V(H → WW*) in Run 1

Higgs Hunting 2015

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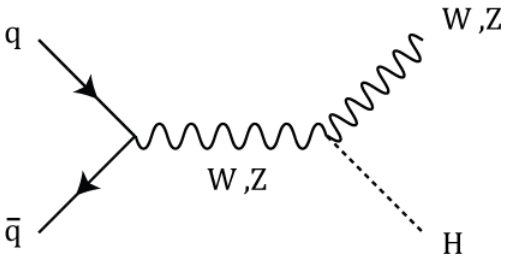
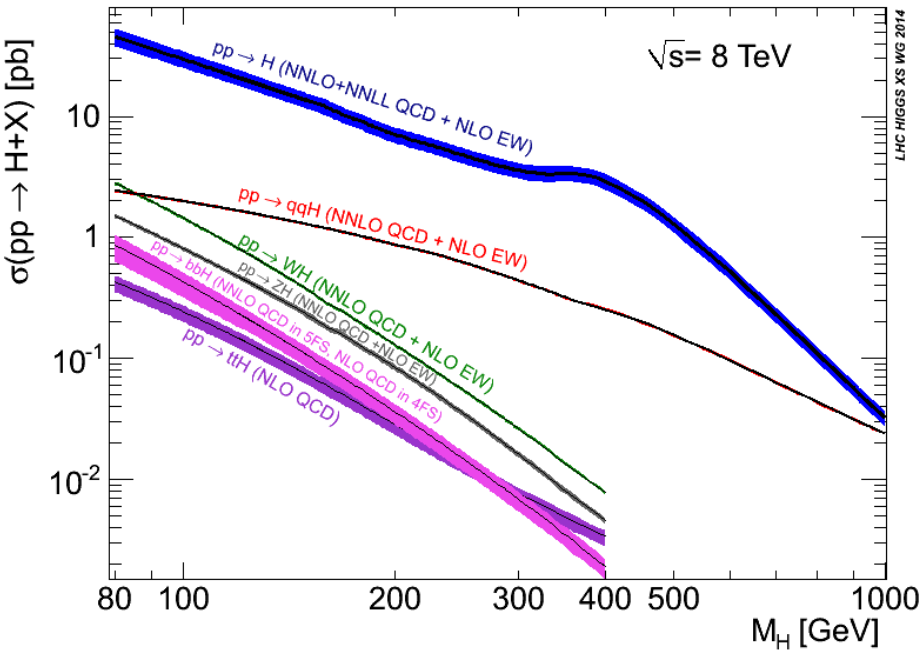
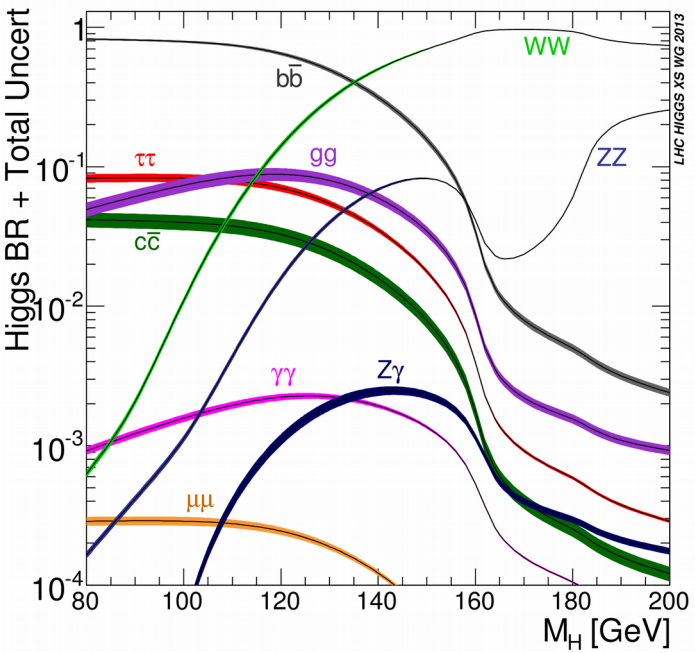
On behalf of the ATLAS collaboration

July 30th 2015

Introduction to V(H → WW*)





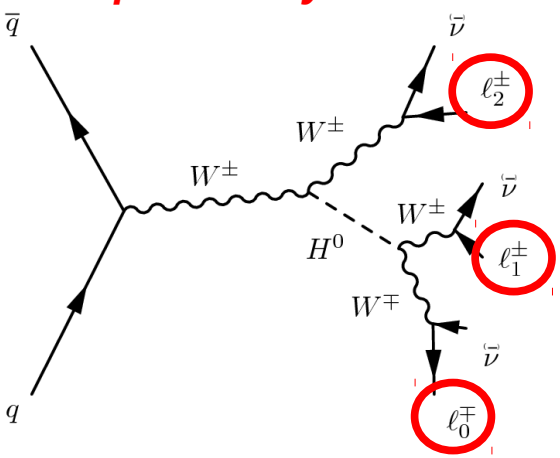


- WH and ZH have 3rd and 4th highest cross-sections at the LHC for mH ~ 125 GeV
- H → WW* 2nd largest branching fraction for mH ~ 125 GeV
- Access to tree-level Higgs-Vector boson coupling strength (κV)
- Run 1 V(H → WW*) paper on arXiv (arXiv:1506.06641) and accepted by JHEP

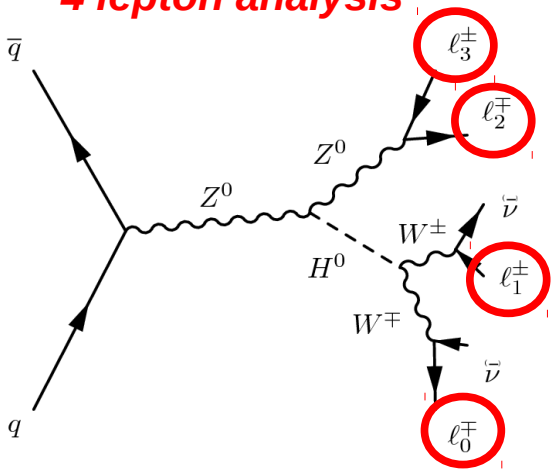
Global analysis strategy in Run1

Two fully leptonic and two semi-leptonic channels:

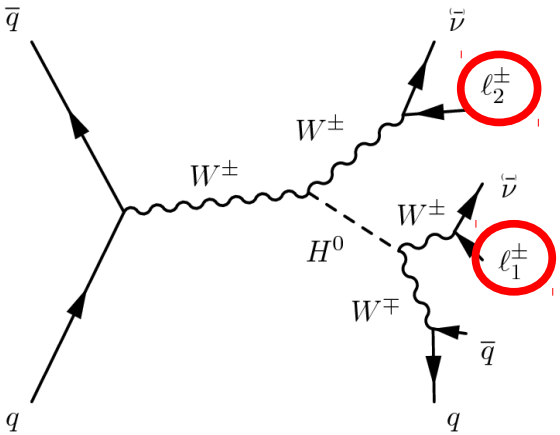
W(H → WW*) → lvlvlv
3 lepton analysis



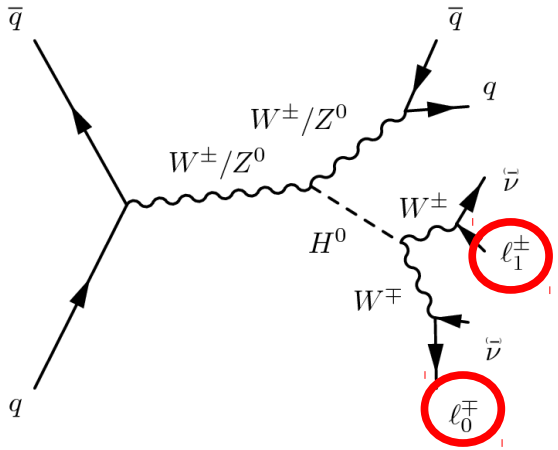
Z(H → WW*) → lllvlv
4 lepton analysis



W(H → WW*) → lvlvqq
Same sign dilepton analysis

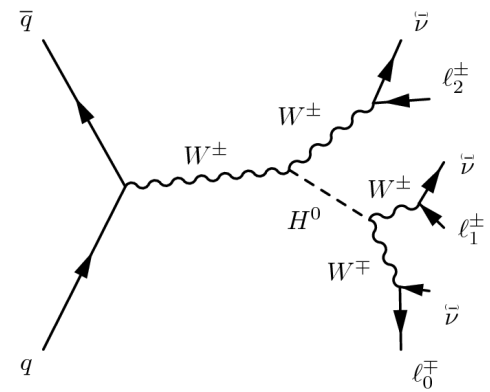


W/Z(H → WW*) → qqlvlv
Opposite sign dilepton analysis



- Use lepton multiplicity and charge to divide processes into different signal regions
- Cut & count experiments with each process also having several signal regions (jet multiplicity, lepton flavour, etc)
- Shape fit only in WH channel with 3 lepton final state
- Signal region selections optimized independently
- Combine results with ggF and VBF analysis for couplings measurement

WH → 3 lepton analysis



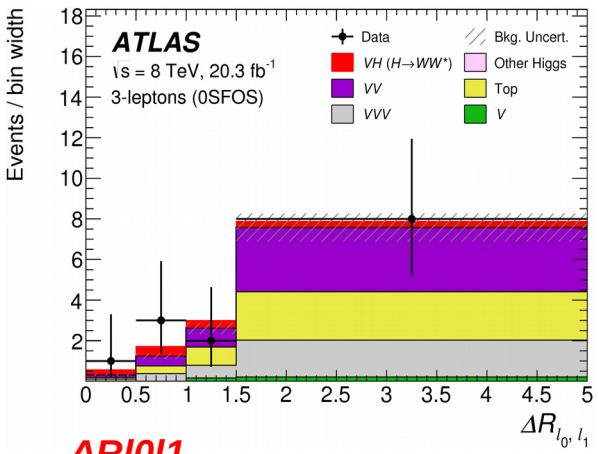
- Major backgrounds are **WZ/Wy***, **ZZ***, VVV
- Split into Z enriched and Z depleted regions using number of same flavour (SF) opposite sign (OS) lepton pairs
- Both cut&count and shape fit (BDT) analyses

Backgrounds in bold are normalized via a CR

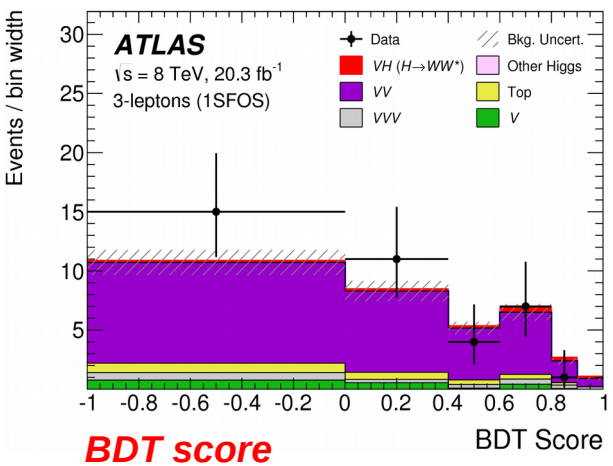
SR selections

Channel	3ℓ		
Category	3SF	1SFOS	0SFOS
Trigger	single-lepton triggers		
Num. of leptons	3	3	3
$p_{\mathrm{T,leptons}}$ [GeV]	> 15	> 15	> 15
Total lepton charge	± 1	± 1	± 1
Num. of SFOS pairs	2	1	0
Num. of jets	≤ 1	≤ 1	≤ 1
$p_{\mathrm{T,jets}}$ [GeV]	> 25 (30)	> 25 (30)	> 25 (30)
Num. of b-tagged jets	0	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 30	> 30	—
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20	> 20	—
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	> 25	> 25	—
Min. $m_{\ell\ell}$ [GeV]	> 12	> 12	> 6
Max. $m_{\ell\ell}$ [GeV]	< 200	< 200	< 200
$\Delta R_{\ell_0\ell_1}$	< 2.0	< 2.0	—

Boxed cuts are unique/important to the analysis



ΔRl0l1
(Z depleted region)

