On the experimental status of Composite Higgs Models

Charanjit Kaur Khosa
University of Sussex

Work in progress
In collaboration with Veronica Sanz

Higgs Couplings 2019, Oxford, UK

Outline

- **Composite Higgs (CH)**
- **Higgs Couplings**
- **Combined Fit**
- **Non-minimal CH models**
- **Summary**

Composite Higgs

- Higgs is a pseudo-Nambu Goldstone boson (pNGB) of a spontaneously broken global symmetry

- **Effective theory for the pNGB (CCWZ formalism)**

$$U = \exp(i\phi^a X^a / f)$$

X^a are the broken generators

- Non-linear transformations

$$U \to gUh^{-1}(g, \phi^a)$$

- One can construct object Σ which has linear transformations

Gauge Couplings

- Kinetic term:

$$\mathscr{L}^{eff}_{kinetic} = \frac{f^2}{4} Tr[D_\mu \Sigma^\dagger D^\mu \Sigma]$$

$$\mathscr{L}^{eff}_{gauge} = g^2 f^2 A_\mu A^\mu \sin^2(H/f)$$

- Expanding around the Higgs VEV: H $\longrightarrow$ <H>+h

$$\mathscr{L}_{gauge} \supset \frac{1}{8} g^2 v^2 W^a_\mu W^{a\mu} + \frac{1}{4} g^2 v \sqrt{1-\xi} W^a_\mu W^{a\mu} h + \frac{1}{8} g^2 (1-2\xi) W^a_\mu W^{a\mu} h^2 \; ; \quad \xi = v^2/f^2$$

$$g^{CH}_{Whh} = \sqrt{1-\xi}\, g^{SM}_{WWh} \quad \Longrightarrow \quad \kappa_V = \sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi$$

Fermion Couplings

κ_F	Models
$\kappa_F^A = \sqrt{1-\xi}$	$SO(5)/SO(4)$ – [3, 11] $SO(6)/SO(4)\times SO(2)$ – [14–16] $SU(5)/SU(4)$ – [17] $SO(8)/SO(7)$ – [21, 22]
$\kappa_F^B = \frac{1-2\xi}{\sqrt{1-\xi}}$	$SO(5)/SO(4)$ – [11–13, 20] $SU(4)/Sp(4)$ – [6] $SU(5)/SO(5)$ – [7] $SO(6)/SO(4)\times SO(2)$ – [14–16]

TABLE I: κ_F in different models.

$SO(5)/SO(4)$

$T_L \in 10, T_R \in 5$

$T_L, T_r \in 5$

$\bar{\psi}\psi sin(H/f)$

$\bar{\psi}\psi sin(H/f)cos(H/f)$

$$\kappa_F^A = \sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi$$

$$\kappa_F^B = \frac{1-2\xi}{\sqrt{1-\xi}} \approx 1 - \frac{3}{2}\xi$$

V. Sanz and J. Setford, Adv. High Energy Phys. (2018) 7168480

κ -Formalism

Channel	Refs.	κ-factors
$ttH\ (H \to \gamma\gamma)$	[43–45]	$\frac{\kappa_t^2 \kappa_\gamma^2}{\kappa_H^2}$
$ttH\ (H \to b\bar{b})$	[43]	$\frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2}$
$ttH\ (H \to \tau^+\tau^-)$	[43]	$\frac{\kappa_t^2 \kappa_\tau^2}{\kappa_H^2}$
$ttH\ (H \to WW^*,\ H \to ZZ^*)$	[43]	$\frac{\kappa_t^2 \kappa_V^2}{\kappa_H^2}$
$ggF\ (H \to \gamma\gamma)$	[44, 45]	$\frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H}$
$ggF\ (H \to \tau^+\tau^-)$	[46]	$\frac{\kappa_g^2 \kappa_\tau^2}{\kappa_H^2}$
$ggF\ (H \to WW^*,\ H \to ZZ^*)$	[47–49]	$\frac{\kappa_g^2 \kappa_Z^2}{\kappa_H^2}$
$HV\ (H \to b\bar{b})$	[50, 51]	$\frac{\kappa_V^2 \kappa_b^2}{\kappa_H^2}$
$VBF,\ HV\ (H \to \gamma\gamma)$	[44, 45]	$\frac{\kappa_V^2 \kappa_\gamma^2}{\kappa_H}$
$VBF,\ HV\ (H \to WW^*,\ H \to ZZ^*)$	[47, 49, 52]	$\frac{\kappa_V^4}{\kappa_H^2}$

