Multiboson Production in CMS

EPS-HEP Conference 2021

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Driven to Discover℠

Monday 26 July 2021

Motivation for Multiboson Studies

Test Non-Abelian Structure of Electroweak Theory

- Boson self-couplings determine:
  - x-sections
  - polarizations
- Deviations predicted by anomalous (triple/quartic) gauge coupling models
  - aTGC & aQGC add higher dimensional operators (EFT) than SM

Probe EWSB in Vector Boson Scattering

- Unitarity preseverd in VBS via Higgs contributions
  - w/o Higgs, $\sigma \sim E^2$
- Deviations from EWSB would manifest in differential cross-sections and in aTGC/aQGC searches

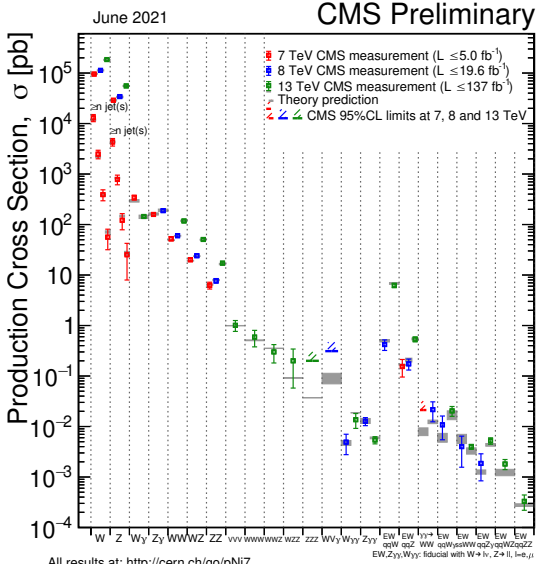
BSM Searches

- Extra dimensions
- New resonances/gauge bosons
- aTGC & aQGC

Validation of Perturbative Calculations

- NNLO QCD
  - MATRIX simulations
- NLO EW

Reviews: PPNP.2019.06.002, PPNP.2018.01.009, RevModPhys.89.035008



- $W\gamma$:
  - Inclusive: PhysRevLett.126.252002
  - Differential: SMP-20-005
- VV ($V = W/Z$):
  - WW: PhysRevD.102.092001
  - WZ: SMP-20-014
    (see Carlos Cid's poster)
  - ZZ: Eur.Phys.J.C81,200(2021)
  - @ 5.02 TeV: SMP-20-012
- VVV: PhysRevLett.125.151802
- $V\gamma\gamma$: SMP-19-013
- VBS (see Meng Lu's talk):
  - $W\gamma$: PhysLetB.2020.135988
  - $Z\gamma$: SMP-20-016
  - Polarized same-sign WW: PhysLetB.2020.136018
  - WZ & same-sign WW: PhysLetB.2020.135710
  - ZZ: PhysLetB.2020.135992

This talk

Event Selection

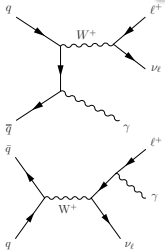
Lepton (e/μ):
- Isolated
- $p_T^e > 30$ GeV, $|\eta^e| < 2.5$
- $p_T^\mu > 35$ GeV, $|\eta^\mu| < 2.4$

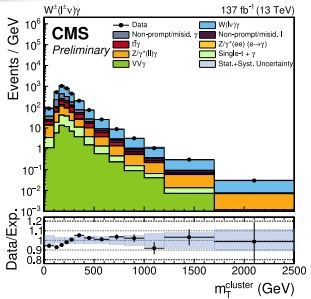
Fiducial region for cross-section:
- $p_T^l > 30$ GeV, $|\eta^l| < 2.5$

Photon:
- Isolated
- $p_T > 30$ GeV, $|\eta| < 2.5$
- $\Delta R(\gamma, l) > 0.7$

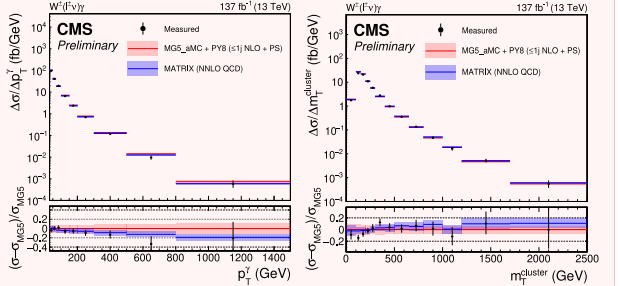
MET:
- $\not{E}_T > 40$ GeV

Veto events with:
- Extra leptons with $p_T > 10$ GeV
- 70 GeV $< m_{\gamma e} <$ 110 GeV
- 70 GeV $< m_{\gamma\mu} <$ 100 GeV



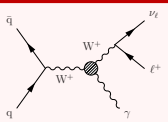


Differential Cross-sections



SMP-20-005

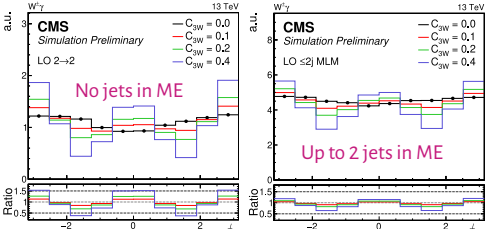
Anomalous $WW\gamma$ Coupling



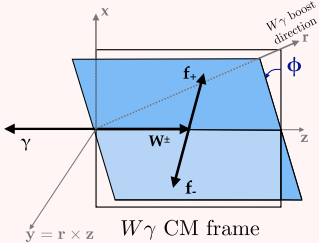
$$\sigma^{\text{tot}} = \sigma_{\text{SM}} + C_{3W}\sigma_{\text{int}} + C_{3W}^2\sigma_{\text{BSM}}$$

aTGC enhancement cuts:

- $p_T^l > 80$ GeV
- $p_T^\gamma > 150$ GeV
- Jet veto ($p_T > 30$ GeV & $|\eta| < 2.5$)

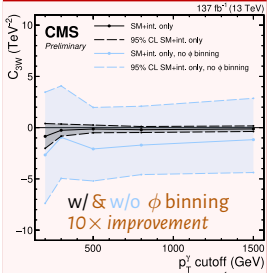


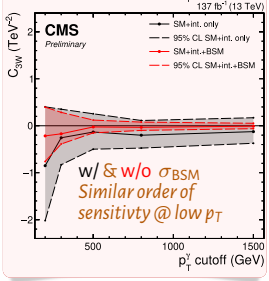
Interference Resurrection



- At $E > m_W$, SM and BSM have different helicity configurations for $W_T V_T$ (PhysLetB.2017.11.068 & JHEP10(2017)027) $\Longrightarrow$ angle-inclusive variables (e.g. p_T^γ) are insensitive to σ_{int}
- **Solution:** Search in 2D space of $|\phi_f|$ and p_T^γ
  - Improved further with jet veto

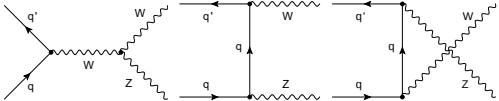
Limits





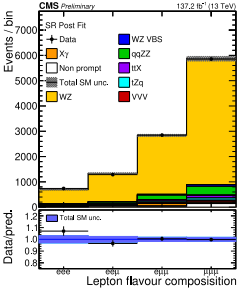
WZ production:

- Primarily q-initiated→sensitive to u & d PDFs
- Dominant trilepton source →understand BG precisely

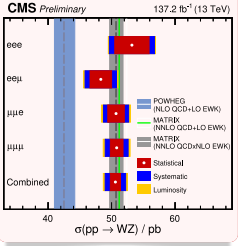


Event Selection

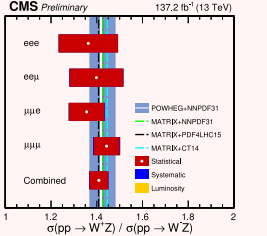
- ≥ 1 opposite-sign same-flavor lepton pair
  - $|\eta^e| < 2.5, |\eta^\mu| < 2.4$
- $p_T(l_{Z1}) > 25\,\text{GeV}, p_T(l_{Z2}) > 10\,\text{GeV}, p_T(l_W) > 25\,\text{GeV}$
- $|m(l_{Z1}, l_{Z2}) - m_Z| < 15\,\text{GeV}$
- $\not{E}_T > 30\,\text{GeV}$ (suppress non-prompt l)
- $m(l_{Z1}, l_{Z2}, l_W) > 100\,\text{GeV}$ (suppress $Z\gamma$)
- b-tag veto (suppress top)
- 4th lepton veto (suppress ZZ)
- $\min\{m(l,l)\} > 4\,\text{GeV}$ (match generator)
- Fiducial region for cross-section:
  - $|\eta^l| < 2.5, 60\,\text{GeV} < m(l_{Z1}, l_{Z2}) < 120\,\text{GeV}$



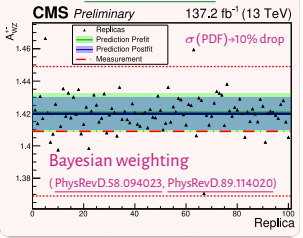
Total Cross-sections



Charge Asymmetry

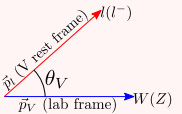


PDF Constraints



- Non-resonant *VV* production yields mostly transversal polarizations
- Anomalies in V-spin observables would be an indirect sign of NP

Polarization Observables

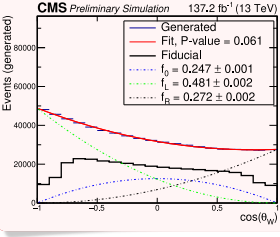


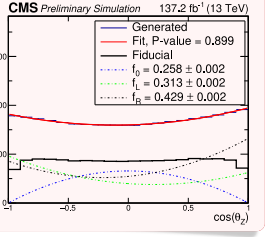
$$\frac{d\sigma}{\sigma\, d\cos\theta_V} = \text{Pol2}_V(\cos\theta_V; f_L^V, f_R^V, f_0^V)$$

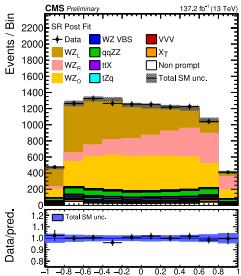
where $V = W/Z$ & $f_L^V + f_R^V + f_0^V = 1$

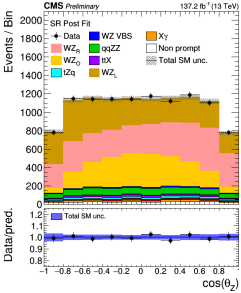
(PhysRevD.93.011301, Eur.Phys.J.C77,234(2017))

