



Recent Higgs measurements

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on behalf of the ATLAS and CMS Collaborations

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- **Observation** of all the **main production processes**;
- **Observation** of decays to bosons and third-generation fermions;
- **Improvement** of m_H precision and CP measurements;
- Off-shell production measurements.
- Now shift focus from *discovery era* to *precision era*
 - Precision unfolded differential measurements;
 - Combined measurements \rightarrow Simplified Template Cross-Section (STXS) framework.

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STXS framework

• Framework for subdividing Higgs Boson measurements into orthogonal regions - STXS bins [defined using generator level information] ggF • $(\sigma \times B)$ measurement for each bin tH• STXS bins chosen such that they: ggF are defined by Higgs production modes; reduce theory uncertainties • isolate regions potentially sensitive to BSM; **VBF+VHhad VBF** • <u>STXS stage 1.2</u> Higgs boson signal split according to • production modes, **VBF** • number of jets H + had. V• p_T^H/p_T^V ; • invariant mass of the leading jets m_{ii} . ttH VHlep VH<u>Advantage</u>: easy to combined different analyses. $q\bar{q} \rightarrow WH$ $t\bar{t}H$ $q\bar{q} \rightarrow ZH$ $gg \rightarrow ZH$

STXS framework

- Framework for **subdividing Higgs Boson measurements into orthogonal regions** *STXS bins* [defined using generator level information]
 - $(\sigma \times B)$ measurement for each bin
- STXS bins chosen such that they:
 - are defined by Higgs production modes;
 - reduce theory uncertainties
 - isolate regions potentially sensitive to BSM;
- <u>STXS stage 1.2</u> Higgs boson signal split according to
 - production modes,
 - number of jets
 - p_T^H/p_T^V ;
 - invariant mass of the leading jets m_{jj} .
- <u>Advantage</u>: easy to combined different analyses.



Outline

In this talk I am focusing on results released in the past one year:

- $H \rightarrow \gamma \gamma$ analysis (CMS)
- $H \rightarrow ZZ \rightarrow 4\ell$ analysis + off-shell production (CMS);
- $H \rightarrow \tau \tau$ analysis (ATLAS);
- $H \rightarrow b\bar{b}$ analysis (ATLAS);
- $H \rightarrow \mu\mu$ analysis (ATLAS, CMS);
- $H \rightarrow Z\gamma$ analysis (ATLAS, CMS);
- Combined Higgs boson measurements (ATLAS).

$H \rightarrow \gamma \gamma$ analysis

- Analysis targets all Higgs production modes: ggF, VBF, VH, ttH, tH
- **Clean final state** topology with two photons
- Simultaneous **binned maximum likelihood fit** to $m_{\gamma\gamma}$ distributions





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- **STXS measurements** in 27 STXS bins ["minimal merging scenario"]
 - Most granular XS measurement performed in a single Higgs decay
 - First measurement of *ttH* in bins of $p_T(H)$;
 - Large uncertainty on tH bin

$H \rightarrow ZZ \rightarrow 4\ell$ and off-shell Higgs production

- Events with same flavor, opposite sign lepton pairs form the Higgs candidate
 - Clear signature \rightarrow targets all the production modes except for *tH*;
- Dominant irreducible background: ZZ*
- Unbinned likelihood fit



- exp) $\frac{STXS measurements in 19 STXS bins.$ $\frac{137 \text{ fb}^{-1} (13 \text{ TeV})}{137 \text{ fb}^{-1} (13 \text{ TeV})}$
- Statistically limited channel
- Results consistent with the SM predictions.



- On-shell analysis combined with off-shell $H \rightarrow ZZ \rightarrow 2\ell 2\nu$ \Rightarrow first evidence of off-shell Higgs production (3.6 σ)
- Comparison of on-shell and off-shell rates yields constrain on Higgs width $\Gamma_H = 3.2 \stackrel{+2.4}{_{-1.7}} \text{MeV} \leftarrow \text{Most precise } \Gamma_H \text{ measurement}$

ATLAS analysis: <u>link</u>

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$H \rightarrow \tau \tau$ analysis





N(jets):

m_{ii} [GeV]: [0, 350]

≥ 1

p_(H) [GeV]: [60, 120] [120, 200] [200, 300]

≥2

[0, 350]

gluon fusion + gg \rightarrow Z(\rightarrow qq)H

≥ 0

≥ 0

[300, ∞[

≥ 2

[0, 200]

≥2

[350, ∞[| [60, 120] [350, ∞[

 $VBF + V(\rightarrow qq)H$

≥2

CMS analysis: <u>link</u> G. Di Gregorio - BF 2021 ttH

$VH, H \rightarrow b\bar{b}$ combination

- $H \rightarrow b\bar{b}$ dominant decay, triggered by leptonic decays of vector boson
- $VH(b\bar{b})$ final states studied by two analyses and significant overlap (~25%) between the two analyses **Resolved analysis Boosted analysis**







- In the combination drop resolved events with $p_T^V > 400$ GeV and use boosted only in $p_T^V > 400$ GeV
- STXS measurements in 7 STXS bins
 - bins with $p_T^V > 400$ GeV are statistically limited
 - Good agreement with SM predictions.

