Higgs Physics: Highlights from the Post-Discovery Era

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On behalf of the ATLAS, CDF, CMS and D0 Collaborations
Introduction and Outline

- Long-sought Higgs boson finally discovered
  - Culmination of decades-long pursuit
    - LEP experiments through 2000
    - Tevatron through Runs 1 and 2
  - Finally, at the LHC:
    - 2012: “A new particle…”
    - 2013: “A Higgs boson…”

- For the remainder of LHC Run 1, the focus shifted from SM searches to measurements and BSM insights:
  - Is this the Higgs boson of the SM?
  - Are there any other Higgs bosons to observe?
  - Is this Higgs boson a window to new physics?
SM Higgs Boson Production at the LHC

**Glue-gluon fusion (ggF)**

- $pp \rightarrow H (\text{NNLO+NNLL QCD + NLO EW})$

**Vector-boson fusion (VBF)**

- $pp \rightarrow ggH (\text{NNLO QCD + NLO EW})$

**W/Z associated production (VH)**

- $pp \rightarrow WH (\text{NNLO QCD + NLO EW})$
- $pp \rightarrow ZZ (\text{NNLO QCD + NLO EW})$
- $pp \rightarrow t\bar{t}H (\text{NLO QCD})$
- $pp \rightarrow bbH (\text{NNLO QCD in 5FS, NLO QCD in 4FS})$

More on $t\bar{t}H$, $bbH$ production later…
Rarer decay modes suffer from statistics but generally have lower levels of mundane processes ("background") obscuring the signal AND have a higher resolution on the mass of the Higgs before decay.
The SM Higgs Program at the LHC

- Comprehensive Higgs pursuit campaign
  - Survey of each accessible production mechanism for each primary decay mode

- All channels contribute to cumulative picture
Is this the Higgs Boson of the Standard Model?
Transition from Searches to Measurements

- In the post-discovery era, focus moves from search to precision measurements
  - First task:
    - Need precise measurements of all of its properties
    - Is this the Higgs Boson of the Standard Model?

- Characteristics of the SM Higgs:
  - Decay modes
  - Couplings to other SM particles
  - Mass
  - Spin and parity
  - Width
  - Self-coupling

\[ L = \left( D_\mu \phi \right)^* \left( D^\mu \phi \right) - \left( \mu^2 \phi^2 + \lambda \phi^4 \right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]

\[ m_H = \sqrt{2} \lambda \nu \]

\[ \lambda, \mu \text{ unknown} \rightarrow m_H \text{ is a free parameter of the SM} \]

\[ g_{HVV} = 2 \frac{m_V^2}{\nu} \quad g_{Hff} = \frac{m_f}{\nu} \]
Higgs Decays to Bosons

**H → γγ**

- CMS
- 
  \( S/(S+B) \) weighted events (GeV)
- \( m_{\gamma\gamma} \) (GeV)
- \( m_{\gamma\gamma} = 124.70 \pm 0.34 \text{ GeV} \)

**H → ZZ**

- Data
- \( Z + X \)
- \( Z' + ZZ \)
- \( m_h = 126 \text{ GeV} \)

**H → WW**

- CMS
- \( m_{\gamma\gamma} \) (GeV)
- \( m_{WW} \) (GeV)
- Background subtraction
- Systematic uncertainty
Higgs Decays to Fermions

H\rightarrow\tau\tau

\begin{align*}
\mu^{+}\mu^{-} & , \tau^{+}\tau^{-} \rightarrow \mu^{+}\mu^{-} \rightarrow \tau^{+}\tau^{-} \\
\text{Higgs} (125 \text{ GeV}) & \rightarrow \tau^{+}\tau^{-} \\
\text{Data} & , \text{Background} \\
\text{SM} & , \text{Electroweak} \\
\text{QCD} & \\
\text{S / (S+B) Weighted d}x / d\,m_{\tau\tau} \text{ [1/GeV]} \\
\text{JHEP 05 (2014) 104}
\end{align*}

H\rightarrow bb

\begin{align*}
\text{CMS, 4.9 fb}^{-1} \text{ at 7 TeV, 19.7 fb}^{-1} \text{ at 8 TeV} \\
\text{Higgs} (125 \text{ GeV}) & \rightarrow b\bar{b} \\
\text{Data} & , \text{Background} \\
\text{VH modes} \\
\text{VBF} \\
\text{CMS-HIG-14-004, submitted to PRD}
\end{align*}

\begin{align*}
\text{VH modes} \\
\text{ATLAS} \\
\text{H\rightarrow \tau\tau VBF+Boosted} \\
\text{1s = 7 TeV, 4.5 fb}^{-1} \\
\text{1s = 8 TeV, 20.3 fb}^{-1} \\
\text{Data} & , \text{H(125) (μ=1.0)} \\
\text{Z\rightarrow \tau\tau} & \\
\text{Others} & \\
\text{Fakes} & \\
\text{Uncert.} & \\
\ln(1+S/B) \text{ w. Events / 10 GeV} \\
\text{JHEP 04 (2015) 117}
\end{align*}

