LHC results on Standard Model measurements and limits on EFTs

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On behalf of the ATLAS and CMS Collaborations

ASPEN 2018

Standard Model Cross Section Measurements

- Latest SM results from ATLAS and CMS:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
- Thanks for spectacular performances of the LHC, ATLAS and CMS detectors, we start to observe processes with fiducial cross sections about sub-fb (1 ZZ→4l event observed at D0 when I gave my Aspen talk in 2008, now >2000 ZZ→4l events observed at ATLAS)

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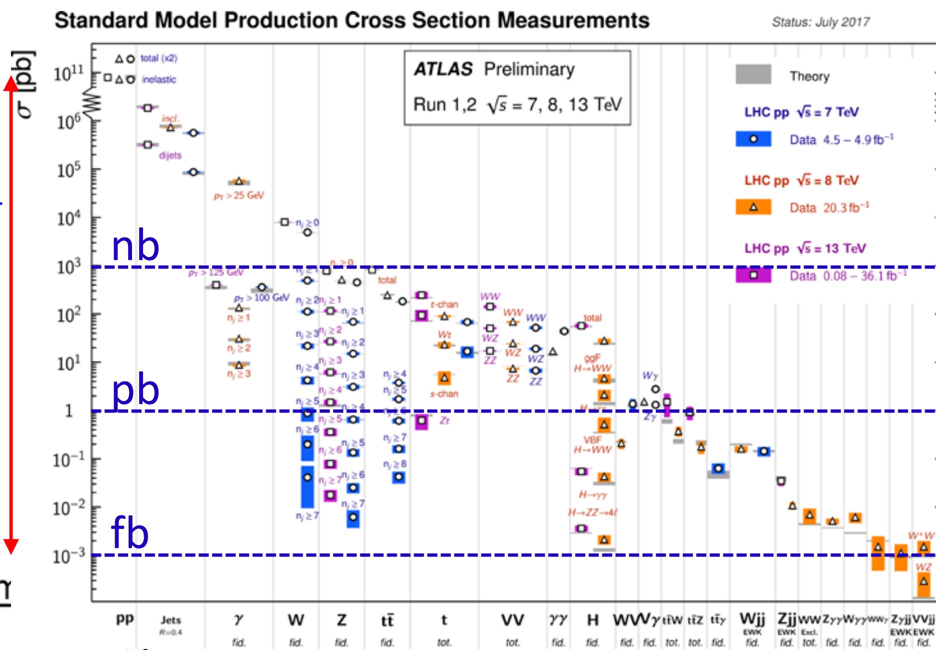
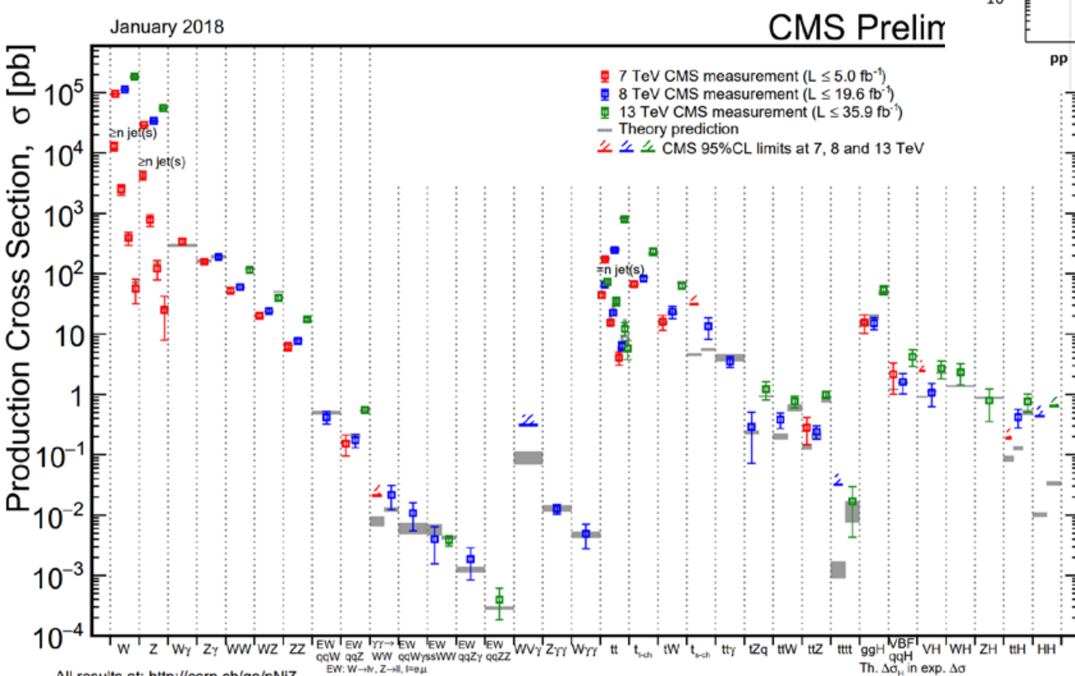
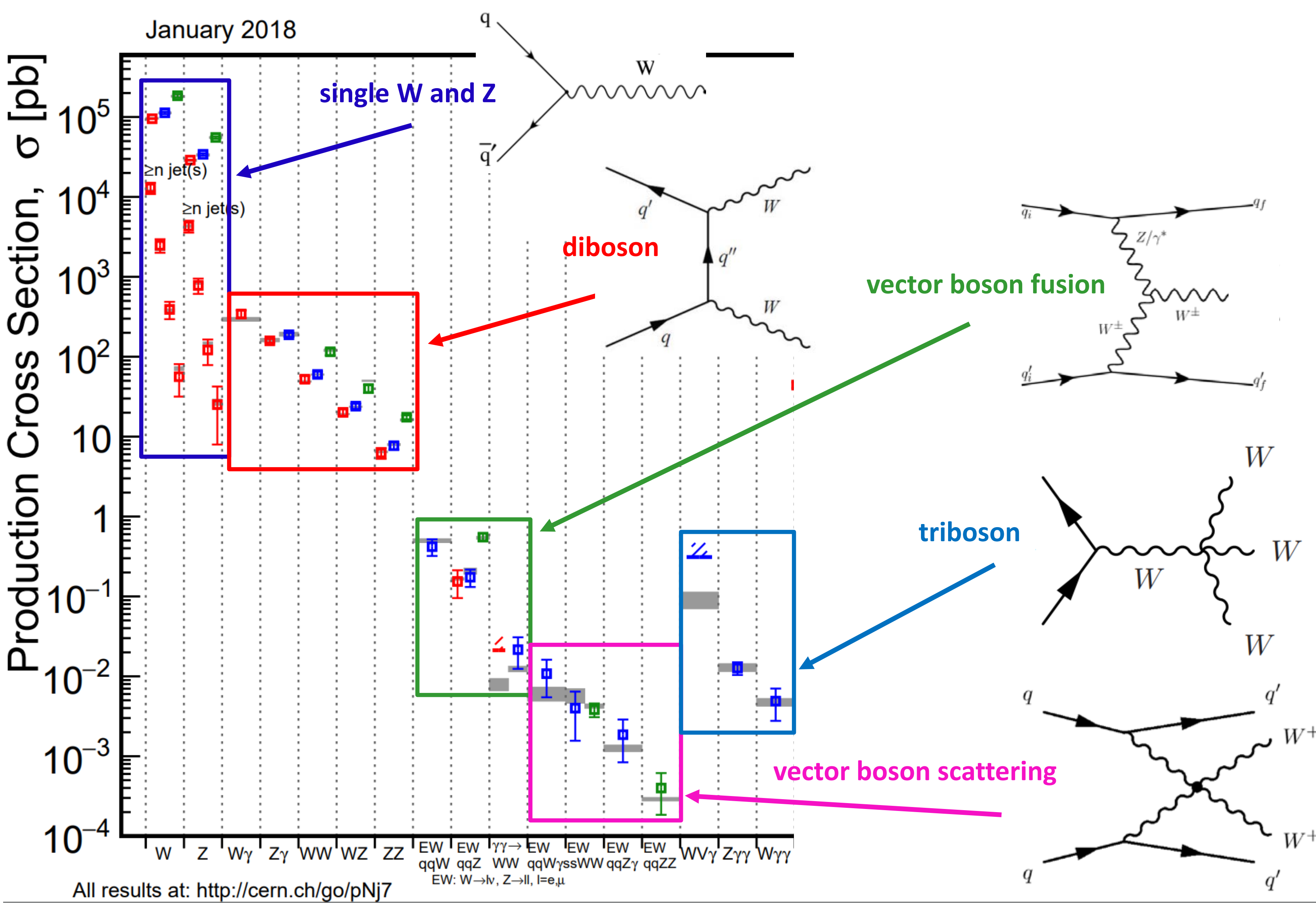




Overall good agreement with theory, some measurements with high precision that can be used to distinguish between NNLO and NLO predictions

Electroweak Measurements



Motivations for Electroweak Measurements

- Diboson, triboson, VBF and VBS are among least-studied processes in the SM
  - Probe gauge-boson self-interactions (TGCs and QGCs)
  - Constrain (or observe) new physics contributions via virtual corrections or modified gauge boson couplings
  - Test high-order QCD and electroweak corrections
- VBS processes are important for a better understanding of the Electroweak Symmetry Breaking mechanism
  - Massless Goldstone bosons from spontaneous symmetry breaking are "eaten" by W and Z bosons and become their longitudinal components
  - Without the SM Higgs bosons, the cross sections of VBS processes increase as a function of the VV center-of-mass energy and violate the unitarity
  - VBS studies provide a good way to study the dynamics of the EWSB
  - Experimental investigations of most VBS processes only become feasible at the LHC
- Important background processes for many BSM searches and Higgs measurements

