Explaining a class of multi-lepton excesses at the LHC with a heavy pseudo-scalar of a 2HDM+S model

Abhaya Kumar Swain

University of the Witwatersrand, Johannesburg, South Africa

Thuso Mathaha, Mukesh Kumar, Bruce Mellado , Xifeng Ruan, AKS, On-going work.

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Multi-lepton Excesses at the LHC:

Expt. multi-lepton searches:-

Data set	Reference	Selection
ATLAS Run 1	ATLAS-EXOT-2013-16 [41]	SS $\ell\ell$ and $\ell\ell\ell$ + b-jets
ATLAS Run 1	ATLAS-TOPQ-2015-02 [26]	OS $e\mu$ + b-jets
CMS Run 2	CMS-PAS-HIG-17-005 [42]	SS $e\mu$, $\mu\mu$ and $\ell\ell\ell$ + b-jets
CMS Run 2	CMS-TOP-17-018 [43]	OS $e\mu$
CMS Run 2	CMS-PAS-SMP-18-002 [44]	$\ell\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ (WZ)
ATLAS Run 2	ATLAS-EXOT-2016-16 [45]	SS $\ell\ell$ and $\ell\ell\ell$ + b-jets
ATLAS Run 2	ATLAS-CONF-2018-027 [46]	OS $e\mu$ + b-jets
ATLAS Run 2	ATLAS-CONF-2018-034 [47]	$\ell\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ (WZ)

A simplified model is considered where the SM is extended with additional scalars, H and S with mass mH = 270 GeV and mS = 150 GeV.

Studies that Explains the multi-lepton excesses:-

Papers by Bruce Mellado, Mukesh Kumar, Xifeng Ruan, Thuso Mathaha et. al.

1. Eur. Phys. J. C (2016) 76:580
2. J.Phys.G 45 (2018) 11, 115003
3. J.Phys. G46 (2019) no.11, 115001
4. JHEP 1910 (2019) 157
5. Chin.Phys.C 44 (2020) 6, 063103
6. Physics Letters B 811 (2020) 135964
7. Eur.Phys.J.C 81 (2021) 365
8. arXiv: 2109.06951, SAIP2021.

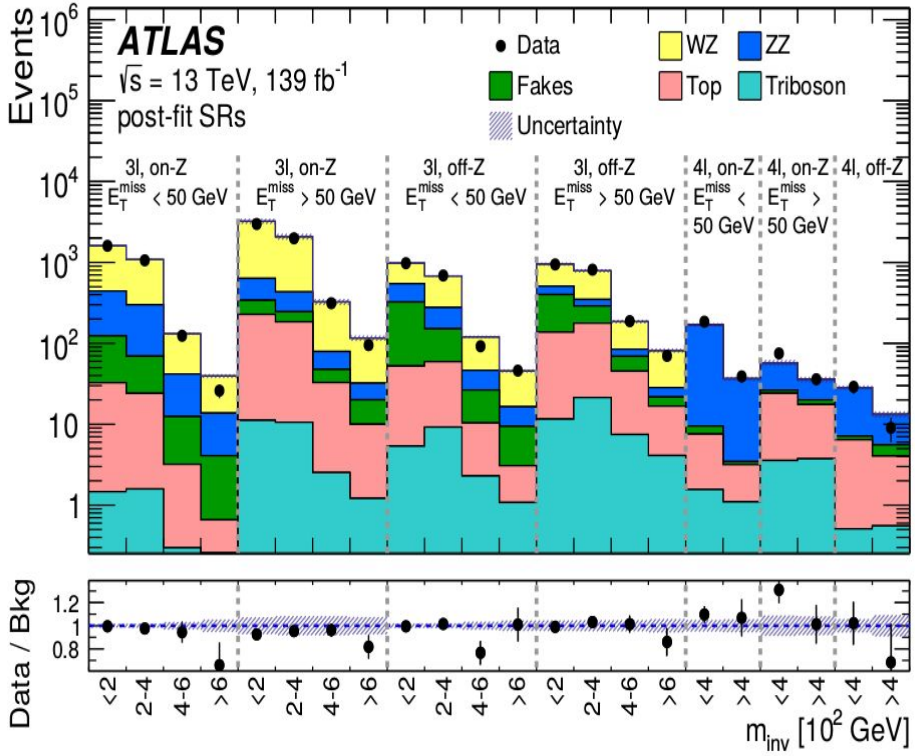
Processes: ttH, tH, ttV, VH, 4 tops, tW, VV, VVV etc., V = W, Z.

Additional Multi-lepton Excesses:

ATLAS 3l/4l Analysis: [arXiv: 2107.00404]:-

Region	Particles	$E_{\mathrm{T}}^{\mathrm{miss}}$	Z-pairs	Other
			Signal regions	
3ℓ	3ℓ	< 50 GeV	1	**veto** event if $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 80$ GeV for off-Z ℓ
	3ℓ	> 50 GeV	1	**veto** event if $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 80$ GeV for off-Z ℓ
	3ℓ	< 50 GeV	0	**veto** event if $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 40$ GeV for off-flavour ℓ
	3ℓ	> 50 GeV	0	**veto** event if $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 40$ GeV for off-flavour ℓ
	3ℓ SRs are divided into m_{inv} ranges of 0–200, 200–400, 400–600 *and* >600 GeV.			
4ℓ	4ℓ	< 50 GeV	1	-
	4ℓ	> 50 GeV	1	-
	4ℓ	-	0	-
	4ℓ SRs are divided in m_{inv} ranges of 0-400 *and* >400 GeV.			

