

A Search for $WW\gamma$ and $WZ\gamma$ Triboson Production and Anomalous Quartic Gauge
Couplings at $\sqrt{s} = 8$ and 13 TeV within the Compact Muon Solenoid

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ABSTRACT

An analysis probing for the standard model production of three electroweak vector bosons, $WV\gamma$ with $V = W$ or Z gauge boson, is presented. The W boson decays leptonically to an electron or muon, or their respective antiparticle, paired with the appropriate neutrino. The second boson V decays hadronically into two jets, and additionally a photon is required in the event. The data analyzed correspond to an integrated luminosity of 19.6 fb^{-1} and 2.3 fb^{-1} from proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ and 13 TeV , respectively, collected in 2012 and 2015 by the CMS detector at the Large Hadron Collider. The event selection criteria used in these analyses yields 322 and 46 observed events in data in 2012 and 2015, respectively, while the estimated background yield from theoretical predictions is 342.1 ± 22.2 and 54.3 ± 17.7 . These observations are consistent with the standard model next-to-leading order QCD predictions. Given the limitation in statistics to measure the cross section for this production process, an upper limit of 3.4 times the standard model predictions is made at a 95% confidence level for $WV\gamma$ with photon p_T greater than 30 GeV and absolute pseudorapidity less than 1.44.

Physics beyond the standard model, such as anomalous couplings between the gauge bosons at the quartic vertex, may lead to enhancement in the number of $WV\gamma$ events produced within high energy collisions. Such enhancements can be observed in kinematic distributions, particularly in the higher energy regions. No evidence of anomalous $WW\gamma\gamma$ and $WWZ\gamma$ quartic gauge boson couplings is found, while 95% confidence level upper limits are obtained for various couplings.

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LIST OF ABBREVIATIONS

AK4: Anti-kT jet with cone radius parameter $R = 0.4$
AK5: Anti-kT jet with cone radius parameter $R = 0.5$
ATGC: Anomalous Triple Gauge Coupling
AQGC: Anomalous Quartic Gauge Coupling
ALICE: A Large Ion Collider Experiment
ATLAS: A Toroidal LHC ApparatuS
BSM: Beyond the Standard Model
BX: Bunch Crossing
CDF: Collider Detector at Fermilab
CERN: European Organization for Nuclear Research
CH: Charged Hadron
CL: Confidence Level
CM: Center-of-Momentum
CMS: Compact Muon Solenoid
CMSSW: CMS SoftWare
COM: Center of Mass
CP: Charge-Parity
CPU: Computer Processing Unit
CSC: Cathode Strip Chamber
CSV: Combined Secondary Vertex
CTEQ: Coordinated Theoretical Experimental project on QCD
CT-PPS: CMS-TOTEM Precision Proton Spectrometer
DAQ: Data AcQuisition system
DT: Drift Tube
EA: cone Effective Area
EB: Barrel ECAL
ECAL: Electromagnetic CALorimeter
EE: Endcap ECAL
EFT: Effective Field Theory
EGamma: Electron-Photon (Gamma) Physics Object Group

EM: ElectroMagnetic
ES: Endcap preShower
EW: Electroweak
EWSB: Electroweak Symmetry Breaking
fb: femtobarns
FSR: Final State Radiation
GC: Gauge Coupling
GeV: Gigaelectronvolt
HB: Hadronic Barrel
HCAL: Hadronic CALorimeter
HE: Hadronic Endcap
HF: Hadronic Forward
HLT: High Level Trigger
HO: Hadronic Outer
ID: Identification
IP: Interaction Point
ISR: Initial State Radiation
JEC: Jet Energy Correction
JES: Jet Energy Scale
JER: Jet Energy Resolution
L1: Level-1 Trigger
LEIR: Low Energy Ion Ring
LEP: Large Electron-Positron Collider
LEP2: Large Electron-Positron Collider II
LHC: Larch Hadron Collider
LHCb: Large Hadron Collider Beauty experiment
LHE: Les Houches Event
LINAC: Linear Accelerator
LINAC2: Linear Accelerator 2
LINAC3: Linear Accelerator 3
LO: Leading Order
LS1: Long Shutdown 1

MC: Monte Carlo
MCFM: Monte Carlo for FeMtobarn processes
MET: Missing Transverse Energy
MeV: Megaelectronvolt
MG5: MadGraph 5
NDOF: Number of degrees of freedom
NH: Neutral Hadron
NLC: Next Linear Collider
NLL: Negative Log Likelihood
NLO: Next-to-Leading Order
NNLL: Next-to-Next-to-Leading-Log
NNLO: Next-to-Next-to-Leading Order
PAG: Physics Analysis Group
PAT: Physics Analysis Tool
PDF: Parton Distribution Function
PF: Particle Flow
POG: Particle Object Group
PS: Proton Synchrotron
PSB: Proton Synchrotron Booster
 p_T : Transverse Momentum
PU: PileUp
PV: Primary Vertex
pQCD: perturbative Quantum ChromoDynamics
QCD: Quantum ChromoDynamics
QED: Quantum ElectroDynamics
QFT: Quantum Field Theory
QGC: Quartic Gauge Coupling
RECO: offline RECOstruction
RelIso: Relative Isolation
RMS: Root-mean-squared
RPC: Resistive Plate Chamber
SF: Scale Factor

SHERPA: Simulation of High-Energy Reactions of PArticles

SM: Standard Model

SMP: Standard Model Physics

SPS: Super Proton Synchrotron

SSB: Spontaneous Symmetry Breaking

SUSY: SuperSYmmetry

TEC: The two End Cap detector system

TeV: Teraelectronvolt

TGC: Triple Gauge Coupling

TIB: The Inner Barrel detector system

TID: The Inner Discs detector system

TnP: Tag and Probe

TOB: The Outter Barrel detector system

VBFNLO: Vector Boson Fusion at Next-to-Leading Order

CHAPTER 1

INTRODUCTION

“It would help us considerably if we knew what we were looking for.”

–Victoria, “The Abominable Snowmen,” *Doctor Who*

Since its conception in the mid to late twentieth century, the standard model (SM) of particle physics has sustained numerous experimental validations and skepticism from the theoretical community. It describes all the known elementary particles and their means of interaction via the strong, weak, and electromagnetic (EM) forces - it has been successful in predicting the existence of once unrealized particles; however, it is not a complete theory due to the vacant arguments for gravity, dark matter, and neutrino oscillations. It is a quantum field theory that provides for the electroweak (EW) interaction mediated by the massive gauge bosons $W^\pm$ and Z^0 , in addition to the mass-less photon γ .

The SM has been extensively probed at increasing center-of-mass (COM) energies with a variety of colliding particle beams over the past several decades and has yielded precise descriptions of experimental data. Accordingly, the SM EW production of gauge bosons is predicted with ever decreasing cross sections as additional bosons are tied to the final state vertex, with the latest experimental measurements of semileptonic diboson W^+W^- and $W^\pm Z$ production being recorded at the Large Hadron Collider (LHC) [1, 2]. The extension of multi-boson production to include a third vector boson has been considered in the second phase of the Large Electron-Positron Collider (LEP II) for the collection of $W^+W^-\gamma$ events [3]; however, the low event statistics restricted the analysis from measuring the production cross section.

The addition of this third boson, an energetic photon, not only stretches the SM to a rarer triboson production process, but it also provides for further insight into modeling of EM radiation in the W^+W^- and $W^\pm Z$ diboson processes. Triple gauge boson production analyses inherit several key components within EW physics, such as precision measurements on gauge boson self interactions, the EW parameters, and the mechanism of spontaneous symmetry breaking (SSB). Working within the SM, gauge boson self interactions are determined by the $SU(2)_L \otimes U(1)_Y$ gauge symmetry; therefore, assessing gauge boson self interactions through experimental analysis

provides an imperative check on the gauge structure of the SM. These studies can also explore the EW symmetry breaking (EWSB) mechanisms, given they provide for the longitudinal components of $W^\pm$ and Z^0 .

The interaction vertex from which the multiple bosons simultaneously emerge from is described via couplings. Triple and quartic gauge boson couplings arise from the SM non-Abelian $SU(2)_L \otimes U(1)_Y$ gauge symmetry. Together with triple gauge boson couplings (TGC), $W^+W^-\gamma$ and W^+W^-Z , the SM provides four quartic gauge boson couplings (QGC), $W^+W^-W^+W^-$, W^+W^-ZZ , $W^+W^-Z\gamma$, and $W^+W^-\gamma\gamma$ [4]. QGC analyses have been performed at several colliders [5, 6, 7, 8, 9, 10, 11]; however, we still lack direct experimental confirmation of QGCs. Particularly, prior to this analysis, the only experimental information on QGCs comes from the LEP and LEP-II experiments [12, 13], where $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow W^+W^-\gamma$ final states have been used to infer the SM triple couplings WWZ and $WW\gamma$, as well as the SM quartic $WW\gamma\gamma$ and $WWZ\gamma$ ones, respectively. Within the LHC community, the latest experimental limits on QGCs are in Refs. [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

There still lacks any significant experimental deviation from the SM, and the study of these types of interactions can further corroborate the SM predictions or grant perspective on new physics at a higher energy scale [25]. Such new physics, expressed in a model-independent way by extending the SM Lagrangian with additional effective operator terms leads to anomalous triple (ATGC) or quartic (AQGC) gauge boson couplings [9, 26, 27, 28]. A full understanding for the low mass Higgs boson's contributions to EWSB, the expectation for dark matter candidates, and comprehending the large hierarchy between the EW and Planck scales are just some of the reasons to expect physics beyond the SM to appear at the LHC; therefore, a model-independent approach is best suited for this analysis in probing the multi-boson vertices.

It is allowed within the SM that triple boson production processes accommodate both TGCs and QGCs; however, the diboson production channels with their increased statistics are better suited for probing the TGC processes. Additionally, as discussed in Ref. [9, 26], QGCs can deviate from SM predictions while the TGCs do not (i.e. the exchange of extra heavy bosons generates tree-level contributions to QGCs while the effect on the triple boson vertex appears only at one-loop and is consequently

suppressed.) In this sense, where ATGCs have not been witnessed in previous diboson analyses, it is assumed the ATGC contribution can be neglected in this analysis and we test what are termed “genuine quartic couplings” that contribute only to the $W^+W^-\gamma\gamma$ and $W^+W^-Z\gamma$ QGCs.

The LHC was constructed at the turn of the new century in an global effort to achieve high enough COM collisions and event statistics to realize new particles, such as the Higgs boson, and search for physics beyond the SM. Two general purpose experiments were included in the development of the LHC ring, A Toroidal LHC ApparatuS (ATLAS) and the Compact Muon Solenoid (CMS). The ability of these experiments to reconstruct each collision event with the final state particles and jets, or highly collimated spray of a collection of particles in a specific direction, allows for analyses to delve into very rare production channels within the framework of the SM. This thesis presents results obtained from analyzing $\sqrt{s} = 8$ TeV and 13 TeV data recorded within the CMS experiment in 2012 and 2015, respectively. The low statistics for this production process, coupled with large systematic uncertainties, prevents direct measurement of the cross section, but instead limits on both the SM cross section and on AQGCs are obtained.

CHAPTER 2

THEORY

Searches for new physics crucially depend on an underlying description of all observable physical quantities such that known background processes can be removed in order to isolate any anomalous signal. The SM theory has done a fair job of providing predictions for most observable data in particle physics, with notable exceptions including dark matter production and neutrino oscillations. Still, vast numbers of analyses spanning several decades have continued to probe and further corroborate the SM picture. In this dissertation, the focus will be to first probe the extremely rare SM production of tribosons and then scan for any anomalous signals within kinematic distributions in a model-independent way via AQGCs in an effective field theory (EFT) approach.

2.1 The Standard Model

It has long been argued that the fundamental forces in nature consist of the strong, weak, EM, and gravitational interactions; however, the truth remains today that all four interactions cannot be explained by any single theory, or *theory of everything*. Gravity as an exception, the other three forces have been combined theoretically under one model and upheld experimentally - the SM of particle physics. The SM theory, as it is known today, is a modified version of its founding principles from the mid twentieth century. The EM and weak interactions were initially combined by Sheldon Glashow in 1961 and was quickly modified to include the Higgs mechanism by Steven Weinberg and Abdus Salam [29, 30, 31, 32]. The strong interaction gained experimental ground in the 1970s when hadrons' compositions were found to be charged quarks [33, 34]. Overall, the SM is a quantum field theory defined by the local gauge symmetry group:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \tag{2.1}$$

The first term, $SU(3)_c$, is a non-Abelian gauge symmetry group accounting for the strong interactions, while the remaining terms unify the EM and weak interactions. The SM has been very successful over different experiments with various beam com-

positions, COM energies, and final state searches, but it fails to provide for the production of dark matter, neutrino oscillations, and various cosmological observations. It did, however, provide for the experimental observations of the top quark, the mediator bosons $W^\pm$ and Z^0 , and the long awaited Higgs boson. What follows is a description of the SM particles and their available interactions.

2.1.1 Particles

A group of elementary particles, collectively named leptons, have half-integer spin and are excluded from strong interactions. Charged leptons can interact with other matter, while neutral leptons, known as neutrinos, rarely interact and thus go undetected in experimental hardware. The charged and neutral leptons are split into three generations each: electronic, muonic, and tauonic leptons, forming a total of six flavored groups. A lepton has an accompanying antiparticle, sharing the same magnitude of intrinsic quantum numbers' values but with opposite sign, such as the electron and the positron, to bring a total of twelve possible lepton particles within the SM. Electrons are the lightest, most stable, and thus most common charged lepton found in nature, while the heavier muons and taus are formed from high energy collisions and quickly decay down to the electron and neutrino flavors.

A different elementary particle within the SM is the quark set. Similar to leptons, there are twelve quarks across six flavors with particle-antiparticle pairing; however, there are no neutral quarks. The six flavors are up, down, top, bottom, charm, and strange, with up and down quarks being the lightest and most stable in the universe. Just as with leptons, quarks have non-integer spin, but they also have non-integer elementary charge. Unlike leptons, quarks are not found in isolation but rather are inferred from the composite particles they make up, known as hadrons. Hadrons can be further classified as either baryons, made up of three quarks, or mesons, which are made up of a quark and an antiquark. All four fundamental forces are capable of influencing quarks.

The visible universe is composed of particles known as fermions and bosons, while there still remains the unknown composition referred to as *dark matter*. Fermions share the trait of non-integer spin and follow the Pauli exclusion principle, which restricts the states in which we expect to find such particles experimentally. Leptons

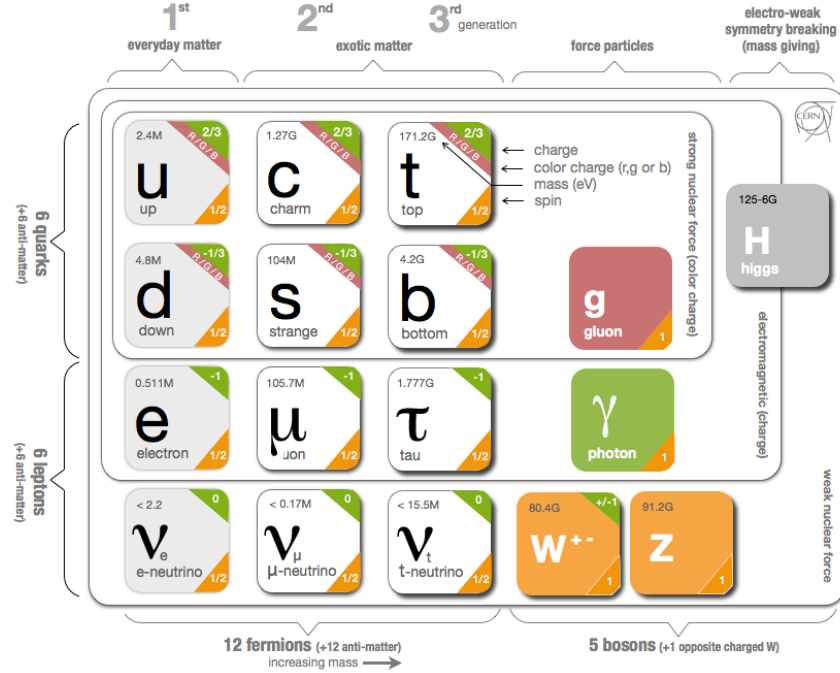


Figure 2.1: The SM particles and their associated spin, charge, mass, and color charge (where applicable). What fundamental forces influence each elementary particle, via the force carrier gauge bosons, is also noted.

and quarks, or any odd-numbered combination of these, are distinguished as fermions. A composite fermion is further restricted in nature by conserving baryon and lepton quantum numbers. Bosons are particles that follow Bose-Einstein statistics and are not restricted by the Pauli exclusion principle. The SM bosons are the gluon, $W^\pm$ and Z^0 , photon, and Higgs particles. Removing the scalar Higgs boson, the remaining four gauge bosons are known as the force carriers in the SM for the strong, weak, and EM forces, respectively. The recently discovered Higgs boson is attributed with assigning mass to all the elementary particles. One last value assigned to quarks and gluons is color charge, which can be red, blue, or green, and stems from quantum chromodynamics (QCD). Figure 2.1 summarizes each of the SM particles and their attributes.

2.1.2 Interactions

The gauge boson force carriers, gluon, γ , $W^\pm$, and Z^0 , mediate interactions to produce the final state particles observed in both nature and collider experiments. The relative strength in which each of the fundamental forces are mediated is quantized by a coupling constant, α . The coupling constant of each interaction is different, and its magnitude affects physical observables, such as a production cross section; therefore, a precise understanding of these types of interactions is imperative in order to isolate any possible new physics materializing in experimental measurements. To be precise, $\alpha_w \approx 10^{-6}$ for weak interactions, $\alpha \approx 1/137$ for EM interactions, and $\alpha_s \approx 1$ for strong interactions, which goes to show that at the subatomic scale the strong force dominates. Although the SM has not incorporated gravity, it has been proposed that the graviton mediates this force, and it would have an approximate $\alpha_g \approx 10^{-39}$ for gravitational interactions. Given that gravity is not understood within the framework of the SM theory, only the other three fundamental interactions, plus one combined interaction between the weak and EM fields, will be discussed.

The strong force, as its name suggests, is the strongest force interacting with elementary particles on the subatomic scale. This force confines quarks into hadrons and the nucleus of an atom together and is mediated by the massless gluon. QCD and the strong interactions are what save quarks from breaking the Pauli exclusion principle via the additional quantum color charge. The resulting color confinement property explains why quarks and gluons are not seen in isolation with emission of the energy from the strong force, but rather new hadrons are emitted.

The weak interaction is carried out by the massive gauge bosons $W^\pm$ and Z^0 , which are not directly observed in experiments, but rather their decay daughter particles can be detected, with the exception of the neutrinos. All of the SM fermions interact via the weak interaction through the emission or absorption of $W^\pm$ or Z^0 , and the weak force itself is responsible for radioactive decay. It is responsible for allowing quarks to change flavor as well, such as with β -decay for a neutron converting to a proton. Depending on which force carrier is involved, and its inherent electric charge, there can be two types of weak interactions at a given emission or absorption vertex, known as charged-current and neutral-current interactions. β -decay, therefore, would also be a charged-current weak interaction. The weak interaction is further restricted

in that it only acts on left-handed fermions or right-handed antifermions.

A property assigned to all fermions under the weak interactions is termed weak isospin, much like electric charge for the EM interactions and color charge for the strong interactions, and weak isospin must be conserved during such interactions. Every fermion has either a weak isospin value of $\pm 1/2$, while the antiparticle must have a value opposite in sign; however, left-handed antiparticles have a weak isospin of zero.

The weak interaction breaks charge and parity symmetry, while the other three fundamental interactions do not. The EW interaction, for which symmetry breaking for the weak interaction is addressed, is thus proposed. This combination of weak and EM interaction is needed to also address the coupling of charged $W^\pm$ bosons to the neutral photon γ .

The EM interaction, like the strong interaction with its gluon, has only one gauge boson as a force carrier between particles, the neutrally charged photon γ . This interaction is described by quantum electrodynamics (QED), another relativistic quantum field theory, and involves all interactions between charged particles that exchange photons. Although the SM Lagrangian for EM interactions has proved very precise in its successful modeling of QED fundamental processes, it was later combined with the weak interaction principles to form the EW interaction.

2.1.3 Lagrangian

Combining the strong and EW interactions with the discovery of the Higgs boson, the complete SM Lagrangian can be used to predict various final state production channels, and, more important to this analysis, processes involving an interaction vertex between four bosons that end in various triboson final state observations. The nonzero SM Lagrangian terms representing EW particle interactions are summarized in Table 2.1, where $\not{D}$ is a covariant derivative [35].

The gauge boson self couplings follow $SU(2)_L \otimes U(1)_Y$ gauge invariance. A model-independent approach to measuring any physics beyond the SM (BSM) predictions regarding the interactions in Table 2.1 can be appended to the SM Lagrangian, such as what is the focus of this analysis regarding quartic $WW\gamma\gamma$ and $WWZ\gamma$ and detailed in Section 2.2.

Table 2.1: Lagrangians representing the nonzero EW particle interactions included in the SM Lagrangian for multiparticle vertices.

Interactions	Two-particle	Three-particle	Four-particle Interactions
$\mathcal{L}_{bosons}$	$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ $-\frac{1}{2}W_{\mu\nu}^+W^{-\mu\nu}$ $M_W^2W^{+\mu}W^{-\mu}$ $-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu}$ $M_Z^2Z_\mu Z^\mu$ $\frac{1}{2}\partial_\mu H\partial^\mu H$ $-\frac{1}{2}M_H^2H^2$	$W^+W^-\gamma$ W^+W^-Z HHH W^+W^-H ZZH	$W^+W^-\gamma\gamma$ W^+W^-ZZ $W^+W^-Z\gamma$ $W^+W^-W^+W^-$ $HHHH$ W^+W^-HH $ZZHH$
$\mathcal{L}_{leptons}$	$\sum_{l=e,\mu,\tau} \bar{l}(i\not{\partial} - m_l)l$ $\sum_{\nu=\nu_e,\nu_\mu,\nu_\tau} \bar{\nu}(i\not{\partial})\nu$	$\bar{l}l\gamma$ $\bar{\nu}lW^+$ $\bar{l}\nu W^-$ $\bar{l}lZ$ $\bar{\nu}\nu Z$ $\bar{l}lH$	
$\mathcal{L}_{quarks}$	$\sum_{q=u,d,c,s,t,b} \bar{q}(i\not{\partial} - m_q)q$	$\bar{q}q\gamma$ $\bar{u}d'W^+$ $\bar{d}'uW^-$ $\bar{q}qZ$ $\bar{q}qH$	

2.2 Anomalous Gauge Coupling

The study of triple and quartic couplings is mainly motivated by the hope that some new physics might result in deviations from the SM [28], even though the SM is so well measured that very strong restrictions on the kinds of new physics are imposed *a priori*. A detailed study of these interactions can either confirm the local gauge invariance of the theory or indicate the existence of physics beyond the SM.

Direct studies of quartic vector-boson interactions can be performed only at the LHC and at the NLC (Next Linear Collider) since they will offer sufficient COM energy for multi-boson production. On the other hand, information on anomalous interactions can also be gathered from the low energy data and from the Z physics results [36].

The set of CP-conserving and $SU(2) \otimes U(1)$ gauge invariant pure anomalous quartic photonic operators, which can be tested through triple vector boson production at colliders, exhibiting $SU(2)_C$ global symmetry were already listed in Ref. [27]. One refers to these quartic operators as *pure* [5, 37, 38], in contrast with those emerging from operators that induce both trilinear $WW\gamma$ and quartic $WW\gamma\gamma$ coupling in a way to preserve gauge invariance. Non-genuine quartic operators can be much more efficiently investigated through processes that induce a triple vertex, such as $pp \rightarrow W^+W^-$. In this context, a pure (or genuine) quartic vertex can only be analyzed in triple vector boson production or through vector boson fusion [5].

2.2.1 Realization of Gauge Symmetries

Gauge boson self-interactions are naturally connected with the SSB section of the Lagrangian. When investigating quartic anomalous couplings using the effective theory approach, one cannot avoid talking about the SSB mechanism. In the past, we have found that this mechanism can be implemented either with or without the appearance of the Higgs boson. With the Higgs boson included, the fundamental part of the model is just the SM. In this case, the $SU(2)_L \otimes U(1)_Y$ gauge symmetry is implemented linearly. Without a Higgs boson, however, due to the nonlinear implementation of the gauge symmetry, renormalizability of the fundamental theory is lost [9, 27].

2.2.1.1 The Nonlinear Formalism

In the non-linear formalism [9, 27], without the Higgs boson, we have to implement the SSB in a different way that still gives rise to gauge bosons with the correct masses and satisfies the experimental bound on the ρ parameter. To construct this model, we first introduce a dimensionless unimodular matrix field $\Sigma(x)$,

$$\Sigma(x) = \exp i\left(\frac{\phi^a(x)\tau^a}{v}\right) \quad (2.2)$$

where $v = 246$ GeV, ϕ^a are fields corresponding to the Goldstone bosons after SSB, and τ^a ($a = 1, 2, 3$) are the Pauli matrices. Then, the $SU(2)_L \otimes U(1)_Y$ covariant derivative of the Σ field is defined as:

$$\mathcal{D}_\mu \Sigma \equiv \partial_\mu \Sigma + ig \frac{\tau^a}{2} W_\mu^a \Sigma - ig' \Sigma \frac{\tau^3}{2} B_\mu \quad (2.3)$$

From the definition of the Σ field you can see the ϕ^a fields transform nonlinearly under gauge transformation of the Σ field. Thus the gauge symmetry is nonlinearly implemented. Now, we can write the Lagrangian of the SSB sector in terms of this matrix field.

$$\begin{aligned} \mathcal{L}_M = -\frac{v^2}{4} \text{Tr}(\mathcal{D}^\mu \Sigma^\dagger \mathcal{D}_\mu \Sigma) &\equiv -\frac{v^2}{4} \text{Tr}(\mathbf{V}_\mu \mathbf{V}_\mu) \\ \mathbf{V}_\mu &= (\mathcal{D}_\mu \Sigma) \Sigma^\dagger \\ M_W &= \frac{gv}{2} \end{aligned} \quad (2.4)$$

Apart from the gauge symmetry, the value of the ρ parameter is found to be restricted by a hidden global symmetry of the SSB sector, that is the so-called custodial symmetry. In the limit of $g' \rightarrow 0$, the SSB sector of the Lagrangian has a global symmetry $SU(2)_L \otimes SU(2)_R$. When the Higgs field acquires a vacuum expectation value, this symmetry is broken to $SU(2)_{L+R}$. The remaining 3 generators of this unbroken subgroup lead to 3 massless Goldstone bosons, which are then “eaten” by the SSB mechanism and provide the W^+, W^-, Z bosons with mass. In this limit, we can see the W^+, W^- , and Z form a triplet of the unbroken global symmetry; thus, we have $M_W = M_Z$, and hence the $\rho = 1$ is protected by the custodial symmetry.

In our analysis, only genuine quartic photonic couplings are of interest. In this formalism, these operators first appear at NNLO, which is dimension 6. With the restriction of $SU(2)_C$ custodial symmetry and separately $\mathcal{C}$ and $\mathcal{P}$ conservation, we have 14 photonic operators.

$$\begin{aligned}
 \mathcal{L} = & \frac{g^2}{\Lambda^2} \left[k_0^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}) \text{Tr}(\mathbf{V}^\alpha \mathbf{V}_\alpha) + k_c^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\alpha}) \text{Tr}(\mathbf{V}^\nu \mathbf{V}_\alpha) + \right. \\
 & + k_1^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}^\alpha) \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}_\alpha) + k_2^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}^\nu) \text{Tr}(\mathbf{W}_{\mu\alpha} \mathbf{V}_\alpha) + \\
 & + k_3^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}_\alpha) \text{Tr}(\mathbf{W}^{\mu\alpha} \mathbf{V}^\nu) \left. \right] + \frac{g'^2}{\Lambda^2} \left[k_0^b \text{Tr}(\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}) \text{Tr}(\mathbf{V}^\alpha \mathbf{V}_\alpha) + \right. \\
 & + k_c^b \text{Tr}(\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\alpha}) \text{Tr}(\mathbf{V}^\nu \mathbf{V}_\alpha) + k_1^b \text{Tr}(\mathbf{B}_{\mu\nu} \mathbf{V}^\alpha) \text{Tr}(\mathbf{B}_{\mu\nu} \mathbf{V}_\alpha) + \\
 & + k_2^b \text{Tr}(\mathbf{B}_{\mu\nu} \mathbf{V}^\nu) \text{Tr}(\mathbf{B}_{\mu\alpha} \mathbf{V}_\alpha) \left. \right] + \frac{gg'}{\Lambda^2} \left[k_0^m \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{B}^{\mu\nu}) \text{Tr}(\mathbf{V}^\alpha \mathbf{V}_\alpha) + \right. \\
 & + k_c^m \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{B}^{\mu\alpha}) \text{Tr}(\mathbf{V}^\nu \mathbf{V}_\alpha) + k_1^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}^\alpha) \text{Tr}(\mathbf{B}_{\mu\nu} \mathbf{V}_\alpha) + \\
 & + k_2^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}^\nu) \text{Tr}(\mathbf{B}_{\mu\alpha} \mathbf{V}_\alpha) + k_3^w \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{V}_\alpha) \text{Tr}(\mathbf{B}^{\mu\alpha} \mathbf{V}^\nu) \left. \right]
 \end{aligned} \tag{2.5}$$

where $\mathbf{B}_{\mu\nu} = \tau^3 B_{\mu\nu}/2$, $\mathbf{W}_{\mu\nu} = \tau^a W_{\mu\nu}^a/2$, and $B_{\mu\nu}$ and $W_{\mu\nu}^a$ correspond to the field strength of the $U(1)_Y$ and $SU(2)_L$ group. Λ here represents the new physics scale.

2.2.1.2 The Linear Formalism

In this dissertation we are going to deal only with genuine quartic photonic couplings based in the linear formalism [28] in addition to some nonlinear formalism components dealt with in 2012. Since the fundamental part of the model is just the SM, the construction of high dimension operators is straightforward. If we use Φ to represent the Higgs doublet and U , as well as arbitrary $SU(2)_L$ transformation, the basic blocks transform as follows:

$$\begin{aligned}
 \Phi & \rightarrow \Phi' = U\Phi \\
 D_\mu \Phi & \rightarrow D'_\mu \Phi' = U D_\mu \Phi \\
 \mathbf{W}_{\mu\nu} \equiv \sum_j W_{\mu\nu}^j \frac{\sigma^j}{2} & \rightarrow \mathbf{W}'_{\mu\nu} = U \mathbf{W}_{\mu\nu} U^\dagger \\
 B_{\mu\nu} & \rightarrow B'_{\mu\nu} = B_{\mu\nu}
 \end{aligned} \tag{2.6}$$

where $B_{\mu\nu}, W_{\mu\nu}^i$ are field strengths of the $U(1)_Y$ and $SU(2)_L$ group. Correspondingly, the covariant derivative is:

$$D_\mu \Phi \equiv \left(\partial_\mu - ig W_\mu^j \frac{\sigma^j}{2} - ig' B_\mu \frac{1}{2} \right) \Phi. \quad (2.7)$$

Following are the selected operators related to this dissertation. The terms containing both the derivative and field strength tensor are:

$$\begin{aligned} \mathcal{L}_{M,0} &= \frac{f_{M0}}{\Lambda^4} \text{Tr} [\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi] \\ \mathcal{L}_{M,1} &= \frac{f_{M1}}{\Lambda^4} \text{Tr} [\mathbf{W}_{\mu\nu} \mathbf{W}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi] \\ \mathcal{L}_{M,2} &= \frac{f_{M2}}{\Lambda^4} \text{Tr} [B_{\mu\nu} B^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi] \\ \mathcal{L}_{M,3} &= \frac{f_{M3}}{\Lambda^4} \text{Tr} [B_{\mu\nu} B^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi] \\ \mathcal{L}_{M,4} &= \frac{f_{M4}}{\Lambda^4} [(D_\mu \Phi)^\dagger \mathbf{W}_{\beta\nu} D^\mu \Phi] \times B^{\beta\nu} \\ \mathcal{L}_{M,5} &= \frac{f_{M5}}{\Lambda^4} [(D_\mu \Phi)^\dagger \mathbf{W}_{\beta\nu} D^\nu \Phi] \times B^{\beta\mu} \\ \mathcal{L}_{M,6} &= \frac{f_{M6}}{\Lambda^4} [(D_\mu \Phi)^\dagger \mathbf{W}_{\beta\nu} \mathbf{W}^{\beta\nu} D^\mu \Phi] \\ \mathcal{L}_{M,7} &= \frac{f_{M7}}{\Lambda^4} [(D_\mu \Phi)^\dagger \mathbf{W}_{\beta\nu} \mathbf{W}^{\beta\mu} D^\nu \Phi] \end{aligned} \quad (2.8)$$

and terms with only field strength tensor are:

$$\begin{aligned}
\mathcal{L}_{T,0} &= \frac{f_{T0}}{\Lambda^4} Tr[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times Tr[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}], \\
\mathcal{L}_{T,1} &= \frac{f_{T1}}{\Lambda^4} Tr[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}], \\
\mathcal{L}_{T,2} &= \frac{f_{T2}}{\Lambda^4} Tr[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}], \\
\mathcal{L}_{T,5} &= \frac{f_{T5}}{\Lambda^4} Tr[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times B_{\alpha\beta} B^{\alpha\beta}, \\
\mathcal{L}_{T,6} &= \frac{f_{T6}}{\Lambda^4} Tr[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times B_{\mu\beta} B^{\alpha\nu}, \\
\mathcal{L}_{T,7} &= \frac{f_{T7}}{\Lambda^4} Tr[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times B_{\beta\nu} B^{\nu\alpha},
\end{aligned} \tag{2.9}$$

Equations 2.2-2.9 exhibit interactions before EWSB, whereas including EWSB generates interactions between the W, Z, and γ bosons via the W and B bosons coalescing together according to a weak mixing angle, commonly referred to as θ_W . The EWSB forms of Eq. 2.8-2.9 are much too intricate to reasonably list explicitly but can be accounted for in several model generators, such as with MadGraph (MG5) [39]. In Ref. [14] we presented an equivalence between the dimension 6 and dimension 8 parameters, for some specific situations. Similar relations can also be found in Section 3 of Ref. [27].

$$\begin{aligned}
\frac{f_{M,0}}{\Lambda^4} &= -\frac{g^4}{M_W^2} \frac{k_0^w}{\Lambda^2} \\
\frac{f_{M,2}}{\Lambda^4} &= -\frac{g^2 g'^2}{2M_W^2} \frac{k_0^b}{\Lambda^2} \\
\frac{f_{M,1}}{\Lambda^4} &= \frac{g^4}{M_W^2} \frac{k_c^w}{\Lambda^2} \\
\frac{f_{M,3}}{\Lambda^4} &= \frac{g^2 g'^2}{2M_W^2} \frac{k_c^b}{\Lambda^2}
\end{aligned} \tag{2.10}$$

where $\frac{f_{M,i}}{\Lambda^4}$ are parameters of the linear formalism.

Therefore, concerning both vertex $WW\gamma\gamma$ and $WWZ\gamma$, the anomalous part of the total Lagrangian (2.11) can be written as

$$\mathcal{L}_{AQGC} = \sum_{i=0,\dots,7} \mathcal{L}_{M,i} + \sum_{j=0,\dots,2,5,\dots,7} \mathcal{L}_{T,j} \quad (2.11)$$

We have used the reweighing feature in MG5 to generate samples with non-zero coefficients for the set of dimension-8 operators (2.8) and (2.9). We generate one LHE file containing unweighted events using the model $\frac{f_{M4}}{\Lambda^4} = 100.123 \text{ TeV}^{-4}$, where Λ is the new physics scale and $\frac{f_{X,Y}}{\Lambda^4}$ is the coefficient of the operator $\mathcal{L}_{X,Y}$. These events are reweighed according to the formula

$$W_{new} = W_{old} \frac{|M_{new}|^2}{|M_{old}|^2} \quad (2.12)$$

to other models with nonzero coefficients for the other operators. Therefore, we have used a single fully simulated sample with 225 weights for each event to constrain the values of these operators. We have applied AQGC models for both $WW\gamma$ and $WZ\gamma$ channels.

2.2.2 Unitarity and Form Factor

The contribution of AQGC operators are strictly prohibited by theory, since any non-zero value of the AQGCs will lead to tree-level unitarity violation at sufficiently high energy [40]. To dampen the effect of non-unitarity, some people make use of form factors. However, the choice of form factors is somewhat arbitrary and subject to dispute, and different choices of form factor make comparison difficult. So, in this dissertation the results are presented without a form factor.

In order to choose a suitable form factor, one can extract a unitarity bound from the S-matrix unitarity condition. In Ref. [40, 41], the author calculated the unitarity bound for inelastic photon scattering processes. Using the unitarity equations in Ref. [40, 41], we can plot the bound as a function of COM energy.

The unitarity condition for AQGC parameters as a function of the form factor scale Λ_u and different values of $\hat{s}$ were studied and compared with the projected sensitivity of this analysis using 20 fb^{-1} of integrated luminosity via the following relation:

$$\alpha \rightarrow \frac{\alpha}{(1 + \hat{s}/\Lambda_u^2)^n}, \quad (2.13)$$

where the α represent the AQGCs, $\hat{s}$ represent the triple gauge boson invariant mass, the parameter Λ_u is a scale of new physics, and the parameter n is fixed to 2. To do this, we fixed the value of $AQGC \times ff$ to the value of $AQGC$ without a form factor. The COM energy dependence is replaced with a fixed effective energy scale representing the typical COM energy with non-zero value of an AQGC. In this analysis, we have used the limits with a form factor in Eq. 2.13, which is the same as former CMS analyses with two photon production of a W boson pair [42], to fix this effective $\sqrt{\hat{s}}$. In this way, we can vary the value of the effective $\sqrt{\hat{s}}$ to estimate uncertainties of our limits. In Figures 2.2-2.6, uncertainty bands with 0.5/2 and 0.25/4 times the effective $\sqrt{\hat{s}}$ are shown. Also drawn is the theoretical unitarity bound with different $\sqrt{\hat{s}}$ upper limits. The results shown in Figures 2.2-2.6 indicate that there is no value of the dipole form factor's scale at which the unitarity condition can be satisfied for all values of $WW\gamma$ invariant mass, given the available amount of data at $\sqrt{s} = 8$ TeV. This motivates the choice of presenting the results without any form factor.

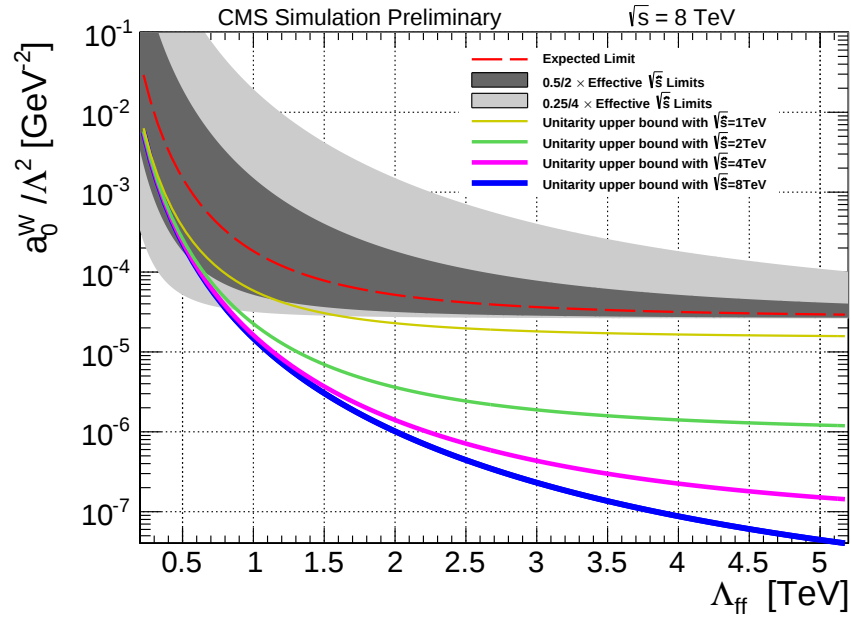


Figure 2.2: The unitarity condition for AQGC parameter a_0^W/Λ^2 as a function of form factor parameter Λ_u and different values of $\hat{s}$ is compared with the projected sensitivity of our analysis using 20 fb^{-1} of integrated luminosity.

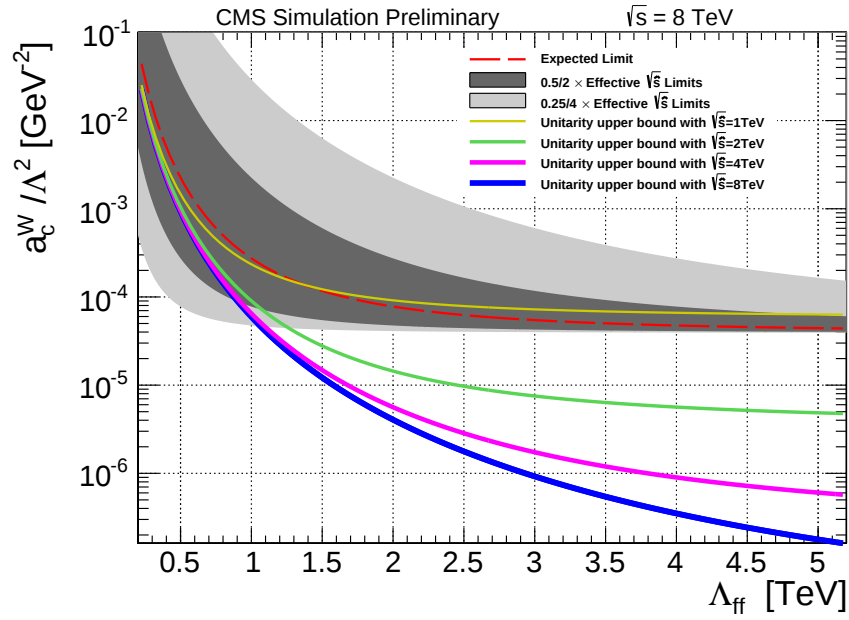


Figure 2.3: The unitarity condition for AQGC parameter a_C^W / Λ^2 as a function of form factor parameter Λ_u and different values of $\hat{s}$ is compared with the projected sensitivity of our analysis using 20 fb⁻¹ of integrated luminosity.

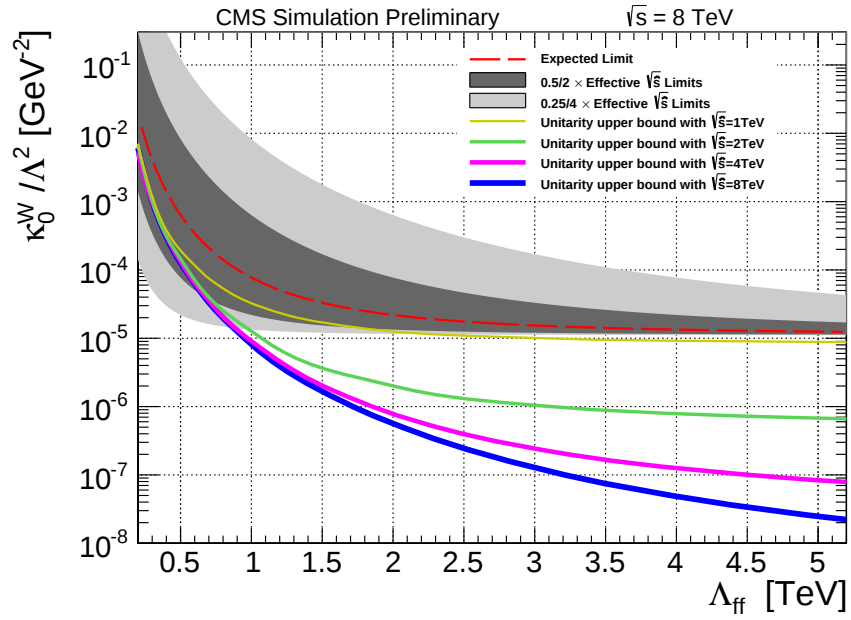


Figure 2.4: The unitarity condition for AQGC parameter κ_0^W/Λ^2 as a function of form factor parameter Λ_u and different values of $\hat{s}$ is compared with the projected sensitivity of our analysis using 20 fb^{-1} of integrated luminosity.

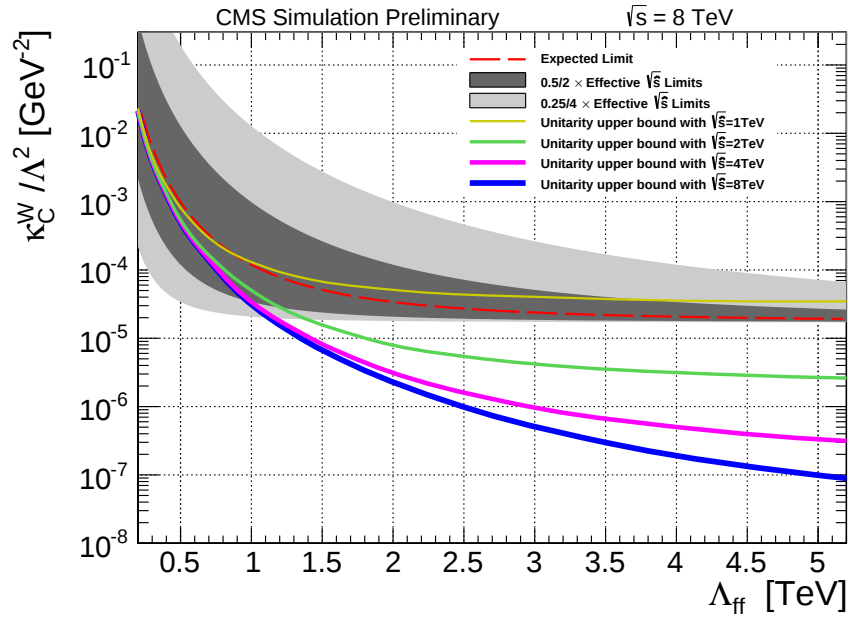


Figure 2.5: The unitarity condition for AQGC parameter κ_C^W / Λ^2 as a function of form factor parameter Λ_u and different values of $\hat{s}$ is compared with the projected sensitivity of our analysis using 20 fb⁻¹ of integrated luminosity.

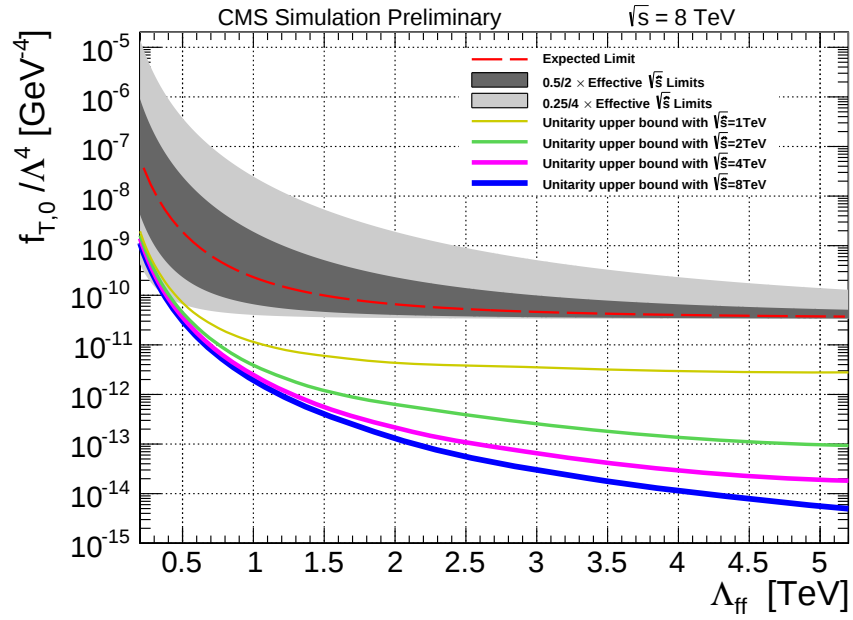


Figure 2.6: The unitarity condition for AQGC parameter $f_{T,0}/\Lambda^4$ as a function of form factor parameter Λ_u and different values of $\hat{s}$ is compared with the projected sensitivity of our analysis using 20 fb^{-1} of integrated luminosity.

CHAPTER 3

THE COMPACT MUON SOLENOID EXPERIMENT

The results provided in this dissertation were obtained with the collaboration of thousands of researchers around the globe. The international effort to develop and construct the largest, most powerful particle accelerator took decades and has resulted in thousands of publications. The $WV\gamma$ search presented here was conducted using data collected by one of the two general purpose detectors at the LHC, where proton-proton collisions have occurred at two different COM energies between 2012 and 2015. The following sections will describe in some detail the components of both the overall LHC ring and the CMS detector.

3.1 The Large Hadron Collider

The LHC was designed and built within existing caverns at the European Organization for Nuclear Research (CERN) on the border of France and Geneva, Switzerland, where existing beam accelerators could be used in stages to prepare the hadronic beams for final collision within the LHC ring. The LHC ring itself is 27 km in circumference and approximately 100 meters underground. The depth was chosen so that the ground above could best shield the collision detectors from background sources, such as cosmic rays. Although the new collider utilizes many repurposed components of previous accelerators at CERN, it is designed to reach the highest collision energy ever produced by humans, where interactions between particles can now reach the TeV scale. The various beam preparation facilities that will be discussed here have and can still be used for several other experiments and detectors other than the four known as A Large Ion Collider Experiment (ALICE), ATLAS, CMS, and Large Hadron Collider beauty (LHCb) located within the LHC ring.

There are two types of beams that the LHC receives from the multistage boosters, either a proton beam or an ionized lead beam. If the beam being circulated is to be populated with protons, then the origin is a hydrogen gas that passes through the Linear Accelerator 2 (LINAC2). If, instead, the beam is to be populated with ionized lead, then the origin is vaporized lead that passes through LINAC3 and the Low Energy Ion Ring (LEIR). Since this dissertation is limited to only proton beams,

the discussion will be limited to the process involving the preparation of this beam type.

The LINAC2 facility is where protons are first collected by stripping away electrons from the hydrogen gas via a strong electric field. A train of alternating charged cylindrical conductors are used to accelerate the protons to an energy of 50 MeV. The alternating charge in the cylinders provides the acceleration when the field behind the proton yields a push and the field in front of the proton yields a pull.

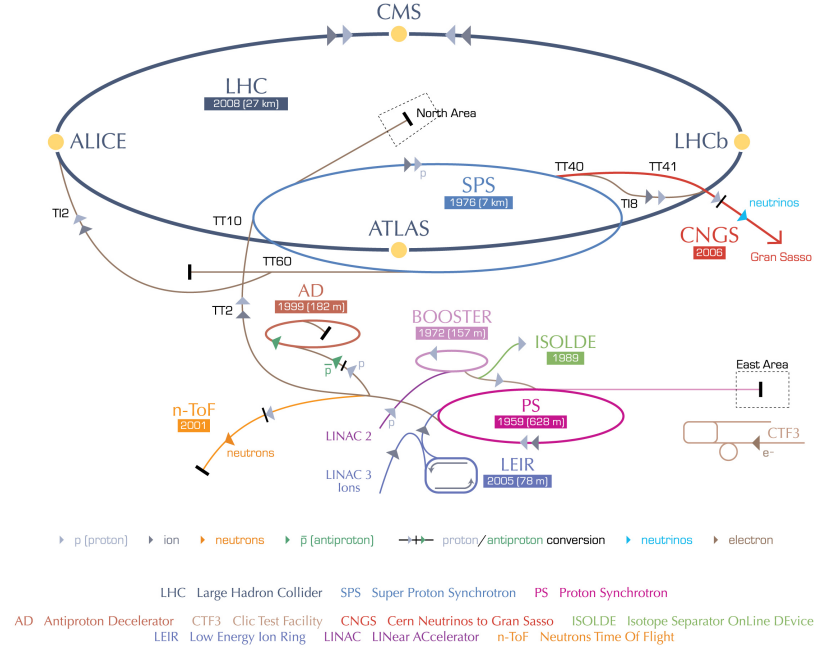
The proton beam is then directed to the Proton Synchrotron Booster (PSB), which is an intermediate step added to the multistage acceleration in 1972 to increase the number of protons the Proton Synchrotron (PS) receives. The PSB consists of four superimposed synchrotron rings and boosts the protons to an energy of 1.4 GeV. Once in the PS facility, which is the first stage that both proton and lead ion beams share in their path towards the LHC ring, the beam is energized to 25 GeV along a ring of 628 m circumference with 277 conventional magnets and 100 dipoles maintaining beam direction.

The Super Proton Synchrotron (SPS) receives the proton beam and accelerates the hadrons around a 7 km ring to 450 GeV. The SPS facility is second in size at CERN only to the LHC ring, and it includes 1317 conventional magnets and 744 dipoles. The SPS not only directs the beam to the LHC ring, but it also provides beams for other experiments in adjacent facilities as well.

Now the beam is directed into the LHC ring, where superconducting electromagnets provide a strong magnetic field to direct the highly energized protons. The single proton beam is actually split into two beams that travel in opposite directions around the LHC ring in two separate beam pipes. Here, 1232 dipole magnets bend the beams, 392 quadrupoles focus the beam, and additional magnets are used to squeeze the beam prior to collisions. The superconducting magnets are kept at -271.3°C with liquid helium, and it is now that the beams are accelerated to 6.5 TeV and allowed to collide within the four experiments along the LHC ring. Figure 3.1 portrays the CERN LHC facilities discussed here [43].

An important measure provided from CERN to the individual experiments is the produced instantaneous luminosity, with which each experiment records data with a certain efficiency and quotes an integrated luminosity over a period that data is

CERN's accelerator complex



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Figure 3.1: Schematic of the CERN facilities that contribute to the LHC beam preparation and collisions.

recorded. An integrated luminosity is the measure of the number of collisions, or events, per unit of area. Knowing the integrated luminosity aids analyses in measuring the experimental cross sections of particular processes, referred to as the probabilities that the given process will occur in a given collision event. The instantaneous luminosity is given by

$$L(t) = \frac{\gamma f k_B N_p^2}{4\pi \epsilon_n \beta^*} F \quad (3.1)$$

where γ is the Lorentz factor, f is the revolution frequency, k_B is the number of proton bunches in the beam, N_p is the number of protons per bunch, ϵ_n is the beam emittance, β^* is the beta function, and F is the reduction factor resulting from beams crossing at a finite angle. The beam parameters changed between 2012 and 2015 for

the new 13 TeV collisions, but the start-up parameters for 2015 can be found in Ref. [44].

3.2 The CMS Detector

The CMS experiment was designed as a general purpose detector, in collaboration with the ATLAS detector, to be used in the LHC for new physics searches. It is located in France 100 m underground and gets part of its name because of how compact it is compared to the ATLAS detector. Weighing in at over 12,000 tons and with dimensions of ~ 15 m in diameter and ~ 30 m in length, it was actually constructed above ground and lowered piece by piece into the cavern below Cessy, France. This cylindrical solenoid consists of an inner tracker system along the beam line, an Electromagnetic Calorimeter (ECAL), a Hadron Calorimeter (HCAL), and a muon system. The superconducting magnet weights 220 tons, is 12.5 m long and 6 m in diameter, and surrounds the tracker and calorimeters. It is segmented into 5 sections and is enclosed by iron to contain the strong magnetic field generated by the superconducting material kept at 4 K by liquid helium. A comprehensive diagram of the CMS experiment is shown in Figure 3.2 [45].