$$\kappa_g^2 = 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t$$

$$\kappa_\gamma^2 = 1.59\kappa_V^2 + 0.07\kappa_t^2 - 0.66\kappa_V\kappa_t$$

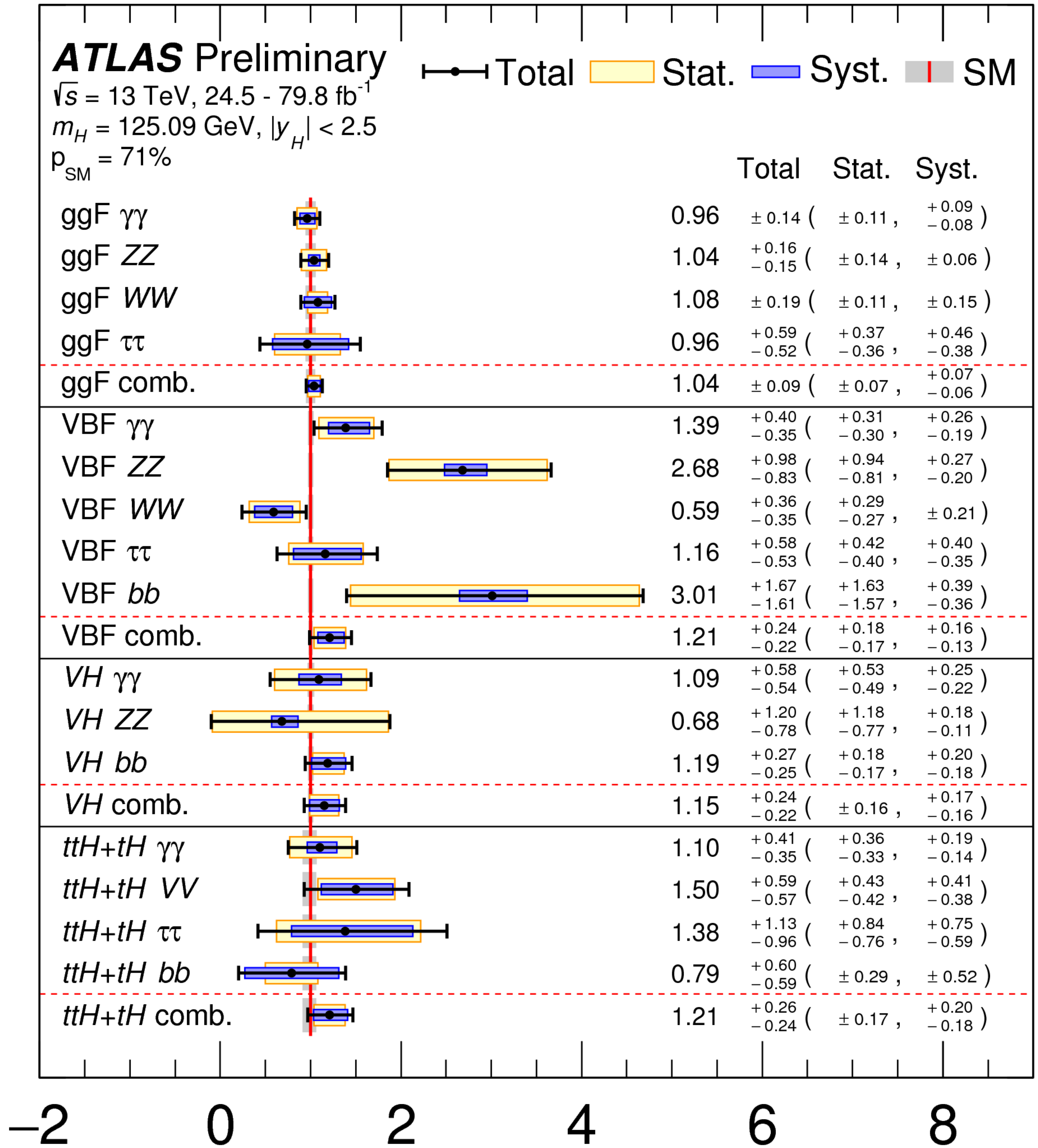
$$\kappa_H^2 \approx 0.57\kappa_b^2 + 0.25\kappa_V^2 + 0.09\kappa_g^2$$