Polarization Templates

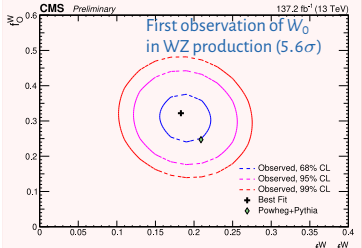


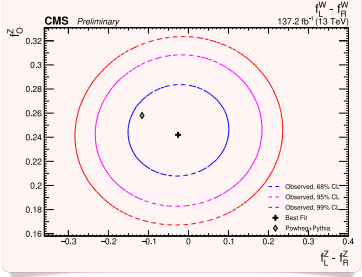




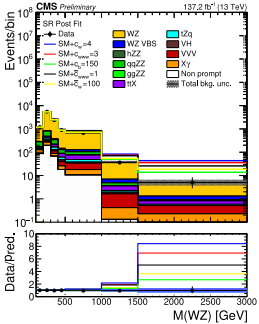


Measured Polarization Fractions

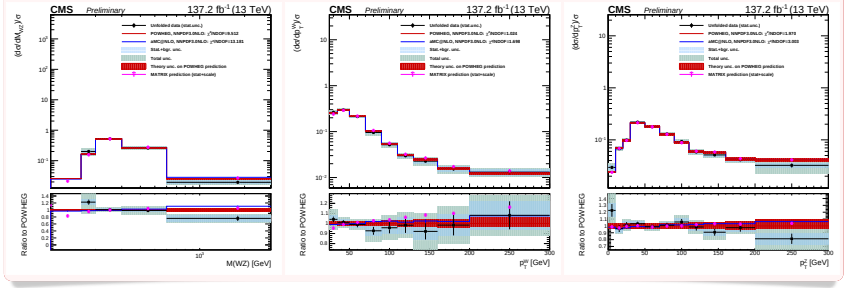




WZ: Differential Cross-sections & aTGC Constraints



Differential Cross-sections



5 EFT operators in dim-6 extension contribute to WZ production:

- 3 CP-conserving:

$$\frac{c_{WWW}}{\Lambda^2}, \frac{c_W}{\Lambda^2}, \frac{c_b}{\Lambda^2}$$

- 2 CP-violating:

$$\frac{\tilde{c}_{WWW}}{\Lambda^2}, \frac{\tilde{c}_W}{\Lambda^2}$$

Search in observable $M(WZ)$

Limits on Anomalous WWZ Couplings

Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_W/Λ^2	$[-2.05, 1.27]$	$[-2.52, 0.33]$	-1.34
c_{WWW}/Λ^2	$[-1.27, 1.33]$	$[-1.04, 1.19]$	0.15
c_b/Λ^2	$[-86.0, 125.0]$	$[-42.7, 113.0]$	43.6
$\tilde{c}_{WWW}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\tilde{c}_W/\Lambda^2$	$[-46.1, 46.1]$	$[-45.9, 45.9]$	0.0

- CP-conserving coupling limits improved by $\times 2$
- First CMS limits on CP-violating WWZ couplings

VV @ 5.02 TeV (302 pb^{-1})

- Low pile-up run: $\mu_{5\,\text{TeV}} = 2$ ($\mu_{13\,\text{TeV}} = 23, 32$)

Categories:

- WW: $2l$
- WZ: (a) $3l$ & (b) 2 same-sign μ's
- ZZ: (a) $4l$ & (b) $2l + 2\nu$

Source	Number of events
Top quark	$9.0 \pm 0.1 \pm 1.1$
WZ+ZZ	$5.6 \pm 1.0 \pm 1.1$
Drell–Yan	$1.8 \pm 0.5 \pm 0.2$
Conversions	$2.7 \pm 0.7 \pm 0.7$
Nonprompt ℓ	$11.2 \pm 1.3 \pm 3.4$
Background	$30.3 \pm 1.9 \pm 3.9$
WW signal	$55.2 \pm 0.3 \pm 1.8$
Data	101

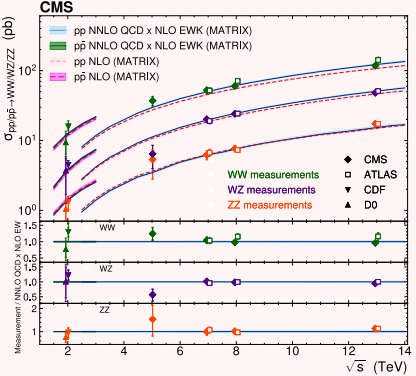
WW Yields

SR	Background	Signal	Data
WZ 3ℓ	$4.0 \pm 0.6 \pm 0.4$	$14.8 \pm 0.1 \pm 0.6$	12
WZ 2μss	$0.6 \pm 0.1 \pm 0.1$	$3.2 \pm 0.8 \pm 0.2$	4
ZZ 4ℓ	$0.5 \pm 0.2 \pm 0.1$	$2.7 \pm 0.0 \pm 0.2$	3
ZZ $2\ell 2\nu$	$4.8 \pm 0.3 \pm 0.7$	$4.0 \pm 0.0 \pm 0.2$	12

WZ & *ZZ* Yields

Cross-sections

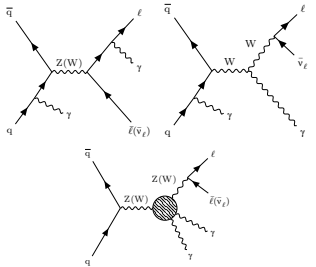
Process	Estimation	Total cross section [pb]
WW	MATRIX	$29.8^{+0.7}_{-0.6}$(scale)
	Measured	$37.0^{+5.5}_{-5.2}(\text{stat})^{+2.7}_{-2.6}$(syst)
WZ	MATRIX	$11.3^{+0.2}_{-0.2}$(scale)
	Measured	$6.4^{+2.5}_{-2.1}(\text{stat})^{+0.5}_{-0.3}$(syst)
ZZ	MATRIX	$3.9^{+0.1}_{-0.1}$(scale)
	Measured	$5.3^{+2.5}_{-2.1}(\text{stat})^{+0.5}_{-0.4}$(syst)



- First measurement @ 5.02 TeV

$V\gamma\gamma$: Cross-sections and aQGC Limits

SMP-19-013 (Submitted to J.HighEnerg.Phys.)