The coordinate system employed by CMS is arranged such that the x-axis is pointed from the interaction point (IP) of the colliding beams towards the center of the LHC ring, the y-axis is pointed directly upwards and perpendicular to the LHC plane, and the z-axis is pointed along the beam direction counterclockwise along the LHC ring. Angular coordinates are also provided such that the azimuthal angle ϕ is in the x-y plane beginning along the positive x-axis, and the polar angle θ is measured from the positive z-axis. Given that interactions in collisions can be longitudinally boosted, it is necessary to express quantities that are invariant under these conditions, such as the conserved transverse momentum p_T and pseudorapidity η . Pseudorapidity can be expressed in the mass-less limit as

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right) \tag{3.2}$$

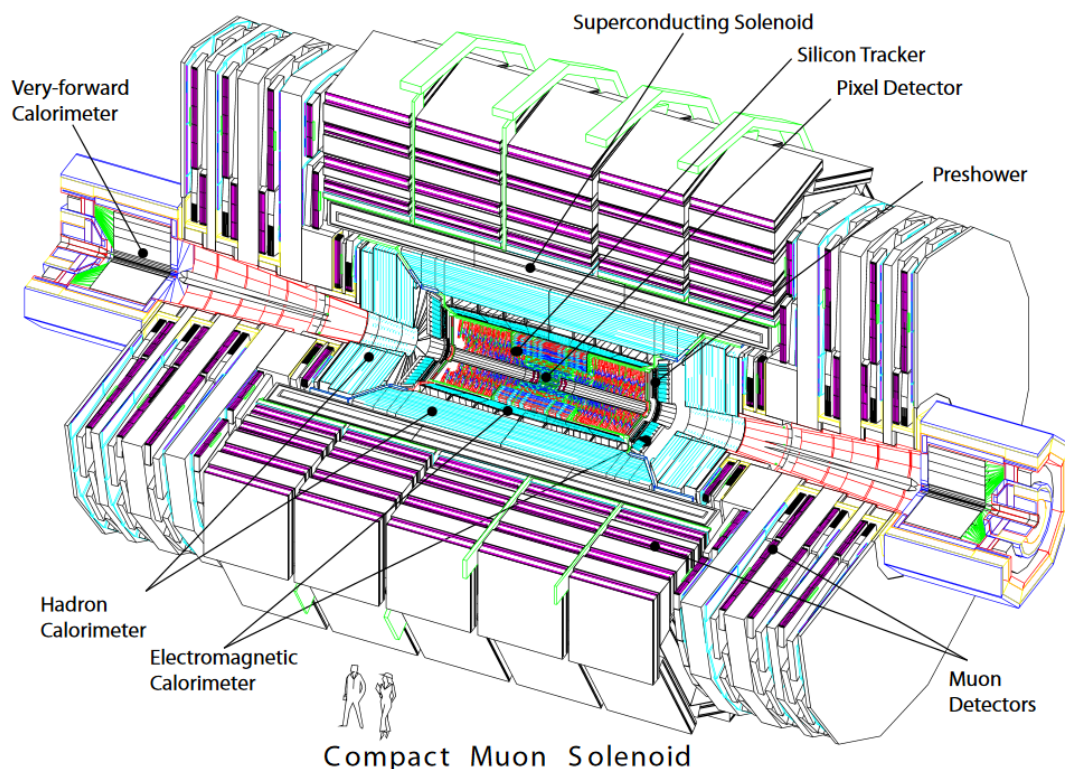


Figure 3.2: Schematic of the CMS experiment.

3.2.1 Tracker

The tracker is the closest subsystem to the beam line and IP. It provides necessary data to discern noisy events, later described as pileup (PU), in a collision from the primary event at the IP. It consists of an inner high resolution pixel tracker and an outer radiation hard silicon strip tracker for a coverage in pseudorapidity $|\eta| < 2.5$.

The pixel tracker has three layers in the barrel region of CMS and two disks in the endcaps. It envelops the beam axis from 4.4 cm to 10.2 cm away from the beam. There are a total of 1440 segmented silicon sensor modules providing a sum of 66 million pixels for a spatial resolution of $20\ \mu\text{m}$ or $15\ \mu\text{m}$ resolution in the r - ϕ direction.

The silicon strip tracker consists of 10 layers in the barrel and nine disks in the endcaps, and it extends coverage from 10 cm to 110 cm from the beam axis. There are 15,148 modules that provide spatial resolution of $230\ \mu\text{m}$ and $\sim 30\ \mu\text{m}$ in the r - ϕ direction. As an example, for particles below 100 GeV, this tracker system can

provide under 2% resolution in momentum for $|\eta| < 1.6$.

3.2.2 Electromagnetic Calorimeter

The ECAL is constructed with lead tungstate crystals that were chosen for their radiation hardness. The intent of the ECAL is to detect the electrons and photons, along with some partial information on jets, within $|\eta| < 3$. It has three regions known as EB, EE, and ES, which are positioned along the barrel of CMS, the endcaps, or just prior to the endcaps and EE, respectively. EB has 61,200 crystals geometrically tapered such that the thin edge has an area of $22 \times 22 \text{ mm}^2$, the wide edge has an area of $26 \times 26 \text{ mm}^2$, and the overall length of each crystal is 23 cm. This provides coverage up to $|\eta| < 1.4$ and is recorded by avalanche photodiodes. The EE has 14,648 crystals, each 22 cm in length, and are readout by vacuum photodiodes. The ES is referred to as the preshower component of ECAL, and rightly so as it is positioned just before EE in order to identify photon pairs from π_0 decay. ES provides a coverage from $1.6 < |\eta| < 2.6$. The ECAL sub-detector and subsystems are displayed in Figure 3.3 [46].

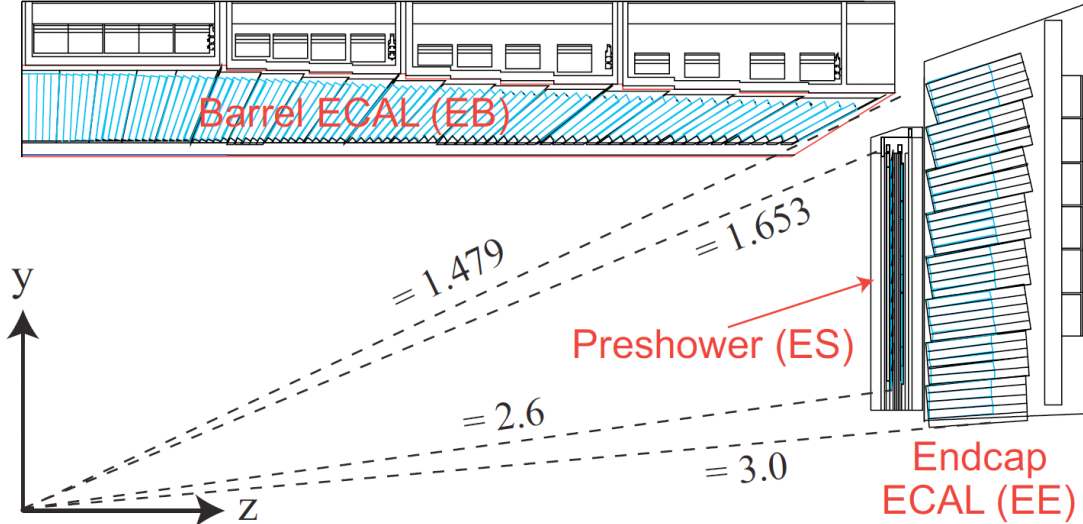


Figure 3.3: Schematic of the ECAL sub-detector.

3.2.3 Hadron Calorimeter

The HCAL surrounds the ECAL and is designed to reconstruct information about jets and missing transverse energy (MET) from neutrinos. Alternating layers of brass absorber and scintillating material make up most of HCAL, with the exception of the forward region known as HF. The brass is 79 mm thick and the scintillating material fills 9 mm gaps. The scintillating material itself is doped plastic read out with hybrid photodiodes. There are four components to HCAL known as HB, HE, HO, and the aforementioned HF. The HB lies outside of EB and is 1.77 m to 2.95 m from the beam line, covering a region with $|\eta| < 1.3$. HE is just beyond EE and covers $1.3 < |\eta| < 3$. HO is outside of the magnet solenoid and is placed to catch showers exiting the enclosed tracker and calorimeters in order to improve energy resolution. HO is limited to $|\eta| < 1.3$. HF placed 11.2 m from the IP along the beam axis and covers $3 < |\eta| < 5$. Since HF is close to the beam axis, it is necessary to be composed of radiation hard materials, such as the steel absorbers instead of brass, and quartz fibers. Similar to how ECAL and HCAL collaborate to distinguish energy deposits from hadronic jet deposits and electron deposits, HF has two different length quartz fibers - the short fibers read out information primarily from electrons while the long fibers collect the information about hadronic processes as well. Figure 3.4 is the layout of HCAL [45].

3.2.4 Muon System

Muons travel further than other charged particles that get detected in the calorimeters of CMS; therefore, CMS is wrapped by a system designed to detect muons as they exit the experiment. The muon system is located outside of HCAL and uses the strong magnetic field to get good resolution of the particle's momentum. There are three components to the muon system, which are drift tubes, cathode strip chambers, and resistive plate chambers. The drift tubes form four concentric layers surrounding HO and are rectangular cells filled with Ar+CO₂ gas and positively charged wires. The passing muon ionizes the gas and produces electrons that provide a current in the wires. The cathode strip chambers are located in the endcap region of CMS where the particle flux is greatest and the magnetic field is non-uniform. The resistive plate chambers are also in the endcap region and are gaseous parallel plates that

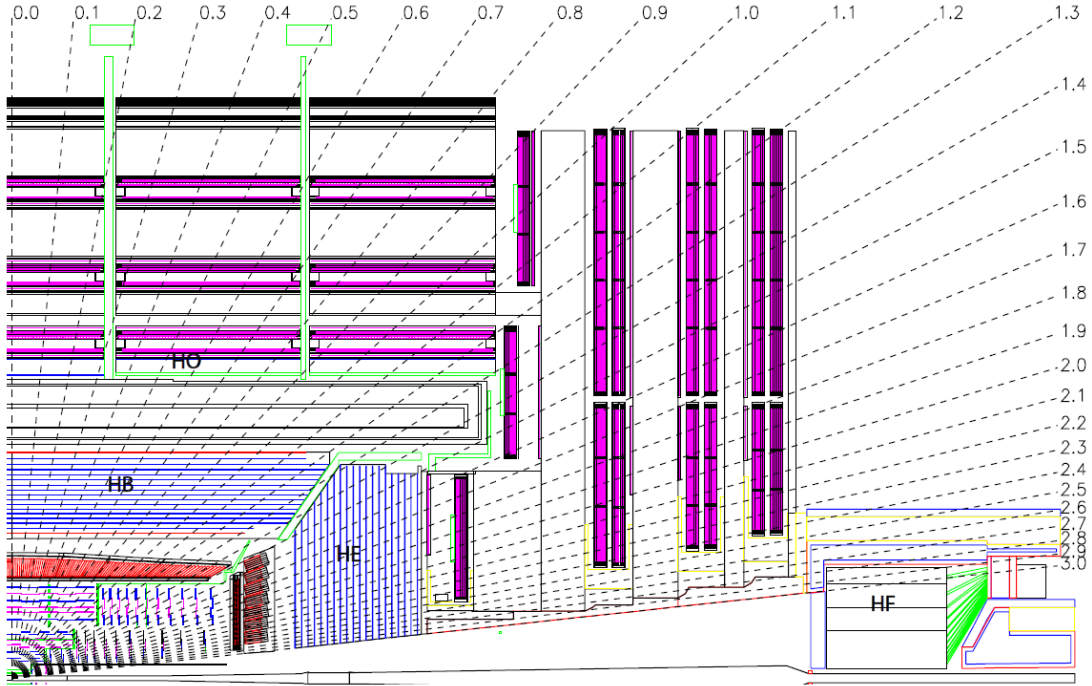


Figure 3.4: Schematic of the HCAL sub-detector.

are used for triggering the detector and complement the drift tubes and cathode strip chambers. Figure 3.5 shows the layout of the muon system in CMS [46].

3.3 Trigger System and Data Acquisition

Within CMS there are collisions occurring every 25 ns, which makes for a substantial amount of data to have to analyze and record, transfer, and store. It is not feasible to record every single collision event due to the ever increasing size of the data files that would have to be cataloged; therefore, CMS employs triggers within the data acquisition (DAQ) system in order to extract meaningful events of interest to the physics community. There are two genres of triggers, the level-1 triggers (L1) and the high level triggers (HLT), where both are meant to reduce the number of recorded events by a factor of 10^6 . The L1 trigger identifies leptons, photons, jets, and MET using coarsely segmented regions of CMS and determines if sub-detector information is to be processed for the HLT. The HLT uses detailed event reconstruction and physics object analysis in order to select out and categorize events by selection

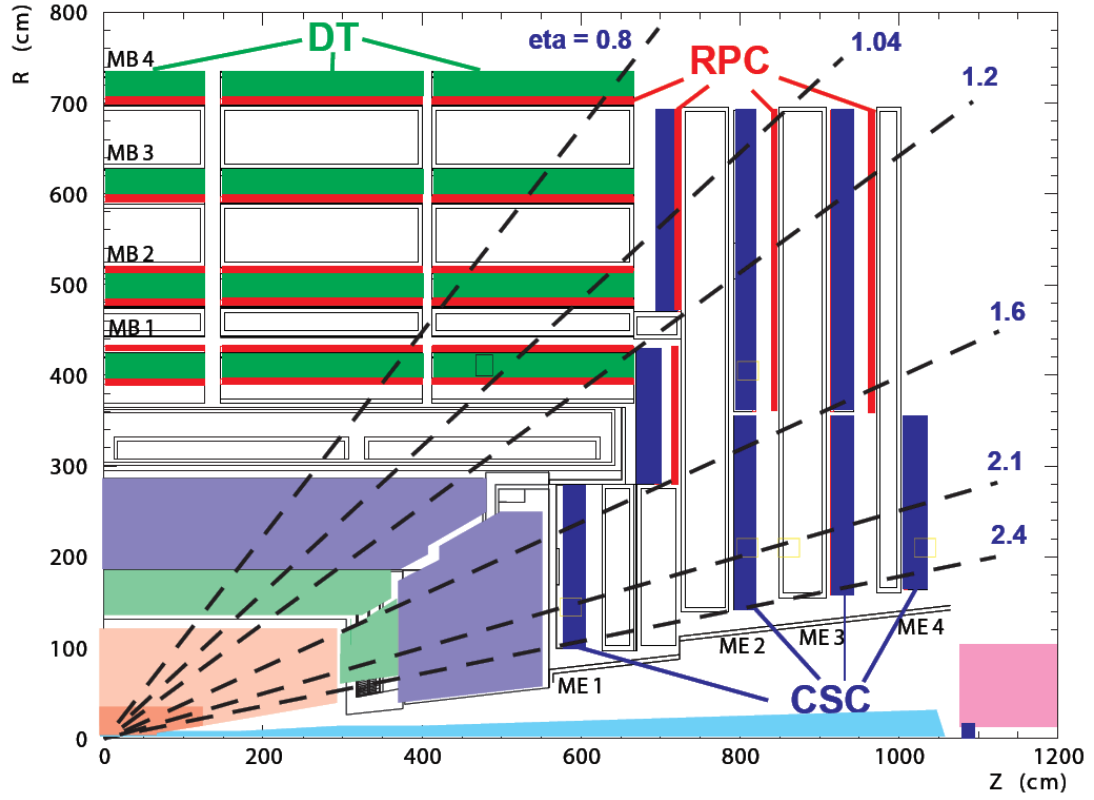


Figure 3.5: Schematic of the muon system.

criteria defined by physics analysis groups (PAG). Events that pass both the L1 trigger and HLT are slated for permanent storage on disk for later analysis. The typical size of one collision event is ~ 1 MB, and with the L1 trigger rate at 100 kHz this provides a readout of approximately 100 GB/s.

CHAPTER 4

SIMULATION AND RECONSTRUCTION SOFTWARE

In order to understand the data observed within the detector, there is a need to accurately model the proton-proton collisions and calculate the very precise interactions that lead to the final kinematic distributions. MC generators accomplish this in multiple steps, where the event generation is produced and then fragmented and hadronized, known as showering. After showering, the theoretical events are then passed through a detector simulation in order to mimic the data recording environment within CMS. From this point onwards, the simulated events are treated the same as data events and comparison plots are produced between the two.

The event generator of choice for this dissertation is MG5 [47]. This software produces output files in LHE format that are almost universal to many followup simulation packages, such as what will be discussed below. This generator is capable of producing events at leading order (LO) accuracy and next-to-leading order (NLO) accuracy. It is common practice to generate events at NLO accuracy with the latest data collected in CMS, but sometimes the heavy load of calculations restricts the software and thus LO events must be pursued. This effect will be seen later when some MC samples were generated at LO instead of NLO. An additional benefit to this software is that the process cross section is provided, which is later used to normalize the MC sample to the integrated luminosity.

The showering software used in this dissertation is Pythia [48]. Pythia is capable of generating events in LHE format as well, but this dissertation restricts its use to showering the events provided by MG5. The GEANT package is then used to take the showered events and produce the digital signals seen in observed data [49]. This software takes into account the many different types of interactions the particles will have with the various sub-detectors within CMS, such as ionization, radiation, elastic scattering, etc. The simulated DAQ readout of the event is then processed and analyzed just as observed data is.

4.1 CMSSW Event Reconstruction

The CMS community has developed sophisticated software algorithms used in CMS simulation and event reconstruction, collectively referred to as CMSSW [50]. Within this package are the algorithms developed and tuned by each separate physics object group (POG) which is used in this dissertation to select events for $WV\gamma$.

4.1.1 Muons

Muon candidates are identified by two different algorithms [51]: one proceeds from the inner tracker outwards, the other one starts from tracks measured in the muon chambers and matches and combines them with tracks reconstructed in the inner tracker. These selection criteria[52] are summarized below:

- The muon candidate is reconstructed both as a global muon and as a tracker muon.
- Number of pixel hits of the Tracker track ≥ 1 ;
- Number of muon system hits of the Global track ≥ 1 ;
- Normalized χ^2 of the Global track < 10.0 .
- Muon $p_T > 23$ GeV.
- Pseudorapidity $|\eta| < 2.1$.
- Impact parameter: We cut on the absolute value of the impact parameter calculated with respect to the primary vertex (PV). We require: $d_0(\text{PV}) < 0.2$ cm.
- In order to make sure that the selected muon and the selected jets come from the same hard interaction and not from pile up events, we require that the z coordinate of the PV of the event and the z coordinate of the muon's inner track vertex lie within a distance of less than 0.5 cm.
- The number of tracker layers with hits from the muon track has to be $N_{\text{layers}} > 5$.

The selected muon candidates also have to be isolated. Particle flow (PF) based relative isolation for muons is defined as

$$\text{RelIso}_{\text{PF}} = \frac{I_{\text{CH}} + \max(0, I_{\text{NH}} + I_{\text{PHOTON}} - (0.5 \cdot p_T^{\text{sumPU}}))}{p_T} \quad (4.1)$$

where I_{CH} , I_{NH} and I_{PHOTON} are the charged hadron, neutral hadron, and photon isolation variables (using an isolation cone of 0.4). The charged hadron isolation variable uses tracks from the primary vertices only. The neutral hadron and photon isolation variables are corrected for contributions from PU using the $\Delta\beta$ correction, $(0.5 \cdot p_T^{\text{sumPU}})$. We require the muon to have $\text{RelIso}_{\text{PF}} < 0.15$ in order to be considered isolated.

4.1.2 Electrons

Electrons are required to pass electron ID cuts according to a cut-based identification technique [53]. This ID takes into account that selected electron candidates are isolated. PF based relative isolation is defined as

$$\text{RelIso}_{\text{PF}} = \frac{I_{\text{CH}} + \max(0, I_{\text{NH}} + I_{\text{PHOTON}} - (\text{EA} \cdot \rho))}{E_T} \quad (4.2)$$

where I_{CH} , I_{NH} and I_{PHOTON} are the charged hadron, neutral hadron and photon isolation variables (using an isolation cone of 0.4). The I_{CH} variable is calculated from charged hadrons, associated to the PV. The neutral hadron and photon isolation variables are corrected for contributions from PU using the effective area correction [54], $(\text{EA} \cdot \rho)$, where EA is the cone effective area and ρ is the average neutral particle density of the event.

In order to reject events in which the electron candidate actually originates from a conversion of a photon into an e^+e^- pair, the ID criteria includes an approach using the vertex fit probability of fully reconstructed conversions combined with the requirement that the number of missed inner tracker layers of the electron track must be exactly zero (i.e. there are no missed layers before the first hit of the electron track from the beam line).

The tightest selection ID is used for the analysis and has been tuned by Electron-Photon (EGamma) POG.

Additionally, we require

- Electron $E_T > 25$ GeV.
- Pseudorapidity $|\eta| < 2.5$. There is an exclusion range due to the ECAL barrel-endcap transition region, defined by $1.4442 < |\eta_{sc}| < 1.566$, where η_{sc} is the pseudorapidity of the ECAL supercluster.

4.1.3 Photons

Photon candidates are reconstructed as *SuperClusters* in the ECAL with $E_T > 30$ GeV in the fiducial barrel region, defined by $|\eta| < 1.4442$. They are required to satisfy 2015 tight cut-based selection [55], which provides 70% signal selection efficiency:

- Single tower H/E < 0.05
- $\sigma_{i\eta i\eta} < 0.01$
- PF charged hadron isolation < 0.76 , with charged hadrons originated from the hard interaction PV.
- PU corrected PF neutral hadron isolation $< 0.97 + 0.014 \times p_T^\gamma + 0.000019 \times (p_T^\gamma)^2$
- PU corrected PF photon isolation $< 0.08 + 0.0053 \times p_T^\gamma$
- Conversion safe electron veto

PU corrected PF isolation is calculated using effective area corrections. The photon candidates are also required to be separated from the lepton by at least 0.5 in $\eta - \phi$ space, which highly reduces the contribution from final state radiation (FSR) to the observed photon rate. The same separation requirements are imposed between the photon candidates and the jets.

4.1.4 Jets

Jets are reconstructed with the anti-KT algorithm [56], starting from the set of objects reconstructed by the PF algorithm [57, 58, 59, 60]. Jets are corrected such that the measured energy of the jet correctly reproduces the energy of the initial particle. The CMS standard L2 (relative) correction makes the jet response flat in η . The standard L3 (absolute) correction brings the jet closer to the p_T of a matched generated jet created using generator level input and a similar jet clustering algorithm. The L2 and L3 corrections are calculated using Monte Carlo (MC), and thus a L2L3 residual correction is applied that fixes the discrepancies between MC and data [61]. We require $|\eta| < 2.4$ so that the jets fall within the tracker acceptance. Jets from PU are identified and removed with *PileupJetID* [62].

Jets are required to pass a set of loose identification criteria; this requirement eliminates jets originating from or being seeded by noisy channels in the calorimeter [63]:

- Fraction of energy due to neutral hadrons < 0.99 .
- Fraction of energy due to neutral EM deposits < 0.99 .
- Number of constituents > 1 .
- Number of charged hadrons candidates > 0 .
- Fraction of energy due to charged hadrons candidates > 0 .
- Fraction of energy due to charged EM deposits < 0.99 .

All energy fractions are calculated from uncorrected jets.

In order to account for electron and muon objects that have been reconstructed as jets, we remove from the jet collection any jet that falls within a cone of radius $R = 0.3$ of a loose electron or a loose muon. This “cleaning” procedure is applied in order to ensure that the same particle is not double counted as two different physics objects.

4.1.5 Missing Transverse Energy

An accurate MET measurement is essential for distinguishing the W signal from QCD backgrounds. We use the MET estimate provided by the PF algorithm. PF

MET showed the best performance among several MET algorithms [64]. The MET is computed as the vector sum of all PF objects and has an energy scale correction (type 1) applied. A good agreement is found between the MET distributions of $W \rightarrow l\nu$ events in data and simulation [65]. The resolution for inclusive multi-jet samples and for $W \rightarrow l\nu$ events is also well reproduced by the simulation. A relative broadening of a few percent is observed in the data compared to MC, and has a negligible impact on the extraction of the W yields [66]. We reject events with small opening angle between MET and any of the two leading jets ($\Delta\phi(\text{MET}, j) < 0.4$). This cut rejects events with fake MET due to a mismeasured jet p_T .

CHAPTER 5

WW γ AND WZ γ PRODUCTION

The research performed for the search of WW γ triboson production within CMS includes data collected at two different COM energies, 8 TeV and 13 TeV. The data recorded in 2012 marked the final year of proton-proton collisions at the LHC prior to the Long Shutdown period (LS1) slated for detector upgrades. At the time, CMS collected a record integrated luminosity of approximately 20 fb $^{-1}$ to which many multi-boson interaction analyses owe their statistics. Following LS1, the COM of the proton collisions was nearly doubled; however, 2015 was intended to be the start up period for the LHC in anticipation of the higher instantaneous luminosity, as well as break in the new hardware. Therefore, 2015 yielded a lower integrated luminosity than 2012, totaling approximately 2.3 fb $^{-1}$ or one-tenth that collected at 8 TeV. There were two important factors that contributed to the lower integrated luminosity within CMS: the initial proton bunch spacing between collisions was 50 ns, to which a couple of months was spent collecting roughly half of one femtobarn of data, and then the spacing was decreased to 25 ns for the remainder of the year, which is the designed spacing intended; the second factor was that the CMS solenoid magnet's cooling system was contaminated with oil, and thus required periodic ramp down of the magnet until the filtering system could be cleaned. This proved to be detrimental to the ability within CMS to record data that provides charge and mass discrepancy between particles, particularly for the leptonic decay of the W boson. Therefore, the data analyzed in this dissertation corresponds to the entire data from 2012 and only 25 ns 2015 data recorded with the magnetic field held steady at 3.8 T.

5.1 Measurements at $\sqrt{s} = 8$ TeV

5.1.1 Simulation and Data Samples

The data sample we use in this analysis was recorded by the CMS experiment in 2012. The data is collected by single muon ($p_T > 23$ GeV) and single electron ($p_T > 27$ GeV) triggers. Only certified runs and luminosity sections are considered, which means that good functioning of all CMS sub-detectors is required. The total statistics analyzed correspond to an integrated luminosity of 19.3 fb $^{-1}$.

Table 5.1: Summary of data samples used and run ranges of applicability.

Data set name	Run range
/SingleMu/Run2012A-13Jul2012-v1/AOD	190456-193621
/SingleElectron/Run2012A-13Jul2012-v1/AOD	
/SingleMu/Run2012A-recover-06Aug2012-v1/AOD	190782-190949
/SingleElectron/Run2012A-recover-06Aug2012-v1/AOD	
/SingleMu/Run2012B-13Jul2012-v1/AOD	193833-196531
/SingleElectron/Run2012B-13Jul2012-v1/AOD	
/SingleMu/Run2012C-24Aug2012-v1/AOD	198022-198913
/SingleElectron/Run2012C-24Aug2012-v1/AOD	
/SingleMu/Run2012C-PromptReco-v2/AOD	198934-203746
/SingleElectron/Run2012C-PromptReco-v2/AOD	
/SingleMu/Run2012D-PromptReco-v1/AOD	203894-208686
/SingleElectron/Run2012D-PromptReco-v1/AOD	

The data set used for the analysis and the corresponding run ranges are listed in Table 5.1. All samples have been processed using a `CMSSW_5_3_2` release version.

Anomalous quartic gauge coupling samples, as well as samples for a variety of EW and QCD-induced background sources, have been generated and showered using different MC generators. To better reproduce the actual data-taking conditions, where there is a significant probability that more than two protons interact in the same bunch crossing (BX), PU events are added on top of the hard scattering. Particle interactions with the detector were reproduced through a detailed description of CMS.

The MadGraph5.1.3.22 generator [47] has been used to produce signal events, and the showering has been performed with PYTHIA6 [48]. The background samples used for the studies are listed in Tables 5.2-5.3. All MC samples considered in this analysis come from the official “Summer12_53X” or private production. Events from all samples were reconstructed making use of a `CMSSW_5_3_X` release version. The simulated samples are reweighed to represent the distribution of the number of pp interactions per BX (pileup), as measured in the data.

A summary of the cross section of the contributing processes is given in Table 5.4

5.1.2 Event Selection

The event should have a good PV. This means selecting the PV with the highest sum of p_T^2 of the tracks associated with it and requiring it to have a number of degrees of freedom (NDOF) ≥ 4 , where NDOF corresponds to the weighted sum of the number of tracks used for the construction of the PV. In addition, the PV must lie in the central detector region of $|z| \leq 24$ cm and $\rho \leq 2$ cm around the nominal IP.

In the electron channel, we select events that contain exactly one tight electron candidate fulfilling the criteria described in Section 4.1.2 and reject events that contain a loose electron or a loose muon in addition to the tight electron. In the muon channel, we select events that contain exactly one tight muon candidate whose criteria are described in Section 4.1.1 and reject events that contain an additional loose lepton. In both channels we require an event to have missing transverse energy MET in excess of 35 GeV and to have transverse mass greater than 30 GeV. These cuts are designed to reduce the background from QCD multijet production.

Further we require two central jets in the event with dijet invariant mass $70 < m_{jj} < 100$ GeV which corresponds to the hadronic decay of the W or Z in the signal process and $\Delta\eta(j, j) < 1.4$ which further suppresses the $W\gamma + jets$ background. Additionally we require both jets to fail the combined secondary vertex (CSV) medium b-tag requirement, which suppresses the $t\bar{t}\gamma$ and single top backgrounds. In the electron channel we require $|M_{e\gamma} - M_Z| > 10$ GeV, which efficiently rejects the $Z + jets$ background, when one of the leptons in e^+e^- pair is misreconstructed as photon.

5.1.3 Efficiencies and Scale Factors

Since the lepton reconstruction, selection, and trigger efficiencies can be slightly different between data and simulation, correction factors have to be applied to the MC to account for these differences. The efficiencies are calculated using a tag and probe (TnP) technique exploiting Z boson decays to a pair of electrons or muons, respectively. One of the leptons is used as tag and has to pass a tight selection, while the second one is used as probe if the tag-probe pair combines to the Z boson mass. The total lepton efficiency can be factorized into three components:

$$\epsilon_{\text{total}} = \epsilon_{\text{Reco}} \cdot \epsilon_{\text{Id}} \cdot \epsilon_{\text{HLT}} \quad (5.1)$$

The TnP method is nearly the same compared to the one already used in the 2011 data analysis for this Higgs search [67, 68]. Therefore, only the most important information will be discussed.

5.1.3.1 Electron Efficiencies

In the electron case, the reconstruction efficiency ϵ_{Reco} characterizes the transition from a super-cluster in the ECAL to a reconstructed PF electron. The ability of a reconstructed electron to pass the offline selection, consisting of several isolation and identification criteria, is given by the identification efficiency ϵ_{Id} . Finally, the selected electron has a certain probability to fire the HLT and the efficiency to fulfill the HLT requirements is parametrized as ϵ_{HLT} . In data, a single electron trigger is used at HLT level, while in MC the HLT requirements are dropped.

Since the HLT efficiency in MC is equal to 100%, the HLT efficiency measured on data is applied directly in the analysis of MC samples, while the other two efficiency components are calculated both for data and MC, so that a data/MC scale factor is applied in the other cases.

In general, since the efficiency depends both on p_T and η of the electron, the measurement is binned in p_T as (30, 35, 40, 45, 50, 200) GeV and in η as (-2.5, -1.5, 0.0, 1.5, 2.5) of the probe electron. The resulting efficiencies and scale factors are summarized in Table 5.5 and shown in Figure 5.1.

Table 5.2: Summary of SM MC samples used in the analysis.

$W\gamma + Jets$	/Wajets.lvaJets_TTU2.SIM/jdamgov-Wajets_RECOTTU2-6c7dff08efc03321df811559605c57f/USER
$W\gamma + Jets, p_T^\gamma > 100 \text{ GeV}$	/WAp23J_100GeVtail_8TeV_CMSSW532_LHE2EDM/jfaulkne-WApJ_highPT_8TeV_CMSSW532_RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
$WZ\gamma$	/WZA_8TeV_CMSSW532_LHE2EDM/jfaulkne-WZA_lvjjA_8TeV_CMSSW532RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
$Z\gamma + Jets$	/ZAp23J_8TeV_CMSSW532_LHE2EDM/jdamgov-ZApJ_8TeV_CMSSW532RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
$t\bar{t}\gamma + Jets$	/TTGJets_8TeV-madgraph/jdamgov-TTbarAJetsRECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
ZZ	/ZZ_TuneZ2star_8TeV_pythia6_tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
Single Top + γ	/T_t-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10START53_V7A-v1/AODSIM /T_s-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM /T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM /Tbar_t-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM /Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53V7A-v1/AODSIM /Tbar_s-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM

Table 5.3: Summary of AQGC MC samples used in the analysis.

FT0 -3	/WWA6-LT0m3-MG/qili-WWAAODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
FT0 -5	/WWA6-LT0m5-MG/qili-WWAAODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
FT0 -8	/WWA6-LT0m8-MG/qili-WWAAODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
FT0 3	/LT0p3_SIM/dyang-LT0p3_AODSIM-a14afa9073215900eeee6c01e24940c2/USER
FT0 5	/LT0p05_SIM/dyang-LT0p5_AODSIM-a14afa9073215900eeee6c01e24940c2/USER
FT0 8	/LT0p8_SIM/dyang-LT0p8_AODSIM-a14afa9073215900eeee6c01e24940c2/USER
a_C^W 3	/WWA6-cm3m5-MG/qili-WWAAODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_C^W 5	/WWA6-cp5m5-MG/qili-WWAAODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_C^W 8	/WWA6-cm8m5-MG/qili-WWAAODSIM-2-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_C^W -3	/dim6KCG_p3m5_SIM_v0/zixu-dim6KCG_p3m5_SIM... ...AODSIM-7d85a48843799f18e4c38abf839f8e2e/USER
a_C^W -5	/cA6p5m5_SIM/zixu-cA6p5m5_AODSIM-7d85a48843799f18e4c38abf839f8e2e/USER
a_C^W -8	/cA6p8_SIM/dyang-cA6p8.2_AODSIM-a14afa9073215900eeee6c01e24940c2/USER
a_0^W -2	/WWA6-p2m5-MG/qili-WWA-AODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_0^W -3	/WWA6-p3m5-MG/qili-WWA-AODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_0^W -5	/WWA6-p5m5-MG/qili-WWA-AODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_0^W 2	/WWA6-m2m5-MG/qili-WWAAODSIM-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
a_0^W 3	/A6m3m5_SIM/zixu-A6m3m5_AODSIM-7d85a48843799f18e4c38abf839f8e2e/USER
a_0^W 5	/A6m5m5_SIM/zixu-A6m5m5_AODSIM-7d85a48843799f18e4c38abf839f8e2e/USER
κ_0^W -2	/aWWA_k0W_m2.8TeV_CMSSW532_GEN/jfaulkne-aWWA_k0W_m2.8TeV... ...CMSSW532_RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
κ_0^W -1	/aWWA_K0W_m1.8TeV_CMSSW532_LHE2EDM/jfaulkne-aWWA_k0W_m1.8TeV... ...CMSSW532_RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
κ_0^W -0.5	/aWWA_k0W_m05.8TeV_CMSSW532_GEN/jfaulkne-aWWA_k0W_m05.8TeV... ...CMSSW532_RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
κ_0^W 0.5	/aWWA_k0W_p05.8TeV_CMSSW532_GEN/jfaulkne-aWWA_k0W_p05.8TeV... ...CMSSW532_RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
κ_0^W 1	/aWWA_k0W_p1.8TeV_CMSSW532_GEN/jdamgov-SQWaT_PAT_53X_Summer12... ...k0Wp1-829f288d768dd564418efaaf3a8ab9aa/USER
κ_0^W 2	/aWWA_K0W_p2.8TeV_CMSSW532_LHE2EDM/jfaulkne-aWWA_k0W_p2.8TeV... ...CMSSW532_RECO-c8f8ed334db8a7d6f56c62266b1dfa5b/USER
κ_C^W -3	/aWWA_kCW_m3.8TeV_CMSSW532_GEN_TTU/jdamgov-SQWaT_PAT_kCWm3... ...8TeV_WWZA-829f288d768dd564418efaaf3a8ab9aa/USER
κ_C^W -2	/aWWA_kCW_m2.8TeV_CMSSW532_GEN_TTU/jdamgov-SQWaT_PAT_kCWm2... ...8TeV_WWZA-829f288d768dd564418efaaf3a8ab9aa/USER
κ_C^W -1	/aWWA_kCW_m1.8TeV_CMSSW532_GEN_TTU/jdamgov-SQWaT_PAT_kCWm1... ...8TeV_WWZA-829f288d768dd564418efaaf3a8ab9aa/USER
κ_C^W 1	/aWWA_kCW_p1.8TeV_CMSSW532_GEN/prebello-SQWaT_PAT_kCWp1... ...8TeV-829f288d768dd564418efaaf3a8ab9aa/USER
κ_C^W 3	/aWWA_kCW_p3.8TeV_CMSSW532_GEN/prebello-SQWaT_PAT_kCWp3... ...8TeV-829f288d768dd564418efaaf3a8ab9aa/USER

Table 5.4: Summary of the SM processes. Photon $p_T > 10$ GeV, $|\eta^\gamma| < 2.5$.

Process	shape modeling	cross section [pb]
SM WW γ	MC	(NLO) 0.0582 ± 0.0138
SM WZ γ	MC	(NLO) 0.0121 ± 0.0029
W γ +Jets	MC	(data) 10.872 ± 0.087
jet $\rightarrow \gamma$	data	data
Z γ +Jets	MC	(LO) 0.632 ± 0.126
$t\bar{t}\gamma$	MC	(LO) 0.615 ± 0.123
Single Top + γ (inclusive)	MC	(NLO) 0.310 ± 0.011

Table 5.5: Electron efficiency and data/MC scale factors for super-cluster to reconstructed electrons (ϵ_{Reco}), reconstructed to selected electrons (ϵ_{ID}) and selected to HLT electrons (ϵ_{HLT}). The errors are statistical only.

$p_{T,\text{min}}$ [GeV]	$p_{T,\text{max}}$ [GeV]	η_{min}	η_{max}	$\epsilon_{\text{Reco,data}}/\epsilon_{\text{Reco,mc}}$	$\epsilon_{\text{ID,data}}/\epsilon_{\text{ID,mc}}$	$\epsilon_{\text{HLT,data}}$
30	35	-2.5	-1.5	1.000 ± 0.002	0.973 ± 0.004	0.639 ± 0.003
30	35	-1.5	0	0.996 ± 0.001	0.981 ± 0.003	0.874 ± 0.001
30	35	0	1.5	0.996 ± 0.001	0.980 ± 0.003	0.874 ± 0.001
30	35	1.5	2.5	1.002 ± 0.001	0.999 ± 0.004	0.650 ± 0.003
35	40	-2.5	-1.5	1.001 ± 0.001	1.005 ± 0.003	0.686 ± 0.002
35	40	-1.5	0	0.999 ± 0.001	0.978 ± 0.002	0.896 ± 0.001
35	40	0	1.5	0.998 ± 0.001	0.978 ± 0.002	0.891 ± 0.002
35	40	1.5	2.5	1.001 ± 0.001	1.003 ± 0.085	0.690 ± 0.002
40	45	-2.5	-1.5	1.001 ± 0.001	1.005 ± 0.003	0.708 ± 0.002
40	45	-1.5	0	0.999 ± 0.001	0.985 ± 0.001	0.909 ± 0.001
40	45	0	1.5	0.999 ± 0.001	0.983 ± 0.001	0.906 ± 0.001
40	45	1.5	2.5	1.000 ± 0.001	1.014 ± 0.003	0.720 ± 0.002
45	50	-2.5	-1.5	1.001 ± 0.001	1.017 ± 0.003	0.724 ± 0.002
45	50	-1.5	0	1.000 ± 0.001	0.984 ± 0.002	0.917 ± 0.001
45	50	0	1.5	0.999 ± 0.001	0.985 ± 0.002	0.911 ± 0.001
45	50	1.5	2.5	1.001 ± 0.001	1.021 ± 0.003	0.733 ± 0.002
50	200	-2.5	-1.5	0.999 ± 0.001	1.023 ± 0.003	0.733 ± 0.003
50	200	-1.5	0	0.999 ± 0.001	0.990 ± 0.002	0.925 ± 0.001
50	200	0	1.5	0.999 ± 0.001	0.991 ± 0.003	0.920 ± 0.001
50	200	1.5	2.5	1.000 ± 0.001	1.019 ± 0.003	0.745 ± 0.003

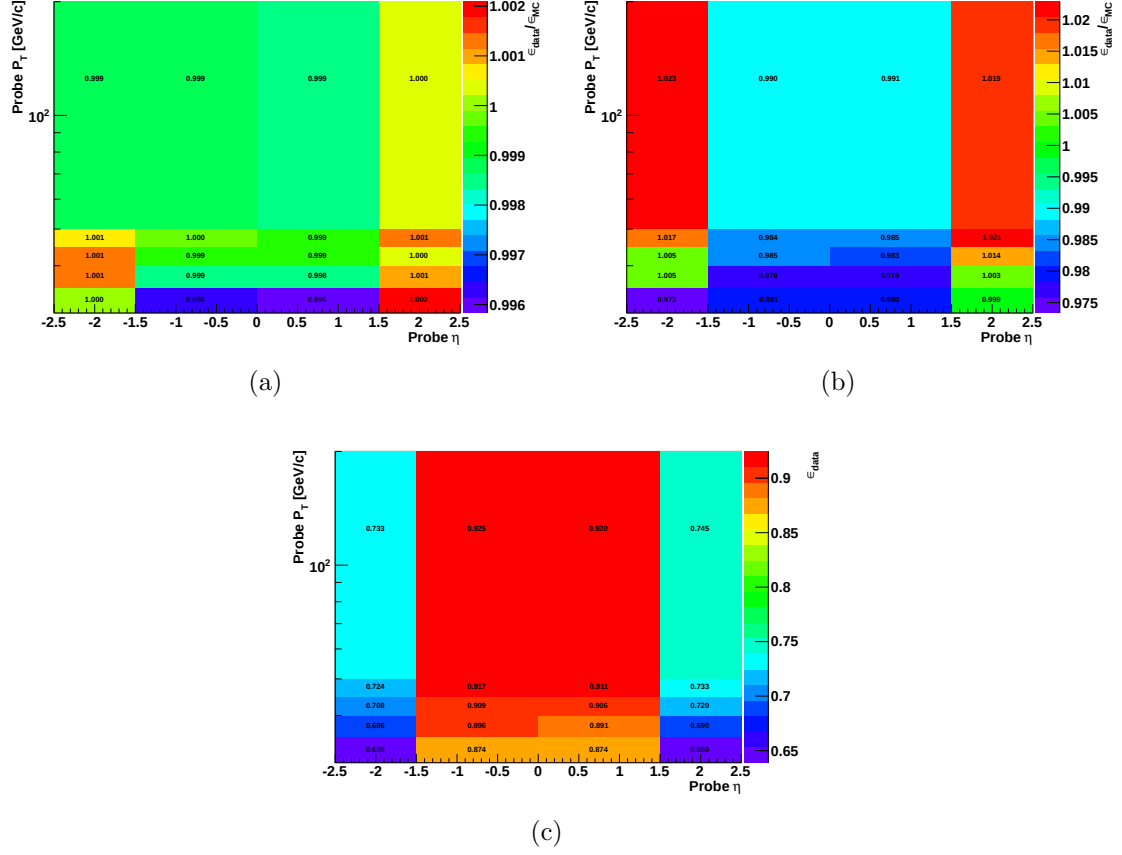


Figure 5.1: Electron efficiency and data/MC scale factors for super-cluster to reconstructed electrons ϵ_{Reco} (a), reconstructed to selected electrons ϵ_{Id} (b) and selected to HLT electrons ϵ_{HLT} (c).

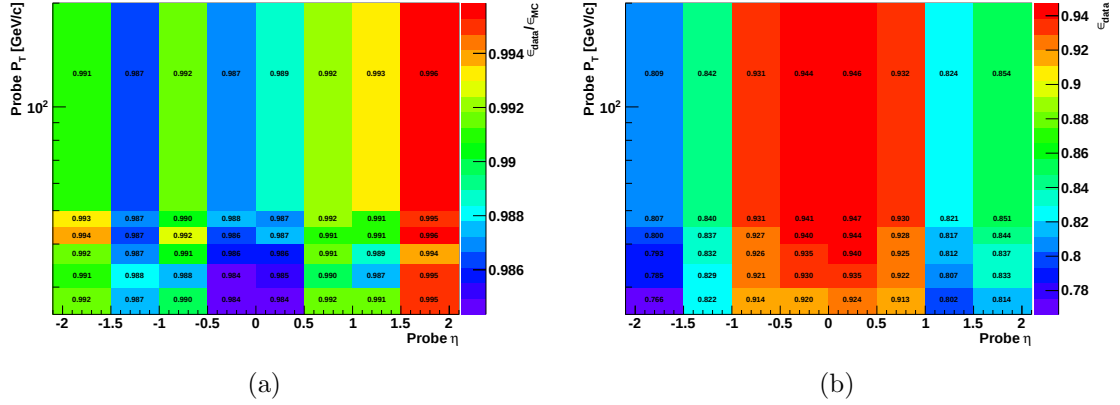


Figure 5.2: Muon scale factors for reconstructed to selected muons $\epsilon_{ID,data}/\epsilon_{ID,mc}$ (a) and efficiency for selected to HLT muons $\epsilon_{HLT,data}$ (b).

5.1.3.2 Muon Efficiencies

In the muon case, the reconstruction efficiency ϵ_{Reco} describes the ability to reconstruct a PF muon starting with a particle track and can be assumed to be one [51]. The identification efficiency ϵ_{Id} gives an estimate for a reconstructed muon to pass the offline selection criteria. It can be computed for both data and simulation and thus a scale factor, the ratio of the two efficiencies, is derived.

The trigger efficiency ϵ_{HLT} is the fraction of selected muons fulfilling the HLT requirements, and, since the HLT requirement is dropped on the MC analysis, the efficiency computed on data is used directly to correct the MC event expectation.

The efficiency measurement is binned both in p_T and η of the probe muon covering the relevant intervals (25, 30, 35, 40, 45, 50, 200) GeV in p_T and (-2.1, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.1) in η . The resulting selection and trigger efficiencies and scale factors are summarized in Table 5.6 and Figure 5.2.

5.1.3.3 Photon Efficiencies

We used photon efficiency scale factors for 2012(A+B+C+D) and tight photon selection described [69], which is EGamma POG approved. The scale factors do not include electron veto selection and are listed in Table 5.7 [69]. The scale factors for electron veto selection are 0.9958 ± 0.0043 ($E_T = [30, 40]$ GeV) and $0.9999 \pm$

0.0067 ($E_T > 40$ GeV).

5.1.4 Photon Fake Rate

The largest background arises from the $W\gamma$ +jets process, while the second important contribution comes from jets or electrons misidentified as a photon. Electrons could be identified as photons due to small track reconstruction inefficiency of the detector. This contribution is relevant to the electron channel, when an electron or positron from $Z \rightarrow ee$ passes the photon identification criteria; therefore, to reduce this background, we impose a $|M_Z - M_{e\gamma}| > 10$ GeV cut. Events with jets misidentified as photons can not be tagged with a simple kinematic requirement, because it resembles the topology of the events with true photons. The adopted approach is to build the expected rate based on the ratio method [70]. The method uses a category of jets(photon-like jets), which resembles the electromagnetic objects in the ECAL, but fail either the isolation or $\sigma_{in\eta}$ requirement. Through simple algebraic conversion it can be made into the photon fake rate, or number of fake photon candidates divided by the total number of all photon candidates. We perform a very similar fake rate estimation using our full 2012 single lepton data set and assign a p_T -dependent systematic uncertainty on the fake rate estimation.

Similar to the EGamma method, for our fake rate estimation we use the full 2012 data set with single lepton triggers (that we use in our analysis) to form a signal and background template that will be normalized to each other's sideband. This is to say that we estimate our data-driven fake rate by: filling the signal distribution in $\sigma_{I\eta I\eta}$ with 2012 tight photons; filling the background distribution in $\sigma_{I\eta I\eta}$ with 2012 photon candidates that fail the tight cut in PF charged and/or neutral isolation, as well as possibly failing the tight $\sigma_{I\eta I\eta}$ cut; and normalizing the background distribution's $\sigma_{I\eta I\eta}$ sideband ($\sigma_{I\eta I\eta} > 0.011$) to the sideband of the signal's distribution. In order to preserve the sidebands of the signal and background $\sigma_{I\eta I\eta}$ distributions, we remove the $\sigma_{I\eta I\eta}$ cut in the 2012 tight photon ID. We normalize the background's sideband to the signal sideband because we call any photon candidates that fail the tight $\sigma_{I\eta I\eta}$ a fake photon, or photon-like jet; therefore, any contribution in the signal distribution above $\sigma_{I\eta I\eta} > 0.011$ comes from the background, or fake photons. Figure 5.3 demonstrates how the backgrounds' sidebands have been normalized to the signals' sidebands for

each photon p_T bin.

With the two distributions' sidebands normalized in each photon p_T bin, we estimate the fake-photon contamination within the signal distribution by integrating the background below $\sigma_{I\eta I\eta}$ of 0.011. Thus, with the number of background, or photon-like jets, and the number of 2012 tight photons below this cut, we can estimate our analysis's p_T -dependent photon fake rate, as shown in Table 5.8. We only estimate the rate for barrel photons currently.

5.1.5 K-factors

5.1.5.1 SM $WV\gamma$

Leading-order samples generated by MG5 are used for this analysis. Generally, LO calculations can provide a good estimation of cross sections and a description of kinematic distributions, but the shortcoming is also obvious. Its dependence on the unphysical renormalization and factorization scales can result in a large theoretical uncertainty, especially for those processes with large logarithms. Therefore, NLO calculations are important for precise analysis. In an experimental analysis, generally one can use a K-factor, which is defined as the ratio of the NLO to LO cross section for a given process, to estimate the NLO effect. However, its dependence on the renormalization and factorization scales, as well as the parton distribution functions (PDFs), should result in large uncertainties. Moreover, the NLO corrections can also lead to shape changes in kinematic distributions, especially when tight cuts are applied. Thus, one needs to make a careful examination to get a reasonable K-factor.

The emerging package aMC@NLO [71, 72] implements automatic event generation with NLO accuracy, which is a great improvement of MC hard events generation. However, we do not use the NLO samples for our analysis. Instead, we investigated the K-factor distribution as a function of the photon p_T , which gives us reasonable K-factors for our $W^\pm V\gamma$ samples.

For our analysis, 200 thousand $W^\pm V\gamma$ signal events, without W decays, are first generated using aMC@NLO. Then the samples are passed to HERWIG [73] to do parton shower. In the framework of aMC@NLO, theoretical uncertainties can also be obtained through a process-independent technique introduced in Ref. [74], which allows aMC@NLO to compute scale and PDF uncertainties in a fully automated way

and at no extra CPU-time cost. The default renormalization and factorization scales are set equal to the sum of transverse masses of all final state particles and partons. To get scale dependence, we vary the μ_R and μ_F independently, considering the set of $(\mu_R, \mu_F) = (\kappa_R \mu_R, \kappa_F \mu_F)$, with $(\kappa_R, \kappa_F) = (1, 1), (1/2, 1/2), (2, 2)$ and the overall scale uncertainty is the maximum deviation of all the sets. The PDF uncertainty is estimated following the method (asymmetric Hessian) illustrated in Ref. [75]. The *MSTW2008nlo68cl* [75] PDF sets are used for this analysis which contains 20 pairs to compute PDF uncertainties.

To make the result close to the experimental analysis, some basic cuts have been applied for the samples. $p_T^\gamma > 10$ GeV and $|\eta_\gamma| < 2.5$ have been used for both LO and NLO calculation. As for photon isolation cut, the cone approach is not infrared safe for NLO calculation. Therefore, we adopted the isolation cut introduced in Ref. [76, 77] instead: if i is a parton with transverse energy E_{T_i} and a separation $R_{i\gamma}$ with a photon of transverse momentum p_T^γ , then the event is accepted only if:

$$\sum_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq p_T^\gamma \frac{1 - \cos\delta}{1 - \cos\delta_0} \quad (\text{for all } \delta \leq \delta_0) \quad (5.2)$$

where δ_0 is fixed to be 0.7.

In Figure 5.4, the K-factor distribution is quite flat; we use a binned likelihood method fit to a constant to get the value of the K-factor. Therefore, the K-factor value, with scale and PDF uncertainties, we use for the SM signal sample is $2.09812 \pm 0.302029\%$ (stat.) $\pm 23.4256\%$ (scale) $\pm 3.55719\%$ (PDF).

5.1.5.2 AQGC $WV\gamma$

MC samples for the AQGC study are generated as SM $WV\gamma$ with added AQGC. The K-factors for two values of a_0^W/Λ^2 and a_C^W/Λ^2 are computed as a function of the photon p_T and are shown in Figure 5.5. At low photon p_T the K-factor resembles the SM $WV\gamma$ K-factor, while with the increase of the photon p_T , most of the contributions are from the quartic diagrams, and one can expect that the value will be similar to the Drell Yan processes. The K-factor for $pp \rightarrow W^+$ and $pp \rightarrow Z$ processes have also been calculated, and the results turned out to be 1.185 and 1.184. As can be seen in Figure 5.5, the AQGC K-factor levels at approximately 1.185 when the photon p_T is greater than 300 GeV. The exact behavior of the K-factor at low photon p_T for the SM $WV\gamma$ with added AQGC depends on type of the AQGC parameter and its value. Figure 5.5 shows the K-factor for two different AQGC parameters, while Figure 5.6 shows the K-factor for two different values of the same AQGC parameters, namely a_0^W/Λ^2 .

In this study we define the visible AQGC signal as the contribution which only originates from the anomalous quartic diagrams. The limit-setting machinery, discussed in Section 5.1.9.2, uses a signal input distribution which is the difference between the SM $WV\gamma$ with added AQGC photon p_T distributions (referred to as “AQGC-SM”). Since virtually all events with a photon p_T above 300 GeV are predicted to be from AQGC, then the input distribution should reflect the K-factor of 1.185. To accomplish this, when preparing the input file for the limit setter, we do not use a K-factor for either the SM or AQGC samples in the AQGC-SM subtraction. With the resulting AQGC-SM distribution being primarily high photon p_T events, and AQGC in nature, then we apply the K-factor of 1.185. Since there are some remaining low photon p_T AQGC events in the AQGC-SM distribution, we are applying a constant K-factor across the board. An illustration of the resulting K-factor from such a procedure is shown in Figure 5.7. Photon p_T distributions for AQGC-SM LO and NLO samples are shown in the left of Figure 5.7, while the resulting K-factor is shown in the right of Figure 5.7.

As an additional cross check, we calculated the K-factors for SM $WV\gamma$ with added AQGC for all values of the a_0^W/Λ^2 parameter and re-calculated the limits on this parameter. The limits are shown in Section 5.1.9.4, while the conclusion is that with

either of the described procedures we arrive to the same constraints on the AQGC values. Thus we have chosen to use the method with a constant Drell Yan like K-factor for AQGC-SM distribution. In this last cross check we have used the following function to fit the K-factor shape for SM $WV\gamma$ with added AQGC:

$$\begin{cases} slp \cdot x + (top - slp \cdot cuta), & x \leq cuta \\ (top - 1.185) \cdot \exp(-tau \cdot (x - cuta)) + 1.185, & x > cuta \end{cases} \quad (5.3)$$

where slp , top , $cuta$, and tau are fit parameters and x represent the p_T^γ . K-factors and the fit are shown in Figure 5.8 for $a_0^W/\Lambda^2 = p \times 10^{-5} \text{ GeV}^{-2}$, where $p = 2, 3, 5$.

5.1.5.3 $W\gamma$ + jets Background Estimation

In order to estimate the normalization of the major background $W\gamma$ +jets, we used a data-driven technique. The background normalization in the signal region is extracted with a binned maximum likelihood fit to the dijet invariant mass distribution m_{jj} of the two leading jets. The signal region corresponding to the W and Z mass windows, $70 \text{ GeV} < m_{jj} < 100 \text{ GeV}$, is excluded from the fit. The $W\gamma$ +jets shape is taken from simulation. The overall normalizations of the $W\gamma$ +jets and fake photon components are allowed to vary in the fit. All other backgrounds, which contribute less than 10% to the total, are based on simulation and are fixed to their SM expectations with uncertainties. The multi-jet background shape is derived from data by relaxing lepton isolation and identification requirements. Its contribution to the total number of events is evaluated from a separate two-component likelihood fit to the MET distribution, and fixed in the m_{jj} fit according to this fraction within uncertainties [78]. Normalization for the $W\gamma$ +jets is measured to be 1.099 ± 0.073 for muons and 1.074 ± 0.085 for electrons. The quality of the fit is illustrated in Figure 5.9

Table 5.9 summarizes the K-factors and cross sections used for each MC sample, as well as the treatment of all backgrounds in the fit.

