# MULTILEPTON SIGNATURES OF BSM SCALAR BOSONS AT THE LHC

## MODEL BUILDING

Mukesh Kumar
*NITHEP, MITP & School of Physics,*
*University of the Witwatersrand*
*Johannesburg, South Africa.*

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On behalf of High Energy Particle Physics Group
University of the Witwatersrand

# PHASE-1

[ArXiv:1506.00612]

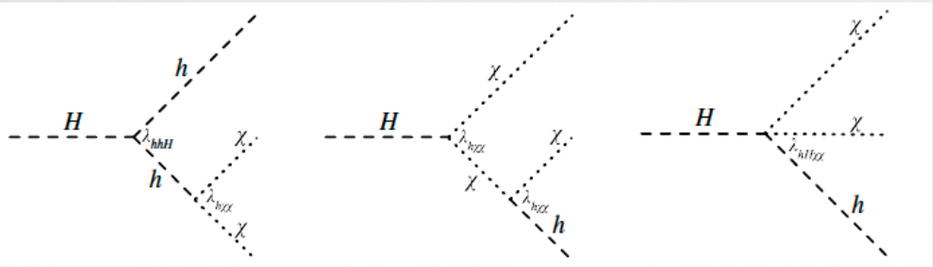
| Result |
|---|
| Differential Higgs boson $p_T$ spectra |
| Di-Higgs boson resonance searches |
| Top associated Higgs boson production |
| $H \to VV$ decays |

$$\mathcal{V}_H = -\frac{1}{4}\,\beta_g \kappa^{\rm SM}_{hgg}\, G_{\mu\nu}G^{\mu\nu}H + \beta_V \kappa^{\rm SM}_{hVV}\, V_\mu V^\mu H,$$

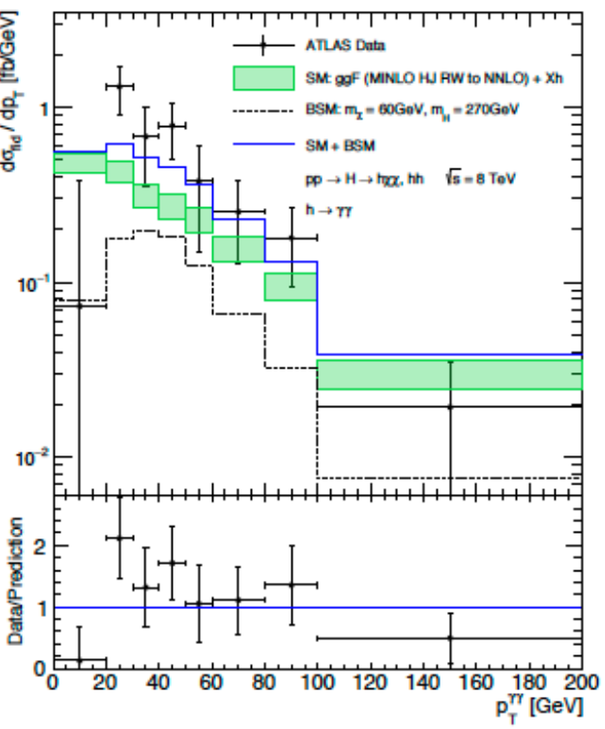
$$\mathcal{V}_{\rm Y} = -\frac{1}{\sqrt{2}}\left[y_{ttH}\,\bar{t}tH + y_{bbH}\,\bar{b}bH\right],$$

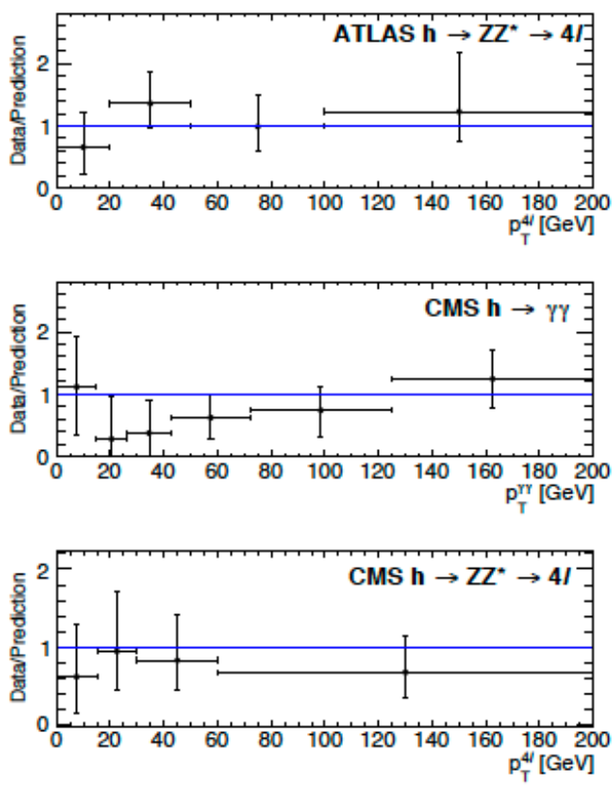
$$\mathcal{V}_{\rm T} = -\frac{1}{2}\,v\left[\lambda_{Hhh}Hhh + \lambda_{h\chi\chi}h\chi\chi + \lambda_{H\chi\chi}H\chi\chi\right],$$

$$\mathcal{V}_{\rm Q} = -\frac{1}{2}\lambda_{Hh\chi\chi}Hh\chi\chi - \frac{1}{4}\lambda_{HHhh}HHhh - \frac{1}{4}\lambda_{hh\chi\chi}hh\chi\chi - \frac{1}{4}\lambda_{HH\chi\chi}HH\chi\chi,$$




