H(125) bosonic decays in the ATLAS experiment

Higgs Hunting 2022

Ruggero Turra
on behalf of the ATLAS Collaboration

INFN Milano

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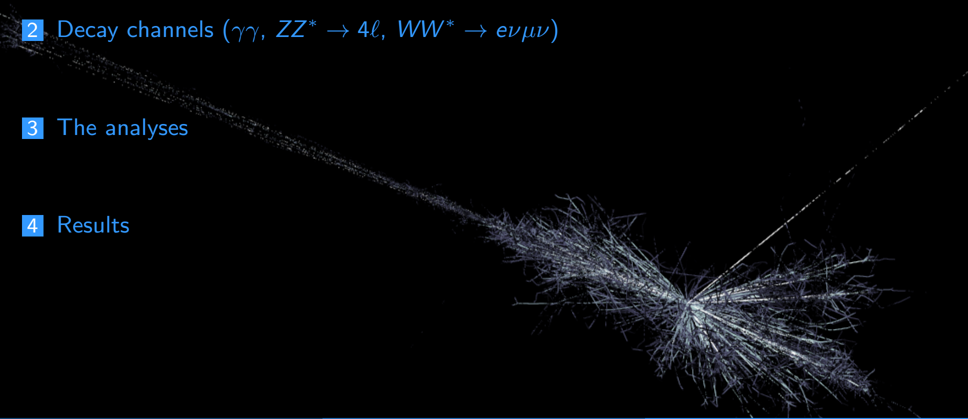

Higgs properties

Excess compatible with Higgs boson firmly established by ATLAS+CMS in 2012.

Measurements

- $\sigma \times BR$: for each production-mode, STXS region (very optimized analyses, acceptance extrapolation, larger SM assumption)
- Inclusive and differential fiducial cross sections (minimal model dependence)
- Mass: m_H known at $< 0.2\%$ (single channel), see talk by Siyuan Yan in the afternoon

Interpretations

- Spin and parity: 0^+, other models excluded in Run 1
- CP structure (see talk by José Gonçalo tomorrow)
- Signal strengths: $\mu_i = \sigma_i/\sigma_i^{SM}$, $\mu_f = BR_f/BR_f^{SM}$ (inclusive, per-production-mode, ...)
- Coupling modifiers to SM particles (kappa-framework)
- EFT interpretations (see talk by Alexander Held tomorrow)

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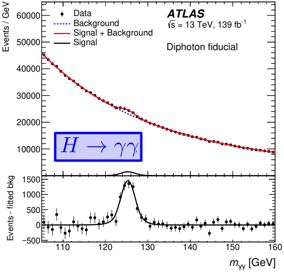
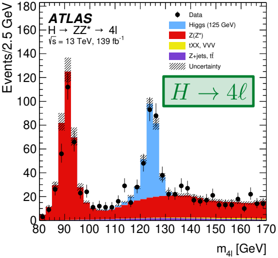
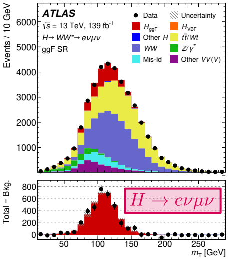
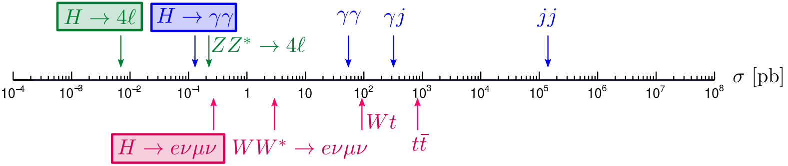
$\gamma\gamma$, $ZZ^* \to 4\ell$, $WW^* \to e\nu\mu\nu$

	BR/10^{-3}	sig. eff.	mass resolution	Backgrounds
$\gamma\gamma$	2.27	39%	1.0–2.2 GeV	Large: $q\bar{q}/gg \to \gamma\gamma$
4ℓ	0.124	16-33%	1.6–2.4 GeV	Very small: $q\bar{q}/gg \to ZZ^*$
$e\nu\mu\nu$	5.04	$\sim$ 11%	Transverse mass	Medium: $q\bar{q}/gg \to WW^*$, $t\bar{t}$, Wt

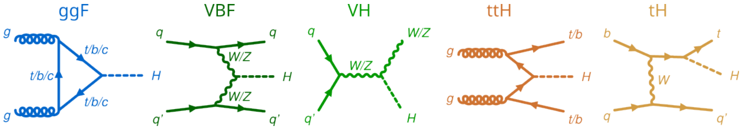






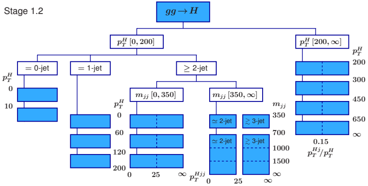


Higgs production and Simplified Template X-Sections (STXS)



1. Split cross sections by production modes
2. Split in exclusive regions of phase space, differently for each production modes

STXS maximize the sensitivity of the measurements while at the same time to minimize their theory dependence

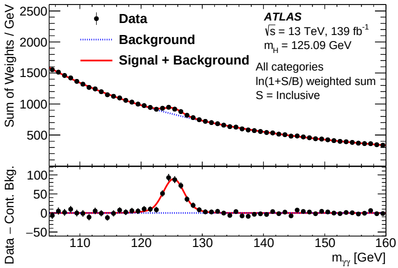


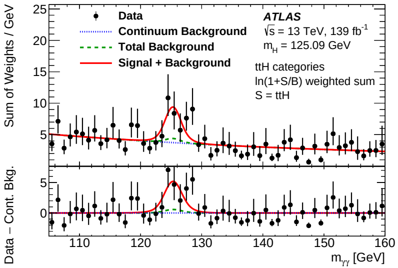
Going to show latest results by ATLAS with full Run2 (139 fb^{-1} at $\sqrt{s} = 13$ TeV)

General strategy

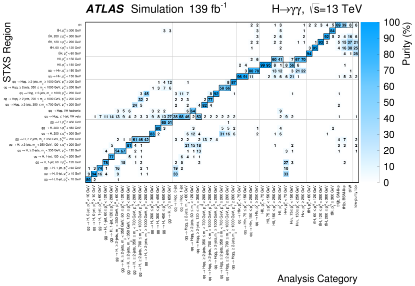
1. Select events to increase S/B
2. Split events into categories using reconstructed quantities, separating the sub-processes you want to measure (e.g. ggF vs VBF, different Higgs p_T ranges, ...)
3. Define control regions to constrain the yield of background processes
4. Quantify the efficiency and migrations for each sub-process and each category (e.g. P[ggF-category|true-VBF-process], ...) with MC
5. Define an observable to estimate background from data (e.g. $m_{\gamma\gamma}$) and model it
6. Minimize a likelihood (matrix method unfolding) to simultaneously measure the cross-sections

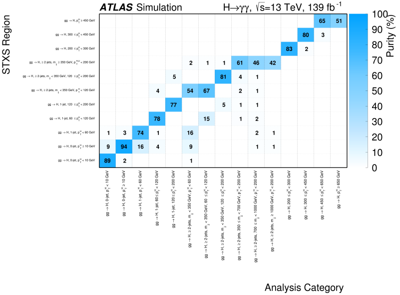
- Using $m_{\gamma\gamma}$ as continuos observables
- Signal shape parametrized using a function fitted on simulations
- Background shape parametrized using a function fitted on data
  - The functional form is chosen with the spurious signal criteria: minimize the signal fitted on a background-only high-statistic simulation



