

A Search for Dark Matter in the Monophoton Final State at CMS

By

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Abstract

The final state of a photon (γ) and missing transverse energy ($\cancel{E}_T$) in pp collisions can be used as a valuable test of the Standard Model. The Standard Model production of $Z(\nu\bar{\nu}) + \gamma$ is a precise process with no dependence on tuned parameters, so it is sensitive to contributions from new physics events. At the same time, this constitutes an irreducible background for new physics searches with the same final state. This dissertation discusses a measurement of associated $Z\gamma$ production, where Z decays into neutrinos. The data are collected in pp collisions at $\sqrt{s} = 7$ TeV by the CMS experiment and correspond to an integrated luminosity of 5.0 fb^{-1} . Descriptions are provided for the methods of reducing and estimating the sources of background. A total number of 73 events are observed, which agrees well with the Standard Model expectation of 75.1 ± 9.5 events.

These results are interpreted in terms of a search for dark matter, which is widely accepted as the nonbaryonic dominant contribution to the matter density of the Universe. Models of production of dark-matter particles (χ) are used to set 90% confidence level upper limits of 13.6 - 15.4 fb on χ production in the $\gamma + \cancel{E}_T$ final state. At the time of publication, these provided the most sensitive upper limits for spin-dependent χ -nucleon scattering for χ masses (M_χ) between 1 and 100 GeV. For spin-independent contributions, the present limits are extended to $M_\chi < 3.5$ GeV.

Acknowledgments

Thank you to everyone who supported, guided, and encouraged me through this adventure so that I could arrive at this moment. I have taken to heart the lessons you've taught me about physics, embracing curiosity, balancing work with a rich life, and packing lightly [1]. Without you, I would not be here.

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CHAPTER 1

Introduction

The truth may be puzzling. It may take some work to grapple with. It may be counterintuitive. It may contradict deeply held prejudices. It may not be consistent with what we desperately want to be true. But our preferences do not determine what's true. - Carl Sagan

The Standard Model of Particle Physics is an elegant and robust theory, coherently describing three of the four known fundamental forces of nature, and unifying two of them, with a field theory that exhibits many satisfying parallels. Developed in the 1960s by Weinberg, Glashow, and Salam, the Standard Model has been experimentally validated repeatedly, motivated Nobel-prize winning work repeatedly, and even now, with evidence of a Higgs-like particle observed at multiple experiments, it remains relevant and central to the field of particle physics. However, some Standard Model variables need to be measured experimentally or deliberately fine-tuned while some phenomena fall beyond the scope of the Standard Model entirely; these points motivate searches for physics beyond the Standard Model. One particular case of phenomena beyond the Standard Model is the existence of dark matter.

Dark matter is widely accepted as the dominant source of matter density in the Universe, we see motivations for its existence from a variety of sources: weak lensing observations, galactic structure, CMB studies, and even an explanation to stabilize fundamental particle masses. At the same time, we don't know much about it other than the fact that it's non-luminous, interacts gravitationally, and there's a lot of it. In this dissertation I measure the associated diboson production of the Z and a photon (γ) with large transverse momentum (p_T) for the two-fold purpose of testing the Standard Model and searching for an indication of dark matter production.

With so little known about dark matter, this analysis makes use of a model-independent theory. The theory explains dark matter interactions in terms of a massive mediator and provides a way to calculate cross sections for dark matter production and dark matter-nucleon interactions that vary by the dark matter candidate mass and the contact interaction scale. The theory also provides a way to connect the two calculations so that the results from this collider-based searches for production can be directly compared to the results from other experiments searching for direct detection of dark matter interacting with nucleons.

This analysis uses data from the Large Hadron Collider and Compact Muon Solenoid detector. Dark matter can be produced with an associated photon at the LHC from quark-antiquark annihilations, which will appear as monophoton events in the detector. The monophoton channel, containing a single photon and missing transverse energy, is a good probe for evidence of dark matter (or anything out of the ordinary). Measuring associated $Z\gamma$ production tests the Standard Model because the production rates are predicted precisely and are independent of tuned parameters, meaning any measured deviation from the Standard Model prediction would be a strong indicator of new physics.

Chapter 2 presents the theoretical framework of the Standard Model, compelling arguments for dark matter, and an explanation of why the associated production of Z and γ is a good choice for this two-prong analysis. The layouts of the Large Hadron Collider and the Compact Muon Solenoid detector are described in chapter 3, and the reconstruction software that translates digitized signals into reconstructed physics objects is summarized in chapter 4, with particular attention to reconstructed photons since they play a prominent role in this analysis. Chapter 5 deals with the analysis, describing the steps taken to select the signal sample from the larger dataset; produce accurate simulated samples for reference; and identify, reduce, and estimate the many backgrounds for a monophoton signal. The measurement of the $Z\gamma$ cross section compared to the expected Standard Model value is included in chapter 5, as well. I will not give away the ending, but in chapter 6 either an excess is found in the $Z\gamma$ channel, which could indicate that new physics is afoot, or a good agreement is found between the data and simulated dark matter predictions and limits are set on the dark matter candidate mass and the dark matter-nucleon production cross sections that surpass all previous measurements.

CHAPTER 2

Theoretical Motivation

To borrow a metaphor from Leon Lederman’s book, “The God Particle,” studying particle physics is like watching a soccer game if you’ve never heard the rules and you can’t see the ball. The curious individual will observe the game, record what she sees, and try to come up with general, broadly applicable rules that explain what has happened and predict what will happen next. Further observation supports or invalidates those rules and a steady regiment of observation, theoretical construction and prediction, and observation continues until we are quite satisfied that we fully understand the rules of the game. Turning back to particle physics, experimentalists observe interactions between particles in the hopes of comprehending the most basic building blocks of ourselves and the universe and how it all works together. The many experiments of the past century have indicated that it all comes down to a handful of fundamental particles interacting via four observable forces: the electromagnetic force, the strong force, the weak force, and the gravitational force. This chapter contains a brief overview of the three forces incorporated into the Standard Model of particle physics (SM), why we search for physics beyond the Standard Model, what motivates searches for dark matter (DM), and a proposed model of dark matter. The explanation of SM largely stems from standard texts on the subject [2, 3, 4].

2.1. The Standard Model

The Standard Model of particle physics is one of the great success stories of physics because, in the tradition of Maxwell’s Equations, it merges the models that define the strong force, the weak force, the electromagnetic (EM) force, and their respective particles into one cohesive theory of group symmetries united by the requirement of local gauge invariance. One of the outstanding aspects of the SM is that it successfully unifies the weak and EM forces into a single force. The SM doesn’t include gravity, but gravity has a low strength when compared to the other forces, and the energy scales of the experiments designed to test fundamental particle interactions are low enough that gravitational effects

are negligible. According to the SM, all matter is composed of particles called fermions and the forces between fermions are manifested as an exchange of bosons.

Fermions can be organized into two elementary categories: quarks and leptons. Quarks and leptons are spin- $\frac{1}{2}$ point-like particles that have no substructure; they are defined by their mass and quantum numbers (like spin, charge, and the less intuitive weak isospin, hypercharge and color). There are 24 elementary fermions: 6 quarks, 6 leptons, and an antiparticle for every particle characterized by the same mass but opposite quantum numbers. Both types of particles can be organized by their mass into three generational pairs. Quarks are never observed alone, they form pairs and trios observed as mesons and baryons, respectively. Each generation of leptons includes two types of particles: a massive, electrically charged lepton and a neutral and (nearly) massless one called a neutrino. Photons mediate the EM force between particles with charge, $W^\pm$ and Z bosons are exchanged among both leptons and quarks through the weak force, and gluons bind quarks together via the strong force.

Each force in the Standard Model is mediated by the exchange of the spin-1 bosons listed in the previous paragraph. Gluons are exchanged via the strong force; $W^\pm$ and Z bosons mediate the weak force; and photons transmit the EM force. Fermions can interact via these forces if their internal quantum numbers transform under the symmetries of the theory. The three theories comprising the SM are constructed as gauge theories, which is covered in the next section.

2.1.1. Gauge Theories. The different components of the SM (electroweak dynamics and quantum chromodynamics) each start as a basic theory to model the interactions of spin- $\frac{1}{2}$ particles with a Dirac Lagrangian:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi \quad (2.1)$$

where ψ are space- and time-dependent fields representing the particles, γ^μ are gamma matrices, and m is the mass of the particles. In each case, the fields of the theory transform under a particular symmetry group. These symmetry groups are chosen to manifest the experimentally observed constraints of the particle interactions represented through the internal quantum numbers. The fields are then adjusted to reflect the local position in

space-time and exhibit invariance under local transformations. Lastly, the Lagrangian is also adjusted, according to the gauge symmetry group, to be locally gauge invariant by introducing the gauge fields, which represent the gauge bosons, via the covariant derivative, D_μ , which replaces the partial derivative, ∂_μ .

2.1.2. Quantum Electrodynamics. EM interactions are formulated by a gauge theory with the symmetry group $U(1)$, which transforms as

$$\psi \rightarrow \psi' = e^{-i\theta} \psi \quad (2.2)$$

where θ is a constant phase term. To make the global symmetry of the $U(1)$ group local, the constant phase transformation is replaced by a space-time position-dependent phase ($\theta \rightarrow \theta(x)$) and an additional vector field is introduced to the Lagrangian via the covariant derivative,

$$\partial_\mu \rightarrow D_\mu \equiv \partial_\mu - ieA_\mu(x) \quad (2.3)$$

where A_μ is a spin-1 vector field and e is the electromagnetic charge of the fermion described by the field. The field A_μ introduces the photon as the gauge boson that mediates the EM force between charged particles. In order to account for the kinetic energy of A_μ , we add the well-known gauge-invariant term $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ to the Lagrangian, where the field-strength tensor is defined as $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ [4]. The complete Lagrangian for the EM interactions between a charged particle and a photon is:

$$\mathcal{L} = \bar{\psi}(x)(iD_\mu - m)\psi(x) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (2.4)$$

This theory is called quantum electrodynamics (QED), and an example Feynman diagram that illustrates an EM vertex, or current, governed by QED is shown in Figure 2.1.

2.1.3. Quantum Chromodynamics. The theory describing the strong force between quarks and gluons, called quantum chromodynamics (QCD), is built in a similar way. Evidence for quarks were first observed in $e - p$ scattering events at SLAC [5, 6]. The fields describing the quarks are composed of members of the $SU(3)$ symmetry group to account for experimental evidence indicating that an additional internal characteristic generates three distinguishable states of quarks that have otherwise identical properties. This new quantum number, color, and its conservation requirements provide an explanation as to

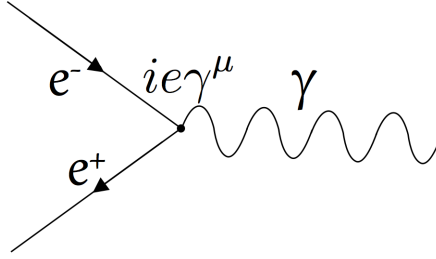


FIGURE 2.1. Feynman diagram: an electron-positron vertex with a photon.

why observed baryons like $\Delta^{++}(uuu)$ don't violate the Pauli Exclusion principle [7], and why quarks are observed in pairs and triplets as color-anticolor mesons and triple color baryons, respectively. Branching ratio studies performed on e^+e^- collisions at SLAC [5, 6] indicate that this characteristic, named "color," comes in three variations [4], denoted as red, green, and blue. The resulting fields that describe quarks in terms of their color charge are written as $q = (q^R, q^G, q^B)$, and the mediating gauge boson, the gluon, appears in the Lagrangian as eight distinct color-anticolor vector fields. To create a locally gauge invariant Lagrangian, the partial is again replaced by a covariant derivative which includes the eight vector boson fields of the gluons, A_μ^i , a term g_s related to the strong coupling constant, and the 3×3 Gell-Man matrices, shown in ??.

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ig_s \frac{\lambda^i}{2} A_\mu^i \quad (2.5)$$

A Feynman diagram of the basic QCD vertex can be seen in Figure 2.2. The magnitude of the force between color-charged particles, which is very small at short distances but increases asymptotically at larger distances, is reflected in the coupling constant $\alpha_s = g_s^2/4\pi$ and the non-Abelian construction of the gauge theory. By expressing a function for a QCD-predicted cross section in terms of a beta function, we find the relationship

$$\frac{1}{\alpha_s} \propto \log(Q/\Lambda) \quad (2.6)$$

relating α_s to Q , the momentum involved in the interaction, and the momentum scale Λ . From this relationship we can see that α_s becomes strong as Q^2 is decreased at a scale set by Λ . Strong interactions become asymptotically strong at distances $\sim 1/\Lambda$, which

roughly correspond to the diameter of light hadrons [3]. The energy required to separate the quarks beyond that distance is greater than the pair production energy; rather than pull two quarks further apart, a new quark and antiquark are produced which form mesons with the originally separated quarks. This phenomenon is referred to as quark confinement.

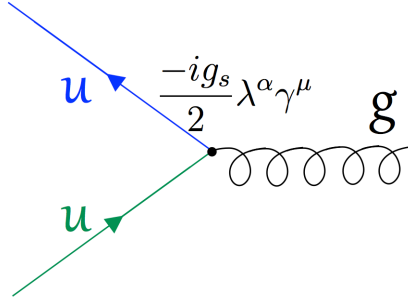


FIGURE 2.2. Feynman diagram: A QCD vertex between two up quarks and a gluon.

2.1.4. Electroweak Theory. The Glashow-Weinberg-Salam electroweak gauge theory [8] is the first successful model that unifies two fundamental forces of nature: the EM and the weak force. The EM force is described earlier in this chapter, and the weak force describes flavor-changing processes in which heavy fermions decay into lighter ones, initially observed in β decay in nuclei: $n \rightarrow p + e^- + \bar{\nu}_e$, which take place among left-handed fermions. Both types of interactions are explained through transformations under the $SU(2)_L \times U(1)_Y$ symmetry group. Only left-handed particles carry the weak isospin quantum number, I_w , which allows for transformations under the $SU(2)$ symmetry group, while both left- and right-handed particles carry weak hypercharge spin, Y , which transforms under $U(1)$ symmetry. As an example, if we consider the first generation of leptons, the electron and electron neutrino, the left-handed field components form a doublet while the right-handed field exists as a singlet:

$$E_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \text{and} \quad E_R = e_R \quad (2.7)$$

which transform under both $SU(2)$ and $U(1)$. In order to make the Lagrangian locally gauge invariant, the covariant derivative introduces four gauge bosons fields, $\vec{W}_\mu$ and B_μ ,

associated with the SU(2) and U(1) symmetry groups, respectively:

$$D_\mu = \partial_\mu - ig \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - ig' \frac{Y}{2} B_\mu \quad (2.8)$$

as well as gauge coupling constants g and g' for SU(2) and U(1), respectively, $\vec{\tau}$ as a vector of SU(2) generator matrices, and the weak hypercharge quantum number Y . Four kinetic energy terms are added to the Lagrangian for the four gauge fields, at which point the physical gauge boson fields can be written as linear combinations of the $\vec{W}$ and B fields:

$$W_\mu^\pm = (W_\mu^1 \mp iW_\mu^2)/\sqrt{2} \quad (2.9)$$

$$Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \quad (2.10)$$

$$A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (2.11)$$

where θ_W is called the weak mixing angle, or the Weinberg angle, and relates the strengths of the coupling constants, $\tan \theta_W = g'/g$. The A_μ field accounts for the photon in an identical manner to QED, and the A_μ and Z fields are constructed in such a way as to preserve the photon as a massless gauge boson while making the Z boson more massive than W such that θ_W also gives us the relationship $\cos \theta_W = M_W/M_Z$, which has been confirmed in many experimental studies. The Z mass has been measured to be $M_Z = 91.1876 \pm 0.002$ GeV [9] and the world average for the $W^\pm$ mass was calculated to be $M_W = 80.385 \pm 0.015$ GeV [10]. The value of θ_W varies as a function of the momentum transfer, and is more commonly used in its trigonometric form. Neutral current and charged current cross sections for neutrinos were compared to find $\sin^2(\theta_W) = 0.222 \pm 0.003$ [11]. The Feynman diagrams for some weak vertices are shown in Figure 2.3.

The mass terms for $W^\pm$ and Z do not automatically come out of the $SU(2) \times U(1)$ theory, though; adding mass terms for the $W^\mp$ and Z bosons would violate local gauge invariance. However, in order for the weak mediators to act at short distances and couple weakly to fermions, the bosons need mass. Introducing mass terms and constructing the four gauge bosons as they appear in ?????? is accomplished through the Higgs mechanism, whereby scalar fields are added to the Lagrangian that cause a spontaneous symmetry breaking, producing mass terms for the weak force while maintaining local gauge invariance. Two complex scalar fields forming an SU(2) doublet, ϕ , are added to the theory, which introduces

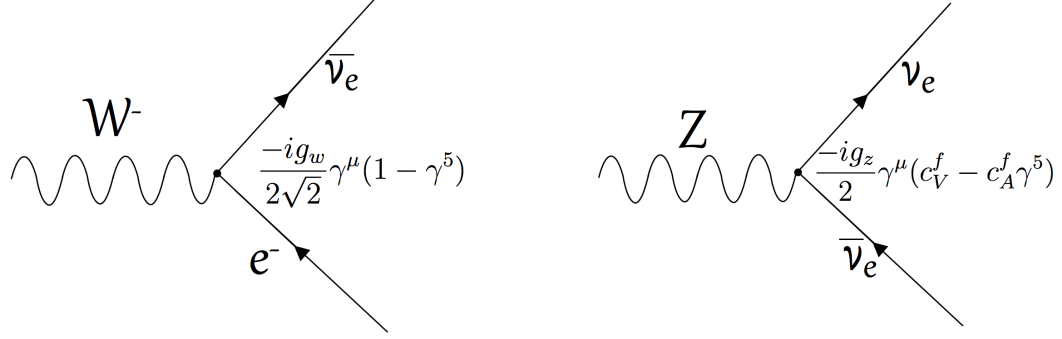


FIGURE 2.3. Feynman diagram of electroweak interactions mediated by a W^- (left) and Z (right).

a potential term. The gauge invariant potential term is given by:

$$V(\phi^\dagger\phi) = m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \quad (2.12)$$

where m^2 and λ are real constants. If we assume the Nambu-Goldstone case that the physical vacuum is not unique, $m^2 < 0$ and $\lambda > 0$ and the potential will have two minima, $\pm\sqrt{-\mu^2/(2\lambda)} = \pm v/\sqrt{2}$. Choosing one of these points as the actual physical vacuum, or the vacuum expectation value (VEV), breaks the $SU(2) \times U(1)$ symmetry of the Lagrangian. Since particle excitations are calculated as fluctuations about the vacuum state, the scalar doublet is redefined in terms of the VEV and excitations. Following the Goldstone theorem, each spontaneously broken symmetry of the scalar doublet due to the existence of the VEV corresponds to a massless field in the doublet. The resulting three massless fields, called Goldstone bosons, are absorbed into the theory as the longitudinal components of the $W^\pm$ and Z gauge bosons, generating mass terms for the weakly interacting bosons and fermions and a relationship between the $W^\pm$ and Z masses. The remaining real scalar field is the Higgs boson.