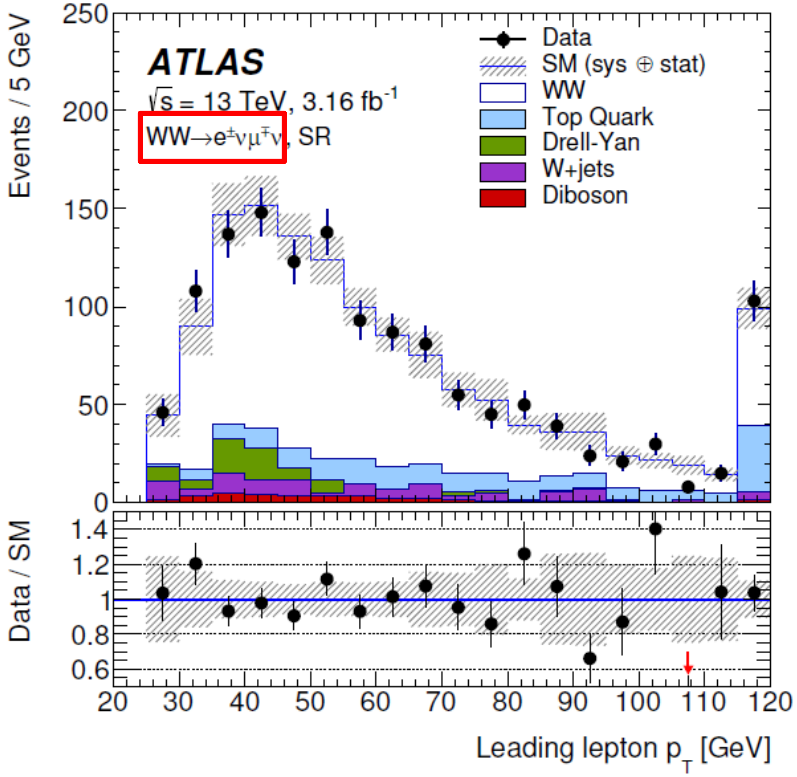
W^+W^- Production at 13 TeV

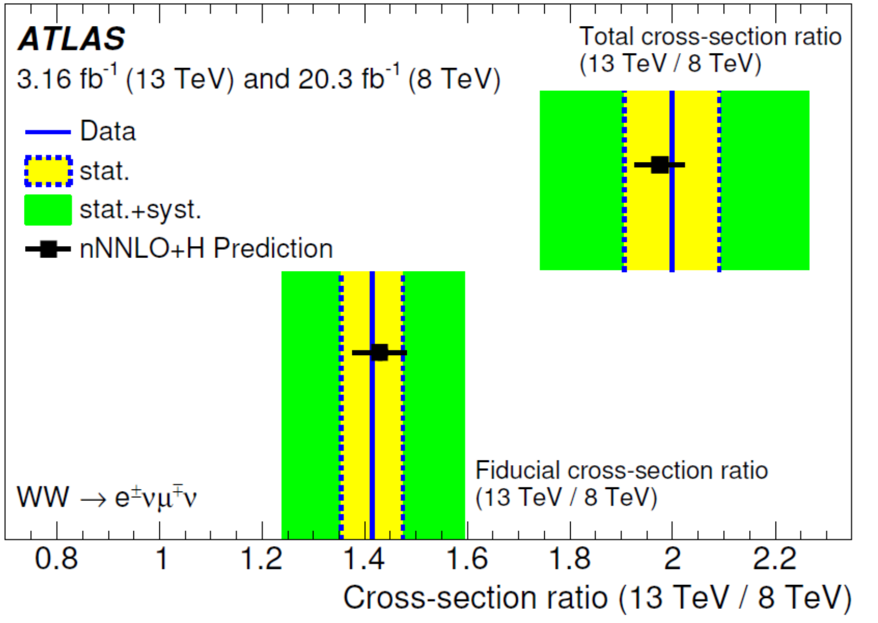
PLB 773 (2017) 354

- Both fiducial and total cross sections are measured
  $\sigma^{fid}(WW \rightarrow e\mu)$=529 ± 55 fb
  $\sigma^{tot}(WW)$=142 ± 14 pb
- Ratios of fiducial and total cross sections at 8 and 13 TeV are also measured

Process	Signal region	Top-quark control region	Drell–Yan control region
WW signal	997 ± 69	49 ± 12	75.3 ± 5.4
Drell–Yan	62 ± 23	49 ± 29	1568 ± 45
$t\bar{t}$+single top	177 ± 33	2057 ± 81	3.5 ± 1.6
W+jets/multi-jet	78 ± 41	70 ± 55	0 ± 17
Other dibosons	38 ± 12	6.3 ± 3.5	19.2 ± 6.1
Total	1351 ± 37	2232 ± 47	1666 ± 41
Data	1351	2232	1666

Scale factor: 1.03±0.03 for DY and 0.875±0.035 for top

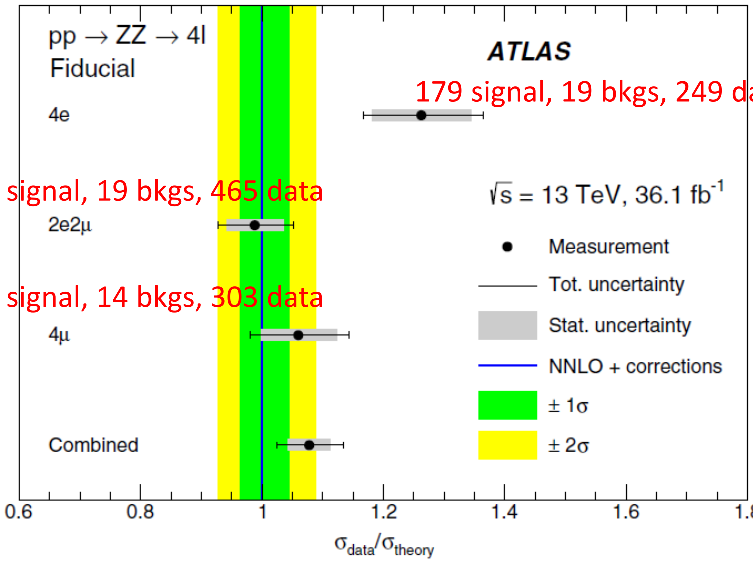




ZZ→4l Production at 13 TeV

- Select events with two Z bosons ($66<m_Z<116$ GeV)
- The lowest lepton p_T cut is 5 (7) GeV for muon (electron)

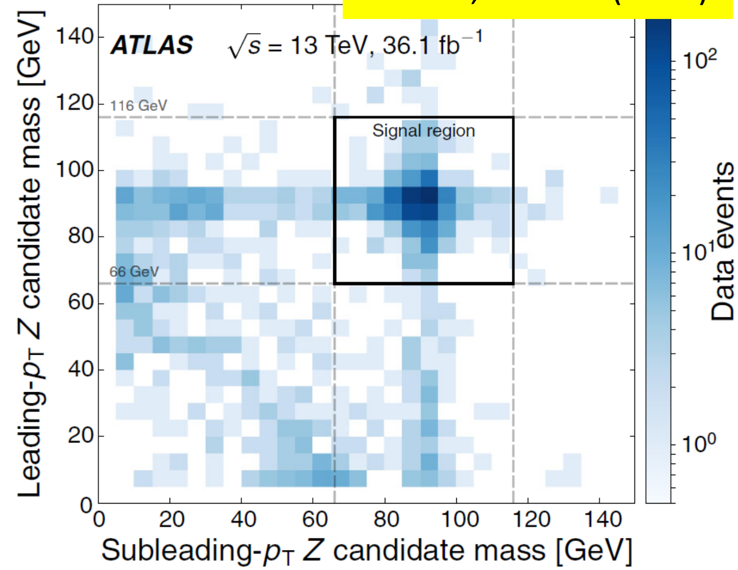
PRD 97, 032005 (2018)

