Should we consider scalar extensions seriously?

Anirban Kundu
University of Calcutta

December 19, 2023
Phoenix, IIT Hyderabad

University of Calcutta

Plan of the talk:

To give an affirmative answer to the question.

Motivation:

- A possible cold dark matter candidate
  - Singlet? Inert 2HDM?

Plan of the talk:

To give an affirmative answer to the question.

Motivation:

- A possible cold dark matter candidate ♣ Singlets? Inert 2HDM?
- A possible source of CP violation ♣ $n_b/n_\gamma|_{SM} \sim 10^9$ times smaller
- A possible way to make the EW phase transition first-order

University of Calcutta

Plan of the talk:

To give an affirmative answer to the question.

Motivation:

- A possible source of CP violation ♣ $n_b/n_\gamma|_{SM} \sim 10^9$ times smaller
- A possible way to make the EW phase transition first-order
- Neutrino mass generation through seesaw ♣ Triplets?
- Consistent formulation of models ♣ e.g., SUSY

University of Calcutta

Plan of the talk:

To give an affirmative answer to the question.

Motivation:

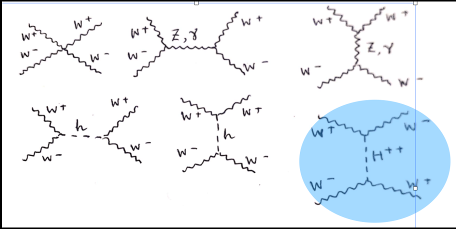
- A possible cold dark matter candidate ♣ Singlets? Inert 2HDM?

- Neutrino mass generation through seesaw ♣ Triplets?
- Consistent formulation of models ♣ e.g., SUSY

University of Calcutta

SM: A renormalisable gauge theory

- The Higgs mechanism makes the EW gauge bosons massive but keeps the theory renormalisable (Veltman and 't Hooft)
- This means that the scattering of gauge bosons does not violate unitarity, the amplitude does not grow monotonically with $\sqrt{s}$. Consider $W_L W_L \to W_L W_L$:



- $$\begin{aligned}\mathcal{M} &= 16\pi \sum_{ell} (2\ell+1) a_\ell(s) P_\ell(\cos\theta)\,, \\ a_\ell &= A\,(q/M_W)^4 + B\,(q/M_W)^2 + C\,,\end{aligned}$$

  where q is the W momentum in the CM frame. Only $\ell = 0, 1, 2$ are relevant.
- The A term cancels with 3- and 4-point gauge vertices but cancellation of B needs the Higgs boson (Lee, Quigg, and Thacker)

UNIVERSITY OF CALCUTTA

Notation

- SM Higgs: h
  Any other scalar of mass M: h_M or H_M
  A SM-like scalar (identical couplings with fermions and gauge bosons) but at a mass M: ϕ_M
  Coupling strength of particles i, j, k: g_{ijk}
- $$\kappa_X = \frac{g_{h_M X\bar{X}}}{g_{hX\bar{X}}}$$
  $$\mu_X = \frac{\sigma(pp \to h_M \to X\bar{X})}{\sigma(pp \to \phi_M \to X\bar{X})}$$
  Thus, μ_X is a function of various κs.

Notation

- SM Higgs: h
  Any other scalar of mass M: h_M or H_M
  A SM-like scalar (identical couplings with fermions and gauge bosons) but at a mass M: ϕ_M
  Coupling strength of particles i, j, k: g_{ijk}

- $$\kappa_X = \frac{g_{h_M X\bar{X}}}{g_{hX\bar{X}}}$$
  $$\mu_X = \frac{\sigma(pp \to h_M \to X\bar{X})}{\sigma(pp \to \phi_M \to X\bar{X})}$$
  Thus, μ_X is a function of various κs.