V. Sanz and J. Setford, Adv. High Energy Phys. (2018) 7168480

CMS Run 2 results

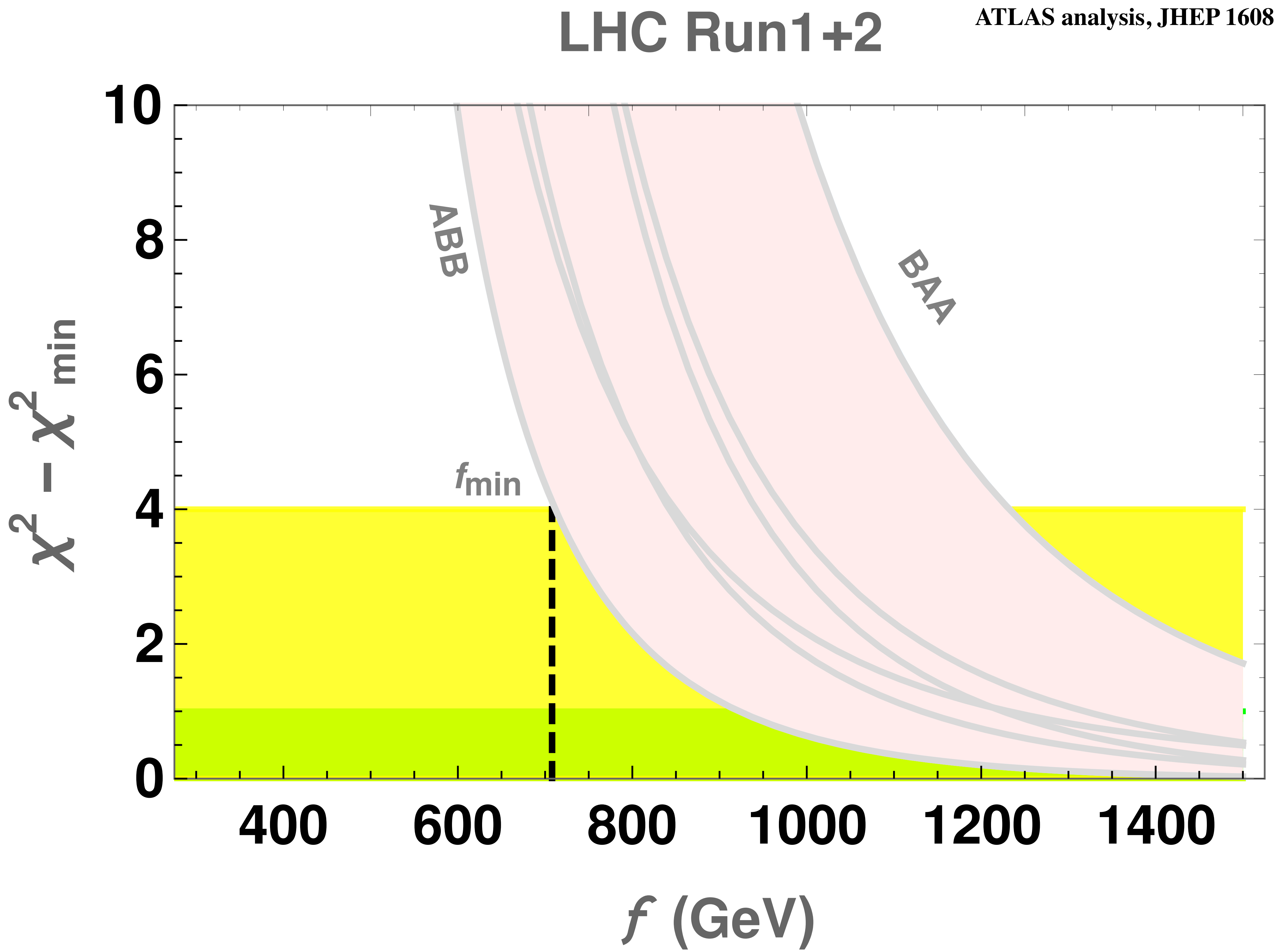
	Reference	Channel	Signal Strength
CMS-PAS-HIG-19-001	$137.1\ \text{fb}^{-1}$	ggH, $H \to ZZ$	$0.97^{+0.13}_{-0.11}$
		VBF, $H \to ZZ$	$0.64^{+0.48}_{-0.37}$
		VH, $H \to ZZ$	$1.15^{+0.93}_{-0.74}$
		$t\bar{t}H, tH$, $H \to ZZ$	$0.13^{+0.93}_{-0.13}$
CMS-PAS-HIG-18-029	$77.4\ \text{fb}^{-1}$	ggF, $H \to \gamma\gamma$	$1.15^{+0.15}_{-0.15}$
		VBF, $H \to \gamma\gamma$	$0.8^{+0.4}_{-0.3}$
JHEP 1811 (2018) 185	$35.9\ \text{fb}^{-1}$	VH, $H \to \gamma\gamma$	$2.4^{+1.1}_{-1.0}$
CMS-PAS-HIG-18-018	$(35.9 + 41.5)\text{fb}^{-1}$	$t\bar{t}H$, $H \to \gamma\gamma$	$1.7^{+0.6}_{-0.5}$
arXiv:1806.05246	$35.9\ \text{fb}^{-1}$	ggF, $H \to WW$	$1.38^{+0.21}_{-0.24}$
		VBF, $H \to WW$	$0.29^{+0.66}_{-0.29}$
		WH, $H \to WW$	$3.27^{+1.88}_{-1.70}$
		ZH, $H \to WW$	$1.00^{+1.57}_{-1.00}$
Phys. Rev. Lett 121 (2018),021801	$5.1\ \text{fb}^{-1}$(7TeV) $+18.9\ \text{fb}^{-1}$(8TeV) $+77.2\text{fb}^{-1}$(13TeV)	VH, $H \to b\bar{b}$	1.01 ± 0.22
		ggF, $H \to b\bar{b}$	2.80 ± 2.45
		VBF, $H \to b\bar{b}$	2.53 ± 1.53
		$t\bar{t}H$, $H \to b\bar{b}$	0.85 ± 0.44
CMS-PAS-HIG-18-032	$77.4\ \text{fb}^{-1}$	gg→H, bbH, $H \to \tau\bar{\tau}$	$0.36^{+0.36}_{-0.37}$
		VBF+V(qq)H, $H \to \tau\bar{\tau}$	$1.03^{+0.30}_{-0.29}$
CMS-PAS-HIG-18-019	$35.9{+}41.5\text{fb}^{-1}$	$t\bar{t}H$, $H \to ML$	$0.96^{+0.34}_{-0.31}$
Phys. ReV. Lett. 122 (2019), 021801	$5.0\ \text{fb}^{-1}$(7TeV) $+19.8\ \text{fb}^{-1}$(8TeV) $+35.9\ \text{fb}^{-1}$(13 TeV)	pp, $H \to \mu\mu$	1.0 ± 1.0

ATLAS Run2 results



ATLAS-CONF-2019-005

Run 1 data is taken from the combined CMS and ATLAS analysis, JHEP 1608 (2016) 045



$$\chi^2(f) = \sum_i^{Run1,Run2} \left(\frac{\mu_i(\kappa(f))^{CH} - \mu_i^{Exp}}{\Delta\mu_i} \right)^2$$

