Overview of multiboson measurements at the LHC

Felix Bührer[1] on behalf of the ATLAS and CMS collaborations

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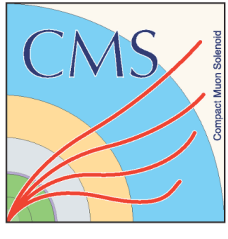
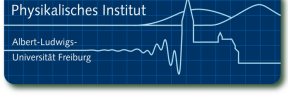
SM@LHC 2016, Pittsburgh 3-6 May 2016

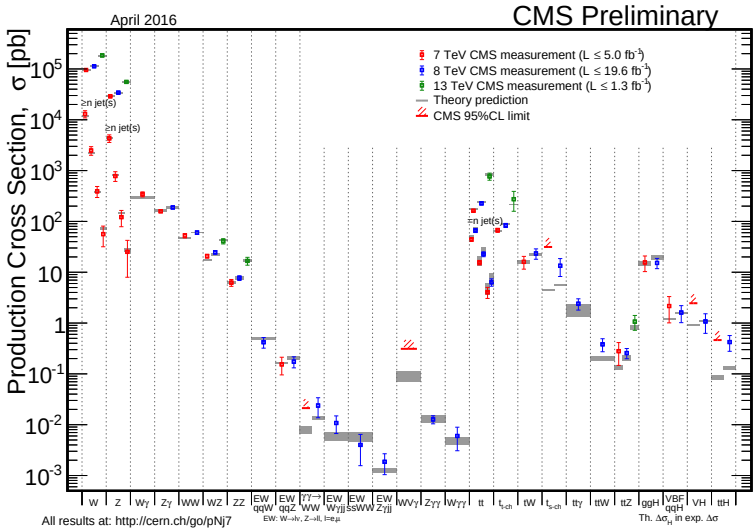




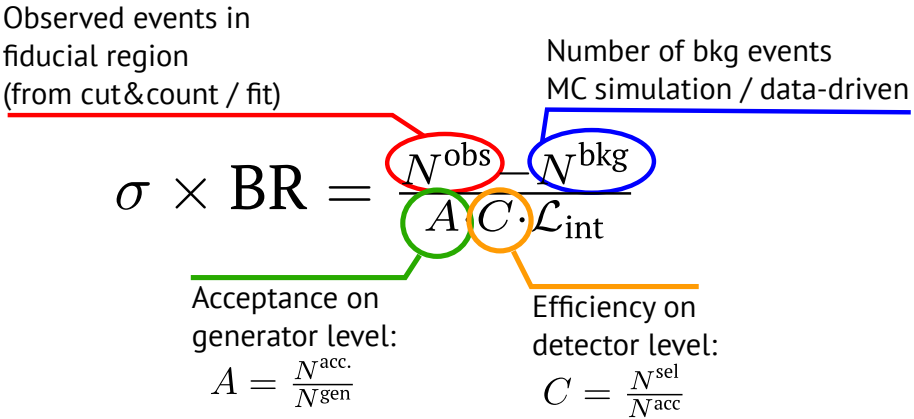
Topics covered

ATLAS and CMS published impressive amount of SM cross section measurements at 7, 8 & 13 TeV CME.
I will focus on:

- First Diboson cross section measurements at $\sqrt{s} = 13$ TeV
- Latest differential Diboson measurements at $\sqrt{s} = 8$ TeV & limits on anomalous triple gauge couplings
- Triboson production at $\sqrt{s} = 8$ TeV & limits on anomalous quartic gauge couplings
  $\rightarrow$ First time that we are sensitive to triboson final states



Cross section measurement in a nutshell



Run2 diboson cross section measurements

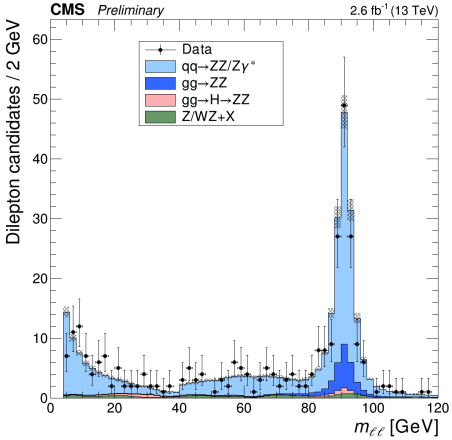
$ZZ \to 4l$ @ 13 TeV

CMS-PAS-SMP-16-001 (Updated result)

Measurement of the ZZ production cross section and $Z \to 4l$ branching fraction

- Using full 2015 dataset ($\mathcal{L} = 2.6\text{fb}^{-1}$)
- fully leptonic channels ($4e, 4\mu, 2e2\mu$)
  $\to$ very clean signature, low statistical precision
- Selecting 2 pairs of OS leptons with $60\text{ GeV} < m_{ll} < 120\text{ GeV}$
- Data-driven estimate of background with misidentified leptons (Z+ jets / WZ)

64 observed events with bkg of 1.4 events



fiducial cross section obtained from combined fit to all 3 final states

Total cross section:

$$\sigma(pp \to ZZ) = 14.6^{+1.9}_{-1.8}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) \pm 0.2(\text{th.}) \pm 0.4(\text{lum})\text{ pb}$$

in agreement with NNLO ($qq \to ZZ$) / NLO ($gg \to ZZ$) prediction:

$$\sigma_{\text{th}} = 16.5^{+0.7}_{-0.5}\text{ pb (MATRIX) / } 15.0^{+0.8}_{-0.6}\text{ pb (MCFM)}$$

$ZZ \to 4l$ @ 13 TeV

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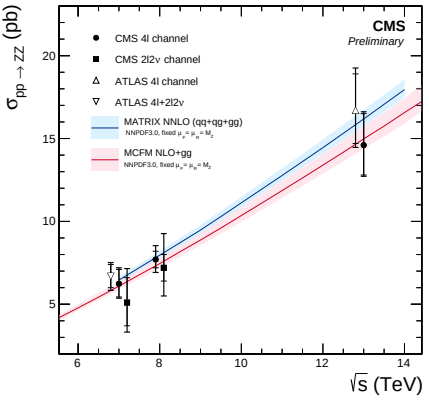
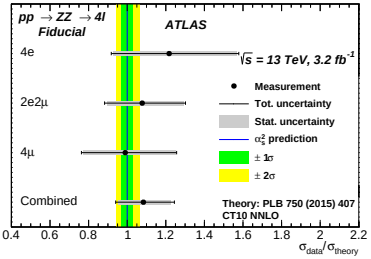