5.1.6 Systematic Uncertainties

5.1.6.1 Misidentified Jets

In order to estimate the systematic uncertainty in the photon fake rate, two separate contributions are considered - the effect of biasing the fake photon template, and the statistical uncertainty in the bias measurement. The known bias is that the fake photon template is constructed using inverted PF isolation in the 2012 photon tight selection ID, where it is assumed that all photon candidates filling this template are in fact jets faking a photon.

To test this bias, a MC sample containing jets misidentified as photons is used (such as W+jets MC), along with its generator information for all jets and photons, to construct the truth and estimate templates. The muon channel of the MC is used for this study in order to remove the photon-faking electron contribution. The generator information is used to remove all initial state radiation (ISR) and FSR photons from the pool of 2012 tight photon candidates in the MC, leaving only those photon candidates that must be jets misidentified as photons - these will fill the truth template. The estimate template is filled using the aforementioned inverted isolation procedure for all photon candidates in the MC. Figure 5.10 demonstrates the shape of both the MC truth and estimate templates, where the estimate template has been normalized to the truth template using the sideband region of $\sigma_{I\eta I\eta} > 0.012$; also, it shows MC shapes compared to the data shapes that are used in determining the fake rate. The two templates are compared using the same prescription described for the data-driven fake rate estimate of the prompt and fake photon templates; however, due to low statistics in MC after removing all prompt photons, the entire photon p_T range is used to fill one truth template and one estimate template. Any deviation from a 100% match between the true and estimate templates is considered to be the measurement of the bias. The bias is measured to be $-6\% \pm 11\%$, or that the truth and estimate templates are in 94% agreement. The uncertainty in this measurement is included in the overall systematic uncertainty in the fake rate.

The photon p_T -dependent statistical uncertainty is estimated using toy MCs - histograms filled with similar statistics as those of the data-driven fake photon templates, using a random filler. The toy MC histograms are then treated as the new fake photon templates, while still using the data-driven prompt photon templates, and the fake

photon rate is remeasured. The root-mean-squared (RMS) value of the measurement of the fake rate for all toy MCs is made the statistically-driven uncertainty in the fake rate systematic uncertainty. Table 5.10 contains the photon p_T -dependent statistical uncertainties in the fake rate. The measured systematic and statistical uncertainties are combined to make the photon p_T -dependent systematic uncertainties listed in Table 5.11.

5.1.6.2 Jet Energy Scale and Resolution

The systematic uncertainty is estimated by varying up and down the jet energy uncertainties and computing the effect on the acceptance. The jet energy scale (JES) uncertainty for $p_T = 30$ GeV in the central region for AK5 PF jets is about 3.5% [79] which results in 4.3% uncertainty on the acceptance.

5.1.6.3 PDF and Renormalization/Factorization

Since all MC samples were produced using MG5, each generated event includes reweight factors to scale the event for various PDFs and theoretical renormalization and factorization fluctuations (σ_F , σ_R). We consider all physical σ_F and σ_R combinations, i.e. $\sigma_{F,R} = 0.0, 0.5, 1.0, 2.0$ excluding any nonphysical combination of $\sigma_{F,R} = 0.5$ with $\sigma_{R,F} = 2.0$. In each case, scale or PDF uncertainty, each reweight factor is extracted per event and used to weight each event for the final kinematic distribution (photon p_T in this case). Then the overall integral of events across the entire kinematic distribution is compared between the nominal case and the newly reweighted (scale or PDF) case to derive the uncertainty.

5.1.6.4 Fragmentation Model

The effect on the efficiency for signal due to changes in the dijet mass distribution based on changes in the fragmentation models (Pythia and Herwig) is investigated. Two MC $t\bar{t}$ samples are used, with following changes to the selection:

- photon selection is removed to gain statistics
- events with 2 b-tagged jets and 2 anti-b-tagged jets (CSVM) with $p_T > 30$ GeV and $|\eta| < 2.4$ are selected

- dijet mass is constructed from the 2 anti-b-tagged jets
- dijet mass distributions are compared in $0 < m_{jj} < 200$ GeV mass window
- fraction of events in $70 < m_{jj} < 200$ GeV normalized to $0 < m_{jj} < 200$ GeV region is computed (For the sample which uses Pythia, this fraction is 0.4866 and for Herwig it is 0.4886.)

The number of events in the sample that pass the modified selection requirement is about 35,000 for the Pythia sample and about 55,000 for Herwig sample. Comparison of m_{jj} between the two samples is shown in Figure 5.11. We conclude that choice of the fragmentation models (Pythia and Herwig) result in vanishing systematic uncertainty on the efficiency for signal.

5.1.6.5 b-jet Tagger

The uncertainty from the b-jet CSV tagging algorithm is 2% on the efficiency correction factor, and is based on measurements with 2012 data, as described in Ref. [80]. This uncertainty propagated through the analysis has an effect of 11% on the $t\bar{t}\gamma$ background, 5% on the single top background, and negligible effect on the signal.

5.1.6.6 Pileup

The average number of PU interaction in a given bunch crossing BX_i is given by the following formula:

$$N_i = \frac{\mathcal{L} \cdot \sigma_{\text{min. bias}}}{\nu_{\text{orbit}}}, \quad (5.4)$$

where $\mathcal{L}$ is the instantaneous luminosity, $\sigma_{\text{min. bias}}$ is the cross-section of minimum bias interactions and ν_{orbit} is the LHC orbit frequency (11246 Hz). Source of uncertainties in the estimation of the number of PU interactions in data then come from the uncertainty on the luminosity, currently 4.4%, and the uncertainty on the minimum-bias cross-section. We have adopted $\sigma_{\text{min. bias}} = 69.3$ mb.

A total variation of 5% in the number of interactions was propagated to the re-weighting procedure for signal samples, and the obtained variation in the signal yield is used as systematics on the signal. The typical effect is less than a percent.

5.1.6.7 HLT and Lepton Selection

Systematic uncertainties in the trigger efficiencies are of the order of 1%. Systematic uncertainties in the lepton reconstruction and identification efficiency scale factors are of the order of 2%. These uncertainties are accounted for in the final systematics that are input to the limit setter.

5.1.6.8 MET

MET directly affects our signal acceptance. The uncertainty prescription is discussed in [81]. In addition, the MET distribution in the data is 3% wider than the MC, and placing a hard $\text{MET} > 35.0$ GeV cut creates an uncertainty. We estimate it by smearing the MET for each event by a Gaussian with a $\sigma = 0.03 \cdot \text{MET}$ and observing how many events pass the cut. Specifically, $(\text{Events Passing After Smearing})/(\text{Events Passing Before Smearing}) = 0.998$ for both muons and electrons.

5.1.6.9 Systematic Uncertainties Summary

In addition, we include the uncertainties described in the companion diboson analysis [78], as shown in Table 5.11, as well as uncertainties in the K-factors described in Section 5.1.5 and photon efficiency scale factors listed in Table 5.7. For the electron channel's QCD contribution, we approximate the systematic uncertainty to be 50%.

5.1.7 Signal and Background Expectations from CMS Simulation

In order to compare the MC processes with observed data, we first normalize each sample to the observed integrated luminosity for both the muon and electron channel of the full 2012 data set, which, after single lepton triggers, is 19.297 fb^{-1} and 19.166 fb^{-1} , respectively. To do this, we use the following calculation

$$N_{events} = K \cdot \sigma \cdot \mathcal{L} \cdot \mathcal{A} \cdot \varepsilon_{MC} \cdot \mathcal{SF} \quad (5.5)$$

where N_{events} is the expected event yield for each MC process after event selection, K is the NLO:LO K-factor, σ is the theoretical cross section for each MC process, $\mathcal{L}$

is the observed integrated luminosity, $\mathcal{A} \cdot \epsilon_{MC}$ is the MC process's acceptance times event selection efficiency, and $\mathcal{SF}$ is the efficiency scale factor for data and MC ($\frac{\epsilon_{data}}{\epsilon_{MC}}$).

We use the functional fit to the photon fake rate discussed in Section 5.1.4 to estimate the number of observed data events that are from the photon-faking jet background. Figures 5.12-5.16 are Data and MC comparison plots for various event kinematic distributions. Event yield is summarized in Table 5.12.

Table 5.6: Muon selection scale factors and HLT efficiencies. The errors are statistical only.

$p_{T,min}$ [GeV]	$p_{T,max}$ [GeV]	η_{min}	η_{max}	$\epsilon_{ID,data}/\epsilon_{ID,mc}$	$\epsilon_{HLT,data}$
25	30	-2.1	-1.5	0.992 ± 0.003	0.766 ± 0.003
25	30	-1.5	-1	0.987 ± 0.003	0.822 ± 0.003
25	30	-1	-0.5	0.990 ± 0.003	0.914 ± 0.002
25	30	-0.5	0	0.984 ± 0.003	0.920 ± 0.002
25	30	0	0.5	0.985 ± 0.003	0.924 ± 0.002
25	30	0.5	1	0.992 ± 0.003	0.913 ± 0.002
25	30	1	1.5	0.991 ± 0.003	0.802 ± 0.003
25	30	1.5	2.1	0.995 ± 0.002	0.814 ± 0.003
30	35	-2.1	-1.5	0.991 ± 0.002	0.785 ± 0.002
30	35	-1.5	-1	0.988 ± 0.002	0.829 ± 0.002
30	35	-1	-0.5	0.988 ± 0.002	0.921 ± 0.002
30	35	-0.5	0	0.984 ± 0.002	0.930 ± 0.001
30	35	0	0.5	0.985 ± 0.002	0.935 ± 0.001
30	35	0.5	1	0.990 ± 0.002	0.922 ± 0.002
30	35	1	1.5	0.987 ± 0.002	0.807 ± 0.002
30	35	1.5	2.1	0.995 ± 0.002	0.833 ± 0.002
35	40	-2.1	-1.5	0.992 ± 0.002	0.793 ± 0.002
35	40	-1.5	-1	0.987 ± 0.002	0.832 ± 0.002
35	40	-1	-0.5	0.991 ± 0.002	0.926 ± 0.001
35	40	-0.5	0	0.986 ± 0.002	0.935 ± 0.001
35	40	0	0.5	0.986 ± 0.002	0.940 ± 0.001
35	40	0.5	1	0.991 ± 0.002	0.925 ± 0.001
35	40	1	1.5	0.989 ± 0.002	0.812 ± 0.002
35	40	1.5	2.1	0.994 ± 0.002	0.837 ± 0.002
40	45	-2.1	-1.5	0.994 ± 0.002	0.800 ± 0.002
40	45	-1.5	-1	0.987 ± 0.001	0.837 ± 0.002
40	45	-1	-0.5	0.992 ± 0.001	0.927 ± 0.001
40	45	-0.5	0	0.986 ± 0.001	0.940 ± 0.001
40	45	0	0.5	0.987 ± 0.001	0.944 ± 0.001
40	45	0.5	1	0.991 ± 0.001	0.928 ± 0.001
40	45	1	1.5	0.991 ± 0.001	0.817 ± 0.002
40	45	1.5	2.1	0.996 ± 0.001	0.844 ± 0.002
45	50	-2.1	-1.5	0.993 ± 0.002	0.807 ± 0.002
45	50	-1.5	-1	0.987 ± 0.002	0.840 ± 0.002
45	50	-1	-0.5	0.990 ± 0.001	0.931 ± 0.001
45	50	-0.5	0	0.988 ± 0.002	0.941 ± 0.001
45	50	0	0.5	0.987 ± 0.002	0.947 ± 0.001
45	50	0.5	1	0.992 ± 0.001	0.930 ± 0.001
45	50	1	1.5	0.991 ± 0.002	0.821 ± 0.002
45	50	1.5	2.1	0.995 ± 0.002	0.851 ± 0.002
50	200	-2.1	-1.5	0.991 ± 0.002	0.809 ± 0.002
50	200	-1.5	-1	0.987 ± 0.002	0.842 ± 0.002
50	200	-1	-0.5	0.992 ± 0.002	0.931 ± 0.001
50	200	-0.5	0	0.987 ± 0.002	0.944 ± 0.001
50	200	0	0.5	0.989 ± 0.002	0.946 ± 0.001
50	200	0.5	1	0.992 ± 0.002	0.932 ± 0.001
50	200	1	1.5	0.993 ± 0.002	0.824 ± 0.002
50	200	1.5	2.1	0.996 ± 0.002	0.854 ± 0.002

Table 5.7: 2012 tight photon ID data/MC efficiency scale factors for given photon p_T and η .

SC η	E_T (GeV)	Scale factor
0.0 - 0.8	30-40	0.9711 ± 0.0020
	40-50	0.9778 ± 0.0024
	50-Inf	0.9718 ± 0.0014
0.8 - 1.4442	30-40	0.9823 ± 0.0052
	40-50	0.9805 ± 0.0024
	50-Inf	0.9768 ± 0.0016

Table 5.8: $WV\gamma$ Fake rate from q-jets and tight 2012 photon ID.

Photon p_T , GeV	Fraction of events with jets, passing tight photon ID
30-50	0.229
50-75	0.156
75-90	0.091
90-135	0.122
135-150	0.080
150-400	0.077

Table 5.9: List of backgrounds, the theoretical K-factors and cross sections used for MC-based backgrounds, and how they are treated in the background normalization template fit. The K-factor for $W\gamma$ +jets sample is listed for both the muon and electron channels.

MC Sample	K	σ [pb]	External constraint on normalization used in $W\gamma$ +jets fit
SM $WW\gamma$	2.1	0.02771	Fixed
SM $WZ\gamma$	2.1	0.00578008	Fixed
anomalous $WWV\gamma$	1.185	-	NA
$W\gamma$ +Jets	1.10(mu),1.07(el)	9.37246	Unconstrained
Fake photon	from data	-	Constrained
Multi-jet	from data	-	Fixed: MET fit in data $\pm 50\%$ (100%) for electrons (muons)
$Z\gamma$ +Jets	1	0.63196	Fixed
$t\bar{t}\gamma$	1	1.44	Fixed
Single Top (s-channel)	NLO	3.89394	Fixed
Single Top (t-channel)	NLO	55.531	Fixed
Single Top (tw-channel)	NLO	11.1773	Fixed
Single Top (ps-channel)	NLO	1.75776	Fixed
Single Top (pt-channel)	NLO	30.0042	Fixed
Single Top (ptw-channel)	NLO	11.1773	Fixed

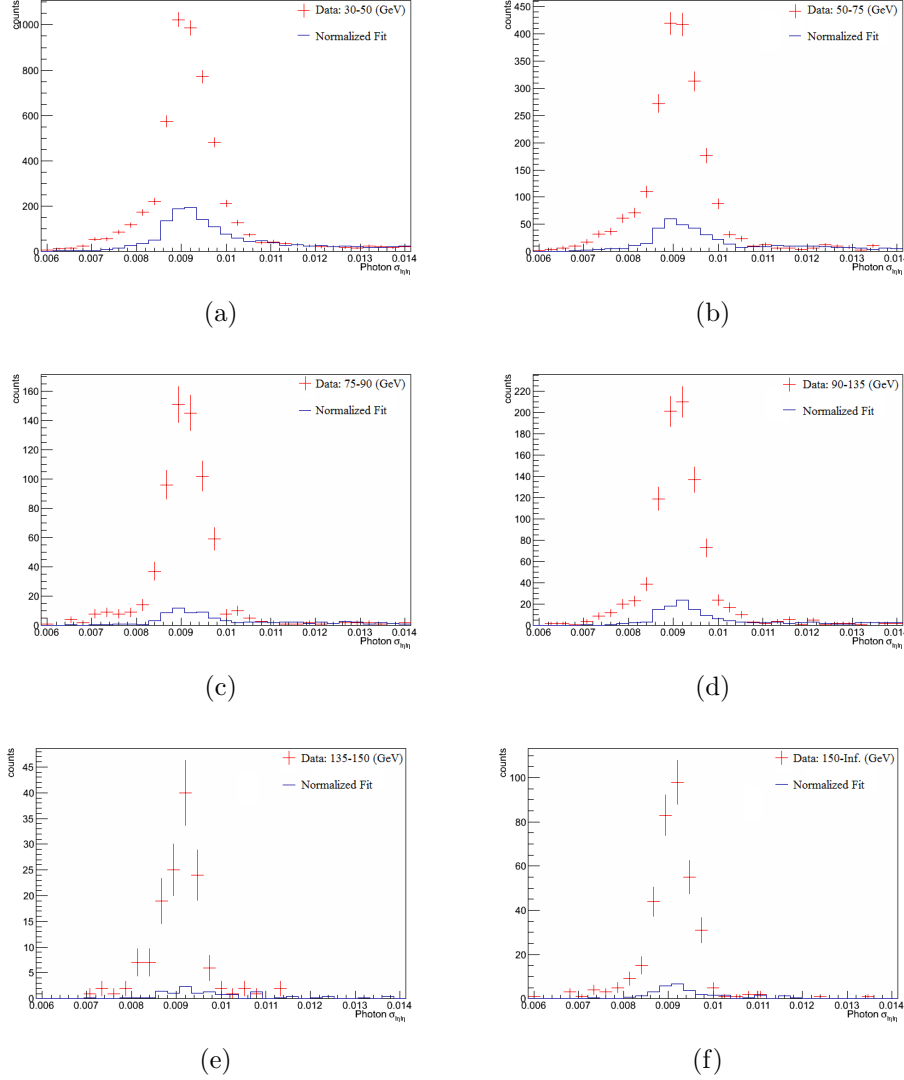


Figure 5.3: Signal and background distributions in $\sigma_{I\eta I\eta}$ used to estimate the fake photon rate. Red points are from 2012 tight photons, while blue points are 2012 photon candidates that fail tight PF charged and/or neutral isolation. The background's sideband (above 0.011) is normalized to the signal. Photon p_T : (a) 30-50 GeV, (b) 50-75 GeV, (c) 75-90 GeV, (d) 90-135 GeV, (e) 135-150 GeV, (f) 150- ∞ GeV.

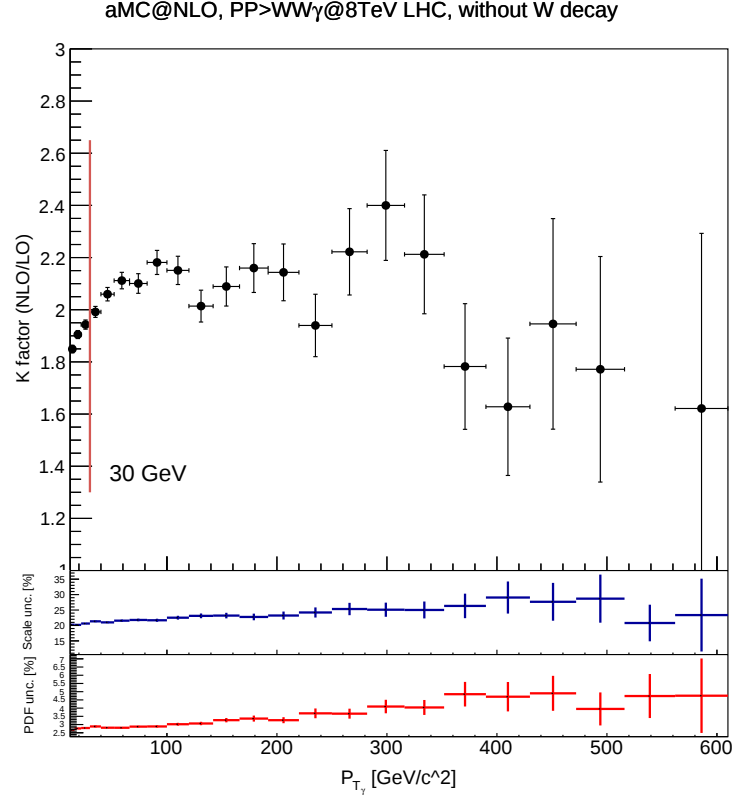


Figure 5.4: $W^\pm V\gamma$ signal sample K-factor distribution as a function of p_T^γ .

Table 5.10: 2012 tight photon ID data-driven photon-faking jet rate plus uncertainties for given photon p_T .

E_T (GeV)	Fake Rate	Stat. Unc.	Stat. Unc. (%)	Bias Stat. Unc. (%)
30-50	0.229	0.0128	5.6	11
50-75	0.156	0.0147	9.4	11
75-90	0.091	0.0184	20	11
90-135	0.122	0.0230	19	11
135-400	0.078	0.0287	37	11

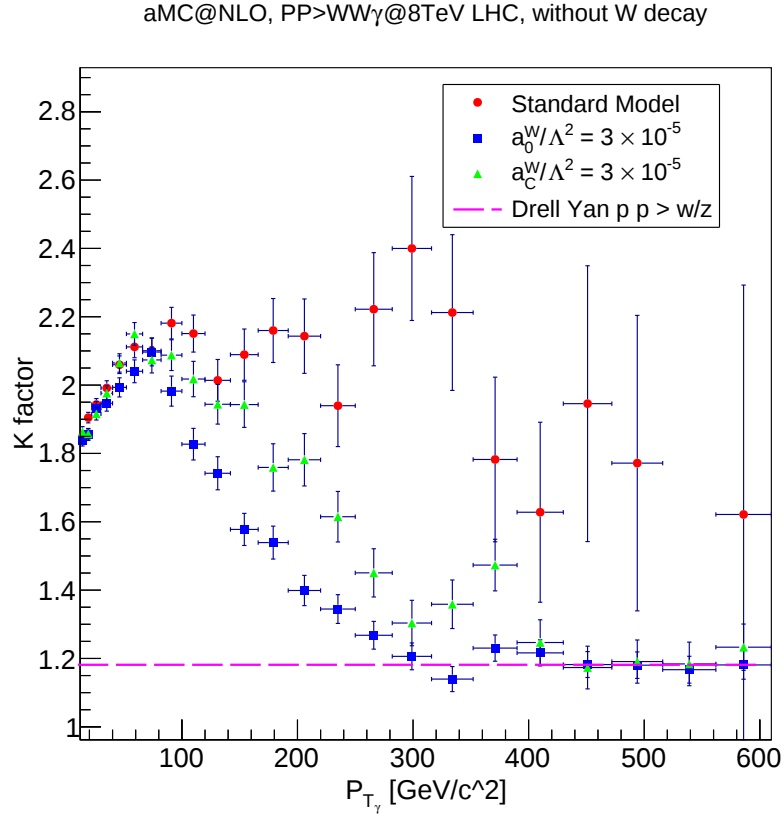


Figure 5.5: $W^\pm V \gamma$ signal AQC sample K-factor distribution as a function of p_T^γ

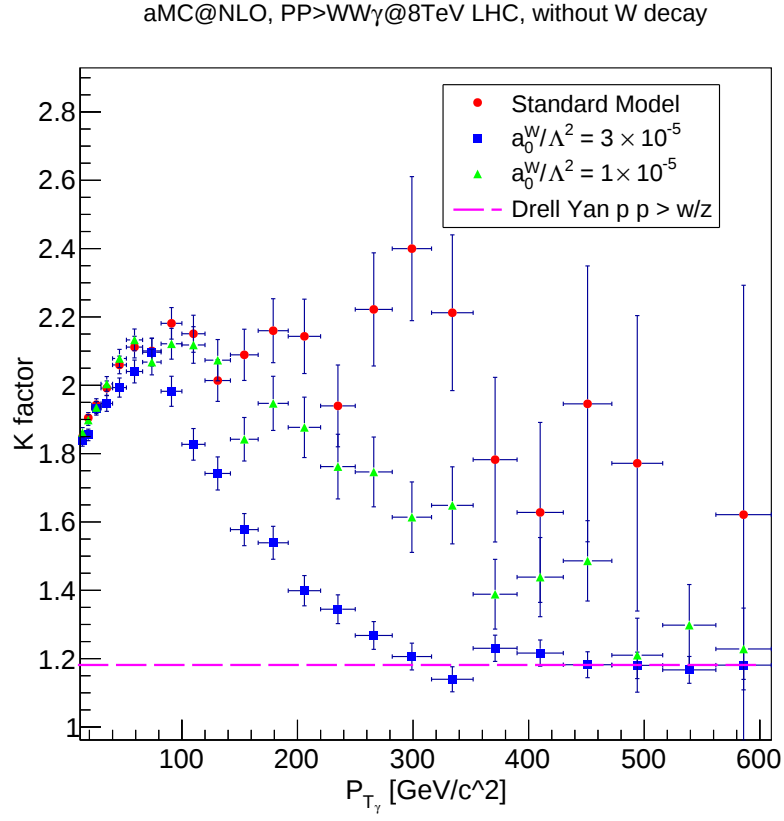


Figure 5.6: $W^\pm V \gamma$ signal AQC sample K-factor distribution with varying a_0^W/Λ^2 values

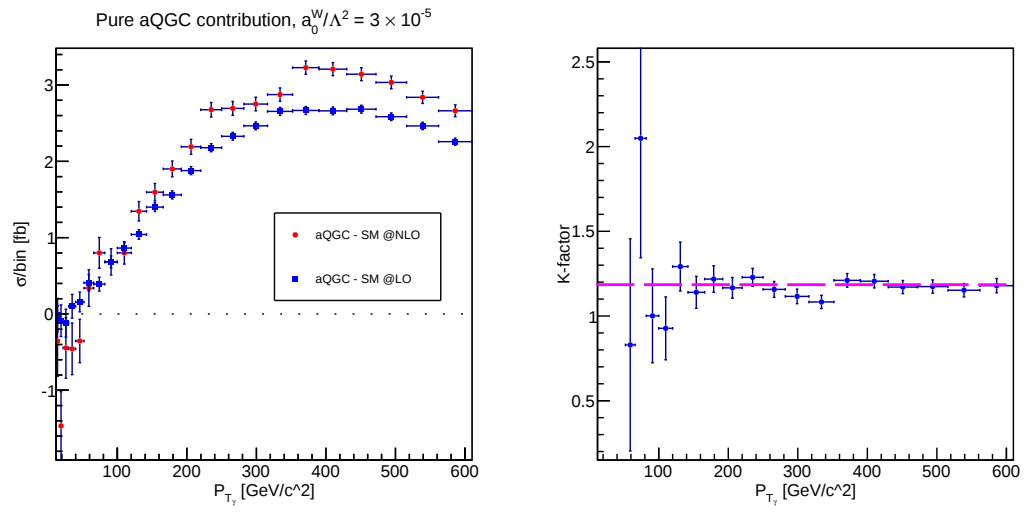


Figure 5.7: $W^\pm V \gamma$ signal aQGC-SM p_T^γ distribution (left) and K-factor distribution (right), with $a_0^W/\Lambda^2 = 3 \times 10^{-5} \text{ GeV}^{-2}$

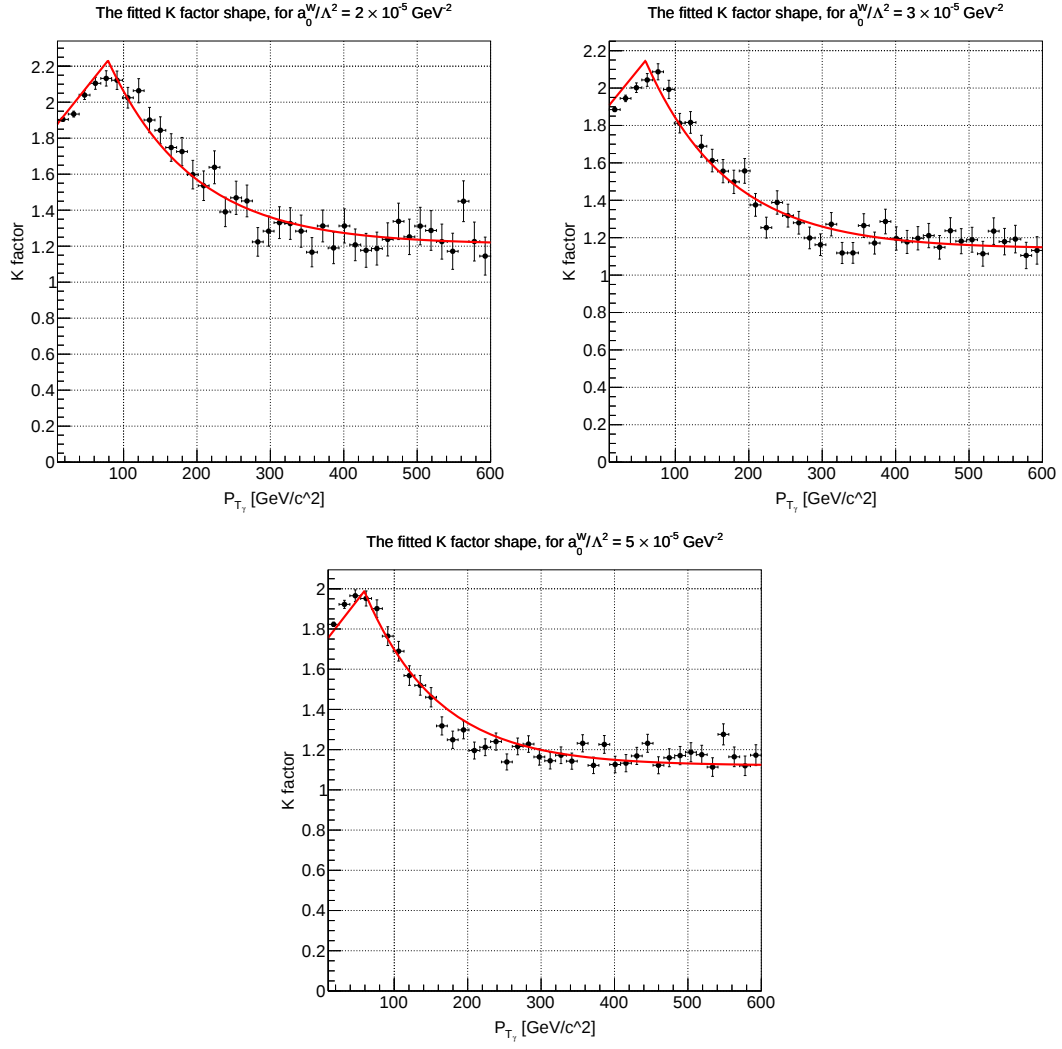


Figure 5.8: K-factor shape fitted with function Eq. 5.3, for $a_0^W/\Lambda^2 = 2, 3, 5 \times 10^{-5} \text{ GeV}^{-2}$.

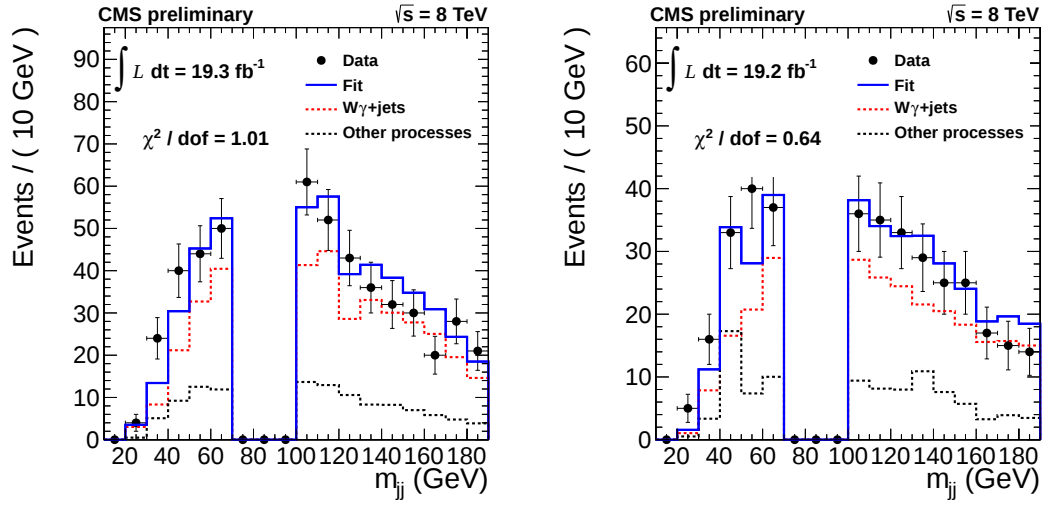


Figure 5.9: Data and MC dijet mass sidebands used to estimate the data-driven $W\gamma$ +jets K-factor.

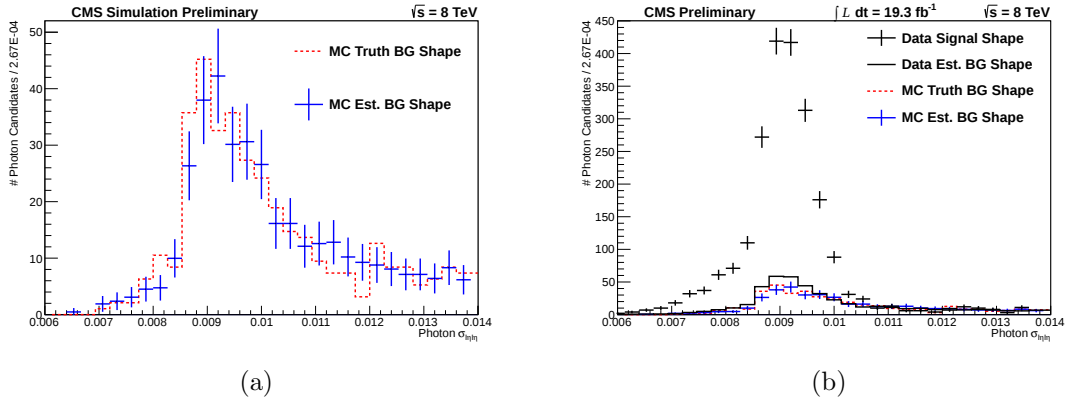


Figure 5.10: Templates for the photon p_T range (> 30 GeV) for (a) MC truth versus estimated photon-faking jet background distribution shapes from the muon channel of a $W+3$ Jets MC. (b) MC photon-faking jet background distribution shapes compared with data's signal (all 2012 tight photon candidates) and background (photon-faking jets) shapes. The MC Truth template has removed all ISR/FSR photons, while the Estimated templates are filled using the fake rate ratio method utilizing inverted photon isolation.

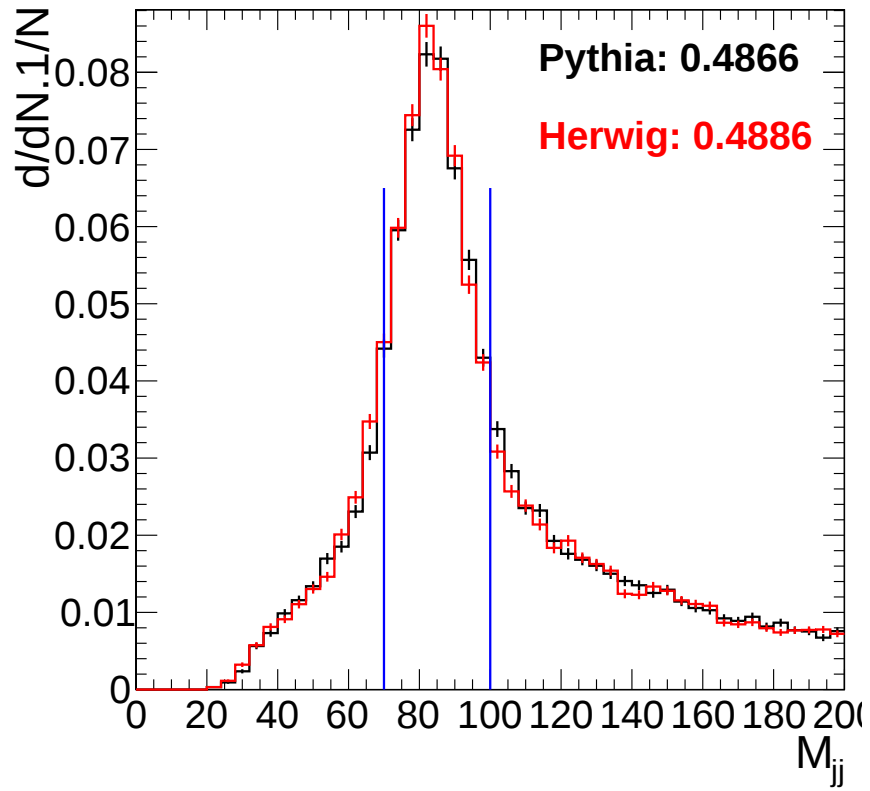


Figure 5.11: Dijet invariant mass distribution comparison for samples, produced with different parton showering models: Pythia and Herwig.

Table 5.11: Summary of the systematic uncertainties.

Source	Uncertainty
W γ + Jets normalization jet $\rightarrow \gamma$	6.7%(mu), 7.9%(el) 12% (30 GeV - 50 GeV) 14% (50 GeV - 75 GeV) 23% (75 GeV - 90 GeV) 22% (90 GeV - 135 GeV) 39% (> 135 GeV)
multijets	50%
Trigger Efficiency	1%
Lepton Selection Efficiency	2%
Photon Reco/ID Efficiency	<0.5%
Jet Energy Resolution	1%
Jet Energy Scale	4.3%
Photon Energy Scale	1%
MET	1%
Anti-b Tag ($t\bar{t}\gamma$)	11%
Anti-b Tag (single top + γ)	5%
Pileup modeling	1%
renormalization/factorization scale	23.4%
PDF	3.6%
Luminosity	4.4%

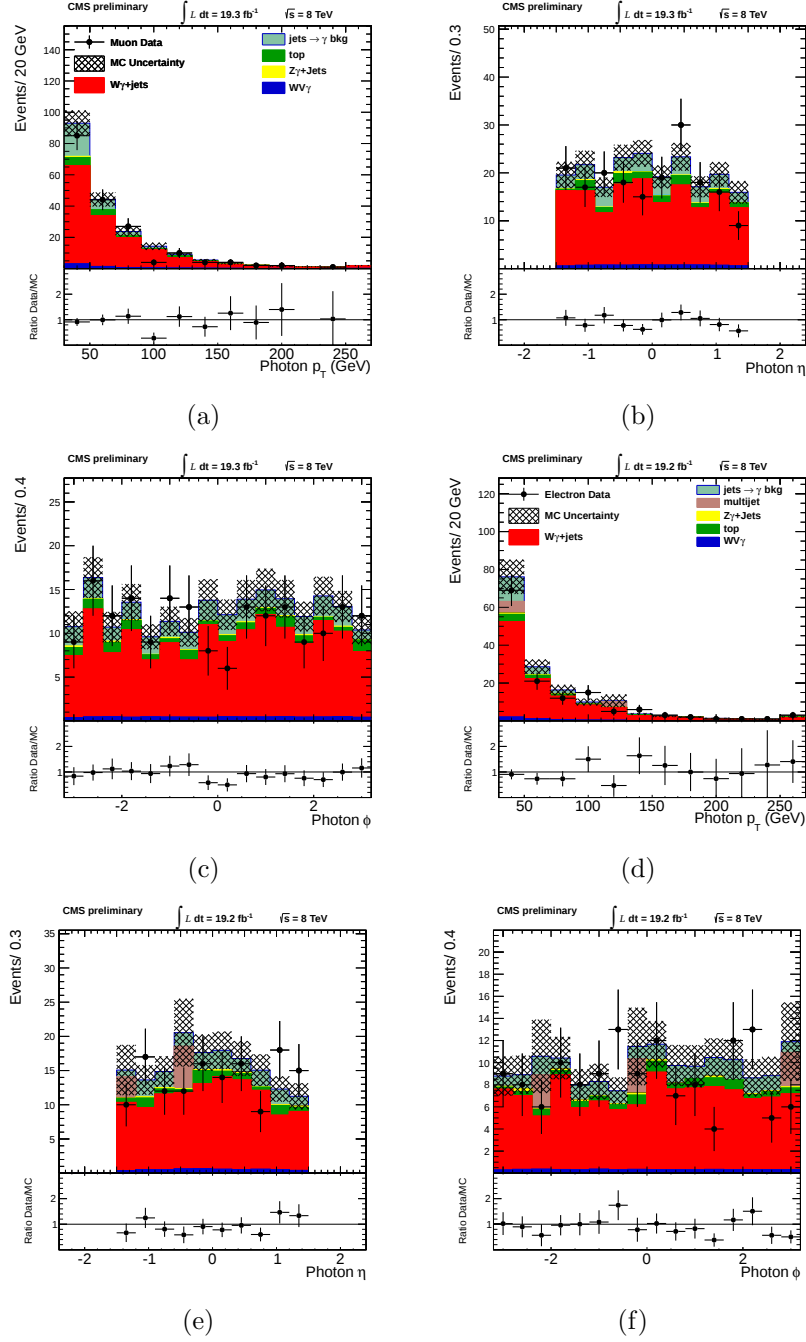


Figure 5.12: Data and MC comparison plots for muon channel photon p_T (a), η (b), ϕ (c), and electron channel photon p_T (d), η (e), ϕ (f)

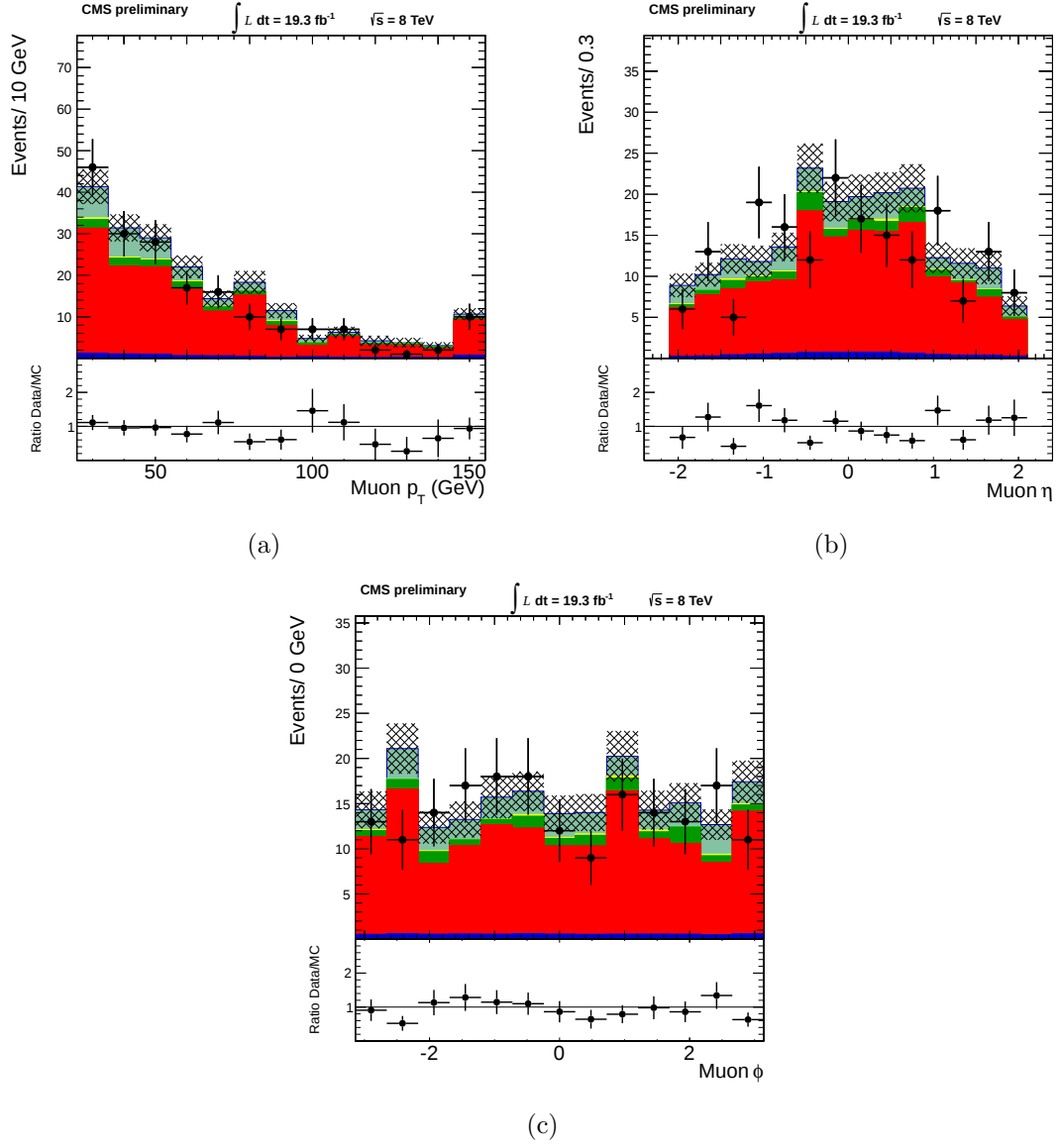


Figure 5.13: Data and MC comparison plots for muon p_T (a), η (b), ϕ (c)

Table 5.12: Expected number of events per process, with statistical, systematic, and luminosity uncertainties quoted.

Process	muon channel number of events	electron channel number of events
$W\gamma$ +Jets	136.9 ± 10.5	101.6 ± 8.5
WV+jet, jet $\rightarrow\gamma$	33.1 ± 4.8	21.3 ± 3.3
MC $t\bar{t}\gamma$	12.5 ± 3.0	9.1 ± 2.2
MC Single Top	2.8 ± 0.8	1.7 ± 0.6
MC $Z\gamma$ +Jets	1.7 ± 0.1	1.5 ± 0.1
multijets	–	7.2 ± 5.1
SM $WW\gamma$	6.6 ± 1.5	5.0 ± 1.1
SM $WZ\gamma$	0.6 ± 0.1	0.5 ± 0.1
Total predicted	194.2 ± 11.5	147.9 ± 10.7
Data	183	139

5.1.8 Limit on the Cross Section

This SM cross sectional measurement’s uncertainties are large due to the low signal statistics, the uncertainties in the K-factors used, and the fake photon rate’s systematic uncertainty of 12-39%; therefore, we cannot claim an observation of WV γ events. An upper limit on the SM WV γ combined cross section is obtained through a profile likelihood asymptotic approximation method [82, 83]. The SM WV γ signal strength is provided in Table 5.25, with the 1- σ and 2- σ bands. A signal strength below 1 suggests we are sensitive to the signal and can measure the cross section; however, we are well above a value of 1 and are therefore not sensitive to the SM signal.

5.1.9 Limits on Anomalous Quartic Gauge Couplings

5.1.9.1 Parametrizations

In order to set limits on anomalous couplings, we compare the observed signal data’s kinematics to those of anomalous signal MC. This process can involve generating many different MC samples for various values of each anomalous quartic coupling parameter, or we could quantify how anomalous couplings affect certain observable kinematic distributions such as photon p_T or WV γ invariant mass.

In order to quantify the affect each coupling parameter has on a kinematic distribution, say photon p_T , we still generate a few MC samples for each anomalous coupling parameter, where the parameter of interest is varied to multiple values and all other coupling parameters set to their SM value. For example, we have five quartic coupling parameters $\frac{a_0^W}{\Lambda^2}$, $\frac{a_C^W}{\Lambda^2}$, $\frac{f_{T,0}}{\Lambda^4}$, $\frac{\kappa_0^W}{\Lambda^2}$, and $\frac{\kappa_C^W}{\Lambda^2}$. In order to parametrize the affect the parameter $\frac{a_0^W}{\Lambda^2}$ has on photon p_T , we vary this parameter's values while fixing $\frac{a_C^W}{\Lambda^2}$, $\frac{f_{T,0}}{\Lambda^4}$, $\frac{\kappa_0^W}{\Lambda^2}$, and $\frac{\kappa_C^W}{\Lambda^2}$ to their SM values of zero.

In addition to the SM sample, we generate six MC AQGC samples for variation in each parameter. Then, after applying event selection cuts described in Section 5.1.2, efficiency and PU weights, and the photon p_T -dependent K-factor described in Section 5.1.5, each sample's photon p_T distribution is divided by the SM photon p_T distribution to form a AQGC/SM ratio for each photon p_T bin. A quadratic distribution is formed by plotting each AQGC/SM ratio value for a specific photon p_T bin, as can be seen in Figures 5.17-5.18 for $\frac{a_0^W}{\Lambda^2}$ in the muon channel. Figure 5.17a exhibits a quadratic fit that decreases with increasing AQGC: (1) this is only found to happen with a_0^W and with this binning and (2) it is allowed because the limits for this parameter fall within the fit's range and thus we benefit from minimizing χ^2 .