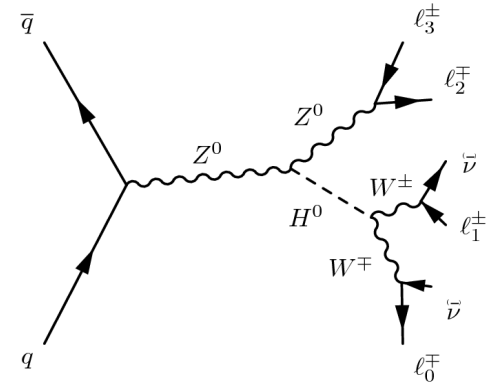


BDT score
(1SFOS SR)

Event yields (8 TeV)

	Signal	Tot. Bkg	Observed
3SF SR	0.7 ± 0.1	22 ± 4	22
1SFOS SR	1.6 ± 0.2	34 ± 6	38
0SFOS SR	1.4 ± 0.2	12 ± 2	14

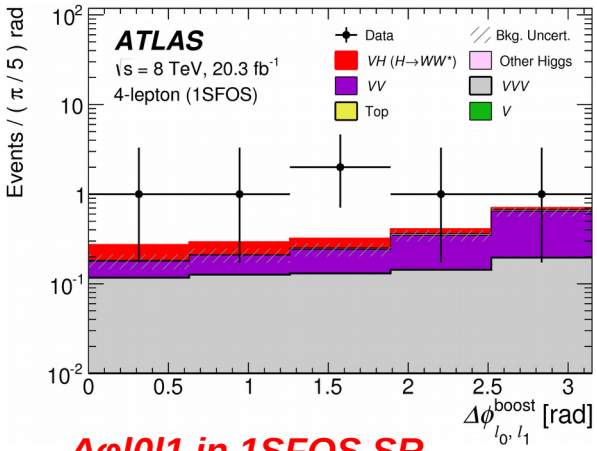
ZH → 4 lepton analysis



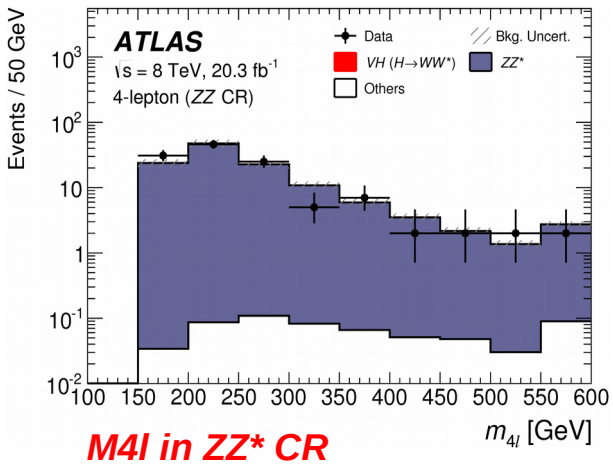
- Main background is **ZZ***
- Split SR into 1SFOS and 2SFOS to better control ZZ* bkg
- Require small Δφ between Higgs cand. leptons

SR selections

Channel	4ℓ	
Category	2SFOS	1SFOS
Trigger	single-lepton triggers	
Num. of leptons	4	4
$p_{T,\text{leptons}}$ [GeV]	$> 25, 20, 15$	$> 25, 20, 15$
Total lepton charge	0	0
Num. of SFOS pairs	2	1
Num. of jets	≤ 1	≤ 1
$p_{T,\text{jets}}$ [GeV]	> 25 (30)	> 25 (30)
Num. of b-tagged jets	0	0
E_T^{miss} [GeV]	> 20	> 20
p_T^{miss} [GeV]	> 15	> 15
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	< 10 ($m_{\ell_2\ell_3}$)	< 10 ($m_{\ell_2\ell_3}$)
Min. $m_{\ell\ell}$ [GeV]	> 10 ($m_{\ell_0\ell_1}$)	> 10 ($m_{\ell_0\ell_1}$)
Max. $m_{\ell\ell}$ [GeV]	< 65 ($m_{\ell_0\ell_1}$)	< 65 ($m_{\ell_0\ell_1}$)
$m_{4\ell}$ [GeV]	> 140	—
$p_{T,4\ell}$ [GeV]	> 30	—
$\Delta\phi_{\ell_0\ell_1}$ [rad]	< 2.5 ($\Delta\phi^{\text{boost}}_{\ell_0\ell_1}$)	< 2.5 ($\Delta\phi^{\text{boost}}_{\ell_0\ell_1}$)



Δφl0l1 in 1SFOS SR (increased stats)

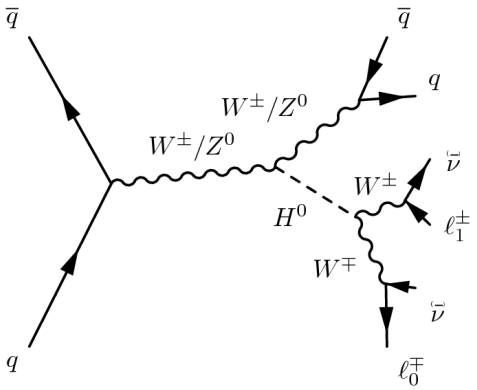


M4l in ZZ* CR

Event yields (8 TeV)

	Signal	Tot. Bkg	Observed
2SFOS SR	0.20 ± 0.03	1.30 ± 0.23	0
1SFOS SR	0.23 ± 0.03	0.41 ± 0.09	3

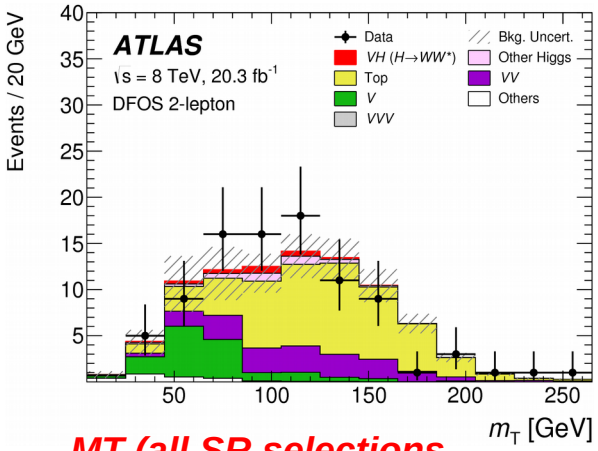
W/ZH → DFOS dilepton analysis



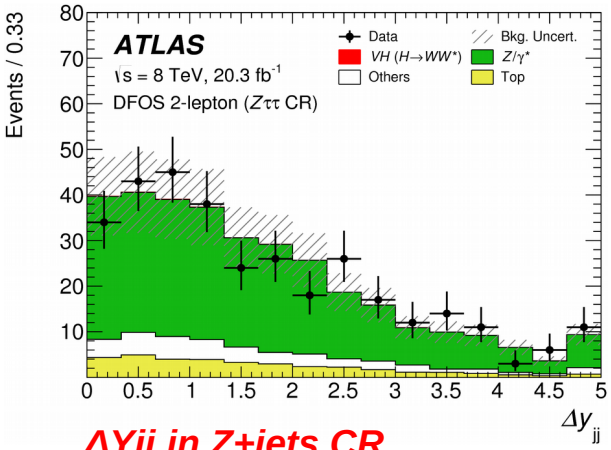
- Major backgrounds are **top** and **Z → τ τ**
- Only consider eμ events to suppress ZDY
- Require dijet invariant mass close to W/Z mass
- VBF contamination suppressed by reversing VBF selections

SR selections

Channel	
Category	DFOS
Trigger	
Num. of leptons	2
$p_{\mathrm{T,leptons}}$ [GeV]	$> 22, 15$
Total lepton charge	0
Num. of SFOS pairs	0
Num. of jets	≥ 2
$p_{\mathrm{T,jets}}$ [GeV]	> 25 (30)
Num. of b-tagged jets	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20
Min. $m_{\ell\ell}$ [GeV]	> 10
Max. $m_{\ell\ell}$ [GeV]	< 50
$m_{\tau\tau}$ [GeV]	$< (m_Z - 25)$
$\Delta\phi_{\ell_0\ell_1}$ [rad]	< 1.8
m_{T} [GeV]	< 125
Δy_{jj}	< 1.2
$\lvert m_{jj} - 85\rvert$ [GeV]	< 15



MT (all SR selections except MT)



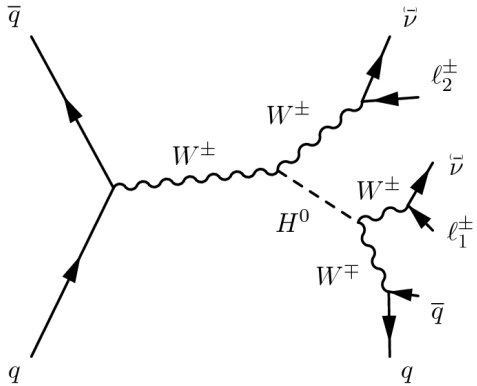
ΔYjj in Z+jets CR

Event yields (8 TeV)

	WH	ZH*	Tot. Bkg	Observed
DFOS SR	1.5 ± 0.1	0.67 ± 0.04	50 ± 5	63

**ZH contamination in the 3l and SS dilepton analysis is less than 10%*

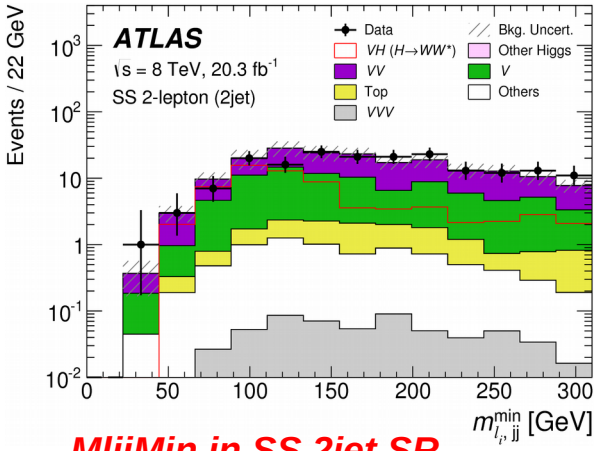
WH → SS dilepton analysis



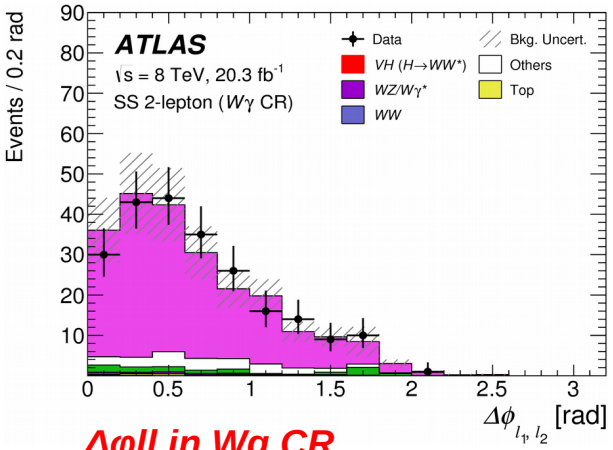
- Major backgrounds are W+jets, **WZ/Wγ***, **Wγ**
- Require SS leptons to suppress SM backgrounds
- Include 1 jet events, often lose a jet in signal for W* → qq
- Split SR by jet multiplicity and lepton flavor

SR selections

Channel	2ℓ	
Category	SS2jet	SS1jet
Trigger	single-lepton & dilepton triggers	
Num. of leptons	2	2
$p_{\mathrm{T,leptons}}$ [GeV]	$> 22, 15$	$> 22, 15$
Total lepton charge	± 2	± 2
Num. of SFOS pairs	0	0
Num. of jets	2	1
$p_{\mathrm{T,jets}}$ [GeV]	> 25 (30)	> 25 (30)
Num. of b-tagged jets	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 50	> 45
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	—	—
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	> 15	> 15
Min. $m_{\ell\ell}$ [GeV]	> 12 ($ee, \mu\mu$) > 10 ($e\mu$)	> 12 ($ee, \mu\mu$) > 10 ($e\mu$)
m_{T} [GeV]	—	> 105 ($m_{\mathrm{T}}^{\mathrm{lead}}$)
Min. $m_{\ell_i j(j)}$ [GeV]	< 115	< 70
Min. $\phi_{\ell_i j}$ [rad]	< 1.5	< 1.5



MljjMin in SS 2jet SR (after Etmiss cut)



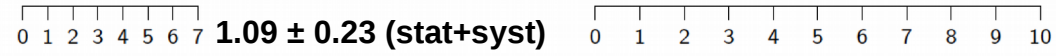
Δφll in Wg CR

Event yields (8 TeV)