$ZZ \to 4l$ @ 13 TeV

Phys. Rev. Lett. 116, 101801 (2016)

- Larger dataset used $\mathcal{L} = \mathbf{3.2}\text{fb}^{-1}$
- Selecting 2 pairs of OS leptons with $\mathbf{66}\ \text{GeV} < \mathbf{m_{ll}} < \mathbf{116}\ \text{GeV}$

fiducial cross section obtained from combined fit to all 3 final states

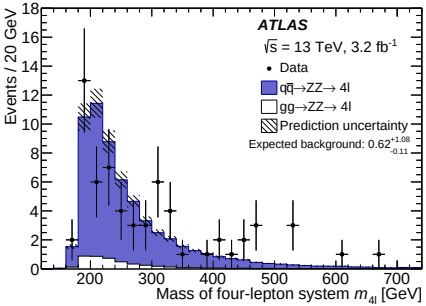


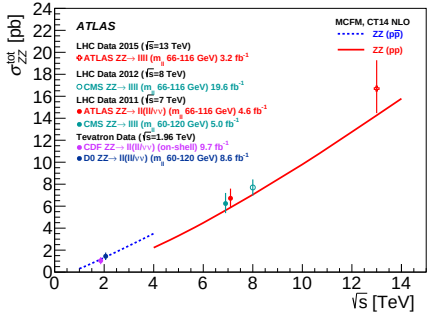
Total cross section:

$$\sigma(pp \to ZZ) = 16.7^{+2.2}_{-2.0}(\text{stat})^{+0.9}_{-0.7}(\text{syst})^{+1.0}_{-0.7}(\text{lumi})\ \text{pb}$$

in agreement with NNLO prediction:

$$\sigma_{\text{th}} = 15.6^{+0.4}_{-0.4}\ \text{pb}$$





$WZ \to l\nu l'l'$ @ 13 TeV

CMS PAS SMP-16-002 (Updated result)

Measurement of the *WZ* production cross section

- Using an integrated luminosity of $\mathcal{L} = 2.3\text{fb}^{-1}$
- fully leptonic channels ($e\nu ee$, $\mu\nu ee$, $e\nu\mu\mu$, $\mu\nu\mu\mu$)
- Dominant backgrounds from processes with misidentified leptons (Z+ jets / $t\bar{t}$) $\to$ improved data-driven estimates

Decay channel	N_{WZ}^{exp}	Background Non-prompt	Background Prompt	Total expected	Observed
Total	$226.09 \pm 1.61^{+9.46}_{-9.25}$	$67.19 \pm 7.08^{+14.43}_{-11.10}$	$33.21 \pm 1.05^{+4.32}_{-3.80}$	$326.50 \pm 7.33^{+18.66}_{-15.90}$	318

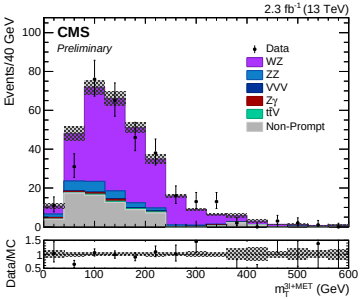
fiducial cross section obtained from combined fit to all decay channels

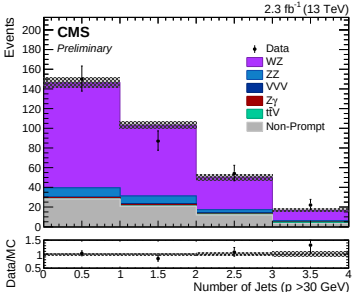
Total cross section:

$$\sigma(pp \to WZ) = 40.9 \pm 3.4(\text{stat})^{+3.1}_{-3.3}(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lum})\ \text{pb}$$

to be compared with recently published MATRIX NNLO prediction:

$$\sigma_{\text{th}} = 49.98^{+2.2\%}_{-2.0\%}\text{pb},\ (42.6^{+1.6}_{-0.8}\ \text{pb from MCFM@NLO})$$





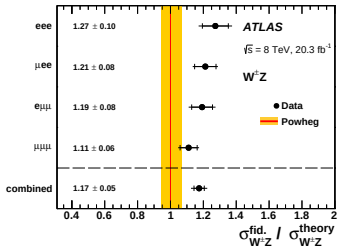
Run1 diboson measurements & aTGC limits

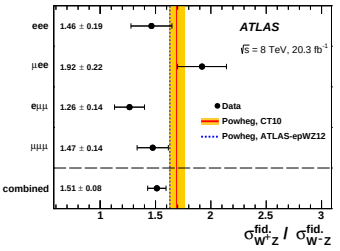
$WZ \to l\nu l'l'$ @ 8 TeV

arXiv:1603.02151 (acc. by PRD)

Measurement of the WZ production cross section (integrated& differential) + limits on anomalous TGCs

- Using an integrated luminosity of $\mathcal{L} = 20.3\text{fb}^{-1}$





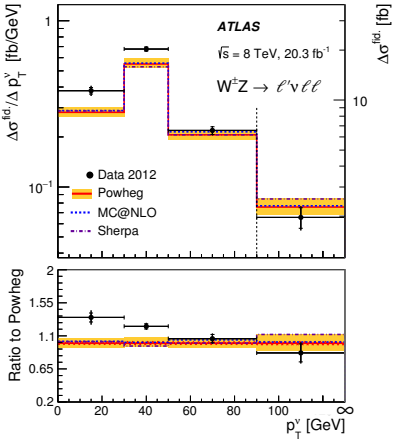
Total cross section:

$$\sigma(pp \to W^{\pm}Z) = 24.3 \pm 0.6(\text{stat}) \pm 0.6(\text{sys}) \pm 0.4(\text{th.}) \pm 0.5(\text{lumi}) \text{ pb}$$

higher than NLO prediction (Powheg+Pythia): $\sigma_{\text{th}} = 21.0 \pm 1.6$ pb

But: Significantly better agreement when comparing to NNLO (MATRIX) calculation:

$$\sigma_{\text{th}} = 23.92^{+1.7\%}_{-1.8\%} \text{ pb}$$



- Generator predictions agree
- Measured xs higher at low p_{T}^{ν}

$WZ \to l\nu l'l'$ @ 8 TeV

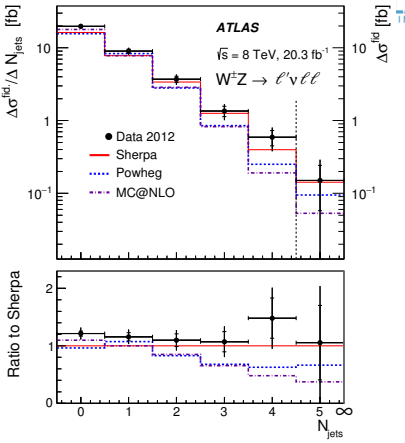
arXiv:1603.02151 (acc. by PRD)