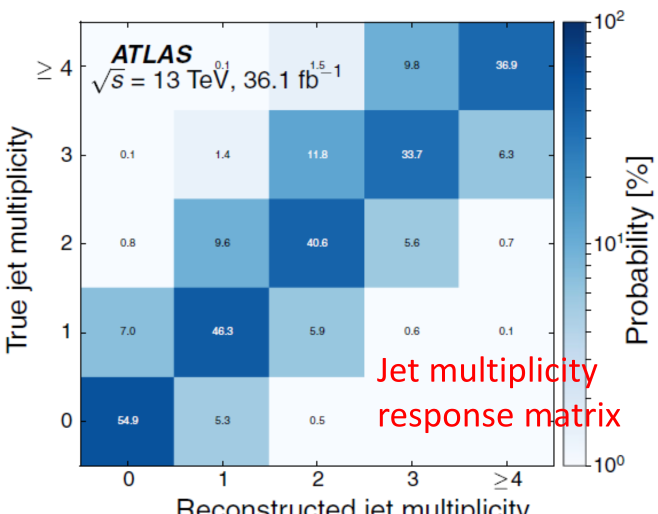


179 signal, 19 bkgs, 249 data

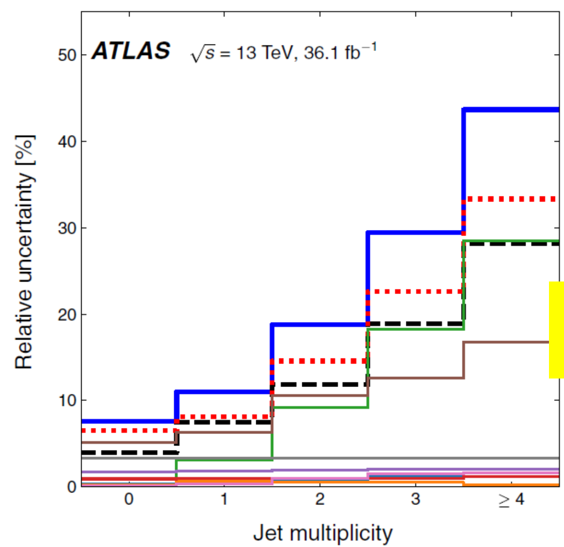
450 signal, 19 bkgs, 465 data

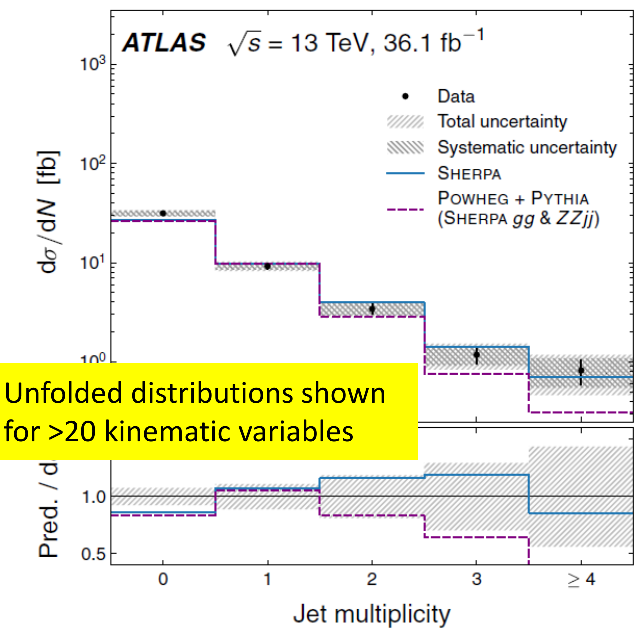
276 signal, 14 bkgs, 303 data





Jet multiplicity response matrix

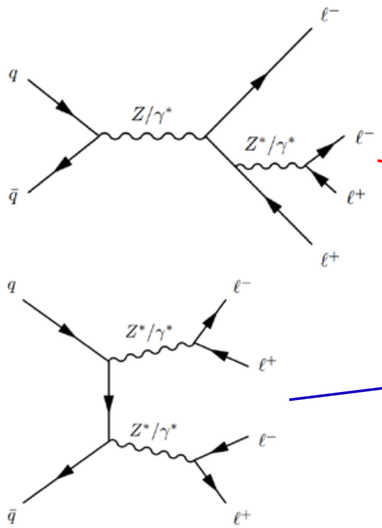


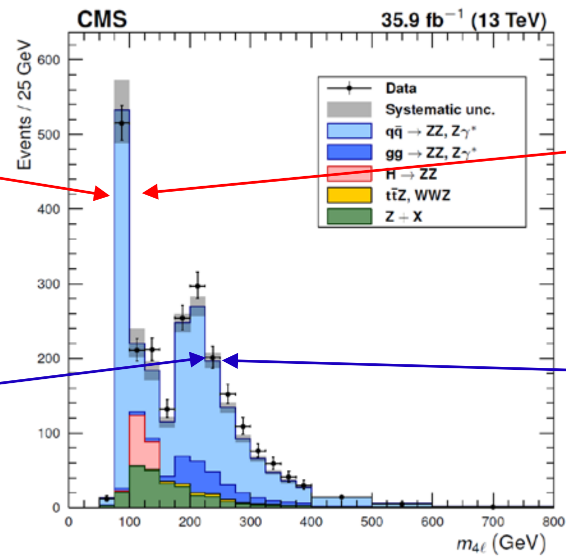


Unfolded distributions shown for >20 kinematic variables

Z/ZZ→4l Production at 13 TeV

arXiv:1709.08601





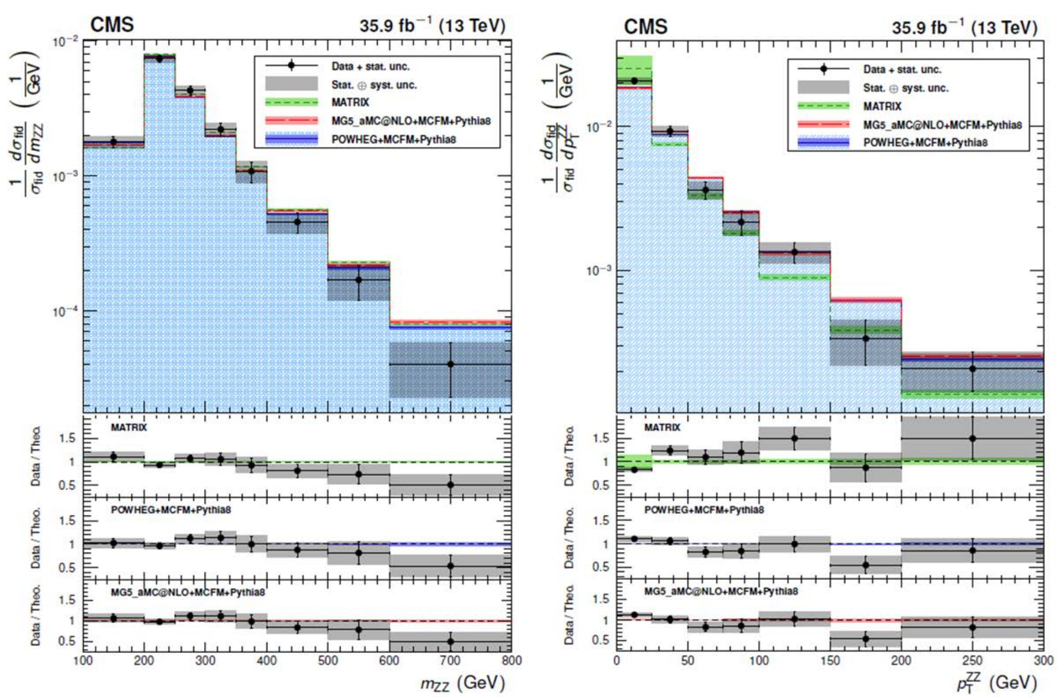
499 signals and 19 bkgs expected

$\sigma^{fid}(pp \to Z \to 4l) = 31.2 \pm 2.7$ fb

$Br(Z \to 4l) = (4.8 \pm 0.3) \times 10^{-6}$

1009 signals and 60 bkgs expected

$\sigma^{fid}(pp \to ZZ \to 4l) = 40.9 \pm 2.2$ fb



WV semileptonic decay at 8 TeV

- WV→lν + jj/J (R=0.4 for small-R jets and R=1 for large-R jets)
- V+jets predictions from MC@NLO, data-driven corrections derived from a V+jets control region with the m_{jj} cut vetoed
- Signal extracted from a global fit to the m_{jj} or m_J distribution

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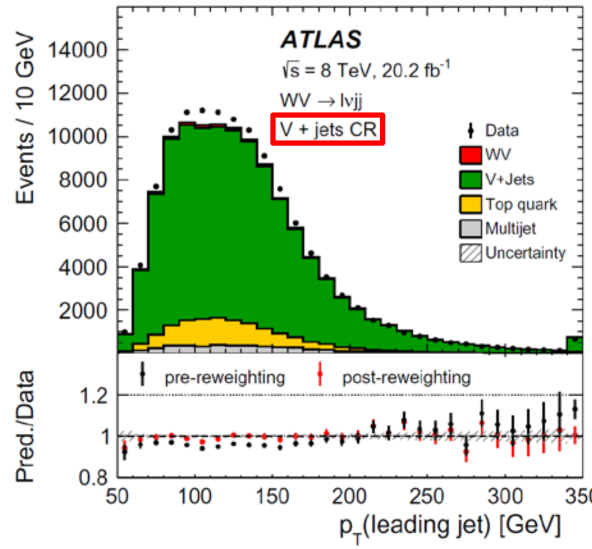

