Resonances all over the place?

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work in collaboration with A. Kundu & P. Mondal

and a lot...a lot of discussions with F. Richard

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Outline

Introductory motivations

Many motivations to go beyond the SM, that we all know!

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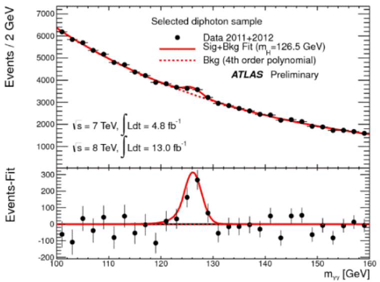
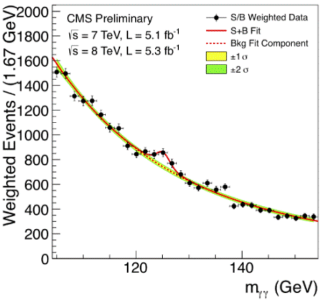
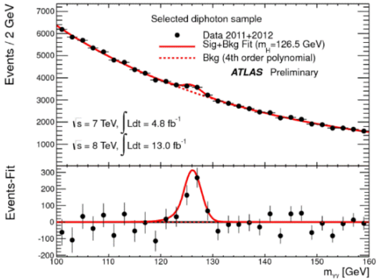
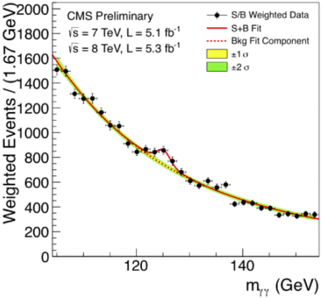




Introductory motivations

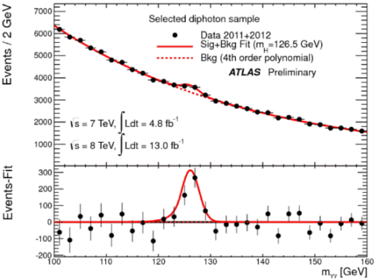


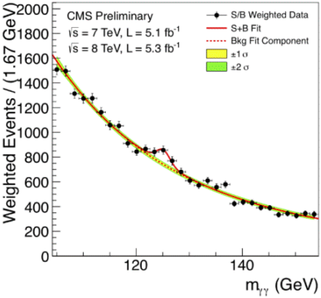


a 'theorem' by Nelson Mandela

(not to be confused with the Coleman-Mandula theorem)

Introductory motivations





The experimental indications

New scalar	Process studied	Local Significance	Global Significance	Combined Significance	Reference
h_{95}	$\to \gamma\gamma$	$2.9\,\sigma$	$1.3\,\sigma$		[6, 7, 18]
	$\to \tau^+\tau^-$	$2.6\text{-}3.1\,\sigma$	$2.3\text{-}2.7\,\sigma$	$2.4\text{-}2.75\,\sigma$	[8]
	$Z^* \to Zh_{95} \to Zb\bar{b}$	$2.3\,\sigma$	not quoted	$3.1\text{-}3.4\,\sigma$	[33]
H_{650}	VBF, $\to W^+W^-$	$3.8\,\sigma$	$(2.6 \pm 0.2)\,\sigma$		[12]
	$\to ZZ$	$2.4\,\sigma$	$0.9\,\sigma$	$\left(4.08^{+0.12}_{-0.11}\right)\,\sigma$	[10, 11]
	$\to h_{95}h_{125}$	$3.8\,\sigma$	$2.8\,\sigma$		[13]
	$\to A_{400}Z \to \ell^+\ell^- t\bar{t}$	2.85σ	2.35σ		[16]
A_{400}	$\to t\bar{t}$	$3.5\,\sigma$	$1.9\,\sigma$	$3.17\,\sigma$	[14]
	$\to ZH_{320} \to Zh_{125}h_{125}$	$3.8\,\sigma$	$2.8\,\sigma$		[15]

