Measurement of the W$\gamma\gamma$ and Z$\gamma\gamma$ Cross Sections and Limits on Dimension-8 Effective Field Theories

Christopher Anelli
on behalf of the CMS collaboration

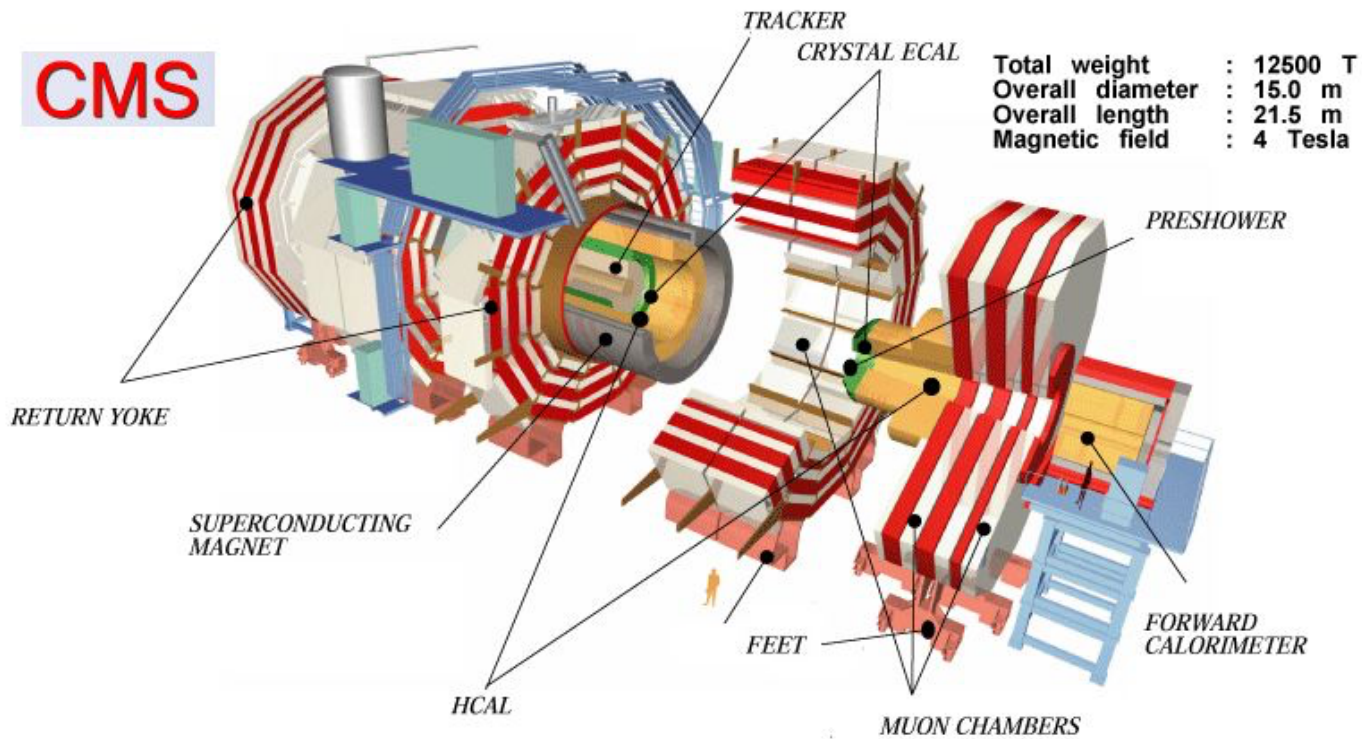
Lake Louise Winter Institute 2016

Overview

- Motivation for studying $W\gamma\gamma$ and $Z\gamma\gamma$
- Description of the Analysis
  - 2D Template Method for Estimating Jet Misidentification Background
  - Definition of Fiducial Region
- Fiducial Cross-Section Measurements
- Limits on Dimension-8 Effective Field Theories

- Reported in CMS-PAS-SMP-15-008: https://cds.cern.ch/record/2130360?ln=en

CMS Experiment



- Measurements made with **8 TeV** Proton-Proton Collisions collected by the CMS detector during the LHC Run 1, 2012.
- Collected events correspond to an integrated luminosity of **19.4 fb^{-1}**.

W$\gamma\gamma$ and Z$\gamma\gamma$

- W$\gamma\gamma$ and Z$\gamma\gamma$ are **rare** SM processes. This (and recent ATLAS results) are the first time these measurements have been made at a hadron collider.

- W$\gamma\gamma$ production is sensitive to **Quartic Gauge Couplings**.

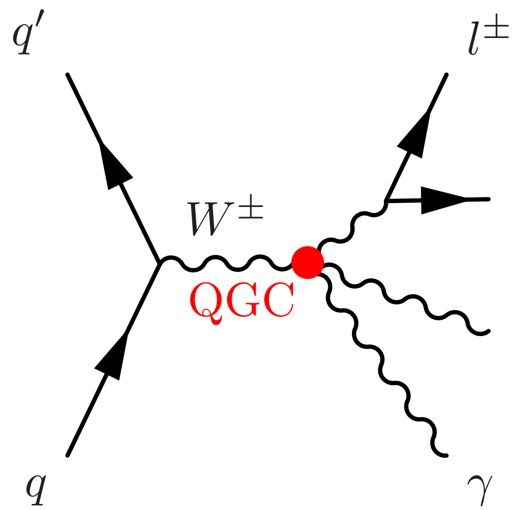
$$\mathcal{L} = \underline{-\frac{1}{4}W^{a\dagger}_{\mu\nu}W^{\mu\nu}_{a}} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

SU(2)$_L$ x U(1)$_Y$ Symmetry

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - \underline{g f_{abc} W^b_\mu W^c_\nu}$$