2.1.5. $Z\gamma$ interactions. Part of this analysis involves a measurement of the associated production of a Z boson and a photon (γ). The Z is produced via a weak quark interaction along with an initial-state radiated photon. This electroweak interaction can be produced in two ways at leading order, for the specific case when the Z boson decays into two neutrinos, illustrated in the Feynman diagrams in Figure 2.4. The rate of these processes in the SM are predicted precisely and involve no tuned parameters so even a small deviation from expectations due to physics beyond the Standard Model (BSM physics) would be observable.

In this way, a measurement of the $Z\gamma$ cross section in conjunction with the the final-state photon E_T spectrum can be a sensitive test of the electroweak sector of the SM. Several studies have been done on the associated production of gauge bosons in the monophoton channel at the Tevatron and the LHC [12, 13, 14], and have found to be in good agreement with SM predictions. As we shall discuss next, there are plenty of reasons to continue to study the $Z\gamma$ channel in search of new physics.

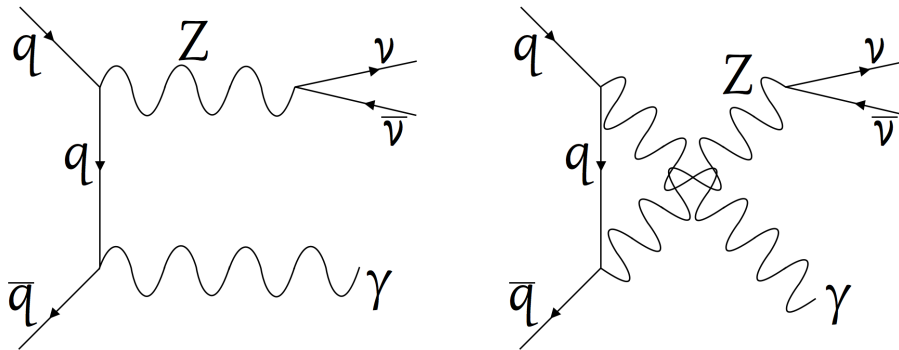


FIGURE 2.4. $Z\gamma$ interactions in t -channel (left) and u -channel (right).

2.1.6. Limitations of the SM. The electroweak theory and the Standard Model, formalized in the 1960s, have been reaffirmed as a successful and robust model by many experiments in the last thirty years. The $W^\pm$ and Z bosons were first observed in 1983 with the UA1 and UA2 experiments at CERN [15, 16], and more recently, a Higgs-like particle was observed at CERN [17, 18]. At the same time, the Standard Model falls short of providing theoretical explanations for everything we observe. The masses and charges of the known particles, the three-generational arrangement of the fermions, and the matter-antimatter asymmetry in the universe are all experimentally observed phenomena that cannot be calculated or explained with the Standard Model alone. A finite value for the Higgs mass doesn't come organically from the SM but requires an extreme fine-tuning of parameters. Additionally, gravity is not incorporated in the SM. Also missing from the model are any candidates to explain dark energy or dark matter. Dark energy, which accounts for 70% of the mass-energy density in the universe, is the name given to whatever is causing the expansion of the universe to accelerate, a phenomenon first observed by the Hubble Space Telescope and confirmed by cosmic microwave background radiation studies. Observations of gravitational effects on astronomical objects indicate that 84% of

the matter, or 25% of the mass-energy density, in the universe is composed of some kind of non-luminous matter, called dark matter [19]. This analysis searches for an indication of BSM physics, and interprets the results specifically in terms of a search for a dark matter candidate, χ .

2.2. Dark Matter

2.2.1. Evidence for dark matter. Multiple different astronomical observations support the widely accepted conclusion that dark matter makes up 25% of the mass-energy content in the universe [20]. These studies invoke the presence of dark matter as a way to reconcile the fact that the electromagnetically observable matter cannot account for the measurable mass-related effects.

Observations have solidly established that galaxies are primarily composed of dark matter. The strongest arguments come from studies of the rotational curves of spiral galaxies. Spiral galaxies are characterized by a central bulge and a disk of stars rotating together around an axis. A “rotational curve” relates the disk velocity of a galaxy, calculated from observations of the redshifts of emission lines from the stars and clouds in the galaxy, in terms of the radius of the galaxy. The brightness of a disk decreases exponentially with its radius and, if the mass profile matched the intensity profile, the velocities of the material in the galaxy should also decrease along the radius. However, Vera Rubin *et al.* showed in the late 1960s that the rotational curves remained flat between 1 and 2 optical radii from the center, corresponding to a distance of 10-20 kpc [21]. The mass of the galaxy could be calculated from the rotation curve by relating the gravitational and centripetal accelerations in terms of the observed rotation curve $v(r)$ and the mass $M(r)$ contained in a sphere of radius r :

$$\frac{v(r)^2}{r} = G \frac{M(r)}{r^2} \quad (2.13)$$

The constant rotational curves lead to a mass distribution directly proportional to r , which then requires a significant dark-matter component to balance the exponentially falling luminous mass distribution in the galaxies. A study of rotation curves for a larger sample of galaxies by Persic, Salucci, and Stel [22] demonstrated the same flatness of the rotational curves, indicating a dark matter mass distribution present in the galaxies. An example rotational curve for the spiral galaxy NGC6503 is shown in Figure 2.5.

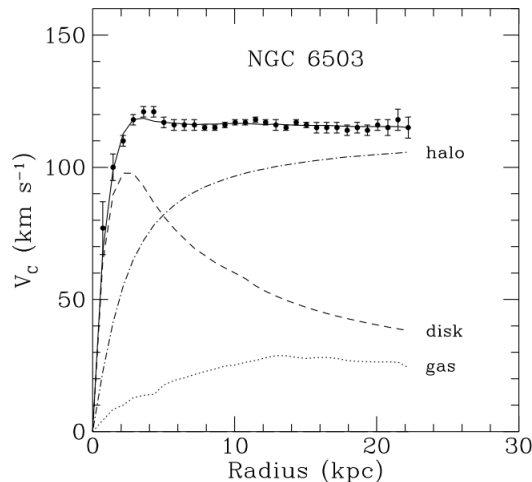


FIGURE 2.5. Rotational curve for the spiral galaxy NGC6503. The data points are measured rotational velocities as a function of distance from the center of the galaxy. The contributions to the rotational velocity from the disk (dashed curve), gas (dotted curve), and dark matter halo (dot-dashed curve) are also shown separately. Figure taken from [23].

Dark matter can be also studied by its gravitational effects on galaxy clusters. The virial theorem, which relates the kinetic and gravitational potential energies, can be applied to a cluster of galaxies to find a relationship between the mass, radius, and velocity dispersion of the cluster. The calculated masses can then be combined with measurements of the optical luminosity of the galaxies in the cluster to calculate the mass-to-light ratios. Fritz Zwicky applied this approach in 1933 to measurements of the Coma cluster of galaxies [24], and Girardi *et al.* did the same in 2000 to a sample of about 100 clusters using multiple surveys [25, 26]; both studies indicated that there was several hundreds of times more matter present than what was observable via EM radiation.

Observations of the X-ray profiles of galaxy clusters are fit to isothermal models in order to calculate the cluster mass, and the combined with optical data to independently calculate the mass-to-light ratio of galaxy clusters. White, Jones, and Forman applied this method to a collection of about 200 clusters that overlapped considerably with the sample used in the Girardi *et al.* study, and good agreement was found, both for the calculated masses of the clusters and the mass-to-light ratios, further strengthening the argument for a large presence of nonluminous matter [27].

Measurements of weak gravitational lensing have also been used to study dark matter in galaxy clusters. In weak lensing, the light from background galaxies is gravitationally

deflected; the ellipticity of background galaxies warp to line up tangent to circles around mass concentrations and their magnitudes are slightly modified. These changes relate linearly to the gravitational potential of the lensing cluster and can be used to map the matter density of the lensing clusters. The most famous example of evidence of dark matter from gravitational lensing comes from the Bullet Cluster. The Bullet Cluster was formed from the collision of a large cluster with a smaller one and is named for a bullet-shaped cloud of gas observed in the X-ray spectrum which contains the majority of the baryonic component. Gravitational lensing maps show that while the X-ray emitting material is mostly located in the central bullet-shaped area of the cluster, the majority of the gravitationally interacting has moved further apart, past the collision vertex of the two clusters. This separation can be explained by postulating that the DM “passed through” without any significant interactions [28].

2.2.2. Weakly Interacting Massive Particles. There are several other examples of studies that provide evidence of dark matter. For example, the WMAP studies of the cosmic microwave background radiation [29] lead to a standard model of cosmology that prescribes a flat universe dominated by dark energy with a significant 25% of the mass-energy density coming from dark matter and a small 5% coming from regular baryonic matter. Another example would be studies of Big Bang nucleosynthesis that predict that most of the material in the universe today is non-baryonic [30]. Possible scenarios require a massive candidate particle, in addition to the baryons and neutrinos, to solve the structure formation issues that arise when trying to model the galaxy structure seen in the universe today. A weakly interacting massive particle, or WIMP, candidate would interact via the gravitational and weak forces and require a mass of at least a few GeV. WIMP candidates with masses in the range of 1-1000 GeV also hold a special significance in particle physics. The Standard Model particles all have experimentally observed masses below or near 200 GeV, but radiative corrections to the Standard Model should raise them to the next unification mass scale, which would be where the strong and electroweak forces unify, $M_{GUT} \sim 10^{16} \text{ GeV}$. The large scale difference between the known masses and the GUT scale might indicate that an intermediate scale exists in the range between the 100 GeV and $\sim 1 \text{ TeV}$ where the masses are stabilized through a restored symmetry [19]. Referring back to the Goldstone

theorem, symmetry breaking usually corresponds to the introduction of new particles the scales at which they break correspond to particle masses. For example, the electroweak scale, $\sim 100 \text{ GeV}$, corresponds to the W and Z masses acquired through spontaneous symmetry breaking. This happy coincidence of scales between cosmology and particle physics is referred to as the “WIMP Miracle.” The cosmological explanation of DM is illustrated in Figure 2.6. The expectation of a new particle in this mass range predicted independently by

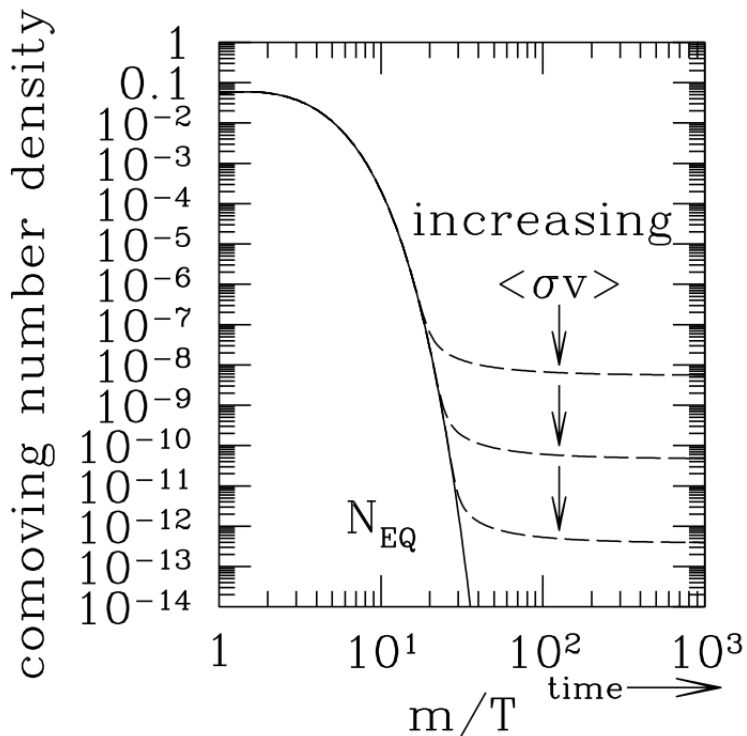


FIGURE 2.6. The progression of the thermal freeze-out of a stable DM WIMP in the early universe. As temperature falls to $< M_\chi$, production stops before annihilation, and as the universe continues to expand, the particles eventually have a low enough density to stop annihilation, leading to a relic population [31].

particle physics and astrophysics is a strong motivation to search for WIMPs in this mass range.

2.3. Experimental Searches for Dark Matter

There are three types of dark matter searches: direct, indirect, and production. Direct searches for a DM candidate, χ , look for evidence of elastic χ –nucleon scattering in detectors that are usually placed deep underground to reduce background interactions. Indirect

searches watch the cosmos for photons or neutrinos produced in $\chi\bar{\chi}$ annihilations. Production searches take place at colliders like the LHC, where dark matter $\chi\bar{\chi}$ pairs may be produced in high energy collisions. As it was mentioned earlier, studies of the $Z\gamma$ channel would be sensitive to new physics like dark matter production at the LHC [32]. The DM could be produced in the reaction $q\bar{q} \rightarrow \chi\bar{\chi}\gamma$, where the photon is radiated by one of the incoming quarks, which would look like an excess of $Z(\nu\bar{\nu})\gamma$ events.

The results of the analysis described in this dissertation are interpreted in terms of recent theoretical work [33, 34, 35, 36] that suggests that DM-and-SM particle interactions involve heavy ($\gtrsim$ a few TeV) mediating particles. The interactions can be described for a range of phenomenologically distinct cases in the framework of an effective theory with the following operators:

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \quad \text{vector, } s\text{-channel} \quad (2.14)$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2} \quad \text{axial vector, } s\text{-channel} \quad (2.15)$$

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R) \quad \text{scalar, } t\text{-channel} \quad (2.16)$$

The DM field is represented by χ , q is a SM quark field, and $P_{R(L)} = (1 \pm \gamma_5)/2$. The contact interaction scale Λ^{-2} is given by $g_\chi g_q M^{-2}$, where M is the mass of the SM-DM mediator and g_χ and g_q are its couplings to dark matter and quarks, respectively. These effective operators are built with the assumption that χ is a Dirac fermion, but if χ was a Majorana fermion the vector operators would disappear but the theory would otherwise remain the same.

Most direct detection searches and production detection searches alike bank on the idea that dark matter must couple to quarks and gluons. The gluon operator predicted by these studies is not expected to generate monophoton events with any measurable significance, but χ -nucleon scattering is modeled through the t -channel with an operator similar to ??, but in terms of nucleons instead of quarks. Production detection searches at colliders, by comparison, rely on DM pair-production, modeled in this case through the s -channel operators shown in ?????. In order to exchange the quark operators for nucleon operators, the SM and DM fields in the coupling terms must be written separately. This is already the case for $\mathcal{O}_V$ and $\mathcal{O}_A$, and $\mathcal{O}_t$ can be converted through a Fierz transformation [34] to

a sum of other operators:

$$\frac{1}{\Lambda^2}(\bar{\chi}P_R q)(\bar{q}P_L \chi) + (L \leftrightarrow R) = \frac{1}{4\Lambda^2}(\mathcal{O}_V - \mathcal{O}_A), \quad (2.17)$$

effectively connecting the t -channel χ -nucleon scattering to the s -channel pair-production mechanisms. Thus, we can express the results of production and direct detection studies in terms of vector operators, which induce spin-independent (SI) scattering, and axial-vector operators which induce spin-dependent (SD) scattering, in a clearly comparable way. If χ is a Dirac fermion, both SI and SD interactions will contribute to $\chi\bar{\chi}$ production at colliders, while the SI interaction will dominate over the SD contribution in direct detection experiments, making this comparison additionally helpful. At the nucleon level, the coupling terms $\mathcal{O}_V$ and $\mathcal{O}_A$ look the same except the quark fields q are replaced by nucleon field terms N and translational coefficients.

DM production searches have some advantages over direct and indirect searches. Unlike direct and indirect searches, collider studies don't have to take into account any astrophysical uncertainties regarding the abundance and velocity distribution of DM. Another strength is that if DM couples through a vector to second- and third-generation quarks, it will be seen from at a collider experiment; this phenomenon would never be seen through direct or indirect detection.

However, colliders are at a disadvantage for cases with a light mediator. The cross section for DM production with a photon or jet can be approximated by

$$\sigma(pp \rightarrow \chi\bar{\chi} + X) \rightarrow \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2 \quad (2.18)$$

where E is the center-of-mass energy of the parton, M is the mass of the mediator, Γ is the mediator width, and q is the four-momentum flowing through the mediator. The cross section for direct detection phenomena is approximately

$$\sigma(\chi N \rightarrow \chi N) \rightarrow \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2. \quad (2.19)$$

For collider experiments, the limit that colliders can set on the coupling constants, $g_q^2 g_\chi^2$, become independent of the mass when $M^2 \ll q^2$; this means that for smaller M values, the limits on the coupling constants become stronger in direct detection studies while they get

weaker in collider studies. The details of each case depend largely on the applied model and the relationship between the mediator mass and the χ mass but, in general, for light mediators with mass $M \lesssim 100$ GeV, the limitations that collider studies can place on direct-detection cross sections are weaker than what is possible in models with greater mediator masses.

In the framework of this theory, the results of a simple counting experiment at the LHC can be used to set limits on a variety of DM couplings that translate into constraints on the $\chi\bar{\chi}$ annihilation cross section as well as the χ -nucleon cross section measured in direct detection experiments. The search for a DM candidate is well motivated by several studies indicating a large amount of non-baryonic matter in the universe that interacts gravitationally, and the monophoton channel provides a clean method of searching for tell-tale signs of physics beyond the Standard Model. As for the monojet channel, similarly composed of events with a single high-energy jet, the predicted cross section is higher than the monophoton channel, but the monophoton channel uncertainties are smaller and the expected contributions from different subprocesses are slightly different. Studies of this sort can at least provide an important comparison for monojet studies and, at best, have the potential to uncover details about the nature of dark matter.

CHAPTER 3

Experimental Apparatus

The study of the associated production of $Z\gamma$ events and the search for DM production presented in this paper uses data collected from proton-proton collisions produced by the Large Hadron Collider experiment (LHC), located at CERN. In addition to being the largest particle collider, the LHC also produces the highest-energy collisions ever recorded at a collider. Most of the year the LHC produces proton-proton collisions, with a few weeks dedicated to colliding lead nuclei for nuclear physics research. The beam collisions occur at four points along the ring inside of detectors: The Compact Muon Solenoid (CMS); A Toroidal LHC Apparatus (ATLAS); LHCbeauty (LHCb); and A Large Ion Collider Experiment (ALICE). Three additional detectors are located along the beam: Total Cross Section, Elastic Scattering and Diffraction Dissociation (TOTEM), LHCforward (LHCf); and the Monopole and Exotics Detector at the LHC (MoEDAL). This analysis uses data gathered by the CMS detector over the 2011 proton collision run. The components of the LHC and CMS are described in the following sections.

