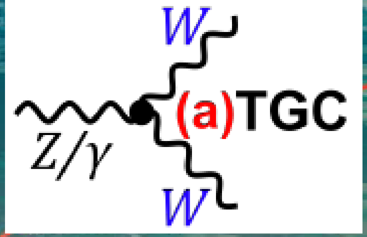
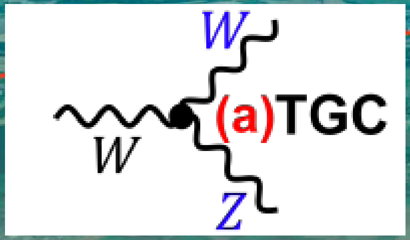
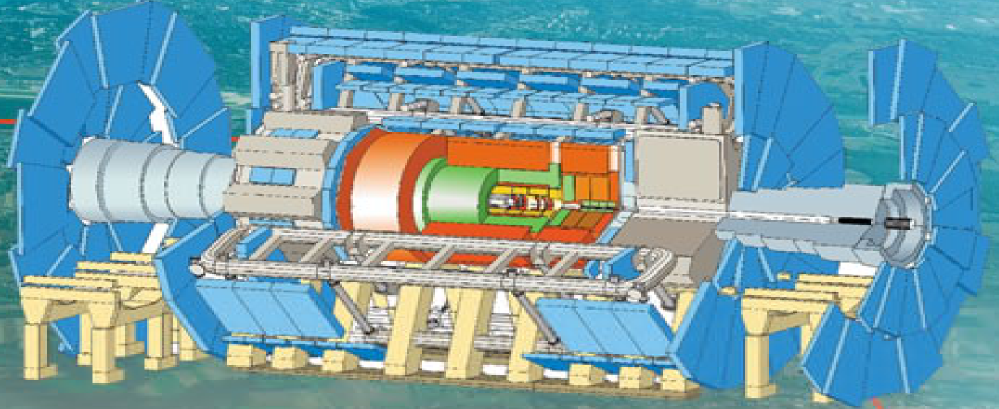
Measurement of the diboson production cross section at 8TeV and 13TeV and limits on anomalous triple gauge couplings with the ATLAS detector







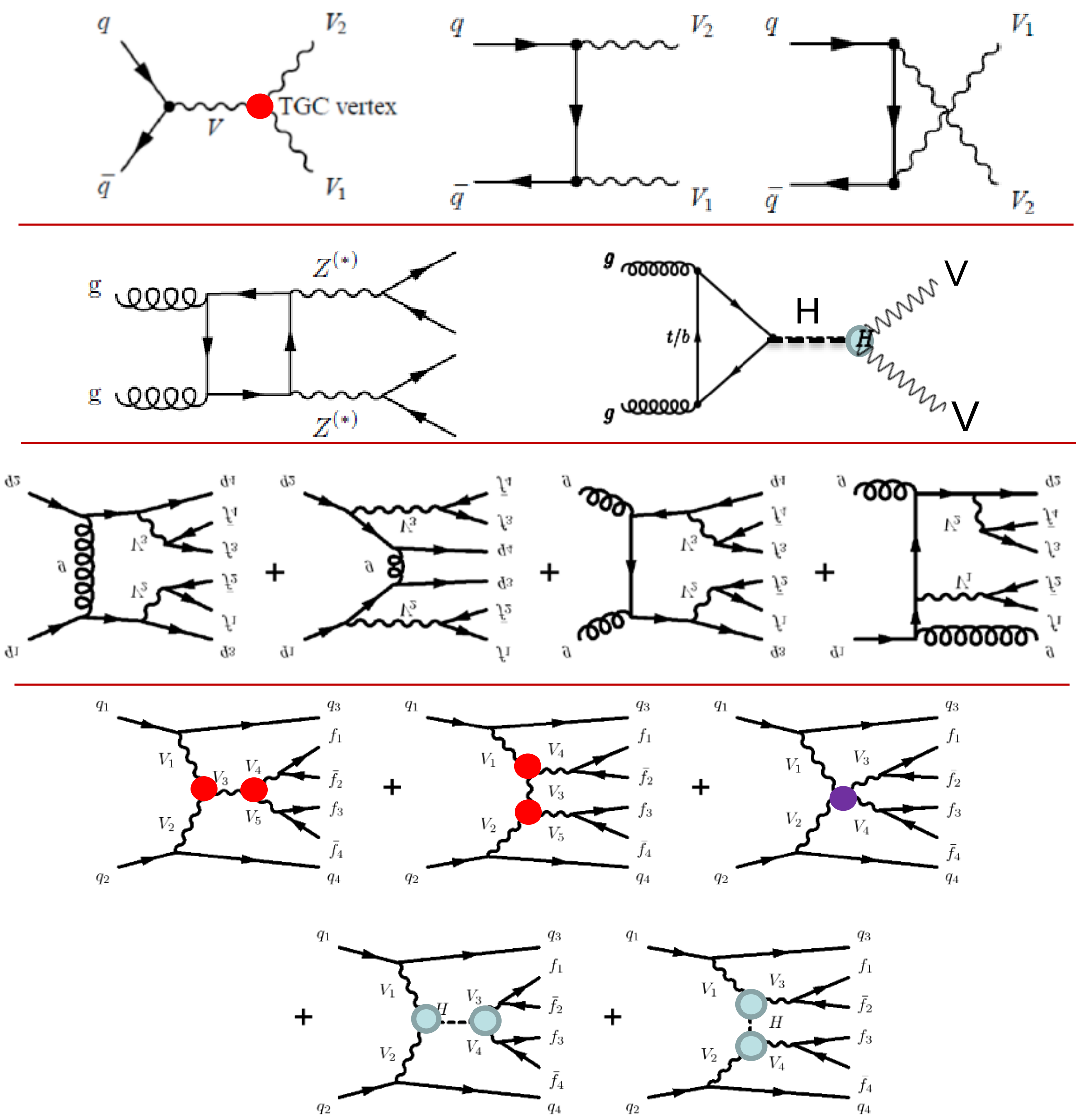
ATLAS detector @LHC

Bing Zhou
The University of Michigan
DIS2018, Kobe, Japan, April 17, 2018

Vector Boson Pair Productions at the LHC

❖ Measurement of Diboson productions at energy frontier is important to test the validity of the Standard Model (SM) through the interplay of electroweak and QCD effects
  - ➢ Relative small electroweak events rates
  - ➢ VBS: $V_L V_L \rightarrow V_L V_L$ →a key to understand EWSB

❖ Study of Triple-gauge Couplings (TGCs) to test :
  - ➢ Vector boson self-interactions – fundamental prediction of SM gauge symmetry
    - • Neutral couplings do not exist in SM
  - ➢ Sensitive to new physics
    - • New, heavy particles that couple to vector bosons ?
    - • Compositeness of vector bosons?



Rel. rate

1

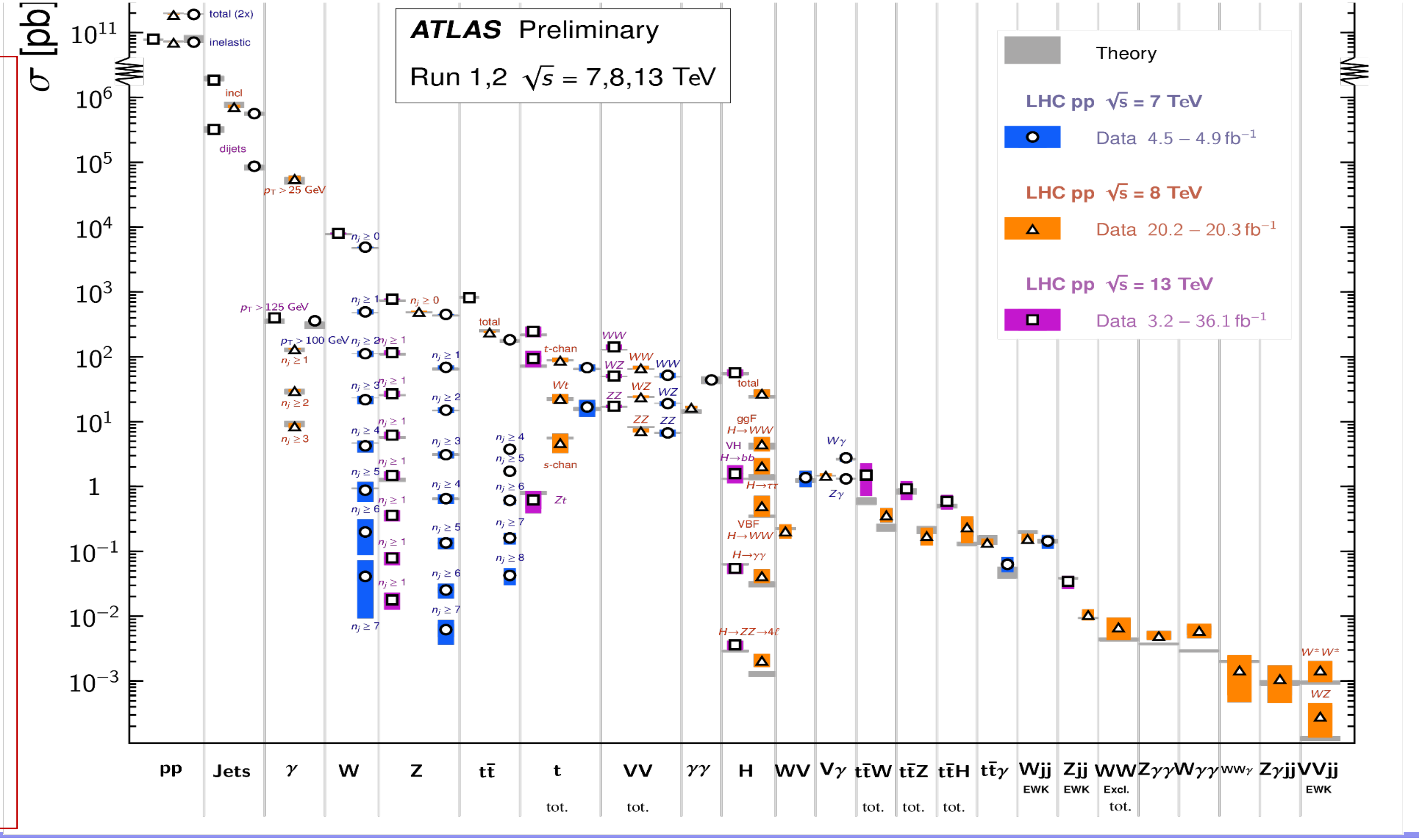
10^{-1}

10^{-2}

10^{-3}

ATLAS Electroweak Measurements

- SM measurements
  O(10^{14}) σ range
- Overall good agreements with the SM predictions
- Sensitive to higher-order QCD and EW perturbative corrections
- This talk will present measurements of diboson production σ & aTGCs with
  - WW (8 & 13 TeV)
  - WZ (8 & 13 TeV)
  - ZZ (8 & 13 TeV)
  - Zγ (8 TeV)



$WW \rightarrow l\nu l'\nu'$

JHEP 09 (2016) 029

Phys. Lett. B 773 (2017) 354

σ^{th}(8TeV) = 63.2 pb

σ^{th}(13TeV) = 128.4 pb

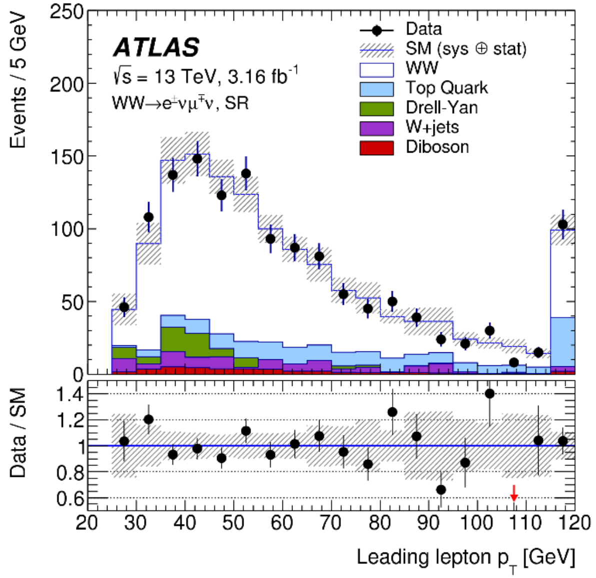
Event selection (8 TeV)

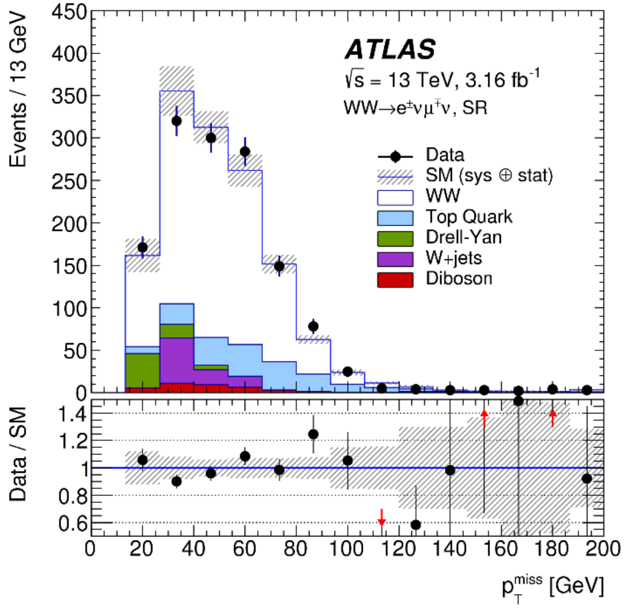
- Two high p_T isolated lepton pairs ee/μμ/eμ each with p_T > 20 (25) GeV for ee/μμ (eμ)
- E_T^{miss} > 45 (20) GeV for ee/μμ (eμ)
- Jet veto (jet pT > 25 GeV, |eta| < 4.5)

