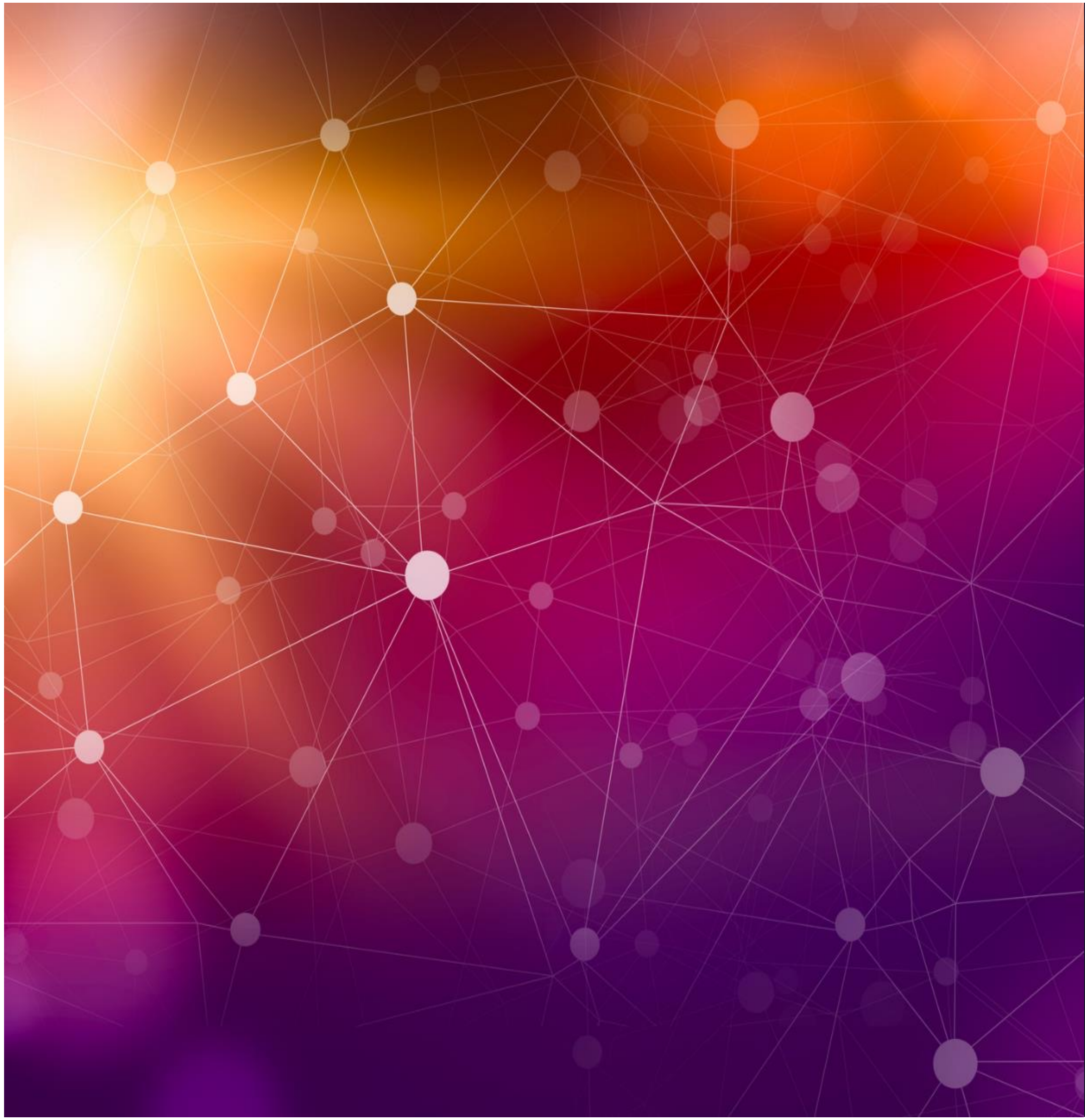

An alternative explanation of the Multi-lepton anomalies at the LHC

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Outline

- ❑ Multi-lepton anomalies at the LHC
  - Di-lepton invariant mass distributions
  - Anatomy of the multi-lepton anomalies
- ❑ Singlet scalar at 151.5 GeV
  - Procedure
  - Candidate of singlet scalar at 151.5 GeV
- ❑ Di-lepton+MET
- ❑ Introduction to the HTM0 Model
  - Lagrangian and Higgs masses
  - Processes
  - Branching ratios and cross-sections
- ❑ Conclusion

Multi-lepton anomalies at the LHC

References:

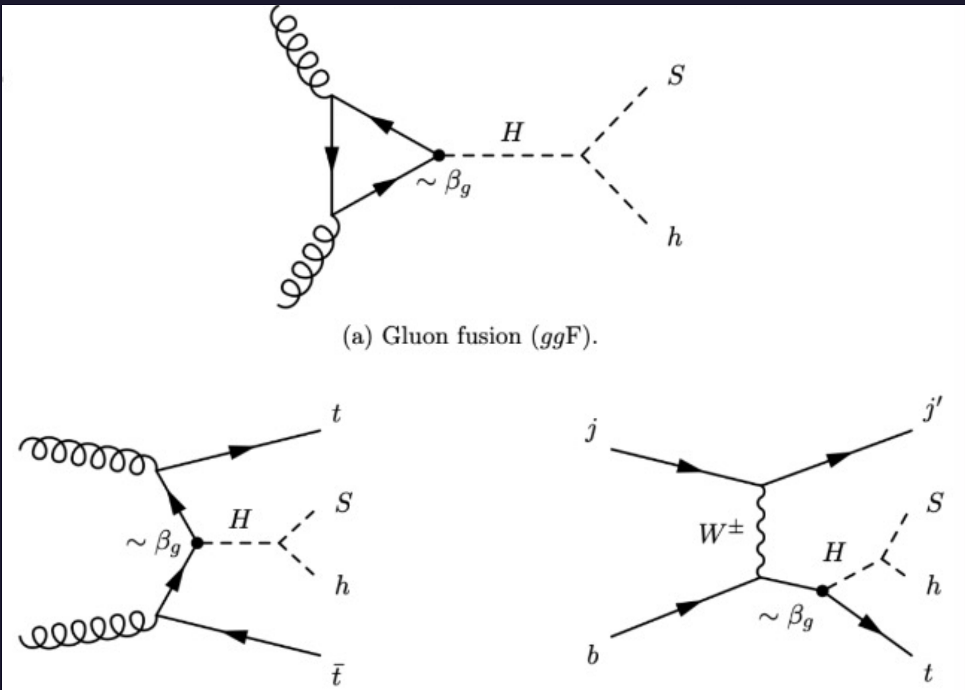
- Eur. Phys. J. C (2016) 76:580
- J.Phys.G45(2018)11,115003
- JHEP10(2019)157
- Eur. Phys. J. C 80 (2020) 528
- Chin.Phys.C44(2020)6,06310
- Physics Letters B 811 (2020) 135964
- Eur.Phys.J.C81(2021)365

Multi-lepton anomalies at the LHC

- The starting point is a boson H, m_H~250GeV-280GeV decaying to two scalars S
- We used a 2HDM+S as a simplified model for this

2HDM+S potential

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



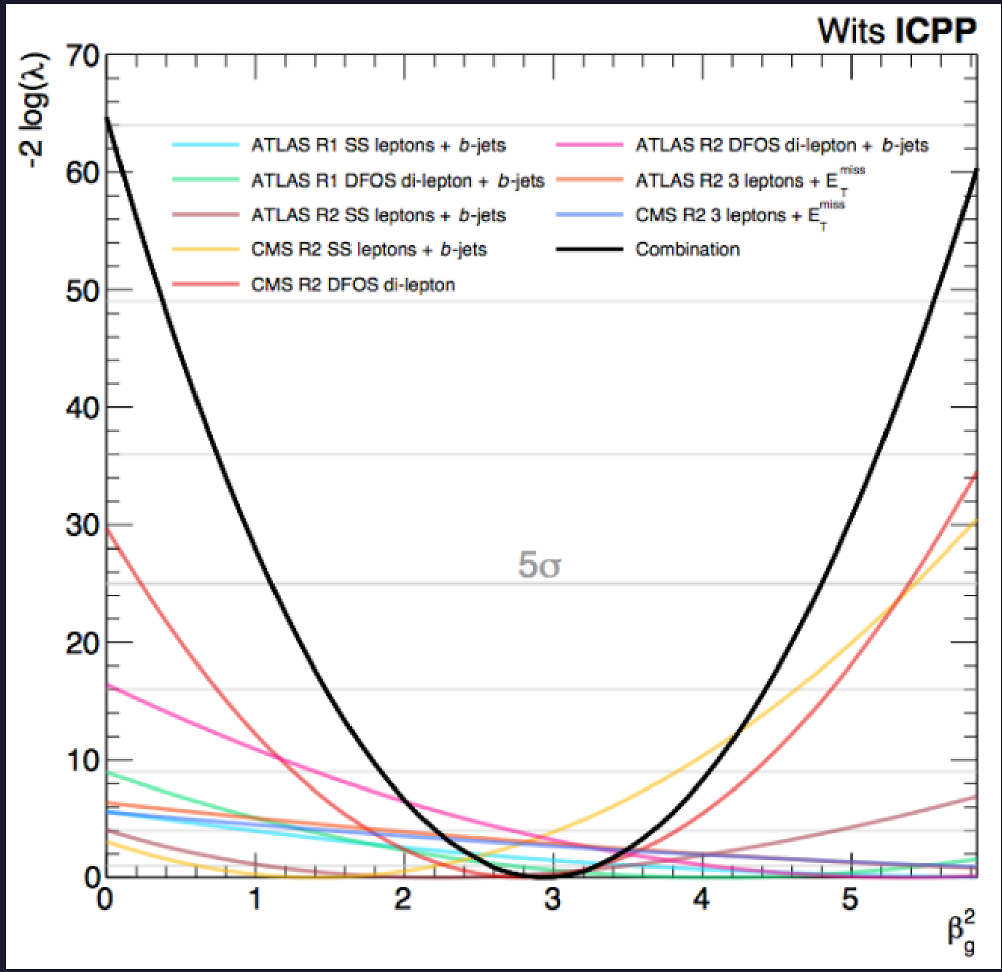
(a) Gluon fusion (ggF).

$$
\mathcal{L}_{\text{int}}\supset-\beta_g\frac{m_t}{v}t\bar{t}H+\beta_V\frac{m_V^2}{v}g_{\mu\nu}\,V^\mu V^\nu H
$$