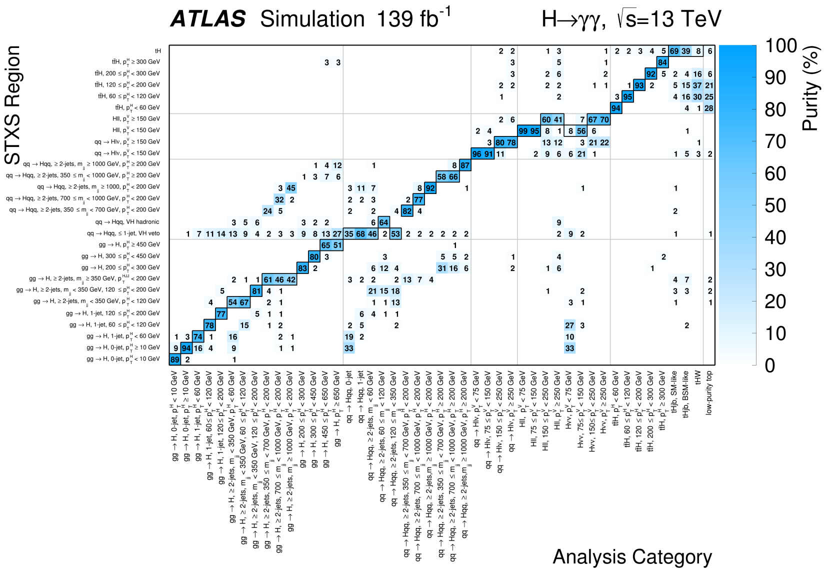


- Measuring 28 STXS bins (45 considered in the design)
- Two steps:
  - A first multiclass BDT separating the signal sub-processes (the STXS bins)
  - Additional splitting to increase purity using a set of binary BDTs: 101 categories!
- Novel approach based on D-optimality: minimize the determinant of the expected covariance matrix of the measurement
  - Implemented tuning a set of weights applied to the outputs of the multiclass
  - Simultaneous optimization for all the STXS bins

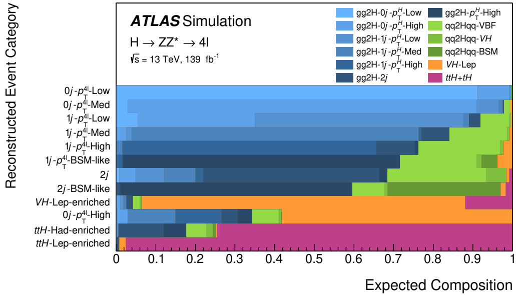


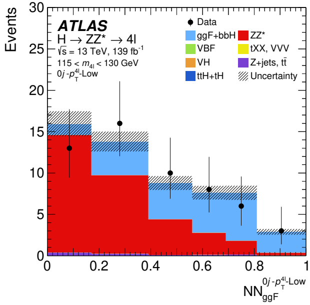


$H \to \gamma\gamma$ STXS categorization



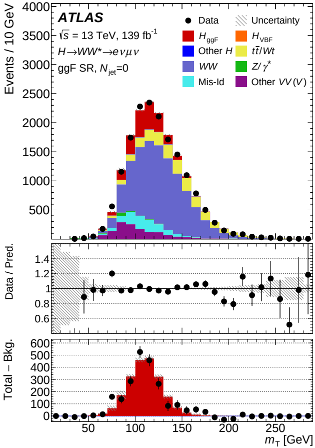
- Targeting 12 STXS 1.1 bins
- Main background from non-resonant ZZ, constrained from data sidebands
- Events split in 12 categories: first select ttH-like events, then split by jet multiplicity. Further splitting according to STXS.
- Fit to a new neural network discriminant. NN combine 2 RNN (for lepton and jet information) into a DNN.





$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ analysis

- Targeting only ggF and VBF and 11 STXS 1.2 bins
- Only different flavour. Categorization: 0jet, 1jet, ≥ 2 jets
  - Background composition different depending on jet multiplicity
  - Additional splitting to target STXS
- Background $qq \rightarrow WW$, top, $Z/\gamma^* \rightarrow \tau\tau$ predictions normalized using several control regions
- Simultaneous fit of signal and control regions, using m_T or DNN (ggF vs VBF) as observable



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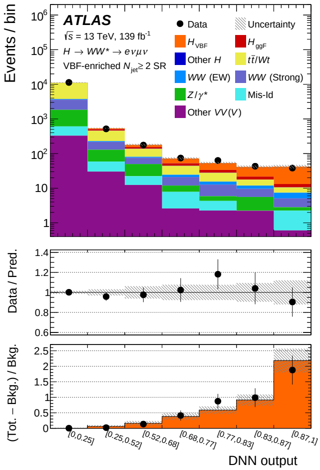
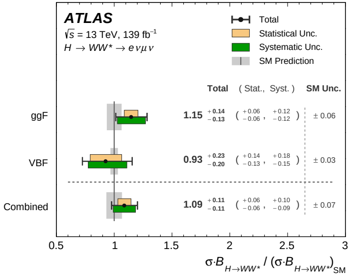
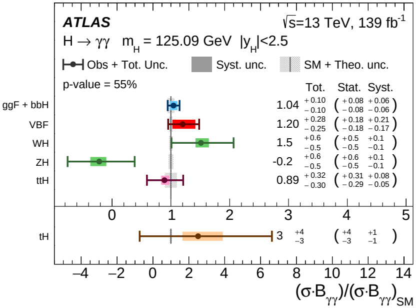


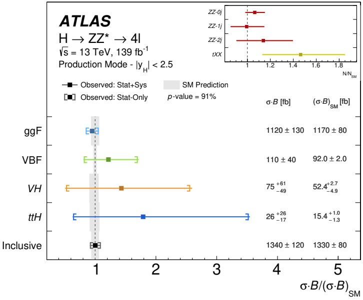
Results: Production mode cross sections

2207.00348, Eur. Phys. J. C 80 (2020) 957, 2207.00338

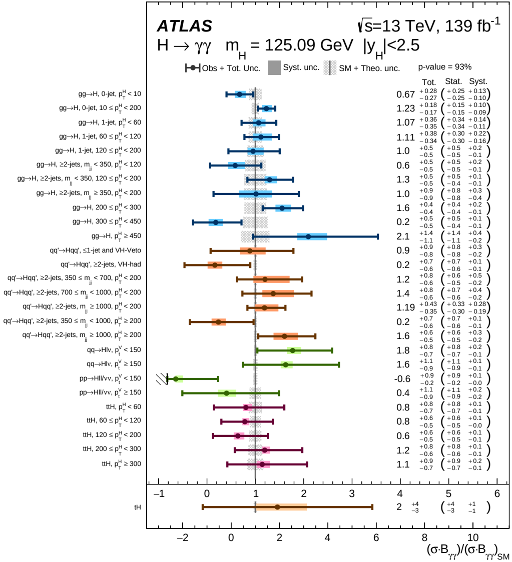
- Good agreement with SM
- ggH $\simeq$ 10%, VBF $\simeq$ 20-30%
- *WW* limited by systematics
- Non-negligible correlation between ggF/VBF, WH/ZH, tH/ttH

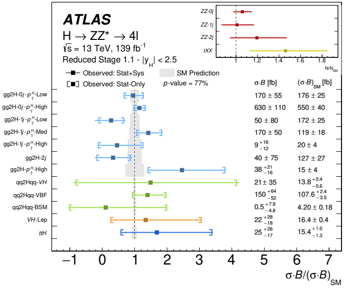


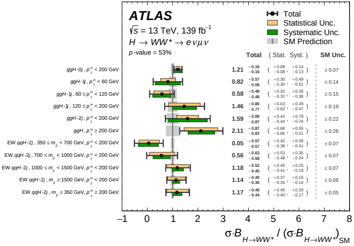




Results: STXS



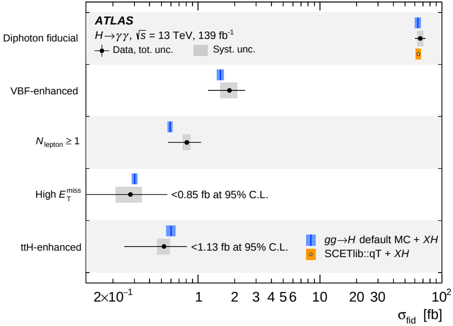


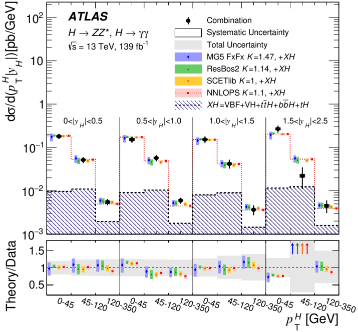


Fiducial cross sections

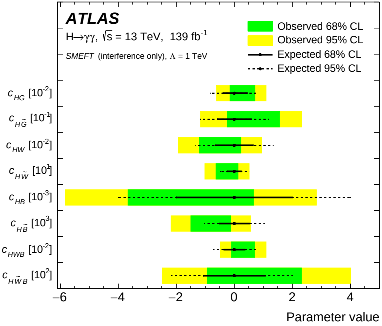
Eur. Phys. J. C 80 (2020) 942, JHEP 08 (2022) 027, 2207.08615

