

Latest status of the Higgs measurement with the ATLAS detector

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Introduction

- A central feature of the SM is the existence of a spineless quantum field that permeates the universe and gives mass to massive elementary particles
- One of main goals of particle physics is testing the existence and properties of the Higgs boson
- Three types of interactions ("couplings") between Higgs and massive particles:
 - Gauge couplings to the mediator of the weak force, the W and Z bosons
 - The Yukawa interaction to fermions
 - "Self-couplings" of the Higgs to itself
- Experimental determination of these couplings
 - A powerful test of nature of Higgs
 - A possible portal to new physics (coupling structure)

Higgs to fermions: 2nd and 3rd generation **Quarks and leptons**

Higgs to bosons: **Discovery in 2012 Evidence of BHE EW** symmetry breaking

> Higgs to invisible: Higgs coupling to neutrinos or dark matter?

Higgs self-coupling: trilinear coupling is directly accessible through Higgs boson pair production



LHC and ATLAS detector



The world's largest and highestenergy particle collider.

The one of two general-purpose detectors at the LHC

A new schedule for the LHC and its successor



DEFINITION





SM Higgs boson production at LHC



- Distinct topology from many production modes •
- Rare/difficult production modes are important for beyond the SM (BSM) scenarios

• Accuracy from theory calculations: inclusive σ (ggF) calculated at N³LO in QCD and NLO in EW, with 5% uncertainty



Higgs boson decay

 The SM predicts 4MeV total width: far below detector resolution!



- Most sensitive decay modes: $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb
 - High invariant mass resolution in $\gamma\gamma$ and ZZ \rightarrow 4I
- More difficult channels: $\mu \mu$, $Z\gamma$, cc,...

Decay channel	SM BR [%] with mH = 125.09 GeV
H→bb	58.1
H→WW	21.5
Η→ττ	6.26
H→ZZ	2.64
$H{ ightarrow}\gamma\gamma$	0.23
H→µµ	0.022
$H \rightarrow Z\gamma$	0.154
H→cc	2.88
H→gg	8.18

Yellow Report 4





Discovery of SM-like Higgs boson



First observations of a new particle in the search for the Standard Model Higgs boson at the LHC





www.elsevier.com/locate/physletb





Nobel Prize Collider." 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron

Discovery opened a new era of particle physics: detailed measurements of the Higgs sector at the LHC



What we got from Run1 (partial)

- ► Spin-0
- Compatible with CP even

Eur. Phys. J. C 75 (2015) 476



Mass known 125.09 ± 0.24 GeV

Phys. Rev. Lett. 114, 191803



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Run2 data taking

- Run2 data-taking successfully finished in 2018
- 139 fb⁻¹ of 13 TeV proton-proton collision data collect thanks to the excellent LHC performance



• 139 fb⁻¹ of 13 TeV proton-proton collision data collected by ATLAS in total after data quality (DQ) requirements



Mean Number of Interactions per Crossing

ATLAS Run 2 Higgs boson property studies

Phys. Lett. B 784 (2018) 345

Phys. Rev. D 99 (2019) 072001





m_H measurements updated

observation of $H \rightarrow \tau \tau$ by a single experiment

- Just with partial Run2 statistics
- and various interpretations of the results

Phys. Lett. B 784 (2018) 173

observation of ttH

Phys. Lett. B 786 (2018) 59



observation of $H \rightarrow bb/VH$

• Our focus will be on the combined measurement of production cross-sections and decay rates of the Higgs boson,





Many hands (from Run2) make light work

- Rich pool of analyses performed by ATLAS
- Major improvements in performance and analysis methodologies (a lot of MVA)
- Analyses trying to provide more granular information on the Higgs

Decay channel	Target Production Modes
$H \to \gamma \gamma$	$ggF, VBF, WH, ZH, t\bar{t}H, tH$
$H \to ZZ^*$	$ggF, VBF, WH, ZH, t\bar{t}H(4\ell)$
	ttH
$II \rightarrow II/II/*$	ggF, VBF
$\Pi \rightarrow VV VV$	$t\bar{t}H$
$H \setminus \pi \pi$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{had}\tau_{had})$
$II \rightarrow II$	$t \overline{t} H$
	WH, ZH
$H \to b \overline{b}$	VBF
	$t \overline{t} H$
$H \to \mu \mu$	$ggF, VBF, VH, t\bar{t}H$
$H \to Z\gamma$	$ggF, VBF, VH, t\bar{t}H$
$H \rightarrow inv$	VBF

• Every measurement consists of one or more signal regions, designed to selected target Higgs production / decay

 $\mathcal{L} [\mathrm{fb}^{-1}]$

36.1

36.1

36.1

139

139

139

139

139

126

139

139

139

139

Higgs 2021 Conf. note:

Inclusive measurement:

- Cross sections (σ)
- Signal Strengths ($\mu = \sigma \cdot Br_{obs}$ / $\sigma \cdot Br^{SM}$)
- Coupling strength scale factor relative to SM (κ framework, $\kappa = 1$ for SM)

Differential measurements:

 Simplified Template Cross Sections STXS) framework



Combination

- Why combination?

 - We can obtain the best results from the combination of the individual.
- Construct combined likelihood model as multiplication of individual channel likelihoods
- Common parameters, e.g. signal cross-sections and **nuisance parameters** for the same systematic uncertainties, are shared between likelihood of individual channels
- Use profile likelihood ratio Λ as **test statistic**:

$$\Lambda(\boldsymbol{\alpha}) = \frac{L(\boldsymbol{\alpha}, \hat{\boldsymbol{\theta}}(\boldsymbol{\alpha}))}{L(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}})}$$

 1-D 68% confidence interval defined by -2lnΛ increasing (asymptotic limit) by I

• The individual analyses is probing different production processes, decays and also different kinematic regions



Inclusive signal strength

- $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03$ (stat.) ± 0.03 (exp.) ± 0.04 (sig. th.) ± 0.02 (bkg. th.)
- The uncertainties on $(\sigma \cdot Br.)^{SM}$ taken into account
- Comparable contribution from statistical, experimental, and signal/bkg. theory uncertainty components

-<mark>7</mark> –

- **10%** improvement in accuracy comparing to <u>ATLAS- CONF-2020-027</u>, 44% improvement comparing to Run1
- Consistent with the SM: $p_{SM} = 35\%$
- The precision is dominantly constrained by the syst. unc.

• Global signal strength (σ · Br.)^{obs.} / (σ · Br.)SM, assuming a common scaling for all production processes and decays





Production mode cross-sections (assuming the SM BRs)

- Precision improves by 2% 27% thanks to improvements in the individual analyses
- All major production modes observed
- Small correlation between measurements of different production modes



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• ggF cross-section now measured with precision of 7%, close to 5% uncertainty on the N³LO cross section prediction







Simplified template cross section (STXS)

- Extension of inclusive-style measurements
- Measure cross-section per production mode in different phase-space regions
 - Reduce model dependence and maximize sensitivity to BSM effects
 - Support kinematic-dependent interpretations (EFT etc.)
- Within each region, use the SM predicted signal templates to fit data









Parameter normalised to SM value 16

STXS results |



ATLAS-CONF-2021-053



10

I I



10 2 6 8 $\left(\right)$ Parameter normalised to SM value

- Most granular, simultaneous measurement (41 POIs: 37 STXS bins for all production modes + 4 BR. ratios)
 - For all bins stat. unc. dominating; only in few syst. unc. matters
 - Overall good compatibility with SM ($p_{SM} = 92\%$)
 - Statistical precision, in particular in most BSM sensitive regions is still limited: more data to help

STXS results ||



2

0

-2

ATLAS-CONF-2021-053

8

10

6

Parameter normalised to SM value

-8





- chosen as 1 TeV)
- New heavy internal particles are integrated out and are represented as vertices in the new effective theory
- gauge symmetries
- Interpretation performed in SMEFT framework

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \dots$$

- SMEFT in a nutshell:
 - \mathscr{L}_{SM} is dim-4, high orders only valid in the low-energy regime E $\ll \Lambda$
 - physics
 - Wilson coefficients $c \equiv 0$ for SM, deviations might indicate new physics

SMEFT

• Introduce new effective operators with free coefficients to capture new physics appearing beyond scale Λ (typically

• Most common: Warsaw-basis (JHEP 10 (2010) 085) forming a complete set of all dim-6 operators allowed by the SM

• terms with odd dimensionality violate lepton and/or baryon symmetry and are usually not considered for LHC