Measurement of the WZ production cross section (integrated& differential) + limits on anomalous TGCs

- Using an integrated luminosity of $\mathcal{L} = 20.3\text{fb}^{-1}$

Unfolded distributions:

- Transverse momenta p_{T}^{W}, p_{T}^{Z}
- Transverse mass of the WZ system m_{T}^{WZ}
- Transverse neutrino momentum p_{T}^{ν}
- Absolute difference between Z and charged lepton from W, $|y_Z - y_{l,W}|$



- Largest deviation at low jet multiplicities
- Data is best described by Sherpa prediction
- MC@NLO & Powheg predict less jets than Sherpa and w.r.t. measurement

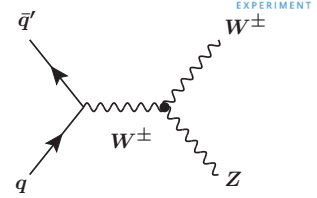
$WZ \to l\nu l'l'$ @ 8 TeV (2)

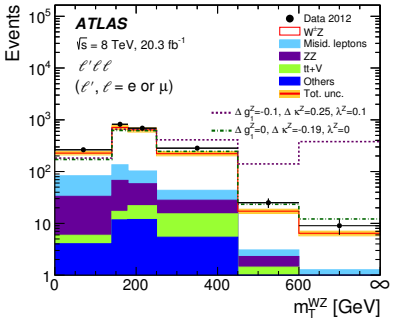
arXiv:1603.02151 (acc. by PRD)

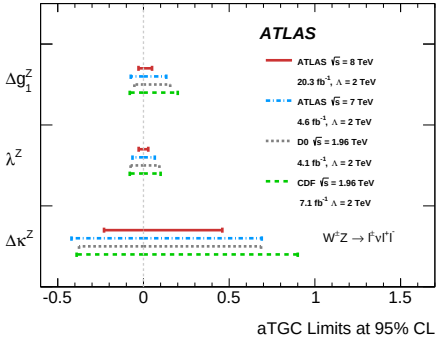
Measurement of the *WZ* production cross section (integrated & differential) + limits on anomalous TGCs

Analysis is sensitive to BSM gauge couplings

- Manifest as rise in cross section over the SM expectation at high p_T
- No deviation observed $\to$ set limits on aTGC parameters







$W^+W^- \to l\nu l\nu$ @ 8 TeV

arXiv:1507.03268 (submitted to EPJC)

Cross section measured separately in 4 final states and combined (profile likelihood fit)

- same- and different-flavour leptons
- Exclusively 0 or 1 reconstructed jet

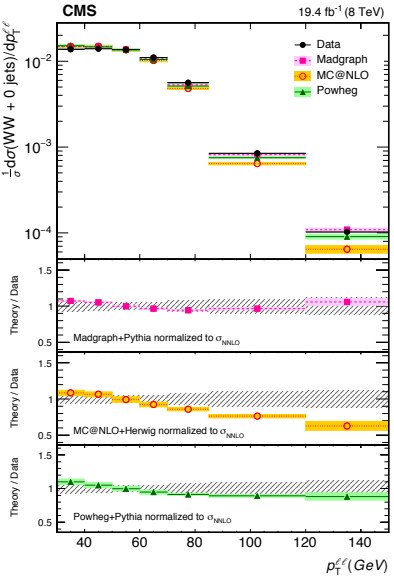
Event category		W^+W^- production cross section (pb)
zero-jet category	Different-flavor	$59.7 \pm 1.1\,(\text{stat}) \pm 3.3\,(\text{exp}) \pm 3.5\,(\text{theo}) \pm 1.6\,(\text{lumi})$
	Same-flavor	$64.3 \pm 2.1\,(\text{stat}) \pm 4.6\,(\text{exp}) \pm 4.3\,(\text{theo}) \pm 1.7\,(\text{lumi})$
one-jet category	Different-flavor	$59.1 \pm 2.8\,(\text{stat}) \pm 6.0\,(\text{exp}) \pm 6.2\,(\text{theo}) \pm 1.6\,(\text{lumi})$
	Same-flavor	$65.1 \pm 5.5\,(\text{stat}) \pm 8.3\,(\text{exp}) \pm 8.0\,(\text{theo}) \pm 1.7\,(\text{lumi})$

Total cross section:

$$\sigma(pp \to W^+W^-) = 60.1 \pm 0.9(\text{stat}) \pm 3.2(\text{exp}) \pm 3.1(\text{th.}) \pm 1.6(\text{lumi})\ \text{pb}$$

in agreement with NNLO prediction:

$$\sigma_{\text{th}} = 59.8^{+1.3}_{-1.1}\ \text{pb}$$



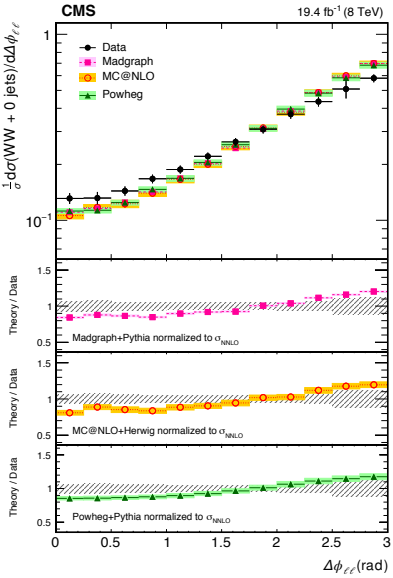
$W^+W^- \to l\nu l\nu$ @ 8 TeV

arXiv:1507.03268 (submitted to EPJC)

Cross section measured separately in 4 final states and combined (profile likelihood fit)

Unfolded distributions:

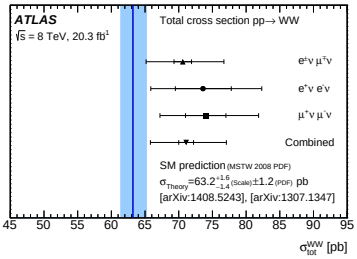
- Transverse momentum of leading lepton $p^l_{T,max}$
- Transverse momentum and mass of dilepton system p^{ll}_T, m_{ll}
- Angular separation in transverse plane between leptons $\Delta\phi_{ll}$