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

Multi-lepton anomalies at the LHC

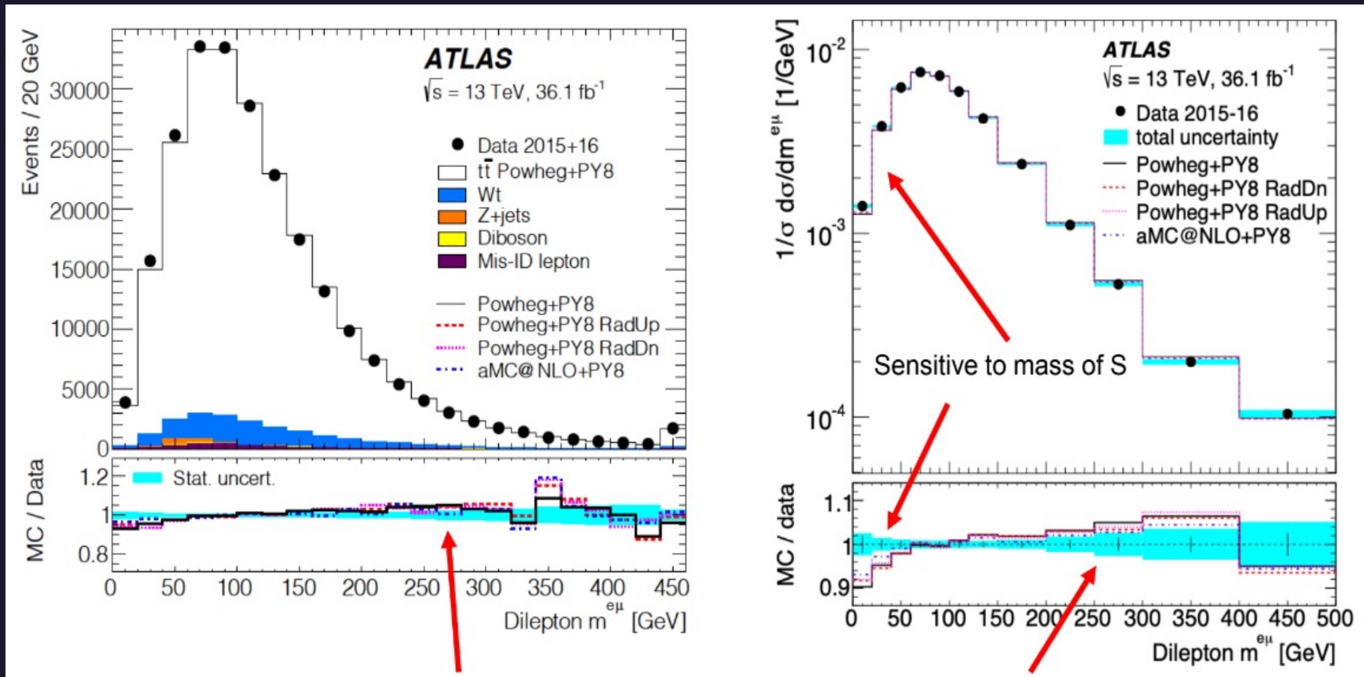
- The multi-lepton anomalies are explained by the production of $H \rightarrow SS$ where H and S are new scalar bosons.
- Data consistent with new bosons: one with a mass around $m_H = 270$ GeV and another around $m_S = 150$ GeV GeV.
- The combined results correspond to a 8.04σ significance.



JHEP10(2019)157

Di-lepton invariant mass distributions

- The di-lepton invariant mass is sensitive to the mass of S. We see that excesses at low di-lepton invariant masses remain prevalent which indicate that effects seen in Run 1 were not statistical fluctuations.
- Using $S \rightarrow WW$, it was predicted in 2017 that the mass of S, through the production mechanism $S \rightarrow WW \rightarrow ll$ is $m_S = 150 \pm 5$ GeV (refer to *J.Phys.G* 45 (2018) 11, 115003)



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Residual discrepancies at high m_{ll} will be fixed with missing NLO QCD and NLO EW corrections.

Anatomy of the multi-lepton anomalies

Final state	Characteristic	Dominant SM process	Significance
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt	>5σ
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW	~3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t	>3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh, (WWW)	4.2σ
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

Anomalies cannot be explained by mismodelling of a particular process, e.g. $t\tilde{t}$ production.

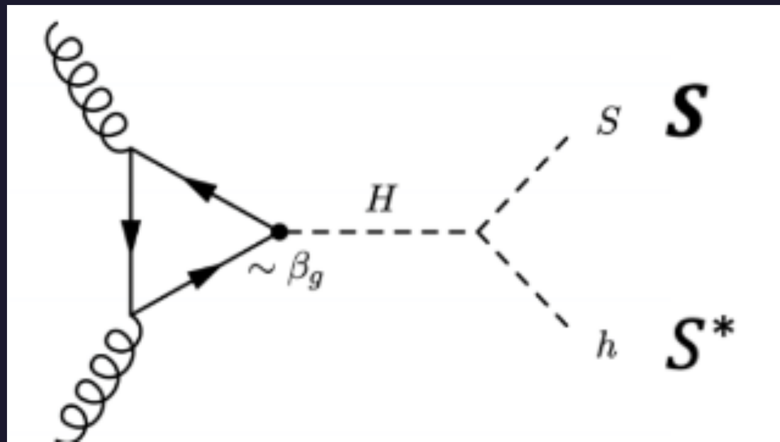
Singlet Scalar at 151.5 GeV

References:

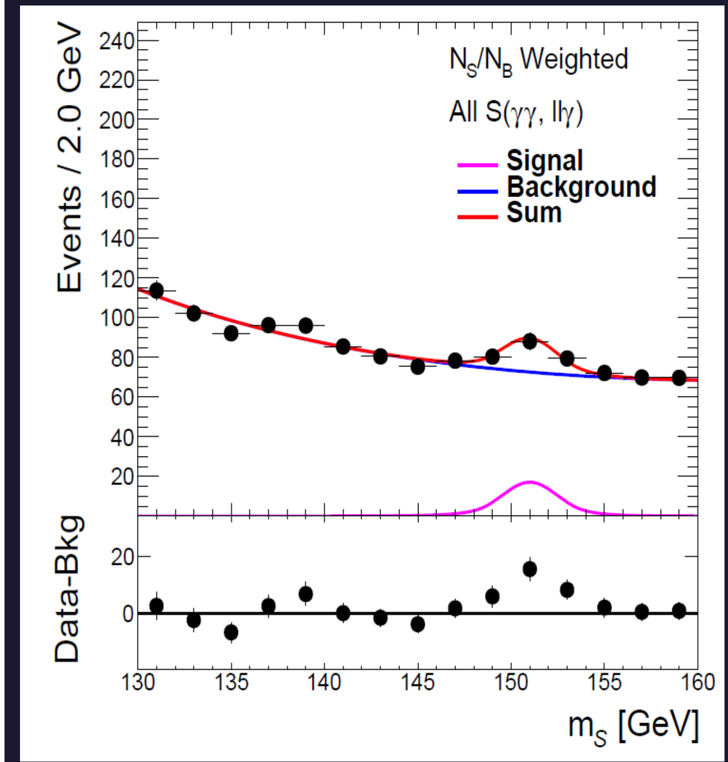
- ➢ arXiv:2109.02650
- ➢ JHEP10(2019)157

Procedure

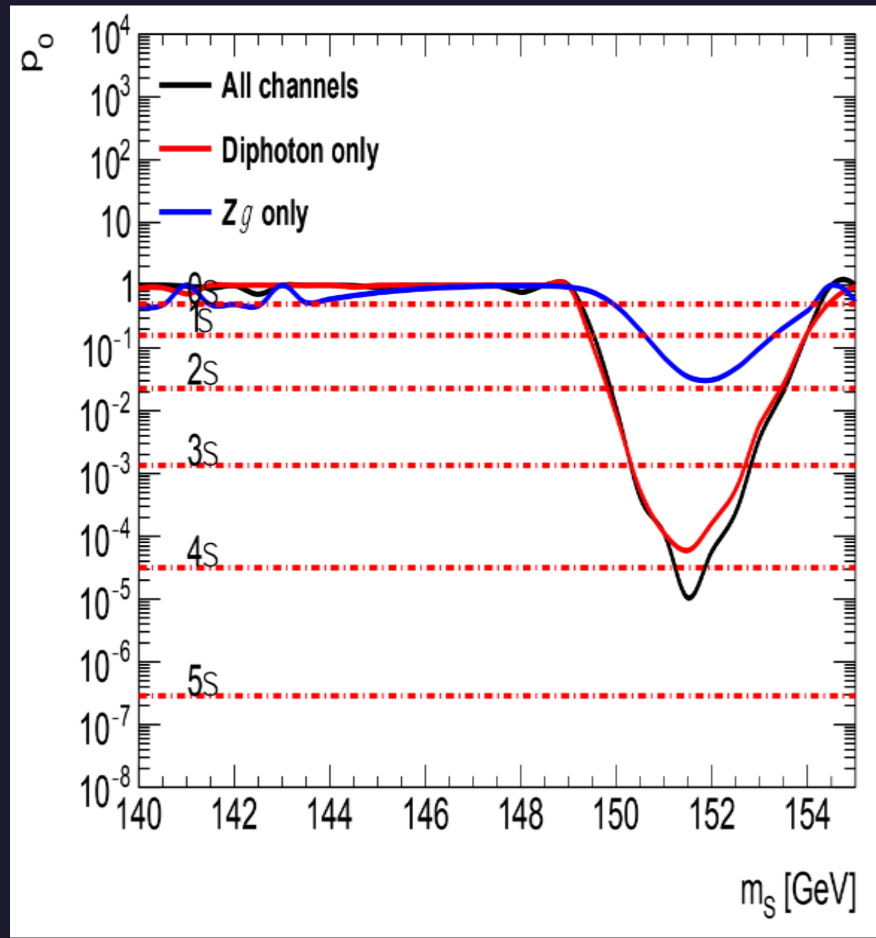
- ❑ Setting a well-defined procedure is essential to the integrity of a search. Performing a scan nullifies significance.
- ❑ From the di-lepton anomalies: $m_h < m_S < 170$ GeV.
- ❑ We focus on $\gamma\gamma$ and $Z\gamma$ decay channels.
- ❑ As per the model that described the multi-lepton anomalies, we select final state according to di-boson signatures. S is produced via the decay of something heavier and not directly. In this setup:
  - Re-use side bands of SM Higgs analysis
  - Remove VBF and boosted topologies that are related to direct production.
- ❑ From Run 1, multi-lepton excesses model-dependent predictions of $m_S = 150 \pm 5$ GeV.



