Higgs potential and BSM opportunity workshop

The multilepton anomalies at the LHC and the prospect of new physics at the EW scale

Abdualazem Fadol, Bruce Mellado,
Yaquan Fang, Xifeng Ruan

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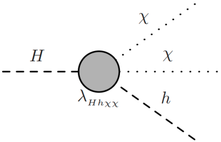
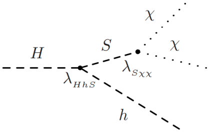
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Institute for Collider Particle Physics
University of the Witwatersrand

Introduction

- Following a study here [1] , it becomes clear that several anomalous in the LHC Run-I datasets can be explained by adding new scalar bosons to the SM.
- Two real scalar χ and S, where χ is dark matter, while S is Higgs-like boson [2] .





- Subsequently, a more sophisticated investigation is performed on Run-II LHC datasets [3] .
- These discrepancies are not likely to be a result of the mismodelling of the SM prediction.

- [1] J.Phys.G 45 (2018) 11, 115003
- [2] Eur. Phys.J.C 76 (2016) 10, 580
- [3] JHEP 10 (2019) 157

The simplified model
Effective Lagrangian approach

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

$$\begin{aligned}\mathcal{L}_{SVV'} = {} & \frac{1}{4}\kappa_{S_{gg}} \frac{\alpha_s}{12\pi v} SG^{a\mu\nu} G^a_{\mu\nu} + \frac{1}{4}\kappa_{S_{\gamma\gamma}} \frac{\alpha}{\pi v} SF^{\mu\nu} F_{\mu\nu} \\ & + \frac{1}{4}\kappa_{S_{ZZ}} \frac{\alpha}{\pi v} SZ^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\kappa_{S_{Z\gamma}} \frac{\alpha}{\pi v} SZ^{\mu\nu} F_{\mu\nu} \\ & + \frac{1}{4}\kappa_{S_{WW}} \frac{2\alpha}{\pi s_w^2 v} SW^{+\mu\nu} W^-_{\mu\nu},\end{aligned}$$

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

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

$$\mathcal{L}_{S\chi} = -\frac{1}{2} v\, \lambda_{_{S\chi\chi}} S\chi\chi - \frac{1}{2} \lambda_{_{SS\chi\chi}} SS\chi\chi.$$

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

$$\mathcal{L}_{\rm G} = -\frac{1}{4}\, \beta_g \kappa_{_{Hgg}}^{\rm SM}\, G_{\mu\nu} G^{\mu\nu} H + \beta_{_V} \kappa_{_{hVV}}^{\rm SM}\, V_\mu V^\mu H,$$

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

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2} m_H^2 HH + \mathcal{L}_{\rm G} + \mathcal{L}_{\rm Y}.$$

$$\mathcal{L}_{\rm tot} = \mathcal{L}_{\rm SM} + \mathcal{L}_H + \mathcal{L}_S.$$

- ☐ Where $\beta_g^2 = y_{ttH}/y_{ttH}^{\rm SM}$ is the scale factor for H production.
- ☐ The total Lagrangian contains the SM, H sector and the real singlet scalar S.

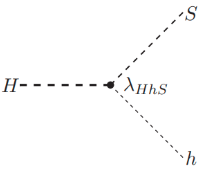
- [1] J.Phys.G 45 (2018) 11, 115003
- [2] Eur. Phys.J.C 76 (2016) 10, 580

The simplified model

The possible decay modes

S. No.	Scalars	Decay modes
D.1	h	$b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $s\bar{s}$, $c\bar{c}$, gg, $\gamma\gamma$, $Z\gamma$, W^+W^-, ZZ
D.2	H	D.1, hh, SS, Sh
D.3	A	D.1, $t\bar{t}$, Zh, ZH, ZS, $W^{\pm}H^{\mp}$
D.4	$H^{\pm}$	$W^{\pm}h$, $W^{\pm}H$, $W^{\pm}S$
D.5	S	D.1, $\chi\chi$