SMEFT Interpretation: operators

• $\Lambda = 1$ TeV and Warsaw-basis

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\square}$	$(H^{\dagger}H)\Box(H^{\dagger}H)$	c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}$
C _{HDD}	$\left(H^{\dagger}D^{\mu}H ight)^{*}\left(H^{\dagger}D_{\mu}H ight)$	c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}$
c_{HG}	$H^{\dagger}H G^{A}_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} E$
C_{HB}	$H^{\dagger}H\dot{B}_{\mu u}B^{\mu u}$	c'_{ll}	$(\bar{l}_p \gamma_\mu l_t) (\bar{l}_r \gamma^\mu l_t)$
\mathcal{C}_{HW}	$H^\dagger H W^I_{\mu u} W^{I\mu u}$	$c_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_t) (\bar{q}_r \gamma^\mu$
C_{HWB}	$H^{\dagger} au^{I}H^{I}W^{I}_{\mu u}B^{\mu u}$	$\mathcal{C}_{oldsymbol{q}oldsymbol{q}}^{(3)}$	$(ar{q}_p \gamma_\mu au^I q_r) (ar{q}_s \gamma^\mu$
C_{eH}	$(H^{\dagger}H)(\bar{l}_{p}e_{r}H)$	c_{qq}	$(ar{q}_p\gamma_\mu q_t)(ar{q}_r\gamma^\mu$
C_{uH}	$(H^{\dagger}H)(\bar{q}_{p}u_{r}\widetilde{H})$	$\mathcal{C}_{oldsymbol{q}oldsymbol{q}}^{(31)}$	$(\bar{q}_p \gamma_\mu \tau^I q_t) (\bar{q}_r \gamma^\mu$
C_{dH}	$(H^{\dagger}H)(ar{q}_{p}d_{r}\widetilde{H})$	C _{uu}	$(\bar{u}_p \gamma_\mu u_r) (\bar{u}_s \gamma^\mu$
$c_{Hl}^{\scriptscriptstyle (1)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\overline{l}_{p}\gamma^{\mu}l_{r})$	$c_{uu}^{(1)}$	$(\bar{u}_p \gamma_\mu u_t) (\bar{u}_r \gamma^\mu$
$c_{Hl}^{(3)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}H)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$	$c^{\scriptscriptstyle (1)}_{oldsymbol{q}oldsymbol{u}}$	$(\bar{q}_p \gamma_\mu q_t) (\bar{u}_r \gamma^\mu$
C_{He}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{e}_{p}\gamma^{\mu}e_{r})$	$c_{ud}^{\scriptscriptstyle (8)}$	$(\bar{u}_p \gamma_\mu T^A u_r) (\bar{d}_s \gamma^\mu$
$c_{Hq}^{(1)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r})$	$c_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r) (\bar{u}_s \gamma^\mu$
$c_{Hq}^{(3)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r})$	$c_{qd}^{\scriptscriptstyle (8)}$	$(\bar{q}_p \gamma_\mu T^A q_r) (\bar{d}_s \gamma^\mu$
c_{Hu}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{u}_{p}\gamma^{\mu}u_{r})$	c_W	$\epsilon^{IJK} W^{I u}_{\mu} W^{J ho}_{ u} W$
C_{Hd}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r})$	c_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{\nu}_{\nu}G^{\mu}_{\nu}G$

- Considering only EFT contributions from the interference between the SM and the dim-6 SMEFT operators
 - pure dim-6 BSM not considered: as being suppressed by a factor $1/\Lambda^4$, expected to be small



$$\begin{array}{l} H \to \tau \tau \\ H \to b b \\ H \to \gamma \gamma \\ H \to W V \end{array}$$

 $H \to ZZ$

Decay BR.



SMEFT Interpretation: measured parameters

- Due to large number of parameters with complicated correlation, Cannot separately constrain all parameters
- Decompose into subspaces, motivated by correlations and physics concerns
- Set parameters with weak eigenvalues to 0 and fit resulting parameter set



ATLAS Preliminary $\sqrt{s} = 13$ TeV, 139 fb⁻¹



SMEFT Interpretation: results

ATLAS-CONF-2021-053

• Parameter measurements



ATLAS-CONF-2020-053

Previous measurements

Compared with the previous results:

- Updated H $\rightarrow \tau \tau$ result, C_{eH} can now be constrained
- VBF and ttH with H \rightarrow bb: CdH and Ctop



Interpretation in the k framework

- Assumption: BSM physics modifies only the strength of the Higgs-boson coupling
- Introduce **coupling-strength modifiers** *k* to the leading-order contributions to each production and decay •

$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}$$

production 000000 H Modifiers on Cross-section and partial decay width for SM process j: 000000 decay • Higgs total decay width: Bi./u.: branching ratio of invisible/undetected BSM decays H -Λ

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}$$

where
$$\kappa_H^2(\kappa, B_{i.}, B_{u.}) = \kappa_H^2(\kappa, B_{i.}, B_{u.}) \Gamma_H^{SN}$$

 $\kappa_H^2(\kappa, B_{i.}, B_{u.}) = \frac{\sum_j B_j^{SM} \kappa_j^2}{(1 - B_{i.} - B_{u.})}$

BSM contributions may manifest themselves as $\kappa_{j} \neq 1$ or $B_{i,/u} \neq 0$.

ATLAS-CONF-2021-053

Generic parameterization

 κ_Z

 K_t

 K_{b}

 K_{τ}

 κ_{μ}

 K_{g}

 K_{γ}

 B_{i}

 $B_{u.}$

- Introduce coupling scale factors for the SM particles where there is sensitivity. Not resolving ggF and $H_{\gamma\gamma}$ effective vertices
- $\kappa z\gamma$: first time included as effective H $\rightarrow Z\gamma$ vertex in the Run2 combination
- Two scenarios for Higgs boson width
 - A. No BSM contributions $(B_{i} = B_{u} = 0)$ (left)
 - B. B_{i} and B_{u} free parameters and include VBF, $H \rightarrow$ invisible to constraint $B_{i.}, \kappa_{V} \leq 1$ to constrain B_{u} (assumed to be positive) (right)
- Using tH and $gg \rightarrow ZH$ process to constrain relative sign of t-H coupling κ_t w.r.t. κ_w and κ_z excluding the negative κ t: 4.3 σ in scenario (A).







Coupling modifier vs. particle mass

- Assume no BSM contribution in loop-induced processes (ggF, $H \rightarrow_{\gamma\gamma}$ etc.) or total width
- Probe all the coupling strengths for which there is sensitivity

 Best fitted values: 	Parameter	Result
	κ _Z	$0.99 \pm$
improved by 9%~44%		1 () 2 .
thanks to newly	κ_W	$1.03 \pm$
updated updated	КЪ	$0.88 \pm$
$H \rightarrow WW$,		
(VBF, VH, ttH) bb	K _t	$0.92 \pm$
and H $\rightarrow \tau \tau$	K_{T}	$0.92 \pm$
comparing to		
<u>ATLAS- CONF-2020-027</u>	κ_{μ}	1.07 _

 Good agreement with the SM within uncertainties across 3 orders of magnitude in particle mass!



Not enough!

- Coupling to Vector Bosons
- Coupling to 3rd-gen. quarks and lepton
- Coupling to 2nd-gen. lepton
- It is also accessible to 2nd-gen. quark, c quark as well:
 - Targeting VH, categories based on # of leptons and (c-)jet
 - Challenging: high QCD background / modelling / c-tag
 - μ < 26(31) x SM obs.(exp.) @ 95% CL and $|\kappa_c|$ <8.5
 - Included in "ATLAS Higgs combination nature paper" for 10th anniversary for the Higgs discovery
 - Submitted to Nature, coming soon!

One may wonder how about Higgs self-coupling?



Higgs self-couplings

- Higgs self-coupling is also crucial
 - Probe of the shape of the Higgs potential

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 \qquad \lambda_{hhh} = \frac{m_h^2}{2v^2}$$
$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4 \qquad \kappa_\lambda = \kappa_3 = \frac{1}{4} \frac{m_h^2}{2v^2} h^4 \qquad \kappa_\lambda = \kappa_\lambda = \frac{1}{4} \frac{m_h^2}{2v^2} h^4 \qquad \kappa_\lambda = \frac{1}{4} \frac{m_h^2}{2v^2$$

- Standard Model (SM) prediction: the Higgs boson self coupling $\lambda = -0.13$
- However, the new physics can alter λ , thus measuring κ_{λ} is important for both studying the Higgs boson and probing physics Beyond the SM (BSM)
- Single Higgs prod. / decay: self-coupling presents in higher order diagram



• Higgs couplings with the elemental particles (μ , τ , b, W, Z, t), compatible with SM prediction, as shown previously

λ_{HHH} N^{SM}_{HHH}









κ_{λ} in Di-Higgs production

• Di-Higgs production provides a direct access to λ



channels to maximize the sensitivity

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

• Around 4k HH events expected to be produced during the Run 2, complementarity and combination of various decay

Measurement performed by recent ATLAS Di-Higgs analysis:

- **HH→bb**γγ : <u>ATLAS-CONF-2021-016</u>
- $HH \rightarrow bb\tau\tau$: <u>ATLAS-CONF-2021-030</u>

And:

Combination: <u>ATLAS-CONF-2021-052</u>



- 0.26% of total HH BR, clean $H \rightarrow \gamma \gamma$ signature for the trigger, selection and excellent resolution
- 2 photons with E_T > 35 (25) GeV; 2b- jets (DL1r, 77%)
- 105 GeV < $m_{\gamma\gamma}$ < 160 GeV \rightarrow final discriminant for fitting simultaneously in 4 categories:



Obs. (exp.) upper limits on σ_{HH} are set as 4.1 (5.5) times the SM prediction at 95% CL

 $5 \times$ improvement comparing with previous result ($25 \times$ SM), $3 \times$ due to analysis improvement

