Multiboson production with W and Z bosons at the ATLAS and CMS detectors

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Outline

WZ production
- Inclusive cross section (also charge-dependent)
- Differential cross section
- Polarization
- aTGCs

WW production
- Inclusive cross section
- Evidence of DPS production
- NEW! Anomalous couplings in semileptonic decays

ZZ production: full Run-II dataset
- Inclusive cross section
- Differential cross section
- Anomalous couplings

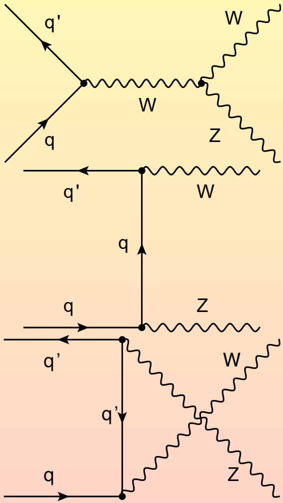
Triboson production
- Evidence of VVV production
- aQGCs

Discussion
- Datasets and production details, publication strategy
- Analysis methods and reporting

Summary

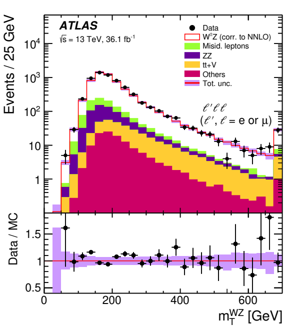
WZ production

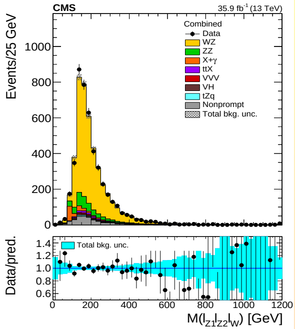
- Sensitive to the trilinear vector boson coupling
    - The only process with a Z in the final state
- Probed in both EWK and VBS production
    - See talk by Kenneth for VBS results
- ATLAS 36 fb^{-1} (cross sections), 13 fb^{-1} (couplings)
    - arXiv:1902.05759 (submitted to EPJC)
    - ATLAS-CONF-2016-043 (conf-note)
- CMS 36 fb^{-1} (cross sections and couplings)
    - DOI: 10.1007/JHEP04(2019)122, arXiv:1901.03428 (published two days ago!)

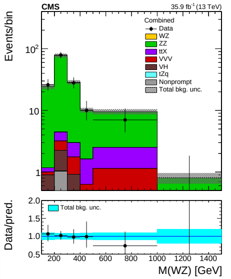


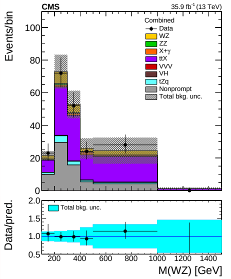
WZ production: object and event selection

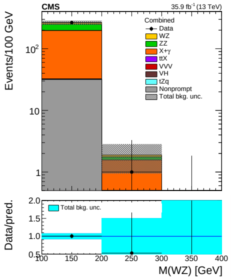
- Triggers: $\sim 100\%$ efficiency
  - ATLAS: 1L triggers, $p_\mathrm{T} \sim 20$–24 GeV, recover efficiency with additional high-p_T triggers
  - CMS: soup of 1L+2L+3L triggers, $p_\mathrm{T} \sim 8$–24 GeV
- Lepton reconstruction
  - ATLAS: cut-based ID
  - CMS: MVA ID tuned against nonprompt leptons
- Similar selection
  - 3L, Z boson assignment
  - ATLAS: tighter ID on ℓ_W
  - CMS: b tagging veto











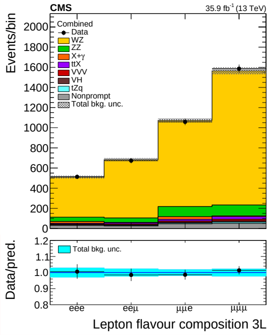
WZ production: fiducial cross section

- NNLO predictions favoured by the data

CMS

Category	Fiducial cross section [fb]
eee	$63.7^{+3.8}_{-3.7}\,(\mathrm{stat})^{+0.6}_{-0.6}\,(\mathrm{theo})^{+5.3}_{-4.7}\,(\mathrm{syst}) \pm 1.9\,(\mathrm{lumi})$
$ee\mu$	$61.6^{+3.0}_{-2.9}\,(\mathrm{stat})^{+0.6}_{-0.5}\,(\mathrm{theo})^{+3.7}_{-3.3}\,(\mathrm{syst}) \pm 1.9\,(\mathrm{lumi})$
$e\mu\mu$	$63.4^{+2.6}_{-2.6}\,(\mathrm{stat})^{+0.6}_{-0.5}\,(\mathrm{theo})^{+3.5}_{-3.2}\,(\mathrm{syst}) \pm 1.9\,(\mathrm{lumi})$
$\mu\mu\mu$	$67.1^{+2.1}_{-2.0}\,(\mathrm{stat})^{+0.6}_{-0.5}\,(\mathrm{theo})^{+3.3}_{-3.0}\,(\mathrm{syst}) \pm 1.9\,(\mathrm{lumi})$
Combined	$257.5^{+5.3}_{-5.0}\,(\mathrm{stat})^{+2.3}_{-2.0}\,(\mathrm{theo})^{+12.8}_{-11.6}\,(\mathrm{syst}) \pm 7.4\,(\mathrm{lumi})$

$\sigma^{\mathrm{POWHEG+PYTHIA}}_{\mathrm{fid,\ NLO}} = 227.6^{+8.8}_{-7.3}(\mathrm{scale}) \pm 3.2(\mathrm{PDF})$ fb



ATLAS

Channel	$\sigma^{\mathrm{fid.}}$ [fb]	$\delta_{\mathrm{stat.}}$ [%]	$\delta_{\mathrm{exp.\ syst.}}$ [%]	$\delta_{\mathrm{mod.\ syst.}}$ [%]	$\delta_{\mathrm{lumi.}}$ [%]	$\delta_{\mathrm{tot.}}$ [%]
	$\sigma^{\mathrm{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell}$					
$e^\pm ee$	65.8	3.6	6.0	0.5	2.2	7.3
$\mu^\pm ee$	61.2	3.3	3.5	0.5	2.2	5.3
$e^\pm\mu\mu$	62.4	3.2	5.4	0.5	2.2	6.6
$\mu^\pm\mu\mu$	65.3	2.7	4.1	0.5	2.2	5.3
Combined	63.7	1.6	3.6	0.5	2.2	4.5
SM prediction (NNLO)	61.5	—	—	—	—	2.3 2.1

- Lepton dressing
  - ATLAS: scale factor scales σ_{Born} to $\sigma_{\mathrm{dressed}}$
  - CMS: dresses each lepton before fiducial cuts
- Xsec calculation and averaging
  - ATLAS: basic formula, HERA-era averaging
  - CMS: likelihood fit both in the four regions and simultaneous
- Reporting uncertainties
  - ATLAS: symmetric, propagating from

$$\sigma^{\mathrm{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell} = \frac{N_{\mathrm{data}} - N_{\mathrm{bkg}}}{\mathcal{L}\cdot C_{WZ}} \times \left(1 - \frac{N_\tau}{N_{\mathrm{all}}}\right)$$