**Best Fit results: mH = 272+12-9 GeV**




# PHASE-2

1. Introduced Two-Higgs doublet Model with hint of "S"

[ArXiv:1603.01208]

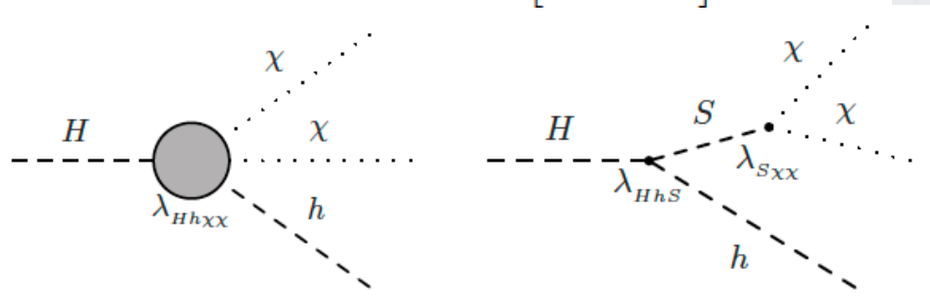
2. Detailed analyses with Constraints with proper Two-Higgs doublet Model and effective theory with possible searches at LHC.

[ArXiv:1606.01674]

$$\mathcal{V}(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right]$$
$$+ \left[\left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]. \qquad (3.2$$

$$\mathcal{V}(\Phi_1,\Phi_2,\chi) = \mathcal{V}(\Phi_1,\Phi_2) + \frac{1}{2}m_\chi^2\chi^2 + \frac{\lambda_{\chi_1}}{2}\Phi_1^\dagger\Phi_1\chi^2 + \frac{\lambda_{\chi_2}}{2}\Phi_2^\dagger\Phi_2\chi^2$$
$$+ \frac{\lambda_{\chi_3}}{4}(\Phi_1^\dagger\Phi_2 + \text{h.c})\chi^2 + \frac{\lambda_{\chi_4}}{8}\chi^4.$$

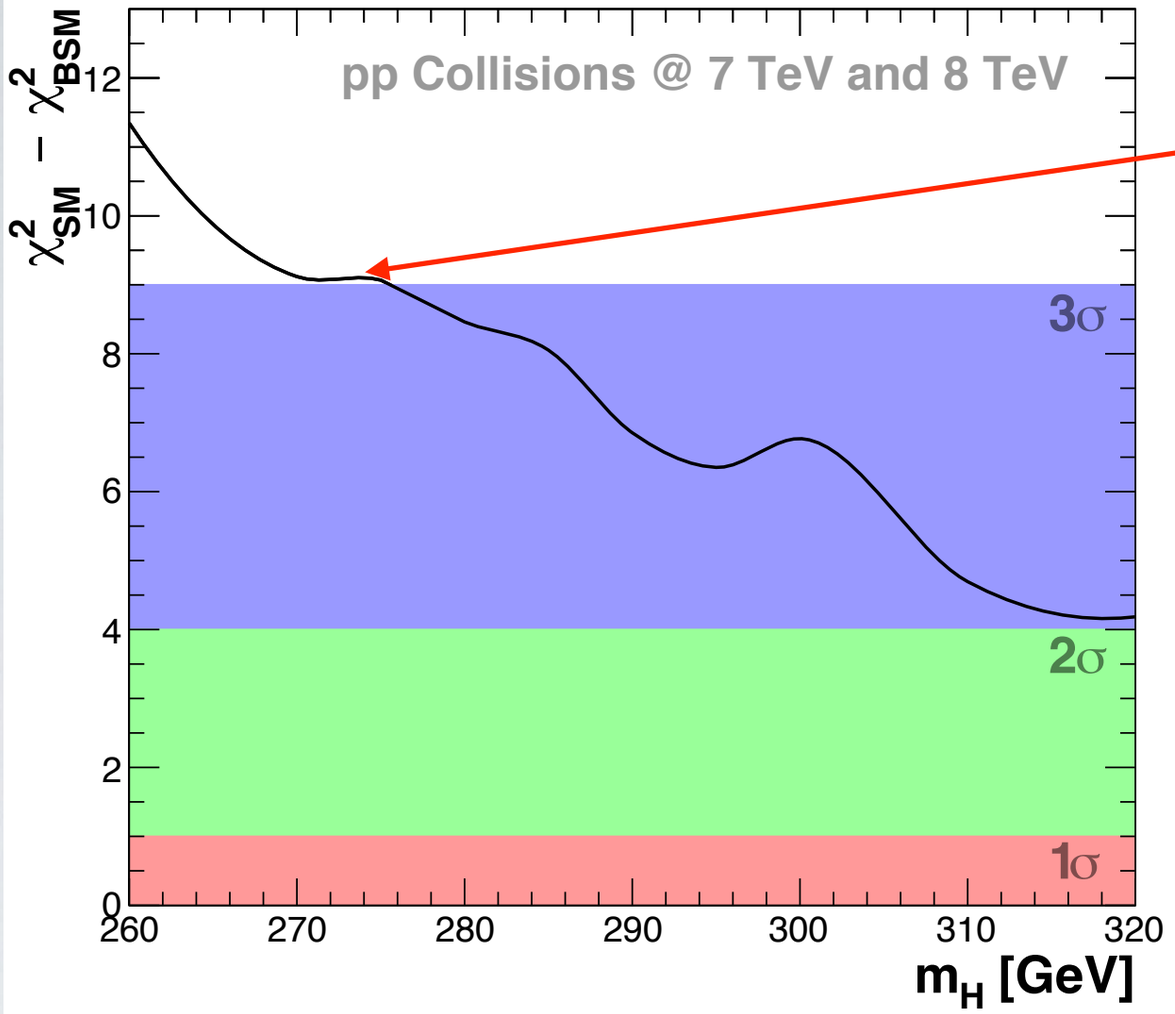
$$\mathcal{V}(\Phi_1,\Phi_2,S) = \mathcal{V}(\Phi_1,\Phi_2) + \frac{1}{2}m_{S_0}^2S^2 + \frac{\lambda_{S_1}}{2}\Phi_1^\dagger\Phi_1S^2 + \frac{\lambda_{S_2}}{2}\Phi_2^\dagger\Phi_2S^2$$
$$+ \frac{\lambda_{S_3}}{4}(\Phi_1^\dagger\Phi_2 + \text{h.c})S^2 + \frac{\lambda_{S_4}}{4!}S^4$$
$$+ \mu_1\Phi_1^\dagger\Phi_1S + \mu_2\Phi_2^\dagger\Phi_2S + \mu_3\left[\Phi_1^\dagger\Phi_2 + \text{h.c}\right]S + \mu_S S^3.$$




