Higgs decays to third-generation fermions at ATLAS and CMS

Christina Reissel
on behalf of the ATLAS and CMS collaborations

LHCP2021, June 7th 2021
Introduction

Higgs-fermion coupling proportional to mass
→ direct searches most promising with 3rd generation fermions

\[ H \to b\bar{b} \]
- dominant decay of the SM Higgs boson
- expected branching ratio: 58%
- large backgrounds from multi-jet production

\[ H \to \tau\bar{\tau} \]
- dominant leptonic decay SM Higgs boson
- expected branching ratio: 6%
- smaller background contribution than \( H \to b\bar{b} \)

updated analysis with full Run II datasets and new interpretations (STXS, effective couplings...)

Christina Reissel
Observation $H \to b\bar{b}$

- observation of $H \to b\bar{b}$ with Run I and partial Run II datasets independently by the ATLAS and CMS collaborations in 2018

- most sensitive Higgs production channel: VH
  → suppression of multi-jet background due to leptonically decaying vector boson

- all measurements so far consistent with the SM
Observation $H \to b\bar{b}$

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- most sensitive Higgs production channel: $VH \to b\bar{b}$ due to leptonically decaying vector boson
- all measurements so far consistent with the SM

**GOOD NEWS**

**EVERYONE**

**ATLAS EXPERIMENT**

**CMS**

Dedicated talk about $ttH$ on Wednesday

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Christina Reissel
Higgs production in association with W/Z boson decaying into leptons (event selection: 0, 1 or 2 charged leptons with two b-jets)

dominant backgrounds: V+jets, tt, single-top quark and diboson

template fit performed with BDT output

improvements to analysis strategy:
• new definition of signal and control regions
• re-optimized multivariate discriminants
• increase number of simulated events
• re-derived background modeling uncertainties

dominant uncertainties: b-tagging, jet & $E_{T,\text{miss}}$, background modelling and signal systematic uncertainties

observed (expected) significance: VH→bb: 6.7 (6.7) $\sigma$
in combination: ZH: 5.0 (5.4) $\sigma$, WH: 6.3 (5.2) $\sigma$
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- dominant uncertainties: b-tagging, jet & $E_{T,\text{miss}}$, background modelling and signal systematic uncertainties
- interpretation: STXS measurement arXiv 1906.02754 and limits on parameters of effective Lagrangian
VH → bb (boosted)

- new, boosted analysis targeting associated production of Higgs boson with W/Z decaying leptonically in the high vector boson transverse regime

- Higgs boson reconstruction as single large R-jet (R=1.0, $p_T > 250$ GeV)

- track jets formed from charged-particle tracks for reconstruction of two-body decay within large R-jet, b tagging performed on track jets

- signal extraction with profile likelihood fit to large R jet-mass

- dominant uncertainties: statistical including floating background normalization, large R-jet calibration, limited MC statistics

- combination with previously presented analysis not straight forward due to significant overlap
**signature:** presence of jets with large rapidity gap and reduced hadronic activity between forward jets and 2 b jets

**event categorization:** adversarial NN decorrelated from $m_{bb}$ (additional suppression of ggF Higgs production)

**dominant backgrounds:** non-resonant QCD multi-jet events $Z \rightarrow bb$ (derived from $Z \rightarrow \mu\mu$ with embedding technique)

**signal strength obtained from simultaneous fit to $m_{bb}$ with observed (expected) significance of 2.6 (2.8) $\sigma$ → very close to evidence in this channel**

**dominant uncertainties:** statistical and background systematics

**combination with VBF $H \rightarrow bb\gamma$ analysis yields observed (expected) significance of 3.0 (3.0) $\sigma$**

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ggF $H \to b\bar{b}$ (boosted)

- Higgs production with $p_T(Higgs) > 450$ GeV in inclusive Higgs production mode

- Higgs bosons reconstructed as single large-R jet ($R=0.8$) with two prong structure and dedicated b tagging technique

- major **backgrounds:**
  - QCD/\ttbar (estimated in control regions)
  - W/Z+jets resonance (used to constrain uncertainties)

- **event categorisation:** $p_T$, DDBT pass/fail

- **improvements:**
  - ggF $p_T(Higgs)$ with HJ-MiNLO generator including effects of finite top quark mass to higher order in QCD
  - development of b tagging algorithm based on DNN (DDBT) for large-R jets

- dominant **uncertainties:** statistical, QCD pass-fail ratio

- observed (expected) significance: 2.5(0.7) $\sigma$ with **1.9 $\sigma$ above SM expectation**
• analysis targets regime with Higgs boson produced at very high transverse momentum up to the TeV scale

• Higgs candidate reconstructed as single large R-jet (R=1.0) associated with track jets

• **event selection:** ≥ two jets, one with $p_T > 450$ GeV and containing two $b$ tagged track jets

• main **backgrounds:** multi-jet production, $V+\text{jets}$, top-quarks

• signal extraction using **reconstructed jet mass distribution**

• major **uncertainties:** statistical, jet mass resolution and jet-mass scale calibration