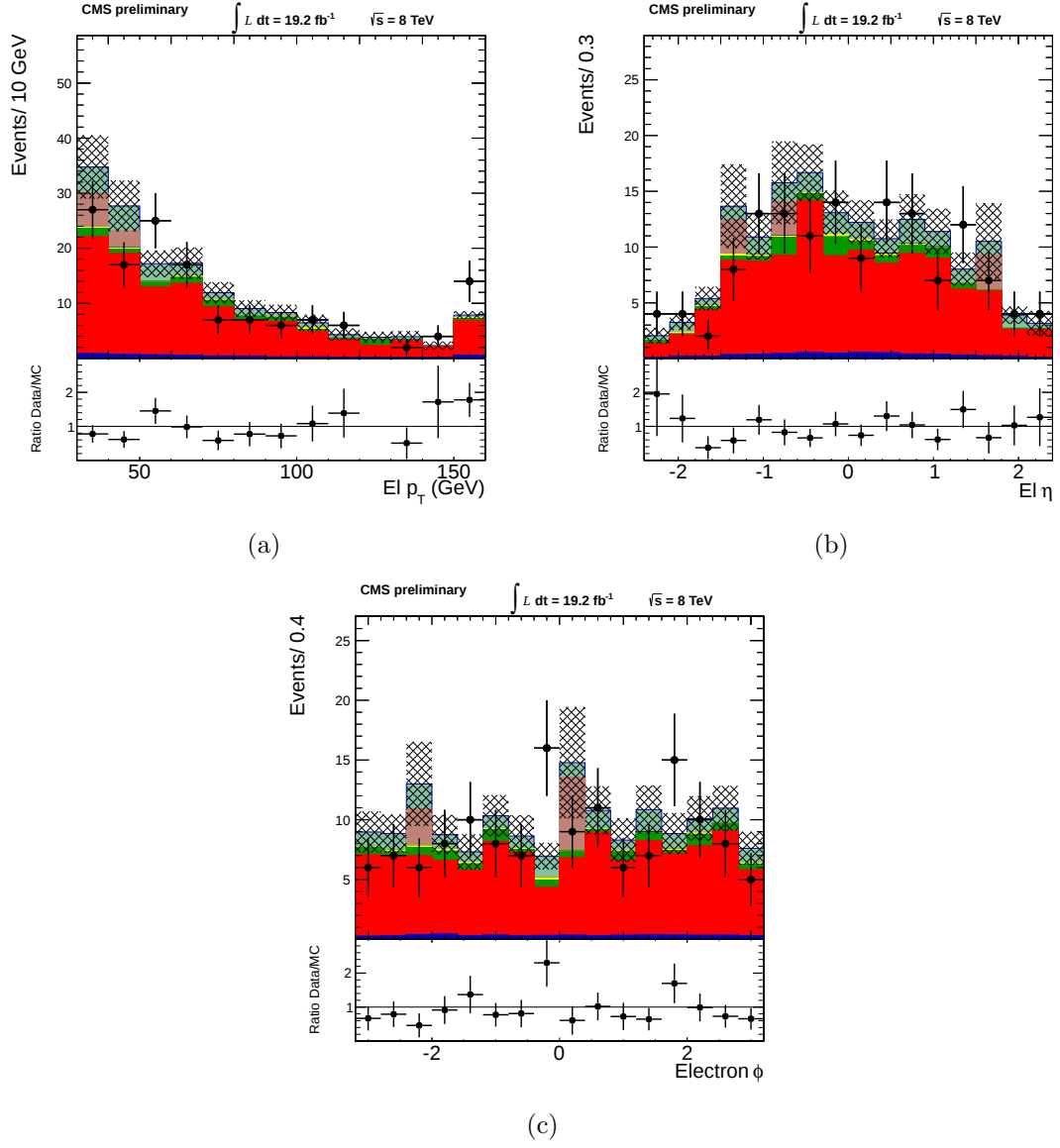


Figure 5.14: Data and MC comparison plots for electron p_T (a), η (b), ϕ (c)

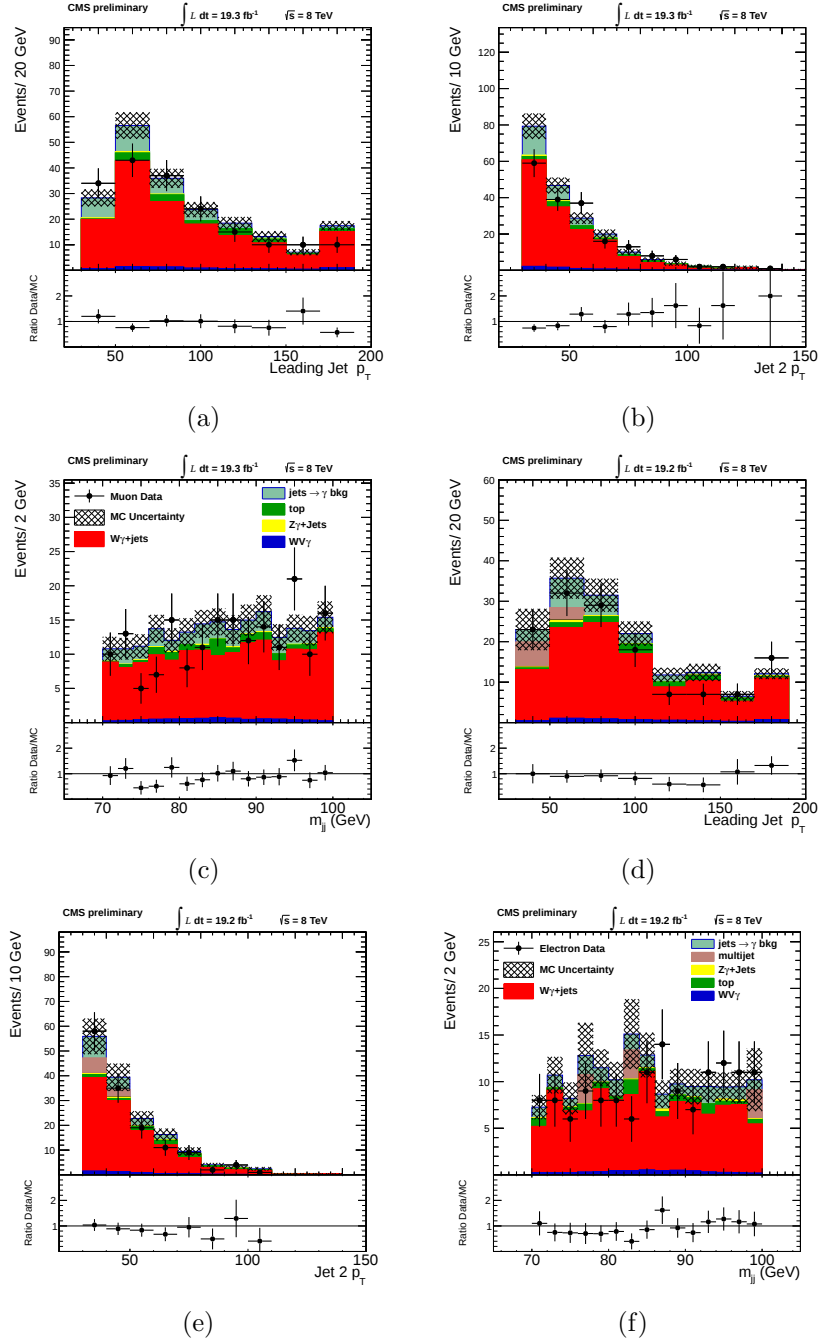


Figure 5.15: Data and MC comparison plots for muon channel leading jet p_T (a) second jet p_T (b), dijet mass (c); electron channel leading jet p_T (d) second jet p_T (e) and dijet mass (f)

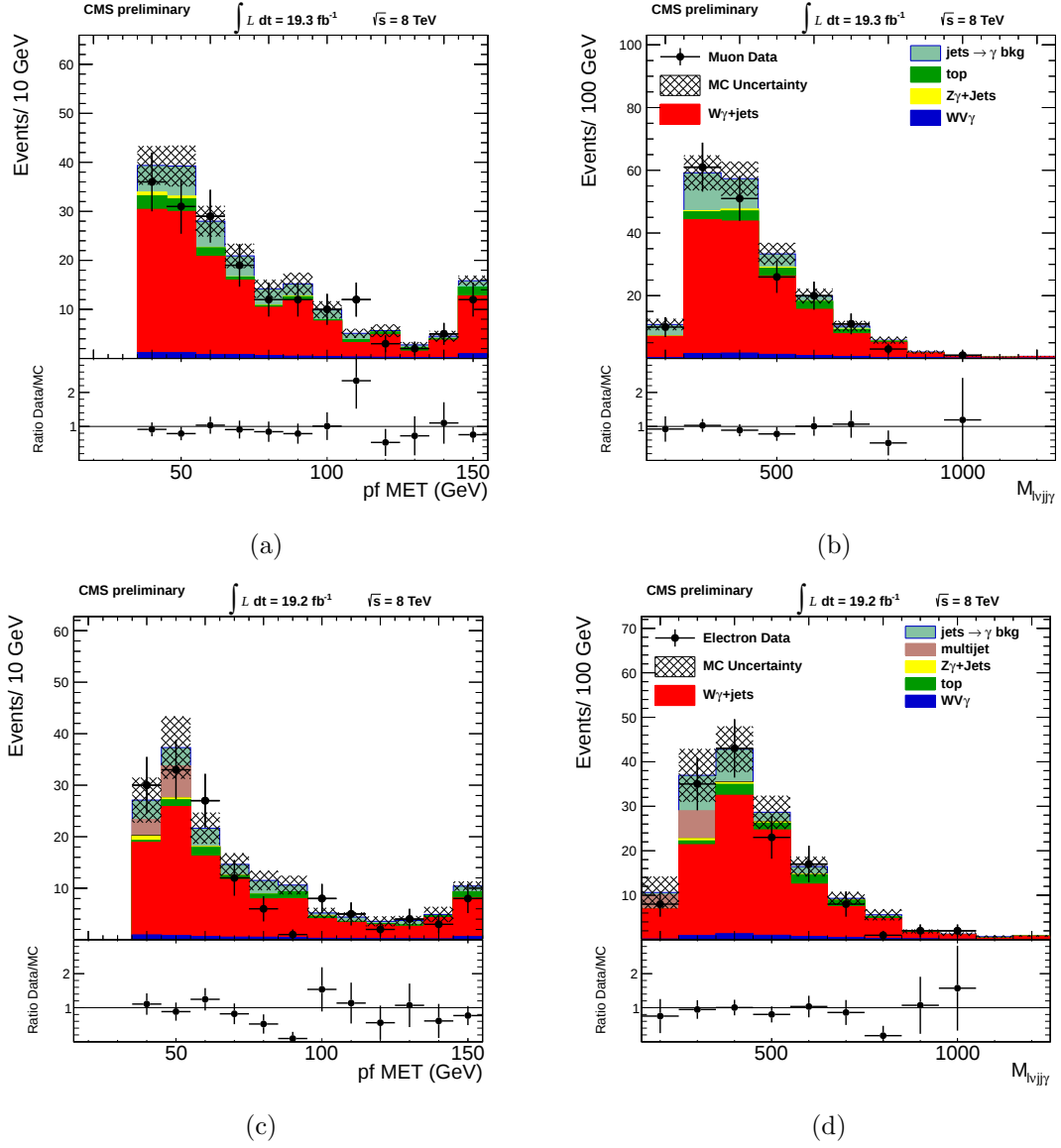


Figure 5.16: Data and MC comparison plots for muon channel MET (a) $M_{lvjj\gamma}$ (b); electron channel MET (c) $M_{lvjj\gamma}$ (d)

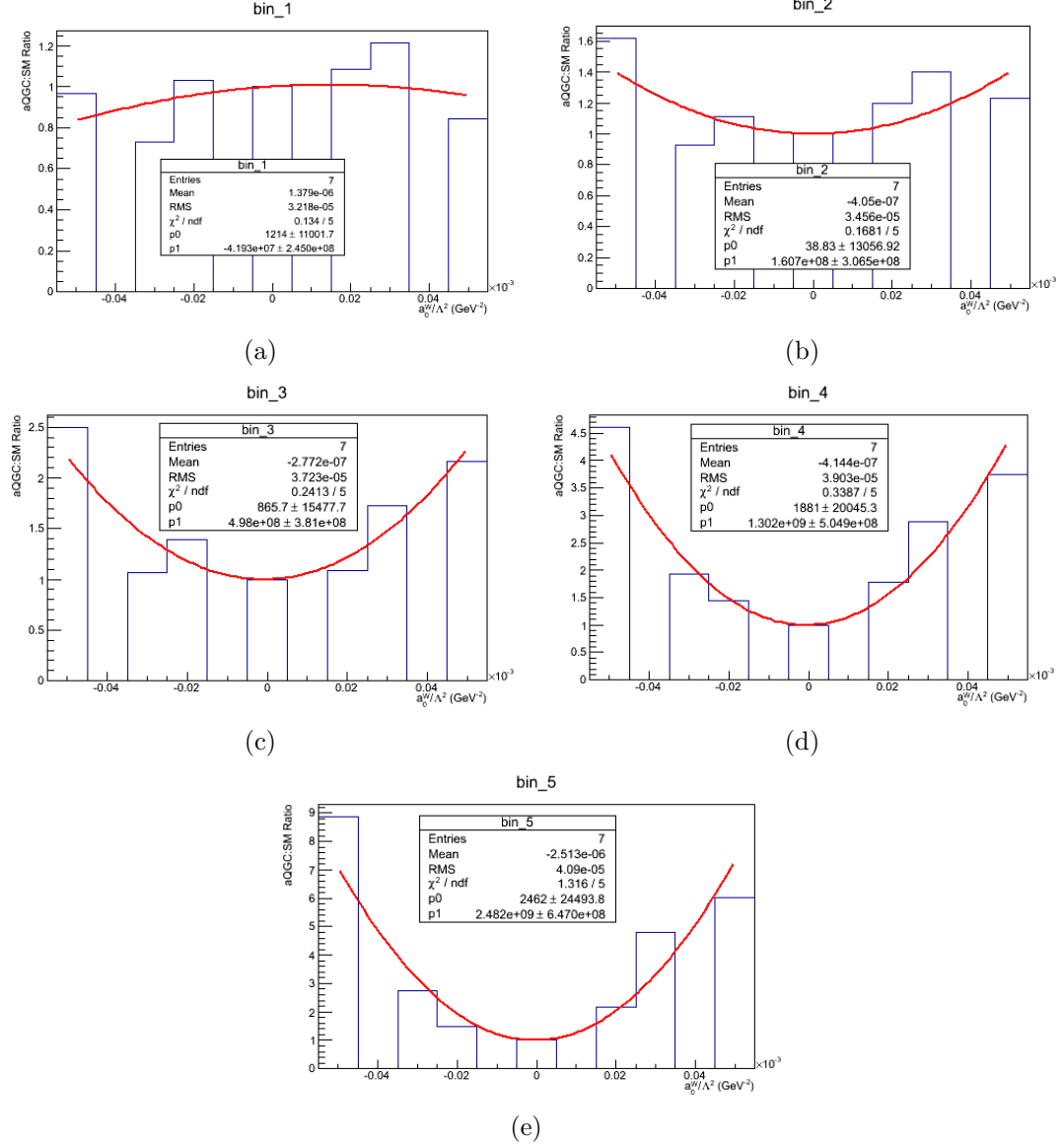


Figure 5.17: AQC/SM ratio values for each a_0^W/Λ^2 MC sample (muon channel) within each of the following photon p_T bins: (a) 30-72 GeV, (b) 72-114 GeV, (c) 114-156 GeV, (d) 156-198 GeV, and (e) 198-240 GeV.

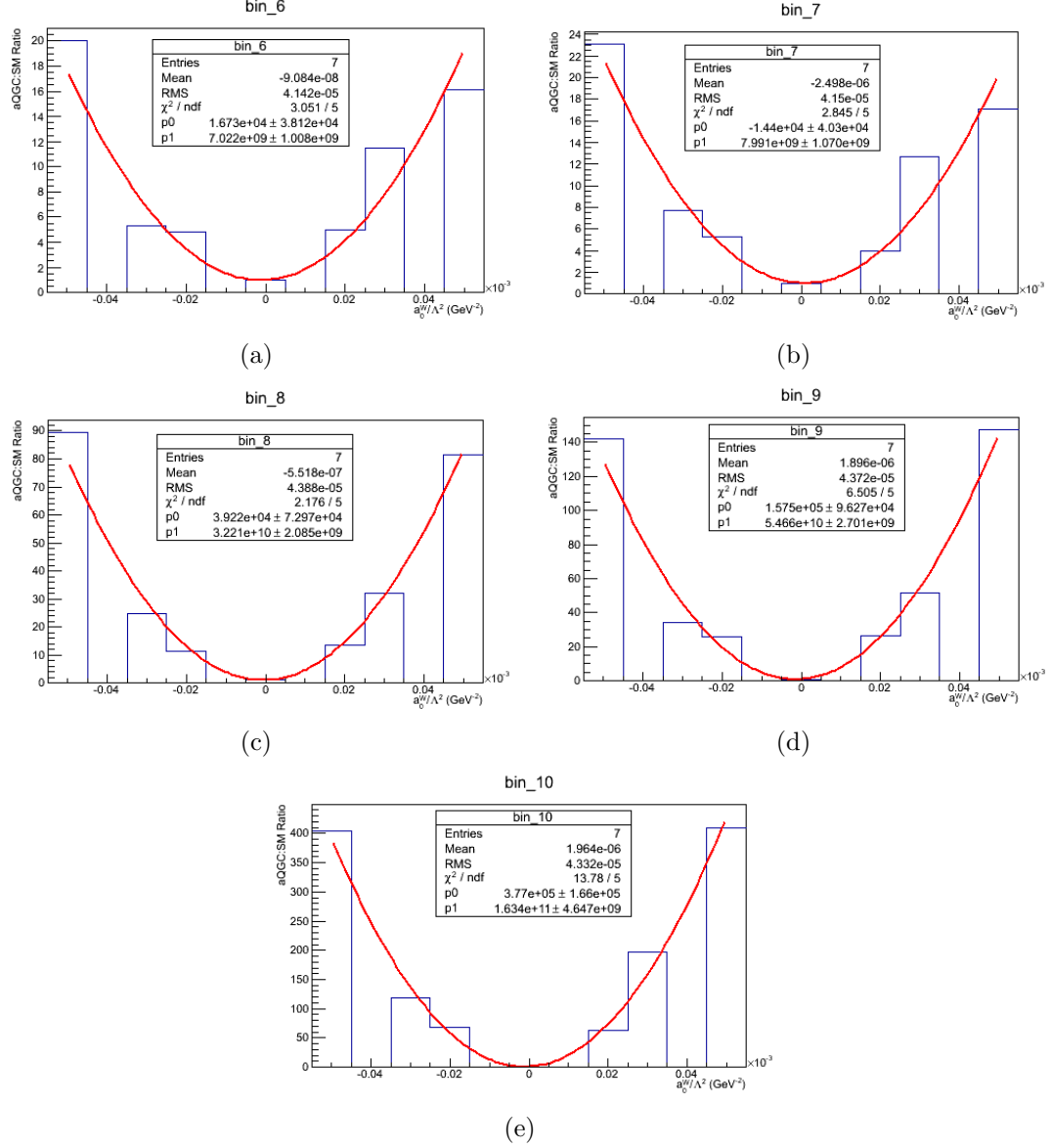


Figure 5.18: AQGC/SM ratio values for each a_0^W/Λ^2 MC sample (muon channel) within each of the following photon p_T bins: (a) 240-282 GeV, (b) 282-324 GeV, (c) 324-366 GeV, (d) 366-408 GeV, and (e) 408- ∞ GeV (overflow bin)

We fit this distribution with a quadratic function that can later be used to predict the AQGC/SM ratio value for any arbitrary anomalous coupling value for that specific coupling parameter and photon p_T bin. It can even be seen in Figure 5.18 that the overflow photon p_T bin has a quadratic behavior in AQGC and thus can be parametrized.

Keeping in mind that the AQGC/SM ratio fit function for a given coupling parameter is a function of the coupling parameter's value and depends on the photon p_T bin, we then plot and fit the coefficients of the AQGC/SM quadratic fit function versus photon p_T in order to obtain the p_T -dependence of the AQGC/SM ratio. Therefore, we obtain a parametrization of the affect each anomalous coupling parameter has on photon p_T by substituting the p_T -dependent coefficient fit functions into the coupling parameter-dependent AQGC/SM ratio fit function, as shown in Eq. 5.6.

$$R(par., p_T) = \frac{AQGC(par., p_T)}{SM(p_T)} = 1 + C_0(p_T) \cdot par. + C_1(p_T) \cdot par.^2 \quad (5.6)$$

A closure test can be performed using Eq. 5.6 as a reweighing function applied to the SM photon p_T spectrum, as can be seen in Figure 5.19 for $\frac{a_0^W}{\Lambda^2}$ where the simulated (parametrized) MC is compared to the generated (true) MC. Furthermore, the ratio between some of the simulated and generated MC of each AQGC parameter can be seen in Figure 5.20, where the deviation in each photon p_T bin remains below 40%. The deviation in the overflow photon p_T bin for each AQGC parameter remains below 15% as well.

5.1.9.2 Limits using Photon p_T

We use the photon p_T distribution as the observable to set limits on anomalous couplings with the ‘‘Higgs Combination’’ (*Combine*) package [84]. This package is a RooStats[85]-based statistical analysis tool recommended by the CMS Higgs PAG and approved by the CMS statistics committee. Limits are obtained through a profile likelihood asymptotic approximation method [82, 83].

We take as inputs the photon p_T distributions for each signal model (*i.e.*, various choices of a_0^W/Λ^2 , a_C^W/Λ^2 , $f_{T,0}/\Lambda^4$, κ_0^W/Λ^2 , and κ_C^W/Λ^2), data, and total background

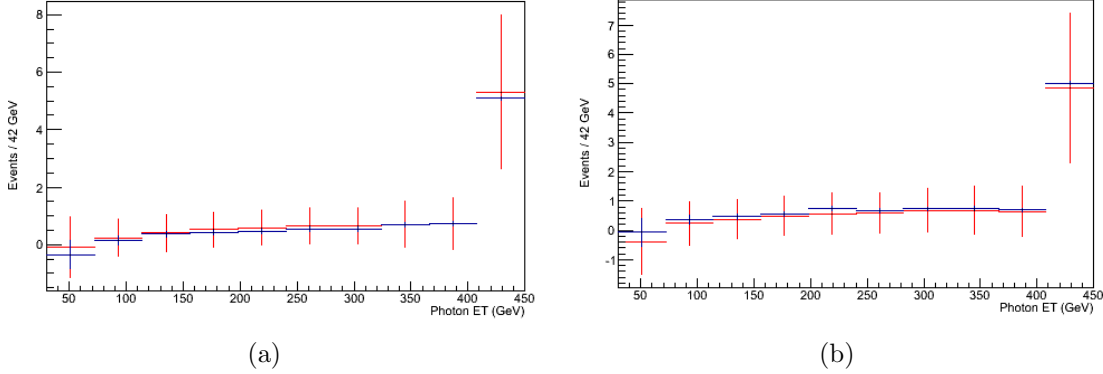


Figure 5.19: Photon p_T of simulated (red) and generated (blue) MC samples for (a) $a_0^W/\Lambda^2 = 5 \times 10^{-5} \text{ GeV}^{-2}$ and (b) $a_0^W/\Lambda^2 = -5 \times 10^{-5} \text{ GeV}^{-2}$ (both are muon channel)

that survive after analysis cuts. All of these distributions are segregated by lepton flavor, which represent independent channel inputs to the limit setter. Figure 5.21 shows the muon channel for given values of AQGC parameters in which the AQGC input is the excess events from the SM prediction. We supply these distributions over the range 30-450 GeV in the form of histograms to the limit setter. The binning is chosen such that the left-most bin begins at the first 2012 data point, and the right-most bin begins just beyond the last 2012 data point. We extend the right-most bin to be an overflow bin, and since it begins just beyond the reach of 2012 data in our events, it represents physics beyond our sensitivity.

The limit setter is then set to utilize the “ProfileLikelihood CL_s ” [86, 87] method. Figure 5.22 is the resulting shape-based observed and expected exclusion limits. Exclusion limits for a_0^W/Λ^2 , a_C^W/Λ^2 , $f_{T,0}/\Lambda^4$, κ_0^W/Λ^2 , and κ_C^W/Λ^2 are computed at the 95% CL and are listed in Table 5.13. Table 5.14 contains the transformed dimension 8 limits from the dimension 6 a_0^W and a_C^W parameters.

5.1.9.3 Limits using $M_{WV\gamma}$

As an additional means of setting limits on AQGC, we performed the same limit setting procedure previously discussed while using the $WV\gamma$ invariant mass as the discriminating distribution. Much like the photon p_T distribution, the $M_{WV\gamma}$ distri-

Table 5.13: 95% CL shape-based exclusion limits listed for both the muon and electron channels of each AQGC parameter using photon p_T .

Observed Limits	Expected Limits
$-21 \text{ (TeV}^{-2}) < a_0^W/\Lambda^2 < 20 \text{ (TeV}^{-2})$	$-24 \text{ (TeV}^{-2}) < a_0^W/\Lambda^2 < 23 \text{ (TeV}^{-2})$
$-34 \text{ (TeV}^{-2}) < a_C^W/\Lambda^2 < 32 \text{ (TeV}^{-2})$	$-37 \text{ (TeV}^{-2}) < a_C^W/\Lambda^2 < 34 \text{ (TeV}^{-2})$
$-25 \text{ (TeV}^{-4}) < f_{T,0}/\Lambda^4 < 24 \text{ (TeV}^{-4})$	$-27 \text{ (TeV}^{-4}) < f_{T,0}/\Lambda^4 < 27 \text{ (TeV}^{-4})$
$-12 \text{ (TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 10 \text{ (TeV}^{-2})$	$-12 \text{ (TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 12 \text{ (TeV}^{-2})$
$-18 \text{ (TeV}^{-2}) < \kappa_C^W/\Lambda^2 < 17 \text{ (TeV}^{-2})$	$-19 \text{ (TeV}^{-2}) < \kappa_C^W/\Lambda^2 < 18 \text{ (TeV}^{-2})$

 Table 5.14: 95% CL shape-based exclusion limits listed for both the muon and electron channels of each dim. 8 AQGC parameter using photon p_T .

Observed Limits	Expected Limits
$-77 \text{ (TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81 \text{ (TeV}^{-4})$	$-89 \text{ (TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93 \text{ (TeV}^{-4})$
$-131 \text{ (TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123 \text{ (TeV}^{-4})$	$-143 \text{ (TeV}^{-4}) < f_{M,1}/\Lambda^4 < 131 \text{ (TeV}^{-4})$
$-39 \text{ (TeV}^{-4}) < f_{M,2}/\Lambda^4 < 40 \text{ (TeV}^{-4})$	$-44 \text{ (TeV}^{-4}) < f_{M,2}/\Lambda^4 < 46 \text{ (TeV}^{-4})$
$-66 \text{ (TeV}^{-4}) < f_{M,3}/\Lambda^4 < 62 \text{ (TeV}^{-4})$	$-71 \text{ (TeV}^{-4}) < f_{M,3}/\Lambda^4 < 66 \text{ (TeV}^{-4})$

bution experiences an increase in the tail end of its spectrum (high-mass region) as a result of AQGC; however, this distribution experiences much destructive interference in the low mass region ($< 700 \text{ GeV}$). We obtain a parametrization of AQGC as a function of the a_0^W/Λ^2 parameter and $WV\gamma$ invariant mass, and Figure 5.23 shows the resulting limits. Table 5.15 lists the observed and expected limits at 95% CL. The behavior of the observed limits and the existence of destructive interference makes this distribution not as optimal as photon p_T .

 Table 5.15: 95% CL shape-based exclusion limits listed for both the muon and electron channels of the AQGC parameter a_0^W/Λ^2 , using $M_{WV\gamma}$.

Observed Limits	Expected Limits
$-19 \text{ (TeV}^{-2}) < a_0^W/\Lambda^2 < 16 \text{ (TeV}^{-2})$	$-31 \text{ (TeV}^{-2}) < a_0^W/\Lambda^2 < 28 \text{ (TeV}^{-2})$

5.1.9.4 a_0^W Limits using Photon p_T -dependent K-factor

In order to verify that our limit setting procedure is not neglecting possible new physics, we produced a photon p_T -dependent K-factor for the parameter a_0^W . Our procedure outlined in Section 5.1.5.2 applies a constant Drell-Yan like K-factor of 1.185

to the resulting spectrum after removing the SM prediction of the signal; the limits shown in Figure 5.24 are derived by first applying a AQGC-and-photon- p_T -dependent K-factor to the predicted AQGC sample and then removing the SM prediction that has had its SM 2.1 K-factor applied. Figure 5.24 and Table 5.16 demonstrate that the effect is minimal.

Table 5.16: 95% CL shape-based exclusion limits listed for both the muon and electron channels of the AQGC parameter a_0^W/Λ^2 , using photon p_T and with a p_T -dependent K-factor.

Observed Limits	Expected Limits
$-24 \text{ (TeV}^{-2}\text{)} < a_0^W/\Lambda^2 < 20 \text{ (TeV}^{-2}\text{)}$	$-27 \text{ (TeV}^{-2}\text{)} < a_0^W/\Lambda^2 < 22 \text{ (TeV}^{-2}\text{)}$

5.2 Measurements at $\sqrt{s} = 13 \text{ TeV}$

5.2.1 Simulation and Data Samples

The data sample we use in this analysis was recorded by the CMS experiment in 2015 and collected by single lepton HLTs. Table 5.17 lists the JSON file specifying certified runs and luminosity sections within CMS as well as each lepton channel’s HLT path employed.

The JSON file listed in Table 5.17 means that good functioning of all CMS sub-detectors is required. The total statistics analyzed correspond to an integrated luminosity of $2.3 \pm 0.1 \text{ fb}^{-1}$, measured using the *Brilcalc* tool with the “OfflineNorm-tagV2.json” tag. The data used for the analysis and the corresponding run ranges are listed in Table 5.18. All samples have been processed using a CMSSW_7_6_3 release version.

AQGC samples, as well as samples for a variety of EW and QCD-induced back-

Table 5.17: Data specifications and HLTs used for both lepton channels, including the JSON file for good events.

JSON	Cert_13TeV_16Dec2015ReReco_Collisions15_25ns_JSON_v2.txt
Mu. Ch. Data HLT	HLT_IsoMu20_v* or HLT_IsoTkMu20_v*
El. Ch. Data HLT	HLT_Ele23_WPLoose_Gsf_v*

Table 5.18: Summary of data samples used and run ranges of applicability.

Data set name	Run range
/SingleMuon/Run2015C_25ns-16Dec2015-v1/MINIAOD	254227-255031, excluding 254833
/SingleElectron/Run2015C_25ns-16Dec2015-v1/MINIAOD	254227-255031, excluding 254833
/SingleMuon/Run2015D-16Dec2015-v1/MINIAOD	256630-260627
/SingleElectron/Run2015D-16Dec2015-v1/MINIAOD	256630-260627

ground sources, have been generated and showered using different MC generators. To better reproduce the actual data-taking conditions, where there is a significant probability that more than two protons interact in the same BX, PU events are added on top of the hard scattering. Particle interactions with the detector were reproduced through a detailed description of CMS.

The MadGraph generator [39] has been used to produce signal events, and the showering has been performed with PYTHIA8 [48]. The background samples used for the studies are listed in Table 5.19. All MC samples considered in this analysis come from the official “RunIIFall15” or private production. Events from all samples were reconstructed making use of a `CMSSW_7_6_3` release version. The simulated samples are reweighted to represent the distribution of PU, as measured in the data.

In order to maintain statistics in the MC samples to perform the measurement on the SM cross section limit, we apply a generator-level minimum photon p_T cut of 20 GeV; however, in order to generate enough statistics in the tail of the high photon p_T distribution used to set limits on AQGC parameters, we increase this minimum photon p_T threshold to 80 GeV for the AQGC samples.

A summary of the cross sections of the contributing processes is given in Table 5.20

5.2.2 Event Selection

The event should have a good PV. This means selecting the PV with the highest sum of p_T^2 of the tracks associated with it and requiring it to have a $\text{NDOF} \geq 4$, where NDOF corresponds to the weighted sum of the number of tracks used for the

construction of the PV. In addition, the PV must lie in the central detector region of $|z| \leq 24$ cm and $\rho \leq 2$ cm around the nominal IP.

In the electron channel, we select events that contain exactly one tight electron candidate fulfilling the criteria described in Section 4.1.2 and reject events that contain a loose electron or a loose muon in addition to the tight electron. In the muon channel, we select events that contain exactly one tight muon candidate whose criteria are described in Section 4.1.1 and reject events that contain an additional loose lepton. In both channels we require an event to have MET in excess of 50 GeV and to have a leptonic W transverse mass greater than 30 GeV. The leptonic W is reconstructed after deriving the longitudinal momentum of the neutrino according to Eq. 5.7. If there are two real solutions to Eq. 5.7, the solution with the smallest absolute value is assigned; in the case of a complex solution, the solution's real part is assigned. These cuts are designed to reduce the background from QCD multijet production.

$$p_z(\nu) = \frac{\mu \cdot p_z^{\text{lepton}}}{(p_T^{\text{lepton}})^2} \pm \sqrt{\frac{\mu^2 \cdot (p_z^{\text{lepton}})^2}{(p_T^{\text{lepton}})^4} - \frac{E_{\text{lepton}}^2 \cdot |\text{MET}|^2 - \mu}{(p_T^{\text{lepton}})^2}} \quad (5.7)$$

$$\mu = \frac{m_W^2}{2} + \vec{p}_T^{\text{lepton}} \cdot \vec{\text{MET}} \quad (5.8)$$

Furthermore, we require two central jets in the event with dijet invariant mass $70 < m_{jj} < 100$ GeV, for the resolved jets which corresponds to the hadronic decay of the W or Z in the signal process. We also require $\Delta\eta(j, j) < 1.4$, which further suppresses the $W\gamma + jets$ background. Additionally we require both jets to fail the CSV medium b-tag requirement, which suppresses the $t\bar{t}\gamma$ and single top backgrounds. In the electron channel we require $|M_{e\gamma} - M_Z| > 10$ GeV, which efficiently rejects the $Z + jets$ background, when one of the leptons in e^+e^- pair is misreconstructed as a photon.

5.2.3 Efficiencies and Scale Factors

Since the lepton reconstruction, selection, and trigger efficiencies can be slightly different between data and simulation, correction factors have to be applied to the MC to account for these differences. The efficiencies are calculated using a TnP technique and are provided by the respective POGs. The total lepton efficiency can

be factorized into three components:

$$\epsilon_{\text{total}} = \epsilon_{\text{Reco}} \cdot \epsilon_{\text{Id}} \cdot \epsilon_{\text{HLT}} \quad (5.9)$$

The TnP method is nearly the same compared to the one already used in the 2011 data analysis for this Higgs search [67, 68]. Therefore, only the most important information will be discussed.

5.2.3.1 Electron Efficiencies

In the electron case, the reconstruction efficiency ϵ_{Reco} characterizes the transition from a super-cluster in the ECAL to a reconstructed PF electron. The ability of a reconstructed electron to pass the offline selection, consisting of several isolation and identification criteria, is given by the identification efficiency ϵ_{Id} . Finally, the selected electron has a certain probability to fire the HLT and the efficiency to fulfill the HLT requirements is parametrized as ϵ_{HLT} . In data, a single electron trigger is used at the HLT level, while in MC the HLT requirements are dropped.

Since the HLT efficiency in MC is equal to 100%, the HLT efficiency measured on data is applied directly in the analysis of MC samples, while the other two efficiency components are calculated both for data and MC, so that a data/MC scale factor is applied in the other cases. In general, since the efficiency depends both on p_T and η of the electron, the measurement is binned in p_T as (10, 20, 30, 40, 50, 200) GeV and in η as (0.0, 0.8, 1.444, 1.566, 2.0, 2.5) of the probe electron. The resulting efficiencies and scale factors are shown in Figure 5.25 and are derived from the EGamma POG [88].

The HLT single electron trigger efficiency was determined for the tight cut-based ID in Ref. [89], where the efficiency “turn on” plateaus at the 30 GeV cut applied in this analysis and is estimated at 98%.

5.2.3.2 Muon Efficiencies

In the muon case, the reconstruction efficiency ϵ_{Reco} describes the ability to reconstruct a PF muon starting with a particle track and can be assumed to be 1.0 [51]. The identification efficiency ϵ_{Id} gives an estimate for a reconstructed muon to pass the offline selection criteria. It can be computed for both data and simulation and thus a scale factor, the ratio of the two efficiencies, is derived. Given that this analysis

includes an additional selection based on PF isolation for the muon, there is a ϵ_{Iso} considered as well.

The trigger efficiency ϵ_{HLT} is the fraction of selected muons fulfilling the HLT requirements, and, since the HLT requirement is dropped on the MC analysis, the efficiency computed on data is used directly to correct the MC event expectation.

The efficiency measurement is binned both in p_T and η of the probe muon covering the relevant intervals (20, 25, 30, 40, 50, 60, 120) GeV in p_T and (0.0, 0.9, 1.2, 2.1, 2.4) in $|\eta|$. The resulting selection and trigger efficiencies and scale factors are shown Figure 5.26 and are derived from the Muon POG [52].

5.2.3.3 Photon Efficiencies

We used photon efficiency scale factors for 2015(C+D) and tight photon selection described in Ref. [88], which is EGamma POG approved. The scale factors do not include electron veto selection and are shown in Figure 5.27.

5.2.4 Photon Fake Rate

The largest background arises from the $W\gamma$ +jets process, while the second important contribution comes from jets or electrons misidentified as a photon. Electrons could be identified as photons due to small track reconstruction inefficiency of the detector. This contribution is relevant to the electron channel, when an electron or positron from $Z \rightarrow ee$ passes the photon identification criteria; therefore, to reduce this background, we impose a $|M_Z - M_{e\gamma}| > 10$ GeV cut. Events with jets misidentified as photons can not be tagged with a simple kinematic requirement, because it resembles the topology of the events with true photons. The adopted approach is to build the expected rate based on the ratio method [70]. The method uses a category of photons, referred to as photon-like jets, which resembles the electromagnetic objects in the ECAL but fail either the isolation or $\sigma_{i\eta i\eta}$ requirement.

A two-template fit is executed in this method, where templates are separated by photon p_T (i.e. the method is performed separately for each photon p_T bin used in the analysis, such as 30-50 GeV, 50-70 GeV, and so on). The overall concept of the method is to build a “Data” template that resembles the type of events included in the analysis, and fit two sub-templates to this distribution. One sub-template is built

from what we expect to be true photons, called the “Truth” template, and the other sub-template is built from what we predict to be fake photons, called the “Fake” template. In all three templates, one of the shower shape selections, specifically the “full 5x5 $\sigma_{i\eta i\eta}$ ”, is removed in order to preserve the full distribution beyond the cut value of 0.01; this is done because the pool of candidates that exist beyond this cut is expected to be mostly fake photons, and the template fit will need to account for the entire shape in both regions. The fake rate measurement is also restricted by photon η , because the statistics is lower in this region, for which this is already a statistics limited search, and other affects must be considered, such as beam halo, that contribute to higher uncertainties.

The “Data” template is filled by data enriched with $W(\gamma)$ +jets, which corresponds to the type of events we are interested in for this analysis. This data control sample comes from the single muon data set from both Run C and D of 2015 for 25 ns bunch spacing. We restrict the sample to the muon decay channel of the W boson to reduce contamination from fake photons from electrons; therefore, we use the same HLT as from the analysis for this channel, and additionally apply the muon and MET selection enforced in the analysis (described in Section 5.2.2). From this control sample, all tight photon candidates, again without the $\sigma_{i\eta i\eta}$ cut, fill the template according to the following specifics:

- Single tower $H/E < 0.05$
- PF charged hadron isolation < 0.76
- PU corrected PF neutral hadron isolation $< 0.97 + 0.014 \times p_T^\gamma + 0.000019 \times (p_T^\gamma)^2$
- PU corrected PF photon isolation $< 0.08 + 0.0053 \times p_T^\gamma$
- $|\eta| < 1.4442$
- Conversion safe electron veto

The “Truth” template is filled using an independent $W\gamma$ +jets NLO MC sample rather than the LO MC used for the SM $W\gamma$ +jets background. Given this is a MC sample with real photons generated, the “Truth” template is built by employing the same tight photon cuts as above.

The “Fake” template is filled by the $W(\gamma)$ +jets enriched data control sample, described above and used to build the “Data” template, with photon candidates that pass a set of loose identification selection cuts provided by the EGamma POG, except that the charged isolation cut is further modified to be much less restrictive. This provides a pool of photon candidates that fail the loosest charged isolation cut provided in CMS, but still resemble a photon within a bound on charged isolation and pass all other identification selections. The description of the new selections enforced for this template are:

- Single tower $H/E < 0.05$
- $3.32 < \text{PF charged hadron isolation} < \text{Min}(5 \times 3.32, 0.2 \times p_T^\gamma)$
- $\text{PU corrected PF neutral hadron isolation} < 0.97 + 0.014 \times p_T^\gamma + 0.000019 \times (p_T^\gamma)^2$
- $\text{PU corrected PF photon isolation} < 0.08 + 0.0053 \times p_T^\gamma$
- $|\eta| < 1.4442$
- Conversion safe electron veto

The *TFractionFitter* within CMSSW is used to perform the template fit, $C_T \cdot \text{Truth}_{\text{template}} + C_F \cdot \text{Fake}_{\text{template}} \approx \text{Data}_{\text{template}}$, where the renormalization constants C_T and C_F are varied to get the best agreement with the template shapes. Figure 5.28 demonstrates how the templates have been fit to the data for each photon p_T bin.

The re-normalized “Fake” and “Truth” templates are then used to extract the fake photon rate (fake photons / all photons) and fake photon ratio (fake photons / real photons). The fake rate is derived by comparing the “Fake” template with the “Data” template to get the fraction of fake photon candidates in the tight photon ID $\sigma_{\text{in}\eta}$ region (< 0.01).

In order to build the contribution from fake photons needed in the kinematic distributions and for limit setting, we need to apply the fake rate to a set of signal-like photon candidate events. Given the fake rate is derived from data in the control region that consists of $W(\gamma)$ +jets, we must then take the $W\gamma$ +jets NLO MC and first normalize it to the cross section and integrated luminosity, and then apply the full analysis selection, including the tight photon cut-based ID. Since we apply the tight

photon ID, the events that pass the total selection in MC are expected to consist of real photons; therefore, we need to take the “Fake” and “Truth” templates used to derive the fake photon rate and apply the ratio (Fake:Truth), according to Eq. 5.10, which will estimate the fake photon events from the $W\gamma$ +jets signal selection. Since the signal selection for this analysis does include the $\sigma_{i\eta i\eta}$ cut from the tight photon ID, the ratio between the “Fake” and “Truth” templates was evaluated below $\sigma_{i\eta i\eta} < 0.01$.

$$\text{Fake Events}(p_T^\gamma) = \sigma_{MC} \cdot \mathcal{L} \cdot (W\gamma + jets(p_T^\gamma)) \cdot \frac{\text{Template}_F(p_T^\gamma, \sigma_{i\eta i\eta} < 0.01)}{\text{Template}_T(p_T^\gamma, \sigma_{i\eta i\eta} < 0.01)} \quad (5.10)$$

5.2.5 K-factors

Generally, LO calculations can provide a good estimation of cross sections and a description of kinematic distributions, but the shortcoming is also obvious. Its dependence on the unphysical renormalization and factorization scales can result in a large theoretical uncertainty, especially for those processes with large logarithms. Therefore, NLO calculations are important for precise analysis. In an experimental analysis, generally one can use a K-factor, which is defined as the ratio of the NLO to LO cross section for a given process, to estimate the NLO effect. However, its dependence on the renormalization and factorization scales, as well as the PDFs, should result in large uncertainties. Moreover, the NLO corrections can also lead to shape changes in kinematic distributions, especially when tight cuts are applied. Thus, one needs to make a careful examination to get a reasonable K-factor.

With a few exceptions, the MC samples used in this analysis are generated with NLO accuracy using MG5’s aMC@NLO [39]. The exceptions include the major background, $W\gamma + (0-3)$ jets, and the AQGC $WV\gamma$ samples; therefore, in order to bring these LO samples to NLO estimations for the kinematic distributions used to determine the final limitations on the SM cross section and AQGC parameters, a K-factor must be determined.

5.2.5.1 SM $WV\gamma$

Although our signal SM $WV\gamma$ MC is a NLO sample, it still proves instrumental in verifying the method used to determine the AQGC K-factor if we compare the Run II SM K-factor with that which was derived for the Run I analysis [14].

The VBFNLO package, described in Ref. [90, 91, 92], was used with the semileptonic $WV\gamma$ decay processes in order to compare LO and NLO distributions. We applied event generation criteria as close to the selection cuts used in this analysis to derive as applicable a K-factor as possible. In particular, this includes the p_T thresholds for the photon, lepton, and jets, as well as the geometric constraints on η discussed in Section 5.2.2. It was also necessary to include the requirement that the dijet mass of each event exist within 20 GeV of the expected parent's invariant mass. This last requirement is necessary because it is possible for events to be generated with an initial radiated jet, thus leaving VBFNLO to only need to generate one additional jet for the event, which will not recombine in the dijet window to the W or Z boson mass.

Unfortunately, in VBFNLO the number of desired statistics to be generated is not an input the user can provide directly; however, by increasing the number of LO and NLO iterations used in the generation, the output statistics will be likewise influenced. Therefore, the figures providing the ratio between the differential cross sections at LO and NLO, the K-factor distribution, include statistical errors.

As can be seen if Figure 5.29, the $WW\gamma$ K-factor provided as a function of the photon p_T is relatively flat above 30 GeV. This distribution is fit by a linear function to provide the constant 2.66 ± 0.96 , which agrees with the value derived in Run I. Figure 5.29 likewise shows the K-factor distribution for $WZ\gamma$, for which even fewer statistics were available in the sample studied. Therefore, given this study shows agreement with the detailed procedure performed in Run I, we adopt the value of 2.09812 ± 0.302029 published from Run I given it included significantly more statistics.

5.2.5.2 AQGC $WV\gamma$

The MC samples for AQGC study are generated as SM $WV\gamma$ with added AQGC. K-factors for two values of each AQGC parameter, one near the existing limit and one

very far from the existing limit (highly anomalous), are computed as a function of the photon p_T and are shown with the SM K-factor in Figures 5.30-5.43. At low photon p_T the K-factor resembles the SM $WW\gamma$ K-factor, while with the increase of the photon p_T , most of the contributions are from the quartic diagrams, and one can expect that the value will be similar to the Drell Yan processes. As can be seen in Figures 5.30-5.43, the AQGC K-factor levels at approximately 1.185 when the photon p_T is greater than 250 GeV. The exact behavior of the K-factor at low photon p_T for the SM $WW\gamma$ with added AQGC depends on type of the AQGC parameter and its value, but it can be concluded that this region is a mix of AQGC and SM events and thus the trend of the K-factor towards 1.185 becomes more dominant with increasingly anomalous parameter values, just as the trend towards the SM value of 2.1 is dominant with decreasingly anomalous parameter values. This is exactly what was seen in the Run I analysis; therefore, we adopt the value published for the AQGC $WV\gamma$ K-factor of 1.185. It must also be noted that across all 14 quartic gauge parameters shown in Figures 5.30-5.43, the behavior is the same - there appears to be no dependence on the specific parameter or on photon p_T , but rather all AQGC events seem to rest at a K-factor value of 1.185 in the dominant high photon p_T region and at 2.1 in the SM low photon p_T region.

In this study we define the AQGC contribution as signal, which excludes the SM contributions. The limit-setting machinery, discussed in Section 5.2.9.2, uses a signal input distribution which is the difference between the SM $WV\gamma$ with added AQGC and SM $WV\gamma$ only photon p_T distributions (referred to as “AQGC-SM”). To accomplish this, when preparing the input file for the limit setter, we first subtract out the LO SM contribution from the AQGC sample and then apply the AQGC K-factor to the remaining distribution. We then use the separately produced NLO SM $WV\gamma$ MC as background.

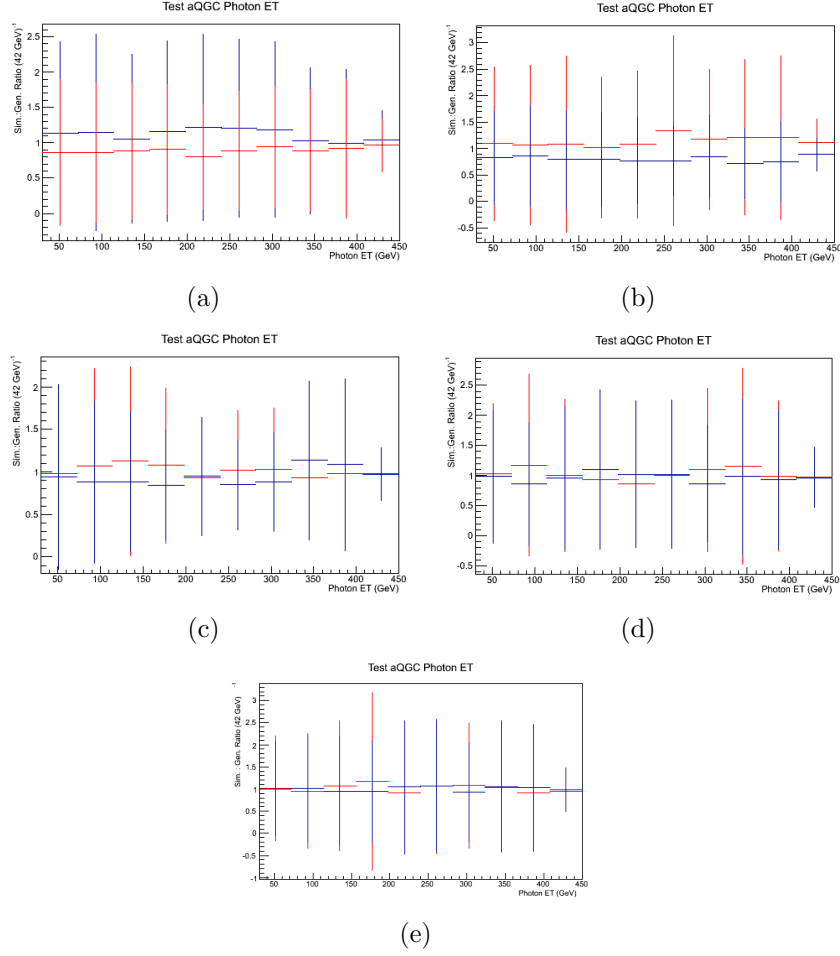


Figure 5.20: Muon channel simulated:generated ratio as a function of photon p_T for (a) $a_0^W/\Lambda^2 = -5 \times 10^{-5} \text{ GeV}^{-2}$ (red), $5 \times 10^{-5} \text{ GeV}^{-2}$ (blue); (b) $a_C^W/\Lambda^2 = -8 \times 10^{-5} \text{ GeV}^{-2}$ (red), $8 \times 10^{-5} \text{ GeV}^{-2}$ (blue); (c) $f_{T,0}/\Lambda^4 = -8 \times 10^{-11} \text{ GeV}^{-2}$ (red), $8 \times 10^{-11} \text{ GeV}^{-2}$ (blue); (d) $\kappa_0^W/\Lambda^2 = -2 \times 10^{-5} \text{ GeV}^{-2}$ (red), $2 \times 10^{-5} \text{ GeV}^{-2}$ (blue); (e) $\kappa_C^W/\Lambda^2 = -3 \times 10^{-5} \text{ GeV}^{-2}$ (red), $3 \times 10^{-5} \text{ GeV}^{-2}$ (blue)

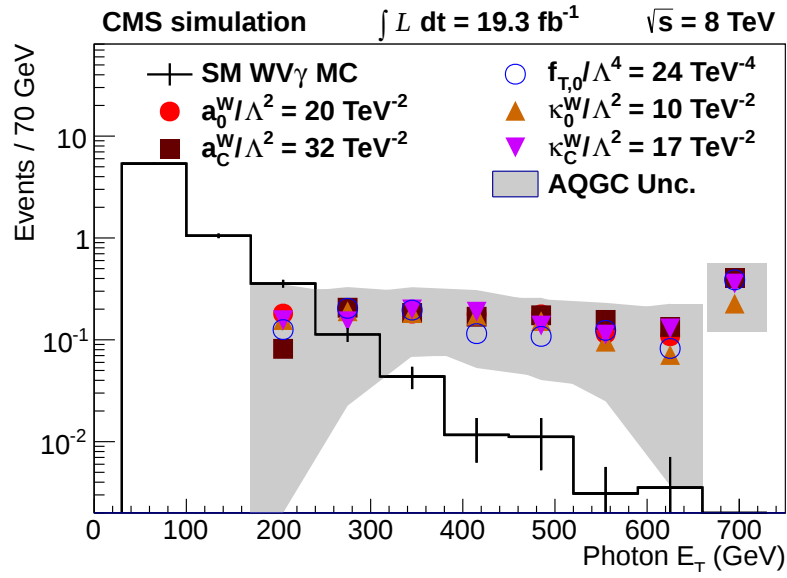


Figure 5.21: Input photon p_T distributions for the limit setter of the muon channel: SM prediction (black); AQGC excess from SM prediction for a_0^W/Λ^2 (red), a_C^W/Λ^2 (green), $f_{T,0}/\Lambda^4$ (blue), κ_0^W/Λ^2 (orange), and κ_C^W/Λ^2 (violet).

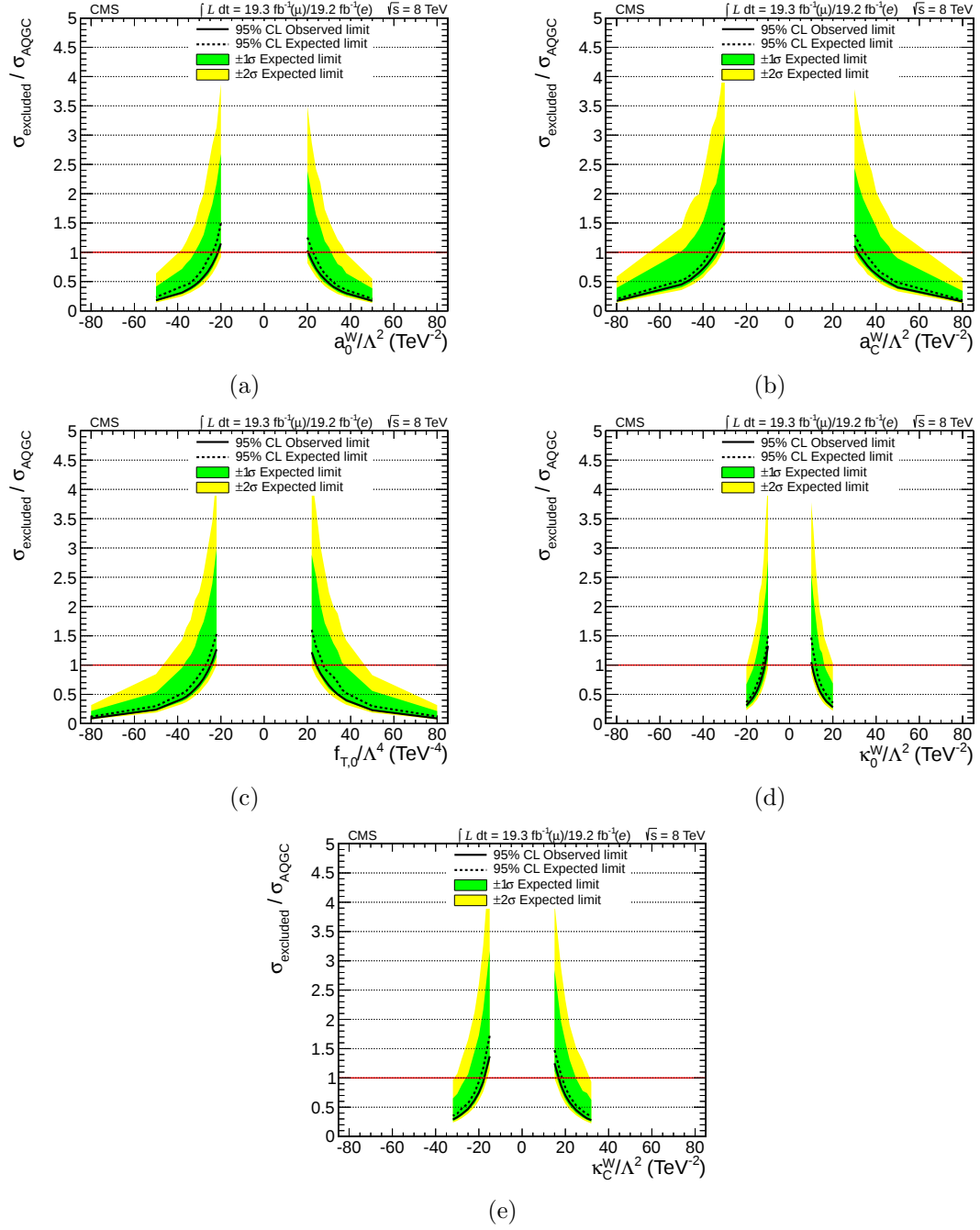


Figure 5.22: Exclusion limits for (a) a_0^W/Λ^2 ; (b) a_C^W/Λ^2 ; (c) $f_{T,0}/\Lambda^4$; (d) κ_0^W/Λ^2 ; (e) κ_C^W/Λ^2 , all at the 95% CL using photon p_T .

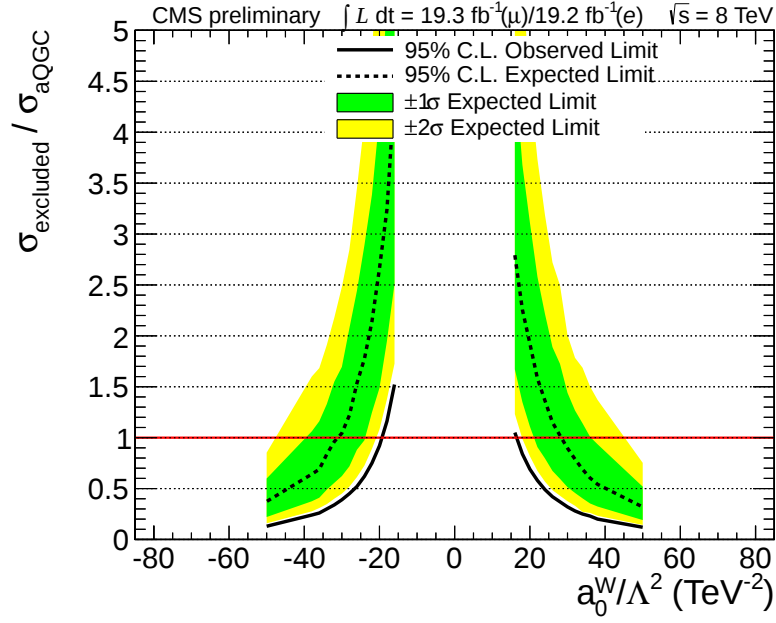


Figure 5.23: Exclusion limits for a_0^W / Λ^2 at 95% CL using $M_{WV\gamma}$.

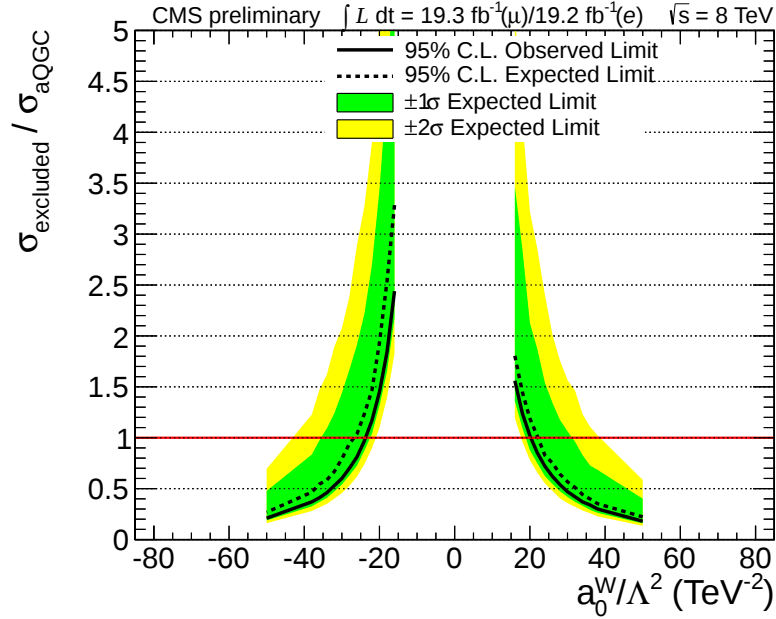


Figure 5.24: Exclusion limits for a_0^W / Λ^2 at 95% CL using photon p_T -dependent functional K-factors.

Table 5.19: Summary of MC samples used in the analysis.

$W\gamma + Jets$ (LO)	/WGToLNuG_TuneCUETP8M1_13TeV-madgraphMLM-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
$W\gamma + Jets$ (LO)	/WGToLNuG_PtG-500_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
$[p_T(\gamma) > 500 \text{ GeV}]$ $W\gamma + Jets$ (NLO)	/RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM /WGToLNuG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
$Z\gamma + Jets$ (NLO)	/ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
$t\bar{t}\gamma + Jets$ (NLO)	/TTGJets_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
Single Top + $\gamma + Jets$ (NLO)	/TGJets_TuneCUETP8M1_13TeV-amcatnlo-madspin-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
$W + Jets$ (LO)	/WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
$WW\gamma$ (NLO)	/WWG_TuneCUETP8M1_13TeV-amcatnlo-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-ext1-v1/MINIAODSIM
$WZ\gamma$ (NLO)	/WZG_TuneCUETP8M1_13TeV-amcatnlo-pythia8 /RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1/MINIAODSIM
$WW\gamma$ aQGC (LO)	/WWAToLNu2jA_4fLO_AQGC_pLHEv5_TuneCUETP8M1_13TeV-amcatnlo-pythia8 /lnujj-RunIIFall15MiniAODv2_76X_mcRun2_asymptotic_v12-17d438ff51ec6b3cada9e499a5a978e0/USER
$WZ\gamma$ aQGC (LO)	/WZAToLNu2jA_4fLO_AQGC_19Jan16_TuneCUETP8M1_13TeV-amcatnlo-pythia8 /lnujj-RunIIFall15MiniAODv2_76X_mcRun2_asymptotic_v12-17d438ff51ec6b3cada9e499a5a978e0/USER

Table 5.20: Summary of the SM processes. Photon $p_T > 20$ GeV, $|\eta^{\gamma,e,\mu}| < 2.5$. The data-driven normalization of $W\gamma$ + jets is described in Sec. 5.2.5, where an additional scaling factor (K-factor) will be applied to the quoted cross section.

