Measurements of gluon fusion production of the Higgs boson in $H \to WW^* \to e\nu\mu\nu$ decays in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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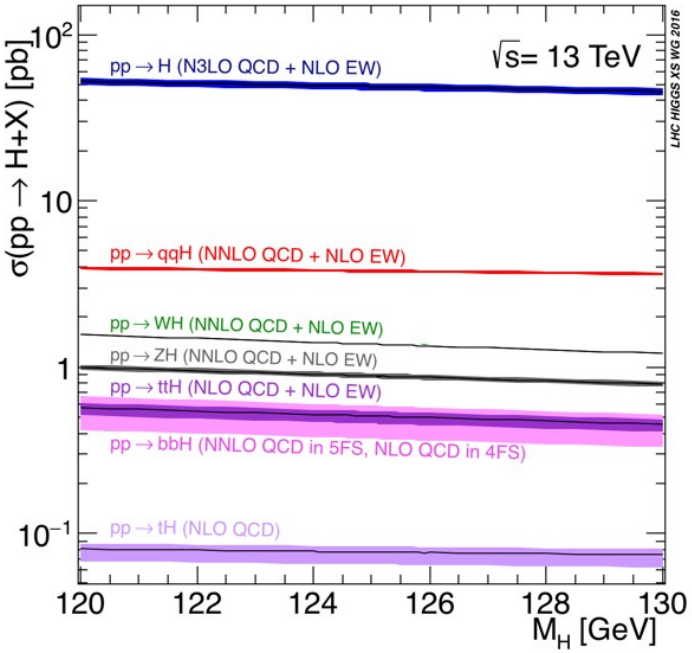
arXiv:2207.00338v1

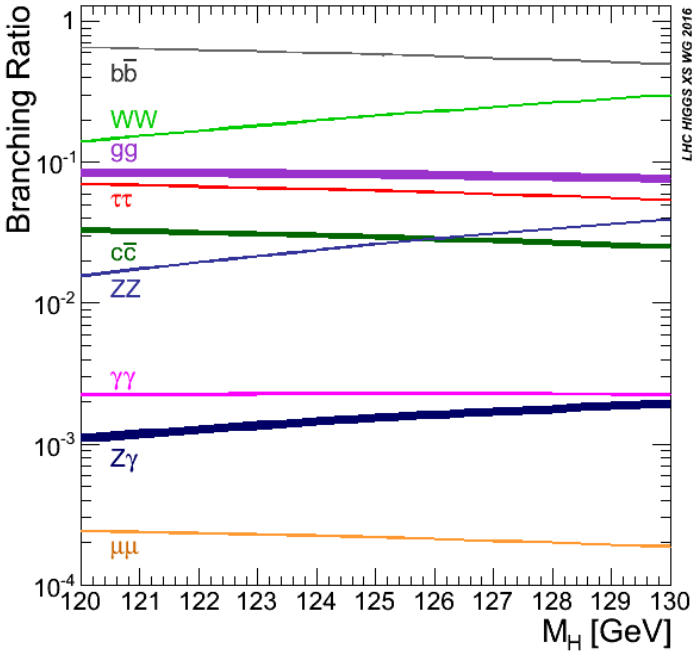
H → WW* → ℓνℓν

twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG?redirectedfrom=LHCPhysics.LHCHXSWG#Latest_plots

H → WW* channel has a large branching ratio ($\mathscr{B} \approx 21.6\%$) and a clear signature — two isolated leptons, sizeable missing E_T, only m_T reconstruction is possible. eνμν final state (0.5% cases from total H BR) is preferred due to absence of DY background Z→ee/μμ, only Z→ττ→eμ+X

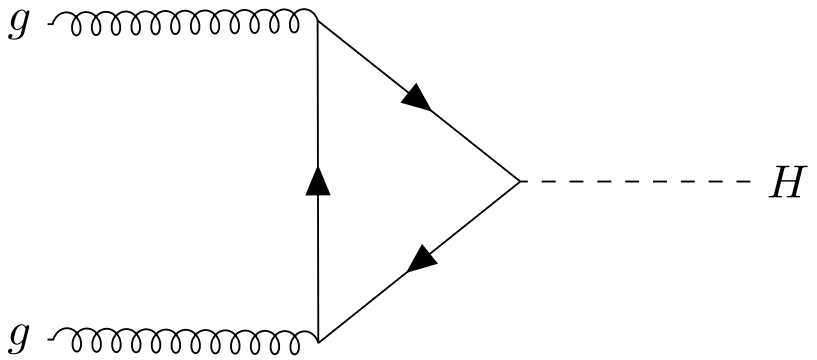
$$m_T = \sqrt{\left(E_T(\ell\ell) + E_T^{miss}\right)^2 - |\vec{p}_T(\ell\ell) + \vec{E}_{T^{miss}}|^2} \quad E_T(\ell\ell) = \sqrt{|\vec{p}_T(\ell\ell)|^2 + m(\ell\ell)^2}$$

