Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data

G. Gaycken on behalf of the ATLAS and CMS Collaboration

La Thuile, March 19, 2017
Introduction

Couplings to fermions and bosons strongly constrained by Run I measurements.

- In combination, search for $H \rightarrow \tau^+\tau^-$ exceeds $5\sigma$.
- But, despite being the dominant decay mode, coupling to $b\bar{b}$ not yet observed.
Search for $H \rightarrow b\bar{b}$

- **Gluon fusion**
  - Large multijet background
  - Challenge for the trigger

- **Vector Boson Fusion (VBF)**
  - Challenge for the trigger

- **Associate production with vector bosons (VH)**
  - Leptons, $E_{T}^{\text{mis}}$
to trigger and suppress backgrounds

- **Associate production with $t\bar{t}$**
  - See previous talk

- **Associate production with single top**
  - Small cross-section

---

G. Gaycken  Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data  La Thuile, March 19, 2017  3
VBF, $H \rightarrow b\bar{b}$

Multivariate classifier to identify VBF like events for events with 1 and 2 b-tagged jets:

Signal extract in simultaneous fit to $m_{bb}$ spectrum in all categories.
$m_{bb}$ resolution

$m_{bb}$ resolution significantly reduced by semileptonic b-decays and gluon radiation outside jet “cone”
→ improve b-jet energy resolution with regression.

Regression inputs:

- jet kinematic,
- EM energy fraction,
- information about soft leptons in the jet,
- secondary vertex information,
- pileup.

FSR correction:
Add jets with $\Delta R < 0.8$. 

---

![Graph showing $1/N \times dN/dM_{bb}$ vs. $M_{bb}$ (GeV) with peaks and FWHMs for Regressed + FSR and Raw data.]
VBF, $H \rightarrow b\bar{b}$

Multivariate classifier to identify VBF like events for events with 1 and 2 b-tagged jets:

Signal extract in simultaneous fit to $m_{bb}$ spectrum in all categories.

Result using $2.3 \text{ fb}^{-1} @ \sqrt{s} = 13 \text{ TeV}$:

$$\mu = -3.7^{+2.4}_{-2.5}$$

Combination with Run I (18 – 19 fb$^{-1}$ @ 8 TeV):

$$\mu = 1.3^{+1.2}_{-1.1}$$
Multijet background in \((q/g)q\bar{b}b\) significantly reduced by extra high \(p_T\gamma\) (destructive interference in bg. but not in WWH).

Analysis strategy:
- MVA for categorisation.
- unbinned log \(\mathcal{L}\)-fit as function of \(m_{b,\bar{b}}\) in various categories.

Signal strength:
\[
\mu = -3.9^{+2.8}_{-2.7}
\]
Limit: \(\frac{\sigma}{\sigma_{SM}} < 4.0\) at the 95% CL.
VH, H → b\bar{b}

2 leptons
ZH → ℓ⁺ ℓ⁻ b\bar{b}

1 lepton
WH → ℓν b\bar{b}

0 lepton
ZH → νν b\bar{b}

- Categories per number of selected charged leptons
- sub categories to increase significance.

One multivariate discriminant per category e.g. 2 jet, \( p_T^V \geq 150 \) GeV, ...
Signal strength $\mu$ extracted in simultaneous likelihood fit of the binned mmultivariate discriminants in all categories.

Candidate events

Run I result @7+8 TeV(4.7+20.3 fb$^{-1}$): $0.52 \pm 0.32$(stat.) $\pm 0.24$(syst.)
Higgs production in single top

- In SM diagrams interfere destructively.
- In BSM scenarios not necessarily e.g. inverted top coupling scenario
  → effective theory with possibly CP violating top Yukawa couplings, and modified couplings to vector bosons.
Modified top Yukawa coupling

Search for $H \rightarrow b\bar{b}$ in association with a single top ($t \rightarrow b\ell\nu$/$b\mu\nu$)

- final state $e/\mu + 3$ or 4 $b$-tagged jets, one non $b$-tagged jet
- MVA to find jet assignment for $t\bar{t}$ and $tHq$ hypothesis
- final discrimination MV classifier kinematics + kinematics interpreted in the two hypothesis.