Non-abelian Term

Neutral Quartic Vertices (ie ZZ$\gamma\gamma$) are forbidden by the SM



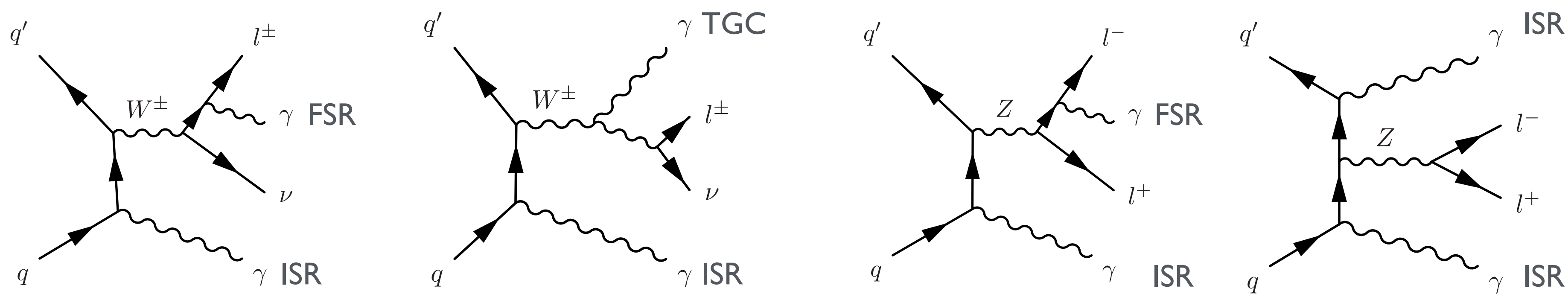
SM predicts value of the coupling strength

- Deviations from the SM prediction are a clear signal of **new physics.**

Additional Feynman Diagrams

Analysis is for **leptonic decay** of W and Z : W → μν† and Z →ℓℓ. (ℓ is e or μ)

Contributing diagrams come for Initial State Radiation (ISR), Final State Radiation (FSR), and Triple Gauge Couplings (TGC).



†W$\gamma\gamma$ electron channel in final stages of approval

---

W$\gamma\gamma$ and Z$\gamma\gamma$ signal samples are simulated at **NLO** with **MadGraph + Pythia.**

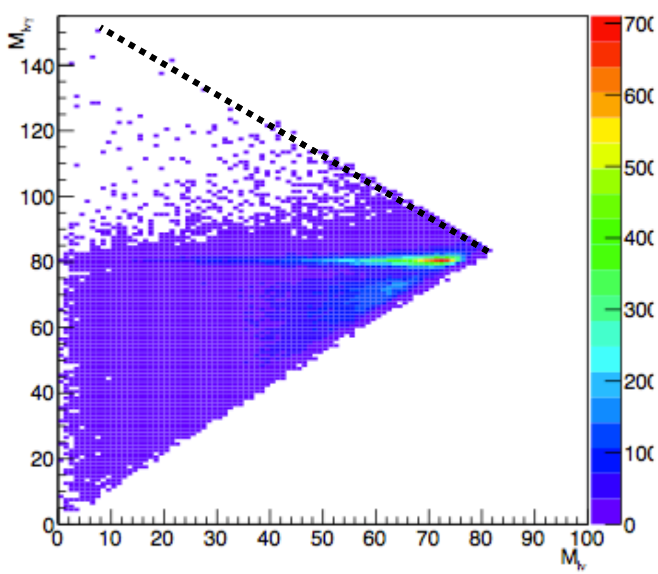
- To ensure W$\gamma\gamma$ QGC events are well sampled, signal split between FSR and ISR enhanced regions

- Separation is made during generation, cut on

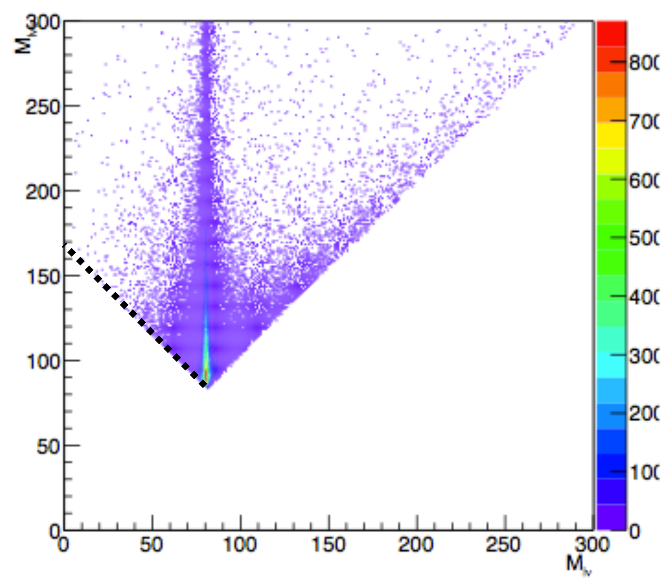
$$M_{\ell\nu\gamma'} + M_{\ell\nu}$$

where γ' is photon closest to the lepton. Cut value is **165** GeV.

FSR



ISR (Includes **TGC** and **QGC**)



Object and Event Selection

$W\gamma\gamma$ - Single Lepton Triggers

- Single Muon: pT Threshold 24 GeV

$Z\gamma\gamma$ - Dilepton Triggers

- Two Electrons: pT Threshold 17 and 8 GeV
- Two Muons: pT Threshold 17 and 8 GeV

Event Categorization

- Categorized by detector region in which the lead and sub-lead photons are reconstructed: **barrel-barrel**, **barrel-endcap**, **endcap-barrel**, and **endcap-endcap**

$W\gamma\gamma$ Selection

- Photons: **pT > 25 GeV**, $|\eta| < 2.5$
- Muons: isolated, pT > 25 GeV, $|\eta| < 2.1$
- Electrons: isolated, pT > 30 GeV, $|\eta| < 2.5$
- Exactly 1 lepton and 2 photons.
- $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma, \ell) > 0.4$
- No endcap-endcap events
- $m_T(\ell, E_T^{miss}) > 40$ GeV