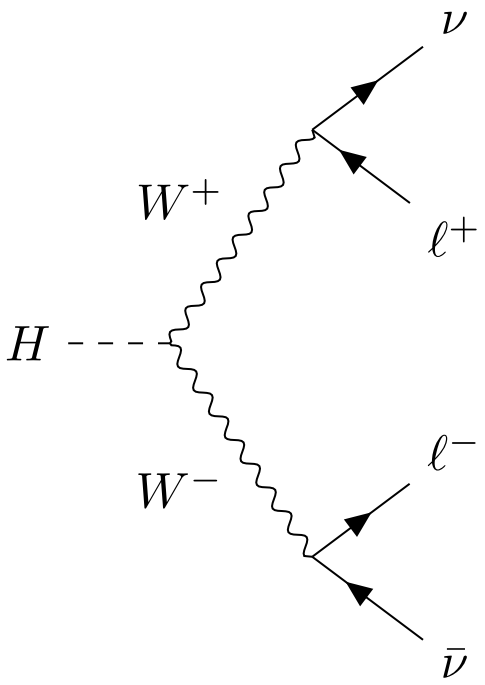


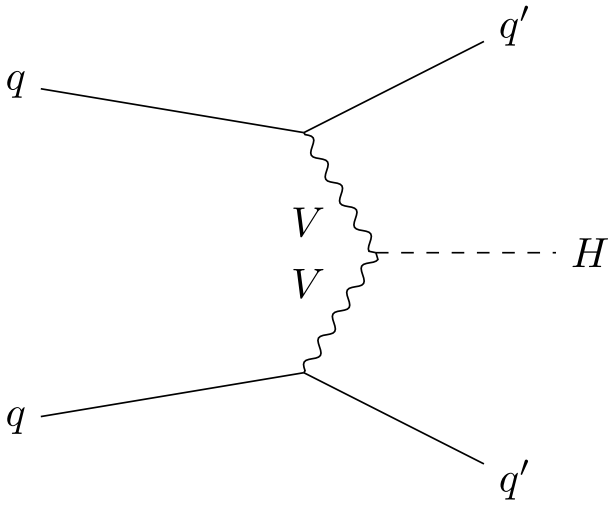


Production cross sections and branching ratios for Higgs boson

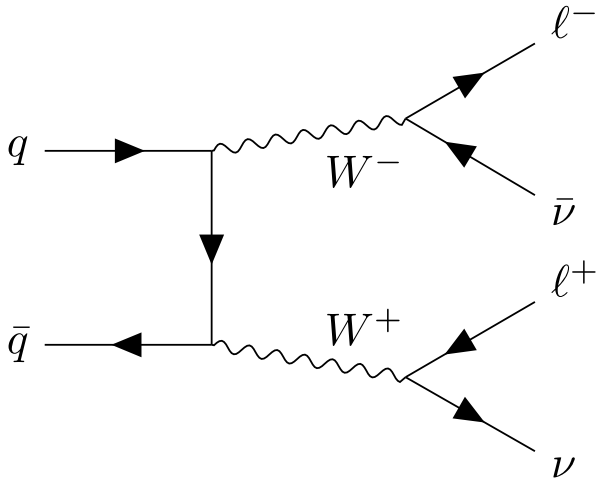
Signal processes

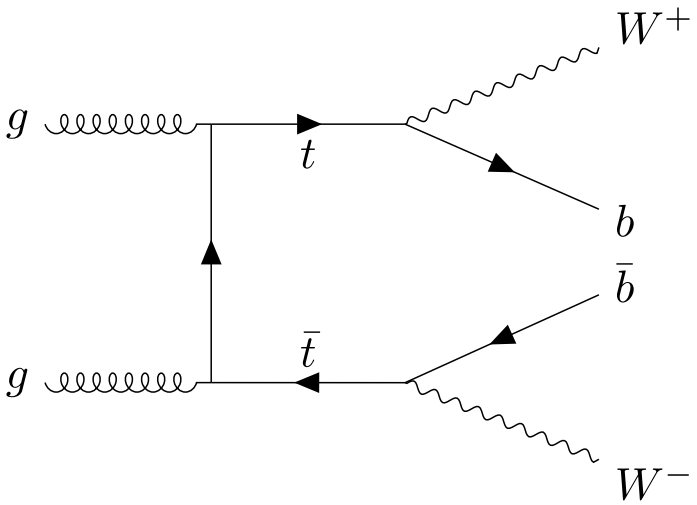


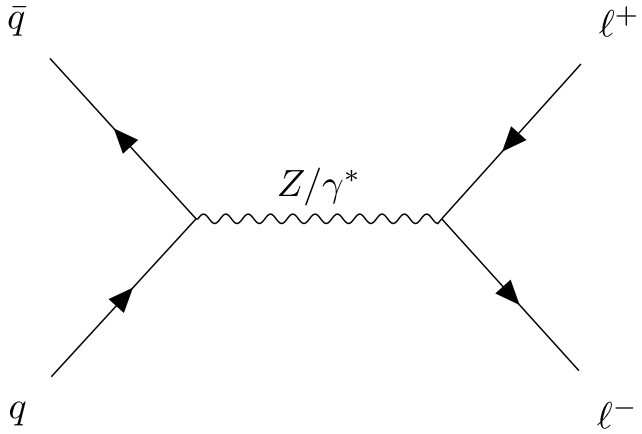


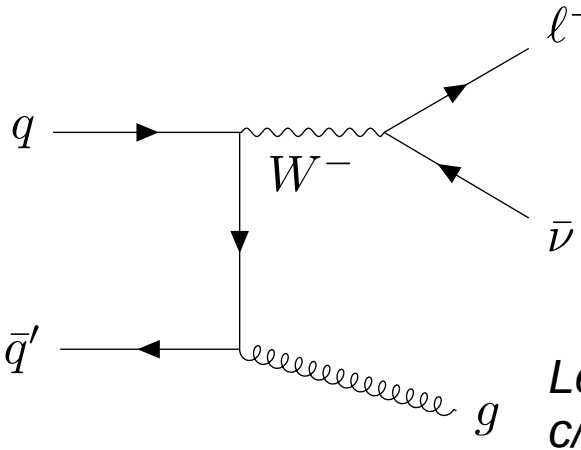


Main background processes



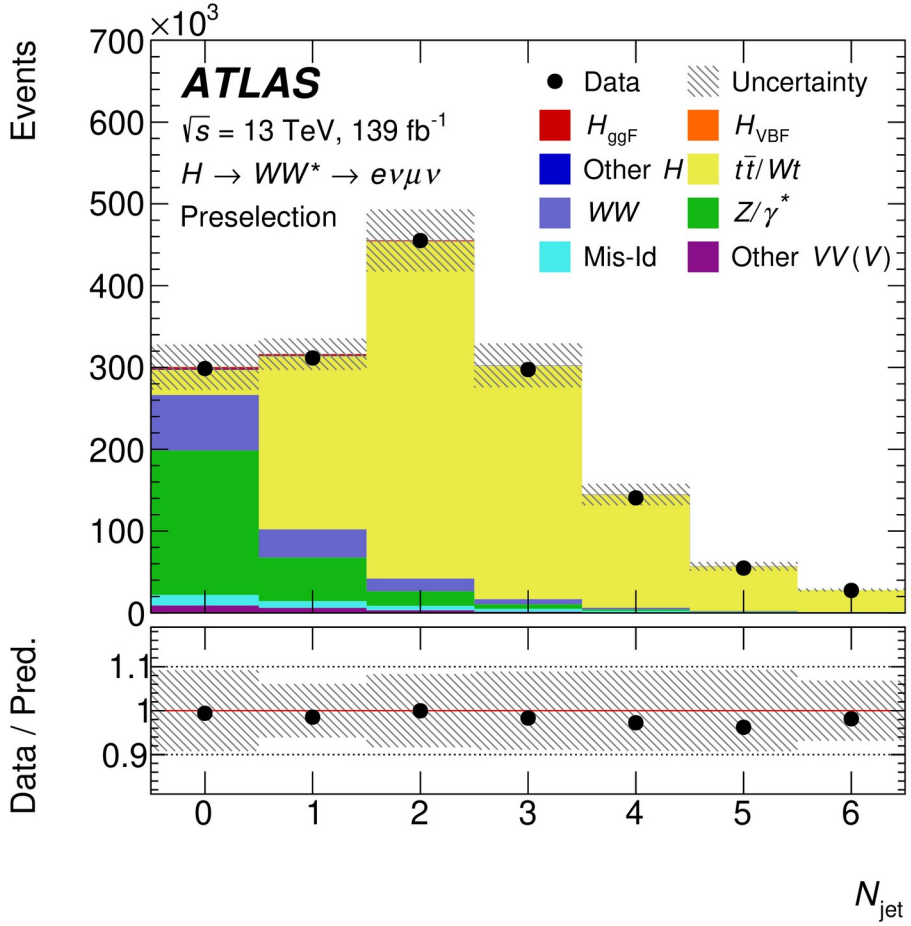






Lepton from c/b decay

Jet multiplicity



- Several signal regions defined in accordance with number of jets present in event
- N_{jets}: 0, 1, 2+
- 2+ is split between ggF and VBF production modes
- Data are well described by MC simulations

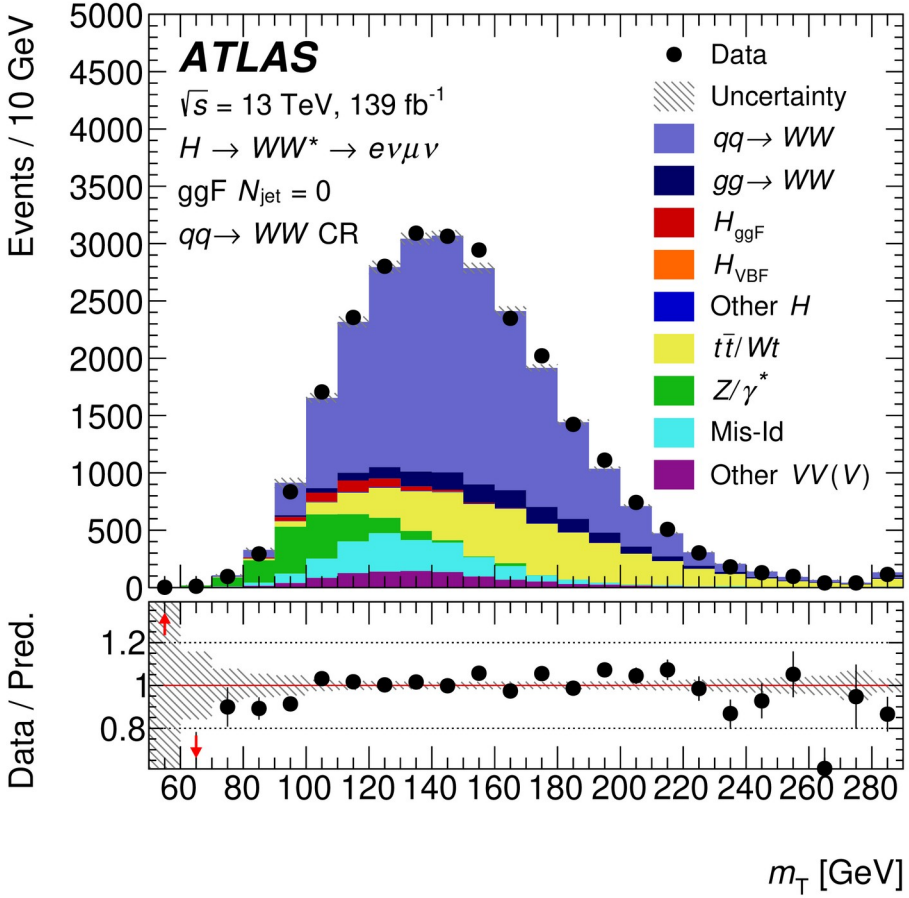
➔ all plots and tables are taken from the reference given on the front page unless stated otherwise

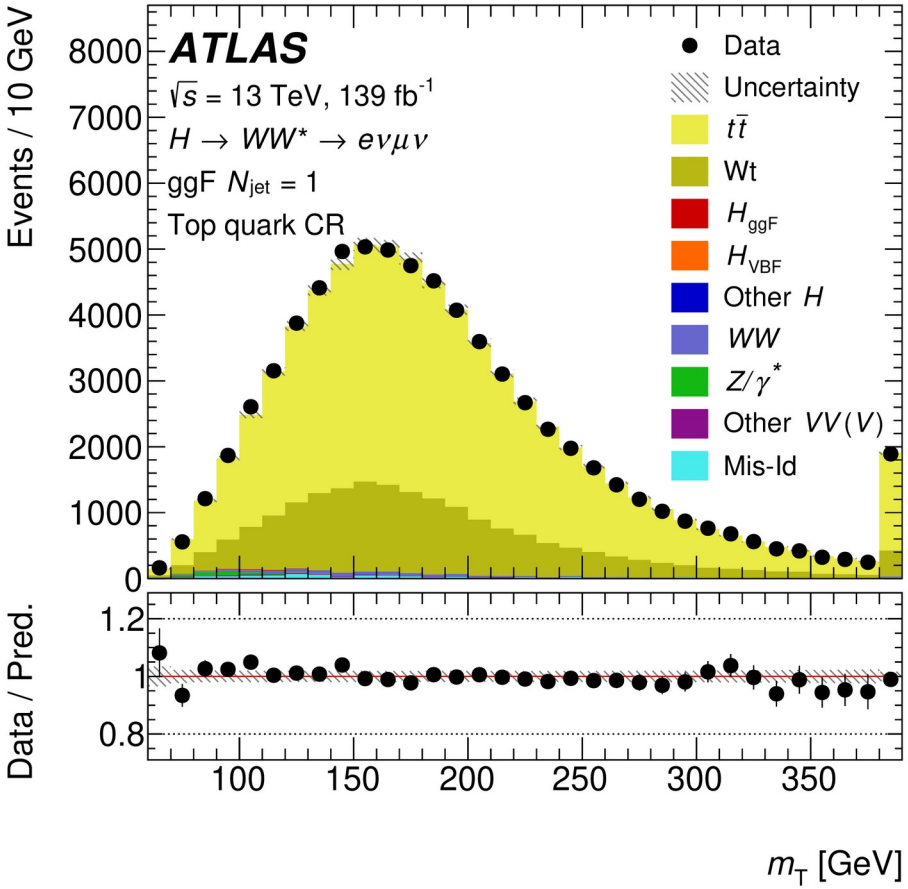
Event selection

Category	$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ ggF
Preselection	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, $p_T^{\text{miss}} > 20$ GeV		
Background rejection	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$		
	$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$ GeV	$m_{\tau\tau} < m_Z - 25$ GeV $\max\left(m_T^{\ell}\right) > 50$ GeV	
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 55$ GeV, $\Delta\phi_{\ell\ell} < 1.8$		
			fail central jet veto OR fail outside lepton veto
			$\lvert m_{jj} - 85\rvert > 15$ GeV OR $\Delta y_{jj} > 1.2$
Discriminating fit variable	m_T		

Anti-CJV (Central Jet Veto) and Anti-OLV (Outside Lepton Veto) provide orthogonality with VBF selection (see Ramakoti's talk)