\begin{align*}
\text{VH modes} \\
\text{ATLAS} \\
\text{H\rightarrow \tau\tau VBF+Boosted} \\
\text{1s = 8 TeV Ldt = 20.3 fb}^{-1} \\
\text{0+1+2 lep., 2+3 jets, 2 tags} \\
\text{Weighted by Higgs S/B} \\
\text{Data 2012} & , \text{VH(bb) (μ=1.0)} \\
\text{Diboson} & \\
\text{Uncertainty} & \\
\text{Weighted events after subtraction / 20 GeV} \\
\text{JHEP01(2015)069}
\end{align*}
Higgs Decays to Fermions

**H→ττ**

- CMS, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
  - \( \mu^+\mu^- \) \( \tau^+\tau^- \) \( \theta \mu \)

**H→bb**

- Phys. Rev. D 89, 012003
  - CMS-­‐‑HIG-­‐‑14-­‐‑004, submiRed to PRD

**VH modes**

- JHEP 04  (2015) 117
  - VH (\( \mu = 1.0 \))
  - Z→ττ
  - Others
  - Fakes
  - Uncert.

**Legacy of Tevatron H→bb:**

- 2-3σ significance for \( M_H = 115-145 \)

Primary Higgs Decay Channels:
Summary of Individual Analyses

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Primary Production Mechanism</th>
<th>Significance of Observation ($\sigma =$ standard deviation)</th>
<th>Signal Strength $\mu = \sigma/\sigma_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CMS Expected</td>
<td>CMS Observed</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>VH, VBF, ttH</td>
<td>2.7$\sigma$</td>
<td>2.6$\sigma$</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>ggF, VBF</td>
<td>5.8$\sigma$</td>
<td>4.3$\sigma$</td>
</tr>
<tr>
<td>$H \to tt$</td>
<td>ggF, VBF, VH</td>
<td>3.7$\sigma$</td>
<td>3.2$\sigma$</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>ggF, VBF</td>
<td>6.7$\sigma$</td>
<td>6.8$\sigma$</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>ggF, VBF</td>
<td>5.2$\sigma$</td>
<td>5.7$\sigma$</td>
</tr>
</tbody>
</table>

- **Significance of Observation:**
  - “3$\sigma$ significance” implies only 1 in 740 probability for background-only data to fluctuate to produce observed excess.
  - “5$\sigma$ significance” = 1 in 3.5 million

- **Signal Strength, $\mu$:**
  - How much signal is observed, in units of the amount predicted from the Standard Model for each search channel ($\mu = 1.0$ implies SM level)
 Rare Decays

- In the SM, BR($H \rightarrow Z\gamma$), BR($H \rightarrow \mu\mu$), and BR($H \rightarrow J/\psi\gamma$) are predicted to be tiny
- But one should look anyways....

95%CL upper limits, $M_H = 125$

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\sigma / \sigma_{SM} &lt; 9.5$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>$\sigma / \sigma_{SM} &lt; 7.4$</td>
<td>9.8</td>
</tr>
<tr>
<td>$H \rightarrow J/\psi\gamma$</td>
<td>BR &lt; 1.5E-3</td>
<td>1.5E-3</td>
</tr>
<tr>
<td>$H \rightarrow \Upsilon (1S,2S,3S)\gamma$</td>
<td>BR &lt; (1.3,1.9,1.3)E-3</td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**

- Observed CL
- Expected CL

- $\sigma = 7$ TeV 4.5 fb$^{-1}$
- $\sigma = 8$ TeV 20.3 fb$^{-1}$

[Graphs and tables from the slides provided by Christopher Neu]
Grand Combination: Signal Strengths

**Combine results from every channel accounting for stat and syst uncertainties, and their correlations**

**Profile likelihood fits are performed with nuisance parameters profiled**

### ATLAS

<table>
<thead>
<tr>
<th>Process</th>
<th>$m_H = 125.36$ GeV</th>
<th>$\sigma$(stat.)</th>
<th>$\sigma$(sys inc.)</th>
<th>$\sigma$(theory)</th>
<th>Total uncertainty $\pm 1\sigma$ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ^{*}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$H \rightarrow WW^{*}$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Signal strengths for primary decay modes look very SM-like**

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*EPJC 75 (2015) 212*

*arXiv:1507.04548, submitted to EPJC*
Grand Combination: Signal Strengths

- Combine results from every channel accounting for stat and syst uncertainties, and their correlations
- Profile likelihood fits are performed with nuisance parameters profiled

Signal strengths for primary production mechanisms look very SM-like

More on ttH production in a few slides…
Grand Combination: Couplings to Particles of the SM