$HH \rightarrow bb\gamma\gamma$

ATLAS-CONF-2021-016

• split by $m^*_{bb\gamma\gamma}$ (= $m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV) at 350 GeV, and then further split by BDT into tight and loose



Obs. (exp.) constraint on κ_{λ} is $-1.5 \le \kappa_{\lambda} \le 6.7$ ($-2.4 \le \kappa_{\lambda} \le 7.7$) at 95%CL Previous limits (36.1 fb⁻¹ analysis): $-8 < \kappa_{\lambda} < 13$





- 7.4% of the total HH branching ratio (BR): relatively clean signature and low background
- Signal signature: two b-tagged jets (DL1r tagger, 77%) and $\tau_{had} \tau_{had}$ / $\tau_{lep} \tau_{had}$ with opposite charge
- Multivariate (MVA) method used for signal and background separation



Observed (expected) upper limits on the SM HH production cross-section are set as 4.7(3.9) times the SM prediction at 95% CL

$HH \rightarrow bb\tau\tau$





κ_{λ} Measurement from the HH combination

- - $bb_{\gamma\gamma}$ outperforms at high κ_{λ} values due to high acceptance



Obs. (exp.) upper limits on σ_{HH} are set as 3.1 (3.1) times SM prediction

• Performed statistical combination for different HH analyses to maximize sensitivity to SM and BSM HH production • including $bb\tau\tau$ and $bb\gamma$: $bb\tau\tau$ has better sensitivity at around $\kappa_{\lambda} = 1$ due to more boosted signal and higher BR, while ATLAS-CONF-2021-052

• Systematics correlated where appropriate (like luminosity, flavor tagging, signal theory uncertainties, etc)



Obs. (exp.) constraint on κ_{λ} is $-1.0 \le \kappa_{\lambda} \le 6.6(-1.2 \le \kappa_{\lambda} \le 7.2)$

The best constraints on HH signal strength and κ_{λ} up to date!





Conclusions and outlook

- Combination of analyses based on up to 139 fb⁻¹ of Run 2 data improves precision **ATLAS-CONF-2021-053**
- All measurements in good agreement with the SM within current uncertainty, but still space for new physics.
- The latest HH searches with $bb\tau\tau$ and $bb\gamma\gamma$ presented, as well as the HH combination ATLAS-CONF-2021-052
- Significant improvement on the results comparing with the previous publications: the best constraints on HH signal strength and κ_{λ} is shown!
- More analyses and combinations in progress using full Run-2 statistics!
 - Full Run-2 and Run-3 will amount to 350-400 fb-1
 - Improvements of analysis methods and treatment of systematics
- The HL-LHC could dramatically expand our Higgs physics reach
 - More challenging environment but 2-4 % precision of the couplings.



Backup and bonus

Reference

- $\sqrt{s} = 13$ TeV collected with the ATLAS experiment <u>ATLAS-CONF-2021-053</u>
- Hyy: <u>ATLAS-CONF-2020-026</u>
- HZZ: <u>Eur. Phys. J. C 80 (2020) 957</u>
- ttHWW/ZZ/tautau: <u>Phys. Rev. D 97 (2018) 072003</u>
- HWW: <u>ATLAS-CONF-2021-014</u>
- $H \rightarrow \tau \tau$: ATLAS-CONF-2021-044
- VHbb: Eur. Phys. J. C 81 (2021) 178 Phys. Lett. B 816 (2021) 136204 ATLAS-CONF-2021-051
- VBFbb: <u>Eur. Phys. J. C. 81 (2021) 537</u>
- ttHbb: <u>CERN-EP-2021-202</u>
- Hmumu: <u>Phys. Lett. B 812 (2021) 135980</u>
- HZy: <u>Phys. Lett. B 809 (2020) 135754</u>
- VBFHinvisible: ATLAS-CONF-2020-008

• Combined measurements of Higgs boson production and decay using up to 139-1 of proton - proton collision data at







- Large background, but excellent sensitivity ensured by very good photon efficiency and resolution
- Analysis categories designed to isolate out events from different production modes
- Also explores different kinematic regions within production modes

$H \rightarrow \gamma \gamma (139 \text{ fb}^{-1})$



ATLAS-CONF-2020-026

100 🛞



$H \rightarrow ZZ \rightarrow 4I (I=e, \mu) (139 \text{ fb}^{-1})$



- Very clean channel with high S/B
- Neural networks (NN) used to further suppress bkg. and increase sensitivity to different production modes



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



$H \rightarrow WW \rightarrow ev\mu v (139 \text{ fb}^{-1})$

Events / bin

 10^{3}

10

/ Pred.

Data

Bkg.) / Bkg

(Tot.

- Vetoing events with jets tagged as from bquark in signal region (suppress ttbar bkg.)
- Dedicated control regions for main background: WW, top quark, $Z/\gamma^* \rightarrow \tau \tau$
- Train DNN to separate VBF from ggF and other bkg in VBF enriched region





- Exploit three di- τ decay channels ($\tau e \tau \mu$, $\tau lep \tau had$, $\tau had \tau had$)
- Analysis targeting VBF and boosted ggF signal events to suppress the Z $\rightarrow \tau \tau$ backgrounds



$H \rightarrow \tau \tau (139 \text{ fb}^{-1})$



VH, $H \rightarrow bb (139 \text{ fb}^{-1})$

- Leading analysis for observation of $H \rightarrow bb$ and VH at LHC
- Exploit Resolved (pTV< 400 GeV) and the Merged regimes (pTV> 400 GeV) •





ttH channels (36.1 - 139 fb-1)

- ttH multi-lepton (36 fb⁻¹): targeting WW, $\tau \tau$, and ZZ decay modes + ttbar with \geq 1 leptonic W decay
- ttH, H \rightarrow bb (139 fb⁻¹): targeting ttbar with \geq 1 leptonic W decay. Divide into single lepton and dilepton regions



• ttH, $H \rightarrow \gamma \gamma$ and ttH, $H \rightarrow ZZ \rightarrow 4I$ analyses included as part of full $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4I$ analyses introduced before



$VBF, H \rightarrow bb (126 \text{ fb}^{-1})$

- VBF, $H \rightarrow bb$: exploit VBF topology for trigger
- ANN used to enhance the signal background separation



• Forward and central channels: presence or absence of a high pT forward (3.2<| η |<4.5) jet in the event (VBF vs ggF)



Eur. Phys. J. C. 81 (2021) 537



- $H \rightarrow \mu \mu$: bump hunting on the large tail of Drell-Yan bkg.



$H \rightarrow \mu \mu (139 \text{ fb}^{-1})$

Phys. Lett. B 812 (2021) 135980

- ttH: dileptonic or semileptonic decay of the ttbar
 - \geq 1 lepton in addition to the opposite sign muon pair and at least one b-tagged jet •
- VH:
 - Not selected in ttH
 - $\bullet \ge 1$ isolated lepton in addition to the opposite sign muon pair
 - no b-tagged jet
- ggF and VBF:
 - Not selected in the VH and ttH
 - Classified into 0-, 1-, 2-jet categories
 - 2-jet: OVBF BDT classifier used to define 4 regions
 - The remaining classified into 4 regions based on 0- / 1- / 2- OggF BDT respectively

$H \rightarrow \mu \mu (139 \text{ fb}^{-1})$

- Very rare decay
- The observed data are consistent with the expected background with a p-value of 1.3%
- First time included into the Run2 combination

$H \rightarrow Z\gamma (139 \text{ fb}^{-1})$

• An upper limit @ 95% C.L. on the production cross-section times the branching ratio is set at 3.6 (2.6 exp.) times SM

H-invisible searches

- $H \rightarrow dark matter)$
- selection

Strong Z+jets background

electroweak VBF Z+jet background

electroweak diboson background

• The SM expectation for H \rightarrow inv. BR is tiny (0.1% from H \rightarrow ZZ \rightarrow 4 ν), but the BR can be enhanced with BSM physics (e.g.

