High-mass Higgs searches at ATLAS and CMS

Scott Snyder
On behalf of the ATLAS and CMS Collaborations

Brookhaven National Laboratory, Upton, NY, USA

Jul 11, 2016
ICNFP, Crete

- Introduction
- Higgs → VV
- Higgs → Higgs
- Higgs → fermions
- Higgs → invisible
- Summary
Introduction

- Observed Higgs boson very consistent with SM expectations.
- Suspect EW sector of SM may not be complete:
  - Naturalness, dark matter, etc.
- Search for a heavier Higgs-like particle.
- LHC started Run 2 at $\sqrt{s} = 13$ TeV.
- Accumulated $\sim 3 \text{ fb}^{-1}$ of usable data in 2015.
Some models with heavy Higgs bosons

- Most studied are two simple extensions to the SM:
  - Electroweak singlet (EWS)
    - New scalar singlet $s$ that mixes with $h$.
  - 2-Higgs-Doublet Model (2HDM)
    - Extra Higgs doublet.
    - Physical particles $h, H, A, H^\pm$.
    - Parameters:
      - Masses: $m_h, m_H, m_A, m_{H^\pm}$.
      - VEV ratio of the two doublets: $\tan \beta$.
      - Mixing angle between $h, H$: $\alpha$.
      - Potential parameter mixing the two doublets: $m_{12}^2$.
    - Different ways to couple doublets with other particles; most studied:
      - Type-I: All quarks couple to only one doublet.
      - Type-II: Up-type quarks couple to one doublet, down-type quarks to the other.
  - MSSM is a subset of 2HDM.
  - Numerous MSSM benchmark models:
    - $h\text{MSSM}, m_h^{\text{mod}+}$, etc.

Denote the 125 GeV resonance as ‘$h$’; $H$ is a heavier resonance.
Searches covered

All results from 13 TeV 2015 data unless otherwise specified.

**Higgs → VV**
- $H \rightarrow ZZ \rightarrow 4\ell$
- $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
- $H \rightarrow ZZ \rightarrow \ell\ell qq$

**Higgs → Higgs**
- $H \rightarrow ZA \rightarrow \ell\ell bb$
- $A \rightarrow Zh \rightarrow \ell\ell bb/\nu\nu bb$

**Higgs → fermions**
- $H^+ \rightarrow tb \ [8 \text{ TeV}]$
- $H^+ \rightarrow \tau\nu$
- $H/A \rightarrow \tau\tau$

**Invisible Higgs decays**
- $ZH \rightarrow \ell\ell + \text{(invisible)}$
- VBF $H \rightarrow \text{(invisible)}$

$H \rightarrow \gamma\gamma$ covered elsewhere.
Higgs $\rightarrow$ VV

- $H \rightarrow ZZ \rightarrow 4\ell$
- $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
- $H \rightarrow ZZ \rightarrow \ell\ell qq$

Covered in Garabed's talk

- Merged channels:
  - $H \rightarrow VV \rightarrow \nu\nu qq, \ell\nu qq, \ell\ell qq, qqqq$
- $H \rightarrow Z\gamma$
$H \rightarrow ZZ \rightarrow 4\ell$

Based on $m_h = 125$ GeV analysis.
2 same-flavor, OS $\ell$ pairs.
One $40 < m_{\ell\ell} < 120$ GeV; other $12 < m_{\ell\ell} < 120$ GeV.

BG mostly $ZZ$, est. from MC

Exclusions for several resonance widths.
Also $\tan \beta$ limits for type-I,II 2HDM.
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$

Require $Z \rightarrow \ell\ell$, large $E_T^{miss}$, no $b$-tags.
Add’l requirements on $\Delta\phi(Z, E_T^{miss})$ and $p_T^Z$.
Discriminating variable: $m_T(\ell\ell, E_T^{miss})$.