- Look for deviations from SM predictions for couplings to vector bosons and fermions

\[ g_{HVV} = 2 \frac{m_V^2}{v} \quad g_{Hff} = \frac{m_f}{v} \]

- Here assume same \( \kappa_V \) for each vector boson, and same \( \kappa_f \) for all fermions

\[ g_{HVV} = \kappa_V \left( 2 \frac{m_V^2}{v} \right) \quad g_{Hff} = \kappa_f \left( \frac{m_f}{v} \right) \]

- \((\kappa_V, \kappa_f) = (1.0, 1.0)\) is the SM
- Data prefers SM-like couplings – agreement within 1\( \sigma \)
Grand Combination: Couplings to Particles of the SM

• Can test alternative models:
  – Here is considered one where only SM particles are considered in loops and no invisible or undetected Higgs boson decay are allowed.
  – Look at scaling factors for each prominent accessible coupling.
Grand Combination: Couplings to Particles of the SM

- Can test alternative models:
  - Here is considered one where only SM particles are considered in loops and no invisible or undetected Higgs boson decay are allowed.
  - Look at scaling factors for each prominent accessible coupling

![Graphs showing coupling strengths and mass spectra with CMS and ATLAS data](image-url)
Many other alternative models tested
– Here shown CMS results only, but similar ones from ATLAS available

Tests of all schemes are largely consistent with expectations from the SM

Interesting:
– Most general model tested (no assumption on width, non-SM couplings allowed in loops as well as direct interaction) sets limits on $\text{BR}(H \rightarrow \text{BSM})$ in $[0.00, 0.57]$ at 95% CL
– Still lots of room for BSM influence in Higgs couplings
The top-Higgs Coupling

- **Fermionic couplings:**
  - LHC analyses have so far only been able to probe the Yukawa couplings $Y_b$ and $Y_\tau$ directly
  - Within the SM, the Higgs coupling to the top quark, $Y_t$, is predicted to be by far the largest of all the fermionic couplings
    - $m_{\text{top}}$ implies relatively large coupling, $Y_t \sim 1$
      - $\sim 30$ larger than $Y_b$
      - $\sim 100$ larger than $Y_\tau$
    - Strongest coupling among all known SM particles

- Also $Y_t$ will be the easiest (and perhaps only) up-type fermion coupling to probe

- Best channel: **ttH production**
  - tHq production also accessible – sensitivity to sign of $Y_t$, negative values still allowed from global coupling fits

**Imperative:** Absolutely need to measure $Y_t$ directly to know the true nature of the couplings of the new boson.
Search for $ttH$ Production

- Suite of $ttH$ analyses not yet achieving sensitivity to level of $ttH$ production predicted in the SM
  - CMS: $\mu = \sigma / \sigma_{SM} < 2.7$ (4.5) expected (observed) at 95% CL  
  [combination]
  - ATLAS: $\mu < 2.2$ (3.4) [H→bb]  
  $\mu < 2.4$ (4.7) [H→multilep]

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CMS

$\sqrt{s} = 7$ TeV, 5.0-5.1 fb$^{-1}$; $\sqrt{s} = 8$ TeV, 19.3-19.7 fb$^{-1}$

- $\gamma\gamma$
- $b\bar{b}$
- $\tau^{-}\tau^{+}$
- $3l$
- $4l$

Best fit $\sigma / \sigma_{SM}$ at $m_{H} = 125.6$ GeV

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ATLAS

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

- Dilepton
  - $ttH$ (H→b$\bar{b}$) (tot) (stat)
  - $2.8 \pm 2.0$ (1.4)

- Lepton+jets
  - $1.2 \pm 1.3$ (0.8)

- Combination
  - $1.5 \pm 1.1$ (0.7)


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JHEP 09 (2014) 087

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arXiv:1506.05988, accepted by PLB
tHq Analyses: Different Approach to $Y_t$

- Hence this process is dependent on the sign of the top-Higgs coupling

- Interference effects suppress tHq production in the SM, but if $Y_t$ is negative there is considerable enhancement:
  - For 8 TeV,
    - $\sigma_{SM}(tHq) = 18$ fb
    - $\sigma(tHq, Y_t = -1) = 230$ fb

- $t\bar{t}H$ is far less sensitive to this negative coupling
tHq Analyses at CMS

**tHq, H → bb**
Leptonic W decay
3-,4-tag categories
MVA for tHq v. ttbar

**tHq, H → WW, ττ**
Same-sign 2lep and 3lep MVA for tHq v. bkgd

**tHq, H → γγ**
Enhancement on production and decay side.
No events survive in data.

Expected (observed) upper limits:
$\sigma/\sigma(Y_t = -1) < 5.1 \ (7.6)$

$\sigma/\sigma(Y_t = -1) < 5.0 \ (6.7)$

$\sigma/\sigma(Y_t = -1) < 4.1 \ (4.1)$
Characterizing the Higgs Boson: Differential Production Cross Sections

- There is more than just simply observing a given Higgs production process—are the observed kinematics reasonable and in agreement with SM predictions?