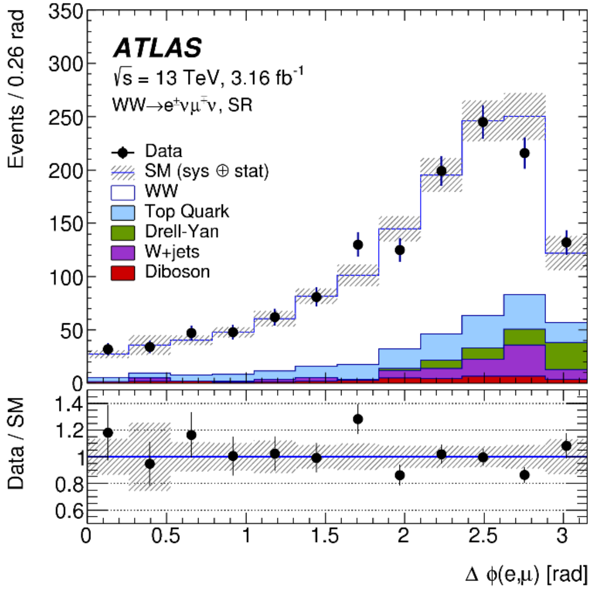
- Major background: top and W/Z+jets events
- Dominant uncertainty: jet veto and jet energy scale and resolution calibrations

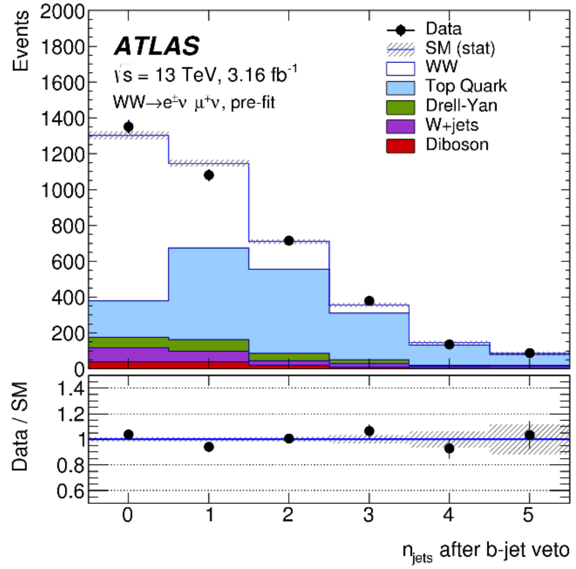
13 TeV: eμ chanel only (selection further optimized)

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
		sf=0.88	sf=1.03





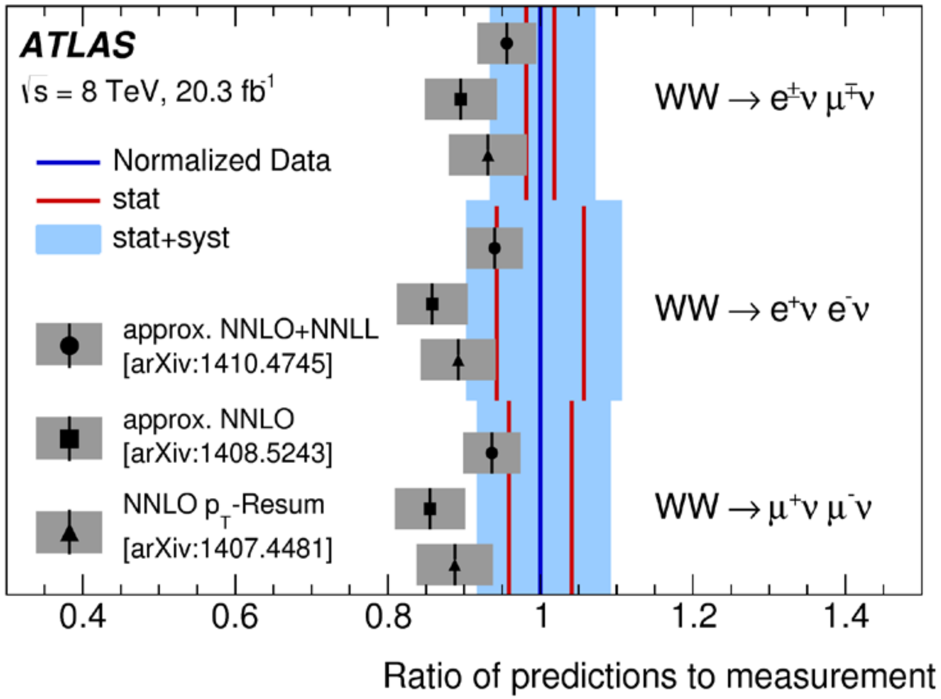


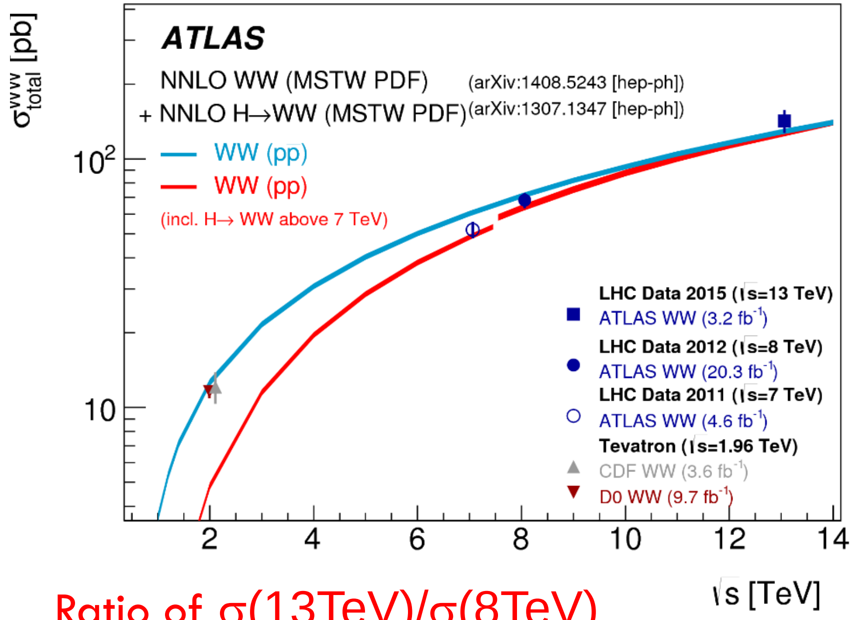


WW Production Cross Section Measurements

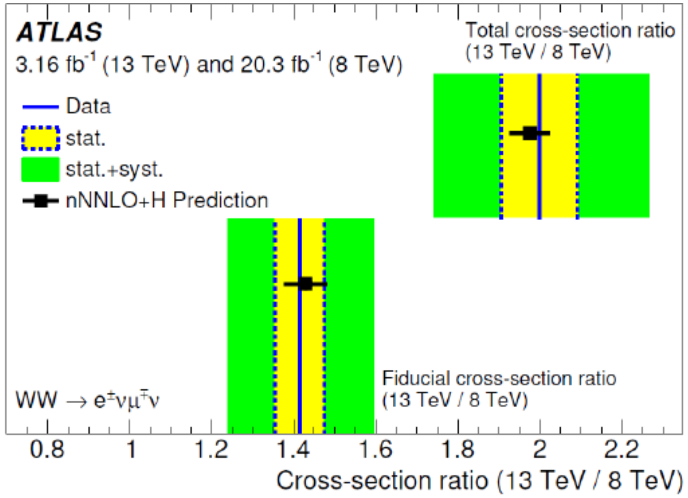
The last ATLAS WW σ measurement at 8 TeV resolved longstanding LHC anomalies in the observed σ_{WW} being more than 2σ higher than the SM prediction (with NLO QCD correction);
→ Pushed theoretical calculations with NNLO and resumed QCD corrections up to NNLL accuracy.

8 TeV JHEP 09 (2016) 029





Ratio of σ(13TeV)/σ(8TeV)



13 TeV Phys. Lett. B 773 (2017) 354

Fiducial and total σ measurements

$\sigma^{fid}(WW \rightarrow e\mu) = 529 \pm 55$ fb → $\sigma(NNLO) = 478 \pm 15$ fb

$\sigma^{tot}(WW) = 142 \pm 14$ pb → $\sigma(NNLO) = 128.4 \pm 3.6$ pb

Theoretical Predictions

Probe aTGC (WWZ, WWγ)

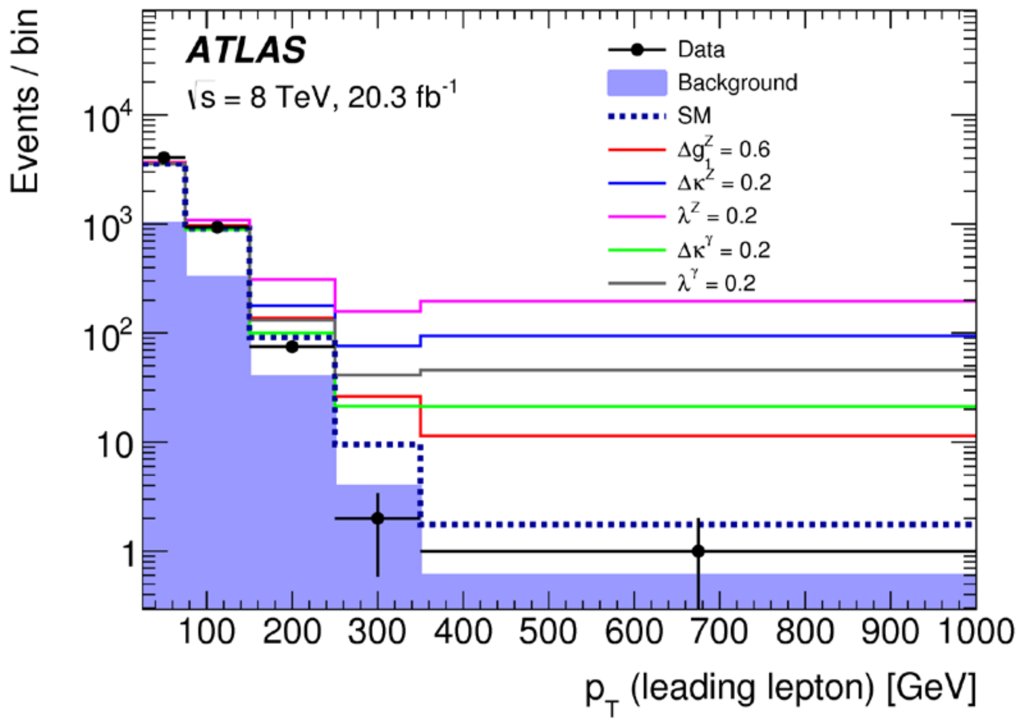
JHEP 09 (2016) 029

Modified Lagrangian with aTGC parameters

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

where $V = Z$ or γ; $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$; $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$

Fit leading lepton pT to extract aTGCs



Scenario	Parameter	Expected $\Lambda = \infty$	Observed $\Lambda = \infty$	Expected $\Lambda = 7$ TeV	Observed $\Lambda = 7$ TeV
No constraints scenario	Δg_1^Z	[−0.498, 0.524]	[−0.215, 0.267]	[−0.519, 0.563]	[−0.226, 0.279]
	Δk^Z	[−0.053, 0.059]	[−0.027, 0.042]	[−0.057, 0.064]	[−0.028, 0.045]
	λ^Z	[−0.039, 0.038]	[−0.024, 0.024]	[−0.043, 0.042]	[−0.026, 0.025]
	Δk^γ	[−0.109, 0.124]	[−0.054, 0.092]	[−0.118, 0.136]	[−0.057, 0.099]
	λ^γ	[−0.081, 0.082]	[−0.051, 0.052]	[−0.088, 0.089]	[−0.055, 0.055]
LEP	Δg_1^Z	[−0.033, 0.037]	[−0.016, 0.027]	[−0.035, 0.041]	[−0.017, 0.029]
	Δk^Z	[−0.037, 0.035]	[−0.025, 0.020]	[−0.041, 0.038]	[−0.027, 0.021]
	λ^Z	[−0.031, 0.031]	[−0.019, 0.019]	[−0.033, 0.033]	[−0.020, 0.020]
HISZ	Δk^Z	[−0.026, 0.030]	[−0.012, 0.022]	[−0.028, 0.033]	[−0.013, 0.024]
	λ^Z	[−0.031, 0.031]	[−0.019, 0.019]	[−0.033, 0.034]	[−0.020, 0.020]
Equal Couplings	Δk^Z	[−0.041, 0.048]	[−0.020, 0.035]	[−0.045, 0.052]	[−0.021, 0.037]
	λ^Z	[−0.030, 0.030]	[−0.019, 0.019]	[−0.034, 0.033]	[−0.020, 0.020]

effective field theory $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$

Scenario	Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
EFT	C_{WWW}/Λ^2	[−7.62, 7.38]	[−4.61, 4.60]
	C_B/Λ^2	[−35.8, 38.4]	[−20.9, 26.3]
	C_W/Λ^2	[−12.58, 14.32]	[−5.87, 10.54]