$VV$: MC
$WZ$: MC normalized to data
$Z + jets$: data-driven
$H \rightarrow ZZ \rightarrow \ell\ell qq$

### Merged analysis

$Z \rightarrow \ell\ell$; small $E_T^{\text{miss}}$

large-$R$ $Z$-tagged jet $w/ p_T > 200$ GeV

$p_T(\ell\ell) > 0.3m_{\ell\ell}$

### Resolved analysis

$Z \rightarrow \ell\ell$; small $E_T^{\text{miss}}$

$2j$ w/ $70 < m_{jj} < 105$ GeV

$\sqrt{p_T^2(\ell\ell) + p_T^2(jj)} > 0.5m_{\ell\ell jj}$

Tagged ($2b$) and untagged ($< 2b$) categories.

### Dominant BG: $Z +$ jets, also $t\bar{t}$.

---

**Merged**

**Resolved**

**Combined**
Higgs → Higgs

Covered in Xiaohu’s and Andrey’s talks
- $H \rightarrow hh \rightarrow bb\tau\tau$
- $H \rightarrow hh \rightarrow bb\gamma\gamma$
- $H \rightarrow hh \rightarrow \ell\nu\ell\nu bb$
- $H \rightarrow hh \rightarrow bbbb$

Covered here: analyses involving CP-odd scalar $A$
- $H \rightarrow ZA \rightarrow \ell\ell bb$
- $A \rightarrow Zh \rightarrow \ell\ell bb/\nu\nu bb$
$H \rightarrow ZA \rightarrow \ell\ell bb$

**Selection**

$Z \rightarrow \ell\ell$, 2 $b$-tags

For different hypothesized $m_A/m_H$ pairs: rectangular window in $m_{bb}/m_{\ell\ell bb}$ plane.

**Backgrounds**

Normalize backgrounds by fitting $m_{\ell\ell}$ outside signal region.

Limits for $m_H = 500$ GeV; also derived for 300 GeV and 800 GeV.

---

**CMS Preliminary**

$1\sigma$, $2\sigma$ and $3\sigma$ uncertainties are shown.

**Observed $s_{CL}$**

$2.3 \text{ fb}^{-1} (13 \text{ TeV})$
$A \rightarrow Zh \rightarrow \ell\ell bb/\nu\nu bb$

Selection

Either no $\ell$ and $E_T^{\text{miss}}$

or $Z \rightarrow \ell\ell$ and small $E_T^{\text{miss}}$.

$bb$ either from two small-R jets ($110 < m_{jj} < 140 \text{ GeV}$) if $p_T^{Z} < 500 \text{ GeV}$ or a large-R jet ($75 < m_{J} < 145 \text{ GeV}$) otherwise.

Either 1 or 2 $b$-tags.

Final discriminant: $m(Zh)/m_T(Zh)$.

Backgrounds

Shapes from MC. $Z + \text{jets}$, $t\bar{t}$ control regions included in final fit to constrain dominant backgrounds.

Scott Snyder (BNL)

High-mass Higgs searches at ATLAS and CMS

ICNFP Jul 11, 2016
A → Zh → ℓℓbb/ννbb (2)

Production via ggf

MSSM interpretations ($M_A = 600$ GeV)

Type-I 2HDM

Type-II 2HDM
Higgs → fermions

Charged Higgs production and decay

For $m_{H^+} > m_t$, production is dominantly $pp \rightarrow t(b)H^+$. 

- $H^+ \rightarrow tb$
- $H^+ \rightarrow \tau\nu$

Decay is dominantly $H^+ \rightarrow tb$.

But $H^+ \rightarrow \tau\nu$ can be significant for high $\tan\beta$.

Also

$H \rightarrow \tau\tau$
$H^+ \to tb, \tau\nu$ [8 TeV]

Produced via $pp \to t(b)H^\pm$. Hadronic channel also sensitive to $t\bar{t} \to bH^\pm bH^\pm, t\bar{t} \to bH^\pm bW$.

$\tau_{\text{had}} + \text{jets (}\tau\nu\text{)}$: $\tau_{\text{had}}, \geq 3j, \geq 1b$, no $\ell$, angular separations. Extract limit from $m_T(\tau_{\text{had}}, E_T^{\text{miss}})$.
BG: $V + j, VV, t \to \tau$: Replace $\mu$ in $\mu + j$ with sim. $\tau$ multijet: from data via fake rate; $t\bar{t}$ w/fake $\tau$ from MC

$\ell \ell (tb/\tau\nu)$: $2\ell, 2j, E_T^{\text{miss}}, \geq 2b$. Extract limit from $n_{\text{btag}}$.
BG: From MC.