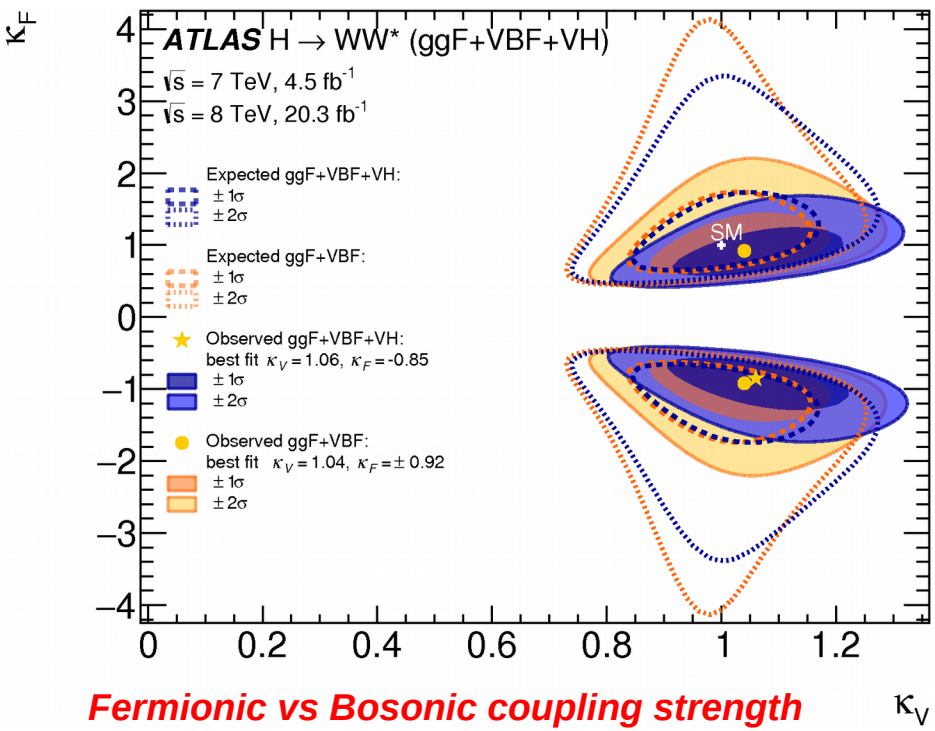
	Signal	Tot. Bkg	Observed
1 jet SR	2.04 ± 0.30	44 ± 6	62
2 jet SR	1.04 ± 0.18	21 ± 5	25

Combined H → WW Results (mH = 125.36 GeV)

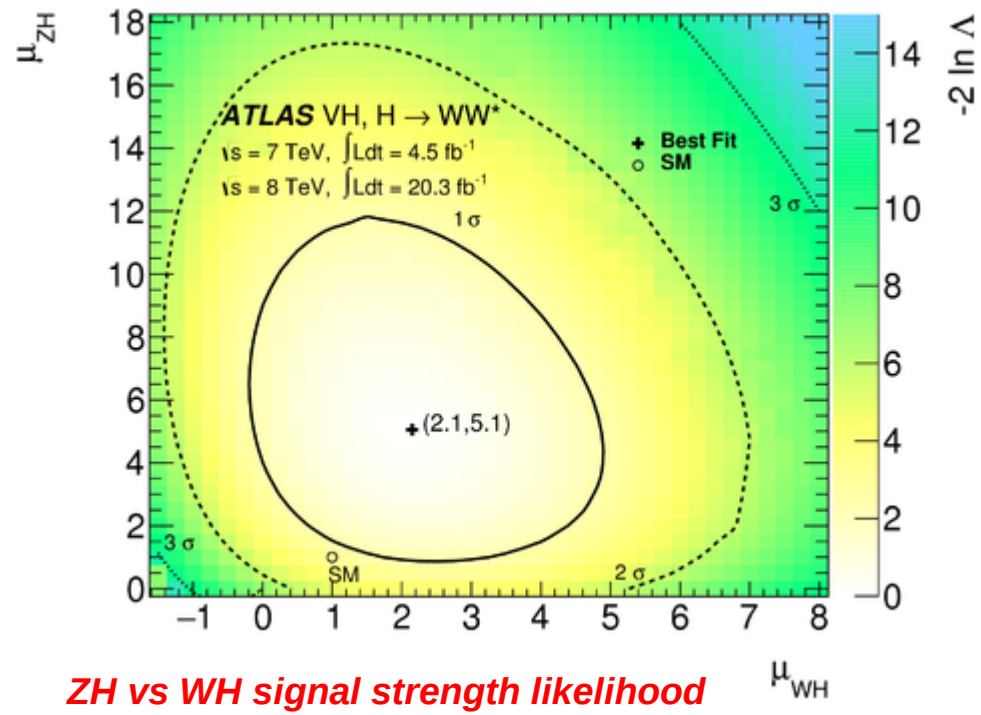
Category	Signal significance Z_0: Exp. Z_0	Obs. Z_0	Obs. Z_0	Observed signal strength μ: μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −
ggF	4.4	4.2		**0.98**	0.29	0.26	0.22	0.18
VBF	2.6	3.2		**1.28**	0.55	0.47	0.32	0.25
VH	0.93	2.5		**3.0**	1.6	1.3	0.95	0.65
WH only	0.77	1.4		**2.1**	1.9	1.6	1.2	0.79
ZH only	0.30	2.0		**5.1**	4.3	3.1	1.9	0.89
ggF+VBF+VH	5.9	6.5		**1.16**	0.24	0.21	0.18	0.15
ggF+VBF	**5.8**	**6.1**		**1.09 ± 0.23 (stat+syst)**				



Significance and signal strength summary table (7 + 8 TeV)



Fermionic vs Bosonic coupling strength likelihood



ZH vs WH signal strength likelihood

THANK YOU!

BACKUPS

MC generators

Process	Generator	$\sigma(\times\mathrm{Br})$ [pb]	Cross-section normalisation
Higgs boson			
VH $(H \to WW^*)$	PYTHIA [25, 26] v8.165, v6.428	0.24, 0.20	NNLO QCD + NLO EW
VH $(H \to \tau\tau)$	PYTHIA v8.165, v6.428	0.07, 0.06	NNLO QCD + NLO EW
$gg \to H$ $(H \to WW^*)$	POWHEG-BOX [27–30] v1.0 (r1655)+ PYTHIA v8.165, v6.428	4.1, 3.3	NNLO+NNLL QCD + NLO EW
VBF $(H \to WW^*)$	POWHEG-BOX [31] v1.0 (r1655)+ PYTHIA v8.165, v6.428	0.34, 0.26	NNLO QCD + NLO EW
$t\bar{t}$H $(H \to WW^*)$	PYTHIA v8.165	0.028, 0.019	NLO
Single boson			
$Z/\gamma^*(\to \ell\ell)$+jets ($m_{\ell\ell} > 10$ GeV)	ALPGEN [32] v2.14 + HERWIG [33] v6.52	16540, 12930	NNLO
HF $Z/\gamma^*(\to \ell\ell)$+jets ($m_{\ell\ell} > 30$ GeV)	ALPGEN v2.14 + HERWIG v6.52	126, 57	NNLO
VBF $Z/\gamma^*(\to \ell\ell)$ ($m_{\ell\ell} > 7$ GeV)	SHERPA [34] v1.4.1	5.3, 2.8	LO
Top-quark			
$t\bar{t}$	POWHEG-BOX[35] v1.0 (r2129)+PYTHIA v6.428 MC@NLO [36] v4.03	250, 180	NNLO+NNLL
$t\bar{t}W/Z$	MADGRAPH [37] v5.1.5.2, v5.1.3.28 +PYTHIA v6.428	0.35, 0.25	LO
tqb	ACERMC [38] v3.8 +PYTHIA v6.428	88, 65	NNLL
tb, tW	POWHEG-BOX [39, 40] v1.0 (r2092)+ PYTHIA v6.428	28, 20	NNLL
tZ	MADGRAPH v5.1.5.2, v5.1.5.11 +PYTHIA v6.428	0.035, 0.025	LO
Dibosons			
$WZ/W\gamma^*(\to \ell\ell\ell\nu)(m_{\ell\ell} > 7$ GeV)	POWHEG-BOX[41] v1.0 (r1508)+PYTHIA v8.165, v6.428	12.7, 10.7	NLO
$WZ/W\gamma^*(\to \ell\ell\ell\nu)$(min. $m_{\ell\ell} < 7$ GeV)	SHERPA v1.4.1	12.2, 10.5	NLO
other WZ	POWHEG-BOX[41] v1.0 (r1508) + PYTHIA v8.165	21.2, 17.2	NLO
$q\bar{q}/qg \to Z^{(*)}Z^{(*)}(\to \ell\ell\ell\ell, \ell\ell\nu\nu)$ ($m_{\ell\ell} > 4$ GeV)	POWHEG-BOX[41] v1.0 (r1556) +PYTHIA v8.165, v6.428	1.24, 0.79	NLO
$q\bar{q}/qg \to Z^{(*)}Z^{(*)}(\to \ell\ell\ell\ell, \ell\ell\nu\nu)$ (min. $m_{\ell\ell} < 4$ GeV)	SHERPA v1.4.1	7.3, 5.9	NLO
other $q\bar{q}/qg \to ZZ$	POWHEG-BOX[41] v1.0 (r1556) + PYTHIA v8.165	6.9, 5.7	NLO
$gg \to Z^{(*)}Z^{(*)}$	gg2ZZ [42] v3.1.2 + HERWIG v6.52 (8 TeV only)	0.59	LO
$q\bar{q}/qg \to WW$	POWHEG-BOX[41] v1.0 (r1556) + PYTHIA v6.428	54, 45	NLO
	SHERPA v1.4.1 (for 2ℓ-DFOS 8 TeV only)	54	NLO
$gg \to WW$	gg2WW [43] v3.1.2 + HERWIG v6.52	1.9, 1.1	LO
VBS WZ, $ZZ(\to \ell\ell\ell\ell, \ell\ell\nu\nu)$ ($m_{\ell\ell} > 7$ GeV), WW	SHERPA v1.4.1	1.2, 0.88	LO
$W\gamma$ ($p_T^\gamma > 8$ GeV)	ALPGEN v2.14 +HERWIG v6.52	1140, 970	NLO
$Z\gamma$ ($p_T^\gamma > 8$ GeV)	SHERPA v1.4.3	960, 810	NLO
Tribosons			
$WWW^*, ZWW^*, ZZZ^*, WW\gamma^*$	MADGRAPH v5.1.3.33, v5.1.5.10 + PYTHIA v6.428	0.44, 0.18	NLO

Background modeling

Channel	4ℓ	3ℓ	2ℓ	
Category	2SFOS, 1SFOS	3SF, 1SFOS, 0SFOS	DFOS	SS2jet, SS1jet
Process				
VVV	MC	MC	MC	MC
$WZ/W\gamma^*$	—	3ℓ-WZ CR, 3ℓ-Zjets CR	MC	2ℓ-WZ CR
ZZ^*	4ℓ-ZZ CR	3ℓ-ZZ CR, 3ℓ-Zjets CR	MC	MC
OS WW	—	MC	MC	2ℓ-WW CR
SS WW	—	MC	—	MC
$W\gamma$	—	—	—	2ℓ-$W\gamma$ CR
$Z\gamma$	—	3ℓ-$Z\gamma$ CR	MC	MC
Z/γ^*	—	3ℓ-Zjets CR, 3ℓ-ZZ CR	2ℓ-$Z\tau\tau$ CR	2ℓ-Zjets CR
W+jets	—	—	Data	Data
Multijets	—	—	Data	Data
Top	MC	3ℓ-Top CR	2ℓ-OSTop CR	2ℓ-SSTop CR

Background modeling summary table

- Many backgrounds are shared, but contribute differently to the different SRs
- CRs are used to normalize important backgrounds
- Fake lepton backgrounds (W+jets and QCD dijet) are estimated using a data driven technique

Control region definitions (3l and 4l)