• Search for missing transverse momentum signature in VBF topology, small contribution form ggF and VH after

ATLAS-CONF-2020-008

Production cross-section in each decay channel

- Good compatibility among production modes and also with the SM
- Anti-correlation most notable for ggF vs. VBF, and VV vs. $\tau \tau$ in ttH multi-lepton analysis

ATLAS Preliminary

 $\sqrt{s} = 13 \text{ TeV}, 36.1 - 139 \text{ fb}^{-1}$ $m_{\mu} = 125.09 \text{ GeV}, \text{ Iy } \text{ I} < 2.5$

			γ	γ	Λ		Z	<u>Z</u> *						τ > Ω	τ	1_	0	b 5	b 2		μ	μ		
		ggF	VBF	НЛ	tīH+tH	99F	VBF	ΗΛ	tīH+tH	ggF	VBF	tīH+tH	ggF	VBF	ΗΛ	tīH+tH	НМ	ΗZ	tīH+tH	ggF+VBF	ggF+ <i>t</i> T H	VBF+VH		-1
n	VBF+VH	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	-0.30	1		_1
η	ggF+t T H	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.01	0.00	-0.02	0.00	0.00	-0.01	-0.01	0.01	0.00	0.00	0.00	0.00	0.00	1	-0.30		-0.0
	ggF+VBF	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00		<u> </u>
$b\bar{t}$	t₹H+tH	0.01	0.01	0.00	0.02	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.02	0.01	0.00	1	0.00	0.00	0.00		-0.0
10	ZH	0.00	0.01	0.03	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	1	0.00	0.00	0.00	0.00		06
	WH	 0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	1	0.01	0.01	0.00	0.00	0.00		-0.4
	t T H+tH	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.01	0.01	-0.32	-0.02	0.01	-0.02	1	0.00	0.00	0.02	0.00	0.00	0.00		0 1
11		0.00	0.23	0.01	0.00	-0.00	0.04	0.00	0.00	-0.02	0.10	0.00	-0.27	0.08	0.08	-0.02	0.00	0.00	0.00	0.01	0.01	0.02		-0.2
	yyı VBE	0.08	-0.02	_0.02	0.00	0.04	0.01	0.00	0.00	0.04	0.03	0.01	_0 27	-0.27	-0.33	-0.02	0.01	0.00	0.00	0.00	-0.01	0.00		0.0
	t₹H+tH	0.01	0.01	0.01	-0.01	0.01	0.00	0.02	-0.11	0.02	0.01	1	0.01	0.00	0.01	-0.32	0.01	0.01	0.00	0.00	0.00	0.00		0
M	VBF	0.02	0.13	0.01	0.00	0.01	0.04	0.01	0.00	-0.10	1	0.01	0.03	0.10	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01		0
٨*	ggF	0.09	0.00	0.01	0.00	0.10	0.00	-0.03	0.00	1	-0.10	0.02	0.04	0.00	-0.02	0.01	0.01	0.01	0.01	0.01	-0.02	0.01		0.2
	t₹H+tH	0.00	0.00	0.00	0.01	0.02	0.00	-0.18	1	0.00	0.00	-0.11	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00		~ ~
Ŋ	VH	0.00	0.01	0.02	0.00	-0.26	-0.04	1	-0.18	-0.03	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	_	0.4
*N	VBF	0.01	0.05	0.01	0.00	-0.22	1	-0.04	0.00	0.00	0.04	0.00	0.01	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01		
	ggF	0.05	0.00	0.00	0.00	1	-0.22	-0.26	0.02	0.10	0.01	0.01	0.04	0.00	-0.01	0.00	0.01	0.01	0.01	0.00	-0.01	0.00		0.6
	t₹H+tH	0.06	0.04	-0.04	1	0.00	0.00	0.00	0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.00		
7	VH	-0.06	0.01	1	-0.04	0.00	0.01	0.02	0.00	0.01	0.01	0.01	0.02	-0.01	0.01	0.00	0.01	0.03	0.00	0.00	0.00	0.00		0.8 5
	VBF	-0.12	1	0.01	0.04	0.00	0.05	0.01	0.00	0.00	0.13	0.01	-0.02	0.23	0.02	0.00	0.01	0.01	0.01	0.01	-0.01	0.02		
	ggF	1	-0.12	-0.06	0.06	0.05	0.01	0.00	0.00	0.09	0.02	0.01	0.08	-0.03	0.00	0.00	0.01	0.00	0.01	0.01	-0.01	0.00		$ ^{1}$ <
																,,						н		

ATLAS Preliminary $\sqrt{s} = 13$ TeV, 36.1 - 139 fb⁻¹ Total Stat. Syst. $m_{H} = 125.09 \text{ GeV}$ $p_{_{SM}} = 79\%$ SM Stat. Total Syst. + 0.07 + 0.08 ggF γγ 1.02 - 0.08 - 0.07 -0.11 + 0.10 + 0.04 ggF ZZ 0.95 -0.11 - 0.10 - 0.03 + 0.06 + 0.12 ggF WW 1.13 - 0.06 - 0.10 + 0.28 + 0.15 + 0.23 ggF ττ 0.87 - 0.20 - 0.25 - 0.15 + 0.77 + 0.91 + 0.49 ggF+ttH μμ 0.52 - 0.38 -0.88 - 0.79 + 0.27 + 0.21 + 0.17 VBF γγ 1.47 - 0.20 -0.24 - 0.14 + 0.50 + 0.11 VBF ZZ 1.31 -0.42 - 0.42 - 0.06 + 0.15 + 0.19 + 0.11 **VBF WW** 1.09 -0.17 - 0.14 - 0.10 + 0.20 + 0.14 + 0.15 $\mathsf{VBF}\ \tau\tau$ 0.99 - 0.14 - 0.12 -0.18 + 0.31 + 0.21 VBF+ggF bb + 0.38 0.98 -0.36 - 0.33 - 0.15 + 1.34 + 1.32 + 0.20 VBF+VH μμ 2.33 - 1.26 - 1.24 - 0.23 + 0.32 + 0.33 + 0.10 **VH** γγ 1.33 - 0.30 - 0.31 - 0.08 + 0.24 + 1.14 + 1.17 VH ZZ 1.51 - 0.94 - 0.93 - 0.16 + 0.59 + 0.49 + 0.33 0.98 VH ττ -0.57 - 0.49 - 0.29 + 0.28 + 0.19 + 0.20 WH bb 1.04 - 0.19 - 0.18 - 0.26 + 0.17 + 0.17 + 0.24 ZH bb 1.00 - 0.14 -0.22 - 0.17 + 0.27 + 0.26 + 0.08 ttH+tH γγ 0.93 - 0.25 - 0.24 - 0.06 + 0.44 + 0.48 ttH+tH WW 1.64 -0.43 ' - 0.43 - 0.61 + 0.37 + 1.69 + 1.65 ttH+tH ZZ 1.69 (-1.09 , -0.16) - 1.10 + 0.86 + 0.66 + 0.54 1.39 ttH+tH ττ -0.62 ' -0.44 -0.76 + 0.28 + 0.34 + 0.20 0.35 ttH+tH bb - 0.33 **(** - 0.20 , - 0.27 -2 2 0 8 6 4

 $\sigma \times B$ normalised to SM

Production and decays ratios

ocess		Observed	J	Uncertainty	r	SM predictio
H < 2.5			Total	Stat.	Syst.	
$\frac{dZ}{gF}$	[pb]	1.16	± 0.11	± 0.10	± 0.04	1.18 ± 0.07
σ_{BF}/σ_{ggF}		0.091	$+ 0.012 \\ - 0.014$	± 0.009	$+ 0.009 \\ - 0.010$	0.079 ± 0.005
$_{VH}/\sigma_{ggF}$		0.042	$+ 0.008 \\ - 0.010$	$+ 0.007 \\- 0.008$	$+ 0.004 \\ - 0.005$	0.0269 ± 0.001
σ_{H}/σ_{ggF}		0.019	$+ 0.005 \\- 0.006$	$+ 0.004 \\- 0.005$	$+ 0.003 \\ - 0.004$	0.0178 ± 0.001
$\sigma_{H+tH}/\sigma_{ggF}$		0.0134	$+ 0.0027 \\- 0.0029$	$+ 0.0021 \\- 0.0022$	$+ 0.0016 \\ - 0.0018$	0.0131 ± 0.001
$_{\prime\gamma}/B_{ZZ}$		0.092	$+ 0.010 \\ - 0.012$	$+ 0.008 \\ - 0.011$	$+ 0.005 \\ - 0.004$	0.086 ± 0.001
$_{VW}/B_{ZZ}$		8.8	$+ 1.0 \\ - 1.2$	$+ 0.8 \\ - 0.9$	$+ 0.6 \\ - 0.7$	8.15 $\pm < 0.$
T_{τ}/B_{ZZ}		2.04	$+ 0.29 \\ - 0.34$	$+ 0.23 \\ - 0.25$	$+ 0.19 \\ - 0.21$	2.369 ± 0.017
$_b/B_{ZZ}$		16.5	$+ 3.5 \\ - 4.0$	$+ 2.7 \\ - 3.4$	± 2.2	22.0 ± 0.5
$_{\mu\mu}/B_{ZZ}$		0.009	± 0.005	± 0.004	$+ 0.001 \\ - 0.002$	$0.0082 \pm < 0.$
$_{Z\gamma}/B_{ZZ}$		0.11	$+ 0.05 \\ - 0.06$	± 0.05	± 0.02	0.0584 ± 0.002