  $E_T^{miss} = -\Sigma$ All PF Objects

  $$m_{\mathrm{T}} = \sqrt{2E_T^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}\left(1-\cos\left(\Delta\phi\left(E_T^{\ell}, E_{\mathrm{T}}^{\mathrm{miss}}\right)\right)\right)}$$
- No additional lepton with pT > 10 GeV $\longleftarrow$ To reduce the $Z\gamma\gamma$ background

$Z\gamma\gamma$ Selection

- Photons: **pT > 15 GeV**, $|\eta| < 2.5$
- Muons: isolated, pT > 10 GeV, $|\eta| < 2.4$
- Electrons: isolated, pT > 10 GeV, $|\eta| < 2.5$
- Exactly 2 opposite sign leptons and 2 photons.
- $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma, \ell) > 0.4$, $\Delta R(\ell, \ell) > 0.4$
- No endcap-endcap events
- $M_{\ell\ell} > 40$ GeV
- Lead lepton pT > 20 GeV

Full details for object identification and isolation are in backup slides.

Misidentified Jet Background

Number of jet misidentified as photons is estimated using a data driven 2D template method. **Charged hadron isolation** is the discriminating variable on the **lead** and **sublead** photons.

Processes

Four processes (V can be W of Z):

- $V\gamma\gamma$, both photons real: α_{RR}
- $V\gamma_{lead}$+jet, lead photon real sub-lead fake: α_{RF}
- $V\gamma_{sub}$+jet, lead photon fake sub-lead real: α_{FR}
- V+jets, both photons fake α_{FF}

Regions

Charged hadron isolation

Sub-lead Photon \ Lead Photon	Tight	Loose
Loose	N_{TL} Sideband Region	N_{LL} Sideband Region
Tight	N_{TT} Signal Region	N_{LT} Sideband Region

Charged hadron isolation

Templates

Real-real, real-fake, and fake-real efficiencies are product of 1D template efficiencies.

- real template: $W\gamma$ MC
- fake template: Z + jet CR

Fake-fake significant correlations

- fake-fake template: Independent sideband.

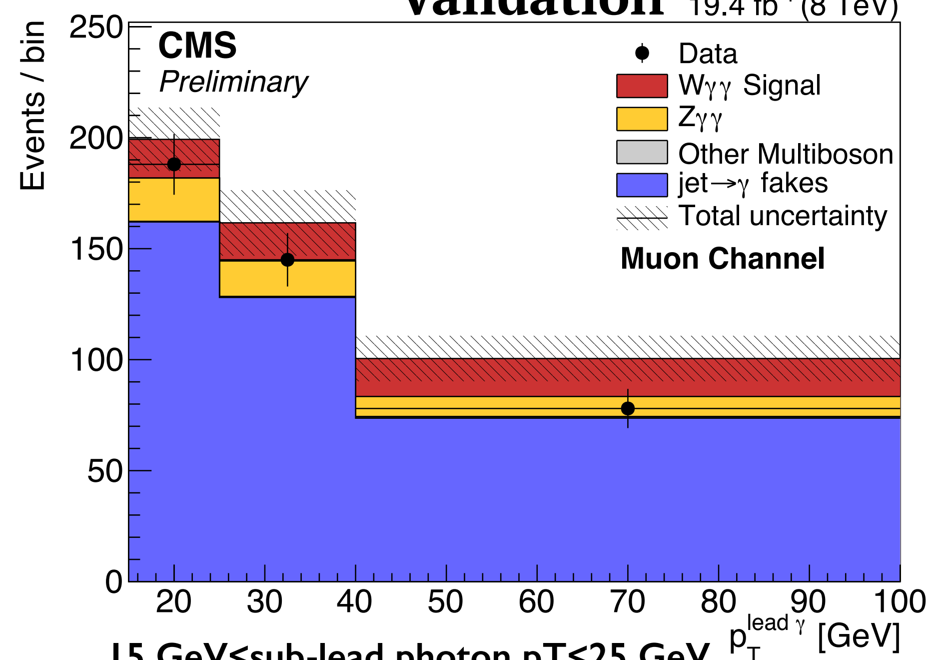
Observed **Efficiencies (Templates)** **Normalization**

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon^{TT}_{RR} & \epsilon^{TT}_{RF} & \epsilon^{TT}_{FR} & \epsilon^{TT}_{FF} \\ \epsilon^{TL}_{RR} & \epsilon^{TL}_{RF} & \epsilon^{TL}_{FR} & \epsilon^{TL}_{FF} \\ \epsilon^{LT}_{RR} & \epsilon^{LT}_{RF} & \epsilon^{LT}_{FR} & \epsilon^{LT}_{FF} \\ \epsilon^{LL}_{RR} & \epsilon^{LL}_{RF} & \epsilon^{LL}_{FR} & \epsilon^{LL}_{FF} \end{pmatrix} \begin{pmatrix} \alpha_{RR} \\ \alpha_{RF} \\ \alpha_{FR} \\ \alpha_{FF} \end{pmatrix}$$

16 efficiencies are calculated.

$$N_{bkgd} = \epsilon^{TT}_{RF}\alpha_{RF} + \epsilon^{TT}_{RF}\alpha_{FR} + \epsilon^{TT}_{FF}\alpha_{FF}$$

Validation



15 GeV<sub-lead photon pT<25 GeV

Other Backgrounds

- For **W$\gamma\gamma$** analysis, Z$\gamma\gamma$ is a background. Estimated using NLO MC.
- For both analyses, small contributions from diphoton processes, WW$\gamma\gamma$, WZ$\gamma\gamma$ ZZ$\gamma\gamma$, tt$\gamma\gamma$.