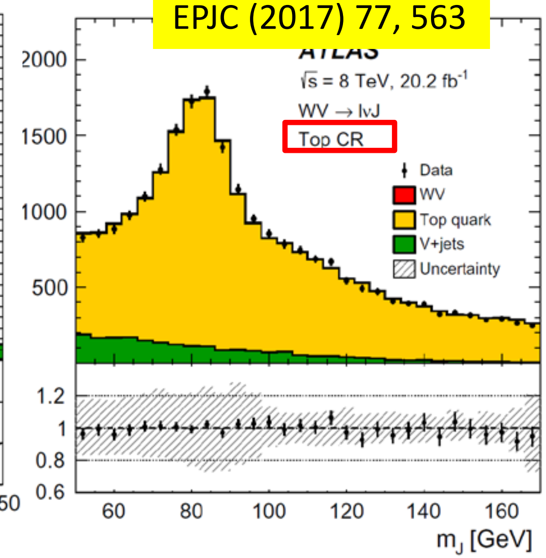

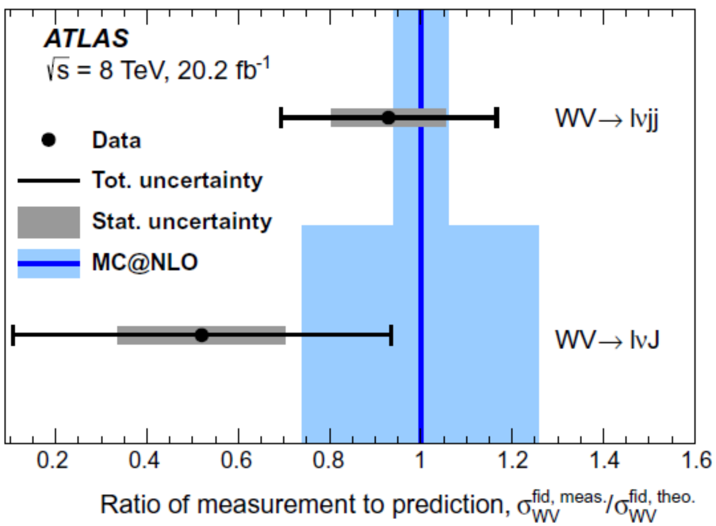

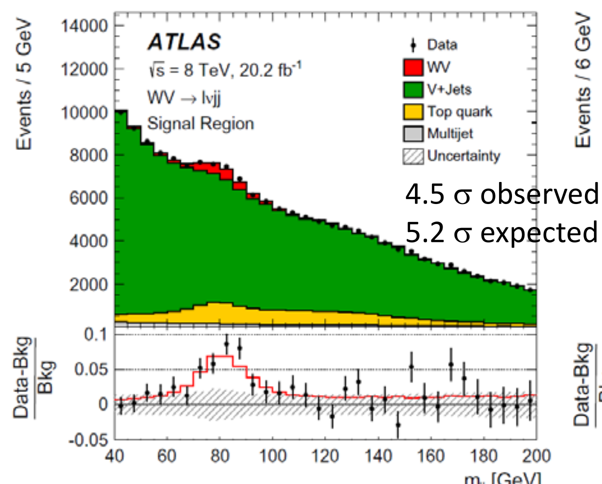

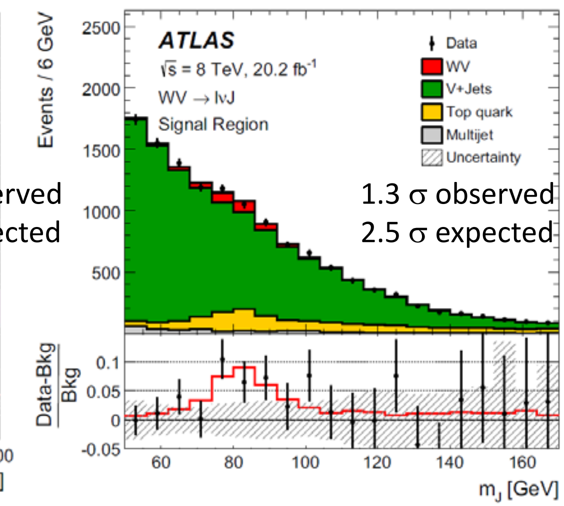

WV semileptonic decay at 8 TeV

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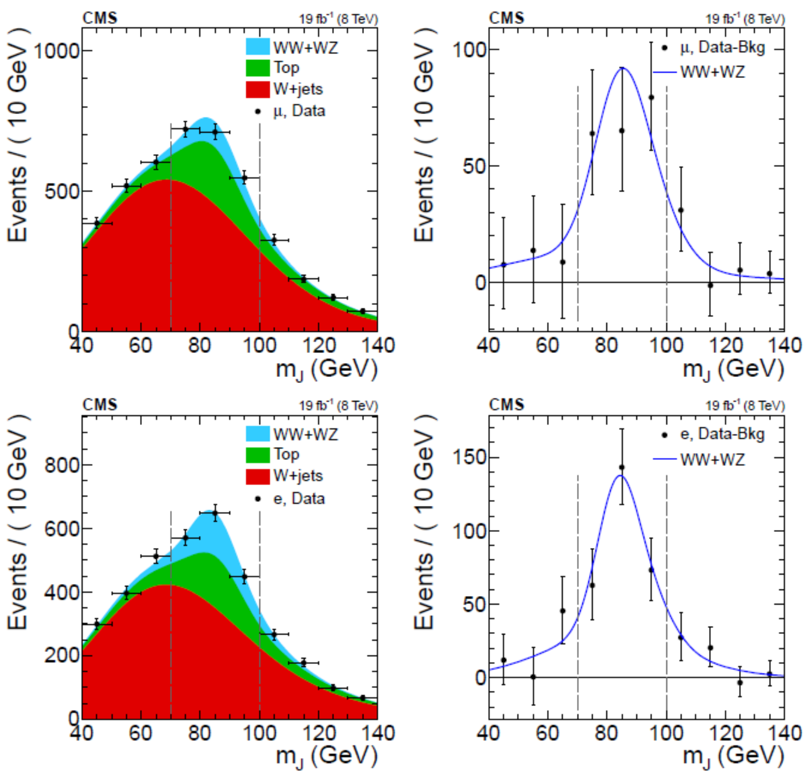
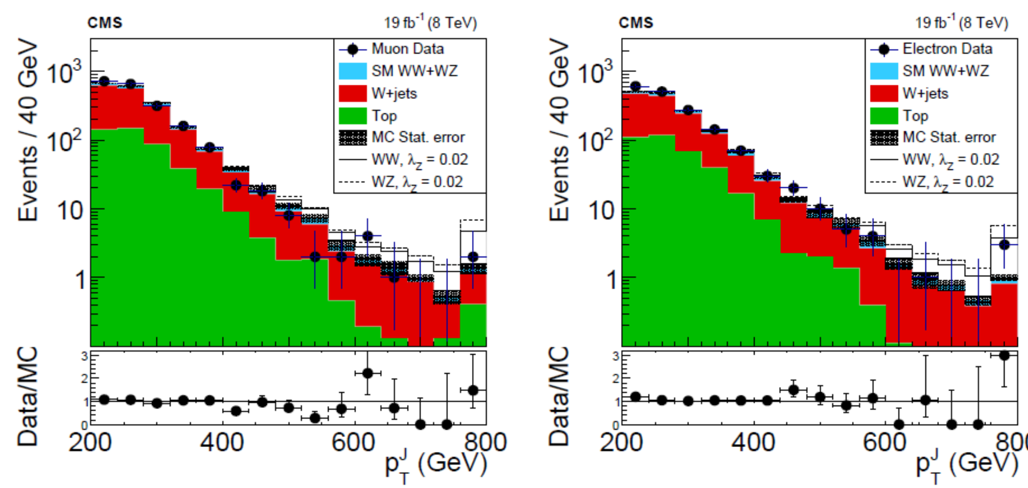
- WV→lν + J (R=0.8 CA jet for V_{had})
- W(→lν) and a fat jet with p_T>200 GeV
- Use the jet-substructure technique N-subjettiness with τ_2/τ_1 to reduce W+jets background



Quantity	μ channel	e channel
Data	1977	1666
W+jets	1318 (1.22 ± 0.06)	1023 (1.17 ± 0.07)
Top quark	450 (1.00 ± 0.08)	364 (1.00 ± 0.10)
WV	204 (1.35 ± 0.77)	285 (2.23 ± 0.84)
$\mathcal{A}\varepsilon$	9.7×10^{-5}	8.3×10^{-5}



EWK production of Z bosons at 13 TeV

- Corrections to the QCD-Zjj MC m_{jj} shape derived from a QCD-enriched region
- Fit of the QCD-Zjj and EW-Zjj simulated m_{jj} distributions to the data

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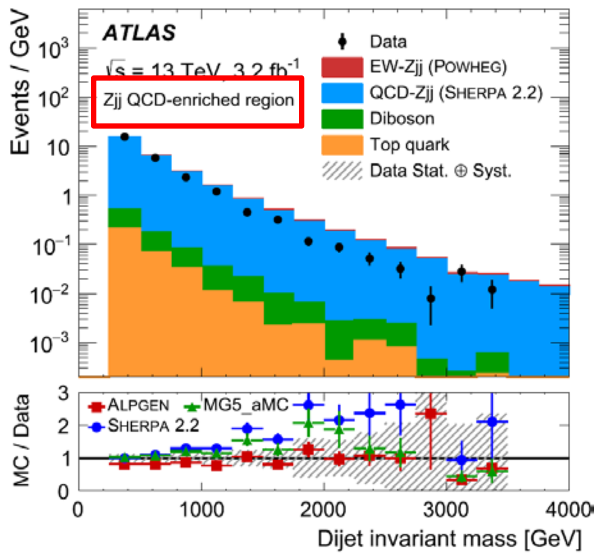
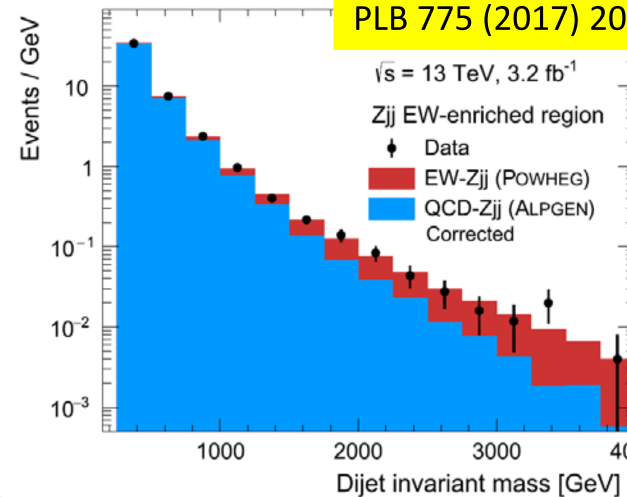
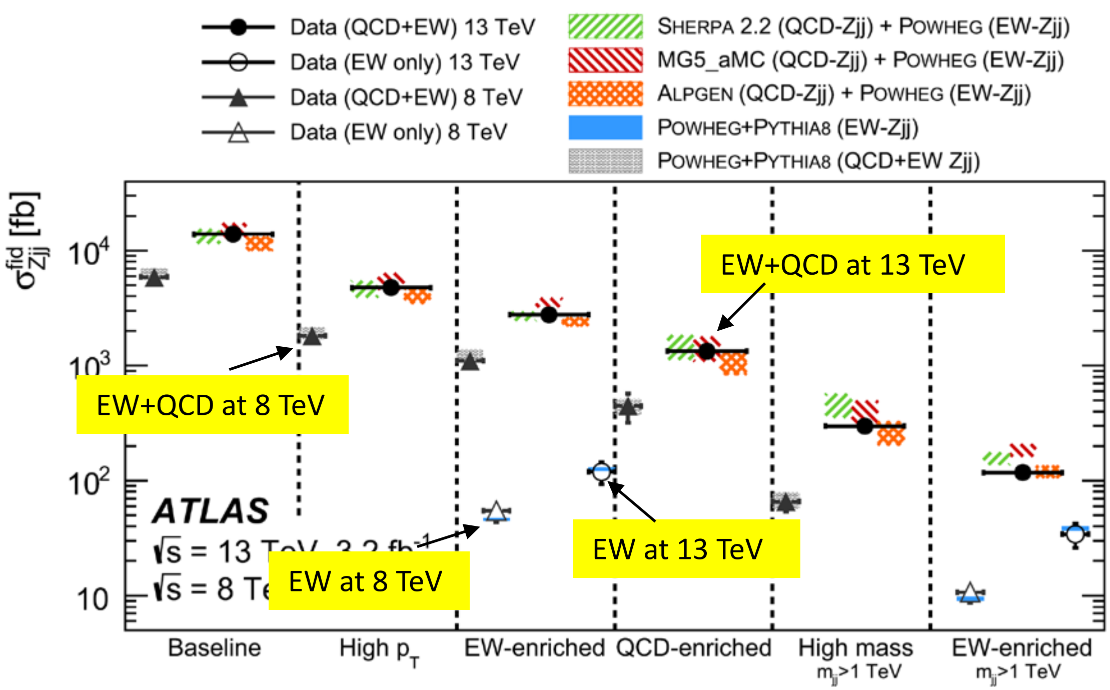