- Some features— for example, the H+jets $N_{jets}$ distribution,
Different behavior in prediction v. observation seen in the differential cross section as a function of $N_{\text{jets}}$ at CMS.

Needs to be understood between experiments.
Characterizing the Higgs Boson: Mass

- Exploit highest mass resolution channels in combination for precise determination of $m_H$
  - $H \rightarrow \gamma \gamma$
  - $H \rightarrow ZZ \rightarrow 4\text{lep}$
- First example of combination of precision Higgs measurement results across LHC exps
- Individual channel results are each compatible within 10%

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Channel} & m_H & \pm \delta_{\text{Stat}} & \pm \delta_{\text{Syst}} \\
\hline
H \rightarrow \gamma \gamma & 125.07 & 0.25 & 0.14 \\
H \rightarrow ZZ & 125.15 & 0.37 & 0.15 \\
\text{Comb} & 125.09 & 0.21 & 0.11 \\
\hline
\end{array}
\]

\[m_H = 125.09 \pm 0.24 \text{ GeV} \quad (\delta m/m_H = 1.9E-3)\]

Phys. Rev. Lett. 114, 191803
The Higgs boson of the SM is a CP-even scalar, $J^P = 0^+$
The Higgs boson of the SM is a CP-even scalar, $J^P = 0^+$

- The spin and parity influence the Higgs decay kinematics in $H \rightarrow VV$ decays
Characterizing the Higgs Boson: Spin and Parity

• The Higgs boson of the SM is a CP-even scalar, $J^P = 0^+$
  – The spin and parity influence the Higgs decay kinematics in $H \rightarrow VV$ decays
  – Alternative spin-parity models can be tested
The Higgs boson of the SM is a CP-even scalar, $J^P = 0^+$

- The spin and parity influence the Higgs decay kinematics in $H \rightarrow VV$ decays
- Alternative spin-parity models can be tested
  - Spin 1 hypothesis disfavored by observation of $H \rightarrow \gamma\gamma$, but tested anyways

![Graph showing the $J^P = 1^+$ hypothesis](https://example.com/GRAPH.png)

*Phys. Rev. D 92 (2015) 012004*
The Higgs boson of the SM is a CP-even scalar, $J^P = 0^+$
- The spin and parity influence the Higgs decay kinematics in $H \rightarrow VV$ decays
- Alternative spin-parity models can be tested
  - Spin 1 hypothesis disfavored by observation of $H \rightarrow \gamma\gamma$, but tested anyways
  - No known fundamental particle has spin 2. Many models predict them, however
• All observations consistent with $J^P = 0^+$
• $J^P = \text{pseudoscalar } 0^-$, vector $1^-$, pseudovector $1^+$ excluded at >99% CL
• Mixed-parity spin-1 state excluded at 99.999% CL
• All tested $J^P = 2^\pm_\chi$ models excluded at >98% CL, many at > 99.99% CL
Spin-0 Higgs: Parity Structure and Higher-Order Interactions

- Scattering amplitude term to $O(q^2)$ for spin-0 H and VV (VV = ZZ, $Z\gamma^*, \gamma^*\gamma^*$, WW):

$$A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 e_{V1}^* e_{V2}^* + a_2^{VV} f_{\mu\nu}^{(1)} f^{(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{(1)} f^{(2),\mu\nu},$$

In SM: large for WW, ZZ

scale of new physics in HVV intxn

CP-even scalar term, tiny in SM

CP-odd pseudoscalar term, really tiny in SM

All observations consistent with SM expectation

ATLAS has similar results: arXiv:1506.05669, submitted to EPJC.
Characterizing the Higgs Boson: Width

- The narrow width approximation is not really adequate for $H \rightarrow ZZ$

\[ \frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{\delta_{ggH}^2 \delta_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \]

- Off-shell contribution is sizable
  - For $m_{ZZ} > 2m_Z$, the contribution is $\sim 8\%$

- Can derive information on the Higgs width from on-shell / off-shell ratio

- Assumptions:
  - off-shell signal couplings are not different from on-shell behavior
  - no new light-mass states

Characterizing the Higgs Boson: Width

These results are ~100 times more precise than direct/on-shell Higgs width limits.