For each detector region, expected background sources, observed events, and simulated signal. (**W$\gamma\gamma$ muon channel**)

Region	jet misID	$Z\gamma\gamma$ + Irreducible	Total Background	Data	Expected signal
Muon Channel					
Barrel-Barrel	25 ± 6	9.6 ± 1.3	34 ± 6	62	16.5 ± 1.8
Barrel-Endcap	17 ± 3	1.9 ± 0.4	19 ± 3	26	4.1 ± 0.5
Endcap-Barrel	21 ± 4	2.5 ± 0.5	24 ± 4	20	4.1 ± 0.5
Sum	63 ± 11	14 ± 2	77 ± 12	108	25 ± 3

Definition of Fiducial Region

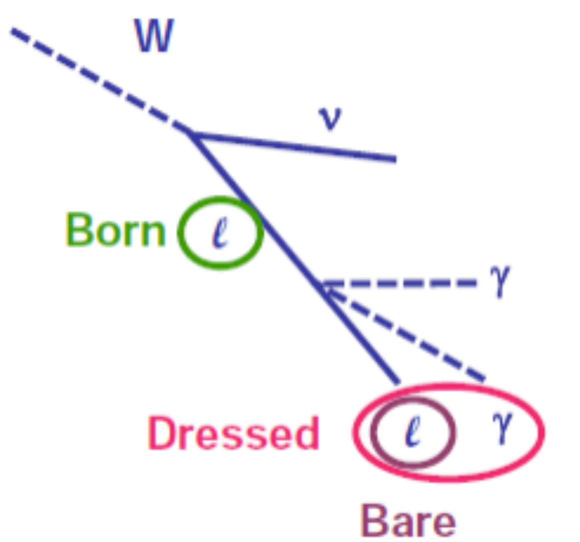
Fiducial region mirrors the off-line selection cuts as closely as possible. Small extrapolations made over pT, η, and photon location.

Definition of $W^{\pm}\gamma\gamma$ Fiducial Region

$p_{T}^{\gamma} > 25\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{T}^{\ell} > 25\,\text{GeV}$, $\lvert\eta^{\ell}\rvert < 2.4$
Exactly one candidate lepton and two candidate photons
$m_{T}(\ell, \nu(s)) > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$

Definition of $Z\gamma\gamma$ Fiducial Region

$p_{T}^{\gamma} > 15\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{T}^{\ell} > 10\,\text{GeV}$, $\lvert\eta^{\ell}\rvert < 2.4$
Exactly two candidate leptons and two candidate photons
lead $p_{T}^{\gamma} > 20\,\text{GeV}$
$M_{\ell\ell} > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$



- **Fiducial Leptons Definition:** When PYTHIA radiates the leptons, electrons are more likely than muons to produce collinear photons.
- Lepton universality restored by dressing the generator leptons with photons within ΔR < 0.1.

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Photons used in dressing are removed from the fiducial selection cuts.

Fiducial Cross Section

$$\sigma(pp \to \ell\nu\gamma\gamma)_{\text{Fiducial}} = (1 - \boxed{f_\tau}) \cdot \frac{N_{\text{obs}} - N_{\text{bkgd}}}{\boxed{C_{W\gamma\gamma}} \cdot \mathcal{L}}$$

$$\boxed{f_\tau = \frac{N_{gen}[W \to \tau\nu\gamma\gamma \to \ell\nu\nu\nu\gamma\gamma(\text{fiducial})]}{N_{gen}[W \to \ell\nu\gamma\gamma(\text{fiducial})] + N_{gen}[W \to \tau\nu\gamma\gamma \to \ell\nu\nu\nu\gamma\gamma(\text{fiducial})]}}$$

Tau Fraction is 2.4% for W$\gamma\gamma$ and 0.3% for Z$\gamma\gamma$

$$\boxed{C_{W^\pm\gamma\gamma} = \frac{N_{\text{reco}}\,[\text{W} \to \ell\nu\gamma\gamma] + N_{\text{reco}}\,[\text{W} \to \tau\nu\gamma\gamma \to \ell\nu\nu\nu\gamma\gamma]}{N_{\text{gen}}\,[\text{W} \to \ell\nu\gamma\gamma(\text{fiducial})] + N_{\text{gen}}\,[\text{W} \to \tau\nu\gamma\gamma \to \ell\nu\nu\nu\gamma\gamma(\text{fiducial})]}}$$

Fiducial Acceptance Factors

	Electron Channel	Muon Channel
$\frac{C_{W^\pm\gamma\gamma}}{1-f_\tau}$	–	$26.7 \pm^{1.2}_{1.1}$ %
$\frac{C_{Z\gamma\gamma}}{1-f_\tau}$	$22.5 \pm^{1.6}_{1.4}$ %	$29.1 \pm^{1.8}_{1.4}$ %

Summary of Systematics

Tables show sources of systematic and statistical uncertainty, their errors are propagated to the fiducial cross-section measurements:

Systematic Uncertainties	$W\gamma\gamma \to \mu\gamma\gamma$	$Z\gamma\gamma \to ee\gamma\gamma$	$Z\gamma\gamma \to \mu\mu\gamma\gamma$
Signal Simulation Systematics	$\delta(\sigma_{W\gamma\gamma})$	$\delta(\sigma_{Z\gamma\gamma})$	
Simulation Statistics	2.40%	3.25%	2.89%
Theory	1.65%	1.69%	1.37%
Data/MC Scale Factor Corrections	2.08%	4.89%	3.18%
Data/MC Energy Scale Corrections	2.52%	2.52%	3.07%
Total Signal Simulation	4.38%	6.60%	5.46%
Background Systematics	$\delta(\sigma_{W\gamma\gamma})$	$\delta(\sigma_{Z\gamma\gamma})$	
Misidentified Jet	37.19%	15.08%	12.51%
Misidentified Electron	-	-	-
$Z\gamma\gamma$	5.44%	-	-
Other Multiboson Backgrounds	1.02%	0.21%	0.26%
Total Background	37.64%	15.08%	12.51%
Statistical Uncertainties	$\delta(\sigma_{W\gamma\gamma})$	$\delta(\sigma_{Z\gamma\gamma})$	
Signal Region	29.30%	16.54%	13.64%
Sidebands	4.39%	1.39%	1.20%
Total Statistical	29.60%	16.60%	13.70%

Main uncertainties are from limited statistics and background systematics.