σ_{WZ} Measurements with WZ→ℓνℓℓ

σ^{th}(8TeV) = 21.0 pb

σ^{th}(13 TeV) = 48.2 pb

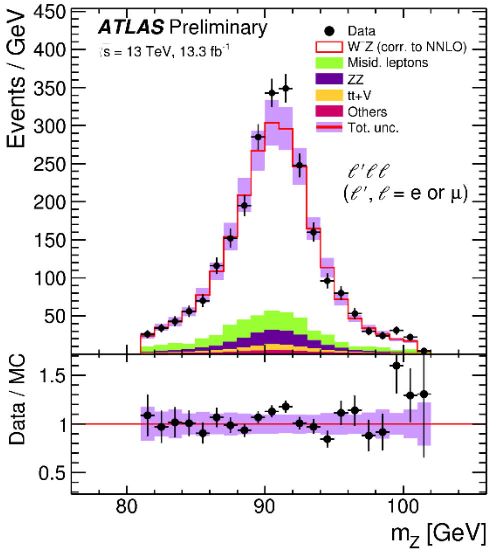
Event selection

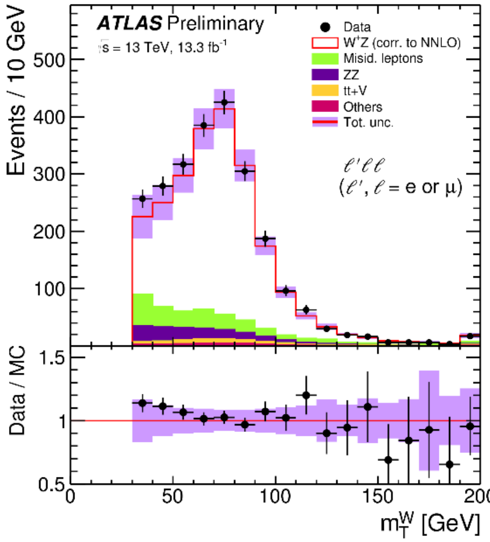
Phys. Rev. D 93, 092004 (2016)

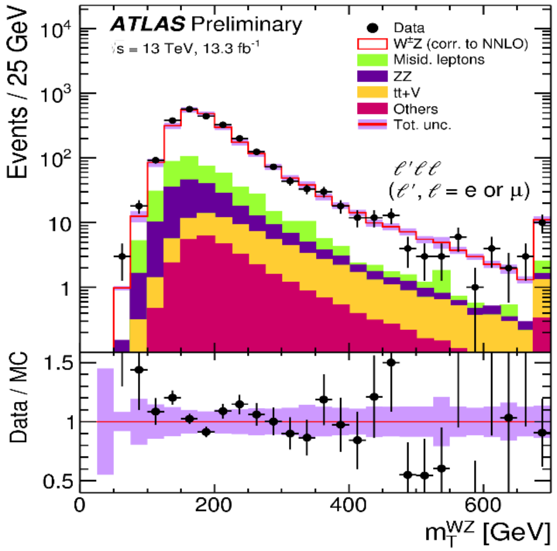
Variable	Total	Fiducial and aTGC	VBS	aQGC
Lepton $\|\eta\|$	—	< 2.5	< 2.5	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	—	> 15, > 20	> 15, > 20	> 15, > 20
m_Z range [GeV]	66 – 116	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$
m_T^W [GeV]	—	> 30	> 30	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	—	> 0.2, > 0.3	> 0.2, > 0.3	> 0.2, > 0.3
p_T two leading jets [GeV]	—	—	> 30	> 30
$\|\eta_j\|$ two leading jets	—	—	< 4.5	< 4.5
Jet multiplicity	—	—	≥ 2	≥ 2
m_{jj} [GeV]	—	—	> 500	> 500
$\Delta R(j, \ell)$	—	—	> 0.3	> 0.3
$\|\Delta\phi(W, Z)\|$	—	—	—	> 2
$\sum \|p_T^\ell\|$ [GeV]	—	—	—	> 250

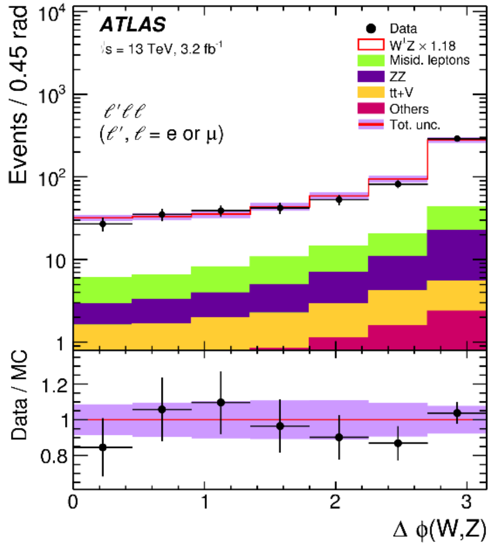
- ❖ Lower background than WW, higher BR than ZZ
- ❖ E_T^{miss} cut replaced by a cut on m_T^W
  - o Ensure that we are at the Z & W resonances
  - o A more stricter control of the backgrounds
- ❖ Cutting E_T^{miss} strongly reduces the phase space
  - o E_T^{miss} cuts would strongly reduce polarization phase space of W

ATLAS-CONF-2016-043



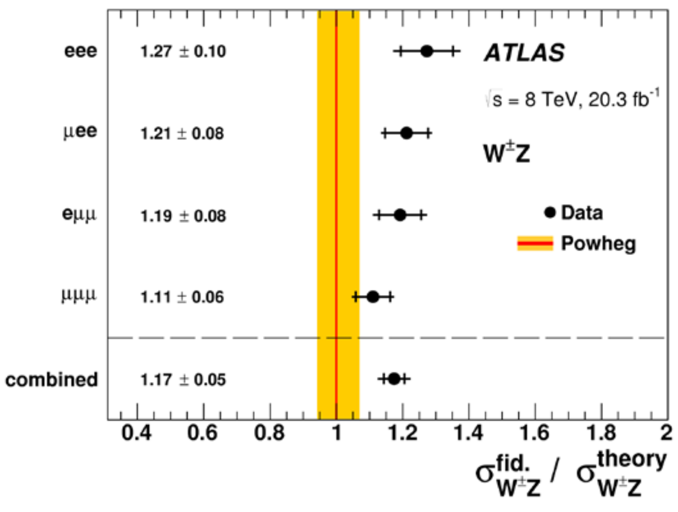




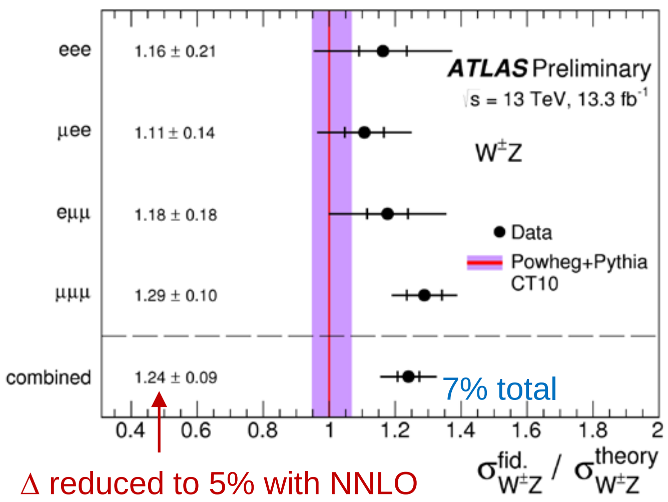


Precision σ Measurement with WZ→ℓνℓℓ

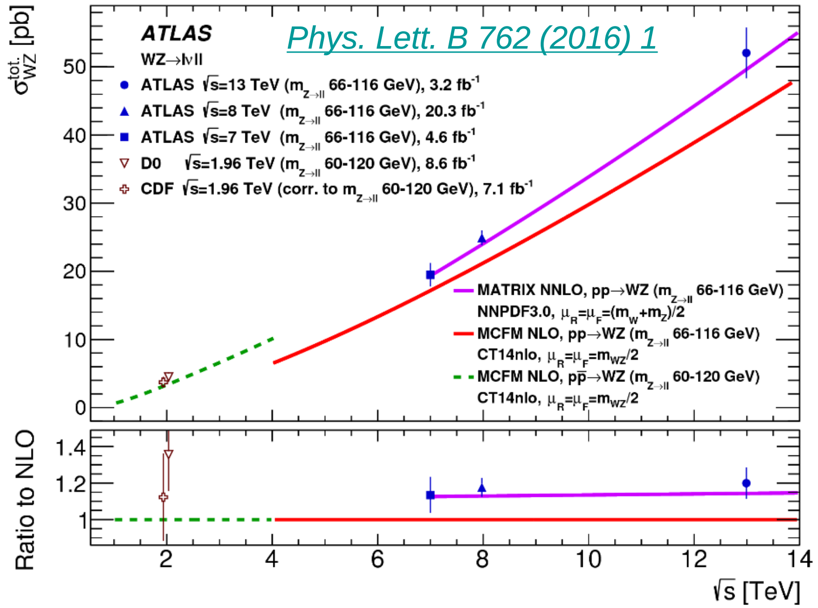
Phys. Rev. D 93, 092004 (2016) (8 TeV)



ATLAS-CONF-2016-043 (13 TeV)



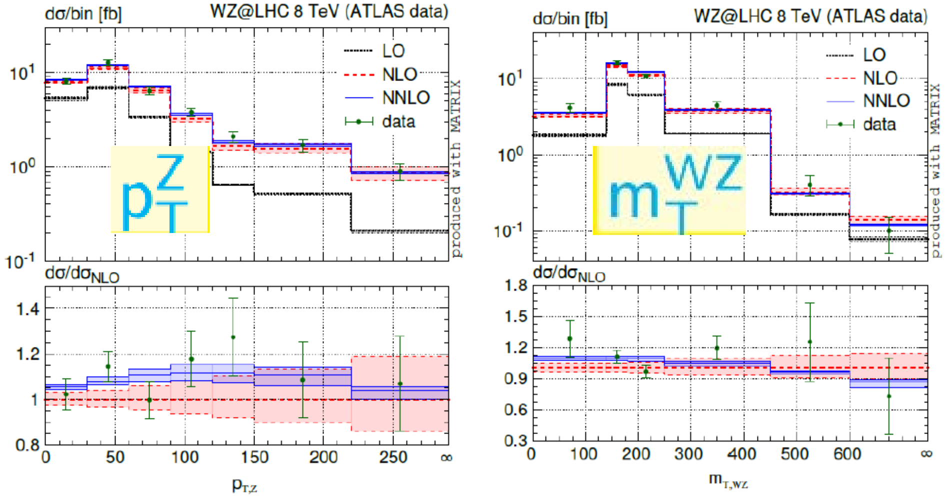
Δ reduced to 5% with NNLO



	eee	μee	eμμ	μμμ	combined
Source	Relative uncertainties [%]				
e energy scale	0.8	0.4	0.4	0.0	0.3
e id. efficiency	2.9	1.8	1.0	0.0	1.0
μ momentum scale	0.0	0.1	0.1	0.1	0.1
μ id. efficiency	0.0	0.7	1.3	2.0	1.4
E_T^{miss} and jets	0.3	0.2	0.2	0.1	0.3
Trigger	0.1	0.1	0.2	0.3	0.2
Pileup	0.3	0.2	0.2	0.1	0.2
Misid. leptons background	2.9	0.9	3.1	0.9	1.3
ZZ background	0.6	0.5	0.6	0.5	0.5
Other backgrounds	0.7	0.7	0.7	0.7	0.7
Uncorrelated	0.7	0.6	0.5	0.5	0.3
Total systematics	4.5	2.6	3.7	2.5	2.4
Luminosity	2.2	2.2	2.2	2.2	2.2
Statistics	6.2	5.4	5.3	4.7	2.7
Total	8.0	6.3	6.8	5.7	4.2

Precision measurement pushed of theoretical calculations (JHEP 01(2017)139)

