Search for BSM scalars in ATLAS

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Introduction

Discovery of a new neutral scalar particle of mass \(\sim 125\) GeV (h) at the LHC.

Within the current uncertainties, the properties of this new scalar are consistent with those expected for the Higgs boson of the SM.

However, this does not exclude a more complicated Higgs sector with additional particles (in addition to h).

Examples of BSM models with additional Higgs bosons:

- Additional EW singlet: h, H
- Two Higgs doublet model (2HDM): h, H, A, H$^\pm$
- Two Higgs doublet + singlet model
- Higgs triplet models (SM doublet + triplet): H$^{\pm\pm}$
Introduction

Various strategies for searches for an extended Higgs sector:

- **Indirect**: Look for non-standard properties of 125 GeV Higgs (couplings, CP, etc)
- **Direct**: Directly search for new particles (BSM Higgs(es)) decaying to SM particles
- **Decays of 125 GeV Higgs**: Directly search for decays of the 125 GeV Higgs to BSM states (light scalars, ...)

Will discuss direct searches and show one search for BSM $h(125)$ decays.

At the end, will confront the limits from the direct searches to those from indirect searches, in the context of a specific, simplified BSM model.

Will not discuss searches that involve hadronic decays of W / Z bosons. When the W or Z is highly boosted, these searches require dedicated reconstruction techniques. ⇒ Dedicated talk by Roland Jansky later in this session.

Will not discuss searches for new resonances that decay to $h h$ (a pair of 125 GeV Higgs bosons). ⇒ Covered in the talk by Michael Kagan yesterday.
Heavy neutral Higgs: \( H \rightarrow ZZ \rightarrow (4l, \ell\ell\nu\nu) \)

In many BSM models, high-mass H scalar can have significant decay rates to final states with weak bosons.

Production of H expected predominantly through gluon fusion (ggF) and vector boson fusion (VBF). Relative rate of the two mechanisms unknown (unless specific model is chosen).

\[ \Rightarrow \text{two selections (ggF- or VBF-enriched)} \]

\( H \rightarrow ZZ \rightarrow 4l \):
- two same-flavour opposite-sign lepton (e or \( \mu \)) pairs
- highly efficient (“loose”) lepton ID
- main discriminating variable: \( m_{4\ell} \)

\( H \rightarrow ZZ \rightarrow \ell\ell\nu\nu \):
- lepton pair (consistent with Z) plus missing transverse energy (\( E_T^{\text{miss}} \))
- main discriminating variable:

\[
m_T = \sqrt{\left(\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2}\right)^2 - (p_T^{\ell\ell} + E_T^{\text{miss}})^2}.
\]

Main backgrounds (standard model ZZ) is well described by the MC simulations (Powheg+Phythia, Sherpa, GG2VV for ZZ, depending on production mechanism and final state) plus k-factor.

Other backgrounds (W+jets, Z+jets, tt, WZ) estimated using control regions in data.
Heavy neutral Higgs: $H \rightarrow ZZ \rightarrow (4l, \ell\ell\nu\nu)$

Limits on production cross-section times branching ratio are set for a new scalar in a way as model-independent as possible.

Limits are function of mass and width of the hypothetical scalar.

Shown here: limits for “narrow width”

Interference between the heavy scalar and the $gg \rightarrow ZZ$ continuum background and the $h$ boson are taken into account.

Also set limits in more specific benchmark models. Shown here: example of the 2HDM Type I (second doublet couples to all quarks and leptons) model with $m_H = 200$ GeV

(narrow width expected for this mass)

$\tan \beta$: ratio of the two vacuum expectation values

$\alpha$: mixing angle between the two CP-even Higgs bosons

arXiv:1712.06386 [hep-ex]
Heavy neutral Higgs: $H \rightarrow WW \rightarrow e\nu\mu\nu$

Like in ZZ search:
- ggF- and VBF-enriched selections
- (but here two VBF categories: 1 jet and $\geq 2$ jets)

Search for opposite-sign lepton pair ($e\mu$) plus missing transverse energy ($E_T^{miss}$)

Main discriminating variable:

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |p_T^{\ell\ell} + E_T^{miss}|^2}.$$

$$E_T^{\ell\ell} = \sqrt{|p_T^{\ell\ell}|^2 + m_{\ell\ell}^2}.$$  

$m_T$ shapes of the dominant backgrounds are well described by simulation (non-resonant WW: Sherpa; events with top: Powheg+Pythia).

Background normalisations determined using simultaneous fit to $m_T$ distributions in signal sample and to event counts in background-enriched control regions.