3.1. The Large Hadron Collider Experiment

The LHC is a superconducting hadron accelerator and collider that runs along a 27 km circumference ring located between 45 m and 170 m below the surface of the French-Swiss border, having been constructed in the pre-existing LEP tunnel at CERN. The ring is composed of two separate vacuum cavities to hold the counter-rotating proton beams, which are kept on track with 1232 superconducting dipole magnets spread out along the ring [37]. The superconducting dipole magnets have a “twin-bore” design, primarily chosen because of space constraints, that accommodates both beam coils in a single cold mass and cryostat and creates the magnetic flux in both vacuums to accelerate the proton bunches in opposite directions. While supercooled superconducting magnets have been used for years for other detectors like the Tevatron, DESY, and RHIC, these magnets operate at a temperature of

1.9 K and each generate a field above 8 T along 14.3 m, pushing the edge of present technology. Four regions along the ring contain superconducting radio frequency (RF) cavities that generate magnetic fields to accelerate the proton bunches along the ring, increasing the proton energies by about 0.5 MeV per turn. In addition, the beam is focused in the x and y directions with 858 superconducting quadrupole magnets along the ring. The beam is generally focused to a transverse size of about $200\ \mu\text{m}$, but a special triplet of quadrupoles near the interaction regions focus the beam to a transverse size of about $16\ \mu\text{m}$. At its peak performance, the LHC is designed to hold 2808 proton bunches and produce collisions every 25 ns with a center of mass energy of $\sqrt{s} = 14\ \text{TeV}$ and luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$, which corresponds to about a billion interactions per second, for CMS and ATLAS, which were designed to collect data from high luminosity collisions. TOEM and LHCb are designed for lower luminosity studies, $10^{29}\ \text{cm}^{-2}\text{s}^{-1}$ and $10^{32}\ \text{cm}^{-2}\text{s}^{-1}$, respectively, and ALICE exclusively studies the lead ion collisions produced with an energy of 2.8 TeV per nucleus and a peak luminosity of $10^{27}\ \text{cm}^{-2}\text{s}^{-1}$. During the time that data was taken for this analysis, the proton bunch collisions occurred every 50 ns with an energy of $\sqrt{s} = 7\ \text{TeV}$, and the maximum luminosity reached was $2.6 \times 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$.

The LHC, at its peak performance, has 3×10^{14} protons circulating in each beam. Those protons are initially obtained from hydrogen gas. The gas is injected into the CERN duoplasmatron and ionized with an electric field, separating the protons and the electrons. The protons then go through an acceleration sequence before they are injected into the LHC. The injection chain, shown in Figure 3.1, brings the protons through the linear accelerator (LINAC2), Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), and Super Proton Synchrotron (SPS) to accelerate them to energies compatible with the LHC design.

The particles leaving the plasmatron are initially accelerated to 750 keV and focused into a segmented beam by a radio frequency quadrupole, then sent through the LINAC2, a multi-chamber resonance cavity. The protons accelerate up to 50 MeV within microseconds moving through the LINAC2 on their way to the PSB. The Proton Synchrotron setup at CERN was the first major particle accelerator built at CERN, but now it's part of the warm-up act for the LHC. The PSB accelerates the protons to 1.4 GeV in 530 ms, and within a microsecond they're injected into the Proton Synchrotron. The PS accelerates the protons to 25 GeV and organizes them into bunch packets with uniform spacing appropriate to the

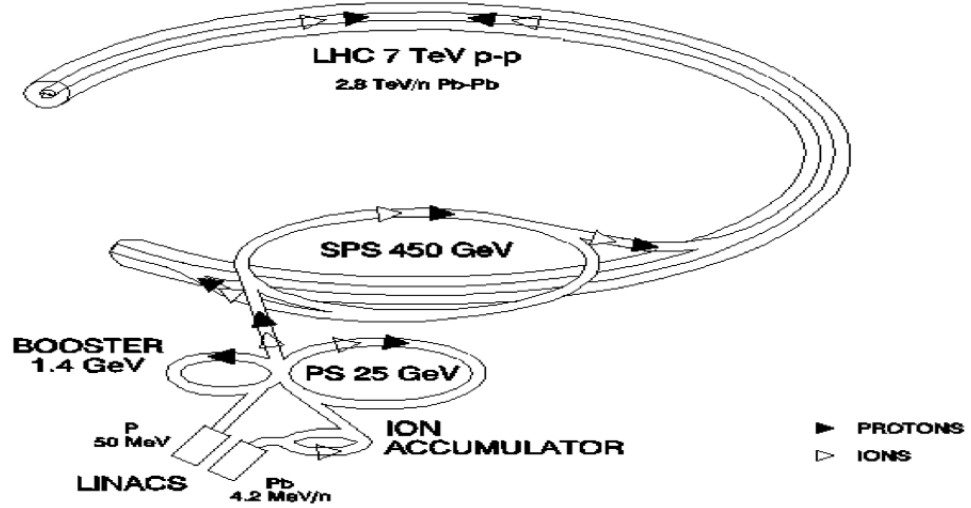


FIGURE 3.1. The injection chain and partial drawing of the LHC Ring. Image taken from [38].

collision rate of the LHC run. At the design performance, 81 bunch packets are formed with a 25 ns, or 8 m, spacing between bunches. Lastly, the protons are accelerated to 450 GeV in 4.3 seconds and sent to the LHC. Once the proton beam is sent to the LHC, the individual proton bunches usually wait to be put in appropriate places along the beamline. Waiting for a proton bunch to be injected and then ramping up to high energy takes about 45 minutes and is the longest part of the injection chain. An image of the injection chain and the LHC ring is shown in Figure 3.1.

3.2. The Compact Muon Solenoid Detector

The Compact Muon Solenoid detector [38] is a general discovery detector located along the LHC about 100 m below the ground near the French town of Cessy. Designing and running this single detector is a collaborative effort that involves over 4300 participants from 179 universities and institutions in 41 countries [39]. The components of the detector are arranged into a central barrel region and two endcaps along the beamline, and all together form a 21.6 m-long, 14.6 m-diameter, 12500 ton machine that is considered compact compared to ATLAS, the other general purpose detector, which takes up 3 times as much space.

The coordinate conventions adopted by CMS set the origin at the nominal collision point inside of the detector. The y -axis points vertically upward, the x -axis points radially

inward toward the center of the LHC, and the z -axis points along the beam line in the counter-clockwise direction from bird's eye view. The azimuthal angle ϕ is measured in the x - y plane perpendicular to the beam axis. The polar angle θ is measured from the z -axis and pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

CMS was designed in the 1990s with an eye toward several different physics goals. Discovering the Higgs was a great motivating factor, but designers also wanted to be able to search for supersymmetric particles, massive vector bosons, extra dimensions, and conduct SM tests and heavy-ion physics. As a result, CMS was designed to include a breadth of detector technologies that could be used to measure a variety of physics objects with good energy and momentum resolution. The components of the detector, listed in the order that the collision products encounter them, are: the tracker, the crystal electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL), a 3.8 T solenoid magnet, and a muon system composed of three different kinds of chambers. The illustration of the CMS detector in Figure 3.2 shows how the different components fit together.

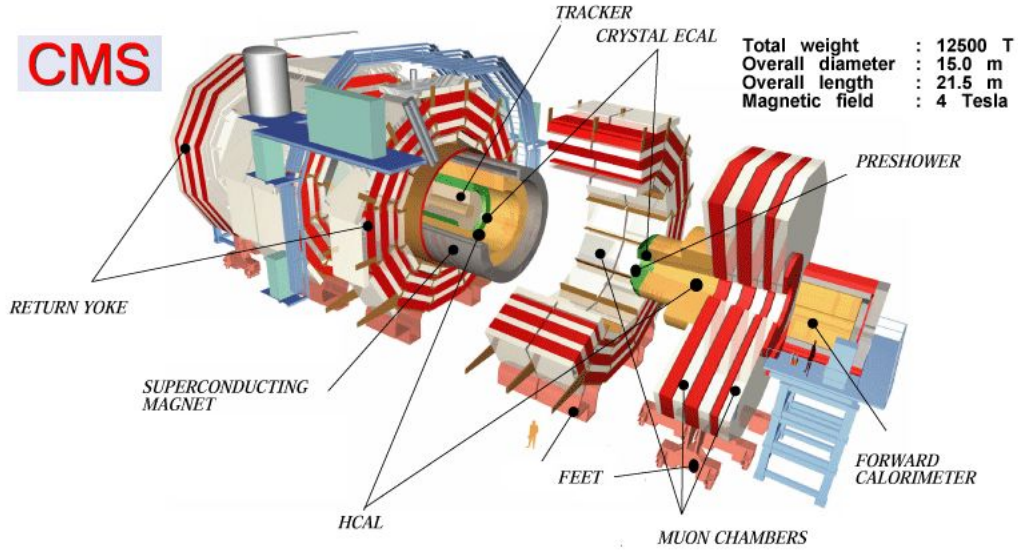


FIGURE 3.2. The Compact Muon Solenoid, pulled apart to show internal structure. Image copyrighted by CERN.

The tracker is composed of both silicon pixel detectors and silicon strip detectors. It covers the pseudorapidity range $|\eta| < 2.5$ and measures the momenta of charged particles. The tracker is surrounded by the ECAL, which uses lead tungstate (PbWO_4) crystals, and the brass-scintillator HCAL. Both calorimeters extend to a pseudorapidity of $|\eta| < 3.0$.

A quartz-fiber and steel Cherenkov forward detector extends the calorimetric coverage to $\eta < 5.0$. The tracker and calorimetry subdetectors are encompassed by the 3.8 T superconducting solenoid, beyond which are the muon systems embedded in the steel return yoke. There are three different muon detectors: cathode strip chambers in the endcaps, drift tubes in the barrel, and resistive plate chambers in both.

With collisions occurring every 50 ns and an average of 16 events being produced by each collision, information is read from the detector at a rate of 20 MHz. However, the computing system can only save information at a rate of 100 Hz, or the information from 100 collisions per second. The CMS trigger system applies selection criteria to the initial energy, timing, and geometric information coming from the detector to select a manageable number of promising events to be saved for further analysis.

The subdetectors and trigger system are described in more detail in the following sections.

3.3. The Silicon Tracker

The silicon tracker is the closest subdetector to the beampipe and measures the momentum of charged particles using the energy deposition positions and the magnetic field of 3.8 T in the region of the tracker. It covers a total length of about 540 cm and extends to nearly 110 cm from the beampipe. A schematic of the tracker configuration can be seen in Figure 3.3. The tracker is designed with as much spatial resolution as possible because the information it collects is used to help reconstruct electrons, muons, hadrons, and jets; differentiate between electrons and photons; and determine the primary interaction vertex as well as the secondary vertices. It is composed of two components: the pixel detector, and the silicon strip detector. The pixel detector is closer to the interaction vertex, where the particle flux is highest, because it provides high resolution information. The silicon strip detector covers the region from about 20 cm to 116 cm away from the beam. This graduated tracking system relies entirely on silicon detector technology to attain the desired spatial precision, signal speed, and radiation hardness necessary for the subdetector located closest to the collision point. The overall design is a compromise between the desire to maximize the aforementioned characteristics, the goal to minimize the amount of extra material present in the detector, such as detector electronics and cooling hardware, that

could cause photon conversion, bremsstrahlung, and other particle interactions unrelated to the collision, and the need to pay for it all.

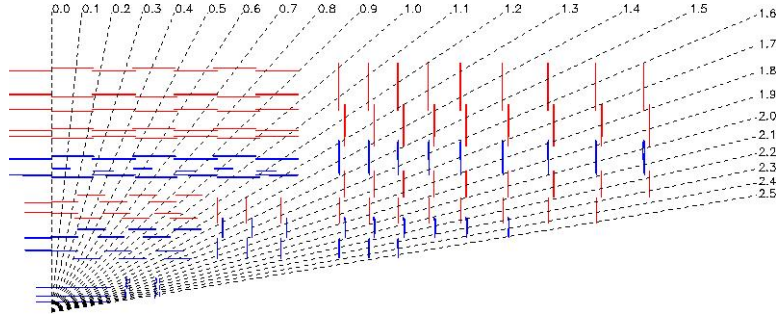


FIGURE 3.3. The layout of the tracker [40].

3.3.1. The Pixel Detector. The pixel detector is designed to be able to make high precision 3D measurements close to the interaction region. In the barrel, the pixel detector has 3 layers that are 53 cm long and are located at a radial distance of 4.4 cm, 7.3 cm, and 10.2 cm from the beam. In the endcaps, the pixel detector is composed of 2 pixel layers arranged in a fan-blade design with a radius of 6 cm and 15 cm and a position of $|z| = 34.5$ cm and $|z| = 46.5$ cm, respectively, from the interaction point, seen in Figure 3.4. There are 48 million pixels in the barrel portion of the pixel detector, and 18 million in the endcaps, covering a total surface area of 1 m^2 . The coverage extends to $|\eta| < 2.5$ so that most charged particles passing through the detector will register at least 2 deposits in the pixel detector.

The silicon pixels measure $100 \times 150 \text{ } \mu\text{m}^2$ and provide a spatial resolution of about $10 \text{ } \mu\text{m}$ in r - ϕ and $20 \text{ } \mu\text{m}$ in the z direction. We are able to achieve the small spatial resolution because the magnetic field in the barrel region is aligned perpendicular to the electron drift in the pixels and deflects the signal charge; When a charged particle deposits energy in the pixel, the magnetic field causes the signal charge in one pixel to spread to its neighbor. These signals can then be interpolated with a weighted algorithm to provide an improved spatial resolution for the deposition. The blades of the endcap disks are rotated by 20° to utilize the same Lorentz effect.

The pixel detector sensors have an n-on-n design: the pixels are composed of high dose n-implants attached to a high resistance n-substrate. This style was chosen to ensure functionality during high particle flux, which is critical since about 1000 particles hit the

tracker from each bunch crossing, leading to a hit rate density of 1 MHz/mm^2 at a radius of 4 cm [38]. Each pixel is bump bonded to its own readout chip for really fast readout. During data-taking periods, the pixel tracker is cooled to operate at around -10°C to reduce radiation damage.

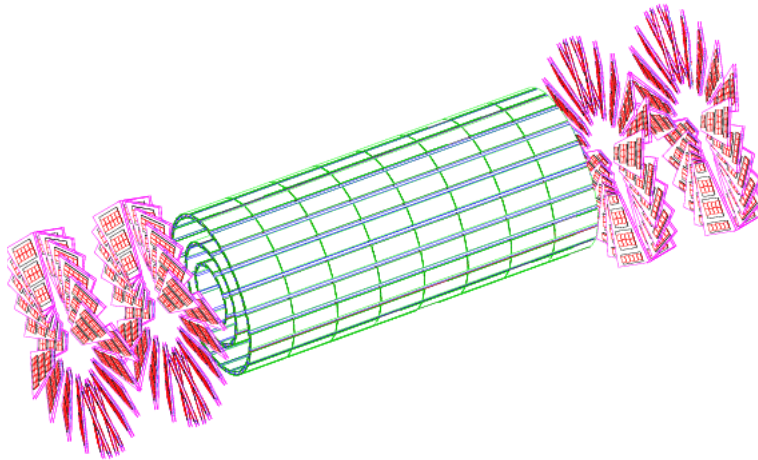


FIGURE 3.4. The configuration of the pixel detector [40].

3.3.2. The Silicon Strip Detector. Beyond the third pixel layer, at a distance of $r = 20 \text{ cm}$ from the beam pipe, the distribution of particles coming from the interaction point are spread out enough to use 10 layers of silicon strip detectors for the rest of the tracker. The silicon strip detector is composed of single-sided p-on-n type silicon sensors and, like the pixel detector, is built to be radiation hard. CMS is the first experiment to use silicon detectors in the outer track region, which was made possible by three new developments: the ability to fabricate sensors on 6 inch wafers instead of 4 inch wafers; front-end readout chips were implemented; and the module assembly was automated, with wire bonding machines with high throughput. These steps all significantly reduced the cost of the detector and, in the case of the last two, improved the signal-to-noise ratio. The silicon strip detector provides coverage out to $r = 116 \text{ cm}$ from the barrel, $|z| = 280 \text{ cm}$, and $|\eta| < 2.4$. The balance between coverage and cost lead to three distinct components of the silicon strip detector, shown in Figure 3.5: the tracker inner barrel (TIB) and tracker inner disks (TID), tracker outer barrel (TOB), and tracker endcaps (TEC).

The TIB and TID contribute four barrel layers and three disks and cover the region of $20 \text{ cm} < r < 55 \text{ cm}$ and provide up to 4 $r - \phi$ measurements from a single trajectory. In

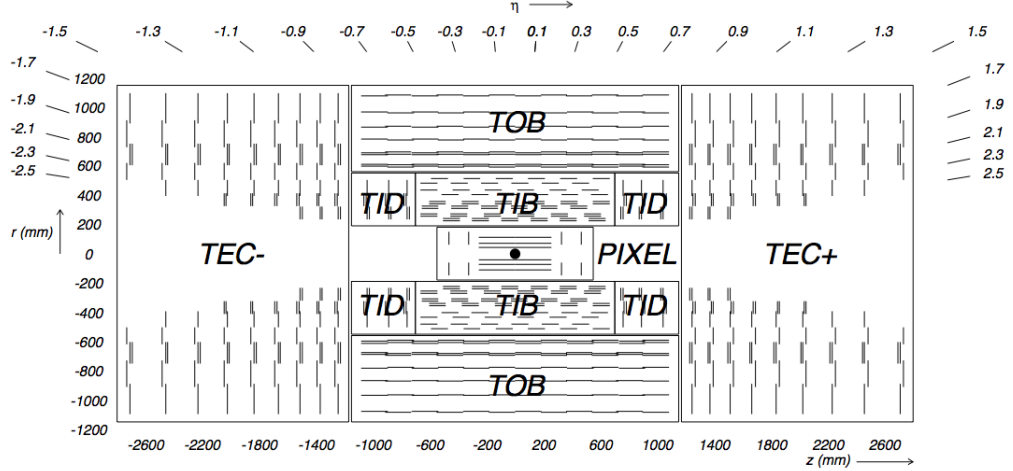


FIGURE 3.5. The configuration of the silicon strip detector [40].

order to avoid shallow track crossing angles, the TIB extends to $|z| = 70$ cm and the TID covers the remaining length of the barrel out to $|z| = 110$ cm. The silicon strip sensors in the TIB and TID are $320 \mu\text{m}$ s long, aligned parallel to the beam axis in the barrel and radially on the disks, and have different strip pitches depending on their location. Layers 1 and 2 in the TIB have a strip pitch of $80 \mu\text{m}$ s and layers 3 and 4 have a $120 \mu\text{m}$ strip pitch, producing a point resolution of 23 and $35 \mu\text{m}$ s, respectively. The mean pitch in the TID varies from 100 to $141 \mu\text{m}$ s.

The TIB and TID are encompassed by 6 layers of the TOB, which extends the tracker to $r = 116$ cm and $|z| = 188$ cm. Because of the further decrease in particle flux, the TOB layers have a thicker pitch strip: $183 \mu\text{m}$ s for the first four and $122 \mu\text{m}$ s for the farthest two. The silicon sensors are also thicker, measuring $500 \mu\text{m}$, to transmit a higher signal and maintain the signal-to-noise ratio.

