Higgs boson measurements in its decays into bosons and in combined analyses with the ATLAS experiment

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Higgs Decays To Bosons

Higgs Decays To Bosons

**H -> WW**
BR: 21%

**H -> ZZ**
BR: 3%

**H -> γγ**
BR: 0.2%

Decays of a 125 GeV Standard-Model Higgs boson

- charm/anti-charm: 3%
- tau/anti-tau: 6%
- 2 gluons: 9%
- W+W-: 21%
- bottom/anti-bottom: 57%
- ZZ: 3%
- WW: 0.2%
- Z+γ: 0.2%
- Others: 0.6%

Then (2012)
Crucial Channels for Higgs Discovery

Now (and in this talk)
Excellent for Higgs precision & properties measurements

Now (and in this talk) and Future
Sensitive Inputs to Constrain EFT & Other Model Parameters

24/08/2021
**Main Higgs Production Modes**

Different production and decay modes provide many handles for precision measurements in various regions of phase space.
Different Higgs Measurements

**Inclusive cross-section ($\sigma$) of production mode**
- Measure inclusive $\sigma$ per production mode
- Maximum sensitivity but model dependent

**Fiducial / differential cross-sections**
- Most model independent but less sensitive (use “simple” analysis cuts)
- Measure $\sigma$ in fiducial volume and multiple distributions

**Simplified Template Cross Sections (STXS)** *
- Measure $\sigma$ in STXS regions defined per production mode and agnostic to Higgs decay
- Combinations encouraged
- Optimized for sensitivity while reducing theory dependence

**EFT & other interpretations**
- Look for new physics (see later slides)

Production & STXS Cross-section Measurements
**H → ZZ**

**Characteristics**
- “Cleanest” Higgs channel, highest signal / bkg

**Strategy**
- Neural networks (NNs) used in individual categories
- Extract cross-sections from fit to NN output

**H → γγ**

**Characteristics**
- Excellent control over background with an analytical model

**Strategy**
- Cascade of boosted decision trees (BDTs)
  - Multi-class BDT to separate signal events from different STXS regions (mitigating migrations!)
  - Binary BDT to separate signal from bkg
- Extract cross-sections from fit to m_{γγ}
Combined Production Cross-sections

Global signal strength: \( \mu = 1.06 \pm 0.07 = 1.06 \pm 0.04 \) (stat.) \( \pm 0.03 \) (exp.) \( ^{+0.05}_{-0.04} \) (sig. th.) \( \pm 0.02 \) (bkg. th.)

- Inputs: \( H\rightarrow ZZ^* \), \( H\rightarrow \gamma\gamma \), \( H\rightarrow WW^* \) (36 fb\(^{-1} \)), \( H\rightarrow \tau\tau \) (36 fb\(^{-1} \)), \( H\rightarrow bb \) (24.5-139 fb\(^{-1} \))
- Simultaneous fit to all channels with 16 parameters of interest (POIs)
- Results in agreement with SM prediction (compatibility: \( p = 87\% \))

\[ \begin{align*}
\text{ATLAS Preliminary} & \quad \begin{array}{c}
\text{Total} \quad \text{Stat.} \quad \text{Syst.} \quad \text{SM}
\end{array} \\
\begin{array}{c}
\text{ggF } \gamma\gamma \\
\text{ggF } ZZ \\
\text{ggF } WW \\
\text{ggF } \tau\tau \\
\text{ggF comb.} \\
\text{VBF } \gamma\gamma \\
\text{VBF } ZZ \\
\text{VBF } WW \\
\text{VBF } \tau\tau \\
\text{VBF bb} \\
\text{VBF comb.} \\
\text{VH } \gamma\gamma \\
\text{VH } ZZ \\
\text{VH } bb \\
\text{VH comb.} \\
\text{ttH+H } \gamma\gamma \\
\text{ttH+H } VV \\
\text{ttH+H } \tau\tau \\
\text{ttH+H } bb \\
\text{ttH+H comb.}
\end{array}
\end{align*} \]
**H -> ZZ* STXS Definition (Example)**