Cross sections for the electron and muon channel are combined using the **Best Linear Unbiased Estimator** (**BLUE**) method.

$Z\gamma\gamma$

Measured Cross Section (Photon pT >15 GeV)

$$\sigma^{\mathrm{fid}}_{\mathrm{Z}\gamma\gamma} \cdot \mathrm{BR}\,(\mathrm{Z} \to \ell\ell) = 12.7 \pm 1.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\,\mathrm{fb}$$

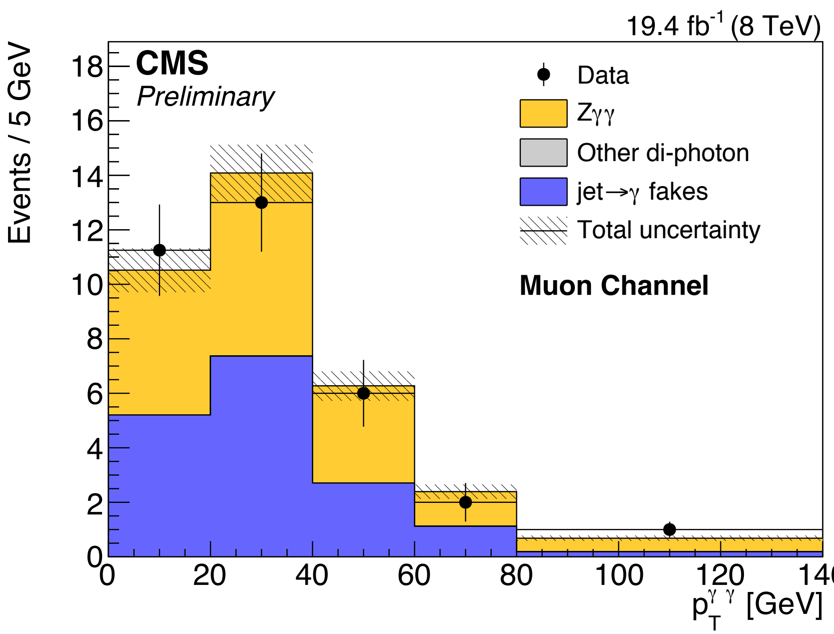
NLO Theory Prediction

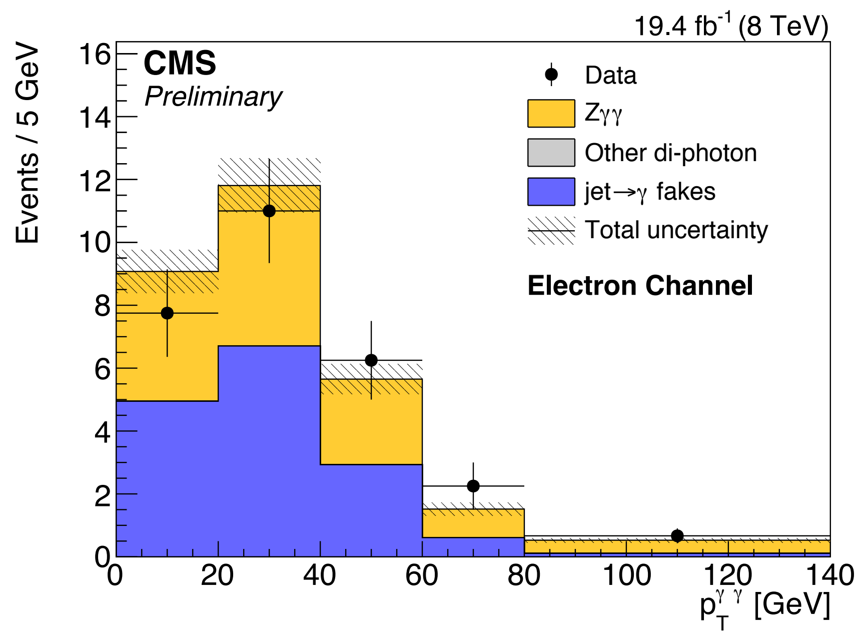
$$\sigma^{\mathrm{NLO}}_{\mathrm{Z}\gamma\gamma} \cdot \mathrm{BR}\,(\mathrm{Z} \to \ell\ell) = 12.95 \pm 1.47\,\mathrm{fb}$$

Significance

5.9 σ

Distribution of data, Z$\gamma\gamma$, and backgrounds events as a function of the diphoton transverse momentum.





W$\gamma\gamma$

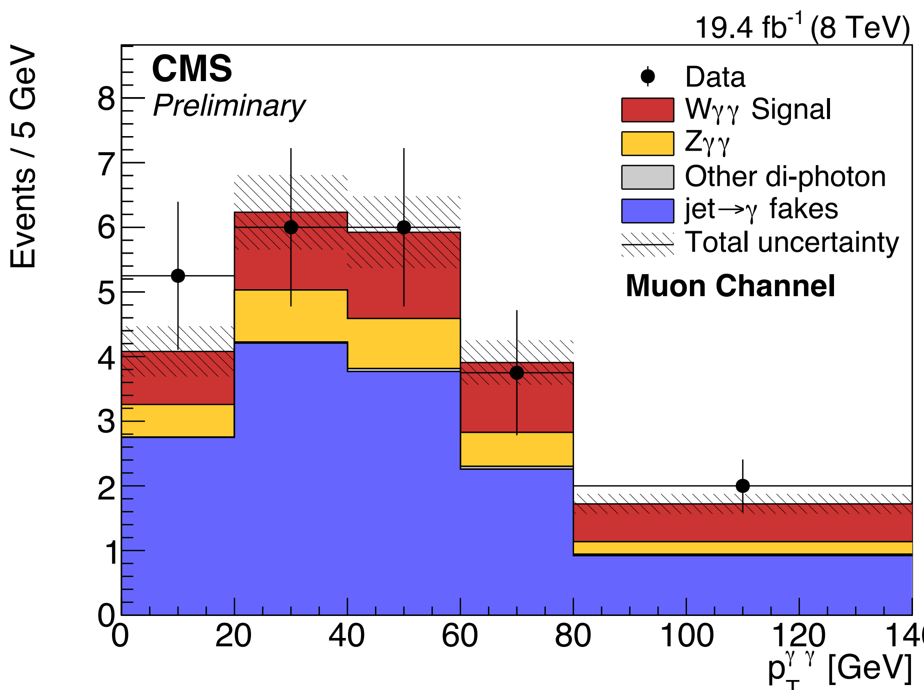
Measured Cross Section (Photon pT >25 GeV)