Combined Significance= our combination of global significances

[6,7,18] CMS-PAS-HIG-14-037; CMS [arXiv:1811.08459 [hep-ex]]; T. Biekötter et al. [arXiv:2203.13180 [hep-ph]]; + many more
[8] CMS-PAS-HIG-21-001
[33] LEP [arXiv:hep-ex/0306033 [hep-ex]]
[12] CMS-PAS-HIG-20-016
[10,11] ATLAS [arXiv:2009.14791 [hep-ex]], [arXiv:2103.01918 [hep-ex]]
[13] CMS-PAS-HIG-21-011
[16] ATLAS [arXiv:2311.04033 [hep-ex]]
[14] CMS [arXiv:1908.01115 [hep-ex]]
[15] ATLAS-CONF-2022-043

CMS PAS HIG-20-016 (2022/03/11)

Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

Scenario	Mass [GeV]	ggF cross sec. [pb]	VBF cross sec. [pb]	Local signi. [σ]	Global signi. [σ]
SM f_{VBF}	800	0.16	0.057	3.2	1.7 ± 0.2
$f_{VBF} = 1$	650	0.0	0.16	3.8	2.6 ± 0.2
$f_{VBF} = 0$	950	0.19	0.0	2.6	0.4 ± 0.6
floating f_{VBF}	650	2.9×10^{-6}	0.16	3.8	2.4 ± 0.2

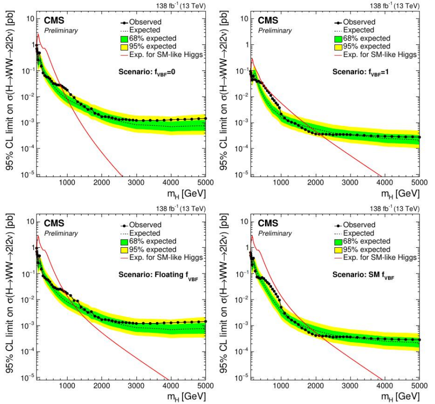


Figure 4: Limits using the combined Run 2 data set for the $f_{VBF} = 0$ (top left), $f_{VBF} = 1$ (top right), floating f_{VBF} (bottom left) and the SM f_{VBF} scenarios (bottom right).

11 Summary

We performed a search for a high mass Higgs boson decaying into a pair of W bosons in the dileptonic channel. We observe an upward fluctuation of data compared to the expected background. The signal hypothesis with the highest significance corresponds to a resonance mass of 650 GeV in the scenario where only VBF production is considered. The global significance of this excess is 2.6 σ.

The presence of a heavy SM-like Higgs boson is excluded at 95% CL up to 2100 GeV, assuming the relative contribution of ggF and VBF production is SM-like and also assuming only VBF production. The exclusion is up to about 800 GeV when considering only ggF production. In the case where the ratio between ggF and VBF production is left floating in the fit, an exclusion of up to 900 GeV is observed.

In MSSM scenarios the analysis is sensitive at low values of m_A and $\tan\beta$ and the exclusion limits extend up to $m_A = 450$ GeV. For m_A between 150 GeV and 400 GeV, we exclude values of $\tan\beta$ between 10 and 3. The sensitivity is similar between the M_h^{125}, $M_h^{125}(\tilde{\chi})$, $M_h^{125}(\tilde{\tau})$, $M_{h,EFT}^{125}$ and $M_{h,EFT}^{125}(\tilde{\chi})$ scenarios. In the M_h^{125}(alignment) scenario, the exclusion limits reach to about $m_A = 400$ GeV.

In THDM scenarios, the limits show an exclusion of up to 750 GeV in THDMs of both Type-I and Type-II. For $\cos(\beta - \alpha) = 0.1$, the limits in $\tan\beta$ extend up to 4 in Type-II and up to 5 in Type-I, with the sensitivity generally becoming lower for higher masses of H. The sensitivity over $\tan\beta$ varies more strongly as a function of $\cos(\beta - \alpha)$.