STXS correlation matrix

0-jet, p_{τ}^{H} < 10 GeV	1 0.02 0.07 0.05 0.11 0.02 0.03 0.01 0.08 0.01 0.10 0.04 0.05 0.03
0-jet, 10 ≤ <i>p</i> ^{<i>H</i>} _{<i>T</i>} < 200 GeV	0.02 1 -0.18 0.18 0.28 -0.07 0.12 -0.04 0.14 0.02 0.28 0.14 0.11 -0.0
1-jet, $p_{T}^{H} < 60 \text{ GeV}$	0.07 <mark>-0.18 1 0.26 0.21 -0.19</mark> -0.01 0.02 0.03 0.02 0.11 0.08 0.04 <mark>-0.3</mark>
$1 \text{-jet}, 120 \le p_T^H \le 200 \text{ GeV}$	0.05 0.18 0.26 1 0.44 -0.02-0.06-0.02 0.04 0.02 0.23 0.17 0.07 <mark>-0.6</mark>
$1 \text{-jet, } 60 \le p_T^n < 120 \text{ GeV}$	0.11 0.28 0.21 0.44 1 -0.01 0.06 <mark>-0.22</mark> 0.07 0.03 0.29 0.19 0.09 <mark>-0.5</mark>
$\Xi \ge 2 \text{-jet}, \ m_{jj} < 350 \text{ GeV}, \ p_{\tau}^{-} < 60 \text{ GeV}$	0.02 -0.07-0.19-0.02 -0.01 1 0.07 -0.01-0.06 0.00 0.04 0.04 0.02 -0.0
$p_{T} = 2^{-1} \text{jet} m_{jj} < 350 \text{ GeV}, 120 \le p_{T}^{+} < 200 \text{ GeV}$	0.03 0.12 -0.01-0.06 0.06 0.07 1 0.16 -0.01 0.05 0.25 0.20 0.11 0.04
O_{3} x ≥ 2-jet, m_{jj} < 350 GeV, 120 ≤ p_{T}^{+} < 120 GeV	0.01 -0.04 0.02 -0.02 -0.22 -0.01 0.16 1 -0.05 0.03 0.13 0.10 0.05 0.02
\geq 2-jel, $m_{jj} \geq$ 350 GeV, $p_T^{tl} < 200$ GeV	
22 -jet, $m_{jj} = 300$ GeV, $p_T = 200^{-1}$ GeV $200 < p^{H} < 300$ GeV	
$300 \le p_T^H \le 450 \text{ GeV}$	
$p_T^H > 450 \text{ GeV}$	
<pre>></pre>	0.03 -0.02 <mark>-0.35-0.60-0.58</mark> -0.03 0.04 0.02 0.00 -0.06-0.23-0.20-0.05
≥ 2-jet, <i>m_{ii}</i> < 350 GeV, <i>VH</i> veto	0.07 0.08 0.04 0.04 0.06 -0.23-0.53-0.40-0.02-0.06-0.27-0.21-0.10*0.00
≥ 2-jet, 350 ≤ <i>m_{ii}</i> < 700 GeV, <i>p</i> ^{<i>H</i>} < 200 GeV	0.02 0.11 0.02 0.07 0.10 0.01 0.07 0.02 -0.55 0.00 0.07 0.04 0.02 -0.0
\breve{F} \geq 2-jet, $m_{ii}^{'} \geq$ 350 GeV, $p_{\tau}^{H} \geq$ 200 GeV	0.19 0.26 0.05 0.09 0.15 -0.02 0.02 -0.04 0.12 0.01 0.03 -0.01 0.03 0.03
$\int_{-\infty}^{\infty} \sum_{i=1}^{n} 2^{-i} jet, m_{ii} < 350 \text{ GeV}, VH \text{ topo}$	0.08 0.09 0.02 0.05 0.06 -0.07-0.28-0.18 0.09 0.00 -0.09-0.07 0.00 0.02
$β$ ≥ 2-jet, 700 ≤ m_{jj} < 1000 GeV, p_{τ}^{H} < 200 GeV	0.07 0.10 0.04 0.08 0.11 0.00 -0.02-0.03 0.09 -0.53 0.06 0.03 0.02 -0.0
≥ 2-jet, 1000 ≤ $m_{jj}^{'}$ < 1500 GeV, p_{T}^{H} < 200 GeV	0.12 0.20 0.05 0.11 0.14 -0.01 0.01 -0.02 0.09 <mark>-0.28</mark> 0.12 0.06 0.04 -0.0
≥ 2-jet, m_{jj} ≥ 1500 GeV, p_T^H < 200 GeV	0.15 0.20 0.06 0.08 0.14 0.00 0.00 -0.02 0.12 -0.20 0.12 0.06 0.05 -0.0
p_{τ}^{ν} < 75 GeV	0.09 0.12 0.01 0.04 0.07 0.00 0.03 0.00 0.07 0.02 0.08 0.04 0.04 0.02
$\frac{2}{T} \text{is} \qquad 75 \le p_T^V < 150 \text{ GeV}$	0.07 0.11 0.02 0.03 0.06 0.00 0.03 0.00 0.06 0.01 0.08 0.04 0.04 0.0
$\uparrow \square \qquad 150 \le p_T^V < 250 \text{ GeV}$	0.10 0.15 0.03 0.05 0.09 0.00 0.03 0.00 0.08 0.00 0.07 0.03 0.04 0.02
$g \times 250 \le p_T^{\nu} < 400 \text{GeV}$	0.11 0.15 0.02 0.05 0.08 0.00 0.03 0.00 0.07 0.01 0.07 0.03 0.04 0.02
$p_T^{\nu} \ge 400 \text{ GeV}$	0.08 0.11 0.02 0.04 0.06 0.00 0.02 0.00 0.05 0.00 0.05 0.02 0.03 0.02
$p_{\tau}^{*} < 150 \text{ GeV}$	0.01 0.01 0.00 -0.01 0.00 0.00 0.01 0.00 0.01 0.02 0.01 0.01
$p_{T} = 250 \text{ GeV}$	0.11 0.16 0.03 0.06 0.09 -0.01 0.03 -0.01 0.08 0.01 0.08 0.04 0.04 0.04
$\mathcal{G} \times \mathcal{G} \times $	
$p_T \ge 400 \text{ GeV}$	
ρ ^H < 60 GeV	
$60 \le p^H \le 120 \text{ GeV}$	
120 $\leq p_{\tau}^{H} < 200 \text{ GeV}$	0.07 0.11 0.02 0.03 0.06 0.00 0.02 0.01 0.06 0.03 0.07 0.06 0.05 0.02
$= 60 \le p_{\tau}^{H} < 120 \text{ GeV}$	0.08 0.11 0.02 0.03 0.06 0.01 0.04 0.01 0.07 0.02 0.07 0.04 0.03 0.02
$+$ 120 ≤ p_{τ}^{H} < 200 GeV	0.02 0.03 0.00 0.01 0.02 0.00 0.01 0.00 0.02 0.01 0.03 -0.02 0.02 0.0
p _T ^H ≥ 200 GeV	0.01 0.01 0.00 0.00 0.01 0.00 0.00 0.00
$B_{\gamma\gamma}/B_{ZZ}$	- <mark>0.34-0.48</mark> -0.08-0.14 <mark>-0.26</mark> 0.00 -0.14 0.00 <mark>-0.23</mark> -0.04 <mark>-0.33</mark> -0.13-0.15-0.0
$B_{b\overline{b}}/B_{ZZ}$	- <mark>0.14-0.21</mark> -0.03-0.07-0.12 0.01 -0.04 0.01 -0.10-0.01-0.10-0.04-0.05-0.0
B_{WW}/B_{ZZ}	- <mark>-0.35-0.47</mark> -0.03-0.09 <mark>-0.23</mark> 0.00 -0.07-0.01 <mark>-0.14</mark> 0.00 <mark>-0.23</mark> -0.12-0.10-0.0
$B_{\tau\tau}/B_{ZZ}$	<mark>-0.23-0.32</mark> -0.05 <mark>-0.16-0.20</mark> 0.03 -0.11 0.01 -0.19-0.01 <mark>-0.28</mark> -0.17-0.11-0.0
	200 200 200 200 200 200 200 200 200 200
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	gg→H
	$\times B_{ZZ^*}$

qq→Hqq qq→HIv gg/qq→Hll ttH $\times B_{ZZ^*}$ $\times B_{ZZ^*}$ $\times B_{ZZ^*}$ $\times B_{ZZ^{\star}}$

kappa parametrization

Production	Loopa	Main	Effective	Posslund modifier
cross section	Loops	interference	modifier	Resolved modifier
$\sigma(\text{ggF})$	\checkmark	t–b	κ_g^2	$1.040\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b - 0.005\kappa_t\kappa_c$
$\sigma({ m VBF})$	-	-	-	$0.733 \kappa_W^2 + 0.267 \kappa_Z^2$
$\sigma(qq/qg \to ZH)$	_	-	-	κ_Z^2
$\sigma(gg\to ZH)$	\checkmark	t–Z	$\kappa_{(ggZH)}$	$2.456 \kappa_Z^2 + 0.456 \kappa_t^2 - 1.903 \kappa_Z \kappa_t \\ - 0.011 \kappa_Z \kappa_b + 0.003 \kappa_t \kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909 \kappa_t^2 + 2.310 \kappa_W^2 - 4.220 \kappa_t \kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633 \kappa_t^2 + 3.578 \kappa_W^2 - 5.211 \kappa_t \kappa_W$
$\sigma(H)$	-	-	-	κ_b^2
Partial decay wid	th			
Γ^{bb}	_	-	_	κ_b^2
Γ^{WW}	_	-	-	κ_W^2
Γ^{gg}	\checkmark	t–b	κ_g^2	$1.111 \kappa_t^2 + 0.012 \kappa_b^2 - 0.123 \kappa_t \kappa_b$
$\Gamma^{ au au}$	_	_	-	$\kappa_{ au}^2$
Γ^{ZZ}	_	-	-	κ_Z^2
Γ^{cc}	_	_	-	$\kappa_c^2 \ (=\kappa_t^2)$
				$1.589 \kappa_W^2 + 0.072 \kappa_t^2 - 0.674 \kappa_W \kappa_t$
$\Gamma^{\gamma\gamma}$	\checkmark	t–W	κ_γ^2	$+0.009 \kappa_W \kappa_\tau + 0.008 \kappa_W \kappa_b$
			,	$-0.002\kappa_t\kappa_b - 0.002\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	\checkmark	t–W	$\kappa^2_{(Z\gamma)}$	$1.118 \kappa_W^2 - 0.125 \kappa_W \kappa_t + 0.004 \kappa_t^2 + 0.003 \kappa_W \kappa_b$
Γ^{ss}	_	_	-	$\kappa_s^2 \ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	_	κ_{μ}^2
Total width $(B_{i.} =$	$= B_{\rm u.} = 0$	0)		
				$0.581 \kappa_b^2 + 0.215 \kappa_W^2 + 0.082 \kappa_q^2$

