Multi-boson Production at 13TeV in ATLAS and CMS

- **WW, WZ and ZZ**
- **WWW and WVZ**

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On behalf of the ATLAS and CMS Collaborations

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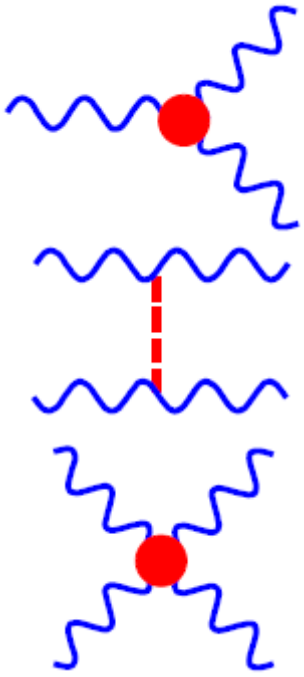
Multi-boson Physics

Physics Processes:

- Diboson Wγ, Zγ, WW, WZ, ZZ productions, probing aTGC
- EWK Vector Boson Fusion (VBF) and Vector Boson Scattering (VBS), Wγjj, Zγjj, WWjj, WZjj – probing Higgs mech. and aQGCs (Covered by other talks)
- Tri-boson productions, probing aQGCs



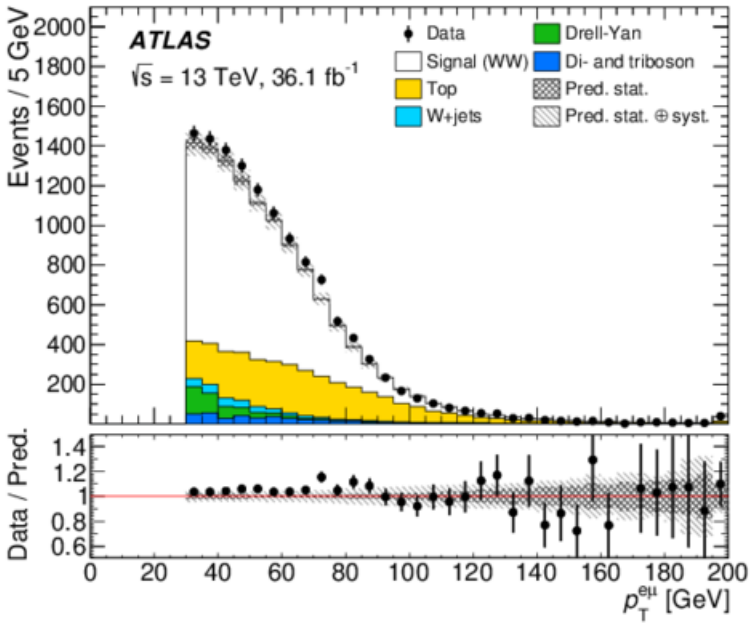
Motivations:

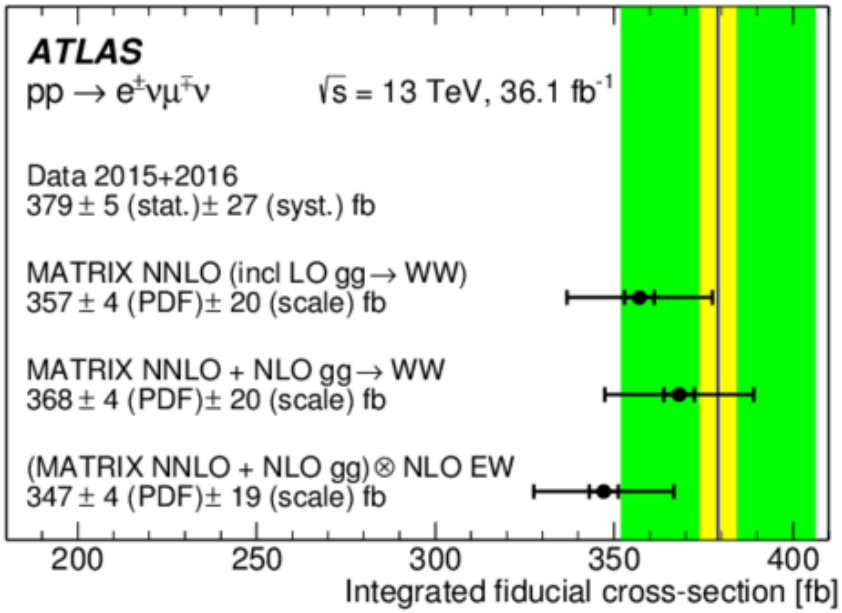
- EWK precision measurements with higher order corrections
- Test pQCD
- Explore new final states never observed before
- Searching for SM breakdown → new physics beyond SM

$W^+W^- \rightarrow e^{\pm}\nu\mu^{\mp}\nu$

arXiv:1905.04242

- **Signature: two high-pt eμ with large MET**
- **Backgrounds:** Top (ttbar, Wt), Z+jets, Other Diboson, W+jets
- **Selection:** eμ final state, veto jet (pT > 35 GeV) and b-jets



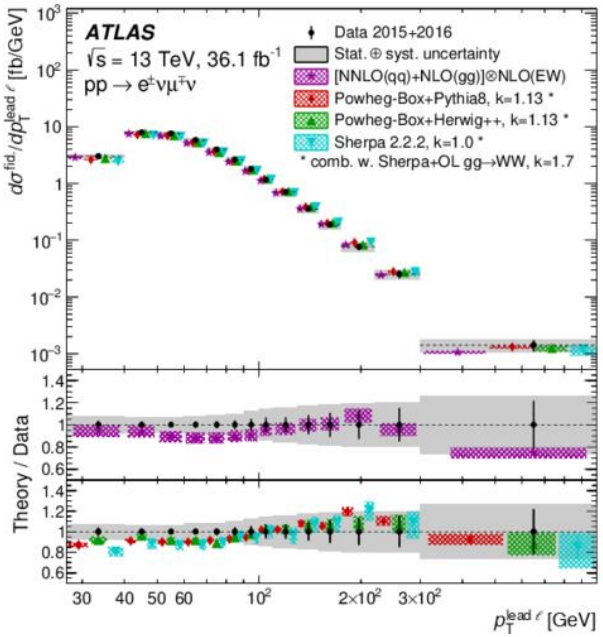


$W^+W^- \rightarrow e^{\pm}\nu\mu^{\mp}\nu$

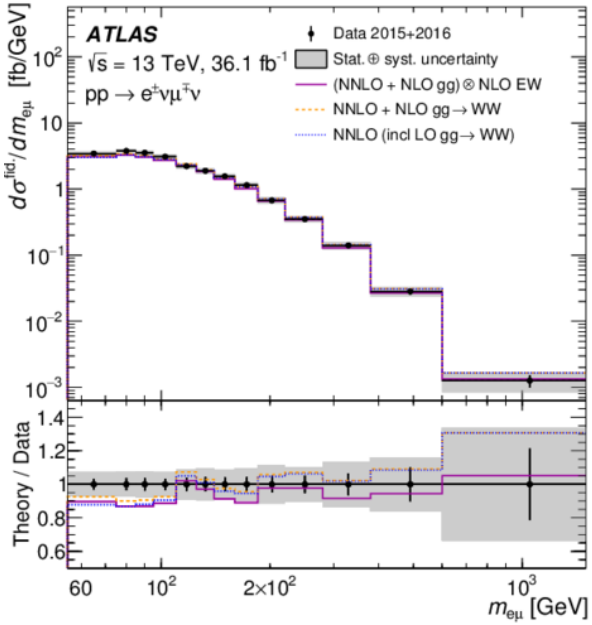
arXiv:1905.04242

1st differential diboson measurement at 13TeV on $p_T(\ell 1)$, $p_T(e\mu)$, $m_{e\mu}$, $|y_{e\mu}|$, $\Delta\phi_{e\mu}$, $|\cos\theta^*| = \tanh(\Delta\eta_{e\mu}/2)|$