University of Calcutta

Theoretical constraints on extra scalars

- $V(\Phi_1, \Phi_2, \cdots \Phi_n)$ must be a gauge and Lorentz scalar
- All dimensionless couplings in V should better be perturbative
- Must be bounded from below along every direction in the field space

$$
\begin{aligned}
V(\Phi_1, \Phi_2) &= \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) \\
&= \left(\sqrt{\lambda_1} \Phi_1^\dagger \Phi_1 - \sqrt{\lambda_2} \Phi_2^\dagger \Phi_2\right)^2 \\
&\quad + \underbrace{\left(\lambda_3 + 2\sqrt{\lambda_1 \lambda_2}\right)}_{>0} \Phi_1^\dagger \Phi_1 \, \Phi_2^\dagger \Phi_2
\end{aligned}
$$

- Partial wave unitarity must be respected in all scattering channels: $\Re(a_\ell) \leq 1/2$

University of Calcutta

Theoretical constraints on extra scalars

- $V(\Phi_1, \Phi_2, \cdots \Phi_n)$ must be a gauge and Lorentz scalar
- All dimensionless couplings in V should better be perturbative
- Must be bounded from below along every direction in the field space

$$\begin{aligned} V(\Phi_1, \Phi_2) &= \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\ &= \left(\sqrt{\lambda_1}\Phi_1^\dagger \Phi_1 - \sqrt{\lambda_2}\Phi_2^\dagger \Phi_2\right)^2 \\ &\quad + \underbrace{\left(\lambda_3 + 2\sqrt{\lambda_1 \lambda_2}\right)}_{>0} \Phi_1^\dagger \Phi_1 \, \Phi_2^\dagger \Phi_2 \end{aligned}$$

- Partial wave unitarity must be respected in all scattering channels: $\Re(a_\ell) \leq 1/2$

University of Calcutta

Theoretical constraints on extra scalars

Custodial symmetry

If an SU(2) gauge symmetry undergoes SSB in a way that the neutral and the charged gauge bosons remain mass-degenerate at the tree-level, there is an SU(2) symmetry in the gauge boson mass terms and is present in the pure gauge terms even in the broken phase.

$$\begin{aligned} \rho_{\rm tree} &= \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1\,, && \text{(Broken by fermions)} \\ \rho_0 &= 1.00038 \pm 0.00020\,, && \text{(Includes top contrib., SM=1)} \end{aligned}$$

Condition

$$\sum c\left[T(T+1) - n^2\right] v^2 = 2 \sum n^2 v^2\,,$$

$$c = \begin{cases} 1 & \text{if the multiplet is complex,} \\ \frac{1}{2} & \text{if the multiplet is real.} \end{cases}$$

T = isospin of the multiplet, $n = T_3$-value of the neutral. Identically satisfied for any singlet ($T = 0$) and doublet ($T = \frac{1}{2}$)

University of Calcutta

Types of Custodial Symmetry

- CS is a symmetry of the entire $\mathcal{L}$. No correction to ρ is generated even in loops[1], disregarding the fermions. Scalar custodial multiplets are mass-degenerate.

  Example: SM, gauge singlets, constrained 2HDM, canonical Georgi-Machacek.

- The kinetic terms after SSB respect CS but the scalar potential does not. The scalar custodial multiplets are not degenerate.

  Example: Most general 2HDM, Generalised Georgi-Machacek.

(AK, Mondal, Pal, PRD 2022)

[1] In SU(2) theories, no $\times U(1)$.

Sum rules

[Gunion, Haber, Wudka, PRD 1991]

- ⟹ The underlying theory is renormalisable, so all scattering amplitudes must respect the unitarity bound
- ⟹ Consider $WW \to WW$, which can be mediated through both neutral and doubly-charged scalars
- ⟹ Similarly, $WZ \to WZ$ goes through neutral and singly-charged scalars

University of Calcutta

$$\underbrace{g^2\left(4M_W^2 - 3\cos^2\theta_W M_Z^2\right)}_{\approx g^2 M_W^2} = \underbrace{\sum_k \eta_k g^2_{WW\phi_k^0} - \sum_k \eta_k g^2_{WW\phi_k^{++}}}_{g^2 M_W^2 \text{ in SM; } \eta=+1(-1) \text{ for CP-even(odd)}} ,$$

$$\frac{g^2\cos^2\theta_W M_Z^4}{M_W^2} = \sum_k \eta_k g_{WW\phi_k^0} g_{ZZ\phi_k^0} - \sum_k \eta_k g^2_{WZ\phi_k^+} .$$

- LHC tells us that $g_{WWh_{125}} \approx g_{WWh}$, saturating the first sum rule.
- So any other neutral scalar with a significant coupling to WW definitely indicates a doubly charged scalar in the spectrum.
- Similarly, any neutral scalar with a significant coupling to both WW and ZZ indicates at least one singly charged scalar.

