Search for high mass bosonic resonances with the ATLAS detector

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Search for extended Higgs sectors

- The 125 GeV Higgs boson discovery in 2012 was a major breakthrough in particle physics
  - A long campaign of measurements of its properties indicates that it’s consistent with the expectations of the SM Higgs boson

- Current experimental data can’t rule out the possibility that it is part of an extended Higgs sector

- Typical benchmark model is 2HDM (two Higgs-doublets models):
  - 5 Higgs bosons in total: two neutral CP-even h and H, one neutral CP-odd A, and two charged H±
  - 6 parameters: 4 masses (m_h, m_H, m_A and m_{H±/}) tanβ (ratio of the vev of the 2 doublets) and α (mixing angle between the 2 CP-even scalars)
  - Several channels considered: diphoton, Zγ, 4l, llvv, llqq, vvqq

https://arxiv.org/abs/1509.00672
H→γγ and H→Zγ
Search for a high mass Higgs in the di-photon channel

Updated to 36.7 fb⁻¹: two selections optimized separately for the search for a heavy Higgs-like scalar or spin-2 (graviton in the Randall-Sundrum model)

- Pre-selection:
  - \( E_{T\gamma_1} > 40 \text{ GeV}, E_{T\gamma_2} > 30 \text{ GeV} \) in \( |\eta_\gamma| < 2.37 \), excluding 1.37-1.52
  - Tight photon identification
  - Photon isolation (calorimetric + track isolation)

Higgs like (spin-0) selection

- \( E_{T\gamma_1} > 0.4 \, m_{\gamma\gamma}, E_{T\gamma_2} > 0.3 \, m_{\gamma\gamma} \) (+20% significance for \( m_X > 600 \text{ GeV} \))
- Effectively deplete forward regions
- Model-independent: limits on the fiducial cross section
- Search range \( m_X = [200 \text{ GeV} - 2.7 \text{ TeV}] \) and \( \Gamma_X/m_X = [0\% - 10\%] \)

Graviton like (spin-2) selection

- Kinematics of the RS graviton used as benchmark
- \( E_{T\gamma_1} > 55 \text{ GeV}, E_{T\gamma_2} > 55 \text{ GeV} \): simple and general selection
- Search range \( m_G = [500 \text{ GeV} - 2.7 \text{ TeV}] \)
- \( \kappa/M_{Pl} = [0.01 - 0.3] \) (\( \Gamma_G/m_G \approx [0.01\% - 11\%] \))

- Background: irreducible from QCD di-photon events (90%) + reducible \( \gamma j \) and \( jj \)
- Background modeling from sidebands in spin-0 search or MC template for spin-2 search
Search for a high mass Higgs in the di-photon channel

**ATLAS Preliminary**

- Data

**Background-only fit**

**Spin-0 Selection**

\( \sqrt{s} = 13 \text{ TeV}, 36.7 \text{ fb}^{-1} \)

**Spin-2 Selection**

\( \sqrt{s} = 13 \text{ TeV}, 36.7 \text{ fb}^{-1} \)
Search for a high mass Higgs in the di-photon channel

Largest excess:
- spin-0: 2.6 $\sigma$ local around 730 GeV for narrow width
- spin-2: 3.0 $\sigma$ local around 710 GeV and large width ($k/\mathcal{M}_{Pl}=0.30$).
- Global signif. <1 $\sigma$
- $m_G > 4.1$ @ 95% CL
- limits 5.7-8.6 TeV on the ultraviolet cutoff scale $M_S$ depending on the number of extra dim and the formalisms
Search for a high mass Higgs in the Z-photon channel

- Two same-flavour opposite-charge leptons ($l = e, \mu$) to form a $Z$ boson candidate and at least one photon candidate.
- Two categories (for the high mass search) for $e^+e^-$ and $\mu^+\mu^-$ events

Main background (irreducible) non-resonant $Z\gamma$ and (reducible) $Z+j$ fitted both on data

No significant excesses: 2.7σ local at $m_H = 960$ GeV, 0.8σ global in [200–2500]
$H \rightarrow ZZ \rightarrow llll / ll\nu\nu / llqq / \nu\nuqq$
High mass higgs in ZZ->llll: analysis strategy

- Two same-flavour opposite sign isolated lepton pairs
- Events are classified into a VBF enriched category and 3 ggF enriched categories (exclusive)
  - VBF enriched category: two (or more) separated jets ($\Delta\eta>3.3$) and $m_{jj}>400$ GeV
  - ggF enriched categories: 4e, 4$\mu$ and 2e2$\mu$
- Main background
  - ZZ(*) non resonant production (~95 %) and EW vector boson scattering (15% for VBF and 1% for ggF) : modelled through MC; typical uncertainties 13% (ggF) and 50 % (VBF)
  - Z+jet and tt from control regions in data
- Look for excesses in the 4l invariant mass spectrum
- Narrow (ggF and VBF) and large width (1-10% of $m_H$, ggF only) signal hypotheses tested
High mass Higgs in ZZ->llνν: analysis strategy