• interpretation in terms of inclusive signal strength, in fiducial and differential regions
Observation $H \rightarrow \tau \tau$

- first observation in combination of ATLAS and CMS Run I measurements
- individual observation of $H \rightarrow \tau \tau$ with each experiment with Run I and partial Run II datasets in 2017
- most sensitive Higgs production channel: VBF followed by ggF
- measurements are fully consistent with predictions from the SM
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ATLAS

CMS

ggF + VBF

• **cut-based** analysis primarily focussing on ggF and VBF Higgs production

• **event selection** based on number of e, μ and τ_h candidates with leptons required to have opposite charge (τ_hτ_h, eμ, eτ_h, μτ_h)

• **major backgrounds:**
  - $Z \rightarrow ττ$ (estimated with embedding technique) [JINST 14 (2019)]
  - $Z \rightarrow ee/μμ$+jets, diboson, tt and single-t jets identified as leptons

• **improvements:**
  - new DNN based $τ_h$ identification
  - further subdivision of the three categories (0 jet, VBF, boosted)

• **discriminant:**
  - $m_{ττ}$ vs. $p_T(τ) / m_jj / p_T(H)$

• **dominant uncertainties:**
  - signal prediction uncertainties, $τ_h$ reconstruction,
  - $Z \rightarrow ττ$ background estimation
• extension of the \( H \rightarrow \tau \tau \) analysis to a differential cross section measurement in terms of \( p_T \) (Higgs), jet multiplicity and \( p_T \) (leading jet)

• **first fiducial differential measurements** of the Higgs boson XS in final states with \( \tau \)'s

• significant improvement over other final states in phase space with large jet multiplicity \( (N_{jets} > 2) \) or high \( p_T \) (Higgs) \( (120 < p_T \) (Higgs) < 600 GeV)

• fit of **2D-distributions** of \( m_{\tau\tau} \) vs. differential variable

• regularized unfolding to obtain generator-level signal strengths

more detailed review in Roberto’s talk
“Higgs Fiducial and differential measurements at ATLAS+CMS” on Thursday!
Summary & Outlook

- measurements of the Higgs-fermion coupling crucial tests of the SM
- in particular important: direct searches accessing these coupling without loop-effects
- Higgs-fermion couplings proportional to mass → direct searches are very promising using 3rd generation fermions
- H → b\overline{b} and H → τ\overline{τ} both observed with partial Run II datasets in combination with Run I results
- major updates with full Run II datasets, for example VH → b\overline{b} by ATLAS and H → τ\overline{τ} by CMS
  - major improvements due to larger statistics and improved analysis strategies
  - new interpretations (STXS, κ-measurements, limits on Wilson-coefficients)
- 3rd generation fermions also interesting tools for BSM searches in Higgs sector and searches for double-Higgs production
- stay tuned!
  still outstanding Run II results
Backup
# VH → bb (boosted)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Categories</th>
<th>250 &lt; $p_T^V$ &lt; 400 GeV</th>
<th>$p_T^V$ ≥ 400 GeV</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>0 add. $b$-track-jets</td>
<td>0 add. $b$-track-jets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥ 1 add. $b$-track-jets</td>
<td>≥ 1 add. $b$-track-jets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 add. small-$R$ jets</td>
<td>0 add. small-$R$ jets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥ 1 add. small-$R$ jets</td>
<td>≥ 1 add. small-$R$ jets</td>
</tr>
<tr>
<td>0-lepton</td>
<td>HP SR</td>
<td>LP SR</td>
<td>CR</td>
</tr>
<tr>
<td>1-lepton</td>
<td>HP SR</td>
<td>LP SR</td>
<td>CR</td>
</tr>
<tr>
<td>2-lepton</td>
<td>SR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- 68% CL
- 95% CL

Boosted VH, H → bb

- Linear (obs.)
- Linear + quadratic (obs.)
- Best-fit (obs.)

**Events / 10 GeV (Weighted, B-subtracted)**

**Weighted by S/B**

**m_j [GeV]**

**Parameter value**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{Hq}^{(3)}$</td>
<td>[×10.0]</td>
</tr>
<tr>
<td>$c_{Hu}$</td>
<td>[×5.0]</td>
</tr>
<tr>
<td>$c_{HW}$</td>
<td>[×2.0]</td>
</tr>
<tr>
<td>$c_{HWB}$</td>
<td>[×0.5]</td>
</tr>
<tr>
<td>$c_{dH}$</td>
<td>[×0.05]</td>
</tr>
</tbody>
</table>
• SM Higgs production in association with high energetic photon (large reduction of multijet background)

• exclusive final state forbidden in ggF and minor contributions from VH → VBF dominant production mode

• signature: 
  ≥ 4 jets of which ≥ 2 b tagged 
  and \( p_T(bb) > 60 \text{ GeV} \) to avoid concavity in \( m_{bb} \) distribution