$W^+W^- \to l\nu l\nu$ @ 8 TeV

arXiv:1603.01702 (submitted to JHEP)

Cross section measured with jet veto only (separately same- and different-flavour lepton channels)

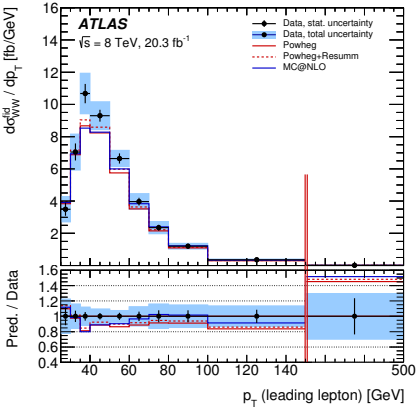


Total cross section:

$$\sigma(pp \to W^+W^-) = 71.1 \pm 1.9(\text{stat})^{+5.7}_{-5.0}(\text{syst}) \pm 1.4(\text{lumi})\ \text{pb}$$

in agreement with NNLO prediction:

$$\sigma_{\text{th}} = 63.2^{+1.6}_{-1.4}(\text{scale}) \pm 1.2(\text{PDF})\ \text{pb}$$



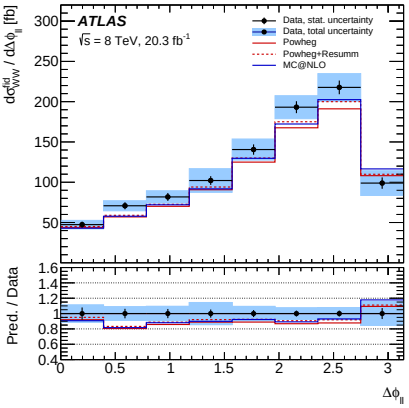
Differential measurements agree well with theoretical predictions within uncertainties

$W^+W^- \to l\nu l\nu$ @ 8 TeV

arXiv:1603.01702 (submitted to JHEP)

Unfolded distributions:

- Transverse momentum of leading lepton $p^l_{T,max}$
- Transverse momentum, rapidity and mass of dilepton system p^{ll}_T, y_{ll},m_{ll}
- Angular separation in transverse plane between leptons $\Delta\phi_{ll}$
- $|\cos(\theta^*)| = |\tanh\left(\frac{\Delta\eta_{ll}}{2}\right)|$



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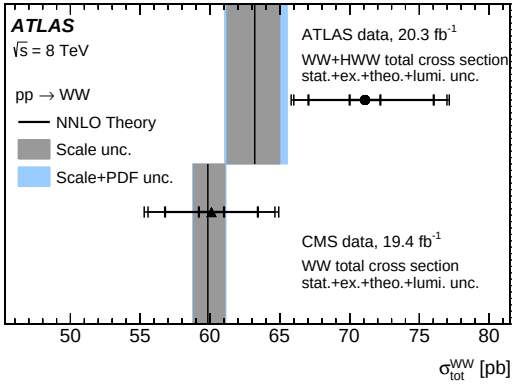
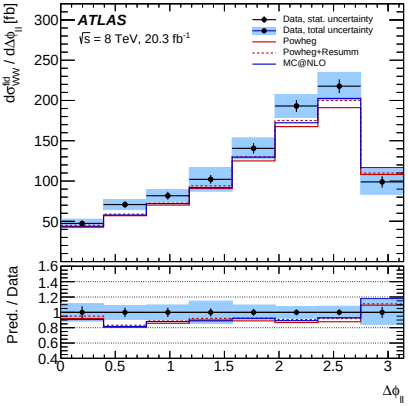


Discrepancy between prediction and measurement in earlier publication significantly reduced by including resummation effects up to NNLL!



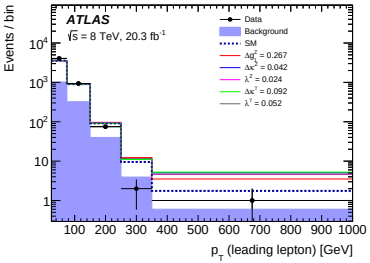
Differential measurements agree well with theoretical predictions within uncertainties

$W^+W^- \to l\nu l\nu$ @ 8 TeV - aTGC limits

Comparing observed limits in EFT parametrization

ATLAS:

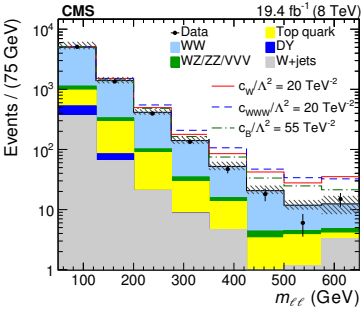
- Only using different-flavour channel
- p_T of the leading lepton found to be most sensitive to aTGCs



Coupling constant	95% CL interval
c_{WWW}/Λ^2	[-4.61,4.60]
c_W/Λ^2	[-5.87,10.54]
c_B/Λ^2	[-20.9,26.3]

CMS:

- Only using 0-jet categories
- m_{ll} distribution used to set limits

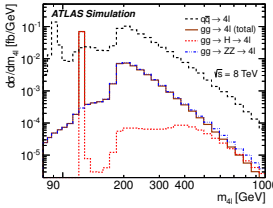


Coupling constant	95% CL interval
c_{WWW}/Λ^2	[-5.7,5.9]
c_W/Λ^2	[-11.4,5.4]
c_B/Λ^2	[-29.2,23.9]

Differential $pp \to 4l$@8 TeV

Physics Letters B 753 (2016) 552-572

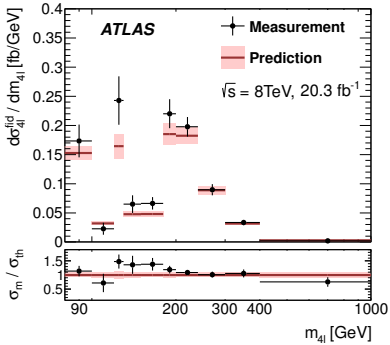
Differential $pp \to 4l$ cross section consists of 3 contributions:

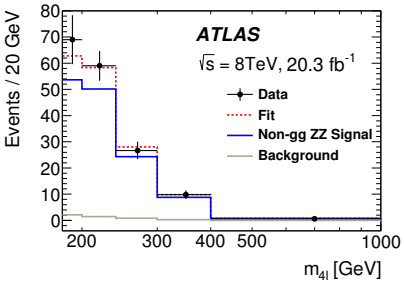


- Non-resonant $gg \to 4l$ (LO)
- Onshell $q\bar{q} \to ZZ \to 4l$ (NNLO QCD + NLO EW)
- Offshell $q\bar{q} \to ZZ \to 4l$ (NLO QCD)
- $H \to 4l$ (NNLO QCD + NLO EWK)

Estimating the signal strength of gg-contribution w.r.t. LO prediction in region $m_{4l} > 180$ GeV

$$\mu_{gg} = 2.4 \pm 1.0(\text{stat}) \pm 0.5(\text{sys}) \pm 0.8(\text{th.})$$





$Z\gamma \to \nu\bar{\nu}\gamma$@8 TeV

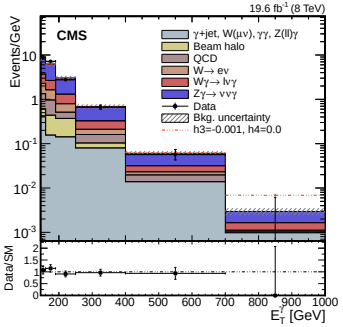
arXiv:1602.07152 (Submitted to Phys. Lett. B)

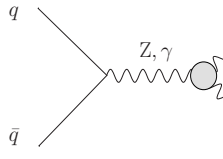
Earlier CMS publication on $Z\gamma \to l^+l^-\gamma$: J. High Energy Phys. 04 (2015) 164

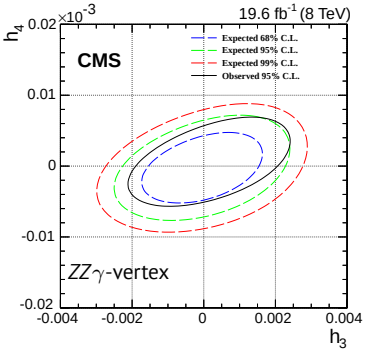
Extract limits on anomalous neutral TGCs:

Events are selected by requiring:

- 1 high-p_T isolated photon
- $E_T^{miss} > 140$ GeV
- $E_T^{miss} > 140$ GeV
- $<= 1$ separated jet
- No separated charged lepton







The measured cross section

$$\sigma_{fid}(pp \to Z\gamma) \times BR(Z \to \nu\bar{\nu}) = 52.7 \pm 2.1(\text{stat}) \pm 6.4(\text{sys}) \pm 1.4(\text{lumi})\ \text{fb}$$

is in good agreement with the NNLO prediction:

$$\sigma_{\text{th}} = 50.0^{+2.4}_{-2.2}\ \text{fb}$$

$Z\gamma \to \nu\bar{\nu}\gamma$@8 TeV

arXiv:1602.07152 (Submitted to Phys. Lett. B)

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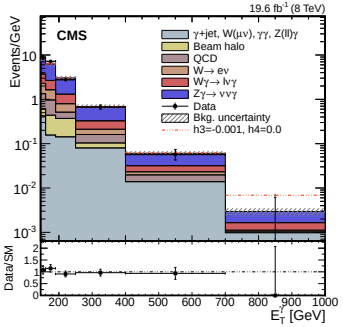
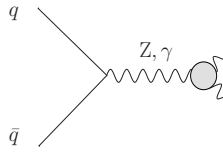
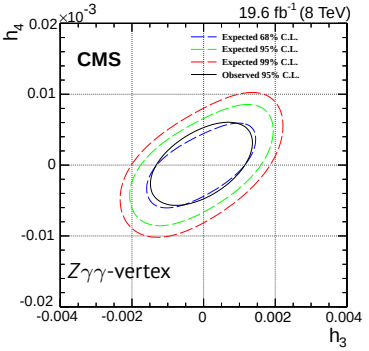
- $<= 1$ separated jet
- No separated charged lepton







The measured cross section

$$\sigma_{fid}(pp \to Z\gamma) \times BR(Z \to \nu\bar{\nu}) = 52.7 \pm 2.1(\text{stat}) \pm 6.4(\text{sys}) \pm 1.4(\text{lumi})\ \text{fb}$$

is in good agreement with the NNLO prediction:

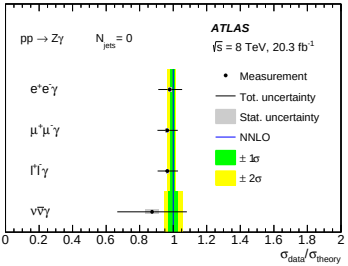
$$\sigma_{\text{th}} = 50.0^{+2.4}_{-2.2}\ \text{fb}$$

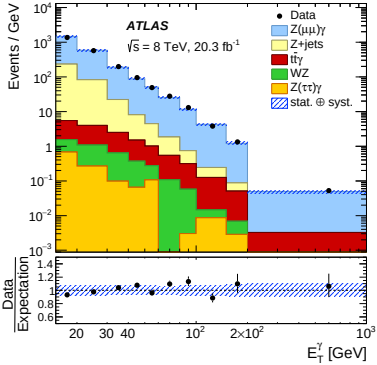
$Z\gamma \to ll\gamma$ and $Z\gamma\gamma \to ll\gamma\gamma$@8 TeV

arXiv:1604.05232 (Submitted to PRD)

Similar selection to CMS analysis, but:

- also $ee\gamma$, $\mu\mu\gamma$ channels
- Separate exclusive (jet-veto) and inclusive selections





Integrated results in agreement with SM prediction

Channel	Measurement [fb]	NNLO prediction [fb]
	$N_{\text{jets}} >= 0$	
$l^+l^-\gamma$	$1507 \pm 10(\text{stat})^{+78}_{-74}(\text{syst})^{+29}_{-28}(\text{lum.})$	1483^{+19}_{-37}
$\nu\bar{\nu}\gamma$	$68 \pm 4(\text{stat})^{+33}_{-32}(\text{syst}) \pm 1(\text{lum.})$	$81.4^{+2.4}_{-2.2}$
	$N_{\text{jets}} = 0$	
$l^+l^-\gamma$	$1189 \pm 9(\text{stat})^{+69}_{-63}(\text{syst})^{+23}_{-22}(\text{lum.})$	1230^{+10}_{-18}
$\nu\bar{\nu}\gamma$	$43 \pm 2(\text{stat}) \pm 10(\text{syst}) \pm 1(\text{lum.})$	$49.21^{+0.61}_{-0.52}$