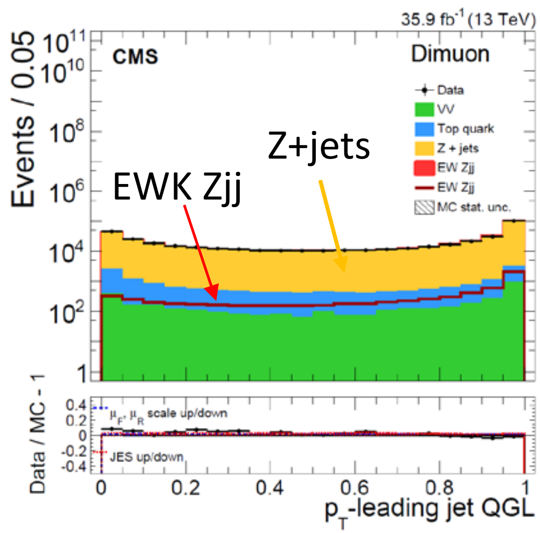


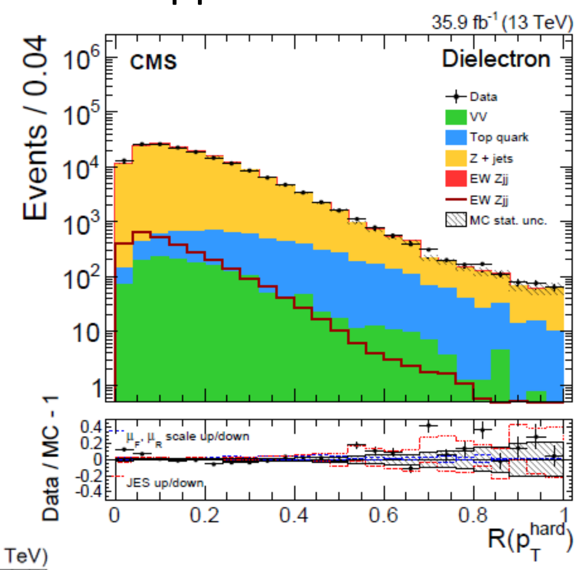


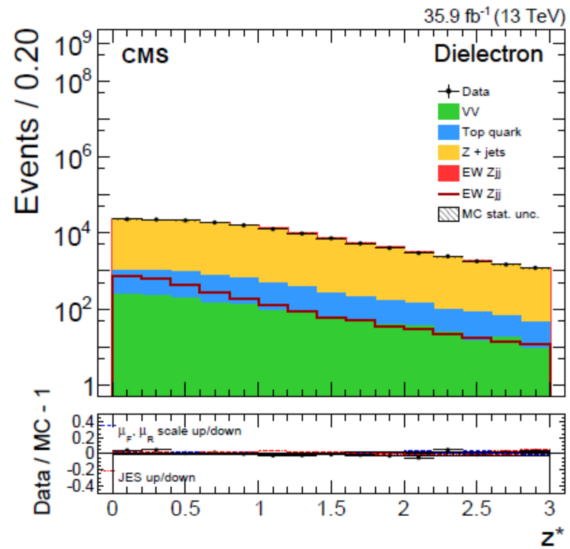
EWK production of Z bosons at 13 TeV

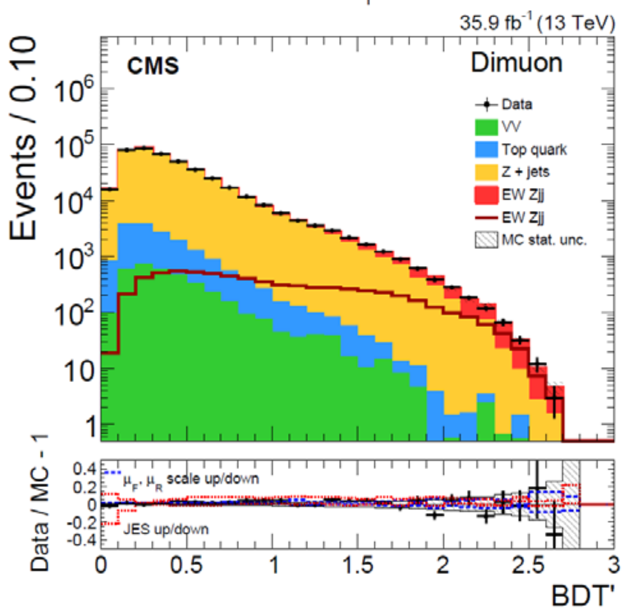
arXiv:1712.09814

- Train a BDT variable using a quark-gluon likelihood discriminant, hardronic-recoil balance, and the Zeppenfeld variable









Sample	Initial		BDT > 0.92	
	ee	$\mu\mu$	ee	$\mu\mu$
WW	62 ± 16	116 ± 22	—	—
WZ	914 ± 38	2151 ± 63	1.6 ± 1.6	1.8 ± 1.8
ZZ	522 ± 17	1324 ± 29	1.8 ± 1.1	2.7 ± 1.3
$t\bar{t}$	5363 ± 48	12938 ± 81	7.1 ± 1.9	7.1 ± 1.9
single top quark	269 ± 18	723 ± 31	—	—
DY Zjj	152750 ± 510	394640 ± 880	273 ± 20	493 ± 31
Total backgrounds	159890 ± 510	411890 ± 890	283 ± 29	505 ± 43
EW Zjj signal	2833 ± 10	6665 ± 16	194.9 ± 2.6	379.7 ± 3.9
Data	163640	422499	418	892

σ(EW Zjj)=552 ± 58 fb

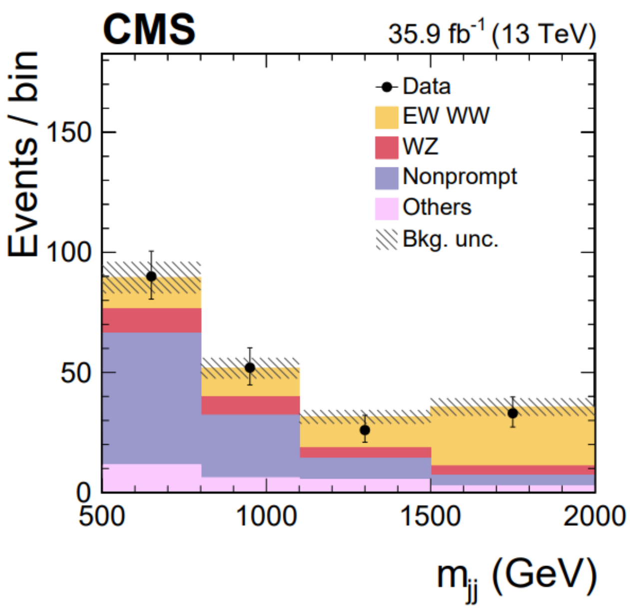
$$\mathrm{BDT}' = \tanh^{-1}((\mathrm{BDT}+1)/2)$$

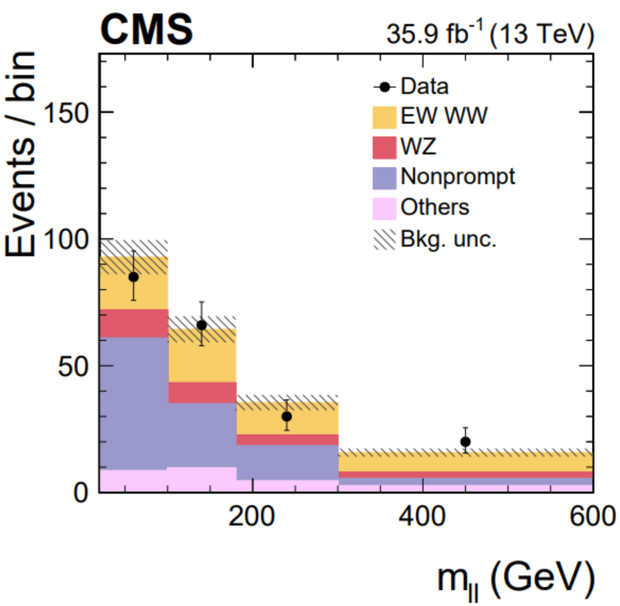
Same-sign WW VBS at 13 TeV

PRL 120, 081801 (2018)

- Observed (expected) significance is 5.5 (5.7)σ
- σ^{fid} = 34.8 ± 0.66(stat) ± 0.35(syst) fb

	e^+e^+	$e^+\mu^+$	$\mu^+\mu^+$	e^-e^-	$e^-\mu^-$	$\mu^-\mu^-$	Total
Data	14	63	40	10	48	26	201
Signal + total bkg.	19.0 ± 1.9	67.6 ± 3.8	44.1 ± 3.4	11.8 ± 1.8	38.9 ± 3.3	23.9 ± 2.8	205 ± 13
Signal	6.2 ± 0.2	24.7 ± 0.4	18.3 ± 0.4	2.5 ± 0.1	8.7 ± 0.2	6.5 ± 0.2	66.9 ± 2.4
Total bkg.	12.8 ± 1.9	42.9 ± 3.8	25.7 ± 3.4	9.4 ± 1.8	30.2 ± 3.3	17.4 ± 2.8	138 ± 13
Nonprompt	5.6 ± 1.7	24.9 ± 3.6	18.4 ± 3.3	5.0 ± 1.6	19.9 ± 3.2	14.2 ± 2.8	88 ± 13
WZ	3.0 ± 0.2	8.5 ± 0.3	4.4 ± 0.2	1.9 ± 0.2	5.2 ± 0.3	2.2 ± 0.1	25.1 ± 1.1
QCD WW	0.6 ± 0.1	1.7 ± 0.1	1.3 ± 0.1	0.2 ± 0.1	0.6 ± 0.1	0.4 ± 0.1	4.8 ± 0.4
Wγ	1.4 ± 0.5	3.6 ± 0.9	0.2 ± 0.2	0.8 ± 0.4	2.3 ± 0.7	—	8.3 ± 1.6
Triboson	0.8 ± 0.2	2.2 ± 0.4	1.2 ± 0.3	0.3 ± 0.1	0.9 ± 0.3	0.5 ± 0.2	5.8 ± 0.8
Wrong sign	1.5 ± 0.6	1.4 ± 0.4	—	1.1 ± 0.5	1.2 ± 0.4	—	5.2 ± 1.1