- Cross sections in fiducial space, defined by detector acceptance and trigger requirements
- Inclusive or (double) differential, also in smaller phase space to study non-ggF
- Unfolded with matrix method in the likelihood fit
- $\gamma\gamma/ZZ$ uses different phase space, so extrapolate to the full phase space in the combination (using SM assumptions)
  - p_T, $|y|$, p_T vs $|y|$, N_{jets}, $p_{T,j1}$
  - many more cross-sections by single channels





- $\gamma\gamma$: EFT constraints on Wilson coefficients
- ZZ: anomalous couplings to H and Z and contact interaction from left- and right-handed leptons to H using m_{12} and m_{34}
- Both: constraints on c- and b-quark Yukawa coupling using shape-only (or with normalization)



Fiducial cross section: interpretations

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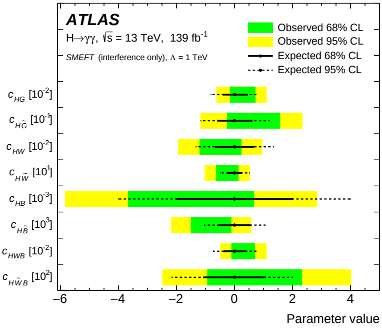

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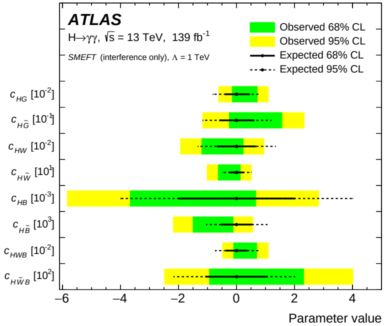
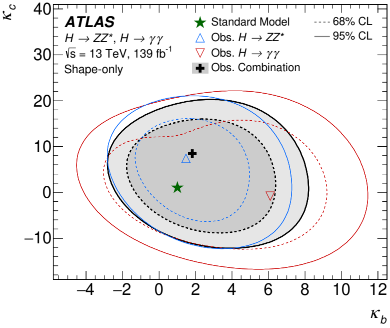
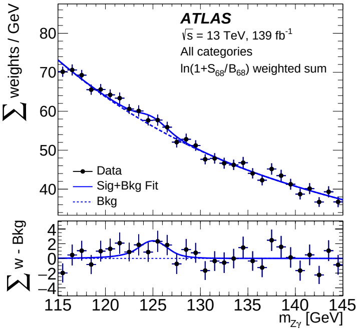




Conclusions

- Published Run2 results for STXS and fiducial cross sections are now available including combination. Everything compatible with SM.
- Several improvements on the analysis side: particle flow jets, improved categorizations, improved discriminants, improved control regions, more cross sections, more interpretations

- Uncertainty from single channel on inclusive fiducial cross section $\simeq 9\%$
- Uncertainty from single channel on ggF: 10% VBF: 20-30%, $ttH(\gamma\gamma)$: 35%
- Several STXS 1.2 bins for ggF and VBF at $< 50\%$ from single channel
- Several interpretations on top of the measurement: EFT interpretations based on STXS or differential cross sections
- $H \to Z\gamma$: 95% CL 3.5$\times$ SM. Significance 2.2σ (expected 1.2σ). Phys. Lett. B 809 (2020) 135754

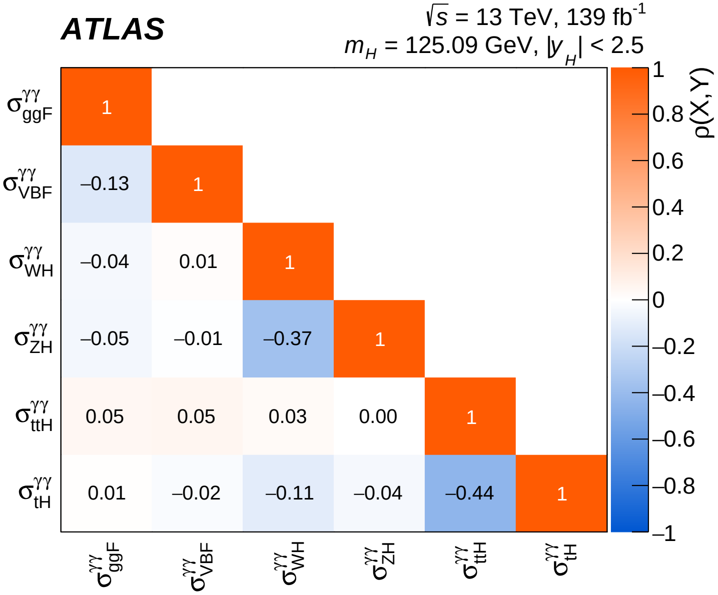


Thanks for your attention

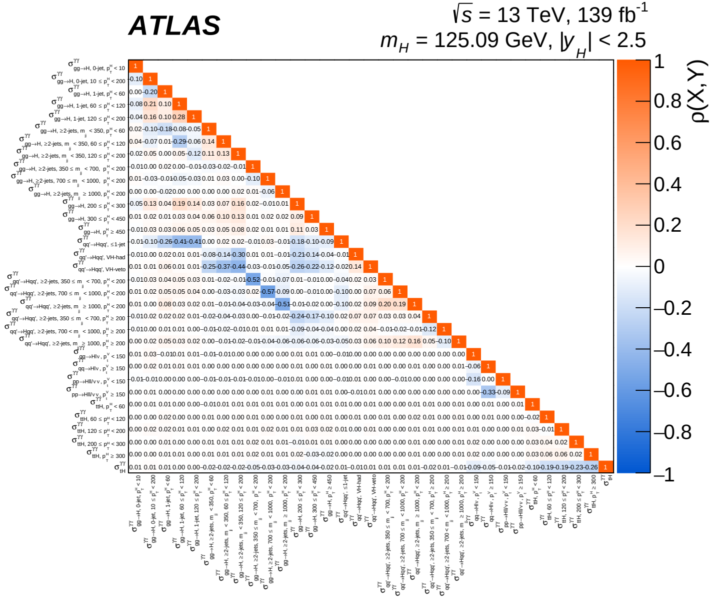
Any questions?

Backup

yy correlation



yy correlation



γγ generators

Table 1: Event generators and PDF sets used to model signal and background processes. The cross-sections of Higgs boson production processes are reported for a centre-of-mass energy of $\sqrt{s}$ = 13 TeV and a Higgs boson mass of m_H = 125.09 GeV. The order of the calculated cross-section is reported in each case. The cross-sections for the background processes are omitted, since the background normalization is determined in fits to the data.

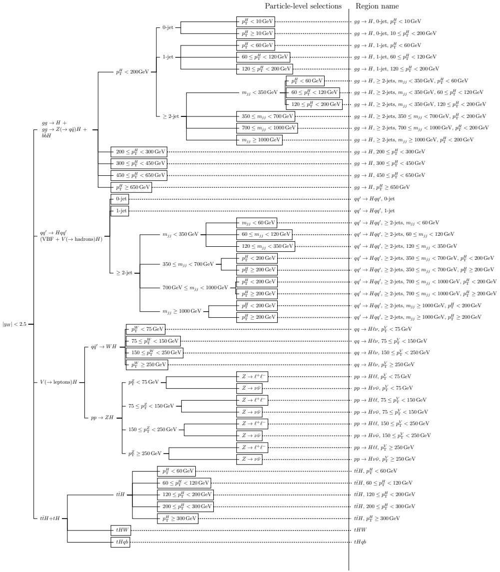
Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s}$ = 13 TeV	Order of σ calculation
ggF	NNLOPS	PYTHIA 8.2	PDF4LHC15	48.5	N^3LO(QCD)+NLO(EW)
VBF	POWHEG BOX	PYTHIA 8.2	PDF4LHC15	3.78	approximate-NNLO(QCD)+NLO(EW)
WH	POWHEG BOX	PYTHIA 8.2	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$qq/qg \to ZH$	POWHEG BOX	PYTHIA 8.2	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg \to ZH$	POWHEG BOX	PYTHIA 8.2	PDF4LHC15	0.12	NLO(QCD)
$t\bar{t}H$	POWHEG BOX	PYTHIA 8.2	PDF4LHC15	0.51	NLO(QCD)+NLO(EW)
$b\bar{b}H$	POWHEG BOX	PYTHIA 8.2	PDF4LHC15	0.49	NNLO(QCD)
$tHqb$	MADGRAPH5_AMC@NLO	PYTHIA 8.2	NNPDF3.0NNLO	0.074	NLO(QCD)
tHW	MADGRAPH5_AMC@NLO	PYTHIA 8.2	NNPDF3.0NNLO	0.015	NLO(QCD)
$\gamma\gamma$	SHERPA	SHERPA	NNPDF3.0NNLO		
$V\gamma\gamma$	SHERPA	SHERPA	NNPDF3.0NNLO		
$t\bar{t}\gamma\gamma$	MADGRAPH5_AMC@NLO	PYTHIA 8	NNPDF2.3LO		