$Z\gamma \to ll\gamma$ and $Z\gamma\gamma \to ll\gamma\gamma$@8 TeV

arXiv:1604.05232 (Submitted to PRD)

Unfolded distributions:

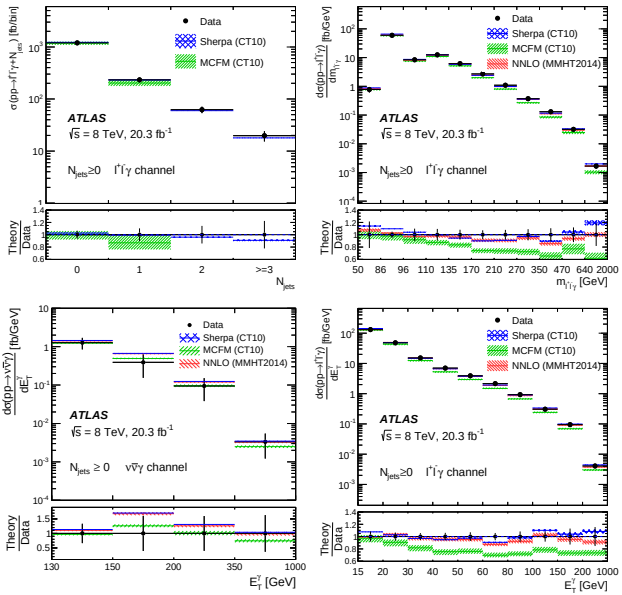
$l^+l^-\gamma$-channel:

- E_T^γ
- $m_{l^+l^-\gamma}$
- N_{jets}

$\nu\bar{\nu}\gamma$-channel:

- E_T^γ

$N_{\text{jets}} >= 0$



$Z\gamma \to ll\gamma$ and $Z\gamma\gamma \to ll\gamma\gamma$@8 TeV

arXiv:1604.05232 (Submitted to PRD)

Unfolded distributions:

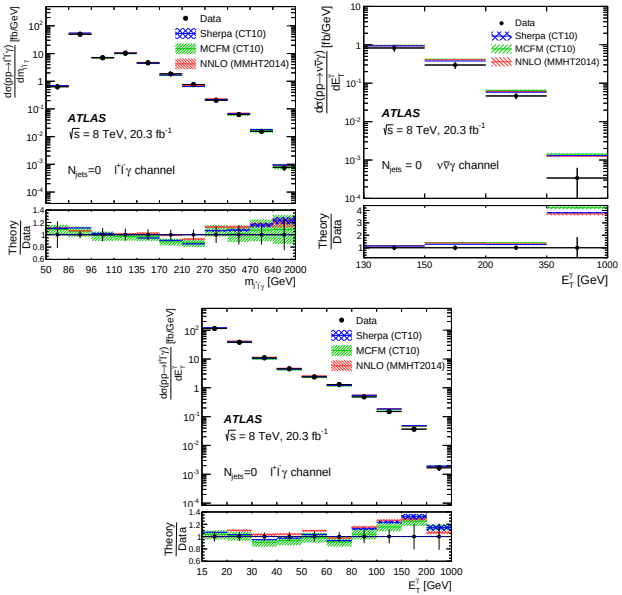
$l^+l^-\gamma$-channel:

- E_T^γ
- $m_{l^+l^-\gamma}$
- N_{jets}

$\nu\bar{\nu}\gamma$-channel:

- E_T^γ

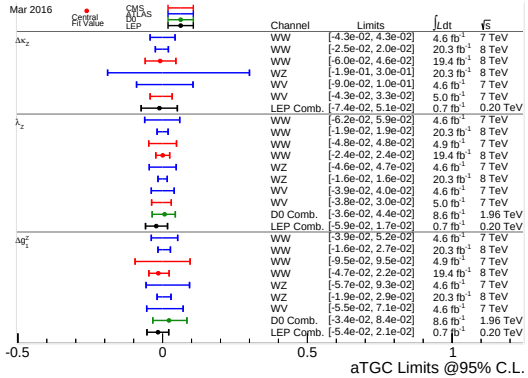
$N_{\text{jets}} = 0$



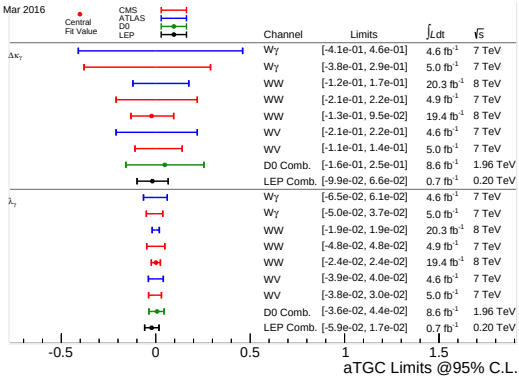
Comparison of aTGC limits

Charged aTGC couplings

WWZ aTGC couplings



WWZ aTGC couplings

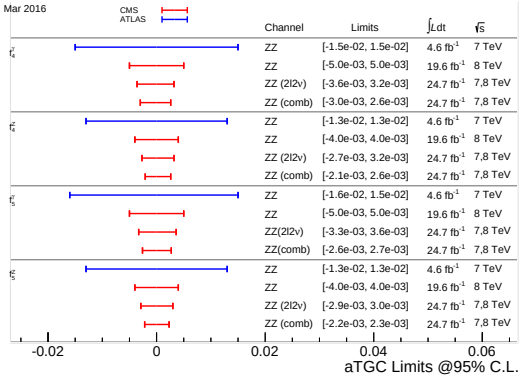


No form factors used for setting limits (only D0 comb.)