- $V\gamma\gamma$ is an important background in VH and BSM searches
  → need precise understanding
- $WW\gamma\gamma$ is the only $VV\gamma\gamma$ coupling in SM
  → deviations would be sign of NP
- Under EFT, 10 dim-8 operators contribute to $V\gamma\gamma$ production
  - Search in $p_T^{\gamma\gamma}$

Event Selection

- $\geq$ 2 photons: $p_T > 20$ GeV
- $W\gamma\gamma$: 1 lepton, $p_T^{e(\mu)} > 35(30)$ GeV
- $Z\gamma\gamma$: 2 same-flavor opposite-sign leptons, $p_T^{e(\mu)} > 35(30)$ GeV, $m_{ll} > 55$ GeV

aQGC Limits

	$W\gamma\gamma$ (TeV^{-4})		$Z\gamma\gamma$ (TeV^{-4})	
Parameter	Expected	Observed	Expected	Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

Cross-sections

Cross Section	Theoretical (fb) MadGraph5_aMC@NLO	Measured (fb)
$W\gamma\gamma$	18.70 $\pm$ 0.03 (MC stat) $\pm$ 0.12 (PDF+scale)	$13.6^{+1.9}_{-1.9}$ (stat) $^{+4}_{-4}$ (syst) $\pm$ 0.08 (PDF+scale)
$Z\gamma\gamma$	5.96 $\pm$ 0.01 (MC stat) $\pm$ 0.06 (PDF+scale)	$5.41^{+0.58}_{-0.55}$ (stat) $^{+0.64}_{-0.70}$ (syst) $\pm$ 0.06 (PDF+scale)

First measurement @13 TeV

Summary

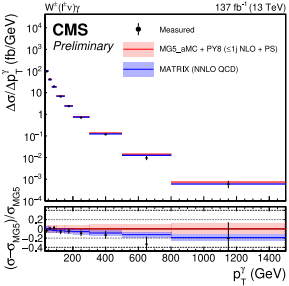
- Presented recent CMS results on multiboson measurements with Run II data
- Observations consistent with SM predictions
- Tightened constraints on anomalous coupling parameters
- First measurements:
  - Observation of logitudinal W in WZ production
  - CMS limits on CP-violating anomalous WWZ coupling
  - VV cross-sections @ 5.02 TeV
  - $V\gamma\gamma$ cross-sections @ 13 TeV
- More Run II multiboson results to come

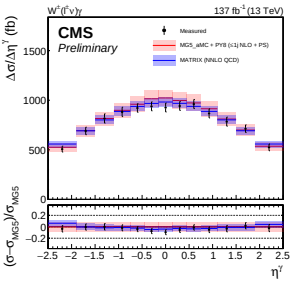
BACKUP

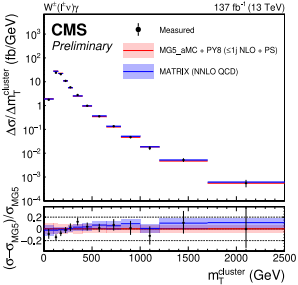
$W + \gamma$: Systematics

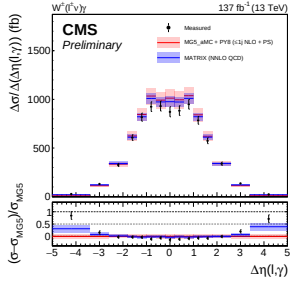
Uncertainty	Affects shape	Corr. years	Relative effect on expected yield
		Experimental	
Integrated luminosity	-	Partial	2.3–2.5%
Pileup modeling	✓	✓	0.2–3.1%
L1 prefiring	✓	✓	0.3–1.1%
Electron ID	✓	✓	0.7–2.8%
Electron ID ($p_T^e > 200\,\text{GeV}$)	✓	-	0.1–1.2%
Electron trigger	-	-	0.5%
Muon ID (stat)	✓	-	0.1–0.6%
Muon ID (syst)	✓	✓	0.2–0.7%
Muon trigger	✓	-	0.1–0.7%
Photon ID	✓	✓	0.6–6.0%
Photon ID ($p_T^\gamma > 200\,\text{GeV}$)	✓	-	2.1–4.7%
Photon ID (high p_T extrapolation)	✓	-	Typically 3.0–9.0%, max. 14%
Photon (e veto)	-	-	1%
Photon energy scale	✓	✓	Typically 0.1–4.8%, max. 13%
Jet energy scale	✓	-	1–4%
p_T^{miss} scale	✓	Partial	0.1–10.1%
$e \to \gamma$ misidentification	✓	-	Typically 6.7–18%, max. 25%
Jet $\to \gamma$ misidentification	✓	-	10–45%
Misidentified e	✓	-	Typically 13–36%, max. 75%
Misidentified μ	✓	-	Typically 16–42%, max. 70%
		Theoretical	
$W^\pm\gamma$ acceptance (scale)	✓	✓	0.3–1.7%
$W^\pm\gamma$ acceptance (PDF)	✓	✓	Typically 0.5–2.2%, max. 7.6%
$W^\pm\gamma$ out-of-acceptance (scale)	✓	✓	5.2–12%
$W^\pm\gamma$ parton shower modeling	✓	✓	0.2–1.3%
Background normalization (scale)	-	✓	2.0–16%
Background normalization (PDF)	-	✓	4.2–4.8%