<table>
<thead>
<tr>
<th>upper limit</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_H$ [MeV]</td>
<td>22</td>
<td>22.7</td>
</tr>
<tr>
<td>$\frac{\Gamma_H}{\Gamma_{SM}}$</td>
<td>5.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>
• Ultimate characterization will come through examination of the Higgs self-coupling
• Accessible through Higgs pair production searches
  – Very low production cross section
• Need significant increase in integrated luminosity:
  – High-luminosity LHC era
• In Run 1 era, can look for Higgs pair production in resonance searches
  – more on this in a few slides...
Are there other Higgs Bosons?
Search for Heavy SM-Like Higgs Bosons

- Several high-mass Higgs searches have been performed
- Look for SM-like Higgs production
- Exploit $H \rightarrow ZZ$ and $H \rightarrow WW$ decay modes (dominant at large $m_H$)

**Graph:**

- **CMS** up to 5.1 fb$^{-1}$ (7 TeV) + up to 19.7 fb$^{-1}$ (8 TeV)
- 95% CL limit on $\sigma/\sigma_{SM}$
- Observed and Expected limits for $H \rightarrow WW$ and $H \rightarrow ZZ$

**Key Points:**

- SM-like Higgs excluded in range $145 < m_H < 1000$

*CMS-HIG-13-031, submitted to JHEP*
Search for Heavy SM-Like Higgs Bosons

- Several high-mass Higgs searches have been performed
- Look for SM-like Higgs production
- Exploit $H \rightarrow ZZ$ and $H \rightarrow WW$ decay modes (dominant at large $m_H$)

No significant deviation from SM expectations. Upper limits on $\sigma \times \text{BR}(H' \rightarrow ZZ)$
Is this Higgs a Window to New Physics?

Many Higgs-related searches performed, this is just a brief survey of a few.
Search for Di-Higgs Production

- Recall, the Higgs self-coupling is an important remaining piece of the characterization campaign
  - Need the HL-LHC dataset

- In the meantime, we can look for high mass BSM particles decaying to pairs of Higgs bosons, with $HH \rightarrow b\bar{b}b\bar{b}$

- Model-independent search for a narrow resonance decaying to a pair of 125 GeV H's
  - Spin-0 radion

ATLAS similar results: arxiv:1506.00285, submitted to PRL
Search for Di-Higgs Production

• Recall, the Higgs self-coupling is an important remaining piece of the characterization campaign
  – Need the HL-LHC dataset

• In the meantime, we can look for high mass BSM particles decaying to pairs of Higgs bosons, with HH→bbbb

• Model-independent search for a narrow resonance decaying to a pair of 125 GeV H’s
  – Spin-0 radion
  – Spin-2 KK-graviton

CMS-HIG-14-013, submitted to PLB

ATLAS similar results: arxiv:1506.00285, submitted to PRL
Search for Di-Higgs Production

CMS-PAS-HIG-13-032

X: spin-0 radion

X: spin-2 KK graviton

• Similar approach in
  – \(X \rightarrow HH \rightarrow bb\gamma\gamma\)
  – \(X \rightarrow HH \rightarrow \text{multileptons, photons}\)

• \(X \rightarrow H \rightarrow bbbb\) most sensitive, ie, provides lowest upper limit on such models
Search for Invisibly Decaying Higgs

- Since the Higgs couples to mass, it could decay to non-interacting massive particles that escape the detector without a trace: Examples:
  - The neutralino of SUSY if LSP
  - Dark matter particles – Higgs could be the conduit between SM and DM
- Signature characterized by large missing $E_T$

<table>
<thead>
<tr>
<th>channel</th>
<th>upper limit BR($H \rightarrow \text{inv}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>0.29</td>
</tr>
<tr>
<td>$(W/Z)_{\text{had}} H$</td>
<td>0.78</td>
</tr>
<tr>
<td>ZH</td>
<td>0.75</td>
</tr>
</tbody>
</table>

CMS similar results: EPJC 74 (2014) 2980, arXiv:1507.00359
"Higgs portal" DM interpretation:

- $H \rightarrow \chi \chi$ possible if $m_\chi < m_H / 2$
- Limits on $\chi$-nucleon cross section as a function of $m_\chi$ for scalar, vector and Majorana fermion hypotheses for $\chi$
Higgs-Dark Matter Production

- Can look for simultaneous production of Higgs and pair-produced DM particles
- Signature: $\gamma \gamma + \text{MET}$
- Small excess over SM-only expectation (1.4$\sigma$)

![Diagram showing the production of Higgs and DM particles](image)

**ATLAS**

- $s = 8$ TeV, $\int L \, dt = 20.3$ fb$^{-1}$
- $H + E_T^{miss}$, $H \rightarrow \gamma\gamma$, $m_H = 125.4$ GeV

**LUX**

- Non-perturbative ($g > 4\pi$)
- No truncation
- Trunc. $g = 4\pi$
- Trunc. $g = 1$

Christopher Neu

arXiv:1506.01081, submitted to PRL
Search for LFV Decaying Higgs

- Search performed looking for LFV decay $H \rightarrow \mu \tau$
  - Search for $\mu \tau_e$ and $\mu \tau_{\text{had}}$

**Table:**

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<thead>
<tr>
<th>BR [%]</th>
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<tbody>
<tr>
<td>upper limit</td>
<td>1.51</td>
<td>1.85</td>
</tr>
<tr>
<td>best-fit</td>
<td>$0.84^{+0.39}_{-0.37}$</td>
<td>$0.77 \pm 0.62$</td>
</tr>
</tbody>
</table>