Channel	4ℓ	3ℓ				
CR	ZZ	WZ	ZZ	Zjets	Top	$Z\gamma$
Number of leptons	4	3	3	3	3	3
Total lepton charge	0	± 1	± 1	± 1	± 1	± 1
Number of SFOS	2	2 or 1	2 or 1	2 or 1	2 or 1	2 or 1
			($ee\mu$ or $\mu\mu\mu$)			($\mu\mu e$ or eee)
Number of jets	≤ 1	≤ 1	≤ 1	≤ 1	≥ 1	≤ 1
Number of b-jets	0	0	0	0	$\geq \mathbf{1}$	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ (and/or) $p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	—	> 30 and > 20	$\mathbf{< 30}$ **or** $\mathbf{< 20}$	$\mathbf{< 30}$ **and** $\mathbf{< 20}$	> 30 and > 20	$\mathbf{< 30}$ **or** $\mathbf{< 20}$
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	$< 10 (m_{\ell_2\ell_3})$	$< \mathbf{25}$	—	$< \mathbf{25}$	> 25	—
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	—	—	< 15	> 15	—	$< \mathbf{15}$
Min. $m_{\ell\ell}$ [GeV]	$> \mathbf{65} (m_{\ell_0\ell_1})$	> 12	> 12	> 12	> 12	> 12
Max. $m_{\ell\ell}$ [GeV]	—	< 200	< 200	< 200	—	< 200
$\Delta R_{\ell_0\ell_1}$	—	< 2.0	< 2.0	< 2.0	—	< 2.0

Control region definitions (dilepton)

Channel	DFOS 2ℓ		SS 2ℓ				
CR	OSTop	$Z \to \tau\tau$	Wγ	WZ	WW	SSTop	Zjets
Number of leptons	2	2	2	**3**	2	2	2
			$\geq$ 1 conversion e				
Total lepton charge	0	0	± 2	± 1	**0**	**0**	**0**
Number of SFOS	0	0	—	—	—	—	—
Number of jets	≥ 2	≥ 2	2 or 1	2 or 1	2 or 1	2 or 1	2 or 1
Number of b-jets	0	0	0	0	0	$\geq$ **1**	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20	> 20	> 45 (1j)	> 45 (1j)	> 85 (1j)	> 45 (1j,$ee, \mu\mu$)	> 45 (1j)
						> 60 (1j,$e\mu$)	< 85 (1j,$e\mu$)
			> 50 (2j)	> 50 (2j)	> 80 (2j)	> 50 (2j,$ee, \mu\mu$)	> 50 (2j,$ee, \mu\mu$)
						> 60 (2j,$e\mu$)	< 80 (2j,$e\mu$)
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	—	—	—	< 15 (OS $ee, \mu\mu$)	> 15 ($ee, \mu\mu$)	> 15 ($ee, \mu\mu$)	$<$ **15** ($ee, \mu\mu$)
Min. $m_{\ell\ell}$ [GeV]	**> 90 (8 TeV)**	> 10	> 12 ($ee, \mu\mu$)	> 12 ($ee, \mu\mu$)	> 12 ($ee, \mu\mu$)	> 12 ($ee, \mu\mu$)	> 12 ($ee, \mu\mu$)
	> 80 (7 TeV)						
			> 10 ($e\mu$)	> 10 ($e\mu$)	> 10 ($e\mu$)	> 12 ($e\mu$)	> 55 ($e\mu$)
Max. $m_{\ell\ell}$ [GeV]	—	< 70	< 50	—	—	—	< 80 ($e\mu$)
$m_{\tau\tau}$ [GeV]	$< (m_Z - 25)$	—	—	—	—	—	
$\Delta\phi_{\ell_0\ell_1}$ [rad]	—	$>$ **2.8**	< 2.5	—	—	—	
m_{T} [GeV]	—	—	> 105 (1j)	> 105 (1j)	> 105 (1j)	> 105 (1j)	—
Min. $m_{\ell_i j}$ [GeV]	—	—	< 70	< 70	< 70	< 70	< 70
Min. $m_{\ell_i jj}$ [GeV]	—	—	< 115	< 115	< 115	< 115	< 115
Min. $\phi_{\ell_i j}$ [rad]	—	—	< 1.5	< 1.5	—	—	—
$p_{\mathrm{T}}^{\ell\ell}$ [GeV]	—	—	> 30	—	—	—	—

Control region event yields

(a) 8 TeV data sample

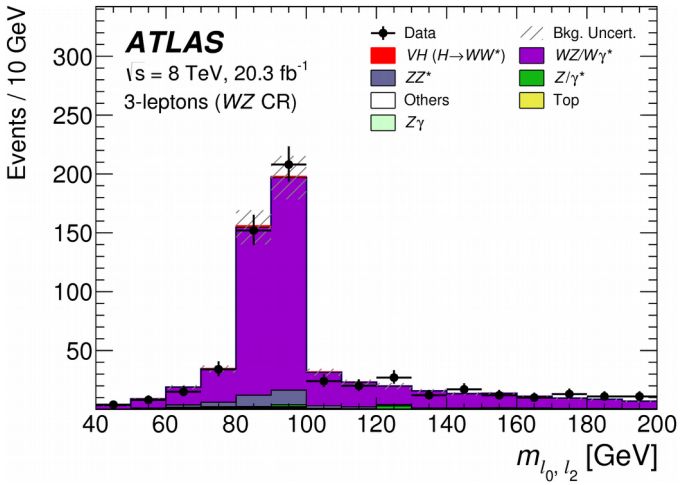
Channel	4ℓ	3ℓ					DFOS 2ℓ	
CR	ZZ	WZ	ZZ	Zjets	Top	$Z\gamma$	$Z\tau\tau$	OSTop
Observed events	122	578	60	251	55	156	328	1169
MC prediction	121±16	576±63	60±10	249±46	55±12	155±31	326±55	1160±150
MC (no NFs)	118±10	543±50	48±4	351±40	48±6	188±17	354±56	1120±140
Composition (%)								
$WZ/W\gamma^*$	—	89.3±1.5	5.5±1.0	25.9±3.5	20±4	1.68±0.31	—	—
ZZ^*	99.49±0.17	6.7±1.2	90.1±2.1	38±5	3.6±1.2	47±6	—	—
$Z\gamma$	—	0.54±0.17	0.6±0.5	5.5±1.5	2.4±0.9	43±7	—	—
Z+jets	—	1.1±0.5	2.1±1.5	29±7	5.50±3.34	8.3±3.4	78.2±2.8	0.7±0.4
Top	0.019±0.012	0.66±0.18	0.27±0.13	0.081±0.034	64±6	0.13±0.06	10.5±1.6	71.3±3.3
Others	0.49±0.17	0.80±0.16	1.16±0.20	0.87±0.13	3.6±0.6	0.33±0.06	11.2±1.9	27.8±3.2
VH ($H \to WW^*$)	0.026±0.006	0.93±0.16	0.26±0.11	0.37±0.09	0.52±0.13	0.052±0.011	0.100±0.018	0.21±0.04

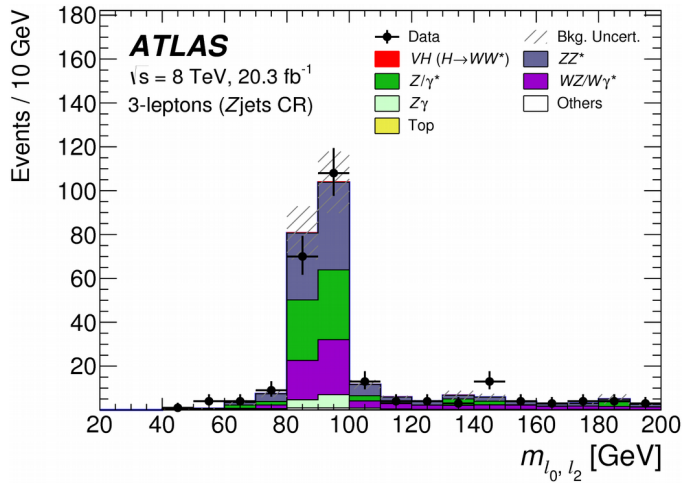
Channel	SS 2ℓ				
CR	$W\gamma$	WZ	WW	SSTop	Zjets
Observed events	228	331	769	5142	39731
MC prediction	229±41	311±66	742±63	5080±350	41000±14000
MC (no NFs)	218±35	335±68	787±58	4930±330	47000±16000
Composition (%)					
$W\gamma$	85.0±2.4	—	0.46±0.14	0.049±0.018	0.022±0.007
$WZ/W\gamma^*$	1.02±0.27	85±4	2.34±0.24	0.200±0.029	0.38±0.09
WW	0.37±0.08	0.028±0.014	23.9±2.3	1.43±0.21	0.57±0.15
Z+jets	4.2±1.6	7.0±3.5	7.0±2.0	2.2±0.7	97.7±0.5
Top	0.68±0.20	1.50±0.29	62.7±2.8	95.5±0.8	0.86±0.21
Others	8.7±1.2	5.3±1.2	3.2±0.4	0.63±0.11	0.44±0.11
VH ($H \to WW^*$)	—	0.77±0.17	0.32±0.04	0.036±0.005	0.0077±0.0020

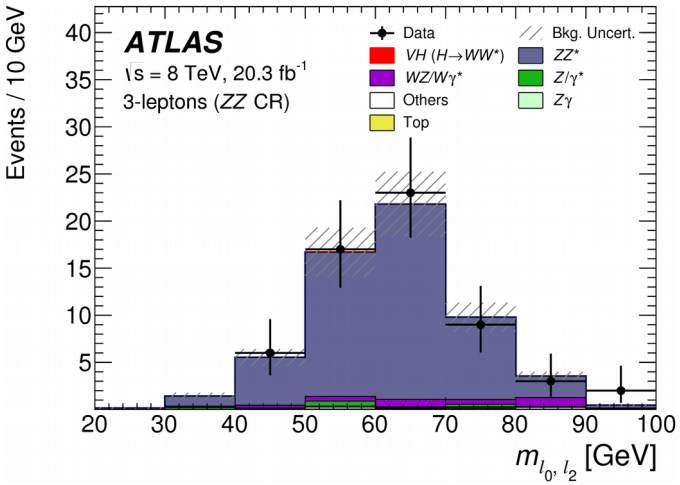
(b) 7 TeV data sample

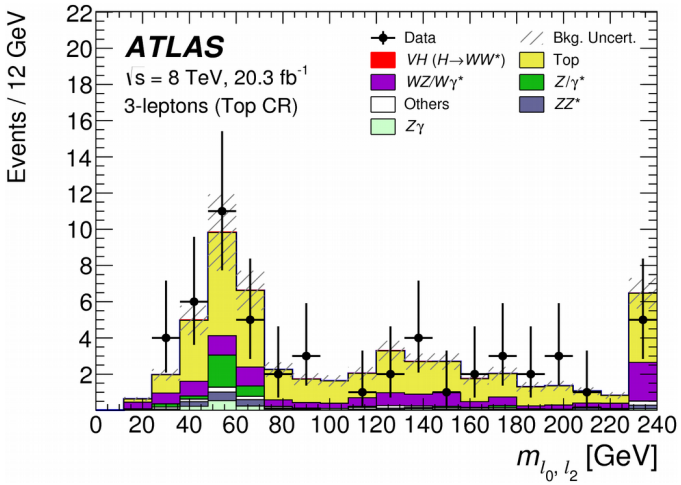
Channel	4ℓ	3ℓ					DFOS 2ℓ	
CR	ZZ	WZ	ZZ	Zjets	Top	$Z\gamma$	$Z\tau\tau$	OSTop
Observed events	24	101	18	68	9	123	55	137
MC prediction	24±8	101±16	18±5	67±15	8±4	123±26	55±15	137±20
MC (no NFs)	15±5	99±10	10.7±0.6	81±7	8.1±1.4	208±12	51±12	145±18
Composition (%)								
$WZ/W\gamma^*$	—	87.5±2.5	3.1±1.1	6.9±1.4	14±5	0.61±0.15	—	—
ZZ^*	99.71±0.12	7.4±2.1	92.7±2.3	26±6	4.2±2.5	32±7	—	—
$Z\gamma$	—	1.8±0.8	0.5±0.4	48±7	6±4	59±7	—	—
Z+jets	—	1.5±0.8	3.0±1.4	19±5	0.4±2.2	8.2±2.1	76±6	0.14±0.15
Top	0.031±0.015	0.7±0.4	0.01±0.20	0.07±0.13	71±10	0.03±0.04	13±5	75.2±3.2
Others	0.23±0.11	0.56±0.11	0.44±0.11	0.115±0.021	4.2±1.4	0.05±0.17	11±4	24.7±3.2
VH ($H \to WW^*$)	0.02±0.31	0.53±0.08	0.106±0.030	0.044±0.008	0.41±0.17	0.0154±0.0027	0.048±0.017	0.135±0.030

