Multi-lepton Anomalies at the LHC and new physics at the EW scale

The Wits ICPP/iThemba LABS with N.Chakrabarty T.Mandal and B.Mukhopadhyaya (HRI/Uppsala) Y.Fang, Y.Zhang and M.Zhu (IHEP)
Outline

- The 2HDM+S model
- Di-lepton or multilepton “problem”
  - Opposite sign di-leptons
  - Same sign leptons and three leptons
  - Three b-jet final states
- Combination
  - Other discrepancies not included
- Outlook and Conclusions

Views expressed here are of the authors only.
The Simplified Model and 2HDM+S

arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674
arXiv:1706.02477
arXiv:1706.06659
arXiv:1709.09419
arXiv:1711.07874
arXiv:1809.06344
arXiv:1901.05300
The Hypothesis

1. The starting point of the hypothesis is the existence of a boson, $H$, that contains Higgs-like interactions, with a mass in the range 250-295 GeV

2. In order to avoid large quartic couplings and to incorporate a mediator with Dark Matter a real scalar, $S$, is introduced. $S$ interacts with the SM:

Also decays to SM
The Decays of $H$

- In the general case, $H$ can have couplings as those displayed by a Higgs boson in addition to decays involving the intermediate scalar and Dark Matter.

$$H \rightarrow WW, ZZ, q\bar{q}, gg, Z\gamma, \gamma\gamma, \chi\chi$$

$$+ \quad H \rightarrow SS, Sh, hh$$

Dominant decays

$$H \rightarrow h(+X), S(+X)$$

Diboson decay
Multi-lepton final states
\[ pp \rightarrow H \rightarrow Sh \rightarrow \ell^+\ell^- + X \]

Expect di-leptons \((m_{ll} < 100 \text{ GeV})\) with jets and b-jets with rates comparable to that of the SM Higgs boson.

Relatively large jet multiplicity compared to the SM Higgs.
Simple selection: One DFOS lepton pair
At least 1 $b$-tagged jet

We fix the normalisation of the SM by scaling it to the data in the region $m_{ll} > 110$ GeV

Scale factor: 0.984
A normalisation systematic of 2% is applied
The fit is done to the region below 110 GeV

Fit results: $\beta_g^2 = 4.09 \pm 1.37$
Recent results from ATLAS with di-leptons with Run II display same tendency as Run I
Simple selection:
- One DFOS lepton pair
- At least 1 $b$-tagged jet

Normalisation systematic: ~6.2%

Shape systematic:
- Discrepancy of SM prediction, particularly at high $\Delta \Phi$
- Choose SM prediction that best describes data (aMC@NLO) → systematic is percentage deviation away from mean SM prediction
- Varies between 1% and 2.6%

Fit results:
- $\beta_g^2 = 5.36 \pm 1.31$
Poor modeling of POWHEG + Pythia8 distribution is improved through reweighting.

We fix the normalisation of the SM by scaling it to the data in the region $m_{ll} > 110$ GeV
- A normalisation systematic of 3% is applied to all but DY
- DY systematic = 6.8%. 3% systematic on $m_{ll}$ shape in top
- The fit is done to the region below 110 GeV

Fit results:
- $\beta_g^2 = 2.79 \pm 0.52$
- Fit is extremely well constrained

Theory systematics still preliminary

Bulk of signal comes from Nb<2

Used conservative assumption that $ll+2b$-jet final state is perfectly described by the SM. The discrepancy comes from events with $N_b<2$. Impact on $h\rightarrow WW\rightarrow ll$?
Are these discrepancies due to mismodelling of Wt/ťt processes?

Discrepancies in similar m_{ll} range also seems to appear in events with a full jet (b-jet) veto with Run I data (in the context of the WW cross-section measurement. Potential impact on h→WW→ll analysis where the WW is normalized with relatively low m_{ll} (factors of 1.1-1.2, different from high masses).

arXiv:1711.07874
Top associated Higgs production
(Multi-lepton final state)s

Reduced cross-section of ttH+tH is compensated by di-boson, (SS, Sh) decay and large Br(S→WW).
Production of same sign leptons, three leptons is enhanced.
Enhanced tH cross-section

Produces SS 2l, 3l with b-jets, including 3 b-jets
Jet multiplicity ($p_{T,j} > 25$ GeV, $|\eta| < 2.4$)

1/\sigma \cdot d\sigma/dN_{jets}

- SM
- BSM

SM: $pp \rightarrow tth + th \rightarrow all$
BSM: $pp \rightarrow ttH + tH \rightarrow all$

$\sqrt{s} = 13$ TeV - $N_{lepton} \geq 2$

1/\sigma \cdot d\sigma/dN_{b-jets}

- SM
- BSM

SM: $pp \rightarrow tth + th \rightarrow all$
BSM: $pp \rightarrow ttH + tH \rightarrow all$

$\sqrt{s} = 13$ TeV - $N_{lepton} \geq 2$

Larger rate of 3b-jets in SS and 3l events
SS leptons: CMS-PAS-HIG-17-005

- CMS search for single top + Higgs production:
  - At least 2 SS leptons
  - At least 1 $b$-tagged jet
- The full analysis uses a BDT, so we compare to pre-selection plots
- Difficulty in estimating the probability of HF decay leptons to fake signal leptons
  - Not enough information in paper
- Fit results:
  - $\beta_g^2 = 1.41 \pm 0.80$
  - Weak measurement due to lack of statistics and large systematics
Fit results: CMS-PAS-HIG-17-005

CMS data, $L = 35.9$ fb$^{-1}$

- SM background
- SM syst. uncertainty
- BSM (tH)
- BSM (TH)
- BSM (ggF)