Normalized fiducial cross sections



Unfolded fiducial cross sections



EFT aTGC limits from $p_T(\ell 1)$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

arXiv:1205.4231

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

DPS $W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu$

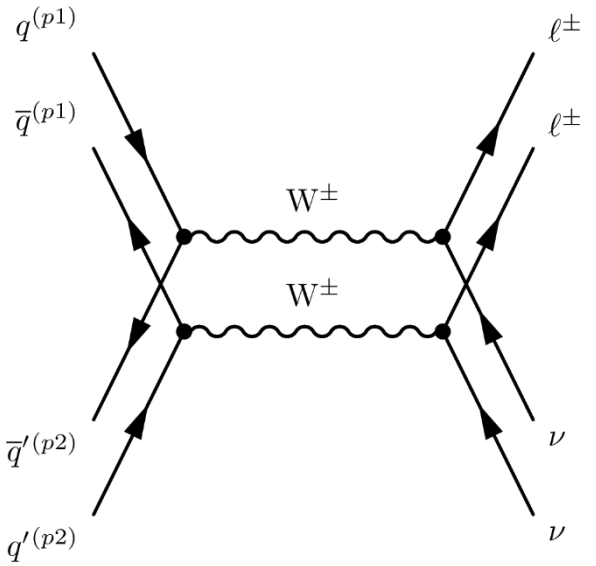
CMS-PAS-SMP-18-015

Motivations:

- To probe the factorization approach used in MC simulation

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

  - A,B are SHS (Single Hard Scattering) processes
  - n=1 (A,B identical) n=2 (A,B distinguishable processes)
- Background for new physics searches



Selections:

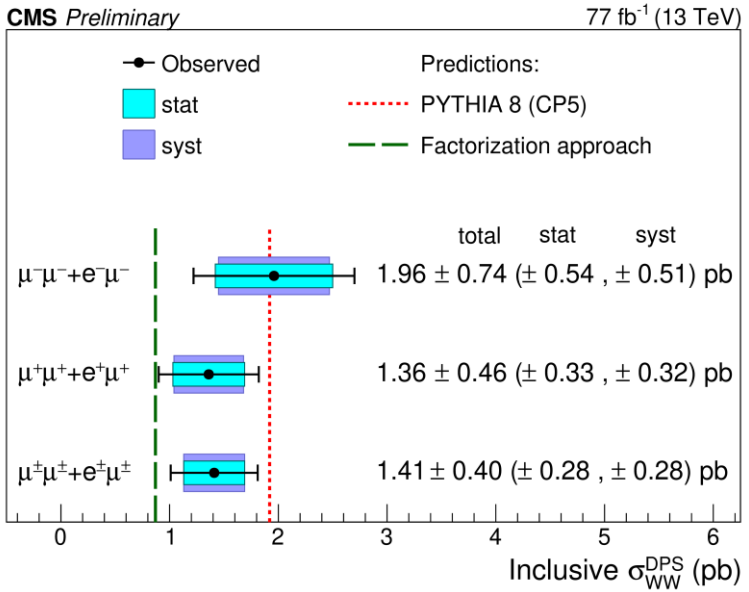
- 2 same-sign leptons + Missing transverse energy (MET)
- 0/1 jet only (no jets at LO, 10% of signal have 1 jet)
- veto b-tagged jets
- Signal extracted using multivariate analysis techniques

Results:

- 1st evidence of DPS WW with 13TeV data (2016-2017)
- Sensitivity : 3.9 σ

$$\sigma_{DSPWW,obs} = 1.41 \pm 0.28\,(stat) \pm 0.28\,(syst)\ pb$$

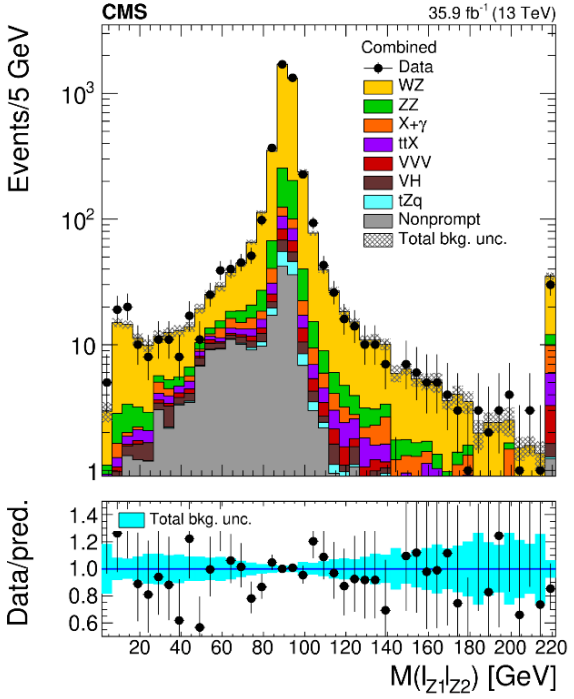
The measurement lies in between the predictions of PYTHIA8 1.92 pb and the factorization approach 0.87 pb



WZ Production

CMS [JHEP 04 (2019) 122](#)
ATLAS [arXiv:1902.05759](#)

- ***WZ→ℓ'νℓℓ selection:***
  - 3 lepton (e,μ) consistent with MET
  - one opposite sign same flavor 2ℓ compatible with m_Z
- **Fake background measured from data;**

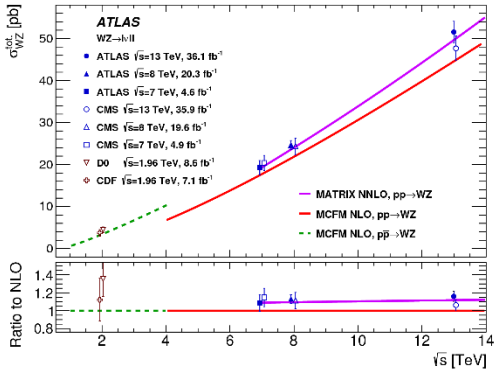


$\sigma_{TOT}(pp \to WZ)$ extrapolated from fiducial cross section:

CMS $48.09\ ^{+1.00}_{-0.96}\ (\text{stat})\ ^{+0.44}_{-0.37}\ (\text{theo})\ ^{+2.39}_{-2.17}\ (\text{syst}) \pm 1.39\ (\text{lumi})\ \text{pb}$

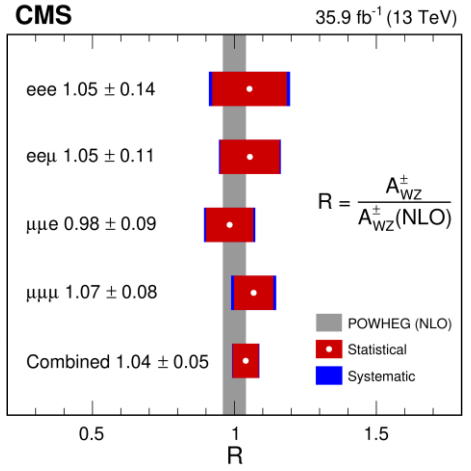
ATLAS $51.0 \pm 0.8\,(\text{stat.}) \pm 1.8\,(\text{exp. syst.}) \pm 0.9\,(\text{mod. syst.}) \pm 1.1\,(\text{lumi.})\ \text{pb}$

MATRIX $\sigma_{NNLO}(pp \to WZ) = 49.98^{+2.2\%}_{-2.0\%}$ pb [arXiv:1711.06631](#)



Charge-dependent measurements:

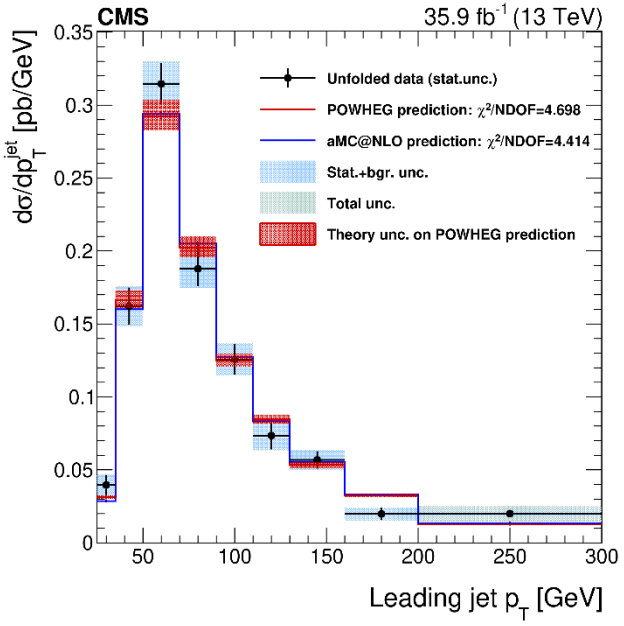
ATLAS $\dfrac{\sigma^{\text{fid.}}_{W^+Z\to\ell'\nu\ell\ell}}{\sigma^{\text{fid.}}_{W^-Z\to\ell'\nu\ell\ell}} = 1.47 \pm 0.05\,(\text{stat.}) \pm 0.02\,(\text{syst.})$