3. Proper Mass-diagonalisation and possible models.

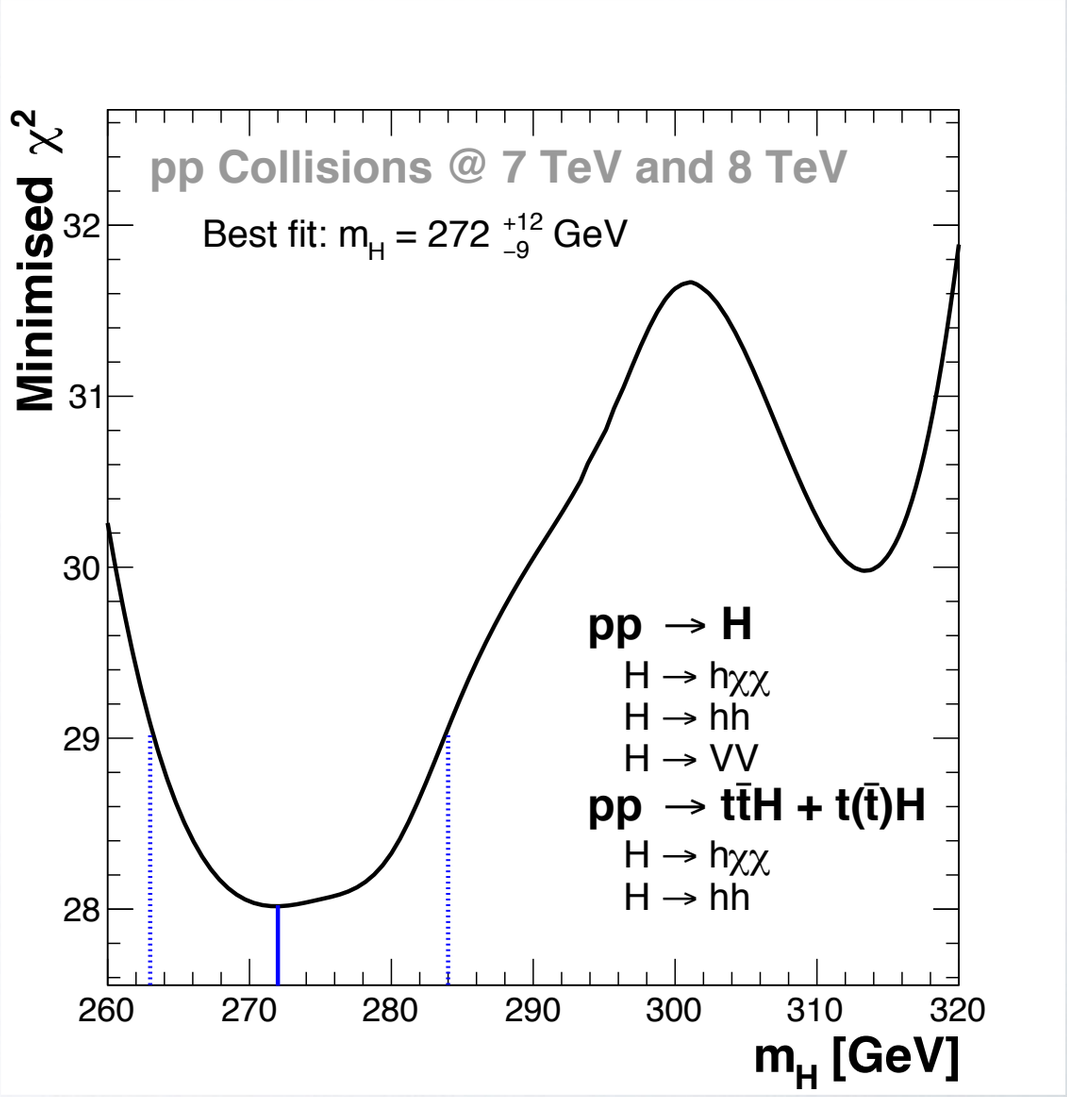
[ArXiv:1608.03466]