$m_h = 270$ GeV / $m_{g} = 150$ GeV

$\beta^2 = 1.41$

CMS_PAS_HIG_17_005

Data / SM

$N(\text{jets, } p_T > 25 \text{ GeV, } |\eta| < 2.4)$

$\Delta\phi$ of highest $p_T$ same-sign lepton pair
SS ll+b-jets: JHEP 10 (2015) 150

- Final state search topology:
  - 2 or 3 leptons (must be a same-sign pair)
  - At least 2 untagged jets
  - $E_T^{\text{miss}} > 40$ GeV, $H_T > 400$ GeV (binned into different signal regions)

- Systematic uncertainty is large:
  - In the fit, treated as a single normalisation uncertainty correlated over all SRs

- Fit results:
  - $\beta_{\tilde{g}}^2 = 6.51 \pm 2.99$
  - This is relatively high compared to other fit results
SS ll+ b-jets: ATLAS-EXOT-2016-16

- Run 2 version of SS + b-jet search:
  - At least 2 SS leptons
  - At least 1 b-tagged jet
  - Large $E_T^{\text{miss}}$ and $H_T$

- Fit to inclusive SR distributions (auxiliary figures)

- Shows the strength of the model to fit the 3 b-jet excesses

- Fit results:
  - $\beta_g^2 = 2.22 \pm 1.19$
SS II + b-jets: ATLAS-EXOT-2016-16

Events / 40 GeV

Events / 300 GeV

Data / SM

Events

Data / SM

$\ell + b$-jets: ATLAS-EXOT-2016-16

ATLAS data, $L = 36.1 \text{ fb}^{-1}$

SM background

SM syst. uncertainty

BSM (thH)

BSM (H)

BSM (ggF)

$m_\ell = 270 \text{ GeV} / m_t = 150 \text{ GeV}$

$p_T^\ell = 2.22$

ATLAS_EXOT_2016_16

ATLAS data, $L = 36.1 \text{ fb}^{-1}$

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BSM (thH)

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BSM (ggF)

$m_\ell = 270 \text{ GeV} / m_t = 150 \text{ GeV}$

$p_T^\ell = 2.22$

ATLAS_EXOT_2016_16
3l with $Z \rightarrow ll$ (ZW cross-section)

CMS PAS SMP-18-002

Errors in the plot are dominated by the 15% uncertainty on normalization to account NLO/NNLO differences. The uncertainty of the shape is much smaller of order of few %

<table>
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<th>Source</th>
<th>Combined</th>
<th>eee</th>
<th>e$\mu$</th>
<th>$\mu\mu$</th>
<th>$\mu$$\mu$$\mu$</th>
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<td>Pileup</td>
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<td>0.3</td>
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<td>1.4</td>
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<td>ZZ</td>
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<td>Nonprompt norm.</td>
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<td>X+$\gamma$ norm.</td>
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Systematics that will directly affect the shape

arXiv:1711.07874
# 3l with Z→ll (ZW cross-section)

**ATLAS-CONF-2018-034**

Systematics that will directly affect the shape stand at few %

<table>
<thead>
<tr>
<th></th>
<th>$\text{ee}$</th>
<th>$\mu\mu$</th>
<th>$\mu\mu$</th>
<th>$\mu\mu\mu$</th>
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<td>$e$ energy scale</td>
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<tr>
<td>$e$ id. efficiency</td>
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<td>1.8</td>
<td>1.0</td>
<td>&lt; 0.1</td>
<td>1.1</td>
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<tr>
<td>$\mu$ momentum scale</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$\mu$ id. efficiency</td>
<td>&lt; 0.1</td>
<td>1.3</td>
<td>1.6</td>
<td>2.8</td>
<td>1.5</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}}$ and jets</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.3</td>
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<tr>
<td>Trigger</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.0</td>
<td>1.5</td>
<td>1.2</td>
<td>1.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

- **Misid. leptons background**: 4.7, 1.1, 4.5, 1.6, 1.9
- **ZZ background**: 1.0, 1.0, 1.1, 1.0, 1.0
- **Other backgrounds**: 1.6, 1.5, 1.4, 1.2, 1.4

**Uncorrelated**: 0.7, 0.6, 0.7, 0.5, 0.3

**Total systematics**: 6.0, 3.5, 5.4, 4.1, 3.6

**Luminosity**: 2.4, 2.4, 2.4, 2.4, 2.4

**Modelling**: 0.5, 0.5, 0.5, 0.5, 0.5

**Statistics**: 3.6, 3.3, 3.2, 2.7, 1.6

**Total**: 7.4, 5.4, 6.7, 5.4, 4.6

[Graph showing data and MC comparison with various backgrounds highlighted]
The following **assumptions** are made:

- **a.** The masses of $H$ and $S$ are fixed to $m_H = 270$ GeV and $m_S = 150$ GeV
- **b.** The only significant production mechanisms of $H$ come from the $t\bar{t}H$ Yukawa coupling:
  - Gluon fusion
  - Top associated production
- **c.** The Yukawa coupling is scaled away from the SM Higgs-like value by the free parameter $\beta_g$
- **d.** The BR of $H \rightarrow Sh$ is fixed to 100%
- **e.** The BRs of $S$ are Higgs-like