ATLAS 3l/4l Analysis: [arXiv: 2107.00404]:



4ℓ, On-Z, $E_T^{miss} > 50$ GeV		
Sample	0–400 GeV	>400 GeV
Top	20.6 ± 2.2	13.8 ± 1.7
Triboson	3.6 ± 0.5	3.7 ± 0.6
ZZ	31 ± 4	15.6 ± 1.8
Fakes	2.2 ± 1.5	2.5 ± 1.3
Total	57 ± 5	35.5 ± 2.9
Data	75	36
Signal	18 ± 10	0 ± 7

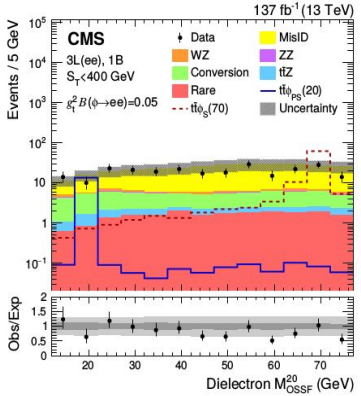
CMS 3l Analysis: [arXiv: 1911.04968]:

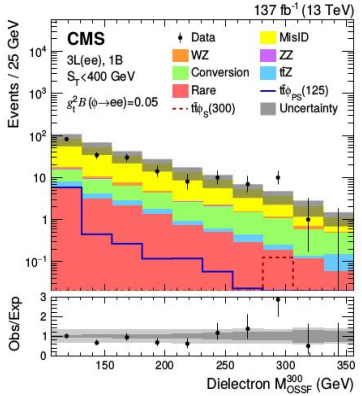
Label	N_{leptons}	N_{OSSF}	M_{OSSF}	N_{b}	Variable and range (GeV)		Number of bins		
						S_{T} (GeV)	0–400	400–800	>800
3L(ee/$\mu\mu$) 0B	3	1	off-Z	0	M^{20}_{OSSF}	[12, 77]	13	13	5
					M^{300}_{OSSF}	[106, 356]	10	10	10
3L(ee/$\mu\mu$) 1B	3	1	off-Z	≥1	M^{20}_{OSSF}	[12, 77]	13	13	5
					M^{300}_{OSSF}	[106, 356]	10	10	10
						S_{T} (GeV)	0–400	>400	
4L(ee/$\mu\mu$) 0B	≥4	≥1	off-Z	0	M^{20}_{OSSF}	[12, 77]	3	2	
					M^{300}_{OSSF}	[106, 356]	3	2	
						S_{T} inclusive			
4L(ee/$\mu\mu$) 1B	≥4	≥1	off-Z	≥1	M^{20}_{OSSF}	[12, 77]	3		
					M^{300}_{OSSF}	[106, 356]	3		

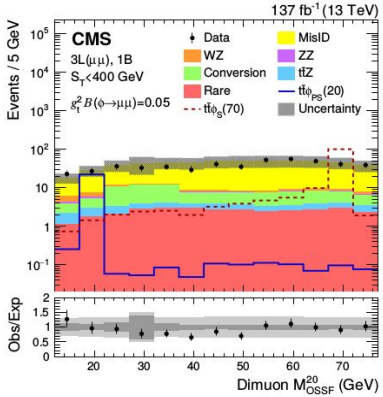
CMS 3l Analysis: [arXiv: 1911.04968]:

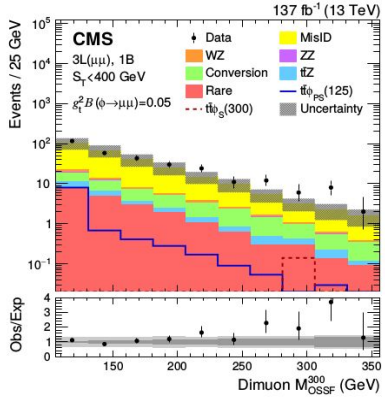
3l(ee) 1B

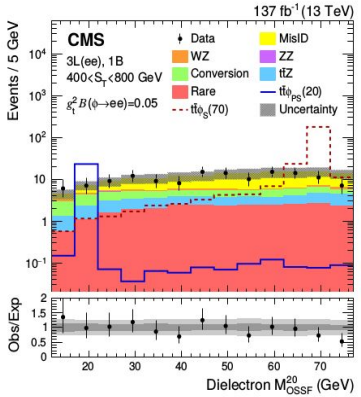
3l(mumu) 1B

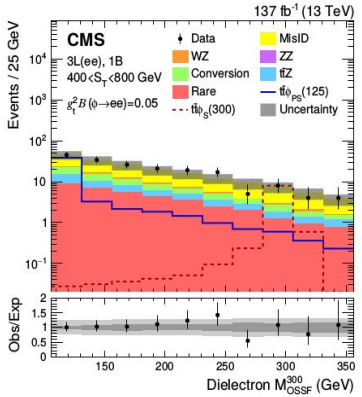


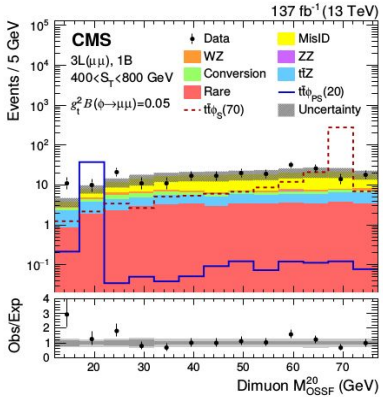


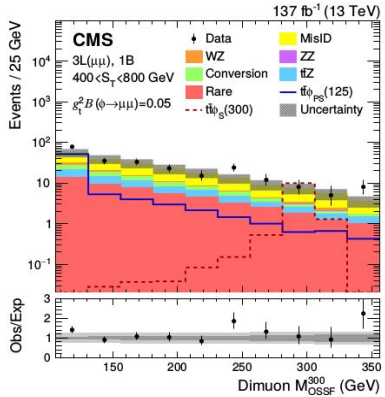












2HDM+S model

$$
\begin{aligned}
V(\Phi_1,\Phi_2,\Phi_S) = {} & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\
& + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right] \\
& + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\left(\Phi_1^\dagger\Phi_1\right)\Phi_S^2 + \frac{\lambda_8}{2}\left(\Phi_2^\dagger\Phi_2\right)\Phi_S^2. \qquad (1)
\end{aligned}
$$

Where,

$$
\Phi_1 = \begin{pmatrix} \phi_1^\pm \\ \frac{1}{\sqrt{2}}\left(v_1 + \rho_1 + i\eta_1\right) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^\pm \\ \frac{1}{\sqrt{2}}\left(v_2 + \rho_2 + i\eta_2\right) \end{pmatrix}, \qquad \Phi_S = v_S + \rho_S,
$$

2HDM+S model

$$M^2_{H^\pm} = \begin{pmatrix} -\left(2m^2_{12} + (\lambda_4+\lambda_5)v_1v_2\right)\frac{v_2}{2v_1} & m^2_{12} + \frac{1}{2}(\lambda_4+\lambda_5)v_1v_2 \\ m^2_{12} + \frac{1}{2}(\lambda_4+\lambda_5)v_1v_2 & -\left(2m^2_{12} + (\lambda_4+\lambda_5)v_1v_2\right)\frac{v_2}{2v_1} \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix},$$

$$M^2_A = \begin{pmatrix} -\left(m^2_{12} + \lambda_5 v_1 v_2\right)\frac{v_2}{v_1} & m^2_{12} + \lambda_5 v_1 v_2 \\ m^2_{12} + \lambda_5 v_1 v_2 & -\left(m^2_{12} + \lambda_5 v_1 v_2\right)\frac{v_2}{v_1} \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$M^2_{CP-even} = \begin{pmatrix} \lambda_1 c^2_\beta v^2 + t_\beta m^2_{12} & -m^2_{12} + \lambda_{345} c_\beta s_\beta v^2 & \lambda_7 c_\beta v v_S \\ -m^2_{12} + \lambda_{345} c_\beta s_\beta v^2 & \lambda_2 s^2_\beta v^2 + m^2_{12}/t_\beta & \lambda_8 s_\beta v v_S \\ \lambda_7 c_\beta v v_S & \lambda_8 s_\beta v v_S & \lambda_6 v_S^2 \end{pmatrix}$$

$$\mathscr{R} = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -\left(c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} + s_{\alpha_1}c_{\alpha_3}\right) & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ -c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} + s_{\alpha_1}s_{\alpha_3} & -\left(c_{\alpha_1}s_{\alpha_3} + s_{\alpha_1}s_{\alpha_2}c_{\alpha_3}\right) & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}$$

Refs:
arXiv: 1612.01309
arXiv: 1809.06344

$$\begin{pmatrix} h \\ S \\ H \end{pmatrix} = \mathscr{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

2HDM+S model

$$\frac{\partial V}{\partial \Phi_1} = 0 \rightarrow m_{11}^2 = -\frac{1}{2}\left(v_1^2\lambda_1 + v_2^2\lambda_{345} + v_S^2\lambda_7\right) + \frac{v_2}{v_1}m_{12}^2,$$

$$\frac{\partial V}{\partial \Phi_2} = 0 \rightarrow m_{22}^2 = -\frac{1}{2}\left(v_2^2\lambda_2 + v_1^2\lambda_{345} + v_S^2\lambda_8\right) + \frac{v_2}{v_1}m_{12}^2,$$

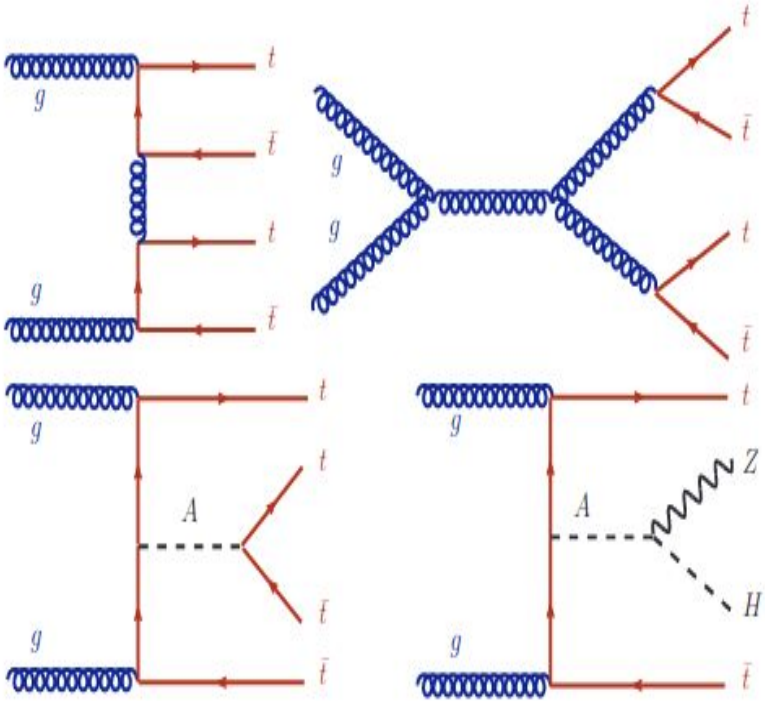
$$\frac{\partial V}{\partial \Phi_S} = 0 \rightarrow m_S^2 = -\frac{1}{2}\left(v_1^2\lambda_7 + v_2^2\lambda_8 + v_S^2\lambda_6\right),$$