• main backgrounds: 
  non-resonant backgrounds \( bbyjj \) and resonant \( Z(\rightarrow bb)yjj \) background

• event categorization: \( m_{bb} \) decorrelated BDT

• signal extracted from unbinned fit of Higgs boson candidate mass distribution

• improvements: updated BDT, more precise MC modelling

• significance: observed (expected) 1.3(1.0) sigma

• dominant uncertainties: statistics of data sample, background fits and spurious-signal uncertainty
ggF $H \rightarrow b\bar{b}$ (boosted)

CMS

$450 < p_T < 1200$ GeV
Deep double-$b$ tagger
Passing region

Events / 7 GeV

$137 \text{ fb}^{-1}$ (13 TeV)

[800, 1200] GeV
$\mu_H = 9.1^{+3.5}_{-3.1}$

[675, 800] GeV
$\mu_H = 8.7^{+3.4}_{-3.1}$

[600, 675] GeV
$\mu_H = 8.3^{+3.0}_{-3.7}$

[550, 600] GeV
$\mu_H = 3.7^{+2.7}_{-2.6}$

[500, 550] GeV
$\mu_H = -3.6^{+2.5}_{-2.8}$

[450, 500] GeV
$\mu_H = -0.5^{+2.3}_{-2.7}$

CMS

$\mu_Z = 0.61^{+0.25}_{-0.21}$

[675, 800] GeV
$\mu_Z = 0.78^{+0.24}_{-0.20}$

[600, 675] GeV
$\mu_Z = 0.87^{+0.24}_{-0.20}$

[550, 600] GeV
$\mu_Z = 0.93^{+0.25}_{-0.21}$

[500, 550] GeV
$\mu_Z = 0.85^{+0.22}_{-0.18}$

[450, 500] GeV
$\mu_Z = 1.24^{+0.30}_{-0.24}$
ggF $H \rightarrow b\bar{b} + \text{jet}$ (boosted)
CMS Preliminary

$H \rightarrow \tau \tau$

e$\mu$, VBF low $p_T^H$

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

- Obs. $\tau \tau$ bkg.
- $t\bar{t}$ + jets
- jet$\rightarrow$ e/\mu mis-ID
- Others
- Unc.
- $H \rightarrow \tau \tau$ ($\mu = 0.85$)

Events/bin

- $350 < m_{\tau} < 700$ GeV
- $700 < m_{\tau} < 1000$ GeV
- $1000 < m_{\tau} < 1500$ GeV
- $m_{\tau} > 1500$ GeV

(Obs. - bkg.) / Bkg. unc.

$\mu_{VBF}$

$\kappa_F$

CMS Preliminary

68% CL
95% CL
Best fit
SM expected

CMS Preliminary

68% CL
95% CL
Best fit
SM expected
CMS Preliminary

137 fb⁻¹ (13 TeV)

Observed ±1σ (stat.) ±3σ

Uncertainty in SM prediction

H → ττ

Stage 1.2

ggH 0 jet

= 0-jet

= 1-jet

ggH low m_j

m_j [0, 350]

≥ 2-jet

Medium m_j

m_j [350, ∞]

≥ 2-jet

≥ 3-jet

ggH 1 jet low p_T

p_T [0, 200]

≥ 2-jet

≥ 3-jet

ggH 1 jet med. p_T

p_T [200, ∞]

≥ 2-jet

≥ 3-jet

ggH 1 jet high p_T

ggH p_T > 300 GeV

Stage 1.2

EW qqH

= VBF + V(→ qq)H

= 0-jet

= 1-jet

≥ 2-jet

qH low m_j

m_j [0, 350]

Medium m_j

m_j [350, ∞]

qq H BSM

qH non-VBF topology

p_T [0, 200]

≥ 2-jet

≥ 3-jet

p_T [200, ∞]

≥ 2-jet

≥ 3-jet

CMS PAS-HIG-19-010
H → μτ/ητ

- lepton-flavour violating decays (BSM) arise in a wide range of models
- indirect constrains, e.g. \( \mu \rightarrow e\gamma \), rare lepton decays and measurements of the e/μ magnetic moment
- event selection: e/μ and oppositely charged τ
- event categorization:
  - four channels: \( \muτ_h \), \( \muτ_e \), \( eτ_h \) and \( eτ_μ \)
  - further divided by number of jets & \( m_{jj} \)
- backgrounds:
  - \( Z \rightarrow ττ \)
  - events with misidentified leptons
  - ττ process
- dominant contribution from systematic uncertainties
- no significant access
- improvements due to larger dataset
  - updated background estimation techniques
  - BDT discriminant
Embedding technique: $Z \rightarrow \tau \bar{\tau}$

$Z \rightarrow \tau \tau$ Simulation

Simulate $\tau$ leptons with same kinematic properties as muons.

$Z \rightarrow \mu \mu$ Selection

$Z \rightarrow \tau \tau$ Hybrid

Merge simulated and cleaned event.

$Z \rightarrow \mu \mu$ Cleaning

Remove energy deposits from muons.