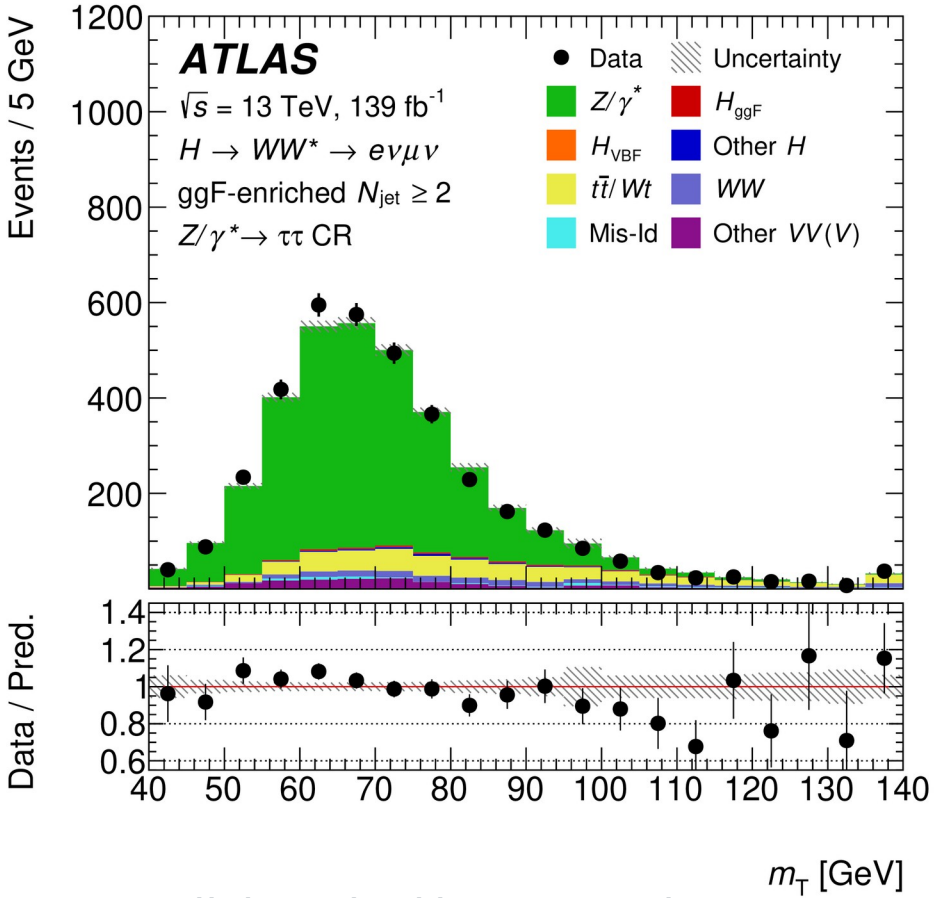
Control Regions for the most interesting background, 0/1 jet

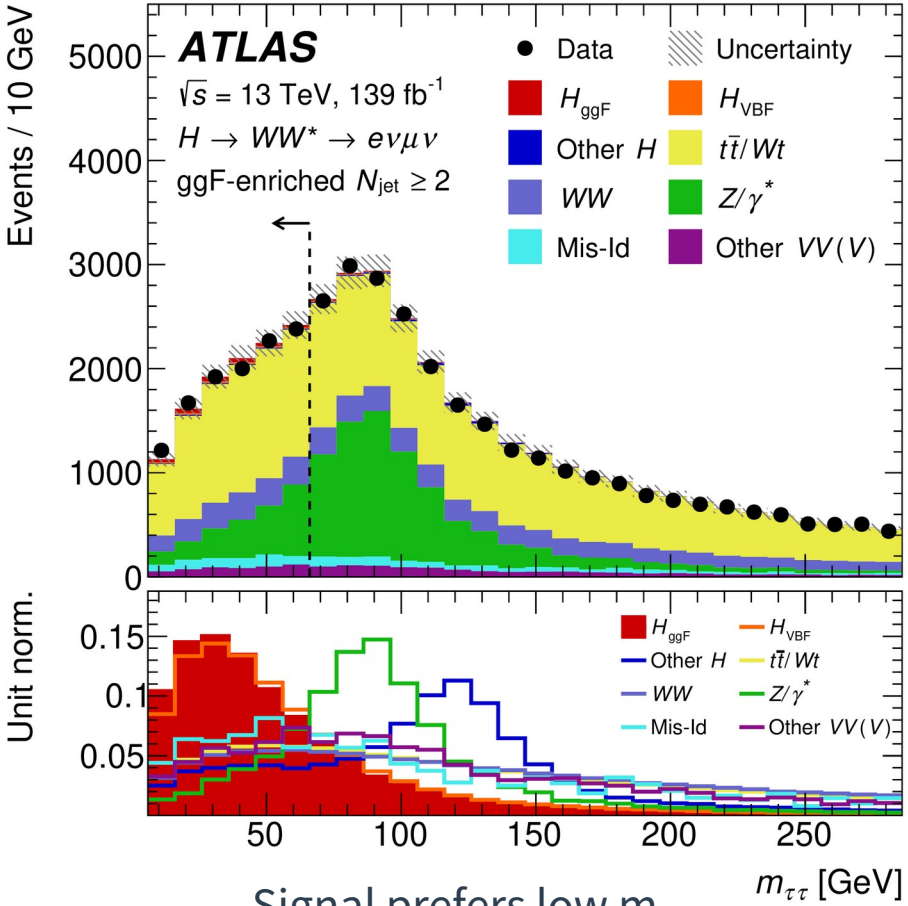




Data are well described by MC simulations

2 jet Z→ττ Control Region and SR selection





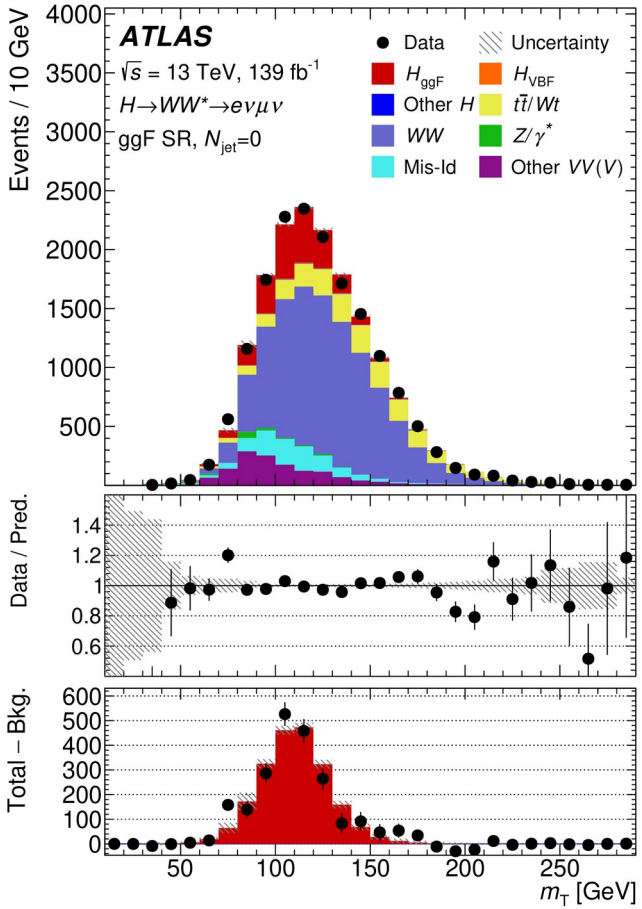
Data are well described by MC simulations

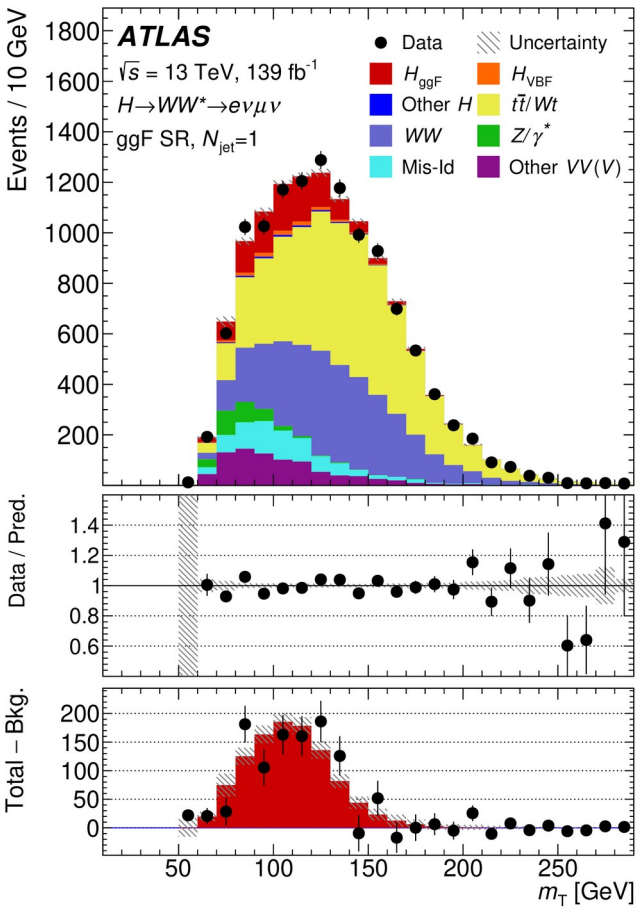
Signal prefers low $m_{\tau\tau}$

Post-fit yields in SRs

Process	$N_{\text{jet}} = 0$ ggF	$N_{\text{jet}} = 1$ ggF	$N_{\text{jet}} \geq 2$ ggF
H_{ggF}	2100 ± 220	1100 ± 130	440 ± 90
H_{VBF}	23 ± 9	103 ± 30	46 ± 12
Other Higgs	40 ± 20	55 ± 28	55 ± 27
WW	9700 ± 350	3500 ± 410	1500 ± 470
$t\bar{t}/Wt$	2200 ± 210	5300 ± 340	6100 ± 500
Z/γ^*	140 ± 50	280 ± 40	930 ± 70
Other VV	1400 ± 130	840 ± 100	470 ± 90
Mis-Id	1200 ± 130	720 ± 90	470 ± 50
Total	$16\,770 \pm 130$	$11\,940 \pm 110$	$10\,030 \pm 100$
Observed	16 726	11 917	9 982