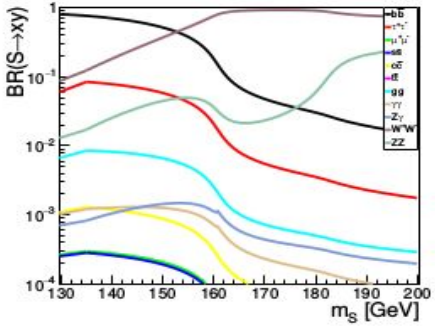
$$\begin{aligned}
\lambda_1 &= \frac{1}{v^2 c_\beta^2}\left(-\tilde{\mu}^2 s_\beta^2 + \sum_{i=1}^{3} m_{H_i}^2 R_{i1}^2\right) \\
\lambda_2 &= \frac{1}{v^2 s_\beta^2}\left(-\tilde{\mu}^2 c_\beta^2 + \sum_{i=1}^{3} m_{H_i}^2 R_{i2}^2\right) \\
\lambda_3 &= \frac{1}{v^2}\left(-\tilde{\mu}^2 + \frac{1}{s_\beta c_\beta}\sum_{i=1}^{3} m_{H_i}^2 R_{i1} R_{i2} + 2m_{H^\pm}^2\right) \\
\lambda_4 &= \frac{1}{v^2}\left(\tilde{\mu}^2 + m_A^2 - 2m_{H^\pm}^2\right) \\
\lambda_5 &= \frac{1}{v^2}\left(\tilde{\mu}^2 - m_A^2\right) \\
\lambda_6 &= \frac{1}{v_S^2}\sum_{i=1}^{3} m_{H_i}^2 R_{i3}^2 \\
\lambda_7 &= \frac{1}{v v_S c_\beta}\sum_{i=1}^{3} m_{H_i}^2 R_{i1} R_{i3} \\
\lambda_8 &= \frac{1}{v v_S s_\beta}\sum_{i=1}^{3} m_{H_i}^2 R_{i2} R_{i3} \ .
\end{aligned}$$

Input Parameters:

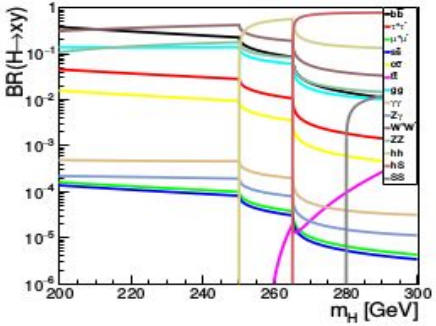
$$\alpha_1\ ,\quad \alpha_2\ ,\quad \alpha_3\ ,\quad t_\beta\ ,\quad v\ ,\quad v_S\ ,\quad m_{H_{1,2,3}}\ ,\quad m_A\ ,\quad m_{H^\pm}\ ,\quad m_{12}^2\ .$$

Multi-lepton Analysis @2HDM+S

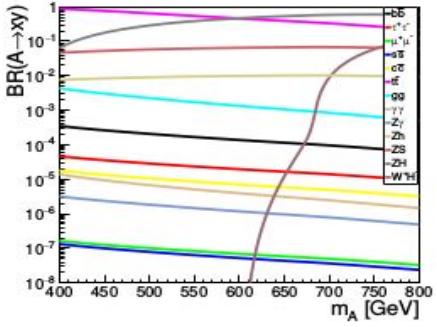




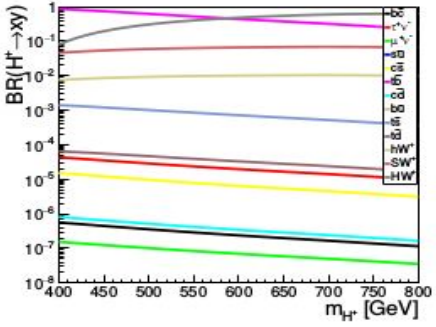
(a)



(b)



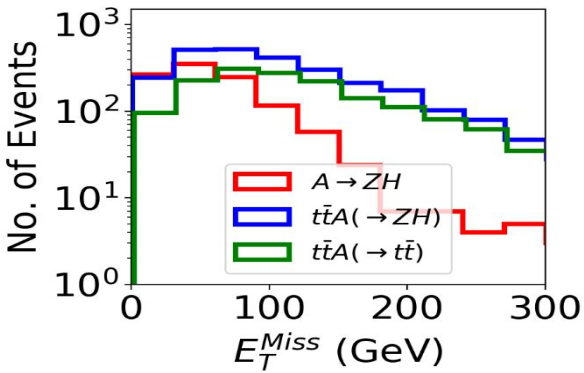
(c)