# In terms of significance

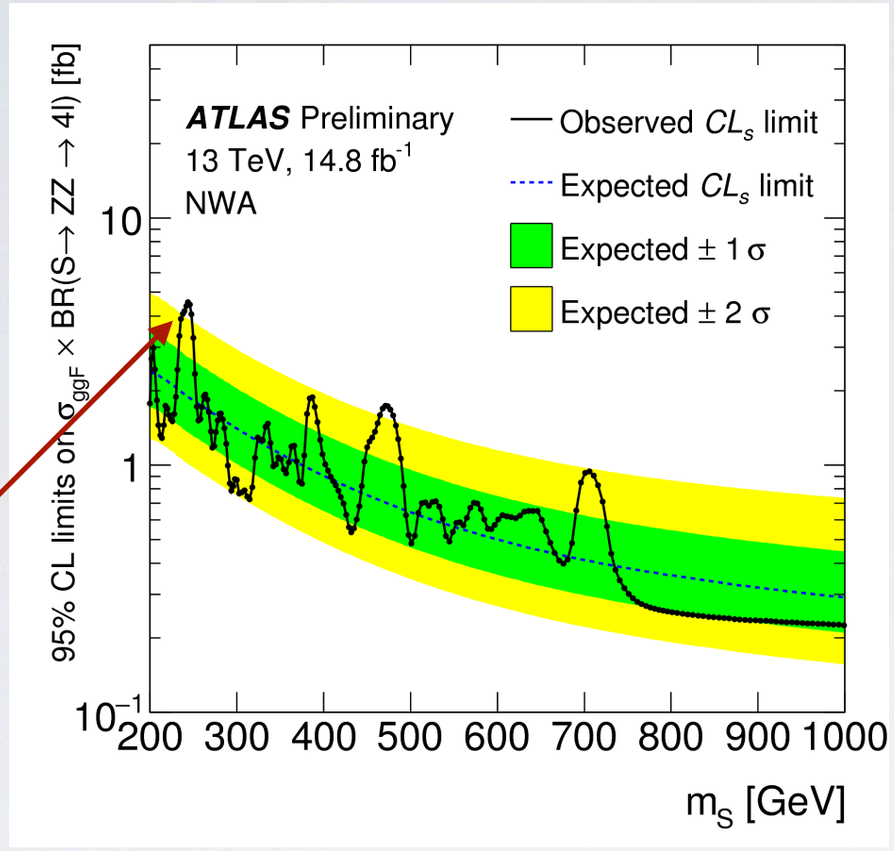



3σ

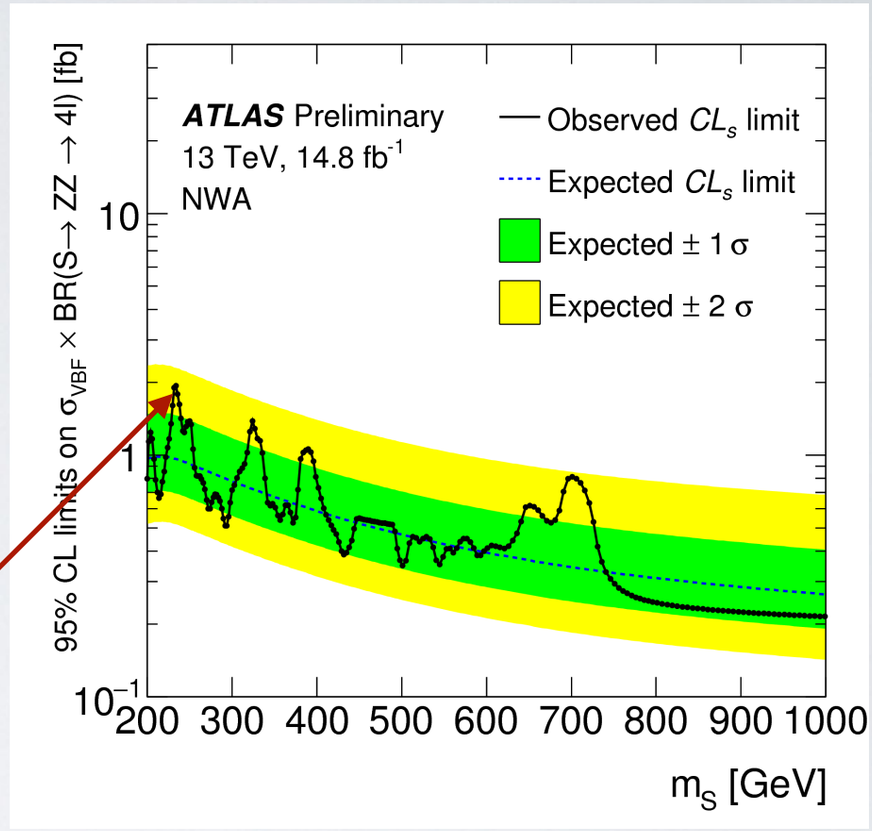
# Combining all of the results



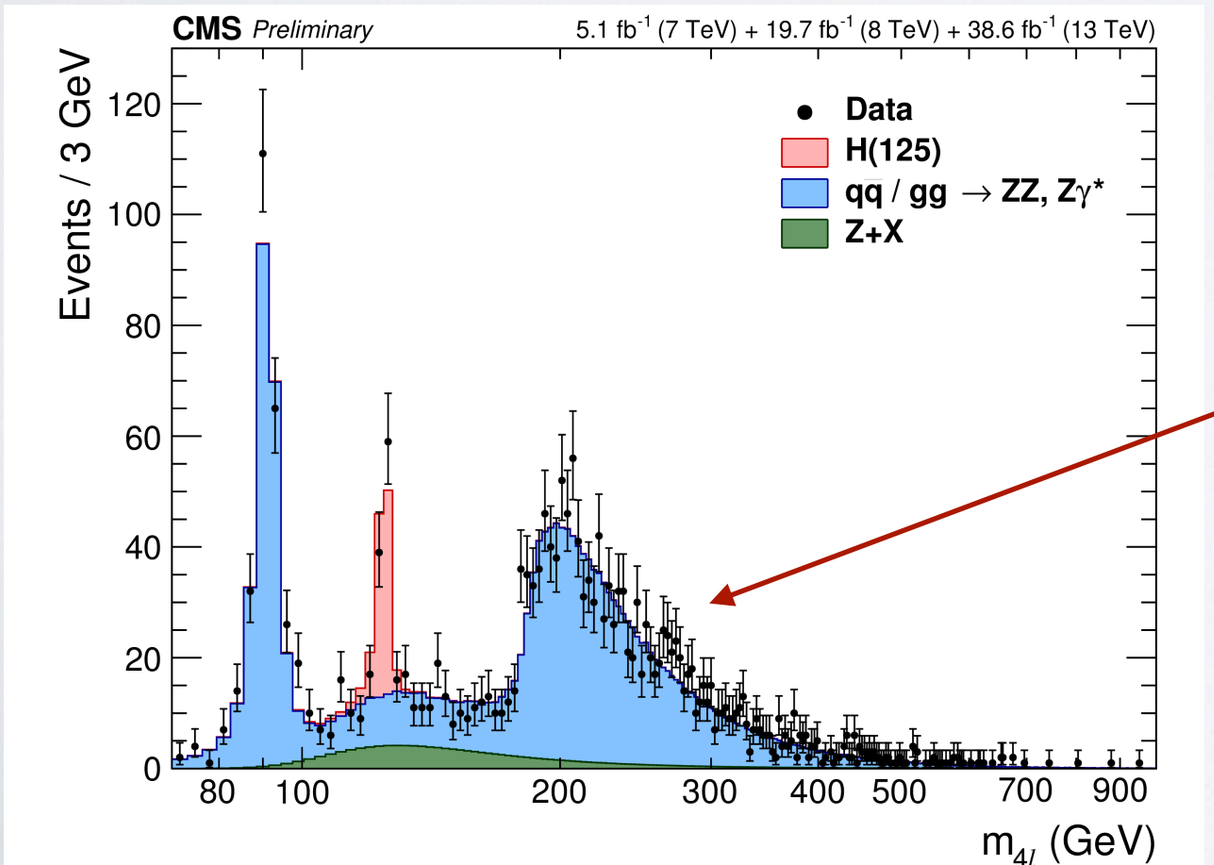
# Run-II



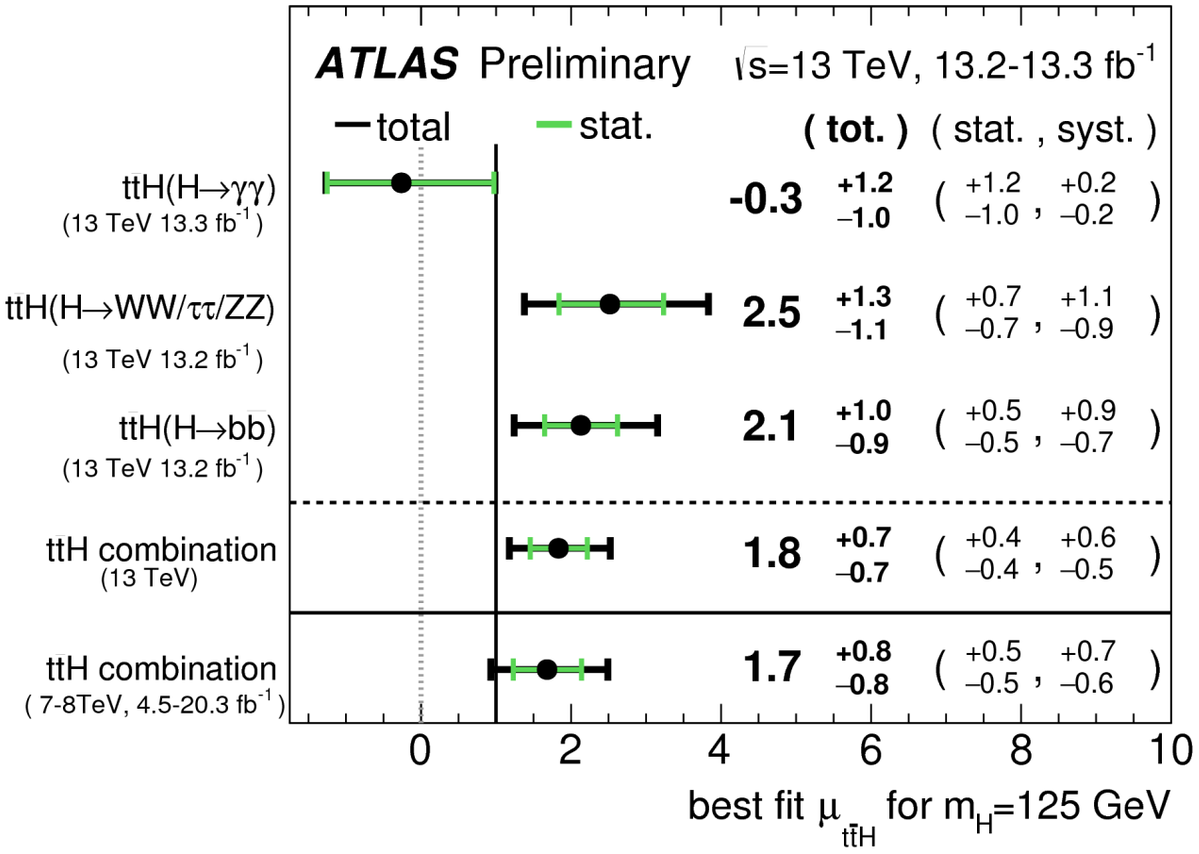

2σ




2σ




**Excess of ~20 events in the range 252-272 corresponding to 2.5σ**

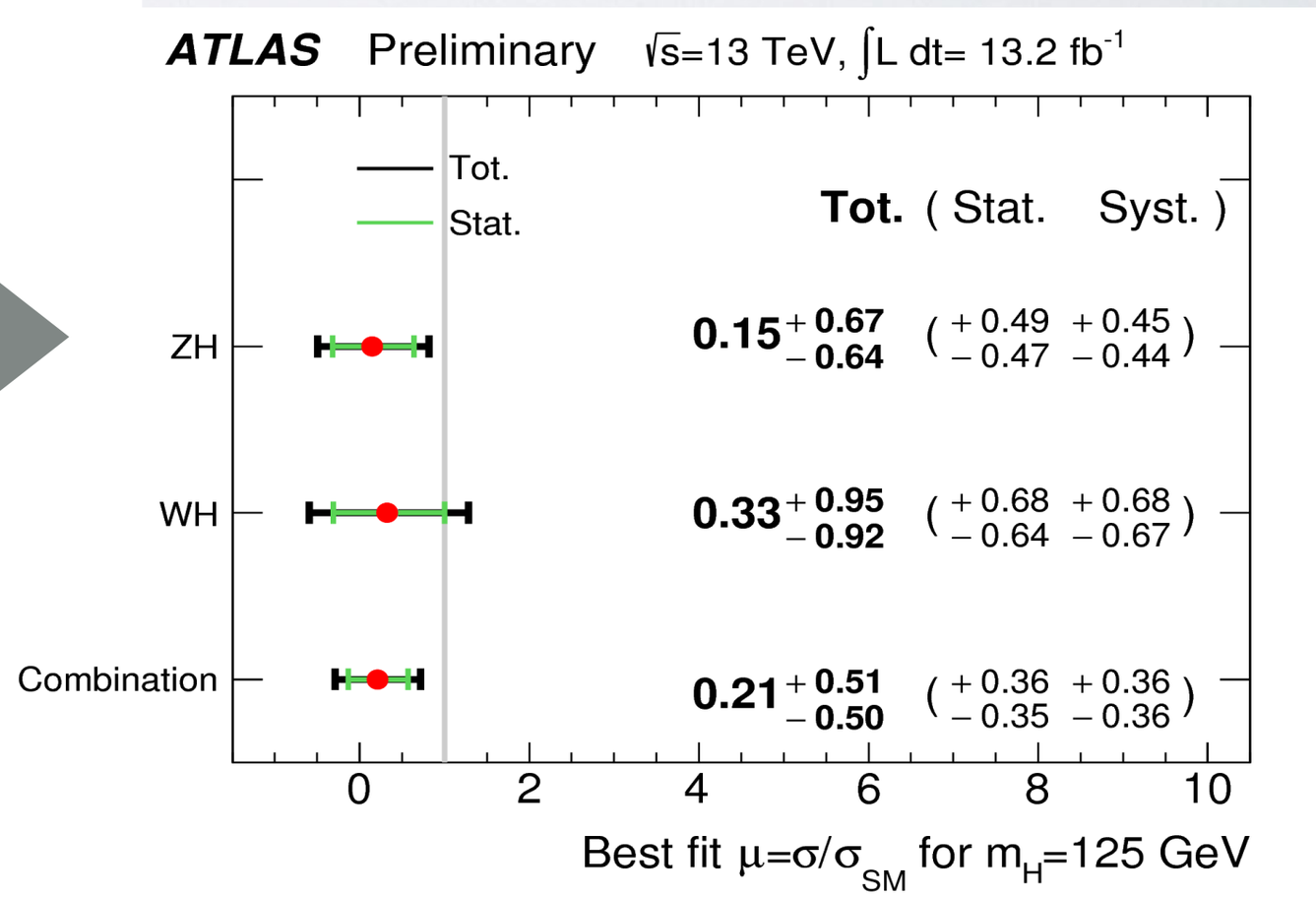



Signal strength in ttH

Signal strength in VH(bb~)

$$\mu = 0.57 \pm 0.26$$

More on Bruce's Talk



| Reference | Channel | Measured $\mu_{tth}$ |
|---|---|---|
| CMS Run 1 [35] | Same-sign $2\ell$ | $5.3^{+2.1}_{-1.8}$ |
