Search and measurement of the SM Higgs boson

Silvio Donato (University of Zürich) on behalf of the CMS and ATLAS collaborations
Introduction

- The legacy of the LHC Run-1 has been a huge success with the discovery of the Higgs boson and the first measurement of its properties and couplings.
  - No significant deviation from the SM has been found so far.
- \(gg\rightarrow H\) and VBF production, and \(ZZ, \gamma\gamma, WW\) decays observed
  - many other channels to be observed.
- ATLAS and CMS collaborations obtained many new results with 36 fb\(^{-1}\) of 13 TeV data → they are summarized in this talk.

<table>
<thead>
<tr>
<th>Production process</th>
<th>Measured significance ((\sigma))</th>
<th>Expected significance ((\sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>5.4</td>
<td>4.6</td>
</tr>
<tr>
<td>WH</td>
<td>2.4</td>
<td>2.7</td>
</tr>
<tr>
<td>ZH</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>VH</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>(ttH)</td>
<td>4.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Measured significance ((\sigma))</th>
<th>Expected significance ((\sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow \tau\tau)</td>
<td>5.5</td>
<td>5.0</td>
</tr>
<tr>
<td>(H \rightarrow bb)</td>
<td>2.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Outline

• Introduction

• Big news:
  - Single experiment observation of $H \to \tau\tau$;
  - Evidence for $ttH$;
  - Evidence for $VH \to bb$.

• Other SM Higgs searches:
  - $VH \to cc$;
  - boosted $H \to bb$;
  - $H \to \mu\mu$;
  - $H \to Z\gamma$;
  - $H \to$ light quarks.

• Towards precision SM Higgs measurements with $H \to \gamma\gamma$ and $H \to ZZ$:
  - simplified template cross section;
  - differential cross section;
  - couplings;

• Conclusions.
Big news
The $H \rightarrow \tau \tau$ can decay into $e\mu$, $\mu\tau$, $e\tau$, $\tau\tau$ ($\tau=\tau\rightarrow$ hadr.).

- All final states have been exploited.
- Three categories with different purities: 0-jet, VBF, boosted.
- $\tau_h$ identified by a MVA discriminant.
  - energy calibrated for different $\tau_h$ final states using $Z \rightarrow \tau\tau$;
  - $m_{\tau\tau}$ reconstructed combining $\tau$ momenta with MET (SVFIT).
- Opposite charge and lepton isolation $\rightarrow$ QCD rejection.
- $[e\tau_h, \mu\tau_h]$ Transverse mass $< 50$ GeV $\rightarrow$ $W+jets$ rejection.
- $[e\mu]$ Large MET projected along di-tau axis $\rightarrow$ $t\bar{t}$ rejection.
- Main backgrounds:
  - $Z \rightarrow \tau\tau$ simulation is corrected using $Z \rightarrow \mu\mu$ data;
  - $W+jets$ and $t\bar{t}$ simulations are normalized to data inverting rejection cuts;
  - QCD fully estimated from data $\rightarrow$ ABCD method inverting charge and isolation cuts.
• Signal extraction:
  - 1D or 2D fit of the most discriminating variables, eg. \( m_{jj}, m_{\tau\tau} \) for \( \tau_h \tau_h \) VBF.

• Results [CMS]:
  - \( \mu = 1.09^{+0.15}_{-0.15} \text{(stat)}^{+0.16}_{-0.15} \text{(syst)}^{+0.10}_{-0.08} \text{(theo)}^{+0.13}_{-0.12} \text{(bkg stat)} \) 
  - corresponding to a sign. of 4.9\( \sigma \) (exp. 4.7\( \sigma \)).

• 13 TeV + 8 TeV combination:
  - \( \mu = 0.98 \pm 0.18 \rightarrow \text{sign. 5.9}\( \sigma \) (exp. 5.9\( \sigma \)).

First observation of \( H \rightarrow \tau\tau \) by a single experiment
**ttH multilepton**

- **In ttH**, the Higgs boson can decay into leptons (e, μ, τ) through the decay $H \rightarrow WW$, $ZZ$, $ττ$
  
  - up to two other leptons can be originated from the top decays in ttH

- The presence of at least two **same-sign leptons** can be used to eliminate the large Z/W+jets and tt background.