The different lines correspond to different choice of fermion couplings $\kappa_F^{A/B}$ for $(\kappa_t, \kappa_b, \kappa_\tau)$

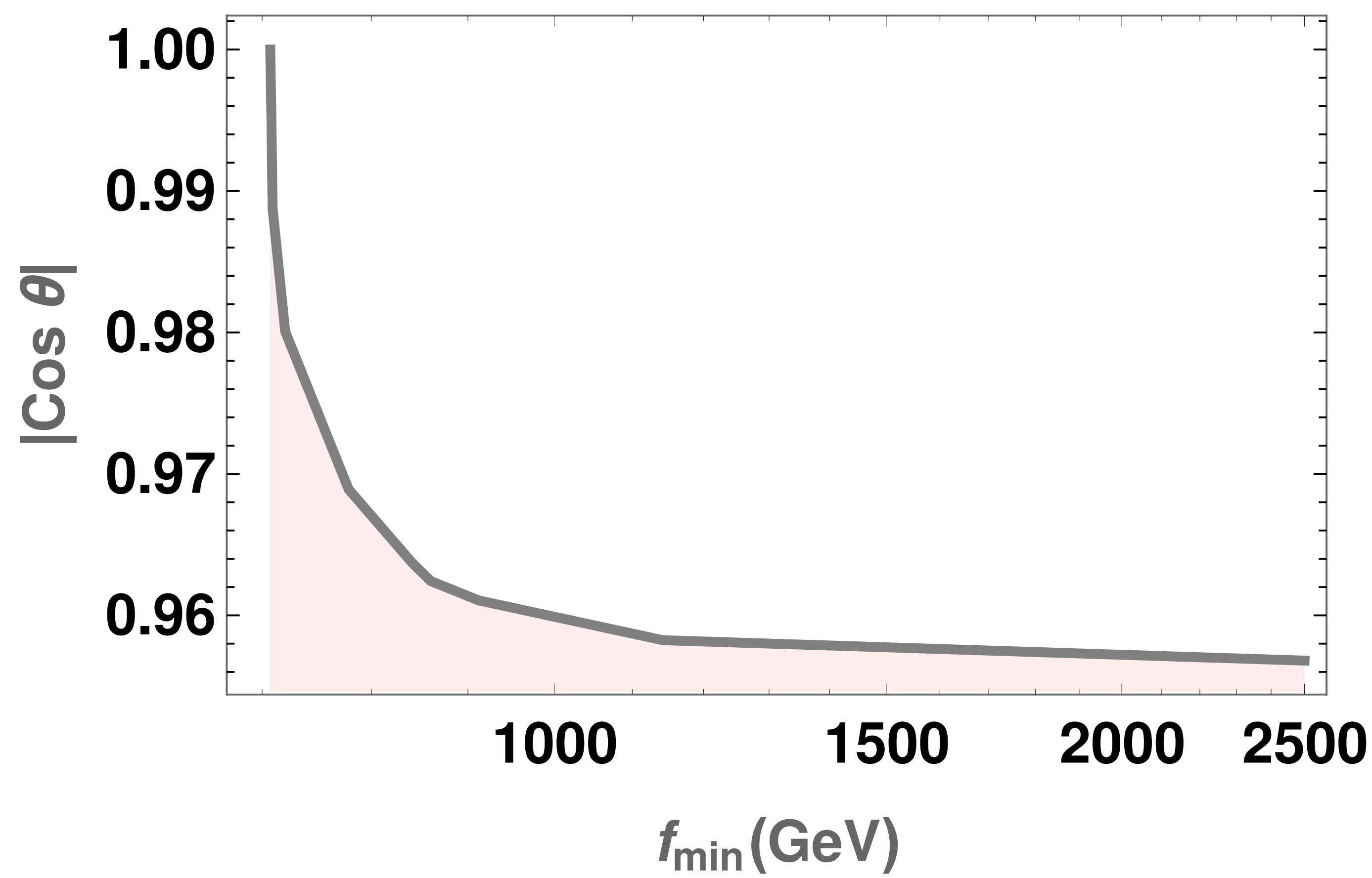
Extra singlet: Tree Level Effects

$$\kappa_V = \cos\theta\sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi - \frac{1}{2}\theta^2$$

$$\cos\theta = \cos\left(\lambda\left(\frac{v_s}{v}\right)\left(\frac{v^2}{m_s^2}\right)\right)$$

$$\kappa_F^A = \cos\theta\sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi - \frac{1}{2}\theta^2$$

$$\kappa_F^B = \cos\theta\frac{1-2\xi}{\sqrt{1-\xi}} \approx 1 - \frac{3}{2}\xi - \frac{1}{2}\theta^2$$