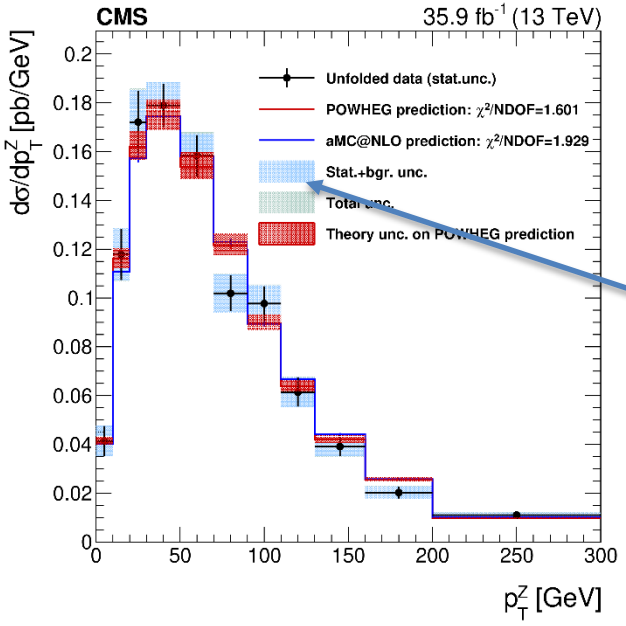


CMS $A^{+-}_{WZ} = \dfrac{\sigma_{tot}(pp \to W^+Z)}{\sigma_{tot}(pp \to W^-Z)} = 1.48 \pm 0.06\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.01\,(\text{theo})$

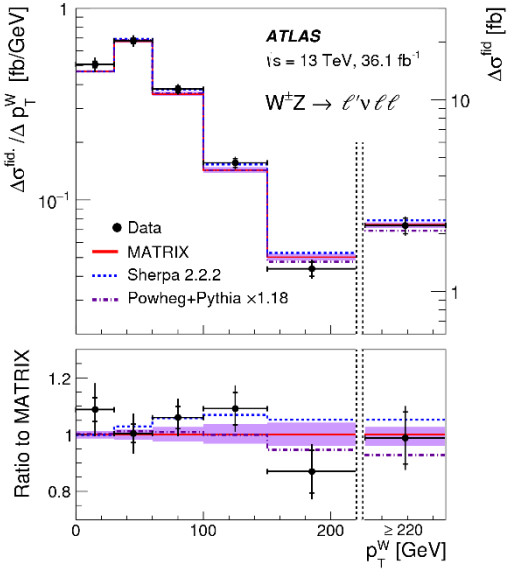
WZ Differential Cross-sections

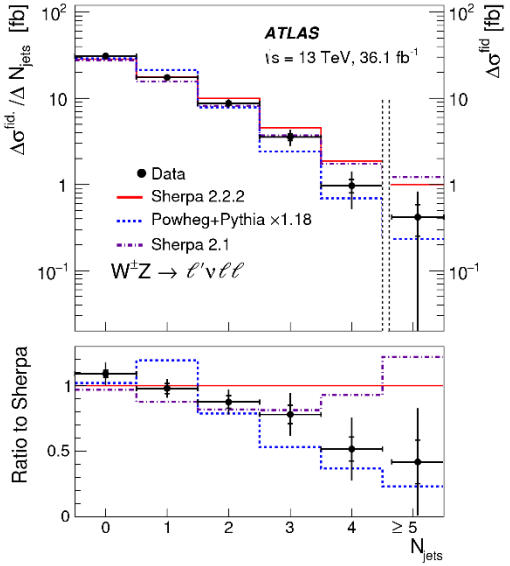
CMS JHEP 04 (2019) 122
ATLAS arXiv:1902.05759





Still statistical uncertainties dominate

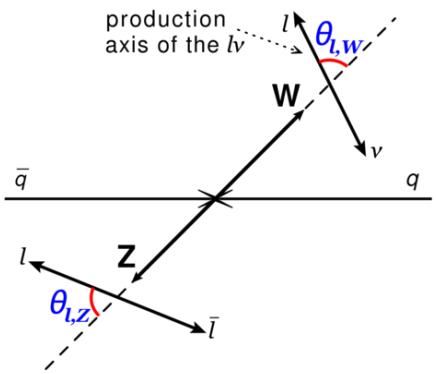


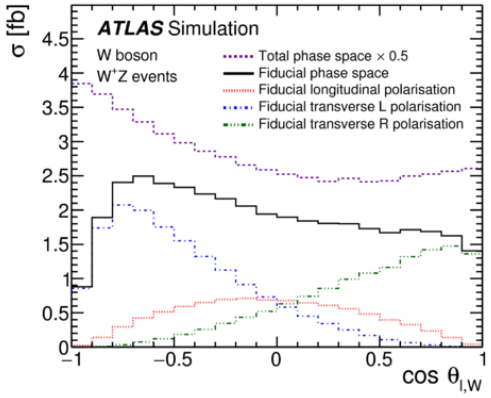


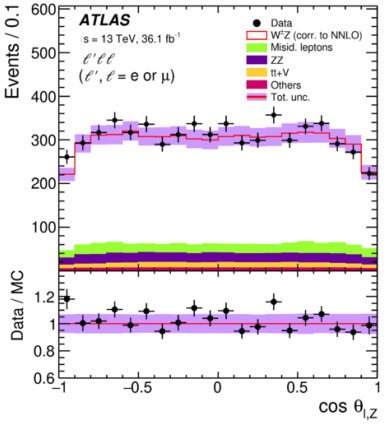
WZ Polarization

ATLAS arXiv:1902.05759

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

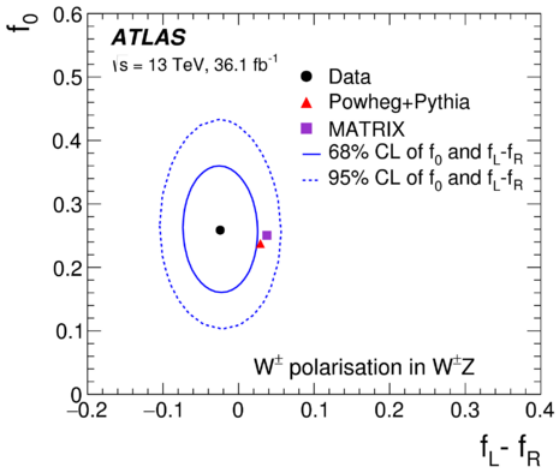


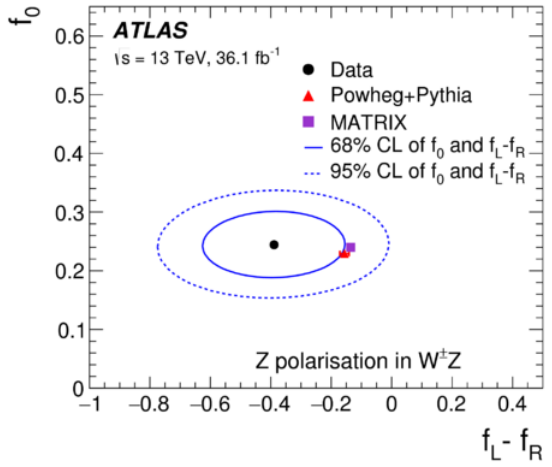




Measurements: extract polarization f_0(longitudinal) and $f_L - f_R$(transverse) by fit of $q_\ell \cdot \cos\theta(\ell,W)$ and $\cos\theta(\ell,Z)$

f_0	Measured	SM (NLO QCD)	Significance	Expected
W	0.26 ± 0.06	0.238 ± 0.003	4.2σ	3.8σ
Z	0.24 ± 0.24	0.230 ± 0.003	6.5σ	6.1σ