Therefore, the only free parameter in the fits is $\beta_g^2$
<table>
<thead>
<tr>
<th>Selection</th>
<th>Best-fit $\beta^2_{q}$</th>
<th>Significance</th>
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</thead>
<tbody>
<tr>
<td>ATLAS Run 1 SS $\ell\ell$ and $\ell\ell\ell + b$-jets</td>
<td>6.51 ± 2.99</td>
<td>2.37σ</td>
</tr>
<tr>
<td>ATLAS Run 1 OS $e\mu + b$-jets</td>
<td>4.09 ± 1.37</td>
<td>2.99σ</td>
</tr>
<tr>
<td>CMS Run 2 SS $e\mu$, $\mu\mu$ and $\ell\ell\ell + b$-jets</td>
<td>1.41 ± 0.80</td>
<td>1.75σ</td>
</tr>
<tr>
<td>CMS Run 2 OS $e\mu$</td>
<td>2.79 ± 0.52</td>
<td>5.45σ</td>
</tr>
<tr>
<td>CMS Run 2 $\ell\ell\ell + E_T^{miss}$ ($WZ$)</td>
<td>9.70 ± 3.88</td>
<td>2.36σ</td>
</tr>
<tr>
<td>ATLAS Run 2 SS $\ell\ell$ and $\ell\ell\ell + b$-jets</td>
<td>2.22 ± 1.19</td>
<td>2.01σ</td>
</tr>
<tr>
<td>ATLAS Run 2 OS $e\mu + b$-jets</td>
<td>5.42 ± 1.28</td>
<td>4.06σ</td>
</tr>
<tr>
<td>ATLAS Run 2 $\ell\ell\ell + E_T^{miss}$ ($WZ$)</td>
<td>9.05 ± 3.35</td>
<td>2.52σ</td>
</tr>
<tr>
<td>Combination</td>
<td>2.92 ± 0.35</td>
<td>8.04σ</td>
</tr>
</tbody>
</table>
Combination of fit results

- Simultaneous fit for all measurements:
- To the right: (-2 log) profile likelihood ratio for each individual result and the combination of them all
- The significance for each fit is calculated as

$$\sqrt{-2 \log \lambda(0)}$$

- Best-fit: \(\beta_g^2 = 2.92 \pm 0.35\)
- Corresponds to 7.64\(\sigma\)

Interpretation: Measure of the inability of current MC tools to describe multiple-lepton data and how a simplified model with \(H \rightarrow Sh\) is able to capture the effect with one parameter
Outlook and Conclusions

- Discrepancies in multi-lepton final states with current MC tools are strong
  - While significance is dominated by OS di-lepton final states, discrepancies appear in SS ll and 3l
  - They appear in corners of the phase-space dominated by different processes: Wt/tt, WW, ZW
- Discrepancies interpreted with simplified model where $H \rightarrow Sh$, S is treated as SM Higgs-like and one parameter is floated: strength of H Yukawa coupling top quarks
- Simplified model is embedded into a 2HDM+S model
  - Model is now good shape for use by experiments to explore the multi-lepton discrepancies
- Run 2 will provide four times the data set
Additional Slides
The Lagrangian

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM} \]

\[ \mathcal{L}_{BSM} = \mathcal{L}_K + \mathcal{L}_T + \mathcal{L}_Q + \mathcal{L}_{Hgg} + \mathcal{L}_{HVV} \]

\[ \mathcal{L}_K = \frac{1}{2} \partial_\mu X \partial^\mu X + \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} M_X^2 X^2 - \frac{1}{2} M_H^2 H^2 \]

\[ \mathcal{L}_T = -\frac{1}{2} \mu_1 h^2 H - \frac{1}{2} \mu_2 X^2 h - \frac{1}{2} \mu_3 X^2 H \]

\[ \mathcal{L}_Q = -\frac{1}{4} \lambda_1 H^2 h^2 - \frac{1}{4} \lambda_2 X^2 h^2 - \frac{1}{4} \lambda_3 H^2 X^2 - \frac{1}{2} \lambda_4 H h X^2 \]

\[ \mathcal{L}_{Hgg} = -\frac{1}{4} \beta_g \kappa_{hgg}^{SM} G_{\mu\nu} G^{\mu\nu} H \]

\[ \mathcal{L}_{HVV} = \frac{2 M_W^2}{v} \beta_W W_\mu W^\mu H + \frac{M_Z^2}{v} \beta_Z Z_\mu Z^\mu H \]
Main decay modes of $H$

Decay to single Higgs and a dark matter (DM) candidate
- DM is assumed scalar for simplicity
- This was our strategy, but we can infer different physics in the blob

Used effective coupling

Decay to double Higgs pair.

Decay to vector boson pairs.
The intermediate scalar, $S$

- Dark Matter is introduced in the form of a scalar and the decay $H \rightarrow h\chi\chi$ via effective quartic couplings.

\[
\mathcal{L}_Q = -\frac{1}{2} \lambda_{H_h\chi\chi} H h \chi \chi - \frac{1}{4} \lambda_{H_Hh_h} H H h h - \frac{1}{4} \lambda_{h_h\chi\chi} h h \chi \chi - \frac{1}{4} \lambda_{H_H\chi\chi} H H \chi \chi
\]

- Due to gauge invariance we encounter an awkward situation where a three body decay may be larger or comparable to a two body decay. This can be naturally explained by introducing an intermediate real scalar $S$.

Also decays to SM
The 2HDM+S

arXiv:1606.01674

2HDM potential, \( \mathcal{V}(\Phi_1, \Phi_2) \)

\[
= m_1^2 \phi_1^\dagger \phi_1 + m_2^2 \phi_2^\dagger \phi_2 - m_{12}^2 (\phi_1^\dagger \phi_2 + \text{h.c.}) \\
+ \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 \\
+ \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 |\phi_1^\dagger \phi_2|^2 \\
+ \frac{1}{2} \lambda_5 \left[ (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \right] \\
+ \left\{ \left[ \lambda_6 (\phi_1^\dagger \phi_1) + \lambda_7 (\phi_2^\dagger \phi_2) \right] \phi_1^\dagger \phi_2 + \text{h.c.} \right\}
\]

Out of considerations of simplicity, assume S to be Higgs-like, which is not too far fetched (see below)

2HDM+S potential

\[
\mathcal{V}(\Phi_1, \Phi_2) + \frac{1}{2} m_{S_0}^2 S^2 + \frac{\lambda_{S_1}}{2} \phi_1^\dagger \phi_1 S^2 \\
+ \frac{\lambda_{S_2}}{2} \phi_2^\dagger \phi_2 S^2 + \frac{\lambda_{S_3}}{4} (\phi_1^\dagger \phi_2 + \text{h.c.}) S^2 \\
+ \frac{\lambda_{S_4}}{4!} S^4 + \mu_1 \phi_1^\dagger \phi_1 S + \mu_2 \phi_2^\dagger \phi_2 S \\
+ \mu_3 \left[ \phi_1^\dagger \phi_2 + \text{h.c.} \right] S + \mu_S S^3.
\]
The model leads to rich phenomenology. Of particular interest are multilepton signatures.