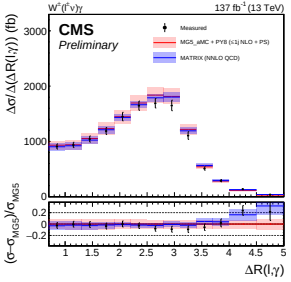
$W + \gamma$: Differential Cross-sections



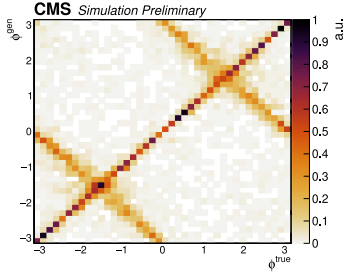


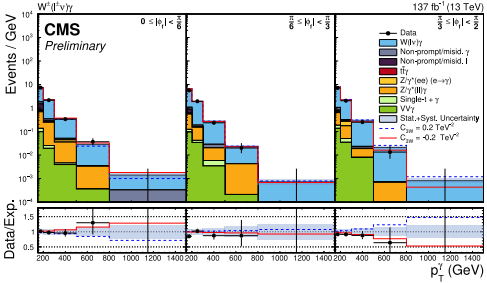






$W + \gamma$: Interference Resurrection





WZ: Systematics

Source	2016	2017	2018	Correlation scheme	Processes
Electron efficiency	0 – 3.3	0 – 3.0	0 – 2.8	Partially correlated	All MC
Muon efficiency	0 – 2.4	0 – 2.1	0 – 2.0	Partially correlated	All MC
Muon energy scale	0 – 5	0 – 5	0 – 5	Correlated	All MC
Electron energy scale	0 – 5	0 – 5	0 – 5	Correlated	All MC
Trigger efficiency	−1.0/0.6	−0.7/0.6	−0.7/0.6	Partially correlated	All MC
Jet energy scale	0.9	0.7	1.1	Partially correlated	All MC
B-tagging (heavy)	1.0	0.7	0.9	Correlated	All MC
B-tagging (light)	0.5	0.4	0.3	Correlated	All MC
Pileup	0.9	0.8	0.8	Correlated	ALL MC
ISR	0.2 – 20	0.2 – 20	0.2 – 20	Correlated	WZ
Nonprompt norm.	30	30	30	Correlated	nonprompt
VVV norm.	50	50	50	Correlated	VVV
VH norm.	25	25	25	Correlated	VH
WZ VBS norm.	20	20	20	Correlated	WZ VBS
ZZ	Free	Free	Free	Correlated	ZZ
$t\bar{t}Z$ norm.	Free	Free	Free	Correlated	$t\bar{t}X$
tZq norm.	Free	Free	Free	Correlated	tZq
$X\gamma$ norm.	Free	Free	Free	Correlated	$X\gamma$
Luminosity	2.5	2.3	2.5	Partially correlated	All MC
Statistical uncertainties	By bin	By bin	By bin	Decorrelated	All MC
Theoretical (PDF + Scale)	0.9	0.9	0.9	Correlated	WZ

WZ: Cross-sections

$$\sigma_{\text{fid}}(pp \to WZ) = \frac{N_{\text{SR}}}{\epsilon\mathcal{L}}\left(\frac{N_{\text{fid}}^{\text{SR}}}{N_{\text{tot}}^{\text{SR}}}\right)$$

$$\sigma_{\text{tot}}(pp \to WZ) = \frac{N_{\text{SR}}}{\text{BR}(W \to l\nu)\,\text{BR}(Z \to l'\bar{l}')\mathcal{A}\epsilon\mathcal{L}}\left(\frac{N_{\text{fid}}^{\text{SR}}}{N_{\text{tot}}^{\text{SR}}}\right)$$

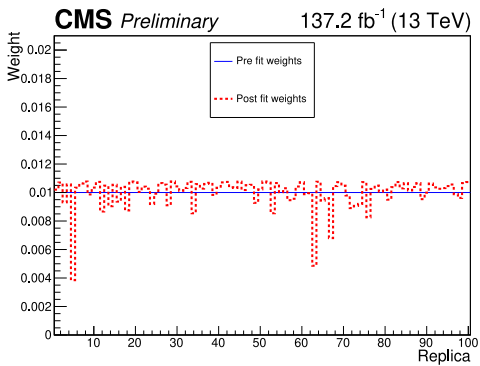
Quantity	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Inclusive
Efficiency	0.0507 ± 0.0006	0.1044 ± 0.0008	0.2166 ± 0.0011	0.4582 ± 0.0013	0.2074 ± 0.0005
Acceptance	0.0447 ± 0.0001	0.0448 ± 0.0001	0.0448 ± 0.0001	0.0446 ± 0.0001	0.1789 ± 0.0002
$N_{fid}^{SR}/N_{tot}^{SR}$	0.950 ± 0.002	0.952 ± 0.001	0.946 ± 0.001	0.948 ± 0.001	0.949 ± 0.001