ggF 0Jet, 1 Jet Signal Regions: m_T distributions

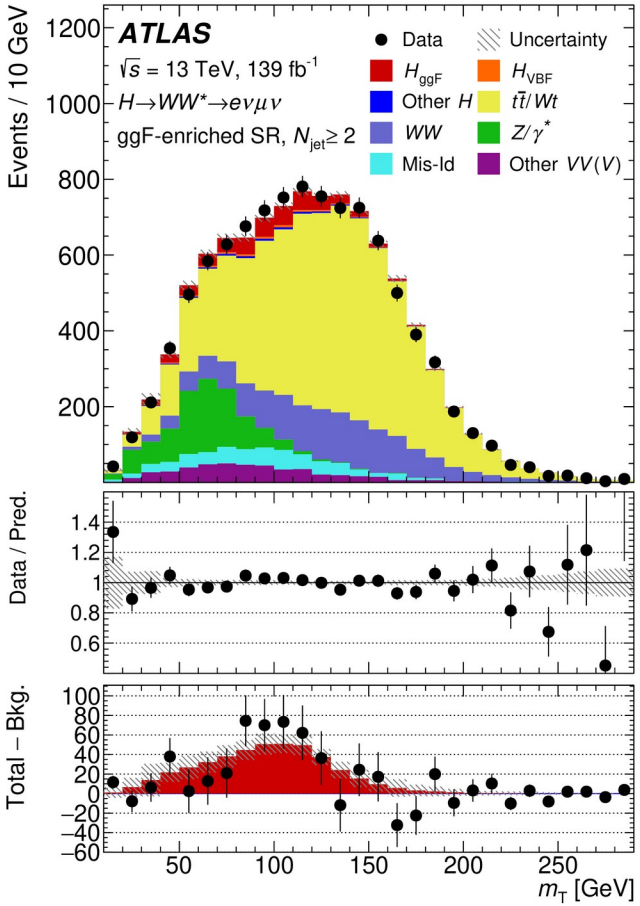


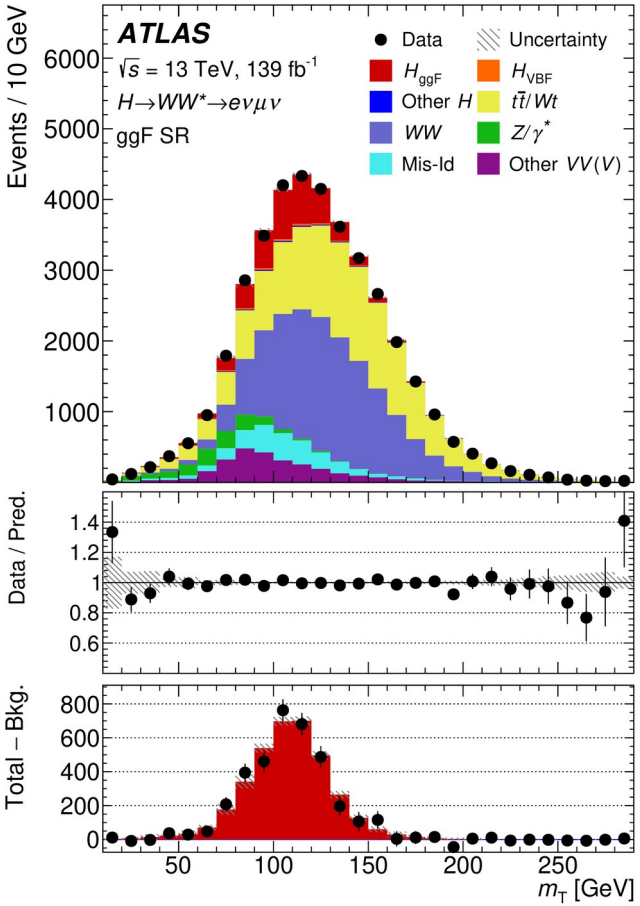


Clear signal is seen after background subrtraction.

The maximum is wide due to moderate m_T-resolution mostly due to rather poor E_T^{miss} resolution.

ggF 2Jets Signal Region, Total ggF: m_T distributions

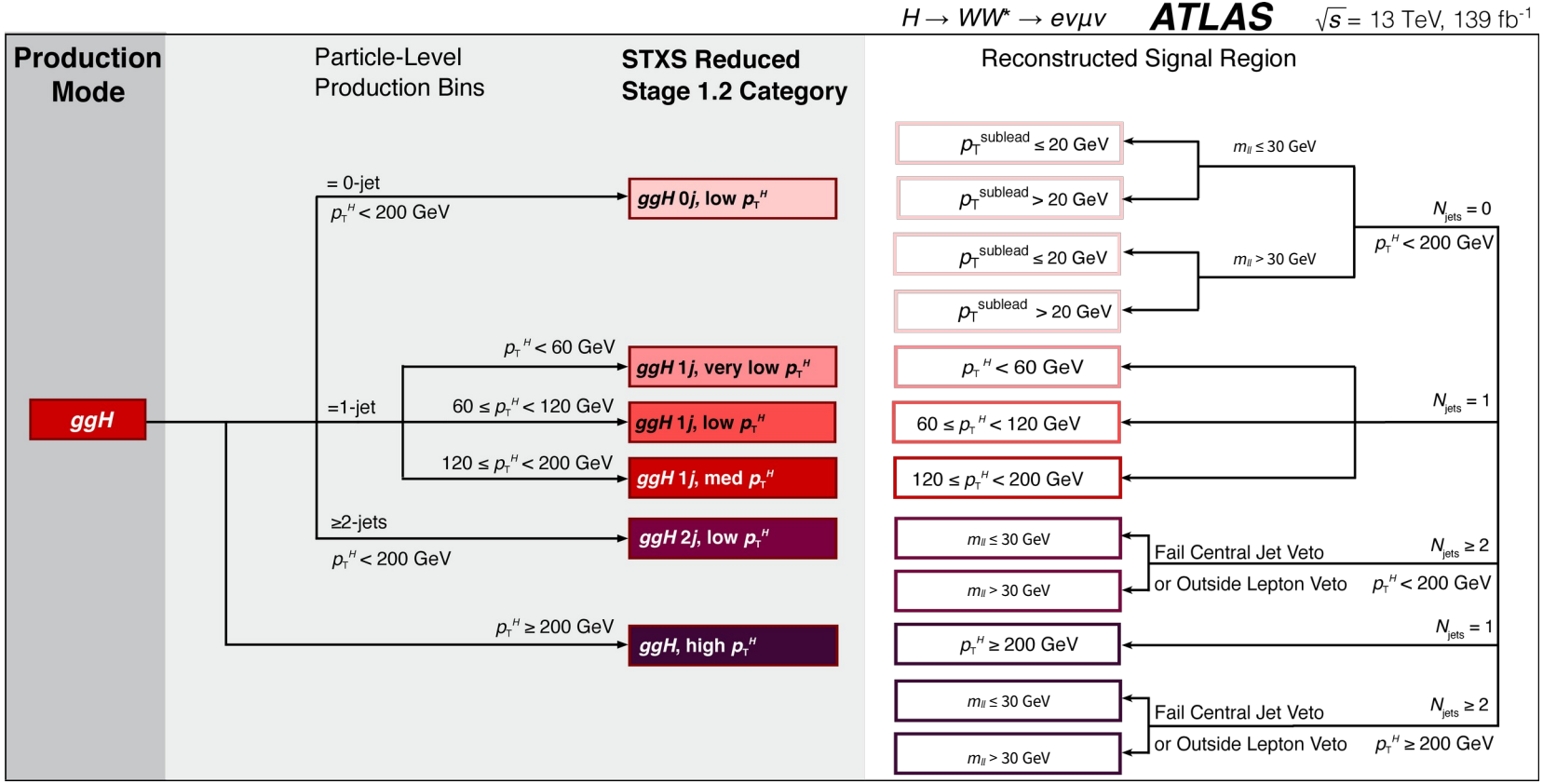




Clear signal is seen after background subrtraction.

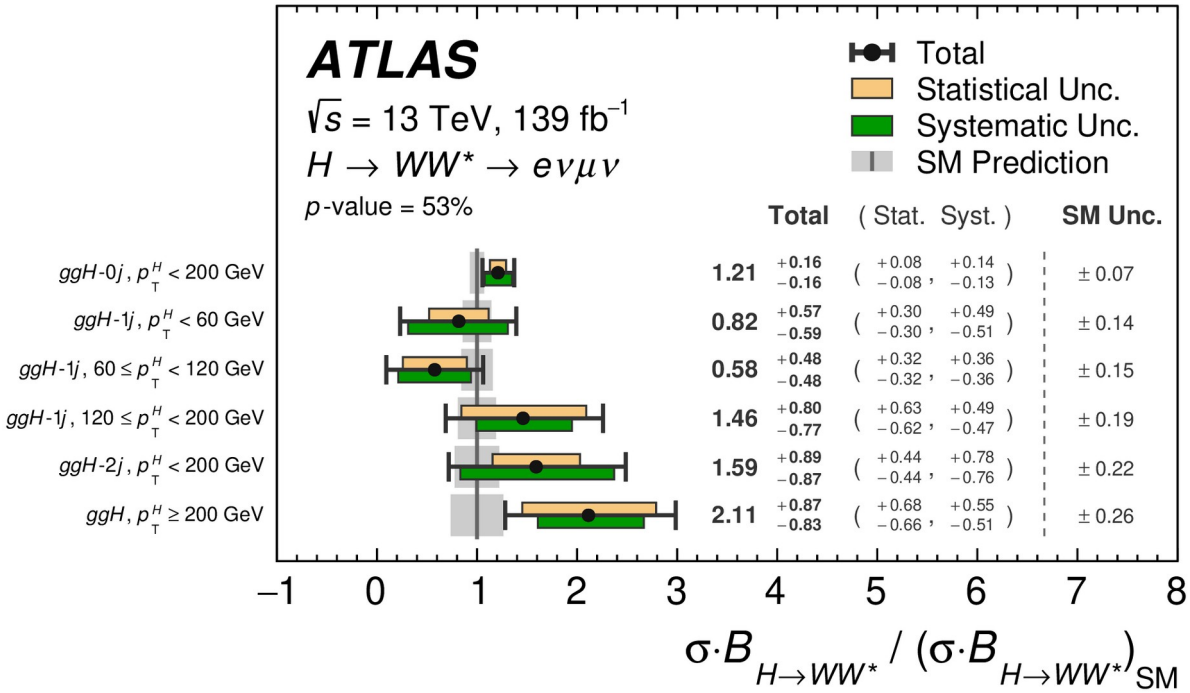
The maximum is wide due to moderate m_T-resolution mostly due to rather poor E_T^{miss} resolution.