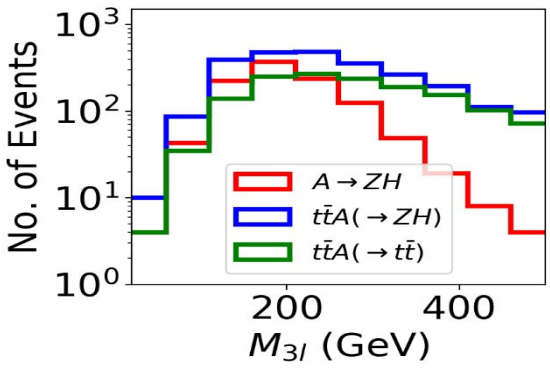


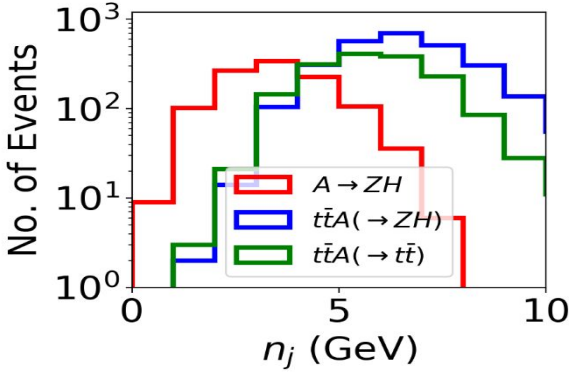
(d)

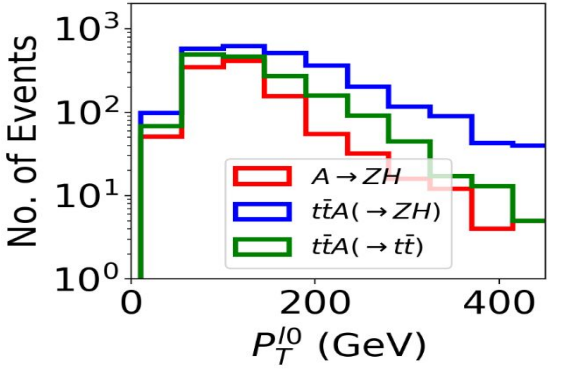
Results:-

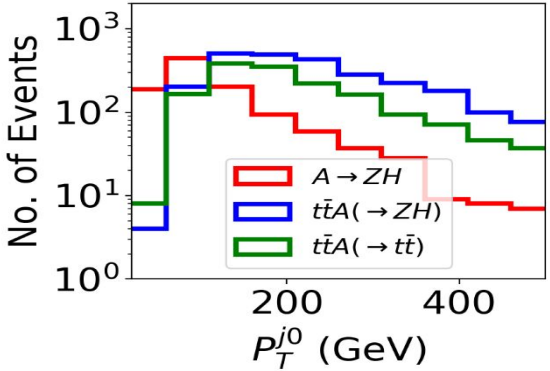
3l

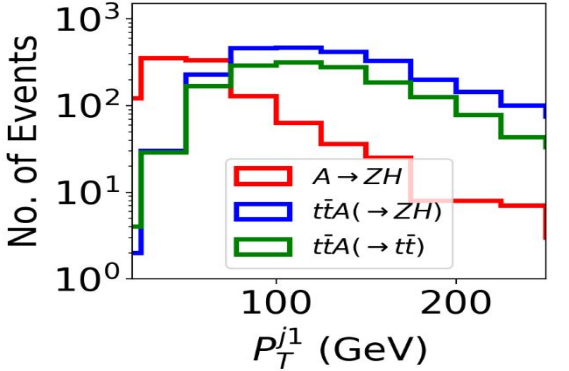

No. of Events
10^3
10^2
10^1
10^0
0
100
200
300
E_T^{Miss} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$


No. of Events
10^3
10^2
10^1
10^0
200
400
M_{3l} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$


No. of Events
10^3
10^2
10^1
10^0
0
5
10
n_j (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

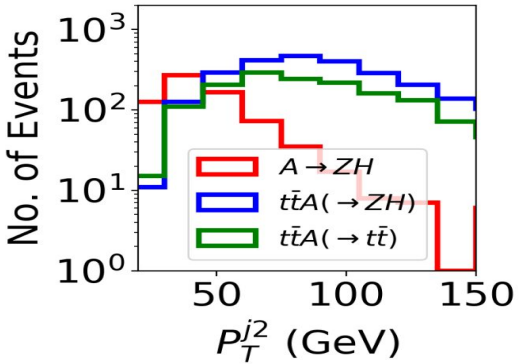

No. of Events
10^3
10^2
10^1
10^0
0
200
400
P_T^{l0} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

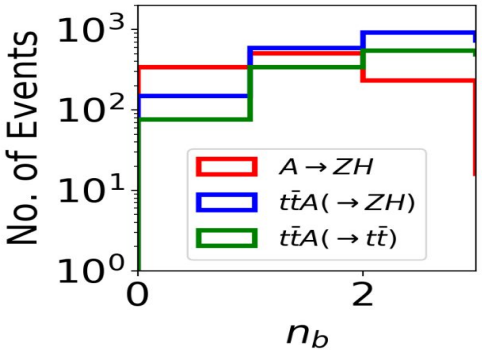

No. of Events
10^3
10^2
10^1
10^0
200
400
P_T^{j0} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