 Γ_H

$\kappa_{H}^{2} + 0.063 \kappa_{\tau}^{2} + 0.026 \kappa_{Z}^{2} + 0.029 \kappa_{c}^{2} + 0.0023 \kappa_{\gamma}^{2} + 0.0015 \kappa_{(Z\gamma)}^{2} + 0.0004 \kappa_{s}^{2} + 0.00022 \kappa_{\mu}^{2}$		$0.581 \kappa_b^2 + 0.215 \kappa_W^2 + 0.082 \kappa_g^2$	
$\kappa_{H} + 0.0023 \kappa_{\gamma}^{2} + 0.0015 \kappa_{(Z\gamma)}^{2} + 0.0004 \kappa_{s}^{2} + 0.00022 \kappa_{\mu}^{2}$	2	$+0.063 \kappa_{ au}^2 + 0.026 \kappa_Z^2 + 0.029 \kappa_c^2$	
$+0.0004 \kappa_s^2 + 0.00022 \kappa_u^2$	κ_H	$+0.0023 \kappa_{\gamma}^2 + 0.0015 \kappa_{(Z\gamma)}^2$	
- μ		$+0.0004 \kappa_s^2 + 0.00022 \kappa_\mu^2$	

- Unify coupling for all the fermions and vector-bosons.
- Assume no BSM physics in loop-induced processes or total width
- Best fit values: •

KV VS. KF

- Focus on ggF and $H_{\gamma\gamma}$ interactions, with other coupling strengths fixed to the SM
- Loop-induced in the SM, sensitive to new physics
- Can also determine $B_{inv.}$ and $B_{undet.}$ contributions at the same time by including H \rightarrow inv. searches

Generic parameterization

Parameter	(a) $B_{i.} = B_{u.} =$
κ _Z	0.99 ± 0.06
κ _W	1.06 ± 0.06
КЪ	0.87 ± 0.11
K _t	0.92 ± 0.10
κ _μ	$1.07 \ ^{+}_{-} \ ^{0.25}_{0.30}$
K_{T}	0.92 ± 0.07
κ_{γ}	1.04 ± 0.06
$\kappa_{Z\gamma}$	$1.37 \begin{array}{c} + \ 0.31 \\ - \ 0.37 \end{array}$
Kg	$0.92 \ {}^{+\ 0.07}_{-\ 0.06}$
$B_{i.}$	_
$B_{\rm u.}$	_

(b) $B_{i.}$ free, $B_{u.} \ge 0$, $\kappa_{W,Z} \le 1$ = 0 $0.96 \begin{array}{c} + \ 0.04 \\ - \ 0.05 \end{array}$ 1.00 + 0.00 - 0.03 0.81 ± 0.08 0.90 ± 0.10 1.03 + 0.23 - 0.29 0.88 ± 0.06 1.00 ± 0.05 $1.33 \begin{array}{c} + \ 0.29 \\ - \ 0.35 \end{array}$ $0.89 \ ^{+ \ 0.07}_{- \ 0.06}$ < 0.09 at 95% CL < 0.16 at 95% CL

Expressed as ratios of scale factors

No need for the assumption on the total decay width modification

- physics in ggF process
- $\lambda \mu \tau = \kappa \mu / \kappa \tau$: deviation of Higgs Yukawa couplings to the second/third generation fermions

Parameter	Definition in terms of κ modifiers	Result			
K _{gZ}	<i>κ_gκ</i> _Z / <i>κ</i> _H	0.98 ± 0.05			
λ_{tg}	κ_t/κ_g	1.00 ± 0.11			
λ_{Zg}	κ_Z/κ_g	1.07 ± 0.09			
λ_{WZ}	κ_W/κ_Z	1.07 ± 0.06			
$\lambda_{\gamma Z}$	κ_{γ}/κ_Z	1.05 ± 0.06			
$\lambda_{Z\gamma Z}$	$\kappa_{Z\gamma}/\kappa_Z$	$1.39 \begin{array}{c} + 0.31 \\ - 0.37 \end{array}$			
$\lambda_{ au Z}$	κ_{τ}/κ_{Z}	0.93 ± 0.07			
λ_{bZ}	κ_b/κ_Z	$0.89 \stackrel{+ 0.10}{- 0.09}$			
$\lambda_{\mu au}$	$\kappa_{\mu}/\kappa_{\tau}$	$1.16 \begin{array}{c} + & 0.28 \\ - & 0.33 \end{array}$			

• $\lambda_{tg} = \kappa_t / \kappa_g$: κ_t direct determination through ttH compared with indirect determination in the ggF loop (κ_g). Probe new

• $\lambda \gamma z = \kappa \gamma / \kappa z$ or $\lambda z \gamma z$: new particle contribute to $H \rightarrow \gamma \gamma / Z \gamma$ loop ($\kappa \gamma$) unlike $H \rightarrow Z Z$. Probe new physics in $H \rightarrow \gamma \gamma / Z \gamma$

SMEFT: impacts

Parametrized their impact on the signal yields in each STXS bin x 5 BR

Many parameters: for illustration, focus on a set

Model-dependent interpretation: 2HDM

The two-Higgs-doublet model (2HDM):	4 2HDM types can be defined w/o tree-level flavour-changing neutral currents						
• Extended Higgs sector (2 nd SU(2) doublet) \rightarrow 5 Higgs boson:							
 Two neutral CP-even: h,H 	• variation over allowed couplings to Sivi particles						
One neutral CP-odd: A	Coupling scale factor	Type I	Type II	Lepton-specific	Flipped		
 Two charged Higgs boson H[±] 	κ _V	$\sin(\beta - \alpha)$					
• α : mixing angle between two CP-even Higgs bosons (h, H)	K _u	$\cos(\alpha)/\sin(\beta)$					
• $\tan\beta$: ratio of the vacuum expectation values of the two SU(2) doublets	К _d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\alpha)$		
• $H_{SM} = h \cdot sin(\beta - \alpha) + H \cdot cos(\beta - \alpha)$	κ _l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\alpha)$		
• $\cos(\beta - \alpha) = 0$ (alignment limit) \Rightarrow h indistinguishable from H _{SM}							

Limits on $\cos(\beta - \alpha)$ vs $\tan\beta$ (Type I and II shown here, Lepton-specific and Flipped in backup)

The data is consistent with the alignment limit within 1 σ or even better

"petal" allowed regions: correspond to regions with $\cos(\beta + \alpha) \approx 0$, some fermion couplings have the same magnitude as in the SM, but the opposite sign