The TEC on both sides are made up of 9 disks carrying up to 7 rings of silicon detectors and provide coverage in the region of $124 \text{ cm} < |z| < 282 \text{ cm}$ and $22.5 \text{ cm} < r < 113.5 \text{ cm}$. Like the other detector components, the strip thickness and pitch of the detectors on the rings varies by distance from the interaction point. The inner 4 rings are $320 \mu\text{m}$ s thick and the outer 3 are $500 \mu\text{m}$ thick, with an average pitch between $97 \mu\text{m}$ and $184 \mu\text{m}$. Altogether, the TEC can make up to 9 ϕ measurements on a passing charged particle.

To optimize the track reconstruction accuracy, several of the layers and rings have a second strip detector mounted on the back. The first two layers of the TIB and TOP,

the first two rings of the TID, and rings 1, 2, and 5 of the TEC are back-to-back with another microstrip detector module that is mounted with a stereo angle offset of 100 millirad. This offset second detector module allows the silicon strips to measure a second position coordinate, providing a z coordinate in the barrel and an r coordinate in the disks. While the point resolution varies between $230 \mu\text{ms}$ and $530 \mu\text{ms}$ in the barrel and depends on the pitch in the disks, it means that at least four hits in the silicon strip tracker within $|\eta| < 2.4$ will provide 2D information for the track.

3.4. The Electromagnetic Calorimeter

The ECAL [41], shown in Figure 3.6, is composed of 75848 PbWO_4 crystals. Unlike the tracker, which measures small deposits of energy from charged particles, calorimeters measure the energy of charged and neutral particles. They do so by causing the particles to decay within the calorimeter, through electromagnetic showers in the case of the ECAL, and then measuring the deposited energy. With this motivation in mind, lead tungstate is a good choice for this detector. It has a high density of 8.28 g/cm^3 , short radiation length of $X_0 = 0.89 \text{ cm}$, and small Molière radius of 2.2 cm [41]. Together, these features give the ECAL a high granularity and allow it to be relatively compact. The crystals are also fast, emitting 80% of the light from interactions within 25 ns , and are radiation hard. The light emitted by the crystals during the scintillation is blue-green.

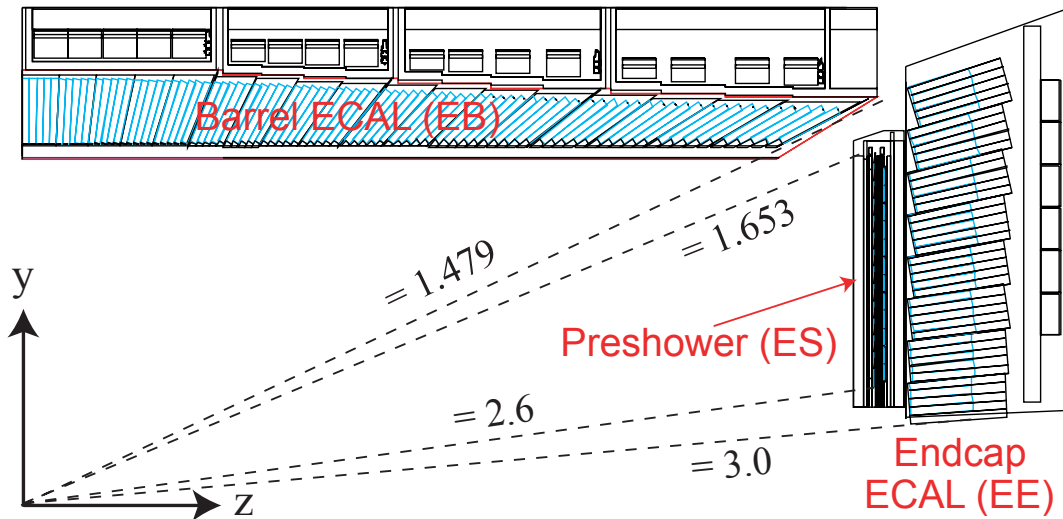


FIGURE 3.6. Geometrical configuration of the ECAL shown in the y - z plane. [41].

The majority of the PbWO_4 crystals, 61200, can be found in the barrel section of the ECAL (EB), while 7324 crystals sit in each of the endcaps (EE). The crystals in the barrel are 230 mm long, or 25.8 radiation lengths, and measure $22 \times 22 \text{ mm}^2$ across the face closest to the interaction point, covering an area of 0.0174×0.0174 in $\eta - \phi$ space, and $26 \times 26 \text{ mm}^2$ on the far side. In the EB, the crystals are arranged in a cylinder 2×85 crystals long in the $|z|$ direction with a circumference of 360 crystals in ϕ to provide continuous coverage out to $|\eta| < 1.479$. They are aligned in a quasi-projective manner with respect to an axis about 3° off of the nominal interaction point, shown in Figure 3.7, in order to avoid lining cracks up with particle trajectories. The crystals in the EE have a face measuring

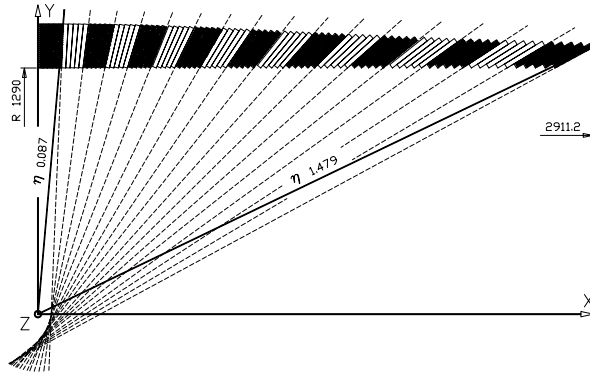


FIGURE 3.7. The crystals in the ECAL are offset by 3° [41].

$28.6 \times 28.6 \text{ mm}^2$ and a length of 220 mm, and the EE extend the ECAL coverage to include the range $1.479 < |\eta| < 3.0$. Detector coordinates can be given in $i\eta$ and $i\phi$, where each crystal corresponds to a single $(i\eta, i\phi)$ coordinate and $i\phi = 1$ begins at the x -axis and the crystals on either side of $\eta = 0$ are $i\eta = \pm 1$, depending on the side. Avalanche photodiodes collect the scintillation light emitted by the crystals in the barrel and vacuum phototriodes collect the scintillation light from the crystals in the endcaps. An ECAL preshower detector made up of lead disks and 2 planes of silicon strip detectors sits in front of the EE for extra spatial precision on ECAL measurements, helping to distinguish between single high-energy photons and collimated photon pairs from π^0 decays.

The energy resolution of the ECAL was studied in a test beam and can be expressed as a function of energy in terms of its individual components:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{12\%}{E}\right)^2 + 0.3\%^2 \quad (3.1)$$

where the $1/\sqrt{E}$ term is related to stochastic fluctuations in EM showers, the $1/E$ term is related to the electronics noise, and the constant includes calibration errors.

3.5. The Hadron Calorimeter

The HCAL [42] is a sampling calorimeter composed of alternating layers of brass or steel absorber and plastic scintillator. It is used to measure hadronic jets and neutrinos or other exotic sources of missing transverse energy. Hadronic particles pass through the dense absorber and interact with the nuclei, producing secondary particles which also interact with the absorber material and produce a cascade of particles, also known as a hadronic shower. The cascade particles then pass through the scintillator and interact, causing the scintillator to fluoresce, and the signals collected in the different layers of scintillator are combined to measure the energy of the hadrons.

The HCAL is constructed out of layers of brass absorber and Kuraray SCSN81 plastic scintillator [40]. The plastic scintillator was chosen for its stability and radiation hardness, and the brass was chosen because it is dense, nonmagnetic, and structurally stable. When the scintillator fluoresces, it emits light in the blue-violet range which goes through wavelength-shifting fibers embedded in the scintillator to hybrid photodiodes, which convert the signals into electrical pulses. There are about 70000 scintillator tiles in the HCAL, which are sandwiched between brass absorber layers to form projective towers that measure hadronic energy showers.

The HCAL coverage is divided into three parts: $|\eta| < 1.4$ is the barrel region, the HCAL endcap component (HE) covers $1.4 < |\eta| < 3.0$, and the forward component (HF) extends the coverage to $3.0 < |\eta| < 5.2$. In the HCAL barrel component (HB), 17 scintillator/absorber layers are arranged into projective towers that extend 5° in ϕ , 0.087 in η , and $1.77 \text{ m} < |z| < 2.95 \text{ m}$ along the beam. The first and last two absorber layers are stainless steel for structural purposes, and the brass scintillator layers in the middle are 50.5 to 56.5 mm thick, becoming progressively thicker farther away from the beam pipe. The first layer of scintillator is 99 mm thick to sample showers coming out of the ECAL, and the remaining HB scintillator layers are 3.7 mm thick. Hadronic showers are long and require about a meter of material to be accurately measured, but the size of the HCAL

is constrained by the other elements of the detector. As a result, the HCAL barrel component (HB) fills the space between the ECAL and the solenoid and an additional outer calorimeter (HO) catches the tails of showers just beyond the magnet. The solenoid acts as an additional layer of absorber and the HO is located in the first 5 layers of the iron return yoke beyond the solenoid, extending the HCAL coverage to uniformly measure 11.8 nuclear radiation lengths (including the ECAL).

The HE, shown in Figure 3.8 with the HB and HO, is divided into $\phi = 5^\circ, 10^\circ$, and 20° segments, decreasing in coverage with increasing η . The HE is also composed of 17 layers

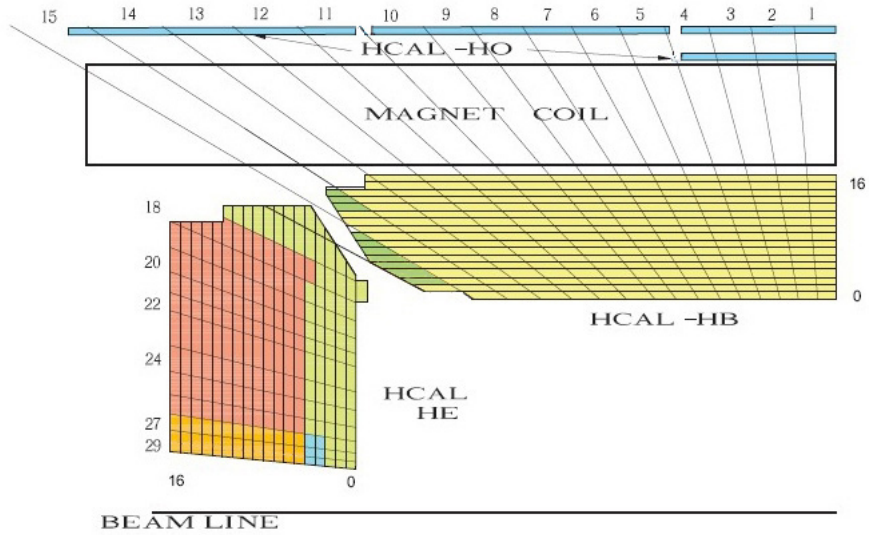


FIGURE 3.8. The layout of the HCAL barrel and endcap components shown in r - z [42].

of scintillator and absorber, but the brass plates are 79 mm thick and the scintillator is 3.7 mm thick. The HF is 11m from the interaction point but very close to the beam and is designed with steel absorbers and quartz scintillating fibers, which were selected because of their radiation-hard properties that will survive the particle flux at high η , which will deposit nearly 8 times as much energy compared to activity in the barrel. In the forward region, signals are read out with photomultiplier tubes.

The energy resolution in the HCAL is estimated with simulated samples of jet events for different η and energy ranges [40].

3.6. The Muon System

As the name implies, the CMS design places a lot of importance on the muon system. Many interesting predicted physics phenomena decay to muons, such as the SM Higgs decaying to ZZ or ZZ^* , and muon signals are clean, with fewer backgrounds than electrons or jets thanks to their long lifetime and distinctive energy deposit pattern. The CMS muon system was designed with three goals in mind: robust muon identification, precise muon p_T measurement, and reliable triggering for muon events. Three different gaseous detector designs were implemented into CMS to address these goals: the drift tube (DT) chambers, cathode strip chambers (CSCs), and Resistive Plate Chambers (RPCs), all shown in Figure 3.9. The DT are in the barrel region of CMS, covering the central region out to $|\eta| < 1.2$, the CSCs provide endcap coverage in $1.2 < |\eta| < 2.4$, and the RPCs are distributed in both the barrel and the endcap out to $|\eta| < 1.6$.

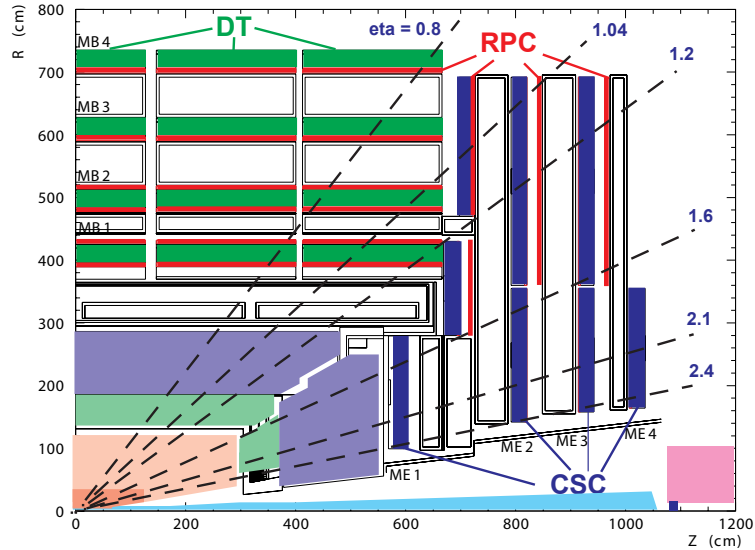


FIGURE 3.9. Geometrical configuration of the ECAL shown in the y - z plane. [40].

3.6.1. Drift Tube Chambers. The DT chambers are located in the barrel region because the muon and background rates are both low and the magnetic field is uniform. Each DT measures 40 mm wide, 13 mm high, and 2 to 4 m long. They are filled with an 85/15 mixture of Ar and CO_2 gas and contain a uniform electric field. Muons that pass through the tubes ionize the gas, liberating electrons that drift through the tube toward

the central 3600V anode wire and produce an electron avalanche near the wire, creating a signal.

The DTs are organized into four layers of DT cells, called superlayers (SLs), that are staggered by a half cell to prevent muons from slipping through the cracks. The first three layers of DT chambers have three SLs: two with wires running parallel to the beam that make ϕ measurements that sandwich a third SL oriented perpendicular to the beam that measures a muon's location in z , as shown in Figure 3.10. In the fourth layer, the DT

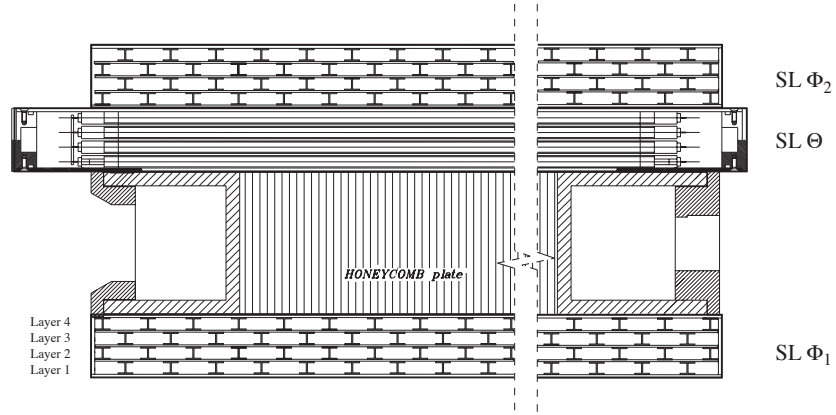


FIGURE 3.10. Schematic of a drift tube chamber with three superlayers. [41].

chambers each have two SLs that are both oriented to make ϕ measurements. A honeycomb plate is placed between the first and second SL in the chambers to provide structure and lengthen the lever arm of the chamber measurement, improving the p_T resolution.

The DT chambers record the position of passing muons with a resolution of 150 to 200 μms . The drift time is long, between 375 ± 6 and 385 ± 4 nanoseconds, which is fine for measurements given the low occupancy rate in the barrel, but it further underscores the importance of the RPCs for trigger purposes.

3.6.2. Cathode Strip Chambers. The CSCs are used for muon measurements in the endcaps, where the muon rates are high and the magnetic field is large and uneven. They are radiation hard, provide a fast response time for trigger purposes, and are finely segmented which helps with reconstruction.

The CSCs are also gas-filled detectors that measure ionization. The chambers are trapezoidal in shape, filled with a mixture of Ar, CO₂, and CF₄ gases, and segmented into six layers, each with a layer of cathode strips aligned radially and held at a negative voltage

and a perpendicular layer of anode wires held at a positive voltage. When a muon passes through a layer it ionizes the gas and electrons drift toward the anode wire, creating a cascade in its wake, while an accompanying positive charge is registered on the cathode strips, shown in Figure 3.11. The combined signal creates a 2D measurement, the cathode strips providing a location in ϕ -space and the anode wires measuring the radial distance from the beam line.

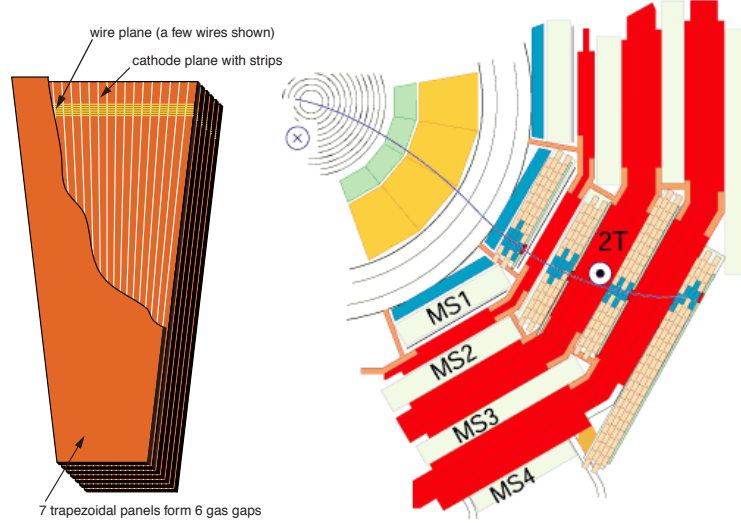


FIGURE 3.11. (left) View of a CSC chamber. (right) A muon shown depositing energy in the CSCs in a wedge view of CMS transverse to the beamline [40].

The chambers are arranged in each endcap as four disks, or “stations”, of concentric rings formed by the chambers interleaved with the iron in the return yoke, also shown in Fig. 3.11. The orientation of the rings is staggered in ϕ in order to reduce the gaps in coverage. In the range of $1.2 < |\eta| < 2.4$, a muon will cross three to four CSCs.