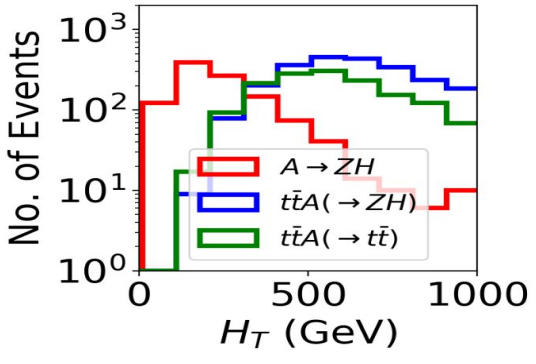

No. of Events
10^3
10^2
10^1
10^0
100
200
P_T^{j1} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

Results:-

3l


No. of Events
10^3
10^2
10^1
10^0
50
100
150
P_T^{j2} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$


No. of Events
10^3
10^2
10^1
10^0
0
2
n_b
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$


No. of Events
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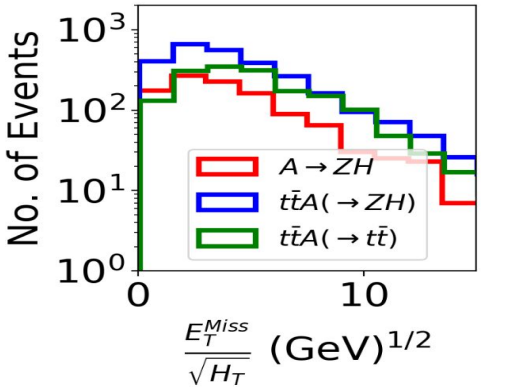
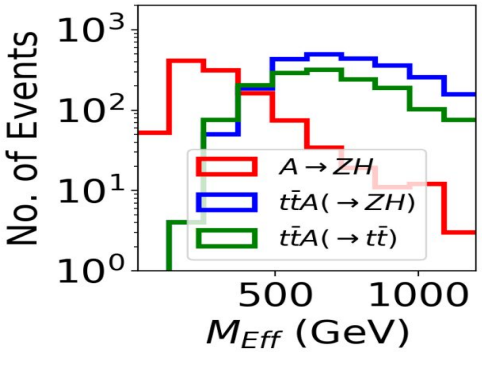
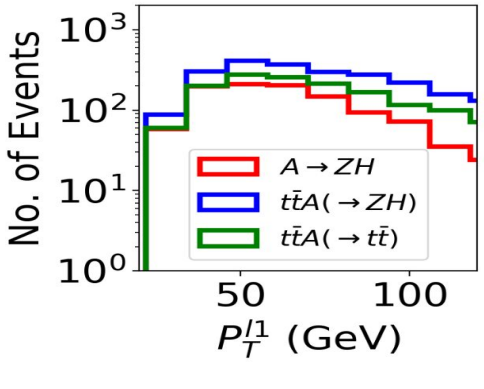
10^2
10^1
10^0
0
500
1000
H_T (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

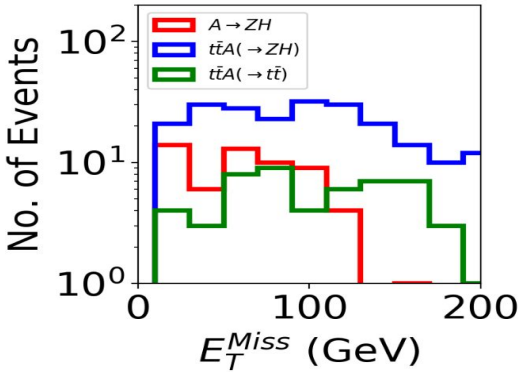

No. of Events
10^3
10^2
10^1
10^0
0
10
$\frac{E_T^{Miss}}{\sqrt{H_T}}$ $(\text{GeV})^{1/2}$
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

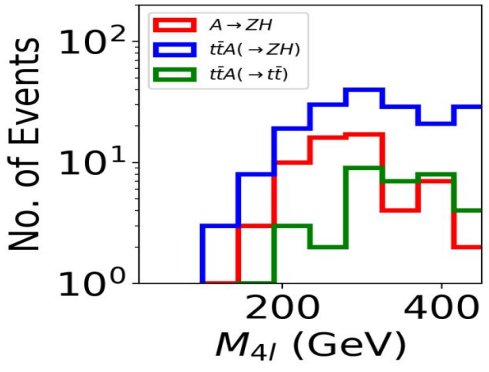

No. of Events
10^3
10^2
10^1
10^0
500
1000
M_{Eff} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

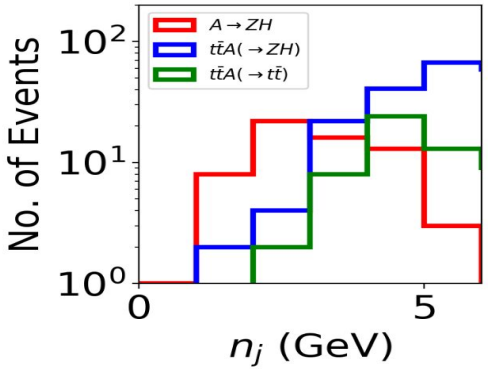

No. of Events
10^3
10^2
10^1
10^0
50
100
P_T^{l1} (GeV)
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$