Constraints on new phenomena

Alternative models

STXS results

ATLAS	Preliminary	_ .		· · · · ·	• •	Total S	Stat. Syst.
<i>√s</i> = 13 TeV,	139 fb ⁻¹	$B_{\gamma\gamma}/B_{ZZ^*}$		÷	1.09	+0.14 (+	+0.12 -0.11, ±0.06)
$m_{H} = 125.09$	GeV, <i>y</i> _ < 2.5	$B_{b\overline{b}}/B_{ZZ^*}$		■≑・	0.78	+ 0.28 - 0.21	+0.23 +0.16)
$p_{cM} = 92\%$	~ H.	B_{WW}/B_{ZZ^*}			1.06	+0.14 (+	(+0.11 + 0.09) - 0.10 + 0.08
- SM	Stat	$B_{\tau\tau}/B_{ZZ^*}$			0.86	+0.16 (-	(+0.12 + 0.10) + 0.10 + 0.10 + 0.10 + 0.10 + 0.09
Syst.	SM		0.5	· · · · ·	1.5		tal Stat. Syst. 0.14 (+0.12 0.12 (-0.11, ±0.06) 0.28 (+0.23 +0.16) 0.21 (-0.18, -0.11) 0.14 (+0.11 +0.09) 0.13 (-0.10, -0.08) 0.16 (+0.12 +0.10) 0.14 (+0.12 +0.10) 0.14 (±0.12 +0.09) 0.14 (±0.12 +0.09) 0.14 (±0.22 +0.18) 0.28 (+0.22 +0.18) 0.28 (+0.22 +0.13) 0.28 (+0.22 +0.13) 0.28 (+0.25 +0.13) 0.28 (±0.25 +0.13) 0.28 (±0.26 +0.13) 0.39 (±0.46 ±0.26) 0.44 (±0.38 ±0.23) 0.53 (±0.46 ±0.26) 0.44 (±0.38 ±0.23) 0.44 (±0.38 ±0.23) 0.55 (±0.29 ±0.19) 0.51 (±0.27 ±0.15) 0.47 (±0.42 ±0.21) 0.43 (±0.39 ±0.47) 1.06 (±0.27 ±0.15) 0.47 (±0.42 ±0.21) 0.47 (±0.42 ±0.21) 0.47 (±0.44 ±0.22) 1.10 (±1.02 ±0.40) 0.58 (±0.51 ±0.28) 0.52 (±0.57 ±0.31) 0.57 (±0.50 ±0.29) 0.49 (±0.44 ±0.22) 0.71 (±0.62 ±0.35) 1.64 (±1.46 ±0.75) 0.58 (±0.51 ±0.28) 0.58 (±0.51 ±0.28) 0.58 (±0.51 ±0.28) 0.58 (±0.57 ±0.21) 0.39 (±0.35 ±0.18) 0.57 (±0.50 ±0.29) 0.49 (±0.44 ±0.22) 0.74 (±0.61 ±0.42) 0.74 (±0.61 ±0.42) 0.74 (±0.61 ±0.42) 0.74 (±0.61 ±0.42) 0.74 (±0.61 ±0.42) 0.74 (±0.61 ±0.42) 0.74 (±0.61 ±0.42) 0.73 (±0.64 ±0.36) 0.58 (±0.72 ±0.29) 0.74 (±0.63 ±0.35) 0.63 (±0.53 ±0.34) 0.72 (±0.63 ±0.35) 0.63 (±0.53 ±0.34) 0.73 (±0.64 ±0.36) 0.74 (±0.41 ±0.22) 0.73 (±0.64 ±0.36) 0.74 (±0.54 ±0.46) 0.74 (±0.54 ±0.42) 0.73 (±0.64 ±0.36) 0.74 (±0.74 ±0.74) 1.14 (±0.91 ±0.68) 0.75 (±0.59 ±0.23) 0.72 (±0.63 ±0.23) 0.72 (±0.63 ±0.23) 0.73 (±0.64 ±0.36) 0.74 (±0.74 ±0.74) 1.74 (±0.74 ±0.74) 1.75 (±0.59 ±0.23) 0.75 (±0.59
						Total	Stat. Svst.
	0-jet, <i>p</i> _{_{_{_{_{_{_{_{_{_{_{_{_{_{_{_{_{_{_{	e de la companya de l			0.89	+ 0.22	+0.19 +0.11
	0-jet, $10 \le p_{\pm}^{H} < 200 \text{ GeV}$	Ta l			1.14	+0.15	$\pm 0.12 + 0.09 \\ \pm 0.12 + 0.07 $
	1-jet, $p_{\tau}^{H} < 60$ GeV	HERE I			0.57	- 0.14 (± 0.28 (+0.22 0.21, ± 0.18)
	1-jet, $60 \le p_{\pm}^{H} < 120 \text{ GeV}$				1.06	+ 0.28	+0.25 + 0.13
	1-jet, $120 \le p_{\tau}^{H} < 200 \text{ GeV}$				0.66	+0.27 (+0.36 + 0.19
$gg \rightarrow H \times B_{ZZ^*}$	\geq 2-jet, m_{ii} < 350 GeV, p_{τ}^{H} < 60 GeV				0.47	+ 1.09	± 0.98 , ± 0.47)
	\geq 2-jet, m_{ii}^{r} < 350 GeV, $60 \leq p_{\tau}^{H}$ < 120 GeV				0.25	± 0.53 (± 0.46 ,± 0.26)
	\ge 2-jet, m_{jj} < 350 GeV, 120 $\le p_T^H$ < 200 GeV	H			0.54	+0.44	+0.38 $+0.23$ -0.36 -0.22)
	\geq 2-jet, 350 \leq m_{jj} < 700 GeV, p_T^H < 200 GeV				2.76	$^{+1.11}_{-1.04}$	$+0.99 + 0.52 \\ -0.93 - 0.45$
\geq 2-jet, $m_{jj} \geq$ 700 GeV, $p_T^H <$ 200 GeV					0.74	+ 1.54 - 1.43 ((+1.33, +0.76) (-1.29, -0.63)
	$200 \le p_{\tau}^H < 300 \text{ GeV}$				1.06	+ 0.35 - 0.31 ($^{+0.29}_{-0.27}$, $^{+0.19}_{-0.15}$)
	$300 \le p_{\tau}^H < 450 \text{ GeV}$				0.65	+ 0.47 - 0.43 ($^{+0.42}_{-0.39}$ $^{+0.21}_{-0.16}$)
	$p_T^H \ge 450 \text{ GeV}$		• •••• •		1.86	+ 1.47 - 1.19 (+1.37 +0.52 -1.12 ,-0.42)
						+ 1 10 7	+1.02 +0.40
	\leq 1-jet > 2-jet m < 350 GeV VH veto			_ .	1.40	- 0.99 (+ 1.64 (-0.93, -0.35) +1.46 +0.75
	\geq 2-jet, $m_{ij} < 350$ GeV, VH topo				2.98	- 1.52 (+ 0.58 ((-1.37, -0.66) + 0.51, + 0.28
	\geq 2-jet, $m_{ij} < 600 \text{ GeV}$, $m_{ij} < 200 \text{ GeV}$				0.33	- 0.52 (+ 0.49 ((-0.47, -0.23) +0.44, +0.22
	\geq 2-jet, 700 $\leq m_{ii} <$ 1000 GeV, $p_{T}^{H} <$ 200 GeV				0.95	- 0.47 (+ 0.71 (-0.41 '-0.24 ' +0.62 +0.35
$qq \rightarrow Hqq \times B_{ZZ^*}$	\geq 2-jet, 1000 $\leq m_{ii}$ < 1500 GeV, p_{-}^{H} < 200 GeV	eV	4		1.38	-0.65 ($(-0.57)^{2} - 0.31^{7}$ $(+0.50)^{2} + 0.29$
	\geq 2-jet, $m_{ii} \geq$ 1500 GeV, p_{τ}^{H} < 200 GeV		-		1.15	+0.39 ((-0.45, -0.21) (+0.35, +0.18)
	\geq 2-jet, $m_{jj}^{*} \geq$ 350 GeV, $p_{T}^{H} \geq$ 200 GeV				1.21	+0.31 -0.27	$+0.27 +0.15 \\ -0.24 , -0.12$
	м —					4 . 7	. 1 15 0.00
	$p_T^{\nu} < 75 \text{ GeV}$				2.47	+ 1.17 ($+1.15 +0.22 \\ -1.02 , -0.12 $
	$75 \le p_T^{\nu} < 150 \text{ GeV}$				1.64	+0.99 (-0.80 (+0.74 ((+0.97, +0.20) (-0.79, -0.12) (+0.61, +0.42)
$qq \rightarrow HIv \times B_{ZZ^*}$	$150 \le p_{\tau}^{V} < 250 \text{ GeV}$				1.42	-0.58 (+0.72 ((-0.48, -0.33)
	$250 \leq \beta_T^{\gamma} < 400 \text{ GeV}$	1			1.36	- 0.53 (+ 1.45 (-0.48, -0.22) +1.22 +0.79
	$p_{T} \ge 400 \text{ GeV}$				1.91	- 1.08 (-0.95 ,-0.50)
	<i>p</i> ^{<i>V</i>} ₇ < 150 GeV ⊢				0.21	+ 0.71	± 0.54 , + 0.46)
	$150 \le p_{\tau}^{V} < 250 \text{ GeV}$		} •		1.30	+0.63	(+0.53 + 0.34)
$gg/qq \rightarrow HII \times B_{ZZ^*}$	$250 \le p_{\tau}^{V} < 400 \text{ GeV}$		- 		1.28	+0.73	$+0.64 + 0.36 \\ -0.48 - 0.23$
	$p_{\tau}^{V} \ge 400 \text{ GeV}$				0.39	+ 1.28 - 1.14	(+1.04 + 0.74) (-0.91 - 0.68)
	//						. 0.72 . 0.00
	$p_T^{T} < 60 \text{ GeV}$				0.75	$^{+0.78}_{-0.66}$	(+0.72 + 0.29) (-0.63 , -0.21) (+0.49 + 0.20)
	$bU \leq p_T' < 12U \text{ GeV}$				0.69	-0.44 (-0.42, -0.15) +0.50, +0.23
$t\overline{t}H \times B_{ZZ^*}$	$120 \le p_T^H < 200 \text{ GeV}$				0.86	- 0.47 (+ 0.62 /	-0.43 ,-0.19) +0.56 +0.25 \
	$200 \le p_T < 000 \text{ GeV}$ $300 \le p^H \le 450 \text{ GeV}$				0.96	- 0.52 (+ 0.79 /	(-0.48, -0.20) + 0.66 + 0.43
	$p^{H} \ge 450 \text{ GeV}$		_		0.20 0.16	- 0.70 (+ 1.93 (-0.59 ;-0.38) +1.44 +1.28)
	· <i>T</i>					- 1.76 \	- 1.24 '- 1.25 /
$tH \times B_{ZZ^*}$					2.90	+ 3.63 - 2.87 (+3.35 +1.39 -2.73 ,-0.89)
-8 -	6 –4 –2	0	2 4	6	I	8	10