Multiple sources have been used to study the position and timing resolution in the CSCs. The position resolution depends on a number of variables including the pitch of the chamber, the position in the chamber, and the recorded charge, but the spatial resolution varies in the range of $58\text{--}236\text{ }\mu\text{m}$ s, and angular resolution is of the order of 0.5° in ϕ [38, 43]. The CSCs are read out at 50 ns intervals around a hit. The first two bins act as a dynamic pedestal for the measurement and timing information from multiple hits in a segmented track results in a time resolution of round 2 ns, which compares well to the 30 ns it takes for the muons to reach the CSCs [38, 43].

3.6.3. Resistive Plate Chambers. CMS uses double-gap RPCs to obtain fast muon information for trigger purposes. The RPCs are made of two layered gas chambers held at a high potential difference by the positively charged anode plates on the top and bottom (based on the orientation in the detector) and the pair of negatively charged cathode strips sandwiched between the chambers, shown in Figure 3.12. The sandwich design allows the

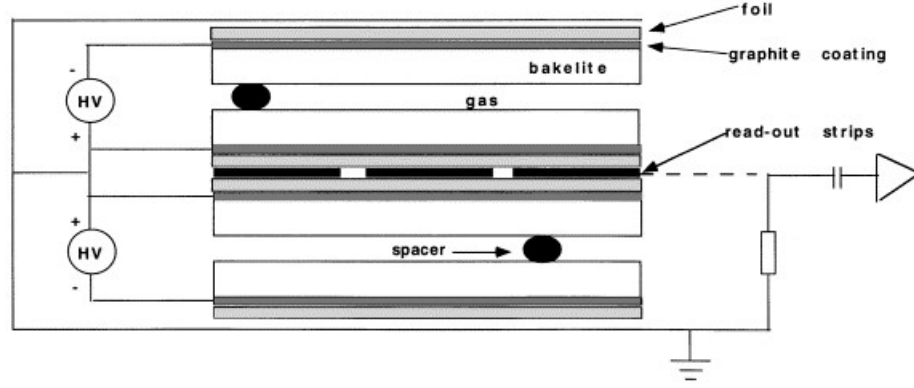


FIGURE 3.12. Configuration of the RPC. [40].

single gaps to operate with a higher effective efficiency than a single-gap detector at the same voltage. Each chamber is 2 mm thick, filled with a gas mixture of $C_2H_2F_4$, C_4H_{10} , and SF_6 . A charged particle passing through the RPC will ionize the gas, and the electric field will produce a local electron avalanche, immediately inducing a charge on the cathode readout strips. The signal from the RPC is the combination of the signals from the pair of cathode strips.

The RPC readout strips are aligned to measure the ϕ direction and vary in size to match the DT and CSC coverage in the barrel and endcaps, respectively. Six layers of RPCs are embedded in the barrel, with two in the first two muon chambers and one in each consecutive chamber. More RPCs are placed in the stations closer to the beam to detect lower- p_T muons for the sake of triggering. In the endcaps, the RPCs were designed to extend to $|\eta| < 2.1$ in four layers, but budget realities limited the RPCs to three layers built in $|\eta| < 1.6$.

The spatial resolution of the RPC measurements varies from 0.86 cm to 1.32 cm depending on the region of the detector. However, the RPCs primary function is to provide fast, accurate timing information to use in triggering and to assign muons to the correct

bunch crossing during reconstruction, and studies have shown that the RPCs are able to tag events within the 25 ns bunch crossing time with a resolution better than 2 ns.

3.7. The Trigger System

At its peak performance, the LHC produces 40 million collisions in the CMS detector every second. There is not enough time to process that much information, and even if there was, most of the collisions will produce scattering events and other low-energy interactions that are unlikely to include new physics. The trigger system [44] uses the information from the subdetectors to select potentially interesting events and reduce the flow of information from 40 million collisions per second to about a hundred collisions per second. In order to maintain a high selection efficiency with the given time and computing constraints, the trigger selection process is split into two steps: The Level-1 (L1) trigger and the High Level Trigger (HLT).

The L1 trigger is an intermediate step designed to reduce the rate of collisions saved for further processing from 40 MHz to less than 100 kHz. Digitized signals from the detectors are first processed into single vectors called trigger primitives which contain information like position, direction, bunch crossing, and quality information. The trigger primitives are collected and built into larger objects to see if the event passes local, regional, and finally global selection thresholds while the rest of the event information is held in the pipeline. The selection thresholds, collectively referred to as the trigger menu, do not change unless the beam energy or instantaneous luminosity increases, in which case they are raised or prescaled. The L1 selection must be accomplished within $\sim 1 \mu\text{s}$; the front-end electronics can store event information for three microseconds, corresponding to the information from 128 bunch crossings, and time is lost due to latency and processing. Based on the reduced intermediate rate event, the L1 trigger sends an event to the HLT once every $10 \mu\text{s}$.

While L1 is controlled by mostly preprogrammed electronics, the HLT is a fully programmable software system run on commercial processors. The HLT, which is run by the Data Acquisition (DAQ) system, has access to all of the subdetector information from each event and is able to build physics objects, like jets and photons, and execute complex calculations on par with the offline reconstruction as part of the selection process. The processing

time for a single event it about 1 s, and the HLT reduces the data flow to 100 Hz, which is a level that can be read out and stored to disk.

The DAQ reads out the front-end electronics to the HLT when an event passes the L1 trigger. It is in charge of running the HLT selection algorithms and sending the interesting events along to be read out and stored to disk, along with a small sample of events that fail the trigger system. In addition, the DAQ operates the Detector Control System, which runs and monitors all of the detector components and infrastructure elements, and makes changes to the L1 trigger menu when necessary. An important tool used by the DAQ for optimizing the performance of the CMS machine is the instantaneous luminosity, which is measured every few seconds with a statistical accuracy great than 1% using signals from the HF. The instantaneous luminosity information provides useful feedback to the LHC accelerator team in order to maximize the delivered luminosity, and is stored for each 23.3-second-long luminosity section by CMS for offline data analysis.

CHAPTER 4

Event Reconstruction

The reconstruction process, like the trigger system, progresses in steps. The first step in reconstruction is to convert the digitized signals from the subdetectors into “hits” which include energy, timing, and global detector position information. Various algorithms are used to combine these hits into 4-vector information associated with more complex objects or particle candidates. In many cases, some of these first steps are accomplished by the trigger as a means of identifying collisions with events of interest and are later rerun offline during reconstruction. In this chapter, the first section includes a brief discuss of the reconstruction approach for electrons, muons, jets, and missing transverse energy ($\cancel{E}_T$), and the second section goes into more detail for photon reconstruction.

4.1. Particle Reconstruction

4.1.1. Track Reconstruction. A track is a physics object that is reconstructed from a collection of hits in consecutive tracker system layers. Tracks are fundamentally important to the reconstruction of particle candidates that are expected to deposit energy in the tracker, like muons and jets, when used in conjunction with information from other subdetectors. The track reconstruction steps rely on the fact that the tracker system has extensive coverage out to high η , and that the magnetic field is nearly constant in a large part of the tracker. The well-understood and uniform magnetic field, spacing between tracker layers, and precise modeling of the material between sensors allows us to reconstruct tracks with great accuracy using a helical model. Being able to precisely reconstruct the curvature of the tracks in the known magnetic field also allows us to measure the transverse momentum of the physics object with great precision.

Once the signals from the pixels and strips are converted into hits, there are three steps in the track reconstruction process: track seed identification, pattern recognition, ambiguity resolution, and a “final fit” [40]. A track seed is built from an aligned pair or triplet of hits in the pixel detector and defines the initial trajectory and errors for the track. A standard

Kalman filter is used to search along that trajectory, layer by layer, in an iterative manner; the measurements from each new collected hit constrain the search and define the track with greater resolution. Several concurrent iterative searches reconstruct tracks, and some of the tracks can wind up sharing hits, so an additional step is taken to make sure hits are only assigned to a single track, resolving ambiguities with a χ^2 fit measurement. In the last reconstruction step, a Kalman filter is also used to optimize the final fit of the trajectory of the track as a whole. Reconstructed tracks must have at least 8 hits in the tracker, with no more than one empty tracker layer among the successive hits, and must have $p_T > 0.8 \text{ GeV}$.

The position resolution of the track is calculated in the silicon strips as a function of the track width on the sensor in the plane perpendicular to the strips, and the error on the position is estimated based on the spatial agreement of the reconstructed trajectories and the Kalman filter predictions. A greater resolution is achieved by comparing the hit positions in two overlapping modules in the same layer from a single passing track, and was measured in a single module to be $12.8 \pm 0.9 \text{ } \mu\text{m}$ in x and $32.4 \pm 1.4 \text{ } \mu\text{m}$ along y [45]. Studies done with data from the early 2010 LHC run were able to test the position and momentum resolution in the tracker by reconstructing very well-known resonant particles that decayed into dimuon pairs, like the upsilon shown in Figure 4.1 and the J/ψ , and particles that decay into long-lived particles like V^0 , which decays to K_S^0 and Λ^0 where $V^0 \rightarrow \pi^+\pi^-$ and $\Lambda^0 \rightarrow p\pi^-$. The momentum resolution was tested by reconstructing these physics objects from muon pairs because the muon objects are very well measured and identified from the combined tracker and muon system information. The K_S^0 and Λ^0 resonances were reconstructed from oppositely charged tracks that originated from well-defined secondary vertices in the tracker, and their measurements reported the track positions with a resolution of $12.8 \pm 0.9 \text{ } \mu\text{m}$ in x and $32.4 \pm 1.4 \text{ } \mu\text{m}$ in y [45]. By expressing the p_T resolution as a function of the kinematics of the muons in the decay $J/\psi \rightarrow \mu^+\mu^-$, the data agrees well with results from simulation studies, which indicate the p_T resolution in the tracker to be within 1% [46].

Track reconstruction is important for reconstruction of the event as a whole because reconstructed tracks determine the initial interaction point, referred to as the primary vertex, and the position of the primary vertex is used with shower information from the calorimeters to calculate the momentum of a particle candidate. Vertices are reconstructed in a 2

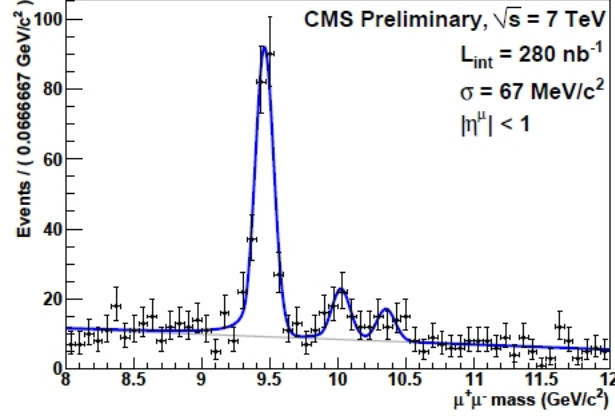


FIGURE 4.1. Invariant mass distributions of Υ 1S, 2S, and 3S reconstructed from muon pairs using tracks. Copyright CERN.

step method employing an adaptive Kalman filter, first by grouping tracks into vertex candidates and then determining the candidate with the best estimate of the source position, covariance matrix, and fit indicators like χ^2 . Multiple vertices are reconstructed in an event, corresponding to the multiple pp interactions that occur in each collision due to the high luminosity of the LHC. The primary vertex is defined as the vertex that corresponds to the largest sum of the squares of the associated track p_T values. The efficiency and resolution of the primary vertex are measured in a tag and probe study that splits the tracks coming from a vertex to test how well they match to the assigned primary vertex, the results of which are shown in Figure 4.2. The primary vertex efficiency is estimated to be 100% for vertices made out of at least five tracks.

4.1.2. The Particle-Flow Algorithm. Jets and $\cancel{E}_T$ are both higher-order objects that are reconstructed using information from multiple subdetectors. Different methods exist for reconstructing both objects, but in this analysis the particle-flow algorithm is used to reconstruct both of them. The particle-flow algorithm [48] sequentially aggregates the information from all of the subdetectors for a single collision to form a complete picture of the event. The signals from the subdetectors are initially combined into “elements” of charged-particle tracks, calorimeter clusters, and muon tracks. The elements are linked within and between subdetectors into blocks with a linking algorithm that assigns a quality value to each link that is inversely proportional to the distance between elements. Muon candidates are reconstructed first and their elements are removed from the blocks; electron

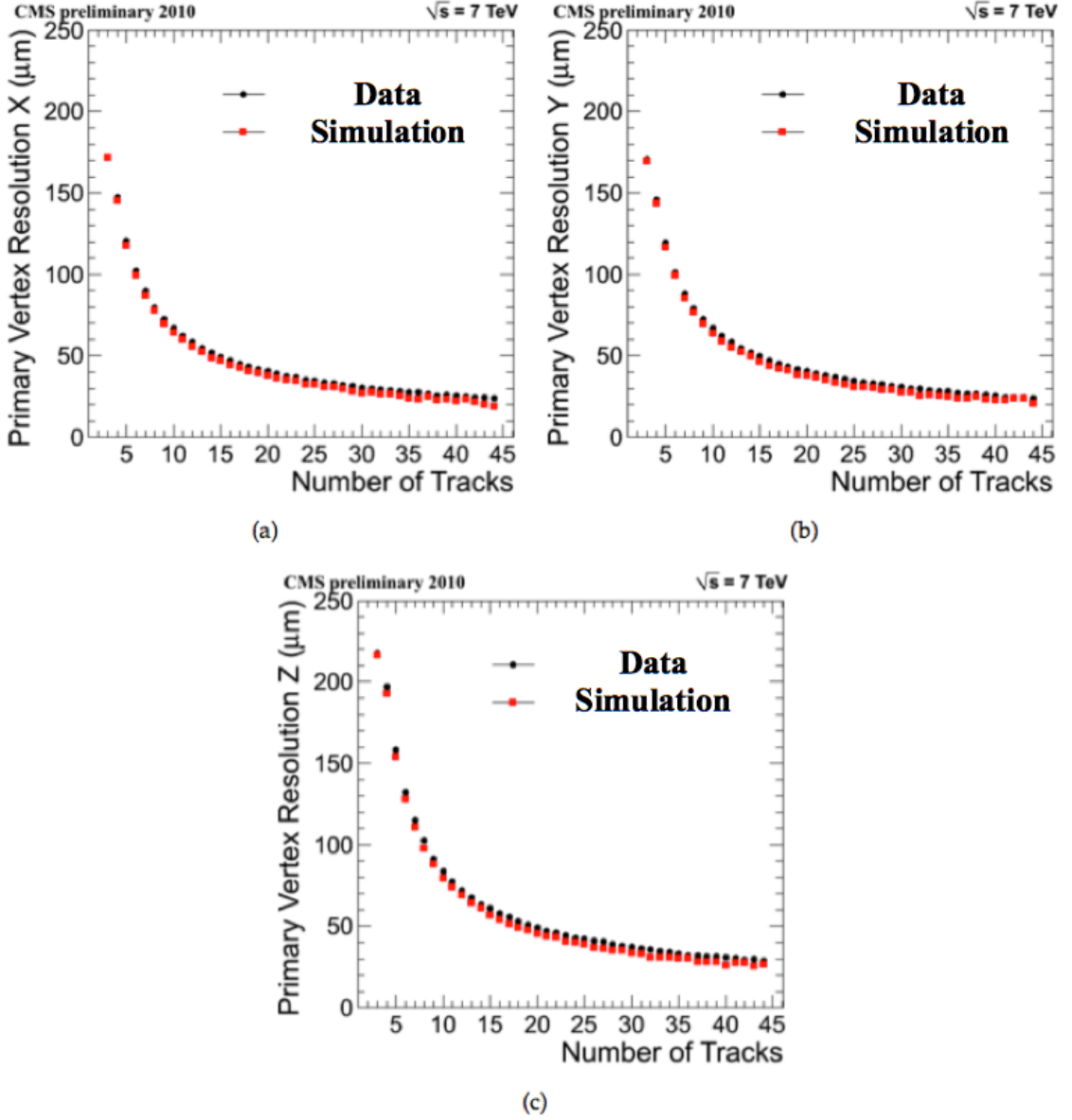


FIGURE 4.2. Primary vertex resolution as a function of the number of tracks in the vertex along the (a) x , (b) y , and (c) z axes [47].

reconstruction follows, and the remaining information is reconstructed into photons, hadrons and, rarely, additional photons [48]. These particle-flow reconstructed particles have been successfully used to reconstruct more complex objects like tau leptons and leptons and photons with isolation requirements. Jets and missing transverse energy, which are relevant to this study, are also reconstructed using the particle-flow algorithm. Good agreement has been shown between particle-flow reconstructed data and simulated events with dijet samples, as is visible in Figure 4.3.

4.1.3. Jets. Jets are relatively collimated streams of particles, primarily composed of hadrons and other particles that originate from a single parton. In this analysis, the jet candidates are reconstructed from particle-flow constituent particles like charged hadrons, neutral hadrons, photons, electrons and muons by the anti- k_t algorithm [49]. The anti- k_t algorithm is a combination of the k_t and Cambridge/Aachen jet-finding algorithms. This algorithm is infrared- and collinear-safe, and is used because the reconstructed jet shape isn't influenced by soft radiation, which means that the reconstruction method is less susceptible to pileup than comparable methods.

In general terms, the algorithm proceeds to build a cluster by comparing the variables d_{ij} and d_{iB} , where d_{ij} corresponds to the distance between two particles or clustered pseudojets, i and j , and d_{iB} corresponds to the distance between i and the beam. If d_{ij} is the smaller distance, the two objects are clustered into the same jet and the algorithm continues to make comparisons between i and other neighboring objects. If d_{iB} is the smaller distance, i is considered a complete jet and removed from the algorithm; this process is repeated until no objects are left to compare. The variables d_{ij} and d_{iB} are defined as:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \Delta_{ij}^2 / R^2 \quad d_{iB} = k_{ti}^{2p} \quad (4.1)$$

where Δ_{ij} is the distance between the two objects in $\eta - \phi$ space, k_{ti} is the transverse momentum of object i , R is the jet radius in $\eta - \phi$ space, and p controls the relative strength of the energy-geometry relationship. The anti- k_t algorithm is given by $p = -1$, which means that soft particles will be attached to nearby hard particles, which have a larger- p_T and penetrate well into the HCAL, before they cluster with other soft particles. There are three clustering scenarios: if a hard particle has no hard neighbors within a distance of $\Delta_{ij} = 2R$, a conical jet will be reconstructed; if two hard particles are within $R < \Delta_{ij} < 2R$, two jets will be reconstructed and one or both of them will be have a non-conical shape, with the separation determined by their relative k_t ; if two hard particles are within $\Delta_{ij} < R$, they will cluster to form a single non-conical jet. In the end, hard jets are reconstructed with a circular radius and soft jets have more complex cone shapes, which helps to discriminate against pileup. The jets in this analysis are reconstructed with a radius $R = 0.5$.

Jet energies must be corrected for poor HCAL resolution, pileup, and the nonlinear nature of the detector response in η . The particle-flow reconstruction of jets, shown in Figure 4.3, was commissioned with 7 TeV data [50] and found to have a residual jet energy scale correction on the order of 5% in the barrel when compared to simulation. Previous studies [48] have shown that 90% of the jet energy can be reconstructed with good quantitative and directional precision by the particle-flow algorithm, and that jets with $p_T > 25$ GeV showed an efficiency of 80% matching reconstructed data to simulation, while jets with $p_T > 40$ GeV reached a 100% match rate.