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<tr>
<th>S. No.</th>
<th>Scalars</th>
<th>Decay modes</th>
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<tr>
<td>D.1</td>
<td>$h$</td>
<td>$b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $s\bar{s}$, $c\bar{c}$, $gg$, $\gamma\gamma$, $Z\gamma$, $W^+W^-$, $ZZ$</td>
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<td>$H$</td>
<td>D.1, $hh$, $SS$, $Sh$</td>
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<td>D.3</td>
<td>$A$</td>
<td>D.1, $t\bar{t}$, $Zh$, $ZH$, $ZS$, $W^\pm H^\mp$</td>
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<td>D.4</td>
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<td>D.5</td>
<td>$S$</td>
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<table>
<thead>
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<th>Scalar</th>
<th>Production mode</th>
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<tr>
<td>$H$</td>
<td>$gg \rightarrow H, Hjj$ ($ggF$ and VBF)</td>
<td>Direct SM decays as in Table 1, $SS/Sh \rightarrow 4W \rightarrow 4\ell + E_T^{miss}$, $hh \rightarrow \gamma\gamma b\bar{b}$, $b\bar{b}\tau\tau$, $4b$, $\gamma\gamma WW$ etc., $Sh$ where $S \rightarrow \chi\chi \Rightarrow \gamma\gamma$, $b\bar{b}$, $4\ell + E_T^{miss}$</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow Z(W^\pm)H$ ($H \rightarrow SS/Sh$)</td>
<td>$6(5)\ell + E_T^{miss}$, $4(3)\ell + 2j + E_T^{miss}$, $2(1)\ell + 4j + E_T^{miss}$</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow t\bar{t}H, (t+\bar{t})H$ ($H \rightarrow SS/Sh$)</td>
<td>$2W + 2Z + E_T^{miss}$ and $b$-jets, $6W \rightarrow 3$ same sign leptons + jets and $E_T^{miss}$</td>
</tr>
<tr>
<td>$H^\pm$</td>
<td>$pp \rightarrow tH^\pm$ ($H^\pm \rightarrow W^\pm H$)</td>
<td>$6W \rightarrow 3$ same sign leptons + jets and $E_T^{miss}$</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow t\bar{b}H^\pm$ ($H^\pm \rightarrow W^\pm H$)</td>
<td>Same as above with extra $b$-jet</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow H^\pm H^\mp$ ($H^\pm \rightarrow HW^\pm$)</td>
<td>$6W \rightarrow 3$ same sign leptons + jets and $E_T^{miss}$</td>
</tr>
<tr>
<td></td>
<td>$pp \rightarrow H^\pm W^\pm$ ($H^\pm \rightarrow HW^\pm$)</td>
<td>$6W \rightarrow 3$ same sign leptons + jets and $E_T^{miss}$</td>
</tr>
<tr>
<td>$A$</td>
<td>$gg \rightarrow A$ ($ggF$)</td>
<td>$t\bar{t}$, $\gamma\gamma$</td>
</tr>
<tr>
<td></td>
<td>$gg \rightarrow A \rightarrow ZH$ ($H \rightarrow SS/Sh$)</td>
<td>Same as $pp \rightarrow ZH$ above, but with resonance structure over final state objects</td>
</tr>
<tr>
<td></td>
<td>$gg \rightarrow A \rightarrow W^\pm H^\mp$ ($H^\mp \rightarrow W^\pm H$)</td>
<td>$6W$ signature with resonance structure over final state objects</td>
</tr>
</tbody>
</table>
For simplicity we will assume that the S decays like the SM Higgs boson.

Results using N2HDECAY (arXiv:1612.01309) for one benchmark point.
Results using N2HDECAY (arXiv:1612.01309) for one benchmark point.
Results using N2HDECAY (arXiv:1612.01309) for one benchmark point
The data reported with Run I and Run II by ATLAS overshoots the MC with $M_T<200$ GeV. The 4W prediction is not excluded with the current results.
Minimised sum of combinatoric opposite sign lepton $\Delta \phi$

Minimised $\Delta R$ of opposite sign lepton pairs

Minimised $\Delta R$ of $\Delta \phi$ matched lepton pairs

Transverse momentum of four lepton system
Impact on h boson measurements

- The most prominent feature pertains to additional production mechanism (i.e. $H \rightarrow Sh$) of $h$ with large jet activity (from $S \rightarrow$ jets, model dependency). Expect distortion of the $p_T$ spectrum, as well.

- At this point we are studying the contamination of the $H \rightarrow Sh$ production mechanism on measurement with hadronic final states: $h+\geq 2j$, VBF, $V(\rightarrow jj)h$, $Vh(\rightarrow bb)$ (not discussed here) $h$ signal strengths.
\[ \sigma(H) = 10 \text{ pb} \]

Table 1. Expected yields for 36 fb\(^{-1}\) of integrated luminosity for 13 TeV proton-proton center of mass energy for the VBF, \(\nu h\) event selections described in Secs. 3.1 and 3.2. The \(H \to S h\) production mechanism is compared to SM associated production mechanisms. Errors correspond to the statistical error of the MC sample.