(Reduced) STXS Stage 1.2 (Simplified Template Cross Sections)



Each SR and corresponding CR is further divided providing independent XS measurements in kinematically different sub-regions

Measured ggF cross-sections, total and STXS



$$\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 12.0 \pm 1.4 \text{ pb}$$

$$= 12.0 \pm 0.6 \text{ (stat.)}^{+0.9}_{-0.8} \text{ (exp. syst.)}^{+0.6}_{-0.5} \text{ (sig. theo.)} \pm 0.8 \text{ (bkg. theo.) pb}$$

compared to the SM predicted values of 10.4 ± 0.5 pb

ATLAS and CMS results for ggF H→WW*

- **ATLAS Run1** PRD 92 (2015) 012006 $\mu_{ggF} = 1.02^{+0.29}_{-0.26}$
- **ATLAS Run2 36 fb^{-1}** Phys. Lett. B 789 (2019) 508 $\mu_{ggF} = 1.10^{+0.21}_{-0.20}$
- **ATLAS Run2 139 fb^{-1}** Current $\mu_{ggF} = 1.15^{+0.14}_{-0.13}$
  Factor of 1.5 improvement
- **CMS Run1** JHEP01 (2014) 096 $\mu_{ggF} = 0.76 \pm 0.21$
- **CMS 138 fb^{-1}** arXiv:2206.09466 $\mu_{ggF} = 0.92^{+0.11}_{-0.10}$
  same-flavour channel included
- Signal strength is measured with ~12% precision in both experiments

Conclusion

The H→WW*→eνμν decay channel was used to measure Higgs boson production by gluon–gluon fusion.

1) The ggF cross section times the H→WW* branching ratio is measured to be 12.0 ± 1.4 pb, in agreement with the Standard Model prediction of 10.4 ± 0.6 pb.
2) This measurement is significantly more precise than the previous results from ATLAS because of several improvements to the analysis in addition to the larger dataset, most notably the inclusion of a dedicated ggF ⩾2jets signal region.
3) Higgs boson production in the H→ WW* decay channel is further characterized through STXS measurements in a total of 6 categories.
4) The STXS results are compatible with the Standard Model predictions.

backup

Event selections for Control Regions

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
$qq \to WW$	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$		
	$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$ 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 $\Delta y_{jj} > 1.2$
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
	$\Delta\phi_{\ell\ell} > 2.8$	$m_{\tau\tau} > m_Z - 25$ GeV	
		$\max\left(m_T^{\ell}\right) > 50$ GeV	fail central jet veto or fail outside lepton veto
			$\lvert m_{jj} - 85 \rvert > 15$ GeV or $\Delta y_{jj} > 1.2$

Event selections for Control Regions

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
$t\bar{t}/Wt$	$N_{b\text{-jet},(20<p_T<30\text{ GeV})} > 0$ $\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$ GeV $\Delta\phi_{\ell\ell} < 2.8$	$N_{b\text{-jet},(p_T>30\text{ GeV})} = 1$ $N_{b\text{-jet},(20<p_T<30\text{ GeV})} = 0$	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$
		$m_{\tau\tau} < m_Z - 25$ 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
			$\lvert m_{jj} - 85\rvert > 15$ GeV or $\Delta y_{jj} > 1.2$

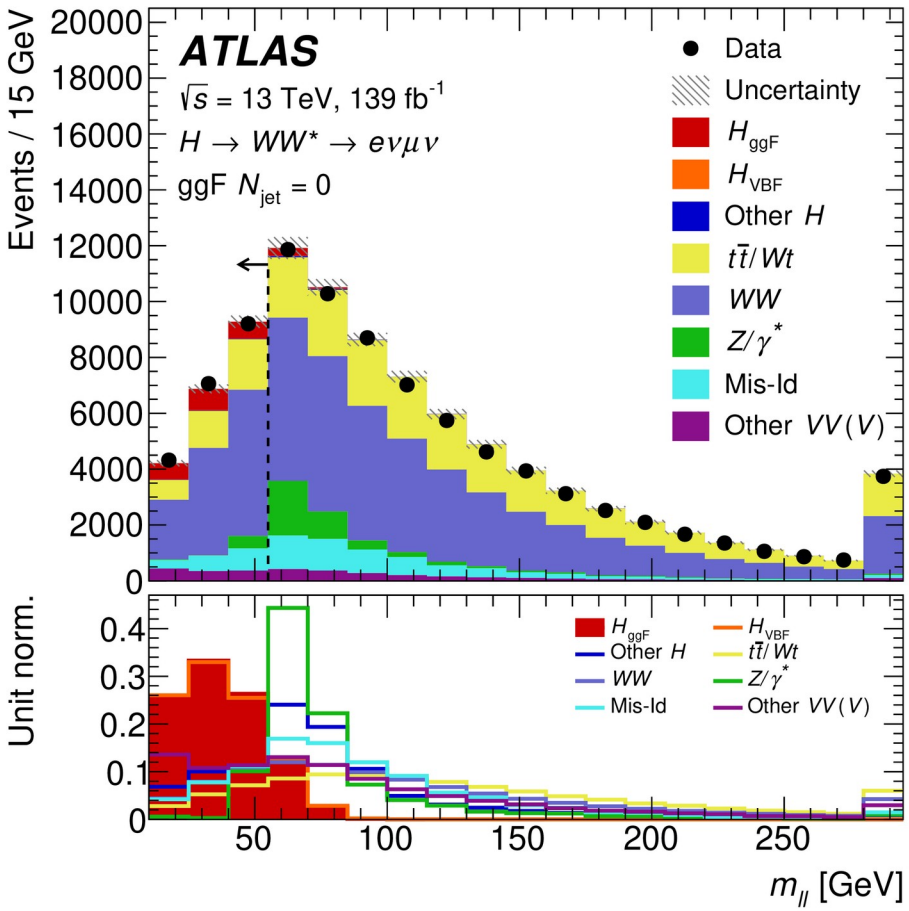
MT2 definition

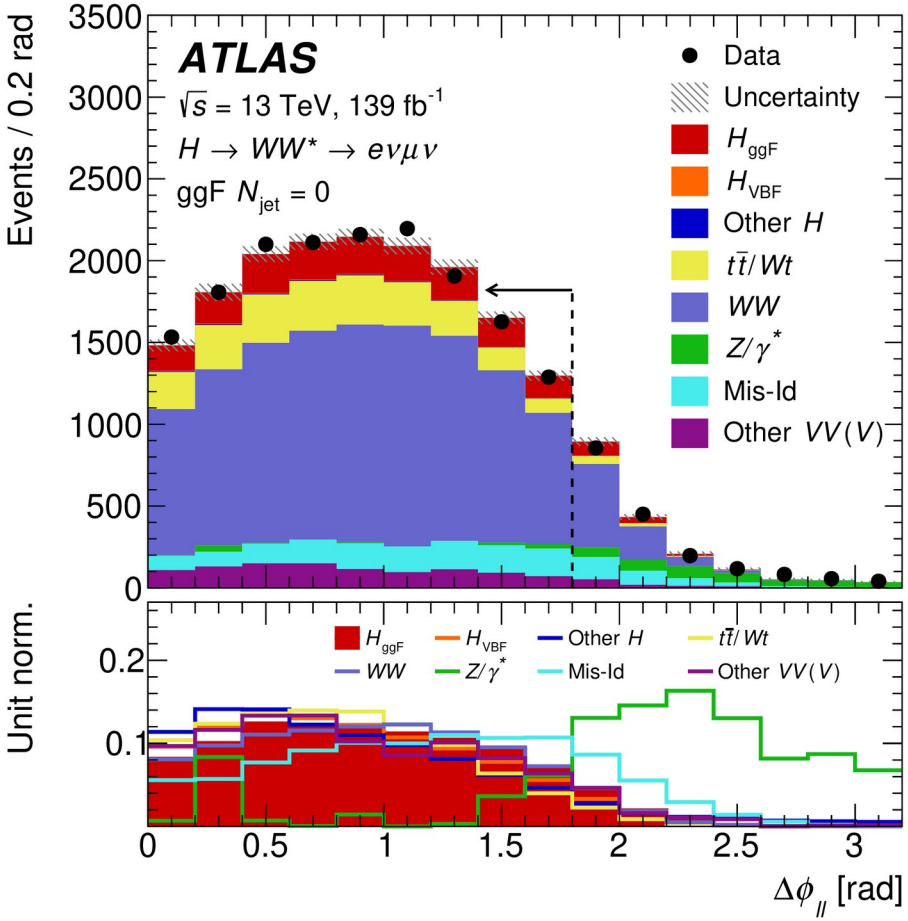
$$m_{\mathrm{T2}}^2 = \min_{\not{p}_1+\not{p}_2=\not{p}_{\mathrm{T}}} \left[\max\{m_{\mathrm{T}}^2(p_{\mathrm{T}}^a, \not{p}_1), m_{\mathrm{T}}^2(p_{\mathrm{T}}^b, \not{p}_2)\}\right]$$

where the minimization is over all possible two-momenta, $\bar{p}_{1,2}$, such that their sum gives the observed missing transverse momentum $\bar{p}_T$, and where each of p_T^a and p_T^b is the combined transverse momentum of a charged lepton and a jet.