Extrapolation studies were performed to evaluate the expected gain in sensitivity for the Phase-2 operations of the HL-LHC. The upper limits on the product of the cross section and branching ratio of a new resonance are expected to be improved by almost one order of magnitude. The expected exclusion range in MSSM scenarios increases by only about 50 GeV along the m_A axis. The increase in sensitivity is more noticeable for a general THDM, with the exclusion extending from 1000 GeV up to 1500 GeV for low values of $\tan\beta$.

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$$\underset{\text{(SM)}}{g^2_{WWh}} = \sum_i g^2_{W^+W^-\phi^0_i} - \sum_k |g_{W^-W^-\phi^{0\,++}_k}|^2$$

$\rightarrow$ at least one doubly-charged scalar is needed!

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$\rightarrow$ opens new possibilities: can fit the three (CP-even) states h_{125}, h_{95}, H_{650} + an extra H_{320}

a Model

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

$$\begin{pmatrix} \mathcal{H}_1 \\ \mathcal{H}_2 \\ \mathcal{H}_3 \\ \mathcal{H}_4 \end{pmatrix} = \mathcal{X}_{4\times 4} \begin{pmatrix} \mathrm{Re}\phi_1^0 \\ \mathrm{Re}\phi_2^0 \\ \mathrm{Re}\chi^0 \\ \xi^0 \end{pmatrix}, \quad \mathcal{X}^\dagger \mathcal{X} = \mathcal{X}\mathcal{X}^\dagger = 1, \ \ [\mathcal{X}]_{ij} \equiv x_{ij}$$

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$\rightarrow$ extended Georgi-Machacek, $\langle \phi_1^0 \rangle \sim v_1, \langle \phi_2^0 \rangle \sim v_2, \langle \chi \rangle = \langle \xi \rangle \sim u$

a Model

Coupling to two gauge bosons

$$\mathcal{L}_{\rm cubic} = \frac{g^2 v_1}{2\sqrt{2}} S_1 \, W \cdot W + \frac{g^2 v_2}{2\sqrt{2}} S_2 \, W \cdot W + \frac{2 g^2 u}{\sqrt{3}} S_3 \, W \cdot W + g^2 u \, [W \otimes W] \cdot F$$

$$\begin{aligned} v \kappa_W^{\mathcal{H}_a} =& v_1 x_{a1} + v_2 x_{a2} + 2u (x_{a3} + \sqrt{2} x_{a4}), \\ v \kappa_Z^{\mathcal{H}_a} =& v_1 x_{a1} + v_2 x_{a2} + 4 u x_{a3}, \\ v^2 =& v_1^2 + v_2^2 + 4u^2 \simeq \left(\frac{246}{\sqrt{2}} \right)^2, \end{aligned}$$

Yukawa couplings:

$$\text{Type} - \text{II 2HDM}: \quad \kappa_d^{\mathcal{H}_a} = \frac{v}{v_1} x_{a1} \, , \quad \kappa_u^{\mathcal{H}_a} = \frac{v}{v_2} x_{a2}$$

$$\text{Type} - \text{I 2HDM}: \quad \kappa_d^{\mathcal{H}_a} = \kappa_u^{\mathcal{H}_a} = \frac{v}{v_2} x_{a2}$$

SM-like h_{125}

$$v\kappa_W^{h_{125}} = v_1 x_{21} + v_2 x_{22} + 2u(x_{23} + \sqrt{2}x_{24}),$$
$$v\kappa_Z^{h_{125}} = v_1 x_{21} + v_2 x_{22} + 4u x_{23}$$
$$v^2 = v_1^2 + v_2^2 + 4u^2 \simeq \left(246/\sqrt{2}\right)^2$$

$$\kappa_W^{h_{125}} \simeq \kappa_Z^{h_{125}} \simeq 1 \Rightarrow x_{23} - \sqrt{2}x_{24} = 0$$

$$\mathrm{Type-II\,2HDM} \Rightarrow u^2 = \frac{3}{4}\frac{1-\kappa_Z^{h_{125}}}{3 - sign(u)2\sqrt{6}} v^2 \Rightarrow u\,\mathrm{very small} \rightarrow \mathrm{disvavoured}$$