| | $3\ell$ | $3.1^{+2.4}_{-2.0}$ |
| | $4\ell$ | $-4.7^{+5.0}_{-1.3}$ |
| | **Combination** | $2.8^{+1.0}_{-0.9}$ |
| ATLAS Run 1 [36] | $2\ell 0\tau_{\text{had}}$ | $2.8^{+2.1}_{-1.9}$ |
| | $3\ell$ | $2.8^{+2.2}_{-1.8}$ |
| | $2\ell 1\tau_{\text{had}}$ | $-0.9^{+3.1}_{-2.0}$ |
| | $4\ell$ | $1.8^{+6.9}_{-2.0}$ |
| | $1\ell 2\tau_{\text{had}}$ | $-9.6^{+9.6}_{-9.7}$ |
| | **Combination** | $2.1^{+1.4}_{-1.2}$ |
| CMS Run 2 [37] | Same-sign $2\ell$ | $1.7^{+0.6}_{-0.5}$ |
| | $3\ell$ | $1.0^{+0.8}_{-0.7}$ |
| | $4\ell$ | $0.9^{+2.3}_{-1.6}$ |
| | **Combination** | $1.5^{+0.5}_{-0.5}$ |
| ATLAS Run 2 [38] | $2\ell 0\tau_{\text{had}}$ | $4.0^{+2.1}_{-1.7}$ |
| | $3\ell$ | $0.5^{+1.7}_{-1.6}$ |
| | $2\ell 1\tau_{\text{had}}$ | $6.2^{+3.6}_{-2.7}$ |
| | $4\ell$ | $< 2.2$ |
| | **Combination** | $2.5^{+1.3}_{-1.1}$ |
| **Error weighted mean** | | $1.92 \pm 0.38$ |

Table with signal strength w.r.t the SM in the search for tth with multiple leptons

This table includes all data before Moriond QCD 2017
There CMS reported μ=1.5±0.5, resulting in:

$$\mu = 1.92 \pm 0.38$$

Very important to see results with the complete Run 2 data set.

