Measurements of Higgs boson decaying into tau leptons using 139 fb^{-1} at the ATLAS experiment

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Higgs potential and BSM opportunities

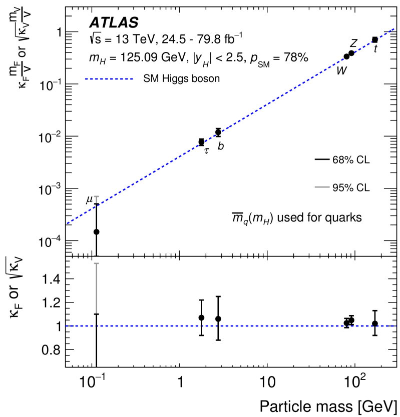
Higgs boson in the Standard Model

- The SM Higgs boson couplings can be summarised in the Lagrangian

$$\mathcal{L} = -\frac{m_f}{v} f\bar{f}H + \frac{m_H^2}{2v}H^3 + \frac{m_H^2}{8v^2}H^4 + \delta_V V_\mu V^\mu \left(\frac{2m_V^2}{v}H + \frac{m_V^2}{v^2}H^2\right)$$

- Coupling with SM particles proportional to:
  - m_F for fermions $\rightarrow$ main couplings with third generation of quark and leptons (b and τ)
  - m_V^2 for bosons $\rightarrow$ main couplings with W and Z

- Coupling as function of particle mass in good agreement with SM prediction over 3 order of magnitude



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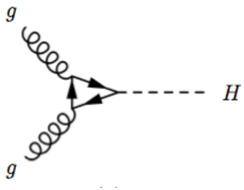
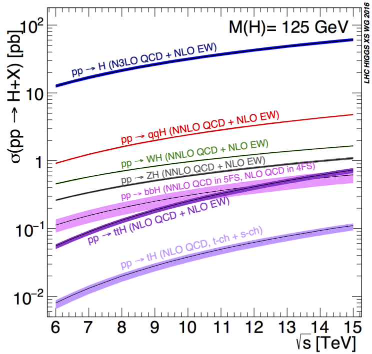
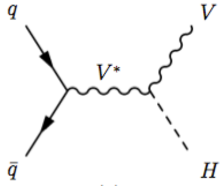
Higgs boson production modes



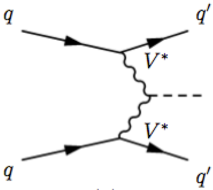
gluon fusion (ggF)
Cross section : 48.6 pb.*



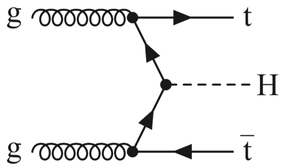
Higgs boson production cross section



associated production with a gauge boson (VH).
Cross section : 2.3 pb.*



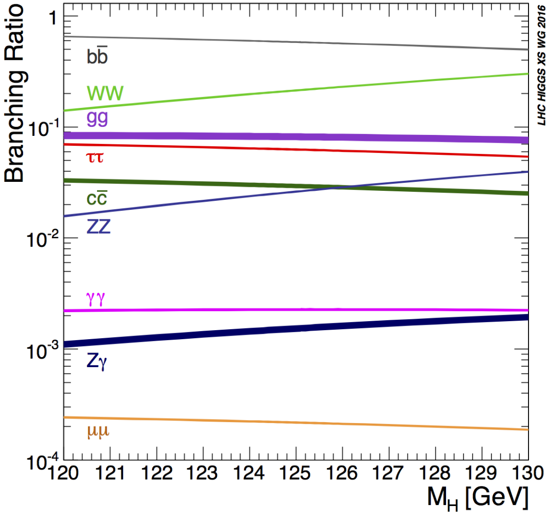
vector boson fusion (VBF).
Cross section : 3.8 pb.*



associated production with a $t\bar{t}$ pair (ttH).
Cross section : 0.5 pb.*

* predicted cross section for m_H=125 GeV at $\sqrt{s}$=13 TeV

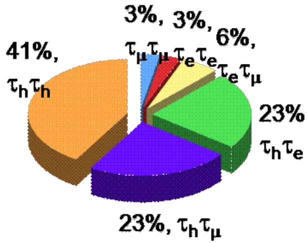
Higgs boson decay branching ratios



- Larger branching ratio (BR) for $H \to b\bar{b}$, $H \to WW^*$ and $H \to \tau\tau$, however poor mass resolution and large background contamination
- $H \to \gamma\gamma$ and $H \to ZZ^*(\to 4l)$ have lower BR, but high mass resolution; can be used for precision measurements
- $H \to Z\gamma$ and $H \to \mu\mu$ becoming now accessible thanks to large Run 2 dataset and the good detector performance