yy multiclass inputs

η_{γ_1}, η_{γ_2}, $p_{\mathrm{T}}^{\gamma\gamma}$, $y_{\gamma\gamma}$,
$p_{\mathrm{T},jj}^{\dagger}$, m_{jj}, and Δy, $\Delta\phi$, $\Delta\eta$ between j_1 and j_2,
$p_{\mathrm{T},\gamma\gamma j_1}$, $m_{\gamma\gamma j_1}$, $p_{\mathrm{T},\gamma\gamma jj}$†, $m_{\gamma\gamma jj}$
Δy, $\Delta\phi$ between the $\gamma\gamma$ and jj systems,
minimum ΔR between jets and photons,
invariant mass of the system comprising all jets in the event,
dilepton p_{T}, di-e or di-μ invariant mass (leptons are required to be oppositely charged),
$E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T} and transverse mass of the lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ system,
p_{T}, η, ϕ of top-quark candidates, $m_{t_1 t_2}$
Number of jets†, of central jets ($\lvert\eta\rvert < 2.5$)†, of b-jets† and of leptons,
p_{T} of the highest-p_{T} jet, scalar sum of the p_{T} of all jets,
scalar sum of the transverse energies of all particles ($\sum E_{\mathrm{T}}$), $E_{\mathrm{T}}^{\mathrm{miss}}$ significance,
$\left\lvert E_{\mathrm{T}}^{\mathrm{miss}} - E_{\mathrm{T}}^{\mathrm{miss}}(\text{primary vertex with the highest } \sum p_{\mathrm{T,track}}^2)\right\rvert > 30\,\mathrm{GeV}$
Top reconstruction BDT of the top-quark candidates,
$\Delta R(W,b)$ of t_2,
η_{j_F}, $m_{\gamma\gamma j_F}$
Average number of interactions per bunch crossing.

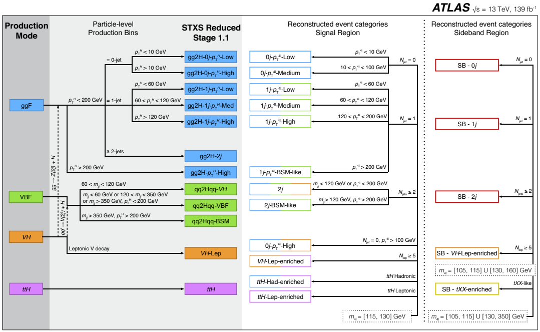
STXS classes	Variables
Individual STXS classes from $gg \to H$, $qq' \to Hqq'$, $qq \to H\ell\nu$, $pp \to H\ell\ell$, $pp \to H\nu\bar{\nu}$	All multiclass BDT variables, $\boldsymbol{p}_{\mathrm{T}}^{\gamma\gamma}$ projected to the thrust axis of the $\gamma\gamma$ system ($p_{\mathrm{Tt}}^{\gamma\gamma}$), $\Delta\eta_{\gamma\gamma}$, $\eta^{\mathrm{Zepp}} = \frac{\eta_{\gamma\gamma}-\eta_{jj}}{2}$, $\phi^*_{\gamma\gamma} = \tan\left(\frac{\pi-\lvert\Delta\phi_{\gamma\gamma}\rvert}{2}\right)\sqrt{1-\tanh^2\left(\frac{\Delta\eta_{\gamma\gamma}}{2}\right)}$, $\cos\theta^*_{\gamma\gamma} = \left\lvert\frac{(E^{\gamma_1}+p_z^{\gamma_1})\cdot(E^{\gamma_2}-p_z^{\gamma_2})-(E^{\gamma_1}-p_z^{\gamma_1})\cdot(E^{\gamma_2}+p_z^{\gamma_2})}{m_{\gamma\gamma}+\sqrt{m_{\gamma\gamma}^2+(p_{\mathrm{T}}^{\gamma\gamma})^2}}\right\rvert$ Number of electrons and muons.
all $t\bar{t}H$ and tHW STXS classes combined	p_{T}, η, ϕ of γ_1 and γ_2, p_{T}, η, ϕ and b-tagging scores of the six highest-p_{T} jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance, $E_{\mathrm{T}}^{\mathrm{miss}}$ azimuthal angle, Top reconstruction BDT scores of the top-quark candidates, p_{T}, η, ϕ of the two highest-p_{T} leptons.
$tHqb$	$p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma}$, $\eta_{\gamma\gamma}$, p_{T}, invariant mass, BDT score and $\Delta R(W,b)$ of t_1, p_{T}, η of t_2, p_{T}, η of j_F, Angular variables: $\Delta\eta_{\gamma\gamma t_1}$, $\Delta\theta_{\gamma\gamma t_2}$, $\Delta\theta_{t_1 j_F}$, $\Delta\theta_{t_2 j_F}$, $\Delta\theta_{\gamma\gamma j_F}$ Invariant mass variables: $m_{\gamma\gamma j_F}$, $m_{t_1 j_F}$, $m_{t_2 j_F}$, $m_{\gamma\gamma t_1}$ Number of jets with $p_{\mathrm{T}} > 25$ GeV, Number of b-jets with $p_{\mathrm{T}} > 25$ GeV*; Number of leptons*, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance*