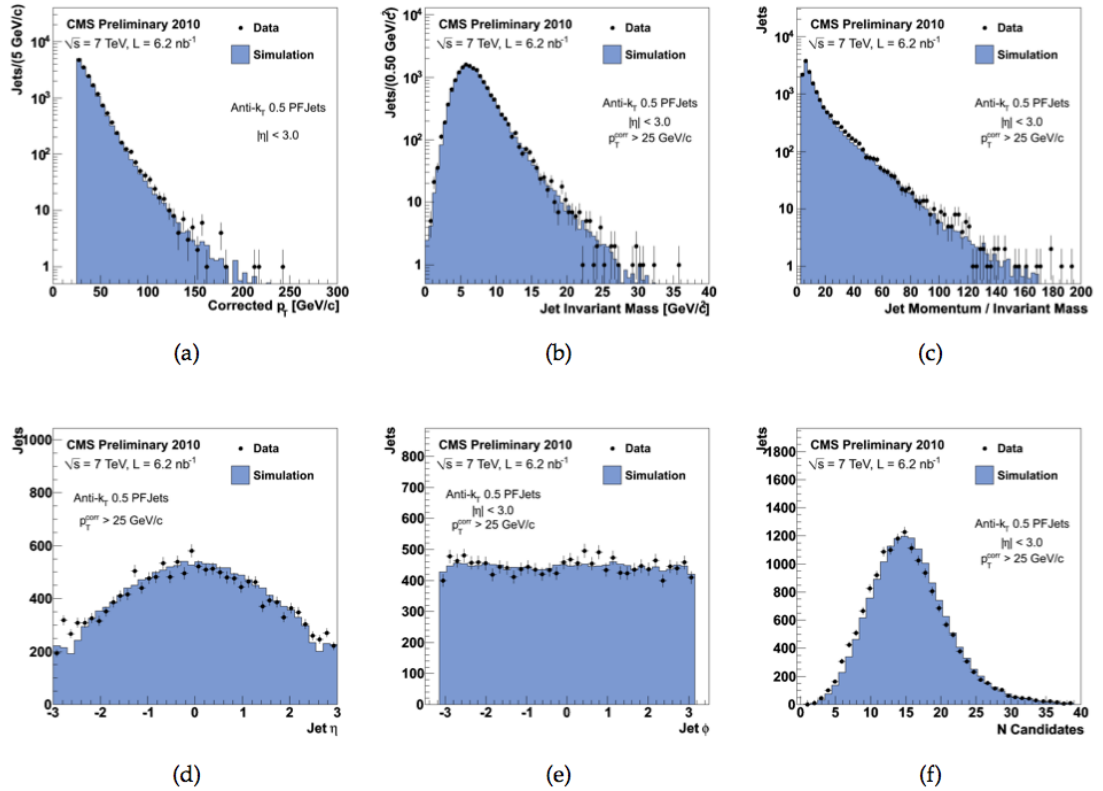


FIGURE 4.3. Basic jet properties measured in dijet events, with data points in black and simulations in blue. Distributions of (a) the jet p_T ; (b) jet invariant mass; (c) the ratio of jet momentum to jet inverse mass; (d) jet pseudorapidity; (e) jet azimuth; and (f) the number of constituent particles in a jet [50].

Understanding jet reconstruction is important for this analysis for two reasons. The first reason is that the largest source of background in this study comes from jets which are misidentified as photons. A clear understanding of jet reconstruction plays an important role in minimizing and identifying the background contribution from jet events, and improved

identification techniques will play an important role in reducing this background in future studies. The second reason is that the signal of interest in this analysis is composed of a high- p_T photon balanced by missing transverse energy, and the accuracy of the jet reconstruction in an event will affect how accurately the missing transverse energy is measured, which is discussed in the next section.

4.1.4. Missing Transverse Energy. The $\cancel{E}_T$ in an event is calculated as the modulus of the vector component that balances the p_T sum of all of the other components in the event, it has a magnitude and a direction component. While the general definition is the same, there are multiple ways to reconstruct $\cancel{E}_T$, and for this analysis the particle-flow MET algorithm [50] is used, where MET and $\cancel{E}_T$ both stand for the same thing: missing transverse energy¹. The particle-flow algorithm reconstructs all of the particles in the event, and assigns the $\cancel{E}_T$ vector to be the negative of the vector sum over all particle-flow particles of their transverse momentum [51]. While the $\cancel{E}_T$ is reconstructed with fairly good accuracy [50], it is not possible to reconstruct the missing longitudinal energy because of the inherent uncertainty in the net longitudinal energy of the two quarks within the proton bunches that produce the event of interest.

The event E_T reconstruction, which will lead directly to the particle-flow $\cancel{E}_T$ assignment, is tested with samples of MinBias and QCD multijet events, which are expected to be momentum-balanced in the plane transverse to the beam axis and have minimal $\cancel{E}_T$, if any. Reconstructing events that should already be balance in E_T allows for the fine-tuning of calorimeter noise cleaning, which removes anomalous signals due to electronics in the ECAL and HCAL, and indicates how well $\cancel{E}_T$ is reconstructed. When run on simulated events, the particle-flow algorithm correctly reconstructs 80% of the E_T in an entire event PFT-10-002. The reconstructed $\cancel{E}_T$ is assigned a type-I correction to adjust the energies of the jets in the event that have p_T above some threshold. As shown in Figure 4.4, a threshold of $p_T > 10$ GeV is selected to optimize the effect of correcting for missing hadronic energy in jets while minimizing the effect of low-energy jets from pileup.

The $\cancel{E}_T$ scale and resolution were studied using events with a jet and a reconstructed isolated photon or Z boson. The events did not contain real $\cancel{E}_T$, but the neutral boson

¹The use of “energy” and “momentum” are not typos in this section, while $\cancel{E}_T$ traditionally stands for missing transverse energy, the $\cancel{E}_T$ object reconstructed by CMSSW is built using the transverse momentum vectors of the accompanying particles in the event.

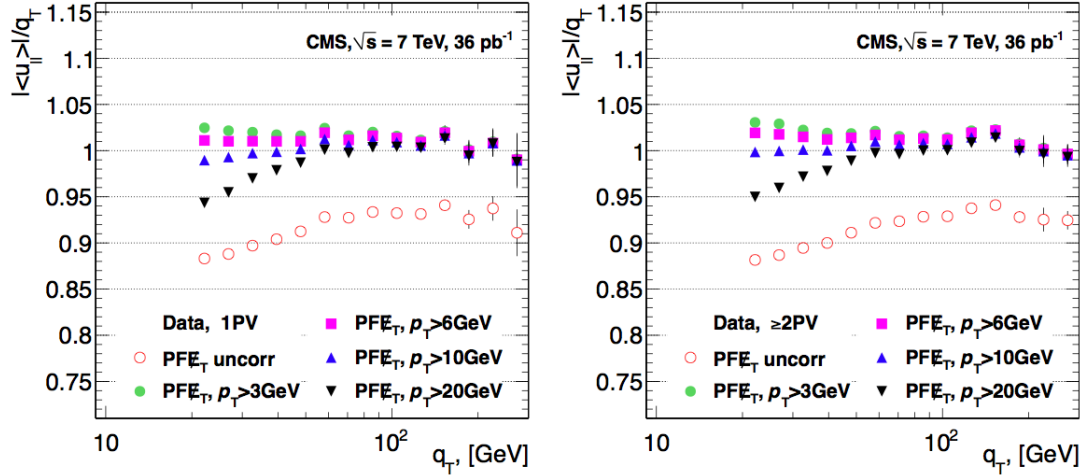


FIGURE 4.4. The response for particle-flow $\cancel{E}_T$ versus γ q_T (vector boson p_T) for various jet correction thresholds in γ candidate events with (left) 1 primary vertex and (right) multiple primary vertices [51].

was removed to create an event with well-measured and well-understood $\cancel{E}_T$ that could be compared to the reconstructed particle-flow $\cancel{E}_T$. The vector boson momentum in the transverse plane is denoted as q_T and the components of the recoil calculated from the particle-flow $\cancel{E}_T$ that are parallel and perpendicular to the boson axis are $u_{\parallel}$ and $u_{\perp}$, respectively.

The response curves for γ +jet, $Z(ee)$ +jet, and $Z(\mu\mu)$ +jet events are shown in Figure 4.5 for the $\cancel{E}_T$ reconstructed by the particle-flow algorithm, showing good agreement between data and simulation as well as between the reconstructed boson and the $\cancel{E}_T$ reconstructed in its place. The response curve for particle-flow $\cancel{E}_T$ is low for low p_T because it doesn't include corrections for detector response.

4.1.5. Muons. As muons travel the entire length of the detector, they deposit energy in every successive subdetector. Since object reconstruction begins locally during the trigger stage, the tracks in the muon system and tracker system are reconstructed separately. As a result, two muon reconstruction methods are applied concurrently: global muon reconstruction and tracker muon reconstruction [52]. Global muon reconstruction begins with the Standalone muon tracks, which are constructed solely from the muon system information, and tries to match each standalone muon to a track in the tracker with a Kalman filter. The tracker muon approach works in the opposite direction, treating every tracker

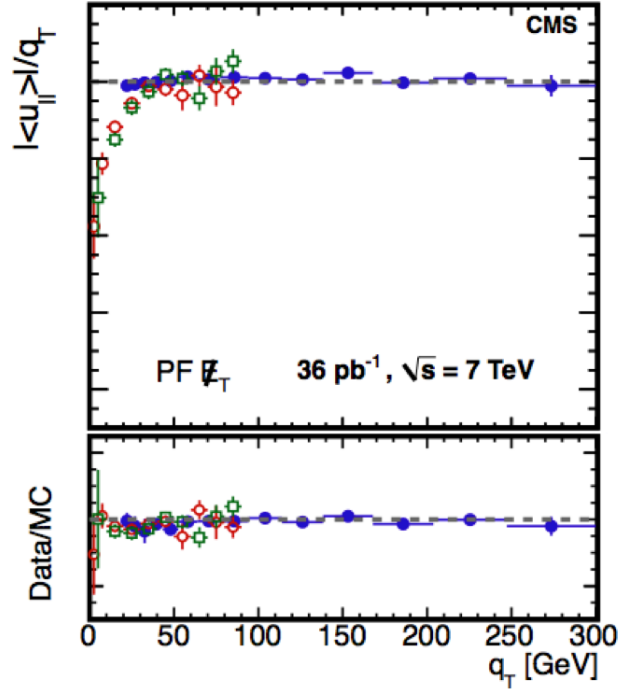


FIGURE 4.5. Response curves for events with one primary vertex for particle-flow $\cancel{E}_T$. Results are shown for photon events (full blue circles), $Z(ee)$ events (open red circles), and $Z(\mu\mu)$ events (open green squares). The upper frame shows the response in data, the lower frame shows the data-to-simulation ratio [51].

track with $p_T > 0.5$ GeV and $p_{\text{tot}} > 2.5$ GeV as a potential muon and extrapolating their trajectory out to the muon systems using their momentum information. If at least one muon segment (associated DT and CSC hits) aligns with the tracker muon trajectory, the track is considered a reconstructed muon and a Kalman filter is used to complete the fit between the tracker track and the aligning hits in the muon trackers.

The primary motivation for building CMS with a high magnetic field was to be able to measure charged tracks, most notably muons, with excellent resolution. While the tracker muon algorithm is slightly more efficient at low momentum, the high efficiency of the tracker track reconstruction and the high efficiency of the muon segment reconstruction results in about 99% of the muons produced in collisions in the geometrical acceptance of the detector being reconstructed by one method or the other, and often both. In the case of duplicate reconstructed candidates, the candidate information is merged. The combined tracker- and muon-system reconstructed efficiency has been tested repeatedly in studies of resonances with dimuon decay channels, several examples of which are shown in Figure 4.6.

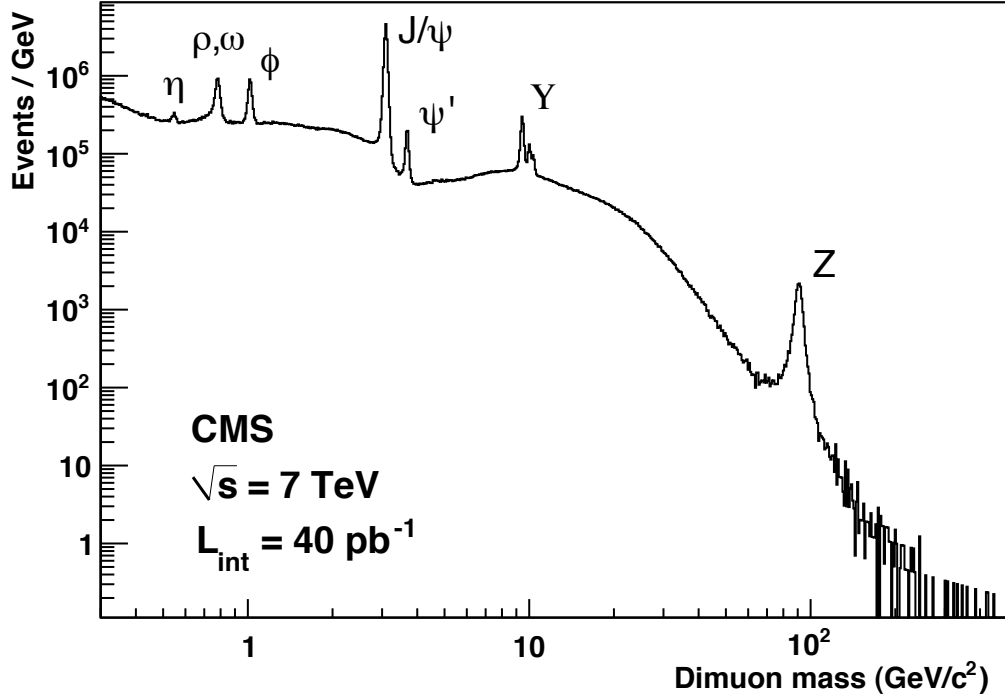


FIGURE 4.6. The invariant dimuon mass of several reconstructed particles using data from the dimuon triggers with no p_T threshold [52].

Particle-flow muons are muons that have already been reconstructed with either of the two algorithms but are required to pass additional muon identification criteria. As a result, non-isolated particle-flow muons, like muons found in jets, are identified with a high efficiency, which helps reduce bias in jet and $\cancel{E}_T$ measurements from mis-assigned event energy. Particle-flow muons reach an efficiency plateau at about $p_T \sim 6$ GeV [52].

The muon objects that are most relevant to this study are cosmic muons and beam-halo muons. The cosmic muon algorithm reconstructs muon objects by connecting track segments between the tracker subsystems and/or muon subsystems to create a candidate that looks like a back-to-back decay. The impact parameter d_{xy} can act as a strong discriminator between cosmic muons and collision muons, where d_{xy} is defined as the shortest distance from the interaction point to the track in the x - y plane; tracks originating from the collision generally have an impact parameter very close to zero while cosmic muons have a flat d_{xy} distribution. Cosmic muons are usually suppressed from the candidate sample by requiring $|d_{xy}| < 0.2$ cm and by requiring that the track energy be deposited in a time window corresponding to the collision, since cosmic muons also have a flat time distribution [52]. These two requirements are effective at suppressing, or conversely collecting, cosmic muons.

Beam-halo muons are produced by protons in the circulating bunches that collide with either a gas molecule or the side of the beam pipe and interact. They reach the detector around the same time as the bunch, leaving deposits in the detector that can lead to errors in the reconstruction of events. However, beam-halo muons can be reconstructed; the CSCs extend far enough in η to detect muons traveling parallel to the beam pipe and provide information in order to distinguish them from muons that originate from the collision. There are three standard approaches to identify beam-halo muons: a trigger that looks for CSC hits that are parallel to the beam pipe, CSC trigger primitives that are early in time compared to the collision, and standalone muons that are reconstructed with a trajectory parallel to the beam line. Applying the first two criteria is considered loose beam-halo identification, all three make up the tight beam-halo identification. When applied to a sample of beam halo muons, 89% passed the loose beam-halo Identification and 73% were categorized as tight beam halo candidates. Even though time and trajectory requirements significantly suppress beam-halo muons from data samples, it remains one of the largest background contributions in this analysis

4.1.6. Electrons. Reconstructed electrons [53] are used in control studies related to this analysis to test the photon identification efficiency and veto efficiency. The control studies use electrons instead of photons because the $Z \rightarrow ee$ channel is very clean, as can be seen in Figure 5.17, and electron and photon objects undergo a similar energy clustering process in the ECAL, which is the primary means of identifying photons. However, when electrons move through the detector they deposit energy in both the ECAL and the tracker systems, so electrons are reconstructed from a combination of information in two subdetectors. Electron reconstruction proceeds by two complimentary algorithms to match the subdetector information, much like muon reconstruction, one of which starts in the ECAL and another which starts in the tracker.

The ECAL-driven algorithm begins by reconstructing the clusters of energy associated with the EM shower deposited by the electron into a supercluster object. While the supercluster from a photon will have a greater distribution in ϕ due to the curvature of the electron trajectory, the identical reconstruction method is applied for photon reconstruction and is described in more detail in Sec. 4.2. The energy-weighted position of the supercluster

is backwards-propagated to the interaction point to search for a pixel seed, which is a pattern of two consecutive hits in the pixel detector that is consistent with the trajectory of an electron track for this supercluster [53]. Two trajectories are projected back to the tracker, one for electrons and one for positrons, to find a pair of pixel hits, the second position of which is further constrained as the pixel seed is built. Once a supercluster is matched to a pixel seed, an electron track is built from hits in the rest of the tracker. The energy loss of an electron in the tracker is non-gaussian due to bremsstrahlung, so a special extension of the Kalman filter, the Gaussian Sum Filter, is used to reconstruct the electron track. A tracker-driven reconstruction algorithm begins with hits in the tracker system and iteratively builds a track with the Combinatorial Track Finder [40], again taking into account the model of energy loss for electrons, then matches that track to an ECAL supercluster. The tracker-driven approach performs better for low p_T electrons and electrons inside of jets.

Good agreement is found between electrons reconstructed in simulated events and in data. A study of minimum bias events shown in Figure 4.7 compared the electron position and energy information from the tracker and ECAL components of the reconstructed electrons, in both data and simulation, and found good agreement. The reconstruction efficiency also measured in a tag and probe study of $Z \rightarrow ee$ events in 2010 data, and found to be $99.3 \pm 1.4\%$ in the barrel, which compares well with the predicted efficiency of 98.5% from simulation. The efficiency of the pixel seeds matching to superclusters is measured in $W\gamma$ and $Z\gamma$ events and found to be $99.4 \pm 0.25\%$.