BR($H \rightarrow \mu \tau$) < 1.51% at 95% CL for $m_H = 125$

Slight excess observed (2.5$\sigma$) at CMS

CMS-HIG-14-005, submitted to PLB
Search for Charged Higgs in top Decays

• Charged Higgs bosons play a role in several BSM models

• Look in decays of the top quark
  – SM: BR(t → Wb) ~ 100%
  – But because of large \( m_t \), this is a reasonable strategy to pursue

• Signature: standard ttbar selection
  – 1 isolated high \( p_T \) muon
  – ≥4 jets
  – MET

• Counting experiment, seeing no excess, set upper limit on BR(t → H\(^+\) b)
Search for Heavy Charged Higgs

• Looking for heavy charged Higgs produced via VBF, decaying to WZ
  – hadronic W decays
  – leptonic Z decays
• Look at 4-body mass

• Mass hypotheses between 200 and 1000 GeV
• Set upper limits on $\sigma \times \text{BR}$
Search for SUSY Higgs

- Minimal supersymmetric extension of the standard model (MSSM)
  - Two Higgs doublets
  - Five physical observable Higgs bosons:
    - Light and heavy CP-even states, $h$ and $H$
    - CP-odd state: $A$
    - Charged Higgs: $H^\pm$
  - Two free parameters, typically chosen to be $m_A$ and $\tan\beta = \text{ratio of vevs for two Higgs doublets}$
- Large $\tan\beta \Rightarrow$ enhanced Higgs coupling to down-type fermions
  - Hence associated $b$ production and decay $H \rightarrow \tau\tau$ offer unique opportunities for MSSM-directed searches
Search for SUSY Higgs: $H \rightarrow \tau \tau$

- Test a variety of MSSM “benchmark” scenarios
  - Establish exclusion regions for each in $m_A$ v. $\tan\beta$ plane

**ATLAS** $\sqrt{s}=7$ TeV, $\int L \, dt = 19.5 - 20.3 \, \text{fb}^{-1}$

MSSM $m_{h^{mod+}}$ scenario, $M_{\text{SUSY}} = 1$ TeV, $h/H/A \rightarrow \tau\tau$

- Excludes low $m_A$ region except $\tan\beta < 10-20$
- Larger masses and $\tan\beta \sim 20-50$ still allowed
- Run II will extend search to masses beyond 1 TeV

CMS Preliminary, $h,H,A \rightarrow \tau\tau$, $19.7 \, \text{fb}^{-1}$ (8 TeV) + $4.9 \, \text{fb}^{-1}$ (7 TeV)

CMS-HIG-14-029
Other SUSY+EXO Higgs Results

Wide phase space to explore, cannot detail all of these nice results.

CMS-HIG-14-011, $A \to ZH \to llb\bar{b}$

CMS-HIG-15-001, $H/A \to Z A/H$ in 2HDM

CMS-HIG-13-010, light $hh \to 4\mu$

CP-odd $h \to ZH$, $H \to bb$ or $\tau\tau$
Summary

- Higgs physics has now moved from the search and discovery phase into a precision measurement era

- Characteristics of this Higgs boson need to be measured with high precision. Some have been with the Run 1 data sample; a few crucial ones remain.

- The measurement campaign has so far revealed no significant deviations from the predictions of the SM

- As Run 2 begins, it is clear that much remains to be understood about this new particle and its implications
  - There is much to do

- None of this would have been possible without the excellent performance of the LHC – a testament to the incredible work of the LHC team of physicists and engineers
Backup
Search for $ttH$ Production, $H \rightarrow bb$ with BDTs

- Focus on two primary channels:
  - **Single-lepton channel**: one high $p_T$ isolated $e/\mu$, $\geq 4$ jets, $\geq 2$ b tags
  - **Dilepton channel**: two opposite-sign leptons, $\geq 2$ jets, $\geq 2$ b tags
- Backgrounds: a considerable problem
  - Irreducible: $tt+b$-jets
    - Poorly known, both theoretically and experimentally
  - Experimental:
    - False-positive b-tags in $tt+\text{LF}$-jets
- Split selected events into categories based on jet, b-tag multiplicities
- Exploit BDT discriminant in each category for signal extraction
- Perform simultaneous fit across all categories

**BDT inputs**, discriminating signal from bkgd:
- Object kinematics
- Multi-object characteristics
- Angular variables
- Qualities of b-tagged jets
  - continuous b-tag discriminant

![Graph showing CMS $ttHb\bar{b}$ with Lepton $\geq 6$ jets and $\geq 4$ b-tags](attachment:image.png)

$\sqrt{s} = 8$ TeV, $L = 19.3$ fb$^{-1}$
Search for $ttH$ Production, $H \rightarrow \gamma\gamma$

