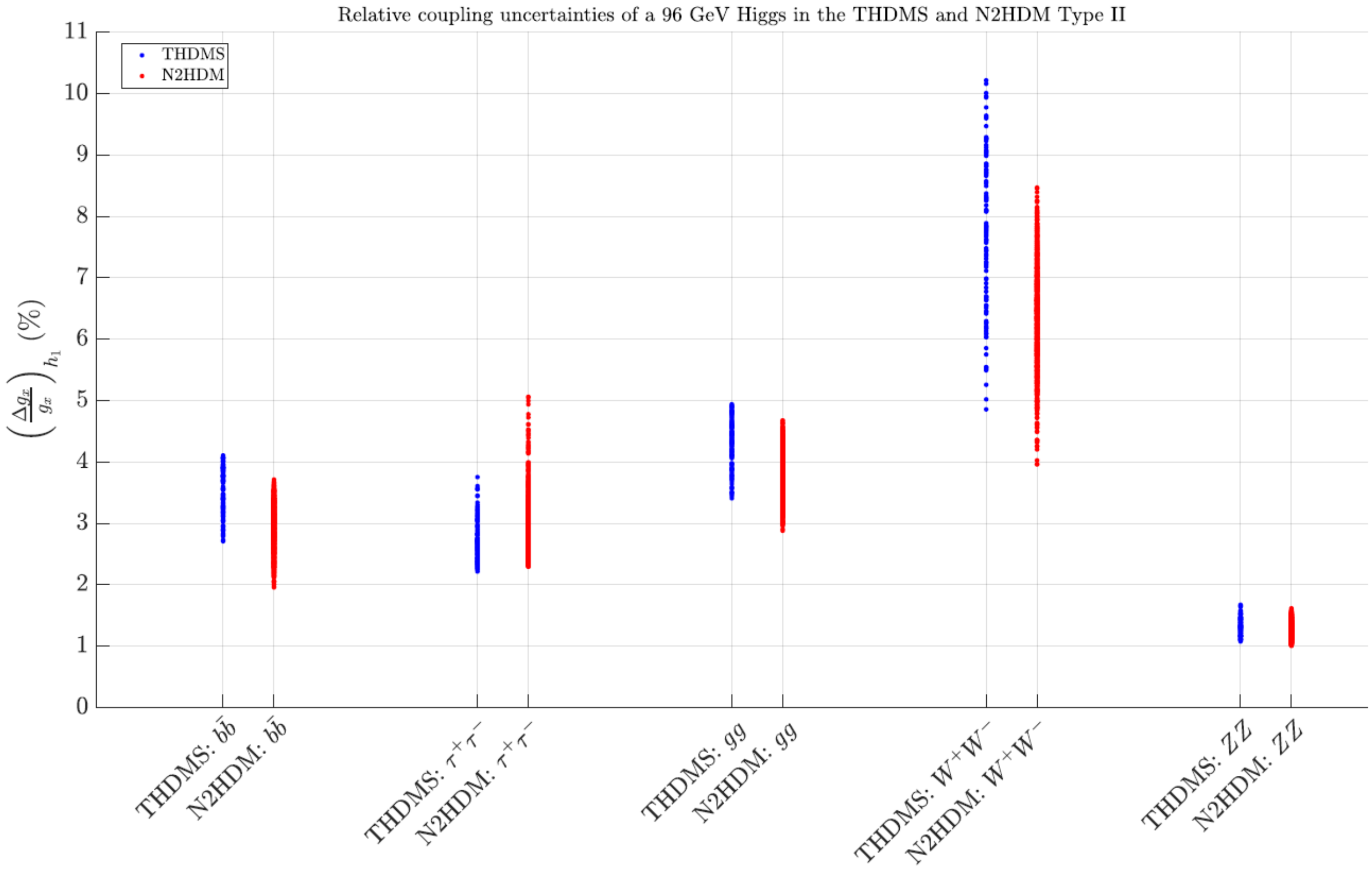
Reproduction



Evaluation

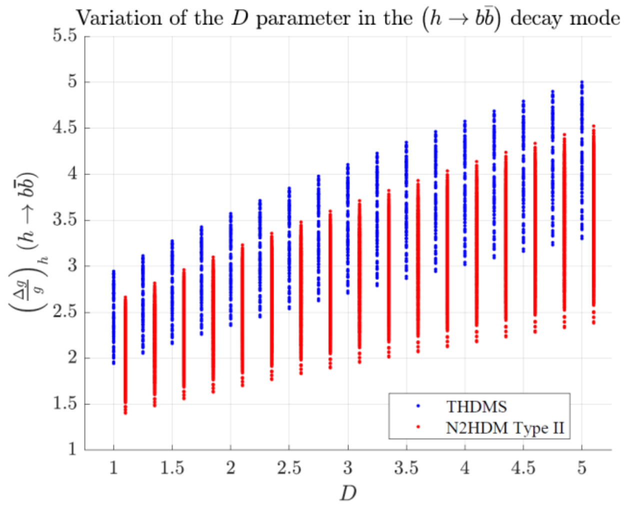
Results

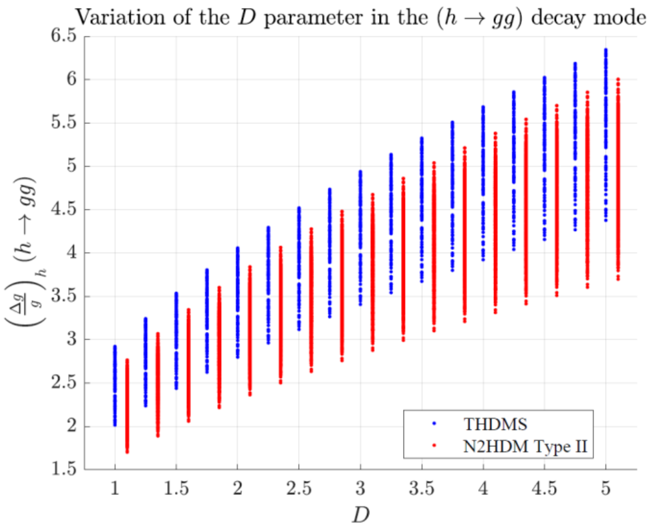
$\left(\frac{\Delta g_x}{g_x}\right)_{h_1}$	range in THDMS [%]	range in N2HDM [%]
$b\bar{b}$	(2.690, 4.08)	(1.966, 3.733)
$\tau^+\tau^-$	(2.200, 3.728)	(2.299, 5.075)
gg	(3.385, 4.907)	(2.906, 4.718)
W^+W^-	(4.824, 10.149)	(3.983, 8.518)
ZZ	(1.069, 1.663)	(0.997, 1.604)