  - CMS: asymmetric intervals from $\ln\mathcal{L}$

WZ production: uncertainties, and extrapolation to total cross section

- Dominant uncertainties in the fiducial cross section reflect ID and strategy choices

CMS (%)

Source	Combined	eee	eeμ	e$\mu\mu$	$\mu\mu\mu$
Electron efficiency	1.9	5.9	3.9	1.9	—
Electron energy scale	0.3	0.9	0.2	0.6	—
Muon efficiency	1.9	—	0.8	1.8	2.6
Muon momentum scale	0.5	—	0.7	0.3	0.9
Trigger efficiency	1.9	2.0	1.9	1.9	1.8
Jet energy scale	0.9	1.6	1.0	1.7	0.8
b-tagging (id.)	2.6	2.7	2.6	2.6	2.4
b-tagging (mis-id.)	0.9	1.0	0.9	1.0	0.7
Pileup	0.8	0.9	0.3	1.3	1.4
ZZ	0.6	0.7	0.4	0.8	0.5
Nonprompt norm.	1.2	2.0	1.2	1.5	1.0
Nonprompt (EWK subtr.)	1.0	1.5	1.0	1.3	0.8
VVV norm.	0.5	0.6	0.6	0.6	0.5
V H norm.	0.2	0.2	0.3	0.2	0.2
$t\bar{t}$ V norm.	0.5	0.5	0.5	0.5	0.5
tZq norm.	0.1	0.1	0.1	0.1	0.1
X+γ norm.	0.3	0.8	< 0.1	0.7	< 0.1
Total systematic	4.7	7.8	5.8	5.4	4.6
Integrated luminosity	2.8	2.9	2.8	2.9	2.8
Statistical	2.1	6.0	4.8	4.1	3.1
Total experimental	6.0	10.8	8.0	7.5	6.3
Theoretical	0.9	0.9	0.9	0.9	0.9

- ATLAS: nonprompt leptons
- CMS: b tagging (veto)

ATLAS

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	Combined
	Relative uncertainties [%]				
e energy scale	0.2	0.1	0.1	< 0.1	0.1
e id. efficiency	2.8	1.8	1.0	< 0.1	1.1
μ momentum scale	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ id. efficiency	< 0.1	1.3	1.6	2.8	1.5
E_T^{miss} and jets	0.2	0.2	0.3	0.5	0.3
Trigger	< 0.1	< 0.1	0.2	0.3	0.2
Pile-up	1.0	1.5	1.2	1.5	1.3
Misid. leptons background	4.7	1.1	4.5	1.6	1.9
ZZ background	1.0	1.0	1.1	1.0	1.0
Other backgrounds	1.6	1.5	1.4	1.2	1.4
Uncorrelated	0.7	0.6	0.7	0.5	0.3
Total systematic uncertainty	6.0	3.5	5.4	4.1	3.6
Luminosity	2.2	2.2	2.2	2.2	2.2
Theoretical modelling	0.5	0.5	0.5	0.5	0.5
Statistics	3.6	3.3	3.2	2.7	1.6
Total	7.3	5.3	6.6	5.3	4.5

- Total cross section compared with MATRIX results (arXiv:1604.08576)

CMS

Category	$\sigma_{tot}(pp \to WZ)$ [pb]
eee	$47.11^{+5.01}_{-4.63}$ (total) $= 47.11^{+2.88}_{-2.79}$ (stat)$^{+0.46}_{-0.41}$ (theo)$^{+3.89}_{-3.47}$ (syst) $\pm$ 1.41 (lumi)
eeμ	$47.16^{+3.87}_{-3.61}$ (total) $= 47.16^{+2.31}_{-2.29}$ (stat)$^{+0.45}_{-0.38}$ (theo)$^{+2.83}_{-2.52}$ (syst) $\pm$ 1.33 (lumi)
e$\mu\mu$	$47.70^{+3.58}_{-3.55}$ (total) $= 47.70^{+2.00}_{-1.96}$ (stat)$^{+0.45}_{-0.39}$ (theo)$^{+2.66}_{-2.61}$ (syst) $\pm$ 1.42 (lumi)
$\mu\mu\mu$	$49.00^{+3.18}_{-3.03}$ (total) $= 49.00^{+1.57}_{-1.53}$ (stat)$^{+0.41}_{-0.35}$ (theo)$^{+2.42}_{-2.22}$ (syst) $\pm$ 1.39 (lumi)

$\sigma_{tot}(pp \to WZ) = 48.09^{+2.98}_{-2.78}$ pb $= 48.09^{+1.00}_{-0.96}$ (stat)$^{+0.44}_{-0.37}$ (theo)$^{+2.39}_{-2.17}$ (syst) $\pm$ 1.39 (lumi) pb,

$$\sigma^{\text{MATRIX}}_{\text{NLO}}(pp \to WZ) = 45.09^{+4.9\%}_{-3.9\%} \text{ pb}$$

$$\sigma^{\text{MATRIX}}_{\text{NNLO}}(pp \to WZ) = 49.98^{+2.2\%}_{-2.0\%} \text{ pb}$$

ATLAS

$\sigma^{tot.}_{W^\pm Z} = 51.0 \pm 0.8$ (stat.) ± 1.8 (exp. syst.) ± 0.9 (mod. syst.) ± 1.1 (lumi.) pb.

$$\sigma^{\text{MATRIX}}_{\text{NNLO}}(pp \to WZ) = 49.1^{+1.1\%}_{-1.0} \text{ (scale) pb}$$

- ATLAS: $\sigma^{\text{MATRIX}}_{\text{NNLO}}$ scaled by 0.99 (QED final-state radiation)
- Fiducial cuts on M_Z: 66/116 GeV (ATLAS), 60/120 GeV (CMS)

WZ production: charge-dependent cross section

- Charge-dependent cross sections

CMS

$\sigma_{\mathrm{tot}}(\mathrm{pp} \to \mathrm{W^+Z}) = 28.91^{+0.63}_{-0.61}\,(\mathrm{stat})^{+0.28}_{-0.25}\,(\mathrm{theo})^{+1.43}_{-1.31}\,(\mathrm{syst}) \pm 0.80\,(\mathrm{lumi})$ pb,

$\sigma_{\mathrm{tot}}(\mathrm{pp} \to \mathrm{W^-Z}) = 19.55^{+0.45}_{-0.44}\,(\mathrm{stat})^{+0.17}_{-0.15}\,(\mathrm{theo})^{+0.97}_{-0.88}\,(\mathrm{syst}) \pm 0.55\,(\mathrm{lumi})$ pb.