Candidate of a singlet Scalar



- New boson with a mass of 150 GeV
- Use $\gamma\gamma$ and $Z\gamma$ spectra in associated production that showed an excess at $m_S = 151$ GeV
- The result is obtained with public results from the LHC experiments.
- Using a simplified model and two degrees of freedom and residual LEE, the global significance drops to 3.9σ at 151.5 GeV.



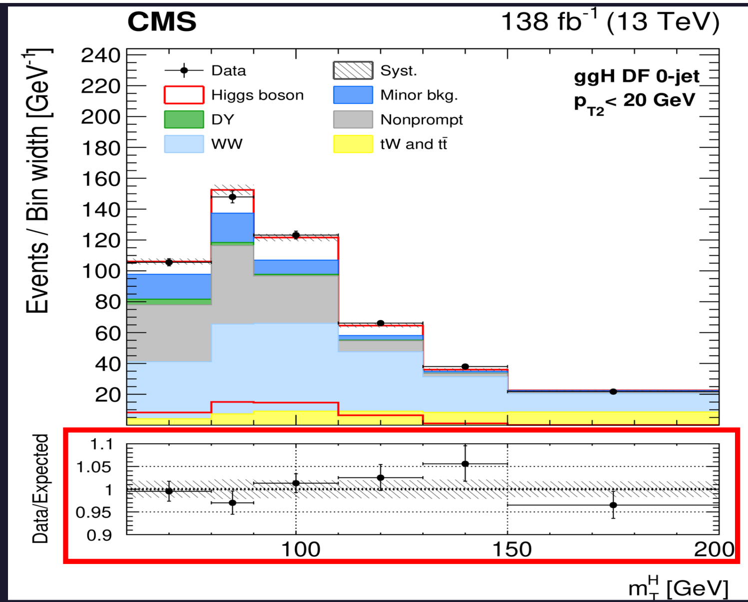
Di-lepton+MET

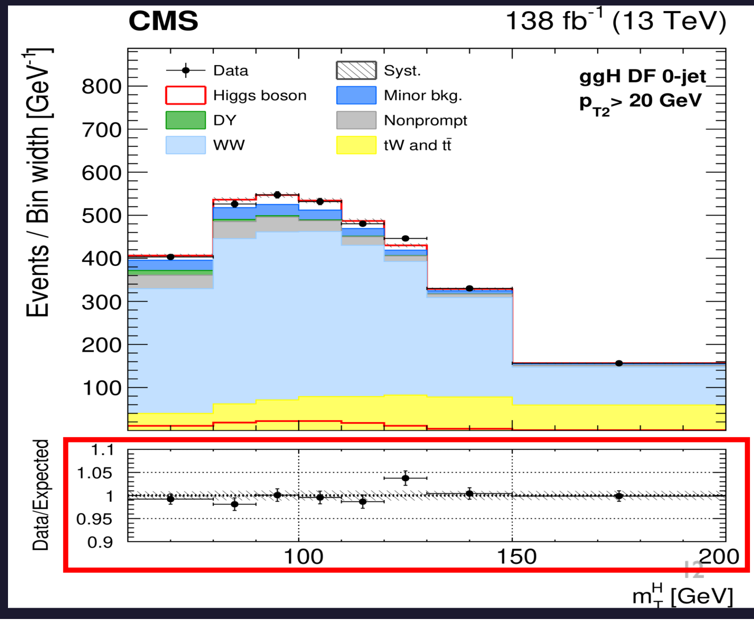
References:

➢ arXiv:2206.09466

Di-lepton+MET

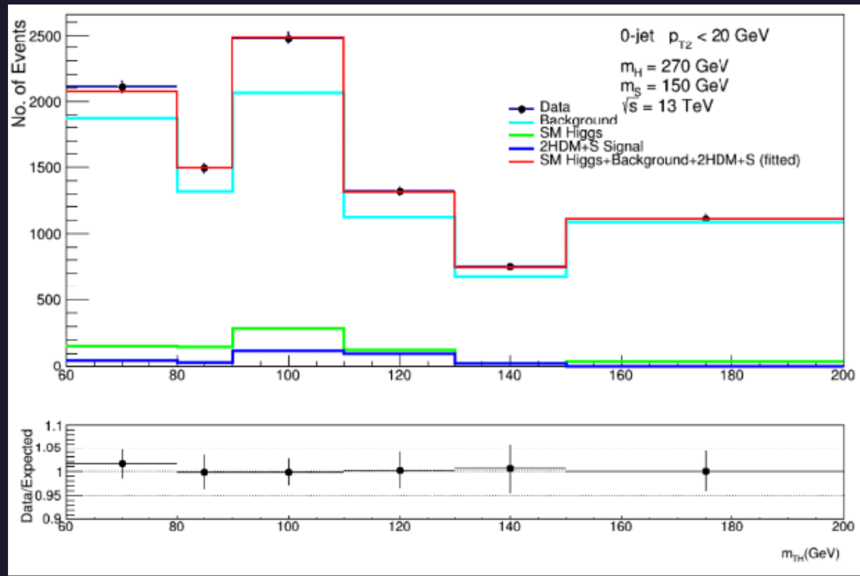
- CMS recently released an analysis in the W boson pair decay channel in pp collisions.
- The results showed an excess at 150 GeV for the $h \rightarrow WW \rightarrow ll + MET$ category.
- Using the 2HDM+S model, an analysis was done where $H \rightarrow SS^*$, with $S \rightarrow WW \rightarrow ll + MET$. In this model, S does not couple to SM particle the way a higgs-like particle does.
- In this simplified model, the mass of S is fixed at $m_S = 151$ GeV.

