Searches for BSM Scalars at ATLAS

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On behalf of the ATLAS Collaboration
University of Michigan
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Motivation

• Searches for Beyond the Standard Model (BSM) physics remain a key component of the LHC physics programme.
• Vast parameter-space of BSM scenarios under exploration, focus on Scalar resonance decays.
  • Axion-like Particles (ALP’s)
  • Light pseudo-scalars (Hidden Abelian Higgs Models)
  • 2(3)HDM Searches
  • Next-to-Minimal Supersymmetric SM (NMSSM)
  • Randall-Sundrum Model
  • (Higgs) EFT-Interpretations
• *All analysis presented use full Run-2 dataset.

<table>
<thead>
<tr>
<th>Scalar Signature</th>
<th>Final-State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm H$</td>
<td>$l^\pm v^\pm jj$</td>
</tr>
<tr>
<td>$X$</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>$X^\pm, X^0$</td>
<td>$W^\pm \gamma, Z\gamma$</td>
</tr>
<tr>
<td>$a$</td>
<td>$\mu\mu$</td>
</tr>
<tr>
<td>$X \rightarrow SH$</td>
<td>$VV\tau\tau$</td>
</tr>
<tr>
<td>$H^{\pm} b_2(W^{\mp} b_1)$</td>
<td>$cbb(lv\bar{b})$</td>
</tr>
<tr>
<td>$A \rightarrow Z(H)$</td>
<td>$ll(t\bar{t})/v\bar{v}(bb)$</td>
</tr>
<tr>
<td>$V_{hh}$</td>
<td>$b\bar{b}b\bar{b}$ $(lv),(vv),(ll)$</td>
</tr>
<tr>
<td>$X^0$</td>
<td>$WW,WW(jj), ZZ, ZZ(jj)$</td>
</tr>
</tbody>
</table>
\[ W^\pm H \rightarrow W^\pm W^\pm W^\mp \]

  - Targets same-sign di-lepton final state \( W^\pm W^\pm W^\mp \rightarrow l^\pm \nu l^\pm \nu j j \)
  - Includes EFT interpretations, scanning across \((f_W, f_{WW})\)
    - Model-Independent, Higgs, \(m_H\): (0.3 \(\rightarrow\) 1.5 TeV)
Boosted Di-photon Resonance Search

- Probes low-mass range by targeting closely spaced photons with $p_T^{\gamma\gamma} > 50$ GeV to overcome trigger thresholds.
  - Prior searches cover only $m_{\gamma\gamma} > 65$ GeV
  - Highest observed excess at $m_\chi = 19.4$ GeV, 3.1σ local (1.5σ global)
High Mass $W\gamma/Z\gamma$ Resonances

- Searches for charged, and neutral resonances, probing $V$ decays in boosted channel.
  - $q\bar{q}' \rightarrow X^\pm \rightarrow W^\pm \gamma$ (*Spin-1*)
  - $gg(q\bar{q}) \rightarrow X^0 \rightarrow Z\gamma$ *Spin-0/(2)*

- 2 sets of complimentary analysis
  - **Hadronic Z decay** (Large-R jet) [arXiv:2304.11962]
    - Best sensitivity for $M_X > 2$ TeV
  - **Leptonic Z decay** *(NEW RESULT!)* [ATLAS-CONF-2023-030]
    - Utilizes dedicated MVA to improve sub leading electron identification
  - **Analytical function to model background**
  - No significant deviations of data from predicted background observed
    - Largest local significance ($2.5\sigma$) @ $m_X=3640$ GeV (*Z-Hadronic*)
**a → μμ in association w/ tt̅**

- Direct pseudo-scalar production, and via charged Higgs boson decay.
- Targets di-muon decays, for high mass resolution.
  - $15 < m_a < 72$ GeV & $120 < m_{H^+} < 160$ GeV
- Overall no significant excesses observed
  - Excess at $m_a = 27$ GeV → $2.7\sigma$ (local)
- Set $\sigma(ttâ)x B(a → μμ)$ upper-limits
  - $(0.5 - 3)$ fb @ 95% CL
- Set $B(t → bH^+ → W^+ a → μμ)$ upper-limits
  - $(0.9 - 3.9) \times 10^{-6}$ @ 95% CL (see backup)
\(X \rightarrow SH \rightarrow VV(\tau\tau)\)