- 1st time measurements in hadronic collisions
- Still room to improve with more data and better MC

WZ aTGC Limits

CMS arXiv:1901.03428

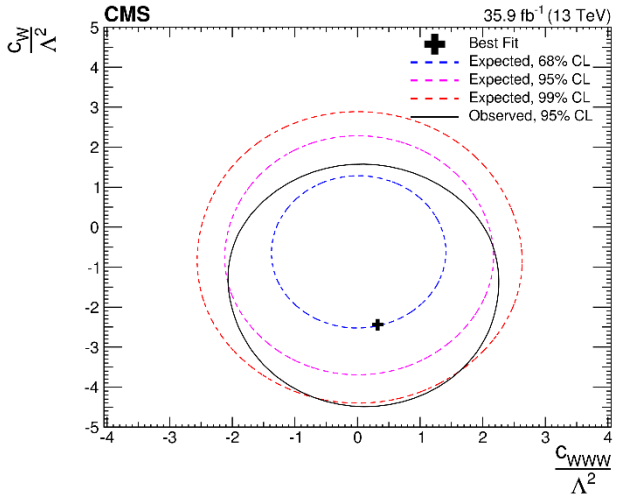
$$\delta\mathcal{L}_{AC} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + \frac{c_W}{\Lambda^2}(D_\mu H)^\dagger W^{\mu\nu}(D_\nu H) + \frac{c_b}{\Lambda^2}(D_\mu H)^\dagger B^{\mu\nu}(D_\nu H)$$

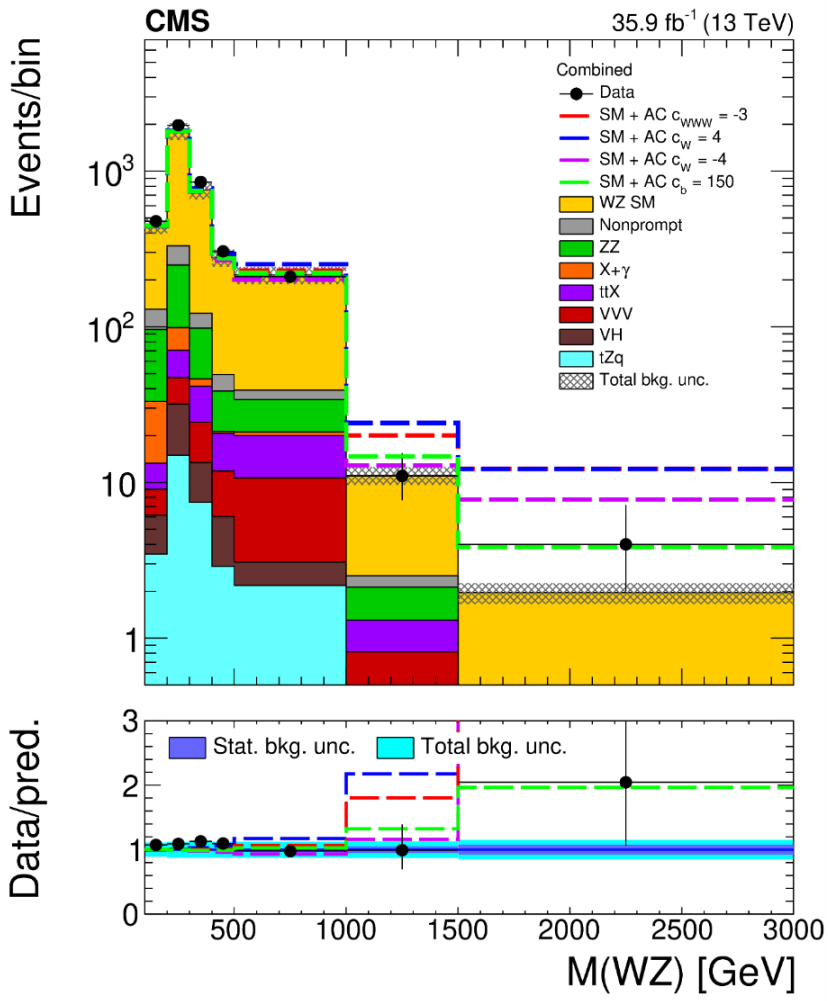
EFT: 6 dimensionless coefficients (c_i) parametrize the strength with which new physics couples to SM particles

aTGC limits by max. likelihood fit on M(WZ)

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	$[-130, 170]$	$[-100, 160]$

Most stringent limits on c_W

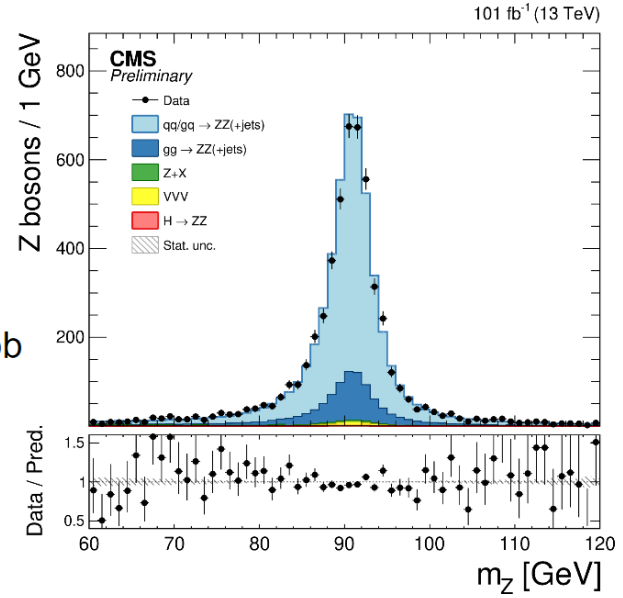




ZZ → 4ℓ Production

CMS [CMS-PAS-SMP-19-001]
ATLAS [arXiv:1902.05892]

- **$ZZ \to \ell\ell\ell'\ell'$:**
  - Smallest cross-section, but cleanest signature almost no BKGs
  - 4 lepton (e,μ) consistent with two Zs:
- **Fake background measured from data.**

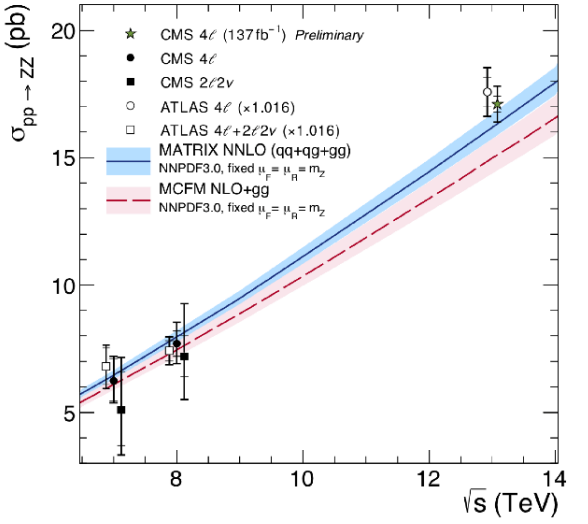


CMS : 137fb^{-1}, most precise diboson measurement

$$\sigma_{tot}(\mathrm{pp} \to \mathrm{ZZ}) = 17.1 \pm 0.3\ (\mathrm{stat}) \pm 0.4\ (\mathrm{syst}) \pm 0.4\ (\mathrm{theo}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb}$$

- **Experimental error down to 3.4%**
- **Dominant experiment uncertainty : lepton ID**
- **Good agreement with MATRIX NNLO prediction and compatible with MCFM NLO calculation**

ATLAS : 36.1fb^{-1}, gg→4l signal strength ($\mu_{gg\to 4l}$) by a likelihood scan in the range m_{4l} ~ [180, 1200] GeV