Process	shape modeling	cross section [pb]
SM $WW\gamma$	MC	(NLO) $0.2147 \pm 2 \times 10^{-4}$
SM $WZ\gamma$	MC	(NLO) $0.04123 \pm 4 \times 10^{-5}$
$W\gamma$ +Jets	MC	(LO) 378.9 ± 1.216
$Z\gamma$ +Jets	MC	(NLO) 112.8 ± 0.522
$t\bar{t}\gamma$	MC	(NLO) 3.697 ± 0.047
Single Top + γ (inclusive)	MC	(NLO) 2.967 ± 0.089

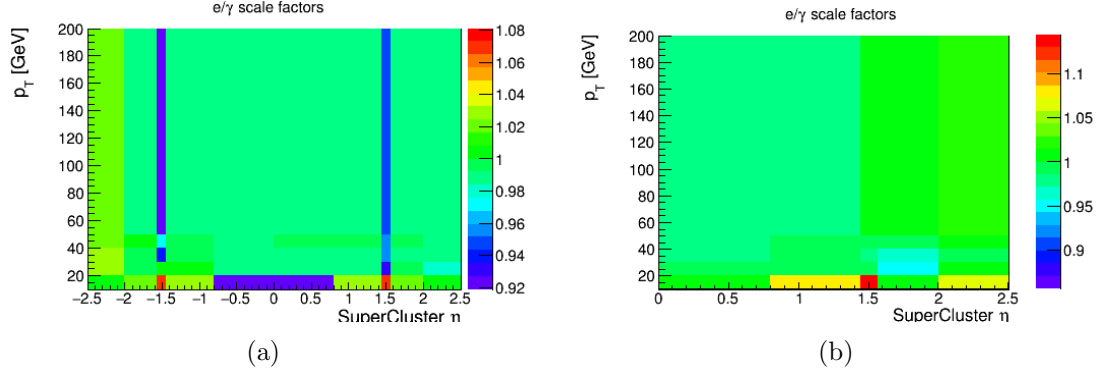


Figure 5.25: Electron efficiency and data/MC scale factors for super-cluster to reconstructed electrons ϵ_{Reco} (a) and reconstructed to selected electrons ϵ_{Id} (b).

Table 5.21: 2015 tight photon ID data-driven photon-faking jet rate plus uncertainties for given photon p_T .

E_T (GeV)	Fake Rate	Stat. Unc.	Stat. Unc. (%)	Bias Stat. Unc. (%)
30-50	0.222	0.013	6	12
50-70	0.183	0.020	11	12
70-90	0.204	0.047	23	12
90-110	0.217	0.052	24	12
110-150	0.102	0.027	26	12
150-inf	0.119	0.043	36	12

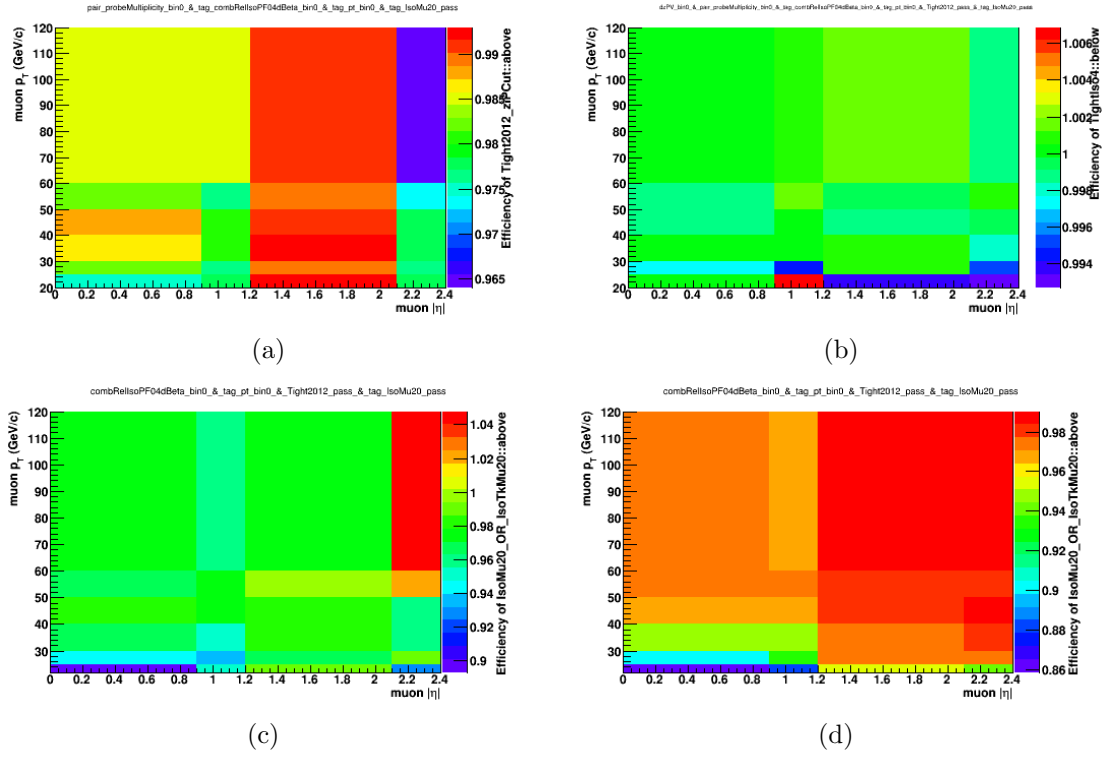


Figure 5.26: Muon scale factors for reconstructed to selected muons $\epsilon_{\text{ID,data}}/\epsilon_{\text{ID,mc}}$ (a), including isolation efficiencies (b), and efficiency for selection of HLT muons $\epsilon_{\text{HLT,data}}$ for Run 2015C (c) and Run 2015D (d).

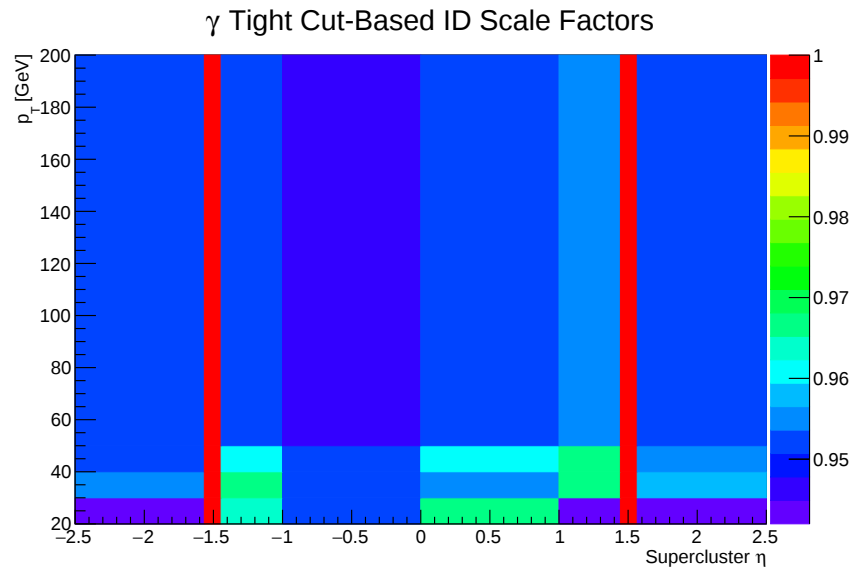


Figure 5.27: 2015 tight photon ID data/MC efficiency scale factors for given photon p_T and η .

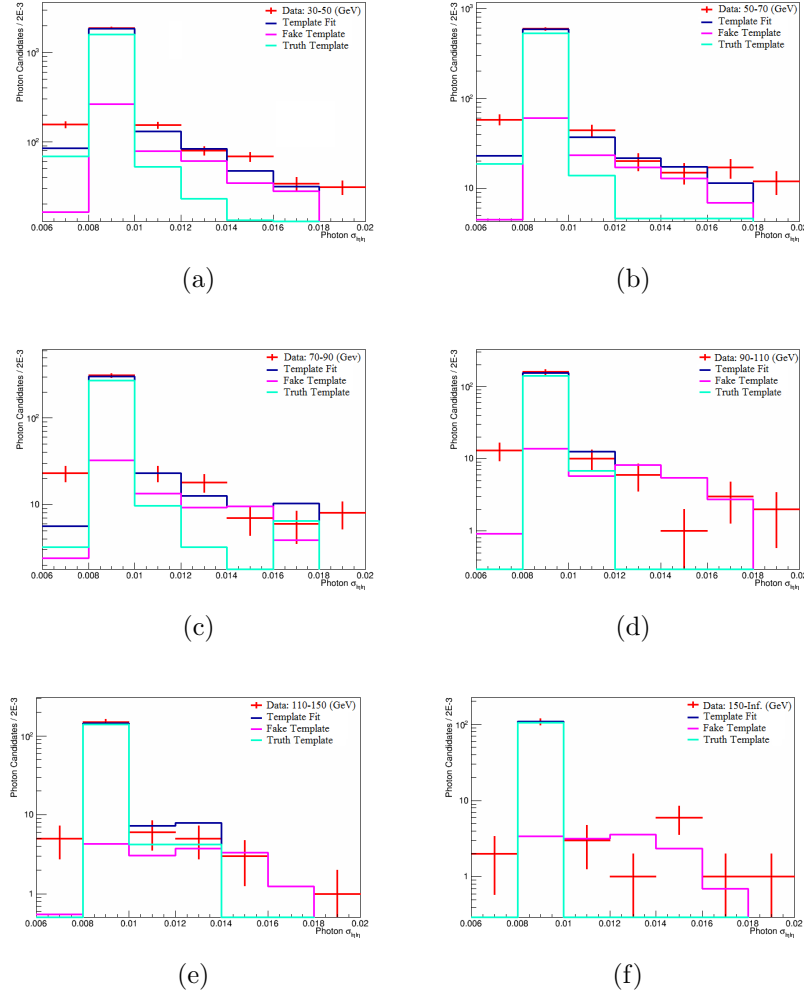


Figure 5.28: Signal and background distributions in $\sigma_{i\eta i\eta}$ used to estimate the $WV\gamma$ photon-like jet, or fake photon, rate. Red points are from 2015 tight photons in data, while blue points are 2015 photon candidates from data that pass very loose PF charged isolation. The MC truth is represented in light blue. Photon p_T : (a) 30-50 GeV, (b) 50-70 GeV, (c) 70-90 GeV, (d) 90-110 GeV, (e) 110-150 GeV, (f) 150- ∞ GeV

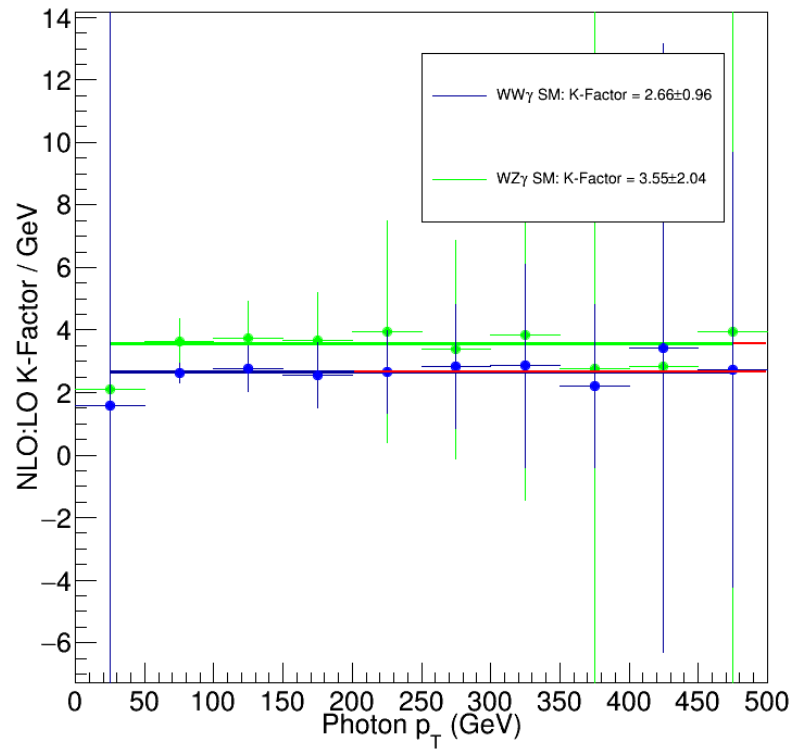


Figure 5.29: $W^\pm V \gamma$ signal SM sample K-factor distributions as a function of photon p_T .

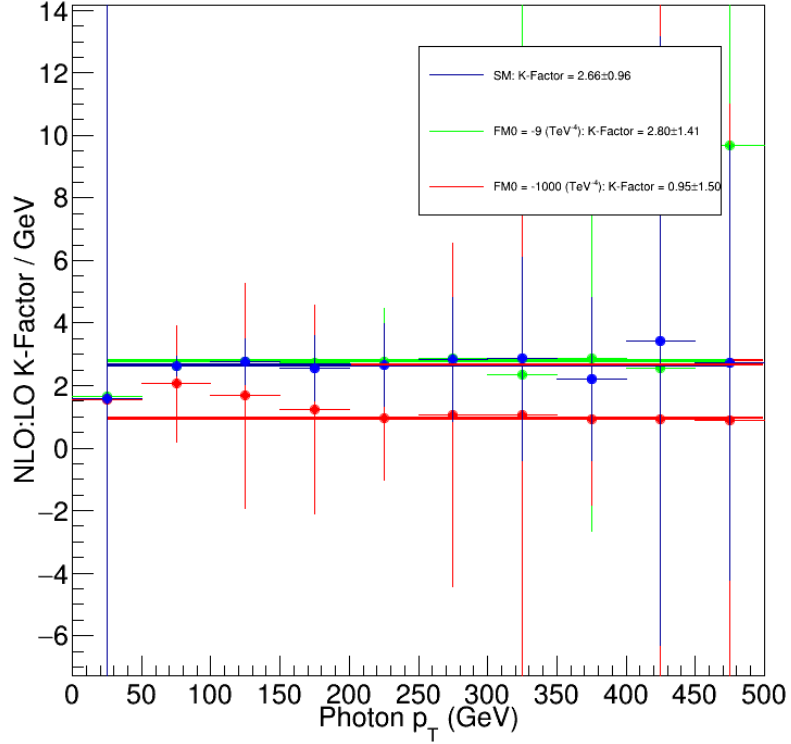


Figure 5.30: $W^\pm V\gamma$ signal AQGC samples' K-factor distributions with different $f_{M,0}$ AQGC values.

5.2.5.3 $W\gamma$ + jets Background Estimation

In order to estimate the normalization of the major background $W\gamma$ +jets, we used a data-driven technique. The background normalization in the signal region is extracted with a binned maximum likelihood fit to the dijet invariant mass distribution m_{jj} of the two leading jets. The signal region corresponding to the W and Z mass windows, $70 \text{ GeV} < m_{jj} < 100 \text{ GeV}$, is excluded from the fit. The $W\gamma$ +jets shape is taken from simulation and the overall normalization is allowed to vary in the fit. All other backgrounds, which contribute less than 38% are based on simulation and are fixed to their SM expectations with uncertainties. Normalization for the $W\gamma$ +jets is measured to be 1.076 ± 0.140 for muon leptonic decay channel and 0.921 ± 0.170 for electron leptonic decay channel. The quality of the fit is illustrated in Figure 5.44

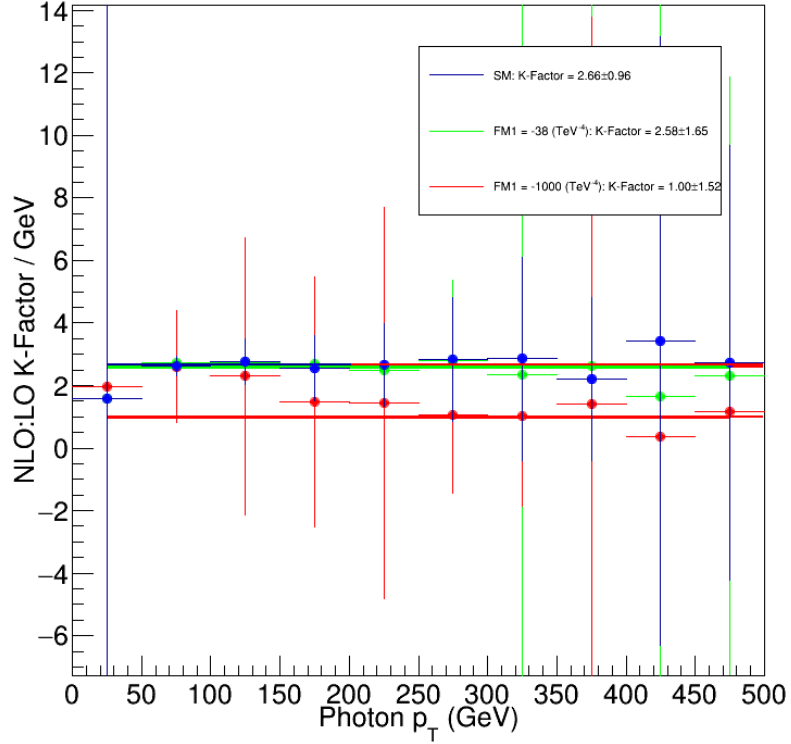


Figure 5.31: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{M,1}$ AQGC values.

Table 5.22 summarizes the K-factors and cross sections used for each MC sample, as well as the treatment of all backgrounds in the fit.

5.2.6 Systematic Uncertainties

5.2.6.1 $W\gamma$ +jets Normalization

The normalization of the $W\gamma$ +jets background is described in Section 5.2.5. The uncertainty in the K-factor is taken from the template fit uncertainty.

5.2.6.2 Misidentified Jets

In order to estimate the systematic uncertainty in the photon fake rate, two separate contributions are considered - the effect of biasing the fake photon template, and the

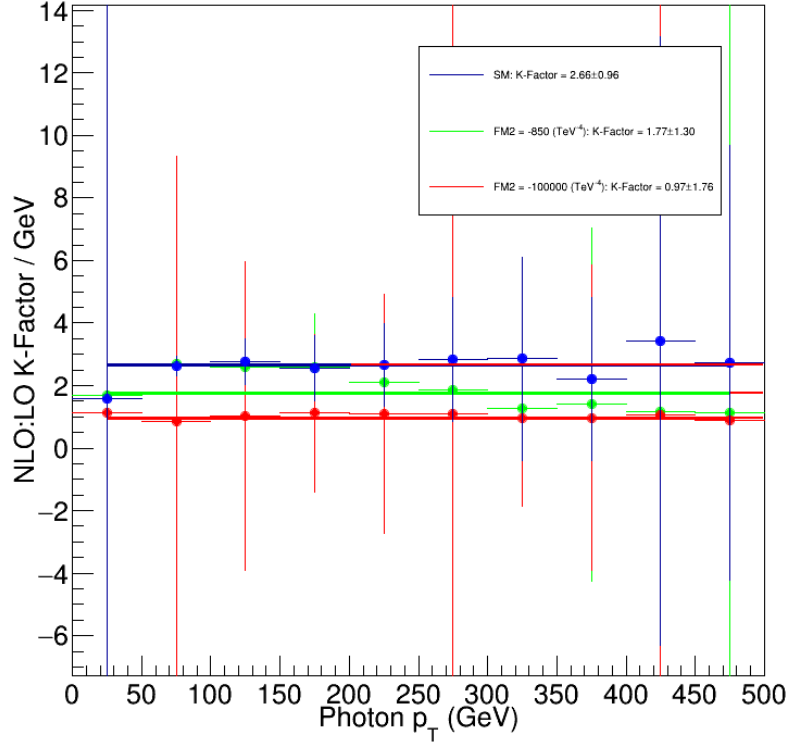


Figure 5.32: $W^\pm V\gamma$ signal AQGC samples' K-factor distributions with different $f_{M,2}$ AQGC values.

statistical uncertainty in the bias measurement. The known bias is that the fake photon template is constructed using inverted PF isolation in the 2015 photon tight selection ID, where it is assumed that all photon candidates filling this template are in fact jets faking a photon.

The uncertainty measurement of the bias in the “Fake” template is estimated entirely from MC. We take the $W\gamma$ +jets NLO MC and remove “IsPrompt” and “IsTrue” photons, as constructed by the EGamma POG. We further remove FSR by requiring isolation of the photon candidates from other objects ($\Delta R > 0.5$). The remaining photon candidates fill one template, where we have defined them to be fake photons from MC according to truth information. A second template is likewise filled with what are believed to be fake photons, but according to the inverted isolation recipe

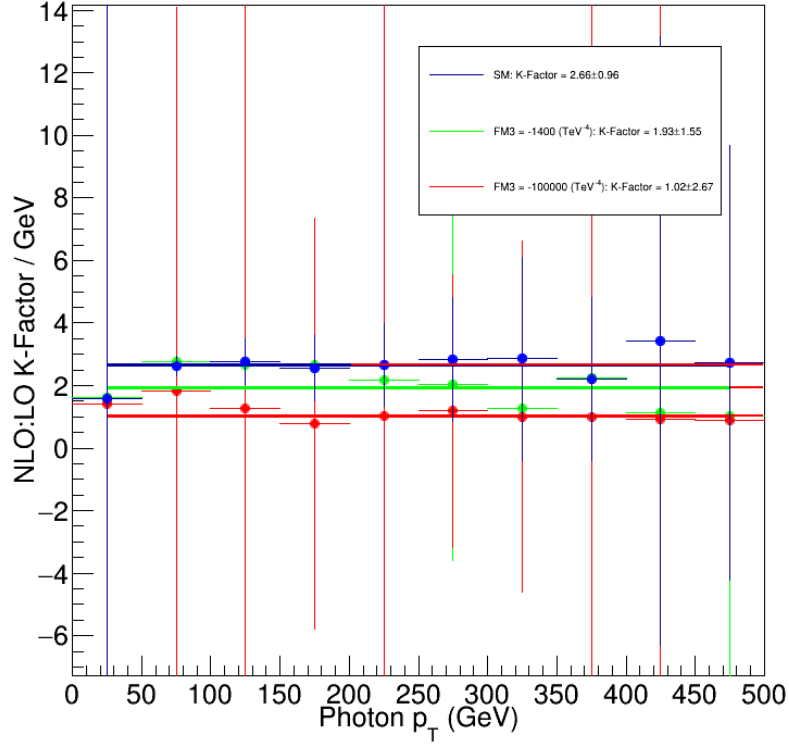


Figure 5.33: $W^\pm V\gamma$ signal AQGC samples' K-factor distributions with different $f_{M,3}$ AQGC values.

(selection cuts) defined in Section 5.2.4. This second template is therefore built from the same $W\gamma$ +jets NLO MC with all photon candidates that pass the “very loose” cuts used to build the “Fake” template previously described. We take this template to be the “estimated” fake photon distribution.

Since there are very few photon candidates that survive to fill Template 1, we no longer segregate the bias measurement by photon p_T bins, but instead combine all photon p_T bins together. We then fit Template 2 to Template 1, where any deviation of a 1.0 renormalize factor is considered the bias uncertainty measurement. The bias is measured to be $8\% \pm 12\%$, or that both templates are in 92% agreement. The uncertainty in this measurement is included in the overall systematic uncertainty in the fake rate, provided in Table 5.21.

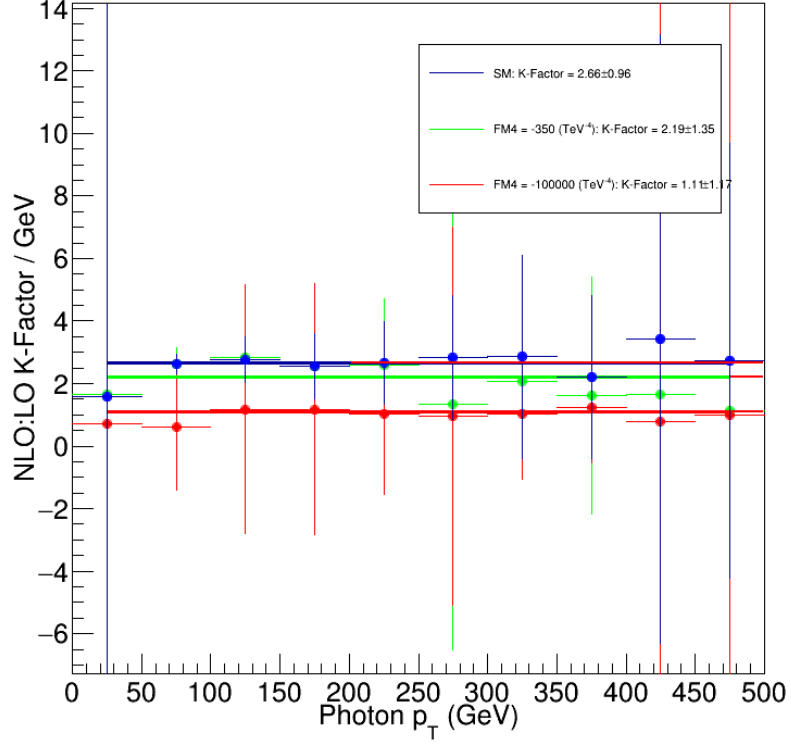


Figure 5.34: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{M,4}$ AQGC values.

To approximate the statistical uncertainty for this method, given that each template of photon p_T suffers from the number of available entries, several “toy” templates are generated. First, we fit each original “Data”, “Truth”, and “Fake” template with a Gaussian function. Then 100 “toy” templates for each contribution (data, real photons, fake photons) are randomly filled according to the Gaussian fit. The template fit method is rerun on these new templates, and the RMS of the “toy” fake rates is considered the statistical uncertainty on the genuine fake rate. This uncertainty is measured for each photon p_T bin and listed in Table 5.21. The measured systematic and statistical uncertainties are combined to make the photon p_T -dependent systematic uncertainties listed in Table 5.23.

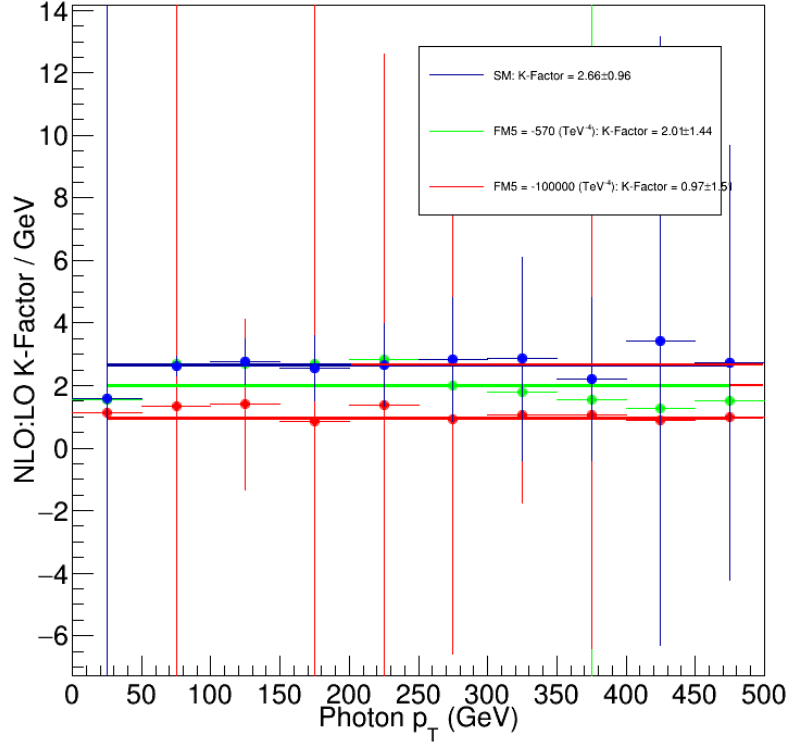


Figure 5.35: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{M,5}$ AQGC values.

5.2.6.3 HLT and Lepton Selection

Systematic uncertainties in the trigger efficiencies are of the order of 2%. Systematic uncertainties in the lepton reconstruction and identification efficiency scale factors are of the order of 14%. These uncertainties are accounted for in the final systematics that are input to the limit setter.

5.2.6.4 MET

MET directly affects our signal acceptance. The uncertainty prescription is discussed in Ref. [81].

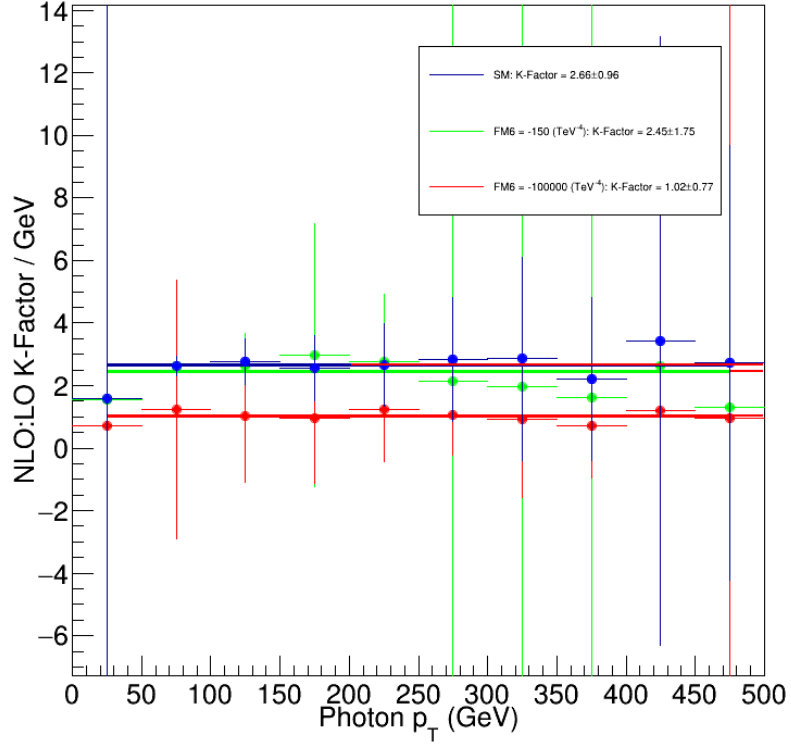


Figure 5.36: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{M,6}$ AQGC values.

5.2.6.5 Jet Energy Scale and Resolution

The systematic uncertainty is estimated by varying up and down the jet energy uncertainties and computing the effect on the acceptance according to the recipe provided by the JetMET group [93].

5.2.6.6 b-jet Tagger

The uncertainty from the b-jet CSV tagging algorithm is 10% on the efficiency correction factor, and is based on measurement with 2015 data, as described in Ref. [94]. This particularly effects the $t\bar{t} + \gamma + \text{jets}$ and single top + γ MC.

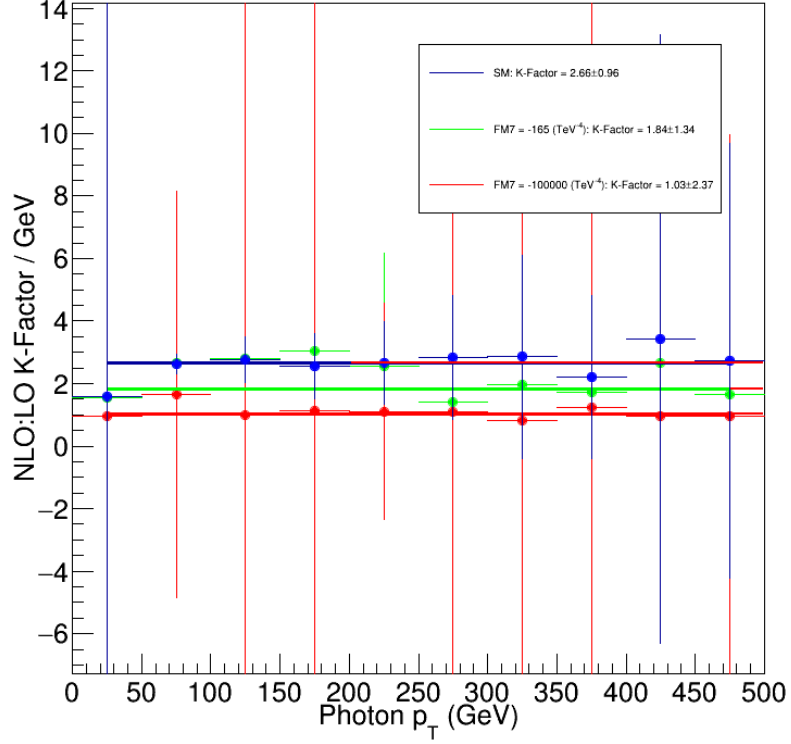


Figure 5.37: $W^\pm V\gamma$ signal AQGC samples' K-factor distributions with different $f_{M,7}$ AQGC values.

5.2.6.7 Pileup

The average number of PU interaction in a given bunch crossing BX_i is given by the following formula:

$$N_i = \frac{\mathcal{L} \cdot \sigma_{\text{min. bias}}}{\nu_{\text{orbit}}}, \quad (5.11)$$

where $\mathcal{L}$ is the instantaneous luminosity, $\sigma_{\text{min. bias}}$ is the cross-section of minimum bias interactions and ν_{orbit} is the LHC orbit frequency. Source of uncertainties in the estimation of the number of PU interactions in data then come from the uncertainty on the luminosity, currently 2.6%, and the uncertainty on the minimum-bias cross-section. We have adopted $\sigma_{\text{min. bias}} = 69 \text{ mb}$.

A total variation of 5% in the number of interactions was propagated to the re-

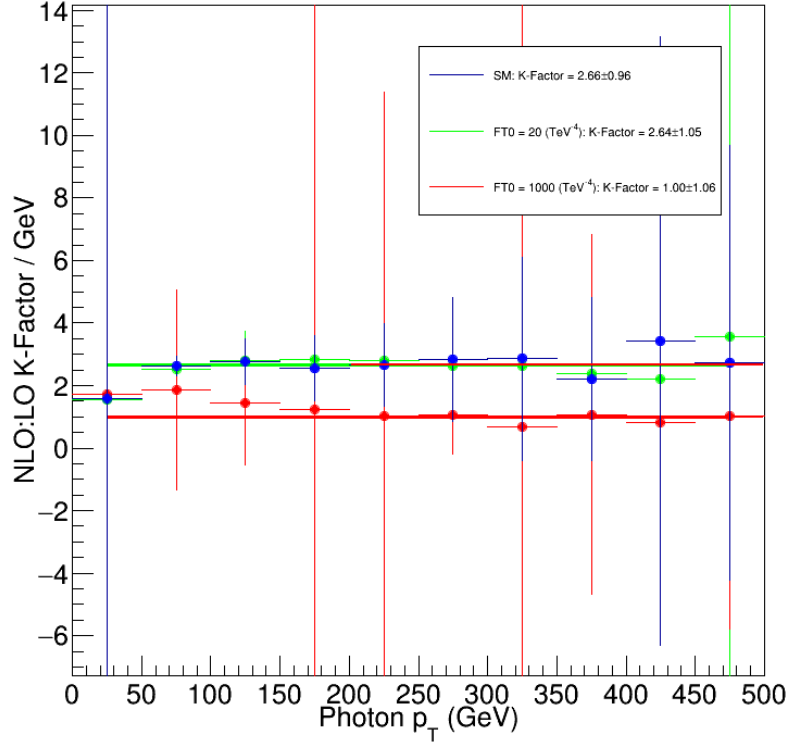


Figure 5.38: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{T,0}$ AQGC values.

weighting procedure for signal samples, and the obtained variation in the signal yield is used as systematics on the signal. The typical effect is less than a percent.

5.2.6.8 PDF and Renormalization/Factorization

Just as was done in Sec. 5.1.6.3, the scale and PDF uncertainties are derived for each background and signal process. PDF weights were considered for *NNPDF30*. The uncertainties will be used in the SM cut-and-count upper cross section limit, while the reweighted kinematic distributions for both scale and PDF will be used in the shape-based AQGC limits measurements. Figures 5.45-5.50 show the maximum scale variations from the nominal distribution of each MC process. Figures 5.51-5.56 show the maximum PDF variations from the nominal distribution. Table 5.23

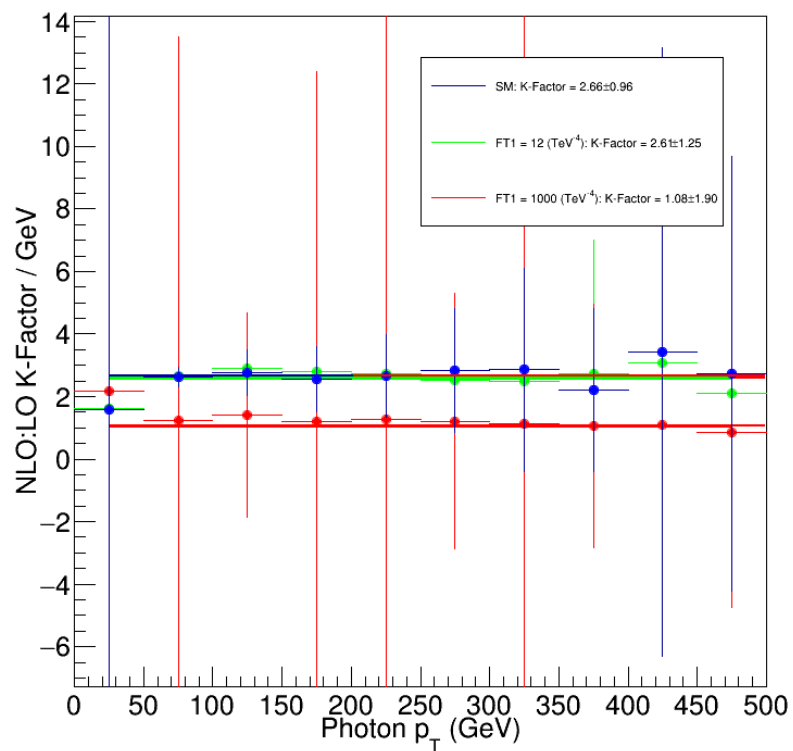


Figure 5.39: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{T,1}$ AQGC values.

contains a summary of all systematic uncertainties considered.

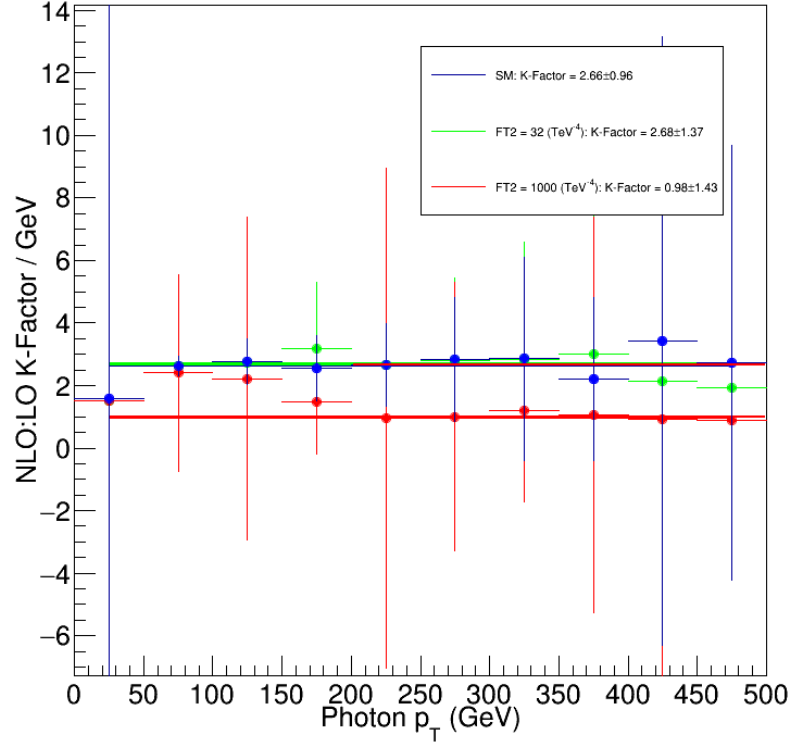


Figure 5.40: $W^\pm V \gamma$ signal AQC samples' K-factor distributions with different $f_{T,2}$ AQC values.

Table 5.22: List of backgrounds, the theoretical K-factors, and how they are treated in the background normalization template fit. The SM $WV\gamma$ MC is at NLO accuracy, and thus the listed K-factor is inherently included in the sample. The data-driven K-factor for $W\gamma$ +jets sample is listed for both the muon and electron channels.

MC Sample	K	External constraint on normalization used in $W\gamma$ +jets fit
SM $WV\gamma$	2.1	Constrained
anomalous $WV\gamma$	1.185	NA
$W\gamma$ +jets (resolved case)	1.08 (mu), 0.92 (el)	Unconstrained
All other backgrounds	1.0	Constrained

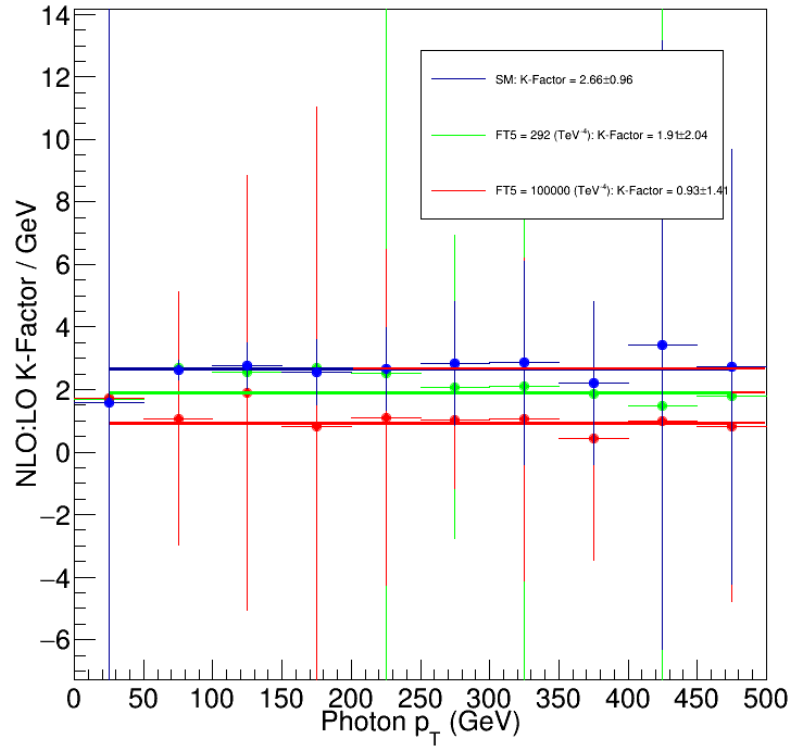


Figure 5.41: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{T,5}$ AQGC values.

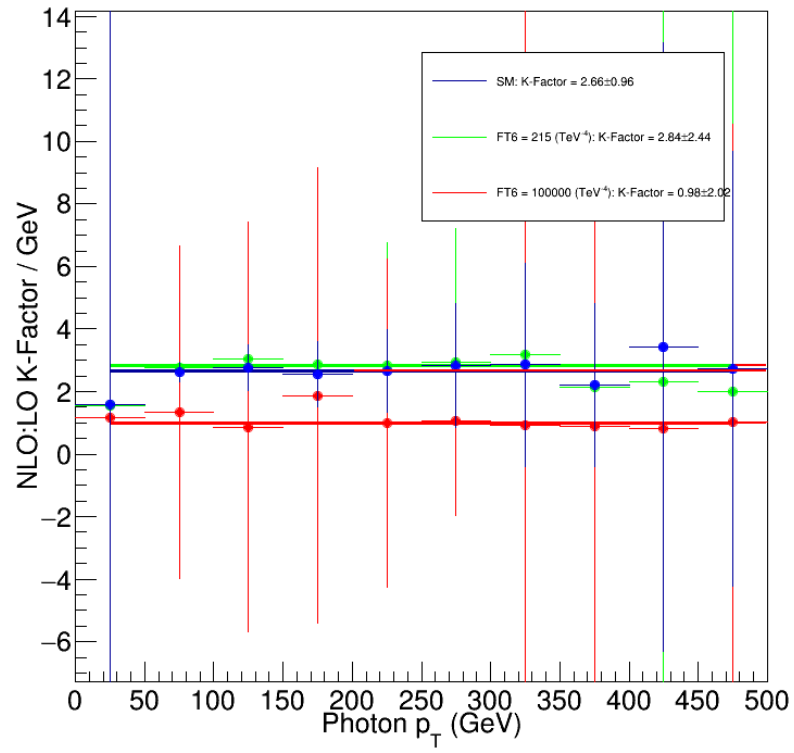


Figure 5.42: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{T,6}$ AQGC values.

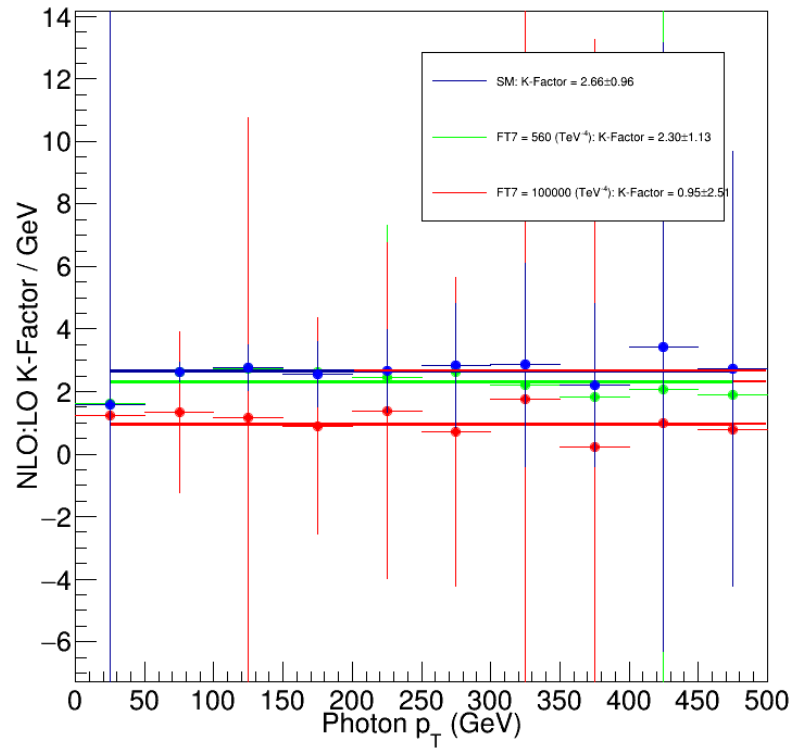


Figure 5.43: $W^\pm V \gamma$ signal AQGC samples' K-factor distributions with different $f_{T,7}$ AQGC values.

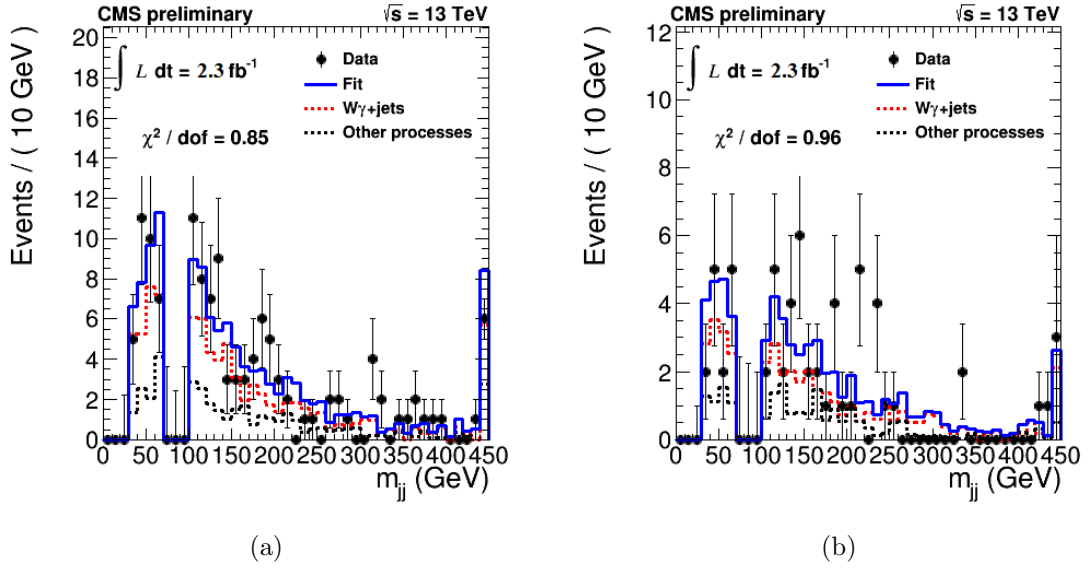


Figure 5.44: Data and MC dijet mass sidebands used to estimate the data-driven $W\gamma$ +jets K-factor. (a) Muon and (b) electron W-lepton channels.

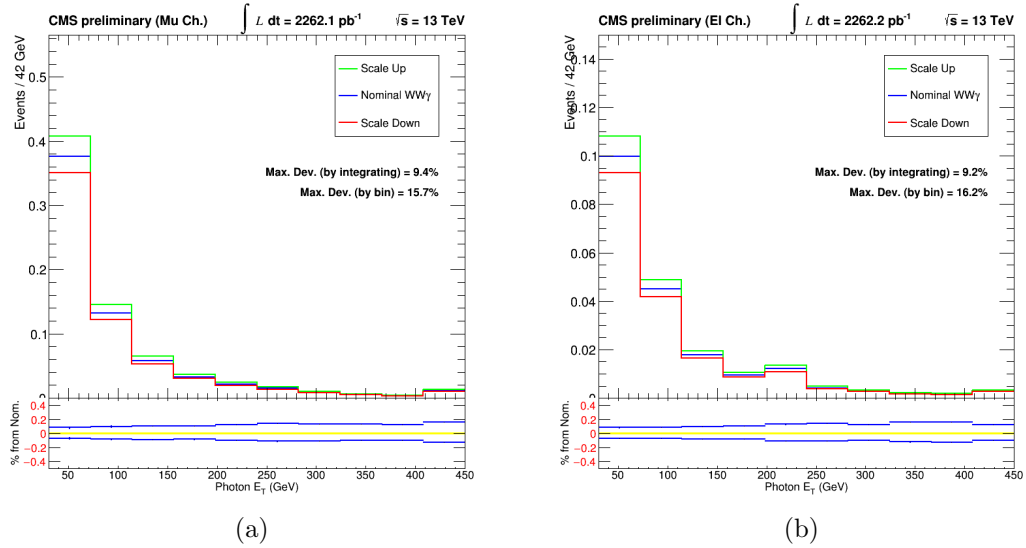


Figure 5.45: Scale up/down variations over photon p_T for $WW\gamma$ in the muon (a) and electron (b) W-lepton channel.

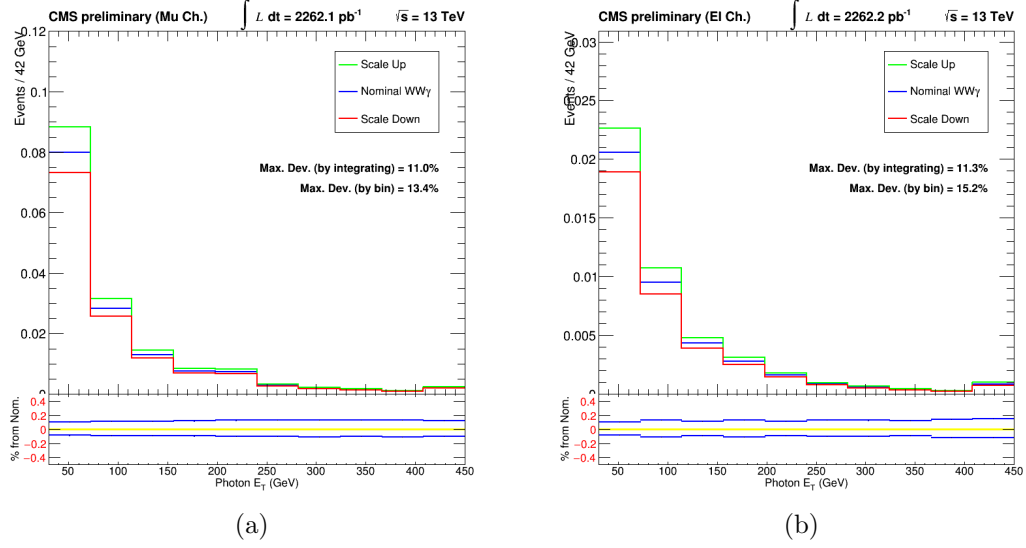


Figure 5.46: Scale up/down variations over photon p_T for $WZ\gamma$ in the muon (a) and electron (b) W-lepton channel.

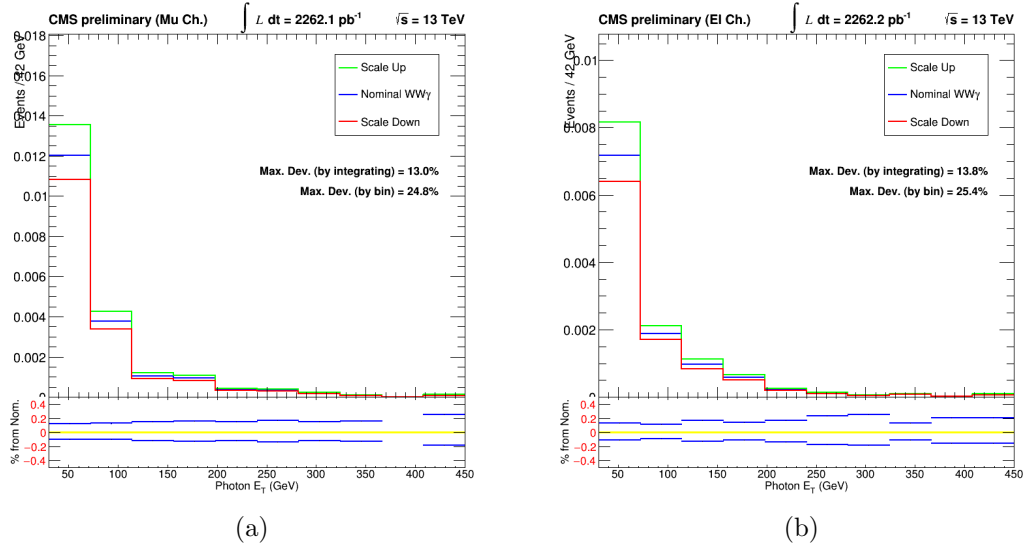


Figure 5.47: Scale up/down variations over photon p_T for $W\gamma + jets$ in the muon (a) and electron (b) W-lepton channel.

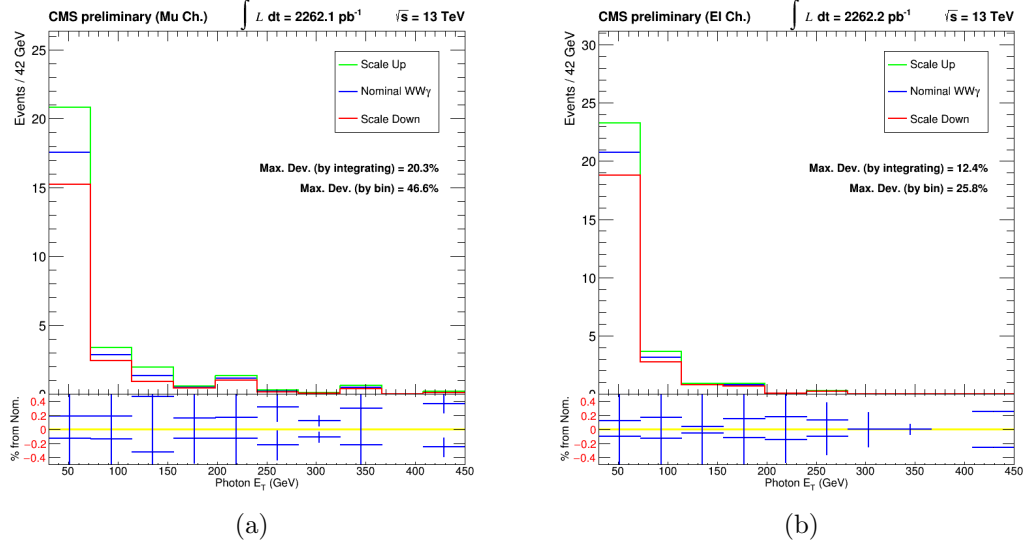


Figure 5.48: Scale up/down variations over photon p_T for $Z\gamma + jets$ in the muon (a) and electron (b) W-lepton channel.