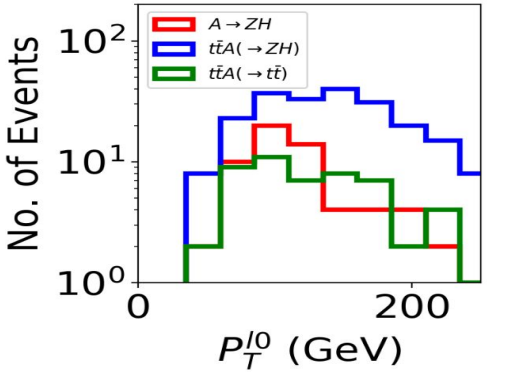
Results:-

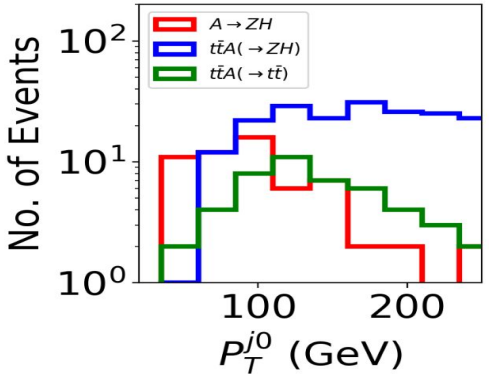
4l

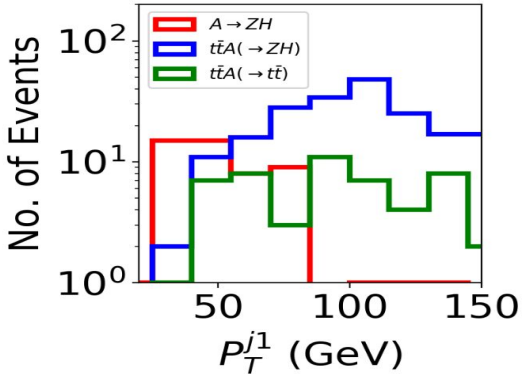

$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
No. of Events
10^2
10^1
10^0
0
100
200
E_T^{Miss} (GeV)


$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
No. of Events
10^2
10^1
10^0
200
400
M_{4l} (GeV)


$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
No. of Events
10^2
10^1
10^0
0
5
n_j (GeV)

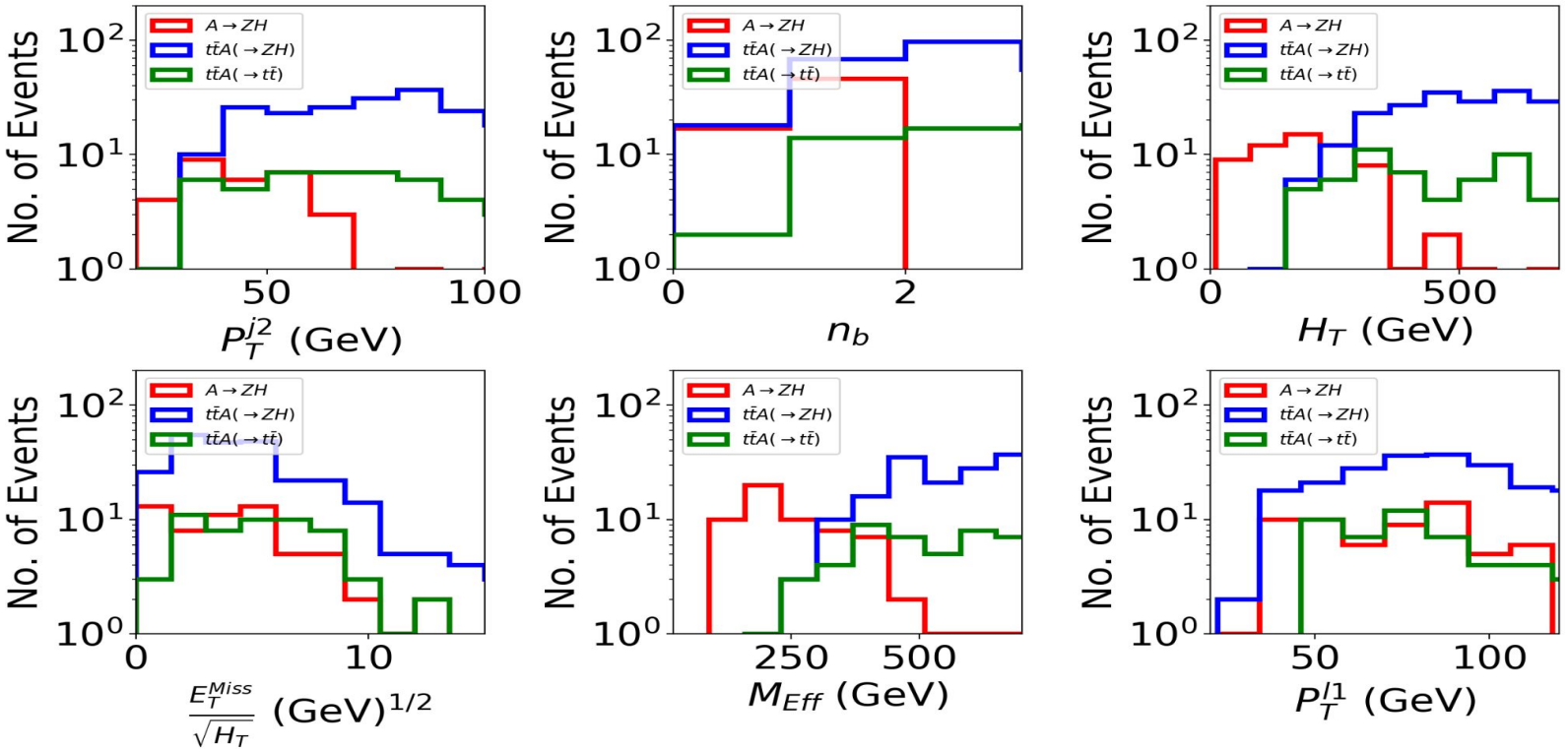

$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
No. of Events
10^2
10^1
10^0
0
200
P_T^{l0} (GeV)