Parameter normalised to SM value

STXS results

ATLAS	Preliminary			· · · ·		· · ·	Total Sta	t. Syst.
<i>√s</i> = 13 TeV,	139 fb ⁻¹	$B_{\gamma\gamma}/B_{ZZ^*}$		÷		1.09	$^{+0.14}_{-0.12}$ ($^{+0.}_{-0.12}$	$\frac{12}{11}$, ± 0.06)
$m_{\mu} = 125.09$	GeV, <i>y</i> _ < 2.5	$B_{b\overline{b}}/B_{ZZ^*}$	H			0.78	$^{+0.28}_{-0.21}$ ($^{+0.}_{-0.21}$	$23 + 0.16 \\ 18 - 0.11$
p = 92%	, H.	B _{WW} /B _{ZZ*}				1.06	$^{+0.14}_{-0.13}$ ($^{+0.}_{-0.13}$	$\begin{pmatrix} 11 & +0.09 \\ 10 & -0.08 \end{pmatrix}$
' SM	Chat	$B_{\tau\tau}/B_{ZZ^*}$		r en en e r		0.86	+0.16 + 0.16 +	$12 + 0.10 \\ 10 - 0.09$
	Stat.			••••••••••••••••••••••••••••••••••••••		1.5		2
	Sivi	0	0.0	•		1.0	Tatal Ot	- at Over
	0 iot $p^{H} < 10$ GoV		N			0.00	+ 0.22 / + 0	ai. Sysi. 0.19 +0.11 v
	0 jet, $p_T < 10 \text{ GeV}$	-				0.89	-0.20 (-0	0.18, -0.10
	$p_{\tau} = p_{\tau} = 200 \text{ GeV}$					1.14	-0.14 (±	$(0.12^{\circ}, -0.07^{\circ})$
	1-jet, $p_T^{\prime} < 60 \text{ GeV}$					0.57	± 0.28 ($-$	$(0.21, \pm 0.18)$
	1-jet, $60 \le p_T'' < 120 \text{ GeV}$					1.06	-0.27 (-0	$(0.23^{\circ} + 0.13^{\circ})$
$g \rightarrow H \times B_{77*}$	1-jet, $120 \le p_T^n < 200 \text{ GeV}$		1			0.66	-0.39	$(0.35^{+0.19})$
0 22	\geq 2-jet, m_{jj} < 350 GeV, p_T^H < 60 GeV					0.47	$^{+1.09}_{-1.06}$ (\pm	0.98 , ^{+0.47})
	\geq 2-jet, m_{jj} < 350 GeV, 60 $\leq p_T^H$ < 120 GeV	H - 220 - H				0.25	± 0.53 (±	0.46 ,± 0.26)
	\geq 2-jet, m_{jj} < 350 GeV, 120 $\leq p_{T}^{H}$ < 200 GeV					0.54	$^{+0.44}_{-0.42} ($ $^{+0}_{-0}$	0.38 +0.23 0.36 ,-0.22)
	\geq 2-jet, 350 \leq m_{jj} < 700 GeV, p_{T}^{H} < 200 GeV					2.76	$^{+1.11}_{-1.04} \begin{pmatrix} +0 \\ -0 \end{pmatrix}$	0.99 +0.52 0.93 ,-0.45)
	\geq 2-jet, $m_{jj} \geq$ 700 GeV, $p_T^H <$ 200 GeV	_				0.74	+ 1.54	(1.33 + 0.76)
	$200 \le p_{\tau}^{H} < 300 \text{ GeV}$					1.06	+0.35 ($+0$	(0.29 + 0.19)
	$300 \le p_{\tau}^{H} < 450 \text{ GeV}$		•			0.65	+0.47 (+0.47	0.42 + 0.21
	$p_{\tau}^{H} \ge 450 \text{ GeV}$	E				1.86	+1.47 ($+1.47$ ($+1.4$	1.37 + 0.52
							-1.19 -	1.12 '-0.42 '
	≤ 1-iet					1.40	+ 1.10 (+	1.02 + 0.40)
	\geq 2-iet, m_{ii} < 350 GeV, VH veto					2.98	-0.99(-0)	0.93' - 0.35' 1.46 + 0.75
	\geq 2-iet. m_{\odot} < 350 GeV. VH topo					1 00	- 1.52 (- 1 + 0.58 (+ 0	1.37 ، – 0.66 / 0.51 + 0.28 م
	> 2 -iet 350 < $m_{\star} < 700$ GeV $p^{H} < 200$ GeV					0.33	- 0.52 - 0 + 0.49 (+ 0	0.47,-0.23, 0.44,+0.22,
	$>$ 2-iet 700 < m_{π} < 1000 GeV p^{H} < 200 Ge					0.00	-0.47 -0.47 $+0.71$ $+0.71$	0.41,-0.24) 0.62,+0.35,
$q \rightarrow Hqq \times B_{ZZ^*}$	$\geq 2 \text{ jet}, 1000 \leq m_{f} < 1500 \text{ GeV}, p_{T}^{H} < 200 \text{ GeV}$					1.00	- 0.65 (- (+ 0.57 / + (0.57,-0.31) 0.50 +0.29)
	≥ 2 jet, $1000 \leq m_{jj} < 1000 \text{ dev}, p_T < 200 \text{ dev}$	cv ¶				1.38	-0.49(-0.49)(-	0.45',-0.21) 0.35'+0.18
	≥ 2 -jet, $m_{jj} \geq 1500$ GeV, $p_T < 200$ GeV					1.15	-0.35(-0.35)	(0.32, -0.14)
	≥ 2 -jet, $m_{jj} \geq 350$ GeV, $p_T^* \geq 200$ GeV					1.21	-0.27 (-().24,-0.12)
	n ^V < 75 GeV					0.47	+ 1.17 / +	1.15 + 0.22
	$p_T < 75 \text{ GeV}$					2.47	-1.02(-1.02)	1.02,-0.12) 0.97,+0.20)
	$75 \le p_T^{\vee} < 150 \text{ GeV}$	-				1.64	-0.80(-0.80)	(0.79, -0.12)
$q \rightarrow HIV \times B_{ZZ^*}$	$150 \le p_{\tau}^{*} < 250 \text{ GeV}$	H				1.42	-0.58 (-0	(0.12)
	$250 \le p_{\tau}^{v} < 400 \text{ GeV}$	•				1.36	-0.53 (-0	(1.22 + 0.22)
	$\rho_{T}^{v} \ge 400 \text{ GeV}$	H				1.91	$^{+1.45}_{-1.08}$ ($^{+}_{-0}$	(0.95, -0.50)
							. 0.71	0.46
	$p_{T}^{v} < 150 \text{ GeV}$					0.21	$^{+0.71}_{-0.76}$ (±	0.54, +0.46, -0.53
ıa/aa→Hll × B	$150 \le p_T^V < 250 \text{ GeV}$	÷				1.30	$^{+0.63}_{-0.46}$ ($^{+0}_{-0}$	(0.53 + 0.34) (0.41, -0.22)
<i>9,99 71 7 2 22</i> *	$250 \le p_{\tau}^{V} < 400 \text{ GeV}$	۹ ۲				1.28	$^{+0.73}_{-0.54}$ ($^{+0}_{-0}$	(0.64 + 0.36) (0.48 - 0.23)
	$p_{T}^{V} \ge 400 \text{ GeV}$					0.39	+ 1.28 (+ 1.14 (- 1	1.04 +0.74 0.91 -0.68)
	p_{τ}^{H} < 60 GeV					0.75	$^{+0.78}_{-0.66} ($ $^{+0}_{-0}$	0.72 +0.29 0.63 -0.21)
	$60 \le p_T^H < 120 \text{ GeV}$		₽			0.69	$^{+0.53}_{-0.44}$ ($^{+0}_{-0}$	0.49 +0.20 0.42 ,-0.15)
	$120 \le p_{_T}^H < 200 \text{ GeV}$					0.86	+ 0.55	0.50 + 0.23).43 , _ 0.19)
н× В _{ZZ*}	$200 \le p_T^H < 300 \text{ GeV}$					0.96	+0.62 (+0.52) (+0.52	(0.56 + 0.25)
	$300 \le p_{\tau}^{H} < 450 \text{ GeV}$					0.28	+0.79 (+0.79	0.66 + 0.43
	$p_T^H \ge 450 \text{ GeV}$					0.16	+1.93 + 1.76 +	1.44 + 1.28 1.24 - 1.25
	,		_				- 1.70 -	$1.24^{\circ} = 1.20^{\circ}$
н × В _{ZZ*}						2.90	+ 3.03 (+ 3 - 2.87 (- 2	$(2.73^{\circ}, -0.89^{\circ})$
-8 —	6 -4 -2	0	2	4	6		8	10

Parameter normalised to SM value

$$\mathbf{tH} [pp \to tH + X]$$

$HH \rightarrow bb\gamma\gamma$

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