<table>
<thead>
<tr>
<th>Production mechanism</th>
<th>VBF (h \to \gamma\gamma)</th>
<th>(V h, V \to j j, h \to \gamma\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H(270) \to S(140)h(\to \gamma\gamma))</td>
<td>2.86(\pm)0.07</td>
<td>0.16(\pm)0.02</td>
</tr>
<tr>
<td>(H(270) \to S(150)h(\to \gamma\gamma))</td>
<td>1.94(\pm)0.06</td>
<td>1.14(\pm)0.04</td>
</tr>
<tr>
<td>(H(270) \to S(160)h(\to \gamma\gamma))</td>
<td>2.89(\pm)0.07</td>
<td>1.97(\pm)0.06</td>
</tr>
<tr>
<td>(W h(\to \gamma\gamma))</td>
<td>0.22(\pm)0.01</td>
<td>1.90(\pm)0.03</td>
</tr>
<tr>
<td>(Z h(\to \gamma\gamma))</td>
<td>0.14(\pm)0.01</td>
<td>1.31(\pm)0.02</td>
</tr>
<tr>
<td>(t t h(\to \gamma\gamma))</td>
<td>0.09(\pm)0.00</td>
<td>0.22(\pm)0.01</td>
</tr>
<tr>
<td>VBF (h(\to \gamma\gamma))</td>
<td>25.81(\pm)0.20</td>
<td>0.30(\pm)0.02</td>
</tr>
</tbody>
</table>
The data is somewhat harder than the SM, but not to a degree that is significant. Plots here are displayed as a consistency check. The Higgs boson $p_T$ on its own does not provide a convincing argument.
# Limits on $h(\rightarrow \gamma\gamma)+\text{MET}$

<table>
<thead>
<tr>
<th>Category</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-Higgs</td>
<td>$S_{E_T}^{miss} &gt; 7 \sqrt{\text{GeV}}, \ p_T^{\gamma\gamma} &gt; 90 \text{ GeV}, \text{ lepton veto}$</td>
</tr>
<tr>
<td>High-$E_T^{miss}$</td>
<td>$S_{E_T}^{miss} &gt; 5.5 \sqrt{\text{GeV}}, \</td>
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<tr>
<td>Intermediate-$E_T^{miss}$</td>
<td>$S_{E_T}^{miss} &gt; 4 \sqrt{\text{GeV}}, \ p_T^{\text{hard}} &gt; 40 \text{ GeV}, \</td>
</tr>
<tr>
<td>Different-Vertex</td>
<td>$S_{E_T}^{miss} &gt; 4 \sqrt{\text{GeV}}, \ p_T^{\text{hard}} &gt; 40 \text{ GeV}, \</td>
</tr>
<tr>
<td>Rest</td>
<td>$p_T^{\gamma\gamma} &gt; 15 \text{ GeV}$</td>
</tr>
</tbody>
</table>

\[
S_{E_T}^{miss} = E_T^{miss} / \sqrt{\sum E_T}
\]
ATLAS, arXiv:1706.03948

\[ \text{Br}(S \rightarrow \chi\chi) < 50\% \]

- Observed
- Expected
- Expected ± 1σ
- Expected ± 2σ
- \( \sigma_{\text{th}} \times \text{B}(H \rightarrow \gamma\gamma\chi\chi) \)

\( pp \rightarrow H \rightarrow h(\gamma\gamma) + \chi\chi \), Heavy scalar model

\( m_\chi = 60 \text{ GeV}, \text{B}(H \rightarrow h\chi\chi) = 100\% \)
Enhancement of tH production

- In experiment, top associated Higgs production is measured as a sum of single top and double top cross sections.

- In the SM, we find that \( \sigma_{th} \ll \sigma_{tth} \)

\[
A = \frac{g}{\sqrt{2}} \left[ (c_F - c_V) \frac{m_t \sqrt{s}}{m_W v} A \left( \frac{t}{s}, \varphi; \xi_t, \xi_b \right) + \left( c_V \frac{2m_W s}{v} - (2c_F - c_V) \frac{m_t^2}{m_W v} \right) B \left( \frac{t}{s}, \varphi; \xi_t, \xi_b \right) \right]
\]

- For the heavy scalar considered here, \( c_V \ll c_F \)

- We expect a sizeable cross section to come from top associated heavy scalar production \( (\sigma_{tH} \approx \sigma_{tth}) \)

Performed scan floating $m_S$ ($m_H=270$ GeV), for $m_{ll}<100$ GeV

Best fit 145$\pm$5 GeV.

\[ N_{Obs.} = 400 \pm 96 \]
\[ N_{Exp.} = 175 \pm 70 \]

For $m_{ll}<100$ GeV

\[ \chi^2_{SM} - \chi^2_{BSM} = 11.44 \]
\[ 3.38 \sigma \]

Normalize MC to data with $m_{ll}>110$ GeV.

Take into account difference between POWHEG and MC@NLO in shape of $m_{ll}$
Fit results: ATLAS-EXOT-2013-16

Events / 10 GeV

Events / 50 GeV

m_{h} = 270 GeV / m_{g} = 150 GeV

\theta_{g}^{2} = 6.51

ATLAS_EXOT_2013_16
Top control sample with exactly two leptons, one b-jet and no more jets. Expect strong relative enhancement of Wt w.r.t. tt. MC studies in progress.
Wt/tt studies