Scalar	Production mode	Search channels
H	$gg \to H, Hjj$ (ggF and VBF)	Direct SM decays as in Table 1 $\to SS/Sh \to 4W \to 4\ell + E_T^{miss}$ $\to hh \to \gamma\gamma b\bar{b}$, $b\bar{b}\tau\tau$, $4b$, $\gamma\gamma WW$ etc. $\to Sh$ where $S \to \chi\chi \implies \gamma\gamma$, $b\bar{b}$, $4\ell + E_T^{miss}$
	$pp \to Z(W^{\pm})H$ ($H \to SS/Sh$)	$\to 6(5)l + E_T^{miss}$ $\to 4(3)l + 2j + E_T^{miss}$ $\to 2(1)l + 4j + E_T^{miss}$
	$pp \to t\bar{t}H, (t+\bar{t})H$ ($H \to SS/Sh$)	$\to 2W + 2Z + E_T^{miss}$ and b-jets $\to 6W \to$ 3 same sign leptons + jets and E_T^{miss}
$H^{\pm}$	$pp \to tH^{\pm}$ ($H^{\pm} \to W^{\pm}H$)	$\to 6W \to$ 3 same sign leptons + jets and E_T^{miss}
	$pp \to tbH^{\pm}$ ($H^{\pm} \to W^{\pm}H$)	Same as above with extra b-jet
	$pp \to H^{\pm}H^{\mp}$ ($H^{\pm} \to HW^{\pm}$)	$\to 6W \to$ 3 same sign leptons + jets and E_T^{miss}
	$pp \to H^{\pm}W^{\pm}$ ($H^{\pm} \to HW^{\pm}$)	$\to 6W \to$ 3 same sign leptons + jets and E_T^{miss}
A	$gg \to A$ (ggF)	$\to t\bar{t}$ $\to \gamma\gamma$
	$gg \to A \to ZH$ ($H \to SS/Sh$)	Same as $pp \to ZH$ above, but with resonance structure over final state objects
	$gg \to A \to W^{\pm}H^{\mp}(H^{\mp} \to W^{\mp}H)$	$6W$ signature with resonance structure over final state objects
S	$gg \to S$ (ggF) or $H \to SS/Sh$ (associated production)	Resonantly through decays as in Table 1 ($\gamma\gamma$, $b\bar{b}$, $\tau\tau$, $ZZ \to 4\ell$) Non-resonantly through multilepton + E_T^{miss} decays

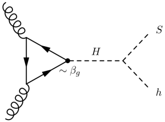


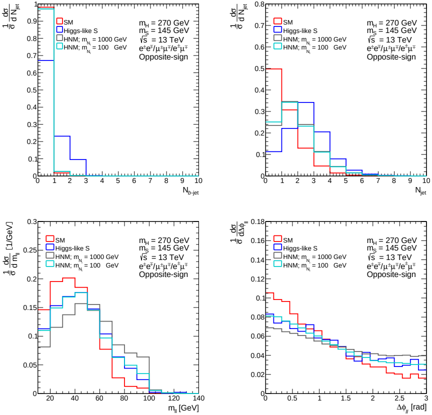
- ☐ Is considered to be completely dominant.

- ☐ A list of potential search channels arising from the addition of the new scalars; which
- ☐ leads to rich phenomenological activities. Of particular interest are multilepton signatures.

The simplified model
Multilepton final states

- ☐ $pp \rightarrow H \rightarrow Sh \rightarrow \ell^+\ell^- + X$

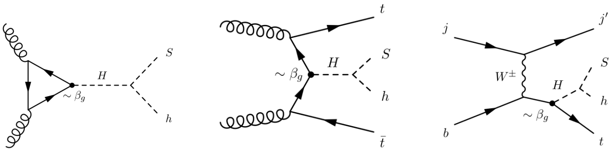




- ☐ Expected to have more jets multiplicity; and
- ☐ di-lepton invariant mass below 100 GeV.
- ☐ Well separated leptons as shown in $\Delta\phi(\ell\ell)$.
- ☐ Efficiency comparable to that of the SM.