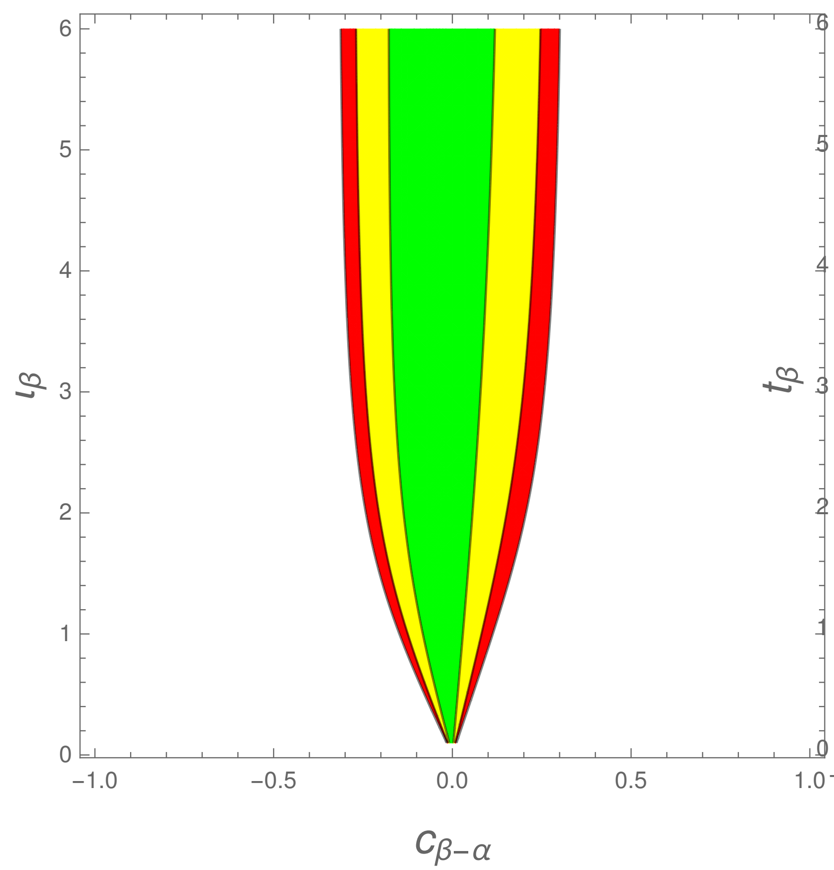


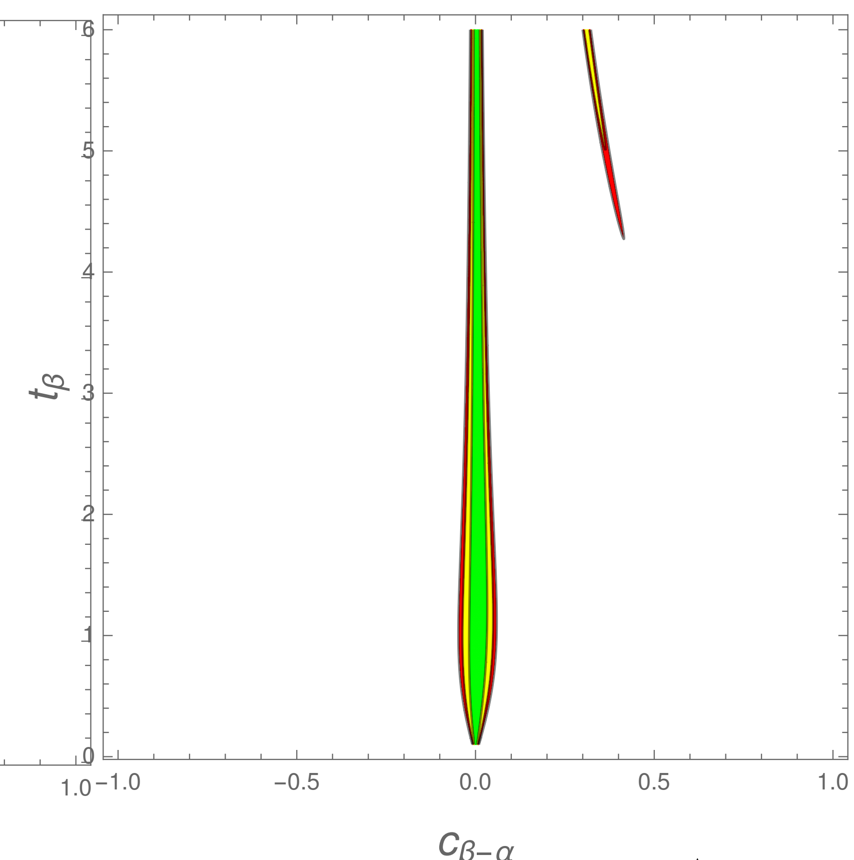
V. Sanz and J. Setford, Adv. High Energy Phys. (2018) 7168480