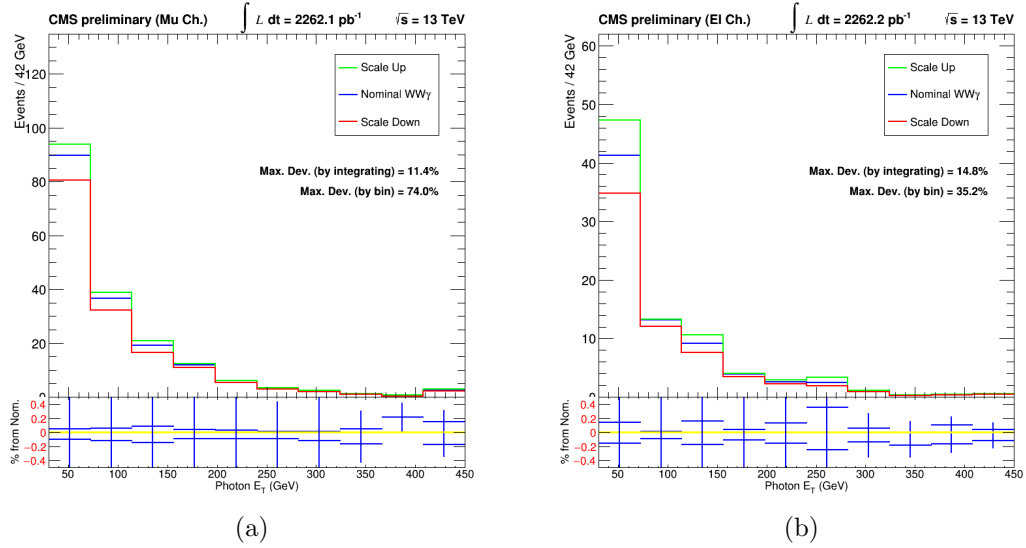


Figure 5.49: Scale up/down variations over photon p_T for $t\bar{t}\gamma + jets$ in the muon (a) and electron (b) W-lepton channel.

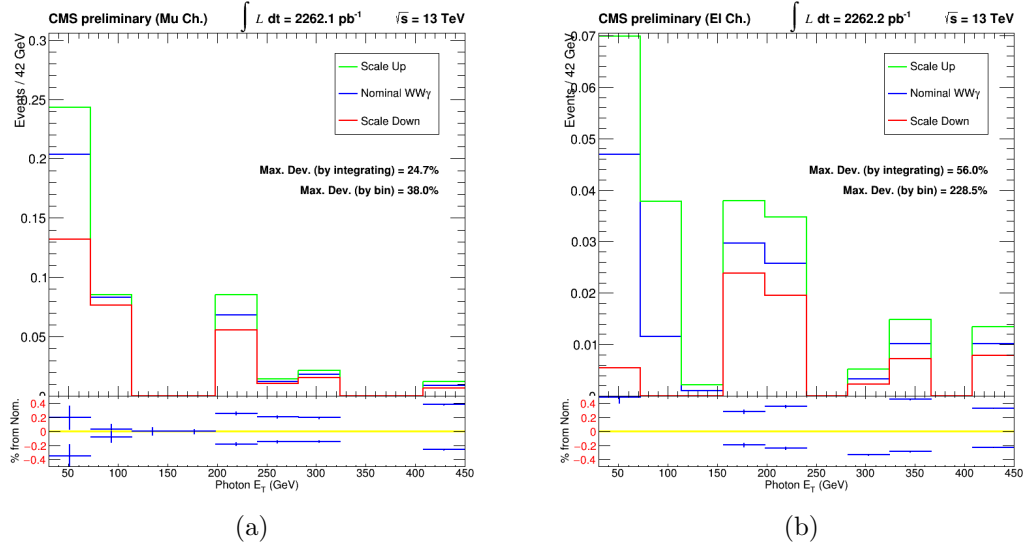


Figure 5.50: Scale up/down variations over photon p_T for Single Top + γ + jets in the muon (a) and electron (b) W-lepton channel.

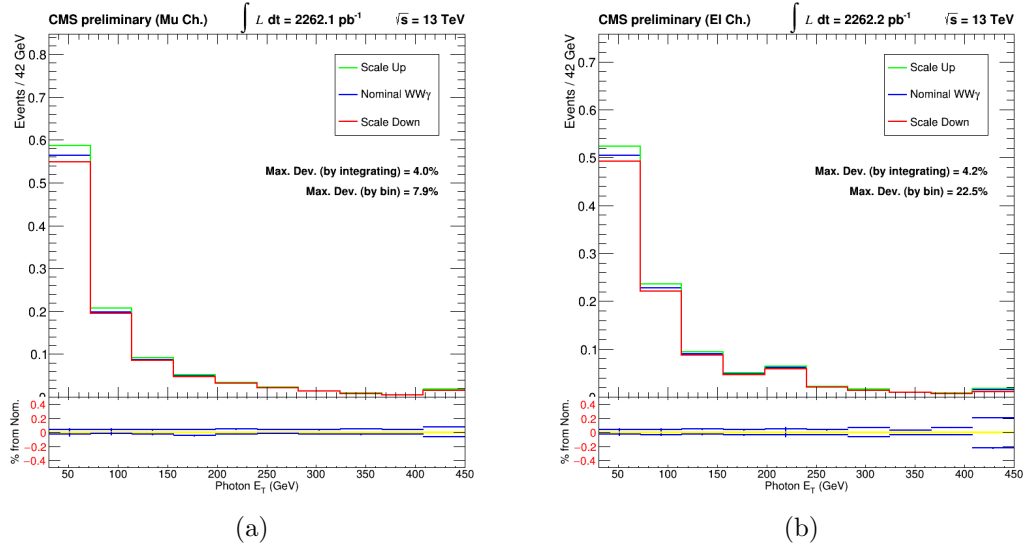


Figure 5.51: PDF up/down variations over photon p_T for $WW\gamma$ in the muon (a) and electron (b) W-lepton channel.

5.2.7 Signal and Background Expectations from CMS Simulation

In order to compare the MC processes with observed data, we first normalize each sample to the observed integrated luminosity for both the muon and electron channel of the full 2015 data set, which, after single lepton triggers, is 2.3 fb^{-1} . To do this, we use Eq. 5.5. We include events with either positive or negative generated weight.

Figures 5.57-5.74 are data and MC comparison plots for various event kinematic distributions. The event yield is summarized in Table 5.24.

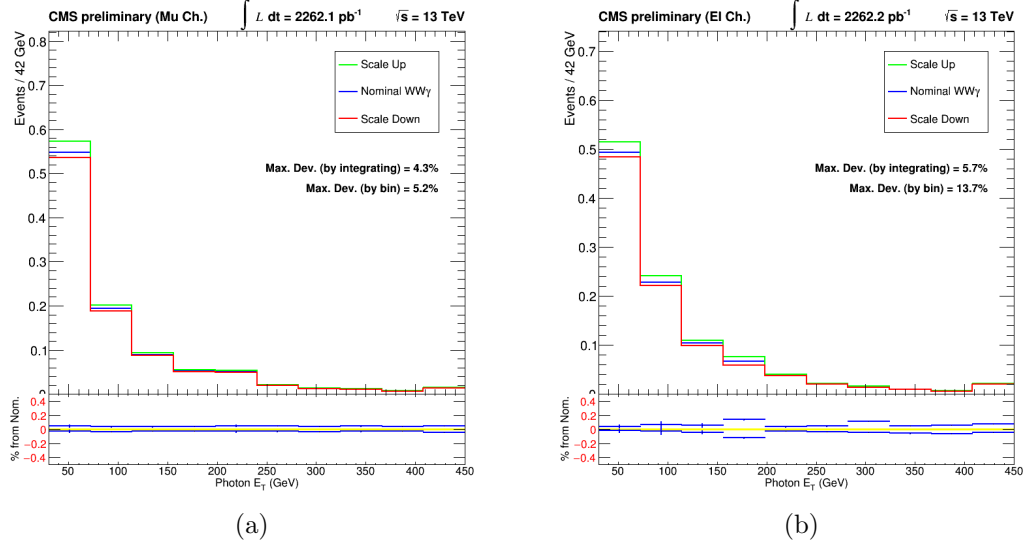


Figure 5.52: PDF up/down variations over photon p_T for $WZ\gamma$ in the muon (a) and electron (b) W-lepton channel.

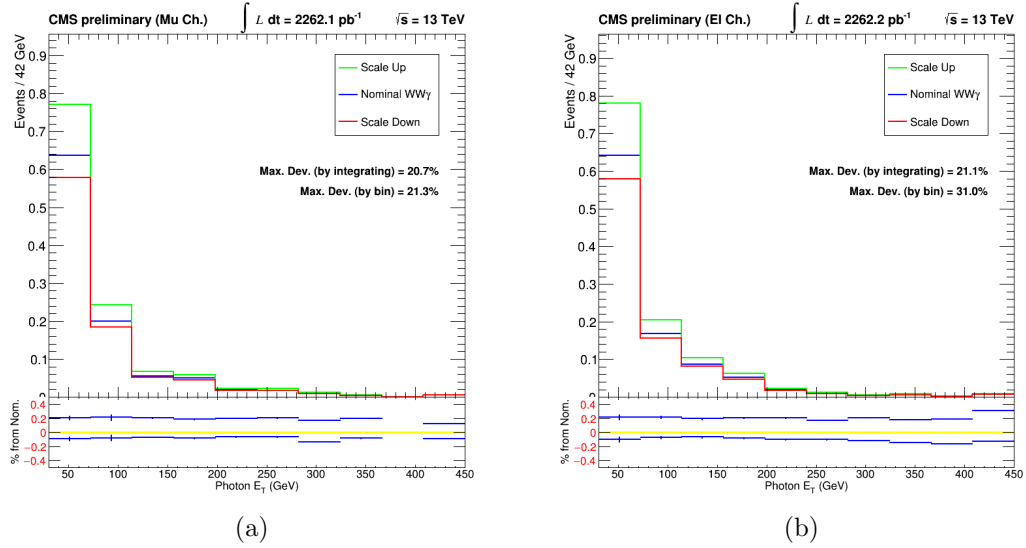


Figure 5.53: PDF up/down variations over photon p_T for $W\gamma + jets$ in the muon (a) and electron (b) W-lepton channel.

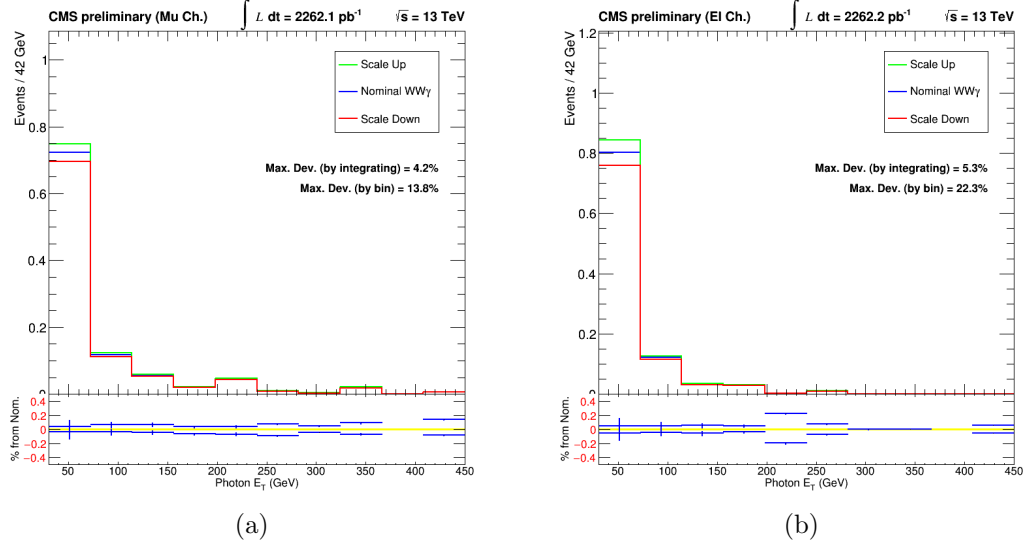


Figure 5.54: PDF up/down variations over photon p_T for $Z\gamma + jets$ in the muon (a) and electron (b) W-lepton channel.

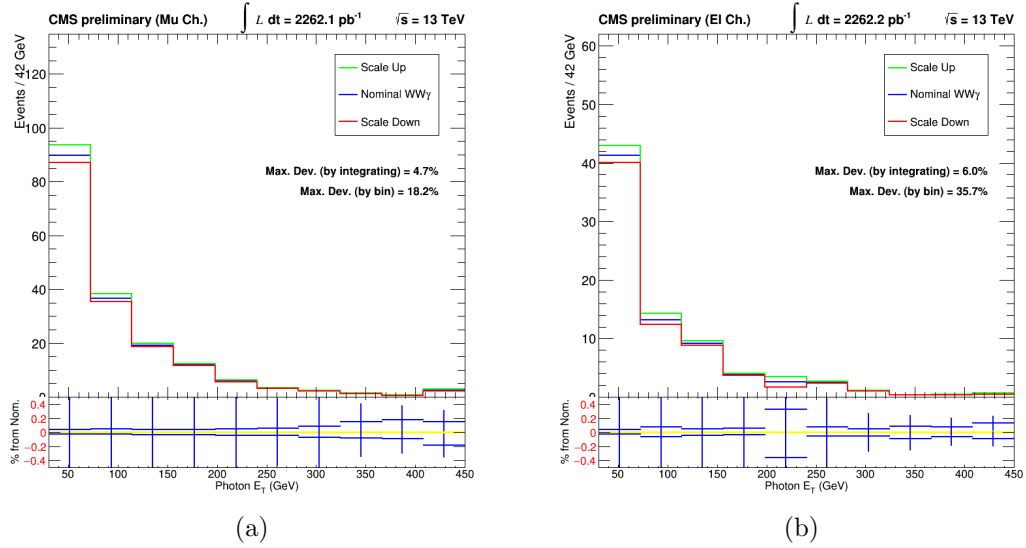


Figure 5.55: PDF up/down variations over photon p_T for $t\bar{t}\gamma + jets$ in the muon (a) and electron (b) W-lepton channel.

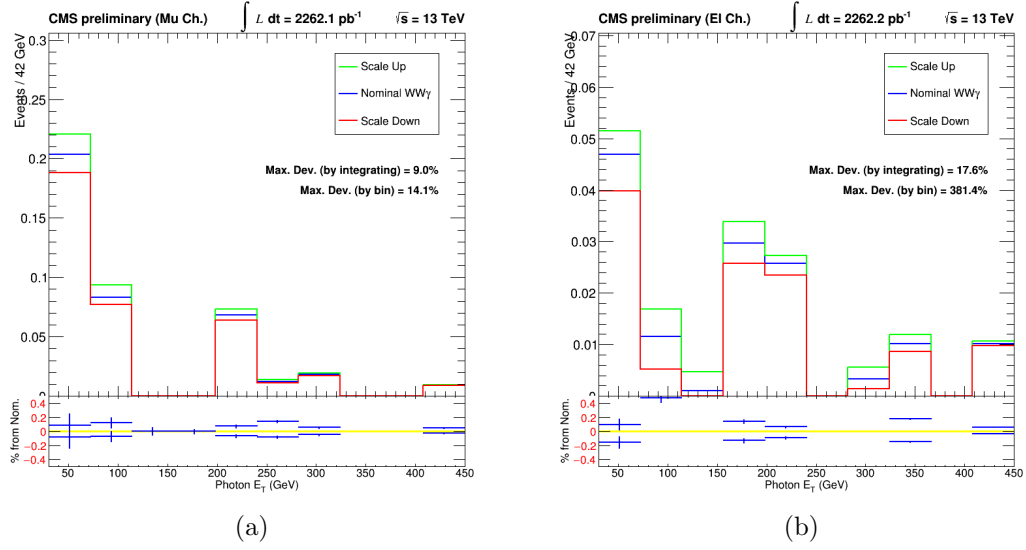


Figure 5.56: PDF up/down variations over photon p_T for Single Top + γ + $jets$ in the muon (a) and electron (b) W-lepton channel.

Table 5.23: Summary of the systematic uncertainties.

Source	Uncertainty
$W\gamma$ +Jets normalization	13%(mu), 18%(el)
$\text{jet} \rightarrow \gamma$	13% (30 GeV - 50 GeV) 16% (50 GeV - 70 GeV) 26% (70 GeV - 90 GeV) 27% (90 GeV - 110 GeV) 29% (110 GeV - 150 GeV) 38% (> 150 GeV)
Trigger Efficiency	2%
Lepton Selection Efficiency	2%
Photon Reco/ID Efficiency	2%
Photon Energy Scale	1%
Anti-b Tag ($t\bar{t}\gamma$)	10%
Anti-b Tag (single top + γ)	10%
Pileup modeling	1%
Luminosity	2.6%
Jet Energy Resolution	1%
Jet Energy Scale	3%
MET	1%
renormalization/factorization scale	
$WW\gamma$	9.4%(mu), 9.2%(el)
$WZ\gamma$	11%(mu), 11.3%(el)
$W\gamma$ +Jets	13%(mu), 13.8%(el)
$Z\gamma$ +Jets	20.3%(mu), 12.4%(el)
$t\bar{t} + \gamma + \text{Jets}$	11.4%(mu), 14.8%(el)
Single Top + γ + Jets	24.7%(mu), 56%(el)
PDF	
$WW\gamma$	4%(mu), 4.2%(el)
$WZ\gamma$	4.3%(mu), 5.7%(el)
$W\gamma$ +Jets	20.7%(mu), 21.1%(el)
$Z\gamma$ +Jets	4.2%(mu), 5.3%(el)
$t\bar{t} + \gamma + \text{Jets}$	4.7%(mu), 6%(el)
Single Top + γ + Jets	9%(mu), 17.6%(el)

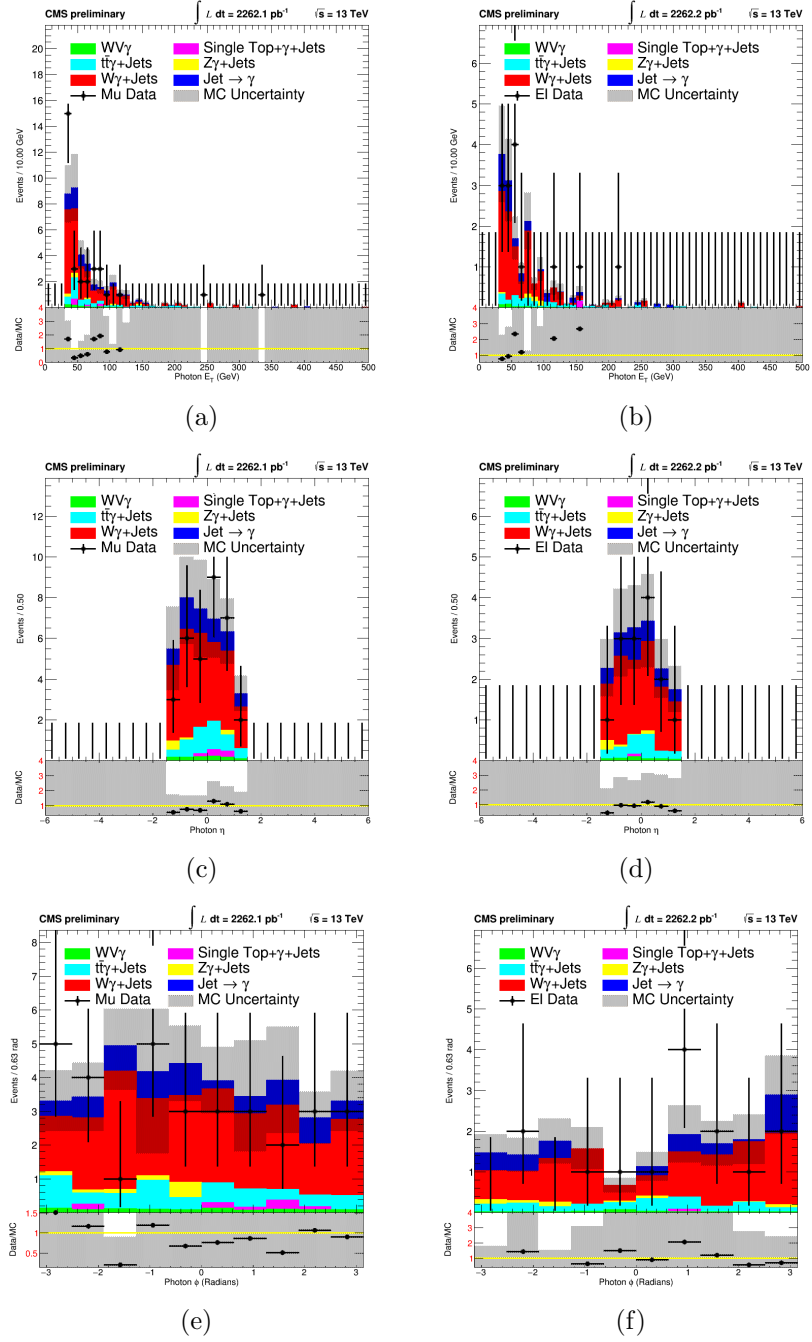


Figure 5.57: Data and MC comparison plots for muon channel photon p_T (a), η (c), ϕ (e), and electron channel photon p_T (b), η (d), ϕ (f).

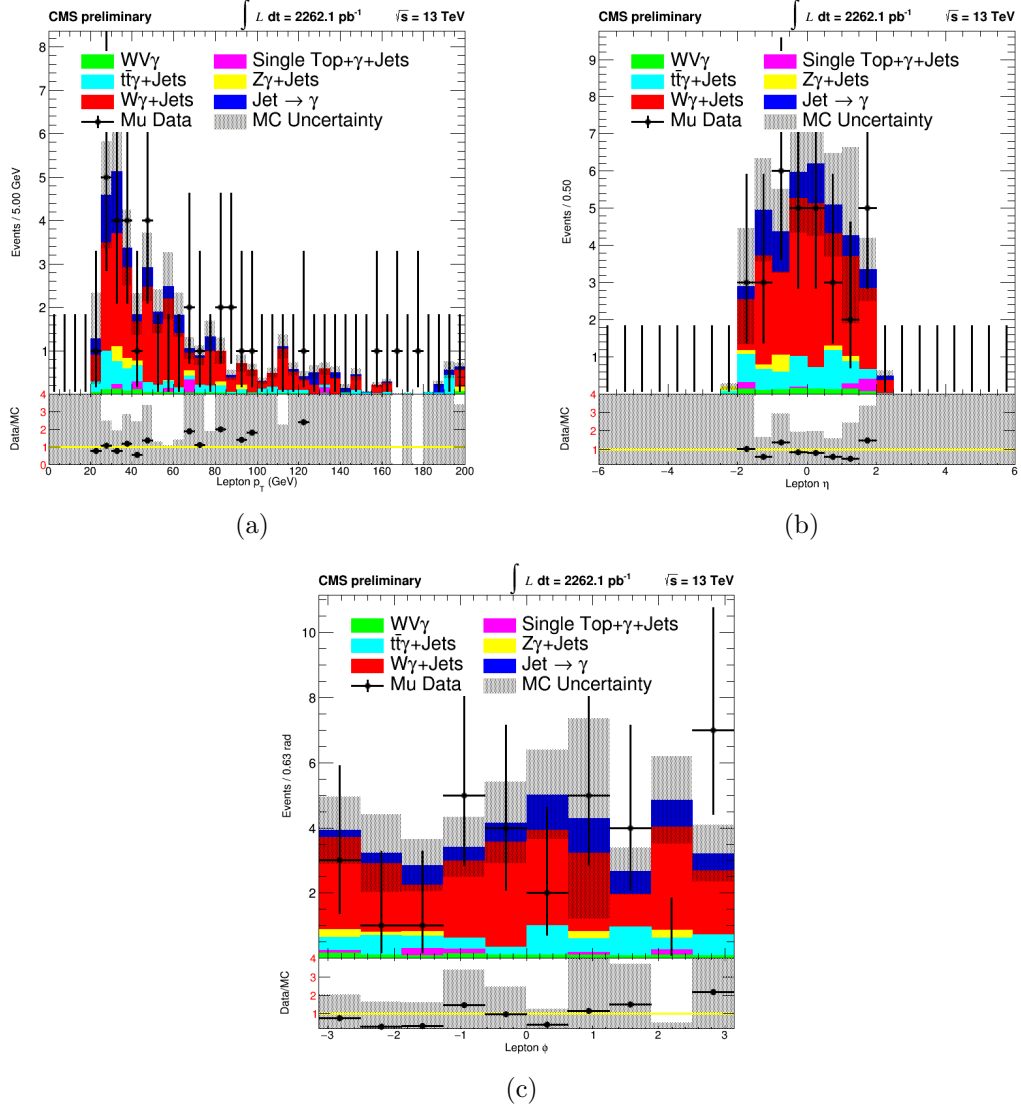
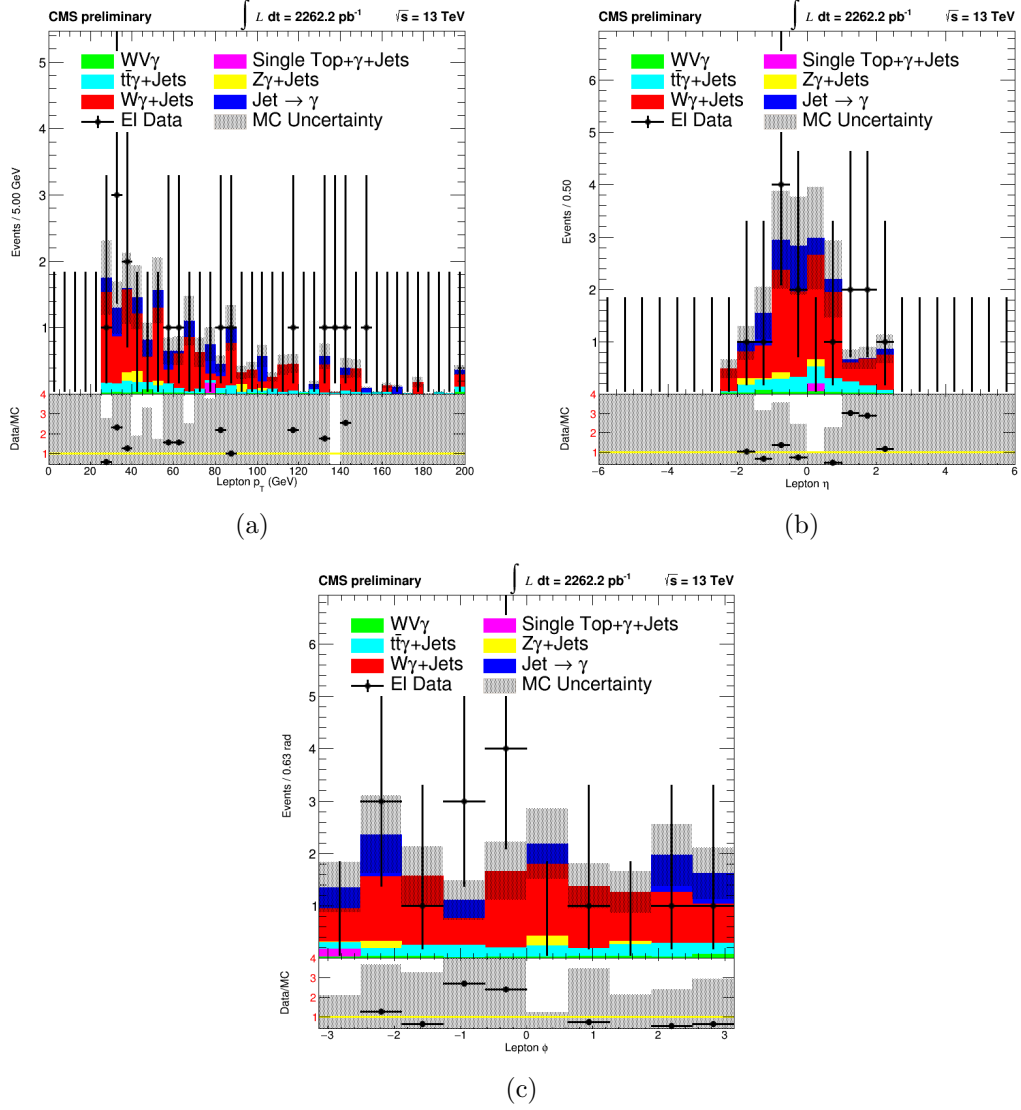


Figure 5.58: Data and MC comparison plots for muon p_T (a), η (b), ϕ (c).


 Figure 5.59: Data and MC comparison plots for electron p_T (a), η (b), ϕ (c).

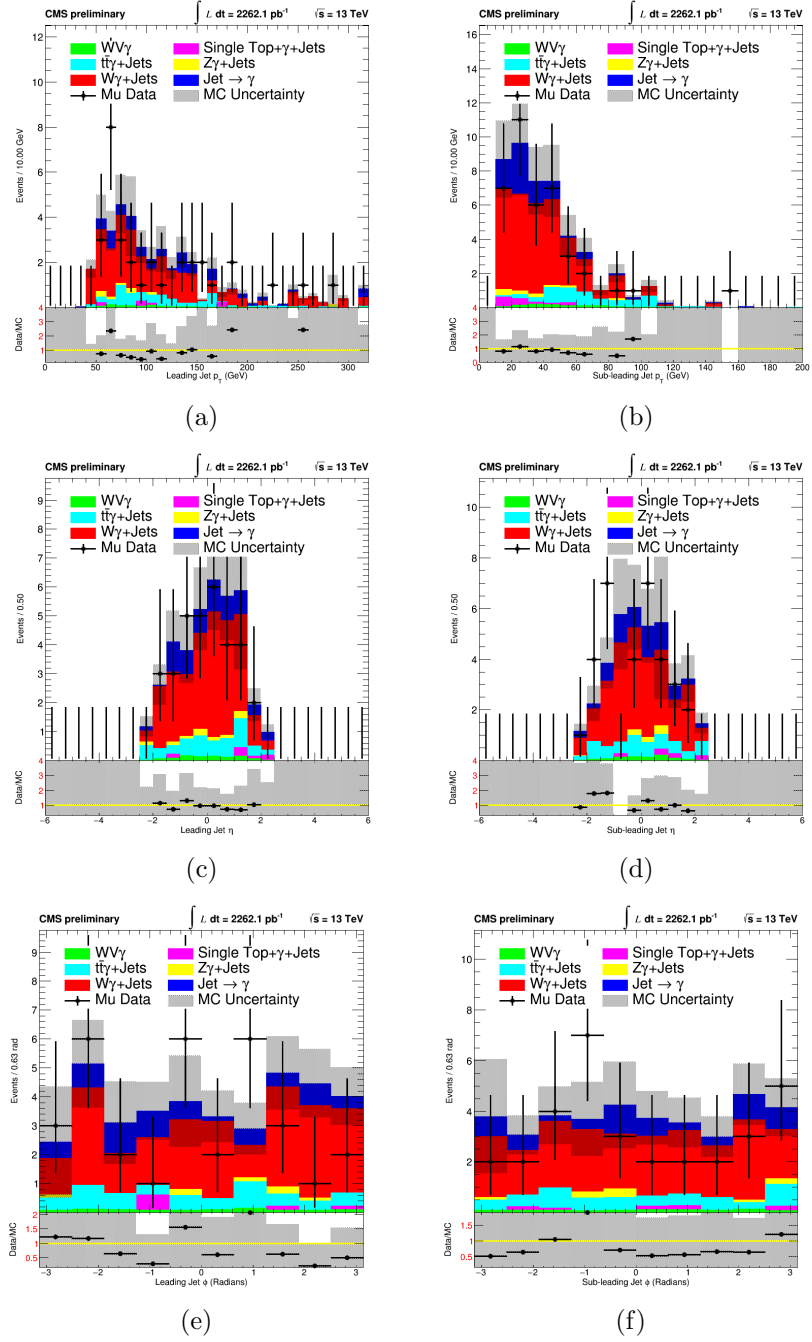


Figure 5.60: Data and MC comparison plots for muon channel leading jet p_T (a), η (c), ϕ (e), and second jet p_T (b), η (d), ϕ (f).

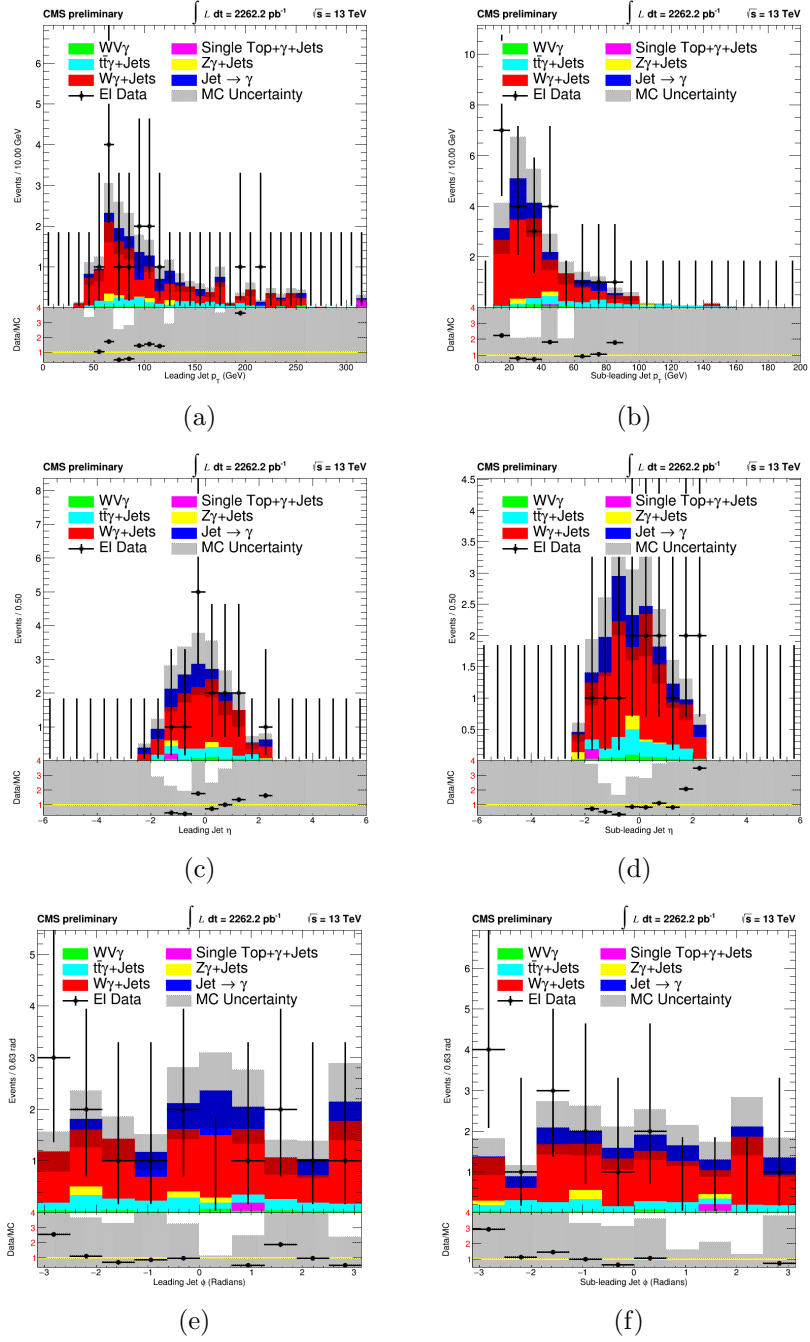


Figure 5.61: Data and MC comparison plots for electron channel leading jet p_T (a), η (c), ϕ (e), and second jet p_T (b), η (d), ϕ (f).

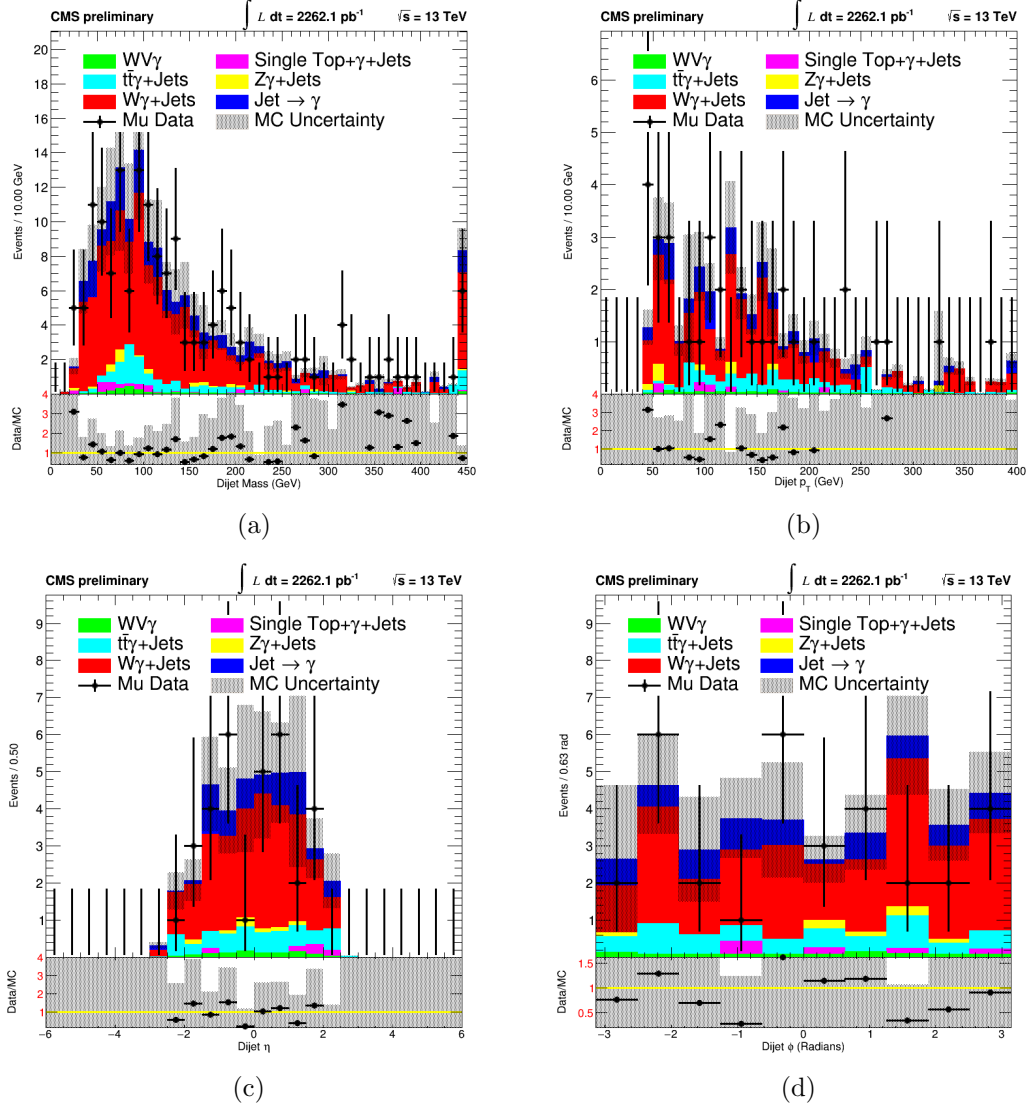


Figure 5.62: Data and MC comparison plots for muon channel dijet mass (a), p_T (b), η (c), ϕ (d).

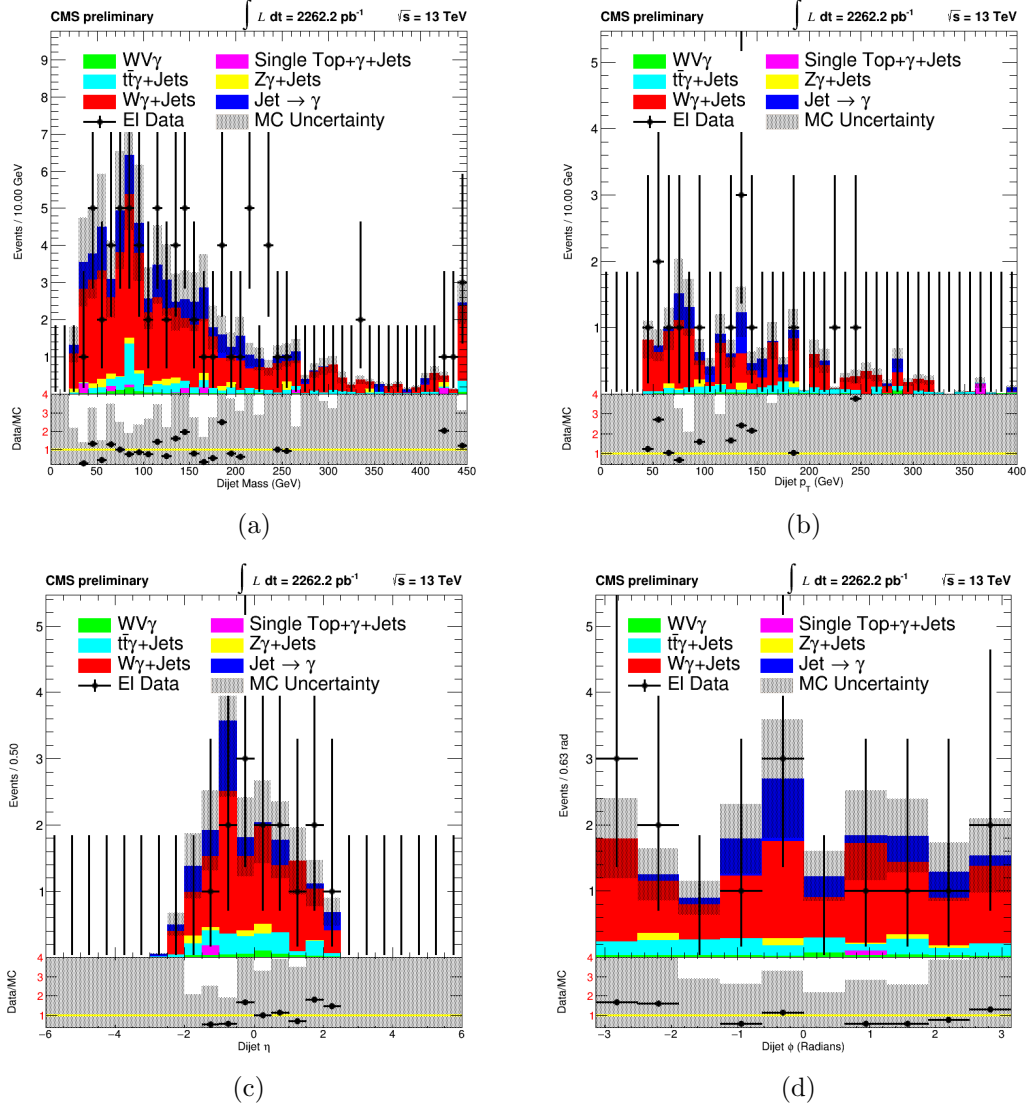


Figure 5.63: Data and MC comparison plots for electron channel dijet mass (a), p_T (b), η (c), ϕ (d).

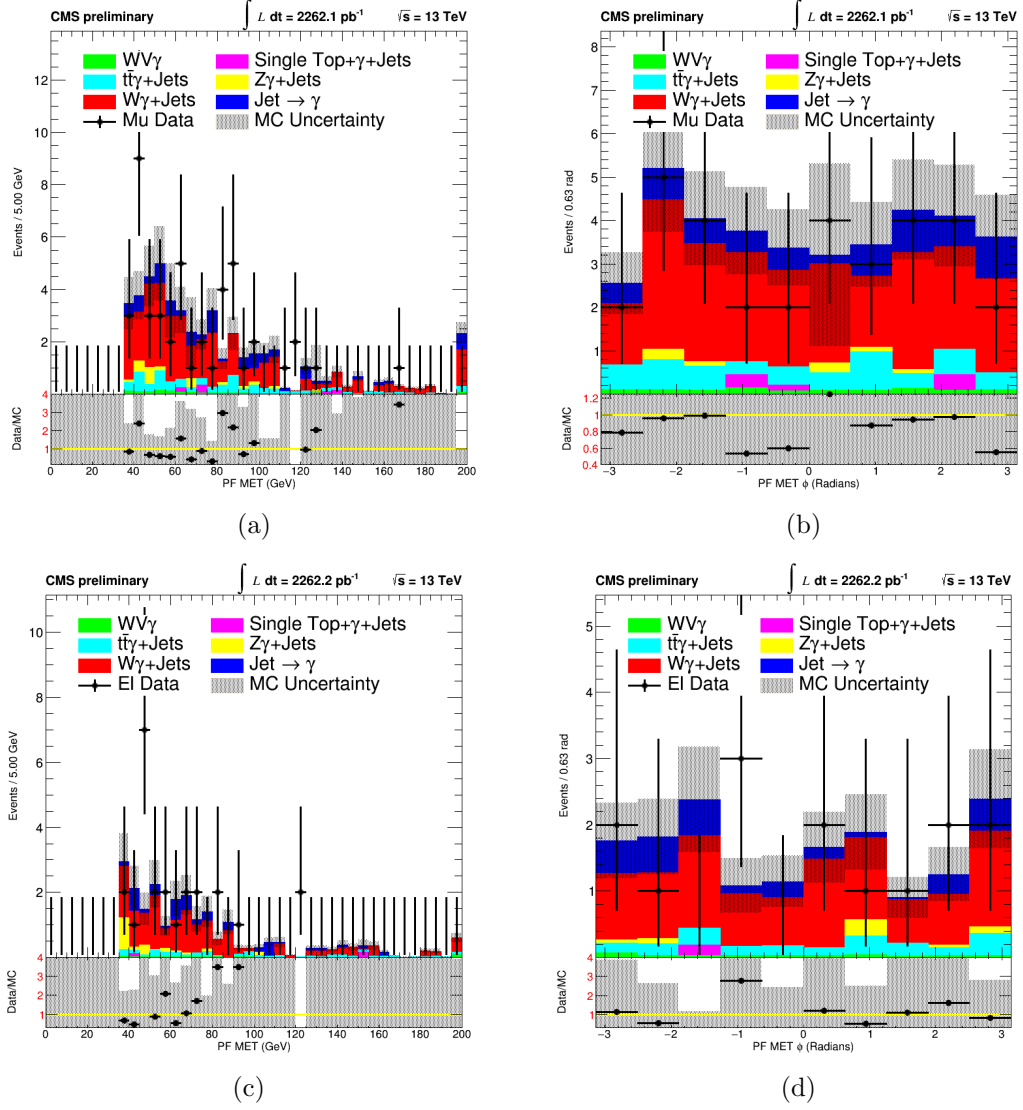


Figure 5.64: Data and MC comparison plots for muon channel MET (a) MET(ϕ) (b); electron channel MET (c) MET(ϕ) (d).

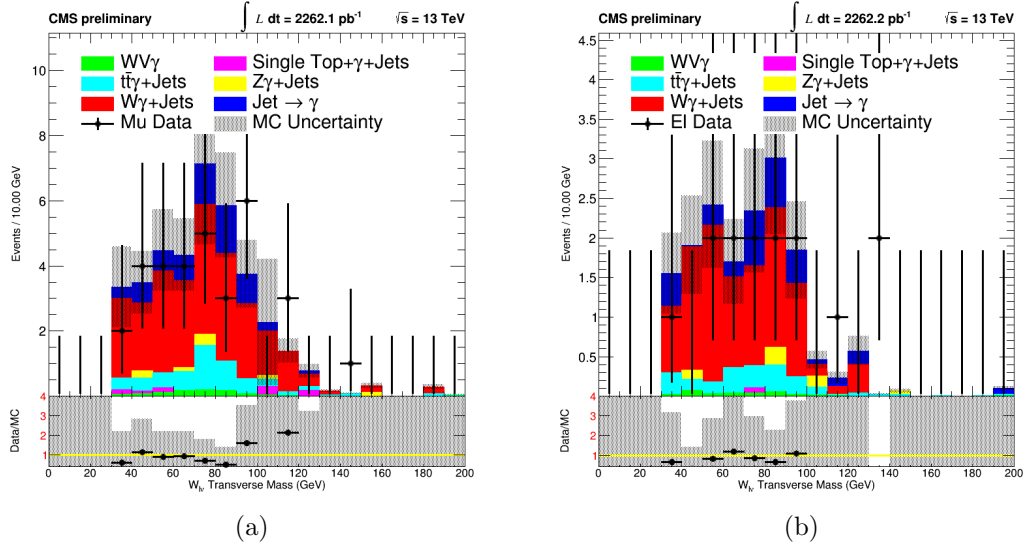


Figure 5.65: Data and MC comparison plots for muon channel $M_T(l\nu)$ (a) and electron channel $M_T(l\nu)$ (b)

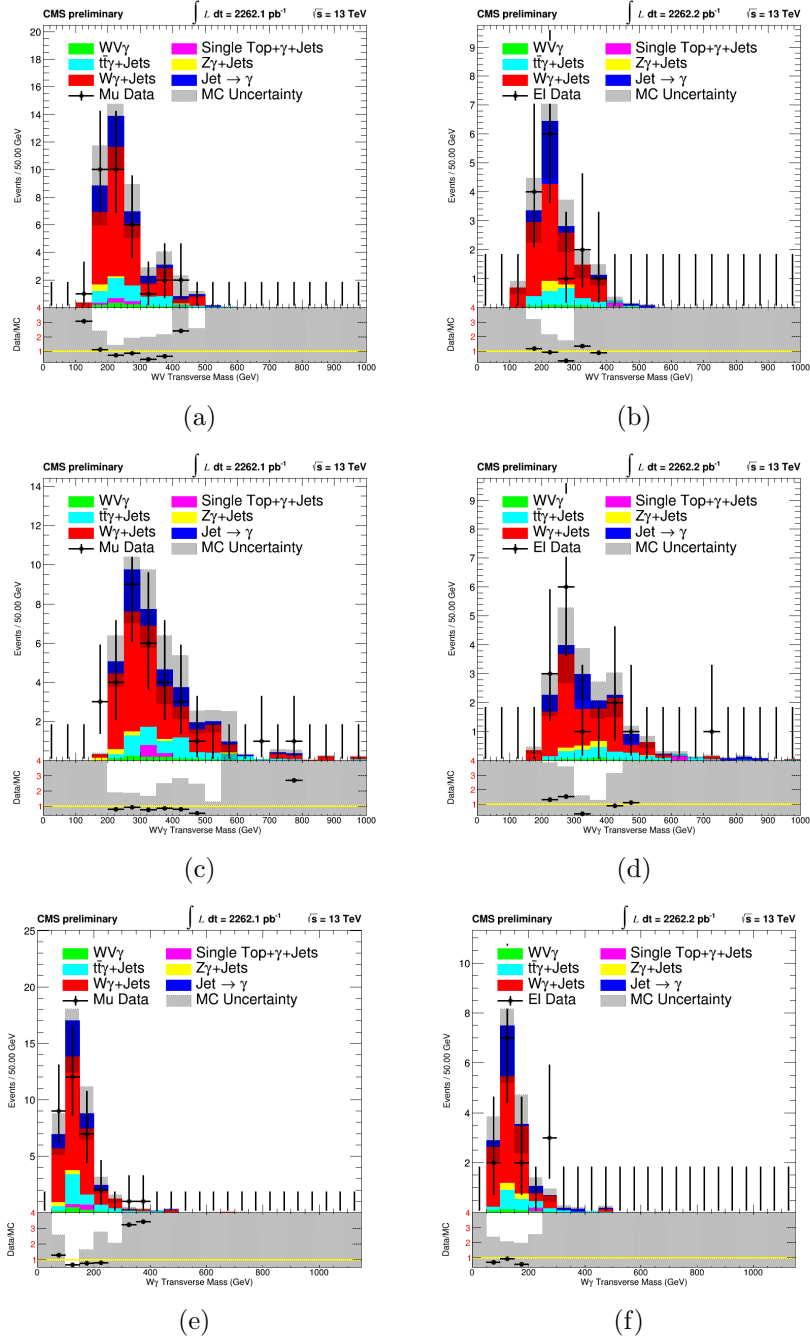


Figure 5.66: Data and MC comparison for mu. ch. $M_T(l\nu jj)$ (a), $M_T(l\nu jj\gamma)$ (c), $M_T(l\nu\gamma)$ (e); el. ch. $M_T(l\nu jj)$ (b), $M_T(l\nu jj\gamma)$ (d), $M_T(l\nu\gamma)$ (f)

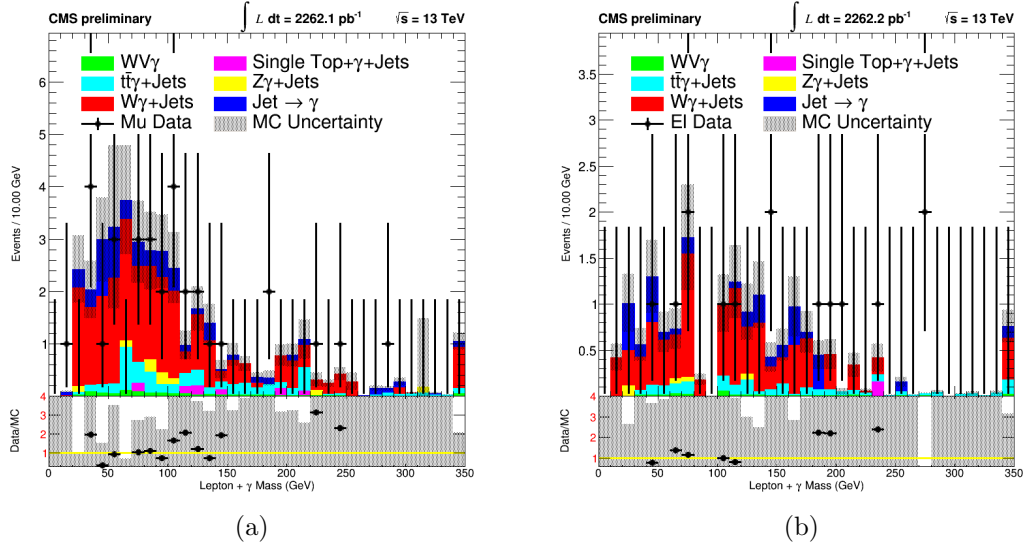


Figure 5.67: Data and MC comparison plots for muon channel $M_{l\gamma}$ (a) and electron channel $M_{l\gamma}$ (b).

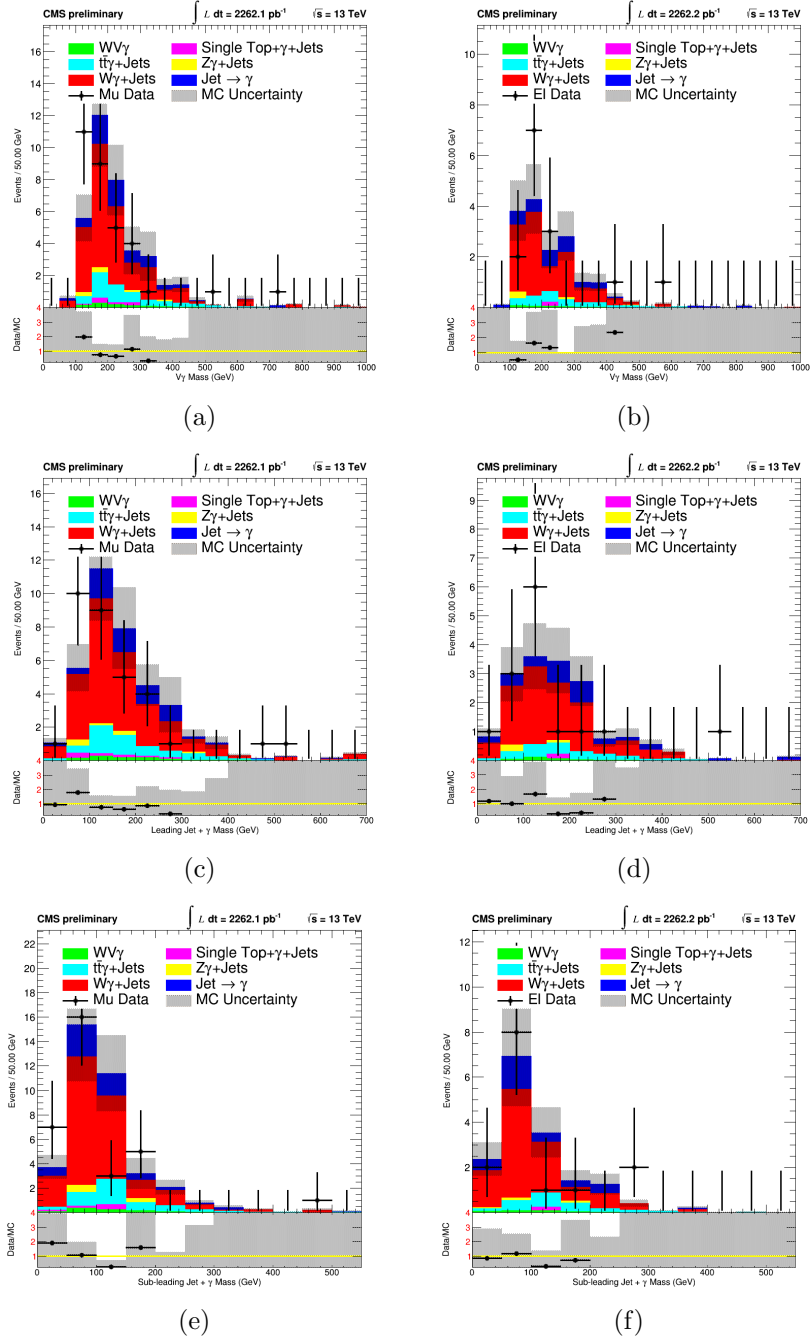


Figure 5.68: Data and MC comparison plots for muon channel $M_{jj\gamma}$ (a), $M_{j1\gamma}$ (c), $M_{j2\gamma}$ (e); electron channel $M_{jj\gamma}$ (b), $M_{j1\gamma}$ (d), $M_{j2\gamma}$ (f).