- **Many final states considered.**

- **Main backgrounds:**
  
  - ttV and VV
    → estimated by **simulations**;
  
  - charge mis-id, fake $τ_h$, non-prompt lept.
    → **data-driven** estimate.
Fit is performed combining most discriminating variables using a BDT.

- In several cases, a multinomial BDT is trained to reject the different backgrounds → combined into a 1D discriminant.

**Results:**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>Final state</th>
<th>Signal strength</th>
<th>Sign.(exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inclusive</td>
<td>$\mu = 1.6^{+0.3}<em>{-0.3}$(stat)$^{+0.4}</em>{-0.3}$(syst)</td>
<td>4.1$\sigma$(2.8$\sigma$)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMS</th>
<th>Final state</th>
<th>Signal strength</th>
<th>Sign.(exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(\tau_h) = 0$</td>
<td>$\mu = 1.5^{+0.3}<em>{-0.3}$(stat)$^{+0.4}</em>{-0.3}$(syst)</td>
<td>3.3$\sigma$(2.4$\sigma$)</td>
<td></td>
</tr>
<tr>
<td>$N(\tau_h) &gt; 0$</td>
<td>$\mu = 0.76^{+0.62}_{-0.53}$</td>
<td>1.4$\sigma$(1.8$\sigma$)</td>
<td></td>
</tr>
</tbody>
</table>
In ttH(bb), 4 b-jets are expected from the top and Higgs decays plus:

- 2 leptons + MET (Dilepton decay);
- 2 jets + 1 lepton + MET (Single lept. decay).

Main background is tt + b/c/light jets.

Events are categorized depending on the number of jets and leptons, and b-tagging discriminant, into:

- 9 signal regions, to select different purities;
- 10 control regions, to constrain the different background components.
**ttH → bb**

- Signal is extracted fitting simultaneously all signal and control regions
  - BDTs are used to enhance the S/B separation.

- **ATLAS results and ttH combination:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Best-fit $\mu$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>Multilepton</td>
<td>1.6 $^{+0.5}_{-0.4}$</td>
<td>1.0 $^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>0.8 $^{+0.6}_{-0.6}$</td>
<td>1.0 $^{+0.6}_{-0.6}$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.6 $^{+0.7}_{-0.6}$</td>
<td>1.0 $^{+0.8}_{-0.6}$</td>
</tr>
<tr>
<td>$H \rightarrow 4\ell$</td>
<td>$&lt;1.9$</td>
<td>1.0 $^{+3.2}_{-1.0}$</td>
</tr>
<tr>
<td>Combined</td>
<td>1.2 $^{+0.3}_{-0.3}$</td>
<td>1.0 $^{+0.3}_{-0.3}$</td>
</tr>
</tbody>
</table>

Evidence for ttH by a single experiment

- CMS results (ICHEP2016, $\sim13$ fb$^{-1}$): $\mu = -0.19^{+0.45}_{-0.44}$ (stat)$^{+0.66}_{-0.68}$ (syst)
Most sensible $H \rightarrow bb$ channel is $VH(bb)$, with a leptonic decay ($Z \rightarrow \ell\ell, W \rightarrow \ell v, Z \rightarrow vv$) to suppress the QCD multijet background.

- $H(bb)$ is also the most sensible VH channel.

**Four channels** (0-lepton, 1-lepton, low and high boosted 2-lepton).

- ATLAS split signal regions depending also on the number of jets (2 or 3).

**Main backgrounds** are $Z+(b)jets$, $W+(b)jets$, $tt$:

- bkg shape modeled using simulations;
- yields are **free parameters** of the final fit;
- control regions added into the final fit to constrain background yields.