$\mu \tau_{\text{had}} (tb/\tau\nu)$: As above with $\mu \tau_{\text{had}}$ instead of $2\ell$ and $\geq 1b$.
BG: From MC, with fake-factor for misidentified $\tau_{\text{had}}$.

$\ell + \text{jets (}tb\text{)}$: $\ell, E_T^{\text{miss}}, 2j, \geq 1b$. Extract limit from $H_T$, binned in $b$-tag multiplicity.
BG: Shapes from MC, normalizations float in fit.

**ATLAS $tb$ analysis:** [arXiv:1512.03704]
$H^+ \rightarrow \tau \nu$

Final state: $(t \rightarrow jjb)b\tau_{\text{had}}\nu$

$\geq 3j, \geq 1b, \tau_{\text{had}}, \ell$ veto,

$E_T^{\text{miss}} > 150 \text{ GeV}, m_T > 50 \text{ GeV}$

Discriminant: $m_T(\tau_{\text{had}}, E_T^{\text{miss}})$

$W/Z$: shape from MC, norm. to data

Multijet: From data

$e, \mu$ faking $\tau$: MC, validated with data
\( H/A \rightarrow \tau \tau \)

**Selection**

Channels: \( \tau e \tau_{\text{had}}, \tau \mu \tau_{\text{had}}, \tau e \tau_{\mu}, \tau_{\text{had}}\tau_{\text{had}} \).

Candidates are OS and well-separated in \( \Delta R \).

\( \tau e \tau_{\text{had}}, \tau \mu \tau_{\text{had}} \): No OS ee or \( \mu \mu \) pairs.

\( m_T(\ell, E_T^{\text{miss}}) < 40 \text{ GeV} \) (e) < 30 GeV (\( \mu \)).

Topological \( t \bar{t} \) rejection in \( \tau e \tau_{\mu} \).

Categorize: 0-tag, \( \geq 1 \) tag.

**Backgrounds**

\( Z \rightarrow \tau \tau \): MC, cross-checked w/ \( Z \rightarrow \mu \mu \).

\( W + \text{jets, multijet} \): From SS and high-\( m_T \) control regions.

\( t \bar{t} \): From MC, cross checked in data CRs.

Also results from associated \( b \) production and other MSSM benchmarks.
$H/A \rightarrow \tau\tau$

**Selection**

Either OS $\tau\ell\tau_{\text{had}} (w/ Z \rightarrow \ell\ell$ veto) or $\tau_{\text{had}}\tau_{\text{had}}$. Select on $\Delta\phi$ and $m_T (\tau, \tau_{\text{had}}, \ell)$. 

$b$-veto (0 tag) and tagged ($\geq 1$ tag) categories. Use $m_T^{\text{tot}}$ as discriminant.

$$(m_T^{\text{tot}})^2 = m_T^2 (E_{\text{miss}}^\tau, \tau_1) + m_T^2 (E_{\text{miss}}^\tau, \tau_2) + m_T^2 (\tau_1, \tau_2)$$

**Backgrounds**

$\tau\ell\tau_{\text{had}}$: BG w/ true $\tau/\ell$ from MC; misidentified $\tau/\ell$ from fake-factor method.

$\tau_{\text{had}}\tau_{\text{had}}$: Multijet BG from fake-factor method; other BGs from MC with fake factors applied.

Also associated $b$ production.
Invisible Higgs decays

Invisible decays of scalars is a feature of models with SUSY (LSP) or large extra dimensions (graviscalar).

Search for invisibly-decaying heavy scalar.

Tag production of scalar by associated production with $Z$ or by vector boson fusion.
Assume $H$ decays *exclusively* to invisible (LSP, etc). Require $Z \rightarrow \ell\ell + E_T^{\text{miss}}$.

$Z \rightarrow \ell\ell$ w/ $p_T^Z > 60$ GeV, $E_T^{\text{miss}} > 100$ GeV, veto leptons, hard jets, $b$-tags.