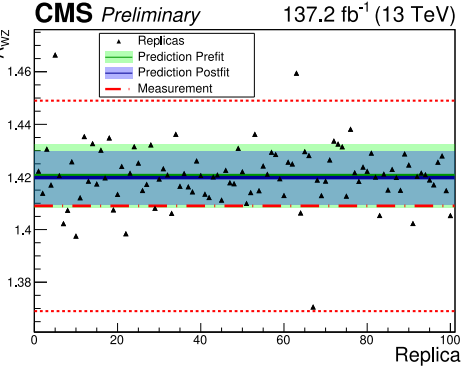
Category (Source)	Fiducial cross-section
eee(POWHEG)	$62.5\ ^{+2.4}_{-2.0}$(scale) $\pm$ 0.9(PDF)fb
eee(MATRIX, NNLO QCD)	$76.8\ ^{+1.8}_{-1.6}$(scale)fb
eee(MATRIX, NNLO QCDxNLO EWK)	$75.3\ ^{+1.7}_{-1.5}$(scale)fb
eee(Measured)	78.6 ± 4.1(stat.) $\pm$ 3.2(syst.) $\pm$ 1.4(lumi.) $\pm$ 0.7(theo.)fb
eeμ(POWHEG)	$62.5\ ^{+2.4}_{-2.0}$(scale) $\pm$ 0.9(PDF)fb
eeμ(MATRIX, NNLO QCD)	$75.3\ ^{+1.8}_{-1.6}$(scale)fb
eeμ(MATRIX, NNLO QCDxNLO EWK)	$73.8\ ^{+1.7}_{-1.5}$(scale)fb
eeμ(Measured)	71.3 ± 2.9(stat.) $\pm$ 2.2(syst.) $\pm$ 1.3(lumi.) $\pm$ 0.7(theo.)fb
$\mu\mu$e(POWHEG)	$62.5\ ^{+2.4}_{-2.0}$(scale) $\pm$ 0.9(PDF)fb
$\mu\mu$e(MATRIX, NNLO QCD)	$75.3\ ^{+1.8}_{-1.6}$(scale)fb
$\mu\mu$e(MATRIX, NNLO QCDxNLO EWK)	$73.8\ ^{+1.7}_{-1.5}$(scale)fb
$\mu\mu$e(Measured)	74.8 ± 1.9(stat.) $\pm$ 2.1(syst.) $\pm$ 1.4(lumi.) $\pm$ 0.7(theo.)fb
$\mu\mu\mu$(POWHEG)	$62.5\ ^{+2.4}_{-2.0}$(scale) $\pm$ 0.9(PDF)fb
$\mu\mu\mu$(MATRIX, NNLO QCD)	$76.8\ ^{+1.8}_{-1.6}$(scale)fb
$\mu\mu\mu$(MATRIX, NNLO QCDxNLO EWK)	$75.3\ ^{+1.7}_{-1.3}$(scale)fb
$\mu\mu\mu$(Measured)	74.9 ± 1.4(stat.) $\pm$ 1.9(syst.) $\pm$ 1.4(lumi.) $\pm$ 0.7(theo.)fb
Inclusive (POWHEG)	$250.0\ ^{+9.7}_{-8.0}$(scale) $\pm$ 3.5(PDF)fb
Inclusive (MATRIX, NNLO QCD)	$304.2\ ^{+7.3}_{-6.5}$(scale)fb
Inclusive (MATRIX, NNLO QCDxNLO EWK)	$298.1\ ^{+6.9}_{-6.3}$(scale)fb
Inclusive (Measured)	298.9 ± 4.8(stat.) $\pm$ 7.7(syst.) $\pm$ 5.4(lumi.) $\pm$ 2.7(theo.)fb

Category	Fiducial cross-section
eee^+ (POWHEG)	$36.7^{+1.3}_{-0.9}$(scale) $\pm$ 0.7(PDF)fb
eee^+ (MATRIX, NNLO QCD)	$45.2^{+1.1}_{-0.9}$(scale)fb
eee^+ (MATRIX, NNLO QCDxNLO EWK)	$44.3^{+1.0}_{-0.9}$(scale)fb
eee^+ (Measured)	49.3 ± 3.4(stat.) $\pm$ 1.9(syst.) $\pm$ 1.0(lumi.) $\pm$ 0.5(theo.)fb
$\mathrm{ee}\mu^+$ (POWHEG)	$36.7^{+1.3}_{-0.9}$(scale) $\pm$ 0.7(PDF)fb
$\mathrm{ee}\mu^+$ (MATRIX, NNLO QCD)	$44.3^{+1.0}_{-0.9}$(scale)fb
$\mathrm{ee}\mu^+$ (MATRIX, NNLO QCDxNLO EWK)	$43.3^{+1.0}_{-0.9}$(scale)fb
$\mathrm{ee}\mu^+$ (Measured)	41.5 ± 1.9(stat.) $\pm$ 1.6(syst.) $\pm$ 0.9(lumi.) $\pm$ 0.4(theo.)fb
$\mu\mu\mathrm{e}^+$ (POWHEG)	$36.7^{+1.3}_{-0.9}$(scale) $\pm$ 0.7(PDF)fb
$\mu\mu\mathrm{e}^+$ (MATRIX, NNLO QCD)	$44.3^{+1.0}_{-0.9}$(scale)fb
$\mu\mu\mathrm{e}^+$ (MATRIX, NNLO QCDxNLO EWK)	$43.3^{+1.0}_{-0.9}$(scale)fb
$\mu\mu\mathrm{e}^+$ (Measured)	43.1 ± 1.4(stat.) $\pm$ 1.5(syst.) $\pm$ 0.9(lumi.) $\pm$ 0.4(theo.)fb
$\mu\mu\mu^+$ (POWHEG)	$36.7^{+1.3}_{-0.9}$(scale) $\pm$ 0.7(PDF)fb
$\mu\mu\mu^+$ (MATRIX, NNLO QCD)	$45.2^{+1.1}_{-0.9}$(scale)fb
$\mu\mu\mu^+$ (MATRIX, NNLO QCDxNLO EWK)	$44.3^{+1.0}_{-0.9}$(scale)fb
$\mu\mu\mu^+$ (Measured)	44.3 ± 1.0(stat.) $\pm$ 1.5(syst.) $\pm$ 1.0(lumi.) $\pm$ 0.4(theo.)fb
Inclusive (+) (POWHEG)	$146.9^{+5.7}_{-4.7}$(scale) $\pm$ 2.1(PDF)fb
Inclusive (+) (MATRIX, NNLO QCD)	$179.0^{+4.3}_{-3.8}$(scale)fb
Inclusive (+) (MATRIX, photon induced)	$1.76^{+0.08}_{-0.08}$(scale)fb
Inclusive (+) (MATRIX, NNLO QCDxNLO EWK)	$175.3^{+4.1}_{-3.7}$(scale)fb
Inclusive (+) (Measured)	175.9 ± 3.0(stat.) $\pm$ 5.6(syst.) $\pm$ 3.6(lumi.) $\pm$ 1.7(theo.)fb