UNIVERSITY OF CALCUTTA

$$\underbrace{g^2\left(4M_W^2 - 3\cos^2\theta_W M_Z^2\right)}_{\approx g^2 M_W^2} = \underbrace{\sum_k \eta_k g^2_{WW\phi_k^0} - \sum_k \eta_k g^2_{WW\phi_k^{++}}}_{g^2 M_W^2 \text{ in SM; } \eta=+1(-1) \text{ for CP-even(odd)}} ,$$

$$\frac{g^2\cos^2\theta_W M_Z^4}{M_W^2} = \sum_k \eta_k g_{WW\phi_k^0} g_{ZZ\phi_k^0} - \sum_k \eta_k g^2_{WZ\phi_k^+} .$$

- LHC tells us that $g_{WWh_{125}} \approx g_{WWh}$, saturating the first sum rule.
- So any other neutral scalar with a significant coupling to WW definitely indicates a doubly charged scalar in the spectrum.
- Similarly, any neutral scalar with a significant coupling to both WW and ZZ indicates at least one singly charged scalar.

UNIVERSITY OF CALCUTTA

Any evidence, or empty talks?

1. Only h_{125} so far, with properties exactly that of h, within experimental accuracy : $h_{125} \approx h$ (CMS, Nature 2022)

$$\kappa_W = 1.02 \pm 0.08\,, \quad \kappa_Z = 1.04 \pm 0.07\,, \quad \kappa_t = 1.01^{+0.11}_{-0.10}\,, \quad \kappa_b = 0.99^{+0.17}_{-0.16}$$

2. Beware: this can be a conspiracy, like 2HDM in alignment limit.
3. **Are there any new scalars?**
— None announced, but *there are indications*, which I'll talk about
— I'll use only published numbers and plots from either ATLAS or CMS, no unofficial combinations (*i.e.*, done by the theoreticians)

University of Calcutta

1. Only h_{125} so far, with properties exactly that of h, within experimental accuracy : $h_{125} \approx h$ (CMS, Nature 2022)

$$\kappa_W = 1.02 \pm 0.08\,, \quad \kappa_Z = 1.04 \pm 0.07\,, \quad \kappa_t = 1.01^{+0.11}_{-0.10}\,, \quad \kappa_b = 0.99^{+0.17}_{-0.16}$$

2. Beware: this can be a conspiracy, like 2HDM in alignment limit.
3. **Are there any new scalars?**
   — None announced, but *there are indications*, which I'll talk about
   — I'll use only published numbers and plots from either ATLAS or CMS, no unofficial combinations (*i.e.*, done by the theoreticians)

University of Calcutta

- When should one feel excited, and what is a discovery?

  3σ is 99% CL, encouraging, 5σ is a discovery
  But be careful, only global significances, not local (LEE)

- For every signal, the p-value gives the probability with which the null hypothesis is rejected
  The higher the σ, the smaller the p-value $\quad (5\sigma \Rightarrow p \approx 3 \times 10^{-7})$
  Combination is tricky, it is not just $p = p_1 p_2$ and so on

  For example, to combine two results with p_1 and p_2:
  $$p = p_1 p_2 \left[1 - \ln(p_1 p_2)\right]$$

- Only those signals indicated by more than one collaboration are considered

University of Calcutta

- For every signal, the p-value gives the probability with which the null hypothesis is rejected
  The higher the σ, the smaller the p-value $(5\sigma \Rightarrow p \approx 3 \times 10^{-7})$
  Combination is tricky, it is not just $p = p_1 p_2$ and so on