- Two isolated leptons consistent with originating from a Z
- Large missing transverse momentum $E_T^{\text{miss}} > 120$ GeV
- Events are classified into a VBF enriched category and 2 ggF enriched categories (exclusive)
  - two well separated jets (delta >4.3) and $m_{jj} > 550$ GeV
  - ggF enriched categories: ee, μμ

- Main background
  - ZZ* non resonant production (60%) from MC
  - WZ (30%) from MC normalised in 3l control region
  - non resonant ll from e-μ control region (WW, tt)
  - Z+jet and W+jets from control regions in data

- Look for excesses in the transverse mass
  \[ m_T \equiv \sqrt{\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} - |p_T^{\ell\ell} + E_T^{\text{miss}}|^2} \]

- Narrow (ggF and VBF) and large width (1-10% of $m_H$, ggF only) signal hypotheses tested
High mass Higgs in ZZ-> llqq final: analysis strategy

- Typically look for ZV events in which V goes into two jets and one Z in the ll or νν
- ggF and VBF searched separately: events are classified into VBF/ggF enriched categories

- Z boson reconstruction: two same flavour leptons with an invariant mass compatible with the Z
- Separation of the ggF/VBF: two jets in the opposite hemisphere, Δη > 4.7 and $m_{jj} > 770$ GeV
- Merged: one large-R jet, boson tagger with 2 different efficiency wp
- Resolved: two categories, 2 b-tag jets, <2 b-tag jets
- Discriminant variable $m_{llJ}$ or $m_{lljj}$

- Z+jets main background: shape from MC normalised in a control region in data
- Top-quark production: from MC normalised in a control region in data
- Diboson (ZZ and ZW) completely from MC simulation
High mass Higgs in ZZ -> vvqq: analysis strategy

- Hadronically decaying V boson recoiling against a large missing transverse momentum
- Only merged analysis
- Look for narrow width Higgs bosons
- Event selection:
  - $E_T^{\text{miss}} > 250$ GeV and veto on loose electrons and muons
  - 1 large-R jet with $p_T > 200$ GeV
- VBF category: $\Delta\eta > 4.7$ and $m_{jj} > 630$ GeV
- Two categories based on the boson tagger $\wp$
- Final discriminant is the transverse mass

$$m_T = \sqrt{(E_{T,J} + E_T^{\text{miss}})^2 - (p_{T,J} + E_T^{\text{miss}})^2}$$

$$E_{T,J} = \sqrt{m_j^2 + p_{T,J}^2}.$$
High mass Higgs in ZZ: results

- Data consistent with the background only expectation
  - No excesses in $ll
  - A $3.6 (2.2)\sigma$ local(global) excess at 240 GeV (mostly 4e)
  - A $3.6 (2.2)\sigma$ local(global) excess at 700 GeV in 4l (excluded by $ll\nu\nu$)
  - Simultaneous fit in 4l and $ll\nu\nu$: largest combined excess at 700 GeV is $2\sigma$ local ($< 1 \sigma$ global)
  - $3.0 (1.9)\sigma$ global (global) deficit at $m_{llJ} \sim 800$ GeV in the $llqq$ ggF high purity category.
Conclusion

- Heavy scalar Higgs-boson searches at $\sqrt{s} = 13\text{TeV}$ being updated to $\sim 36\text{ fb}^{-1}$ for many channels, many new fresh results.

- Several final states considered (documentation will follow shortly):
  - Di-photon
  - $Z\gamma$
  - $ZZ \rightarrow llll/ll\nu\nu$
  - $ZZ \rightarrow llqq/\nu\nuqq$

- Panorama is very rich: for more infos and more interpretations you can look here
  - [https://indico.cern.ch/event/466934/contributions/2574456/] Thomas Meideck
  - [https://indico.cern.ch/event/466934/contributions/2589222/] Kalliopi Iordanidou
  - [https://indico.cern.ch/event/466934/contributions/2589220/] Paolo Mastrandrea
  - [https://indico.cern.ch/event/466934/contributions/2589223/] Wade Cameron Fisher

- No significant excesses observed

- Significantly improved limits on $\sigma \times \text{BR}$ set over wider mass-ranges. Already collecting new data!
High mass Higgs in WW->lνlν: analysis strategy

- Fully-leptonic, different-flavor
- one- and at least two-jets optimised for a (VBF)-like signal and the remaining category is quasi-inclusive for a (ggF)-like signal
  - ≥2 jets with mjj > 500 GeV and |Δyjj| > 4 1 jet with |ηj| > 2.4 and min(|Δηjl|) > 1.75
  - Rest is ggF
- Two different hypotheses are tested:
  - a narrow width approximation (NWA), width of the heavy Higgs boson is smaller than the experimental resolution
  - large width assumption (LWA), widths of 5%, 10%, 15%
- Main background: top-quark and WW additional contributions from W/Z+ jets and the diboson processes WZ, Wγ,Wγ*, and ZZ
  - Ttbar and WW shapes from MC normalized to data, W+jet from data
- Look for excesses in the transverse mass

\[ m_T \equiv \sqrt{\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{miss})^2} - |p_T^{\ell\ell} + E_T^{miss}|^2} \]
No significant excess in the mass range between 300 GeV and 3 TeV.