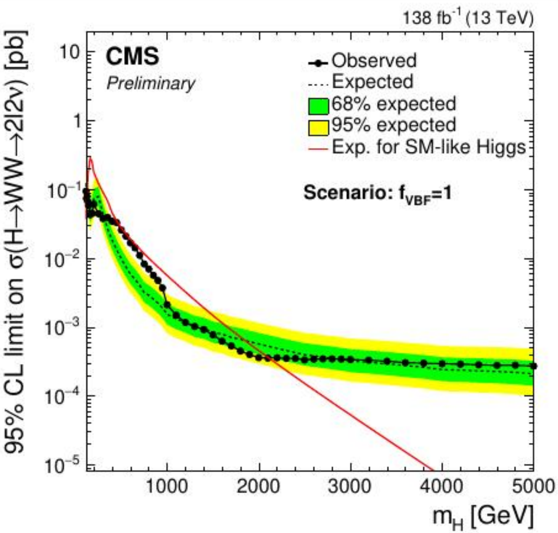
scan strategy

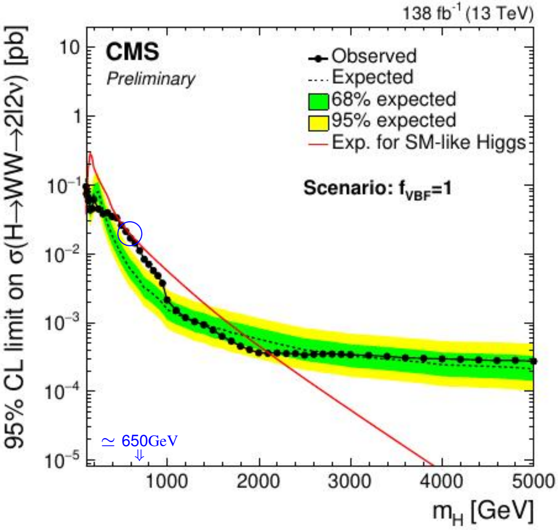
- Stick to Type-I 2HDM-like
- Take $\mathcal{X}$ real, orthogonal
- Needs 6 input: e.g. $\kappa_t^{h_{125}}, \kappa_Z^{h_{125}}, \kappa_W^{h_{125}}, \kappa_t^{h_{95}}, \kappa_W^{h_{95}}, \kappa_W^{H_{650}}$
- $h_{125} \Rightarrow u, v_1, v_2, x_{2i}{}'s$
- subspace orthogonal to x_{2i}, and $h_{95} \Rightarrow x_{1i}{}'s$
- subspace orthogonal to x_{1i}, x_{2i}, and $H_{650} \Rightarrow$ determines $x_{3i}{}'s$ and $x_{4i}{}'s$, four-fold solutions.
- check compatibility with experimental indications

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h_{95} \to \gamma\gamma)}{\sigma(pp \to \phi \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12} \,,$$

$$\mu_{\tau^+\tau^-} = \frac{\sigma(pp \to h_{95} \to \tau^+\tau^-)}{\sigma(pp \to \phi \to \tau^+\tau^-)} = 1.2 \pm 0.5 \,,$$

$$\mu_{b\bar{b}} = \frac{\sigma(e^+e^- \to Zh_{95} \to Zb\bar{b})}{\sigma(e^+e^- \to Z\phi \to Zb\bar{b})} = 0.117 \pm 0.057$$


138 fb^{-1} (13 TeV)
CMS
Preliminary
Observed
Expected
68% expected
95% expected
Exp. for SM-like Higgs
Scenario: f_{VBF}=1
95% CL limit on $\sigma(H\to WW\to 2l2\nu)$ [pb]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1000
2000
3000
4000
5000
m_H [GeV]