Category	Fiducial cross-section
eee^- (POWHEG)	$25.8^{+0.9}_{-0.6}$(scale) $\pm$ 0.6(PDF)fb
eee^- (MATRIX, NNLO QCD)	$31.6^{+0.8}_{-0.7}$(scale)fb
eee^- (MATRIX, NNLO QCDxNLO EWK)	$31.0^{+0.7}_{-0.6}$(scale)fb
eee^- (Measured)	36.2 ± 3.3(stat.) $\pm$ 1.4(syst.) $\pm$ 0.7(lumi.) $\pm$ 0.3(theo.)fb
$\mathrm{ee}\mu^-$ (POWHEG)	$25.8^{+0.9}_{-0.6}$(scale) $\pm$ 0.6(PDF)fb
$\mathrm{ee}\mu^-$ (MATRIX, NNLO QCD)	$31.0^{+0.8}_{-0.7}$(scale)fb
$\mathrm{ee}\mu^-$ (MATRIX, NNLO QCDxNLO EWK)	$30.4^{+0.7}_{-0.6}$(scale)fb
$\mathrm{ee}\mu^-$ (Measured)	29.7 ± 1.7(stat.) $\pm$ 1.1(syst.) $\pm$ 0.6(lumi.) $\pm$ 0.3(theo.)fb
$\mu\mu\mathrm{e}^-$ (POWHEG)	$25.8^{+0.9}_{-0.6}$(scale) $\pm$ 0.6(PDF)fb
$\mu\mu\mathrm{e}^-$ (MATRIX, NNLO QCD)	$31.0^{+0.8}_{-0.7}$(scale)fb
$\mu\mu\mathrm{e}^-$ (MATRIX, NNLO QCDxNLO EWK)	$30.4^{+0.7}_{-0.6}$(scale)fb
$\mu\mu\mathrm{e}^-$ (Measured)	31.8 ± 1.4(stat.) $\pm$ 1.1(syst.) $\pm$ 0.6(lumi.) $\pm$ 0.3(theo.)fb
$\mu\mu\mu^-$ (POWHEG)	$25.8^{+0.9}_{-0.6}$(scale) $\pm$ 0.6(PDF)fb
$\mu\mu\mu^-$ (MATRIX, NNLO QCD)	$31.6^{+0.8}_{-0.7}$(scale)fb
$\mu\mu\mu^-$ (MATRIX, NNLO QCDxNLO EWK)	$31.0^{+0.7}_{-0.6}$(scale)fb
$\mu\mu\mu^-$ (Measured)	30.7 ± 0.9(stat.) $\pm$ 1.0(syst.) $\pm$ 0.7(lumi.) $\pm$ 0.3(theo.)fb
Inclusive (-) (POWHEG)	$103.1^{+4.0}_{-3.3}$(scale) $\pm$ 1.4(PDF)fb
Inclusive (-) (MATRIX, NNLO QCD)	$125.2^{+4.3}_{-3.8}$(scale)fb
Inclusive (-) (MATRIX, NNLO QCDxNLO EWK)	$122.8^{+4.1}_{-3.7}$(scale)fb
Inclusive (-) (Measured)	124.8 ± 2.7(stat.) $\pm$ 4.0(syst.) $\pm$ 2.5(lumi.) $\pm$ 1.1(theo.)fb

NNPDF30_nlo_as118 : one-sided p=0.747





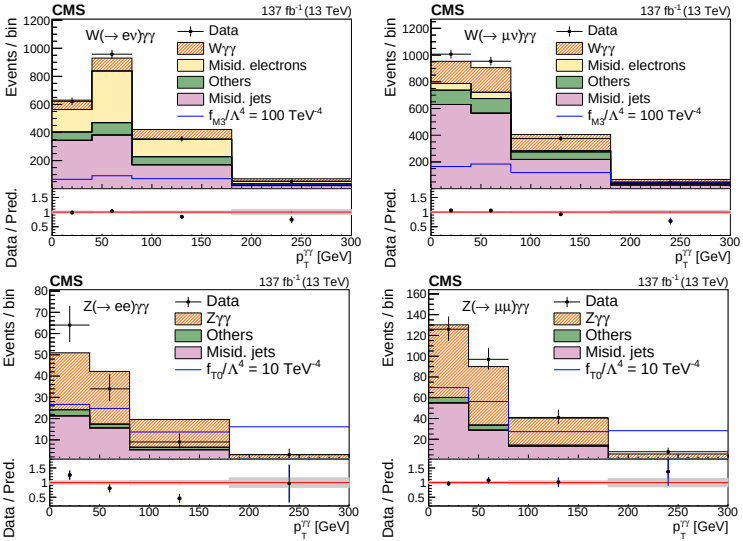
$V\gamma\gamma$: Event Selection, Yields and Systematics