$H \rightarrow \mu \mu$ analysis

- Analysis targets all the production modes;
- <u>Final state</u> with **two muons** \rightarrow good signal resolution but small branching ratio (~2.2x10⁻⁴)
- Large **irreducible bkg** from $Z \rightarrow \mu \mu$
- Simultaneous binned-likelihood fit
- <u>CMS results:</u>
 - $\mu = 1.19 {+0.41 \atop -0.40} (\text{stat}) {+0.17 \atop -0.16} (\text{syst})$
 - \rightarrow Observed (expected) significance 3 (2.5) σ **Evidence!**
 - \rightarrow upper limits on BR of **1.9**×**SM** @ 95% CL
- ATLAS results:
 - $\mu = 1.2 \pm 0.6(\text{stat})^{+0.2}_{-0.1}(\text{syst})$
 - \rightarrow Observed (expected) significance 2.0 σ (1.7 σ)
 - \rightarrow upper limits on BR of 2.2×SM @ 95% CL



$H \rightarrow Z\gamma$ analysis

- Analysis targets all the production modes;
- BR($H \rightarrow Z\gamma$) = 1.54 × 10⁻³
- Final state with one photon and two same flavor opposite charge leptons ($\ell = e, \mu$).
- Binned-maximum likelihood fit to all $m_{Z\gamma}$ distribution
- <u>CMS results</u>:

 $\mu = 2.4 \stackrel{+0.8}{_{-0.9}} (\text{stat}) \stackrel{+0.3}{_{-0.2}} (\text{syst})$

Observed (expected) significance of 2.7 (1.2) σ

 \rightarrow upper limits on ($\sigma \times B$) of 4.1 x SM @ 95% CL

• <u>ATLAS results</u>:

 $\mu = 2.0 \pm 0.9 \text{ (stat)}^{+0.4}_{-0.3} \text{(syst)}$

Observed (expected) significance of 2.2 (1.2) σ

 \rightarrow <u>upper limits on ($\sigma \times B$) of **3.6 x SM** (a 95% CL</u>



Combined Higgs boson measurements Input analyses



ATLAS Preliminary $\sqrt{s} = 13$ TeV, 36.1 - 139 fb ⁻¹ $m_H = 125.09$ GeV $p_{SM} = 79\%$		Total Stat. Syst. SM		
	1.00	Total	Stat.	Syst.
gg⊢γγ	1.02	-0.11 +0.11	- 0.08 , (+ 0.10	- 0.07) + 0.04 \
	0.95	-0.11	(-0.10 ,	+0.12
gg⊢ WW	1.13	-0.12	(<u>-0.06</u> ,	- 0.10)
ggF tt	0.87	-0.25	(-0.15 ,	+ 0.23 - 0.20)
ggF+ttH μμ μ	0.52	-0.88	$\begin{pmatrix} +0.77\\ -0.79 \end{pmatrix}$,	+ 0.49)
VBF γγ	1.47	+0.27 -0.24	$(^{+0.21}_{-0.20},$	+0.17 -0.14)
VBF ZZ	1.31	+0.51 -0.42	$(^{+0.50}_{-0.42},$	+0.11 -0.06)
VBF WW	1.09	+0.19 -0.17	$(^{+0.15}_{-0.14}$,	+ 0.11 - 0.10)
VBF ττ 💼	0.99	+0.20 -0.18	$(^{+0.14}_{-0.14}$,	+ 0.15 - 0.12)
VBF+ggF bb	0.98	+0.38 -0.36	$(^{+0.31}_{-0.33}$,	+ 0.21 - 0.15)
VBF+VH μμ	2.33	+ 1.34 - 1.26	$(\begin{array}{c} +1.32 \\ -1.24 \end{array} ,$	$^{+\ 0.20}_{-\ 0.23}$)
νη γγ	1.33	+0.33 -0.31	$\left(\begin{array}{c} +0.32\\ -0.30 \end{array} \right),$	+0.10 -0.08)
VH ZZ	1.51	+1.17 -0.94	(^{+1.14} ,	+ 0.24 - 0.16)
VH ττ μ<u>τ</u>	0.98	+0.59 -0.57	$(^{+0.49}_{-0.49},$	+ 0.33 - 0.29)
WH bb	1.04	+0.28 -0.26	$(^{+0.19}_{-0.19},$	+ 0.20 - 0.18)
ZH bb	1.00	+0.24 -0.22	$(^{+0.17}_{-0.17},$	+ 0.17 - 0.14)
ttH+tH γγ	0.93	+0.27 -0.25	(^{+0.26} _{-0.24} ,	+ 0.08 - 0.06)
ttH+tH WW	H 1.64	+0.65 -0.61	$(^{+0.44}_{-0.43}$,	+ 0.48 - 0.43)
ttH+tH ZZ	1.69	+ 1.69 - 1.10	(^{+1.65} _{-1.09} ,	+ 0.37 - 0.16)
ttH+tH ττ	1.39	+0.86	$(^{+0.66}_{-0.62},$	+ 0.54 - 0.44)
ttH+tH bb	0.35	+0.34 -0.33	(^{+0.20} _{-0.20} ,	+ 0.28 - 0.27)
-4 -2 0	2 4	6		8