Requirements on $\Delta \phi$ and $E_T^{\text{miss}}/p_T^Z$ balance. 0/1-jet bins.

$Z + \text{ jets}$: From $\gamma + \text{ jets}$

Others: Different-flavor leptons.
Assume $H$ decays exclusively to invisible (LSP, etc). Require VBF jet pair + $E_T^{\text{miss}}$.

2 jets, $\Delta \eta_{jj} > 3.6$, $m_{jj} > 1100$ GeV

$E_T^{\text{miss}} > 200$ GeV, no $\ell$,

$\Delta \phi(j, E_T^{\text{miss}}) > 2.3$

5 control regions

$Z \rightarrow \mu \mu$; single-$e$, $\mu$, or $\tau$;

$\min \Delta \phi(E_T^{\text{miss}}, j) < 0.5$

Norm. BG by fitting to CRs; result from counting experiment.
Summary

- Many searches, many channels ...  
  - ... leave no stone unturned!
- No signal from 2015 data.
- But accumulating more data rapidly.
  - Already have $\sim 10 \text{ fb}^{-1}$ of data recorded — more than all of 2015!
  - Expect first results from these data at ICHEP.
- Stay tuned!
Backup
Selection based on $m_h = 125$ GeV analysis

\begin{align*}
\text{Events/20 GeV} &\quad 1000 \quad 900 \quad 800 \quad 700 \quad 600 \quad 500 \quad 400 \quad 300 \quad 200 \\
\text{m}_{4\ell} \quad [\text{GeV}] &\quad 10^{-2} \quad 10^{-1} \quad 1 \quad 10 \quad 100 \\
\end{align*}

\begin{align*}
\text{Narrow width} &\quad \text{Expected} \quad \text{Observed} \\
\text{Expected} &\quad \pm 1\sigma \quad \pm 2\sigma \\
\text{Observed} &\quad \pm 1\sigma \quad \pm 2\sigma \\
\end{align*}
$H \rightarrow 4\ell$

**CMS Preliminary**

2HDM Type I, $\cos(\beta-\alpha)=0.1$

$m_A = m_H = m_H + 100 \text{ GeV}$

- Obs. 95% CL limit
- Exp. 95% CL limit
- $H \rightarrow ZZ \rightarrow 4\ell$ (HIG-15-004)
- Non-perturbative region

2.8 fb$^{-1}$ (13 TeV)

**CMS Preliminary**

2HDM Type II, $\cos(\beta-\alpha)=0.1$

$m_A = m_H = m_H + 100 \text{ GeV}$

- Obs. 95% CL limit
- Exp. 95% CL limit
- $H \rightarrow ZZ \rightarrow 4\ell$ (HIG-15-004)
- Non-perturbative region

2.8 fb$^{-1}$ (13 TeV)
Require $Z \rightarrow \ell\ell$, $E_T^{miss} > 125$ GeV, no $b$-tags.

3 categories: 0 jet, $\geq 1$ jet, and VBF.

(VBF: 0 cent, 2 fwd jets w/ $\Delta \eta > 4$, $m_{jj} > 500$ GeV)

Discriminating variable: $m_T(\ell\ell, E_T^{miss})$.

$VV$ BG from MC; $Z + \text{jets}$ modelled by $Z + \gamma$.

Exclusion of SM-like heavy Higgs as fcn. of $m_H$ and $\Gamma_H$. $ggF/VBF$ combined.

Interpret as EWS with mixing parameter $C'$.

ATLAS analysis: [ATLAS-CONF-2016-012]
$H \to VV \to XXqq$ (merged)

$\nu\nuqq$

No $\ell$; $E_T^{\text{miss}} > 250$ GeV; $Z$-tagged large-R jet $p_T^{\text{miss}} > 30$ GeV; angular requirements
BG: $W/Z +$ jets, $t\bar{t}$ (shape MC, norm data)

$\ell\nuqq$

$1\ell$; $E_T^{\text{miss}} > 100$ GeV; $W$-tagged large-R jet $p_T, J$ and $p_T, \ell, J > \max(200$ GeV, $0.4m_{\ell, J})$;
Veto on $b$-tag close to $J$
BG: $W +$ jets, $t\bar{t}$ (shape MC, norm data)

$qqqq$

$E_T^{\text{miss}} < 250$ GeV; 2 $W/Z$-tagged large-R jets
0 $\ell$; $p_T, J_1/2 > 450/200$ GeV; other topo req.
BG: multijet (analytic fit)

$llqq$ similar to previous slide.
$H \to XXqq$ (merged) (2)

Set combined exclusion limit for narrow scalar resonance to $VV$.