$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
No. of Events
10^2
10^1
10^0
100
200
P_T^{j0} (GeV)

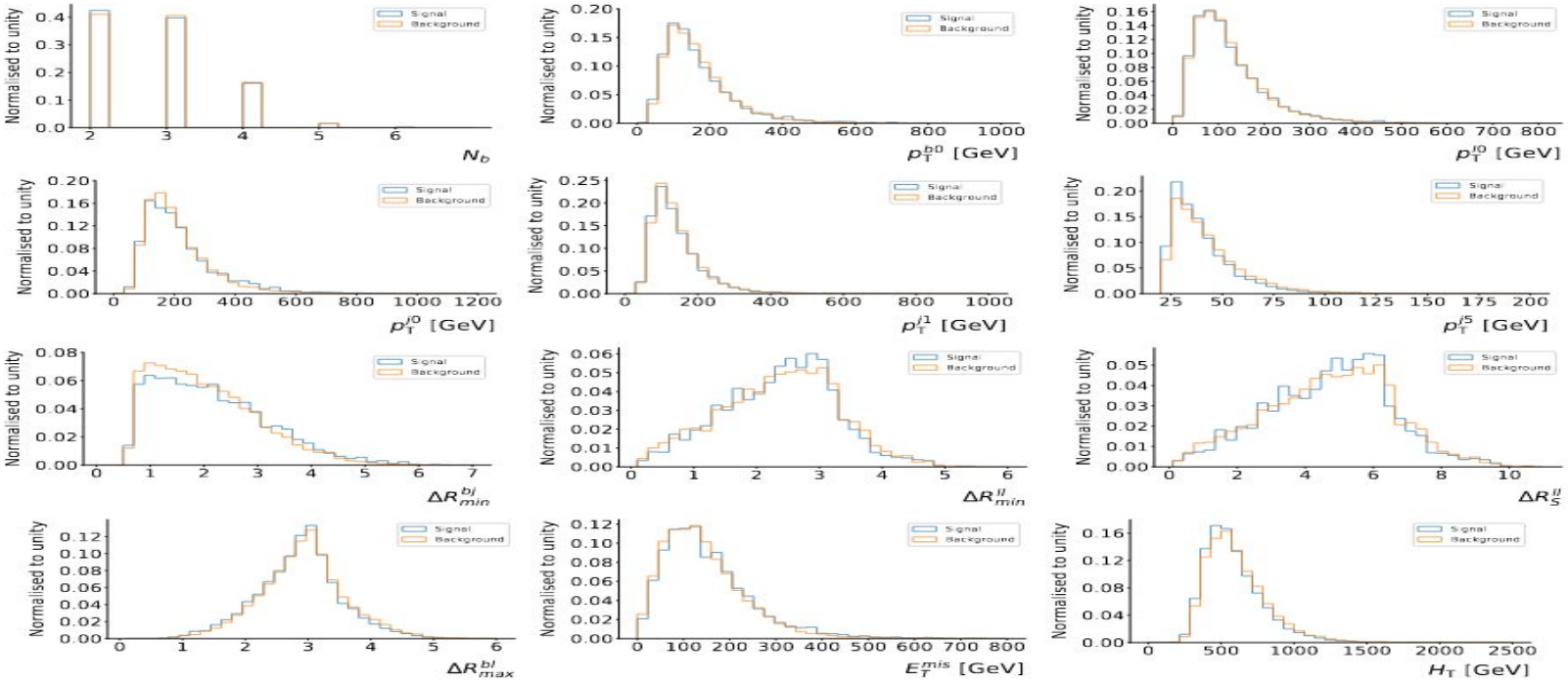

$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
No. of Events
10^2
10^1
10^0
50
100
150
P_T^{j1} (GeV)

Results:-

4l


No. of Events
10^2
10^1
10^0
$A \to ZH$
$t\bar{t}A(\to ZH)$
$t\bar{t}A(\to t\bar{t})$
50
100
P_T^{j2} (GeV)
0
2
n_b
0
500
H_T (GeV)
0
10
$\frac{E_T^{Miss}}{\sqrt{H_T}}$ $(\text{GeV})^{1/2}$
250
500
M_{Eff} (GeV)
50
100
P_T^{l1} (GeV)

4top@2HDM+S



Eur. Phys. J. C 80 (2020) 1085, JHEP 11 (2021) 118, arXiv: 2109.06951, SAIP2021.

Conclusion:-

- Anomalies in the multi-lepton final states at the LHC are evident with respect to the MC samples.
- They appear in the corner of the parameter space of the 2HDM+S in various final states.
- Here we focus that the additional anomalies present in the multi-lepton search presented in the ATLAS and CMS analyses which can also be explained by 2HDM+S.

Collaborators:-

Bruce Mellado
Mukesh Kumar
Xifeng Ruan
Andreas Crivellin
Yaquan Fang
Oliver Fischer
Qiyu Sha
Salah-Eddine Dahbi

Thuso Mathaha
Anza-Tshilidzi Mulaudzi
Finn Stevenson
Benjamin Lieberman
Nidhi Tripathi
Lerato Baloyi
Ntsoko Rapheeha
Elias Malwa

Thank You