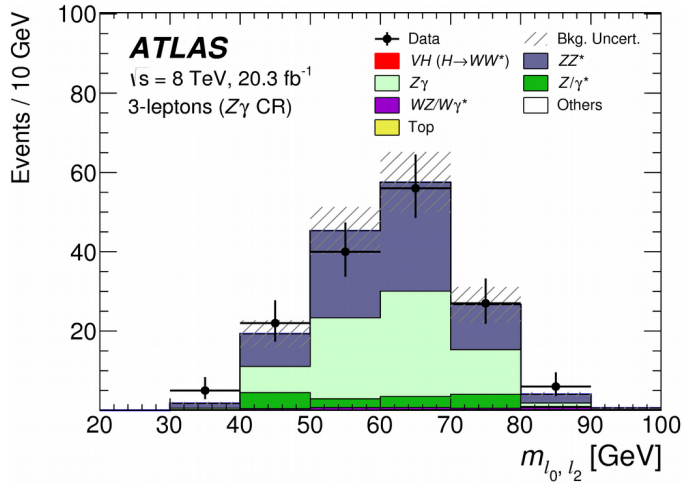
CR distributions (3l)



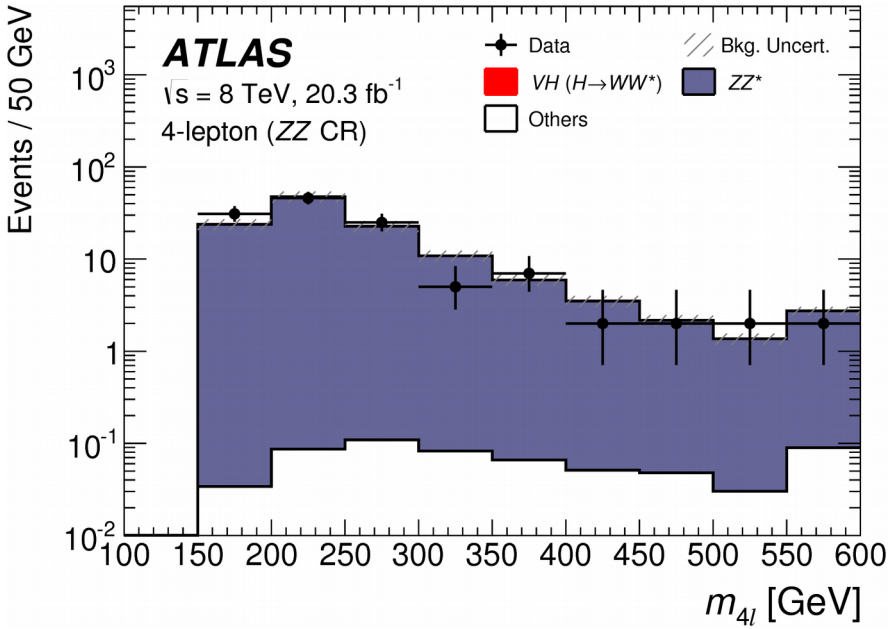


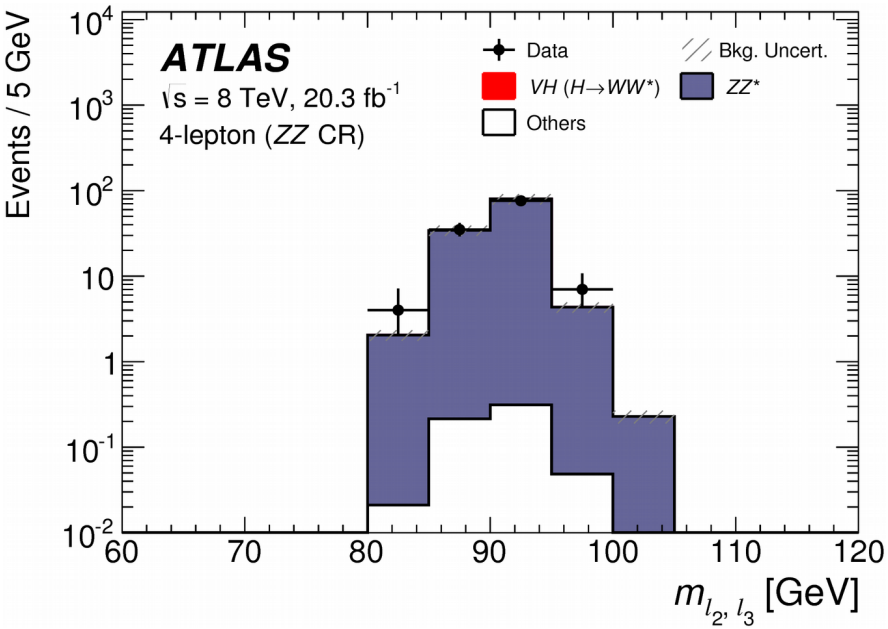


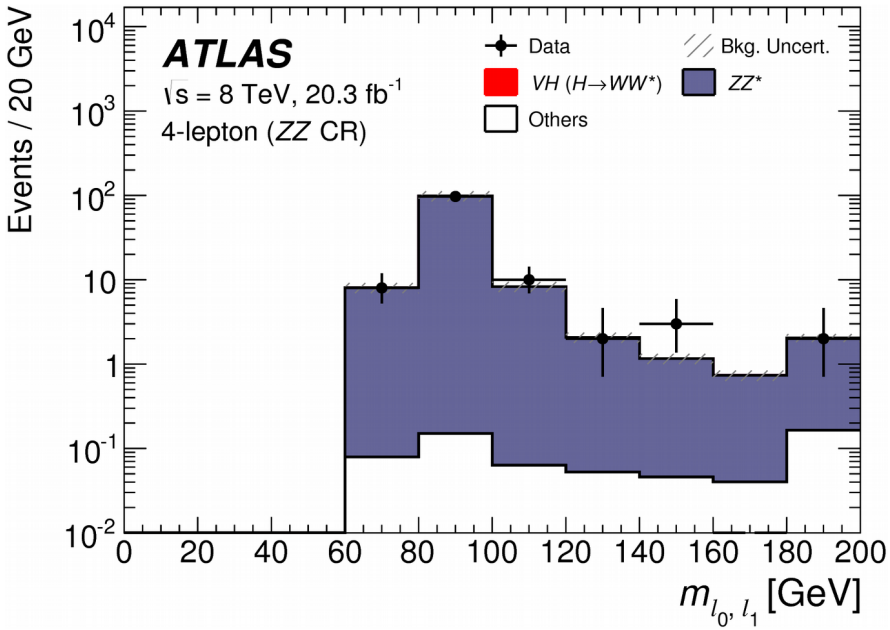




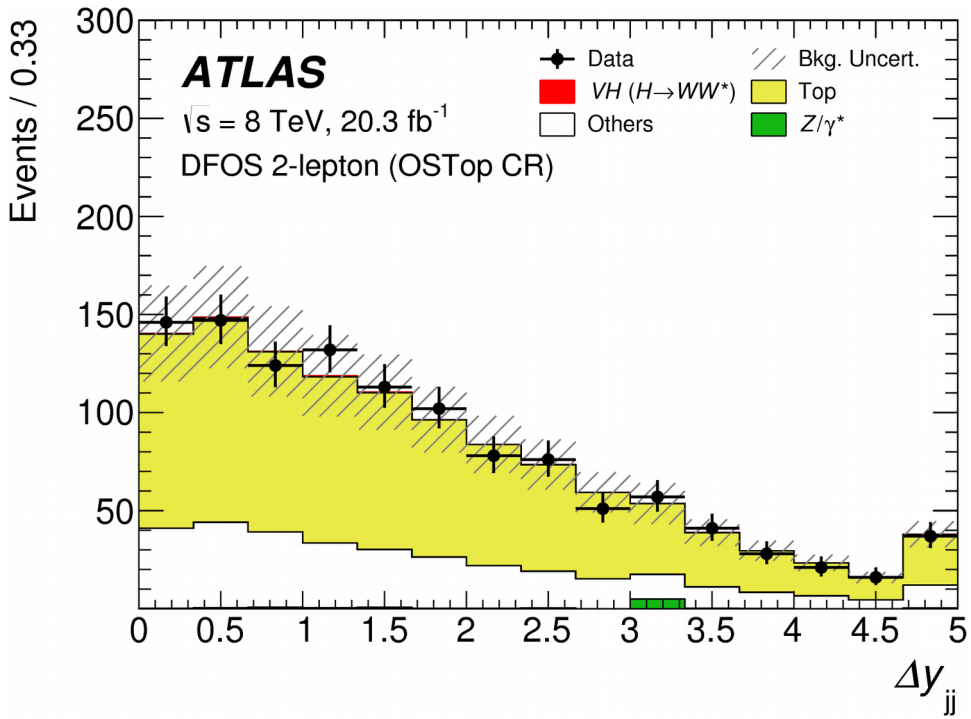
CR distributions (4l)

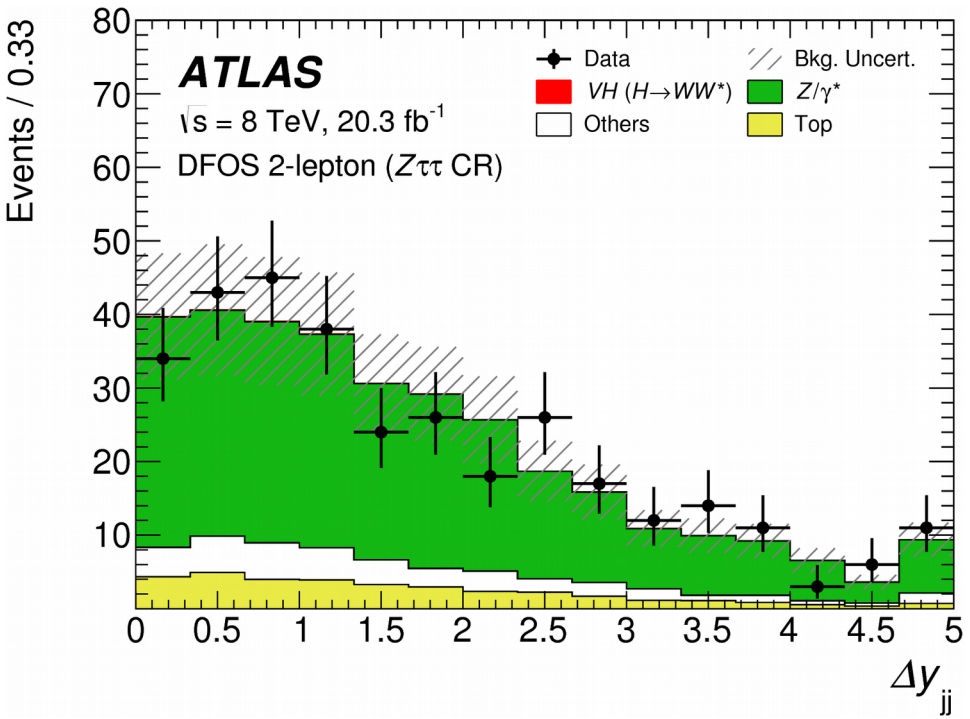




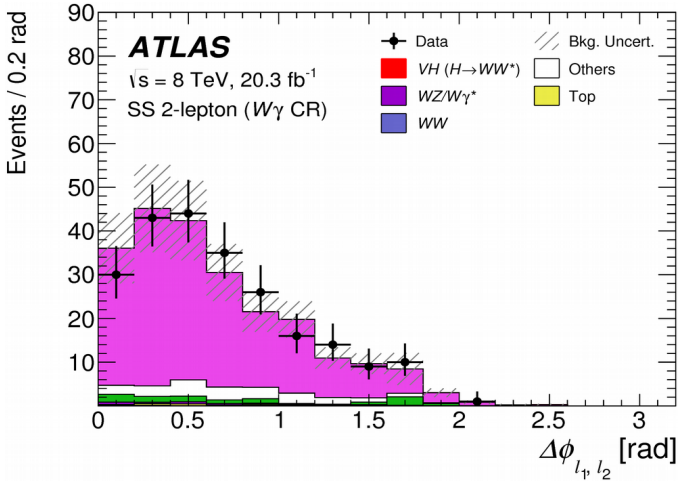


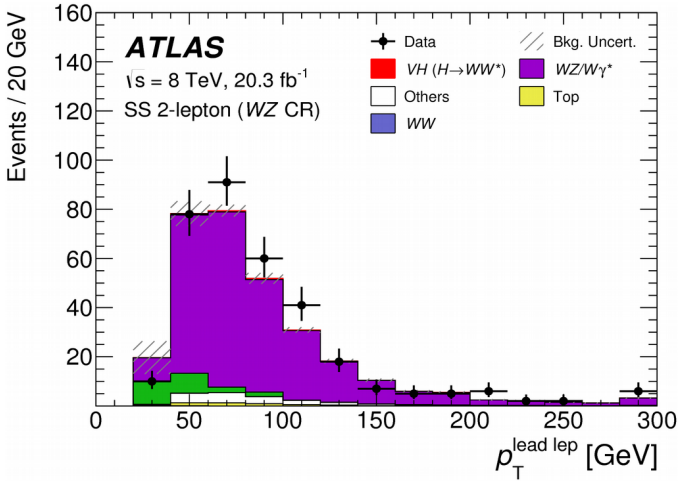
CR distributions (DFOS)