yy STXS

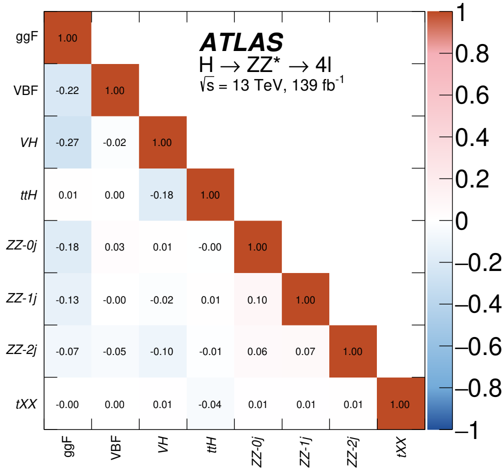


Particle-level selections
Region name
$|y_H| < 2.5$
$gg \to H$ + $gg \to Z(\to q\bar{q})H$ + $b\bar{b}H$
$p_T^H < 200$ GeV
0-jet
1-jet
$\geq$ 2-jet
$p_T^H < 10$ GeV
$p_T^H \geq 10$ GeV
$p_T^H < 60$ GeV
$60 \leq p_T^H < 120$ GeV
$120 \leq p_T^H < 200$ GeV
$m_{jj} < 350$ GeV
$p_T^H < 60$ GeV
$60 \leq p_T^H < 120$ GeV
$120 \leq p_T^H < 200$ GeV
$350 \leq m_{jj} < 700$ GeV
$700 \leq m_{jj} < 1000$ GeV
$m_{jj} \geq 1000$ GeV
$200 \leq p_T^H < 300$ GeV
$300 \leq p_T^H < 450$ GeV
$450 \leq p_T^H < 650$ GeV
$p_T^H \geq 650$ GeV
$gg \to H$, 0-jet, $p_T^H < 10$ GeV
$gg \to H$, 0-jet, $10 \leq p_T^H < 200$ GeV
$gg \to H$, 1-jet, $p_T^H < 60$ GeV
$gg \to H$, 1-jet, $60 \leq p_T^H < 120$ GeV
$gg \to H$, 1-jet, $120 \leq p_T^H < 200$ GeV
$gg \to H$, $\geq$ 2-jets, $m_{jj} < 350$ GeV, $p_T^H < 60$ GeV
$gg \to H$, $\geq$ 2-jets, $m_{jj} < 350$ GeV, $60 \leq p_T^H < 120$ GeV
$gg \to H$, $\geq$ 2-jets, $m_{jj} < 350$ GeV, $120 \leq p_T^H < 200$ GeV
$gg \to H$, $\geq$ 2-jets, $350 \leq m_{jj} < 700$ GeV, $p_T^H < 200$ GeV
$gg \to H$, $\geq$ 2-jets, $700 \leq m_{jj} < 1000$ GeV, $p_T^H < 200$ GeV
$gg \to H$, $\geq$ 2-jets, $m_{jj} \geq 1000$ GeV, $p_T^H < 200$ GeV
$gg \to H$, $200 \leq p_T^H < 300$ GeV
$gg \to H$, $300 \leq p_T^H < 450$ GeV
$gg \to H$, $450 \leq p_T^H < 650$ GeV
$gg \to H$, $p_T^H \geq 650$ GeV
$qq' \to Hqq'$ (VBF + $V(\to$ hadrons$)H$)
0-jet
1-jet
$\geq$ 2-jet
$m_{jj} < 350$ GeV
$m_{jj} < 60$ GeV
$60 \leq m_{jj} < 120$ GeV
$120 \leq m_{jj} < 350$ GeV
$350 \leq m_{jj} < 700$ GeV
700 GeV $\leq m_{jj} < 1000$ GeV
$m_{jj} \geq 1000$ GeV
$p_T^H < 200$ GeV
$p_T^H \geq 200$ GeV
$qq' \to Hqq'$, 0-jet
$qq' \to Hqq'$, 1-jet
$qq' \to Hqq'$, $\geq$ 2-jets, $m_{jj} < 60$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $60 \leq m_{jj} < 120$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $120 \leq m_{jj} < 350$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $350 \leq m_{jj} < 700$ GeV, $p_T^H < 200$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $350 \leq m_{jj} < 700$ GeV, $p_T^H \geq 200$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $700 \leq m_{jj} < 1000$ GeV, $p_T^H < 200$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $700 \leq m_{jj} < 1000$ GeV, $p_T^H \geq 200$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $m_{jj} \geq 1000$ GeV, $p_T^H < 200$ GeV
$qq' \to Hqq'$, $\geq$ 2-jets, $m_{jj} \geq 1000$ GeV, $p_T^H \geq 200$ GeV
$V(\to$ leptons$)H$
$q\bar{q}' \to WH$
$p_T^W < 75$ GeV
$75 \leq p_T^W < 150$ GeV
$150 \leq p_T^W < 250$ GeV
$p_T^W \geq 250$ GeV
$pp \to ZH$
$p_T^Z < 75$ GeV
$75 \leq p_T^Z < 150$ GeV
$150 \leq p_T^Z < 250$ GeV
$p_T^Z \geq 250$ GeV
$Z \to \ell^+\ell^-$
$Z \to \nu\bar{\nu}$
$qq \to H\ell\nu$, $p_T^V < 75$ GeV
$qq \to H\ell\nu$, $75 \leq p_T^V < 150$ GeV
$qq \to H\ell\nu$, $150 \leq p_T^V < 250$ GeV
$qq \to H\ell\nu$, $p_T^V \geq 250$ GeV
$pp \to H\ell\ell$, $p_T^V < 75$ GeV
$pp \to H\nu\bar{\nu}$, $p_T^V < 75$ GeV
$pp \to H\ell\ell$, $75 \leq p_T^V < 150$ GeV
$pp \to H\nu\bar{\nu}$, $75 \leq p_T^V < 150$ GeV
$pp \to H\ell\ell$, $150 \leq p_T^V < 250$ GeV
$pp \to H\nu\bar{\nu}$, $150 \leq p_T^V < 250$ GeV
$pp \to H\ell\ell$, $p_T^V \geq 250$ GeV
$pp \to H\nu\bar{\nu}$, $p_T^V \geq 250$ GeV
$t\bar{t}H$+tH
$t\bar{t}H$
$p_T^H < 60$ GeV
$60 \leq p_T^H < 120$ GeV
$120 \leq p_T^H < 200$ GeV
$200 \leq p_T^H < 300$ GeV
$p_T^H \geq 300$ GeV
tHW
$tHqb$
$t\bar{t}H$, $p_T^H < 60$ GeV
$t\bar{t}H$, $60 \leq p_T^H < 120$ GeV
$t\bar{t}H$, $120 \leq p_T^H < 200$ GeV
$t\bar{t}H$, $200 \leq p_T^H < 300$ GeV
$t\bar{t}H$, $p_T^H \geq 300$ GeV
tHW
$tHqb$

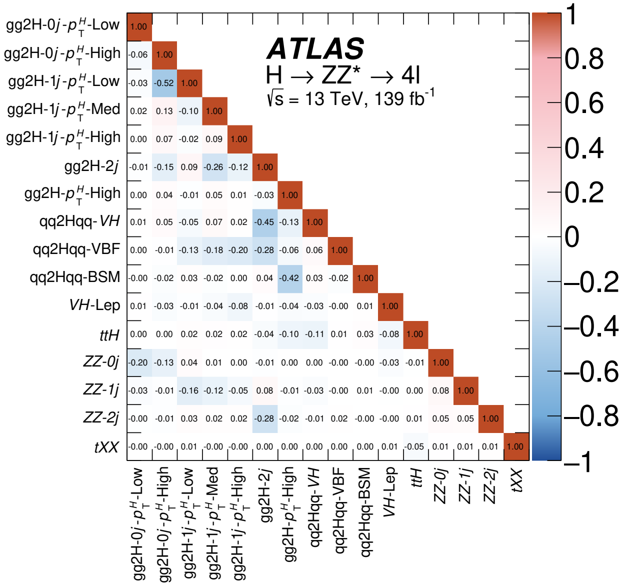
STXS ZZ


ATLAS √s = 13 TeV, 139 fb⁻¹
Production Mode
Particle-level Production Bins
STXS Reduced Stage 1.1
Reconstructed event categories Signal Region
Reconstructed event categories Sideband Region
ggF
VBF
VH
ttH
gg2H-0j-pT^H-Low
gg2H-0j-pT^H-High
gg2H-1j-pT^H-Low
gg2H-1j-pT^H-Med
gg2H-1j-pT^H-High
gg2H-2j
gg2H-pT^H-High
qq2Hqq-VH
qq2Hqq-VBF
qq2Hqq-BSM
VH-Lep
ttH
0j-pT^4l-Low
0j-pT^4l-Medium
1j-pT^4l-Low
1j-pT^4l-Medium
1j-pT^4l-High
1j-pT^4l-BSM-like
2j
2j-BSM-like
0j-pT^4l-High
VH-Lep-enriched
ttH-Had-enriched
ttH-Lep-enriched
SB - 0j
SB - 1j
SB - 2j
SB - VH-Lep-enriched
SB - tXX-enriched
m4l = [115, 130] GeV
m4l = [105, 115] U [130, 160] GeV
m4l = [105, 115] U [130, 350] GeV
Leptonic V decay
ttH Hadronic
ttH Leptonic
tXX-like