**Production Mode**

- **ggF**
- **VBF**
- **VH**
- **ttH**

**Production Bins**

- ggF:
  - gg2H-0j-p_T^H-Low
  - gg2H-0j-p_T^H-Med
  - gg2H-0j-p_T^H-High

- VBF:
  - gg2H-p_T^H-Low

- VH:
  - qq2Hq-VH

- ttH:
  - VH-Lep
  - ttH-Had-enriched
  - ttH-Leptonic-enriched

**STXS Reduced Stage 1.1**

- Particle-level:
  - p_T^H < 10 GeV
  - p_T^H > 10 GeV
  - p_T^H < 60 GeV
  - 60 < p_T^H < 120 GeV
  - p_T^H > 120 GeV

- gg2H-2j

**Reconstructed event categories**

- Signal Region:
  - 0j-p_T^H-Low
  - 0j-p_T^H-Medium
  - 0j-p_T^H-High

- Sideband Region:
  - m_T^H [100, 115] GeV
  - m_T^H > 120 GeV

- m_T^H = 115 GeV

**ATLAS** √s = 13 TeV, 139 fb⁻¹

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$H \rightarrow ZZ^*$ STXS Definition (Example) Ct’d

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

**Production Mode**
- ggF
- VBF
- VH
- ttH

**Reconstructed Event Categories**

- STXS Reduced Stage 1.1
- Signal Region
- Sideband Region

**Expected Composition**

- gg2H-1
- gg2H-0
- qq2Hqq-VBF
- qq2Hqq-BSM
- gg2H-1-jet
- qq2Hqq-BSM
- gg2H-2j
- ttH
- ttH-Lep
- ttH-Had

**ATLAS Simulation**

$H \rightarrow ZZ \rightarrow 4l$

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

**Production Bins**
- $m_H < 200$ GeV
- $m_H > 200$ GeV

**Signatures**
- $\geq 2$-jets
- $T_H > 200$ GeV
- $p_T < 200$ GeV
- $m_H < 60$ GeV or $120 < m_H < 350$ GeV

**Event Categories**
- Had-enriched
- Lep-enriched
- BSM-like
- High
- Medium
- Low

**Signal Regions**
- $m_{\ell\ell} = [105, 115]$ GeV
- $[130, 160]$ GeV

**Production Channels**
- ggF
- ttH

**Expected Composition**

**24/08/2021**
Some bins merged due to limited sensitivity

Limited by data stat.

Results in agreement with SM prediction (compatibility: p = 95%)

Input to κ-framework, Two-Higgs-Doublet Models (not shown), and EFT interpretation (in later slide!)
$H \rightarrow WW^* \rightarrow e\nu\nu$ Prod./STXS Cross-sections

Characteristics
- Complex set of backgrounds with large unc. (top, WW, Mis-ID)

Strategy
- Cut-based approach with fit to $m_T$ in ggF regions, fit to NN in VBF-enriched regions
- Extract 6 (ggF) + 5 (VBF) STXS bins

Results
- SM compatibility: 52%
- Several regions limited by theoretical uncertainties!
- $\sigma$ per production (ggF, VBF)
  
  \[
  \sigma_{\text{ggF}} \times B_{H \rightarrow WW} \] _{\text{obs}} = 12.4 \pm 1.5 \text{ pb} \quad \text{(SM: 10.4 \pm 0.6 pb)}
  \]
  
  \[
  \sigma_{\text{VBF}} \times B_{H \rightarrow WW} \] _{\text{obs}} = 0.79^{+0.19}_{-0.16} \text{ pb} \quad \text{(SM: 0.81 \pm 0.02 pb)}
  
24/08/2021
Fiducial & Differential Measurements
Many distributions measured regarding Higgs kinematics and decays as well as jet activities ($p_T^H$, $Y_H$, $m_{jj}$, $\Delta \Phi_{jj}$, many more) that are sensitive to possible BSM effects

