Searching for new symmetries in the Higgs sector at ATLAS Detector

2021 Discrete Symmetry

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Beyond the standard model

Standard Model (SM):
One Higgs doublet field, only one neutral Higgs boson

SM needs to be **extended**:

*ν* mass, dark matter...

Many **Beyond the Standard Model (BSM)** theories predicts:

✓ **exotic decays of Higgs boson:** exiting precision measurements of the Higgs allow a branching ration of ~30% to exotic decays

✓ **additional Higgs:** Two Higgs Doublet Model (2HDM) + *S* (singlet)

Higgs exotic decays into light scalar particles

scalar (*H*), pseudoscalar (*a*), heavy scalar, two charged.
New results with full data set (139 fb⁻¹) collected by the ATLAS experiment in Run2 from 13 TeV pp collisions

I. $H_{125} \rightarrow$ new light scalar particles (BSM)
   \[ H \rightarrow aa/Za/ Z_dZ_d \rightarrow 4l \]
   \[ H \rightarrow aa \rightarrow bb\mu\mu \]

II. Additional low- and high-mass Higgs bosons
   \[ H \rightarrow ZZ \rightarrow llll \text{ and } ll\nu\nu \]
   \[ H \rightarrow \gamma\gamma \]
   \[ H \rightarrow V + \gamma \]
I. $H_{125} \rightarrow$ new light scalar particles (BSM)

$H \rightarrow aa/Za/ Z_d Z_d \rightarrow 4l$

$H \rightarrow aa \rightarrow bb\mu\mu$
Search for Higgs bosons decaying to new spin-0 or spin-1 particles in four-lepton final states at the ATLAS detector with 139 fb$^{-1}$ of $p\ p$ collision data at $\sqrt{s} = 13$ TeV

Backgrounds: simulation.
- $ZZ^* \rightarrow 4\mu$: simulation
- $H \rightarrow ZZ^* \rightarrow 4\mu$: simulation
- Non-prompt leptons from heavy flavour hadrons: data-driven method

Statistics limited.
H → aa /Z_a /Z_d Z_d → 4l: Limits

- Limits on σ(H → aa/Z_a → 4l)
- Factor 2-4 improvement from previous results.

✓ Larger data sample
✓ Improved lepton reconstruction and identification
✓ Better optimized event selection
H → aa /Za /Z_d Z_d → 4ℓ: Limits

- Used $H \rightarrow Z_d Z_d$ set upper limit on Higgs mixing parameter
- Used $H \rightarrow Z Z_d$ set upper limit on $Z_d$ mixing parameter $\epsilon$

Higgs mixing parameter: $\kappa$

$Z_d$ mixing parameter $\epsilon$
Search for Higgs boson decays into a pair of pseudoscalar particles in the $bb\mu\mu$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV

**SM Backgrounds**

- **DY (Drell-Yan) dimuon + jets:**
  - $bb\mu\mu$ mass side bands control region.
  - Distribution shapes are from data templates with 0 b-jets
- **ttbar:**
  - High-MET control region
  - Distribution shapes are from simulation.
- **Other (diboson, single-top-quark etc.):**
  - Simulation
Overall data are compatible with the SM background
- The largest data excess at 52 GeV is local 3.3 $\sigma$ (global 1.7 $\sigma$)
- Dominant systematic uncertainties.
  - DY background: BDT selection and normalization
  - Signal: $b$-tagging and jet energy related uncertainties

Upper Limits on $\mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu)$ range $(0.2 - 4.0) \times 10^{-4}$
- Factor 2 - 5 improvement from the previous analysis.
- Larger data set (factor ~2).
- Use of BDT (factor ~2).
II. Additional low- and high-mass Higgs bosons

\[ H \rightarrow ZZ \rightarrow llll \text{ and } ll\nu\nu \]

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow V+\gamma \]
Search for heavy resonances decaying into a pair of Z bosons in the $l^+l^-l^+l^-$ and $l^+l^-\nu\overline{\nu}$ final states using 139 fb$^{-1}$ at 13 TeV.

Many channels:
- Productions: gluon-gluon fusion and vector-boson-fusion
  - Decays: $l^+l^-l^+l^-$ and $l^+l^-\nu\overline{\nu}$
  - Width assumptions: narrow-width approximation and large-width assumption (only for the ggF channel)

Interpretation:
- Spins: 0 (two-Higgs-doublet model)
- Spins 2 (Randall–Sundrum).

Mass range: 200-2000 GeV.

Discriminating variable:
- $l^+l^-l^+l^-$: $m_{4l}$ (four-lepton invariant mass).
- $l^+l^-\nu\overline{\nu}$:
Background estimation:
- Minor backgrounds – simulated from MC
- Major backgrounds - shape from MC and normalization from data
- $llll$: dominant non resonant $ZZ$ - using functional form
Upper limits are set at the 95% CL:
- NWA improvement of up to ~40% wrt previous results
  - 200–2.6 fb for ggF.
  - 87–1.9 fb for VBF.
Search for heavy resonances decaying into photon pairs using 139 fb-1 at 13 TeV.