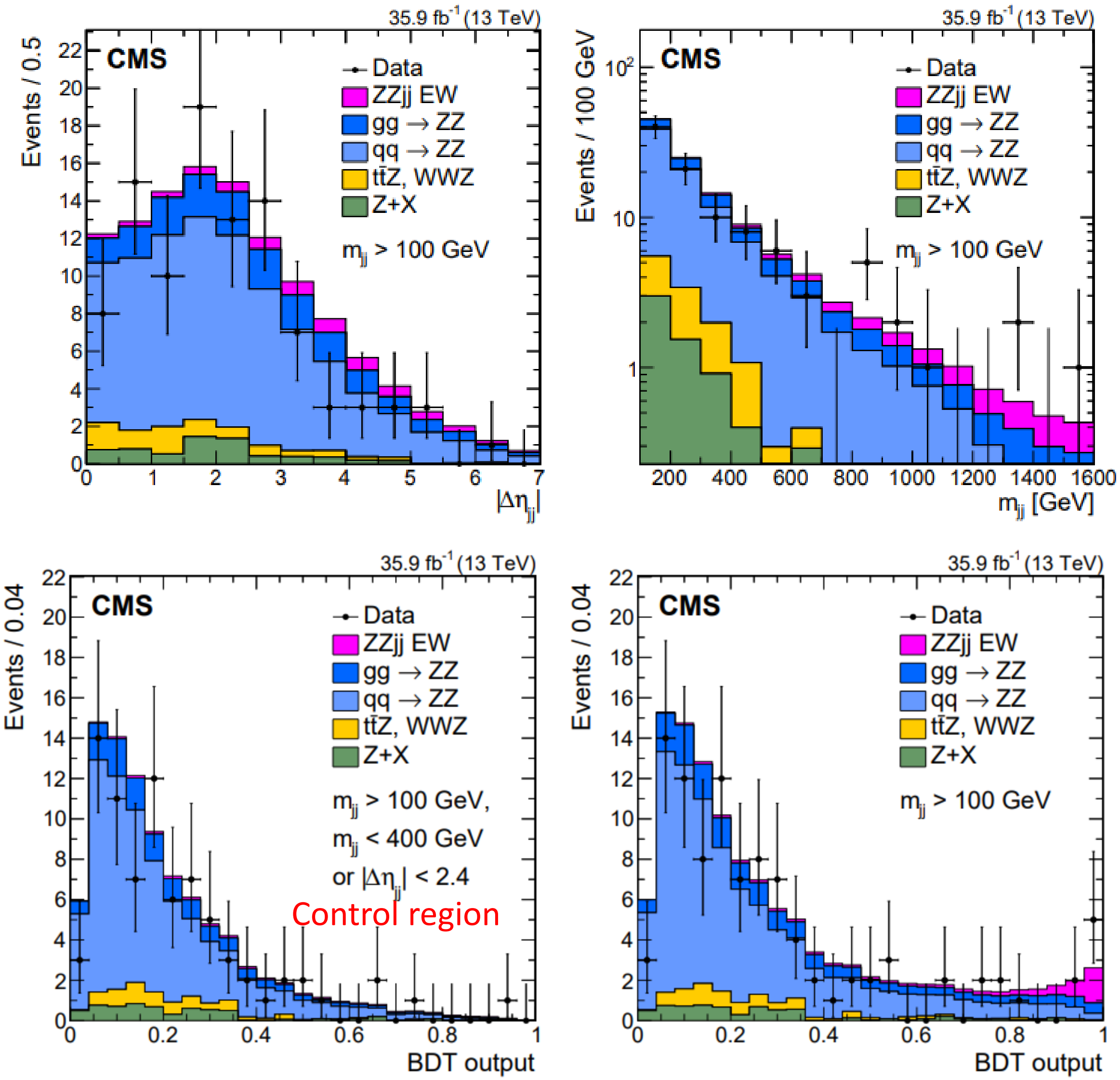




ZZjj VBS at 13 TeV

PLB 774 (2017) 682

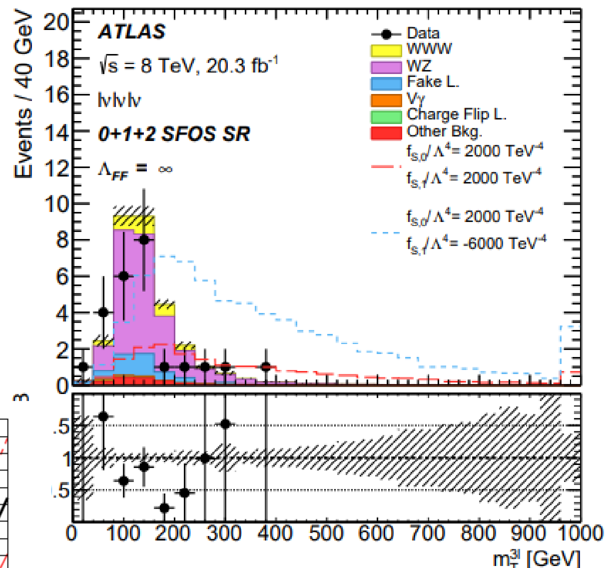
- Train a BDT variable using m_{jj}, $\Delta\eta_{jj}$, m_{ZZ}, Zeppenfeld variable etc
- Observed (expected) significance is 2.7 (1.6)σ

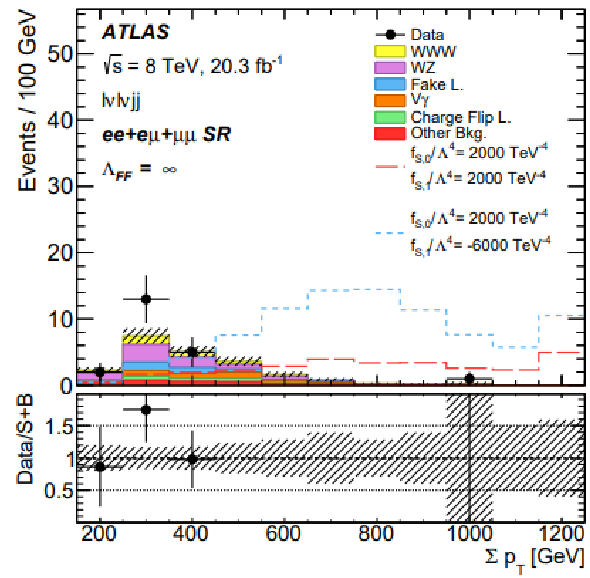


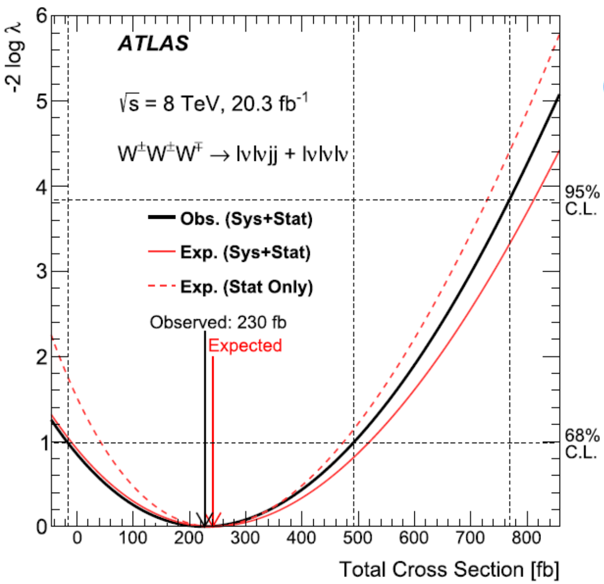
WWW Production at 8 TeV

EPJC (2017) 77, 141

- WWW → lνlνlν, l±νl±νjj and most sensitive channels are:
  - lνlνlν: 0 SFOS (1.3 signal vs 2.4 bkg)
  - l±νl±νjj: e±μ±(1.4 signal vs 9.4 bkg), μ±μ± (1.7 signal vs 5 bkg)





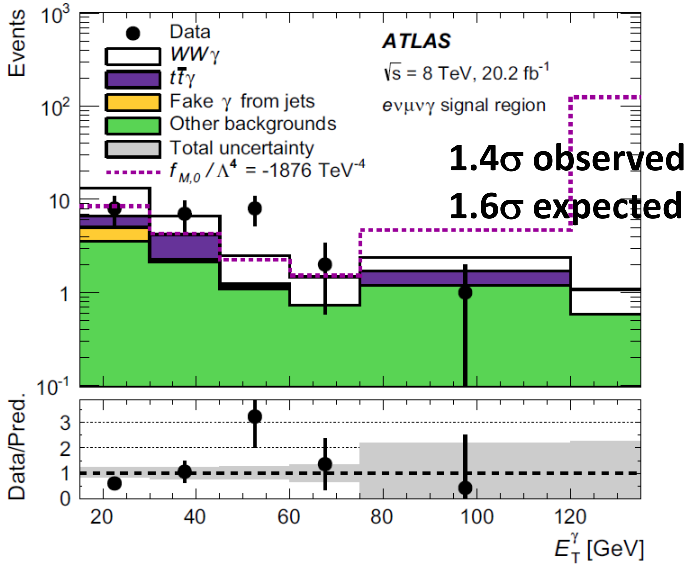


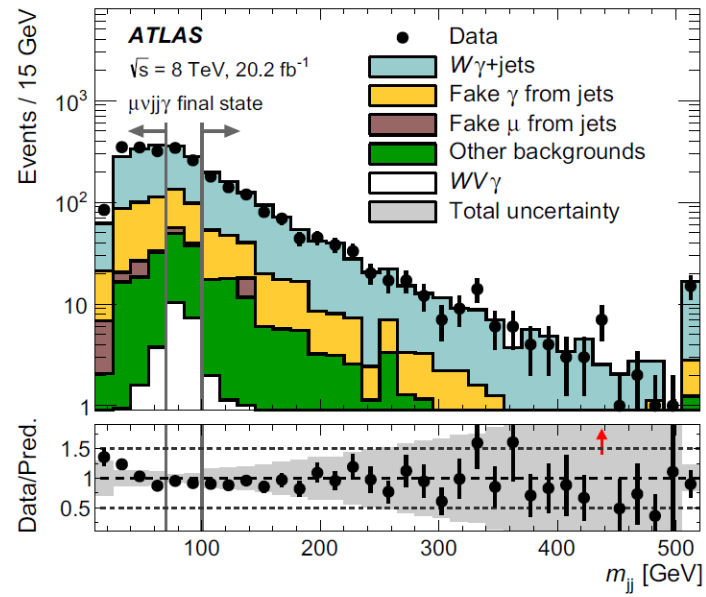
		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.286 ± 0.006 (stat.) ± 0.015 (PDF) ± 0.010 (scale)	$0.24\ ^{+0.39}_{-0.33}$ (stat.) $^{+0.19}_{-0.19}$ (syst.)
Total		241.5 ± 0.1 (stat.) ± 10.3 (PDF) ± 6.3 (scale)	230 ±200 (stat.) $^{+150}_{-160}$ (syst.)