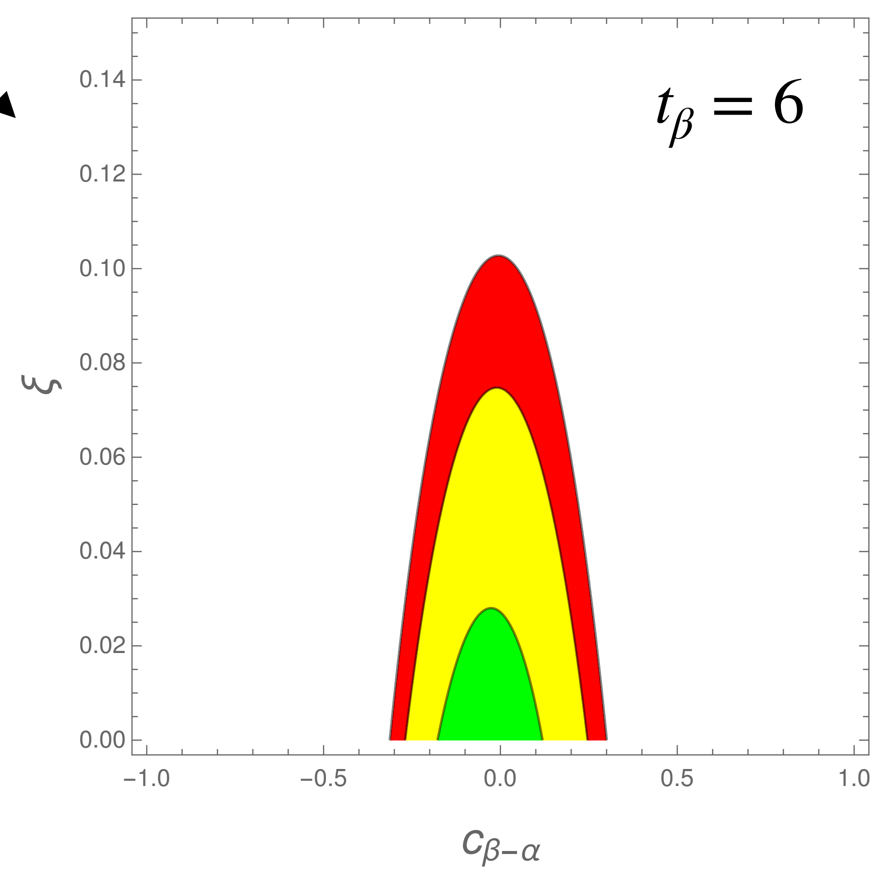
Two Higgs Doublet model

Models	κ_V	κ_F
$\mathrm{Type-I}$	$s_{\beta-\alpha}$	$\kappa_u = \kappa_d = \kappa_\ell = c_{\beta-\alpha}/t_\beta + s_{\beta-\alpha}$
$\mathrm{Type-II}$	$s_{\beta-\alpha}$	$\kappa_u = c_{\beta-\alpha}/t_\beta + s_{\beta-\alpha}$
		$\kappa_d = \kappa_\ell = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
$\ell-\mathrm{Specific}$	$s_{\beta-\alpha}$	$\kappa_u = \kappa_d = c_{\beta-\alpha}/t_\beta + s_{\beta-\alpha}$
		$\kappa_\ell = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
Flipped	$s_{\beta-\alpha}$	$\kappa_u = \kappa_\ell = c_{\beta-\alpha}/t_\beta + s_{\beta-\alpha}$
		$\kappa_d = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$