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Combined Higgs boson measurements: STXS results ATLAS Preliminary (5 = 13 TeV 139 ft⁻¹

Fit parameters for the STXS measurement:



- <u>37 cross-sections measured simultaneously</u>:
 - Excellent agreement with SM prediction

ATLAS	Preliminary			· · · · · ·		Total S	stat. Syst.
√s = 13 TeV.	139 fb ⁻¹	$B_{\gamma\gamma}/B_{ZZ}$		÷	1.09	+0.14	+0.12 0.11, ±0.06
m = 125.09	GeV v < 25	B			0.78	+0.28	+ 0.23 + 0.16
n = 02%	$dov, p_{H} < 2.0$	Busu/B==			1.06	+0.14	-0.18', -0.11 +0.11 +0.09
P _{SM} = 92 %		D _{WW} , D _{ZZ} .			0.00	- 0.13 · · · · · · · · · · · · · · · · · · ·	-0.10 ' -0.08 +0.12 +0.10
- Total	Stat.	D _{TT} /D _{ZZ} ,			0.86	-0.14 (-0.10 ' -0.09
Syst.	SM	<u> </u>	0.5		1.5		2
$gg \rightarrow H \times B_{22}$,	$\begin{array}{l} 0 \text{-jet}, \ \rho_{T}^{H} < 10 \ \text{GeV} \\ 0 \text{-jet}, \ 10 \le p_{T}^{H} < 200 \ \text{GeV} \\ 1 \text{-jet}, \ p_{T}^{H} < 60 \ \text{GeV} \\ 1 \text{-jet}, \ 60 \le p_{T}^{H} < 200 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 350 \ \text{GeV}, \ p_{T}^{H} < 60 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 350 \ \text{GeV}, \ 60 \le p_{T}^{H} < 120 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 350 \ \text{GeV}, \ 60 \le p_{T}^{H} < 120 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 350 \ \text{GeV}, \ 120 \le p_{T}^{H} < 200 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 350 \ \text{GeV}, \ 120 \le p_{T}^{H} < 200 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 350 \ \text{GeV}, \ 120 \le p_{T}^{H} < 200 \ \text{GeV} \\ 2 \text{-jet}, \ m_{J} < 700 \ \text{GeV}, \ p_{T}^{H} < 200 \ \text{GeV} \\ 2 \text{-jet}, \ 300 \ \text{GeV} \\ 300 \le p_{T}^{H} < 450 \ \text{GeV} \\ \end{array}$	Letter Contraction	• •••• ••	•	0.89 1.14 0.57 1.06 0.66 0.47 0.25 0.54 2.76 0.74 1.06 0.65 1.86	$\begin{array}{l} {\rm Total} \\ + 0.22 \ (\\ - 0.20 \ (\\ + 0.15 \ (\\ - 0.34 \ (\\ + 0.28 \ (\\ - 0.27 \ (\\ - 0.44 \ (\\ - 0.39 \ (\\ - 0.39 \ (\\ - 0.39 \ (\\ - 0.39 \ (\\ - 0.39 \ (\\ - 0.331 \ (\\ - 0.331 \ (\\ - 0.43 \ (\\ - 0.43 \ (\\ - 1.19 \ ($	$\begin{array}{c} Stat. Syst. \\ +0.19 + 0.11 \\ -0.18 \\ -0.10 \\ +0.12 \\ +0.29 \\ +0.22 \\ -0.21 \\ +0.22 \\ +0.29 \\ +0.22 \\ +0.21 \\ +0.22 \\ +0.21 \\ +0.22 \\ +0.21 \\ +0.22 \\ +0.21 \\ +0.22 \\ +0.21 \\ +0.25 \\ +0.13 \\ +0.21 \\ +0.25 \\ +0.31 \\ +0.21 \\ +0.25 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ +0.21 \\ +0.31 \\ $