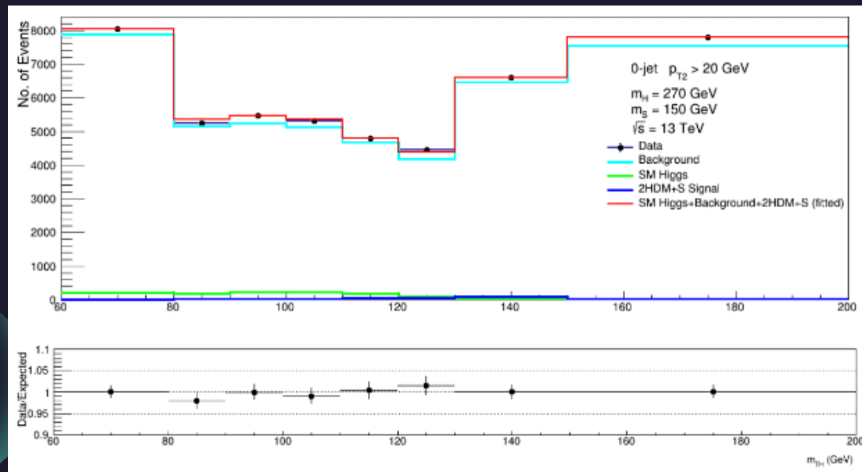




Di-lepton+MET

- A global significance of ~2.7σ (preliminary) has been achieved. The extracted BSM signal strength is consistent with the simplified model described above within statistical errors
- The analysis of ATLAS data is ongoing.
- Results point at somewhat higher jet-veto survival probability compared to the simplified model. This will be taken into account when performing combination with $\gamma\gamma, Z\gamma$ results described above.
- However, it predicts $S \rightarrow ZZ$ which is not observed.
- Therefore, we look at a triplet model where H^0 can only decay to WW and not ZZ.





Introduction to the Higgs Triplet Model

References:

- arXiv:2001.05335v2
- arXiv:1811.03476v1
- Eur. Phys. J. C (2018) 78:873
- DOI:10.1103/PhysRevD.105.112007

Introduction to the Higgs Triplet Model

- The Higgs Triplet Model is an extension of the Standard Model (SM), by an SU(2) Higgs Triplet
- It contains a neutral CP and two charged Higgs bosons $H^{\pm}$.
- The neutral component cannot decay to the ZZ.
- Therefore, we obtain a scalar that decays to WW but not ZZ at tree-level, solving the problem of the 2HDMS

Lagrangian and Higgs masses

- Δ is a $SU(2)_L$ triplet with hypercharge $Y_\Delta = 0$.
- The most general gauge invariant and renormalizable $SU(2)_L \times U(1)_Y$ Lagrangian of the scalar sector is given by

$$\mathcal{L} = \left(D_\mu H\right)^\dagger (D^\mu H) + Tr\left(D_\mu \Delta\right)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{\text{Yukawa}}$$

where

- The covariant derivatives are defined as

$$D_\mu H = \partial_\mu H + igT^\alpha W_\mu^\alpha H + i\frac{g'}{2} B_\mu H$$
$$D_\mu \Delta = \partial_\mu \Delta + ig\left[T^\alpha W_\mu^\alpha, \Delta\right]$$

- The potential $V(H,\Delta)$ can be expressed as

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}\left(H^\dagger H\right)^2 - M_\Delta^2 Tr\left(\Delta^\dagger \Delta\right) + \mu H^\dagger \Delta H$$
$$+\lambda_1 \left(H^\dagger H\right) Tr\left(\Delta^\dagger \Delta\right) + \lambda_2 \left(Tr\Delta^\dagger \Delta\right)^2 + \lambda_3 Tr\left(\Delta^\dagger \Delta\right)^2 + \lambda_4 H^\dagger \Delta^\dagger \Delta H$$

Processes

- ❑ Process 1:

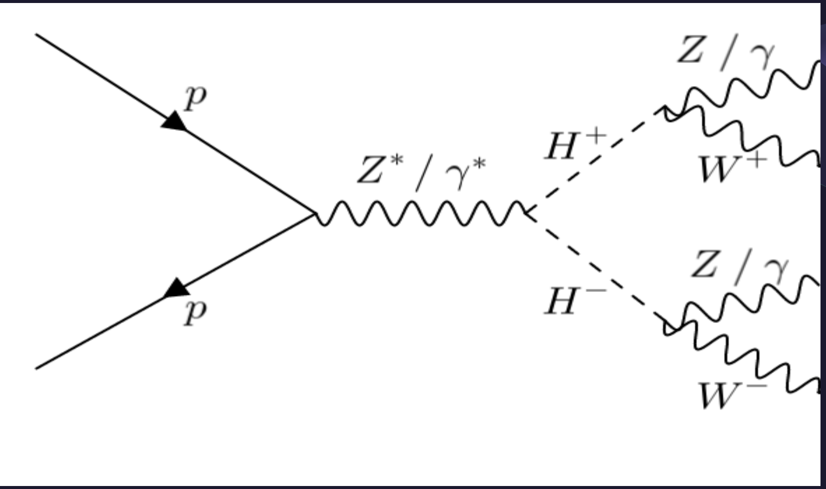
i. $pp \to H^+H^- \, /Z \, j, (hpm \to W\gamma)$