4.2. Photons

Photon candidates are reconstructed from clusters of energy deposited in the ECAL. Photons are expected to deposit most, if not all, of their energy in the crystals of the ECAL, and some spread is expected in the energy deposition since the material in front of the ECAL can result in early conversions and bremsstrahlung from electrons and positrons, and the strong magnet will cause these charge particles to deposit their energy in a broader region in ϕ . For this reason, the first step of photon reconstruction [55] is to group the crystals with energy depositions that appear to come from the same source object using a superclustering algorithm [44]. The Hybrid superclustering algorithm, which is used in

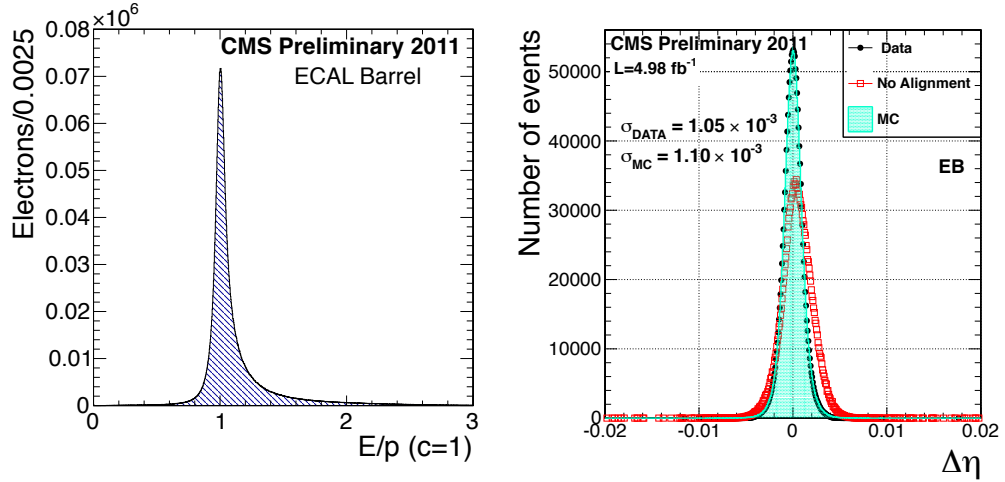


FIGURE 4.7. Electron candidates from 2011 data: (left) E/p ratio of supercluster energy and GSF track momentum in EB from $W(e\nu)$ events, (right) difference in η between the supercluster position and track extrapolation, in simulation and data before and after alignment corrections for $Z(ee)$ and $W(e\nu)$ events [54].

the barrel region of the detector, first searches the trigger towers, which are 25×25 crystal arrays, for a seed crystal. The seed crystal has the highest energy deposition in the tower above some threshold set by the HLT. Once a crystal seed is found, the algorithm adds the energy in a 1×3 or 1×5 domino of crystals surrounding the seed crystal in $i\phi \times i\eta$, where each $(i\phi, i\eta)$ coordinate corresponds to a single crystal. The number of crystals included in the cluster in the η direction depends on how much energy is in the initial 1×3 domino. The algorithm then dynamically scans up to 17 crystal dominos in both directions in ϕ , adding them to the supercluster if the domino energy is above a programmable threshold value [44]. A diagram of these steps can be seen in Figure 4.8. The superclusters in the ECAL endcap and preshower regions are reconstructed in a similar but less segmented manner, by the Multi 5×5 algorithm which adds together fixed 5×5 arrays of clustered crystals [55]. In both cases, once the supercluster has been formed, the supercluster energy is corrected for losses due to interactions with the material in front of the ECAL and the shower containment of the supercluster. A correction is applied to account for: the η dependence of the lateral energy leakage due to the 3° offset in the ECAL; energy lost through interactions with the material in front of the ECAL; and the relation between the E_T of early conversions and bremsstrahlung and the variation in material encountered before the ECAL [55]. These

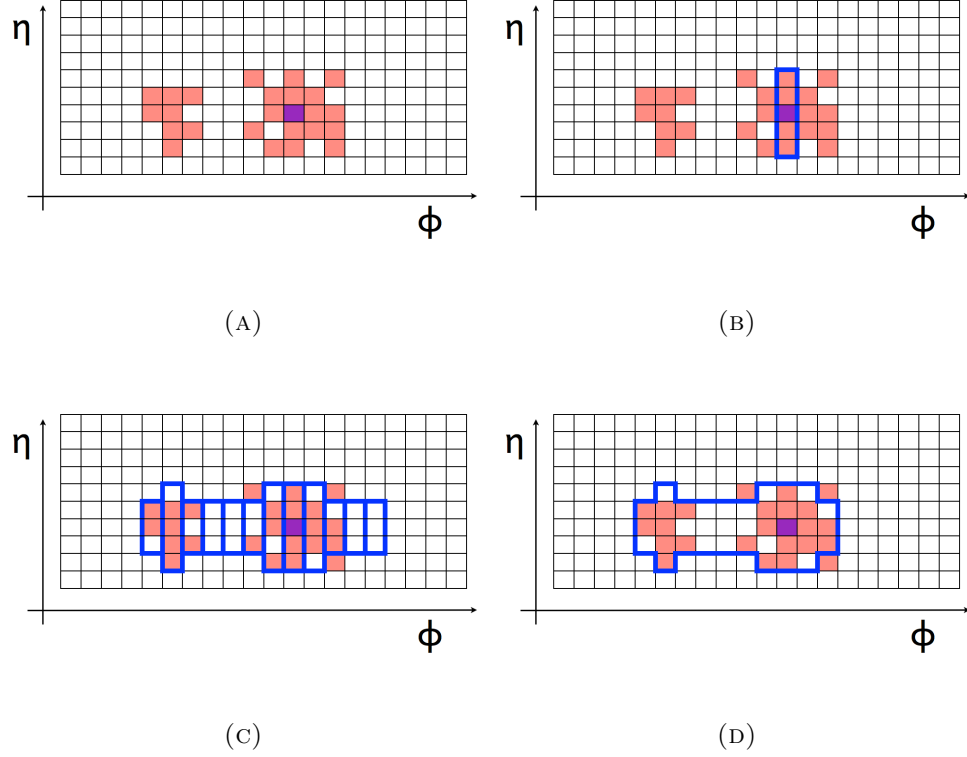


FIGURE 4.8. Hybrid superclustering process: (A) the crystal with local energy maximum identified as crystal seed (purple); (B) a bar of $(\eta, \phi) = 1 \times 3$ or 1×5 crystals is selected around pixel seed, based on E criteria; (C) up to ± 17 bars of 1×3 or 1×5 are added to supercluster along ϕ ; (D) supercluster reconstructed as sum of bars above E threshold.

corrections are developed using simulated samples and usually correspond to 1% of the supercluster energy.

Photon objects are reconstructed by connecting superclusters to the primary vertex in an event, creating a way to calculate the momentum and trajectory of the photon. The energy assigned to the reconstructed photon is calculated in one of two ways, depending on the distribution of the energy in the photon object. The energy distribution is determined by the variable R9, which is defined as the ratio of energy deposited in the 3×3 cluster of crystals around the crystal seed to the energy deposited in the entire supercluster, $R9 = E_{3 \times 3} / E_{SC}$, and shown in Figure 4.9 for data and simulated events. If $R9 < 0.94$, the energy is spread broadly across the shower which could indicate that the photon converted prior to reaching the ECAL and the photon object is assigned the energy of the supercluster. If $R9 > 0.94$, the energy in the supercluster is very collimated and indicative of an unconverted photon;

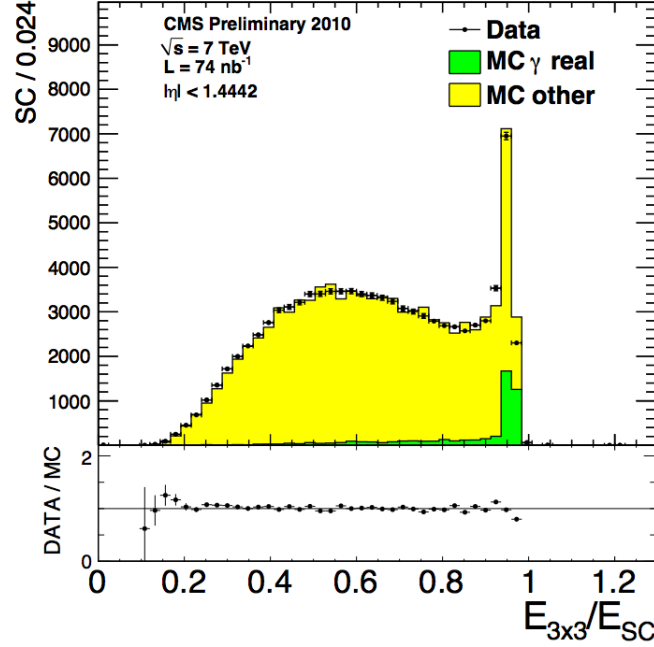


FIGURE 4.9. The R9 ratio of energy in the 3×3 crystal array around the most energetic crystal to the total energy of the supercluster in the barrel. The simulation results are normalized to the number of entries in the data histogram. [55].

the photon object is assigned the energy of the 5×5 crystal array surrounding the crystal seed. The position of the reconstructed photon is subsequently calculated as the log-energy-weighted average position of the crystals in the cluster used to determine the energy.

During photon reconstruction, a number of variables relating to the photon candidate are defined that can be used to further distinguish photons from electrons, jets, and other objects that leave similar energy signals in the ECAL. These variables define the ratio of energy in the ECAL and the HCAL related to the photon object (H/E); the amount of energy deposited in annular cones around the photon object in each subdetector; and the transverse shape of the supercluster, for example. The application of these variables is referred to as photon identification, and is discussed in more detail in the analysis chapter along with other photon collection cleaning methods. The efficiency of the photon reconstruction is measured with a tag-and-probe study of $Z \rightarrow ee$ decays, where electrons are treated as photons that happen to have an associated pixel seed and the track information is not used in the Z reconstruction. A tag-and-probe study used 2010 data to measure the efficiency of the the photon reconstruction, which was found to be $88.4 \pm 0.9\%$ in the barrel,

agreeing well with the simulation result of 86.3% [56]. This study is repeated in the next chapter with data from the 2011 sample and comparable simulation events, measuring a photon reconstruction efficiency of 98.3% with the signal selection criteria applied.

CHAPTER 5

Analysis

Once the collision information gathered by CMS is recorded and reconstructed, several steps are taken to whittle the dataset down to a sample only containing events with a high energy photon and missing transverse energy. The data samples in CMS are organized in sets of events that meet a particular trigger selection criteria, thus providing the first level of event selection. The next step in the analysis is to select events that contain an energy deposition indicative of a well-defined photon with large transverse momentum. What follows is similar to a very high-level game of Guess Who: the myriad backgrounds for the monophoton signal are separately distinguished using a variety of selection criteria and their contributions are estimated and removed from the signal sample. Multiple sources of systematic uncertainty are taken into account, and the resulting signal sample is compared to the expected signal in this channel according to the Standard Model. The SM monophoton signal consists of $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ events, and an excess in this channel would be interpreted as a possible sign of $\chi\bar{\chi}\gamma$ events being present as well.

5.1. Event Simulation

Simulated event samples are used at many stages of this analysis to estimate some of the background processes, to model the signal sample predicted by SM, and finally to set limits on dark matter-nucleon production (which is discussed in Chapter 6). These samples are simulated with the Monte Carlo (MC) generator **PYTHIA 6.424** [57], a program that generates leading-order (LO) parton interactions and the resulting parton showers, using the **CTEQ6L1** [58] parton distribution functions. In order to facilitate a direct comparison with reconstructed data, the MC samples are processed through the **GEANT4**-based simulation of the CMS detector [59, 60], trigger simulation, and the event reconstruction used for data. All of the MC samples used in the analysis are listed in Table 5.1.

Most of the simulated samples used to estimate the background are from the set of officially produced samples simulated in Summer of 2011 by CMS, referred to as the Summer11 production, which were generated with PYTHIA6 and reconstructed using CMSSW release 423. The diboson samples ($Z\gamma$ and $W\gamma$) used in this analysis were privately generated by the CMS $V\gamma$ group. The $W\gamma$ samples, which were used to estimate the number of $W\gamma$ events present as background in the data sample, were generated with MADGRAPH5 [61] interfaced with PYTHIA and the cross section was corrected to reflect next-to-leading order (NLO) effects using a k-factor calculated with MCFM [62]. These private samples were produced using the official tools to remain consistent with the official simulated samples.

A signal sample of $Z(\nu\bar{\nu}) + \gamma$ events was not available in the Summer11 production, so a private sample was generated using the official tools to maintain consistency. The $Z(\nu\bar{\nu}) + \gamma$ sample was also scaled up to reflect NLO contributions using a k-factor calculated using BAUR [63]. A detailed discussion of the procedure used to determine the k-factor can be found in Section 5.5.4. The $Z(\nu\bar{\nu}) + \gamma$ sample was generated with $p_T^\gamma > 130$ GeV.

All of the samples, official and private, were produced with a center of mass energy of 7 TeV, a magnetic field of 3.8 Tesla, and include the effects of out-of-time pileup. Additionally, the simulations reflected standard detector calibration and alignment measurements using START conditions and the energies of particle flow jets are corrected with Jet Energy Correction algorithms *L1FastJet*, *L2Relative* and *L3Absolute* [64]. After the analysis was completed, samples were produced through the official production channels to test the results from the privately produced samples, and the officially produced samples yielded the same results.

5.2. Data

This analysis was performed using the Run2011A and Run2011B data sets collected by CMS corresponding to an integrated luminosity of 5.0 fb^{-1} . Run2011A contains the data collected up until September, when a technical stop halted collisions, and Run2011B contains the data collected from the higher intensity collisions that lasted the rest of the year. The data used to search for monophoton events are selected from the **Photon** datasets reconstructed in the 42X version of CMSSW. The **Photon** datasets used in this analysis are:

- /Photon/Run2011A-May10ReReco-v1/AOD

Process	DataSet Name	Events	Lumi. (pb ⁻¹)
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	private production (Pythia)	100000	2630194
$Z(\rightarrow ll) + \gamma + Jets(ee \text{ and } \mu\mu)$	private production (Madgraph)	754839	54738.1
$W(\rightarrow l\nu) + \gamma + Jets$	private production (Madgraph)	1062987	49649.1
$W \rightarrow e\nu$	/WToENu_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	5304113	671
$W \rightarrow \mu\nu$	/WToMuNu_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	3954916	500
$W \rightarrow \tau\nu$	/WToTauNu_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	3999901	506
Photon+ <i>Jet</i>	/G_Pt30to50_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	2177187	130.41
	/G_Pt-50to80_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	2016427	740.83
	/G_Pt-80to120_TuneZ2.7TeV-pythia6/ Summer11-PU_S4_START42.V11-v1/AODSIM	1625917	3635.80
	/G_Pt-120to170_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	2066070	24546.00
	/G_Pt-170to300_TuneZ2.7TeV-pythia6/ Summer11-PU_S4_START42.V11-v1/AODSIM	1496472	66098.20
	/G_Pt-300to470_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	2070808	1.38715e06
	/G_Pt-470to800_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	2050475	1.55002e07
Diphoton (Born)	/DiPhotonBorn_Pt-25To250.7TeV-pythia6/ Summer11-PU_S4_START42.V11-v2/AODSIM	532860	23820.3
Diphoton (Box)	/DiPhotonBorn_Pt-250.7TeV-pythia6/ Summer11-PU_S4_START42.V11-v2/AODSIM	526156	6.517478e + 07
	/DiPhotonBox_Pt-25To250.7TeV-pythia6/ Summer11-PU_S4_START42.V11-v2/AODSIM	510284	41251.7
	/DiPhotonBox_Pt-250.7TeV-pythia6/ Summer11-PU_S4_START42.V11-v2/AODSIM	256518	1.23325e + 09
QCD	/QCD_Pt-30to50_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	4919871	0.092
	/QCD_Pt-50to80_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	4907406	0.77
	/QCD_Pt-80to120_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	4827473	6.15
	/QCD_Pt-120to170_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	4872513	42.32
	/QCD_Pt-170to300_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	4953963	204.17
	/QCD_Pt-300to470_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	4938811	4226.65
	/QCD_Pt-470to600_TuneZ2.7TeV-pythia6/ Summer11-PU_S3_START42.V11-v2/AODSIM	3934921	56033.70

TABLE 5.1. Details of the simulated samples used for signal and background analysis.

- /Photon/Run2011A-PromptReco-v4/AOD
- /Photon/Run2011A-PromptReco-v6/AOD
- /Photon/Run2011A-05Aug2011-v1/AOD
- /Photon/Run2011B-PromptReco-v1/AOD

The number of events was initially reduced by applying two requirements based upon the energy depositions in the ECAL and HCAL: $E_T^\gamma > 130$ GeV, and the hadronic-to-electromagnetic energy ratio, H/E, had to be less than 0.05. The H/E requirement is a standard photon identification cut to distinguish photons from jets, and the E_T^γ requirement was chosen as the result of an optimization study to select high-energy photons that are collected with good efficiency by the trigger, which is discussed in the next section [65]. As with all data used in CMS analyses, the certified luminosity Java Script Object Notation (JSON) files were applied to select only events that came from good quality luminosity sections.

5.3. Triggers

The first major event selection relies on the L1 and HLT triggers. The kinematic measurements used for the triggers are less precise than their offline counterparts, so analyses usually employ triggers with lower thresholds and looser criteria than their offline counterparts to significantly reduce the sample of possible events. Triggers with lower thresholds have higher frequencies, but the physical limitations of the detector constrain the rate at which can be recorded. To solve this problem, the lower threshold triggers are prescaled so that only a fraction of the events that pass are actually kept. In this analysis, the signal sample is reduced from the entire set of `Photon` datasets to only include events that have passed at least one of the unprescaled single photon triggers listed in Table 5.2, where the integrated luminosity for each trigger is also given. Different triggers provide the lowest unprescaled collection of single photon events at different stages of data taking because as the instantaneous luminosity increases, the single photon trigger threshold correspondingly increased to control the trigger rate.

All of the triggers used in this analysis are seeded by the L1 trigger L1SingleEG20. At the HLT, all three triggers employ a p_T threshold (75, 125, and 135 GeV, respectively). The triggers with the lowest p_T threshold, 75 GeV, also apply very loose ECAL and HCAL isolation cuts and a very loose requirement on the shower shape, noted by the `CalIdVL` in the trigger name. The shower shape requirement of the trigger is very loose compared to the offline photon selection criteria in this analysis (discussed in Section 5.4) and even compared to the expected value from electromagnetic objects, so it is assumed to be fully

Trigger	Integrated Luminosity (pb^{-1})
HLT_Photon75_CaloIdVL_v1	5.962
HLT_Photon75_CaloIdVL_v2	40.69
HLT_Photon75_CaloIdVL_v3	168.2
HLT_Photon125_v1	120.1
HLT_Photon125_v2	535.3
HLT_Photon135_v1	1150.
HLT_Photon135_v2	2974.
Total	4994.