$$\sigma^{\text{fid}}_{W^{\pm}\gamma\gamma} \cdot \text{BR}\,(W \to \mu\nu) = 6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})\,\text{fb}$$

NLO Theory Prediction

$$\sigma^{\text{NLO}}_{W^{\pm}\gamma\gamma} \cdot \text{BR}\,(W \to \mu\nu) = 4.76 \pm 0.53\,\text{fb}$$

Distribution of data, W$\gamma\gamma$ (μ), and backgrounds events as a function of the diphoton transverse momentum.



Effective Field Theories

- Dimension-8 is the lowest order for "purely" quartic anomalous gauge couplings. There are 14 operators that contribute to the WW$\gamma\gamma$ vertex, we look at a subset.

$$\mathcal{L}_{\mathrm{aQGC}} = \mathcal{L}_{\mathcal{SM}} + \sum_i \frac{f_i}{\Lambda^4}\mathcal{O}_i + \ldots$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

- $\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$
- $\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$
- $\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$
- $\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$
- $\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$

γ is a linear combination of the B and W^3

- Effective Field Theories simulated with MadGraph using a reweighing method.
- Extrapolate between simulated coupling strengths with a parabolic fit.
- Modified signal region for the limit setting, **lead photon pT > 70 GeV.** Events are binned by channel and photons' detector region.
- Most the limit setting sensitivity comes from **barrel-barrel** events.

Limits

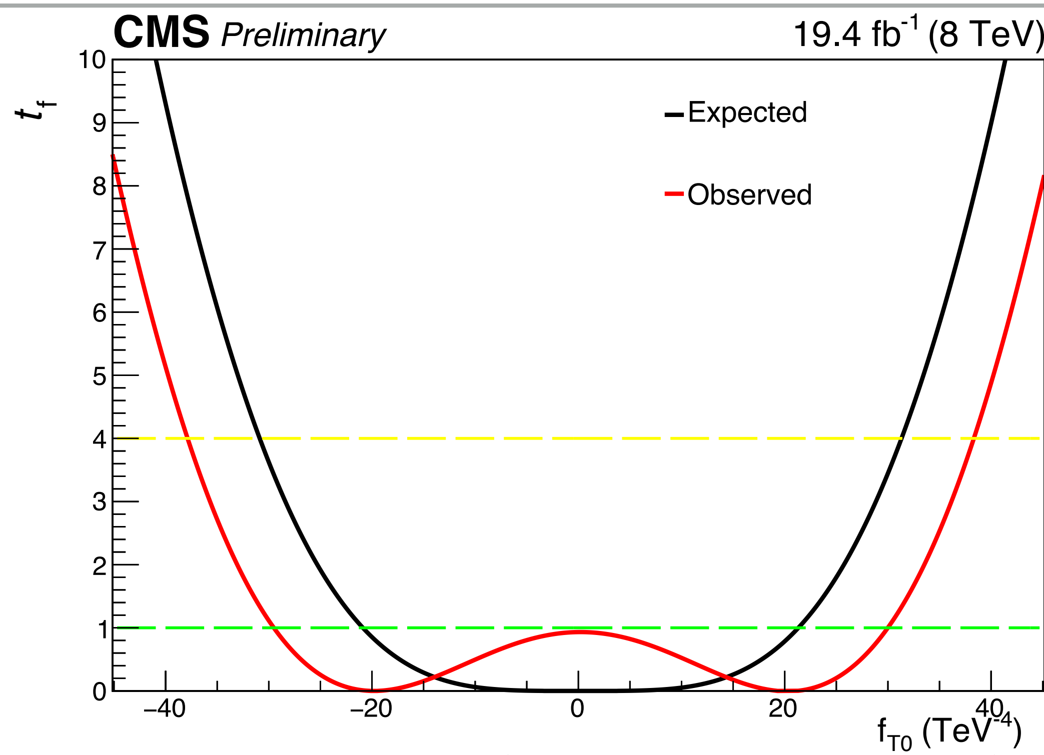
95% confidence interval set using a test statistic, t_f, behaves likes a $\chi 2$ distribution. (Only $W\gamma\gamma$ muon channel).