ATLAS

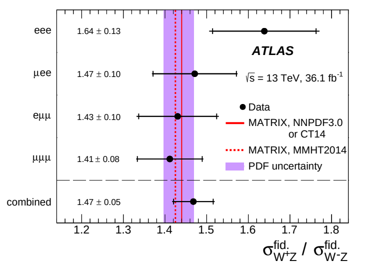
Channel	$\sigma^{\mathrm{fid.}}$ [fb]	$\delta_{\mathrm{stat.}}$ [%]	$\delta_{\mathrm{exp.\,syst.}}$ [%]	$\delta_{\mathrm{mod.\,syst.}}$ [%]	$\delta_{\mathrm{lumi.}}$ [%]	$\delta_{\mathrm{tot.}}$ [%]
	$\sigma^{\mathrm{fid.}}_{W^+Z\to\ell'\nu\ell\ell}$					
e^+ee	40.8	4.6	5.4	0.5	2.2	7.4
μ^+ee	36.5	4.3	3.3	0.5	2.2	5.8
$e^+\mu\mu$	36.7	4.1	5.0	0.5	2.2	6.8
$\mu^+\mu\mu$	38.2	3.5	4.0	0.5	2.2	5.7
Combined	37.9	2.0	3.4	0.5	2.2	4.5
SM prediction	36.3	—	—	—	—	$^{2.2}_{2.0}$
	$\sigma^{\mathrm{fid.}}_{W^-Z\to\ell'\nu\ell\ell}$					
e^-ee	24.9	6.1	7.1	0.5	2.2	9.6
μ^-ee	24.8	5.3	4.0	0.5	2.2	7.0
$e^-\mu\mu$	25.7	5.1	6.2	0.5	2.2	8.3
$\mu^-\mu\mu$	27.1	4.3	4.3	0.5	2.2	6.4
Combined	25.9	8.1	4.0	0.5	2.2	5.2
SM prediction	25.2	—	—	—	—	$^{2.3}_{2.1}$

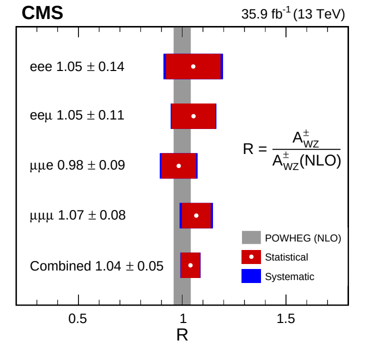
- Asymmetry as ratio of cross sections

CMS

$$A^{+-}_{\mathrm{WZ}} = \frac{\sigma_{\mathrm{tot}}(\mathrm{pp}\to\mathrm{W^+Z})}{\sigma_{\mathrm{tot}}(\mathrm{pp}\to\mathrm{W^-Z})} = 1.48 \pm 0.06\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst}) \pm 0.01\,(\mathrm{theo})$$

- Better coordination on display is desirable
  - ATLAS: fiducial, ratio of xsecs
  - CMS: total, ratio of ratios (as ATLAS previously)

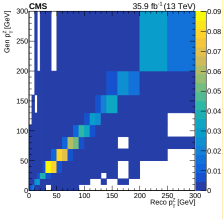


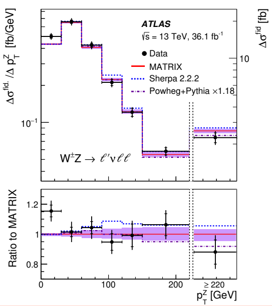


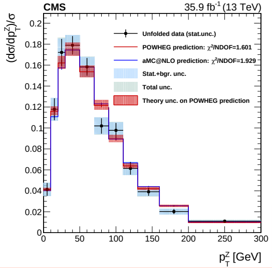
WZ production: differential cross section

- Using available (NLO) MC
  - Constrain normalization to NNLO
- Different sets of observables
  - Somehow a failure of meetings done to agree on observables and such
  - ATLAS: , only for $\mathrm{W}^{\pm}\mathrm{Z}$
  - CMS: $p_{\mathrm{T}}^{\mathrm{Z}}$, $p_{\mathrm{T}}^{\text{jet}}$, M_{WZ}, also split by $\mathrm{W}^{+}\mathrm{Z}$, $\mathrm{W}^{-}\mathrm{Z}$
- Different definitions of observables, e.g. $M_{\mathrm{T}}(\mathrm{WZ})$
  - ATLAS: $\sim M(E_{\mathrm{T}}^{\text{miss}}, \ell_1, \ell_2, \ell_3)$
  - CMS: $\sim M(E_{\mathrm{T}}^{\text{miss}}, \ell\ell\ell)$
  - Headache for theoreticians (true story)
- Uncertainty on response matrix
  - ATLAS: data-driven (reweighting to data)
  - CMS: physics-driven (alternative MC sample)
- Statistical uncertainties dominate the measurement

- Unfolding
  - ATLAS: no detail on technique, response matrix not public
  - CMS: public response matrix, details on χ^2 fit (`TUnfold`) procedure, tabulated results



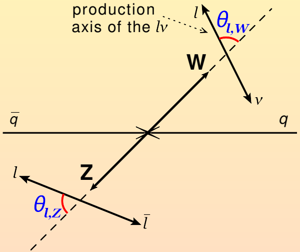


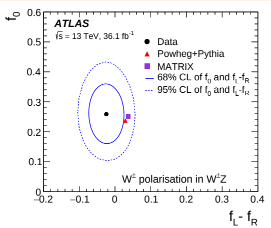


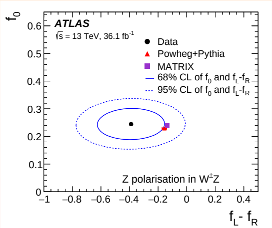
WZ production: accessory measurements

- ATLAS: polarization measurement
  - Measured polarization of both W and Z

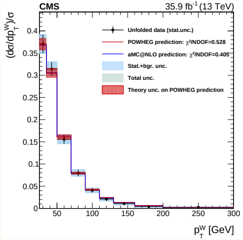
$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L[(1\mp\cos\theta_{\ell,W})^2] + \frac{3}{8}f_R[(1\pm\cos\theta_{\ell,W})^2] + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$



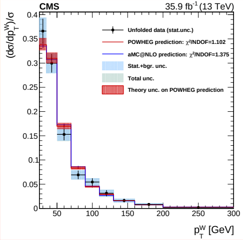




- CMS: differential measurement split by charge
- W^+



- W^+



WZ production: anomalous couplings

- EFT framework, constraining dimension-6 operators
  - c_{WWW}, c_W, c_b are 0 in the SM

$$\delta\mathcal{L}_{AC} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + \frac{c_W}{\Lambda^2}(D_\mu H)^\dagger W^{\mu\nu}(D_\nu H) + \frac{c_b}{\Lambda^2}(D_\mu H)^\dagger B^{\mu\nu}(D_\nu H)$$

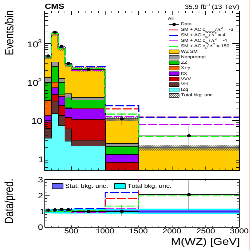
- ATLAS: 1D intervals, 13 fb^{-1}

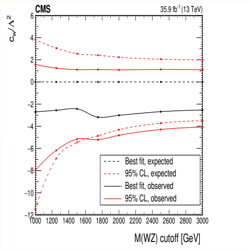
Dataset	Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
ATLAS 8 and 13 TeV	c_W/Λ^2_{NP}	[-3.4; 6.9]	[-3.6; 7.3]
	c_B/Λ^2_{NP}	[-221; 166]	[-253; 136]
	c_{WWW}/Λ^2_{NP}	[-3.2; 3.0]	[-3.3; 3.2]

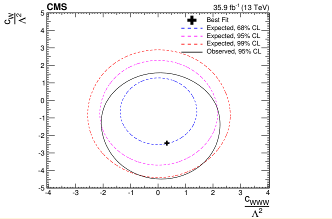
- CMS: 2D and 1D intervals, 36 fb^{-1}
  - 30–50% gain in 1D intervals, even more for 2D regions