qq→Hqq × B _{ZZ} .	$ \begin{split} &\leq 1\text{-jet} \\ &\geq 2\text{-jet}, \ m_{ji} < 350 \ \text{GeV}, \ \text{VH} \ \text{veto} \\ &\geq 2\text{-jet}, \ m_{ji} < 350 \ \text{GeV}, \ \text{VH} \ \text{topo} \\ &\geq 2\text{-jet}, \ 350 \ \text{GeV}, \ \text{VH} \ \text{topo} \\ &\geq 2\text{-jet}, \ 700 \le m_{ji} < 7000 \ \text{GeV}, \ \text{P}_{ij}^{ij} < 200 \ \text{GeV} \\ &\geq 2\text{-jet}, \ 700 \le m_{ji} < 1500 \ \text{GeV}, \ \text{Order}, \ 22\text{-jet}, \ m_{ji} \geq 1500 \ \text{GeV}, \ \text{P}_{ij}^{ij} < 200 \ \text{GeV} \\ &\geq 2\text{-jet}, \ m_{ji} \geq 350 \ \text{GeV}, \ \text{P}_{ji}^{ij} < 200 \ \text{GeV} \\ &\geq 2\text{-jet}, \ m_{ji} \geq 350 \ \text{GeV}, \ \text{P}_{ji}^{ij} \geq 200 \ \text{GeV} \\ \end{split} $		• <u>•</u> •	-	1.40 2.98 1.00 0.33 0.95 1.38 1.15 1.21	$\begin{array}{c} + 1.10 \\ - 0.99 \\ + 1.64 \\ - 1.52 \\ + 0.58 \\ - 0.52 \\ + 0.49 \\ - 0.47 \\ + 0.71 \\ - 0.65 \\ + 0.57 \\ - 0.49 \\ + 0.39 \\ - 0.35 \\ - 0.27 \\ \end{array}$	$\begin{array}{cccc} +1.02 & +0.40 \\ -0.93 & -0.35 \\ +1.46 & +0.75 \\ -1.37 & -0.66 \\ +0.51 & +0.28 \\ +0.51 & +0.28 \\ +0.44 & +0.22 \\ -0.41 & -0.24 \\ +0.62 & +0.35 \\ -0.57 & -0.31 \\ +0.50 & +0.29 \\ -0.45 & -0.21 \\ +0.35 & +0.18 \\ -0.32 & -0.14 \\ -0.32 & -0.14 \\ -0.24 & -0.12 \end{array}$
$qq \rightarrow H l \nu \times B_{Z^*}$	$\begin{array}{l} p_{\gamma}^{\nu} < 75 \; {\rm GeV} \\ 75 < p_{\gamma}^{\nu} < 150 \; {\rm GeV} \\ 150 \le p_{\gamma}^{\nu} < 250 \; {\rm GeV} \\ 250 \le p_{\gamma}^{\nu} < 400 \; {\rm GeV} \\ p_{\gamma}^{\nu} < 400 \; {\rm GeV} \end{array}$				2.47 1.64 1.42 1.36 1.91	+ 1.17 - 1.02 (+ 0.99 - 0.80 (+ 0.74 (+ 0.72 (+ 0.53 (+ 1.45 ($\begin{array}{c} +1.15 & +0.22 \\ -1.02 & +0.12 \\ +0.97 & +0.20 \\ -0.79 & +0.20 \\ +0.61 & +0.42 \\ -0.48 & +0.33 \\ +0.63 & +0.35 \\ +0.63 & +0.35 \\ +1.22 & +0.79 \\ -0.95 & +0.50 \end{array}$
gg/qq→Hll × B _{zz} .	$ \begin{array}{l} p_{_{T}}^{\nu} < 150 \; {\rm GeV} \\ 150 \leq p_{_{T}}^{\nu} < 250 \; {\rm GeV} \\ 250 \leq p_{_{T}}^{\nu} < 400 \; {\rm GeV} \\ p_{_{T}}^{\nu} \geq 400 \; {\rm GeV} \end{array} $		-		0.21 1.30 1.28 0.39	+0.71 (+0.63 (+0.76 (+0.73 (+0.74 (+1.28 ($\begin{array}{c} \pm \ 0.54 & {}^{+} \ 0.46 \\ {}^{*} \ 0.53 & {}^{+} \ 0.53 \\ + \ 0.53 & + \ 0.34 \\ - \ 0.41 & {}^{-} \ 0.22 \\ + \ 0.64 & {}^{+} \ 0.36 \\ - \ 0.48 & {}^{+} \ 0.23 \\ + \ 1.04 & {}^{+} \ 0.74 \\ - \ 0.91 & {}^{-} \ 0.68 \end{array}$
tĨH×B _{ZZ*}	$\begin{array}{l} p_{T}^{H} < 60 \; {\rm GeV} \\ 60 < p_{T}^{H} < 120 \; {\rm GeV} \\ 120 \leq p_{T}^{H} < 200 \; {\rm GeV} \\ 200 \leq p_{T}^{H} < 300 \; {\rm GeV} \\ 300 \leq p_{T}^{H} < 450 \; {\rm GeV} \\ p_{T}^{H} \geq 450 \; {\rm GeV} \end{array}$		_		0.75 0.69 0.86 0.96 0.28 0.16	+0.78 -0.66 +0.53 -0.44 (+0.55 -0.47 +0.62 -0.52 (+0.79 -0.70 (+1.93 -1.76 ($\begin{array}{c} + 0.72 & + 0.29 \\ - 0.63 & ^{\circ} 0.21 \\ + 0.49 & + 0.20 \\ - 0.42 & ^{\circ} - 0.15 \\ + 0.50 & + 0.23 \\ - 0.43 & ^{\circ} - 0.20 \\ + 0.56 & + 0.25 \\ - 0.48 & ^{\circ} - 0.20 \\ + 0.66 & + 0.43 \\ - 0.59 & ^{\circ} - 0.38 \\ + 1.44 & + 1.28 \\ - 1.24 & ^{\circ} - 1.25 \end{array}$
$tH \times B_{ZZ^*}$				1	2.90	+ 3.63 - 2.87 (+3.35 +1.39 -2.73 -0.89
8	<u> </u>	0	2	4 6		8	-2.73 0