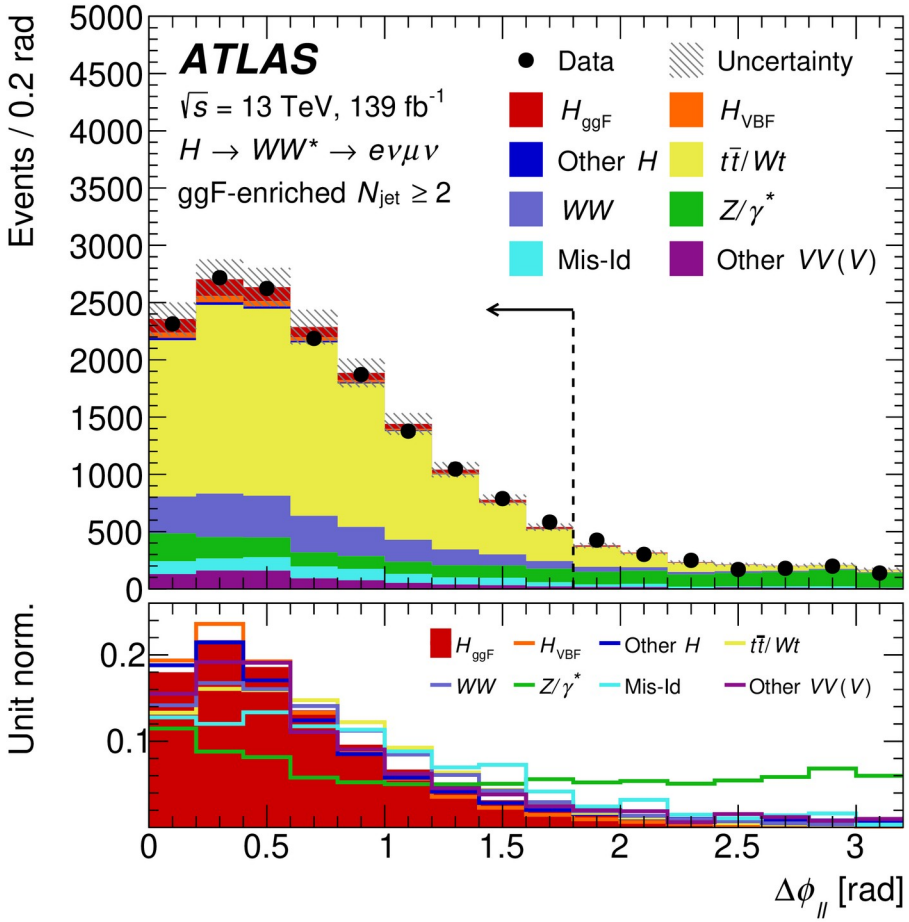
- $m^2_{T2} \leq m^2_W$ (decay of a pair of W each with a single invisible particle)
- $m^2_T \leq m^2_W$ (decay with single invisible particle)

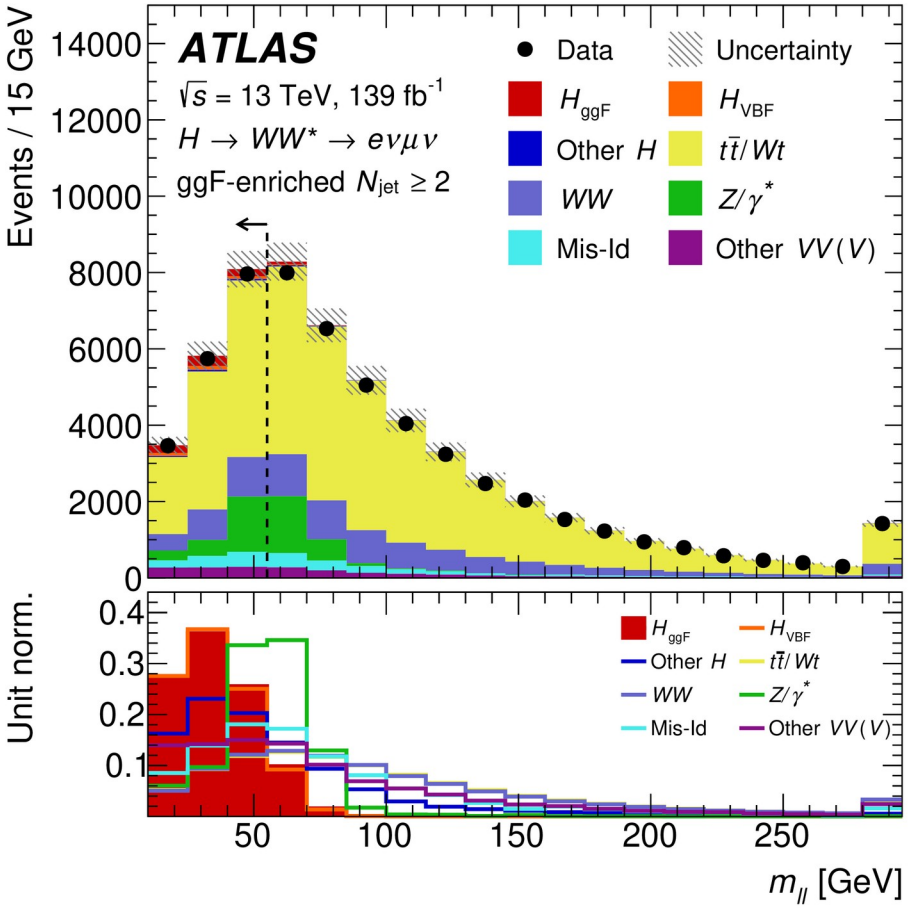
m_{ll} and $\Delta\phi_{ll}$ selection for 0-jet category



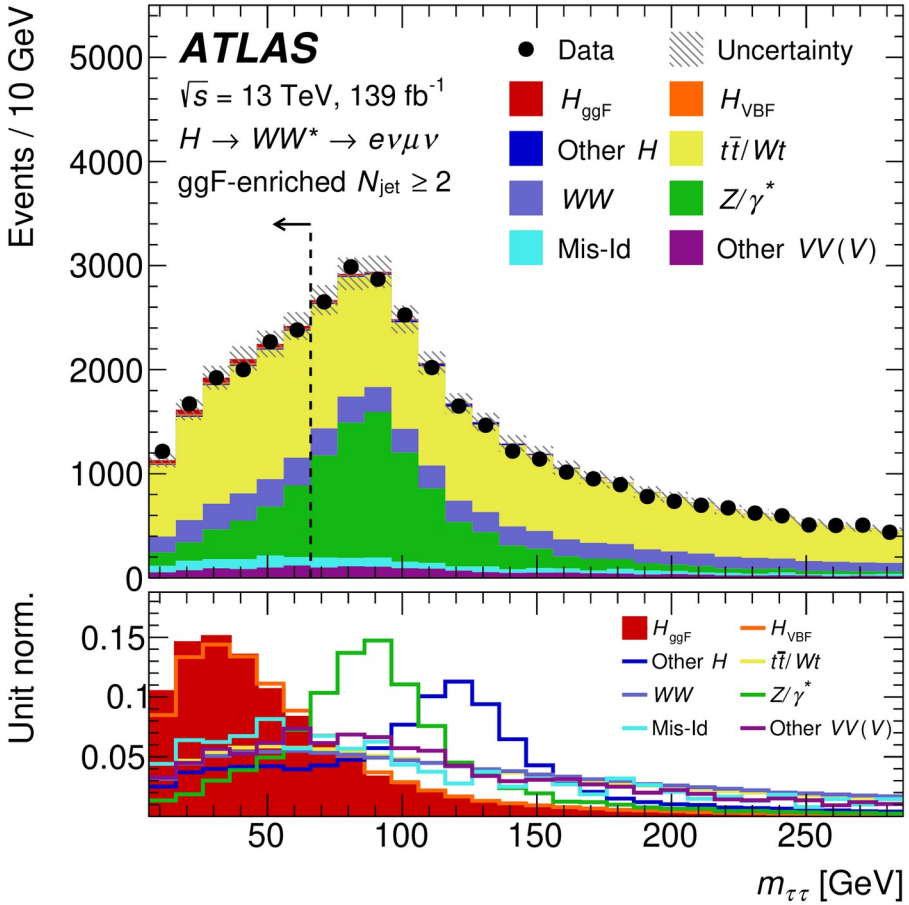


m_{ll} and $\Delta\phi_{ll}$ selection for 2-jet category





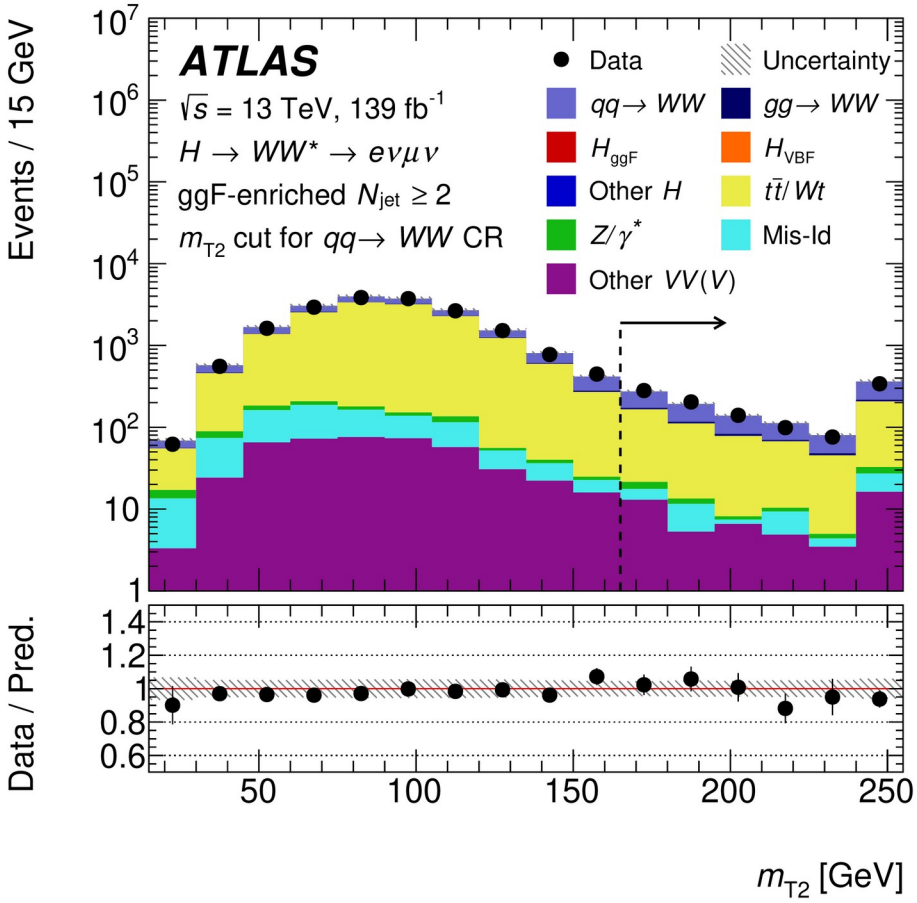
$m_{\tau\tau}$ selection for 2-jet category