138 fb-1 (13 TeV)
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Observed
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68% expected
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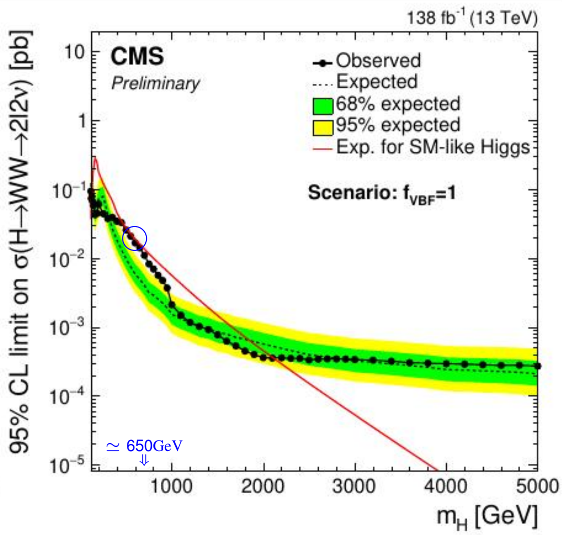
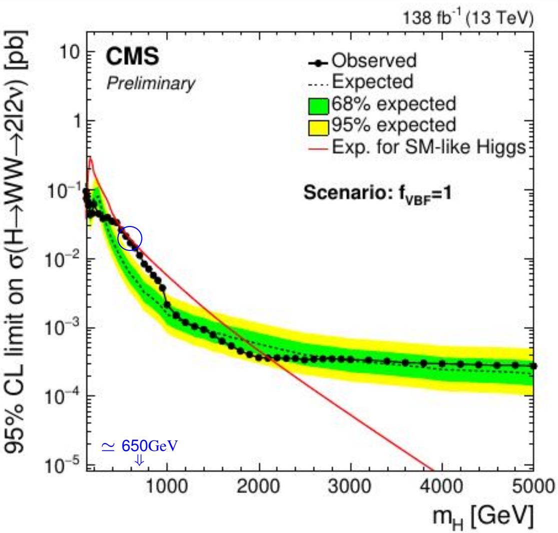
Exp. for SM-like Higgs
Scenario: f_VBF=1
≃ 650GeV
95% CL limit on σ(H→WW→2l2ν) [pb]
m_H [GeV]
10
1
10-1
10-2
10-3
10-4
10-5
1000
2000
3000
4000
5000



$$\sigma_{\text{VBF}} \times \text{BR}^*{}_{H_{650}\to W^+W^-} = c\,\sigma_{\text{VBF}}^{(\text{SM})} \times \text{BR}^{*(\text{SM})}_{H_{650}\to W^+W^-}$$



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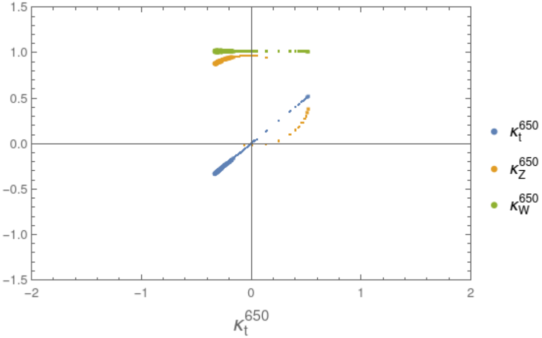
correlations: $\left|\kappa_W^{H_{650}}\right|, \left|\kappa_Z^{H_{650}}\right|, \left|\kappa_t^{H_{650}}\right|, \Rightarrow \left|\kappa_W^{H_{650}}\right| \in [.96, 1.1[$

solutions

e.g. $\kappa_W^{650} = 1.015 \rightarrow u \simeq 69$ GeV, $v_1 \simeq 14$ GeV, $v_2 \simeq 104$ GeV