  For example, to combine two results with p_1 and p_2:
  $$p = p_1 p_2 \left[1 - \ln(p_1 p_2)\right]$$
- Only those signals indicated by more than one collaboration are considered

University of Calcutta

h_{95}

CMS [1811.08459, PLB; 1803.06553, JHEP; CMS-PAS-HIG-21-001]

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h_{95} \to \gamma\gamma)}{\sigma(pp \to \phi_{95} \to \gamma\gamma)} = 0.6 \pm 0.2\,,$$

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

- ggF works, strong $t\bar{t}h_{95}$
- Stronger destructive interference between top and W loop

LEP [hep-ex/0306033, PLB]

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

- Either ZZh_{95} or $b\bar{b}h_{95}$ is suppressed

Combined significance $= 3.9\,\sigma$

University of Calcutta

CMS [1811.08459, PLB; 1803.06553, JHEP; CMS-PAS-HIG-21-001]

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h_{95} \to \gamma\gamma)}{\sigma(pp \to \phi_{95} \to \gamma\gamma)} = 0.6 \pm 0.2\,,$$

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

- ggF works, strong $t\bar{t}h_{95}$
- Stronger destructive interference between top and W loop

LEP [hep-ex/0306033, PLB]

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

- Either ZZh_{95} or $b\bar{b}h_{95}$ is suppressed

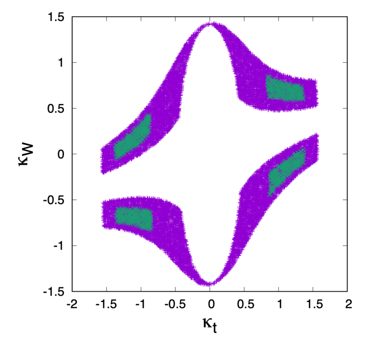
Combined significance = $3.9\,\sigma$

University of Calcutta

Let's start with a 2HDM Type-I, so that $\kappa_t = \kappa_\tau$

Type-I: one doublet couples to all fermions, the other to none. Talk by J. Song yesterday

κ_t-κ_W plane with $\mu_{\tau\tau}$ and $\mu_{\gamma\gamma}$ (ggF:VBF = 90:10)



$\kappa_W^{\text{max.}}(h_{95}) = 0.34\,(1\sigma)\,,\ 0.51\,(2\sigma)$, without H^{++}, still consistent

University of Calcutta

H_{650}

CMS-PAS-HIG-20-016

$H_{650} \to W^+W^-$, both ggF and VBF productions looked at

CMS-PAS-HIG-21-011

$H_{650} \to h_{95} h_{125} \to b\bar{b}\gamma\gamma$

ATLAS, 2103.01918 (JHEP); 2009.14791 (EPJC)

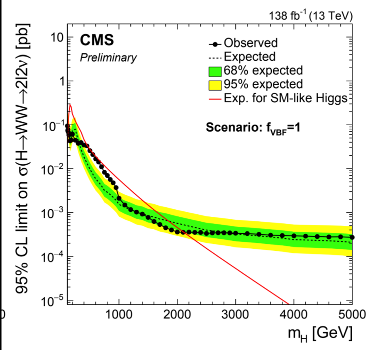
$H_{650} \to ZZ \to 4\ell$

$H_{650} \to W^+W^-$

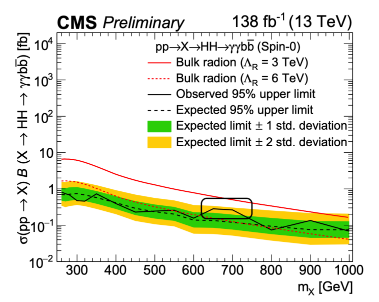
Scenario	Mass [GeV]	ggF cross sec. [pb]	VBF cross sec. [pb]	Local signi. [σ]	Global signi. [σ]
SM f_{VBF}	800	0.16	0.057	3.2	1.7 ± 0.2
$f_{VBF} = 1$	650	0.0	0.16	3.8	2.6 ± 0.2
$f_{VBF} = 0$	950	0.19	0.0	2.6	0.4 ± 0.6
floating f_{VBF}	650	2.9×10^{-6}	0.16	3.8	2.4 ± 0.2