- $\geq$ 2 photons: $p_T > 20$ GeV, $|\eta| < 2.5$
- $p_T^{e/\mu} > 15$ GeV, $|\eta^e| < 2.5$, $|\eta^\mu| < 2.4$
- $\Delta R(\gamma, \gamma/l) > 0.4$
- $|m_{e\gamma} - m_Z| > 5$ GeV, $|m_{e\gamma\gamma} - m_Z| > 5$ GeV
- $W\gamma\gamma$: 1 lepton, $p_T^{e(\mu)} > 35(30)$ GeV
- $Z\gamma\gamma$: 2 same-flavor leptons, $p_T^{e(\mu)} > 35(30)$ GeV, $m_{ll} > 55$ GeV

Process	$e\nu_e\gamma\gamma$	$\mu\nu_\mu\gamma\gamma$
Misid. jets	918 ± 23 (stat) ± 180 (syst)	1441 ± 27 (stat) ± 280 (syst)
Misid. electrons	669 ± 28 (stat) ± 34 (syst)	107 ± 9 (stat) ± 7 (syst)
Others	217 ± 11 (stat) ± 20 (syst)	286 ± 11 (stat) ± 25 (syst)
Total backgrounds	1804 ± 38 (stat) ± 180 (syst)	1834 ± 30 (stat) ± 280 (syst)
Expected signal	248 ± 6 (stat) ± 17 (syst)	500 ± 8 (stat) ± 33 (syst)
Total prediction	2052 ± 38 (stat) ± 180 (syst)	2334 ± 31 (stat) ± 280 (syst)
Data	1987	2384

Process	$ee\gamma\gamma$	$\mu\mu\gamma\gamma$
Misid. jets	42 ± 4 (stat) ± 9 (syst)	98 ± 5 (stat) ± 27 (syst)
Others	6 ± 1 (stat) ± 1 (syst)	11 ± 2 (stat) ± 1 (syst)
Total backgrounds	48 ± 4 (stat) ± 9 (syst)	109 ± 6 (stat) ± 27 (syst)
Expected signal	68 ± 2 (stat) ± 5 (syst)	157 ± 3 (stat) ± 11 (syst)
Total prediction	116 ± 4 (stat) ± 8 (syst)	266 ± 6 (stat) ± 23 (syst)
Data	110	272

Systematic source	$e\nu_e\gamma\gamma$ [%]	$\mu\nu_\mu\gamma\gamma$ [%]	$\ell\nu\gamma\gamma$ [%]	$ee\gamma\gamma$ [%]	$\mu\mu\gamma\gamma$ [%]	$\ell\ell\gamma\gamma$ [%]
Integrated luminosity	<1	2	2	3	1	3
Pile-up	2	<1	<1	2	<1	1
Electron efficiencies	4	—	<1	3	—	1
Muon efficiencies	1	<1	<1	2	<1	1
Photon efficiencies	18	13	12	6	5	5
Jet-photon misid.	25	22	21	6	5	6
Electron-photon misid.	4	<1	<1	—	—	—
$W\gamma$ theoretical cross section	3	3	3	<1	<1	<1
$Z\gamma$ theoretical cross section	4	<1	<1	7	5	6
Other bkgs theoretical cross section	5	2	2	<1	<1	<1
Simulated sample event count	18	7	8	7	3	4


CMS
137 fb-1 (13 TeV)
W(→ eν)γγ
Data
Wγγ
Misid. electrons
Others
Misid. jets
fM3/Λ4 = 100 TeV-4
Events / bin
Data / Pred.
pTγγ [GeV]
CMS
137 fb-1 (13 TeV)
W(→ μν)γγ
Data
Wγγ
Misid. electrons
Others
Misid. jets
fM3/Λ4 = 100 TeV-4
Events / bin
Data / Pred.
pTγγ [GeV]
CMS
137 fb-1 (13 TeV)
Z(→ ee)γγ
Data
Zγγ
Others
Misid. jets
fT0/Λ4 = 10 TeV-4
Events / bin
Data / Pred.
pTγγ [GeV]
CMS
137 fb-1 (13 TeV)
Z(→ μμ)γγ
Data
Zγγ
Others
Misid. jets
fT0/Λ4 = 10 TeV-4
Events / bin
Data / Pred.
pTγγ [GeV]

Cross Section	Theoretical (fb) MadGraph5_aMC@NLO	Measured (fb)	Significance Obs. (Exp.)
$W\gamma\gamma$	18.70 ± 0.03 (MC stat) ± 0.12 (PDF+scale)	$13.6^{+1.9}_{-1.9}$ (stat) $^{+4}_{-4}$ (syst) ± 0.08 (PDF+scale)	$3.1(4.5)\sigma$
$Z\gamma\gamma$	5.96 ± 0.01 (MC stat) ± 0.06 (PDF+scale)	$5.41^{+0.58}_{-0.55}$ (stat) $^{+0.64}_{-0.70}$ (syst) ± 0.06 (PDF+scale)	$4.8(5.8)\sigma$