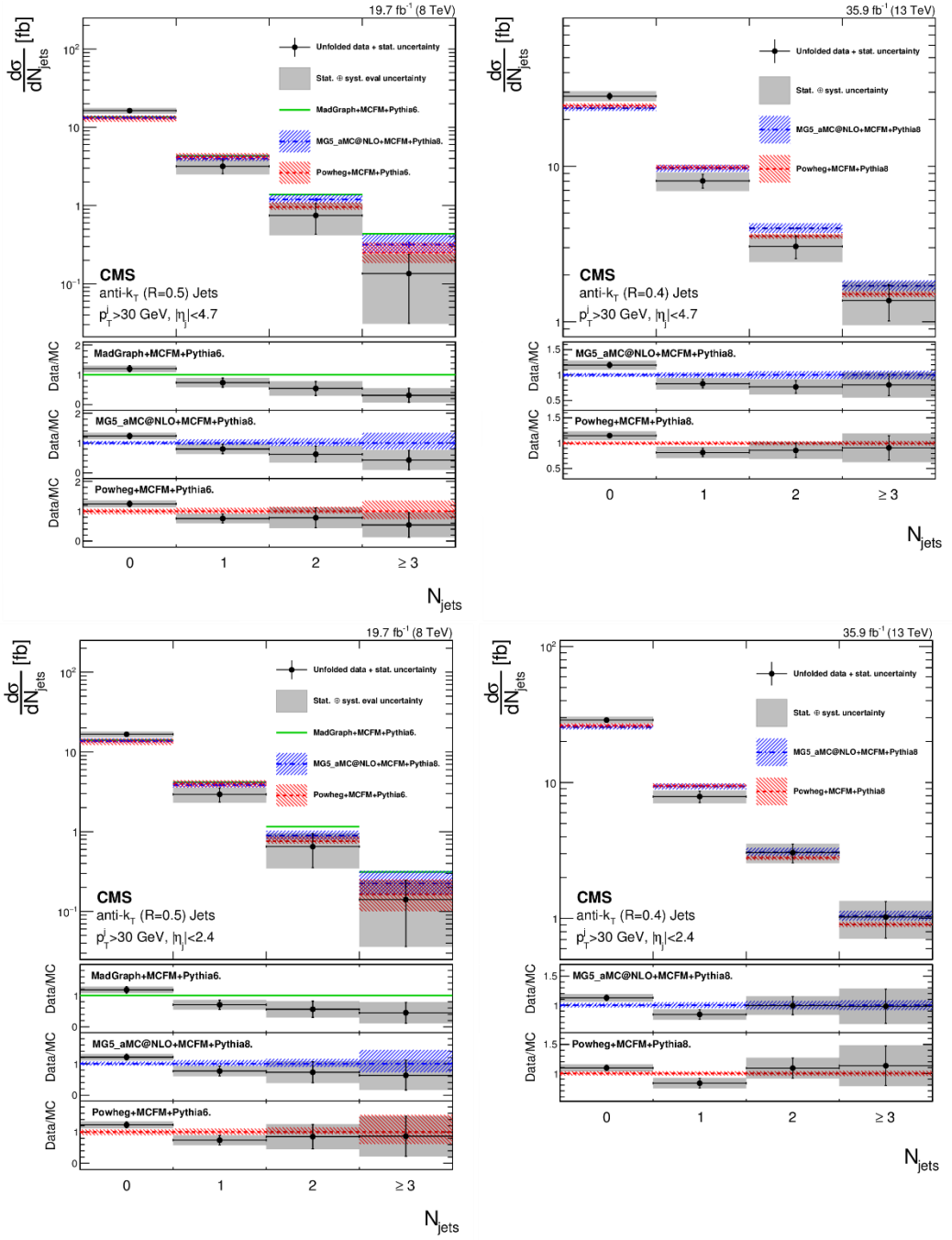


Generator	Observed $\mu_{gg\to 4l}$	Predicted $\mu_{gg\to 4l}$
Sherpa 2.2.2 with K-factor	1.3 ± 0.5	1.0 ± 0.4
MCFM, LO QCD	2.7 ± 0.9	2.2 ± 0.9

ZZ → 4ℓ Differential Cross-section in Association with Jets @8/13TeV

CMS [Phys. Lett. B 789 (2019) 19]

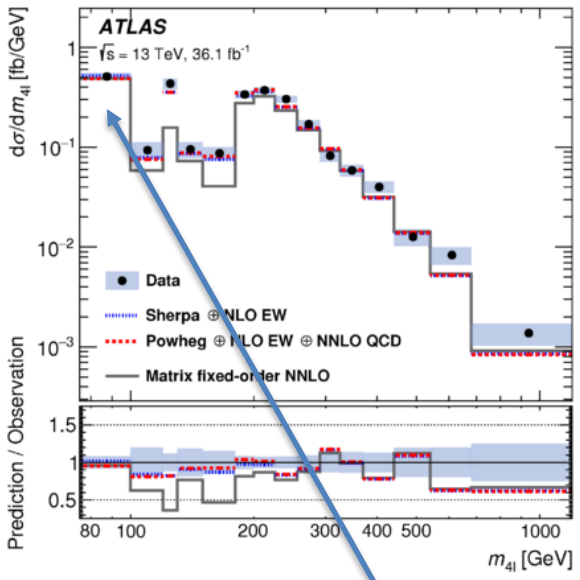
- **Measured different cross-section with at least one or 2 jets against 2 leading jet pT, pseudorapidity and their invariant mass;**
- **Measurements and theoretical predictions are in good agreement within the theoretical and experimental uncertainties.**

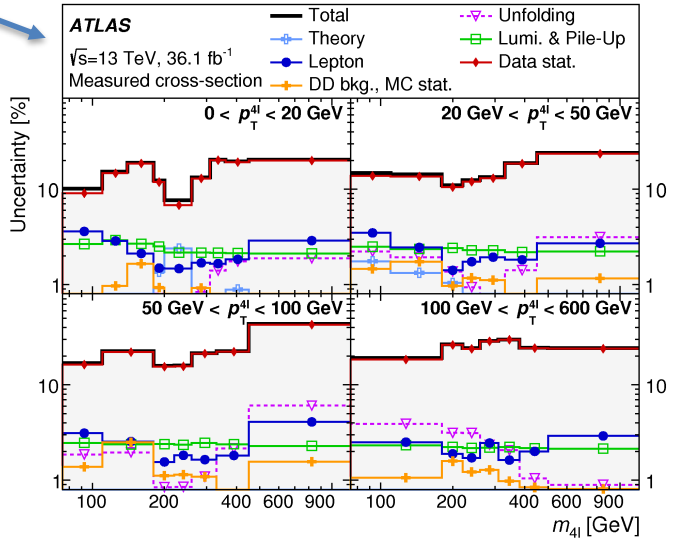


$ZZ^* \rightarrow 4\ell$ Differential Measurements

ATLAS arXiv:1902.05892

- **Unfolded distributions, double differential in $p_T(4\ell)$, $|y_{4\ell}|$, and ℓ flavor**

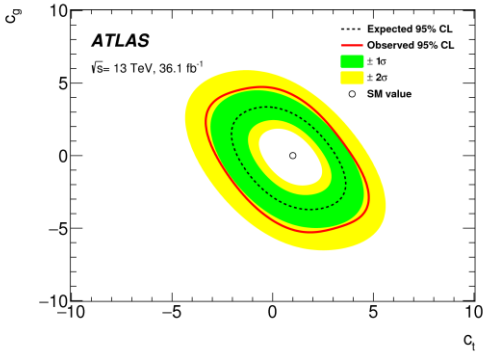




- **4l resonance searches → Br(Z→4l) measurement**
  - Lowest m(4l) bin [75, 100] GeV
  - All the uncertainties are treated uncorrelated.