[CMS-PAS-HIG-20-016]

Local: 3.8σ, **Global: 2.6σ** LE factor $=$ p-value (global)/p-value (local) ≈ 64



$H_{650} \to h_{95} h_{125}$



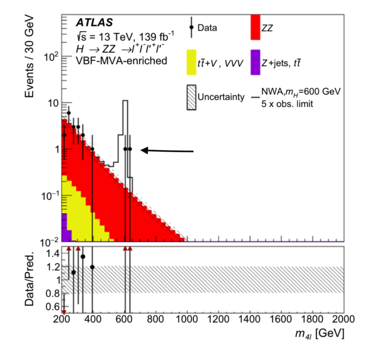
[CMS-PAS-HIG-21-011]

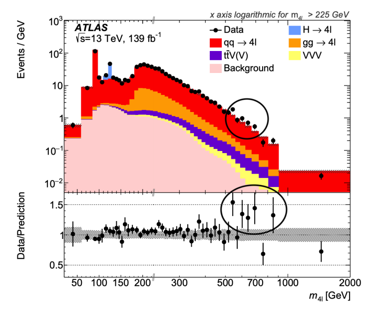
0.90 – 0.04 fb whereas the expected limits are 0.79 – 0.05 fb, with the considered mass ranges in m_X and m_Y. The largest deviation from background-only hypothesis with local (global) significance of 3.8 (2.8) standard deviations is observed for $m_X = 650$ GeV and $m_Y = 90$ GeV. The HH limits are compared with predictions in the warped extra

Local: 3.8σ, **Global: 2.8σ** LE factor ≈ 30

University of Calcutta

$H_{650} \to ZZ$





[ATLAS, EPJC 2021, 2009.14791; JHEP 2021, 2103.01918]

production separately. For the ggF production, the maximum deviation is for a signal mass hypothesis around 240 GeV, with a local significance of 2.0 standard deviations and a global significance of 0.5 standard deviation. 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.

University of Calcutta

H_{650} in summary

- Indicated by both CMS and ATLAS, a broad resonance
  — Definitely through VBF (WW and ZZ fusion), possibly also through ggF
  — Decays, possibly, to WW, $h_{95}h_{125}$, and to ZZ but suppressed
  — $t\bar{t}$ mode not yet observed, but background is huge
- $H_{650}W^+W^-$ coupling is large:

$$\kappa_W = WW/\mathrm{SM} = 0.85 \pm 0.15\,, \qquad \kappa_Z = ZZ/\mathrm{SM} = 0.40 \pm 0.15$$

(This is only a lower limit)

Combined significance $= 4.2\,\sigma$

University of Calcutta

H_{650} in summary

- Indicated by both CMS and ATLAS, a broad resonance
  — Definitely through VBF (WW and ZZ fusion), possibly also through ggF
  — Decays, possibly, to WW, $h_{95}h_{125}$, and to ZZ but suppressed
  — $t\bar{t}$ mode not yet observed, but background is huge
- $H_{650}W^+W^-$ coupling is large:

$$\kappa_W = WW/\mathrm{SM} = 0.85 \pm 0.15\,, \qquad \kappa_Z = ZZ/\mathrm{SM} = 0.40 \pm 0.15$$

(This is only a lower limit)

Combined significance $= 4.2\,\sigma$

- The strongest significance after h_{125}, but ....

University of Calcutta

H_{650} in summary

- Indicated by both CMS and ATLAS, a broad resonance
  — Definitely through VBF (WW and ZZ fusion), possibly also through ggF
  — Decays, possibly, to WW, $h_{95}h_{125}$, and to ZZ but suppressed
  — $t\bar{t}$ mode not yet observed, but background is huge
- $H_{650}W^+W^-$ coupling is large:

$$\kappa_W = WW/\mathrm{SM} = 0.85 \pm 0.15\,, \qquad \kappa_Z = ZZ/\mathrm{SM} = 0.40 \pm 0.15$$

(This is only a lower limit)