**H -> ZZ**

$$\sigma_{\text{fid}} = 3.28 \pm 0.30 \text{ (stat)} \pm 0.11 \text{ (sys)} \text{ fb}$$

$$\sigma_{\text{fid, SM}} = 3.41 \pm 0.18 \text{ fb}$$

- Includes several **double-differential distributions**
- Results used to constrain anomalous Higgs <-> SM particles interaction

**H -> γγ**

$$\sigma_{\text{fid}} = 65.2 \pm 4.5 \text{ (stat)} \pm 5.6 \text{ (sys)} \pm 0.3 \text{ (theo)} \text{ fb}$$

$$\sigma_{\text{fid, SM}} = 63.6 \pm 3.3 \text{ fb}$$

- Limit set on c-quark Yukawa couplings from $p_T^{\gamma\gamma}$ spectrum
- Constraints set on EFT parameters

Observed good agreement with SM expectation
EFT Interpretations
From Production Cross-sections to EFT Interpretations

1. Inclusive prod. xsecs → Fiducial / differential / STXS → EFT Interpretation / constraints

- Reconstructed distributions
- (Pseudo-)unfolded
- Re-parametrized in SMEFT using generator-level simulation

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} \phi_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \phi_i^{(6)} + \ldots \]

- 76 dim-6 operators when assuming U(3)^5 flavour symmetry
- Wilson coefficients \( c_i^{(6)} \) can be constrained experimentally
- Often further # parameter reduction: Identifying groups of Wilson coefficients with similar effect on the available data (Principal Component Analysis)
- Many more details in Brian Moser @Higgs2020, Philip Windischhofer @ HEFT 2021
Combined STXS EFT Interpretation

**ATLAS** Preliminary

- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- $m_H = 125.09$ GeV, $|y_{\nu}| < 2.5$
- SMEFT $\Lambda = 1$ TeV

- **Targets** CP-even operators
- Simultaneous fit to 10 combinations of coefficients (PCA) with **excellent sensitivity**
- Reinterpret combined STXS results in linear and linear+quadratic SMEFT model
- Results consistent with the SM expectation
- $c_{Hq}^{(3)}$ constrained to $\mathcal{O}(0.1)$ probing scales up to 3 TeV!
Combined $H \rightarrow WW$ and $pp \rightarrow WW$ EFT

- **Challenging combination (overlapping regions) of**
  - $H \rightarrow WW$
  - $pp \rightarrow WW$
    - $ggF+VBF$ signal strengths
    - Lead lep. $p_T$ differential $xsec$

- Exploits complementary analyses sensitive to a similar set of dim-6 SMEFT operators

- Fits to 20 individual and 8 combined Wilson coefficients (PCA) in linearized model

- Paving the way for future EFT combinations!
CP & Higgs Properties
**Motivation**

- **ggF + 2-jet** sensitive to **CP properties** of effective Higgs-gluon vertex

**ggF Strategy**

- BDTs to distinguish signal from background
- Fit to 12 categories defined by BDT and $\Delta \eta_{jj}$

**Results**

- Ratio of CP-odd to CP-even coupling strengths of the effective Higgs-gluon vertex constrained to

\[
\kappa_{Agg}/\kappa_{Hgg} = 0.0 \pm 0.4 \text{ (stat)} \pm 0.3 \text{ (sys)}
\]

- **VBF production** used to set constraints on $W$ & $Z$ polarization-dependent coupling-strengths (not shown here)
**Motivation**

- Observed **ttH Higgs** production in 2018*
- Direct probe of CP properties of top-Higgs interaction
- CP-odd contributions are not suppressed by $1 / \Lambda^2$

**Strategy**

- Simultaneous fit to $m_{\gamma\gamma}$ in 20 categories defined by two BDTs
- ggF, $H \rightarrow \gamma\gamma$ constrained by the Higgs boson coupling combination

**Results**

- CP-mixing angle greater than $43^\circ$ excluded at 95% CL
- All measurements statistically limited