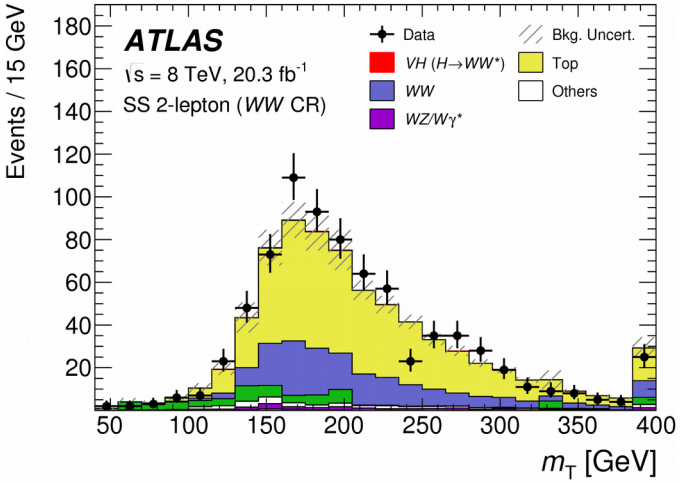


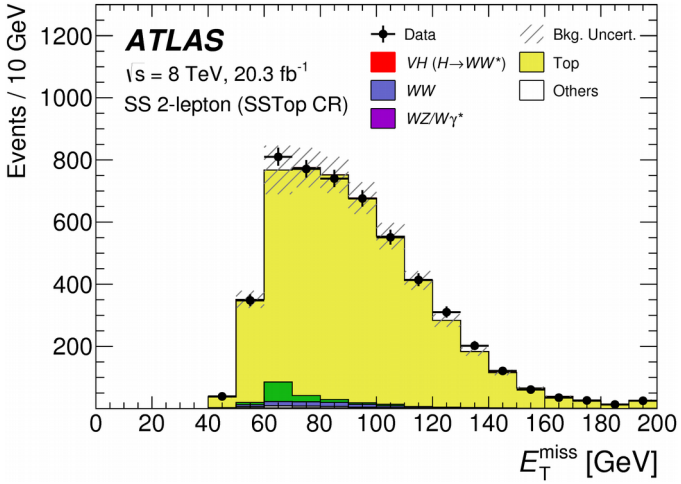


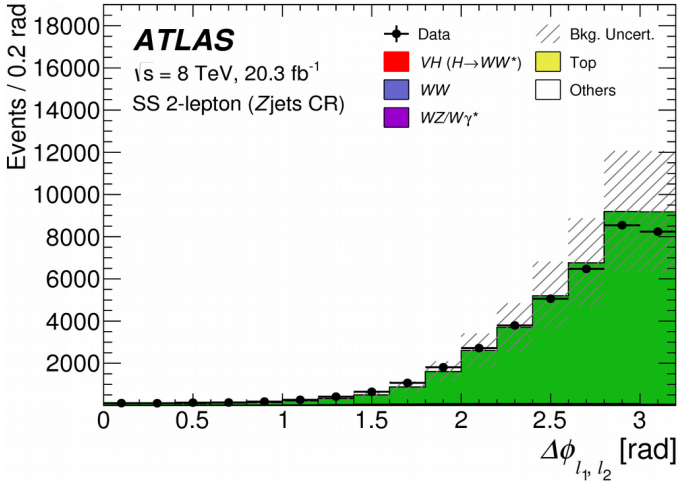
CR distributions (SS)











Systematic uncertainties

(a) Uncertainties on the $VH(H \to WW^*)$ process (%)

Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	3SF	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Theoretical uncertainties								
VH acceptance	9.2	9.3	9.9	9.9	9.9	10	10	9.9
Higgs boson branching fraction	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
QCD scale	3.1	3.0	1.2	1.0	1.0	1.3	1.0	1.0
PDF and α_S	1.0	1.1	2.1	2.2	2.2	1.9	2.3	2.2
VH NLO EW corrections	1.7	1.8	1.9	1.9	1.9	1.9	1.9	1.9
Experimental uncertainties								
Jet	2.0	3.1	2.5	2.5	2.9	3.2	8.9	5.8
E_T^{miss} soft term	0.2	0.3	–	–	–	0.3	0.6	0.2
Electron	2.6	2.8	1.6	2.2	2.2	1.5	2.1	1.7
Muon	2.6	2.4	2.2	1.8	1.7	0.8	1.8	1.9
Trigger efficiency	0.2	–	0.4	0.3	0.3	0.5	0.6	0.5
b-tagging efficiency	0.9	0.9	0.9	0.8	0.8	2.9	3.5	2.4
Pile-up	1.9	0.7	2.0	1.4	0.8	1.7	1.0	2.4
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8

(b) Uncertainties on the total background (%)

Theoretical uncertainties								
QCD scale	0.2	0.1	1.0	0.9	–	3.7	13	2.3
PDF and α_S	0.2	2.4	0.3	0.3	1.6	1.4	0.5	0.6
VVV K-factor	2.8	8.1	1.1	1.9	0.5	–	–	0.3
MC modelling	5.3	4.3	7.0	6.6	–	4.1	0.8	1.4
Experimental uncertainties								
Jet	3.1	2.4	3.2	1.8	4.1	7.2	5.0	3.4
E_T^{miss} soft term	2.3	0.6	1.8	1.9	0.5	1.1	0.2	0.7
Electron	1.0	1.4	1.0	0.4	1.1	0.7	1.1	0.8
Muon	1.1	1.2	0.4	0.7	0.2	0.2	0.4	0.8
Trigger efficiency	–	0.2	0.2	–	–	0.1	–	–
b-tagging efficiency	0.6	0.8	0.6	0.8	2.6	0.7	1.4	0.3
Fake factor	–	–	–	–	–	2.8	10	10
Charge mis-assignment	–	–	–	–	1.4	–	0.7	0.8
Photon conversion rate	–	–	–	–	–	–	1.1	0.9
Pile-up	1.2	1.1	1.4	0.3	1.2	0.9	1.0	1.0
Luminosity	0.4	0.8	0.1	0.2	0.7	–	0.7	0.3
MC statistics	5.3	8.0	3.8	3.2	5.5	3.1	7.3	3.9
CR statistics	8.1	6.6	4.2	3.9	8.8	2.5	2.8	3.5

Event yields

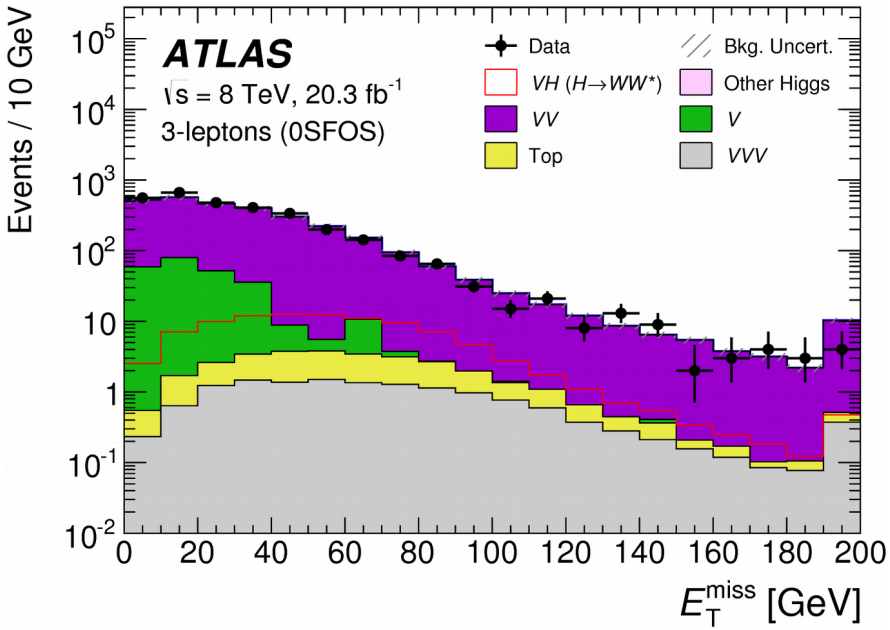
(a) 8 TeV data sample

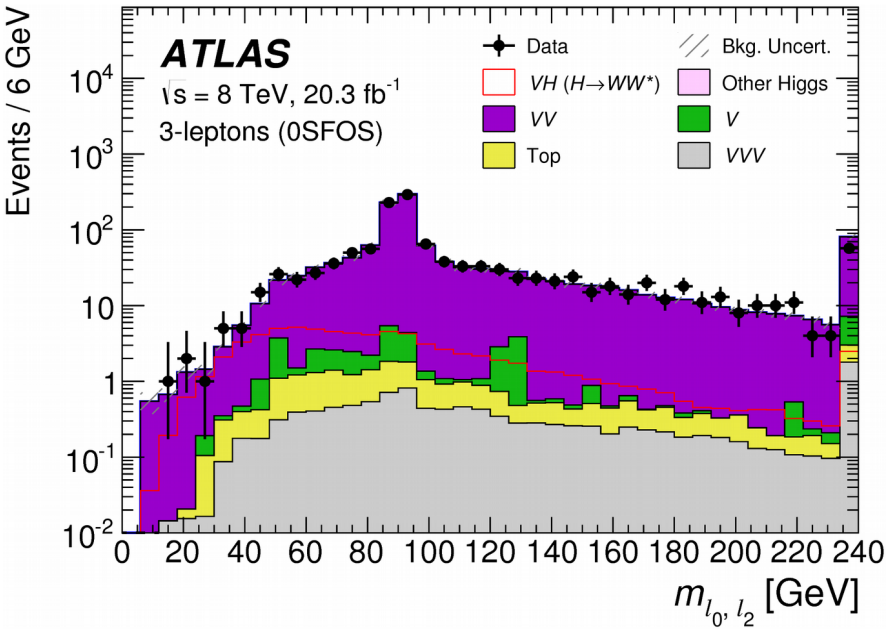
Process	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Higgs boson								
VH $(H \to WW^*)$	0.203±0.030	0.228±0.034	0.73±0.10	1.61±0.18	1.43±0.16	2.15±0.30	1.04±0.18	2.04±0.30
VH $(H \to \tau\tau)$	0.0084±0.0032	0.012±0.004	0.057±0.011	0.152±0.023	0.248±0.035	—	0.036±0.008	0.27±0.04
ggF	—	—	0.076±0.015	0.085±0.018	—	2.4±0.5	—	—
VBF	—	—	—	—	—	0.180±0.025	—	—
ttH	—	—	—	—	—	—	—	—
Background								
V	—	—	0.22±0.16	1.9±0.6	0.37±0.15	14±4	8±4	15±5
VV	1.17±0.20	0.31±0.06	19±3	28±4	4.7±0.6	10.1±1.6	11.2±2.1	26±4
VVV	0.12±0.04	0.10±0.04	0.8±0.3	2.2±0.7	2.93±0.29	—	—	0.47±0.05
Top	0.014±0.011	—	0.91±0.26	2.4±0.6	3.7±0.9	24±4	0.75±0.19	1.3±0.5
Others	—	—	—	—	—	2.3±0.9	0.71±0.30	0.60±0.24
Total	1.30±0.23	0.41±0.09	22±4	34±6	11.7±1.8	50±5	21±5	44±6
Observed events	0	3	22	38	14	63	25	62