Heavy neutral Higgs: $H \rightarrow WW \rightarrow e\nu\mu\nu$

Same approach as for $H \rightarrow ZZ$:

Limits on production cross-section times branching ratio are set for a new scalar in a way as model-independent as possible.

Limits are function of mass and width of the hypothetical scalar.

Shown here: limits for “narrow width”

Also set limits in more specific benchmark models. Shown here: example of the 2HDM Type I model with $m_H = 200$ GeV

Heavy neutral Higgs: $H/A \rightarrow \tau^+ \tau^-$

In the MSSM (type II-like 2HDM) [type II: one doublet couples to up-type quarks, the other to down-type quarks and charged leptons]), the couplings of the heavy Higgs bosons to down-type fermions ($\tau, b$) are strongly enhanced for a large part of the parameter space at large $\tan \beta$.

Search for decay $H/A \rightarrow \tau^+ \tau^-$. Two selections:
- $\tau^+ \tau^-$ and 0 b-jet
- $\tau^+ \tau^-$ and $\geq 1$ b-jet

In both cases: accept both
- fully hadronic final state ($\tau_{\text{had}} \tau_{\text{had}}$)
- semi-leptonic final state ($\tau_{\text{lep}} \tau_{\text{had}}$)

Hadronic final state ($\tau_{\text{had}}$) benefits from large branching ratio. Experimental challenge: need excellent discrimination against jets, $\tau_{\text{had}}$ energy measurement.

Primary background for both channels: jets misidentified as a $\tau$. Data-driven techniques are used to model these backgrounds.

Top quark and $Z \rightarrow \tau^+ \tau^-$ events are also significant backgrounds in the $\tau_{\text{lep}} \tau_{\text{had}}$ channel for events with and without a b-jet respectively.
Heavy neutral Higgs: $H/A \rightarrow \tau^+ \tau^-$

Main discriminating variable:

total transverse mass of $\tau^+ \tau^-$ system.

$$m_T^{\text{tot}} \equiv \sqrt{(p_T^1 + p_T^2 + E_T^{\text{miss}})^2 - (p_T^1 + p_T^2 + E_T^{\text{miss}})^2}$$

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Heavy neutral Higgs: $H/A \rightarrow \tau^+ \tau^-$

Limits on production cross-section times branching ratio are set for a new scalar in a way as model-independent as possible.

Natural width of the new scalar assumed to be negligible compared to experimental resolution (as expected over the probed MSSM parameter space).

Also set limits in more specific benchmark models.
Comparing limits (e.g. in the hMSSM)

hMSSM: simplified version of MSSM, some radiative corrections are neglected, the dominant ones (from loops involving top quarks and stop quarks) are constrained using $m_h$.

At tree level, the properties of the Higgs sector of the MSSM depend on only two non-SM parameters; can be chosen to be $m_A$ and $\tan \beta$.
h(125) → XX → 4ℓ

Non-SM branching ratio of h(125): ≤ 30% at 95% CL

Narrow decay width in SM
  => even small coupling to light state can lead to sizable BR

2HDM+S:

Scalar singlet (S) only couples to the two Higgs fields; no Yukawa couplings (coupling to SM fermions only through mixing with Higgs fields)

a: light pseudo-scalar

potentially large BR(a → μμ)

Dark sector:

additional U(1)\textsubscript{d} dark gauge symmetry

Coupled to SM via kinematic mixing with hypercharge gauge field
  (ε: kinematic mixing angle)

Gauge boson: Z\textsubscript{d} vector boson

If U(1)\textsubscript{d} broken by introduction of dark Higgs (S):

mixing between SM Higgs boson

Higgs portal coupling K
h(125) → XX → 4ℓ

H → XX → 4μ
(1 GeV < m_X < 15 GeV)

selection:
di-muon masses in candidate events

<μ > = 1/2 * (m_{12} + m_{34})

Limits on branching ratios

h(125) → a a

h(125) → Z_d Z_d
More (hypothetical) scalars

ATLAS also searched for other new scalars that are not directly part of an extended Higgs sector, for example supersymmetric partners of the top quark (stop).

This slide shows a summary of exclusion limits from direct searches for stop pairs.
Conclusions

Presented a small selection of recent ATLAS searches for additional scalar Higgs bosons.

They are part of a comprehensive programme that covers a maximum of decay topologies. Many more searches would have deserved to be covered here. Please see the ATLAS public results page:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

So far, no sign of additional Higgs boson seen in the ATLAS data.

Exclusion limits continue to improve, but there is still a lot of model phase space left to explore.