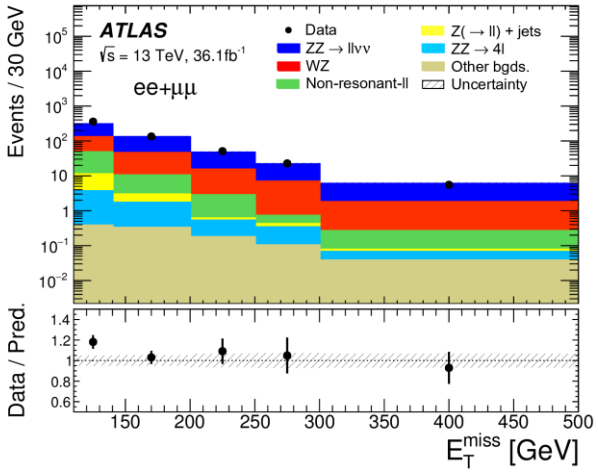
Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s} = 7$ TeV and 8 TeV [8]	$4.31 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})$
CMS, $\sqrt{s} = 13$ TeV [6]	$4.83\ ^{+0.23}_{-0.22}(\text{stat})\ ^{+0.32}_{-0.29}(\text{syst}) \pm 0.08(\text{theo}) \pm 0.12(\text{lumi})$
ATLAS, $\sqrt{s} = 13$ TeV	$\mathbf{4.70 \pm 0.32(stat) \pm 0.21(syst) \pm 0.14(lumi)}$

- **BSM Higgs couplings to top or gluons?**
- **Measured at $m_{4\ell} > 180$ GeV, where c_t and c_g decouple (arXiv:1406.6338)**



ZZ → 2ℓ2ν

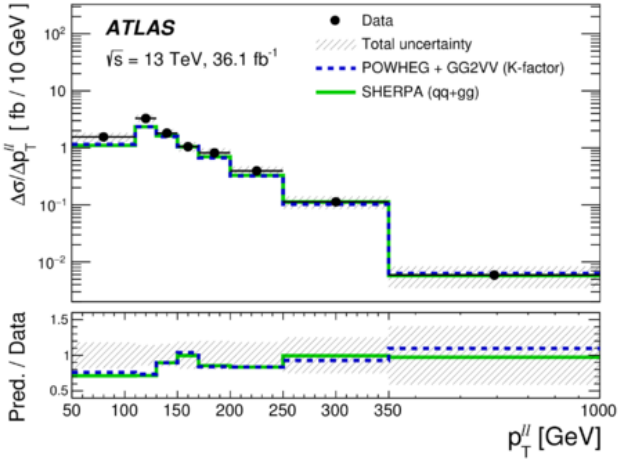
ATLAS arXiv:1902.05892

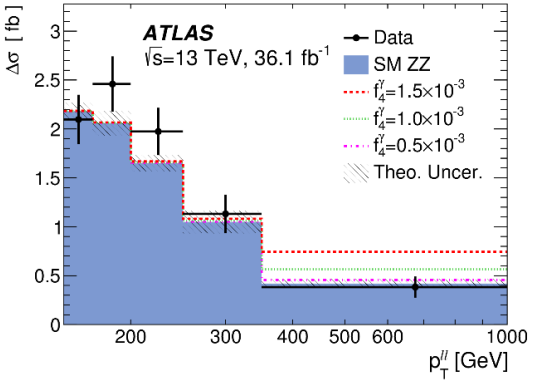


Fit E_T^{miss} distribution to obtain total cross-section

		Measured	Predicted
$\sigma^{fid}_{ZZ\to\ell\ell\nu\nu}$ [fb]	ee	12.2 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$\mu\mu$	13.3 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$ee + \mu\mu$	25.4 ± 1.4 (stat) ± 0.9 (syst) ± 0.5 (lumi)	22.4 ± 1.3
σ^{tot}_{ZZ} [pb]	Total	17.8 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi)	15.7 ± 0.7

Measured the fiducial region differential cross-sections on m_T^{ZZ}, p_T^{ZZ}, $p_T^{\ell\ell}$,$p_T^{\ell 1}$,$y_{\ell\ell}$,$\Delta\varphi_{\ell\ell}$,N_{jets} and p_T^{jet1}

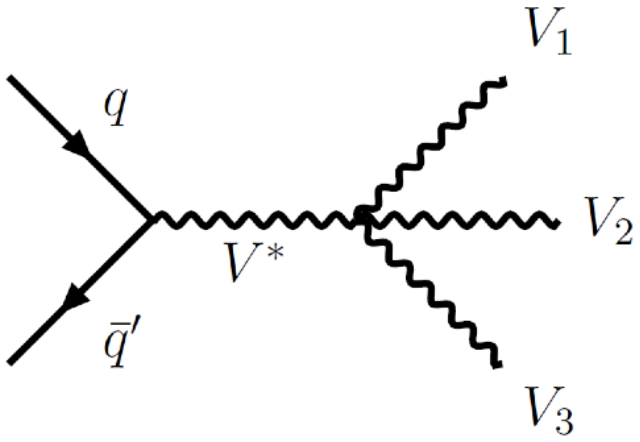


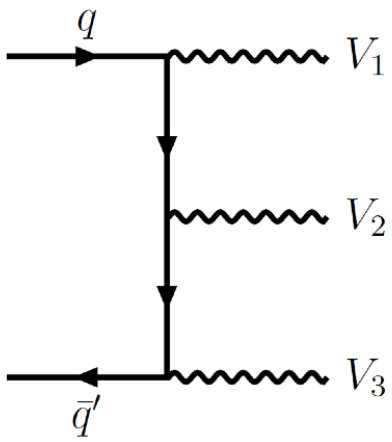


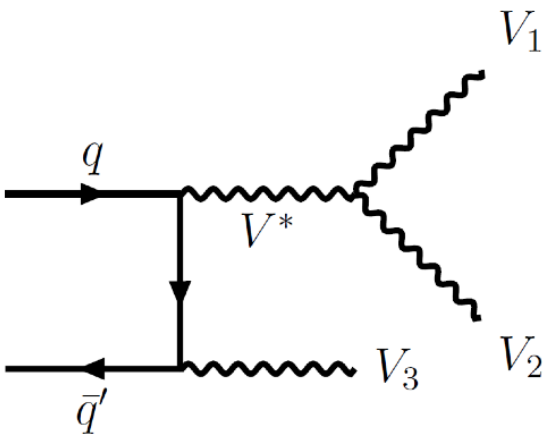
Fit unfolded measured distribution of $p_T^{\ell\ell}$ above 150 GeV to obtain more stringent aTGC limits than ones from ZZ→4ℓ

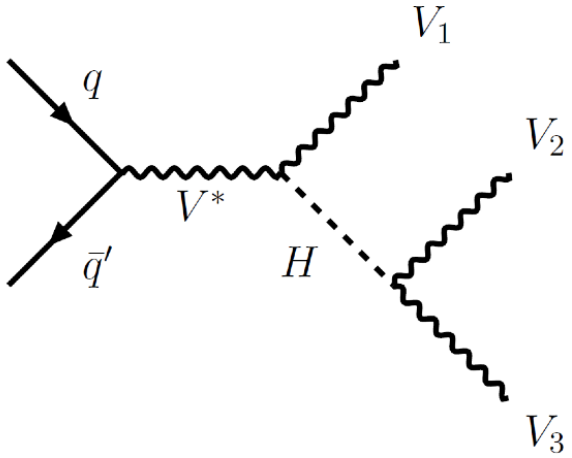
	f_4^γ	f_4^Z	f_5^γ	f_5^Z
Expected $[\times 10^{-3}]$	$[-1.3, 1.3]$	$[-1.1, 1.1]$	$[-1.3, 1.3]$	$[-1.1, 1.1]$
Observed $[\times 10^{-3}]$	$[-1.2, 1.2]$	$[-1.0, 1.0]$	$[-1.2, 1.2]$	$[-1.0, 1.0]$

Triboson Production









WVV Analysis Strategy

WWW Analysis — Cutflow Based

W W W

Avoid Z bosons:

2ℓ2j Analysis - Two same sign leptons

3ℓ Analysis - 0 same flav. opposite sign lep.

2ℓ2j Analysis

- At least 2 jets with b-jet veto.
  - Mjj is used as the discriminant
- Specific cuts to veto ssWW

3ℓ Analysis

- 0SFOS suppresses majority of backgrounds.
- b-jet veto is additionally applied to veto ttbar events.

WVZ Analysis — BDT Based

WVZ

Categorize according to 3ℓ or 4ℓ end-states

Always reconstruct a Z boson with 2 leptons

3ℓ Analysis

- At least one jet with b-jet veto.
- One BDT is trained per jet category:
  - 1, 2, 3+ jets.