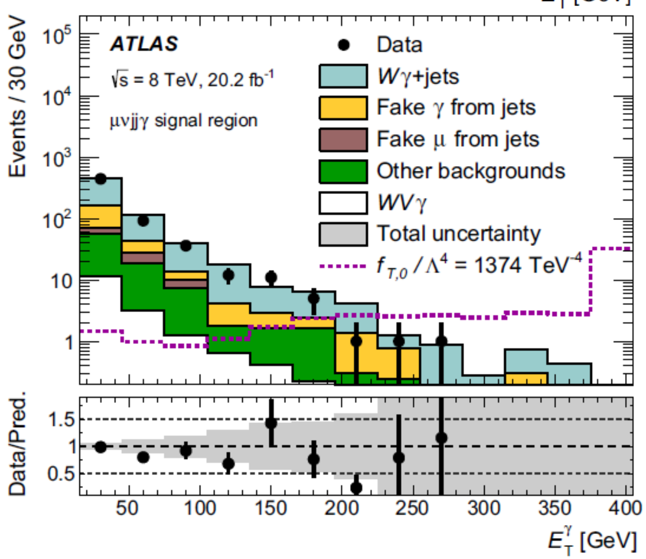
WVγ Production at 8 TeV

EPJC (2017) 77, 646

- WWγ→eνμνγ and WVγ→lνjjγ
- Background determined from a fit to the m_{jj} spectrum with the signal region excluded







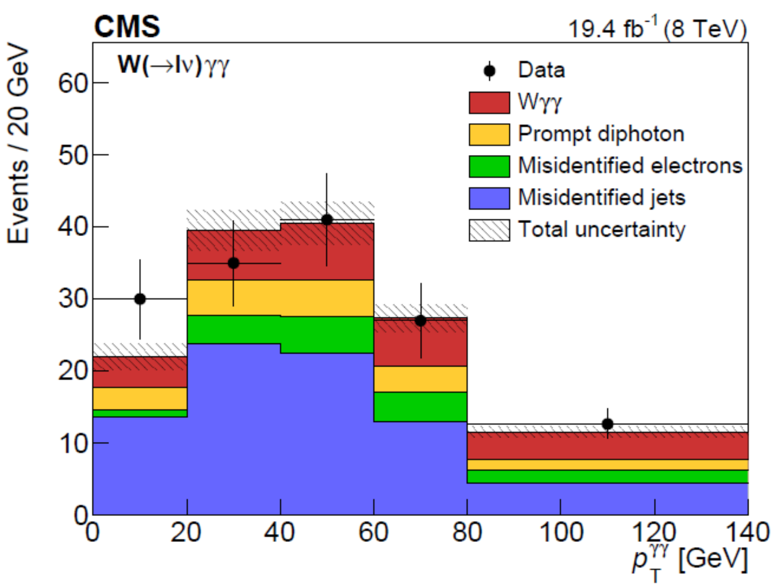
		Observed limit [fb]	Expected limit [fb]	SM Prediction σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0 ± 0.1
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4 ± 0.1
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2 ± 0.1
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3 ± 0.1

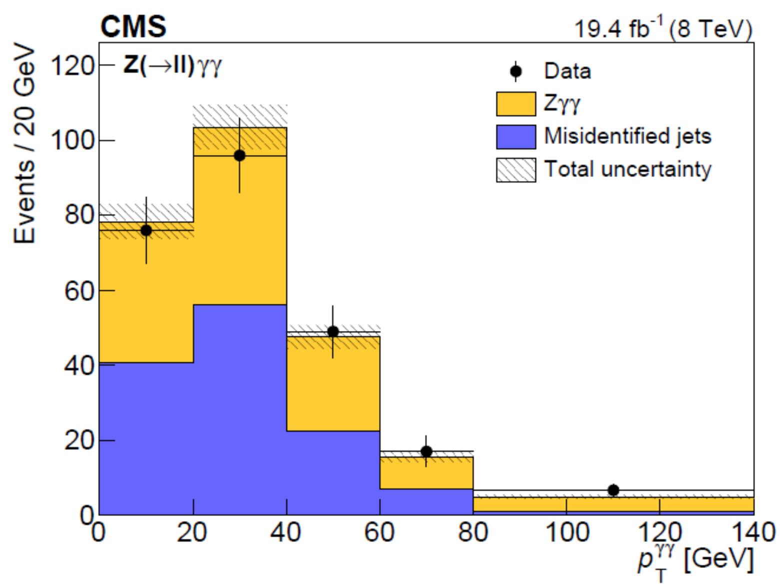
Vγγ Production at 8 TeV

JHEP 10 (2017) 072

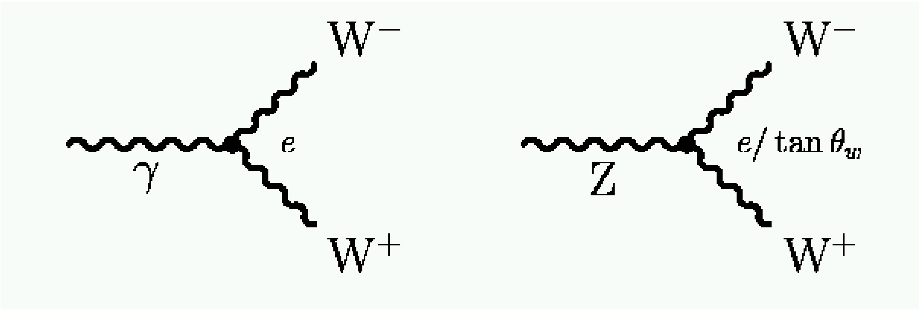
- Observed significance: 2.6 σ for Wγγ and 5.9 σ for Zγγ
  - σ(Wγγ) = 4.9 ± 2.1 fb
  - σ(Zγγ) = 12.7 ± 2.3 fb

Wγγ	Electron channel	Muon channel
Jet → γ misidentification	22 ± 6	63 ± 12
Electron → γ misidentification	20 ± 2	—
Prompt diphoton	7 ± 1	14 ± 2
Total background	49 ± 6	77 ± 12
Expected signal	13 ± 1	25 ± 3
Data	63	108
Zγγ	**Electron channel**	**Muon channel**
Jet → γ misidentification	62 ± 8	68 ± 9
Prompt diphoton	0.3 ± 0.1	0.6 ± 0.2
Total background	62 ± 8	69 ± 9
Expected signal	56 ± 8	73 ± 10
Data	117	141





Triple gauge couplings

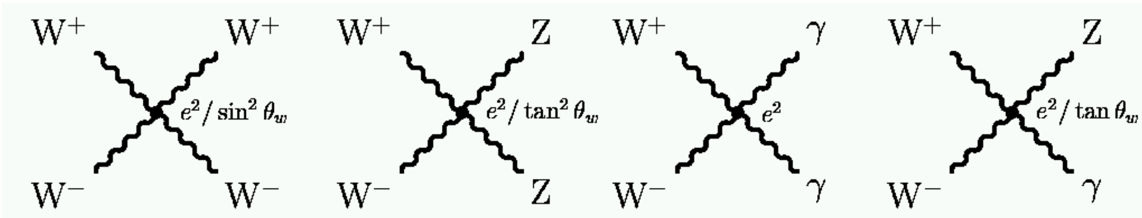


Coupling	*Parameters*	*Channel*
WWγ	$\Delta\kappa_\gamma$, λ_γ	WW, Wγ
WWZ	Δg_1^Z, $\Delta\kappa_Z$, λ_Z	WW, WZ
Zγγ	h_3^Z, h_4^Z	Zγ
ZZγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
γZZ	f_4^γ, f_5^γ	ZZ

- Non-Abelian gauge structure uniquely defines couplings between gauge bosons
- Only charged couplings (WWZ, WWγ) are allowed and pure neutral couplings (ZZZ, ZZγ, Zγγ, γγγ) are forbidden
- A Lagrangian approach with anomalous TGCs is used
- Limits often set based on event kinematics
- Different implementations in different event generators: operator bases, unitarization schemes etc

$$\mathcal{L} = i g_{WWV}\left[g_1^V \left(W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}\right) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho \right]$$

Quartic gauge couplings



no neutral γγγγ, γγγZ, γγZZ, γγγZ, ZZZZ vertices

- In an EFT approach: $\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$
- EFT approach: can be used at both tree level and loop level, incorporates SM gauge symmetries, general enough to describe low-energy effects of BSM physics
- Use experimental data to set limits on coefficients of dim-8 operators
- Build operators using: covariant derivative of the Higgs field $D_\mu\Phi$, SU(2) field strength $W_{\mu\nu}$ and U(1) field strength $B_{\mu\nu}$