Upper limits on the product of the production cross section and the $H\rightarrow$WW branching ratio for narrow width and intermediate widths (of 5, 10, 15% of the heavy Higgs boson mass).
High mass Higgs in the WW/ZZ→qqqq/WW→lvqq channels: results
Boson tagger

FAT JET

- Large radius parameter to collect all radiation
- From the original decay

GROOMING

- Remove PU+UE
- Increase signal/background separation
- Improve resolution of the signal mass peak

TAGGER

- Observables to characterize the underlying jet substructure

Build large radius jets, typically $R = 1$ using anti-$K_T$ algorithm

- Reclustering of constituents of large-$R$ jet into small-$R$ jets of size $R_{sub}$
- Remove subjet $i$ if $p_T^i < f_{cut} \times p_T^{jet}$

- Energy correlations functions (ECFs): combine the $p_T$ and angular separation of all jet constituents (ECF1), all pairs of jet constituents (ECF2) and triplets (ECF3)
- Cut on $D_2^{\beta=1}$ to reject QCD jets

(JHEP 1306 (2013) 108)
2HDM interpretation of the ZZ→4l+llνν results
More on $H \to 4l$ results

<table>
<thead>
<tr>
<th>Process</th>
<th>$e^+e^-$ channel</th>
<th>$\mu^+\mu^-$ channel</th>
<th>VBF-enriched category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ$</td>
<td>$177 \pm 3 \pm 21$</td>
<td>$180 \pm 3 \pm 21$</td>
<td>$2.1 \pm 0.2 \pm 0.7$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$93 \pm 2 \pm 4$</td>
<td>$99.5 \pm 2.3 \pm 3.2$</td>
<td>$1.29 \pm 0.04 \pm 0.27$</td>
</tr>
<tr>
<td>$WW/t\bar{t}/Wt/Z \to \tau\tau$</td>
<td>$9.2 \pm 2.2 \pm 1.4$</td>
<td>$10.7 \pm 2.5 \pm 0.9$</td>
<td>$0.39 \pm 0.24 \pm 0.26$</td>
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<tr>
<td>$Z + \text{jets}$</td>
<td>$17 \pm 1 \pm 11$</td>
<td>$19 \pm 1 \pm 17$</td>
<td>$0.8 \pm 0.1 \pm 0.5$</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>$1.12 \pm 0.04 \pm 0.08$</td>
<td>$1.03 \pm 0.04 \pm 0.08$</td>
<td>$0.03 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>Total background</td>
<td>$297 \pm 4 \pm 24$</td>
<td>$311 \pm 5 \pm 27$</td>
<td>$4.6 \pm 0.4 \pm 0.9$</td>
</tr>
<tr>
<td>Observed</td>
<td>320</td>
<td>352</td>
<td>9</td>
</tr>
</tbody>
</table>

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<tr>
<th>Process</th>
<th>$4\mu$ channel</th>
<th>$2e2\mu$ channel</th>
<th>$4e$ channel</th>
<th>VBF-enriched category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ$</td>
<td>$297 \pm 1 \pm 40$</td>
<td>$480 \pm 1 \pm 60$</td>
<td>$193 \pm 1 \pm 25$</td>
<td>$15 \pm 0.1 \pm 6.0$</td>
</tr>
<tr>
<td>$ZZ$ (EW)</td>
<td>$1.92 \pm 0.11 \pm 0.19$</td>
<td>$3.36 \pm 0.14 \pm 0.33$</td>
<td>$1.88 \pm 0.12 \pm 0.20$</td>
<td>$3.0 \pm 0.1 \pm 2.2$</td>
</tr>
<tr>
<td>$Z + \text{jets}/t\bar{t}/WZ$</td>
<td>$3.7 \pm 0.1 \pm 0.8$</td>
<td>$7.8 \pm 0.1 \pm 1.1$</td>
<td>$4.4 \pm 0.1 \pm 0.8$</td>
<td>$0.37 \pm 0.01 \pm 0.05$</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>$5.1 \pm 0.1 \pm 0.6$</td>
<td>$8.7 \pm 0.1 \pm 1.0$</td>
<td>$4.0 \pm 0.1 \pm 0.5$</td>
<td>$0.80 \pm 0.02 \pm 0.30$</td>
</tr>
<tr>
<td>Total background</td>
<td>$308 \pm 1 \pm 40$</td>
<td>$500 \pm 1 \pm 60$</td>
<td>$203 \pm 1 \pm 25$</td>
<td>$19.5 \pm 0.2 \pm 8.0$</td>
</tr>
<tr>
<td>Observed</td>
<td>357</td>
<td>545</td>
<td>256</td>
<td>31</td>
</tr>
</tbody>
</table>
More on ZZ->llqq