4ℓ Analysis

- 4 leptons with a total charge of 0
- One BDT is trained for each category:
  - Same-flavor on-shell
  - Same-flavor off-shell
  - Different-flavor

- **Used both data-driven and MC-based background estimates with control regions**
- **CMS focus on WWW analysis**

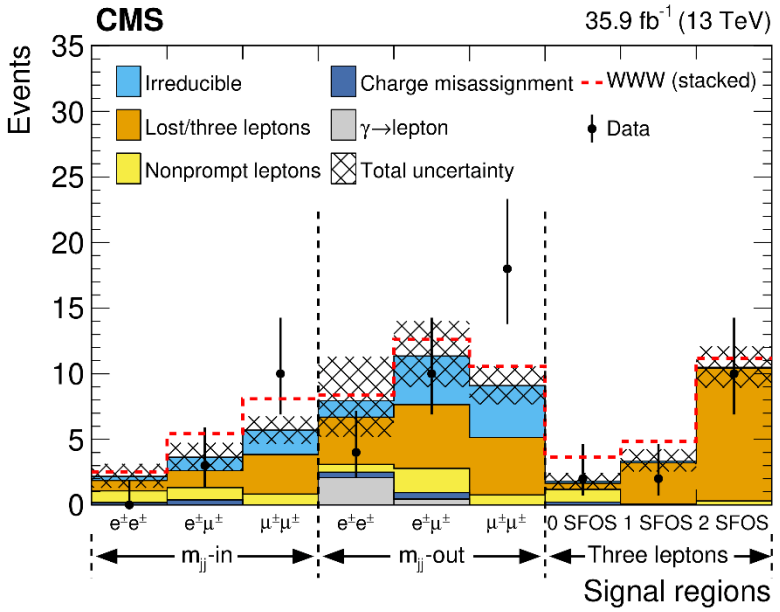
WWW Production

CMS arXiv:1905.04246

- **9 signal regions**
  - **6 from 2ℓ of same sign, m_{jj}-in consistent as W and m_{jj}-out for other selected events**
  - **3 regions from events with 3ℓ**
- **Measurements:**

$$\sigma(pp \to W^{\pm}W^{\pm}W^{\mp}) = 0.17^{+0.32}_{-0.17}\,pb$$

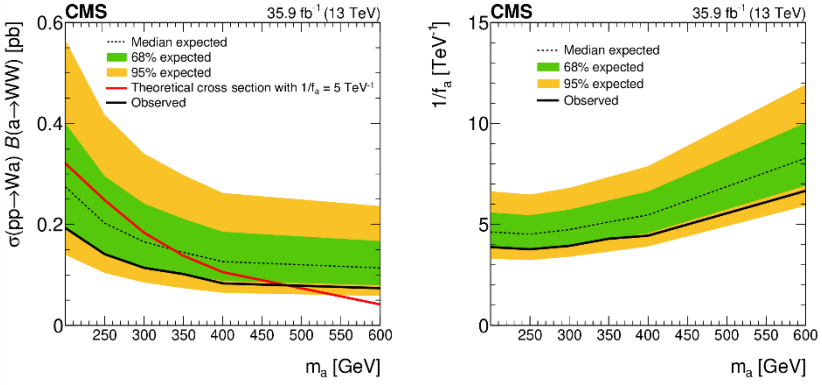
The best fit of signal strength: $0.34^{+0.62}_{-0.34}$



aQGC limits on 3 most sensitive couplings in the absence of any indication for anomalous couplings

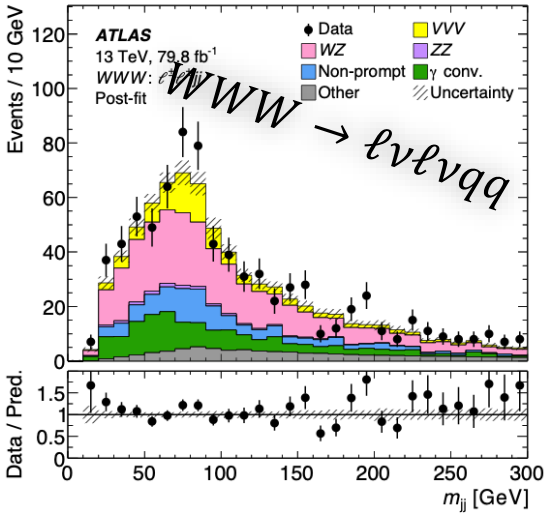
Anomalous coupling	Allowed range (TeV^{-4})	
	Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

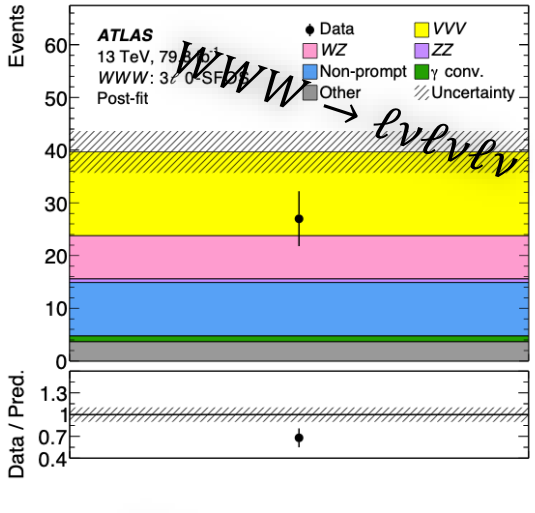
Explore BSM physics based on photophobic axion-like model (ALP: arXiv:1805.06538)
pp → W a (a→ WW) → WWW

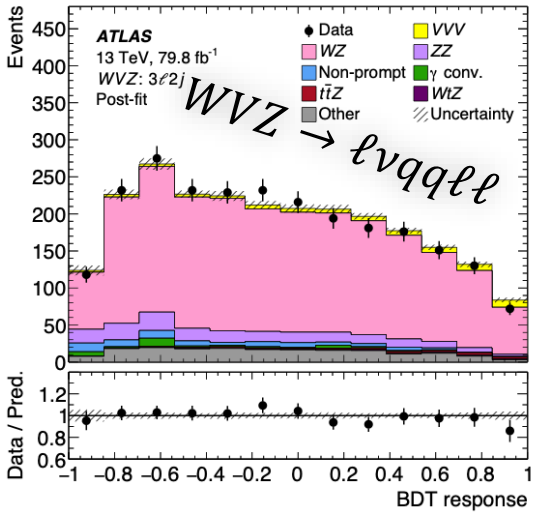


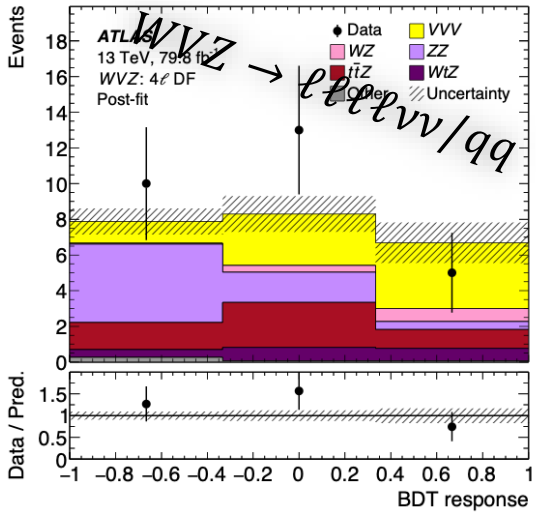
WVV Evidences

ATLAS arXiv:1903.1041

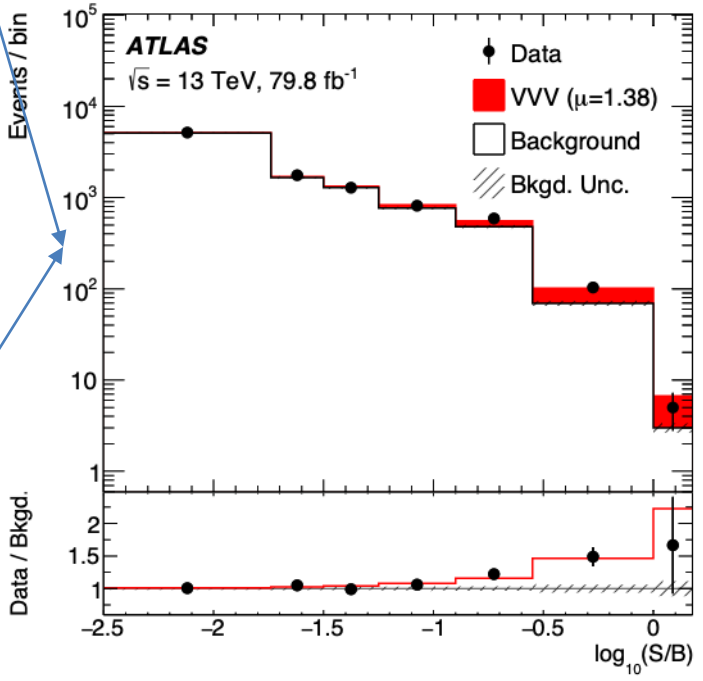








Simultaneous fit to 11 SRs and 1 CR, and combine into a plot of $\log_{10}$(S/B) clearly deviated from BKG only.