 CMS Preliminary

Muon + electron channel
4 tag region
$\kappa_V = 1.0$, $\kappa_\ell = +1.0$

G. Gaycken Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data

La Thuile, March 19, 2017
Search for $H \rightarrow \tau^+\tau^-$

- All Higgs production modes accessible:

- Mass reconstruction challenging, due to neutrinos in the final state.
Search for $H \rightarrow \tau^+ \tau^-$

- All Higgs production modes accessible:

- Mass reconstruction challenging, due to neutrinos in the final state.

No 13 TeV updates to SM analyses for $H \rightarrow \tau^+ \tau^-$ yet, but ...
In some MSSM scenarios, coupling to down-type fermions enhanced → motivates search for scalar boson in association with bottom.
Couplings to fermions might be modified in case of an extended Higgs sector (MSSM, 2HDM, ...). In such models a charged Higgs is predicted.

Search for $H^\pm \rightarrow \tau \nu$ in events with $\geq 3$ jets, $\geq 1$ b-tags

$(pp \rightarrow tbH^\pm, H^\pm W^\mp b\bar{b})$.

Search for $H^\pm \rightarrow tb$ in events with $\geq 4$ jets, $\geq 2$ b-tags.
A more complicated Higgs-sector could allow for lepton flavour violation.

Search for $H \rightarrow \mu \tau / \tau_{\text{had}}$, in categories of 0-2 extra jets.

- Final discriminant visible mass corrected by estimated energy loss from $\nu_{\tau}$

- Limit on LFV Yukawa coupling ($m_{H} = 125$ GeV):

$$\sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$$
Search for di-muon resonance in ggF and VBF like events.

- b-veto to reject $t\bar{t}$
- MVA to identify VBF-like events,
- to enhance significance categorisation in $p_T^{\mu\mu}$, $\eta^\mu$ and the multivariate discriminant to identify VBF.
$H \rightarrow \mu^{+} \mu^{-}$

$m_{\mu\mu}$ in VBF tight category

Signal strength $\mu$ extracted from simultaneous fit to $m_{\mu\mu}$ in all categories.

- **signal**: Crystal-ball + Gaussian
  - Shape fixed to prediction of simulation.

- **background**: exponential + BW $\otimes$ Gaussian ($Z$)
Event yields in mass window around peak position ($m_H = 125$ GeV)

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Signal</th>
<th>Background</th>
<th>S/√B</th>
<th>FWHM</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central low $p_T^{µµ}$</td>
<td>10.9</td>
<td>7400</td>
<td>0.13</td>
<td>5.6 GeV</td>
<td>7885</td>
</tr>
<tr>
<td>Non-central low $p_T^{µµ}$</td>
<td>31.6</td>
<td>36000</td>
<td>0.17</td>
<td>7.0 GeV</td>
<td>38777</td>
</tr>
<tr>
<td>Central medium $p_T^{µµ}$</td>
<td>23.4</td>
<td>6200</td>
<td>0.30</td>
<td>5.7 GeV</td>
<td>6585</td>
</tr>
<tr>
<td>Non-central medium $p_T^{µµ}$</td>
<td>66.5</td>
<td>29000</td>
<td>0.39</td>
<td>7.1 GeV</td>
<td>31291</td>
</tr>
<tr>
<td>Central high $p_T^{µµ}$</td>
<td>15.5</td>
<td>3300</td>
<td>0.27</td>
<td>6.3 GeV</td>
<td>3160</td>
</tr>
<tr>
<td>Non-central high $p_T^{µµ}$</td>
<td>39.7</td>
<td>13000</td>
<td>0.35</td>
<td>7.7 GeV</td>
<td>12829</td>
</tr>
<tr>
<td>VBF loose</td>
<td>3.4</td>
<td>250</td>
<td>0.22</td>
<td>7.6 GeV</td>
<td>274</td>
</tr>
<tr>
<td>VBF tight</td>
<td>3.4</td>
<td>71</td>
<td>0.40</td>
<td>7.5 GeV</td>
<td>79</td>
</tr>
</tbody>
</table>