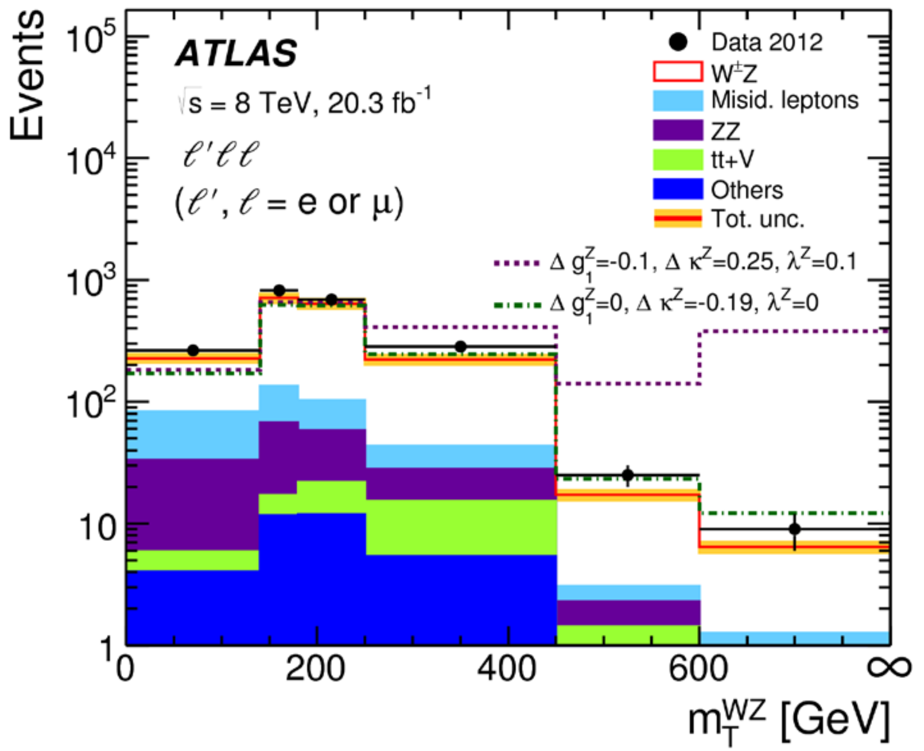
Phys. Rev. D 93, 092004 (2016)



Probe Anomalous TGC (WWZ)

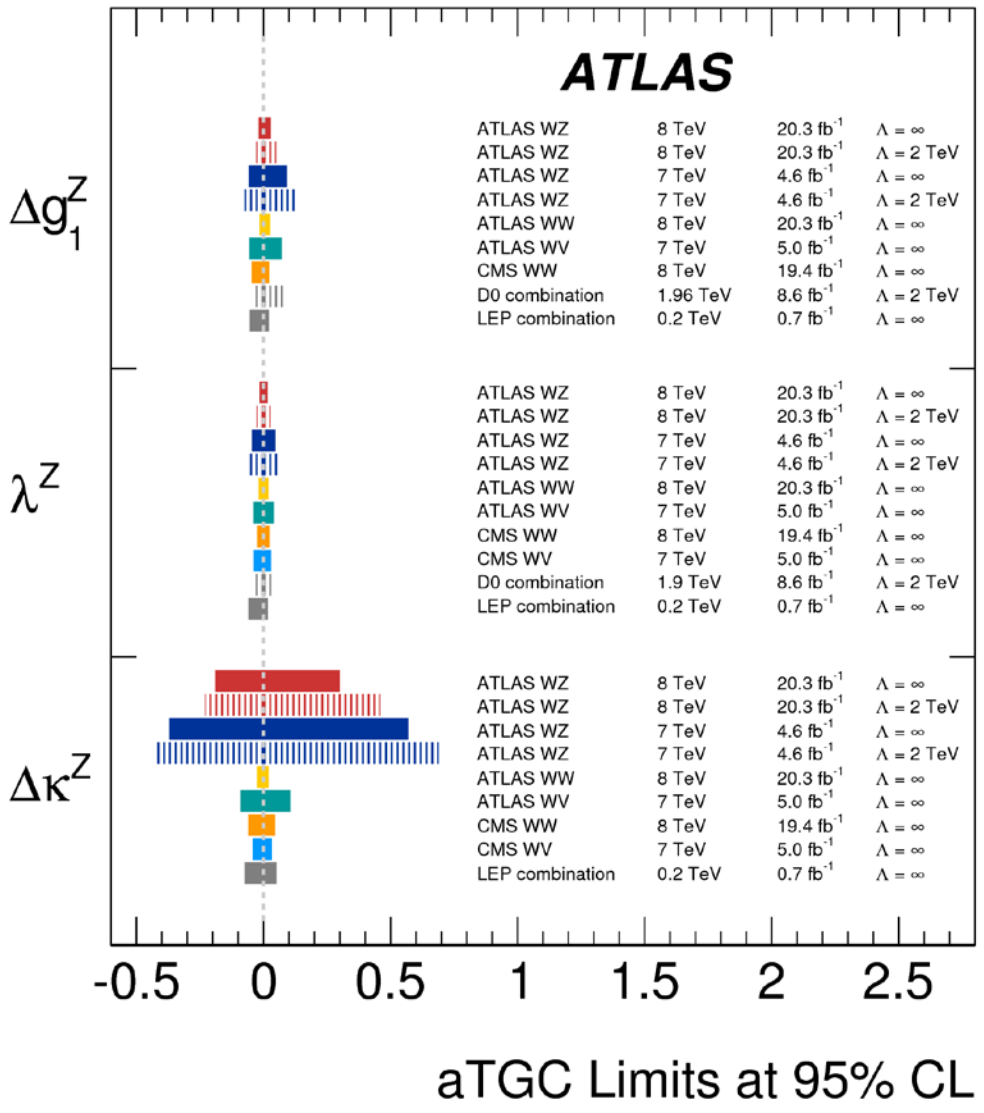
Phys. Rev. D 93, 092004 (2016)

WWZ coupling is independent of the WWγ coupling, in contrast to WW production; Fit mT spectrum to set the aTGC limits.



$$m_T^{WZ} = \sqrt{\left(\sum_{\ell=1}^{3} p_T^{\ell} + E_T^{miss}\right)^2 - \left[\left(\sum_{\ell=1}^{3} p_x^{\ell} + E_x^{miss}\right)^2 + \left(\sum_{\ell=1}^{3} p_y^{\ell} + E_y^{miss}\right)^2\right]}$$

(8 TeV)



WW→lνjj and WZ→lνjj

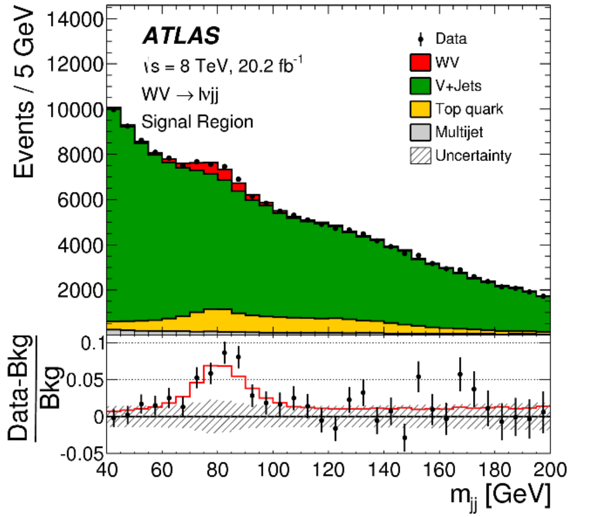
- Detect diboson WV through W→lν, and V→jj
- To maximize sensitivity to aTGC, select dijet from V decay with resolved jj and merged fat-jet J
- Most sensitive aTGC limits, surpass LEP!

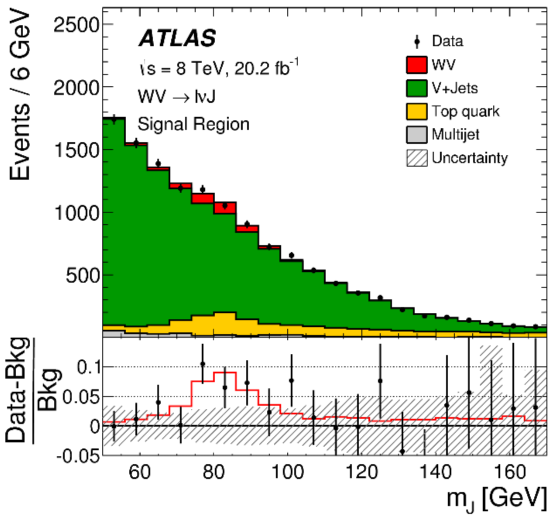
Parameter	Observed $WV \to \ell\nu jj$	Expected $WV \to \ell\nu jj$	Observed $WV \to \ell\nu J$	Expected $WV \to \ell\nu J$
Δg_1^Z	$[-0.027, 0.045]$	$[-0.036, 0.051]$	$[-0.021, 0.024]$	$[-0.024, 0.027]$
$\Delta\kappa_\gamma$	$[-0.11, 0.13]$	$[-0.15, 0.16]$	$[-0.061, 0.064]$	$[-0.071, 0.075]$
$\lambda_Z = \lambda_\gamma$	$[-0.022, 0.022]$	$[-0.027, 0.026]$	$[-0.013, 0.013]$	$[-0.015, 0.015]$

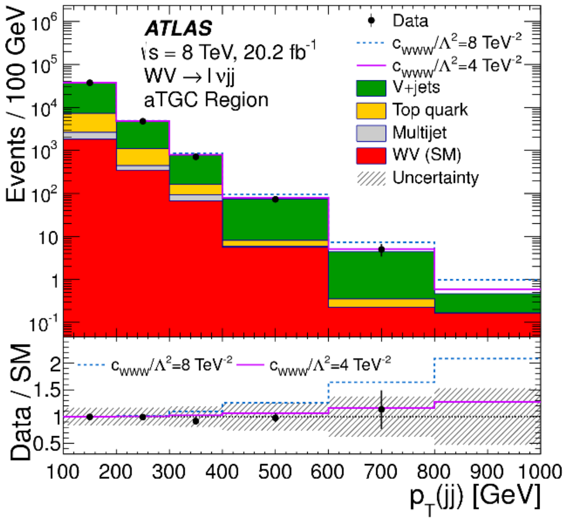
Parameter	Observed [TeV^{-2}] $WV \to \ell\nu jj$	Expected [TeV^{-2}] $WV \to \ell\nu jj$	Observed [TeV^{-2}] $WV \to \ell\nu J$	Expected [TeV^{-2}] $WV \to \ell\nu J$
c_{WWW}/Λ^2	$[-5.3, 5.3]$	$[-6.4, 6.3]$	$[-3.1, 3.1]$	$[-3.6, 3.6]$
c_B/Λ^2	$[-36, 43]$	$[-45, 51]$	$[-19, 20]$	$[-22, 23]$
c_W/Λ^2	$[-6.4, 11]$	$[-8.7, 13]$	$[-5.1, 5.8]$	$[-6.0, 6.7]$

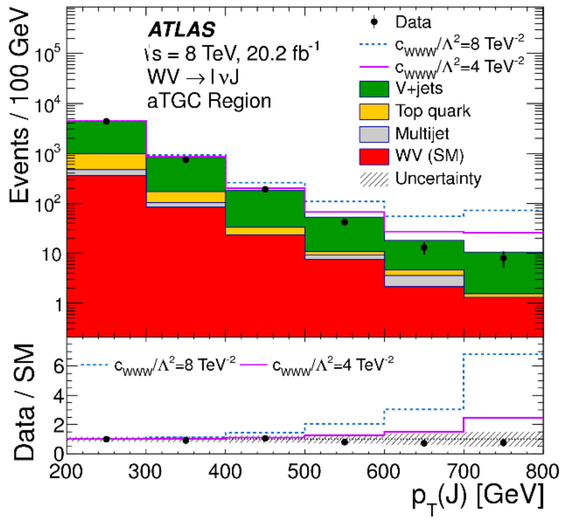
8 TeV	WW→lνlν	WZ→lνll	WV→lνjj
C_{WWW}/Λ^2	[-7.62,7.38]	[-3.9, 4.0]	[-3.1, 3.1]
C_W/Λ^2	[12.58,14.32]	[-4.3, 6.8]	[-5.1, 5.8]
C_B/Λ^2	[-35.8, 38.4]	[-320, 210]	[-19, 20]