- **Very low-rate process but**
  - low background
  - distinctive diphoton peak $M_{\gamma\gamma} \sim M_H$

- **Event selection:**
  - Two reconstructed high $p_T$ photons
  - Leptonic $t\bar{t}b\bar{b}$ category:
    - $\geq 1$ isolated high $p_T$ $e/\mu$
    - $\geq 2$ high $p_T$ jets, $\geq 1$ b-tagged jet
  - Hadronic $t\bar{t}b\bar{b}$ category:
    - $=0$ $e/\mu$
    - $\geq 5$ high $p_T$ jets, $\geq 1$ b-tagged jet

- **Look for a resonance in $M_{\gamma\gamma}$**
  - Describe background as a falling exponential
Search for $ttH$ Production, $H \rightarrow$ Multileptons

**Same-sign dilepton**

- 2 $e/\mu$ with $p_T > 20$
- $\geq 4$ jets with $p_T > 25$
- $\geq 1$ b-tagged jet

**Three lepton**

- 1 $e/\mu$ with $p_T > 20$
- 1 $e/\mu$ with $p_T > 10$
- 1 $e(\mu)$ with $p_T > 7(5)$
- $\geq 2$ jets with $p_T > 25$
- $\geq 1$ b-tagged jet
- Veto $M_{ll} \sim M_Z$

**Four lepton**

- 1 $e/\mu$ with $p_T > 20$
- 1 $e/\mu$ with $p_T > 10$
- 2 $e(\mu)$ with $p_T > 7(5)$
- $\geq 2$ jets with $p_T > 25$
- $\geq 1$ b-tagged jet
- Veto $M_{ll} \sim M_Z$

Low-rate but low-background signatures.
### Search for ttH Production, $H \rightarrow \text{Multileptons}$

**Expected and observed yield in 19.6/fb at 8 TeV**

<table>
<thead>
<tr>
<th>Source</th>
<th>ee</th>
<th>eμ</th>
<th>μμ</th>
<th>3l</th>
<th>4l</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH, $H \rightarrow WW$</td>
<td>1.0 ± 0.1</td>
<td>3.2 ± 0.4</td>
<td>2.4 ± 0.3</td>
<td>3.4 ± 0.5</td>
<td>0.29 ± 0.04</td>
</tr>
<tr>
<td>ttH, $H \rightarrow ZZ$</td>
<td>—</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.2 ± 0.0</td>
<td>0.09 ± 0.02</td>
</tr>
<tr>
<td>ttH, $H \rightarrow \tau\tau$</td>
<td>0.3 ± 0.0</td>
<td>1.0 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>1.1 ± 0.2</td>
<td>0.15 ± 0.02</td>
</tr>
<tr>
<td>tt $W$</td>
<td>4.3 ± 0.6</td>
<td>16.5 ± 2.3</td>
<td>10.4 ± 1.5</td>
<td>10.3 ± 1.9</td>
<td>—</td>
</tr>
<tr>
<td>tt $Z/\gamma^*$</td>
<td>1.8 ± 0.4</td>
<td>4.9 ± 0.9</td>
<td>2.9 ± 0.5</td>
<td>8.4 ± 1.7</td>
<td>1.12 ± 0.62</td>
</tr>
<tr>
<td>tt $WW$</td>
<td>0.1 ± 0.0</td>
<td>0.4 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>0.4 ± 0.1</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>tt $\gamma$</td>
<td>1.3 ± 0.3</td>
<td>1.9 ± 0.5</td>
<td>—</td>
<td>2.6 ± 0.6</td>
<td>—</td>
</tr>
<tr>
<td>WZ</td>
<td>0.6 ± 0.6</td>
<td>1.5 ± 1.7</td>
<td>1.0 ± 1.1</td>
<td>3.9 ± 0.7</td>
<td>—</td>
</tr>
<tr>
<td>ZZ</td>
<td>—</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.3 ± 0.1</td>
<td>0.47 ± 0.10</td>
</tr>
<tr>
<td>Rare SM bkg.</td>
<td>0.4 ± 0.1</td>
<td>1.6 ± 0.4</td>
<td>1.1 ± 0.3</td>
<td>0.8 ± 0.3</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>7.6 ± 2.5</td>
<td>20.0 ± 4.4</td>
<td>11.9 ± 4.2</td>
<td>33.3 ± 7.5</td>
<td>0.43 ± 0.22</td>
</tr>
<tr>
<td>Charge misidentified</td>
<td>1.8 ± 0.5</td>
<td>2.3 ± 0.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>All signals</td>
<td>1.4 ± 0.2</td>
<td>4.3 ± 0.6</td>
<td>3.1 ± 0.4</td>
<td>4.7 ± 0.7</td>
<td>0.54 ± 0.08</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>18.0 ± 2.7</td>
<td>49.3 ± 5.4</td>
<td>27.7 ± 4.7</td>
<td>59.8 ± 8.0</td>
<td>2.07 ± 0.67</td>
</tr>
<tr>
<td>Data</td>
<td>19</td>
<td>51</td>
<td>41</td>
<td>68</td>
<td>1</td>
</tr>
</tbody>
</table>