Interpret as new heavy neutral scalar:
- $\Lambda$: energy scale
- $c_H$: Coupling to SM Higgs.
- $c_3$: Coupling to gluons.

Use naive dimensional analysis (NDA) and unsuppressed benchmarks.
$H \rightarrow Z \gamma$

$Z \rightarrow ee, \mu\mu + \gamma$ Also $Z \rightarrow jj$ using large-R jets ($p_T^\gamma > 250$ GeV)

Plot $m(Z\gamma)$; fit background outside signal region with an analytic function.

Limits for narrow signal width.
$H \to Z\gamma$

$Z \to ee, \mu\mu + \gamma$

Plot $m(Z\gamma)$; fit background outside signal region with an analytic function.

Limits for two signal widths.
$H \rightarrow hh \rightarrow bb\tau\tau$

3 channels: $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$.

**Selection**

2 OS $\tau$’s; 2 b-tagged jets

$80 < m_{\tau\tau}, m_{bb} < 160$ GeV

Discriminant is $m_{\tau\tau}bb$; found from a kinematic fit.

**Backgrounds**

$Z + \text{jets}$: MC shape, normalized to $\mu\mu$ data

Multijet: From SS data

$t\bar{t} + \text{other}$: MC

**Signal model**: Narrow CP-even resonance decaying to $hh$

Scott Snyder (BNL)  
High-mass Higgs searches at ATLAS and CMS  
ICNFP Jul 11, 2016 30 / 40
$H \rightarrow hh \rightarrow bb\gamma\gamma$

**Selection**

2 $\gamma$; exactly 2 $b$-tagged jets  
$|m_{\gamma\gamma} - m_h|/2 < \sigma(m_{\gamma\gamma})$ [1.55 GeV]  
$95 < m_{bb} < 135$ GeV

Final window cut in $m_{\gamma\gamma bb}$ around each hypothesized mass keeping 95% of signal (width 20–50 GeV).

**Backgrounds**

From data using sidebands in $m_{\gamma\gamma}$ and $m_{\gamma\gamma bb}$. Extrapolation to signal region derived from 0-tag sample.

Non-resonant search not covered here.
Selection

2 OS leptons; 2 $b$-tagged jets

BDT trained at $m_H = 400$ GeV (for $m < 450$ GeV) or $m_H = 650$ GeV.

BDT variables

$m_{\ell\ell}, \Delta R_{\ell\ell}, \Delta R_{jj}, \Delta \phi_{\ell\ell,jj}, p_T^{\ell\ell}, p_T^{jj}, \min \Delta R_{\ell,j}, M_T$

Backgrounds

Fit BDT output to signal+bkg model in 4 bins: signal region plus BDT/$m_{jj}$ sidebands.
Resolved: 4 $b$-tagged small-R jets
Boosted: 2 large-R jets w/3 or 4 associated $b$-tagged track jets
$tt\bar{t}$ veto
Mass-dependent requirements on $p_T$ of jet pairs/large-R jets.

$$\sqrt{\left(\frac{m_{h1}-124\text{GeV}}{0.1m_{h1}}\right)^2 + \left(\frac{m_{h2}-124\text{GeV}}{0.1m_{h2}}\right)^2} < 1.6$$

Boosted, $\geq 2$ tags

Non-resonant search not covered here.
$H \to hh \to bbbb$

4 $b$-tagged small-R jets

Low mass (260–400 GeV):

$\sigma_h = 17$ GeV

High mass (400–1200 GeV):

$\sigma_h = 23$ GeV

$$\sqrt{\left(\frac{m_{h1}-115\text{GeV}}{\sigma_h}\right)^2 + \left(\frac{m_{h2}-115\text{GeV}}{\sigma_h}\right)^2} < 1$$

Backgrounds

Fit curve to $m_{bbbb}$ from sideband regions.