$H \to \tau\tau$ measurements - ATLAS-CONF-2021-044

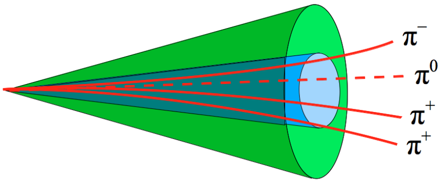
- In the SM, $H \to \tau\tau$ is currently the only accessible decay at LHC to establish Higgs-Yukawa coupling to leptons
- Consider all main Higgs boson production modes
- Aim to measure full cross-section, as well as cross section in the *STXS* framework



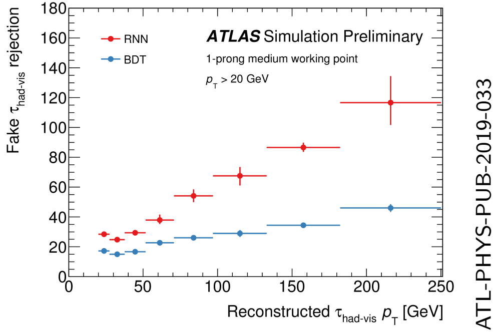
<table>
<tr><th></th><th>$\tau_{lep}\tau_{lep}$</th><th>$\tau_{lep}\tau_{had}$</th><th>$\tau_{had}\tau_{had}$</th></tr>
<tr><td>VBF inclusive</td><td colspan="3">sub-leading jet $p_{\mathrm{T}} > 30\,\mathrm{GeV}$
$m_{jj} > 350\,\mathrm{GeV}$, $|\Delta\eta_{jj}| > 3$
$\eta(j_0) \times \eta(j_1) < 0$
lepton centrality: visible decay products of the τ leptons between VBF jets</td></tr>
<tr><td>VH inclusive</td><td colspan="3">$60\,\mathrm{GeV} < m_{jj} < 120\,\mathrm{GeV}$
sub-leading jet $p_{\mathrm{T}} > 30\,\mathrm{GeV}$</td></tr>
<tr><td>tt(0L)$H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$</td><td colspan="2"></td><td># of jets ≥ 6 and # of b-jets ≥ 1
or # of jets ≥ 5 and # of b-jets ≥ 2</td></tr>
<tr><td>Boost inclusive</td><td colspan="3">Not VBF inclusive
Not VH inclusive
$p_{\mathrm{T}}(\mathrm{H}) > 100\,\mathrm{GeV}$</td></tr>
</table>

Tau Reconstruction/Identification

- Attempt to reconstruct only hadronically decay taus
- Tau candidates are seeded by anti-k_t LC jets with a distance parameter R = 0.4
- Track selected in the *core* ($0 < \Delta R < 0.2$) and *isolation* ($0.2 < \Delta R < 0.4$) regions around the tau candidate axis.
- Identification algorithm based on RNN to reject background from q/g jets
  - RNN trained using track and cluster information
  - highly supersede performance from BDT based identification

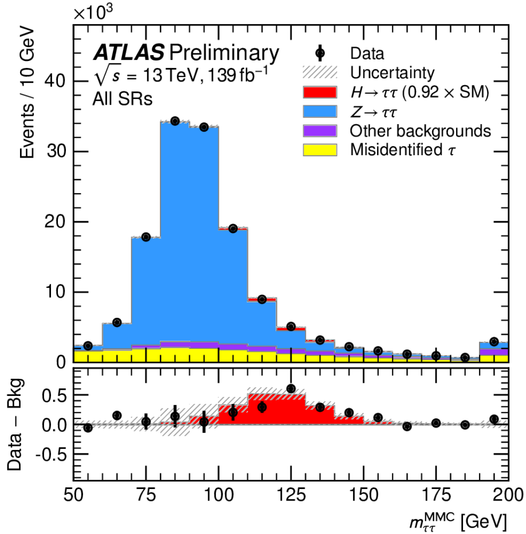


had τ Decay Mode	BR (%)
$h^\pm$	11.5
$h^\pm\pi^0$	30.0
$h^\pm \geqslant 2\pi^0$	10.6
$3h^\pm$	9.5
$3h^\pm \geqslant 2\pi^0$	5.1