- To understand structure in the transverse mass spectrum reported in the previous slide, have been trying to understand theoretical uncertainties with state-of-the-art MCs. This includes:
  - DR vs DS schemes of double counting removal
  - PDF studies
  - Scale uncertainties
  - Pythia versus Herwig (in progress) PS
  - Using 2b4l, which contains the complete set of WWbb diagrams (in progress)
  - Need to incorporate the MC@NLO MC (in progress)
| Region | $N_{\ell}$ | $p_T\{\ell_{Z_1},\ell_{Z_2},\ell_W,\ell\}$ [GeV] | $N_{\text{OSSF}}$ | $|M(\ell_{Z_1}\ell_{Z_2})-m_Z|$ [GeV] | $p_T^{\text{miss}}$ [GeV] | $N_{\text{b tag}}$ | $\min(M(\ell\ell'))$ [GeV] | $M(\ell_{Z_1}\ell_{Z_2}\ell_W)$ [GeV] |
|--------|-------------|-----------------|----------------|-------------------------------|-----------------|--------------|----------------|-----------------------------|
| SR     | 3           | > \{25, 10, 25\} | $\geq 1$ | $< 15$ | $> 30$ | $= 0$ | $> 4$ | $> 100$ |
| CR-top | 3           | > \{25, 10, 25\} | $\geq 1$ | $> 5$ | $> 30$ | $> 0$ | $> 4$ | $> 100$ |
| CR-ZZ  | 4           | > \{25, 10, 25, 10\} | $\geq 1$ | $< 15$ | $> 30$ | $= 0$ | $> 4$ | $> 100$ |
| CR-Conv| 3           | > \{25, 10, 25\} | $\geq 1$ | $> 15$ | $\leq 30$ | $= 0$ | $> 4$ | $< 100$ |
The distortion of the $\Delta \phi_{ll}$ spectrum is already present in Run 1, although statistically less compelling than in Run 2 for obvious reasons.

**CMS**

- 19.5 fb$^{-1}$ (8 TeV)
- Data
- $t\bar{t} \rightarrow l^+l^-$
- Background

**ATLAS**

- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- Data
- SM $t\bar{t}$
- $t\bar{t}$ (A=0)
- Background
- $t\bar{t}$, 180 GeV
- $t\bar{t}$, 180 GeV
- Fit

**MC@NLO**

- 3.41
- 4.06

**HERWIG**

- 6.520
- 6.520

**CTEQ6M**

- CT10
\[ p_{T\ell} > 25 \text{ GeV} \]
\[ p_{Tb} > 25 \text{ GeV} \]
\[ N_{bjet} \geq 1 \]

Discrepancy in ATLAS is localized at small values of \( m_{ll} \)
Event selection with exactly two leptons (e,μ), \( m_{ll} > 20 \text{ GeV} \) and at least 2b-jets

Some MC describe \( m_{ll} \), but fail the b-jet kinematics
Correct Powheg to describe \( m_{ll} \) distribution (see below)
None of the MCs studied is able to describe simultaneously the kinematics of top decay products. $M_T$ of the dilepton and MET system is not shown.

Table 3: The $\chi^2$/ndof and p values quantifying the agreement between theoretical predictions and data for normalised, particle-level measurements are shown.

<table>
<thead>
<tr>
<th></th>
<th>PowHEG+PyTHIA8</th>
<th>PowHEG+HERWIG++</th>
<th>MG5_aMC@NLO+PYTHIA8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^l$ (leading)</td>
<td>244/4</td>
<td>$&lt; 10^{-3}$</td>
<td>5/4</td>
</tr>
<tr>
<td>$p_T^l$ (trailing)</td>
<td>163/4</td>
<td>$&lt; 10^{-3}$</td>
<td>9/4</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>143/7</td>
<td>$&lt; 10^{-3}$</td>
<td>4/7</td>
</tr>
<tr>
<td>$\Delta\phi(l,\ell)$</td>
<td>35/9</td>
<td>$&lt; 10^{-3}$</td>
<td>17/9</td>
</tr>
<tr>
<td>$\Delta</td>
<td>\eta</td>
<td>(l,\ell)$</td>
<td>7/9</td>
</tr>
<tr>
<td>$N_{\text{jets}}$</td>
<td>13/5</td>
<td>0.022</td>
<td>38/5</td>
</tr>
<tr>
<td>$p_T^b$ (leading)</td>
<td>32/4</td>
<td>$&lt; 10^{-3}$</td>
<td>75/4</td>
</tr>
<tr>
<td>$p_T^b$ (trailing)</td>
<td>28/4</td>
<td>$&lt; 10^{-3}$</td>
<td>135/4</td>
</tr>
<tr>
<td>$\eta_b$ (leading)</td>
<td>12/7</td>
<td>0.114</td>
<td>15/7</td>
</tr>
<tr>
<td>$\eta_b$ (trailing)</td>
<td>16/7</td>
<td>0.024</td>
<td>16/7</td>
</tr>
<tr>
<td>$p_T^{bb}$</td>
<td>25/4</td>
<td>$&lt; 10^{-3}$</td>
<td>326/4</td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>3/3</td>
<td>0.371</td>
<td>17/3</td>
</tr>
</tbody>
</table>
## SS ll+b-jets: JHEP 10 (2015) 150