- Probes \(H \rightarrow \tau\tau\) (hadronic) and \(V \rightarrow \) (leptonically)
  - Explores \(M_X \rightarrow \{500,1500\} \text{ GeV}, M_S \rightarrow \{200,500\} \text{ GeV}\) parameter-space
  - Targets \((ZZ) \ 2l2\tau_{\text{had}}, (WW) \ 2l2\tau_{\text{had}}, (WW) \ 1l2\tau_{\text{had}}\) final states

- \(V+\text{jets} \rightarrow \) fake \(\tau_{\text{had}}\) dominant background
  - Estimated with FF method
  - B-jet veto for background suppression

- Utilizes BDT discriminant parametrized over \(M_X\)

- Production x-section upper limits derived (@ 95%CL):
  - \(\sigma(pp \rightarrow X \rightarrow SH) \leftrightarrow 542 \text{ fb's}\)
  - \(\sigma(pp \rightarrow X \rightarrow SH \rightarrow ZZ\tau\tau) \leftrightarrow 33 \text{ fb's}\)
  - \(\sigma(pp \rightarrow X \rightarrow SH \rightarrow WW\tau\tau) \leftrightarrow 26 \text{ fb's}\)
Light, charged Higgs Production

- Search for $t\bar{t} \rightarrow H^\pm b(W^\mp b) \rightarrow cbb(lvb)$
  - 3HDM interpretations cast
- Segments analysis regions based on jet and b-jet multiplicities
  - Allows data-driven corrections to $t\bar{t}$ (mis)modelling
- Employs NN (parametrized over $m_{H^\pm}$) discriminant for enhanced signal-background separation
- Largest excess: $m_{H^\pm} = 130$ GeV
  - Local (global) significance 3\(\sigma\) (2.5\(\sigma\))
- Upper-limits on $\text{Br}(t \rightarrow H^\pm b) \times \text{Br}(H^\pm \rightarrow cb)$ derived
  - $(0.15 - 0.42)\%$ for $60 < m_{H^\pm} < 160$ GeV (assuming SM $t\bar{t}$ production)
  - Similar CMS-search reports upper-limits of $(0.8 - 0.5)\%$ for $90 < m_{H^\pm} < 150$ GeV
(CP-odd) $A \rightarrow ZH$ (Heavy Higgs)

- Prior $A \rightarrow ZH$ searches look for $Z \rightarrow ll, H \rightarrow b\bar{b}, WW, \tau\tau, hh$
- Probes (2) novel final-states $A \rightarrow Z(H) \rightarrow ll(t\bar{t})/\nu\bar{\nu}(b\bar{b})$
  - Search covers $(m_A, m_H) > (800,300)$ GeV (narrow-width H)
- $ll(t\bar{t})$ Channel
  - Exactly 3 leptons, 2 b-jets, and $\geq 4$ jets, (sliding) mass window $|M_H^{\text{Cand}} - M_H^{\text{hypo}}| \text{ cut}$
  - Targets unexplored $m_H > 2*m_{\text{top}}$ parameter-space
  - Novel LHC search at 13 TeV!
- $\nu\bar{\nu}(b\bar{b})$
  - $\geq 2$ jets, (==2 or $\geq 3$) b-tag jets categories
  - $E_T^{\text{Miss}} > 150$ GeV, (sliding) mass window $|M_H^{\text{Cand}} - M_H^{\text{hypo}}| < 0.2 * M_H^{\text{hypo}}$
  - First LHC search for high $m_{b\bar{b}}$ resonances + MET
- Search effectively probes $m_H > 350$ GeV and high $m_A$ for $m_H < 350$ GeV

NEW RESULT!
ATLAS-CONF-2023-034
(CP-odd) $A \rightarrow ZH$ (Heavy Higgs) Results