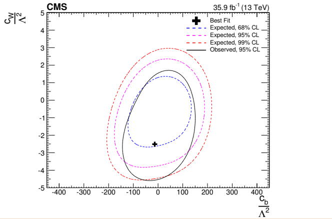
Parameter	95% CI (expected) [TeV^{-2}]	95% CI (observed) [TeV^{-2}]
c_W/Λ^2	$[-3.3, 2.0]$	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-1.8, 1.9]$	$[-2.0, 2.1]$
c_b/Λ^2	$[-130, 170]$	$[-100, 160]$

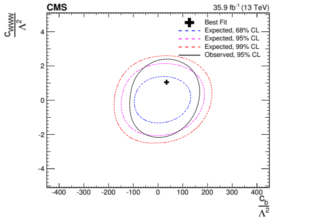
CMS











- ATLAS: Phys. Lett. B 773 (2017) 354 (arXiv:1702.04519), 3 fb^{-1}
  - VBS WW result with 35 fb^{-1} in Kenneth's talk
- CMS: inclusive result, and a brand new result on anomalous couplings!
  - CMS-SMP-18-015 inclusive cross section (PAS, paper in preparation), 77 fb^{-1}
  - NEW!!! CMS-SMP-18-008 anomalous couplings in semileptonic channels (PAS, paper in preparation), 36 fb^{-1}
  - VBS same-sign WW and semileptonic WW results in Kenneth's talk

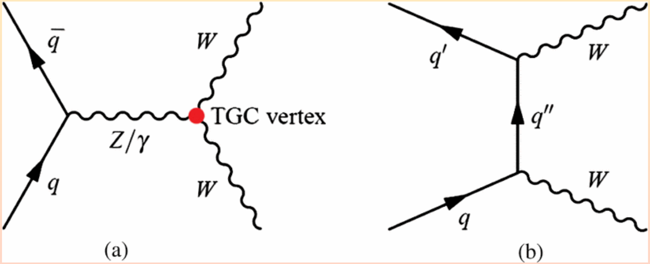
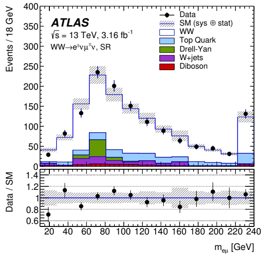
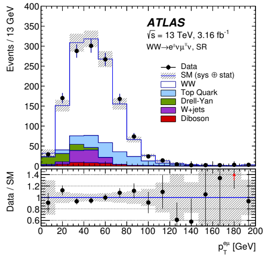


diagram from ATLAS 7 TeV paper

WW production: inclusive cross section

- 1L+2L triggers, $p_T \sim 20$–24 GeV (99% efficiency)
- Exclude same-flavours events (high DY contamination)
- b tagging: $\sim 3.5\%$ mistag rate
- Estimate $t\bar{t}$, DY, and W+jets in data
- Larger source of uncertainty: jet selection and calibration
- Exemplary section describing details of fiducial region





ATLAS

Fiducial selection requirement	Cut value
p_T^{ℓ}	> 25 GeV
$\lvert\eta_\ell\rvert$	< 2.5
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $\lvert\eta\rvert < 2.5(4.5)$	0
$E_{T, Rel}^{miss}$	> 15 GeV
E_T^{miss}	> 20 GeV

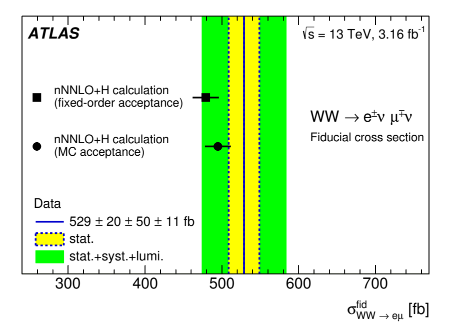
Sources of uncertainty	Relative uncertainty for $\sigma^{fid}_{WW\to e\mu}$
Jet selection and energy scale & resolution	7.3%
b-tagging	1.3%
E_T^{miss} and p_T^{miss}	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell–Yan background theory	1.5%
W+jet and multi-jet background	3.8%
Other diboson backgrounds	1.1%
Parton shower	3.1%
PDF	0.2%
QCD scale	0.2%
MC statistics	1.2%
Data statistics	3.7%
Total uncertainty	11%

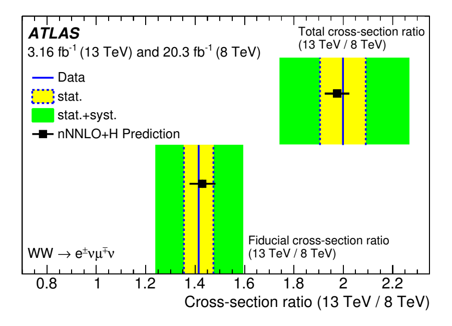
- Fiducial measurement dominated by systematic uncertainties (mostly jet selection and calibration

$$\sigma^{\text{fid}}_{WW\to e\mu} = 529 \pm 20\ (\text{stat.}) \pm 50\ (\text{syst.}) \pm 11\ (\text{lumi.})\ \text{fb}.$$

- Ratio to 8 TeV is compatible with predictions (both fiducial and total)

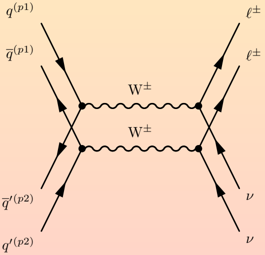
$$\frac{\sigma^{\text{fid}}_{13\ \text{TeV},WW\to e\mu}}{\sigma^{\text{fid}}_{8\ \text{TeV},WW\to e\mu}} = 1.41 \pm 0.06\ (\text{stat.}) \pm 0.16\ (\text{syst.}) \pm 0.04(\text{lumi.})$$

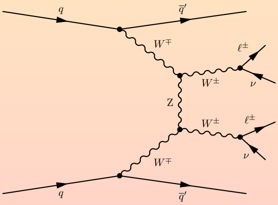


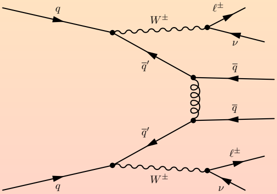


WW **double-parton-scattering evidence**

- CMS evidence: CMS-SMP-18-015 (PAS, paper in preparation)
- Two main mechanisms at LO
  - DPS: both hard scatterings give rise to a W boson
  - SHS: two additional high-p_{T} partons suppressed at matrix-element level
  - Discriminate DPS from SHS: DPS with same charge has no jets from hard process
  - $\sigma_{\mathrm{AB}}^{\mathrm{DPS}} = \frac{n}{2} \frac{\sigma_{\mathrm{A}} \sigma_{\mathrm{B}}}{\sigma_{eff}}$; A, B SHS processes ($n = 1$: indistinguishable A,B; $n = 2$ otherwise)
- Probe for the validity of the factorization approach used in MC
- Background to searches (e.g. SUSY ewkino searches)