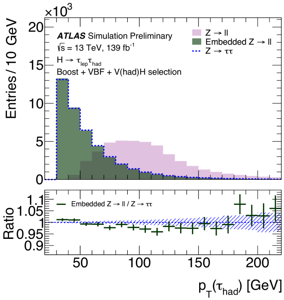
Background estimation

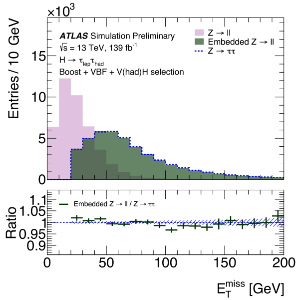
- MC based except for *misidentified* τ, which is data-driven
- Z$\rightarrow \tau\tau$ (70-90%) : validated + normalised using embedded Z$\rightarrow$ *ll* CRs
- Misidentified τ (5-20 %) : estimated using Matrix Method ($\tau_{lep}\tau_{lep}$) and Fake Factor Method ($\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$)
- Top ($<$ 5% but 35-50% in ttH SRs) : validated in Top CRs
- Other backgrounds : small, evaluated through MC



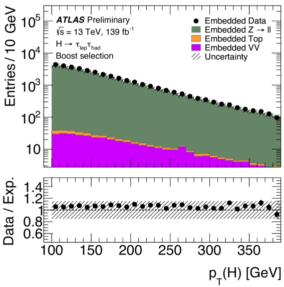
Kinematic Embedding procedure

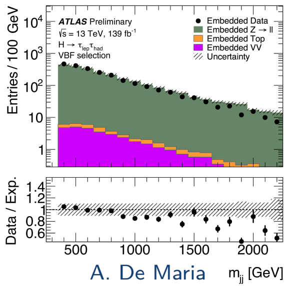
- Select Z$\rightarrow$ *ll* + jets events in CRs defined orthogonal to the signal region
- *Unfold* Z$\rightarrow$ *ll* events taking into account lepton reconstruction efficiencies
- *Mimic* Z$\rightarrow \tau\tau$ events through kinematic parameterisation of τ decay products