- Binned profile likelihood of $m_A - m_H$ ($ll\bar{t}\bar{t}$), $m_{T'}^A$ ($vvbb$)
  - No significant data excesses from bkg-only hypothesis found
  - Small Excess: $(m_A, m_H) = (650,450)$ GeV in $ll\bar{t}\bar{t}$-channel w/ 2.85$\sigma$ (local)
Resonant and SM Vhh Production

- Search for Higgs boson pair-production in association with a $V$ boson
  - Targets $hh \rightarrow b\bar{b}b\bar{b}$ w/ $(W/Z) \rightarrow lv, vv, ll$ final states
- Probes $VH \rightarrow Vhh$ (Higgstrahlung) & $A \rightarrow ZH$ (2HDM)
  - Overall several data-excesses observed!

Large excess @ $(m_A, m_H) = (420,320)$ GeV
- local (global) $3.8\sigma$ ($2.8\sigma$)

95%-CL Upper-limit couplings (ATLAS)
- $-34.4$ (-24.1) $< K_\lambda < 33.3$ (22.9)
- $-8.6$ (-5.7) $< K_{2V} < 10.0$ (7.1)
- $\mu_{obs}$ (exp) $= 183$ ($87^{+41}_{-24}$)

95%-CL Upper-limit couplings (CMS)
- $-37.7$ (-30.1) $< K_\lambda < 37.2$ (28.9)
- $-12.2$ (-7.64) $< K_{2V} < 13.5$ (8.9)
- $\mu_{obs}$ (exp) $= 294$ (124)

Small excess @ $(m_H) = (315)$ GeV
- local (global) $2.5\sigma$ ($1.3\sigma$)
Di-boson Resonance Summary

• Summary of all ATLAS Run-2 di-boson searches
  • \(WW, WZ, ZZ, WH, ZH, \gamma\gamma\).

95% CL-Exclusion limits for \(X \rightarrow WW\) in ggF (Left) and VBF (Right) production. (Interpreted in context of RS-model)

95% CL-Exclusion limits for \(X \rightarrow ZZ\) in ggF (Left) and VBF (Right) production. (Interpreted in context of narrow-width X approximation)
Closing Thoughts

• Many interesting new Run-2 analyses searching for BSM scalars!
  • Please see Miaoran’s and Rocky’s talks
  • Wide variety of models, parameter space under exploration!
  • No direct evidence of new physics yet, but several hints of where to look in Run-3.

• Expected improved object identification, and reconstruction from major Run-2 upgrades (LAr Calorimeter, NSW, Trigger & DAQ)

• Novel analysis techniques continue to be developed
  • Combined with more data → expect improved search performance

• Thank you!

5/23/2023
Backup
VH-Channel Generic Heavy Higgs Production

- Utilizes a separate boosted and resolved category.
- Applies a data-driven techniques to estimate fake and non-prompt lepton backgrounds.
- Effective mass ($m_{\text{eff}}$) defined as sum of $p_T$ and MET of all final-state objects.
Boosted Di-photon Resonance Search

- Performs $m_{\gamma\gamma}$ fit using a double-sided Crystal Ball and analytic function (tuned to account for SS and applied GP-Reduction)
  - $\gamma j$ & $jj$ contributions built from data CR’s, $\gamma\gamma$ from MC
  - Less than (1%) differences of the fitted signal yield

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-up modelling</td>
<td>$\pm 3.5$ (at 10 GeV) to $\pm 2$ (beyond 15 GeV), mass dependent</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>$\pm 2.5$ to $\pm 2.7$, mass dependent</td>
</tr>
<tr>
<td>Scale and PDFs uncertainties</td>
<td>$\pm 2.5$ to $\pm 0.5$, mass dependent</td>
</tr>
<tr>
<td>Trigger on closely spaced photons</td>
<td>$\pm 2$ (at 10 GeV) to $&lt;0.1$ (beyond 35 GeV), mass dependent</td>
</tr>
<tr>
<td>Photon identification</td>
<td>$\pm 2.0$</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>$\pm 2.0$</td>
</tr>
<tr>
<td>Luminosity (2015–2018)</td>
<td>$\pm 1.7$</td>
</tr>
<tr>
<td>Trigger</td>
<td>$\pm 1.0$</td>
</tr>
<tr>
<td>Signal shape modelling</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>negligible</td>
</tr>
</tbody>
</table>