Type I







Type II

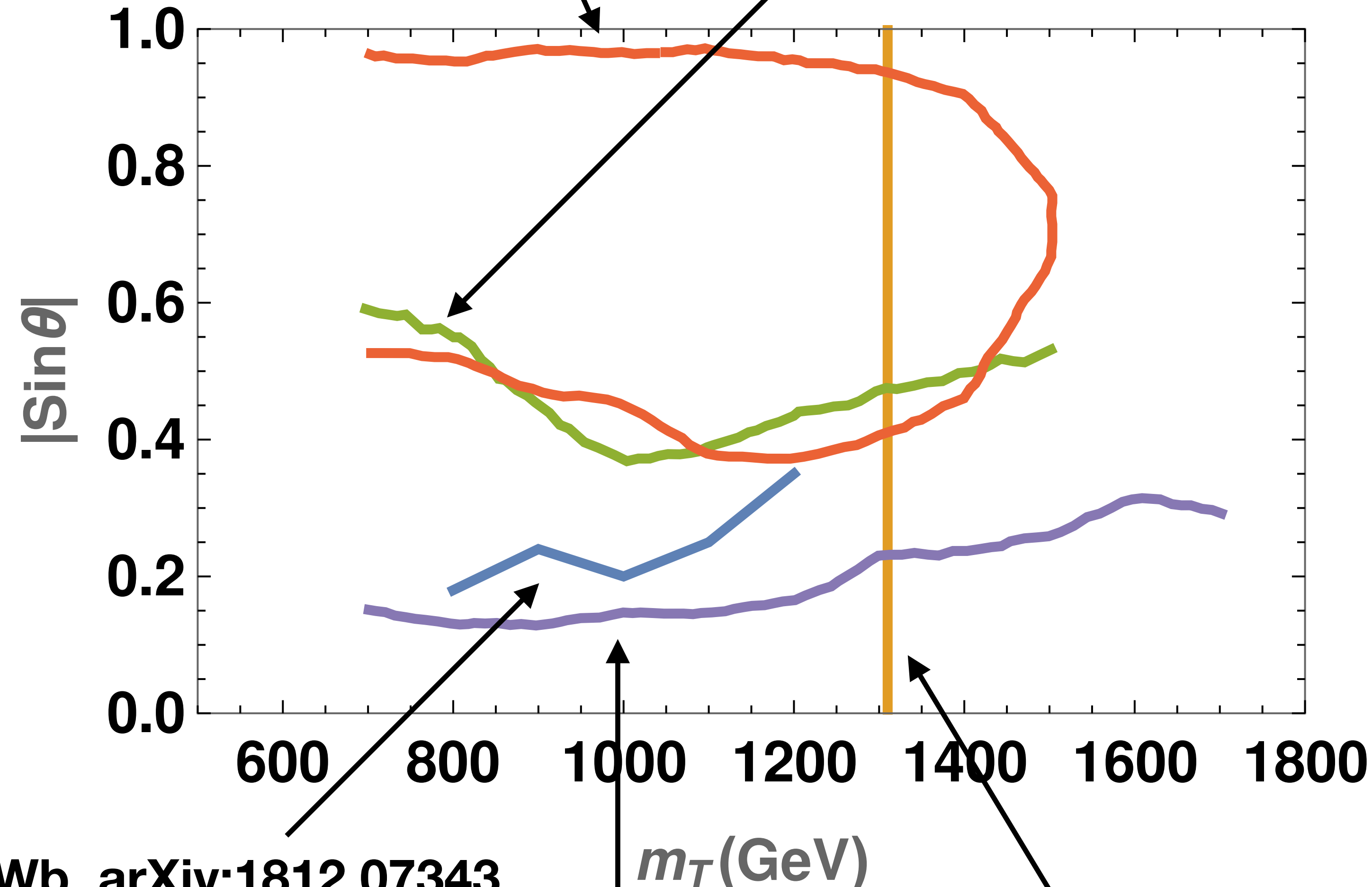
Top Partners

$$\begin{pmatrix}\bar{t}_L & \bar{T}_L\end{pmatrix}\begin{pmatrix}\frac{y_t h}{\sqrt{2}} & \Delta \\ 0 & M\end{pmatrix}\begin{pmatrix}t_R \\ T_R\end{pmatrix} \qquad \theta_R = \frac{1}{2}\sin^{-1}\left(\frac{2 m_t M_T \Delta}{(M_T^2 - m_t^2) M}\right) \qquad \tan\theta_L = \frac{m_T}{m_t}\tan\theta_R$$

$$\delta(p_T^{\rm cut}, M_T, \sin\theta, \mu) = \frac{\sigma_{t+T}(p_T > p_T^{\rm cut}, \mu, M_T, \sin\theta) - \sigma_t(p_T > p_T^{\rm cut}, \mu)}{\sigma_t(p_T > p_T^{\rm cut}, \mu)} .$$