<table>
<thead>
<tr>
<th>Definition</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm e^\pm + e^\pm \mu^\pm + \mu^\pm \mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu, N_j \geq 2$</td>
<td></td>
</tr>
<tr>
<td>$400 &lt; H_T &lt; 700$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 40$ GeV</td>
</tr>
<tr>
<td>$N_b = 1$</td>
<td>SRVLQ0</td>
</tr>
<tr>
<td>$N_b = 2$</td>
<td>SRVLQ1</td>
</tr>
<tr>
<td>$N_b \geq 3$</td>
<td>SRVLQ2</td>
</tr>
<tr>
<td>$H_T \geq 700$ GeV</td>
<td></td>
</tr>
<tr>
<td>$N_b = 1$</td>
<td>$40 &lt; E_T^{\text{miss}} &lt; 100$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} \geq 100$ GeV</td>
<td>SRVLQ3</td>
</tr>
<tr>
<td>$N_b = 2$</td>
<td>$40 &lt; E_T^{\text{miss}} &lt; 100$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} \geq 100$ GeV</td>
<td>SRVLQ5</td>
</tr>
<tr>
<td>$N_b \geq 3$</td>
<td>$E_T^{\text{miss}} &gt; 40$ GeV</td>
</tr>
<tr>
<td>$e^+e^+, e^+\mu^+, \mu^+\mu^+, N_j \in [2,4], \Delta \phi_{\ell\ell} &gt; 2.5$</td>
<td></td>
</tr>
<tr>
<td>$H_T &gt; 450$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 40$ GeV</td>
</tr>
<tr>
<td>$N_b \geq 1$</td>
<td>SRtt\text{ee}, SRtt\text{e}\mu, SRtt\mu\mu</td>
</tr>
</tbody>
</table>
# SS II + b-jets: ATLAS-EXOT-2016-16

<table>
<thead>
<tr>
<th>Region name</th>
<th>$N_j$</th>
<th>$N_b$</th>
<th>$N_\ell$</th>
<th>Lepton charges</th>
<th>Kinematic criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR1$b2\ell$</td>
<td>$\geq 1$</td>
<td>1</td>
<td>2</td>
<td>++ or --</td>
<td>$400 &lt; H_T &lt; 2400 \text{ GeV}$ or $E_T^{\text{miss}} &lt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td>SR1$b2\ell$</td>
<td>$\geq 1$</td>
<td>1</td>
<td>2</td>
<td>++ or --</td>
<td>$H_T &gt; 1000 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 180 \text{ GeV}$</td>
</tr>
<tr>
<td>VR2$b2\ell$</td>
<td>$\geq 2$</td>
<td>2</td>
<td>2</td>
<td>++ or --</td>
<td>$H_T &gt; 400 \text{ GeV}$</td>
</tr>
<tr>
<td>SR2$b2\ell$</td>
<td>$\geq 2$</td>
<td>2</td>
<td>2</td>
<td>++ or --</td>
<td>$H_T &gt; 1200 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td>VR3$b2\ell$</td>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
<td>2</td>
<td>++ or --</td>
<td>$400 &lt; H_T &lt; 1400 \text{ GeV}$ or $E_T^{\text{miss}} &lt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td><strong>SR3$b2\ell$</strong></td>
<td><strong>$\geq 7$</strong></td>
<td><strong>$\geq 3$</strong></td>
<td>2</td>
<td>++ or --</td>
<td>$500 &lt; H_T &lt; 1200 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td><strong>SR3$b2\ell$</strong></td>
<td><strong>$\geq 3$</strong></td>
<td><strong>$\geq 3$</strong></td>
<td>2</td>
<td>++ or --</td>
<td>$H_T &gt; 1200 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 100 \text{ GeV}$</td>
</tr>
<tr>
<td>VR1$b3\ell$</td>
<td>$\geq 1$</td>
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<td>3</td>
<td>any</td>
<td>$400 &lt; H_T &lt; 2000 \text{ GeV}$ or $E_T^{\text{miss}} &lt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td>SR1$b3\ell$</td>
<td>$\geq 1$</td>
<td>1</td>
<td>3</td>
<td>any</td>
<td>$H_T &gt; 1000 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 140 \text{ GeV}$</td>
</tr>
<tr>
<td>VR2$b3\ell$</td>
<td>$\geq 2$</td>
<td>2</td>
<td>3</td>
<td>any</td>
<td>$400 &lt; H_T &lt; 2400 \text{ GeV}$ or $E_T^{\text{miss}} &lt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td>SR2$b3\ell$</td>
<td>$\geq 2$</td>
<td>2</td>
<td>3</td>
<td>any</td>
<td>$H_T &gt; 1200 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 100 \text{ GeV}$</td>
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<tr>
<td>VR3$b3\ell$</td>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
<td>3</td>
<td>any</td>
<td>$H_T &gt; 400 \text{ GeV}$</td>
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<tr>
<td><strong>SR3$b3\ell$</strong></td>
<td><strong>$\geq 5$</strong></td>
<td><strong>$\geq 3$</strong></td>
<td>3</td>
<td>any</td>
<td>$500 &lt; H_T &lt; 1000 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 40 \text{ GeV}$</td>
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<tr>
<td><strong>SR3$b3\ell$</strong></td>
<td><strong>$\geq 3$</strong></td>
<td><strong>$\geq 3$</strong></td>
<td>3</td>
<td>any</td>
<td>$H_T &gt; 1000 \text{ GeV}$ and $E_T^{\text{miss}} &gt; 40 \text{ GeV}$</td>
</tr>
</tbody>
</table>
Compatibility with Higgs data

- Signal strength from fiducial cross-sections with diphotons and \( h \to ZZ^* \to 4l \) and \( H \to WW \to ll \) with Run 2 results stands at \( 1.15 \pm 0.06 \) (exp), which would lead to \( \beta_g^2 \approx 1 \). This would have some tension with the result of \( \beta_g^2 = 2.80 \pm 0.35 \) obtained above.

- Within the 2HDM+S this can be resolved by either considering \( H \to SS \) decays or allowing \( m_H < m_S + m_h \). The latter leads to \( H \to S^* h, S h^* \), resolving the tension.

- Recent results from ATLAS using \( H \to SS \to 4W \to 4l \) decays rule out \( m_H > 280 \) GeV decaying to SS (on-shell).