Eur. Phys. J. C 77 (2017) 563





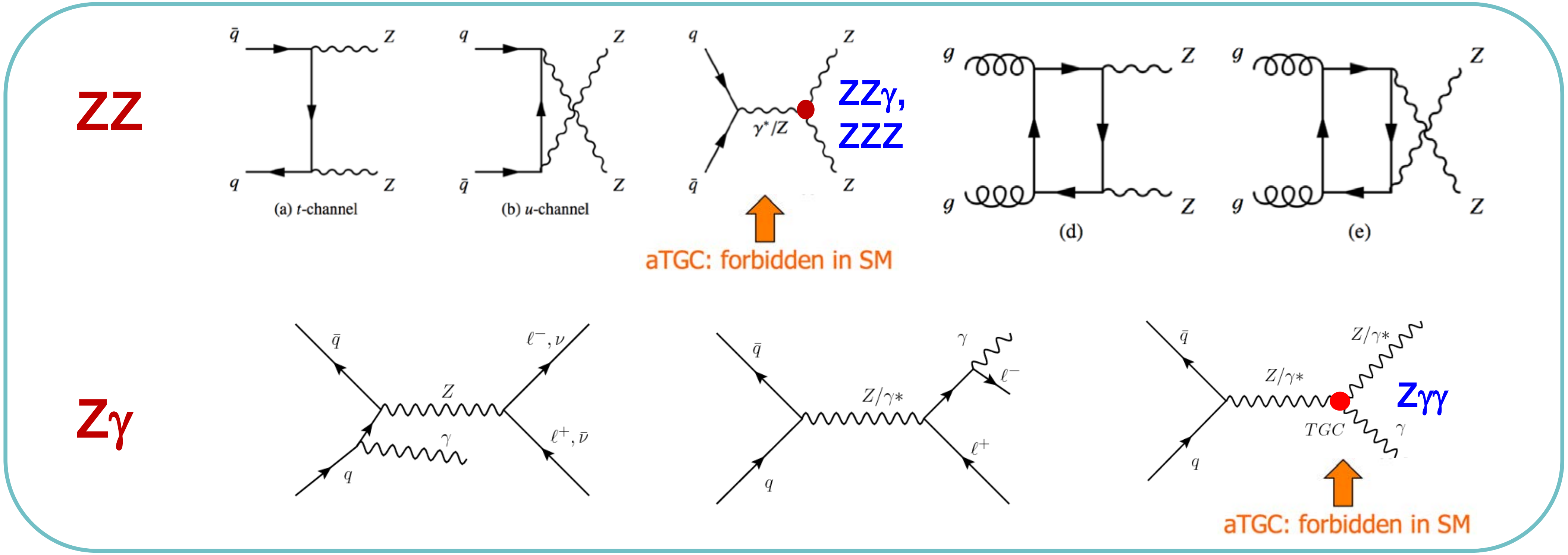




Measurements of ZZ and Zγ Productions

Phys. Rev. D 97 (2018) 032005 (13 TeV ZZ) JHEP 01 (2017) 099 **(8 TeV ZZ)** **Phys. Rev. D 93,** *112002 (2016)* **(8 TeV Zγ)**

- **Test SM: measurements of σ^{total}, σ^{diff} , and couplings with leptonic final states: 4ℓ, $\ell\ell\nu\nu$, and $\ell\ell\gamma$, $\nu\nu\gamma$**
- **Search for new physics with anomalous neutral triple-gauge couplings**



Measurement of ZZ Production σ

[Phys. Rev. D 97 (2018) 032005](#)

[JHEP 01 (2017) 099](#)

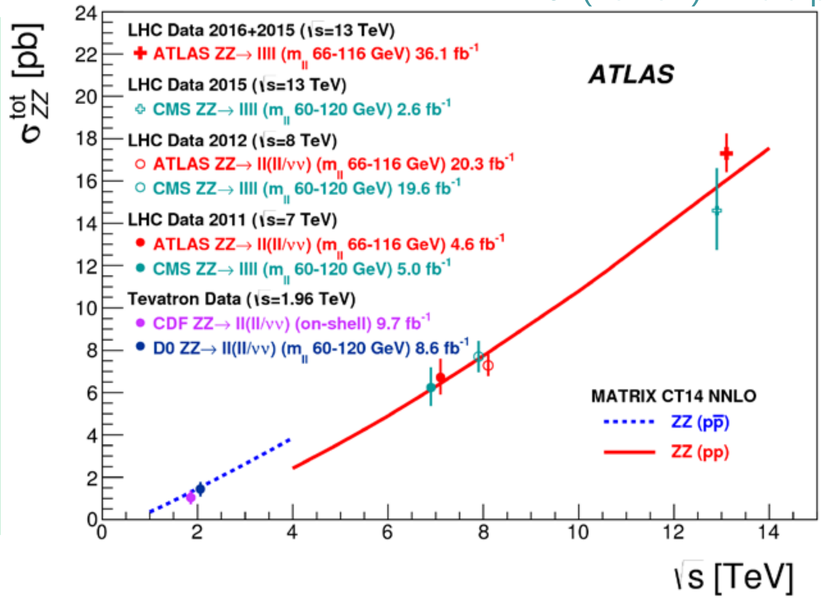
- ZZ Production σ^{total}, σ^{dif} cross section measurements through 4l & 2l2ν channels (8 TeV), and 4l channel (13 TeV).
- 4l channel requires both Z's on-shell, very clean, but the measurement uncertainty is still dominant by statistics (1017 events for 36.1 fb^{-1} at 13 TeV)
- Differential cross sections measured as a function of 20 observables, including mjj and Δy(jj), which are particularly sensitive to the EWK-ZZjj process

- Best available SM predictions are based on fixed-order MATRIX NNLO QCD calculations:
  - NNLO QCD +NLO QCD gg initiated contributions
  - \+ NLO EWK corrections
  - \+ EWK-ZZjj

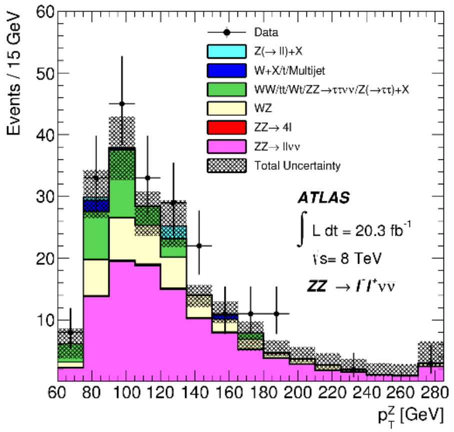
Total cross section

σ^{th}(8 TeV) = 6.6 pb

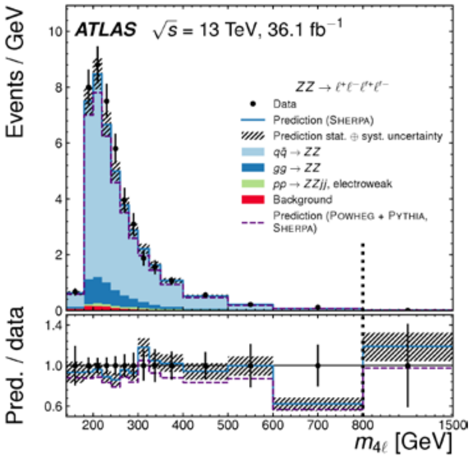
σ^{th}(13 TeV) = 16.9 pb



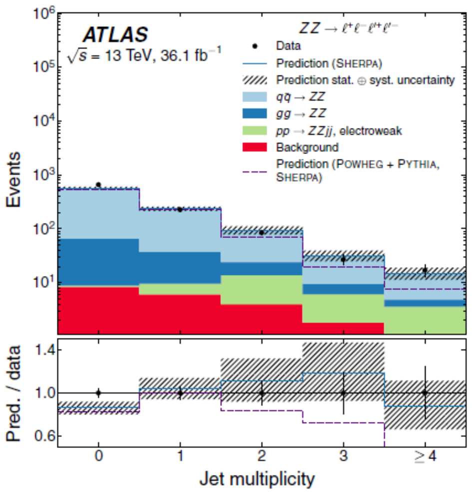
8 TeV



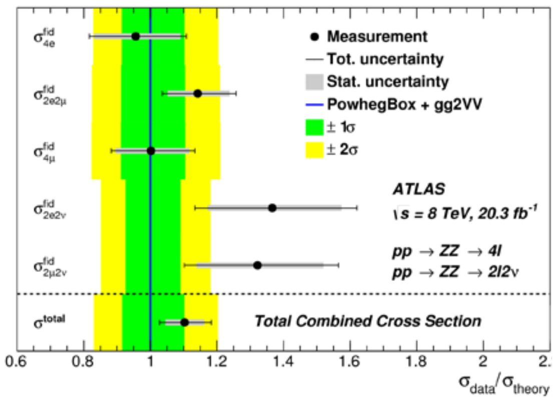
13 TeV

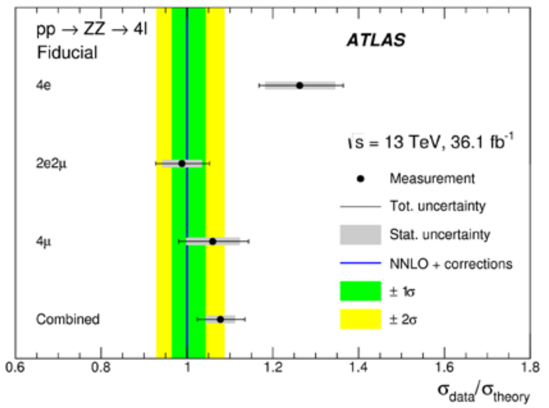


13 TeV



Fiducial cross sections (8 &13 TeV)





Differential Cross Section Measurements at 13 TeV

Phys. Rev. D 97 (2018) 032005

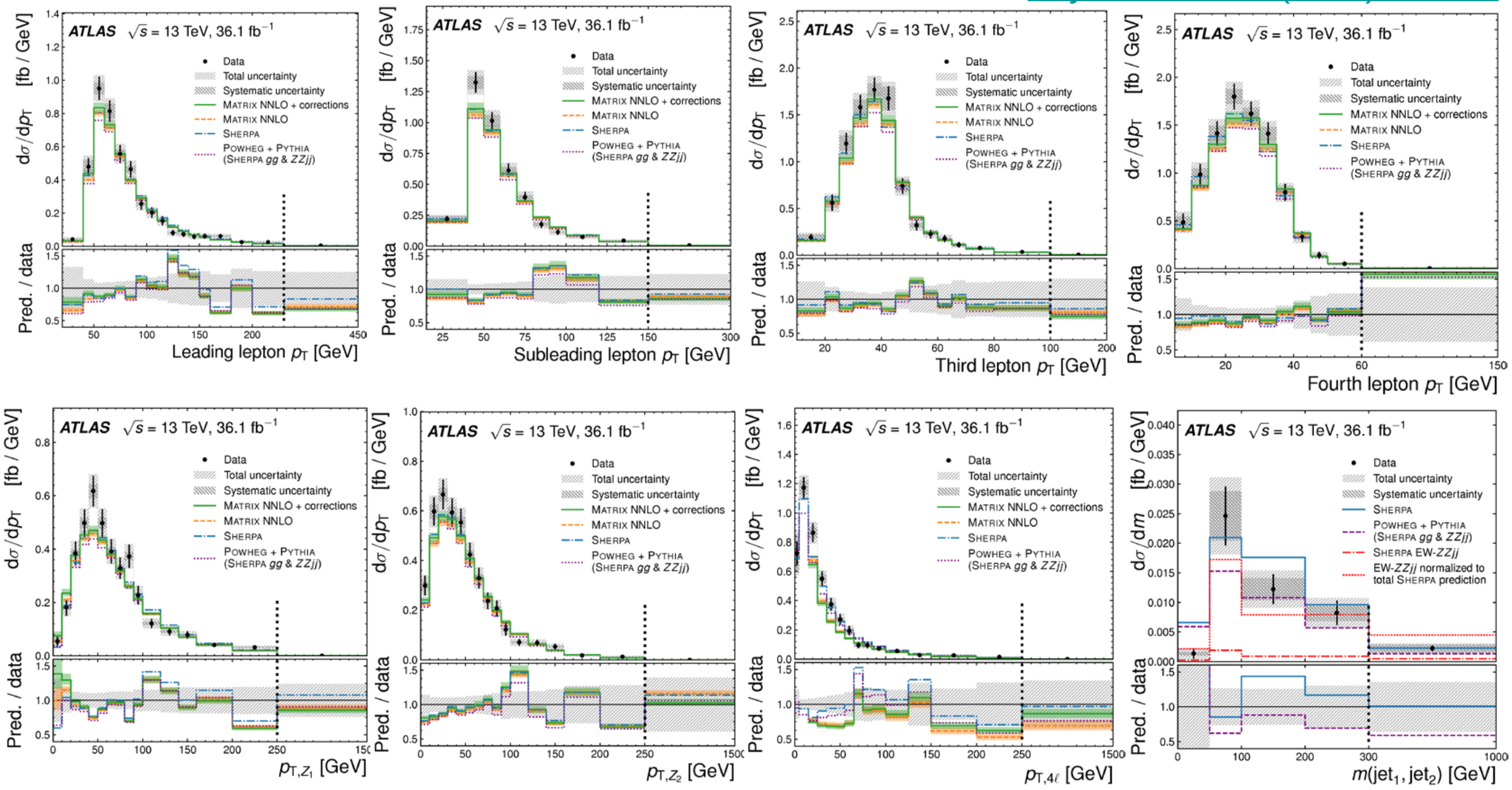
unfolding
ZZ→4l

$d\sigma/dp_T$
l_1, l_2, l_3, l_4
Z_1, Z_2, & ZZ
J1, j2, $\sum P_T^j$

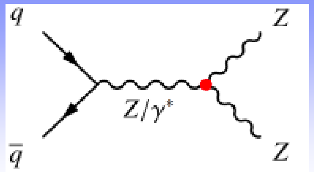
$d\sigma/dN$
N_{jet}
N_{jet} (central)
N_{jet} (pT>60GeV)

Angular $d\sigma$
Y_{ZZ}
$\Delta\phi$ (Z_1, Z_2)
$\Delta Y(Z_1, Z_2)$
η_{j1}, η_{j2}
$\Delta Y(j_1, j_2)$