Correlation ZZ



Correlation ZZ

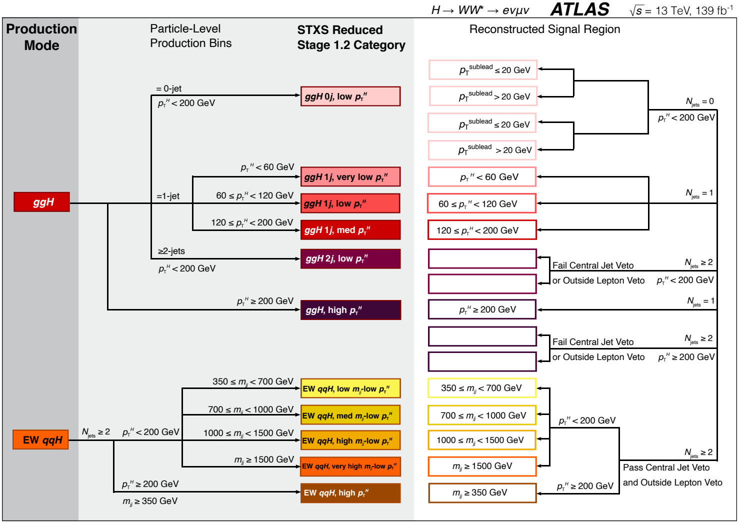


Selection ZZ

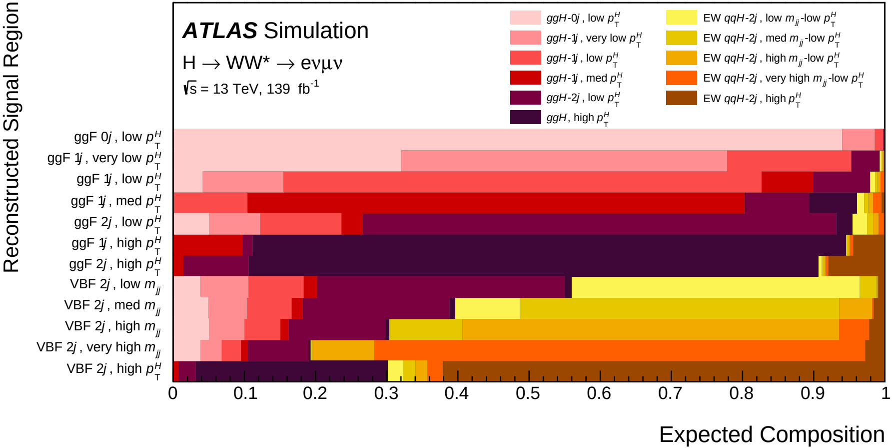
TRIGGER	
Combination of single-lepton, dilepton and trilepton triggers	
LEPTONS AND JETS	
ELECTRONS	$E_{\mathrm{T}} > 7$ GeV and $\lvert\eta\rvert < 2.47$
MUONS	$p_{\mathrm{T}} > 5$ GeV and $\lvert\eta\rvert < 2.7$, calorimeter-tagged: $p_{\mathrm{T}} > 15$ GeV
JETS	$p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$
QUADRUPLETS	
All combinations of two same-flavour and opposite-charge lepton pairs - Leading lepton pair: lepton pair with invariant mass m_{12} closest to the Z boson mass m_Z - Subleading lepton pair: lepton pair with invariant mass m_{34} second closest to the Z boson mass m_Z Classification according to the decay final state: 4μ, $2e2\mu$, $2\mu2e$, $4e$	
REQUIREMENTS ON EACH QUADRUPLET	
LEPTON RECONSTRUCTION	- Three highest-p_{T} leptons must have p_{T} greater than 20, 15 and 10 GeV - At most one calorimeter-tagged or stand-alone muon
LEPTON PAIRS	- Leading lepton pair: $50 < m_{12} < 106$ GeV - Subleading lepton pair: $m_{\mathrm{min}} < m_{34} < 115$ GeV - Alternative same-flavour opposite-charge lepton pair: $m_{\ell\ell} > 5$ GeV - $\Delta R(\ell, \ell') > 0.10$ for all lepton pairs
LEPTON ISOLATION	- The amount of isolation E_{T} after summing the track-based and 40% of the calorimeter-based contribution must be smaller than 16% of the lepton p_{T}
IMPACT PARAMETER SIGNIFICANCE	- Electrons: $\lvert d_0\rvert/\sigma(d_0) < 5$ - Muons: $\lvert d_0\rvert/\sigma(d_0) < 3$
COMMON VERTEX	- χ^2-requirement on the fit of the four lepton tracks to their common vertex
SELECTION OF THE BEST QUADRUPLET	
- Select quadruplet with m_{12} closest to m_Z from one decay final state in decreasing order of priority: 4μ, $2e2\mu$, $2\mu2e$ and $4e$ - If at least one additional (fifth) lepton with $p_{\mathrm{T}} > 12$ GeV meets the isolation, impact parameter and angular separation criteria, select the quadruplet with the highest matrix-element value	
HIGGS BOSON MASS WINDOW	
- Correction of the four-lepton invariant mass due to the FSR photons in Z boson decays - Four-lepton invariant mass window in the signal region: $115 < m_{4\ell} < 130$ GeV - Four-lepton invariant mass window in the sideband region: $105 < m_{4\ell} < 115$ GeV or $130 < m_{4\ell} < 160$ (350) GeV	

NN ZZ

Category	Processes	MLP	Lepton RNN	Jet RNN	Discriminant
$0j$-$p_T^{4\ell}$-Low $0j$-$p_T^{4\ell}$-Med	ggF, ZZ^*	$p_T^{4\ell}$, D_{ZZ^*}, m_{12}, m_{34}, $\lvert\cos\theta^*\rvert$, $\cos\theta_1$, ϕ_{ZZ}	p_T^ℓ, η_ℓ	-	$\mathrm{NN}_{\mathrm{ggF}}$
$1j$-$p_T^{4\ell}$-Low	ggF, VBF, ZZ^*	$p_T^{4\ell}$, p_T^j, η_j, $\Delta R_{4\ell j}$, D_{ZZ^*}	p_T^ℓ, η_ℓ	-	$\mathrm{NN}_{\mathrm{VBF}}$ for $\mathrm{NN}_{ZZ} < 0.25$ NN_{ZZ} for $\mathrm{NN}_{ZZ} > 0.25$
$1j$-$p_T^{4\ell}$-Med	ggF, VBF, ZZ^*	$p_T^{4\ell}$, p_T^j, η_j, E_T^{miss}, $\Delta R_{4\ell j}$, D_{ZZ^*}, $\eta_{4\ell}$	p_T^ℓ, η_ℓ	-	$\mathrm{NN}_{\mathrm{VBF}}$ for $\mathrm{NN}_{ZZ} < 0.25$ NN_{ZZ} for $\mathrm{NN}_{ZZ} > 0.25$
$1j$-$p_T^{4\ell}$-High	ggF, VBF	$p_T^{4\ell}$, p_T^j, η_j, E_T^{miss}, $\Delta R_{4\ell j}$, $\eta_{4\ell}$	p_T^ℓ, η_ℓ	-	$\mathrm{NN}_{\mathrm{VBF}}$
$2j$	ggF, VBF, VH	m_{jj}, $p_T^{4\ell jj}$	p_T^ℓ, η_ℓ	p_T^j, η_j	$\mathrm{NN}_{\mathrm{VBF}}$ for $\mathrm{NN}_{VH} < 0.2$ NN_{VH} for $\mathrm{NN}_{VH} > 0.2$
$2j$-BSM-like	ggF, VBF	$\eta_{ZZ}^{\mathrm{Zepp}}$, $p_T^{4\ell jj}$	p_T^ℓ, η_ℓ	p_T^j, η_j	$\mathrm{NN}_{\mathrm{VBF}}$
VH-Lep-enriched	VH, ttH	N_{jets}, $N_{b\text{-jets},70\%}$, E_T^{miss}, H_T	p_T^ℓ	-	NN_{ttH}
ttH-Had-enriched	ggF, ttH, tXX	$p_T^{4\ell}$, m_{jj}, $\Delta R_{4\ell j}$, $N_{b\text{-jets},70\%}$,	p_T^ℓ, η_ℓ	p_T^j, η_j	NN_{ttH} for $\mathrm{NN}_{tXX} < 0.4$ NN_{tXX} for $\mathrm{NN}_{tXX} > 0.4$


