Searches for high-mass Higgs-like resonances with the ATLAS detector
Introduction

- Huge success of the discovery of Higgs Boson predicted by Standard Model (SM).

Questions: Is the 125 GeV Higgs the only one?

- Many models of Beyond SM (BSM) include extensions to the Higgs sector.
- All allow for SM-like Higgs phenomenology with smaller or larger coupling modification.

4 July 2012, The discovery of the Higgs boson was announced at CERN
Introduction

- Focuses on the explicit searches for high-mass Higgs-like resonances.
- What next when no significant deviation from the SM is observed?
  - How much of the BSM scenarios can current data exclude?
- Shows results based on full Run-2 data (139 fb$^{-1}$)

- Outline
  - $H \to \gamma\gamma$ high-mass search
  - $H \to ZZ$ high-mass search
Searches for $\gamma\gamma$ resonances in high mass spectrum ($m_{\gamma\gamma} > 160$ GeV) using full Run-2 data ($139.0 \pm 2.4$ fb$^{-1}$).

- Spin-0 as predicted by theories with an extended Higgs sector.
  - For spin-0, search on narrow-width (NW) and large-width (LW) resonances.
- Spin-2 graviton benchmark is also considered (not covered in this talk).

Final state provides excellent invariant mass resolution and smoothly falling background.

The mass range of the search has reached 3 TeV.
Analysis overview

- **Event selections**
  - at least two photon candidates with $E_T > 22$ GeV and $|\eta| < 2.37$.
  - $E_T(\gamma_1)/m_{\gamma\gamma} > 0.3$, $E_T(\gamma_2)/m_{\gamma\gamma} > 0.25$

- **Signal modelling:**
  - Double-sided Crystal Ball function (DSCB) convolved with relativistic Breit-Wigner function and mass-dependent factors which are derived from the simulation.
H→ γγ high-mass search

Analysis overview

● **Background modelling:**
  ○ Analytic function which determined by fitting a template built from simulated Monte Carlo γγ events and γj events.

● The overall γγ purity of the selected events increases with $m_{γγ}$ from ~ 89% (150–200 GeV) to ~ 97% (> 400 GeV).

● The search region for a resonant signal covers the region 160–3000 GeV (NW signal) and 400–2800 GeV (LW signal).

● Interference effects between the resonant signal and all background processes are expected to be small for a NW signal and are neglected in this analysis.

Largest background (97% above 400 GeV) comes from non-resonant production of QCD photon pairs (γγ events) .
Analysis overview

- **Background modelling:**
  - To suppress the statistical fluctuations, a **smoothing process** is employed:
    - a). fit the pseudo-experiment, resulting in a smoothed template.
    - b). estimate spurious signal by fitting the smoothed template with the signal-plus-background model.
    - c). repeat the process and take mean value.
    - d). the use of smoothed templates leads to a limit improvement of 2–28%.
H-$\gamma\gamma$ high-mass search

Results

- No significant excess observed.
  - limits are placed on the production cross-section times branching ratio, $\sigma \times B(X \rightarrow \gamma\gamma)$.
- The most significant excess for the spin-0 NWA model is $3.29 \sigma$ (local), $1.30 \sigma$ (global) at $m_x = 684$ GeV.

Observed upper limits at 95% CL on NWA:
- $12.5$ fb (160 GeV) to $0.03$ fb (2800 GeV)
H→ZZ high-mass search

- Searches for heavy resonances in high mass spectrum using full Run-2 data.
  - $ZZ \rightarrow 4l$ : good mass resolution.
  - $ZZ \rightarrow ll\nu\nu$ ($l=e,\mu$) : large branching ratio.
- Combination of $4l$ and $ll\nu\nu$ final states improve overall sensitivity.
- Interpretation of results in terms of Narrow Width (NW) and Large Width (LW) heavy Higgs for spin-0 resonance.
- Covering mass range 200 GeV to 2 TeV.
- Look for an excess in $m_{4l}$ ($4l$) and $m_T(ll\nu\nu)$.

$$m_T \equiv \sqrt{\sqrt{m_Z^2 + (p_T^\ell \ell)^2} + \sqrt{m_Z^2 + (E_T^{miss})^2}} - |p_T^{\ell \ell} + E_T^{miss}|^2,$$
Analysis overview \((ZZ \rightarrow 4l)\)

- **Event selections**
  - Lepton-quadruplet: two same-flavour, opposite-charge lepton pairs \((4\mu, 2e2\mu, 4e)\)
  - \(e(\mu)\ p_T > 7\ (5\ \text{GeV}), |\eta| < 2.5\ (2.7)\)
  - \(p_T(Lep_1^{th}) > 20\ \text{GeV}, p_T(Lep_2^{nd}) > 15\ \text{GeV}, p_T(Lep_3^{rd}) > 10\ \text{GeV}\).
  - lepton pair closest to Z mass
    - \(50\ \text{GeV} < m_{12}\) (leading pair) < 106 GeV
    - \(50\ \text{GeV} < m_{34}\) (subleading pair) < 115 GeV
  - Leptons cut: impact-parameter requirements & track- and calorimeter-based isolation to reduce the Z+jets and ttbar background contributions.
Analysis overview \((ZZ \rightarrow 4l)\)