$d\sigma/dmjj$



Search for Neutral aTGCs



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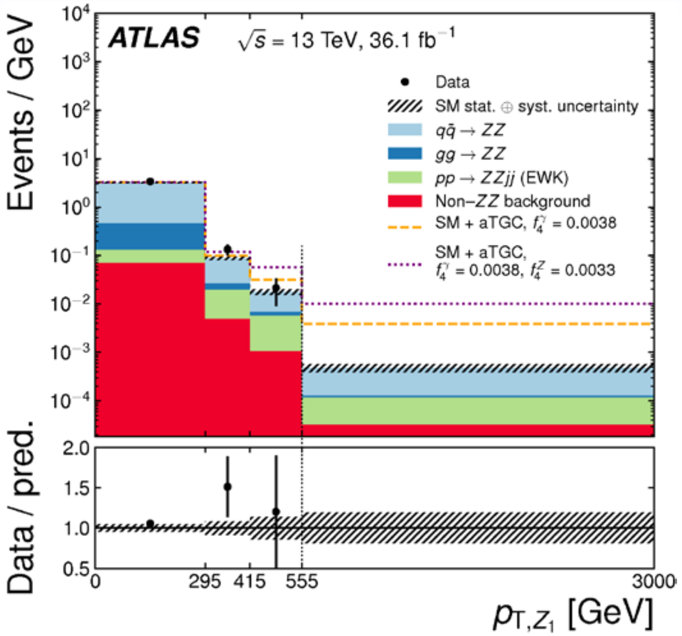
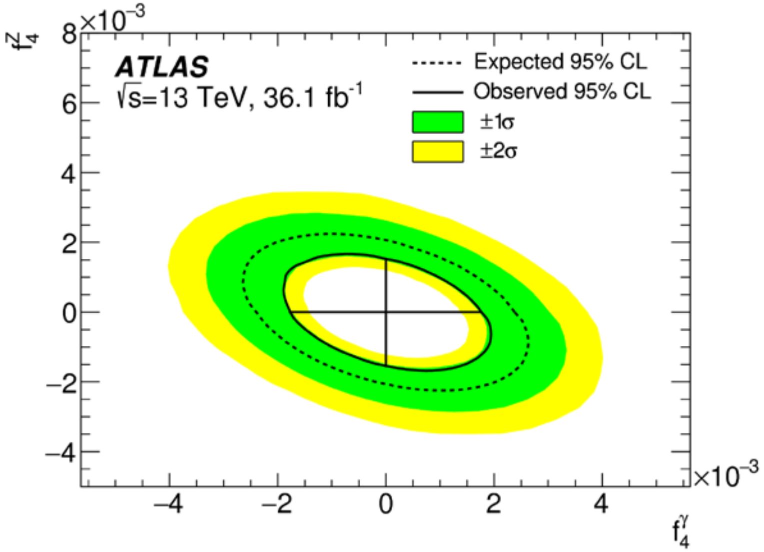
- Search for neutral aTGC from p_T^Z spectra with 4l (and 2l2ν) final states;
- SHERPA MC is used by ATLAS to model the anomalous coupling (ZZγ, and ZZZ) signals with parameters: f_4^γ, f_4^Z, f_5^γ, f_5^Z

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

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

EFT parameter	Expected 95% CL $[\text{TeV}^{-4}]$	Observed 95% CL $[\text{TeV}^{-4}]$
$C_{\tilde{B}W}/\Lambda^4$	−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

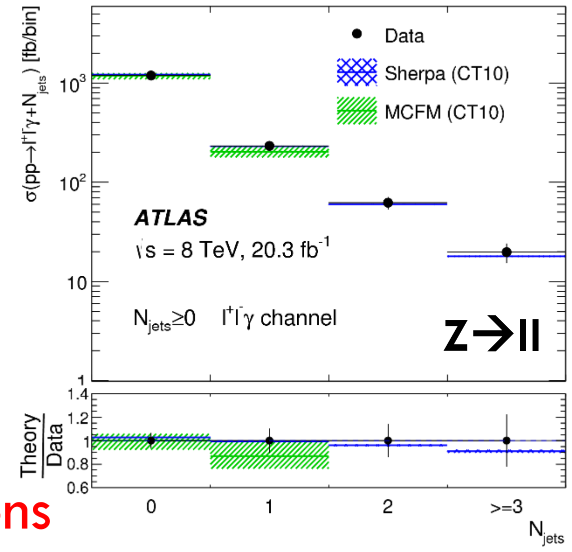


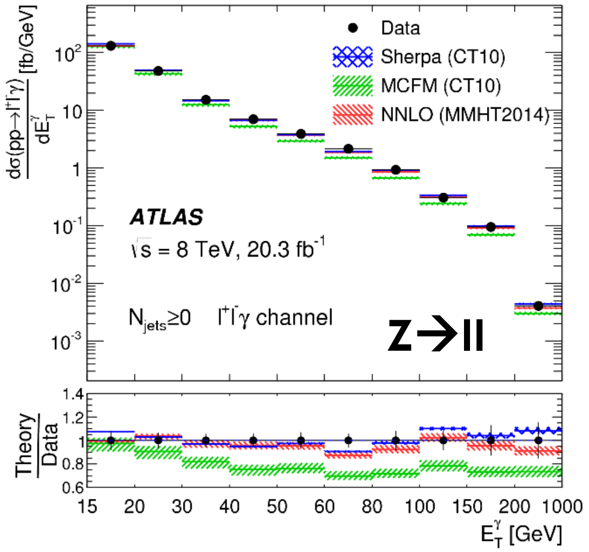


Measurement of Zγ Production with Z→ll (l=e,μ) and Z→νν Channels

Phys. Rev. D 93, 112002 (2016)

- ❖ **Z→ll channel (p_T^l >25 GeV, E_T^γ >15 GeV)**
  - o Major background from Z+jets (estimated from data)
- ❖ **Z→νν channel (E_T^{miss} >100 GeV, E_T^γ >130 GeV)**
  - o Major backgrounds from γ+jet and W+γ (estimated from data)
- ❖ **Exclusive channel defined with jet veto (for jet pT>30 GeV)**
  - o Study high order calculation on Zγ channel

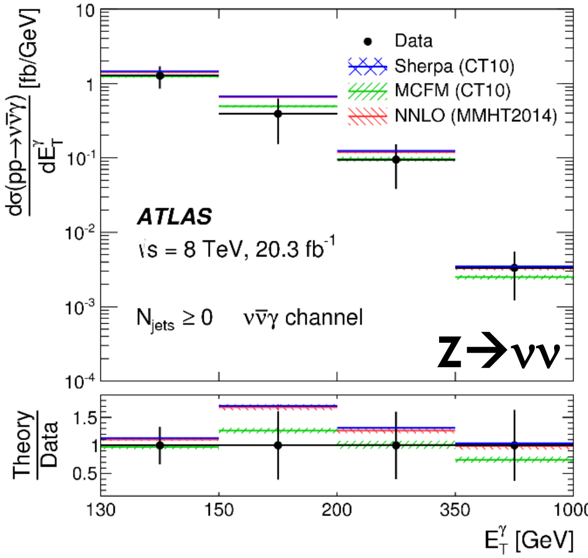




Total cross-section measurements vs SM predictions

Channel	Measurement (fb)	MCFM Prediction (fb)	NNLO Prediction (fb)
	$N_{\text{jets}} \geq 0$		
$e^+e^-\gamma$	$1510 \pm 15(\text{stat})^{+91}_{-84}(\text{syst})^{+30}_{-28}(\text{lumi})$		
$\mu^+\mu^-\gamma$	$1507 \pm 13(\text{stat})^{+78}_{-73}(\text{syst})^{+29}_{-28}(\text{lumi})$	1345^{+66}_{-82}	1483^{+19}_{-37}
$\ell^+\ell^-\gamma$	$1507 \pm 10(\text{stat})^{+78}_{-73}(\text{syst})^{+29}_{-28}(\text{lumi})$		
$\nu\bar{\nu}\gamma$	$68 \pm 4(\text{stat})^{+33}_{-32}(\text{syst}) \pm 1(\text{lumi})$	68.2 ± 2.2	$81.4^{+2.4}_{-2.2}$
	$N_{\text{jets}} = 0$		
$e^+e^-\gamma$	$1205 \pm 14(\text{stat})^{+84}_{-75}(\text{syst}) \pm 23(\text{lumi})$		
$\mu^+\mu^-\gamma$	$1188 \pm 12(\text{stat})^{+68}_{-63}(\text{syst})^{+23}_{-22}(\text{lumi})$	1191^{+71}_{-89}	1230^{+10}_{-18}
$\ell^+\ell^-\gamma$	$1189 \pm 9(\text{stat})^{+69}_{-63}(\text{syst})^{+23}_{-22}(\text{lumi})$		
$\nu\bar{\nu}\gamma$	$43 \pm 2(\text{stat}) \pm 10(\text{syst}) \pm 1(\text{lumi})$	$51.0^{+2.1}_{-2.3}$	$49.21^{+0.61}_{-0.52}$

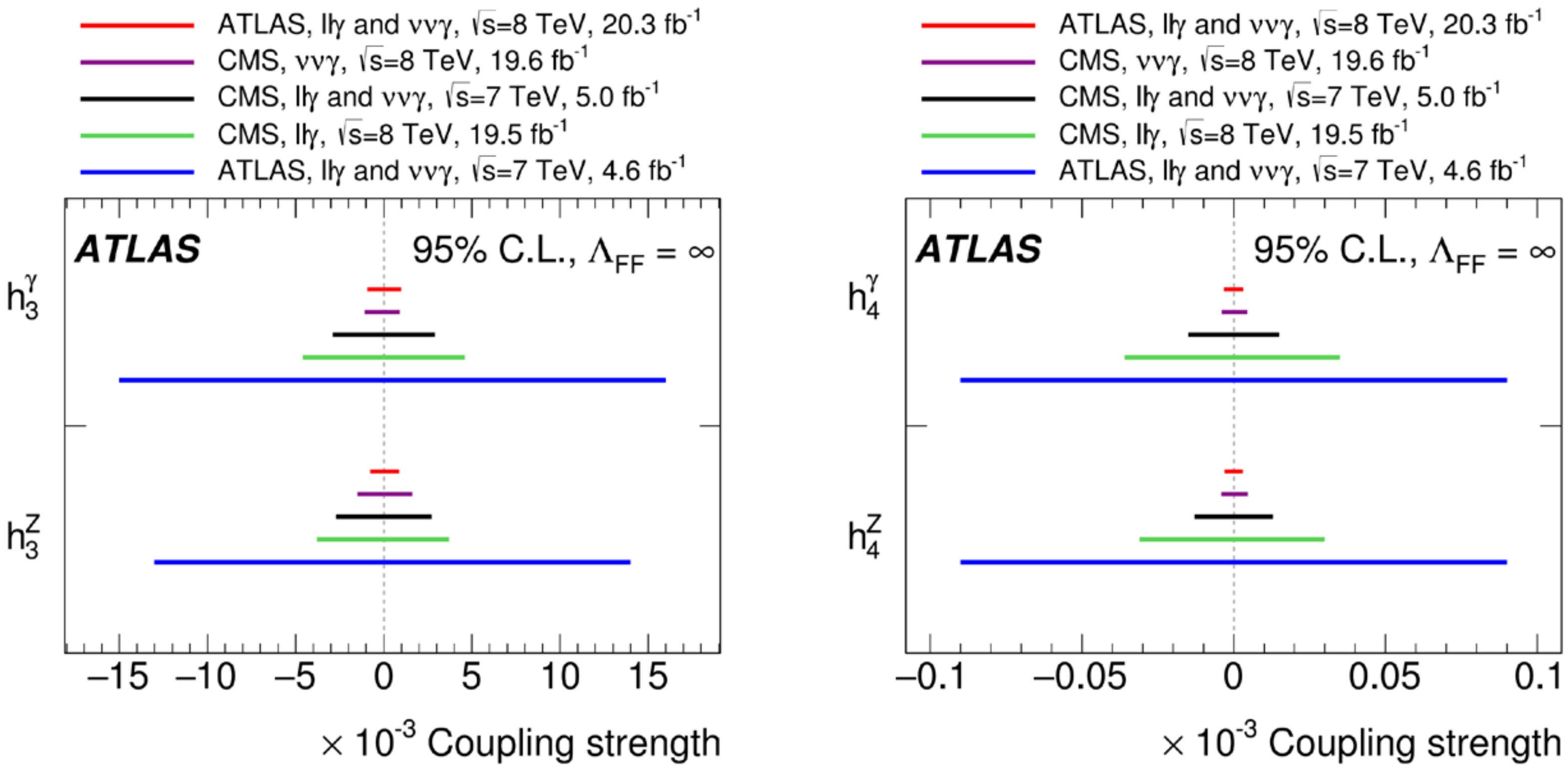
Total σ measurement Δσ/σ ~5.5%
Need NNLO correction