Rare Decays and Searches
More Results in the Higgs <-> Bosons Realm

**Combination of $H\rightarrow\text{Invisible}$**

ATLAS-CONF-2020-052

upper limit on the $H\rightarrow\text{invisible}$ branching ratio of $0.11 (0.11^{+0.04}_{-0.03})$ at 95% CL is observed (expected)

**$H\rightarrow Z\gamma (Z\rightarrow ee/\mu\mu)$ Search**


Upper limit of 3.6 (2.6) times the SM exception at 95% CL (with SM Higgs)

**$H\rightarrow l\gamma (\text{Low Mass})$**


“Evidence for the $H\rightarrow l\gamma$ process (with $m_{ll} < 30$ GeV) is found with a significance of 3.2 over the background-only hypothesis”
First Full Run 2 STXS measurements and combinations provide unprecedented sensitivity of measured Higgs cross-sections.

Exciting new EFT interpretations with excellent sensitivity

Stepping stone for future global combinations!

Higgs properties measurement and searches show no sign of BSM physics yet...

...but many more analyses are under way, and Run 3 around the corner so...

Stay Tuned!
Thank you for your attention!
**Strategy**

- Signal regions split by number of jets
  - ggF 0, 1, 2-jet*, and VBF SR
- VBF analysis uses DNN trained with 15 variables
  
  \[ \Delta y_{jj}, m_{jj}, \eta_{\ell}, m_{\ell 1j1}, m_{\ell 1j2}, m_{\ell 2j1}, m_{\ell 2j2}, p_{T}^{\text{jet}_1}, p_{T}^{\text{jet}_2}, p_{T}^{\text{jet}_3} \]

  \( H \to WW \) decay: \( \Delta \phi_{\ell \ell}, m_{\ell \ell}, m_T \),

  Top suppression: \( p_T^{\text{tot}}, \text{MET significance} \)

**Results**

\[
\sigma_{\text{ggF}} \cdot B_{H\to WW} = 12.4 \pm 1.5 \text{ pb}
\]

\[
= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp syst.)} ^{+0.7}_{-0.6} \text{ (sig theo.)} \pm 1.0 \text{ (bkg theo.)} \text{ pb}
\]

\[
\sigma_{\text{VBF}} \cdot B_{H\to WW} = 0.79 \pm 0.19 \text{ pb}
\]

\[
= 0.79 \pm 0.11 \text{ (stat.)} \pm 0.06 \text{ (exp syst.)} \pm 0.13 \pm 0.09 \text{ (sig theo.)} \pm 0.08 \text{ (bkg theo.)} \text{ pb},
\]
Uncertainty Breakdown for $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ STXS Cross-sections

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

ATLAS Preliminary

ATLAS-CONF-2021-014
H -> ZZ* Prod./STXS Cross-sections

**Characteristics**

- “Cleanest” Higgs channel, highest S/B

**Strategy**

- Neural networks used in individual categories as discriminant in stat. Analysis
- Measure 6 (ggF) + 3 (EW qqH) + VH-lep + ttH STXS regions

**Results**

- Results in STXS bins in agreement with SM prediction (compatibility: 77%)
- Xsecs per production (ggF, VBF, VH, ttH) and inclusively
  \[(\sigma \times B_{H\rightarrow ZZ})_{\text{obs}} = 1.34 \pm 0.12 \text{ pb} \quad (\text{SM: } 1.33 \pm 0.08 \text{ pb})\]
- Results also interpreted with k-framework and EFT

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Production: ALL (ggF, VBF, VH, bbH, ttH+tH)
**Strategy**

- Cascade of BDTs:
  - Multi-class BDT to separate signal events from different STXS regions (mitigating migrations!)
  - Binary BDT to separate signal from bkg
- Measure 27 STXS regions by fitting $m_{\gamma\gamma}$

**Results**

- Results in STXS bins in agreement with SM prediction (compatibility: 60%)
- Xsecs per production (ggF+bbH, VBF, ZH, WH, ttH+tH) and inclusively ($|y_{H}| < 2.5$)

\[
(\sigma \times B_{H \rightarrow \gamma\gamma})_{\text{obs}} = 127 \pm 7 \text{ (stat)} \pm 7 \text{ (sys)} \text{ fb} \quad \text{(SM: 116 \pm 5 pb)}
\]
Strategy