Prediction of the simulation

<table>
<thead>
<tr>
<th>Energy</th>
<th>Signal Strength $\mu$</th>
<th>Limit @ 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 TeV</td>
<td>$-0.07^{+1.5}_{-1.5}$</td>
<td>$&lt; 3.0 (3.1)$</td>
</tr>
<tr>
<td>7+8+13 TeV</td>
<td>$-0.13^{+1.4}_{-1.4}$</td>
<td>$&lt; 2.8 (2.9)$</td>
</tr>
</tbody>
</table>
2nd, 3rd generation couplings

Measured signal strength $\mu$ and 95% CL limit on $\sigma \times \text{Br}$ relative to the SM expectation for $m_H = 125 \text{ GeV}$:

<table>
<thead>
<tr>
<th>Process</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS $H \rightarrow \mu\mu$ 7+8+13 TeV</td>
<td>$-0.13 \pm 1.4$</td>
<td>ATLAS-CONF-2017-014</td>
</tr>
<tr>
<td>ATLAS+CMS $H \rightarrow \mu\mu$ 7+8 TeV</td>
<td>$0.1 \pm 2.5$</td>
<td>JHEP08(2016)045</td>
</tr>
<tr>
<td>CMS $H \rightarrow \mu\mu$ 7+8 TeV</td>
<td>$0.8^{+3.5}_{-3.4}$</td>
<td>Phys. Lett. B 744 (2015) 184</td>
</tr>
<tr>
<td>ATLAS+CMS $H \rightarrow \tau\tau$ 7+8 TeV</td>
<td>$1.11^{+0.24}_{-0.22}$</td>
<td>JHEP08(2016)045</td>
</tr>
<tr>
<td>CMS $H \rightarrow \tau\tau$ 7+8 TeV</td>
<td>$0.78 \pm 0.27$</td>
<td>JHEP 05 (2014) 104</td>
</tr>
<tr>
<td>ATLAS $H \rightarrow \tau\tau$ 7+8 TeV</td>
<td>$1.43^{+0.42}_{-0.37}$</td>
<td>JHEP 04 (2015) 117</td>
</tr>
<tr>
<td>CMS VBF $H \rightarrow b\bar{b}$ 8+13 TeV</td>
<td>$1.3^{+1.2}_{-1.1}$</td>
<td>CMS-PAS-HIG-16-003</td>
</tr>
<tr>
<td>ATLAS VBF $γ H \rightarrow b\bar{b}$ 13 TeV</td>
<td>$-3.9^{+2.8}_{-2.7}$</td>
<td>ATLAS-CONF-2016-063</td>
</tr>
<tr>
<td>ATLAS VH $H \rightarrow b\bar{b}$ 13 TeV</td>
<td>$0.21 \pm 0.50$</td>
<td>ATLAS-CONF-2016-091</td>
</tr>
<tr>
<td>ATLAS+CMS $H \rightarrow b\bar{b}$ 7+8 TeV</td>
<td>$0.7^{+0.29}_{-0.27}$</td>
<td>JHEP08(2016)045</td>
</tr>
<tr>
<td>ATLAS VBF $H \rightarrow b\bar{b}$ 8 TeV</td>
<td>$-0.8 \pm 2.3$</td>
<td>JHEP 11 (2016) 112</td>
</tr>
<tr>
<td>CMS VH $H \rightarrow b\bar{b}$ 7+8 TeV</td>
<td>$1.0 \pm 0.5$</td>
<td>Phys. Rev. D 89, 012003 (2014)</td>
</tr>
<tr>
<td>ATLAS VH $H \rightarrow b\bar{b}$ 7+8 TeV</td>
<td>$0.52 \pm 0.4$</td>
<td>JHEP01(2015)069</td>
</tr>
</tbody>
</table>

G. Gaycken  Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data  La Thuile, March 19, 2017  20
First searches for $H \rightarrow b\bar{b}, \mu \mu$ using 13 TeV data performed.

No deviation from SM predictions observed.

Not yet sensitive to $H \rightarrow b\bar{b}$ (assuming SM couplings).