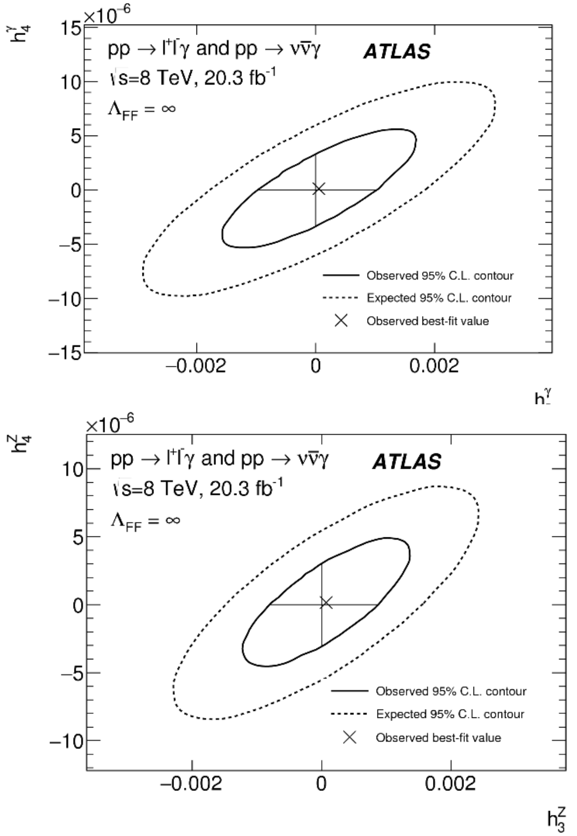


Explore aTGC in Zγ production

Using effective lagrangian approach: aTGC parameters $h_3^Z, h_3^\gamma, h_4^Z, h_4^\gamma$ (Phys. Rev. D 47, (1993) 4889)

- ❖ Use the event yield with photon $E_T > 250$ ($\ell\ell\gamma$) and 400 ($\nu\nu\gamma$) GeV with jet veto for limit setting
- ❖ Set limit on the CP-conserving couplings: h_3^Z and h_4^Z from ZZγ vertex and h_3^γ and h_4^γ from Zγγ vertex
- ❖ γ E_T spectra are used to explore the aTGC in analyses





Summary

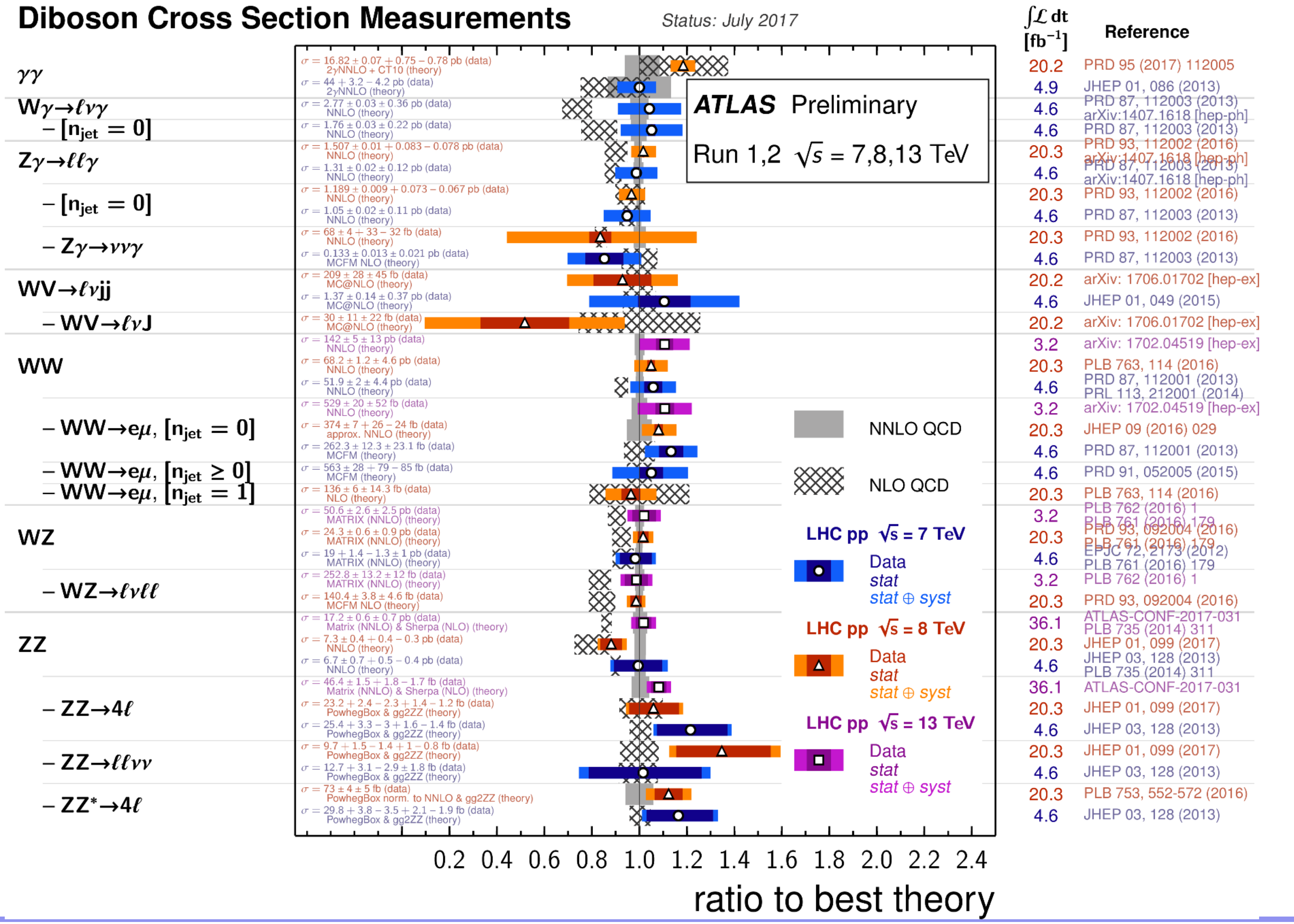
- About 50 ATLAS papers published on diboson physics studies
- Entering precision measurement era (σ^{sys} < 5%) to test SM at highest energy scale
- Sensitivities of aTGC surpass the LEP combined limits!

For charged aTGCs

- $\Delta\kappa_\gamma$ limits ~6x10^{-2}
- λ_γ limits ~1.3x10^{-2}
- $\Delta\kappa_Z$ limits ~2x10^{-2}
- λ_Z limits ~1.3x10^{-2}
- Δg_1^Z limits ~2x10^{-2}

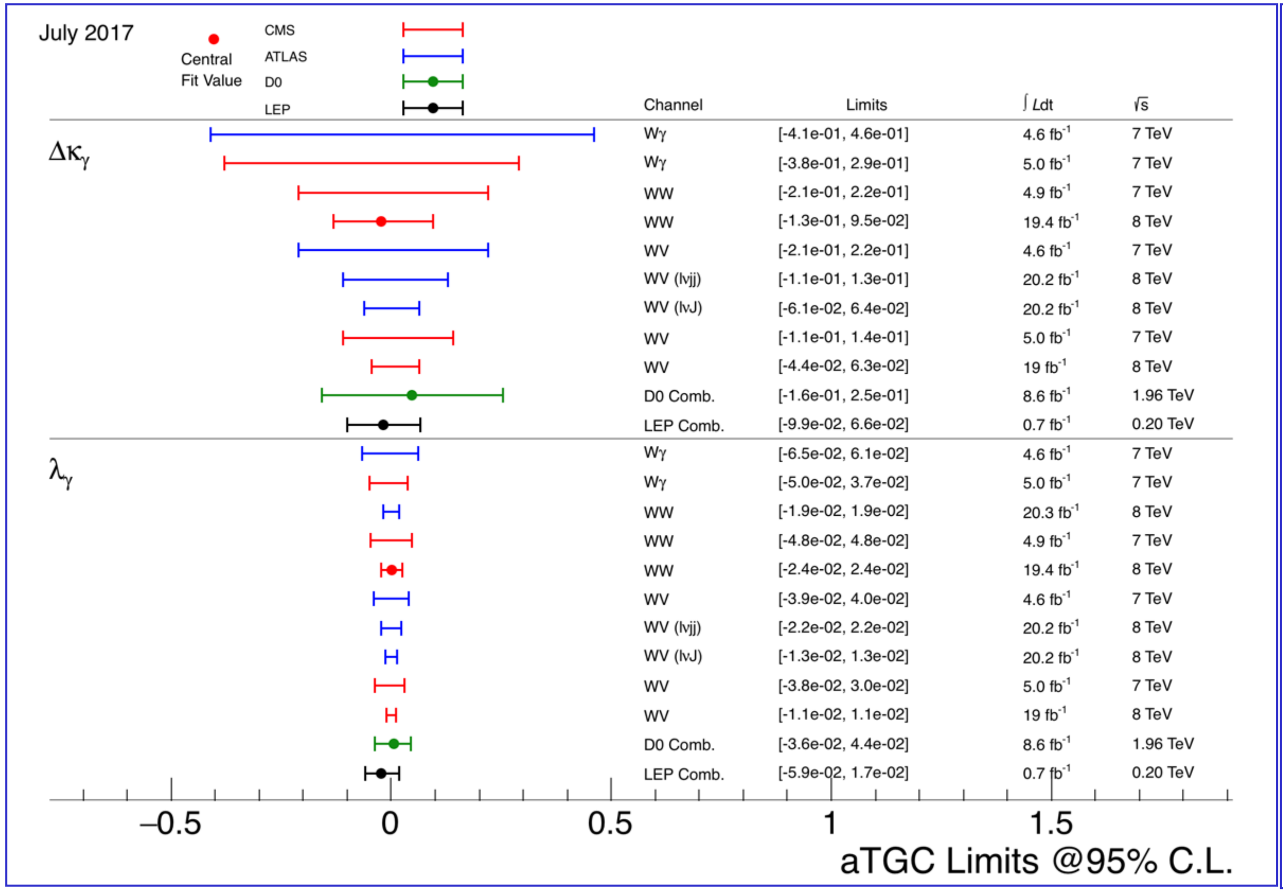
For neutral aTGCs

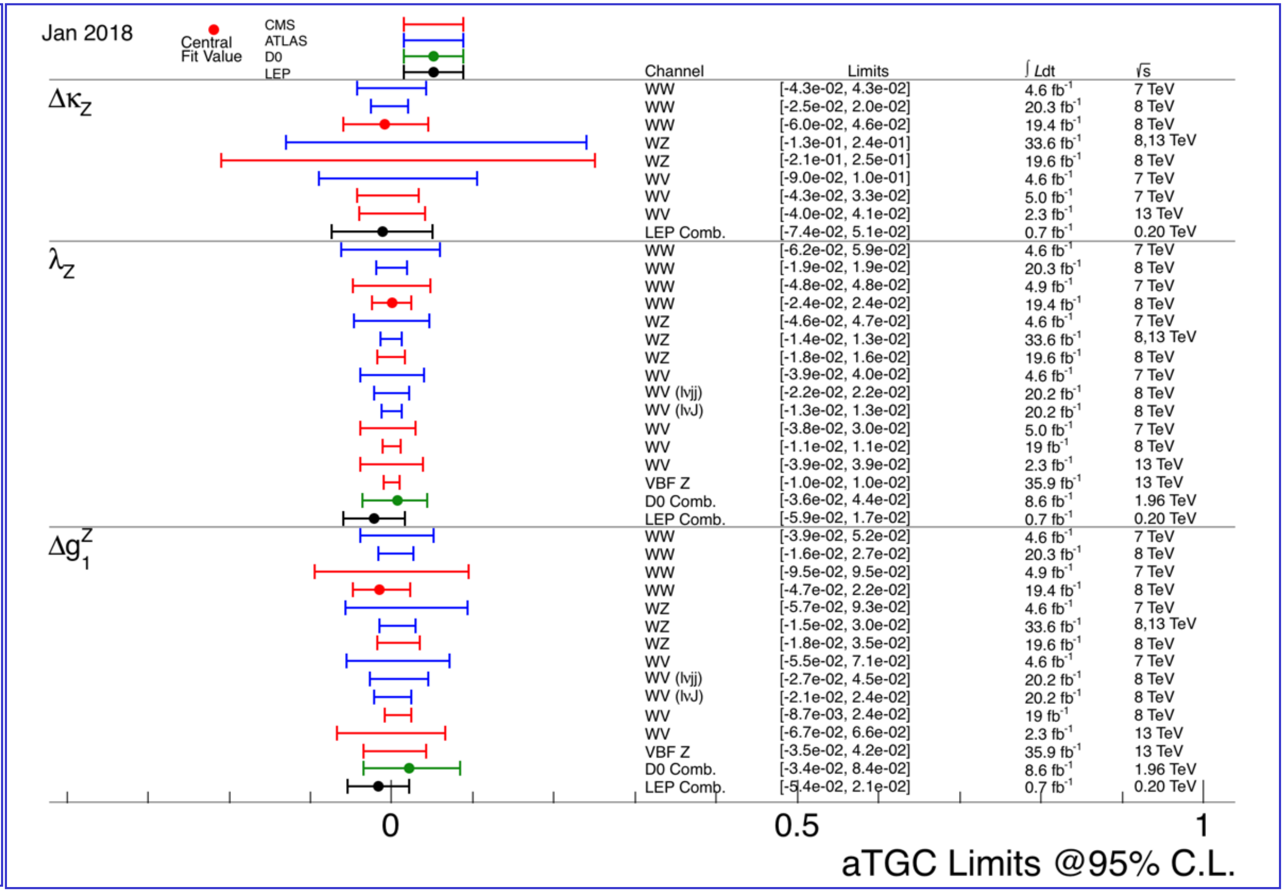
- h_i^V limits ~10^{-4} – 10^{-6}
- f_i^V limits ~10^{-3}