H → WW* → eνμν
ATLAS
√s = 13 TeV, 139 fb-1
Production Mode
Particle-Level Production Bins
STXS Reduced Stage 1.2 Category
Reconstructed Signal Region
ggH
EW qqH
= 0-jet
pTH < 200 GeV
=1-jet
≥2-jets
pTH < 60 GeV
60 ≤ pTH < 120 GeV
120 ≤ pTH < 200 GeV
pTH ≥ 200 GeV
Njets ≥ 2
pTH < 200 GeV
350 ≤ mjj < 700 GeV
700 ≤ mjj < 1000 GeV
1000 ≤ mjj < 1500 GeV
mjj ≥ 1500 GeV
mjj ≥ 350 GeV
ggH 0j, low pTH
ggH 1j, very low pTH
ggH 1j, low pTH
ggH 1j, med pTH
ggH 2j, low pTH
ggH, high pTH
EW qqH, low mjj-low pTH
EW qqH, med mjj-low pTH
EW qqH, high mjj-low pTH
EW qqH, very high mjj-low pTH
EW qqH, high pTH
pTsublead ≤ 20 GeV
pTsublead > 20 GeV
Njets = 0
Njets = 1
Fail Central Jet Veto
or Outside Lepton Veto
Njets ≥ 2
pTH ≥ 200 GeV
Pass Central Jet Veto
and Outside Lepton Veto

WW purity


ATLAS Simulation
H → WW* → eνμν
√s = 13 TeV, 139 fb-1
ggH-0j , low p_T^H
ggH-1j , very low p_T^H
ggH-1j , low p_T^H
ggH-1j , med p_T^H
ggH-2j , low p_T^H
ggH, high p_T^H
EW qqH-2j , low m_jj-low p_T^H
EW qqH-2j , med m_jj-low p_T^H
EW qqH-2j , high m_jj-low p_T^H
EW qqH-2j , very high m_jj-low p_T^H
EW qqH-2j , high p_T^H
Reconstructed Signal Region
ggF 0j , low p_T^H
ggF 1j , very low p_T^H
ggF 1j , low p_T^H
ggF 1j , med p_T^H
ggF 2j , low p_T^H
ggF 1j , high p_T^H
ggF 2j , high p_T^H
VBF 2j , low m_jj
VBF 2j , med m_jj
VBF 2j , high m_jj
VBF 2j , very high m_jj
VBF 2j , high p_T^H
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Expected Composition

WW generators

Process	Matrix element (alternative)	PDF set	UEPS model (alternative model)	Prediction order for total cross section
ggF H	POWHEG BOX v2 NNLOPS (MG5_aMC@NLO)	PDF4LHC15NNLO	PYTHIA 8 (HERWIG 7)	$\mathrm{N^3LO}$ QCD + NLO EW
VBF H	POWHEG BOX v2 (MG5_aMC@NLO)	PDF4LHC15NLO	PYTHIA 8 (HERWIG 7)	NNLO QCD + NLO EW
VH excl. $gg \to ZH$	POWHEG BOX v2	PDF4LHC15NLO	PYTHIA 8	NNLO QCD + NLO EW
$t\bar{t}H$	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8	NLO
$gg \to ZH$	POWHEG BOX v2	PDF4LHC15NLO	PYTHIA 8	NNLO QCD + NLO EW
$qq \to WW$	SHERPA 2.2.2 (Q_{cut})	NNPDF3.0NNLO	SHERPA 2.2.2 (SHERPA 2.2.2 ; μ_{q})	NLO
$qq \to WWqq$	MG5_aMC@NLO	NNPDF3.0NLO	PYTHIA 8 (HERWIG 7)	LO
$gg \to WW/ZZ$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	NLO
$WZ/V\gamma^*/ZZ$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	NLO
$V\gamma$	SHERPA 2.2.8	NNPDF3.0NNLO	SHERPA 2.2.8	NLO
VVV	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	NLO
$t\bar{t}$	POWHEG BOX v2 (MG5_aMC@NLO)	NNPDF3.0NLO	PYTHIA 8 (HERWIG 7)	NNLO+NNLL
Wt	POWHEG BOX v2 (MG5_aMC@NLO)	NNPDF3.0NLO	PYTHIA 8 (HERWIG 7)	NNLO
Z/γ^*	SHERPA 2.2.1 (MG5_aMC@NLO)	NNPDF3.0NNLO	SHERPA 2.2.1	NNLO

WW systematics

Source	$\frac{\Delta\sigma_{\text{ggF+VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{ggF+VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{ggF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{ggF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	4.6	5.1	15
Total systematic uncertainties	9.5	11	18
MC statistical uncertainties	3.0	3.8	4.9
Experimental uncertainties	5.2	6.3	6.7
Flavor tagging	2.3	2.7	1.0
Jet energy scale	0.9	1.1	3.7
Jet energy resolution	2.0	2.4	2.1
$E_{\text{T}}^{\text{miss}}$	0.7	2.2	4.9
Muons	1.8	2.1	0.8
Electrons	1.3	1.6	0.4
Fake factors	2.1	2.4	0.8
Pileup	2.4	2.5	1.3
Luminosity	2.1	2.0	2.2
Theoretical uncertainties	6.8	7.8	16
ggF	3.8	4.3	4.6
VBF	3.2	0.7	12
WW	3.5	4.2	5.5
Top	2.9	3.8	6.4
$Z\tau\tau$	1.8	2.3	1.0
Other VV	2.3	2.9	1.5
Other Higgs	0.9	0.4	0.4
Background normalizations	3.6	4.5	4.9
WW	2.2	2.8	0.6
Top	1.9	2.3	3.4
$Z\tau\tau$	2.7	3.1	3.4
Total	10	12	23

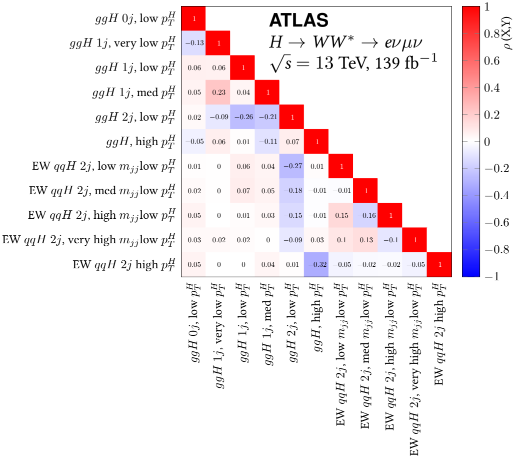
WW signal regions selection

<table>
<tr><th>Category</th><th>$N_{\text{jet},(p_T>30\text{ GeV})}=0$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})}=1$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})}\geq 2$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})}\geq 2$ VBF</th></tr>
<tr><td rowspan="2">Preselection</td><td colspan="4">Two isolated, different-flavor leptons ($\ell = e, \mu$) with opposite charge
$p_T^{\text{lead}} > 22$ GeV , $p_T^{\text{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="3">$p_T^{\text{miss}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="4">$N_{b\text{-jet},(p_T>20\text{ GeV})}=0$</td></tr>
<tr><td rowspan="2">$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$
$p_T^{\ell\ell} > 30$ GeV</td><td colspan="3">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$\max\left(m_T^{\ell}\right) > 50$ GeV</td><td colspan="2"></td></tr>
<tr><td rowspan="3">$H\to WW^*\to e\nu\mu\nu$
topology</td><td colspan="3">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td rowspan="3">central jet veto
outside lepton veto
$m_{jj} > 120$ GeV</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>fail central jet veto
or
fail outside lepton veto</td></tr>
<tr><td>$|m_{jj} - 85| > 15$ GeV
or
$\Delta y_{jj} > 1.2$</td></tr>
<tr><td>Discriminating fit variable</td><td colspan="3">m_T</td><td>DNN</td></tr>
</table>