Parameter normalized to SM value

CMS analysis: link

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Conclusions

- Using Run 2 dataset, XS measurements in many channels;
 - Results are in good agreement with SM expectations
- Combination of individual Higgs boson production and decay measurements
 - Almost all the analyses use full Run-2 dataset
 - Easy combination of the analyses thanks to the STXS framework;
 - Combination provides unprecedented precision

	γγ	ZZ	WW	au au	bb	μμ	Zγ	inv	CC	Analysis with full Run 2 dataset
ggF										considered in the combination
VBF										Analysis with partial Run 2 dataset
VH										considered in the combination
ttH										Analysis with full Run 2 dataset not
tH										yet considered in the combination

• Stay tuned, more precise results are coming!







Run: 338349 Event: 616525246 2017-10-16 20:24:46 CEST

Additional material

Full list of analysis

- Combination:
 - ATLAS: <u>ATLAS-CONF-2021-053</u>
 - CMS: <u>CMS-PAS-HIG-19-005</u>
- $H \rightarrow \gamma \gamma$
 - ATLAS: <u>ATLAS-CONF-2002-026</u>
 - CMS: <u>JHEP 2017 (2021) 027</u>
- $H \to ZZ \to 4\ell$
 - ATLAS: Eur. Phys. J. C 80 (2020) 957
 - CMS (on-shell): <u>Eur. Phys. J. C 81 (2021) 488</u>
 - CMS (off-shell): <u>CMS-PAS-HIG-21-013</u>
- $H \rightarrow \tau \tau$:
 - ATLAS: ATLAS-CONF-2021-044
 - CMS: <u>CMS-PAS-HIG-19-010</u>
- $H \rightarrow b \bar{b}$
 - ATLAS (resolved): Eur. Phys. J. C 81 (2021) 178
 - ATLAS (boosted): Phys. Lett. B 816 (2021) 13204
 - ATLAS (combination): <u>ATLAS-CONF-2021-051</u>
- $H \rightarrow \mu \mu$:
 - ATLAS: JHEP 01 (2021) 148
 - CMS: Phys. Lett. B 812 (2021) 135980
- $H \rightarrow Z\gamma$
 - ATLAS: Phys. Lett. B 809 (2020) 135754
 - CMS: <u>CMS-PAG-HIG-19-014</u>

$H \rightarrow \gamma \gamma$ analysis (CMS)



- <u>Maximal merging scheme</u>: STXS bins merged until their expected unc is < 150%;
- <u>Minimal merging scheme</u>: STXS bins merged ensuring that parameters do not become too anticorrelated (<90%)