**Special calibration of b-jet energy** in order to improve $m_{bb}$ resolution.
- BDT trained against all bkg in each SR, combining discriminating variables (eg. $m_{bb}$, b-tag)
- A simultaneous fit of all SR and CR is performed for the signal extraction.
- [ATLAS] Cross-check analysis w/o BDT

**ATLAS**

<table>
<thead>
<tr>
<th>Channel</th>
<th>SR/CR</th>
<th>Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>SR</td>
<td>BDT</td>
</tr>
<tr>
<td>1-lepton</td>
<td>SR</td>
<td>BDT</td>
</tr>
<tr>
<td>2-lepton</td>
<td>SR (high $p_T^{VH}$)</td>
<td>BDT</td>
</tr>
<tr>
<td></td>
<td>SR (low $p_T^{VH}$)</td>
<td>BDT</td>
</tr>
<tr>
<td>1-lepton</td>
<td>$W + HF$ CR</td>
<td>Yield</td>
</tr>
<tr>
<td>2-L (high $p_T^{VH}$)</td>
<td>$t\bar{t}(\mu)$ CR</td>
<td>Yield</td>
</tr>
<tr>
<td>2-L (low $p_T^{VH}$)</td>
<td>$t\bar{t}(\mu)$ CR</td>
<td>$m_{bb}$</td>
</tr>
</tbody>
</table>

**VZ(bb) measurement:**
- CMS: $\mu = 1.02 \pm 0.22$
- ATLAS: $\mu = 1.11 \pm 0.23$

**Results (Run1+Run2):**
- CMS: $3.8\sigma$ (exp. $3.8\sigma$) $\mu = 1.06^{+0.31}_{-0.29}$
- ATLAS: $3.6\sigma(exp. \ 4.0\sigma$) $\mu = 0.90 \pm 0.18(stat)_{+0.21}^{+0.19} (syst)$
Other SM Higgs boson searches
• As for $H \to bb$, $H \to cc$ has been searched in the $Z(\ell\ell)H(cc)$ channel.

• Two **c-tagger** discriminators have been trained against $b$-jets and light-jets:
  - calibrated in data using $t \to Wb$ and $W \to cs/cd$.

• **Challenges:** c-tagger, $\text{BR}(H \to cc) \sim 2.9\%$, $Z+cc$ bkg.

• A validation analysis has been performed looking for $Z(\ell\ell)W(cs)$ and $Z(\ell\ell)Z(cc)$.
  - $\mu = 0.6^{+0.5}_{-0.4} \to 1.4\sigma$ (exp. $2.2\sigma$)

• Results: $\mu = -69 \pm 101$
  - upper limit $\mu < 100$ (exp. 150).
Boosted $H \rightarrow bb$

- Brand new analysis: boosted $gg \rightarrow H \rightarrow bb$.
- Large QCD multijet background.
- **AK8 jet** with $p_T > 450$ GeV:
  - pileup per particle identification (PUPPI);
  - soft drop grooming and two subjets ($N_{2\Delta}$ variable);
  - **double b-tagger** specifically designed for $H(bb)$.
- **QCD** estimated inverting b-tag cut and propagated to SR with a transfer function $R_p/f = f(\log(m_{SD}/p_T),p_T)$.
- Other backgrounds estimated by simulations → b-tag fake rate and efficiency constrained from data.
- Challenging signal cross-section computation in boosted $gg \rightarrow H$:
  - approximate NLO $H+0,1,2$ jet merged with finite $m_t$;
  - $k$-factor $\sim 1.3$, systematic unc. $\sim 30\%$ on normalization and slope.
- **Results**: $\mu = 2.3 \pm 1.5 (stat)^{+1.0}_{-0.4} (syst) \rightarrow 1.5\sigma$ (exp. $0.7\sigma$)
• $H \rightarrow \mu\mu$ can be found as a peak in a smoothly falling background.

• The analysis is split in categories with different di-muon mass resolution and signal purity → a BDT is used to enhance S/B separation.
  - VBF-enriched categories have the largest purity and sensitivity.

• Results. CMS: $\mu = 0.9^{+1.0}_{-0.9} \rightarrow 0.98\sigma(1.09\sigma)$; ATLAS: $\mu = -0.1 \pm 1.4$
Higgs boson decays into Zγ through loops.

- BR similar to H → γγ, but only 6.6% Z → μμ/ee.

- m_{Zγ} resolution improved recovering the FSR emitted close to the lepton and with a **kinematic fit**.

- Analysis divided in several categories with different purities
  - VBF category has the largest purity and sensitivity.