Summary of Charged aTGC Limits

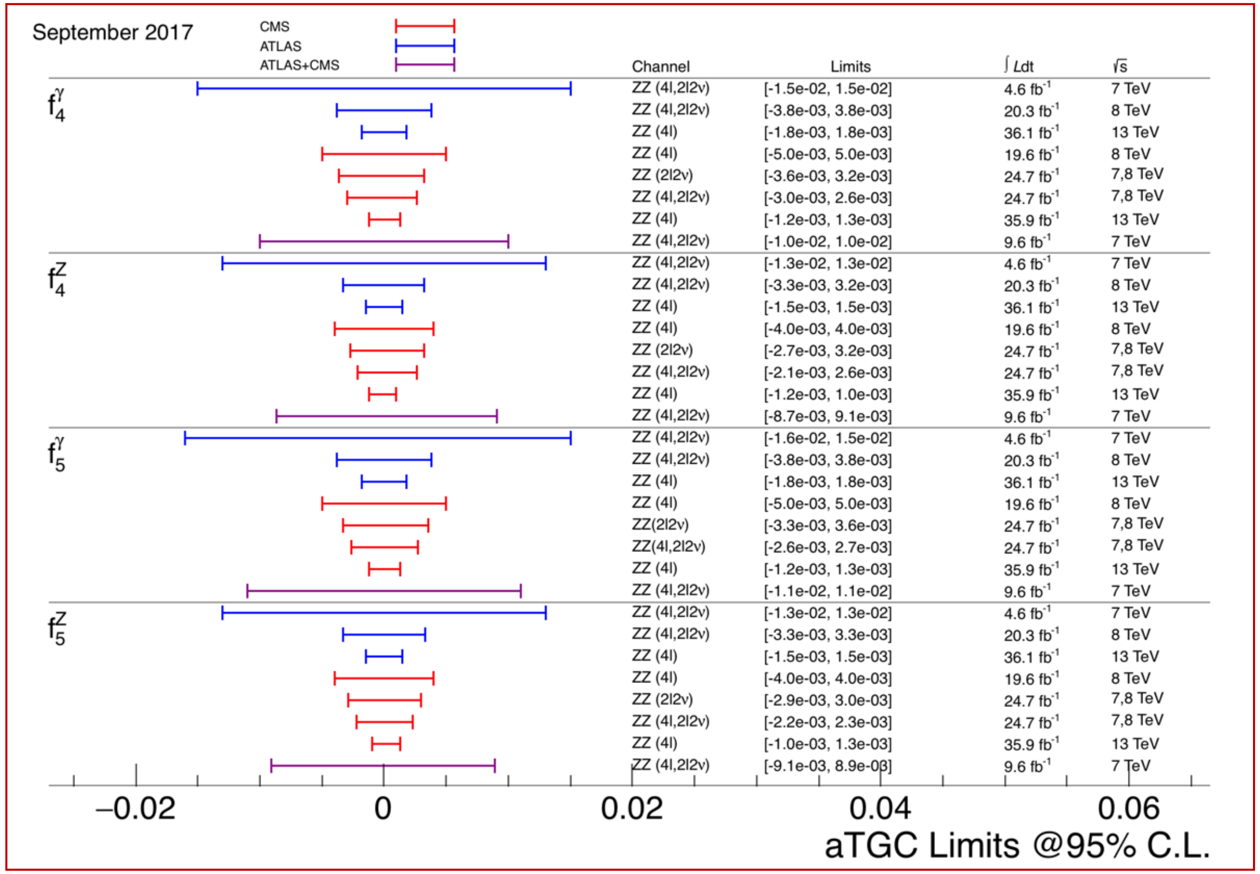
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

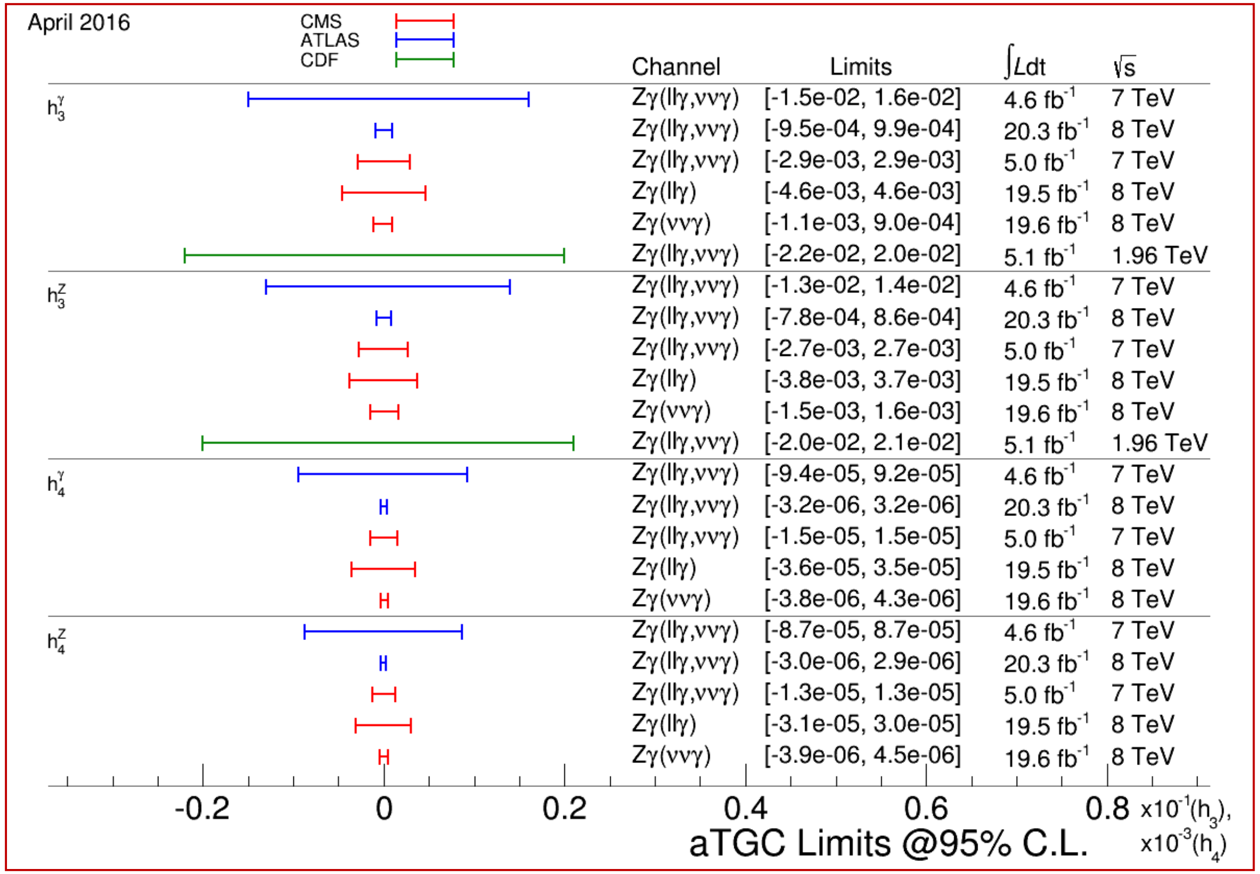




Summary of Neutral aTGC Limits

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC





Backup slides

aTGC parameters

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$$\mathcal{L} = ig_{WWV}\left[g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + k^V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho\right], \quad (10.1)$$

where $V = Z$ or γ; $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$; $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$. The overall coupling constants g_{WWV} are given by $g_{WW\gamma} = -e$ and $g_{WWZ} = -e\cot\theta_W$, where θ_W is the weak mixing angle.

Electromagnetic gauge invariance requires that $g_1^\gamma = 1$. The three other coupling parameters that are non-zero in the SM are $g_1^Z = 1$, $k^Z = 1$, and $k^\gamma = 1$. Deviations from the SM are introduced as

$$\Delta g_1^Z = 1 - g_1^Z; \qquad \Delta k^Z = 1 - k^Z; \qquad \Delta k^\gamma = 1 - k^\gamma. \quad (10.2)$$

The remaining couplings are zero in the SM, $\lambda^\gamma = \lambda^Z = 0$. A significant non-zero value for any of the parameters Δg_1^Z, Δk^Z, Δk^γ, λ^γ and λ^Z would be evidence of new interactions not included in the SM.

aTGC Form-Factor Scale

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If anomalous couplings occur, these extra terms in the Lagrangian would contribute and would induce a violation of unitarity at sufficiently high energies. Therefore, form factors are introduced to dampen the rise of the WW production cross section so that it takes physical values even at the highest partonic centre-of-mass energies relevant for 8 TeV pp collisions:

$$\Delta g_1^V \rightarrow \frac{\Delta g_1^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}, \qquad \Delta k^V \rightarrow \frac{\Delta k^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}, \qquad \lambda^V \rightarrow \frac{\lambda^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}, \tag{10.3}$$

where $\hat{s}$ is the square of the invariant mass of the vector boson pair. The form-factor scale, Λ, is typically taken to be in the TeV range. Upper bounds on the size of the anomalous gauge boson couplings can be derived as a function of Λ based on unitarity considerations [86].

Coupling Constraint Scenario

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the *Equal Couplings* $g_1^Z = g_1^\gamma = 1$ which leaves only two independent parameters: $\Delta k^\gamma = \Delta k^Z \quad \lambda^\gamma = \lambda^Z$.

the *LEP* constraint $\Delta g_1^Z = \Delta k^Z + \tan^2\theta_W \Delta k^\gamma, \quad \lambda^\gamma = \lambda^Z,$ where θ_W is the weak mixing angle.

the *Hagiwara-Ishihara-Szalapski-Zeppenfeld (HISZ)* constraint scenario

$$\Delta g_1^Z = \frac{\Delta k^Z}{\cos^2\theta_W - \sin^2\theta_W},$$
$$\Delta k^\gamma = 2\Delta k^Z \frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W},$$
$$\lambda^\gamma = \lambda^Z.$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

The dimensionless coefficients, C_i, parameterise the strength of the coupling between new physics and SM particles:

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu],$$
$$\mathcal{O}_W = (D_\mu\phi^0)^\dagger W^{\mu\nu}(D_\nu\phi^0),$$
$$\mathcal{O}_B = (D_\mu\phi^0)^\dagger B^{\mu\nu}(D_\nu\phi^0),$$

$$D_\mu = \partial_\mu + \frac{i}{2}g\tau^I W_\mu^I + \frac{i}{2}g' B_\mu,$$
$$W_{\mu\nu} = \frac{i}{2}g\tau^I\left(\partial_\mu W_\nu^I - \partial_\nu W_\mu^I + g\epsilon_{IJK}W_\mu^J W_\nu^K\right),$$
$$B_{\mu\nu} = \frac{i}{2}g'\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right),$$

ZZ Observation vs Prediction at 13 TeV

TABLE II. Observed and predicted yields, using the nominal SHERPA setup for the signal predictions. All statistical and systematic uncertainties are included in the prediction uncertainties. An alternative total prediction is given, using SHERPA reweighted to the total NNLO prediction from MATRIX with NLO EW corrections, adding the contribution of the EW-$ZZjj$ process generated with SHERPA, to predict the signal yield. A second alternative total prediction, identical to the nominal SHERPA setup, except using POWHEG + PYTHIA with NNLO QCD and NLO EW corrections applied event by event to simulate the $q\bar{q}$-initiated process, is shown at the bottom.

Contribution	$4e$	$2e2\mu$	4μ	Combined
Data	249	465	303	1017
Total prediction (SHERPA)	198^{+16}_{-14}	469^{+35}_{-31}	290^{+22}_{-21}	958^{+70}_{-63}
Signal ($q\bar{q}$-initiated)	168^{+14}_{-13}	400^{+31}_{-28}	246^{+19}_{-18}	814^{+63}_{-57}
Signal (gg-initiated)	21.3 ± 3.5	50.2 ± 8.2	29.7 ± 4.9	101 ± 17
Signal (EW-$ZZjj$)	4.36 ± 0.42	10.23 ± 0.72	6.43 ± 0.55	21.0 ± 1.2
$ZZ \to \tau^+\tau^-[\ell^+\ell^-, \tau^+\tau^-]$	0.59 ± 0.09	0.55 ± 0.08	0.55 ± 0.09	1.69 ± 0.16
Triboson	0.68 ± 0.21	1.50 ± 0.46	0.96 ± 0.30	3.14 ± 0.30
$t\bar{t}Z$	0.81 ± 0.25	1.86 ± 0.56	1.42 ± 0.43	4.1 ± 1.2
Misid. lepton background	2.1 ± 2.1	4.9 ± 3.9	5.3 ± 5.2	12.3 ± 8.3
Total prediction (MATRIX + corrections)	197^{+15}_{-14}	470^{+34}_{-31}	286^{+22}_{-21}	953^{+69}_{-64}
Total prediction (POWHEG + PYTHIA with higher-order corrections, SHERPA)	193 ± 11	456 ± 24	286 ± 17	934 ± 50