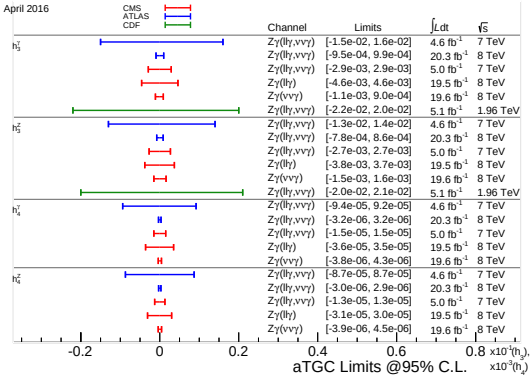
Comparison of aTGC limits

Neutral aTGC couplings

$ZZ\gamma$&ZZZ aTGC couplings



$Z\gamma\gamma$&$ZZ\gamma$ aTGC couplings



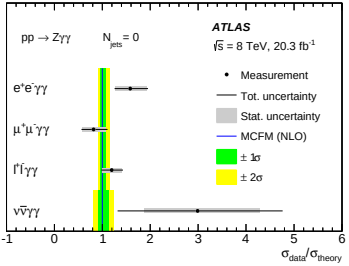
Run1 triboson measurements, aQGC limits & other rare processes

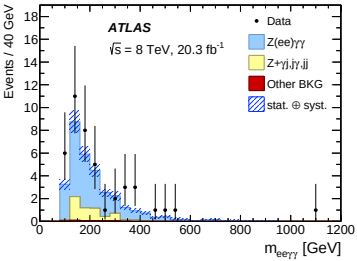
$Z\gamma \to ll\gamma$ and $Z\gamma\gamma \to ll\gamma\gamma$@8 TeV

arXiv:1604.05232 (Submitted to PRD)

Similar selection to CMS analysis, but:

- Similar selection as in $Z\gamma$-analysis
- Both $e\gamma\gamma$ and $\mu\gamma\gamma$-channel
- Separate exclusive (jet-veto) and inclusive selections





$Z\gamma\gamma$ observed with $> 5\sigma$

Integrated results in agreement with SM prediction

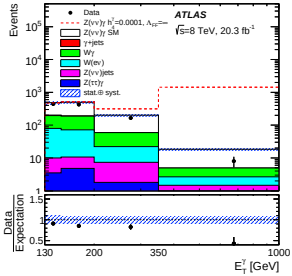
Channel	Measurement [fb]	MCFM prediction [fb]
	$N_{\text{jets}} >= 0$	
$l^+l^-\gamma\gamma$	$5.07^{+0.73}_{-0.68}(\text{stat})^{+0.41}_{-0.38}(\text{syst}) \pm 0.10(\text{lum.})$	$3.70^{+0.21}_{-0.11}$
$\nu\bar{\nu}\gamma\gamma$	$2.5^{+1.0}_{-0.9}(\text{stat}) \pm 1.1(\text{syst}) \pm 0.11(\text{lum.})$	$0.737^{+0.039}_{-0.032}$
	$N_{\text{jets}} = 0$	
$l^+l^-\gamma\gamma$	$3.48^{+0.61}_{-0.56}(\text{stat})^{+0.29}_{-0.25}(\text{syst}) \pm 0.07(\text{lum.})$	$2.91^{+0.23}_{-0.12}$
$\nu\bar{\nu}\gamma\gamma$	$1.18^{+0.52}_{-0.44}(\text{stat})^{+0.48}_{-0.49}(\text{syst}) \pm 0.02(\text{lum.})$	$0.395^{+0.049}_{-0.037}$

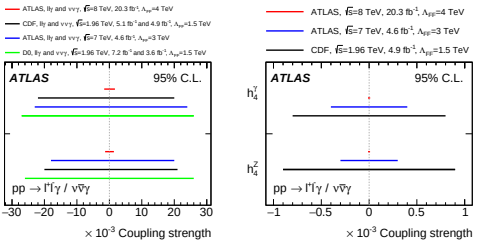
$Z\gamma \to ll\gamma$ and $Z\gamma\gamma \to ll\gamma\gamma$ @ 8 TeV - aGC results

arXiv:1604.05232 (Submitted to PRD)

$Z\gamma$:

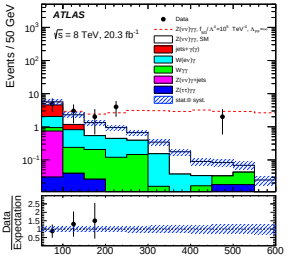
- Obtain limits on neutral TGCs by fit to E_T^γ

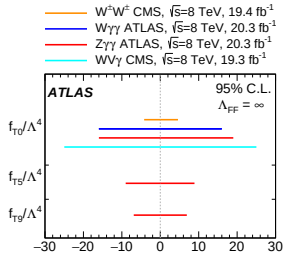




$Z\gamma\gamma$:

- Limits on anomalous quartic GC by fit to $m_{\gamma\gamma}$





$pp \to W\gamma\gamma$ and $pp \to Z\gamma\gamma$ @ 8 TeV

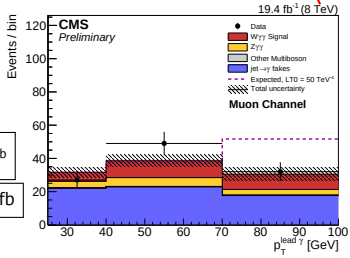
CMS PAS SMP-15-008

$W\gamma\gamma$

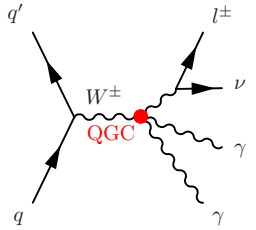
- Muon channel only
- Observed with significance of 2.4σ

$$\sigma^{fid}_{W^{\pm}\gamma\gamma} \times BR = 6.0 \pm 1.8(\text{stat}) \pm 2.3(\text{sys}) \pm 0.2(\text{lumi})\ \text{fb}$$

In agreement with prediction: $\sigma_{th} = 4.76 \pm 0.53$ fb



Extract limits on aQGCs:



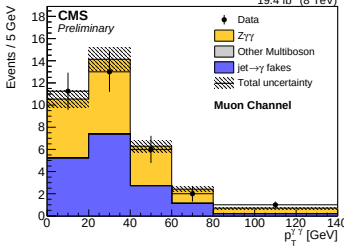
Observed Limits (TeV^{-4})
$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

$Z\gamma\gamma$

- e and μ channel
- Observed with significance of 5.9σ

$$\sigma^{fid}_{Z\gamma\gamma} \times BR = 12.7 \pm 1.4(\text{stat}) \pm 1.8(\text{sys}) \pm 0.3(\text{lumi})\ \text{fb}$$

In agreement with prediction: $\sigma_{th} = 12.95 \pm 1.47$ fb



Evidence for $W\gamma\gamma$ production @ 8 TeV

Phys. Rev. Lett. 115, 031802 (2015)

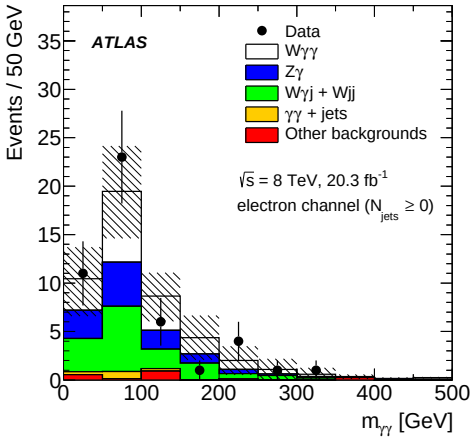
- Using both $W \to e\nu$ and $W \to \mu\nu$ decay channels
- Combined significance $> 3\sigma$

fiducial cross section obtained from fit to the combined $e\nu$ and $\mu\nu$ channel and separate:

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

Measured cross section ~1.9σ higher w.r.t. NLO prediction. Better agreement when adding jet veto

Same behavior has been seen in measurement of $W\gamma$ before NNLO calculations were available.