- This leaves the option where \( m_H < m_S + m_h \) to be investigated as it is not excluded with the current limits and requires re-optimization.
The GAMBIT collaboration, arXiv:1809.02097

Study of multi-leptons, where largest excess comes from the ATAS recursive jigsaw search with three leptons

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Best expected SRs</th>
<th>All SRs; neglect correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local signif. (σ)</td>
<td>SM fit (σ)</td>
</tr>
<tr>
<td>Higgs invisible width</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Z invisible width</td>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>ATLAS_4b</td>
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<td>0</td>
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<td>0</td>
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<tr>
<td>ATLAS_MultiLep_3lep</td>
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<td>ATLAS_RJ_2lep_2jet</td>
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<td>0.3</td>
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</tr>
<tr>
<td>CMS_1lep_2b</td>
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<tr>
<td>CMS_2lep_soft</td>
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</tr>
<tr>
<td>CMS_2OSlep</td>
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</tr>
<tr>
<td>CMS_MultiLep_2SSlep</td>
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<td>0</td>
</tr>
<tr>
<td>CMS_MultiLep_3lep</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Combined</td>
<td>3.5</td>
<td>1.5</td>
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</tbody>
</table>
(Z→ll)+l' with m_T>100 GeV

### ATLAS, arXiv:1806.02293

<table>
<thead>
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<tbody>
<tr>
<td>CR3ℓ-VV</td>
<td>3</td>
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<td>&gt; 60</td>
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<td>&gt; 40</td>
<td>&gt; 30</td>
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<table>
<thead>
<tr>
<th>Region</th>
<th>m_{ll} [GeV]</th>
<th>m_T^W [GeV]</th>
<th>H_{3,1}^{PP} [GeV]</th>
<th>\frac{p_{T}^{ll}}{p_{T}^{W,PP}}</th>
<th>\frac{H_{3,1}^{PP}}{H_{3,1}^{W}}</th>
<th>H_{3,1}^{W}</th>
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<tbody>
<tr>
<td>CR3ℓ-VV</td>
<td>(75, 105)</td>
<td>(0, 70)</td>
<td>&gt; 250</td>
<td>&lt; 0.2</td>
<td>&gt; 0.75</td>
<td>-</td>
</tr>
<tr>
<td>VR3ℓ-VV</td>
<td>(75, 105)</td>
<td>(70, 100)</td>
<td>&gt; 250</td>
<td>&lt; 0.2</td>
<td>&gt; 0.75</td>
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<tr>
<td>SR3ℓ_High</td>
<td>(75, 105)</td>
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<td>SR3ℓ_Int</td>
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<td>&gt; 450</td>
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<td>&gt; 250</td>
<td>&lt; 0.05</td>
<td>&gt; 0.9</td>
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</table>

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**ATLAS**

*ls = 13 TeV, 36.1 fb^{-1}*

**SR3ℓ_Low**

- Data
- VV
- Other
- VVV
- Bkg. Uncert.

**SR3ℓ_ISR**

- Data
- VV
- Bkg. Uncert.
BSM inputs to the fit

The following assumptions are made:

a. The masses of $H$ and $S$ are fixed to $m_H = 270$ GeV and $m_S = 150$ GeV

b. The only significant production mechanisms of $H$ come from the $t\bar{t}-H$ Yukawa coupling:
   - Gluon fusion
   - Top associated production

c. The Yukawa coupling is scaled away from the SM Higgs-like value by the free parameter $\beta_g$

d. The BR of $H \rightarrow Sh$ is fixed to 100%

e. The BRs of $S$ are Higgs-like

Therefore, the only free parameter in the fits is $\beta_g^2$
The HistFactory method

- Constructs a likelihood function from template histograms
- Allows for a simple implementation of systematic uncertainties that affect normalisation and/or shape

\[
P(n_{cb}, a_p | \phi_p, \alpha_p, \gamma_b) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}) \cdot G(L_0 | \lambda, \Delta L) \cdot \prod_{p \in S + \Gamma} f_p(a_p | \alpha_p)
\]

In our case, each “channel” is a different measurement.
The Poisson probability for the “expected” and “observed” number of events per bin.
Functional form of luminosity and its variations (not necessary for us).
Functional form of systematic variation with nuisance parameter \( \alpha_p \).

The fitting procedure

- The RooStats workspace is made by HistFactory
- From the workspace, a profile likelihood ratio is calculated,
  \[
  \lambda (\beta_g^2) = \frac{L(\beta_g^2 | \hat{\theta})}{L(\hat{\beta}_g^2 | \hat{\theta})}
  \]
  (here \( \theta \) denotes the nuisance parameters)

- The best-fit value of \( \beta_g^2 \) is then calculated as the minimum of \(-2\log(\lambda)\), with an error corresponding to a unit of deviation in this quantity from the best-fit point
- The significance is calculated as \( \sqrt{-2 \log \lambda(0)} \), since \( \beta_g^2 = 0 \) corresponds to the SM-only hypothesis
Measurements considered in the fit

- Results sensitive to the production of multiple leptons in association with jets, including $b$-tagged jets

<table>
<thead>
<tr>
<th>Report number</th>
<th>Description</th>
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<tbody>
<tr>
<td>ATLAS-EXOT-2013-16</td>
<td>ATLAS Run 1 search for 2 or 3 same-sign leptons with multiple $b$-tagged jets (with a VLQ interpretation)</td>
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<td>ATLAS-TOPQ-2015-02</td>
<td>ATLAS Run 1 differential distributions for top pair production</td>
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<td>ATLAS-EXOT-2016-16</td>
<td>ATLAS Run 2 search for 2 or 3 same-sign leptons with multiple $b$-tagged jets</td>
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<td>CMS-PAS-HIG-17-005</td>
<td>CMS Run 2 search for 2 or 3 same-sign leptons with multiple $b$-tagged jets</td>
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<td>CMS-TOP-17-018</td>
<td>CMS Run 2 single top production cross section measurement</td>
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<td>ATLAS-CONF-2018-027</td>
<td>ATLAS Run 2 spin correlations for top pair production</td>
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