Not all analyses updated to all available data → updates in the very near future.

By the end of this year, 13 TeV data expected to double at least.
Backup
VH, H → b¯b – ATLAS

ATLAS Preliminary \( \sqrt{s} = 13 \text{ TeV}, \int L \, dt = 13.2 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th></th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Best fit \( \mu = \sigma/\sigma_{SM} \) for \( m_H = 125 \text{ GeV} \)

\( 0.15 \pm 0.67 - 0.64 \) \((+0.49 + 0.45) - (-0.47 - 0.44)\)

\( 0.33 \pm 0.95 - 0.92 \) \((+0.68 + 0.68) - (-0.64 - 0.67)\)

\( 0.21 \pm 0.51 - 0.50 \) \((+0.36 + 0.36) - (-0.35 - 0.36)\)

ATLAS Preliminary \( \sqrt{s} = 13 \text{ TeV}, \int L \, dt = 13.2 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th></th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 lepton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 lepton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 lepton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Best fit \( \mu = \sigma/\sigma_{SM} \) for \( m_H = 125 \text{ GeV} \)

\( -0.24 \pm 0.90 - 0.84 \) \((+0.64 + 0.63) - (-0.58 - 0.60)\)

\( 0.25 \pm 0.94 - 0.92 \) \((+0.67 + 0.67) - (-0.64 - 0.67)\)

\( 0.47 \pm 0.73 - 0.69 \) \((+0.59 + 0.44) - (-0.55 - 0.42)\)

\( 0.21 \pm 0.51 - 0.50 \) \((+0.36 + 0.36) - (-0.35 - 0.36)\)

ATLAS-CONF-2016-091
VBF $m_{b\bar{b}}$ and BDT output
## VBF – CMS categories

<table>
<thead>
<tr>
<th>BDT boundary values</th>
<th>SingleB</th>
<th>DoubleB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cat. 1</td>
<td>Cat. 2</td>
</tr>
<tr>
<td>0.28 – 0.72</td>
<td>0.72 – 0.87</td>
<td>0.87 – 0.93</td>
</tr>
<tr>
<td>Data</td>
<td>25298</td>
<td>5834</td>
</tr>
<tr>
<td>Z +jets</td>
<td>49± 4</td>
<td>12.5± 2.0</td>
</tr>
<tr>
<td>W +jets</td>
<td>25.8± 3.5</td>
<td>1.6± 0.9</td>
</tr>
<tr>
<td>tf</td>
<td>53± 1</td>
<td>5.1± 0.2</td>
</tr>
<tr>
<td>Single t</td>
<td>52± 1</td>
<td>9.7± 0.5</td>
</tr>
<tr>
<td>VBF ( m_H(125) )</td>
<td>19.5± 0.2</td>
<td>13.7± 0.1</td>
</tr>
<tr>
<td>GF ( m_H(125) )</td>
<td>5.5± 0.2</td>
<td>1.8± 0.1</td>
</tr>
</tbody>
</table>

**CMS-PAS-HIG-16-003**
VBF $m_{bb^-}$ fit – background hypo

**Single B**

**Double B**

CMS-PAS-HIG-16-003
VBF+γ, $H \rightarrow b\bar{b}$

- BDT used to define categories.
- BDT inputs uncorrelated with $m_{bb}$.
- Signal strength $\mu$ computed in unbinned likelihood fit as a function of $m_{bb}$.
$\Phi \rightarrow \tau^+ \tau^-$ – signal categories

- **b-veto**
- **b-tag**
- $E_T^{\text{mis}}$

<table>
<thead>
<tr>
<th>$m_{\tau\tau} \text{ [GeV]}$</th>
<th>Events / GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Pred</td>
</tr>
<tr>
<td>100 200 300 400 500 600</td>
<td></td>
</tr>
<tr>
<td>1 10 100 1000</td>
<td></td>
</tr>
</tbody>
</table>

$\overline{\text{b-veto}}$

$\overline{\text{b-tag}}$

$E_T^{\text{mis}}$

$\overline{m_{\text{tot}}}$ total transverse mass of $\tau\tau$ system.