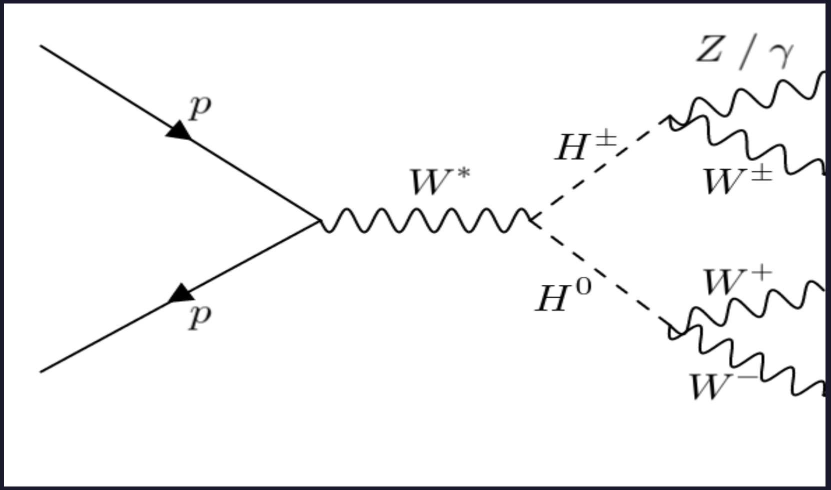
ii. $pp \to H^+H^- \, /\gamma \, j, (hpm \to WZ)$

- ❑ Process 2:

i. $pp \to H^-H^0 \, , (H^- \to WZ, W\gamma, H^0W), (H^0 \to WW)$

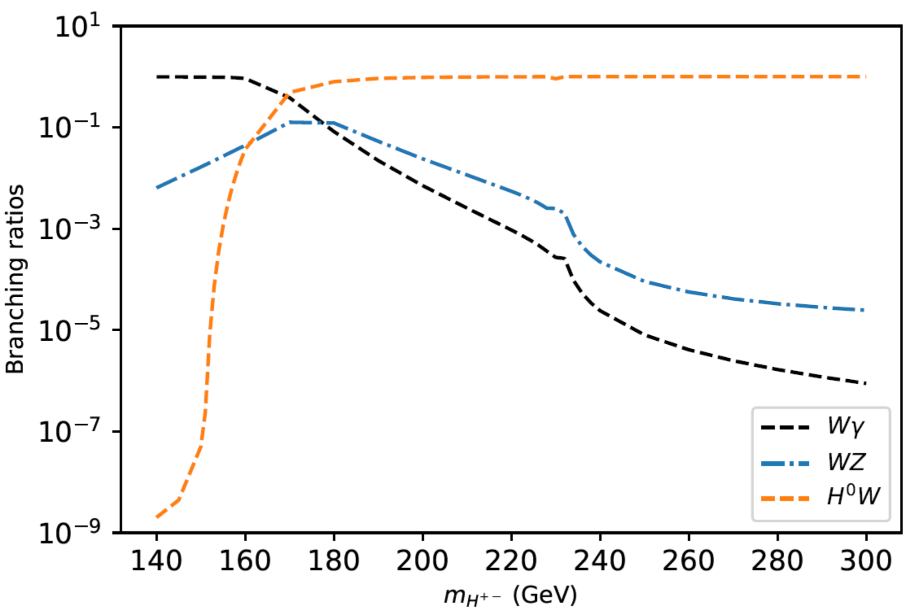
ii. $pp \to H^+H^0 \, , (H^+ \to WZ, W\gamma, H^0W \,), (H^0 \to WW)$

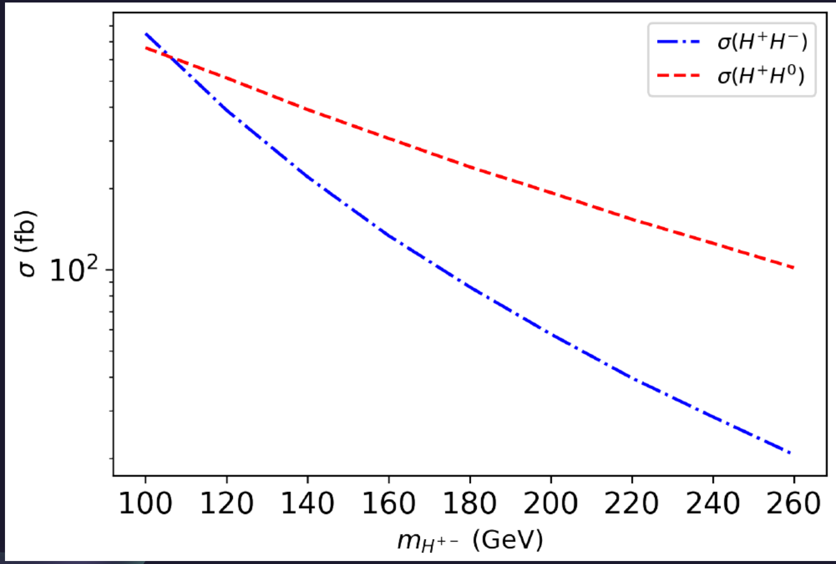




Branching ratio and cross-sections

- Branching ratio for the $H^+ \rightarrow W\gamma, WZ$ and H^0W decay channels.
- $m_{H^0} = 150$ GeV.