Combined significance $= 4.2\,\sigma$

- **The strongest significance after h_{125}, but ....**

H_{650} in summary

- Indicated by both CMS and ATLAS, a broad resonance
  — Definitely through VBF (WW and ZZ fusion), possibly also through ggF
  — Decays, possibly, to WW, $h_{95}h_{125}$, and to ZZ but suppressed
  — $t\bar{t}$ mode not yet observed, but background is huge
- $H_{650}W^+W^-$ coupling is large:

$$\kappa_W = WW/\mathrm{SM} = 0.85 \pm 0.15\,, \qquad \kappa_Z = ZZ/\mathrm{SM} = 0.40 \pm 0.15$$

(This is only a lower limit)

Combined significance $= 4.2\,\sigma$

- **The strongest significance after h_{125}, but ....**

- 

How significant is H_{650} ?

- Only two CMS published (WW and $b\bar{b}\gamma\gamma$) This is the most conservative number — 3.6σ

- These two plus ATLAS without paying the LE price — 4.2σ

University of Calcutta

How significant is H_{650} ?

- Only two CMS published (WW and $b\bar{b}\gamma\gamma$)
  This is the most conservative number

3.6σ

- These two plus ATLAS without paying the LE price

4.2σ

$$g^2\left(4M_W^2 - 3\cos^2\theta_W M_Z^2\right) = \sum_k \eta_k g^2_{WW\phi_k^0} - \sum_k \eta_k g^2_{WW\phi_k^{++}}\,,$$
$$\frac{g^2\cos^2\theta_W M_Z^4}{M_W^2} = \sum_k \eta_k g_{WW\phi_k^0} g_{ZZ\phi_k^0} - \sum_k \eta_k g^2_{WZ\phi_k^+}\,.$$

- $$\frac{g^2_{W^+W^+H^{--}}}{g^2_{hWW,\ \mathrm{SM}}} = 1.30 \pm 0.57\,, \qquad \frac{g^2_{W^+ZH^-}}{g_{hWW}g_{hZZ}} = 0.60 \pm 0.42\,,$$
- This leads to
$$\Gamma(H^{++}\to W^+W^+) = 16\pm 5\ \mathrm{GeV}\,, \quad \Gamma(H^+ \to W^+Z) = 13\pm 4\ \mathrm{GeV}\,.$$
- This is only with h_{125} and H_{650}. Stronger $W^+W^+H^{--}$ if we consider h_{95} too

University of Calcutta

$$
\begin{aligned}
g^2\left(4M_W^2 - 3\cos^2\theta_W M_Z^2\right) &= \sum_k \eta_k g^2_{WW\phi_k^0} - \sum_k \eta_k g^2_{WW\phi_k^{++}}\,,\\
\frac{g^2\cos^2\theta_W M_Z^4}{M_W^2} &= \sum_k \eta_k g_{WW\phi_k^0} g_{ZZ\phi_k^0} - \sum_k \eta_k g^2_{WZ\phi_k^+}\,.
\end{aligned}
$$

- $$\frac{g^2_{W^+W^+H^{--}}}{g^2_{hWW,\ \mathrm{SM}}} = 1.30 \pm 0.57\,, \qquad \frac{g^2_{W^+ZH^-}}{g_{hWW}\, g_{hZZ}} = 0.60 \pm 0.42\,,$$
- This leads to

$$\Gamma(H^{++} \to W^+W^+) = 16{\pm}5\ \mathrm{GeV}\,, \quad \Gamma(H^+ \to W^+Z) = 13{\pm}4\ \mathrm{GeV}\,.$$

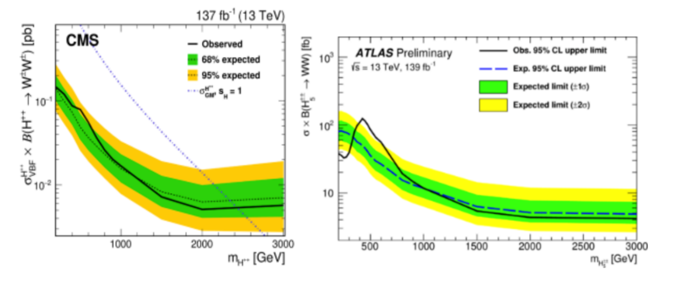
- This is only with h_{125} and H_{650}. Stronger $W^+W^+H^{--}$ if we consider h_{95} too