ATLAS Preliminary Stat. Syst. SM H Total $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ • Events with at least 2 photons $\rho_{SM} = 60\%$ Total Stat. Syst. H→γγ, m_⊔ = 125.09 GeV $^{+0.31}_{-0.30}$ (± 0.26, $^{+0.18}_{-0.16}$ $gg \rightarrow H 0J 0 < p_T^H 10$ 0.76 • MVA techniques to categorize the events and +0.20 -0.19 (± 0.15, +0.13 $gg \rightarrow H 0J p_{\tau}^{H} > 10$ 1.17 +0.44 -0.43 (± 0.40, +0.19 discriminate signal from bkgs. $gg \rightarrow H 1J 0 < p_{-}^{H} < 60$ 0.91 -0.16 +0.39 -0.37 (± 0.37, +0.15, $gg \rightarrow H \ 1J \ 60 < p_{_T}^H < 120$ 1.18 -0.06 gg→H 1J 120 < p^H₋ < 200 $0.70 \pm 0.52 \ (\pm 0.50,$ ලි 3000 Data ATLAS Preliminary +1.28 (+1.16 +0.55, -1.21 (-1.15, -0.38) +0.55 $gg \rightarrow H \ge 2J \ 0 < m_{JJ} < 350, \ 0 < p_{T}^{H} < 60$ 0.47 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ Background $0.28 \pm 0.59 (^{+0.57}_{-0.58})$ +0.13Weights $gg \rightarrow H \ge 2J \ 0 < m_{II} < 350, \ 60 < p_{\tau}^H < 120$ 2500 m_µ = 125.09 GeV -0.12 +0.48 +0.17 Signal + Background gg→H ≥2J 0 < m_{,1} < 350, 120 < p_T^H < 200 0.60 $_{-0.47}^{+0.46}$ (± 0.45, $_{-0.14}^{+0.17}$ All categories 2000 +0.99 (+0.88, -0.91 (-0.87, +0.47 ln(1+S/B) weighted sum = gg→H ≥2J m 1 > 350, 0 < p_+^H < 200 2.25 Jo 1500 -0.29 1500 S = Inclusive +0.40 , +0.38 +0.13 gg→H 200 < p_^H < 300 1.00 -0.37 (-0.36 -0.09 +0.57 ± 0.55 ± 0.14 $gg \rightarrow H 300 < p_{_{T}}^{H} < 450$ 0.20 -0.50 (-0.49 500 +1.45+1.44+0.17 $gg \rightarrow H p_{-}^{H} > 450$ -1 16 (-1 16 -0.06 +1.23 +1.15+0.44qq→Hqq ≤ 1J 1.55 -1.08 -1.02 -0.38 - Cont. Bkg 100 +1.84 +0.71+1.70qq→Hqq ≥2J 0 < m., < 60 || 120 <m., < 350 -1.72 -1.62 50 +0.95 +0.91+0.25 qq→Hqq ≥2J 60 < m, < 120 0.76 -0.83 -0.80 -0.24 +0.73 +0.62 +0.38 qq→Hqq ≥2J 350 < m, < 700, 0 < p_{T}^{H} < 200 -50 -0.56 Data 110 120 130 140 150 16 +0.35+0.28+0.21 $qq \rightarrow Hqq \ge 2J m_{\downarrow} > 700, 0 < p_{\tau}^{H} < 200$ (-0.26 m_{γγ} [GeV] -0.31 -0.17 +0.46 +0.41 +0.20 $qq \rightarrow Hqq \ge 2J m_{11} > 350, p_{T}^{H} > 200$ 1.35 -0.40 (-0.36, -0.17 +0.71 +0.22 $qq \rightarrow Hlv \ 0 < p_{\star}^V < 150$ 2.41 (± 0.67, ATLAS Preliminary -0.70 -0.19 Hotal Stat. Syst. SM $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ +1.16 +1.14 +0.19 qq→Hlv p^V > 150 $H \rightarrow \gamma \gamma$, $m_{\mu} = 125.09 \text{ GeV}$ -0.99 -0.97 -0.17Total Stat. Syst +0.99+0.96 +0.26 HII $0 < p_1^V < 150$ -1.08 -0.87 -0.85 -0.20 1.02 ± 0.11 (± 0.08 , ± 0.07 ggF + bbH Hll p^V > 150 +1.11+1.10+0.16-0.10 -0.93 (-0.91) +0.83 , +0.80 +0.21 $1.34 \pm {0.26 \atop 0.24}$ (± 0.18 , $\pm {0.18 \atop 0.16}$) $ttH \ 0 < p_{_{\rm T}}^{\rm H} < 60$ 0.76 VBF -0.70 -0.68 -0.17Strong correlation +0.54 , +0.53 +0.10 $ttH 60 < p_{T}^{H} < 120$ (-0.46 $2.33 \pm {}^{0.55}_{0.50}$ ($\pm {}^{0.53}_{0.49}$, $\pm {}^{0.13}_{0.10}$ -0.46 -0.08 WH +0.63 , +0.61 +0.17 ttH 120 < p_{τ}^{H} < 200 1.06 (-0.52, -0.54 -0.14 between WH and ZH -0.64 $\pm \begin{array}{c} 0.61 \\ 0.57 \end{array}$ ($\pm \begin{array}{c} 0.61 \\ 0.56 \end{array}$, $\pm \begin{array}{c} 0.07 \\ 0.08 \end{array}$ +0.53 , +0.52 +0.12ΖH ttH $p_{T}^{H} > 200$ 0.96 -0.46 (-0.45, -0.10) +3.28 , +3.13 +0.97 (O(40%))0.85 $0.92\pm \begin{smallmatrix} 0.27\\ 0.24 \end{smallmatrix}$ ($\pm \begin{smallmatrix} 0.25\\ 0.23 \end{smallmatrix}$, $\pm \begin{smallmatrix} 0.09\\ 0.07 \end{smallmatrix}$ (-2.21, ttH + tH2 -2 n 6 3 5 0 2 Upper limit on tH $\sigma^{\gamma\gamma}/\sigma^{\gamma\gamma}_{SM}$ $\sigma_{\rm H}\!/\sigma_{\rm u}^{\rm SM}$