top+MET, arXiv:1812.09743

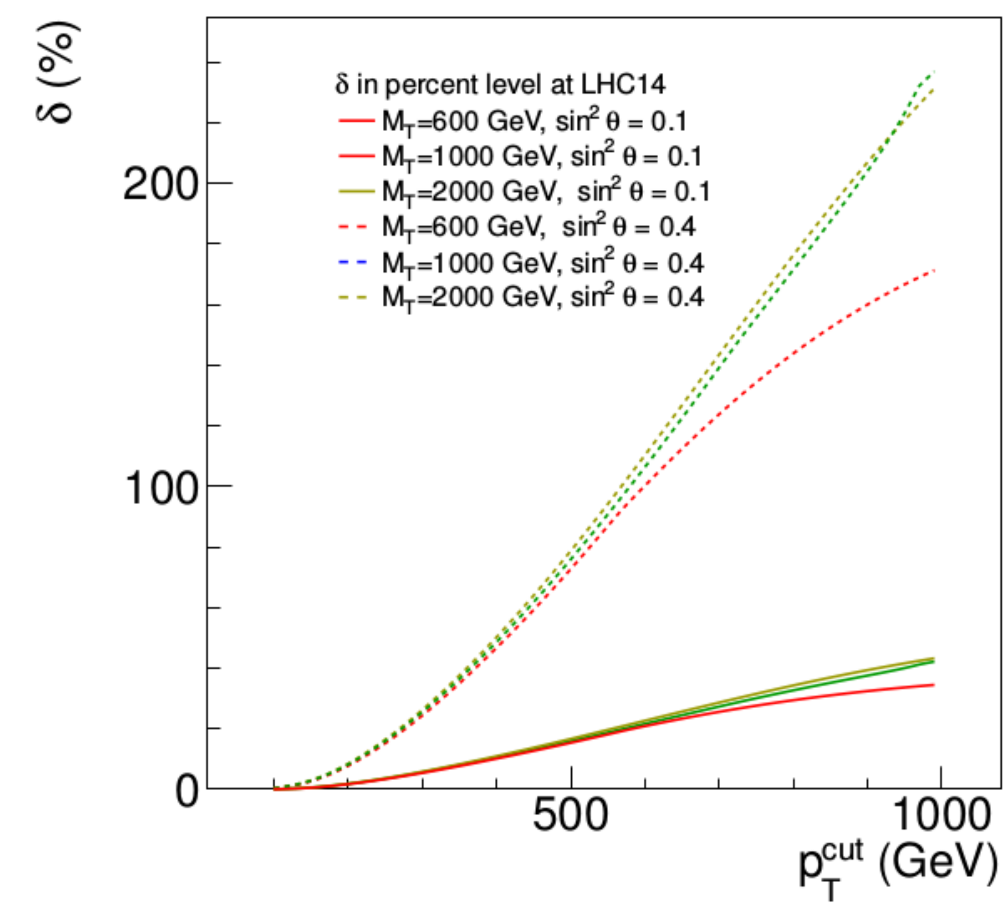
CMS, Wb, Phys. Lett. B 772 (2017) 634



Wb, arXiv:1812.07343

Phys.Rev. Lett. 121 (2018), 211801

CMS, Zt, Phys. Lett. B 781 (2018) 574

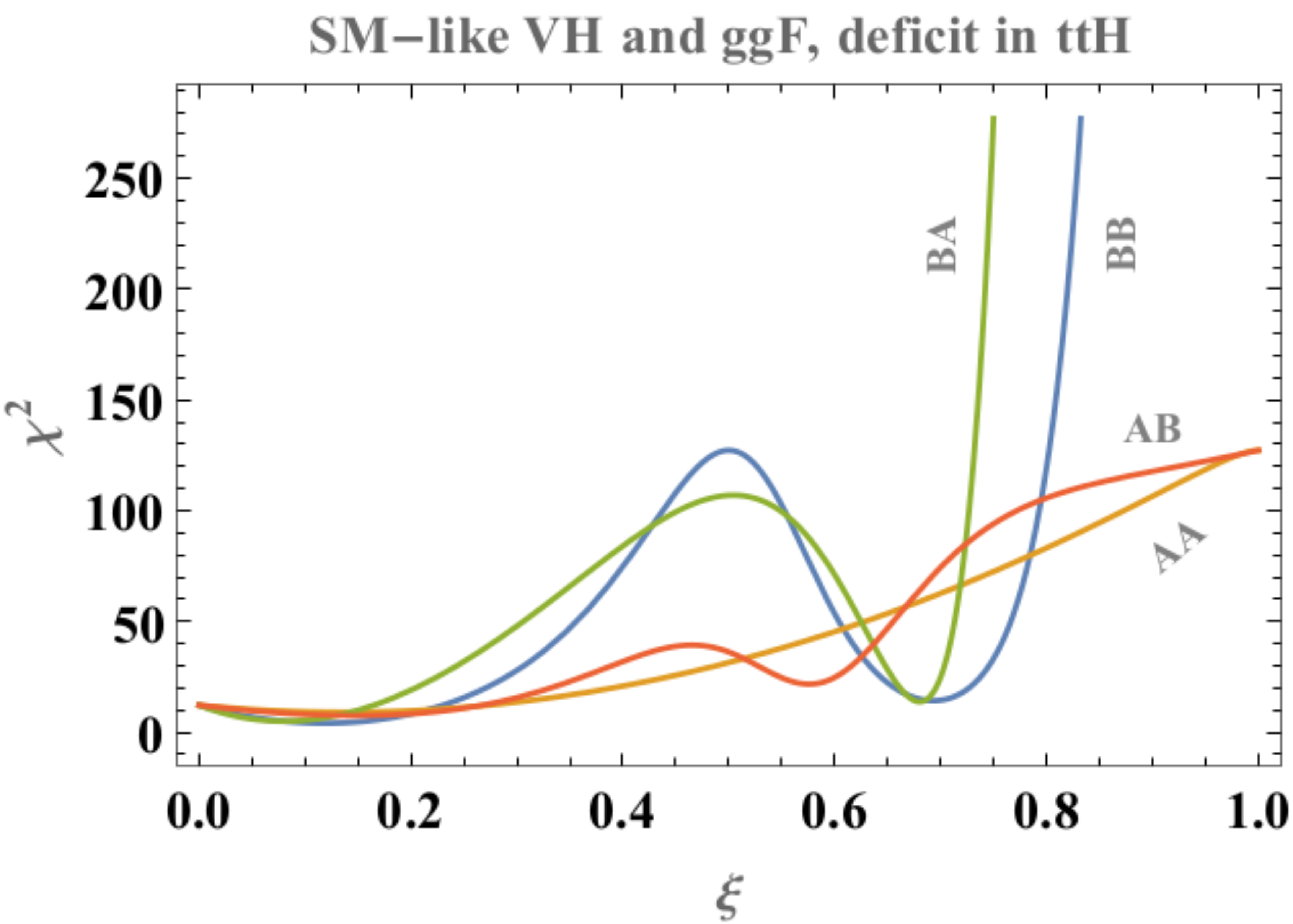


A.Banfi, A.Martin and V.Sanz, JHEP 1408 (2014) 053

Summary

- **We provide the status of composite Higgs models with latest Run 2 LHC data**
- **Generic modifications for the fermion and gauge boson couplings**
- **Bound on the new physics scale f from the data**
- **The sensitivity of the bound on mixing angle with other Higgs in case of singlet and doublet mixing**
- **Calculation of a bound on the top partner masses and mixing angle from Higgs + jets is in progress**

Thanks



V. Sanz and J. Setford, Adv. High Energy Phys. (2018) 7168480

Production	Channel	Signal Strength
ggF	$\gamma\gamma$	0.96 ± 0.14
	ZZ	$1.04^{+0.16}_{-0.15}$
	WW	1.08 ± 0.19
	$\tau\tau$	$0.96^{+0.59}_{-0.52}$
VBF	$\gamma\gamma$	$1.39^{+0.40}_{-0.35}$
	ZZ	$2.68^{+0.98}_{-0.83}$
	WW	$0.59^{+0.36}_{-0.35}$
	$\tau\tau$	$1.16^{+0.58}_{-0.53}$
	bb	$3.01^{+1.67}_{-1.61}$
VH	$\gamma\gamma$	$1.09^{+0.58}_{-0.54}$
	ZZ	$0.68^{+1.20}_{-0.78}$
	bb	$1.19^{+0.27}_{-0.25}$
	WW	$2.5^{+0.9}_{-0.8}$
$ttH + tH$	$\gamma\gamma$	$1.10^{+0.41}_{-0.35}$
	VV	$1.50^{+0.59}_{-0.57}$
	$\tau\tau$	$1.38^{+1.13}_{-0.96}$
	bb	$0.79^{+0.60}_{-0.59}$