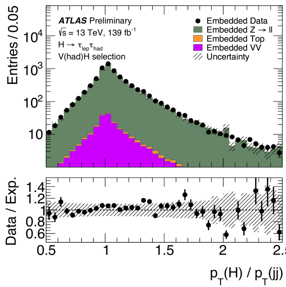




- Procedure validated in different kinematic phase spaces

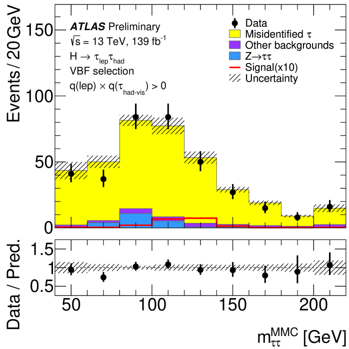


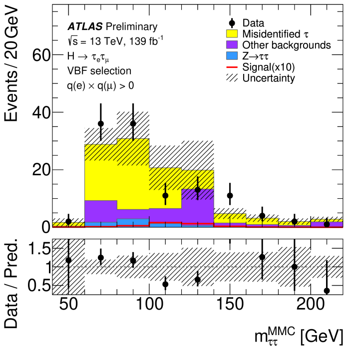


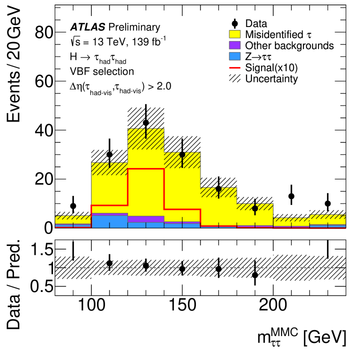


Misidentified τ background estimation

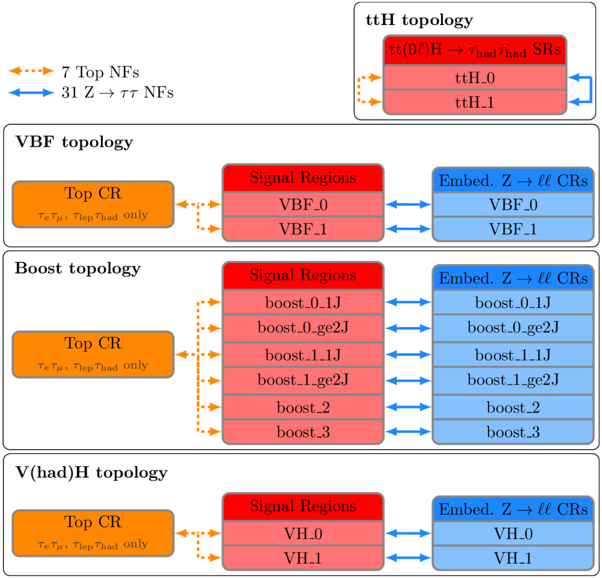
- Aim to estimate jet mis-identified as τ (light leptons) in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ ($\tau_{lep}\tau_{lep}$) final states
- Validated in dedicated CRs and residual mis-modelling assigned as systematic uncertainty





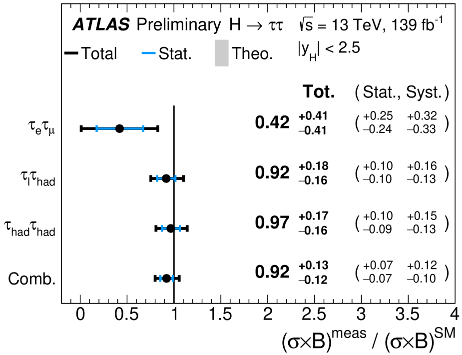


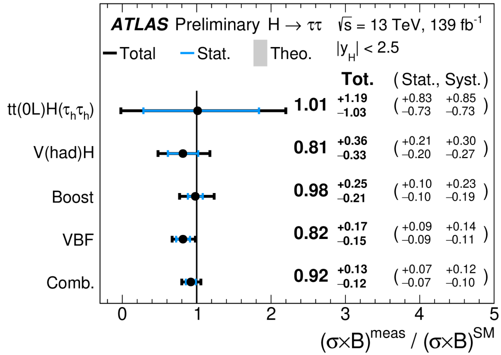
Fit Model



- VBF, VH(had) and ttH signal regions split using taggers
- Boost region split according to the STXS scheme
- Use di-τ mass (MMC) as fit variable in the SRs
- Use embedded Z$\rightarrow$ *ll* (Top) CRs to normalize Z$\rightarrow \tau\tau$ (Top) background

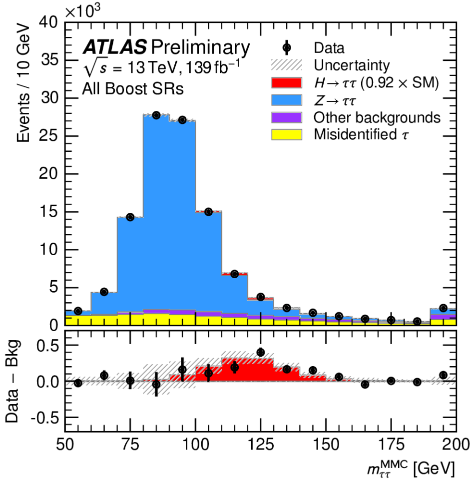
Inclusive cross section measurement

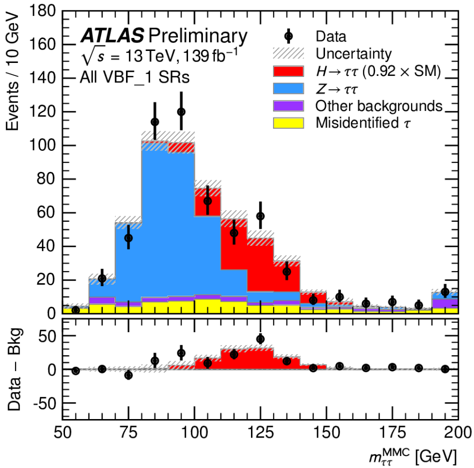




- Largest sensitivity from $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ final states
  - expected from H$\rightarrow$ $\tau\tau$ branching ratios
- Sensitivity driven by VBF and Boost categories
  - expected from Higgs boson production mode cross-section
- Lower sensitivity from V(had)H and ttH categories
  - First attempt to define these categories for this analysis