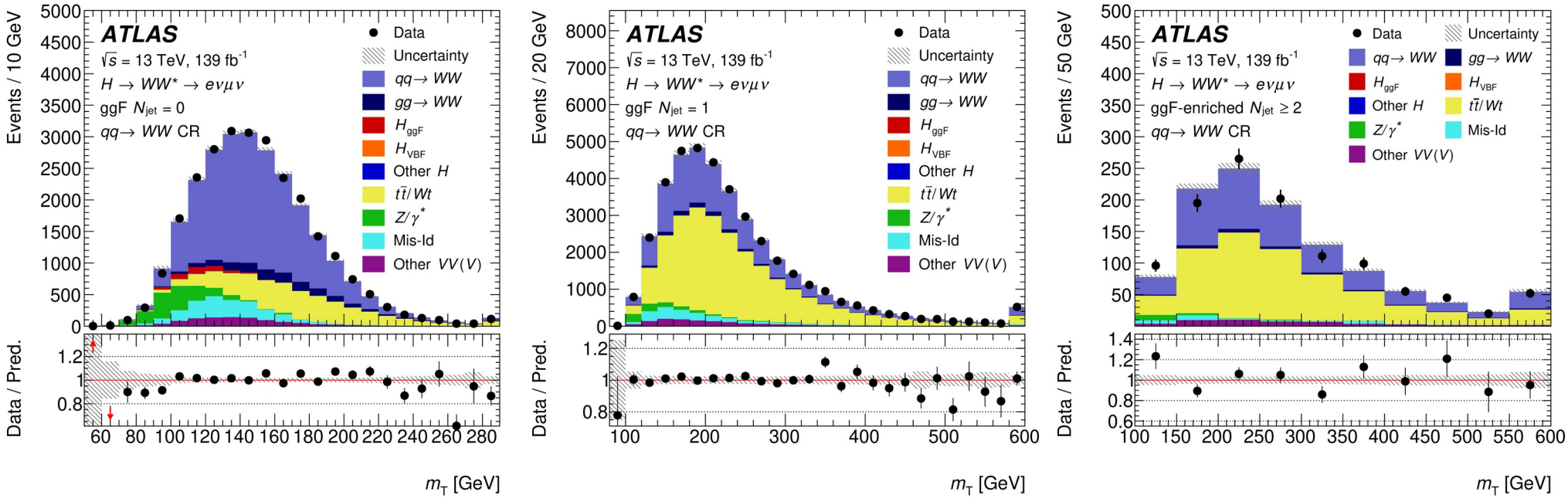
Post-fit normalization factors for backgrounds

Category	WW	$t\bar{t}/Wt$	Z/γ^*
$N_{\text{jet}} = 0$ ggF	$1.02^{+0.07}_{-0.07}$	$0.93^{+0.22}_{-0.17}$	$0.96^{+0.07}_{-0.06}$
$N_{\text{jet}} = 1$ ggF	$0.85^{+0.16}_{-0.15}$	$1.05^{+0.19}_{-0.16}$	$0.98^{+0.10}_{-0.09}$
$N_{\text{jet}} \geq 2$ ggF	$0.81^{+0.34}_{-0.33}$	$0.96^{+0.23}_{-0.18}$	$0.98^{+0.18}_{-0.17}$