- Many unfolded distributions measured
  - Higgs kinematics: $p_T$, $|y_{4l}|$
  - Higgs decay information: invariant masses of the lepton pairs, angular variables (sensitive to anomalous $H\rightarrow ZZ$ couplings)
  - Jet activities: # jets, # b-jets, $p_T^{jet1}$, $m_{jj}$, $\Delta\Phi_{jj}$
  - Several double-differential distributions

Results

- Inclusive fiducial cross section
  \[ \sigma_{\text{fid}} = 3.28 \pm 0.30 \text{ (stat)} \pm 0.11 \text{ (sys)} \text{ fb} \]
  \[ \sigma_{\text{fid}, \text{SM}} = 3.41 \pm 0.18 \text{ fb} \]  
  Limited by stat uncs

- Overall good agreement with the SM expectation

- Results used to constrain anomalous Higgs <-> SM particles interaction
**Strategy**

- Several distributions sensitive to new physics effects
- Many unfolded distributions measured
  - Higgs kinematics: $p_{T\gamma\gamma}$, $|y_{\gamma\gamma}|$
  - Jet activities: # jets, $p_{T\text{jet1}}$, $m_{jj}$, $\Delta\Phi_{jj}$

**Results**

- Inclusive fiducial cross-section
  
  \[
  \sigma_{\text{fid}} = 65.2 \pm 4.5 \text{ (stat)} \pm 5.6 \text{ (sys)} \pm 0.3 \text{ (theo)} \text{ fb} \\
  \sigma_{\text{fid, SM}} = 63.6 \pm 3.3 \text{ fb}
  \]

- Limit set on c-quark Yukawa couplings from $p_{T\gamma\gamma}$ spectrum

- Constraints set on EFT parameters
  - Example: Effect of CP-odd SMEFT Wilson coefficients on 5 of the measured distributions
Impact of Wilson Coefficients On STXS EFT Interpretation

Analysis: EFT Interpretation of Comb. STXS Results

In Warsaw Basis

After Principal Component Analysis
Combination of $H\rightarrow$Invisible

Motivation

- Many dark matter models predict that light DM can be produced in Higgs decays at the LHC, invisible to the detector.

Strategy

- Combination of VBF, H→Inv and ttH, H→inv as well as Run 1 combination of H→Inv.

Results

- upper limit on the $H\rightarrow$invisible branching ratio of 0.11 (0.11$^{+0.04}_{-0.03}$) at 95% CL is observed (expected).

- Results also interpreted in Higgs portal dark matter models.
**Motivation**

- Decay possible through loop diagrams, $B(H \to Z\gamma) = \mathcal{O}(10^{-3})$
- Differences from SM expected for several scenarios, for example: Composite state Higgs, additional colourless charged scalars, leptons or vector bosons with Higgs couplings

**Strategy**

- Fit to $m_{Z\gamma}$ in 6 categories separating production modes and lepton flavours and $p_{Tt} = 40$ GeV

**Results**

- Upper limit of 3.6 (2.6) times the SM exception at 95% CL (with SM Higgs)
- $\mu = 2.0^{+1.0}_{-0.9}$ Limited by stat uncs
**Motivation**

- Rare decays sensitive to possible new physics

**Strategy**

- Different categories defined depending on the lepton types and event topologies
- Simultaneous fit to $m_{ll\gamma}$ with analytical modelling for background

**Results**

- Figure showing results for different categories:
  - $ee$ resolved VBF-enriched
  - $ee$ merged VBF-enriched
  - $\mu\mu$ VBF-enriched
  - $ee$ resolved high-$p_{Tr}$
  - $ee$ merged high-$p_{Tr}$
  - $\mu\mu$ high-$p_{Tr}$
  - $ee$ resolved low-$p_{Tr}$
  - $ee$ merged low-$p_{Tr}$
  - $\mu\mu$ low-$p_{Tr}$

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

- Limited by stat uncs