$$t_f = -2\ln\frac{L(f,\hat{\hat{\theta}})}{L(\hat{f},\hat{\theta})}$$

← Likelihood for specific *f*

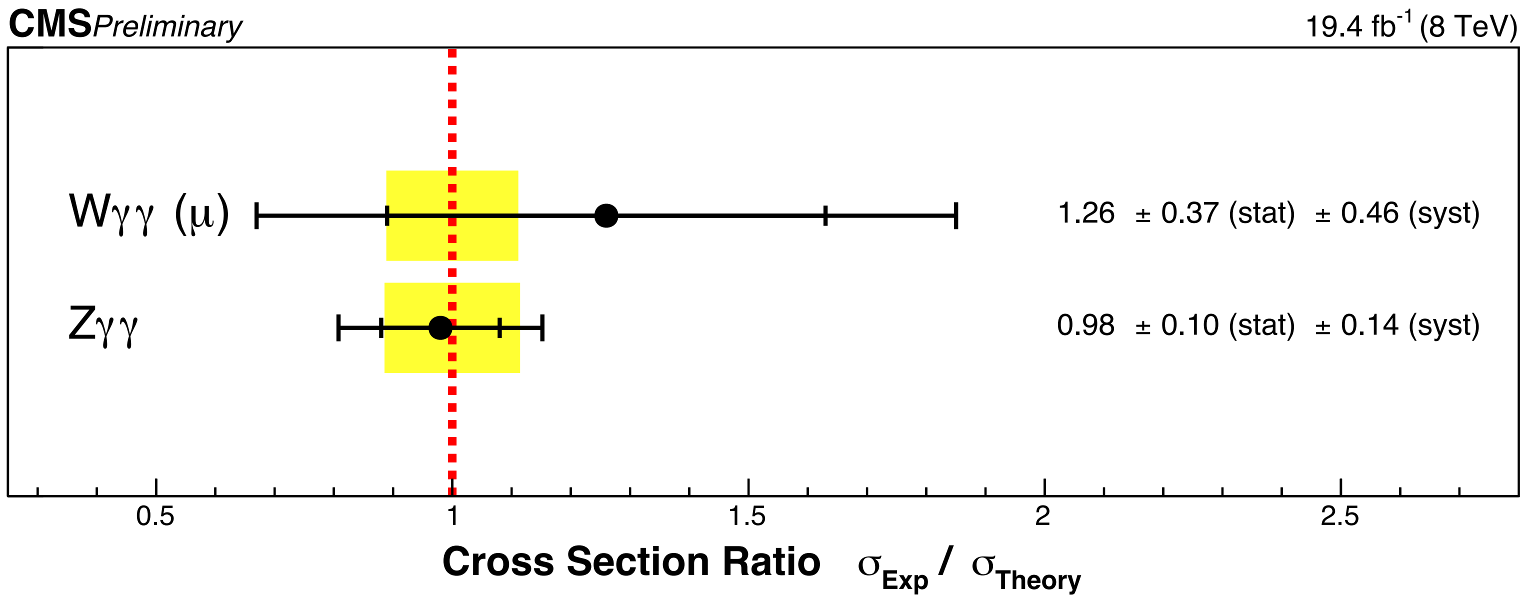
← Likelihood for best fit *f*

Expected and observed test statistic as a function of the f_{T0} coupling strength.



Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$\boxed{-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1}$	$\boxed{-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1}$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

Conclusion



- Fiducial cross sections for $W\gamma\gamma$ and $Z\gamma\gamma$ are measured and found to be consistent with the SM predictions.

- With $W\gamma\gamma$ (μ) events limits are set on EFT couplings, in particular the $\mathbf{f_{T0}}$ coupling:

$$\text{Expected:}\ \ -30.5 < f_{T0} < 31.1$$

$$\text{Observed:}\ \ -37.5 < f_{T0} < 38.1$$

- For the future: Approval of the $W\gamma\gamma$ electron channel. Also dimension-8 EFTs can introduce forbidden, neutral quartic gauge couplings. Set limits with $Z\gamma\gamma$.

More Information

1D Template Example

Most important background in the analysis if from jets misidentified as photons. The background is estimated using a data-driven, template method.

1D Template Example, Estimating **Wγ** background using $\boldsymbol{\sigma_{i\eta i\eta}}$ as the discriminating variable:

Processes

Two processes of unknown **normalization**:

Wγ process, real photons

Normalization α_R

W+jets process, fake photons

Normalization α_F

Regions

Photon $\sigma_{i\eta i\eta}$

N_T Signal Region	N_L Sideband Region
Tight	Loose

A.U. / 0.001

Count events in signal region, **Tight** (pass $\sigma_{i\eta i\eta}$) and sideband region, **Loose** ($\sigma_{i\eta i\eta}$ cut inverted).

Templates

Linear equations relate regions to the template efficiencies and normalizations

$$N_T = \varepsilon_R{}^T\alpha_R + \varepsilon_F{}^T\alpha_F$$

$$N_L = \varepsilon_R{}^L\alpha_R + \varepsilon_F{}^L\alpha_F$$

Invert matrix to solve for normalizations

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R^T & \epsilon_F^T \\ \epsilon_R^L & \epsilon_F^L \end{pmatrix} \begin{pmatrix} \alpha_R \\ \alpha_F \end{pmatrix}$$

Estimate Background

$$N_{bkgd} = \epsilon_F^T \alpha_F$$

Object Selection

As closely as possible, our analysis cuts match the definition of the Fiducial Region (have highlighted kinematic extrapolations).

Electrons

- MVA Electron ID
  - $|\eta| < 0.8$: MVA > 0.94
  - $0.8 < |\eta| < 1.48$: MVA > 0.85
  - $0.148 < |\eta| < 2.5$: MVA > 0.92
  - pfIso / pT < 0.15
  - No Missed Hits on Track
  - Conversion Veto
- Overlap Removal
  - $\Delta R(e,\mu) < 0.4$
- pT > 30 GeV
- $|\eta| < 2.4$

https://twiki.cern.ch/twiki/bin/viewauth/CMS/MultivariateElectronIdentification

Muons

- Tight Muon ID
  - Global and PF Muon
  - Global Track Fit $\chi 2 < 10$
  - 1+ hit in Muon Chamber
  - Muon segs. in 2 + stations
  - d0 < 0.2
  - z0 < 0.5
  - 1+ Pixel hits on ID Track
  - 5+ track layers on ID Track
  - PF Isolation

$$\mathrm{RelIso}_{\mathrm{PF}} = \frac{I_{\mathrm{CH}} + \max(0, I_{\mathrm{NH}} + I_{\gamma} - \Delta\beta * I_{\mathrm{CH\text{-}PU}})}{p_t^{\mathrm{muon}}},$$