Motivation:

- Spin 0 - extended Higgs sector.
- Spin 2 - warped extra-dimension model.

- Require at least two photons with $E_T > 35(25) \text{ GeV}$ and additional $E_T/m_{\gamma\gamma} > 0.3 (0.25)$ for leading (subleading) $\gamma$.

- Search range: $m_{\gamma\gamma} > 150 \text{ GeV}$

- **Signal model:**
  
  Breit-Wigner
  
  True lineshape width
  
  Variety of width hypotheses
  
  $\Gamma/m_x = [1,10\%]$  
  $k/M_{p1} = [0.01,0.1]$
Background estimation:
- Irreducible ($\gamma\gamma$) from MC.
- Reducible ($\gamma j, j\gamma, jj$) from data driven methods.
- Mixed according to data-driven purities.
- Fluctuations suppressed using the functional decomposition method.

Up to 25% gain on the limit wrt using the default MC.
Upper limits on the fiducial $\sigma \times \text{BR}$ are set at the 95\% CL:

- Spin 0: $12.5\pm 0.03 \text{ fb}$.  
- Spin 2: $3.2\pm 0.04 \text{ fb}$.  
- Most significant excess at $m_\chi = 684 \text{ GeV}$ with a local (global) significance of $3.29\sigma (1.36\sigma)$

Spin 0: Extended Higgs sector  
Spin 2 - warped extra-dimension model
Search BSM heavy Higgs via $H \gamma$ resonance

$$p+p \rightarrow X \rightarrow V \gamma (V=W/Z)$$

**Interpretation:**

- Spin-0 $gg \rightarrow X^0 \rightarrow Z\gamma$
- Spin-2 $gg \rightarrow X^0 \rightarrow Z\gamma$
- Spin-2 $q\bar{q} \rightarrow X^0 \rightarrow Z\gamma$
- Spin-1 $q\bar{q}' \rightarrow X^{\pm} \rightarrow W\gamma$

**Signal selection:**

- Photon: $P_T > 200\text{GeV}, |\eta| < 1.37$
- Jet with large radius: $P_T > 200\text{GeV}, |\eta| < 2.0$
H → V + γ

Background: dominated by γ + jet events, estimated with the analytic function
Results: No significant signal found! Set $\sigma \times B$ upper limit at $m_x [1\text{TeV}, 6.8\text{TeV}]$
ATLAS is searching for a new physics in various production and decay modes, under different spin assumptions. Unfortunately, no significant deviation from the SM prediction has been observed. Many more exciting results to come using the full Run 2 dataset.
Thank you for attention!
Backup
• $pp\to H_{125}\to\text{BSM}$
  - $H\to Z(\ell)\alpha$, Z(\ell)hc , Z(\ell)J/\gamma$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , PRL 125, 221802 (2020), submitted Apr., published Nov. 2020
  - $H\to aa\to bb\mu\mu$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , CERN-EP-2021-157, submitted Oct. 2021 to PRD
  - $H\to aa\to bbbb$, Run 2, $\sqrt{s}=13$ TeV, L=36 fb$^{-1}$ , PRD 102, 112006 (2020), submitted May 2020, published Dec. 2020
  - $Z(\ell)H\to\text{inv}$, 2HDM+a, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , ATLAS-CONF-2021-029, released July 2021 Dark matter combination, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , ATLAS-CONF-2021-036, released July 2021
  - NMSSM, $Z(\ell)H(\chi^2 0 \chi^1 0 \to a \chi^1 0 \chi^1 0)$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , CERN-EP-2021-098, submitted Sept. 2021 to JHEP
  - $H\to XX\to 4l$, H\to ZX \to 4l, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , ATLAS-CONF-2021-034, released August 2021
  - $H\to WW$, Run 2, $\sqrt{s}=13$ TeV, L=36.1 fb$^{-1}$ , CERN-EP-2021-096, submitted Sept. 2021 to EPJC

**Charged Higgs**

- $H^\pm\to cb$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , ATLAS-CONF-2021-037, released Aug. 2021
- $H^\pm\to tb$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , JHEP 06, 145 (2021), submitted Feb., published June 2021
- $H^\pm\to W^\pm A\to W^\pm (\text{en})\mu\mu$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , ATLAS-CONF-2021-047, released Sept. 2021
- $H^{\pm\pm}$, Run 2, $\sqrt{s}=13$ TeV, L=139 fb$^{-1}$ , JHEP 06, 146 (2021), submitted Jan., published June 2021
low- and high-mass Higgs bosons

Search for high-mass \( W\gamma W\gamma \) and \( Z\gamma Z\gamma \) resonances in the hadronic final state using 139 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS Detector

A search for high-mass charged and neutral bosons decaying to \( W\gamma W\gamma \) and \( Z\gamma Z\gamma \) final states is presented in this note. [...] 


ATLAS Collaboration, Search for heavy neutral Higgs bosons produced in association with \( b \)-quarks and decaying into \( \bar{b}b \)-quarks at \( \sqrt{s} = 13 \) TeV with the ATLAS detector, Phys. Rev. D 102 (2020) 032004, arXiv: 1907.02749 [hep-ex] (cit. on p. 2)