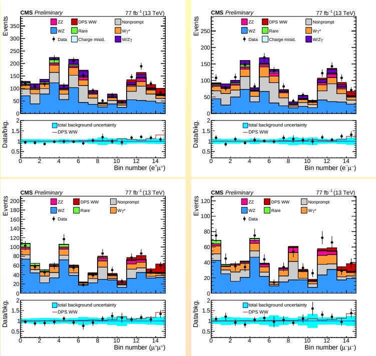


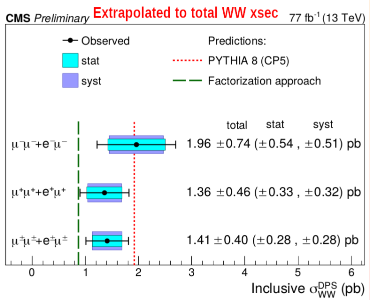


WW double-parton-scattering evidence

- 1L+2L triggers soup, $p_{\mathrm{T}} \sim 8$–35 GeV
- Lepton MVA ID against nonprompt leptons
- Selection: 2 same-charge leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$
  - At most 1 jet
  - Veto b jets
- DPS prediction affected by large uncertainties
  - Imprecise knowledge of σ_{eff} (different final states yield different results)
  - Cross section prediced from simulation depends on the UE tuning
- Observed cross sections depend only on generator kinematics
  - Comparable with different predictions
  - σ_{eff}^{obs} computable using preductions for inclusive W boson production

CMS	obtained value Fiducial	significance (standard deviations)
$\sigma^{\mathrm{PYTHIA8}}_{\mathrm{DPS\,WW,exp}}$	1.92 pb	5.4
$\sigma^{\mathrm{factorized}}_{\mathrm{DPS\,WW,exp}}$	0.87 pb	2.5
$\sigma_{\mathrm{DPS\,WW,obs}}$	1.41 ± 0.28 (stat) ± 0.28 (syst) pb	3.9
σ_{eff}	$12.7^{+5.0}_{-2.9}$ mb	–

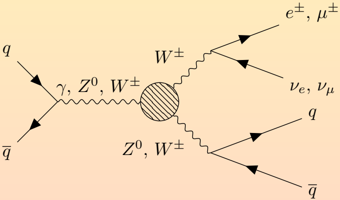




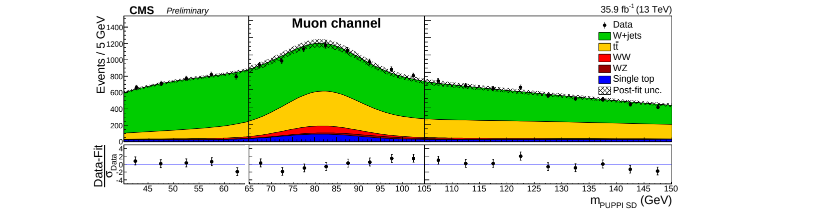
NEW!!! Anomalous couplings in $\ell + jets$ WW and WZ decays

- Semileptonic decays: larger branching fraction, but also larger backgrounds (QCD multijet)

- Triggers: 1L, $p_{T} = 45(50)$ GeV, $|\eta| < 2.5(2.4)$ for electrons (muons)
- Full reconstruction of diboson system ($65 < M_{(}\mathrm{WW}) < 85 < M_{\mathrm{WZ}} < 105$ GeV)
  - W: $p_{T} > 200$ GeV from lepton+E_{T}^{miss} (p_{z}^{ν} from W mass constraint
    - Smallest of the two real solutions, or $Re()$ of the complex one



- W+jets and $t\bar{t}$ backgrounds in sidebands of diboson mass
- Anti-k_{T} jets: cone 0.4 (bkg rejection) and 0.8 (hadronic boson decay)
  - Boson candidate: p_{T}-leading AK8 jet (soft drop and τ_{21} to reject quarks and gluons)
  - Reject AK4 b-tagged jets to reject $t\bar{t}$...
  - ...but only if $\Delta R > 0.8$ w/ hadronic W (to not reject WZ, $Z \rightarrow b\bar{b}$)
  - Mass after soft-drop and pileup-per-particle subtraction (PUPPI) used as M_{WV}
- Back-to-back topology, avoid modelling turn-on in bkg description by $M_{\mathrm{WV}} > 900$ GeV
  - $\Delta R(\text{AK8 jet}, \ell) > \pi/2$
  - $\Delta\phi(\text{AK8 jet}, E_{T}^{miss}) > 2$
  - $\Delta\phi(\text{AK8 jet}), \mathrm{W}_{lep}) > 2$



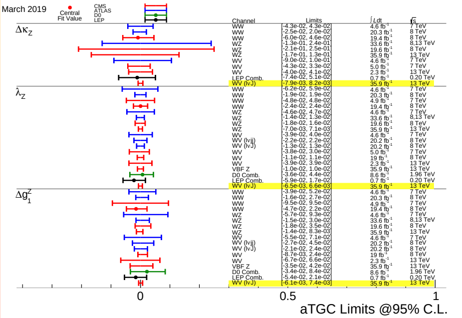
Anomalous couplings in semileptonic WW and WZ decays

$$F_{\text{signal}}(m_{WV}) = N_{SM}\left(e^{a_0 m_{WV}} + e^{a_{\text{corr}} m_{WV}}\right) + \sum_{i}\left(N_{c_i,1} c_i^2 e^{a_{i,1} m_{WV}} \left(\frac{1+\text{Erf}((m_{WV}-a_{0,i})/a_{w,i})}{2}\right) + N_{c_i,2} c_i e^{a_{i,2} m_{WV}}\right) + \sum_{i\neq j}^{i<j}\left(N_{c_i,c_j} c_i c_j e^{a_{ij} m_{WV}}\right)$$

- Signal modelling: $M_{WV} \sim$ exponentially falling
  - SM shape and normalization from aTGC simulated samples (MG5@NLO)
  - SM-aTGC interference from comparison with aTGC with opposite sign
  - Pure aTGC from simultaneous fit
  - aTGC-aTGC from comparison of samples with suitable pairs of couplings on/off
  - Erf models turn-on of the aTGC
  - Small c_{WWW}-SM, c_{WWW}-c_b, and erf on c_b neglected
- Largest prefit normalization uncertainty: V-tagging, scale, and JES (no postfit quoted)

- Results at the level of the WZ multilepton ones

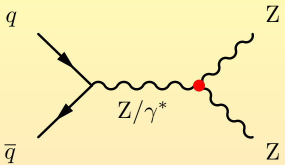
Parametrization	aTGC	Expected limit	Observed limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]
LEP	λ_Z	[-0.0060, 0.0061]	[-0.0065, 0.0066]
	Δg_1^Z	[-0.0070, 0.0061]	[-0.0061, 0.0074]
	$\Delta\kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0082]

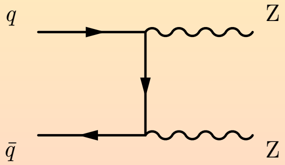


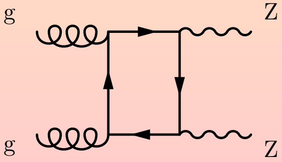
ZZ production

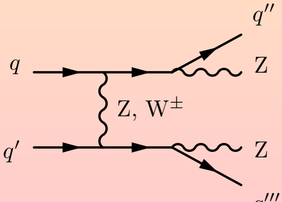
CMS UCLouvain Institut de recherche en mathématique et physique

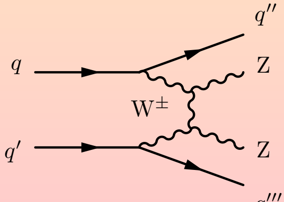
- ATLAS: four-lepton result with 36 fb^{-1} (2016)
  - Phys. Rev. D 97, 032005 (2018) (arXiv:1709.07703), 36 fb^{-1}
- CMS: four-lepton result with full Run-II data!
  - $ZZ \to 4\ell$: CMS-PAS-SMP-19-001, 137 fb^{-1}!!!
  - ZZ+jets: Phys. Lett. B 789 (2019) 19 (arXiv:1806.11073), 20 (8 TeV) and 36 (13 TeV) fb^{-1}
  - VBS ZZ+2jets in Kenneth's talk