Postfit distributions





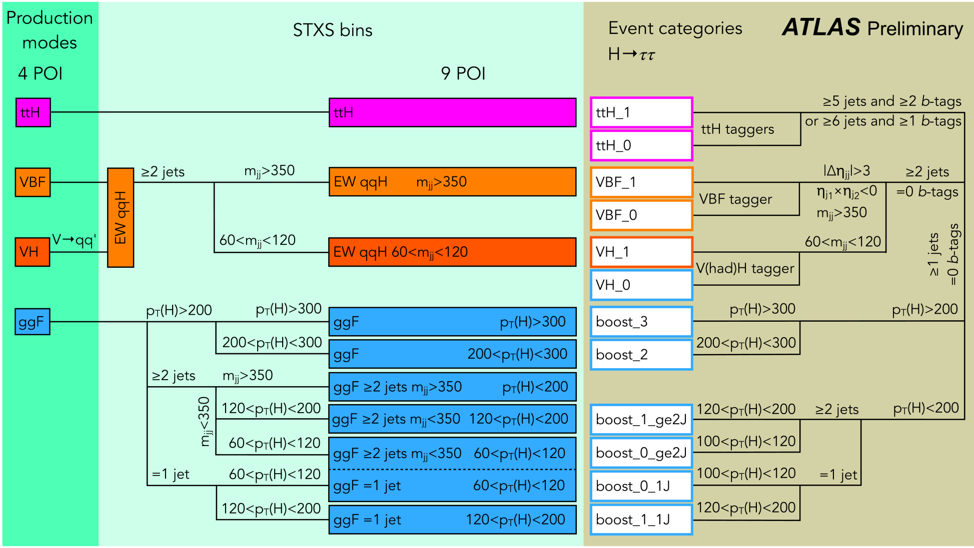
- Clear signal excess over background prediction in the most sensitive region

Measurement uncertainties

Source of uncertainty	Impact on $\Delta\sigma\,/\,\sigma(pp \to H \to \tau\tau)$ [%] Observed	Expected
Theoretical uncertainty in signal	8.1	8.6
Jet and $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$	4.2	4.1
Background sample size	3.7	3.4
Hadronic τ decays	2.0	2.1
Misidentified τ	1.9	1.8
Luminosity	1.7	1.8
Theoretical uncertainty in Top processes	1.4	1.2
Theoretical uncertainty in Z+jets processes	1.1	1.1
Flavor tagging	0.5	0.5
Electrons and muons	0.4	0.3
Total systematic uncertainty	11.1	11.0
Data sample size	6.6	6.3
Total	12.8	12.5

- Total uncertainty $\simeq$ 13%; $\simeq$ factor 2 improvement respect to previous publication
- Uncertainty dominated by systematic component
- Largest source of uncertainty from Theory, Jet/E_T^{miss} and MC sample statistics

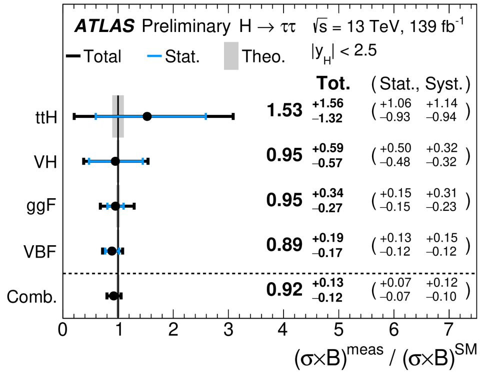
Production and STXS measurement



- STXS bins definition: maximize sensitivity, minimize theory dependence
- Bins defined to enrich events of certain production mode