University of Calcutta

H^{++}_{450} H^{+}_{375}

Enter the charged scalars

- Strong $H^{++}W^-W^- \implies M_{H^{++}} > 2$ TeV with 100% BR (CMS)
- Anything less means $H^{++} \to h_1^+ h_2^+, h^+ W^+$

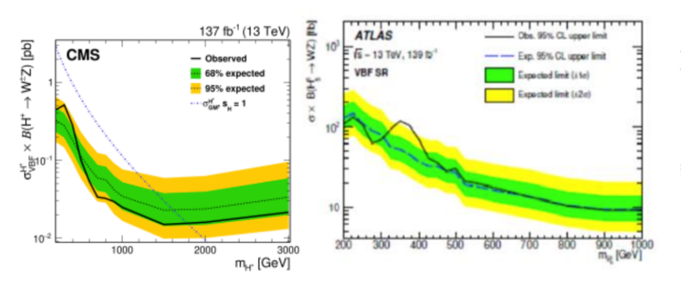


[CMS, EPJC 2021, 2104.04762; ATLAS-CONF-23-023]

There is an indication of H^{++} at around 450 GeV:

Combined significance $= 2.6\,\sigma$

University of Calcutta



[CMS, EPJC 2021, 2104.04762; ATLAS, 2207.03925]

H^+ at around 375 GeV

Combined significance $= 2.7\,\sigma$

Final stock taking: What they can and cannot be

- h_{95} and H_{650} indications are strong and from more than one collab. There are several weak indications too, some of them we discussed
- H_{650} couples strongly to W^+W^-
  Extensions with only singlets and/or doublets are out[2]

[2]As the data stands.

Final stock taking: What they can and cannot be

- h_{95} and H_{650} indications are strong and from more than one collab. There are several weak indications too, some of them we discussed
- H_{650} couples strongly to W^+W^-
  Extensions with only singlets and/or doublets are out[2]
- Custodial symmetry has to be respected. Georgi-Machacek?
  2 custodial singlets, one triplet, one 5-plet, members of multiplets mass-degenerate in minimal version, only custodial singlets couple to fermions

[2] As the data stands.

Final stock taking: What they can and cannot be

- h_{95} and H_{650} indications are strong and from more than one collab. There are several weak indications too, some of them we discussed
- H_{650} couples strongly to W^+W^-
  Extensions with only singlets and/or doublets are out[2]
- Custodial symmetry has to be respected. Georgi-Machacek?
  2 custodial singlets, one triplet, one 5-plet, members of multiplets mass-degenerate in minimal version, only custodial singlets couple to fermions
- If both h_{95} and H_{650} couple to fermions, even canonical GM is out. Also out if $H_{650}WW > H_{650}ZZ$, as indicated

[2] As the data stands.

University of Calcutta

Final stock taking: What they can and cannot be

- h_{95} and H_{650} indications are strong and from more than one collab. There are several weak indications too, some of them we discussed
- H_{650} couples strongly to W^+W^-
  Extensions with only singlets and/or doublets are out[2]
- Custodial symmetry has to be respected. Georgi-Machacek?
  2 custodial singlets, one triplet, one 5-plet, members of multiplets mass-degenerate in minimal version, only custodial singlets couple to fermions
- If both h_{95} and H_{650} couple to fermions, even canonical GM is out. Also out if $H_{650}WW > H_{650}ZZ$, as indicated
- **Shameless self-ad**: We are working on a minimal version, will soon be in the arXiv
  (AK, P. Mondal, G. Moultaka, F. Richard, A. le Yaouanc)

[2] As the data stands.