only contain $D_\mu\Phi$, sensitive to longitudinal components

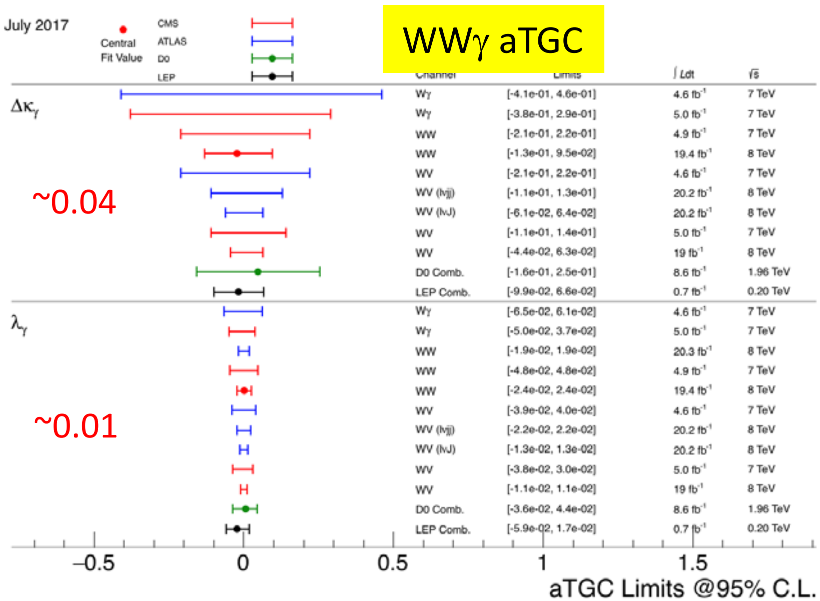
arXiv: 1310.6708

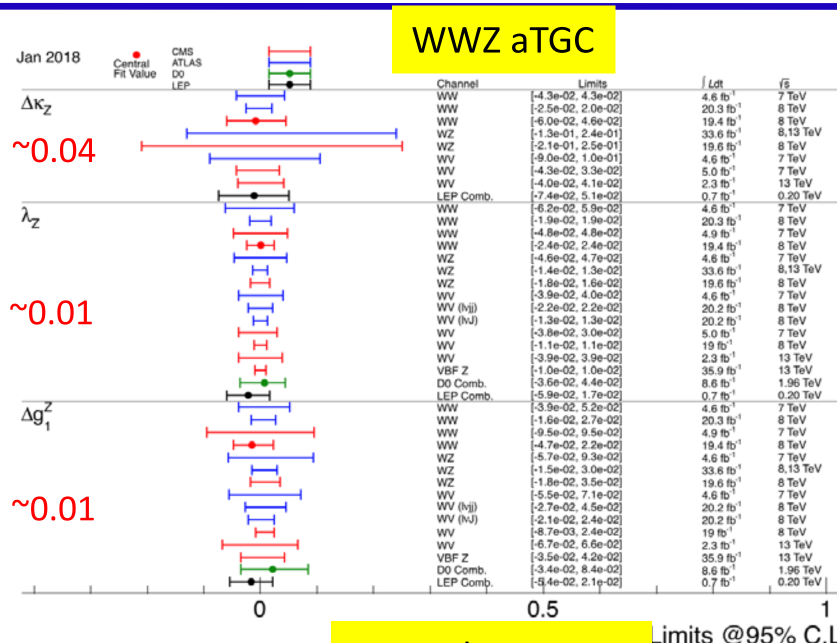
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

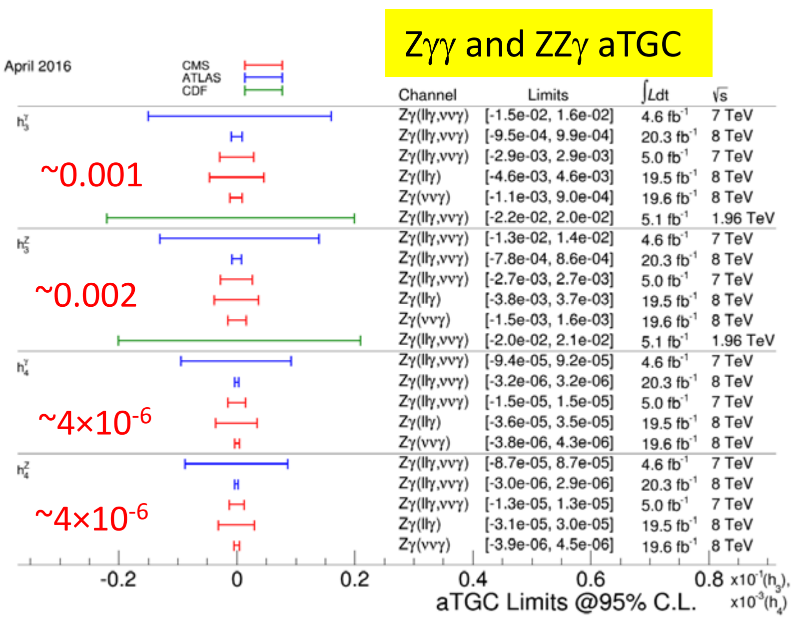
contain a mixture of $D_\mu\Phi$, $W_{\mu\nu}$ and $B_{\mu\nu}$

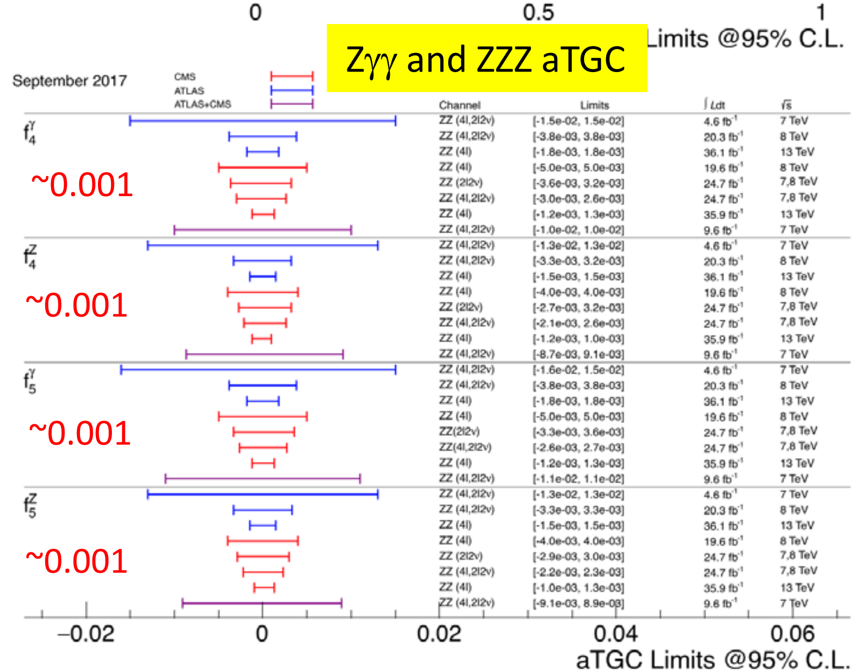
only contain field strengths $W_{\mu\nu}$ and $B_{\mu\nu}$, sensitive to transversal components

Summary of aTGC limits

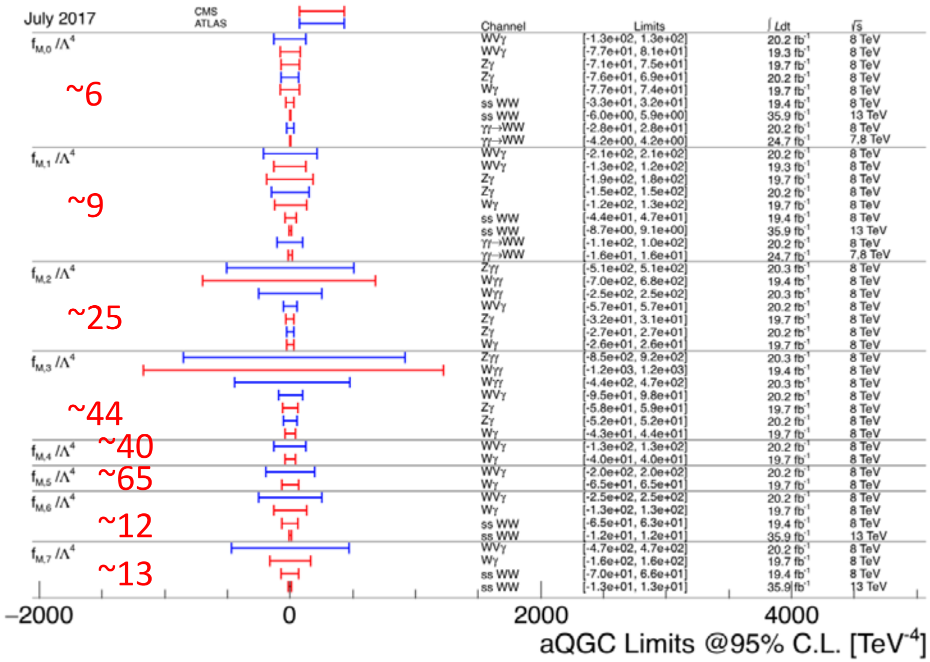


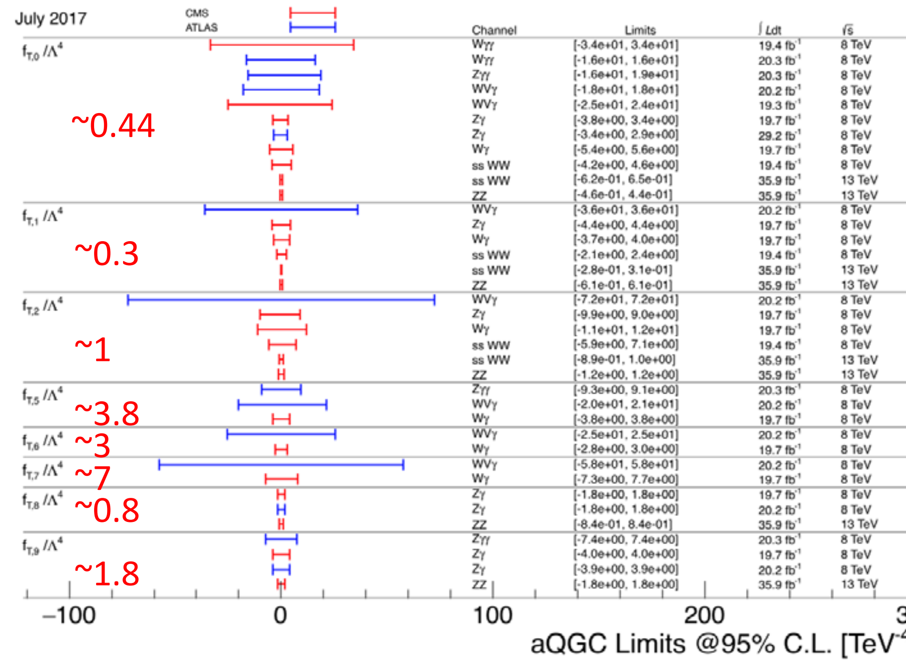






Summary of EFT coefficient limits





Conclusions

- Rich electroweak physics programs at ATLAS and CMS
  - All diboson and EWK production of a single boson processes have been observed and ongoing precise measurements
    - Experimental results match with theory predictions
    - Higher order corrections (~NNLO QCD + NLO EW) are desirable
  - Approaching triboson and VBS processes with cross section around sub-fb
    - Observed $Z\gamma\gamma$ and same-sign WW VBS processes
    - Will follow up with other processes and move to more precise measurements using 13-14 TeV data
    - Study VV longitudinal scattering using VBS processes
    - Need to have higher order corrections for triboson and VBS processes soon
  - Need to have a consistent way for aTGC and aQGC studies (ongoing discussions between theory and experimental groups at LPCC)