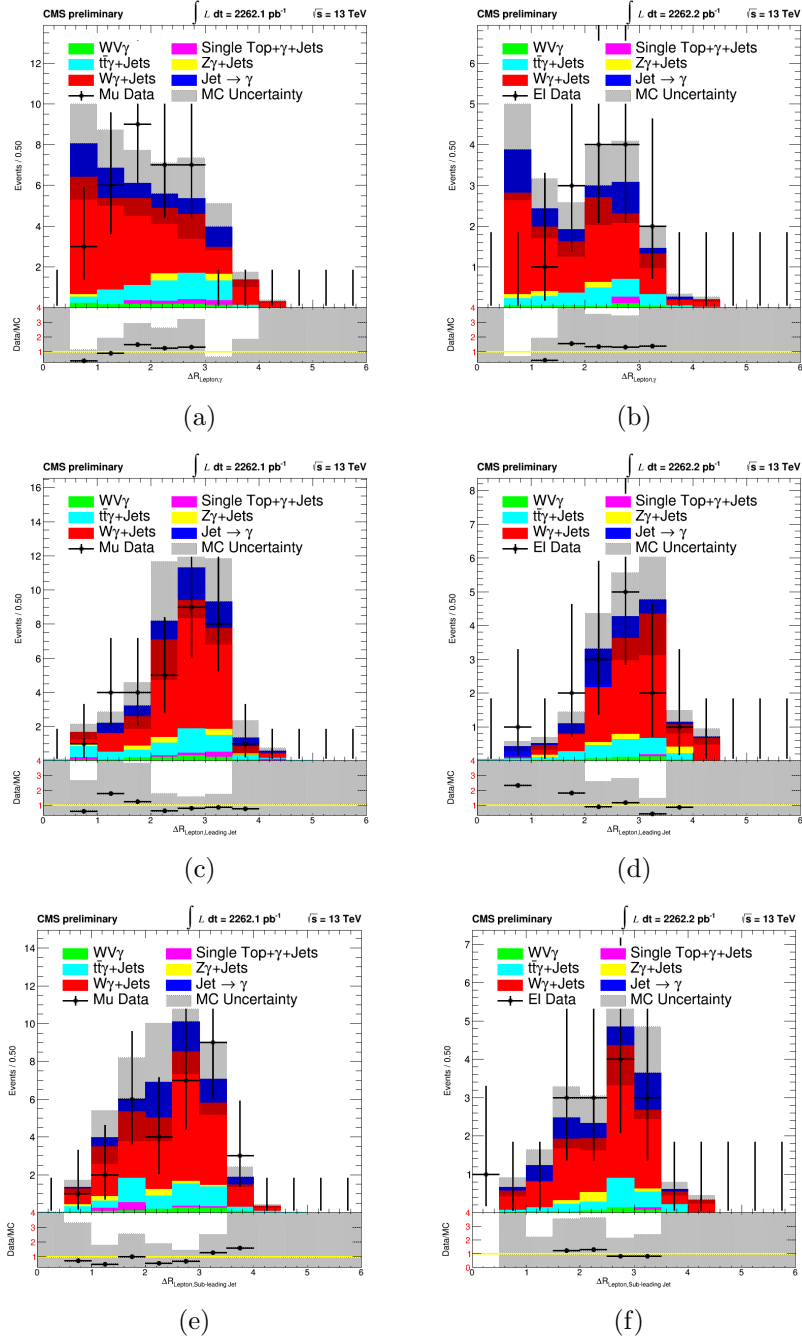


Figure 5.69: Data and MC comparison plots for mu. ch. $\Delta R(l, \gamma)$ (a), $\Delta R(l, j_1)$ (c), $\Delta R(l, j_2)$ (e); el. ch. $\Delta R(l, \gamma)$ (b), $\Delta R(l, j_1)$ (d), $\Delta R(l, j_2)$ (f).

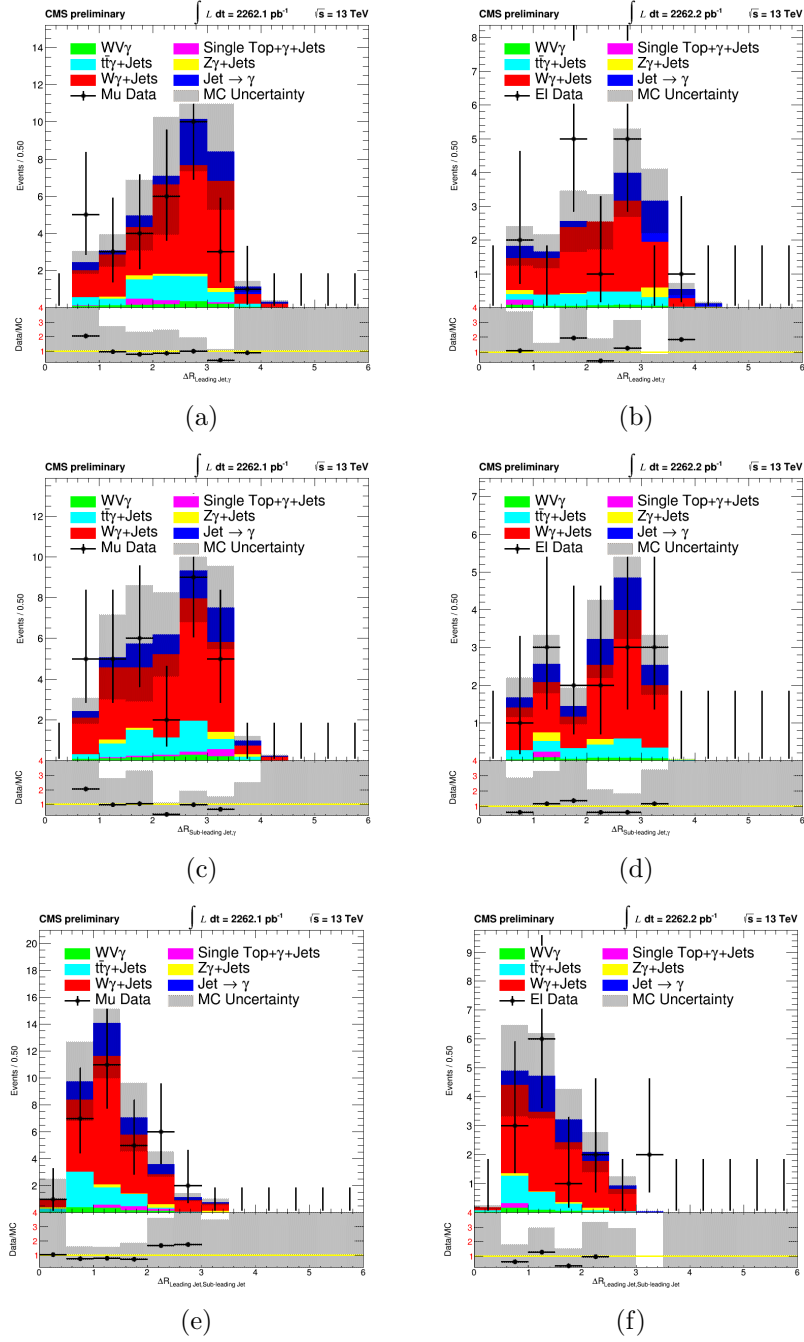


Figure 5.70: Data and MC comparison for mu. channel $\Delta R(j_1, \gamma)$ (a), $\Delta R(j_2, \gamma)$ (c), ΔR_{jj} (e); el. channel $\Delta R(j_1, \gamma)$ (b), $\Delta R(j_2, \gamma)$ (d), ΔR_{jj} (f)

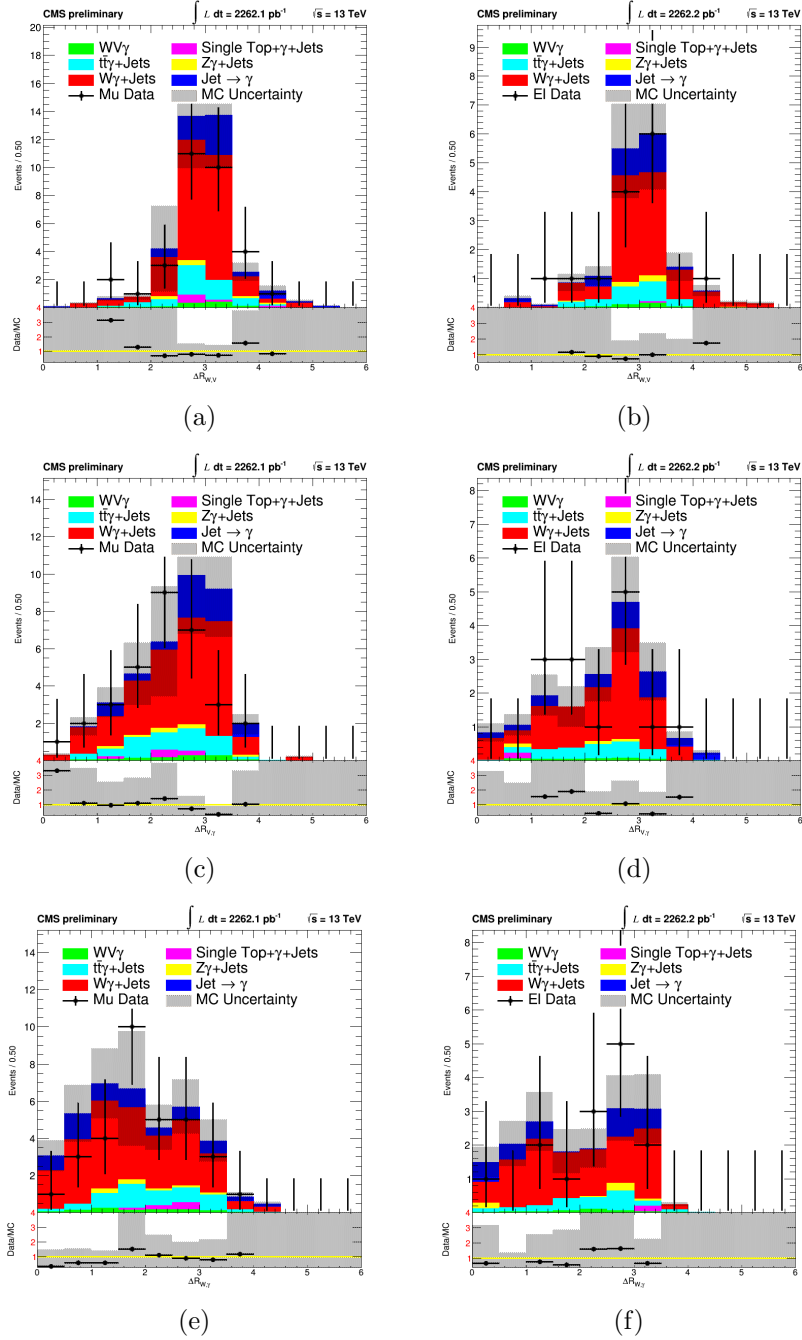


Figure 5.71: Data and MC comparison for mu. channel $\Delta R(W, V)$ (a), $\Delta R(V, \gamma)$ (c), $\Delta R_{W, \gamma}$ (e); el. channel $\Delta R(W, V)$ (b), $\Delta R(V, \gamma)$ (d), $\Delta R_{W, \gamma}$ (f)

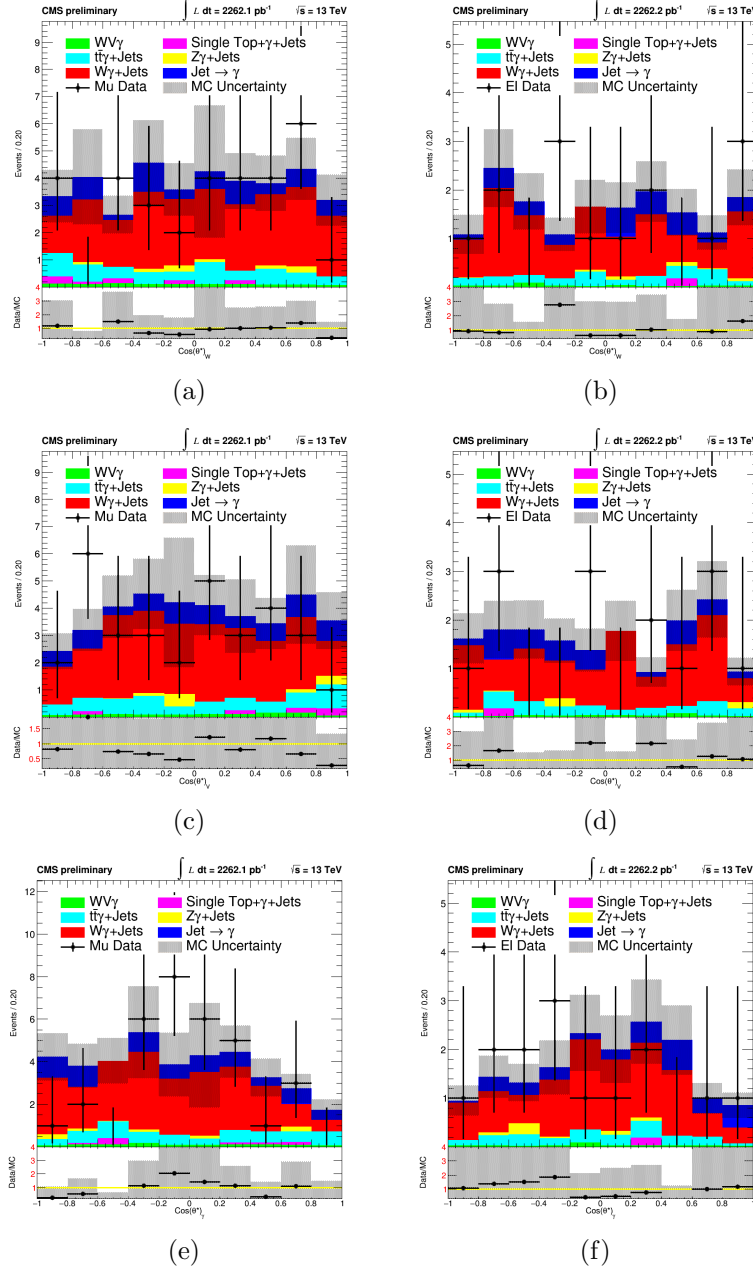


Figure 5.72: Data and MC comparison for mu. channel $\cos(\theta^*)_W$ (a), $\cos(\theta^*)_V$ (c), $\cos(\theta^*)_\gamma$ (e); el. channel $\cos(\theta^*)_W$ (b), $\cos(\theta^*)_V$ (d), $\cos(\theta^*)_\gamma$ (f). θ^* is the angle between the proton's momentum vector and the boson's momentum vector.

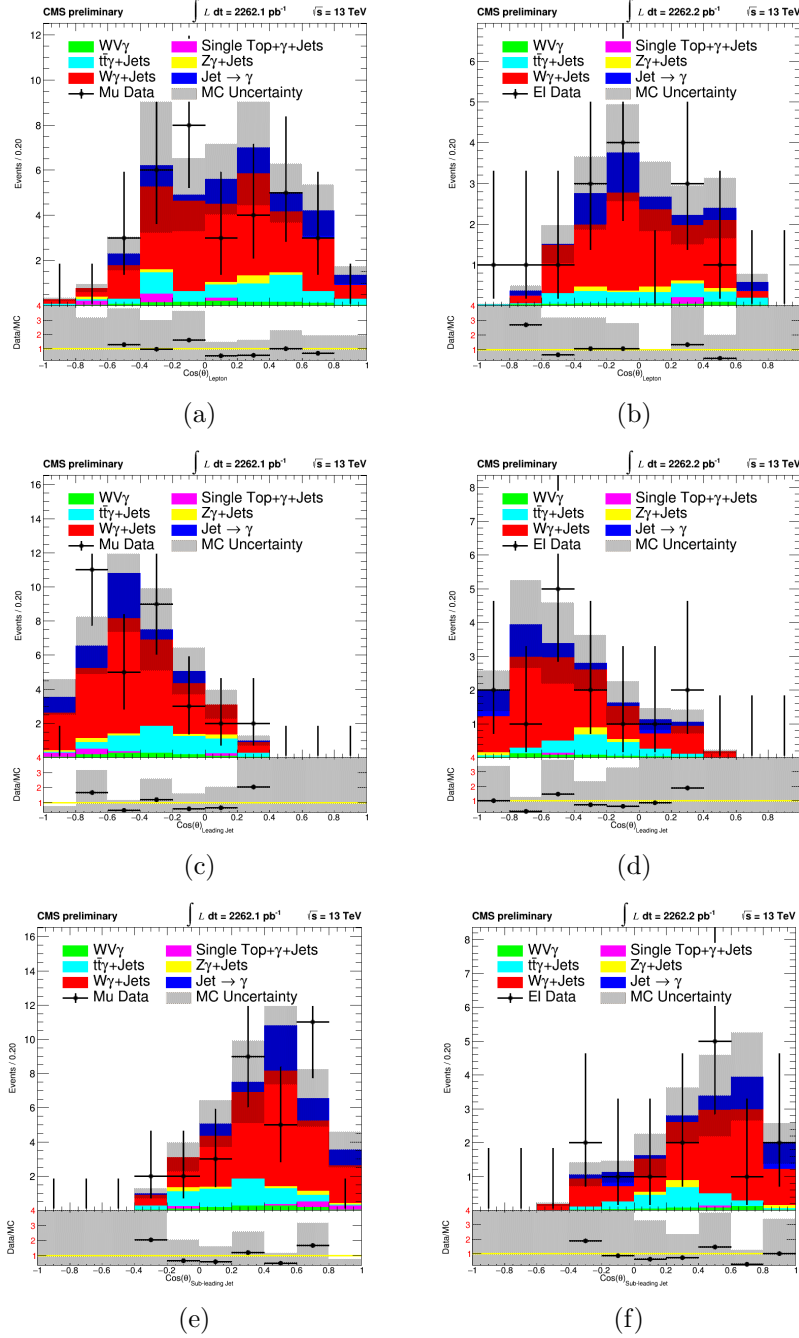


Figure 5.73: Data and MC comparison for mu. channel $\text{Cos}(\theta_1)_l$ (a), $\text{Cos}(\theta_1)_{j_1}$ (c), $\text{Cos}(\theta_1)_{j_2}$ (e); el. channel $\text{Cos}(\theta_1)_l$ (b), $\text{Cos}(\theta_1)_{j_1}$ (d), $\text{Cos}(\theta_1)_{j_2}$ (f). θ_1 is the angle between the boson's momentum vector and the daughter's momentum vector.

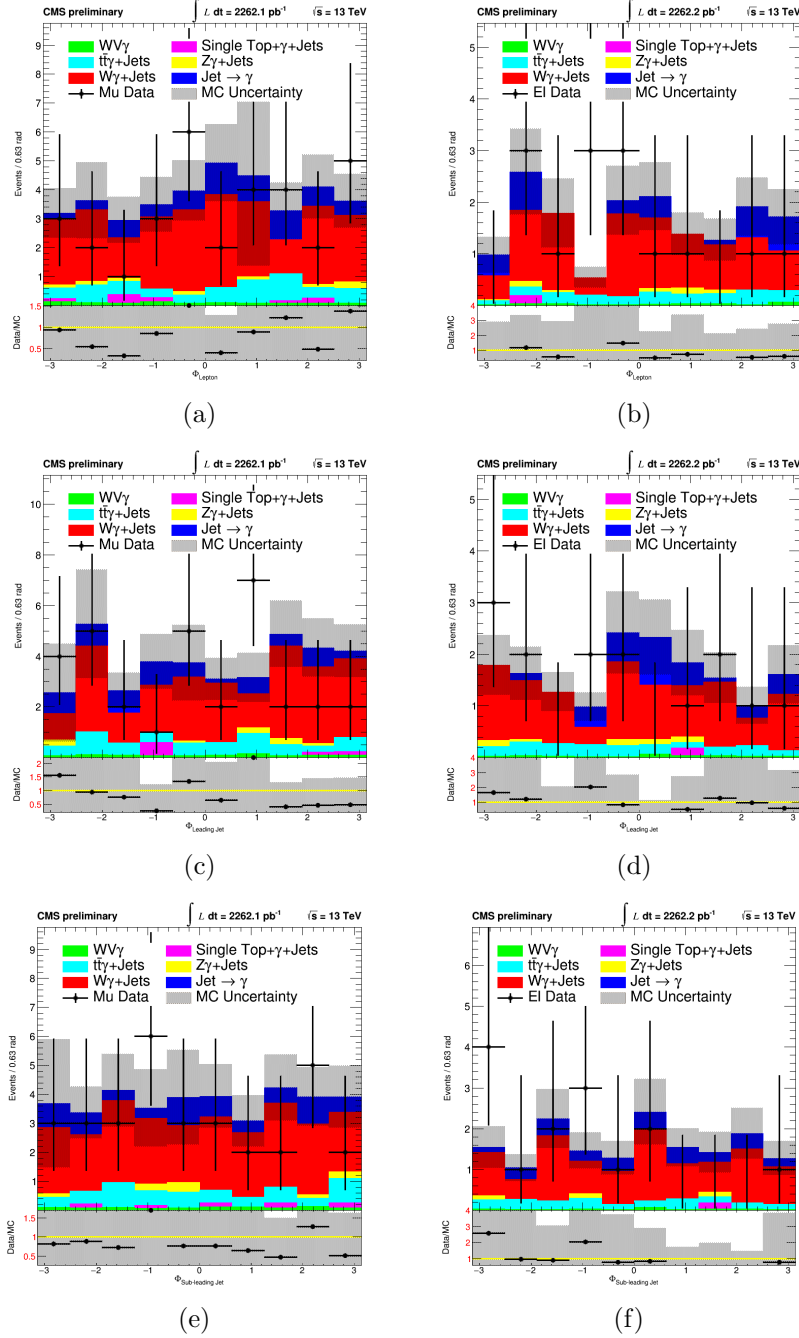


Figure 5.74: Data and MC comparison plots for muon channel Φ_l (a), Φ_{j_1} (c), Φ_{j_2} (e); electron channel Φ_l (b), Φ_{j_1} (d), Φ_{j_2} (f). Φ is the angle between the proton's momentum vector and the daughter's momentum vector.

Table 5.24: Expected number of events per process with statistical, systematic, and luminosity uncertainties quoted respectively.

Process	muon channel number of events	electron channel number of events
WV γ	$1.1 \pm 0.2 \pm 0.1 \pm 0.0$	$0.4 \pm 0.1 \pm 0.0 \pm 0.0$
W γ +Jets	$23.4 \pm 3.1 \pm 6.7 \pm 0.0$	$10.4 \pm 1.8 \pm 4.1 \pm 0.0$
Z γ +Jets	$0.9 \pm 0.2 \pm 0.2 \pm 0.0$	$0.4 \pm 0.1 \pm 0.1 \pm 0.0$
$t\bar{t}\gamma$ +Jets	$5.2 \pm 0.1 \pm 1.5 \pm 0.1$	$2.0 \pm 0.1 \pm 0.6 \pm 0.1$
Single Top + γ + Jets	$0.8 \pm 0.1 \pm 0.2 \pm 0.0$	$0.2 \pm 0.0 \pm 0.1 \pm 0.0$
jet $\rightarrow \gamma$	$6.4 \pm 0.1 \pm 2.1 \pm 0.0$	$3.1 \pm 0.1 \pm 1.0 \pm 0.0$
Total predicted	$37.8 \pm 3.8 \pm 10.8 \pm 0.1$	$16.5 \pm 2.2 \pm 5.9 \pm 0.1$
Data	32	14

5.2.8 Limit on the Cross Section

This SM cross sectional measurement's uncertainties are large due to the low signal statistics, the uncertainties in the K-factors used, and the fake photon rate's systematic uncertainty of 13-38%; therefore, we cannot claim an observation of WV γ events.

We use the *Combine* tool developed by the Higgs group for combining limits between ATLAS and CMS and set 95% CL upper bounds on the SM cross section [84]. An upper limit on the SM WV γ combined cross section is obtained through a profile likelihood asymptotic approximation method [82, 83]. We are able to combine the results from this analysis with those obtained in Run I to set an upper limit. The data cards from Run I were kept, and similar to how the lepton channels are combined to set a single analysis upper limit, the two analysis' data cards are combined to set the combined 8 TeV and 13 TeV limit.

The SM WV γ signal strength was 3.4 times the SM prediction in Run I, while it becomes 10.0 times the SM prediction in this analysis. Table 5.25 shows the observed and expected limits with the 1- σ and 2- σ bands for both analyses, and finally the combined result. A signal strength below 1 suggests we are sensitive to the signal and can measure the cross section; however, we are well above a value of 1 and are therefore not sensitive to the SM signal.

Table 5.25: 95% CL upper cross section limits on the SM $WV\gamma$ processes, including the $1\text{-}\sigma$ and $2\text{-}\sigma$ bands.

Signal Strength (times SM prediction)	Run I	Run II	Combined
Expected	4.4	13.9	4.3
Observed	3.4	10.0	3.3
$1\text{-}\sigma$ Band	[3.1,6.6]	[9.6,21.3]	[3.0,6.5]
$2\text{-}\sigma$ Band	[2.3,9.8]	[7.0,32.3]	[2.2,9.5]

5.2.9 Limits on Anomalous Quartic Gauge Couplings

5.2.9.1 Parametrizations

In order to set limits on anomalous couplings, we compare the observed signal data's kinematics to those of anomalous signal MC. This process can involve generating many different MC samples for various values of each anomalous quartic coupling parameter, or we could quantify how anomalous couplings affect certain observable kinematic distributions such as photon p_T .

In order to quantify the affect each coupling parameter has on a kinematic distribution, say photon p_T , we still generate a few MC working points within the aMC@NLO reweighing framework for each anomalous coupling parameter, where the parameter of interest is varied to multiple values and all other coupling parameters are set to their SM value. For example, we have 14 quartic coupling parameters $\frac{f_{M,0-7}}{\Lambda^4}$, $\frac{f_{T,0-2}}{\Lambda^4}$, and $\frac{f_{T,5-7}}{\Lambda^4}$. In order to parametrize the affect the parameter $\frac{f_{M,0}}{\Lambda^4}$ has on photon p_T , we vary this parameter's values while fixing $\frac{f_{M,1-7}}{\Lambda^4}$, $\frac{f_{T,0-2}}{\Lambda^4}$, and $\frac{f_{T,5-7}}{\Lambda^4}$ to their SM values of zero.

In addition to the SM central weight of the aMC@NLO sample, we generate 16 AQGC variations in each parameter, 8 in the positive phase space ($5 \times 10^{10}, 1 \times 10^{10}, 5 \times 10^{11}, 1 \times 10^{11}, 5 \times 10^{12}, 1 \times 10^{12}, 5 \times 10^{13}, 1 \times 10^{13}[\text{GeV}^{-4}]$) and 8 in the negative phase space of the parameter ($-5 \times 10^{10}, -1 \times 10^{10}, -5 \times 10^{11}, -1 \times 10^{11}, -5 \times 10^{12}, -1 \times 10^{12}, -5 \times 10^{13}, -1 \times 10^{13}[\text{GeV}^{-4}]$). Then, after applying event selection cuts described in Section 5.2.2, efficiency and PU weights, and the photon p_T -dependent K-factor described in Section 5.2.5, each AQGC working point's photon p_T distribution is divided by the SM photon p_T distribution to form a AQGC/SM ratio for each photon p_T bin. A quadratic distribution is formed by plotting each AQGC/SM ratio value for

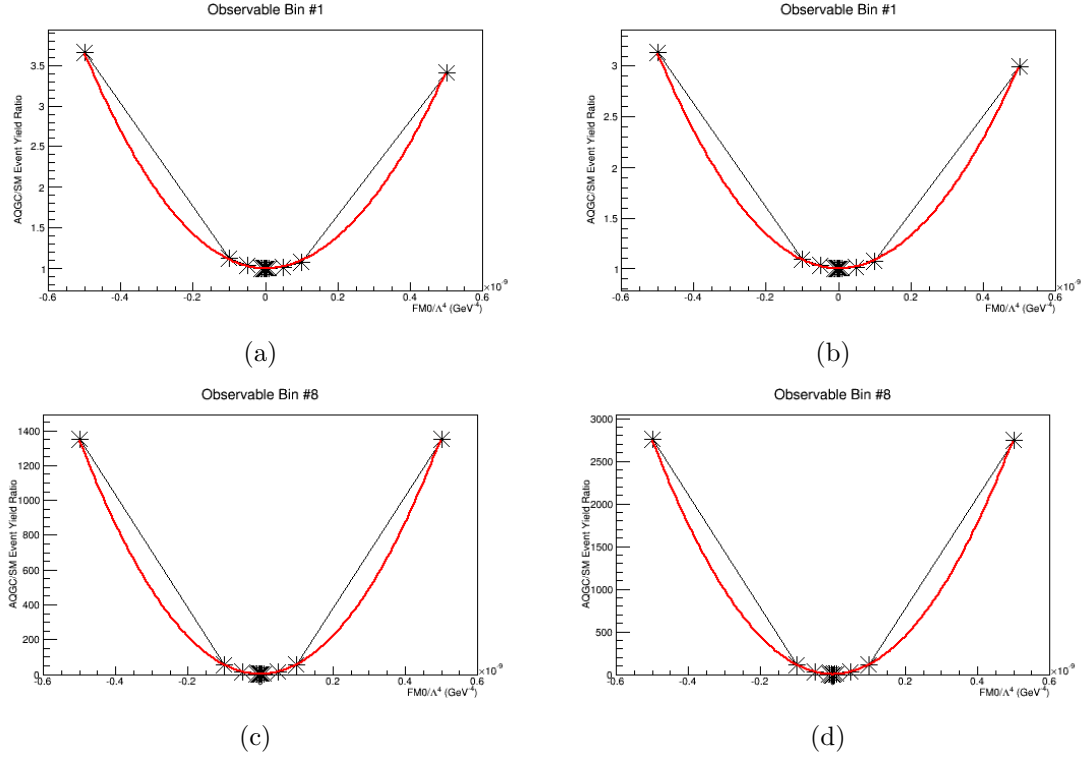


Figure 5.75: AQGC/SM ratio values for each $f_{M,0}/\Lambda^4$ MC working point within each of the following photon p_T bins: 90-140 GeV for muon channel (a) and electron channel (b); > 440 GeV (overflow bin) for muon channel (c) and electron channel (d).

a specific photon p_T bin, as can be seen in Figure 5.75 for $\frac{f_{M,0}}{\Lambda^4}$ in the muon channel.

We fit this distribution with a quadratic function that can later be used to predict the AQGC/SM ratio value for any arbitrary anomalous coupling value for that specific coupling parameter and photon p_T bin. It can even be seen in Figure 5.75 that the overflow photon p_T bin has a quadratic behavior in AQGC and thus can be parametrized. In this analysis, we bin photon p_T with 8 bins from 90-490 GeV, where the overflow bin contains all events with $p_T > 440$ GeV.

To estimate the uncertainty from the parametrization, in order to provide it with the shifted negative log likelihood (ΔNLL) limits, we first derive the AQGC limits without any statistical or systematic uncertainties included from the analysis. We take the value of the AQGC parameter at 95% CL and plug it into the parametriza-

tion fit function to derive a new AQGC photon p_T distribution. We likewise plug this AQGC limit value into the parametrization fit function, but with the fit parameters altered by their uncertainties. We compare the integral difference between the AQGC distributions in photon p_T , the numerator being the distribution from the parametrization altered by its fit parameters' uncertainties, and the denominator being from the distribution from the parametrization unaltered. In all 14 AQGC parameters' cases, the integral difference between the two cases is less than 1%; therefore, we apply an additional flat uncertainty of 1% to the signal in the ΔNLL limit machinery to represent this uncertainty.

5.2.9.2 Limits using Photon p_T

We use the photon p_T distribution as the observable to limit anomalous couplings. We use the *Combine* package [84] for setting exclusion limits. This package is a RooStats[85]-based statistical analysis tool-set recommended by the CMS Higgs PAG and approved by the CMS statistics committee.

All distributions are segregated by lepton flavor, which represent independent channel inputs to the limit setter. We supply these distributions over the range 90-490 GeV in the form of histograms to the limit setter. The binning is chosen such that the left-most bin begins at the first MC point available from the AQGC samples, and the right-most bin begins just beyond the last 2015 data point seen, in this case, in the muon channel around 350 GeV. We extend the right-most bin to be an overflow bin, and since it begins just beyond the reach of 2015 data in our events, it represents physics beyond our sensitivity. Figure 5.76 shows the input distributions between the muon and electron channels for the SM processes and observed data.

The uncertainties, both statistical and systematic, from the analysis (listed in Table 5.23 and Table 5.24), are accounted for in the limit machinery via flat uncertainties or shape up and down fluctuations for each process. The limit setter is then set to formulate ΔNLL limits, or $-2 \cdot \ln(\lambda)$ shifted from the best fit point, where λ is the ratio of profile likelihoods in the asymptotic regime, as discussed in Appendix B and Ref. [82, 83, 95, 96]. Two-dimensional histograms are provided as input: photon p_T along one axis, and AQGC value along the other, which creates bins filled by the AQGC/SM yield ratio. An Asimov data set is created from this input and a ΔNLL

value relative to the best fit point is determined. The 95% CL limits are extracted for $\Delta\text{NLL} < 3.84$. Figures 5.105-5.107 are the resulting shape-based observed exclusion limits, and Figures 5.77-5.104 demonstrate where the corresponding AQGC kinematic distributions lie with respect to the SM $WV\gamma$ process. Observed and expected exclusion limits for $f_{M,0-7}/\Lambda^4$, $f_{T,0-2}/\Lambda^4$, and $f_{T,5-7}/\Lambda^4$ are computed at the 95% CL and are listed in Table 5.26.

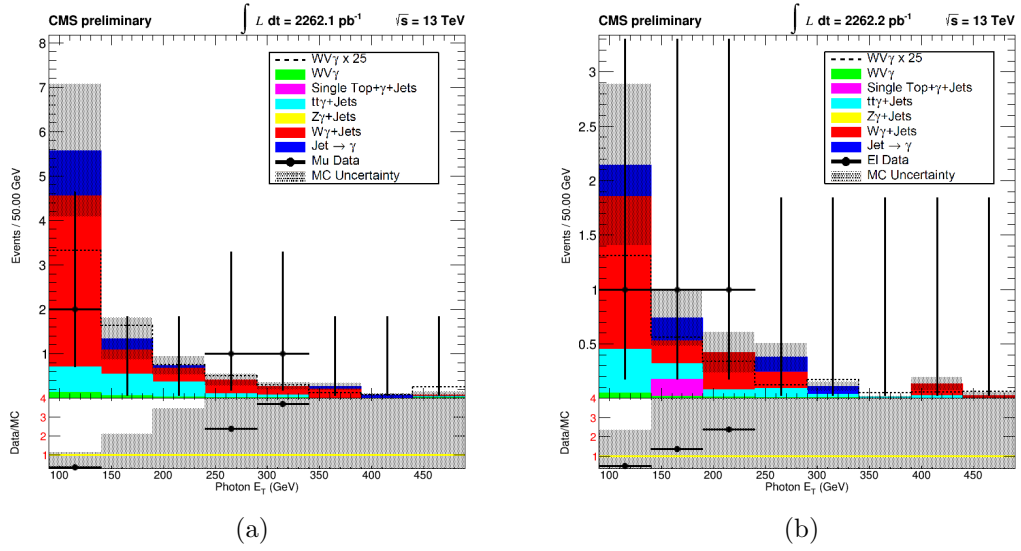


Figure 5.76: Photon p_T distribution for SM processes in the muon (a) and electron (b) channel. The SM $WV\gamma$ process has also been enlarged to show its shape in each channel.

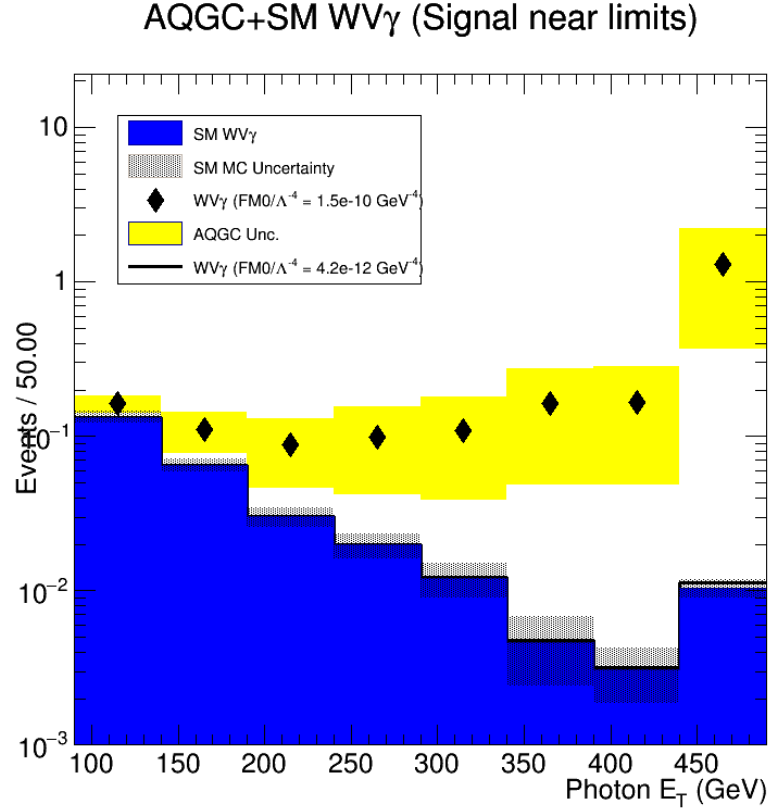


Figure 5.77: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,0}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

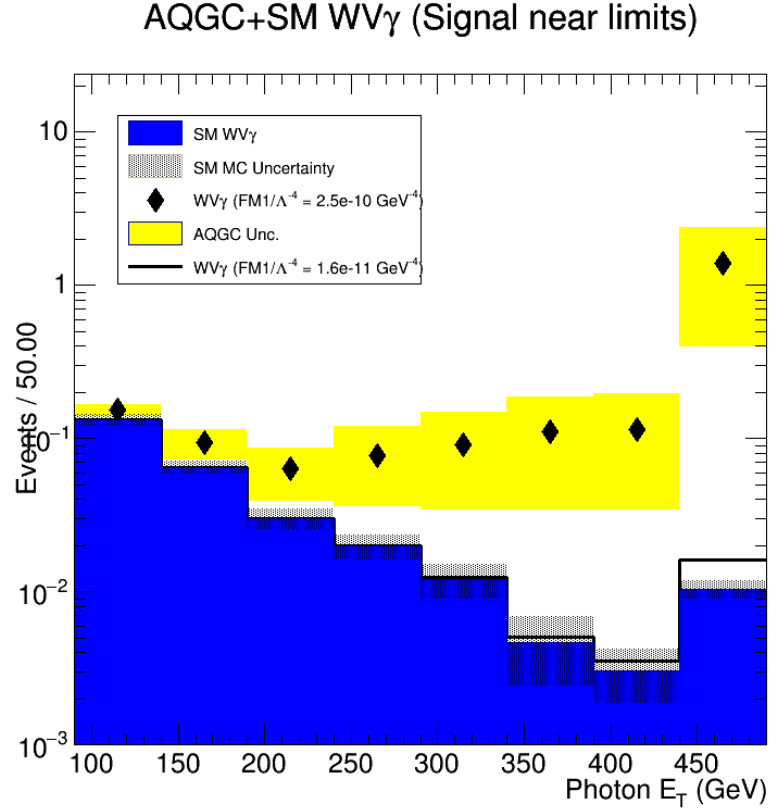


Figure 5.78: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,1}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

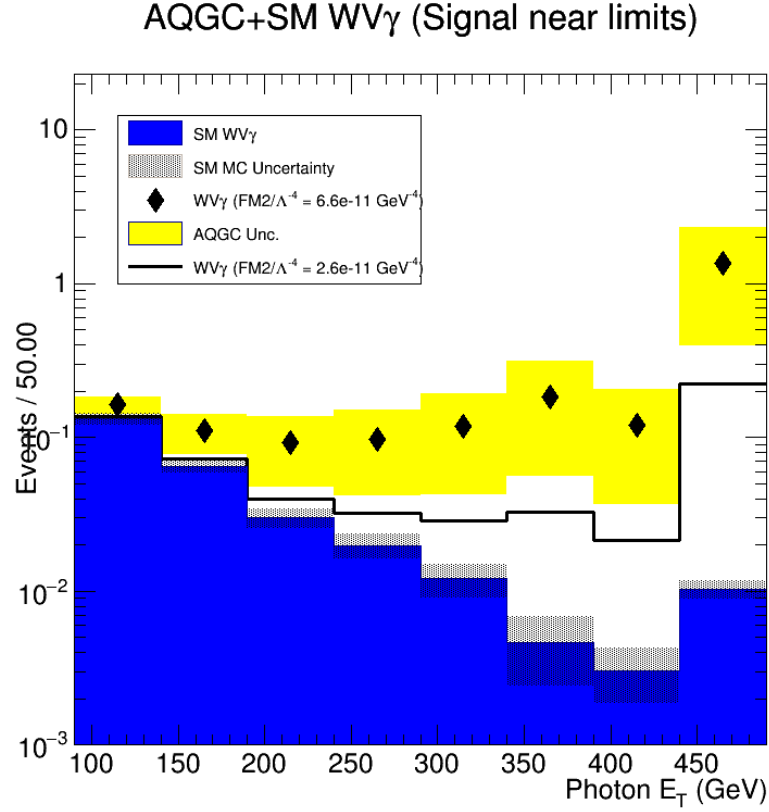


Figure 5.79: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL Δ NLL limits are observed for $f_{M,2}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

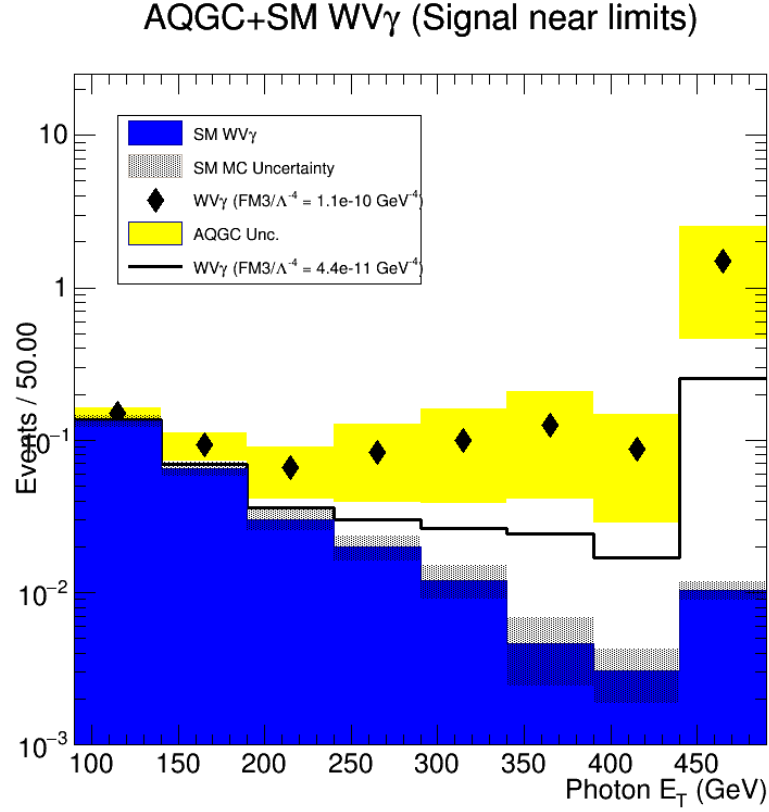


Figure 5.80: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,3}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

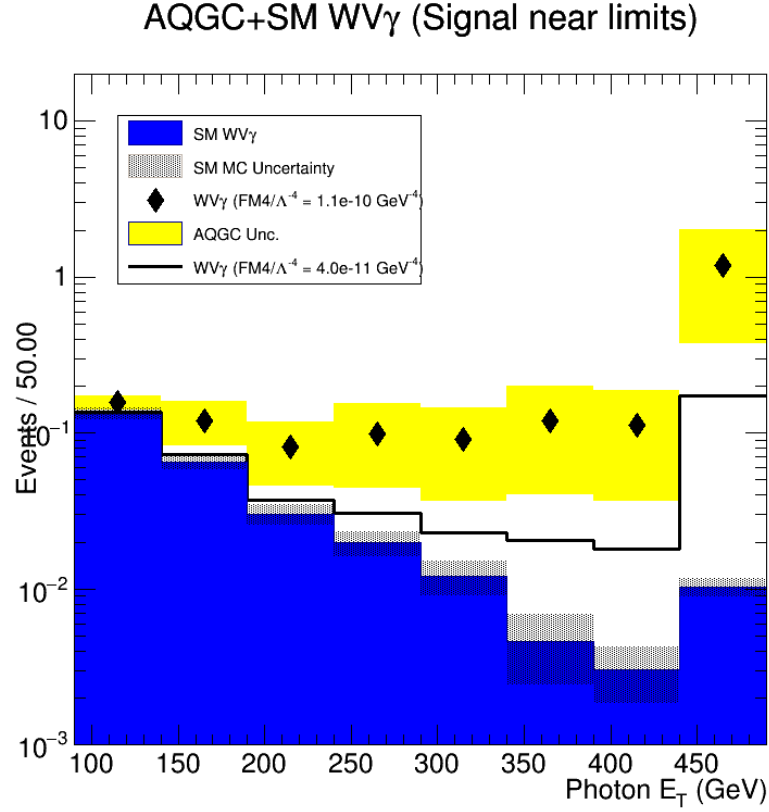


Figure 5.81: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,4}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

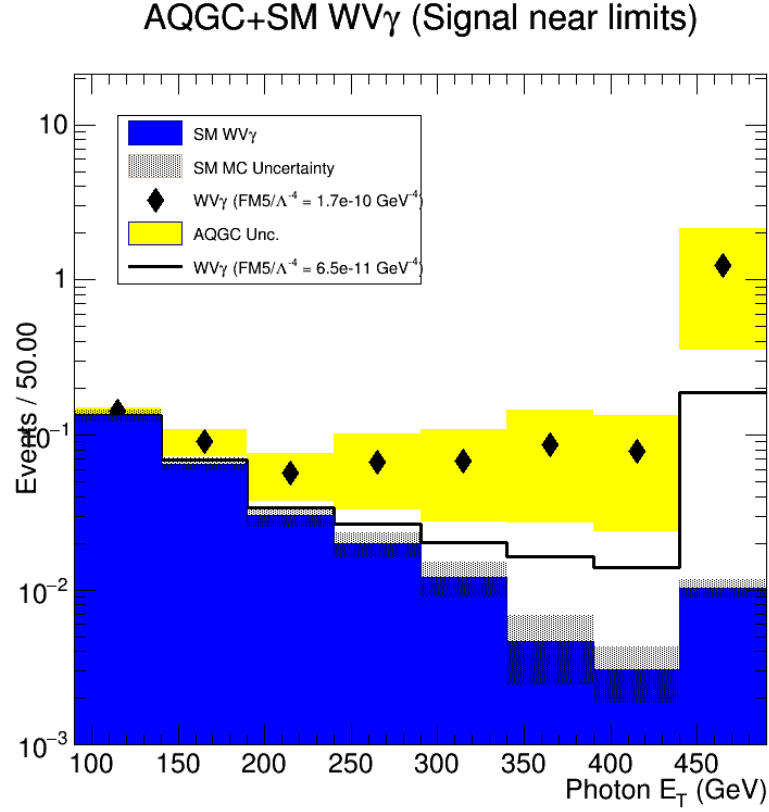


Figure 5.82: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,5}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

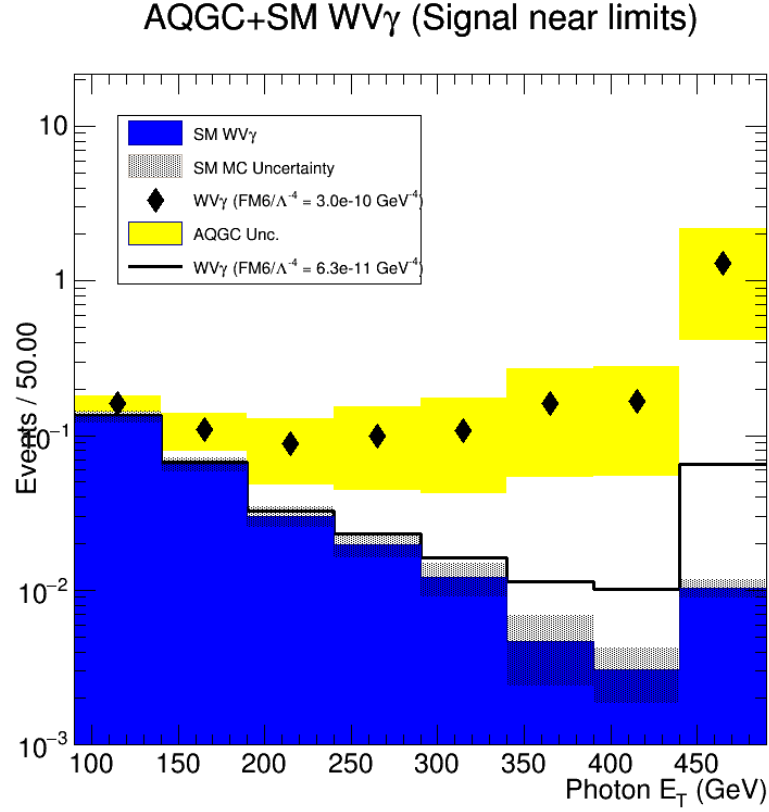


Figure 5.83: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,6}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

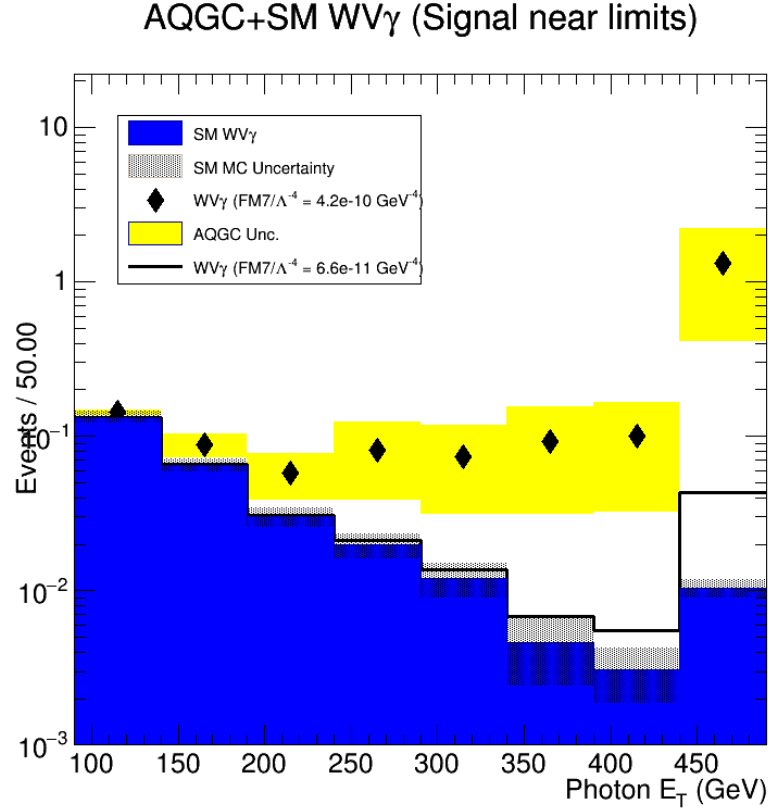


Figure 5.84: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL Δ NLL limits are observed for $f_{M,7}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

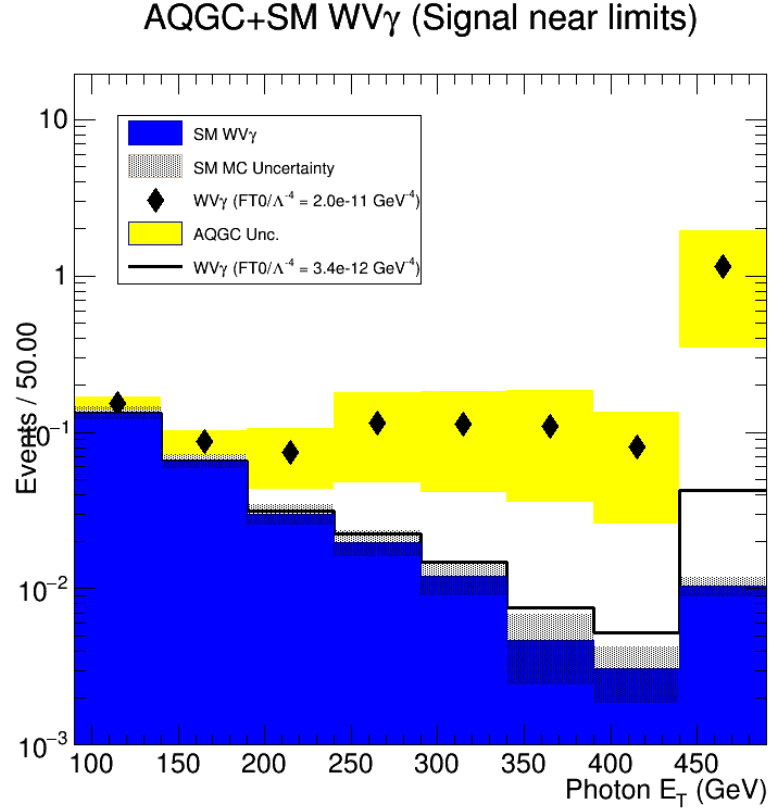


Figure 5.85: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,0}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