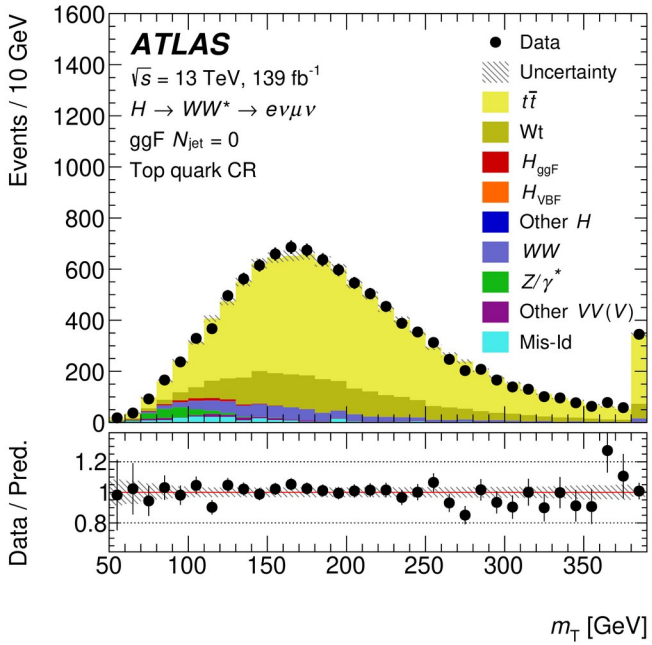
2 jet WW CR selection: m_{T2}

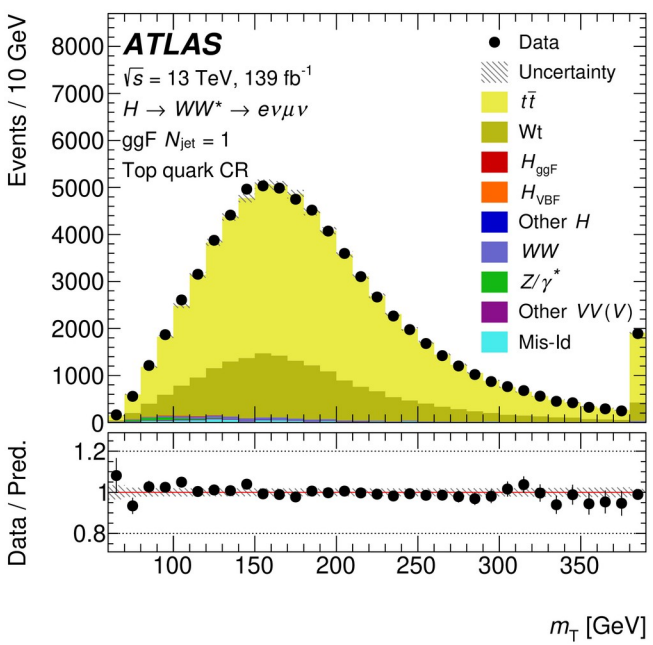


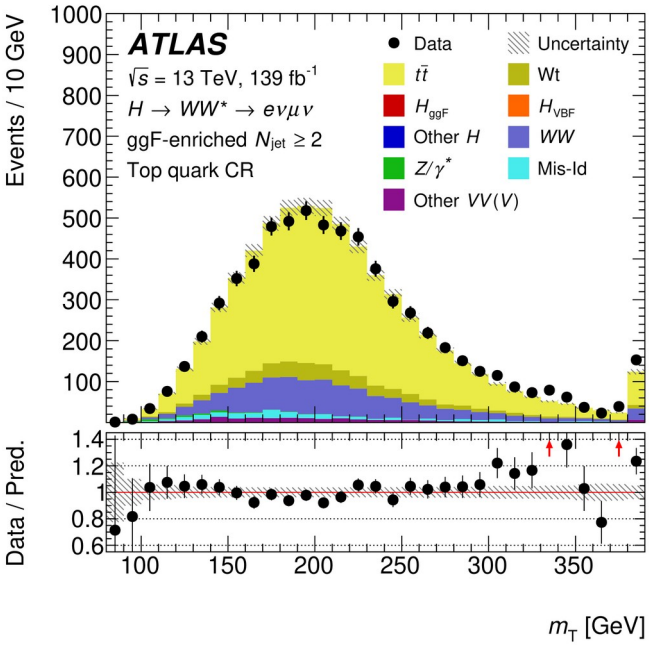
WW Control Regions m_T distributions



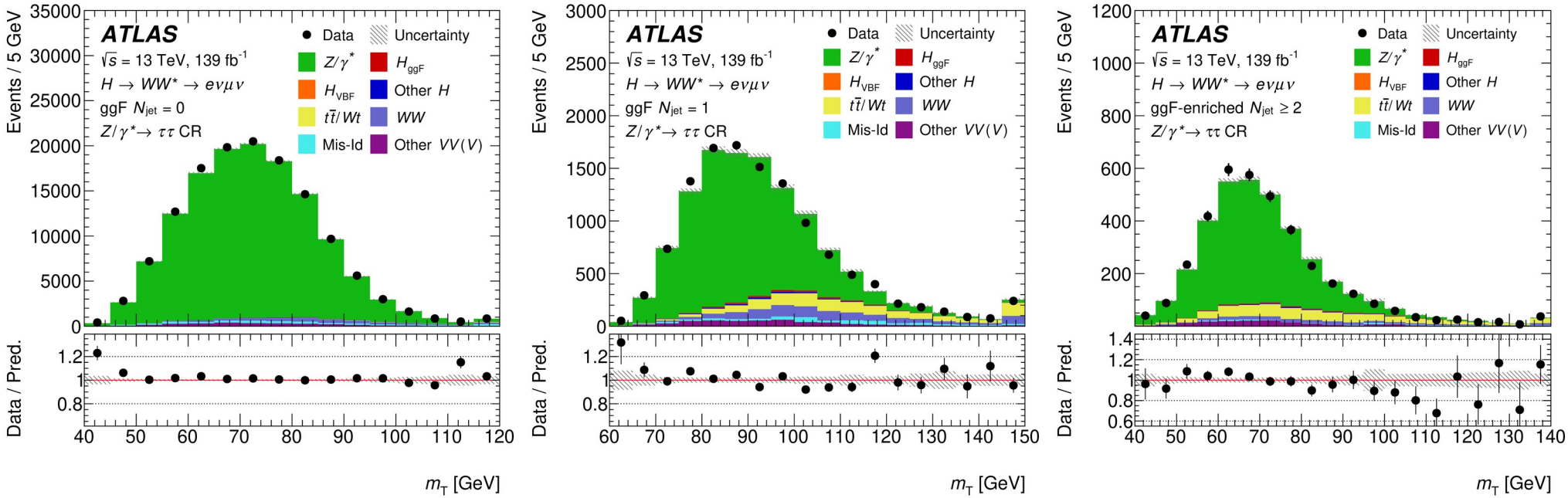
Top Control Regions m_T distributions



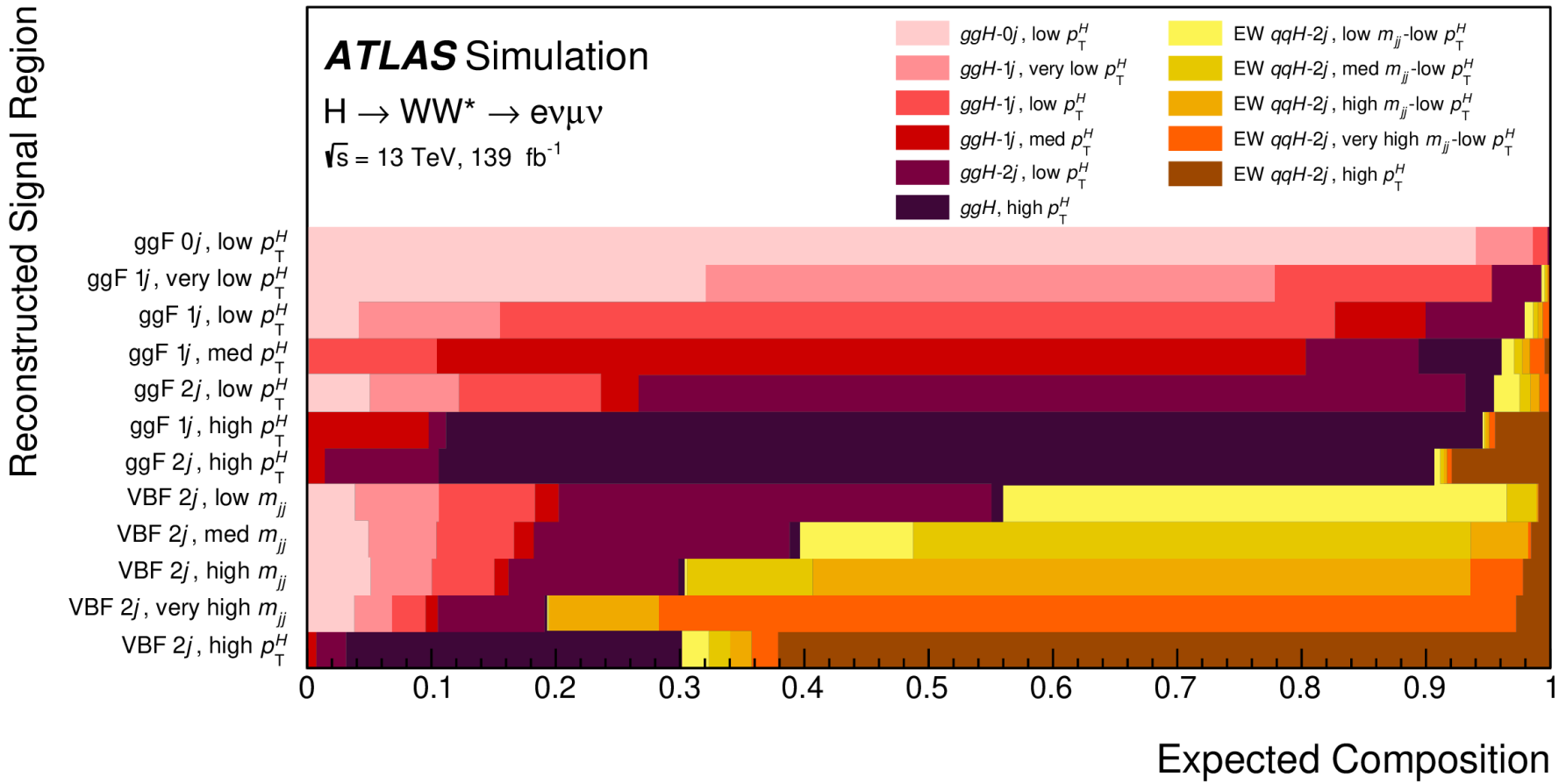




Zττ Control Regions m_T distributions



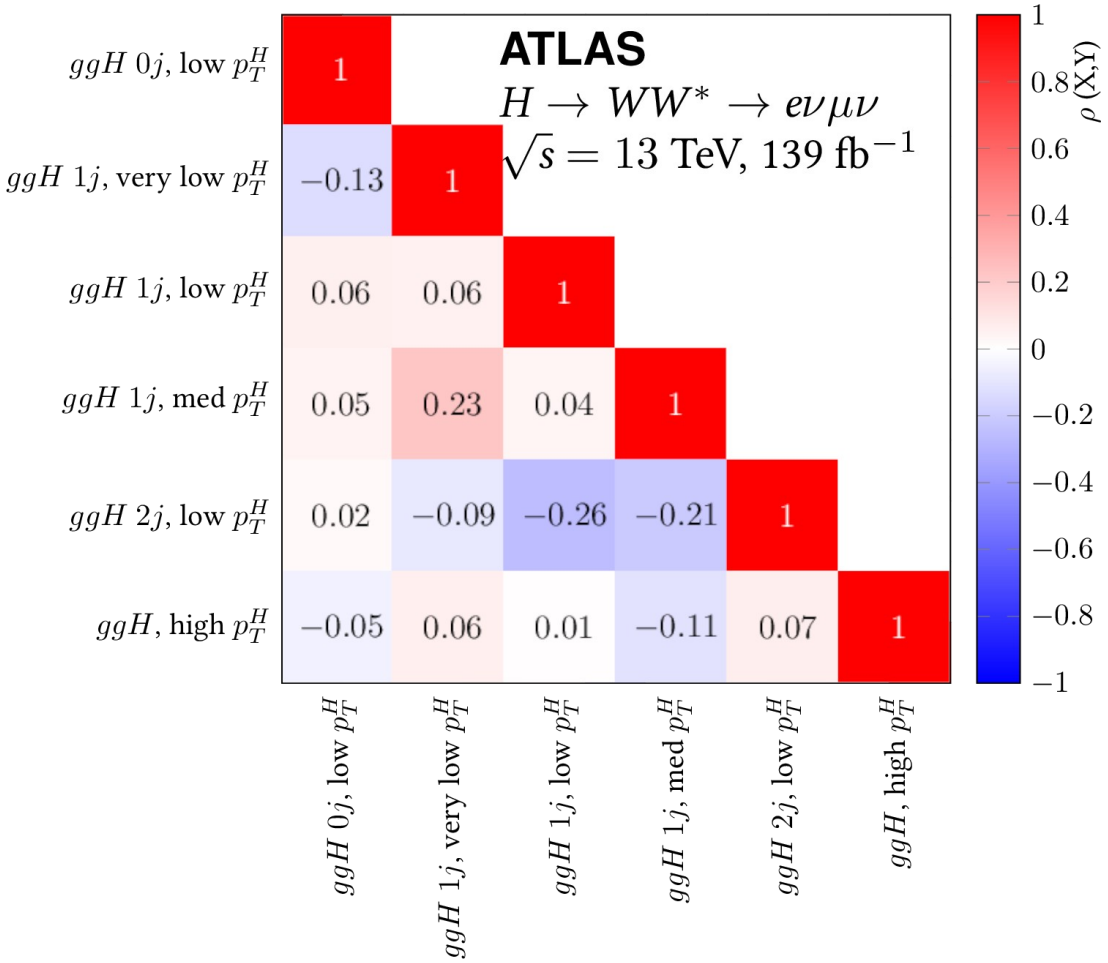
STXS Composition



Breakdown of the main contributions to the total uncertainty

Source	$\frac{\Delta\sigma_{\mathrm{ggF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\mathrm{ggF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	5.1
Total systematic uncertainties	11
MC statistical uncertainties	3.8
Experimental uncertainties	6.3
Flavor tagging	2.7
Jet energy scale	1.1
Jet energy resolution	2.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	2.2
Muons	2.1
Electrons	1.6
Fake factors	2.4
Pileup	2.5
Luminosity	2.0
Theoretical uncertainties	7.8
ggF	4.3
VBF	0.7
WW	4.2
Top	3.8
$Z\tau\tau$	2.3
Other VV	2.9
Other Higgs	0.4
Background normalizations	4.5
WW	2.8
Top	2.3
$Z\tau\tau$	3.1
Total	12

Correlations between the cross-section measurements



Generators

Process	Matrix element (alternative)	PDF set	UEPS model (alternative model)	Prediction order for total cross section
ggF H	Powheg Box v2 [23–27] NNLOPS [26, 30, 43] (MG5_aMC@NLO) [49, 86]	PDF4LHC15nnlo [57]	Pythia 8 [28] (Herwig 7) [48]	N^3LO QCD + NLO EW [11, 33–42]
VBF H	Powheg Box v2 [23–25, 43] (MG5_aMC@NLO)	PDF4LHC15nlo	Pythia 8 (Herwig 7)	NNLO QCD + NLO EW [44–46]
VH excl. $gg \to ZH$	Powheg Box v2	PDF4LHC15nlo	Pythia 8	NNLO QCD + NLO EW [52–56]
$t\bar{t}H$	Powheg Box v2	NNPDF3.0nlo	Pythia 8	NLO [11]
$gg \to ZH$	Powheg Box v2	PDF4LHC15nlo	Pythia 8	NNLO QCD + NLO EW [90, 91]
$qq \to WW$	Sherpa 2.2.2 [69] (Q_{cut})	NNPDF3.0nnlo [50]	Sherpa 2.2.2 [70, 71, 73–76] (Sherpa 2.2.2 [71, 72]; μ_{q})	NLO [77, 78, 92]
$qq \to WWqq$	MG5_aMC@NLO [49]	NNPDF3.0nlo	Pythia 8 (Herwig 7)	LO
$gg \to WW/ZZ$	Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.2	NLO [93]
$WZ/V\gamma^*/ZZ$	Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.2	NLO [94]
$V\gamma$	Sherpa 2.2.8 [69]	NNPDF3.0nnlo	Sherpa 2.2.8	NLO [94]
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 [95–101]
Wt	Powheg Box v2 (MG5_aMC@NLO)	NNPDF3.0nlo	Pythia 8 (Herwig 7)	NNLO [102, 103]
Z/γ^*	Sherpa 2.2.1 (MG5_aMC@NLO)	NNPDF3.0nnlo	Sherpa 2.2.1	NNLO [79]

Projection from 36 fb^{-1} to HL-LHC 3000 fb^{-1} ATL-PHYS-PUB-2018-054

Prod. mode	Scenario	Δ_{tot}/σ_{SM}	$\Delta_{stat}/\sigma_{SM}$	Δ_{exp}/σ_{SM}	Δ_{sig}/σ_{SM}	Δ_{bkg}/σ_{SM}
ggF	Run 2, 36 fb^{-1}	$^{+0.191}_{-0.189}$	$^{+0.099}_{-0.098}$	$^{+0.112}_{-0.110}$	$^{+0.047}_{-0.036}$	$^{+0.092}_{-0.096}$
	HL-LHC S1	$^{+0.064}_{-0.065}$	$^{+0.010}_{-0.010}$	$^{+0.037}_{-0.037}$	$^{+0.040}_{-0.039}$	$^{+0.033}_{-0.036}$
	HL-LHC S2	$^{+0.046}_{-0.044}$	$^{+0.010}_{-0.010}$	$^{+0.030}_{-0.029}$	$^{+0.023}_{-0.020}$	$^{+0.025}_{-0.025}$