The BSM signal assumptions

- The masses of the H and S bosons were fixed to 270 GeV and 150 GeV respectively.
- The SM Higgs boson is taken to be 125.09 GeV.
- **Including significant production mechanisms only:**



- The branching ratio for the $H \to Sh$ is fixed to 100%.
- The S is assumed to have Higgs-like branching ratio.
- The only free parameter left out in the fit is β_g of the size of the Yukawa couplings.

LHC multilepton measurements

- ☐ ATLAS and CMS multilepton measurements;
- ☐ with a simple baseline selection is shown.
- ☐ Most of the results are from the Run-II datasets.
- ☐ These were not included in the previous results [3] .

Data set	Reference	Selection
ATLAS Run 1	ATLAS-EXOT-2013-16 [4]	SS $\ell\ell$ and $\ell\ell\ell$ + b-jets
ATLAS Run 1	ATLAS-TOPQ-2015-02 [5]	OS $e\mu$ + b-jets
CMS Run 2	CMS-PAS-HIG-17-005 [6]	SS $e\mu$, $\mu\mu$ and $\ell\ell\ell$ + b-jets
CMS Run 2	CMS-TOP-17-018 [7]	OS $e\mu$
CMS Run 2	CMS-PAS-SMP-18-002 [8]	$\ell\ell\ell + E_{\rm T}^{\rm miss}$ (WZ)
ATLAS Run 2	ATLAS-EXOT-2016-16 [9]	SS $\ell\ell$ and $\ell\ell\ell$ + b-jets
ATLAS Run 2	ATLAS-CONF-2018-027 [10]	OS $e\mu$ + b-jets
ATLAS Run 2	ATLAS-CONF-2018-034 [11]	$\ell\ell\ell + E_{\rm T}^{\rm miss}$ (WZ)

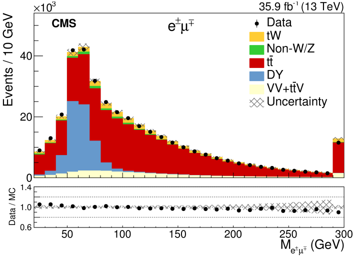
- [3] J.Phys.G 45 (2018) 11, 11500

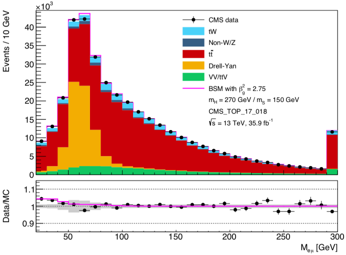
- [4] JHEP 10 (2015) 150
- [5] Eur. Phys. J. C 77 (2017) 804
- [6] CMS-PAS-HIG-17-005 (2017)
- [7] JHEP 10 (2018) 117
- [8] CMS-PAS-SMP-18-002 (2018)
- [9] JHEP 12 (2018) 039
- [10] ATLAS-CONF-2018-027 (2018)
- [11] ATLAS-CONF-2018-034 (2018)

LHC multilepton measurements

CMS fit example with the BSM signal

- Poor modelling of POWHEG+Pythia8 distribution is improved through reweighting.
- We fix the normalisation of the SM by scaling it to the data in the region $m_{\ell\ell} > 110$ GeV.
- A normalisation systematic of 3% is applied to all but DY.
- DY systematic = 6.8%. 3% systematic on $m_{\ell\ell}$ shape in top
- Fit results:
  - $\beta_g^2 = 2.79 \pm 0.52$
  - Fit is extremely well constrained.

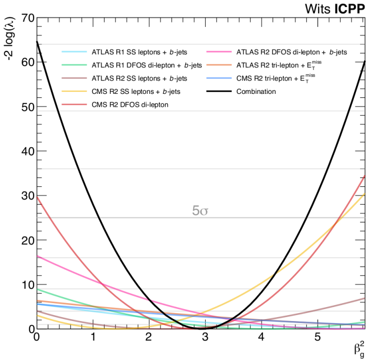




- Used conservative assumption that $\ell^+\ell^- + 2b$ final state is perfectly described by the SM.
- The discrepancy comes from events with $N_{b-\text{jets}}$, and excess unlikely due to $t\bar{t}$.