Final stock taking: What they can and cannot be

- h_{95} and H_{650} indications are strong and from more than one collab. There are several weak indications too, some of them we discussed
- H_{650} couples strongly to W^+W^-
  Extensions with only singlets and/or doublets are out[2]
- Custodial symmetry has to be respected. Georgi-Machacek?
  2 custodial singlets, one triplet, one 5-plet, members of multiplets mass-degenerate in minimal version, only custodial singlets couple to fermions
- If both h_{95} and H_{650} couple to fermions, even canonical GM is out. Also out if $H_{650}WW > H_{650}ZZ$, as indicated
- **Shameless self-ad**: We are working on a minimal version, will soon be in the arXiv
  (AK, P. Mondal, G. Moultaka, F. Richard, A. le Yaouanc)

[2] As the data stands.

University of Calcutta

- *** After h_{125}, the combined significance of H_{650} passes 4σ
  — It has a strong coupling to WW and ZZ, indicates H^{++}
  — Whether it couples to fermions is not yet clear
- ** h_{95} is also close to 4σ
- * There are indications for H^{+} and H^{++} too, none above 3σ at present. These are all global significances
- We should wait for more data and an official combination, but if the trend continues $\cdots$
- Extension by only SU(2) singlets and doublets are ruled out, even if H^{++} hint goes away
- There must be *at least* SU(2) triplet scalars, but more than one such triplets to preserve custodial symmetry $\Rightarrow$ something like Georgi-Machacek?

University of Calcutta

- We should wait for more data and an official combination, but if the trend continues $\cdots$
- Extension by only SU(2) singlets and doublets are ruled out, even if H^{++} hint goes away
- There must be *at least* SU(2) triplet scalars, but more than one such triplets to preserve custodial symmetry $\Rightarrow$ something like Georgi-Machacek?

University of Calcutta

Thank you for your patience

Backup slides

Backup: Combination of p-values

- p-value is *not* the probability that the null hypothesis H_0 is true. But it tells you at what CL you can reject H_0.
- Be careful while combining two p-values, it is not just $p_* = p_1 p_2$, as p_* is not uniformly distributed over the unit interval (0:1).
- Suppose there are k independent tests with $p_1, p_2, \cdots, p_k$, and let $p_* = p_1 p_2 \cdots p_k$.
- Assuming H_0, compute the probability $R_k(\rho)$ such that $p_* \leq \rho$.
- Quote $R_k(p_*)$ as the combined p-value.

University of Calcutta

Backup: Combination of *p*-values

- $k = 2$:

$$R_2(\rho) = \rho(1 - \ln \rho)\,.$$

- For $k \geq 2$:

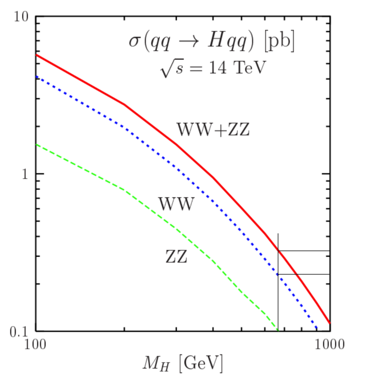
$$R_k(\rho) = \rho + \int_{\rho}^{1} R_{k-1}(\rho/p)\, dp\,,$$

so that

$$R_3(\rho) = \rho \left\{1 - \ln \rho + \tfrac{1}{2}(\ln \rho)^2\right\}\,.$$

University of Calcutta

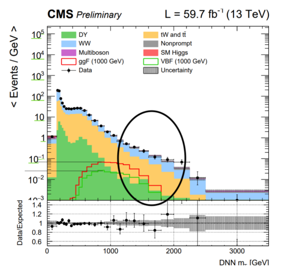
Backup: H_{650} κ-values

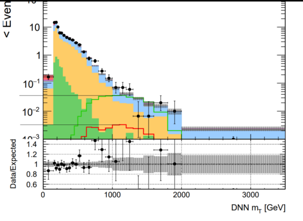


Compare SM-like production x-sec and the CMS number, goes as κ_W^2

$\sqrt{160/220} = 0.85$

University of Calcutta





ggF has a large contamination from VBF: 7.0×10^{-2} and 2.5×10^{-2}

VBF is pure but the efficiency is less: 3.1×10^{-3} and 3.5×10^{-2}