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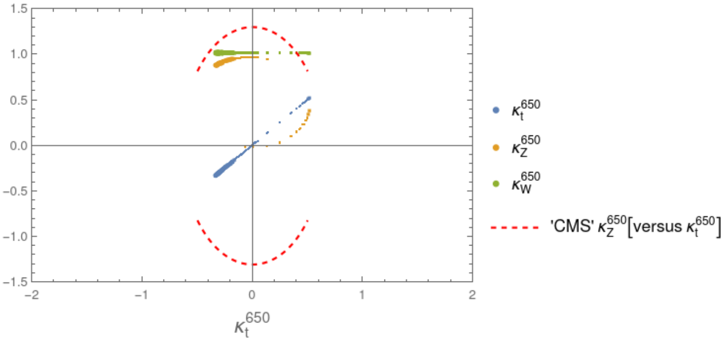

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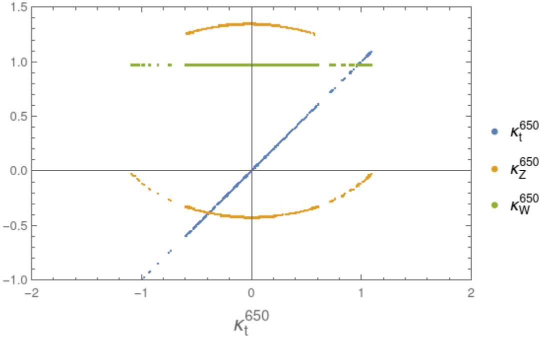

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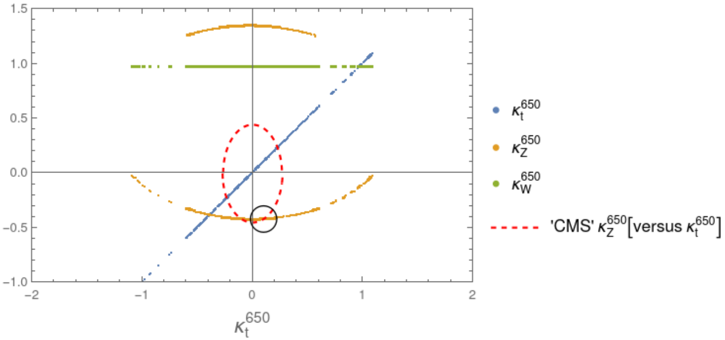

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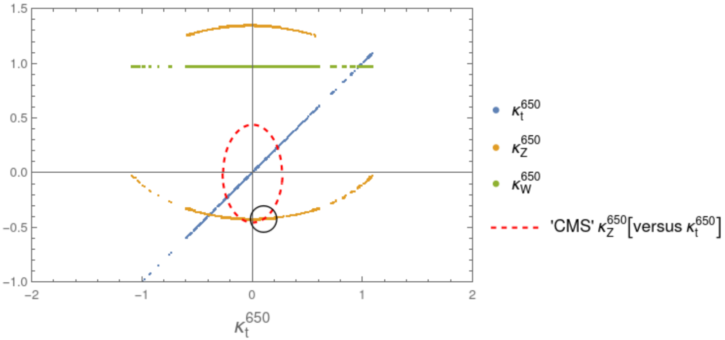
	x_{i1}	x_{i2}	x_{i3}	x_{i4}	κ_t	κ_Z	κ_W
h_{95}	0.6	-0.25	-0.76	-0.01	-0.58	-1.41	-0.74
h_{125}	0.73	0.43	0.44	0.29	0.99	1.04	1.02
H_{320}	0.17	-0.86	0.43	0.2	-1.98	0.4	0.27
H_{650}	-0.26	0.05	-0.23	0.93	0.1	-0.42	0.97



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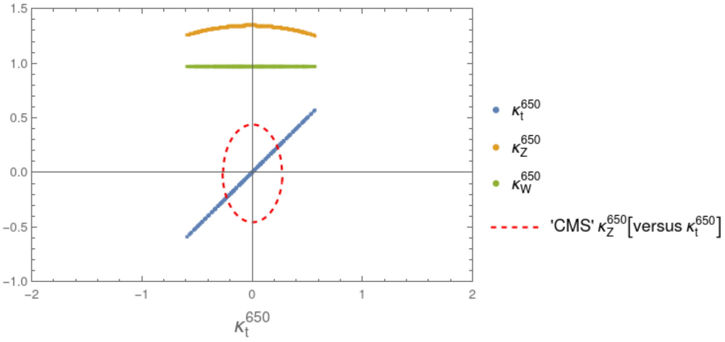
h_{125}	0.73	0.43	0.44	0.29	0.99	1.04	1.02
H_{320}	0.17	-0.86	0.43	0.2	-1.98	0.4	0.27
H_{650}	-0.26	0.05	-0.23	0.93	0.1	-0.42	0.97