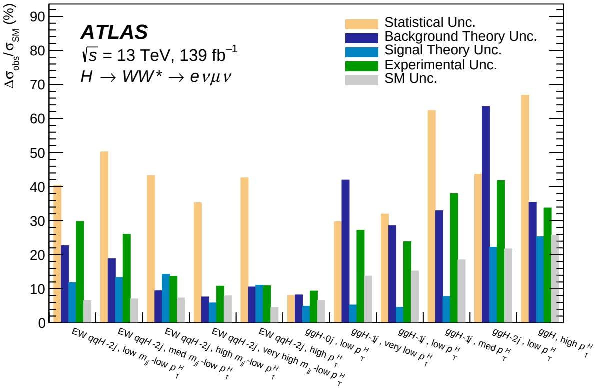
WW control regions selection

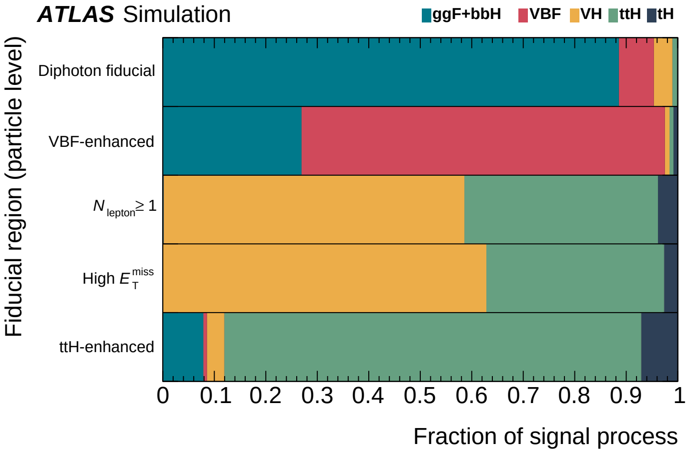
CR	$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF
$qq \to WW$	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$			
	$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$ GeV $55 < m_{\ell\ell} < 110$ GeV $\Delta\phi_{\ell\ell} < 2.6$	$m_{\ell\ell} > 80$ GeV		
		$\lvert m_{\tau\tau} - m_Z \rvert > 25$ GeV $\max\left(m_T^{\ell}\right) > 50$ GeV	$m_{\tau\tau} < m_Z - 25$ GeV $m_{T2} > 165$ GeV	
			fail central jet veto or fail outside lepton veto	
			$\lvert m_{jj} - 85 \rvert > 15$ GeV or $\Delta y_{jj} > 1.2$	
$t\bar{t}/Wt$	$N_{b\text{-jet},(20<p_T<30\text{ GeV})} > 0$	$N_{b\text{-jet},(p_T>30\text{ GeV})} = 1$ $N_{b\text{-jet},(20<p_T<30\text{ GeV})} = 0$	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 1$
	$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$ GeV $\Delta\phi_{\ell\ell} < 2.8$	$m_{\tau\tau} < m_Z - 25$ GeV		
		$\max\left(m_T^{\ell}\right) > 50$ GeV	$m_{\ell\ell} > 80$ GeV $\Delta\phi_{\ell\ell} < 1.8$ $m_{T2} < 165$ GeV	
			fail central jet veto or fail outside lepton veto	central jet veto outside lepton veto
			$\lvert m_{jj} - 85 \rvert > 15$ GeV or $\Delta y_{jj} > 1.2$	
Z/γ^*	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$			
	$m_{\ell\ell} < 80$ GeV no p_T^{miss} requirement		$m_{\ell\ell} < 55$ GeV	$m_{\ell\ell} < 70$ GeV
	$\Delta\phi_{\ell\ell} > 2.8$	$m_{\tau\tau} > m_Z - 25$ GeV		$\lvert m_{\tau\tau} - m_Z \rvert \leq 25$ GeV
		$\max\left(m_T^{\ell}\right) > 50$ GeV	fail central jet veto or fail outside lepton veto	central jet veto outside lepton veto
			$\lvert m_{jj} - 85 \rvert > 15$ GeV or $\Delta y_{jj} > 1.2$	

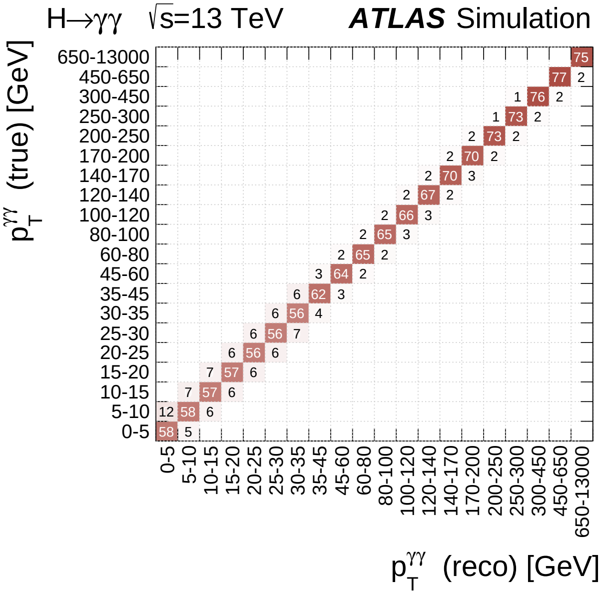
WW correlations

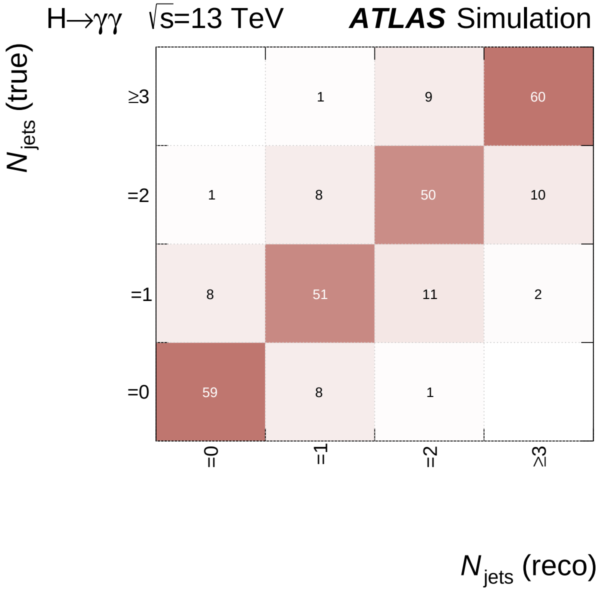


WW Systematics

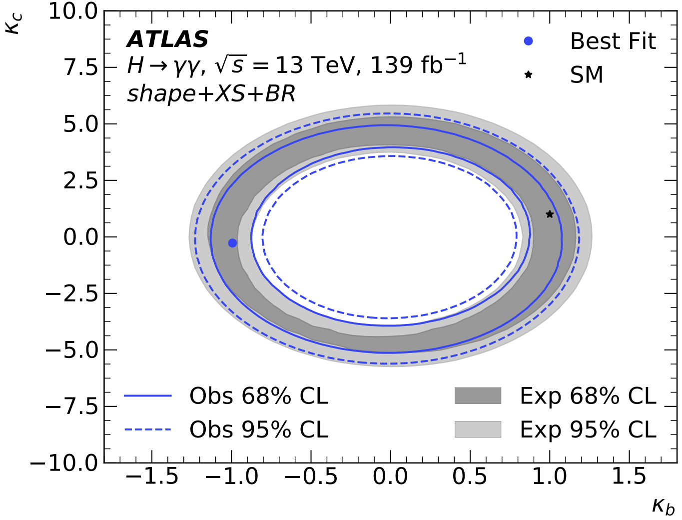



ATLAS Simulation
ggF+bbH
VBF
VH
ttH
tH
Fiducial region (particle level)
Diphoton fiducial
VBF-enhanced
$N_{lepton} \geq 1$
High E_T^{miss}
ttH-enhanced
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Fraction of signal process


H→γγ √s=13 TeV
ATLAS Simulation
$p_T^{\gamma\gamma}$ (true) [GeV]
$p_T^{\gamma\gamma}$ (reco) [GeV]
650-13000
450-650
300-450
250-300
200-250
170-200
140-170
120-140
100-120
80-100
60-80
45-60
35-45
30-35
25-30
20-25
15-20
10-15
5-10
0-5
75
77 2
1 76 2
1 73 2
2 73 2
2 70 2
2 70 3
2 67 2
2 66 3
2 65 3
2 65 2
3 64 2
6 62 3
6 56 4
6 56 7
6 56 6
7 57 6
7 57 6
12 58 6
58 5


H→γγ √s=13 TeV
ATLAS Simulation
N_jets (true)
≥3
=2
=1
=0
1
9
60
1
8
50
10
8
51
11
2
59
8
1
=0
=1
=2
≥3
N_jets (reco)

xsec yy quark couplings with shape



xsec yy inclusive systematics

Source	Uncertainty [%]
Statistical uncertainty	7.5
Systematic uncertainties	6.4
Background modelling (spurious signal)	3.8
Photon energy scale & resolution	3.6
Photon selection efficiency	2.6
Luminosity	1.8
Pile-up modelling	1.4
Trigger efficiency	1.0
Theoretical modelling	0.4
Total	9.8

Higgs boson and LHC productions