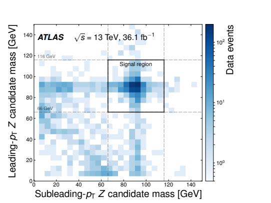


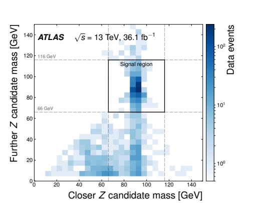


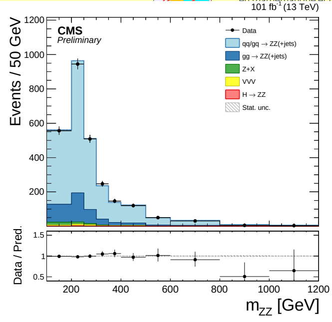


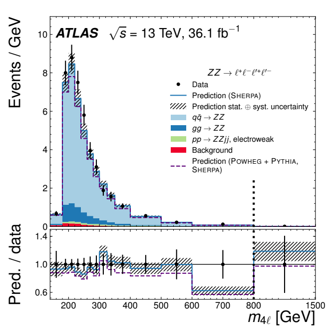
ZZ production: object and event selection

- Different generators for signal
  - ATLAS: SHERPA (POWHEG as alternative prediction)
  - CMS: POWHEG
- Trigger strategies
  - ATLAS: 1L+2L+3L soup, $\sim 100\%$ efficiency
  - CMS: 2L triggers, $p_{\mathrm{T}} \sim 8$–17 GeV, $> 98\%$ efficiency
- 4ℓ Selection
  - ATLAS: relaxed ID on at most 1 muon, $66 < M(Z_i) < 166$ GeV
  - CMS:no relaxed ID, $M(Z_i) > 60$ GeV
- Background estimation: Z, VV, $\mathrm{t\bar{t}}$ from sidebands
  - ATLAS+CMS: trasfer factors accounting for nonprompt estimates









ZZ production: fiducial cross section

- Different reporting of uncertainties
- Dominant uncertainties
  - ATLAS: PDF/QCD scales
  - CMS: lepton ID
- Good agreement with NNLO predictions
  - Including NLO EW and QCD corrections

ATLAS

Source	Effect on total predicted yield [%]
MC statistical uncertainty	0.4
Electron efficiency	0.9
Electron energy scale & resolution	< 0.1
Muon efficiency	1.7
Muon momentum scale & resolution	< 0.1
Pileup modeling	1.2
Luminosity	3.2
QCD scales	$^{+5.2}_{-4.7}$
PDFs	$^{+2.7}_{-1.7}$
Background prediction	0.9
Total	$^{+7.4}_{-6.6}$

CMS (effect on xsec measurement)

Uncertainty	Range of values
Lepton efficiency	2–8%
Trigger efficiency	1–2%
Background	0.6–1.3%
Pileup	1%
PDF	1%
μ_R, μ_F	1%
Integrated luminosity	2.3% (2017) 2.5% (2018)

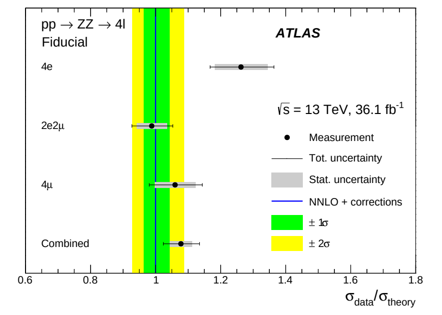
ATLAS fiducial

Channel	Measurement [fb]	Prediction [fb]
$4e$	$13.7^{+1.1}_{-1.0}$ [± 0.9 (stat.) ±0.4 (syst.) $^{+0.5}_{-0.4}$ (lumi.)]	$10.9^{+0.5}_{-0.4}$
$2e2\mu$	$20.9^{+1.4}_{-1.3}$ [± 1.0 (stat.) ±0.6 (syst.) $^{+0.7}_{-0.6}$ (lumi.)]	$21.2^{+0.9}_{-0.8}$
4μ	$11.5^{+0.9}_{-0.9}$ [± 0.7 (stat.) ±0.4 (syst.) ±0.4 (lumi.)]	$10.9^{+0.5}_{-0.4}$
Combined	$46.2^{+2.5}_{-2.3}$ [± 1.5 (stat.) $^{+1.2}_{-1.1}$(syst.) $^{+1.6}_{-1.4}$ (lumi.)]	$42.9^{+1.9}_{-1.5}$

CMS

Year	Fiducial cross section, fb
2016 [5]	40.9 ± 1.3 (stat) ± 1.4 (syst) ± 1.0 (lumi)
2017	39.1 ± 1.2 (stat) ± 1.2 (syst) ± 1.0 (lumi)
2018	39.2 ± 1.0 (stat) ± 1.3 (syst) ± 1.0 (lumi)
Combined	39.9 ± 0.7 (stat) ± 1.0 (syst) ± 0.7 (lumi)

CMS pred: $\sigma_{\text{fid}}^{\text{POWHEG+MCFM}} = 34.4^{+0.7}_{-0.6}(\text{PDF}) \pm 0.5(\text{scale})$ fb



ZZ production: extrapolation to total cross section

UCLouvain
Institut de recherche en mathématique et physique

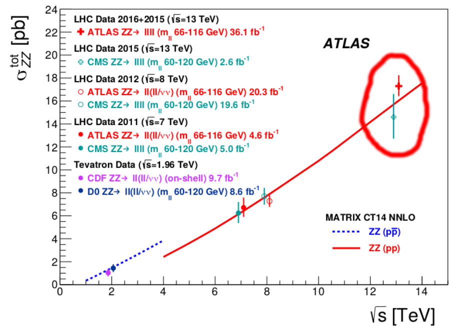
Year	CMS Total cross section, pb
2016 [5]	$17.5^{+0.6}_{-0.5}\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2017	$16.8 \pm 0.5\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$16.8 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.1 \pm 0.3\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$

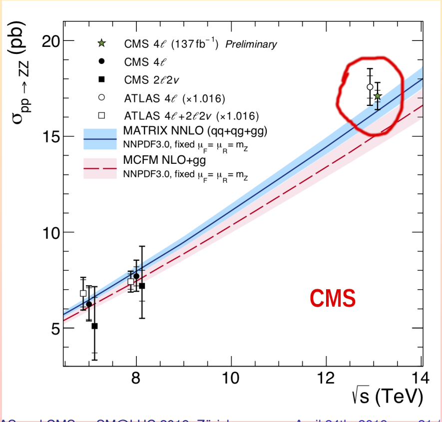
- Extrapolation to full phase space
  - ATLAS: $66 < M(Z) < 116$ GeV, any SM decay
  - CMS: $60 < M(Z) < 120$ GeV, any SM decay

$$\sigma_{\text{tot}}^{\text{POWHEG+MCFM}} = 14.5^{+0.5}_{-0.4}(\text{PDF}) \pm 0.2(\text{scale})\ \text{pb}$$

$$\sigma_{\text{tot}}^{\text{MATRIX 1.0 NNLO}} = 16.2^{+0.6}_{-0.4}\ \text{pb}$$

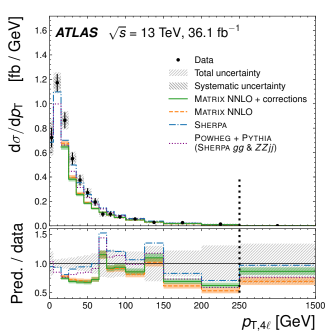
$$\sigma_{\text{tot, +LO } gg\to ZZ}^{\text{MCFM NLO-QCD}} = 16.2^{+0.6}_{-0.4}\ \text{pb}$$