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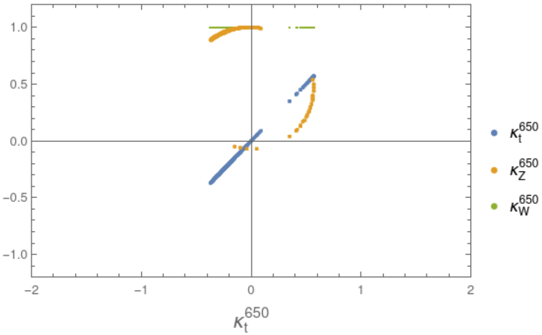

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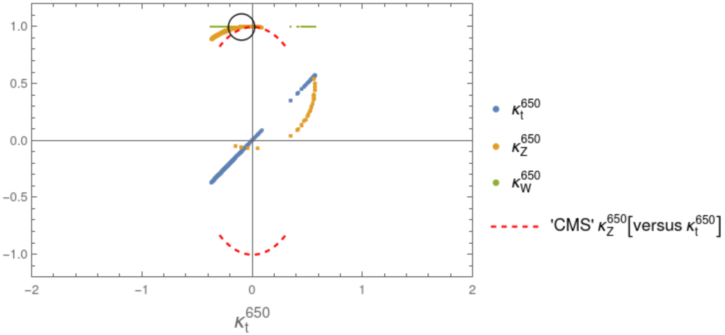

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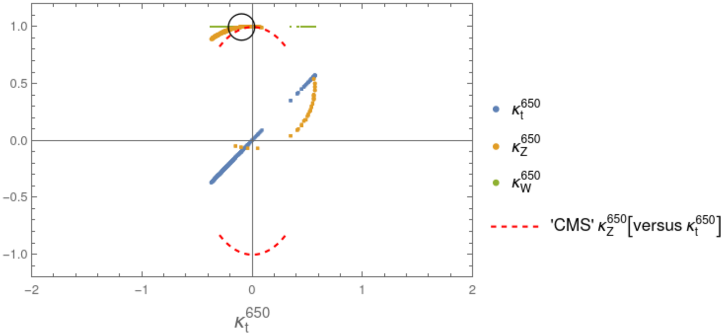
h_{95}	0.23	−0.34	−0.42	0.81	−0.56	−0.85	0.4
h_{125}	0.65	0.59	0.4	0.26	0.99	1.04	1.02
H_{320}	−0.47	0.73	−0.46	0.2	1.21	−0.33	0.26
H_{650}	−0.55	−0.06	0.68	0.48	−0.1	1.	1.



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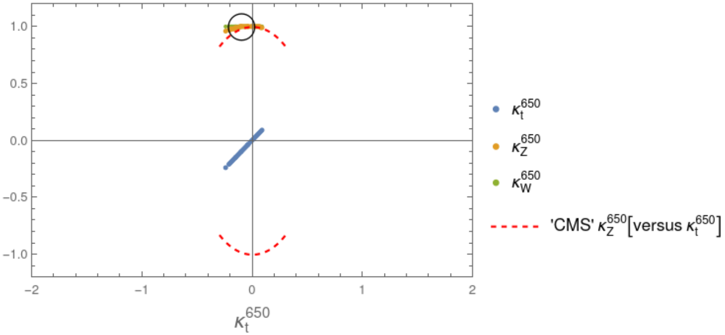
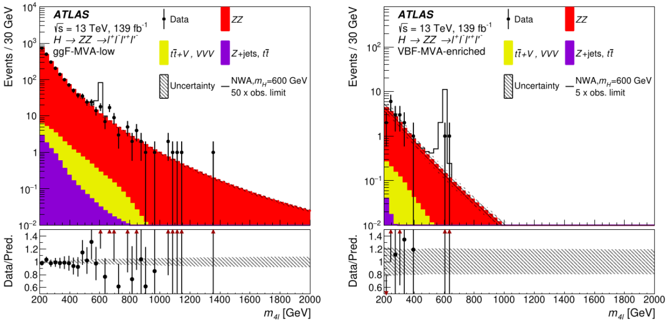
e.g. $\kappa_W^{650} = 1. \rightarrow u \simeq 69\,\text{GeV},\ v_1 \simeq 14\,\text{GeV},\ v_2 \simeq 104\,\text{GeV}$