- pT > 25 GeV
- $|\eta| < 2.1$

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

Photons

- Medium Photon ID
  - PF Photon
  - H/E < 0.05
  - Barrel **(Endcap)**
  - $\sigma_{i\eta i\eta} < 0.011$ **(0.033)**
  - Charged Hadron Isolation < 1.5 **(1.2)**
  - Neutral Hadron Isolation < 1.0 **(1.5)**+ 0.04*pT
  - Photon Isolation < 0.7 **(1.0)** + 0.005*pT
- Overlap Removal
  - $\Delta R(\ell, \gamma) < 0.4$
- pT > 15 GeV
- $|\eta| < 2.5$
- No Endcap Endcap γ's

https://twiki.cern.ch/twiki/bin/viewauth/CMS/CutBasedPhotonID2012

Negligible Backgrounds

Negligible backgrounds includes: jets faking a leptons, photons faking leptons, and multiple collisions (no vertex associated with the photon)

MadGraph Reweighting

MadGraph is used to simulate the Effective Field Theories. Use Reweighting Method.

$$W_{new} = |M_{new}|^2 / |M_{old}|^2 * W_{old} \, .$$

For the analysis, generate a range of coupling strengths for each EFT.

Dimension-8 Theory	Coupling Strength Range	Step Size	Generated Events
$L_{T,0}$ & $L_{T,1}$ & $L_{T,2}$	-50×10^{-12} : 50×10^{-12}	5×10^{-12}	119,875
$L_{M,0}$ & $L_{M,1}$	-5000×10^{-12} : 5000×10^{-12}	500×10^{-12}	120,665
$L_{M,2}$ & $L_{M,3}$	-1000×10^{-12} : 1000×10^{-12}	100×10^{-12}	120,665

Likelihood

For likelihood, observed number of events follows a Poisson distribution. Product over channels and detector regions.

SM signal Estimated Background

$$\mathcal{L}(f) = \prod_{i=1}^{nbins} Pois(x_i | \mu(f) \cdot s_i(\theta) + b_i(\theta)) \times P_n(\theta)$$

Observed Events aQGC/SM ratio Nuisance Parameters

Other Triboson Measurements

An 8TeV **W$\gamma\gamma$** measurement is also carried out by ATLAS (http://arxiv.org/abs/1503.03243), and an 8TeV **WVγ** measurement, V can be a W or Z, by CMS (http://arxiv.org/abs/1404.4619).

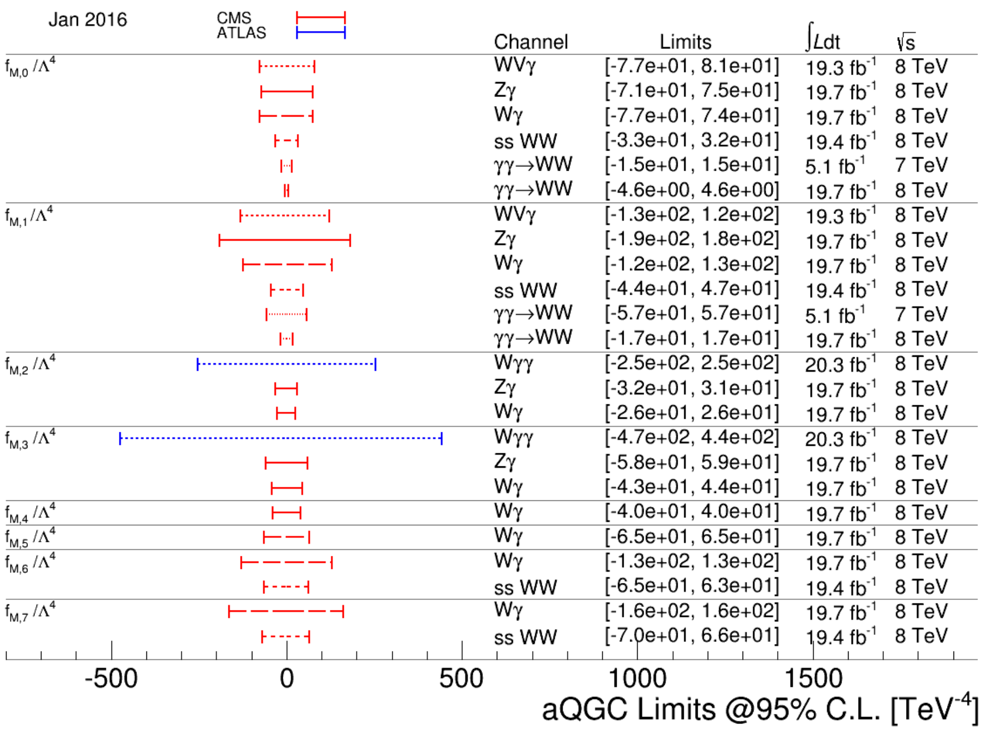
- Cannot directly compare two fiducial cross-section measurements (especially for final states containing photons) without considering the different fiducial definitions.
- ATLAS measures a **W$\gamma\gamma$** inclusive (jets) fiducial cross section 1.9σ above their SM prediction.
- CMS sets a 95% CL upper limit on the **WVγ** cross section that is a factor of 3.4 above their SM prediction.
- Comparison of the observed and expected limits on the f_{T0} EFT coupling:

Limits	ATLAS $W\gamma\gamma$	CMS $W\gamma\gamma$ (μ)	CMS $WV\gamma$
Observed	$16 < \frac{f_{T0}}{\Lambda^4} < 16$	$-38 < \frac{f_{T0}}{\Lambda^4} < 38$	$-25 < \frac{f_{T0}}{\Lambda^4} < 24$
Expected	$22 < \frac{f_{T0}}{\Lambda^4} < 22$	$-31 < \frac{f_{T0}}{\Lambda^4} < 31$	$-27 < \frac{f_{T0}}{\Lambda^4} < 27$

Other Dimension-8 EFT Limits

Public CMS results for the limits on the $f_{M,i}$ and $f_{T,i}$ couplings. In addition to triboson measurements limits are also set by measurements of vector boson scattering (VBS).

Dimension 8 $f_{M,i}$



Dimension 8 $f_{T,i}$