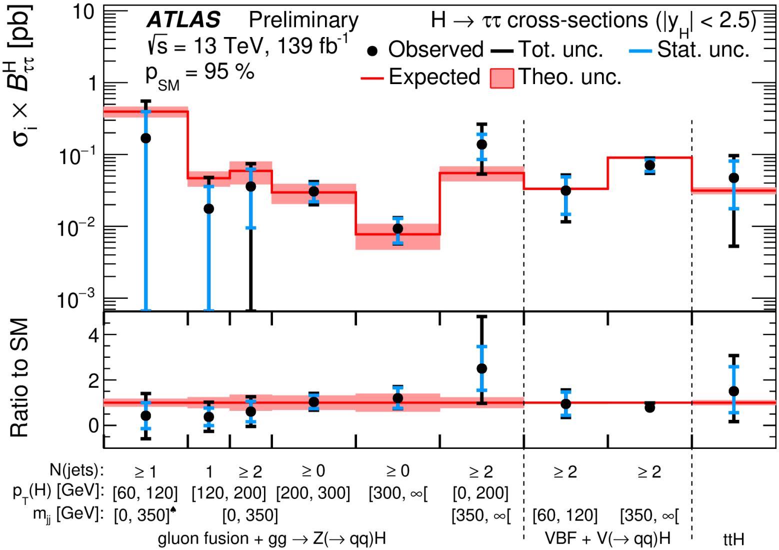
Production mode measurement results

- Observation of the VBF H$\to \tau\tau$ with significance of 5.3 (6.2) σ observed (expected)
- Evidence of the ggH H$\to \tau\tau$ with significance of 3.9 (4.6) σ observed (expected)
- All the measurements in agreement with SM prediction



Production Mode	SM prediction [pb]	Result [pb]	Stat. unc. [pb]	Syst. unc. [pb]		
				Th. sig.	Th. bkg.	Exp.
$t\bar{t}H$	0.031 ± 0.003	0.048 ± 0.045	± 0.027	± 0.011	± 0.027	± 0.018
VH	0.118 ± 0.003	0.11 ± 0.04	± 0.02	± 0.02	± 0.01	± 0.02
ggF	2.8 ± 0.1	2.7 ± 0.9	± 0.4	± 0.6	± 0.1	± 0.5
VBF	0.22 ± 0.01	0.196 ± 0.040	± 0.026	± 0.024	± 0.005	± 0.016
$pp \to H$	3.15 ± 0.09	2.90 ± 0.40	± 0.22	± 0.26	± 0.06	± 0.22

STXS measurement results



- Measurement performed in 9 STXS bins
- Largest sensitivity from ggH with high p_T^H and VBF bins

Summary

- The most recent measurements in the H$\rightarrow \tau\tau$ channels have been presented
- Aim was to measure the inclusive, production mode and STXS bins cross-sections
- Inclusive cross-section measured with $\simeq$ 13% uncertainty and in agreement with SM prediction
  - uncertainty by systematic uncertainty from Theory, Jet/E_T^{miss} and MC sample statistics
- Observation (evidence) of the VBF (ggH) production mode with observed significance of 5.3 (3.9) σ
- Cross-section measured also in 9 STXS bins with best results from ggH with high p_T^H and VBF bins

Thanks For Your Attention

Backup

STXS measurement resullts

STXS bin				SM prediction	Result	Stat. unc.	Syst. unc. [pb]		
Process	m_{jj} [GeV]	$p_{\mathrm{T}}(H)$ [GeV]	$\mathrm{N_{jets}}$	[pb]	[pb]	[pb]	Th. sig.	Th. bkg.	Exp.
ggF + $gg \to Z(\to qq)H$	[0, 350]♠	[60, 120]	≥ 1	0.39 ± 0.06	0.17 ± 0.39	± 0.22	± 0.06	± 0.15	± 0.29
		[120, 200]	$= 1$	0.047 ± 0.011	0.018 ± 0.030	± 0.018	± 0.004	± 0.004	± 0.019
	[0, 350]	[120, 200]	≥ 2	0.059 ± 0.020	0.036 ± 0.039	± 0.027	± 0.009	± 0.009	± 0.025
		[200, 300]	≥ 0	0.030 ± 0.009	0.031 ± 0.011	± 0.009	± 0.003	± 0.001	± 0.006
		[300, ∞[	≥ 0	0.008 ± 0.003	0.009 ± 0.004	± 0.003	± 0.001	± 0.000	± 0.001
	[350, ∞[	[0, 200]	≥ 2	0.055 ± 0.013	0.14 ± 0.11	± 0.05	± 0.06	± 0.01	± 0.07
EWK	[60, 120]		≥ 2	0.033 ± 0.001	0.031 ± 0.020	± 0.017	± 0.003	± 0.001	± 0.010
	[350, ∞[		≥ 2	0.090 ± 0.002	0.071 ± 0.017	± 0.014	± 0.010	± 0.002	± 0.006
$t\bar{t}H$				0.031 ± 0.003	0.047 ± 0.046	± 0.032	± 0.011	± 0.027	± 0.018