- **Result**: Upper limit 6.6 times the SM (exp. 5.2).
H → light quarks

- H → φγ and H → ρ(770)γ have been proposed as channel to probe the Higgs coupling with the s quark and u/d quarks, respectively.
- The expected SM BR are 2.3 · 10⁻⁶ and 1.7 · 10⁻⁵.
- They have been searched in the φ→K+K⁻ and ρ→π+π⁻ decays.
- One isolated photon with p_T>35 GeV.
- Two isolated tracks with p_T>15 GeV and mass compatible to ρ or φ.
- **Data driven background estimate:**
  - validated in ρ and φ side bands.
- **Results:**
  - upper limit BR(φγ) 4.8(4.2) · 10⁻⁴ → μ<208(182);
  - upper limit BR(ργ) 8.8(8.4) · 10⁻⁴ → μ<52(50).
Precision SM Higgs boson measurements
The $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$ are the most sensitive channel to provide precision measurement of the Higgs boson.

- ATLAS has already provided the combination $H \rightarrow 4\ell + H \rightarrow \gamma\gamma$.

13 TeV analyses confirm SM expectation:

- measurement cross-section vs $\sqrt{s}$.
The growing signal allows to measure the **differential** cross section as a function of variable eg. $p_T(H)$, $N_{\text{jet}}$, $\eta(H)$, ...

Here the measurement of $p_T(H)$ in $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$.

The cross section is measured in a **fiducial** phase space in order to allow a good comparison with theory.
Simplified Template
Cross Section (STXC)

Handbook of LHC Higgs cross sections: 4
arXiv:1610.07922
• We are going towards the measurement of the Higgs boson cross-section using stage-1 STXC.

• The first step (stage-0) is the measurement of the cross-section per production channel (ggH, VBF, VH, ttH).

• ATLAS already provided a reduced stage-1 set of measurements with the combination of $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$. 
The first measurements of the coupling modifiers $\kappa$ at 13 TeV are available.

Example:
- fermionic vs bosonic couplings ($k_f$ vs $k_V$);
- loop couplings: photons vs gluons ($k_\gamma$ vs $k_g$).

Compatible with SM within $1\sigma$. 

$\kappa_g$ vs $\kappa_g$

ATLAS

$\kappa_f$ vs $\kappa_V$

CMS-PAS-HIG-17-015

ATLAS-CONF-2017-047
Conclusions
Conclusions

- CMS and ATLAS collaborations published many important Higgs results in the last year.
  - single-experiment observation of $H \to \tau\tau$;
  - evidence for $H \to bb$ and $ttH$;
  - new Higgs channel (eg. boosted $H \to bb$);
  - large improvement in $H \to \mu\mu$.

- $H \to 4\ell$ and $H \to \gamma\gamma$ are now channels for precision measurements
  - differential cross sections, and couplings.

- All results have been obtained using 2015-16 data (36 fb$^{-1}$):
  - LHC doubled the integrated luminosity in 2017 and even more luminosity is expected in 2018.

- Many more results are expected in the next months/years!
Thank you for your attention!
Backup
ZH → invisible

- H → invisible decay can be enhanced by New Physics (eg. dark matter).
  - SM prediction BR(H→ZZ→inv.)~10^{-3}

- Analysis performed in $Z(\ell\ell)H(\text{inv.})$ channel.

- Main backgrounds:
  - Diboson: estimated by simulation and scaled by a data-driven scale factor
  - $Z$+jets, non-resonant(ll) : estimated by data.

- Results on BR(H→inv.):
  - upper limit 67% (exp. 39%).
• Measurement of the Higgs mass and width.

• ATLAS:
  - combination $H(\gamma\gamma)$ with $H(4\ell)$;
  - combination with LHC Run-1.

• CMS:
  - only $H(4\ell)$ available:

$$m_H = 125.26 \pm 0.20 \text{(stat)} \pm 0.08 \text{(syst)} \text{GeV}$$

$$\Gamma_H < 1.10 \text{GeV (95\% CL)}$$
H → bb (History)

- Significance @125 GeV (expected):
  - CDF: ~2.8σ (~1.5σ)
  - ATLAS: 1.7σ (2.7σ) – Run-1
    3.5σ (3.0σ) – Run-2
    3.6σ (4.0σ) – Run-1+Run-2
  - ATLAS: 2.0σ (2.5σ) – Run-1
    3.3σ (2.8σ) – Run-2
    3.8σ (3.8σ) – Run-1+Run-2