- Signal dominated in each category by $H \rightarrow WW$ mode
- Significant excess over expectation in SS 2lep μμ channel
Search for ttH Production, H → Multileptons

Signal extraction:
• BDT used in SS 2-lep and 3-lep categories
• N_{jets} alone used for 4-lep category
• Excess in μμ channel

JHEP 09 (2014) 087
Search for $t\bar{t}H$ Production: All Channels

arXiv:1408.1682, Accepted by JHEP

- Can perform same kind of coupling-modifier study as described earlier

- Value in performing this solely within $t\bar{t}H$ analyses
Matrix-element method (MEM) provides a powerful device for signal discrimination

- Integrate over unreconstructed or poorly measured particles
- Marginalize over unknown quark-to-jet assignments
- Assign event weight under $ttH$ or $tt+bb$ hypotheses

Consider just events in which the S or B interpretation is feasible:

- 1 lepton, $\geq 5$ jets
- 2 leptons, $\geq 4$ jets

Alternative event-level likelihood ratio $b$-jet ID selection

$$F(\xi) = \frac{f(\xi|tt+hf)}{f(\xi|tt+hf) + f(\xi|tt+hf)}.$$
<table>
<thead>
<tr>
<th>SL Cat 1</th>
<th>SL Cat 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttH \rightarrow blv \ bqq + bb$</td>
<td>$ttH \rightarrow blv \ bq q + g + bb$</td>
</tr>
<tr>
<td>$\geq 6$ jets</td>
<td>$\geq 6$ jets</td>
</tr>
<tr>
<td>All quarks reconstructed</td>
<td>All quarks reconstructed – except for one $W$ daughter – and $\geq 1$ gluon</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SL Cat 3</th>
<th>DIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttH \rightarrow blv \ bq q + bb$</td>
<td>$ttH \rightarrow blv \ blv + bb$</td>
</tr>
<tr>
<td>$5$ jets</td>
<td>$\geq 4$ jets</td>
</tr>
<tr>
<td>All quarks reconstructed – except for one $W$ daughter</td>
<td>All quarks reconstructed</td>
</tr>
</tbody>
</table>
Categorize events according to what is reconstructed in the event – rather than just $N_{\text{jets}}$ and $N_{\text{tags}}$

Build probability densities for S,B from ME and likelihood used in $F$

Final discriminant: $P_{s/b} = \text{ratio of ttH, ttbb probabilities}$

- Good a priori separation
- Well-behaved in data
ttH, H→bb with MEM

- Categorize events according to what is reconstructed in the event – rather than just $N_{\text{jets}}$ and $N_{\text{tags}}$

- Build probability densities for S,B from ME and likelihood used in $F$

- **Final discriminant:**
  \[ P_{s/b} = \text{ratio of } \text{ttH, ttbb probabilities} \]
  - Good a priori separation
  - Well-behaved in data

- Perform simultaneous fit across categories and set upper limits

\[ \mu = \sigma / \sigma_{\text{SM}} < 3.3 \ (4.2) \text{ expected (observed) at 95\% CL} \]

Significant improvement in upper limit over kinematic BDT in ttH.H→bb.

Next step: combine approaches
Several BSM models predict high mass Higgs states
• Good mass resolution in diphoton signature allows for resonance scans
Search for High-Mass Scalar Resonances in $Z\gamma$

- $A \to Z\gamma \to ll\gamma$
- Bump-hunting in the 3-body system mass spectrum
- Made possible by good mass resolution for this final state
- Consider both narrow and wide resonance hypotheses
Search for Heavy Charged Higgs

- Search performed looking for heavy charged Higgs produced via $gg \rightarrow H^+ tb$
  - Important for case $m_{H^+} > m_{\text{top}}$
- Consider two decay modes:
  - $H^+ \rightarrow tb$
  - $H^+ \rightarrow \tau \nu$
- Significant synthesis with existing ttbar cross section measurements
Search for Not-So Heavy Singly- and Doubly-Charged Higgs

- Search performed looking for charged Higgs produced via
  - Case 1: $p \rightarrow t\bar{t} \rightarrow H^+ b Wb$
    - important for case $m_{H^+} < (m_{top} - m_b)$
  - Case 2: $pp \rightarrow t\bar{b} b H^+$ and $pp \rightarrow t b\bar{b} H^-$
    - important for case $m_{H^+} > (m_{top} - m_b)$

- Consider two decay modes:
  - $H^+ \rightarrow \tau \nu$
  - fully-hadronic final state

Upper limits on BR for Case 1 and $xsec \times BR$ for Case 2