Need insight into the kinematics of the leptons and jet activity of these events.

arXiv: 1706.02477

## Beyond Standard Model:

- Additional scalar/vector - bosons, fermions - heavy neutrinos, vector-like quarks, fourth generation quarks (t', b')

- Minimal extension : two Higgs doublet model adding one more Higgs doublet

- Left-right symmetric model : extending right-handed SU(2)_R symmetry ⟷ Amir's Talk

- Composite Higgs models …. etc.

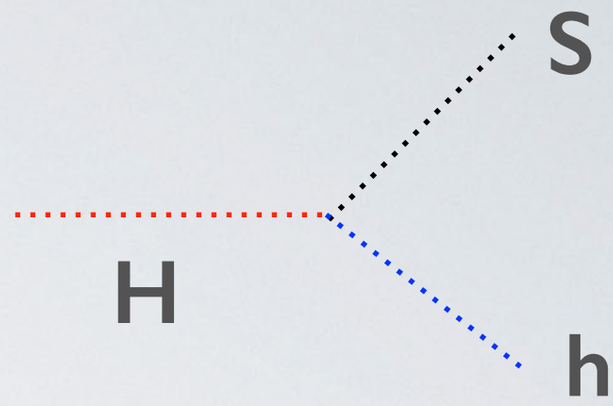
## Phenomenology:

- Probing the scalar sector and heavy neutrinos (possible DM candidate).

- Building appropriate model (start with Effective approach)

- Constraint the model parameters through all possible leptonic final states

## Effective Model for Higgs-like S (HLS):




$$\mathcal{L}_S = \mathcal{L}_{\rm K} + \mathcal{L}_{SVV'} + \mathcal{L}_{Sf\bar{f}} + \mathcal{L}_{hHS}$$

$$\mathcal{L}_{\rm K} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 SS$$

$$\begin{aligned}\mathcal{L}_{SVV'} = & \frac{1}{4}\kappa_{Sgg}\frac{\alpha_s}{12\pi v} S G^{a\mu\nu} G^a_{\mu\nu} + \frac{1}{4}\kappa_{S\gamma\gamma}\frac{\alpha}{\pi v} S F^{\mu\nu} F_{\mu\nu} \\ & + \frac{1}{4}\kappa_{SZZ}\frac{\alpha}{\pi v} S Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\kappa_{SZ\gamma}\frac{\alpha}{\pi v} S Z^{\mu\nu} F_{\mu\nu} \\ & + \frac{1}{4}\kappa_{SWW}\frac{2\alpha}{\pi s_w^2 v} S W^{+\mu\nu} W^-_{\mu\nu}\end{aligned}$$

$$\mathcal{L}_{Sf\bar{f}} = -\sum_f \kappa_{Sf}\frac{m_f}{v} S\bar{f}f$$

$$\begin{aligned}\mathcal{L}_{HhS} = & -\frac{1}{2}\, v\Big[\lambda_{hhS} hhS + \lambda_{hSS} hSS + \lambda_{HHS} HHS \\ & + \lambda_{HSS} HSS + \lambda_{HhS} HhS\Big]\end{aligned}$$

**Here,** $V, V' \equiv g, \gamma, Z, W^\pm \qquad D_\mu W^\pm_\nu = [\partial_\mu \pm ieA_\mu] W^\pm_\nu$

$$W^\pm_{\mu\nu} = D_\mu W^\pm_\nu - D_\nu W^\pm_\mu,$$

# Heavy Neutrino Model (SNN):

$$\nu_l = \sum_{m=1}^{3} U_{lm}\nu_m + \sum_{m'=1}^{n} V_{lm'}N^c_{m'}$$

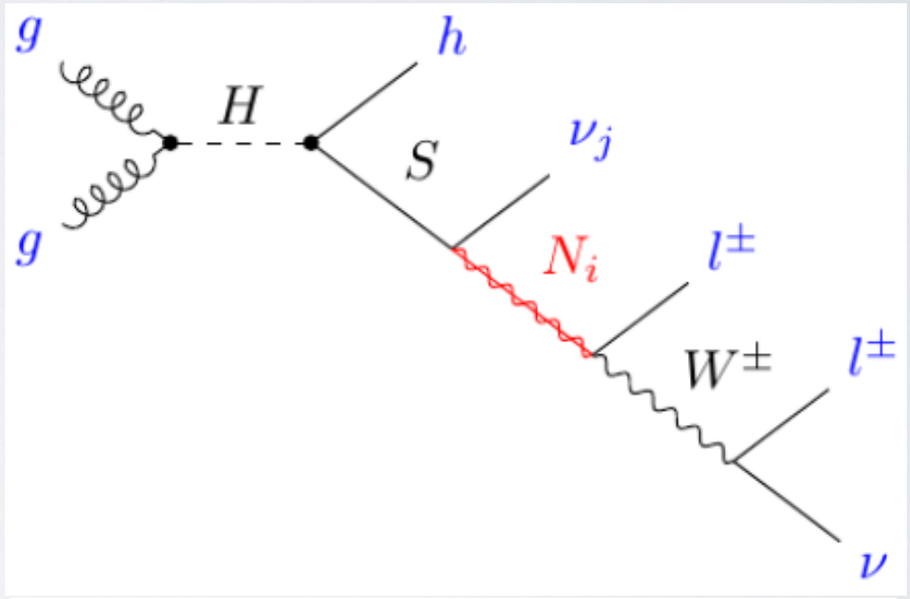

$$\mathcal{L}_{\rm Int} = -\frac{g}{\sqrt{2}}W^+_\mu \sum_{l=e}^{\tau}\sum_{m=1}^{3}\bar{\nu_m}U^*_{lm}\gamma^\mu P_L l^-$$