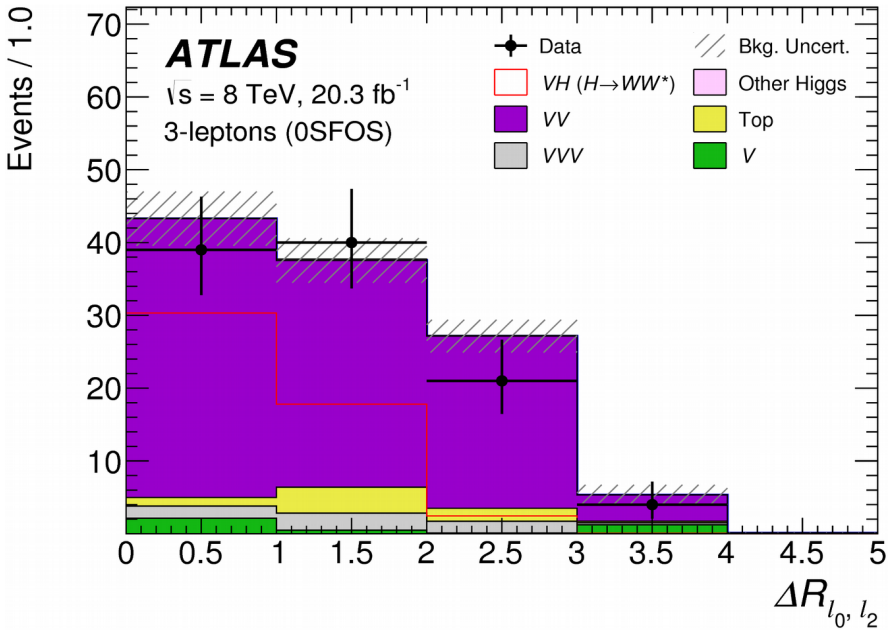
7 TeV data sample

Process	4ℓ		3ℓ			2ℓ
Category	2SFOS	1SFOS	3SF	1SFOS	0SFOS	DFOS
Higgs boson						
$V(H \to WW^*)$	0.0226±0.0033	0.0208±0.0031	0.129±0.013	0.325±0.034	0.291±0.031	0.28±0.05
$V(H \to \tau\tau)$	0.0031±0.0012	0.0014±0.0008	0.0163±0.0035	0.041±0.006	0.067±0.010	0.0075±0.0032
ggF	—	—	0.0045±0.0015	0.0045±0.0019	0.0048±0.0027	0.32±0.09
VBF	—	—	—	—	—	0.021±0.004
$t\bar{t}$H	—	—	—	0.006±0.004	0.0041±0.0032	—
Background						
V	—	—	0.36±0.30	0.59±0.34	0.36±0.22	3.4±1.3
VV	0.37±0.14	0.031±0.013	4.1±0.6	5.7±1.0	1.3±0.2	0.89±0.27
VVV	0.014±0.005	0.0095±0.0033	0.082±0.028	0.21±0.07	0.338±0.031	—
Top	0.006±0.004	—	0.12±0.14	0.4±0.3	0.44±0.29	3.2±0.8
Others	—	—	—	—	—	—
Total	0.39±0.15	0.041±0.016	4.6±1.1	7.0±1.9	2.5±0.7	7.5±1.7
Observed events	1	0	5	6	2	7

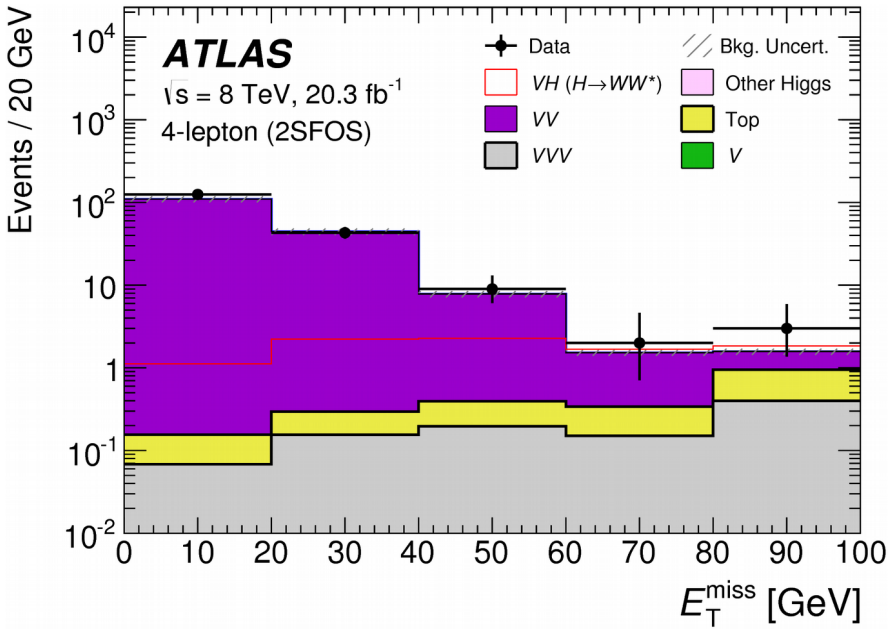
Kinematic variable distributions (3l)

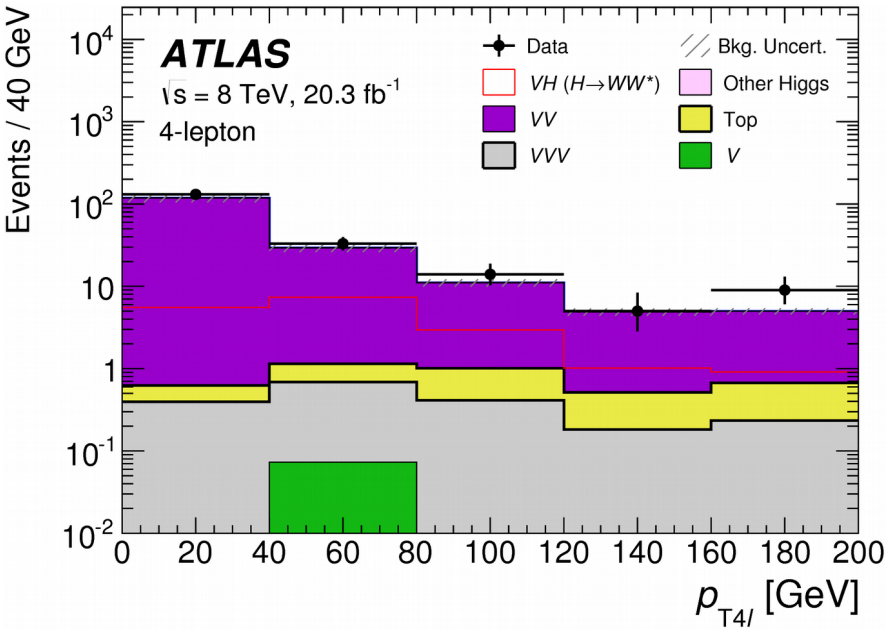


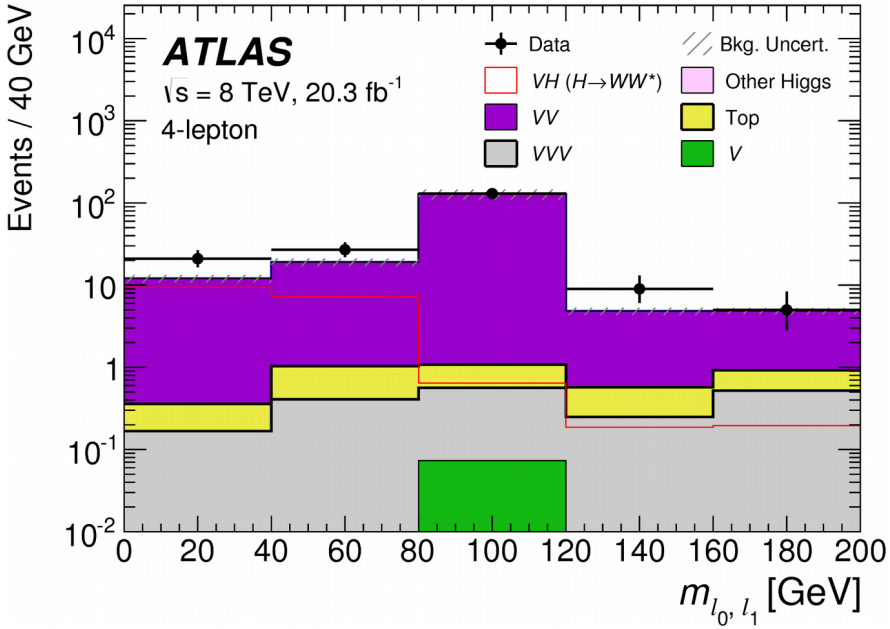




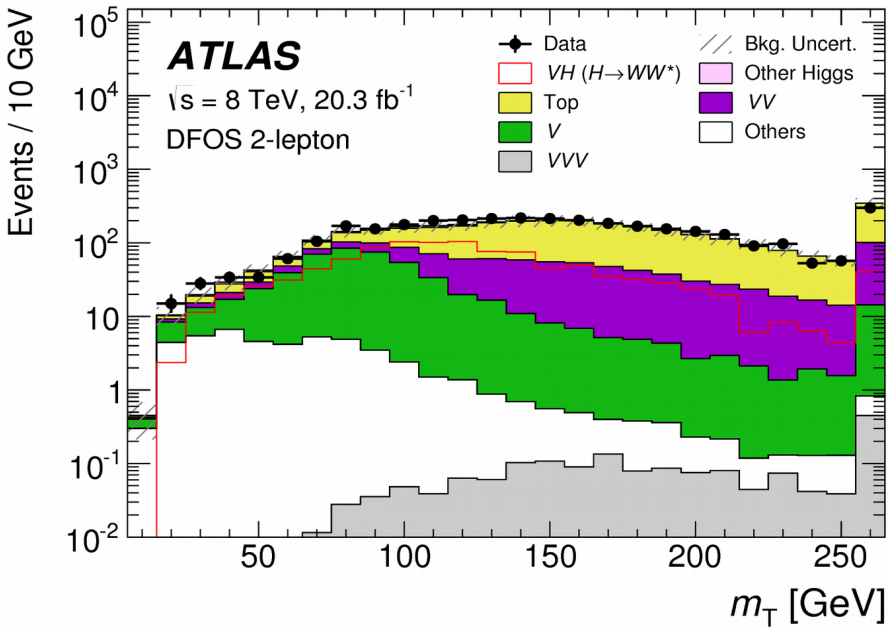
Kinematic variable distributions (4l)