The combined fit results

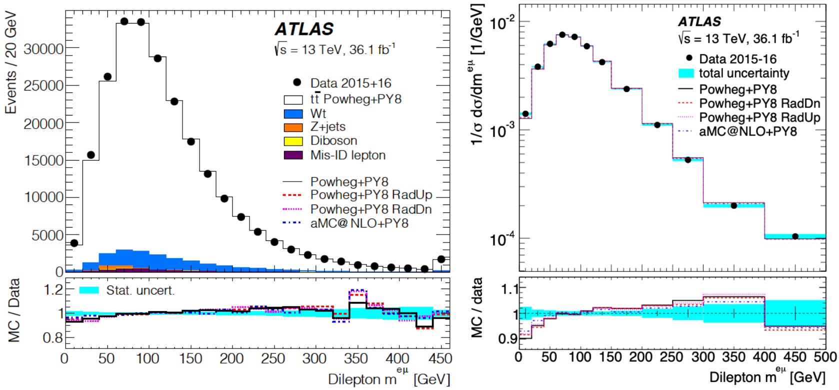
- Fitting ATLAS and CMS measurements simultaneously.
- The profile-likelihood ratio as a function of β_g^2.
- The combined best-fit for β_g^2 is 2.92 ± 0.35.
- This is equivalent to a significance of 8.04σ.
- Which is calculated by:
  - $Z = \sqrt{-2 \log \lambda(0)}$
- The multilepton discrepancy can be explained using only one parameter.
- The inconsistencies have been growing since Run-I of the LHC.



- [3] JHEP 10 (2019) 157

LHC multilepton measurements

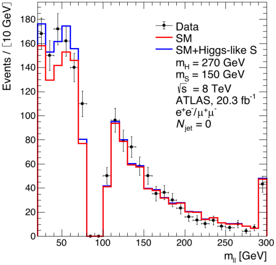
Results not included in the combination

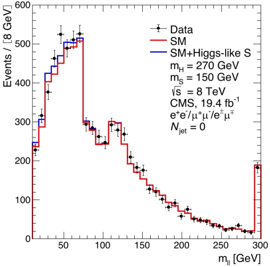


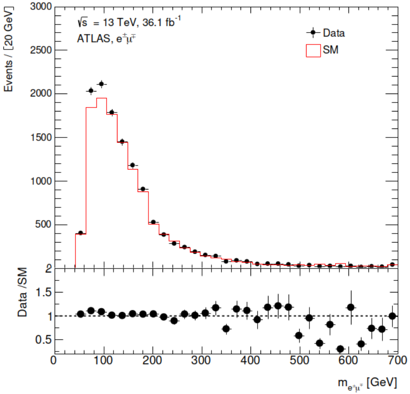
- ☐ Residual discrepancies at high $m_{\ell\ell}$ will be fixed with missing NNLO QCD and NLO EW corrections.
- ☐ Excess at low $m_{\ell\ell}$ remains prevalent, indicating that effects seen in Run 1 were not statistical fluctuations.
- ☐ NNLO QCD corrections do not fix the issue (see Mitov et al.)

LHC multilepton measurements

Excesses in di-leptons with full-jet veto not included in the combination







- ☐ QCD NNLO to $q\bar{q} \rightarrow WW$ NLO QCD to $gg \rightarrow WW$ and NLO EW corrections is applied

Anatomy of the multilepton 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	~4.5σ
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

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

Summary

- ☐ The current multilepton excesses in the LHC data are not due to statistical fluctuation;
- ☐ nor are coming from SM prediction mismodelling.
- ☐ These discrepancies are interpreted with a simplified model;
- ☐ where $H \to SS, Sh$ and S is treated as SM Higgs-like.
- ☐ The masses of the H and S bosons were fixed while β_g is set free.
- ☐ The combined significance measures the inability of MC tools to describe multilepton data; and
- ☐ how a simplified model with $H \to Sh$ is able to capture the effect with one parameter.

Thank you!