	Observed [TeV^{-4}]	Expected [TeV^{-4}]
f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$

Evidence for $W\gamma\gamma$ production @ 8 TeV

Phys. Rev. Lett. 115, 031802 (2015)

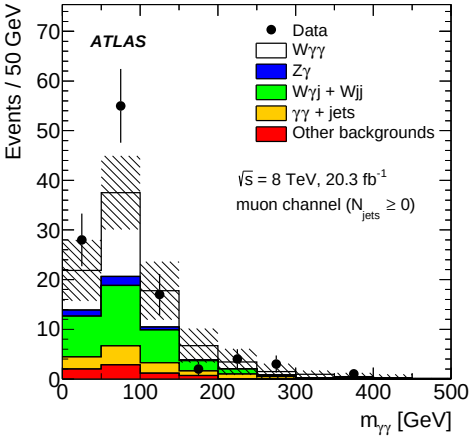
- Using both $W \to e\nu$ and $W \to \mu\nu$ decay channels
- Combined significance $> 3\sigma$

fiducial cross section obtained from fit to the combined $e\nu$ and $\mu\nu$ channel and separate:

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

Measured cross section ~1.9σ higher w.r.t. NLO prediction. Better agreement when adding jet veto

Same behavior has been seen in measurement of $W\gamma$ before NNLO calculations were available.

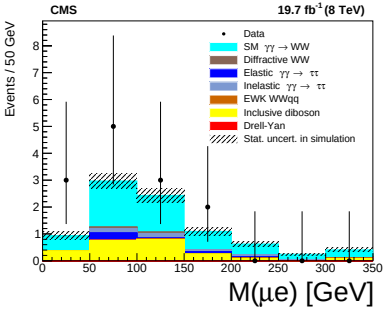


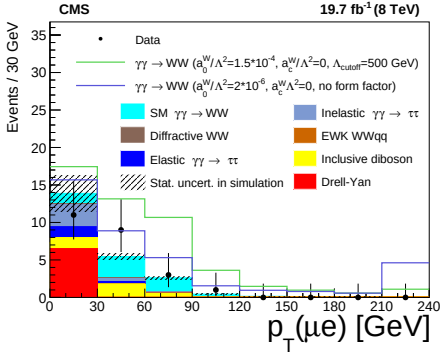
	Observed [TeV^{-4}]	Expected [TeV^{-4}]
f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$

Evidence for exclusive $\gamma\gamma \to W^+W^-$ production @ 7&8 TeV

arXiv:1604.04464 (Submitted to J. High Energy Phys.)

- Search for exclusive $\gamma\gamma \to WW$ in the $\mu^\pm e^\pm$ final state
- Combination of 7TeV and 8TeV results
- Combined significance 3.4σ over background-only hypothesis (2.1σ expected)



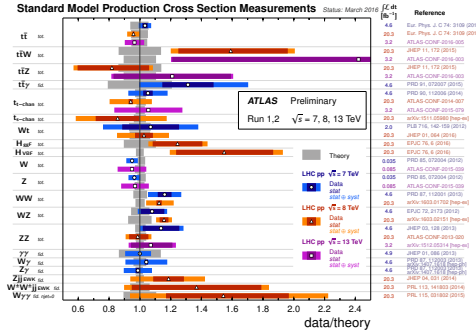


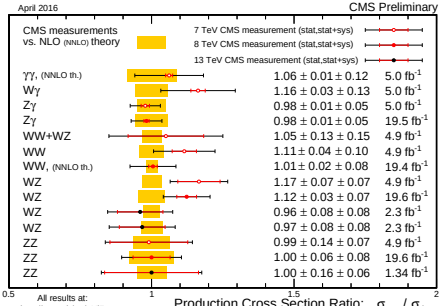
Interpreted as cross section:

$$\sigma(pp \to p^*W^+W^-p^{(*)} \to p^*\mu^\pm e^\pm p^{(*)}) = 11.9^{+5.6}_{-4.5}\ \text{fb}$$
$$\sigma_{th} = 6.9 \pm 0.6\ \text{fb}$$

Dimension-8 AQGC parameter	7 TeV ($\times 10^{-12}\,\text{GeV}^{-4}$)	8 TeV ($\times 10^{-12}\,\text{GeV}^{-4}$)	7+8 TeV ($\times 10^{-12}\,\text{GeV}^{-4}$)
$f_{M,0}/\Lambda^4$(no form factor)	$-15 < f_{M,0}/\Lambda^4 < 15$	$-4.6 < f_{M,0}/\Lambda^4 < 4.6$	$-4.2 < f_{M,0}/\Lambda^4 < 4.2$
$f_{M,1}/\Lambda^4$(no form factor)	$-57 < f_{M,1}/\Lambda^4 < 57$	$-17 < f_{M,1}/\Lambda^4 < 17$	$-16 < f_{M,1}/\Lambda^4 < 16$
$f_{M,2}/\Lambda^4$(no form factor)	$-7.6 < f_{M,2}/\Lambda^4 < 7.6$	$-2.3 < f_{M,2}/\Lambda^4 < 2.3$	$-2.1 < f_{M,2}/\Lambda^4 < 2.1$
$f_{M,3}/\Lambda^4$(no form factor)	$-28 < f_{M,3}/\Lambda^4 < 28$	$-8.4 < f_{M,3}/\Lambda^4 < 8.4$	$-7.8 < f_{M,3}/\Lambda^4 < 7.8$

Summary





- First Di-boson cross sections measured with Run2 data - consistent with SM expectations
- Latest Run1 results reach accuracy of few percent - mostly in good agreement with latest NNLO calculations
- Many differential measurements published
- aTGC analyses show no deviations from the SM - stringent limits placed
- First evidence of triboson production and sensitivity to aQGCs from Run1
  → looking forward to results from Run2

Backup Material