$H \rightarrow \gamma \gamma$ analysis (ATLAS)

G. Di Gregorio - BF 2021

ATLAS-CONF-2020-026

$H \rightarrow ZZ \rightarrow 4l$ (CMS)

- Events with same flavor, opposite sign lepton pairs form the Higgs candidate
 - Clear signature \rightarrow targets all the production modes except for *tH*;
- Combined results from ZZ decays channels: 4e, 4μ , $2e2\mu$;
- Events categorized according to # jets, # b-tagged jets and # additional leptons →22 event categories

 ^{CMS}
 ^{137 fb⁻¹(13 TeV)}
 ²⁵⁰
- Dominant irreducible background: ZZ*
- Unbinned likelihood fit





- STXS measurements in 19 STXS bins.
 - Statistically limited channel → coarse bins
 - Results consistent with the SM predictions.

$H \rightarrow ZZ \rightarrow 4l$ (ATLAS)

Eur. Phys. J. C 80 (2020) 957

- Clean signature fully reconstructed final states and high S/B
- Events with same flavor, opposite sign lepton ($\ell = e, \mu$) pairs form the Higgs candidate
- MVA technique to define analysis categories
- Likelihood fit

 $\mu = 1.01 \pm 0.08(\text{stat}) \pm 0.04(\text{exp}) \pm 0.05(\text{theo})$





$H \rightarrow WW \rightarrow e \nu \mu \nu$ (ATLAS)

- Analysis targets VBF and ggF production modes
- <u>Final state</u> with **2 charged leptons** with **different flavor** and **opposite charge**.
- Control regions (CRs) to extract normalization of the dominant bkgs (WW, tt̄/Wt̄, Z/γ*)
- Profiled likelihood fit to data:

 $\mu_{ggF} = 1.20 \pm 0.05 \text{ (stat)}^{+0.09}_{-0.08} (\exp \text{ systs})^{+0.10}_{-0.08} (\operatorname{sig} \text{ theo})^{+0.12}_{-0.11} (\operatorname{bkg} \text{ theo})$

 $\mu_{VBF} = 0.99 + 0.13_{-0.12} (\text{stat}) + 0.07_{-0.06} (\text{exp systs}) + 0.17_{-0.12} (\text{sig theo}) + 0.10_{-0.08} (\text{bkg theo})$

→ measurements **dominated by systematic sources**

- STXS measurements in 11 STXS bins
 - Most of the STXS bins statistically-limited
 - Results compatible with SM prediction





$H \rightarrow \tau \tau$ analysis (CMS)

- Analysis targets primarily ggF and VBF
- Events classification: $\tau_h \tau_h$, $e \tau_h$, $\mu \tau_h$, $e \mu$.
- MVA techniques to reconstruct τ_h and reject fakes.
- Main bkgs ($Z \rightarrow \tau \tau$, τ mis-ID) estimated with data-driven techniques.

σB (fb)

10⁴ 2960

10

10²

10

Ratio to SM

• **Binned maximum likelihood fit** to extract the results:

$$\mu_{ggF} = 0.98^{+0.12}_{-0.09} \text{(theo)} \pm 0.09 \text{(stat)} \pm 0.12 \text{(syst)} \pm 0.06 \text{(bbb)}$$

$$\mu_{qqH} = 0.67^{+0.06}_{-0.05} \text{(theo)}^{+0.19}_{-0.18} \text{(stat)}^{+0.09}_{-0.08} \text{(syst)} \pm 0.08 \text{(bbb)}$$

- STXS measurements in 11 STXS bins.
 - Results **consistent** with the **SM predictions**.
 - **Good sensitivity** to Higgs produced with high p_T
 - Results **dominated** by **stat. uncertainty**

CMS-PAS-HIG-19-010



$H \rightarrow \mu\mu$ analysis (CMS)

- Analysis targets all the production modes;
- <u>Final state</u> with **two muons** \rightarrow good signal resolution but small branching ratio (~2.2x10⁻⁴)
- Large **irreducible bkg** from $Z \rightarrow \mu \mu$
- Simultaneous binned-likelihood fit

 $\mu = 1.19 + 0.41 - 0.40 (\text{stat}) + 0.17 - 0.16 (\text{syst})$

- \rightarrow Observed (expected) significance 3 (2.5) σ **Evidence!**
- \rightarrow Upper limits on BR of 1.9×SM @ 95% CL



Best-fit u

CMS

VBF-cat.

ggH-cat.

ttH-cat.