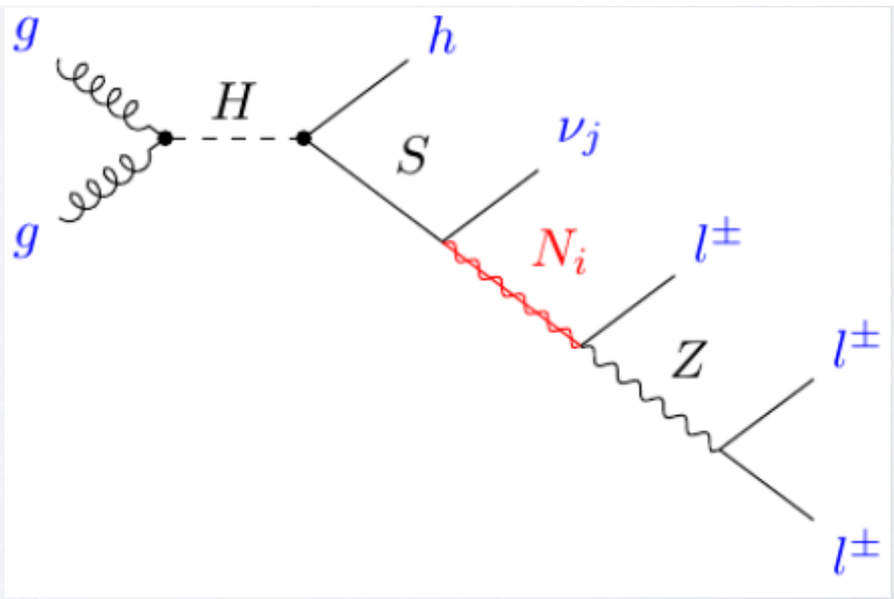
$$-\frac{g}{\sqrt{2}}W^+_\mu \sum_{l=e}^{\tau}\bar{N^c}V^*_{lN}\gamma^\mu P_L l^-$$

$$-\frac{g}{2\ \cos\theta_W}Z_\mu \sum_{l=e}^{\tau}\sum_{m=1}^{3}\bar{\nu_m}U^*_{lm}\gamma^\mu P_L \nu_l$$

$$-\frac{g}{2\ \cos\theta_W}Z_\mu \sum_{l=e}^{\tau}\bar{N^c}V^*_{lN}\gamma^\mu P_L \nu_l$$

$$-\frac{gm_N}{2M_W}S\sum_{l=e}^{\tau}\bar{N^c}V^*_{lN}\gamma^\mu P_L \nu_l + \text{H.c.}$$



## Model derived from Dim-6 operator (SWW):

$$\mathcal{L}^{(3)}_{SWW} = -g[\frac{g^{(1)}_{SWW}}{2m_W}W^{\mu\nu}W^{\dagger}_{\mu\nu}S + \frac{g^{(2)}_{SWW}}{m_W}(W^{\nu}\partial^{\mu}W^{\dagger}_{\mu\nu}S + \mathrm{h.c}) + \frac{\tilde{g}_{SWW}}{2m_W}W^{\mu\nu}\widetilde{W}^{\dagger}_{\mu\nu}S]$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(3)}_{SWW}$$

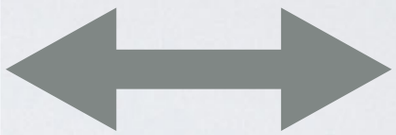
$$\Gamma_{SW^-W^+} = gm_W[\{1 + \frac{g^{(1)}_{SWW}}{m^2_W}p_2\cdot p_3 + \frac{g^{(2)}_{SWW}}{m^2_W}(p^2_2 + p^2_3)\}\eta^{\mu_2\mu_3} - \frac{g^{(1)}_{SWW}}{m^2_W}p^{\mu_3}_2 p^{\mu_2}_3 - \frac{g^{(2)}_{SWW}}{m^2_W}(p^{\mu_2}_2 p^{\mu_3}_2 + p^{\mu_2}_3 p^{\mu_3}_3) - i\frac{\tilde{g}_{SWW}}{m^2_W}\epsilon_{\mu_2\mu_3\mu\nu}p^{\mu}_2 p^{\nu}_3]$$

## Multi - Lepton searches:

$H \to Sh,$

$S \to W^+W^-, ZZ, ..$

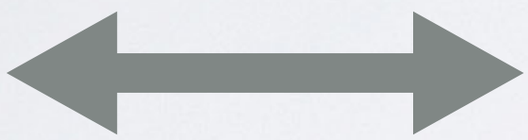
$S \to N\nu, N \to W^{\pm}(Z)l^{\mp}$



Abduala's talk

$t\bar{t}H$

$t(\bar{t})H$



Stefan's talk

$S \to W^+W^- \to 4l$

**using higher dimension effective vertices for CP-studies**

# Impact of extended tensor structure of SWW is small