Search for a high mass neutral Higgs boson in fermion final states with the ATLAS detector

Trevor Vickey
(on behalf of the ATLAS Collaboration)

University of Sheffield, United Kingdom

December 14, 2017

SUSY-2017 — Mumbai, India
If the (light) Higgs mass is \( \sim 125 \) GeV, what next?

- Suppose that this is not the Standard Model Higgs…
- Higgs with different couplings? \( \Rightarrow \) 2HDM, Fermiophobic, Higgs impostor
- More complicated Higgs sector? \( \Rightarrow \) MSSM, Doubly-charged Higgs, Composite
- Light scalar Higgs? \( \Rightarrow \) NMSSM (Next-to-Minimal SUSY extension to SM)
- Hidden Higgs sector? \( \Rightarrow \) Higgs to long-lived particles / decays into Dark Matter
Neutral MSSM Higgs Searches

- The MSSM (h, A, H, H±) is compatible with a 125 GeV Higgs... for example:
  - **hMSSM scenario:** the measured value of 125 GeV can be used to predict masses and decay branching ratios of the other Higgs bosons (all SUSY particles are heavy)
  - **m_{h}^{mod} scenario:** top-squark mixing parameter is chosen such that the mass of the lightest CP-even Higgs boson is close to the mass of the one observed at the LHC (historical)

- Two recent ATLAS high-mass neutral Higgs searches using fermions to show you...
  - A/H to ττ using 36.1 fb^{-1} of 13 TeV pp collision data
  - A/H to ttbar using 20.3 fb^{-1} of 8 TeV pp collision data

Theory projections for 2σ sensitivity are shown

A/H to ττ and A/H to ttbar are each very important channels at mid- to high-m_{A}

Djouadi, A., Maiani, L., Polosa, A. et al.
JHEP 06 (2015) 168

arXiv: 1709.07242
PRL 119 (2017) 191803
MSSM Higgs Search ($A/H \rightarrow \tau^+\tau^-$)

- Latest ATLAS MSSM neutral Higgs search uses 36.1 fb$^{-1}$ of 13 TeV data from Run-2
- New result recently submitted to JHEP: arXiv:1709.07242

- Can use different categories to target main production mechanisms:
  - “no b-tag” targets gluon-fusion (dominant production mode at small $\tan\beta$)
  - “b-tag” (70%) targets b-associated production (dominant production mode at large $\tan\beta$)

- Can also separate based on the $\tau$ lepton decay mode (for a total of 4 categories):
  - Lepton-Hadron: high-$p_T$ single lepton triggers (e or $\mu$); one hadronic tau (55%)
  - Hadron-Hadron: high-$p_T$ hadronic tau trigger; two hadronic taus (60%, 55%)

- Monte Carlo samples used:
  - $A/H$ to $\tau\tau$ signal: Powheg-Box+Pythia8 (ggH) and MG5_aMC@NLO + Pythia8 (bbH)
  - Backgrounds:
    - Powheg+Pythia8 ($Z$+jets, $W$+jets in lep-had, and top)
    - Sherpa ($W$+jets in had-had and dibosons)
Background Estimation ($A/H \rightarrow \tau^+\tau^-$)

**lepton-hadron final state**

- Jet $\rightarrow \tau$ fake
- $Z/\gamma^* \rightarrow \tau\tau$
- $Z/\gamma^* \rightarrow ll$
- Top
- Diboson

- Largest background: Jets faking taus; not well-modeled in Monte Carlo
  - Separate fake factors are derived from data control regions for $W$+jets, top and multijets
  - These fake factors are parameterized by tau $p_T$ and number of tracks

- Z+jets, other top and diboson are estimated using Monte Carlo and the $t\bar{t}$bar normalization is done using a top-rich control region in the data

**hadron-hadron final state**

- Multijet
- $Z/\gamma^* \rightarrow \tau\tau$
- $W \rightarrow \tau\nu$
- Top
- Others

- Largest background: Multi-jets faking taus; not well-modeled in Monte Carlo
  - A fake factor is derived from data control regions, and then applied to the anti-ID regions to obtain estimates for the signal regions
  - This fake factor is parameterized by tau $p_T$ and number of tracks

- For Z+jets, W+jets and top backgrounds, different dedicated data-driven corrections to Monte Carlo are used
Post-fit Plots for the 4 Categories ($A/H \rightarrow \tau^+\tau^-$)

- Discriminant used is the $m_{T_{\text{tot}}}$ variable, as it offers good separation of signal from backgrounds due to fake $\tau$s.

- Signal superimposed with $m_{A/H} = 300$, 500 and 800 GeV (assuming hMSSM and $\tan\beta = 10$)

$$m_{T_{\text{tot}}} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_{T_{\text{miss}}})^2 - (p_T^{\tau_1} + p_T^{\tau_2} + E_{T_{\text{miss}}})^2}$$

arXiv: 1709.07242
MSSM Neutral Higgs Search \((A/H \rightarrow \tau^+\tau^-)\)

- Dominant systematics: \(\tau\) energy scale, \(\tau\) trigger (had-had), \(\tau\) identification efficiency, fakes
- Statistically combine the \(\tau_{\text{lep}}-\tau_{\text{had}}\) and \(\tau_{\text{had}}-\tau_{\text{had}}\) channels for one exclusion limit
- We determine a \(\sigma \times \text{BR}\) limit \((A/H \rightarrow \tau\tau)\) for gluon-fusion and b-associated production
- Exclusions range from 0.78 pb – 5.8 fb for gluon-fusion and 0.70 pb – 3.7 fb for b-associated in the range of 200 GeV – 2.25 TeV

\[ \sigma \times B(\phi \rightarrow \tau\tau) \text{ [pb]} \]

\[ \sigma \times B(\phi \rightarrow \tau\tau) \text{ [pb]} \]

\[ m_\phi \text{ [GeV]} \]

\[ m_\phi \text{ [GeV]} \]