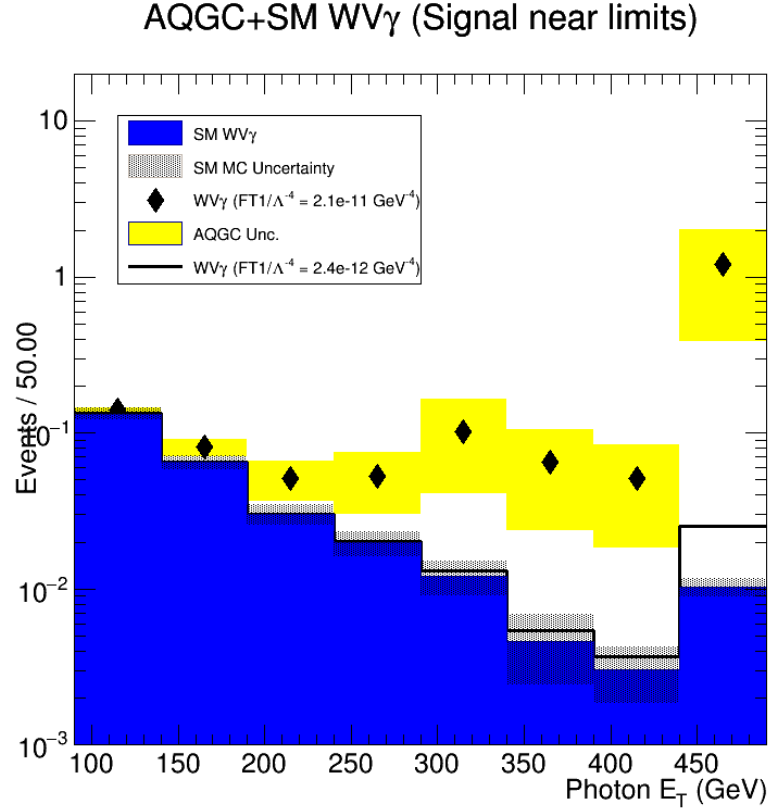


Figure 5.86: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,1}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

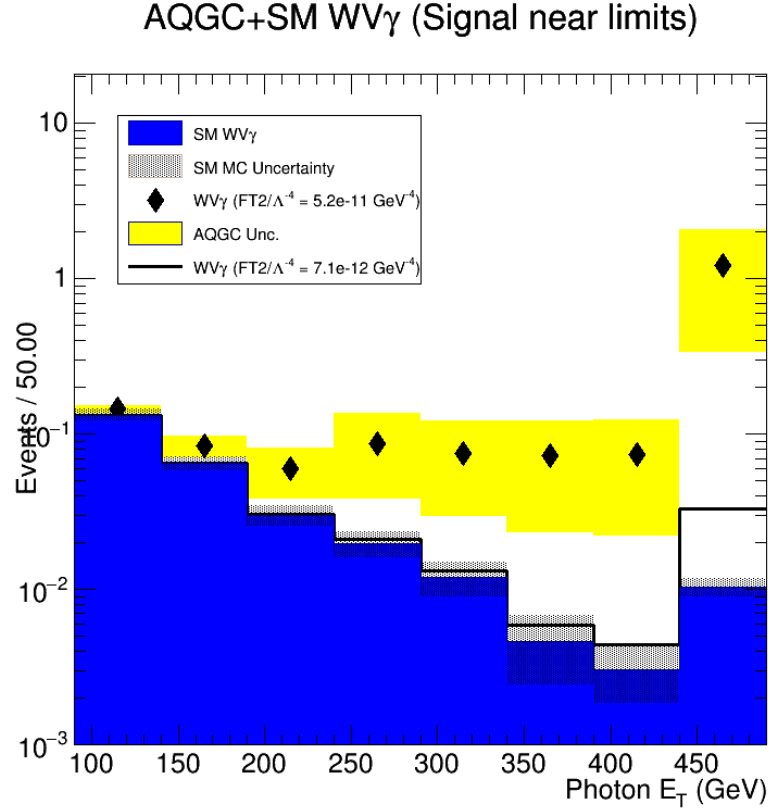


Figure 5.87: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,2}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

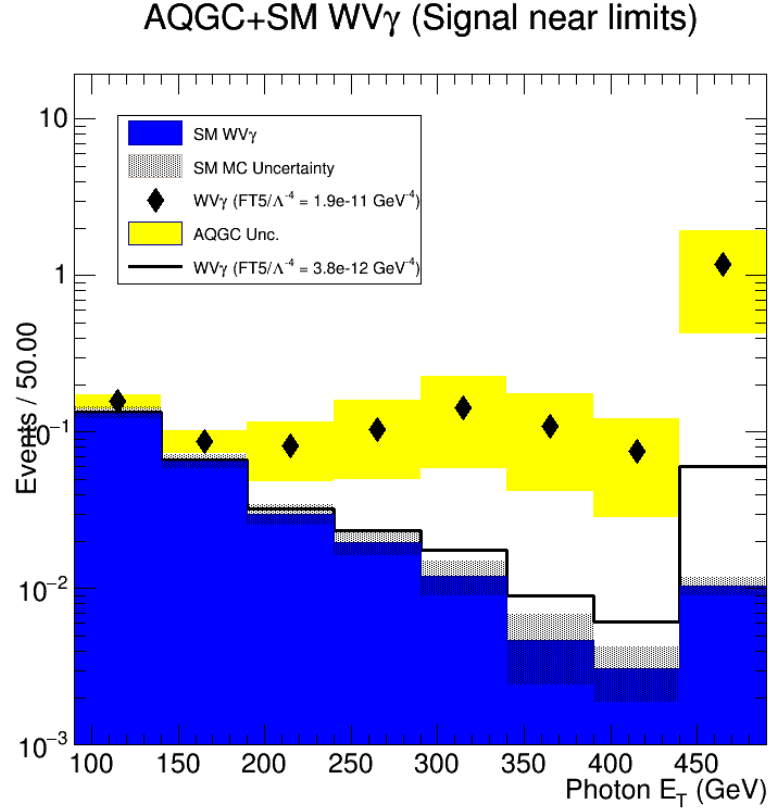


Figure 5.88: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,5}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

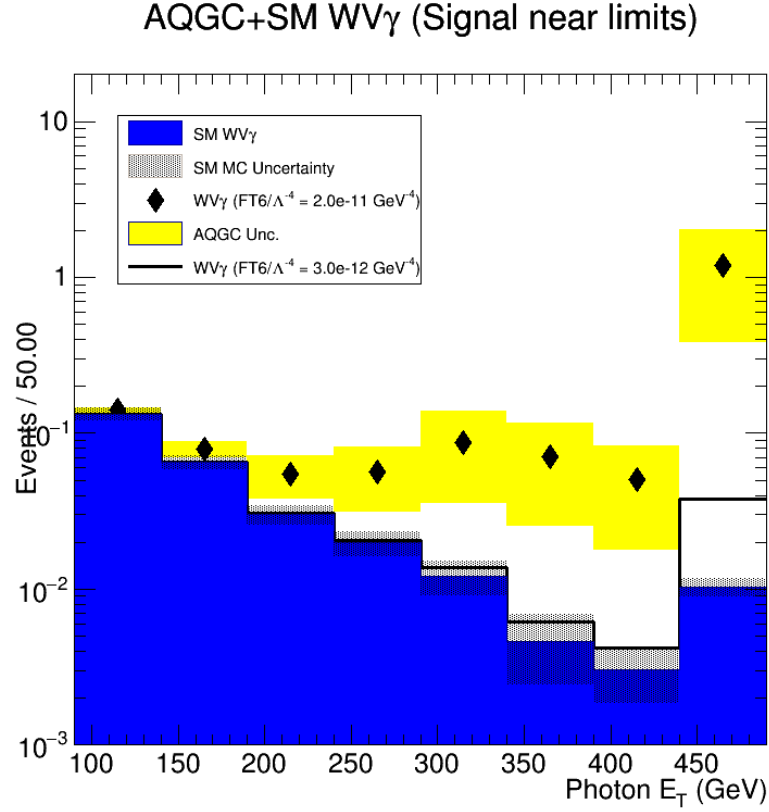


Figure 5.89: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,6}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

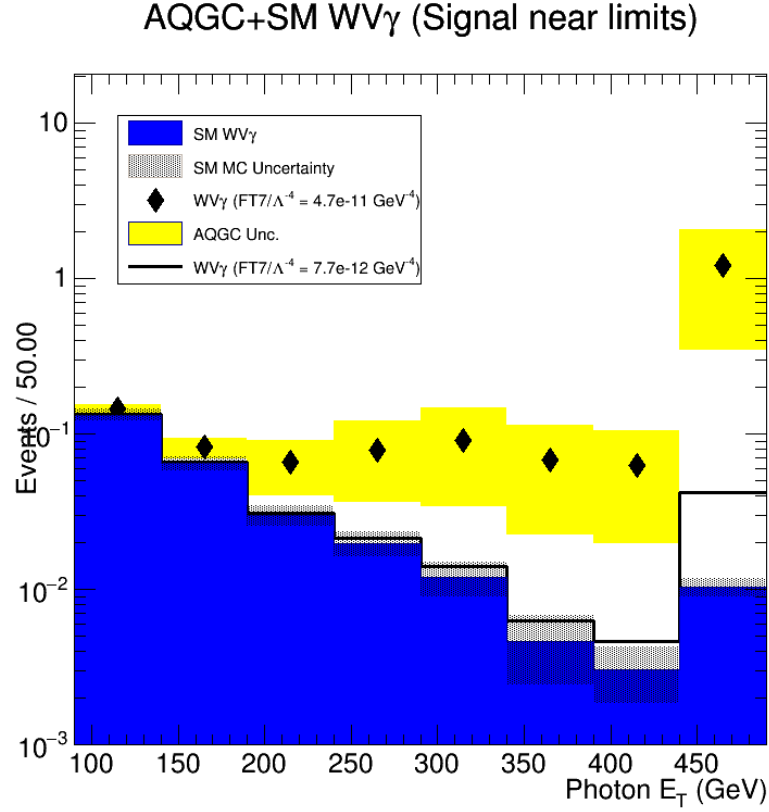


Figure 5.90: Comparison for the muon channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL Δ NLL limits are observed for $f_{T,7}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

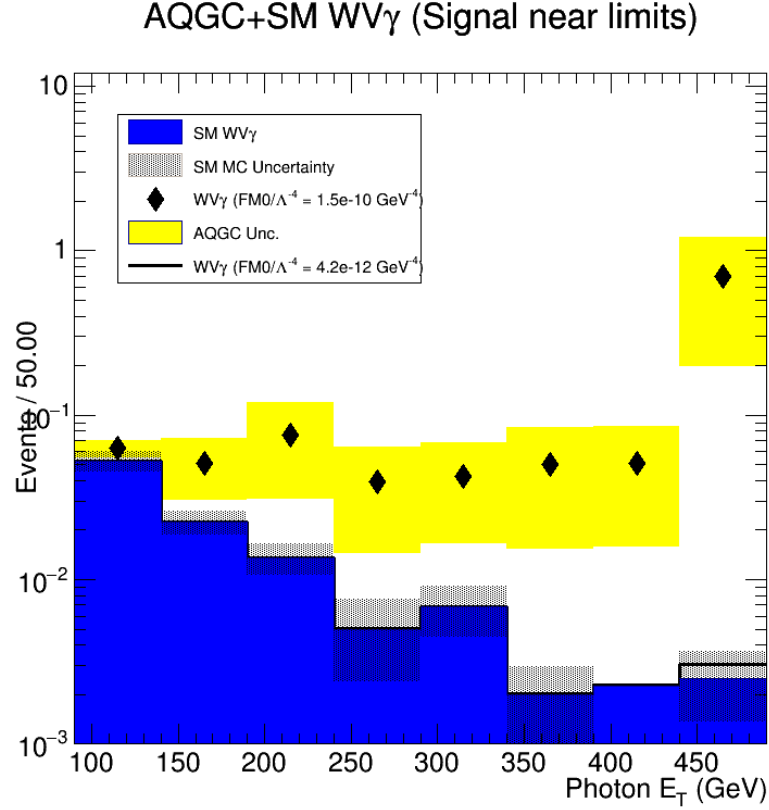


Figure 5.91: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,0}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

It is the policy of the CMS SMP group that AQGC limits be provided without any form factor, which is a means to conserve unitarity. This is largely because the scale of new physics, nor its structure, is known *a priori*. These results can be rescaled via theoretical mechanisms, such as a form factor or K-matrix, from theorists interested in a particular physics model.

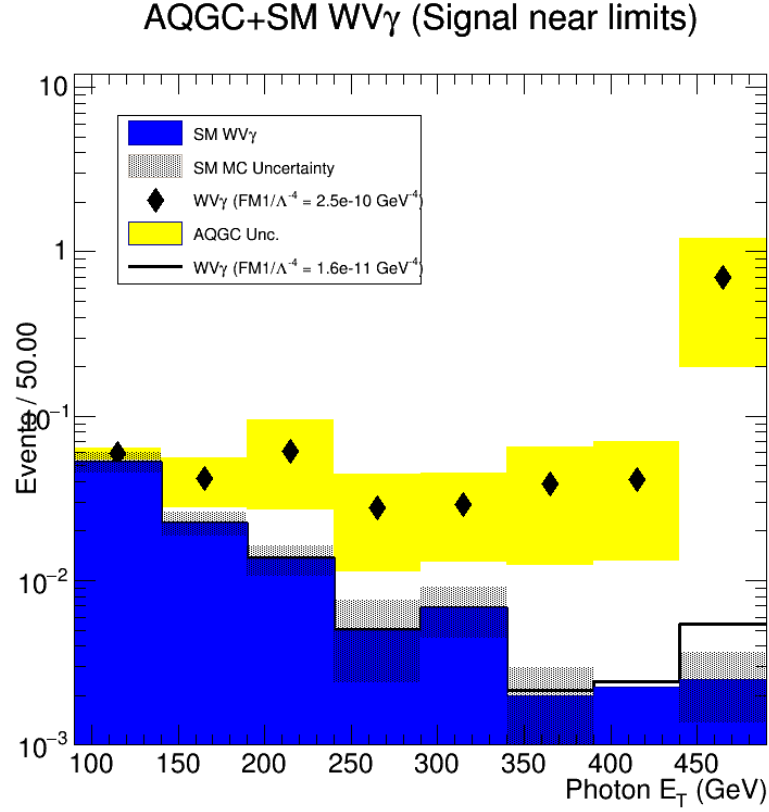


Figure 5.92: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,1}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

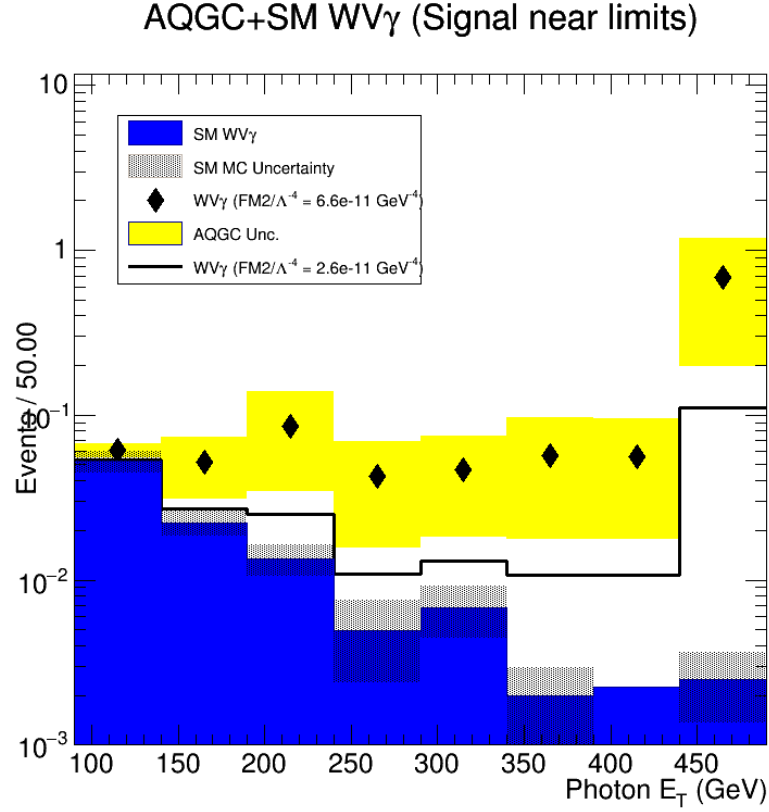


Figure 5.93: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,2}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

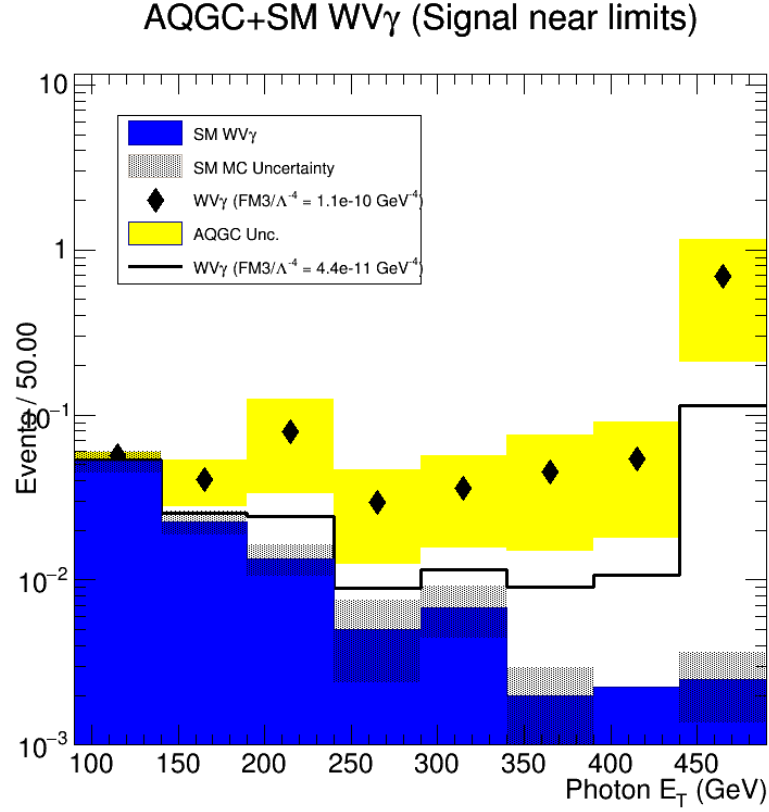


Figure 5.94: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,3}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

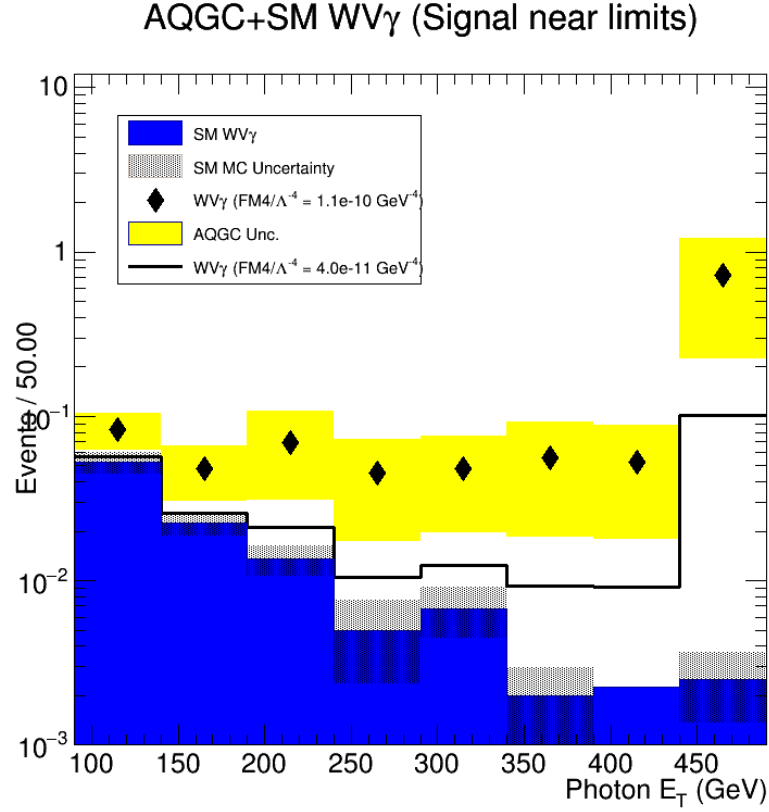


Figure 5.95: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,4}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

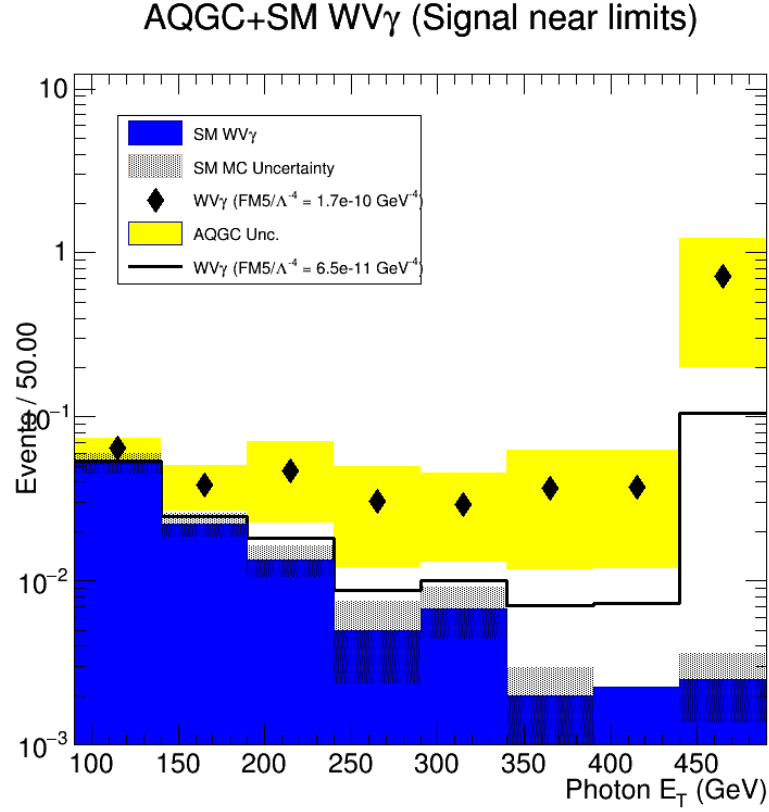


Figure 5.96: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,5}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

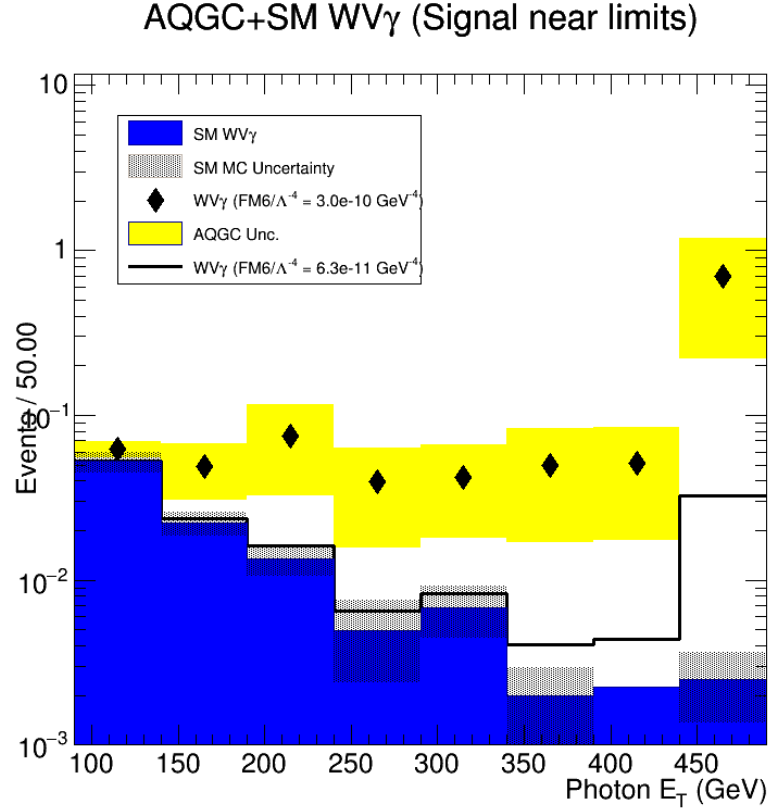


Figure 5.97: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,6}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

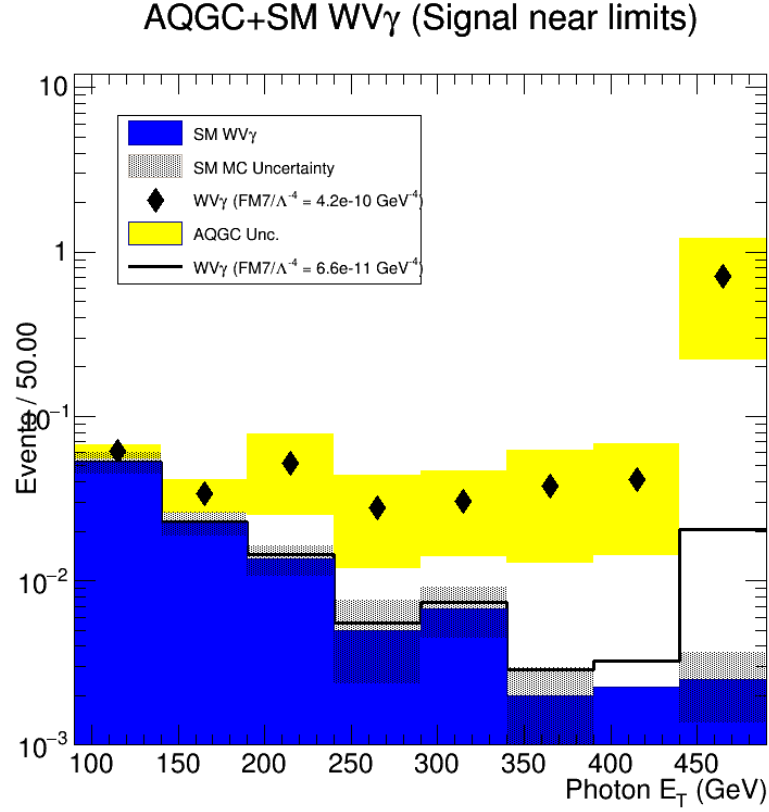


Figure 5.98: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{M,7}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

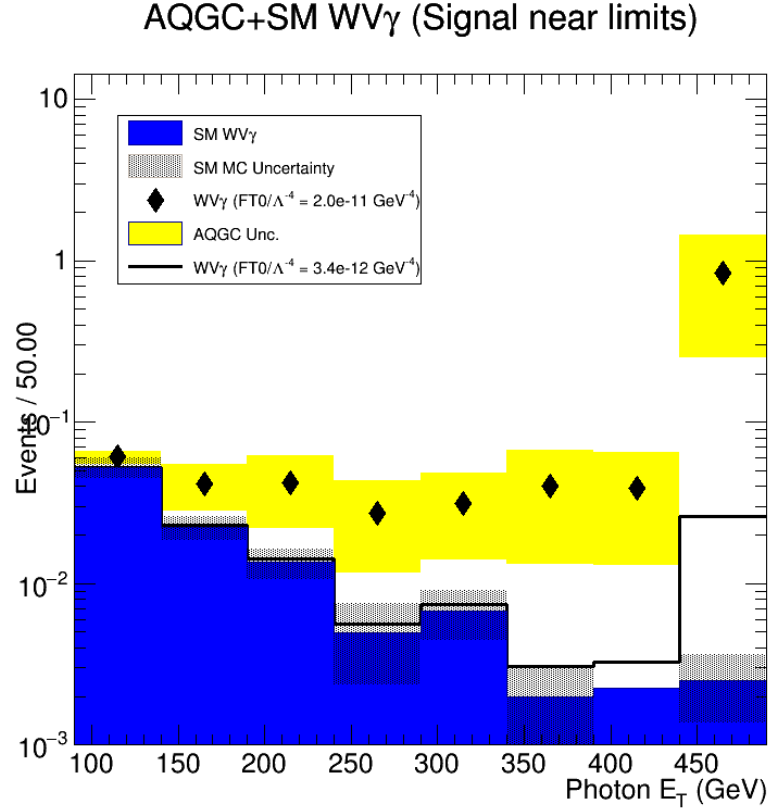


Figure 5.99: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,0}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

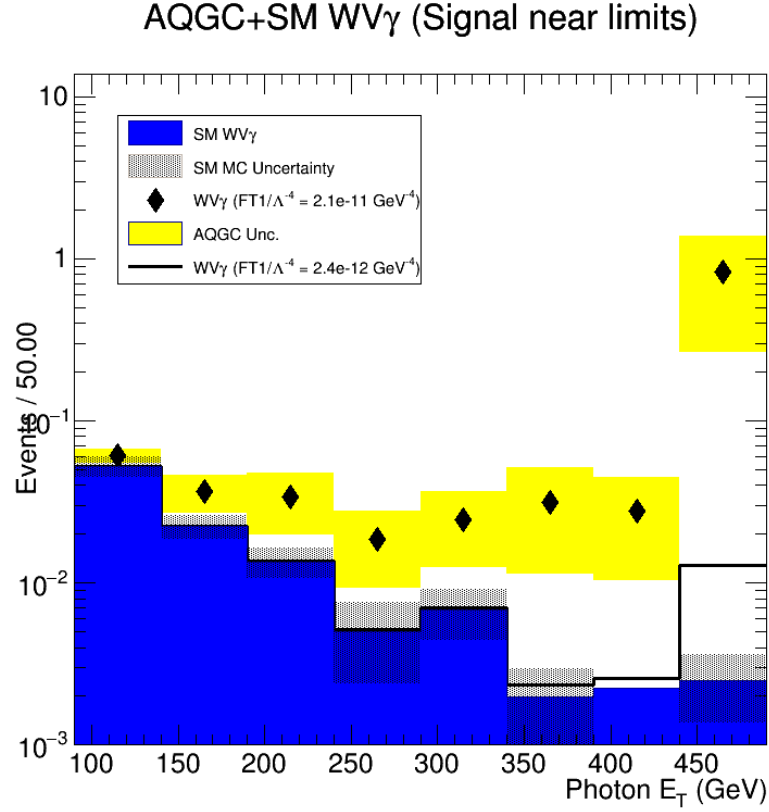


Figure 5.100: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,1}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

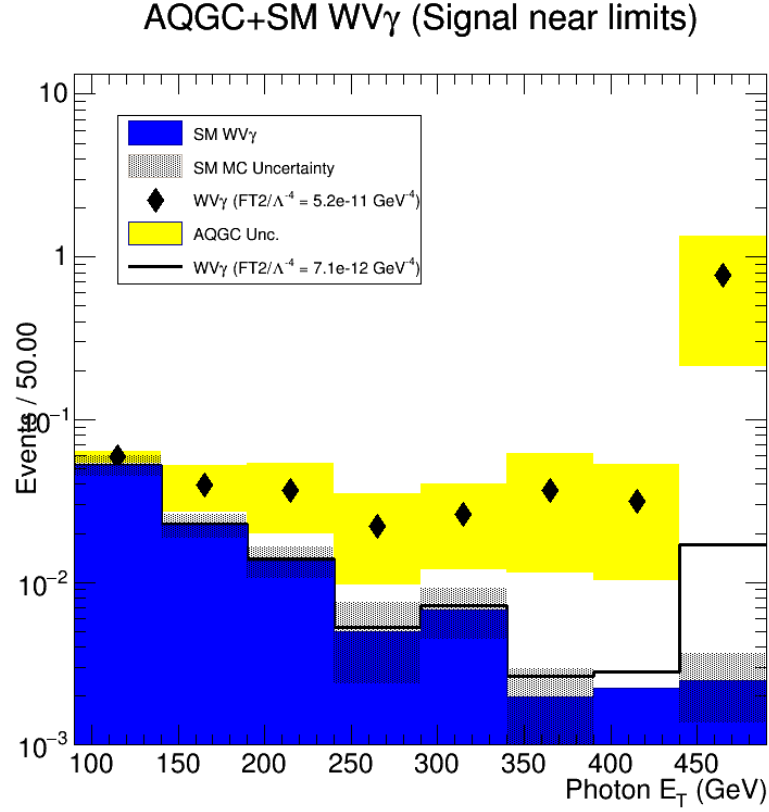


Figure 5.101: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,2}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

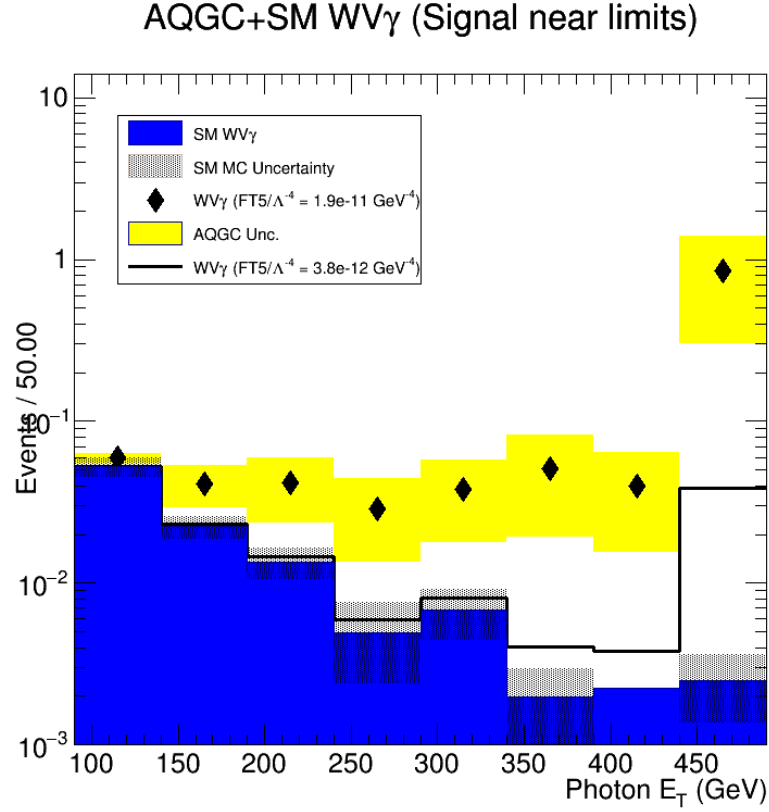


Figure 5.102: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL Δ NLL limits are observed for $f_{T,5}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

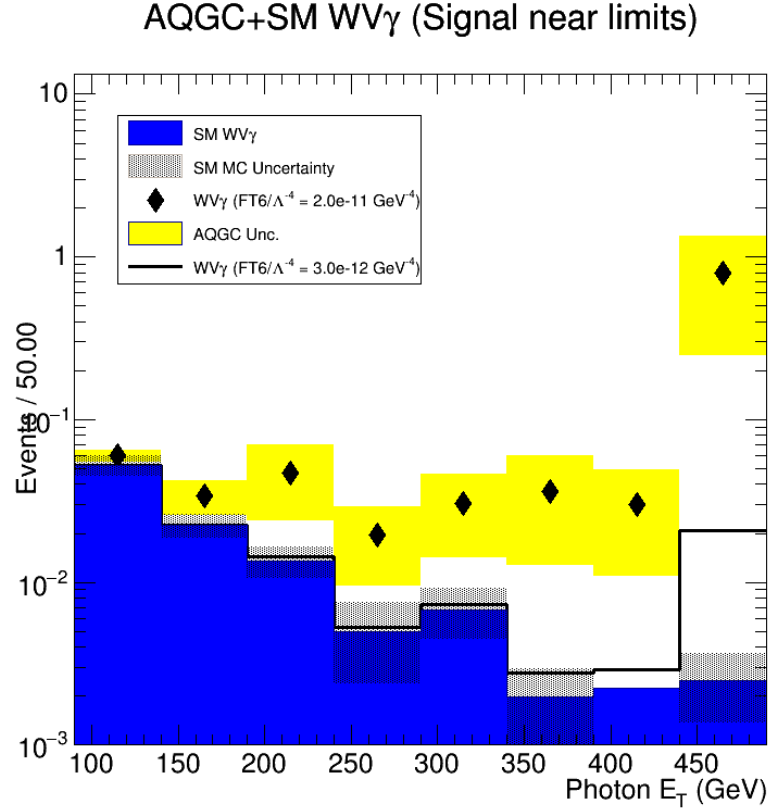


Figure 5.103: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL Δ NLL limits are observed for $f_{T,6}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

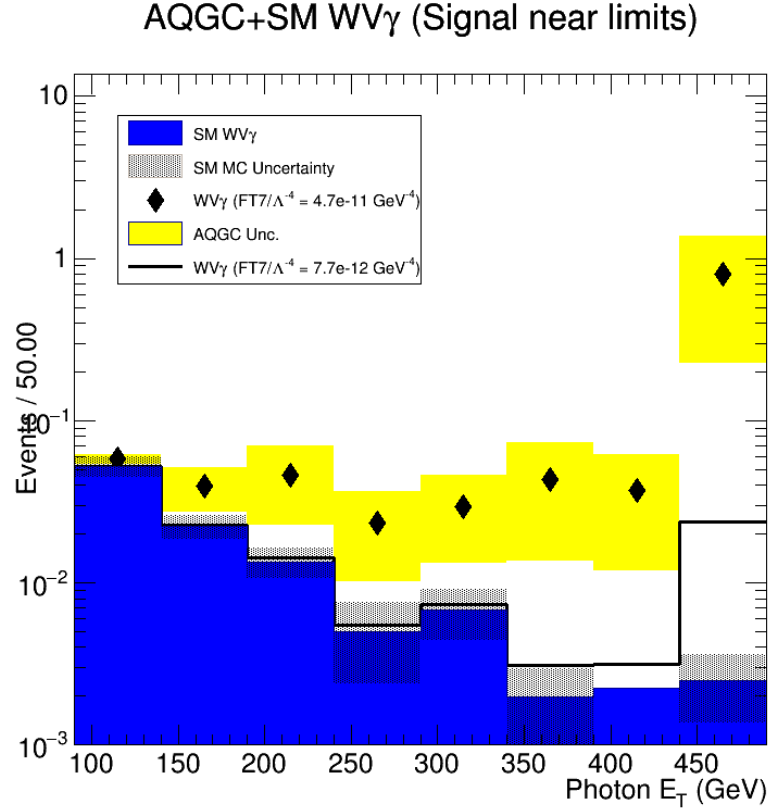


Figure 5.104: Comparison for the electron channel between the SM $WV\gamma$ process and the kinematic distribution around where the 95% CL ΔNLL limits are observed for $f_{T,7}/\Lambda^4$. Also, the published AQGC limit distribution is provided for reference.

Table 5.26: 95% CL shape-based exclusion limits listed for the combined lepton channels of each dim. 8 AQGC parameter using photon p_T .

Observed Limits	Expected Limits
$-150 \text{ (TeV}^{-4}) < f_{M,0}/\Lambda^4 < 151 \text{ (TeV}^{-4})$	$-145 \text{ (TeV}^{-4}) < f_{M,0}/\Lambda^4 < 146 \text{ (TeV}^{-4})$
$-245 \text{ (TeV}^{-4}) < f_{M,1}/\Lambda^4 < 244 \text{ (TeV}^{-4})$	$-239 \text{ (TeV}^{-4}) < f_{M,1}/\Lambda^4 < 237 \text{ (TeV}^{-4})$
$-64.9 \text{ (TeV}^{-4}) < f_{M,2}/\Lambda^4 < 65.1 \text{ (TeV}^{-4})$	$-62.1 \text{ (TeV}^{-4}) < f_{M,2}/\Lambda^4 < 62.5 \text{ (TeV}^{-4})$
$-108 \text{ (TeV}^{-4}) < f_{M,3}/\Lambda^4 < 108 \text{ (TeV}^{-4})$	$-104 \text{ (TeV}^{-4}) < f_{M,3}/\Lambda^4 < 104 \text{ (TeV}^{-4})$
$-108 \text{ (TeV}^{-4}) < f_{M,4}/\Lambda^4 < 108 \text{ (TeV}^{-4})$	$-104 \text{ (TeV}^{-4}) < f_{M,4}/\Lambda^4 < 105 \text{ (TeV}^{-4})$
$-170 \text{ (TeV}^{-4}) < f_{M,5}/\Lambda^4 < 170 \text{ (TeV}^{-4})$	$-168 \text{ (TeV}^{-4}) < f_{M,5}/\Lambda^4 < 169 \text{ (TeV}^{-4})$
$-301 \text{ (TeV}^{-4}) < f_{M,6}/\Lambda^4 < 301 \text{ (TeV}^{-4})$	$-290 \text{ (TeV}^{-4}) < f_{M,6}/\Lambda^4 < 291 \text{ (TeV}^{-4})$
$-411 \text{ (TeV}^{-4}) < f_{M,7}/\Lambda^4 < 414 \text{ (TeV}^{-4})$	$-401 \text{ (TeV}^{-4}) < f_{M,7}/\Lambda^4 < 406 \text{ (TeV}^{-4})$
$-20.1 \text{ (TeV}^{-4}) < f_{T,0}/\Lambda^4 < 20.3 \text{ (TeV}^{-4})$	$-19.1 \text{ (TeV}^{-4}) < f_{T,0}/\Lambda^4 < 19.3 \text{ (TeV}^{-4})$
$-20.9 \text{ (TeV}^{-4}) < f_{T,1}/\Lambda^4 < 21.1 \text{ (TeV}^{-4})$	$-20.3 \text{ (TeV}^{-4}) < f_{T,1}/\Lambda^4 < 20.5 \text{ (TeV}^{-4})$
$-51.5 \text{ (TeV}^{-4}) < f_{T,2}/\Lambda^4 < 51.7 \text{ (TeV}^{-4})$	$-50.1 \text{ (TeV}^{-4}) < f_{T,2}/\Lambda^4 < 50.1 \text{ (TeV}^{-4})$
$-18.3 \text{ (TeV}^{-4}) < f_{T,5}/\Lambda^4 < 18.3 \text{ (TeV}^{-4})$	$-17.1 \text{ (TeV}^{-4}) < f_{T,5}/\Lambda^4 < 17.3 \text{ (TeV}^{-4})$
$-19.5 \text{ (TeV}^{-4}) < f_{T,6}/\Lambda^4 < 19.7 \text{ (TeV}^{-4})$	$-18.9 \text{ (TeV}^{-4}) < f_{T,6}/\Lambda^4 < 19.1 \text{ (TeV}^{-4})$
$-47.1 \text{ (TeV}^{-4}) < f_{T,7}/\Lambda^4 < 47.1 \text{ (TeV}^{-4})$	$-45.1 \text{ (TeV}^{-4}) < f_{T,7}/\Lambda^4 < 45.3 \text{ (TeV}^{-4})$

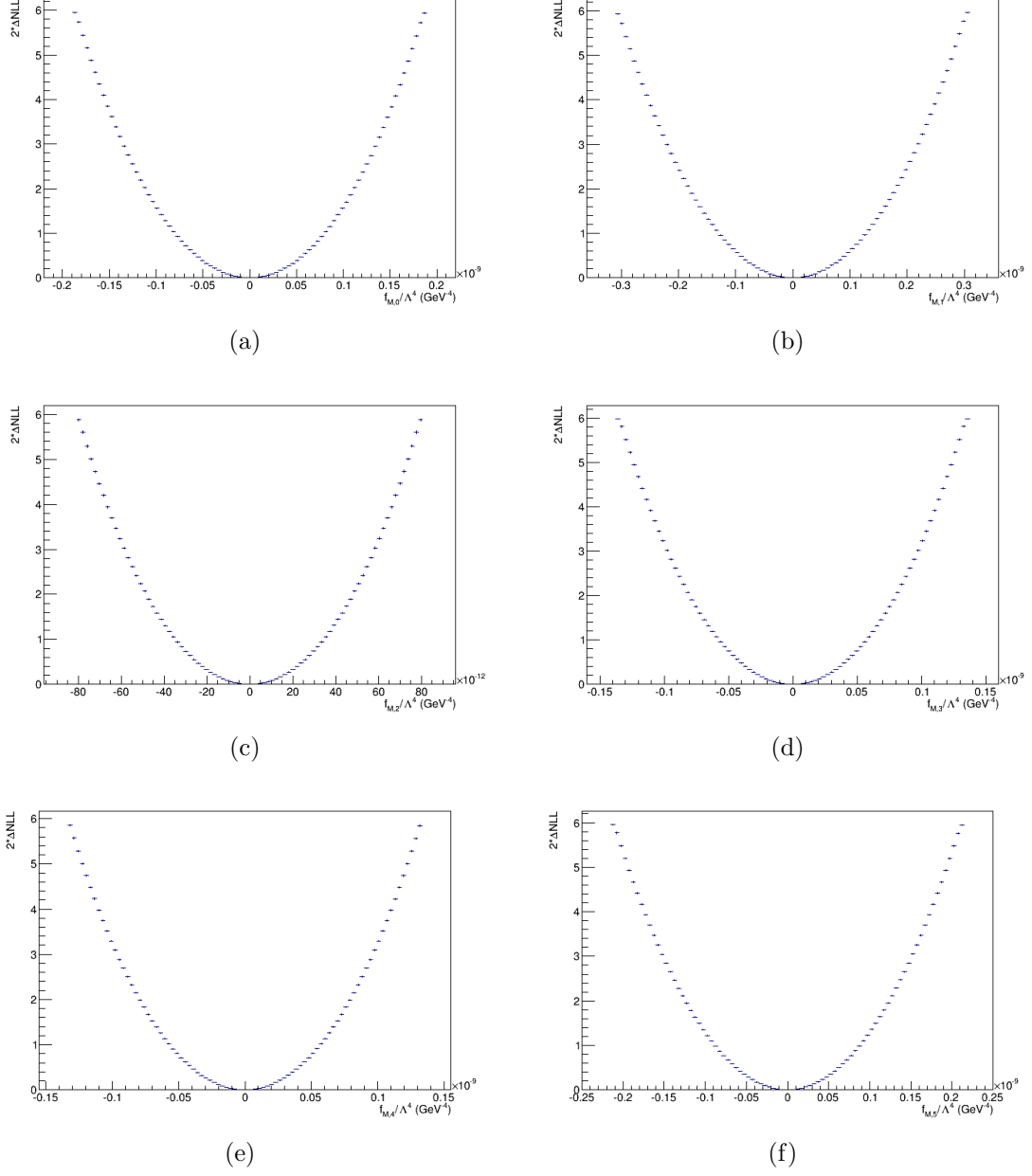


Figure 5.105: Combined observed exclusion limits for (a) $f_{M,0}/\Lambda^4$; (b) $f_{M,1}/\Lambda^4$; (c) $f_{M,2}/\Lambda^4$; (d) $f_{M,3}/\Lambda^4$; (e) $f_{M,4}/\Lambda^4$; (f) $f_{M,5}/\Lambda^4$

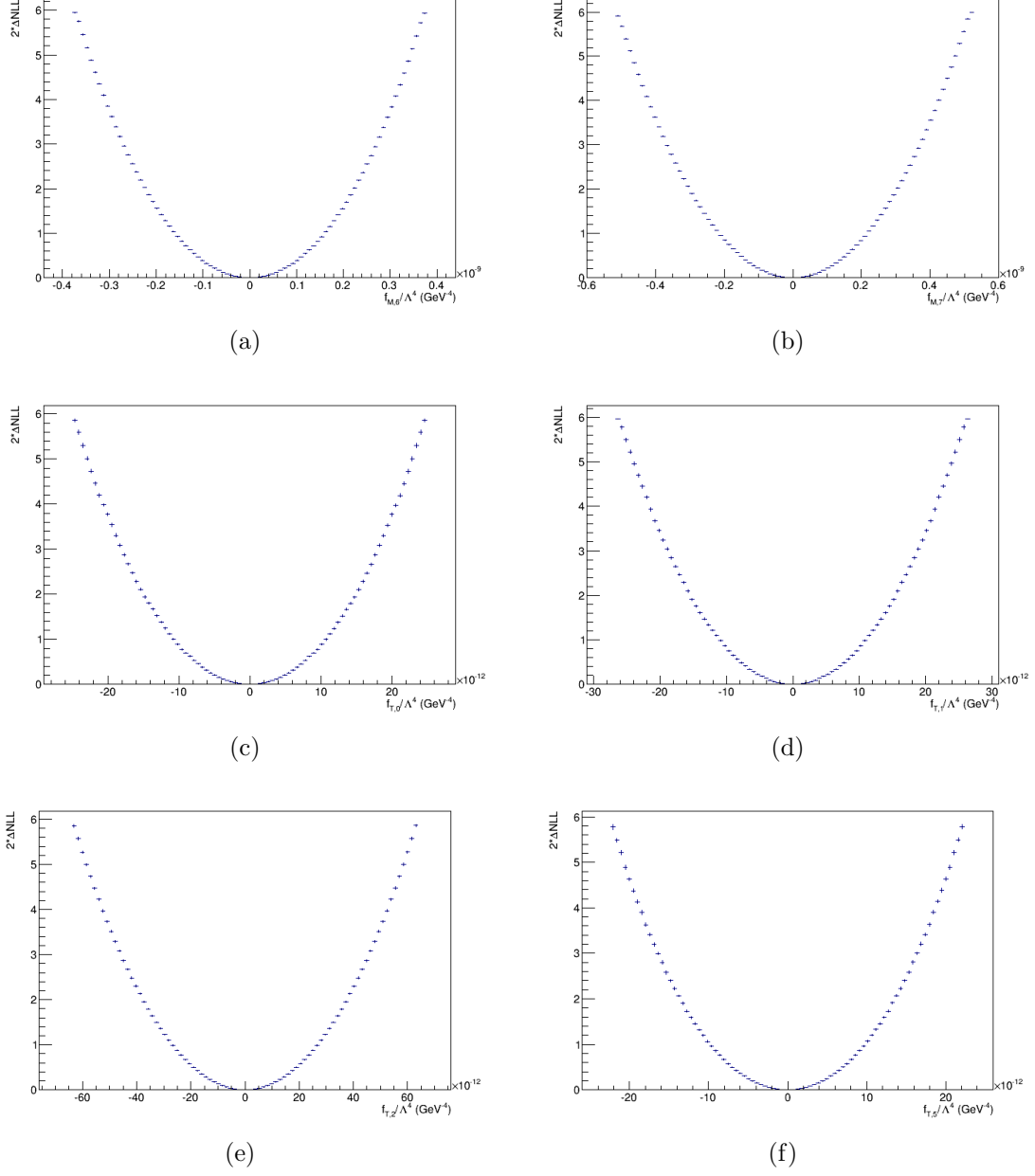


Figure 5.106: Combined observed exclusion limits for (a) $f_{M,6}/\Lambda^4$; (b) $f_{M,7}/\Lambda^4$; (c) $f_{T,0}/\Lambda^4$; (d) $f_{T,1}/\Lambda^4$; (e) $f_{T,2}/\Lambda^4$; (f) $f_{T,5}/\Lambda^4$

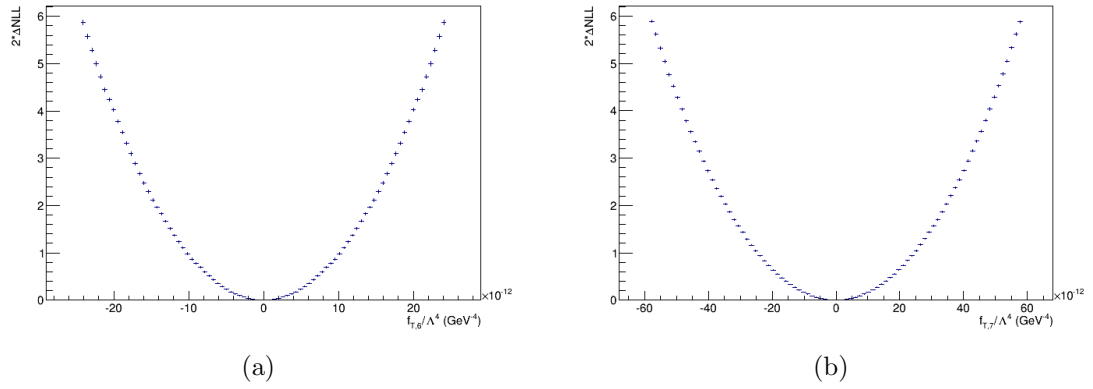


Figure 5.107: Combined (between lepton channels) observed exclusion limits for (a) $f_{T,6}/\Lambda^4$; (b) $f_{T,7}/\Lambda^4$.

CHAPTER 6

CONCLUSION

Here we aim to improve upon the first three boson production upper cross section limit for $WV\gamma$ set in Run I. This is a very difficult cross section to measure due to very low statistics and large systematic and statistical uncertainties. Moreover, the measurement is very sensitive to applied K-factors.

On the other hand, $WV\gamma$ final states may be sensitive to anomalous contributions to the SM $WW\gamma\gamma$ and $WWZ\gamma$ quartic couplings. Quartic gauge boson couplings can be probed in final states with three vector bosons produced as well as through vector boson fusion mediated reactions. These final states are kinematically reachable at the LHC, where one anticipated measurement includes exclusive WW production within the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) project. There are also prospects between ATLAS and CMS for vector boson fusion/scattering production of various final states, including same-sign WW production and $V\gamma + \text{jets}$ with $V = W$ or Z , as well as numerous other triboson final states, such as $W\gamma\gamma$ and WWW . New physics models contributing to AQGC can include warped extra-dimension models with the spin-2 graviton, various composite Higgs models, as well as the optical theorem where unitarization of the S operator is inherent [97].

We present 95% C.L. shape-based exclusion limits on quartic coupling parameters $f_{M,0-7}/\Lambda^4$, $f_{T,0-2}/\Lambda^4$, and $f_{T,5-7}/\Lambda^4$. Several of these parameters are new to the $WV\gamma$ Run II analysis, for which there are no limits from the Run I analysis in order to combine. Also, given the low statistics from the 2015 data, the sensitivity to these parameters is very limited; however, the limits obtained are on par with what has been established from across CMS and ATLAS in Run I.

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APPENDIX A: TAG AND PROBE

There is a discrepancy seen between simulated events and observed data that can be accounted for by application of efficiency scaling factors, $\epsilon_{data}/\epsilon_{MC}$, where ϵ is the efficiency a particular object identification or measurement has with either data or simulated events. This efficiency differs from unity because of detector effects and object reconstruction accuracy; therefore, theoretical predictions for a given well known and easily identified final state in particle physics may not agree with the observed data, and we must then have a means to probe the reconstruction and identification used in order to bring back agreement. One such method of measuring the various efficiencies used in this dissertation is the TnP approach, and more details can be found in Refs. [98, 99].

In the TnP approach, a control sample containing the final state objects being reconstructed or identified is used. A “tag” object is an object that passes the explicit reconstruction or identification criteria under scrutiny, while the “probe” object is required to pass a much more relaxed set of rules. Then an efficiency of the tagged object is measured by comparing the number of events with tagged objects passing the requirements, probed objects passing the relaxed requirements, and objects failing either the tight or relaxed requirements. Efficiencies are obtained using a purely simulated MC control sample for ϵ_{MC} and a pure data control sample for ϵ_{data} . The ratio, or scale factor, is then created in order to apply to MC in this dissertation and scale up or down each event to data. Appropriate uncertainties are measured and assigned to the efficiencies and propagated to the final results quoted.

APPENDIX B: Δ NLL ALGORITHM

Following along Wilk's method for approximating the ratio of likelihood functions for testing hypothesis, detailed in Ref. [95]:

$$\lambda = \frac{L_w(\theta_n)}{L_\Omega(\theta_n)} \quad (6.1)$$

where $L_\Omega(\theta_n)$ is the least upper bound of the profile likelihood in the asymptotic approximation for the test hypotheses in the set, Ω , of all admissible hypotheses and $L_w(\theta_n)$ is the least upper bound of the profile likelihood in the asymptotic approximation for a given value of the parameter of interest. In this dissertation, the parameter of interest is the particular AQGC parameter being limited, while the nuisance parameters include the systematic uncertainties in each of the provided background kinematic distributions and the fitted parameters for the AQGC parametrization described in Section 5.2.9.1.

The likelihood functions are formed from the kinematic distributions provided for the signal and background processes. The goal is to then maximize the ratio, λ , which is related to χ^2 (neglecting additional terms that vanish with large data sets):

$$\lambda \approx e^{-\frac{1}{2}\chi^2} \quad (6.2)$$

which can also be done by minimizing the natural logarithm of λ , or

$$\ln(\lambda) \approx -\frac{\chi^2}{2} \quad (6.3)$$

This relation then becomes the negative log likelihood that is more often quoted:

$$-2\ln(\lambda) \approx \chi^2 \quad (6.4)$$

The negative log likelihood value is then shifted to the best fit point and becomes Δ NLL to which we set 95% CL limits at a value of approximately 3.84.