- **Event categorization**
  - **NWA signal:**
    - multivariate analysis (MVA)
      - VBF classifier (flavor inclusive)
      - ggF classifier (channels: 4\(\mu\), 2\(e\)2\(\mu\), 4\(e\))
    - cut-based analysis (CBA)
      - VBF, when two or more jets \(p_T > 30\) GeV, \(m_{jj} > 400\) GeV, \(\Delta\eta_{jj} > 3.3\) (flavor inclusive)
      - ggF, otherwise (channels: 4\(\mu\), 2\(e\)2\(\mu\), 4\(e\))
  - **LWA signal:**
    - ggF-enriched CBA
Analysis overview \((ZZ \rightarrow 4l)\)

- **Signal and background modelling**
  - **NWA Signal**: detector resolution modelled by the sum of a Crystal Ball function and a Gaussian function.
  - **LWA Signal**: theoretical calculation convolved with the detector resolution.
  - **Background**:
    - 97% comes from non-resonant SM ZZ production \((qq/gg\rightarrow ZZ\ (96\%)\ or\ EW\ vector-boson\ scattering\ (1\%))\): Parameterised with analytic functions estimated from MC.
    - Z+jets, ttbar: Data-driven estimate.
    - ttbarV, VVV: MC simulation.
Analysis overview ($ZZ \rightarrow 4l$)

- Interference modelling
  - The gluon-initiated production of a heavy scalar $H$, the SM Higgs $h$ and the $gg \rightarrow ZZ$ continuum background $B$ all share the same initial and final state.
  - The effect could modify the integrated cross section by up to $O(10\%)$, and would be enhanced as the width of the heavy scalar increases.
  - Therefore, search in LWA must take them into account.
    - $H-h$ interference: reweighting function.
    - $H-B$ interference: empirical function fit to MC.
H→ZZ high-mass search

Analysis overview **(ZZ→ 4l)**

- **4l Results**
  - Simulated $m_H = 600$ GeV signal is normalised to a cross section corresponding to 50 (5) times the obs. limit.
  - The error bars on the data points indicate the statistical uncertainty.
  - The lower panels show the ratio of data to prediction.
H→ZZ high-mass search

Analysis overview \((ZZ\rightarrow ll\nu\nu)\)

- **Event selections**
  - Two same flavor leptons with opposite charges
  - \(E_T^{\text{miss}} > 120\) GeV
  - \(76\) GeV < \(m_{ll}\) < \(106\) GeV

- **Cut-based categorization**
  - VBF: at least two selected jets with \(p_T > 30\) GeV, \(m_{jj} > 550\) GeV and \(\Delta\eta_{jj} > 4.4\)
  - ggF: otherwise
  - Both with channels: ee and \(\mu\mu\)

- **Backgrounds modelling:**
  - Mainly ZZ (60%) and WZ (30%)
  - Smaller comes from non-resonant \(ll\) (5%), \(Z+\text{jets}(4%),\text{VVV and ttbarV} < 1\%\)
  - Data-driven estimate

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H→ZZ high-mass search

Analysis overview \((ZZ\rightarrow ll\nu\nu)\)

- \(ll\nu\nu\) Results
  - Simulated \(m_H = 600\) GeV (1.5 TeV) signals are normalised to a cross section corresponding to
    - 50 (5) times the obs. Limit in ggF
    - 5 (1) times the obs. limit in VBF
    (the two mass points were selected for demonstration purpose only)
  - The error bars on the data points indicate the statistical uncertainty.
  - The lower panels show the ratio of data to prediction.
Combined Results

- No significant excess observed
- upper limits are set on Spin-0 resonances with NWA
  - fits for the ggF and VBF processes are done separately.
    - the ratio of the two production mechanisms unknown

The most significant excess is $2.1 \sigma$ (local), $0.5 \sigma$ (global) at a mass of $\approx 240$ GeV.

The most significant excess is $2.6 \sigma$ (local), $1.2 \sigma$ (global) at a mass of $\approx 660$ GeV.
Combined Results

- No significant excess observed
- upper limits are set on Spin-0 resonances with LWA
  - Only ggF process is considered.
  - The limits are set for masses of $m_H > 400$ GeV.
  - Interference effects taken into account.
Combined Results

- No significant excess observed
- upper limits are set on **Two-Higgs-doublet model**
  - Type-I: Second Higgs doublet ($\Phi_2$) couples to all quarks and leptons.
  - Type-II: $\Phi_1$ couples to down-type quarks and leptons and $\Phi_2$ couples to up-type quarks.
  - $\tan \beta$: the ratio of the vacuum expectation values of the two Higgs doublets.
  - $\cos(\beta - \alpha)$ ~ the coupling of the heavier CP-even Higgs boson to vector bosons.
Conclusion

- Search for heavy Higgs-like resonances with ATLAS Run-2 data of 139 fb⁻¹
  - Several models studied:
    - Narrow-width spin-0 resonance.
    - Large-width spin-0 resonance with widths of 1, 5, 10, 15% of signal mass.
    - Type-I and Type-II 2HDM models on the assumption of NW signal.
- No evidence for BSM phenomena in the scalar sector.
  - Analyses managed to place exclusion limits on various BSM scenarios
- The mass range of the search has reached 3 TeV \((H \rightarrow \gamma\gamma)\) and 2 TeV \((H \rightarrow ZZ)\).
- Upper limits of production cross section of heavy resonances improved by up to 60% since previous paper.
- Expect higher sensitivities with Run-3 dataset and the beyond.
Thank you