- The cross-sections for $pp \rightarrow H^+H^-$ and $pp \rightarrow H^{\pm}H^0$ decay channels.

Conclusions

- The deviations in the multi-lepton final states at the LHC with respect to Monte Carlo simulations are not statistical fluctuations.
- The features of Higgs data from the LHC agree with predictions made from the BSM models used.
- Excesses appear in $ll + MET$ Higgs Transverse mass spectrums. However, the BSM used here does not explain $S \rightarrow ZZ$ directly.
- This motivates us to use a Triplet model where we obtain a scalar that couples to WW but not ZZ at tree-level.

Thank you!

Additional slides

Lagrangian and Higgs masses

- The $\mathcal{L}_{Yukawa}$ contains all the Yukawa sector of the SM plus an extra Yukawa term that leads after spontaneous symmetry breaking to (Majorana) mass terms for the neutrinos, without requiring right-handed neutrino states.
- The two Higgs multiplets are written as

$$\Delta = \frac{1}{2}\begin{pmatrix} \delta^0 & \sqrt{2}\,\delta^+ \\ \sqrt{2}\,\delta^- & -\delta^0 \end{pmatrix}, \qquad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad (5)$$

- In this setup, we define the electric charge as $Q = I_3 + \frac{Y}{2}$, where I denotes the isospin.
- Assuming that spontaneous electroweak symmetry breaking (EWSB) is taking place at some electrically neutral point in the field space and denoting the corresponding vacuum expectation values (VEVs) by

$$\langle\Delta\rangle = \frac{1}{2}\begin{pmatrix} v_t & 0 \\ 0 & -v_t \end{pmatrix}, \qquad \langle H\rangle = \begin{pmatrix} 0 \\ v_d/\sqrt{2} \end{pmatrix}$$

Lagrangian and Higgs masses

- We see that after the minimisation of the potential, we require the following conditions:

$$M_\Delta^2 = \frac{\lambda_a}{2} v_d^2 - \frac{\mu v_d^2}{4 v_t} + \lambda_b v_t^2 \tag{6}$$

$$m_H^2 = \frac{\lambda}{4} v_d^2 - \frac{\mu v_t}{2} + \frac{\lambda_a}{2} v_t^2 \tag{7}$$

- These two conditions are used to construct the squared matrices $\mathcal{M}_\pm^2$ and $\mathcal{M}_{CP_{even}}^2$. The mass-matrix for a singly charged field is

$$\mathcal{M}_\pm^2 = \mu \begin{pmatrix} v_t & v_d/2 \\ v_d/2 & v_d^2/4v_t \end{pmatrix}$$

- Among the two eigenvalues of $\mathcal{M}_\pm^2$, one is equal to zero, identifying the Goldstone boson $G^\pm$, while the other one corresponds to the mass of a singly charged Higgs bosons $H^\pm$ given by

$$m_{H^\pm}^2 = \frac{(v_d^2 + 4 v_t^2)}{4 v_t} \mu \tag{8}$$

Lagrangian and Higgs masses

- The neutral scalar's mass-matrix reads:

$$\mathcal{M}^2_{CP_{even}} = \begin{pmatrix} A & B \\ B & C \end{pmatrix}$$

where

$$A = \frac{\lambda}{2} v_d^2, \qquad B = \frac{v_d[-\mu + 2\lambda_a v_t]}{2\sqrt{2}}, \qquad C = \frac{\mu v_d^2 + 8\lambda_b v_t^3}{8 v_t} \qquad (9)$$

- We can diagonalise $\mathcal{M}^2_{CP_{even}}$ by a rotation matrix R_α where α is the rotation angle in the CP-even sector. After diagonalising $\mathcal{M}^2_{CP_{even}}$, we get two massive even-parity physical states h^0 and H^0 that are defined by,

$$h^0 = +c_\alpha h_1 + s_\alpha h_2 \qquad (10)$$
$$H^0 = -s_\alpha h_1 + c_\alpha h_2 \qquad (11)$$

so that $m_{H^0} > m_{h^0}$.

- Once the eigenmasses for the CP-even are known, we can determine the rotation angle α which controls the field content of the physical states. Therefore, we have

$$C = s_\alpha^2 m_{h^0}^2 + c_\alpha^2 m_{H^0}^2 \qquad (12)$$
$$B = \frac{sin2\alpha}{2}\left(m_{h^0}^2 - m_{H^0}^2\right) \qquad (13)$$
$$A = c_\alpha^2 m_{h^0}^2 + s_\alpha^2 m_{H^0}^2 \qquad (14)$$

- The signs of s_α and c_α are not definite.

Lagrangian and Higgs masses

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