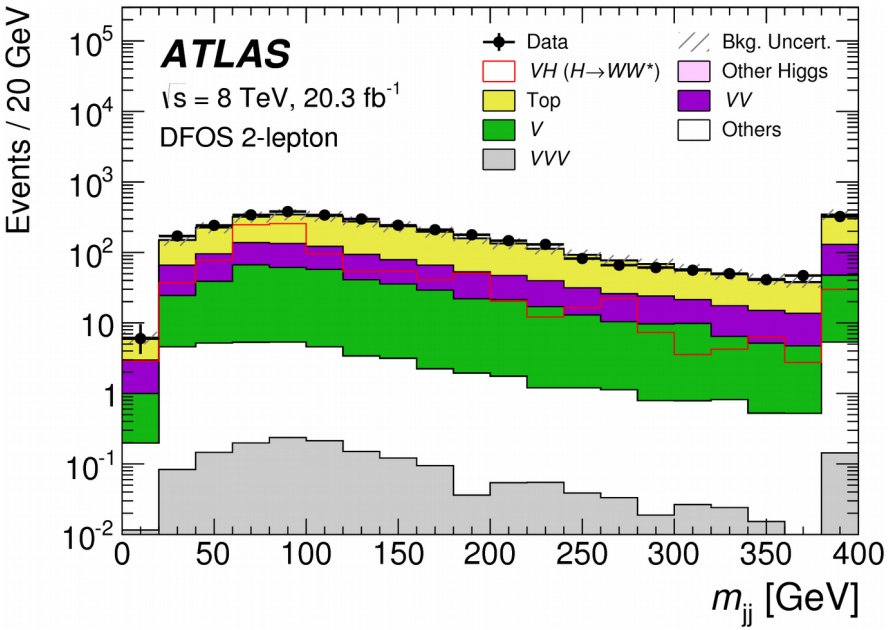




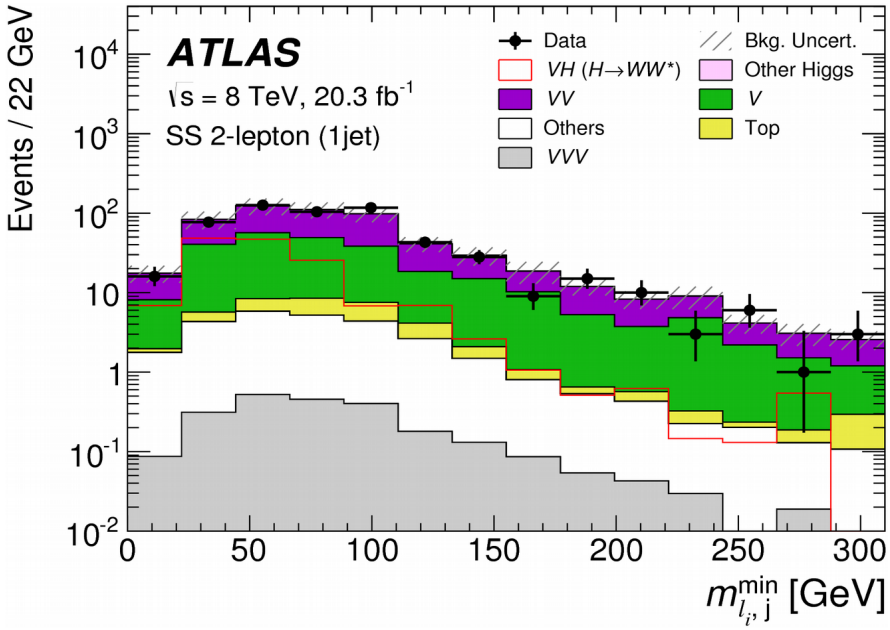


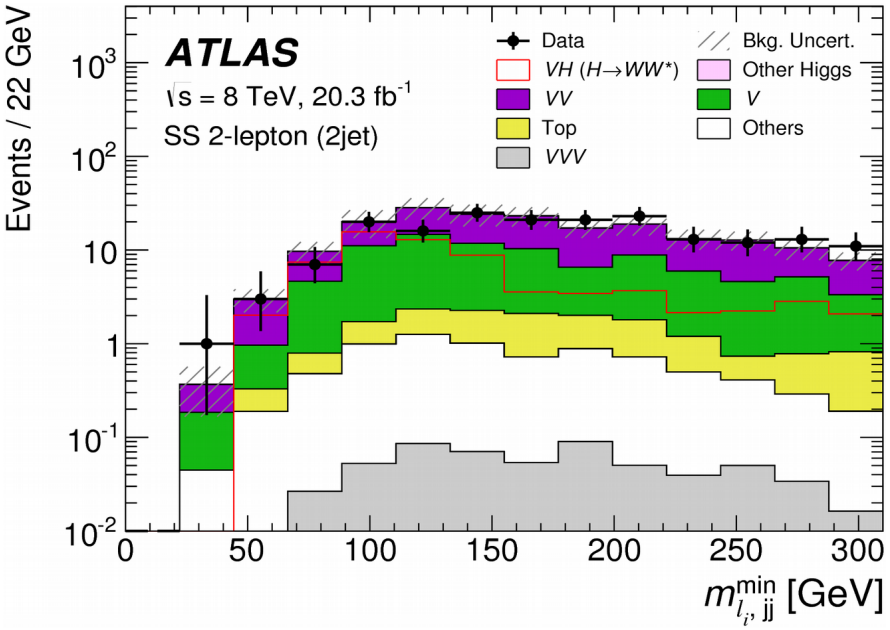
Kinematic variable distributions (DFOS)

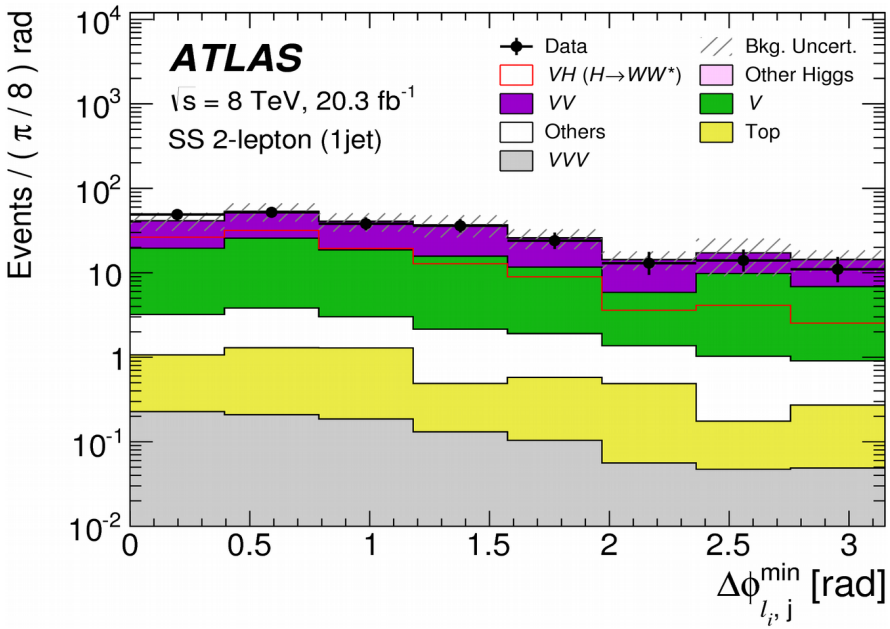


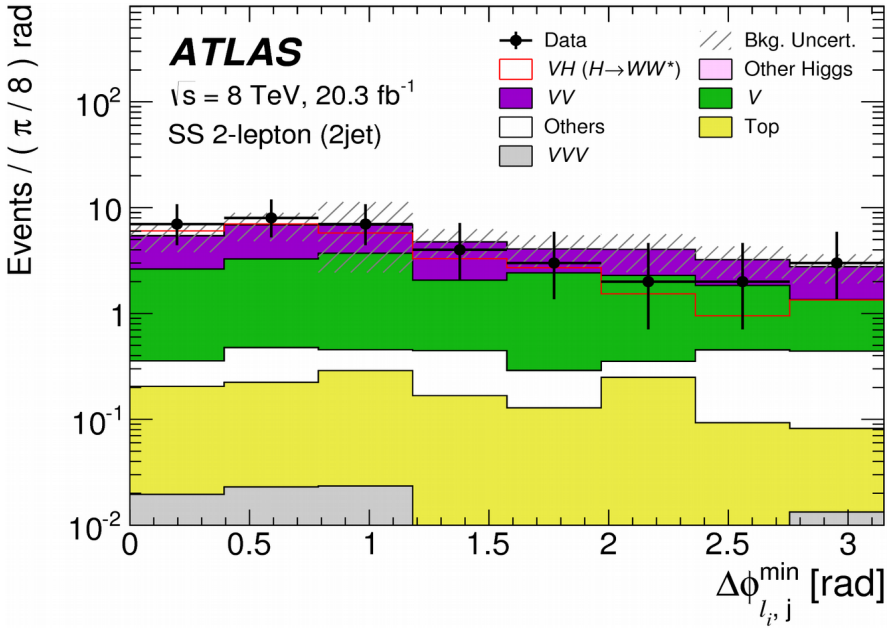


Kinematic variable distributions (SS)





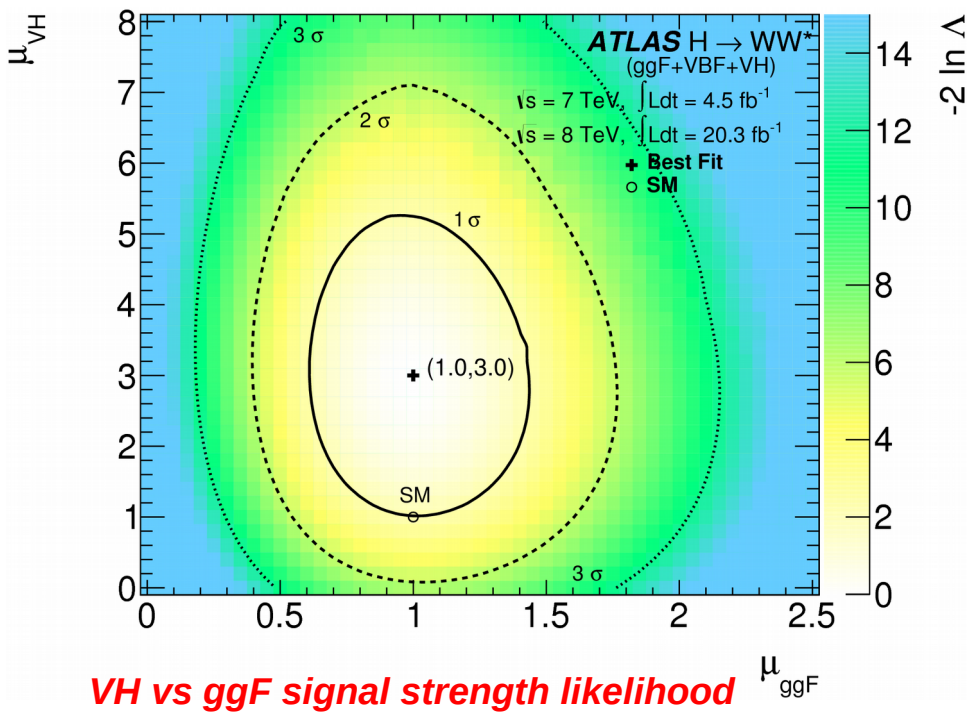




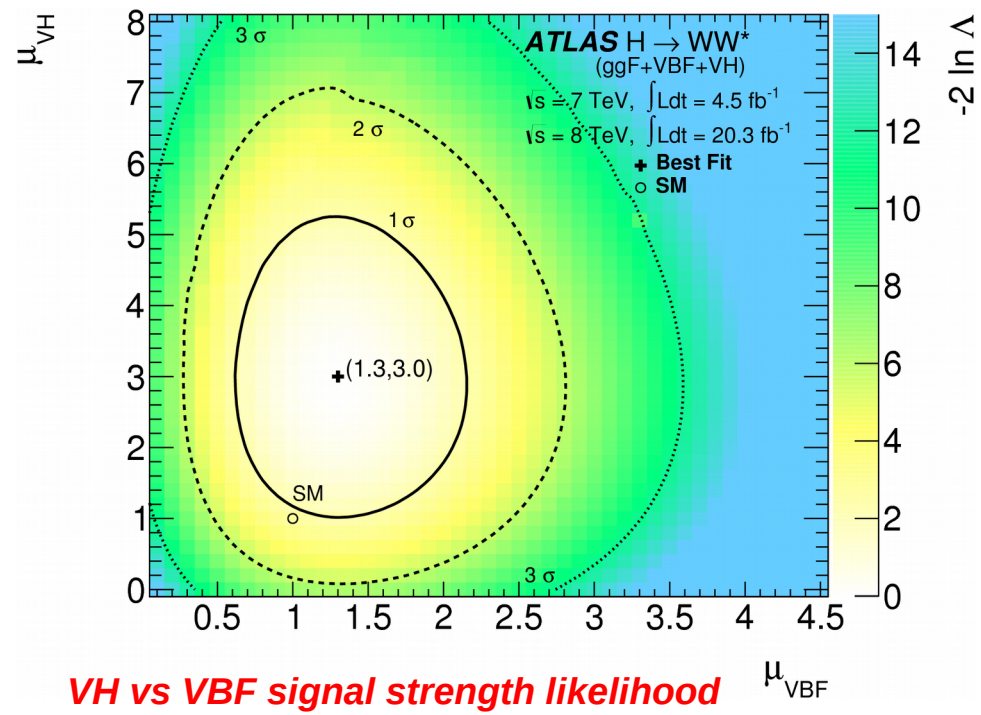
VH Results (mH = 125.36 GeV)

Category	Signal significance Z_0: Exp. Z_0	Obs. Z_0	Obs. Z_0	Observed signal strength μ: μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −
4ℓ	0.41	1.9		**4.9**	4.6	3.1	1.1	0.40
2SFOS	0.19	0		**−5.9**	6.8	4.1	0.33	0.72
1SFOS	0.36	2.5		**9.6**	8.1	5.4	2.1	0.64
3ℓ	0.79	0.66		**0.72**	1.3	1.1	0.40	0.29
1SFOS and 3SF	0.41	0		**−2.9**	2.7	2.1	1.2	0.92
0SFOS	0.68	1.2		**1.7**	1.9	1.4	0.51	0.29
2ℓ	0.59	2.1		**3.7**	1.9	1.5	1.1	1.1
DFOS	0.54	1.2		**2.2**	2.0	1.9	1.0	1.1
SS2jet	0.17	1.4		**7.6**	6.0	5.4	3.2	3.2
SS1jet	0.27	2.3		**8.4**	4.3	3.8	2.3	2.0

Significance and signal strength summary table (7 + 8 TeV)



VH vs ggF signal strength likelihood



VH vs VBF signal strength likelihood