	x_{i1}	x_{i2}	x_{i3}	x_{i4}	κ_t	κ_Z	κ_W
h_{95}	0.23	−0.34	−0.42	0.81	−0.56	−0.85	0.4
h_{125}	0.65	0.59	0.4	0.26	0.99	1.04	1.02
H_{320}	−0.47	0.73	−0.46	0.2	1.21	−0.33	0.26
H_{650}	−0.55	−0.06	0.68	0.48	−0.1	1.	1.



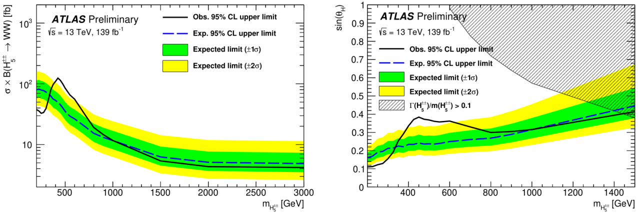
What else?



For the VBF production, the maximum deviation is for a signal mass hypothesis around 620 GeV, with a local significance of 2.4 standard deviations and a global significance of 0.9 standard deviation.

Still awaiting CMS to release its ZZ/4lepton analysis!

What else?



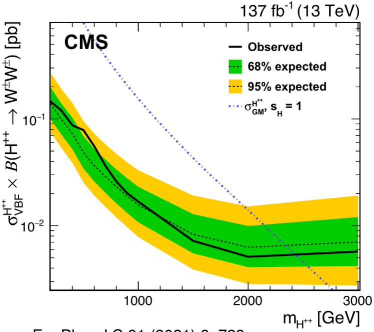
(a) (b)

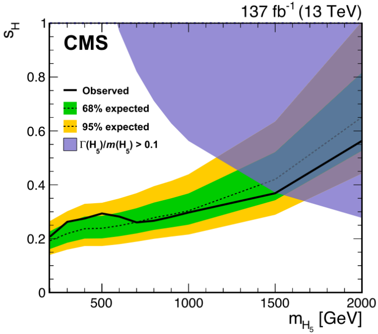
ATLAS-CONF-2023-023: Local excess at a resonance mass around 450 GeV, 2.5 (global).

BUT $\sin\theta_H \lesssim 0.4 \rightarrow u \lesssim 35$ GeV $\rightarrow$ too small!

Perhaps other decay channels, e.g. to singly charged Higgs, or allow complex $\mathcal{X} \rightarrow$ possible new sources of CP-violation?

What else?





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Situation unclear!

Conclusions

- Given the huge data taking at LHC, excesses are occasionally observed in searches for new resonances, that might or might not stand the test of time.
- But if they occur at roughly the same invariant mass, maybe something real is round the corner
- Recent indications for a 650 GeV in various channels, 4σ combined (global) implies $SU(2)_L$ triplets $\rightarrow$ new neutral, charged, and doubly-charged scalars to look for.
- But not easy to implement $\rightarrow$ extended Georgi-Machacek, including consistently, the 125 GeV, a 95 GeV, and perhaps a $\simeq$ 300 GeV CP-even neutral scalars.
- wait and see what happens with future data...