\text{arXiv: 1709.07242}
MSSM Neutral Higgs Search (A/H $\rightarrow \tau^+\tau^-$)

- We also show limits in the $m_h^{\text{mod}+}$ and hMSSM benchmark scenarios.
- In the $m_h^{\text{mod}+}$, we exclude $\tan\beta > 5.1$ for $m_A = 250$ GeV and $\tan\beta > 51$ for $m_A = 1.5$ TeV.
- In the hMSSM, we have sensitivity to exclude the low $m_A$-low $\tan\beta$ corner and the island around 350 GeV. Note: the features around 350 GeV are related to the $\sigma \times \text{BR}$ evolution near the A/H $\rightarrow \text{ttbar}$ threshold.
- hMSSM plot shows Run-1 couplings exclusion ($K_V$, $K_u$ and $K_d$)
High-mass Higgs Search (A/H→ttbar)

• We revisit a Run-1 generic scalar ttbar resonance search that used 20.3 fb⁻¹ of 8 TeV proton-proton collision data: ATLAS collaboration, JHEP 08 (2015) 148
• The 2017 analysis (PRL 119 (2017) 191803) uses the ttbar lepton+jets channel, specifically targets A/H, and takes the interference between the signal and ttbar background production modes into account for the first time

Monte Carlo samples used:
• A/H to ttbar signal: MadGraph5+Pythia6
• Backgrounds:
  • ttbar: Powheg-Box+Pythia6
  • ttbar + V: MadGraph5+Pythia6
  • single top: Powheg+Pythia6
  • W+jets and Z+jets: Alpgen+Pythia6
  • Diboson: Sherpa

MadGraph5 used for both “indirect” (S+I+B) and “direct” (S+I) A/H signal generation (direct used; difference taken as a modeling systematic)
Signal Modeling (A/H→\textbf{ttbar})

- The signal process is simulated using the generator MadGraph5 v2.0.1 with the Higgs Effective Couplings Form Factor model (implements the production of scalar and pseudoscalar particles through loop-induced gluon fusion)
- Loop contributions from both bottom and top quarks are taken into account
- Signal shape is distorted from a simple Breit-Wigner peak, to a peak-dip structure
- Statistical interpretation of measured event rates in data are compared to the total sum of Signal + Interference + Background (S + I + B)
- The mass of the SM-like Higgs boson, \( h \), is chosen to be 125 GeV and \( \sin(\alpha-\beta) \) is set to 1 (i.e., the “alignment limit”, where \( h \) has decays as expected in the SM)

![Graph 1](image1)

![Graph 2](image2)
Event Selection / Mass Reconstruction ($A/H \rightarrow ttbar$)

- Analysis targets the $ttbar$ lepton+jets channel (one $W$ to hadrons one to leptons)
  - Single electron or single muon triggers are used—2 categories (one for $e$; one for $\mu$)
  - One high $p_T$ electron or muon; high MET from the escaping neutrino; presence of at least 4 high $p_T$ jets in the event; at least one jet originating from $b$ quarks must be tagged (70%)

- A chi-squared fit is used for assignment of the decay products, then $m_{tt}$ is reconstructed
  - Events further classified depending on the $b$-tagged jet(s) assignment—3 categories
High-mass Higgs Search Results ($A/H \rightarrow ttbar$)

- No significant excess or deficit from the Standard Model background expectation is observed.

- The 95% CL expected and observed upper limits on the signal strength $\mu$ are shown for a Type-II 2HDM in the alignment limit considering only a pseudoscalar $A$ (left), only a scalar $H$ (middle), and the mass-degenerate scenario $m_A = m_H$ (right).

- Blue points indicate parameter values at which signal samples are available. Values at intermediate points are obtained from a linear triangular interpolation. The observed (expected) exclusion region for the Type-II 2HDM ($\mu = 1$) is indicated by a solid (dashed) line.
Conclusions and Outlook

- ATLAS has performed new searches for high-mass neutral Higgs bosons decaying to fermions
  - The new $\mathrm{A/H} \rightarrow \tau\tau$ analysis uses up to 36.1 fb$^{-1}$ of 13 TeV collision data recorded during Run-2; this result improves on an earlier ATLAS paper published in EPJC
  - The $\mathrm{A/H} \rightarrow \tau\tau$ analysis is an extension of a generic Run-1 scalar $\tau\bar{\tau}$ resonance search in 20.3 fb$^{-1}$ of 8 TeV data and takes the interference between $\mathrm{A/H}$ signal and ggF $\tau\bar{\tau}$ into account for the first time

- No significant excess is observed in the data from either search, and 95% CL limits are set
  - $\mathrm{A/H} \rightarrow \tau\tau$: We determine a $\sigma \times \text{BR}$ limit for gluon-fusion and b-associated production separately; exclusions range from 0.70 pb – 3.7 fb for masses in the range of 0.2–2.25 TeV
  - $\mathrm{A/H} \rightarrow \tau\tau$: We also show limits in the $m_h^{\text{mod}+}$ and hMSSM benchmark scenarios; e.g., in the hMSSM scenario the most stringent constraints exclude $\tan\beta > 1.0$ for $m_A=0.25$ TeV (>42 for $m_A=1.5$ TeV)
  - $\mathrm{A/H} \rightarrow \tau\tau$: For the mass-degenerate case ($m_A=m_H$) with a mass of 500 GeV, parameter values of $\tan\beta < 1.55$ in the Type-II 2HDM (in the alignment limit) are excluded at the 95% CL.

- Stay tuned for more results from Run-II of the LHC; these are very exciting times!