**Background modelling**
- Spurious signal (relative to $\delta S$) 30-65 events (10%-30%), mass dependent
High Mass $W\gamma/Z\gamma$ Resonances

\[ \mathcal{B}(m_{J\gamma}; p) = (1 - x)^{p_1}x^{p_2}p_3 \log(x) \]

\[ S(m_{J\gamma}, N, \mu, \sigma, \alpha_1, \alpha_2, \rho) = N \cdot \exp \left( \frac{(m_{J\gamma} - \mu)^2}{2\sigma^2} \right) \left[ \frac{\exp \left( \frac{m_{J\gamma} - \mu}{\sigma} \right)}{2\sigma} \left( \frac{m_{J\gamma} - \mu}{\sigma} \right) \right] \]

\[ -\alpha_1 \leq \frac{m_{J\gamma} - \mu}{\sigma} \leq \alpha_1, \quad -\alpha_2 \leq \frac{m_{J\gamma} - \mu}{\sigma} \leq \alpha_2 \]

\[ 0 < m_{J\gamma} < \sigma. \]

\[ m_{J\gamma} \text{ in GeV} \]

\[ m_x \text{ in GeV} \]

\[ 5/23/2023 \]
a → 𝜇𝜇 in Association w/ tt̅
$X \rightarrow SH \rightarrow VV(\tau\tau)$

<table>
<thead>
<tr>
<th>Channels</th>
<th>Selections</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW1\ell2\tau_{\text{had}}$</td>
<td>exactly one light lepton (electron or muon): $p_T &gt; 27$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>exactly two RNN medium $\tau_{\text{had}}$ with opposite-sign: $p_T &gt; 20$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>$\Delta R$ between two $\tau_{\text{had}}$ candidates: $\Delta R(\tau_{\ell}, \tau_{\tau}) \leq 2$</td>
</tr>
<tr>
<td></td>
<td>number of jets and $b$-jets: $N_{\text{jets}} \geq 2$ and $N_{b-jets} = 0$</td>
</tr>
<tr>
<td>$WW2\ell2\tau_{\text{had}}$</td>
<td>exactly two light leptons with opposite-sign: $p_T &gt; 10$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>exactly two RNN medium $\tau_{\text{had}}$ with opposite-sign: $p_T &gt; 20$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>invariant dilepton mass: $m_{\ell\ell} &gt; 12$ GeV</td>
</tr>
<tr>
<td></td>
<td>$Z$-veto ($</td>
</tr>
<tr>
<td></td>
<td>$\Delta R(\ell_{\tau}, \tau_{\tau}) \leq 2$</td>
</tr>
<tr>
<td></td>
<td>$N_{b-jets} = 0$</td>
</tr>
<tr>
<td>$ZZ2\ell2\tau_{\text{had}}$</td>
<td>exactly two same-flavor light leptons with opposite-sign: $p_T &gt; 10$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>exactly two RNN medium $\tau_{\text{had}}$ with opposite-sign: $p_T &gt; 20$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>$Z$-peak selection ($</td>
</tr>
<tr>
<td></td>
<td>$\Delta R(\ell_{\tau}, \tau_{\tau}) \leq 2$</td>
</tr>
<tr>
<td></td>
<td>$N_{b-jets} = 0$</td>
</tr>
</tbody>
</table>