---

Scott Snyder (BNL)

High-mass Higgs searches at ATLAS and CMS

[ICNFP Jul 11, 2016 34 / 40]
$H \rightarrow ZA \rightarrow \ell\ell b\bar{b}$

$m_H = 300 \text{ GeV}$

$2.3 \text{ fb}^{-1} (13 \text{ TeV})$

$m_H = 800 \text{ GeV}$

$2.3 \text{ fb}^{-1} (13 \text{ TeV})$
Search for $t\bar{t} \rightarrow \ell + \text{jets} \geq 1$ additional $b$.

Fit data to 4 CR and one SR:

\[ 5j(2\text{b}), 4j(\geq 3\text{b}), 4j(2\text{b}), \geq 6j(2\text{b}) \rightarrow H_T \geq 5j(\geq 3\text{b}) \rightarrow \text{BDT} \]

BDT incl. $p_T(j_1)$, $H_T$, $m_{bb}$, $\Delta R(bb)$, 2nd Fox-Wolfram mom.

BG: $t\bar{t}$: MC + data-based $p_T$-reweight; multijet from data; others from MC.

Plot:

- ATLAS
- Post bkg-only fit
- Data
- $t\bar{t}+\text{LF}$
- $t\bar{t}+\text{cc}$
- $t\bar{t}+\text{bb}$
- Other bkg
- Total unc.

- Total bkg
  - in sig+bkg fit
  - $H^+ 500 \text{ GeV}$ shape

- Observed limit (CLs)
- Expected limit (CLs)
- Exp. limit with injected signal
  - $m_H=300 \text{ GeV}, \sigma\times\text{BR}=1.65 \text{ pb}$
Type-II seesaw model for generating neutrino masses includes a scalar triplet with physical particles $\Phi^{++}$, $\Phi^+$, $\Phi^0$.
Produced as either $Z/\gamma \to \Phi^{++}\Phi^{--}$ or $W^+ \to \Phi^{++}\Phi^-$. 
Primary decay $\Phi^{++} \to \ell^+\ell^+$ (decay to $W^+W^+$ suppressed for realistic neutrino masses).

Interpret in terms of benchmark points of type-II seesaw model. 
BP1: Neutrino sector with a massless neutrino and normal mass hierarchy.
Other benchmark points in paper.

Search in categories $\ell\ell\tau_{\text{had}}$, $\ell\ell\ell\tau_{\text{had}}$, $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$ ($\ell \equiv e, \mu$, flavors may be mixed in a category).
Plot mass of same-sign lepton pairs.

95% CL: $m(\Phi^{++}) > 383$ GeV (BP1)
Select primary vertex using photon pointing and NN discriminant.

\[ p_T(\gamma) > 55 \text{ GeV}; \ m_{\gamma\gamma} > 200 \text{ GeV} \]
\[ p_T(\gamma_1) > 0.4m_{\gamma\gamma}; \ p_T(\gamma_2) > 0.4m_{\gamma\gamma} \]

\[ p_T(\gamma) > 75 \text{ GeV} \]
EBEB: Both \( \gamma \) in barrel; \( m_{\gamma\gamma} > 230 \text{ GeV} \)
EBEE: 1 barrel \( \gamma \), 1 endcap \( \gamma \); \( m_{\gamma\gamma} > 330 \text{ GeV} \)
Also categorize on \( \gamma \) shape and \( B \) field on/off.
Exclusion limits for narrow scalar resonance from 13 TeV data.

Results also available for other widths.
$H \rightarrow \gamma\gamma$ (3)

$m_{\gamma\gamma}$ from 8 TeV data

**ATLAS**

- Data
- Background-only fit

Spin-2 Selection

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

**CMS**

- Data
- Fit model

$19.7$ fb$^{-1}$ (8 TeV)

EBEB $\min(R_{EBEB}) > 0.94$

$\sigma(data-fit)/2 - 0$

$stat$