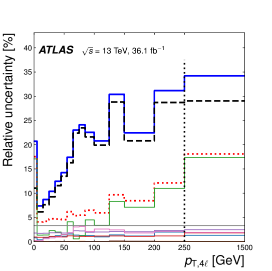


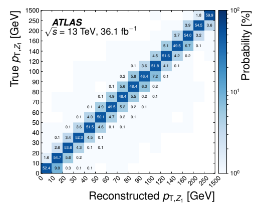


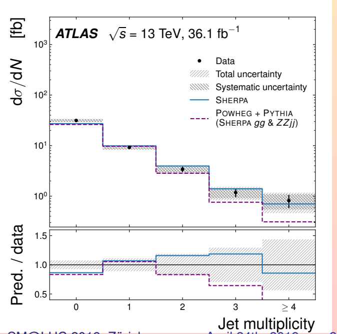
ZZ production: differential cross section

- D'Agostini unfolding: minimize overall uncertainty
  - Results in 2–3 iterations
  - More iterations: higher statistical uncertainty
  - Fewer iterations: higher unfolding method uncertainty (stronger dependence on theoretical prediction)
- Modelling uncertainty
  - Unfold POWHEG spectrum nominal SHERPA response matrix
  - Use difference as uncertainty
- Modelling and regularization bias: 1–22% uncertainty
- Statistical uncertainty due to fluctuations in data
  - 2000 Poisson pseudodata



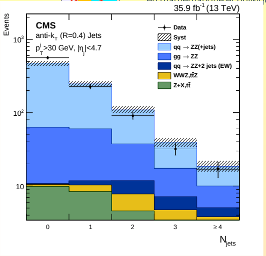


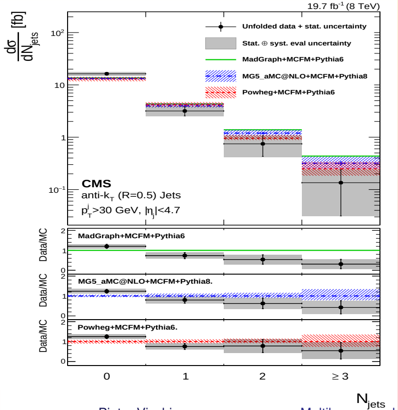


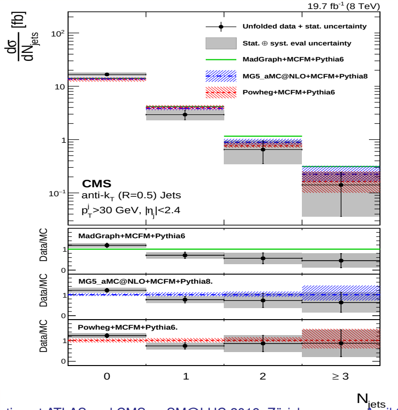


ZZ+jets production: differential cross section

- Unfold at particle level (dressed leptons)
- D'Agostini unfolding: 4 iterations
  - Default number of iterations
  - Cross-checked with SVD unfolding
- Modelling uncertainty
  - Unfold nominal spectrum using different response matrices
  - Use difference as uncertainty







ZZ production: anomalous couplings

- Use p_{T,Z_1} to probe aTGC
  - $M_{4\ell}$ similar sensitivity but no NLO EW correction binned in $M_{4\ell}$ available
- Model CP-violating/conserving lagrangian
  - 2 CP-violating ($f4, f4Z$) and 2 CP-conserving ($f5, f5Z$) couplings
  - No unitarizing form factor (sensitivity is within unitarity bounds)

$$N\left(f_4^\gamma, f_4^Z, f_5^\gamma, f_5^Z\right) = N_{\mathrm{SM}} + f_4^\gamma N_{01} + f_4^Z N_{02} + f_5^\gamma N_{03} + f_5^Z N_{04} + \left(f_4^\gamma\right)^2 N_{11} + f_4^\gamma f_4^Z N_{12} + f_4^\gamma f_5^\gamma N_{13} + f_4^\gamma f_5^Z N_{14} + \left(f_4^Z\right)^2 N_{22} + f_4^Z f_5^\gamma N_{23} + f_4^Z f_5^Z N_{24} + \left(f_5^\gamma\right)^2 N_{33} + f_5^\gamma f_5^Z N_{34} + \left(f_5^Z\right)^2 N_{44},$$

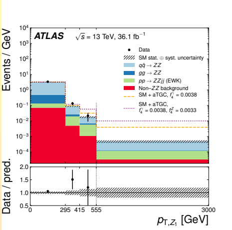
ATLAS

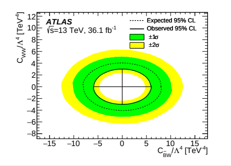
Coupling strength	Expected 95% CL [$\times 10^{-3}$]	Observed 95% CL [$\times 10^{-3}$]
f_4^γ	−2.4, 2.4	−1.8, 1.8
f_4^Z	−2.1, 2.1	−1.5, 1.5
f_5^γ	−2.4, 2.4	−1.8, 1.8
f_5^Z	−2.0, 2.0	−1.5, 1.5

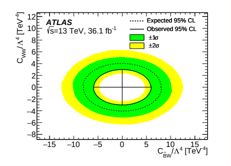
ATLAS

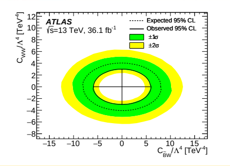
EFT parameter	Expected 95% CL [TeV^{-4}]	Observed 95% CL [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	−8.1, 8.1	−5.9 , 5.9
C_{WW}/Λ^4	−4.0, 4.0	−3.0 , 3.0
C_{BW}/Λ^4	−4.4, 4.4	−3.3 , 3.3
C_{BB}/Λ^4	−3.7, 3.7	−2.7 , 2.8

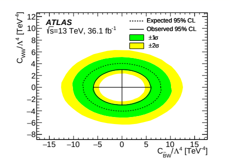
ATLAS

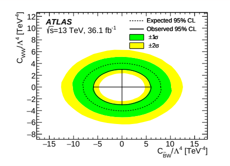


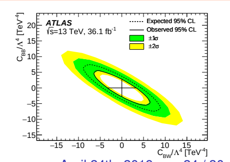




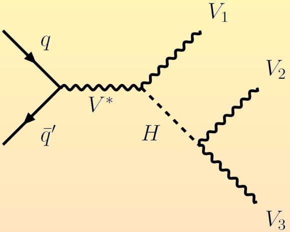


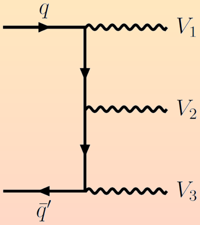


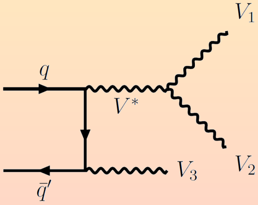


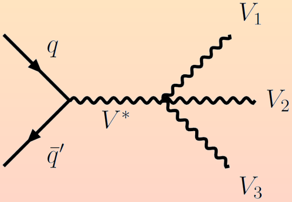


- ATLAS: evidence for VVV production 1903.10415, 80 fb^{-1}
- CMS: WWW search CMS-PAS-SMP-17-013, 36 fb^{-1}