ATLAS-CONF-2016-085
\[ \Phi \rightarrow \tau^+ \tau^- \] – Combined limits

ATLAS Preliminary

H/A → \tau \tau, 95 \% CL limits
\[^{\gamma}S = 13 \text{ TeV}, \leq 13.3 \text{ fb}^{-1}\]
m_{\text{had}}^\ell, M_{\text{SUSY}} = 1\text{TeV}

- Observed
- Expected
- \pm \alpha
- \pm 2\alpha
- 2015, 3.2 fb^{-1} (Obs.)

- \tau_{\text{had}}^{\text{had}} (Exp.)
- \tau_{\text{lep}}^{\text{had}} (Exp.)

\[ m_A \text{ [GeV]} \]

\[ \beta \tan \theta \]

Preliminary

ATLAS

H/A → \tau \tau, 95 \% CL limits
\[^{\gamma}S = 13 \text{ TeV}, \leq 13.3 \text{ fb}^{-1}\]
m_{\text{had}}^\ell, M_{\text{SUSY}} = 1\text{TeV}

- Observed
- Expected
- \pm \alpha
- \pm 2\alpha
- 2015, 3.2 fb^{-1} (Obs.)

- \tau_{\text{had}}^{\text{had}} (Exp.)
- \tau_{\text{lep}}^{\text{had}} (Exp.)

\[ m_A \text{ [GeV]} \]

- Observed
- Expected
- \pm \alpha
- \pm 2\alpha
- 2015, 3.2 fb^{-1} (Obs.)

\[ \tau_{\ell} \tau_{\text{had}}, \tau_{\text{had}} \tau_{\text{had}} \]

combined

ATLAS-CONF-2016-085
In some MSSM scenarios, coupling to down-type fermions enhanced \( \Phi \rightarrow \tau^+ \tau^- \) motivates search for scalar boson in association with bottom.

**b-tag category, \( \tau_\ell \tau_\text{had} \)**

**Limit on \( \sigma \times \text{Br} \)**

G. Gaycken  Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data   La Thuile, March 19, 2017  30
G. Gaycken  Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data  La Thuile, March 19, 2017  31

$$\Phi \rightarrow \tau^+ \tau^-$$ signal categories

- $e\tau_{\text{had}}$
- $\mu \tau_{\text{had}}$
- $\tau_{\text{had}} \tau_{\text{had}}$

b-veto

- $e\tau_{\text{had}}$
- $\mu \tau_{\text{had}}$
- $\tau_{\text{had}} \tau_{\text{had}}$

b-tag

- $e\tau_{\text{had}}$
- $\mu \tau_{\text{had}}$
- $\tau_{\text{had}} \tau_{\text{had}}$

CMS-PAS-HIG-16-037
$\Phi \rightarrow \tau^+ \tau^-$ – Combined limits

- limits using $e\mu$, $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$
  combined

CMS-PAS-HIG-16-037

G. Gaycken  Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data  La Thuile, March 19, 2017  32
Couplings to fermions might be modified in case of an extended Higgs sector

→ Search in more exotic scenarios

ATLAS-CONF-2016-089
H \rightarrow \mu^+ \mu^-

$P_T^{\mu\mu}$

$M_{\mu\mu}$

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

*ATLAS* Preliminary

Data / 5 GeV

Events / 5 GeV

Events / 2 GeV

Data / 2 GeV

Data / MC

Data / MC

Drell-Yan

VBF

Top

VH

Diboson

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

*ATLAS* Preliminary

Data / 5 GeV

Events / 5 GeV

Events / 2 GeV

Data / 2 GeV

Data / MC

Data / MC

Drell-Yan

VBF

Top

VH

Diboson

ATLAS-CONF-2017-014

G. Gaycken  Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data  La Thuile, March 19, 2017  34
$p_T^{\mu\mu}$ medium

$\noncentral p_T^{\mu\mu}$

$\cent p_T^{\mu\mu}$

$\VBF p_T^{\mu\mu}$

$\noncentral \VBF p_T^{\mu\mu}$

$\cent \VBF p_T^{\mu\mu}$