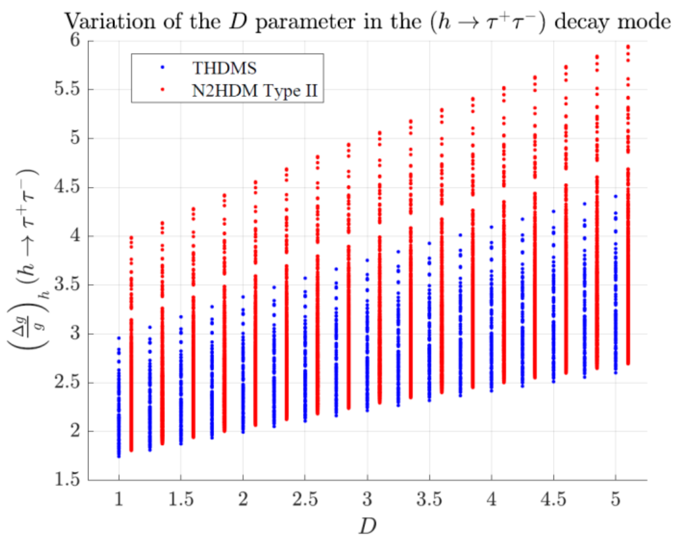


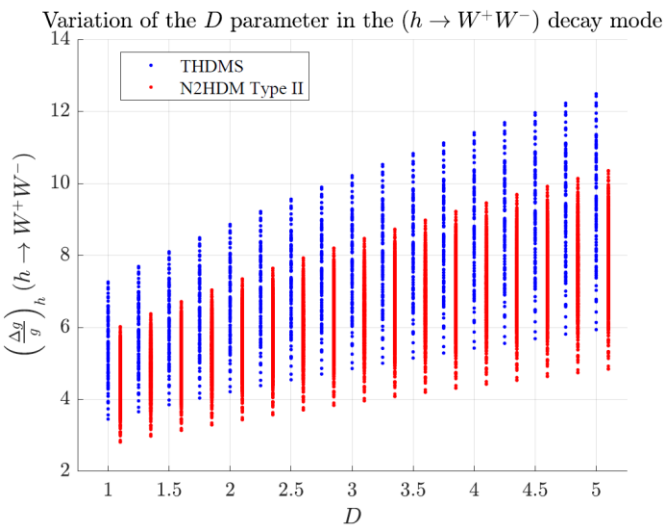
Evaluation

Dependence on D



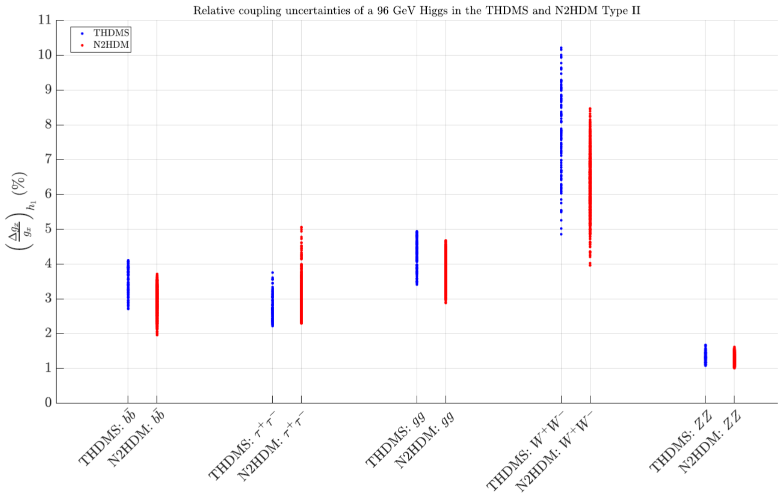






Conclusion

- THDMS shows similar behaviour as the N2HDM
- THDMS shows slight tendency for higher uncertainties
- $\tan\beta$ value helps in differentiating between THDMS and N2HDM
- Fewer points compared to the N2HDM may shift the results



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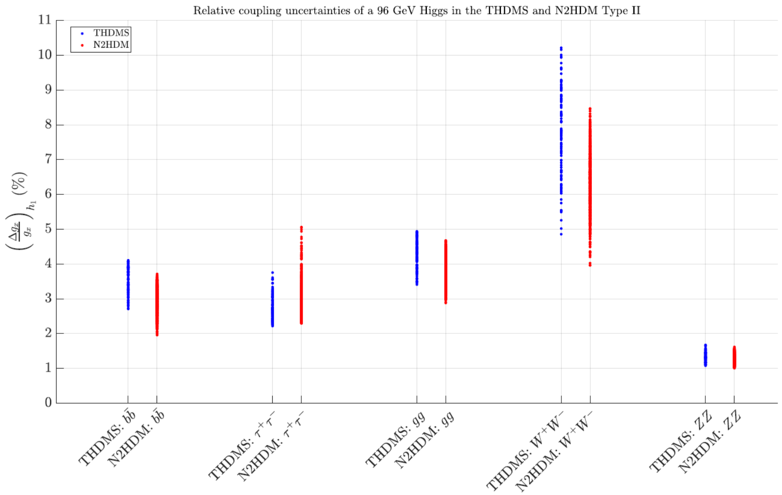
Conclusion

Next steps

- More thorough scan
  - Greater ranges
  - Higher values
- Inclusion of vacuum stability constraints
- Find a way to clearly differentiate between THDMS and N2HDM



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Thank you