Analyses shown here use a fraction of the data that we expect to collect during Run 2 (150 fb$^{-1}$ expected by the end of this year).

The HL-LHC will provide 3000 fb$^{-1}$ of data!
Additional material
Heavy neutral Higgs: $H \rightarrow ZZ \rightarrow (4\ell, \ell\ell\nu\nu)$

arXiv:1712.06386 [hep-ex]

$H \rightarrow ZZ \rightarrow 4\ell$

(same plots as on slide 4)

Two excesses at $m_{4\ell} = 240$ GeV and $m_{4\ell} = 700$ GeV.

Each excess individually:
Local significance: 3.6σ
Global significance: 2.2σ

$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$

$4\ell$ excess at 240 GeV is not covered by the $\ell\ell\nu\nu$ search

$4\ell$ excess a 700 GeV is excluded at 95 % CL by the $\ell\ell\nu\nu$ search
Comparing limits (e.g. in the hMSSM)

Same plot as on slide 11, but extended $m_A$ range.
H → XX → 4ℓ
(15 GeV < m_X < 60 GeV)
sélection

di-muon masses
in candidate
events

\[ m_{34} \text{ vs } m_{12} \]

\[ \langle m_\mu \rangle = \frac{1}{2} \times (m_{12} + m_{34}) \]
\[ h(125) \rightarrow Z\gamma \quad \text{and} \quad X \rightarrow Z\gamma \]

In SM, \( h(125) \rightarrow Z\gamma \) proceeds through loop diagrams similar to those in \( h(125) \rightarrow \gamma\gamma \) and has a similar branching ratio.

**Modifications of \( h(125) \rightarrow Z\gamma \) branching ratio w.r.t. SM are expected if:**

- \( H \) is a composite state
- In models with additional colourless charged scalars, leptons or vector bosons that couple to the \( h(125) \) and are exchanged in the \( h(125) \rightarrow Z\gamma \) loop.

**Search for \( h(125) \rightarrow Z\gamma \):**

- Search in \( \ell\ell\gamma \) (\( \ell = e, \mu \)) final states
- Kinematic fit to improve the \( m_{\ell\ell\gamma} \) resolution
- 6 event categories (different mass resolution, purity) to enhance sensitivity

**Expected 95% CL limit on \( \sigma(pp \rightarrow h) * B(h \rightarrow Z\gamma) \) assuming no (a SM) Higgs boson decay is 4.4 (5.2) times the SM prediction**
Extend search to higher masses.

Two event categories (ee and $\mu\mu$).

Background modelled using functional form.

Largest excess w.r.t. background-only hypothesis around $m_X = 960$ GeV.

Local significance: $2.7\sigma$
Global significance: $0.8\sigma$

Plot shows limits for a spin-0 resonance produced via gluon fusion.
Diphotons: search for spin-0 resonance

Selection optimised for Higgs-like signal:
- two photons (tight identification)
- photons required to be isolated
- photon transverse energies:
  \[ E_T(\gamma_1) > 0.4 \text{ m}_{\gamma\gamma} \]
  \[ E_T(\gamma_2) > 0.3 \text{ m}_{\gamma\gamma} \]
  (effectively depletes forward regions)

Background modelled using fit to functional form
Diphotons: search for spin-0 resonance

Perform 2D p₀ scan (as function of mass and width of the hypothetical resonance).

Largest deviation from background-only hypothesis: near 730 GeV
width: narrow width approximation

Local significance:  2.6σ
Global significance: null

Report limits on fiducial cross section as a function of mass hypothesis, for several width hypotheses.

Example shown here: narrow-width approximation

Diphotons: search for spin-2 resonance

**Selection** with “angular” cut that is relaxed compared to the search reported on previous slides:

- two Photons (tight identification)
- photons required to be isolated
- Photon transverse energies:
  \[ E_T(\gamma_1) > 55 \text{ GeV} \]
  \[ E_T(\gamma_2) > 55 \text{ GeV} \]

**Background model**
Using detailed prediction of the shape (NLO prediction of SM di-photons; small contributions of fake photons from data control samples).

- reliable background estimate up to the highest masses
- sensitive to broad non-resonant signals

Diphotons: search for spin-2 resonance

Perform 2D $p_0$ scan (as function of mass and width [i.e. coupling] of the hypothetical resonance).

Largest deviation from background-only hypothesis:
- near 708 GeV
- $\kappa/M_{Pl} \approx 0.30$

Local significance: 3.0$\sigma$
Global significance: 0.8$\sigma$

Report limits on cross section as a function of mass hypothesis, for several width hypotheses.

Example shown here: $\kappa/M_{Pl} = 0.10$