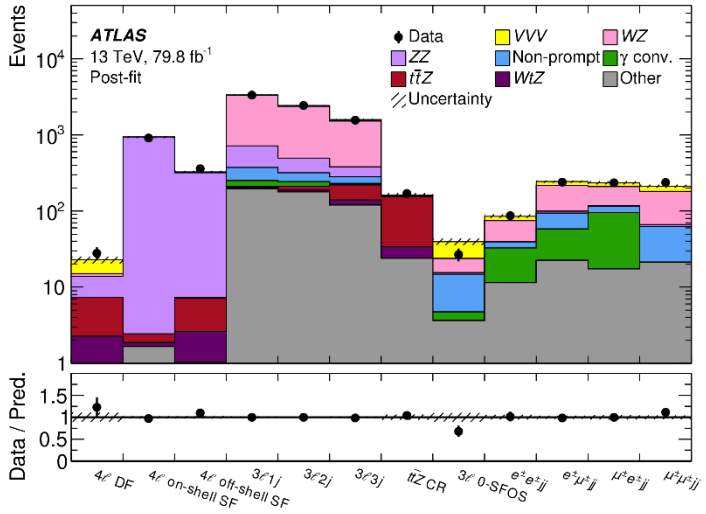


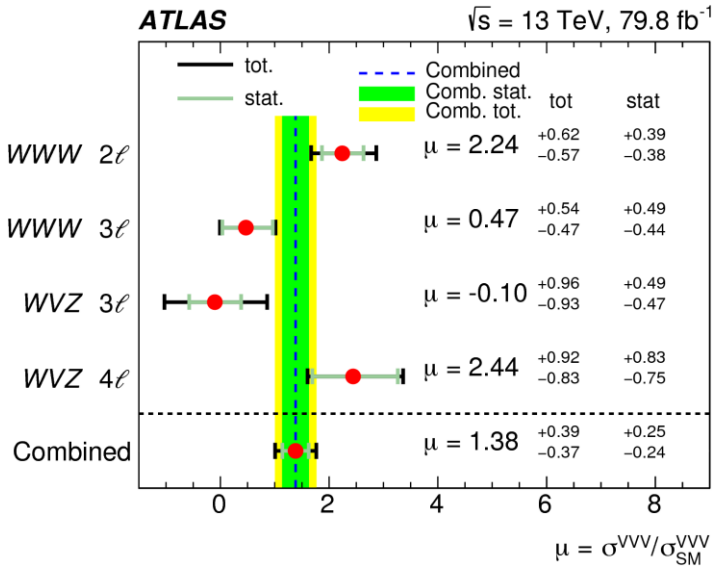
Comment: most measurements are shown in 4 grouped regions

WVV Production

ATLAS arXiv:1903.1041

12 region distributions after fit (DF=Different ℓ Flavor, SF=Same ℓ Flavor)





*** First evidence of VVV production in *pp* events has been observed with a significance of 4 σ compared to expected 3.1 σ**

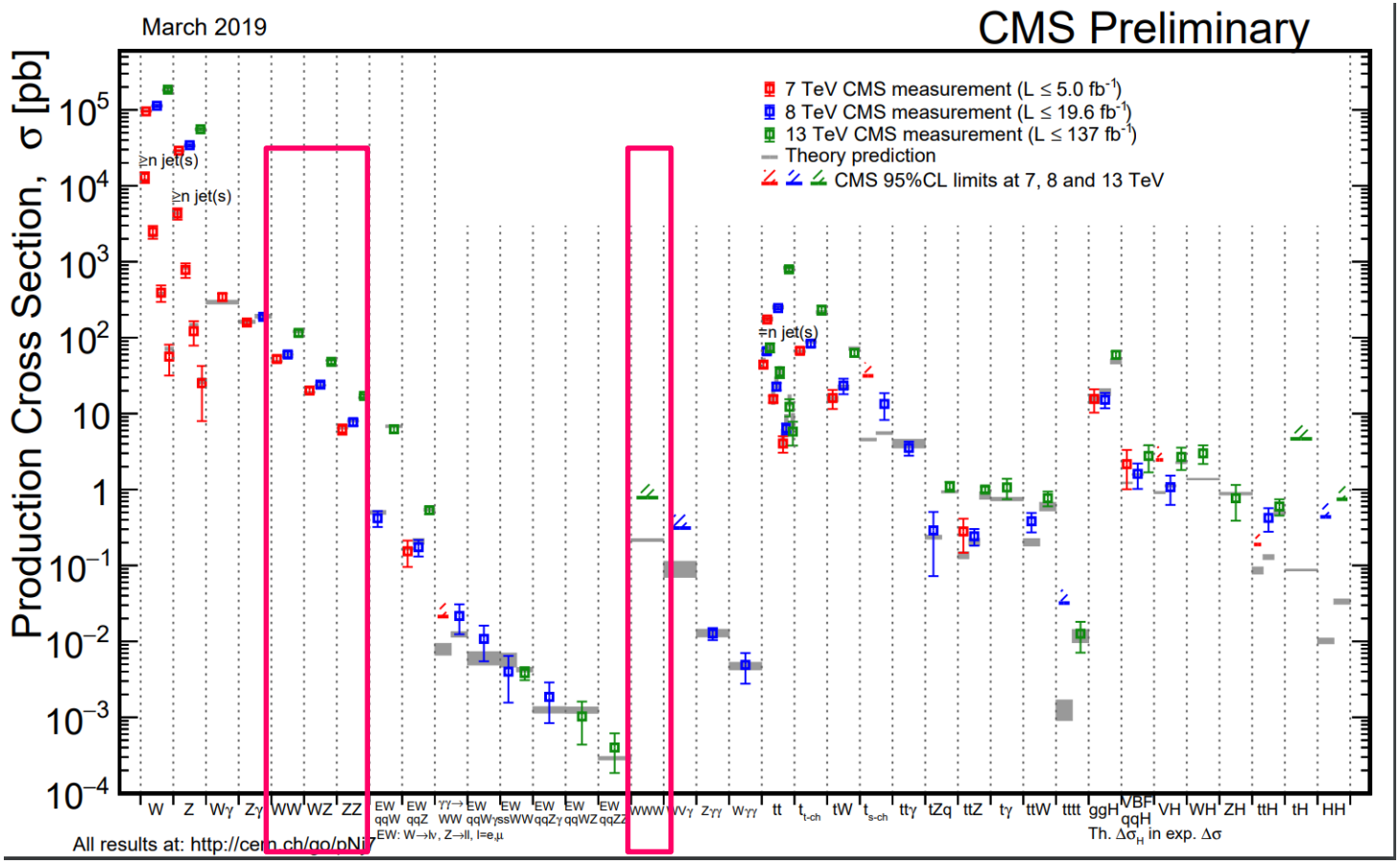
*** WVV cross-section measurements, consistent with SM predictions**

$$\sigma_{WWW} = 0.68^{+0.16}_{-0.15}\,(\text{stat.})\,^{+0.16}_{-0.15}\,(\text{syst.})\ \text{pb}$$

$$\sigma_{WWZ} = 0.49 \pm 0.14\,(\text{stat.})\,^{+0.14}_{-0.13}\,(\text{syst.})\ \text{pb}$$

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

Conclusion



- **Improved measurements@13TeV agree with SM predictions (NNLO QCD)**
- **1st evidence of triple boson product at 4σ**
- **Explored aTGC with good sensitivities.**

Thank you!!!

Backup

ATLAS SM Cross-section Results