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**Variable**

- $m_X, m_{\ell\tau}$: truth mass of $X$ generated
- $\Delta R(\tau_{\ell}, \ell_{\tau})$: angular distance between the leading lepton and the $di$-$\tau$ system
- $\text{min}(|\Delta R(\ell_{\tau}, j)|)$: minimum angular distance between a jet and the $di$-$\tau$ system
- $\Delta R(\ell, j)$: angular distance between two leptons
- $\Delta R(\ell, \tau)$: azimuthal angle between the di-$\tau$ system and $E_T^{\text{miss}}$
- $E_T^{\text{miss}} + \Sigma p_T(\text{jets})$: sum of $E_T^{\text{miss}}$ momentum and $p_T$ of jets
- $p_{T0}$: leading $\tau$-lepton $p_T$
- $m_{\tau\tau}$: visible invariant mass of the di-$\tau$ system
- $m_{\ell\tau}$: invariant mass of the dilepton system
- $\text{min}(|\Delta R(\ell, j)|)$: minimum angular distance between a jet and the lepton
- $\text{min}(|\Delta R(\ell, j)|)$: minimum angular distance between two jets
- $p_{T0}$: subleading $\tau$-lepton $p_T$
- $m_T$: transverse mass calculated from the lepton(s) and $E_T^{\text{miss}}$ in the event
- $\text{dilep.type}$: dilepton type of $\mu\mu$, $e\tau$ or $\mu\tau$, and $ee$

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**ATLAS Preliminary**

<table>
<thead>
<tr>
<th>$m_{\ell\tau}$</th>
<th>WW</th>
<th>WW</th>
<th>ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 GeV</td>
<td>$x$</td>
<td>$x$</td>
<td>$x$</td>
</tr>
<tr>
<td>30 GeV</td>
<td>$x$</td>
<td>$x$</td>
<td>$x$</td>
</tr>
<tr>
<td>40 GeV</td>
<td>$x$</td>
<td>$x$</td>
<td>$x$</td>
</tr>
<tr>
<td>50 GeV</td>
<td>$x$</td>
<td>$x$</td>
<td>$x$</td>
</tr>
<tr>
<td>60 GeV</td>
<td>$x$</td>
<td>$x$</td>
<td>$x$</td>
</tr>
</tbody>
</table>

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5/23/2023
# Light, Charged Higgs Production

<table>
<thead>
<tr>
<th>$N_j$</th>
<th>$N_b$</th>
<th>(2b + 1b): exactly two (b)-tagged jets (60% OP) plus one loose (b)-tagged jet (70% OP)</th>
<th>(3b): exactly three (b)-tagged jets (60% OP)</th>
<th>(≥4b): at least four (b)-tagged jets (60% OP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4j: exactly four jets</td>
<td>(\sqrt{sTet}) (data-based (\sqrt{s}) corrections, 10 bins)</td>
<td>(\sqrt{sTet}) (signal region, 10 bins)</td>
<td>(\sqrt{sTet}) (signal region, 10 bins)</td>
<td></td>
</tr>
<tr>
<td>5j: exactly five jets</td>
<td>(\sqrt{sTet}) (data-based (\sqrt{s}) corrections, 10 bins)</td>
<td>(\sqrt{sTet}) (signal region, 10 bins)</td>
<td>(\sqrt{sTet}) (signal region, 10 bins)</td>
<td></td>
</tr>
<tr>
<td>6j: exactly six jets</td>
<td>(\sqrt{sTet}) (data-based (\sqrt{s}) corrections, 10 bins)</td>
<td>(\sqrt{sTet}) (signal region, shape correction for the NN discriminant in low S/B bins, 10 bins)</td>
<td>(\sqrt{sTet}) (signal region, shape correction for the NN discriminant in low S/B bins, 10 bins)</td>
<td></td>
</tr>
</tbody>
</table>

**Input variables**
- \(p_T\), \(\eta\), and \(\phi\) of the first six leading jets
- \(b\)-tagging score of the fourth, fifth, and sixth jets
- Lepton \(p_T\), \(\eta\), and \(\phi\)
- Missing transverse energy and its \(\phi\) angle
- Invariant mass between each of the three leading jets and the fourth jet

**Number of variables**
| \(p_T\), \(\eta\), and \(\phi\) | 3 |
| \(b\)-tagging score | 3 |
| Lepton \(p_T\), \(\eta\), and \(\phi\) | 2 |
| Missing transverse energy and its \(\phi\) angle | 3 |
| Total | 29 |
(CP-odd) $A \to ZH$ (Heavy Higgs)