VH-cat.

 $\mu = 1.36^{+0.69}_{-0.61}$

 $\mu = 0.63^{+0.65}_{_{-0.64}}$

 $\mu = 2.32^{+2.27}_{-1.95}$

 $\mu = 5.48^{+3.10}_{-2.83}$

-2

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$H \rightarrow \mu\mu$ analysis (ATLAS)

700[Weighted Events / 2 GeV ATLAS • Analysis targets all the production modes; 600 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ $H \rightarrow \mu\mu$, ln(1 + S/B) weighted 500 F • Final state with **two muons** \rightarrow good signal 400E resolution but small branching ratio ($\sim 2.2 \times 10^{-4}$) 300E 200E • Large irreducible bkg from $Z \rightarrow \mu \mu$ 100E • Simultaneous binned-likelihood fit to $m_{\nu\nu}$ Data - Bkg. $\mu = 1.2 \pm 0.6(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ \rightarrow Observed (expected) significance 2.0 σ (1.7 σ) 110 120 125 130 135 140 115 \rightarrow Upper limits on BR of 4.7x10⁻⁴ ATLAS $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ $H \rightarrow \mu\mu$ Total Stat. Syst. **I ← I** Total Stat. 📃 Syst. SM VH and ttH categories $5.0 \pm 3.5 \ (\ \pm 3.3 \ ,\ \pm 1.1 \)$

ggF 0-jet categories

ggF 2-jet categories

-5

0

5

10

ggF 1-jet categories

VBF categories

Combined

-10

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🔶 Data

145

 $-0.4 \pm 1.6 \ (\ \pm 1.5 \ ,\ \pm 0.3 \)$

 $2.4 \pm 1.2 \ (\pm 1.2 \ , \pm 0.3 \)$

 $-0.6 \pm 1.2 \ (\pm 1.2 \ , \pm 0.3 \)$

1.8 \pm 1.0 (\pm 1.0 , \pm 0.2) 1.2 \pm 0.6 (\pm 0.6 , $^{+0.2}_{-0.1}$)

15

Signal strength

20

150

155

m_{uu} [GeV]

160

— Total pdf

--- Bka. pdf

Signal pdf

$H \rightarrow Z\gamma$ analysis (ATLAS)

- Analysis targets all the production modes;
- BR($H \rightarrow Z\gamma$) = 1.54 × 10⁻³
- Final state with one photons and two same flavor opposite charge leptons (ℓ = e,μ)
- MVA techniques to categorise the events
- **Simultaneous likelihood fit** to all $m_{Z\gamma}$ distributions

 $\mu = 2.0 \pm 0.9 \text{ (stat)}^{+0.4}_{-0.3} \text{(syst)}$

Observed significance of 2.2σ

 \rightarrow upper limits on ($\sigma \times B$) of **3.6 x SM**



$H \rightarrow Z\gamma$ analysis (CMS)

- Analysis targets all the production modes;
- BR($H \rightarrow Z\gamma$) = 1.54 × 10⁻³
- Final state with one photons and two same flavor opposite charge leptons (ℓ = e,μ) and m_{ℓ+ℓ-}> 50 GeV
- Binned-maximum likelihood fit to all $m_{Z\gamma}$ distribution

 $\mu = 2.4 \pm {}^{+0.8}_{-0.9} \text{ (stat)} {}^{+0.3}_{-0.2} \text{(syst)}$

Observed (expected) significance of 2.7 (1.2) σ

 \rightarrow <u>upper limits on ($\sigma \times B$) of 4.1 x SM @95% CL</u>



CMS-PAG-HIG-19-014

$H \rightarrow cc$ analysis (ATLAS)

- BR($H \rightarrow cc$) = 3%
- Search in VH production mode
- Categorization depending on the decay of the vector boson
- Events with at least one c-jet + b-veto
- Final discriminant m_{cc}



 $\mu_{VH(cc)} = -9 \pm 10(\text{stat})^{+12}_{-11}(\text{syst}) \rightarrow \text{compatibility with SM: 83\%}$

- Observed VH(cc) limit of 26 x SM \rightarrow best limit on VH(cc) yet!
- Diboson cross-check measurements:
 - VZ(cc) significance of 2.6σ
 - VW(cq) significance of 3.8σ

 \rightarrow First measurement of VZ(cc) and VW(cq) using c-tagging!