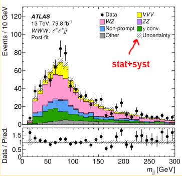


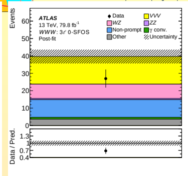


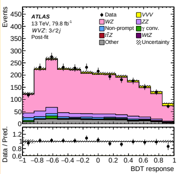


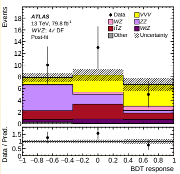
Triboson production: object and event selection

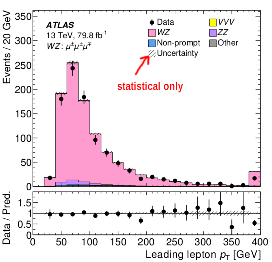
- Trigger strategy
  - ATLAS: 1L triggers, $p_T \sim 20$–60 GeV
  - CMS: 2L triggers, $p_T \sim 8$–23 GeV
- Selection: BDT vs manual classification
  - ATLAS: BDT classifier, no detail on training
  - CMS: exploit ID, $M(jj)$, M_T
- Background
  - ATLAS: WZ and ttZ estimated and validated in sidebands
  - CMS: lost (below threshold) and nonprompt leptons from sidebands

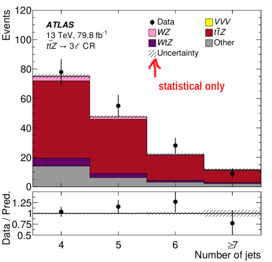


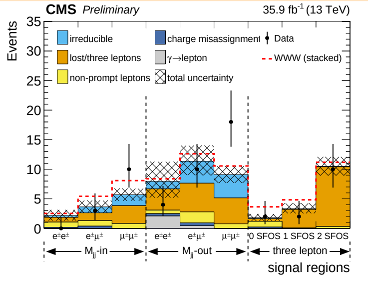












Evidence and quartic gauge couplings

- ATLAS: evidence for VVV production
  - No detail on systematics!
- CMS: $\sigma(\mathrm{pp} \to \mathrm{WWW}) = 173^{+326}_{-173}$ fb
  - Under background-only: $782(599)$ fb 95%CL obs(exp)
  - Confidence intervals for aQGC (dim-8 operators)
  - Limits on photophobic axion-like particles

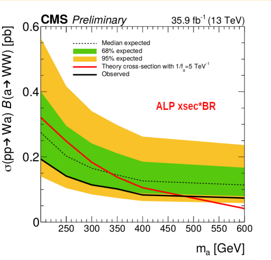
Table 8: Limits on anomalous quartic couplings at 95% CL

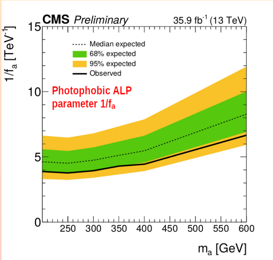
CMS

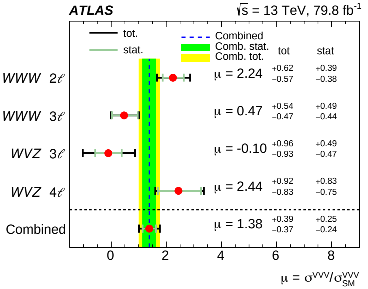
Anomalous coupling	Allowed range (TeV^{-4})	
	Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

ATLAS

Decay channel	Significance	
	Observed	Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ







For discussion: datasets, samples

- We need precision measurements to improve constraints on aTGC/aQGC couplings
- Data set widly incoherent among and within collaborations
  - Soup of comparisons with 3, 13, 36, 70–80, $101\ \mathrm{fb}^{-1}$: even a comparison of 3 vs 77 fb^{-1}!
  - Collaboration strategy? Personpower?
- Agree on the choice of main/alternative generators?
  - Often different generators used (POWHEG vs SHERPA; etc)
- Level of detail provided as public material should be dramatically improved
  - Sometimes the collaborations push against too much detail
- Presentation of results
  - Same formulas, same comparisons
- Not only between ATLAS and CMS: even within ATLAS and CMS individually!!!

For discussion: analysis-specific topics

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- Phase space definitions: discrepancies and reporting
  - Some justified by the detector structure
  - Some perhaps could be agreed upon
  - Publish the details of the definitions (theoreticians need them for using results in global fits)
- Machine learning: don't let it be a black box
  - Training samples and methodology should be clearly mentioned
  - The relevant hyperparameters of your classifier are interesting and deserve to be mentioned!
- Systematics: don't be afraid of detailing them!
  - At the very minimum, table detailing the postfit uncertainties split by source
  - Even better, impact plots with pulls and constraints: particularly interesting for theory uncertainties!!!
- Differential measurements could profit from better reporting and agreements
  - Unfolding is an open topic, many discussions (ATLAS StatForum and CMS StatComm)
  - Use methods correctly (do not use defaults!)
    - Sometimes no unique "right" answer
    - Mostly we know what we should **not** do
  - Can we at least agree on this?
    - Publish the response matrix
    - Publish the tabulated results
    - Publish the details of the unfolding (e.g. number of iterations, choice of regularization, etc)
- Combinations: it is time, is it?
  - Cross section: wait for full Run-II?
  - Couplings: start combining current results, or wait for full Run-II?

Summary of multiboson production studies

- Large landscape of precision measurements (and check out Kenneth's talk on VBS production modes!)
- We are now in the era of the couplings
- WZ production: data point to NNLO predictions
  - Ratios and asymmetries all consistent with SM predictions
  - Statistical uncertainties dominate differential measurement
  - Confidence regions for aTGC shrinking dramatically!
- WW production: data compatible with nNNLO
  - Systematic-dominated, but still profit from more data (currently: 3 fb^{-1}!)
  - Evidence for DPS WW production (and good agreement with CMS-tuned PYTHIA 8)
  - NEW!!! anomalous couplings constrained in VWproduction at the level of the latest multilepton result!
- ZZ production: impressive detail of 36 fb^{-1} analysis, plus first look at Full Run-II w/ 101 fb^{-1}!
  - Data agree well with NNLO predictions with NLO EW and QCD corrections
- Triboson production: establishing evidence, and constraints on quartic couplings
  - VVV production emerging, but evidence (3σ exp) only combining all VVV, so far: must go further
  - Sensitive to quartic couplings (dimension 8 operators!)
  - Sensitive to axion-like models
- NNLO predictions favoured everywhere, but generators kinematics still NLO
- The NNLO revolution is ongoing: when do we get NNLO MC spectra? ☺

Stay tuned on the ArXiv for a small contribution on the issues in reporting I outlined in this talk

THANKS FOR THE ATTENTION!

Backup