TABLE 5.2. Integrated luminosity by trigger.

efficient. However, the turn-on curve must be determined for the threshold and, in the case of the HLT_Photon75_CaloIdVL trigger, the isolation with respect to the more accurately measured quantities used in the offline analysis. To do this, prescaled backup triggers with lower thresholds (and the same CaloIdVL selection criteria for Photon75) were run concurrently with the unprescaled triggers used in the signal selection. By selecting events that passed the lower threshold triggers with a tight photon candidate and $\cancel{E}_T > 130$ GeV, and comparing that population to the events that passed the same requirement for our unprescaled triggers, a turn-on curve can be produced that indicates when the triggers become fully efficient. All three HLT triggers were shown to become fully efficient before the offline selection threshold of 145 GeV [65], as can be seen in Figures 5.1, 5.2, and 5.3.

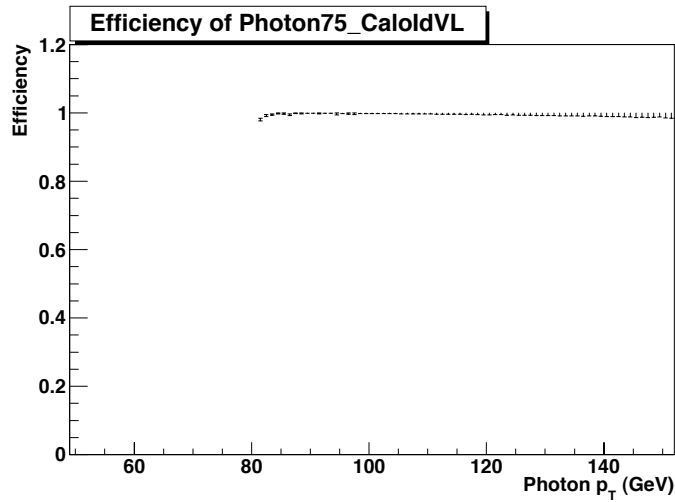


FIGURE 5.1. Efficiency of single photon trigger (HLT_Photon75).

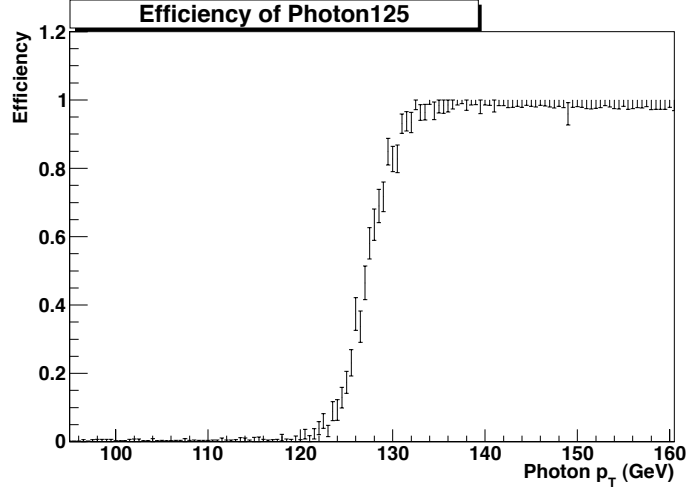


FIGURE 5.2. Efficiency of single photon trigger (HLT_Photon125).

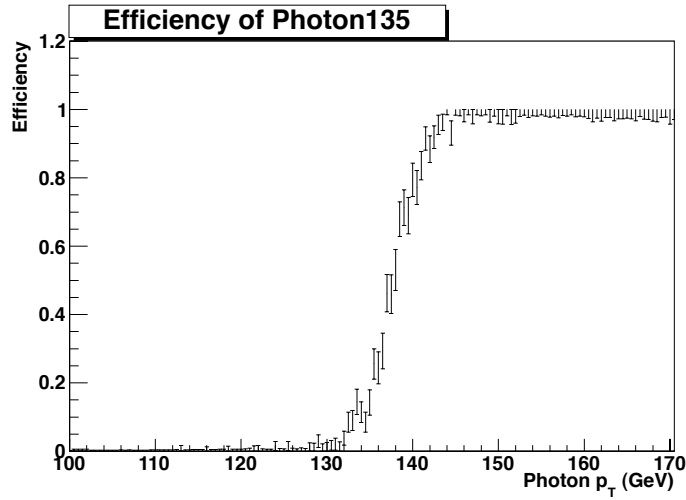


FIGURE 5.3. Efficiency of single photon trigger (HLT_Photon135).

5.4. Event Selection

A series of requirements are placed on the energy, p_T , distribution, and composition of the events that pass the triggers in order to produce a sample with candidate signal events containing a high-energy photon candidate and significant $\cancel{E}_T$. A few initial requirements related to the quality of the event remove events that may not have been reconstructed well. In each event there must be fewer than 10 tracks, or at least 25% of the tracks are required to pass “high purity” criteria [45], which involve the proximity of the track to the beam spot and the HLT primary vertex and the number of tracker that produce the track.

This requirement reduces the number of “scraping events,” which include many track that do not originate from the interaction region. Events are required to have at least one good primary vertex which fulfills the following criteria: it has a position along the beam line z within 24 cm of the center of the CMS detector, a position in the transverse plane within 2 cm of the beam line, and $\text{NDOF} > 4$, where NDOF is the number of degrees of freedom and is calculated by the number and compatibility of nearby tracks [47].

The majority of the requirements focus on the photon candidate. The photon candidates in this analysis are required to pass a p_T cut of $p_T^\gamma > 145$ GeV and be in the central barrel region of the detector, $|\eta^\gamma| < 1.44$, where purity is highest. Multiple calorimetric selections are applied in order to distinguish photon candidates from jets and electrons. For one, the ratio of energy deposited in the HCAL to that deposited in the ECAL within a cone of $\Delta R = 0.15$ around the photon supercluster (described in Section 4.2), referred to as H/E, is required to be less than 0.05, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ is defined relative to the photon candidate and the azimuthal angle ϕ is measured in the plane perpendicular to the beam axis. This cut distinguishes photon candidates, which deposit energy nearly exclusively in the ECAL, from jets which generally deposit significant amounts of energy in both the HCAL and ECAL. For another, photon candidates must have a shower distribution in the ECAL which is consistent with expectations for a photon [56]. The electromagnetic shower distribution, commonly referred to as the shower shape, is determined by its width in $i\eta$ -space using the variable $\sigma_{i\eta i\eta}$ which is calculated as follows:

$$\sigma_{i\eta i\eta}^2 = \frac{\sum_i^{5 \times 5} \omega_i (\eta_i - \eta_{seed})^2}{\sum_i^{5 \times 5} \omega_i}, \text{ where } \omega_i = \max(0, 4.7 + \ln \frac{E_i}{E_{5 \times 5}}) \quad (5.1)$$

In other words, $\sigma_{i\eta i\eta}$ measures how broadly the energy is spread along η in the 5×5 crystal cluster around the crystal that seeds the SuperCluster [56]. Photon showers tend to be collimated and have a lower $\sigma_{i\eta i\eta}$ value compared to the measurements from the broader showers of jets and electrons, so the shower shape is required to have $\sigma_{i\eta i\eta} < 0.013$.

Several isolation cuts are also applied, limiting the amount of energy that can be found in an annulus surrounding a candidate, to select isolated photon candidates [56]. The photon candidates must pass the following isolation requirements in the tracker, ECAL, and HCAL, with p_T in GeV units:

- the scalar sum of p_T depositions in the ECAL within a hollow cone of $0.06 < \Delta R < 0.40$, excluding depositions within $|\Delta\eta| = 0.04$ of the supercluster center, must be less than $4.2 \text{ GeV} + 0.006 \times p_T^\gamma$
- the scalar sum of p_T depositions in the HCAL within a hollow cone of $0.15 < \Delta R < 0.40$ must be less than $2.2 \text{ GeV} + 0.0025 \times p_T^\gamma$
- the scalar sum of track p_T values in a hollow cone of $0.04 < \Delta R < 0.40$, excluding depositions within $|\Delta\eta| = 0.015$ of the supercluster center, must be less than $2.0 \text{ GeV} + 0.001 \times p_T^\gamma$

The $|\Delta\eta|$ sections are excluded from the isolation cuts in the ECAL and the tracker so as not to remove photons that initiate EM showers within the tracker. The tracker isolation requirement is calculated using tracks that originate from the primary vertex.

The primary vertex, defined in the previous chapter 4.1.1, is assigned to be the vertex of origin for the photon [56]. However, the high luminosity of the LHC yields multiple pp interactions per bunch crossing and leads to several reconstructed vertices per event. As a safeguard, the tracker isolation requirement is computed in the same manner for every reconstructed vertex in the event. This ensures that the photon object in an event is isolated from charged particle tracks even in the event that the candidate is matched to the wrong different vertex. The event is kept in the signal sample if all of the tracker isolation values calculated for the different vertices pass the standard track isolation requirement.

Photons can be mimicked by muons in the beam halo or in cosmic rays that can induce bremsstrahlung and produce showers in the ECAL, but these contributions are reduced in two ways. One way is to compare the timing of the seed crystal, defined as the crystal with the highest energy deposition within the supercluster, to the timing of the event to make sure the deposition is consistent with a collision. The event is kept if the seed crystal of the photon supercluster is deposited within $\pm 3\text{ns}$ of the time expected for particles from a collision. Both types of contributions are also reduced by rejecting events if a CosmicMuon is reconstructed in the muon detectors, which is defined a muon that is reconstructed from individual muon system segments that align to project back to the collision point. These non-projective muons could be from the beam halo or cosmic rays.

Requirements are also placed on the spatial, deposition time, and energy distribution within a supercluster defining a photon candidate. Collision event data from CMS are

subject to spurious high-energy signals from single crystals embedded within EM showers in the ECAL, but these signals can be identified by their spike-like energy distribution within the shower, and by their spike-like energy and spatial distributions when they appear outside of a real EM shower. This instrumental background contribution is reduced in several ways. The shower shape of the photon candidate must fulfill minimum spatial requirements $\sigma_{i\eta i\eta} > 0.001$ and $\sigma_{i\phi i\phi} > 0.001$, where $\sigma_{i\phi i\phi}$ is calculated in $i\phi$ space in a manner similar to $\sigma_{i\eta i\eta}$. A limit is also placed on the variation between deposition times within a cluster: the largest intracluster time difference (LICTD) between crystals with more than 1 GeV of deposited energy must have an absolute value less than 5 ns. Events in the signal sample are required to have photon candidates with energy distribution corresponding to $R9 < 1$, which is defined in Sec. 4.2. To further reduce the number of events with electrons misidentified as photons, the photon candidate is required not to have an associate pixel seed.

The neutrinos (and the χ particles) are not expected to deposit energy in the detector, so their presence will be induced by a momentum imbalance in an event based on the measured particle depositions. The missing transverse energy in the event, $\cancel{E}_T$, is a quantity defined by the magnitude of the vector sum of the transverse energies of all of the reconstructed objects in the event, and is computed using a particle-flow algorithm [50]. The candidate events for this study are required to have significant missing energy, passing an $\cancel{E}_T > 130$ GeV cut.

Lastly, a limit is placed on the amount of hadronic activity surrounding the photon candidate. This minimizes the contribution from W +jet, γ +jet, and other events which can include a high energy photon candidate and missing energy along with jet activity. An event is vetoed if it contains a track with $p_T > 20$ GeV that is located $\Delta R > 0.04$ away from the photon candidate. The ΔR selection was chosen by comparing the ΔR values between the tracks and the photon candidate in MC samples of $W(e\nu)$ and $Z(\nu\bar{\nu})\gamma$ events, which can be seen in Figure 5.4. When plotted, the tracks associated with early photon conversion appear as a distinct spike within $\Delta R = 0.04$ of the photon, while tracks outside of this cut likely stem from extraneous event activity [65]. An event is also vetoed if it contains a jet of significant energy in close proximity to the photon candidate. If a jet is reconstructed with $p_T > 40$ GeV using the anti- k_T [49] particle-flow algorithm [50] within

$|\eta| < 3.0$ and $\Delta R < 0.5$ of the axis of the photon candidate, that event is removed from the signal sample.

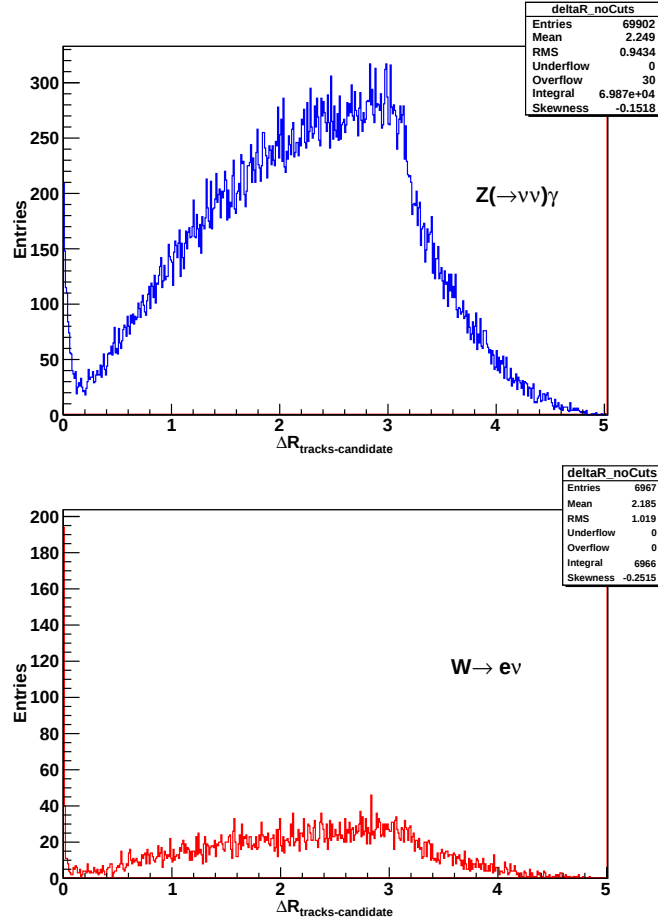


FIGURE 5.4. The ΔR values between all the tracks and the candidate photon in the simulated (top) $Z(\nu\bar{\nu})$ and (bottom) $W(e\nu)$ sample events. The bin size of ΔR is 0.01.

5.5. Backgrounds

After applying the selection criteria for this analysis to reduce the number of background events, 75 candidate events remain in the signal sample. However, a signal dependent upon a single physics object, a photon, and missing transverse energy has several irreducible sources of background. These different backgrounds are studied to estimate their contribution.

The discussion of the background estimation can be split into three categories based on how the backgrounds were treated: non-collision backgrounds, data-driven estimates, and

simulation-driven estimates. The non-collision phenomena were discussed earlier in Section 5.4, where selection cuts reduced the number of events with spikes in the ECAL and bremsstrahlung produced by muons from the beam halo and cosmic ray muons. While the non-collision contribution was reduced, it was not entirely removed. Data-driven techniques are used to estimate the contributions from $W(e\nu)$ events, in which the electron is reconstructed as a photon, and QCD multijet events, which can contribute to the background if a jet fakes a photon and badly measured hadronic activity results in a $\cancel{E}_T$ mismeasurement. Simulated event samples are used to estimate the background contributions from $W\gamma$, γ +jets, and diphoton events. A MC sample of $Z(\nu\bar{\nu})\gamma$ events is also used to compare the final number of estimated events to the SM prediction when the result of the $Z(\nu\bar{\nu})\gamma$ measurement is interpreted as a search for evidence of dark matter.

5.5.1. Non-collision backgrounds. There are three major sources of non-collision backgrounds: EM showers produced by beam halo muons; EM showers produced by cosmic ray muons; and anomalous electronic signals known as spikes in the ECAL. All three of these phenomena can produce a reconstructed photon candidate accompanied by $\cancel{E}_T$, effectively mimicking our signal. None of the above processes are well modeled by simulation, but they can be estimated from data because they all differ from collision data in two ways: shower shape and the timing of the seed crystal in the ECAL cluster.

A collection of ECAL clusters without any of the selection criteria is available, and that collection is used to reconstruct every possible photon candidate. The same criteria are applied to the p_T , η position, and isolation of the photon candidates, but the hadronic activity vetoes aren't applied and no cuts are made on the shower shape or the timing of the seed crystal. By plotting the times of the seed crystals with respect to the deposition time consistent with a collision, the sample separates into several distinct populations, as seen in Figure 5.5. The populations correspond to the in-time collisions and different non-collision background sources that can be isolated and identified. Shower shape and energy distribution information is used to form a series of seed time templates for these different sources. The templates for the backgrounds and collision events are then scaled to the timing distribution of the full collection, providing an estimate of the residual background contributions to the signal sample.

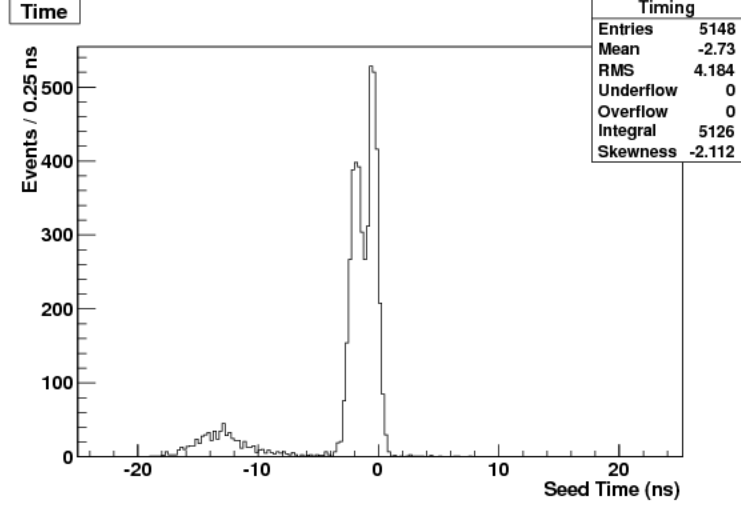


FIGURE 5.5. The timing distribution of photons passing tight photon criteria, with no restriction on the hadronic activity, shower shape, or seed crystal timing. Looking from left to right, the contributions are from anomalous calorimeter signals, beam halo, and the peak near seed time = 0 ns corresponds to prompt (collision activity) events.

5.5.1.1. *Anomalous signal template.* Anomalous signals are characterized by a high-energy signal coming from a single crystal in the ECAL. The creation of the $R9$ criteria for photon candidates was motivated by the desire to identify and remove these atypical signals, which have been observed since the first data was analyzed in 2009. To isolate anomalous signal events, the reversed $R9$ requirement is applied to the full photon collection. The photon objects that pass the $R9 \geq 1.0$ requirement are used to generate an anomalous signal template, shown in Figure 5.6.

5.5.1.2. *Beam halo template.* A beam halo refers to the small fraction of protons that acquire enough transverse energy to form a halo around the beam. These halo particles interact with the walls of the beam pipe and can produce muons that bremsstrahlung and deposit energy in the detector. A commonly used indicator that an event contains energy from the beam halo is if an energy deposition in the HCAL endcap (HE) is aligned in ϕ with a cluster in the ECAL. This beam halo identification method has been developed for other photon analyses and for accurately calculating $\cancel{E}_T$ [66], and a modified version is applied in this analysis. The individual HE hits are traditionally used to tag beam halo events, but that information is not stored in the datasets used in this analysis, so the hadronic energy information is taken from the CaloTowers, objects built from energy deposits in both the

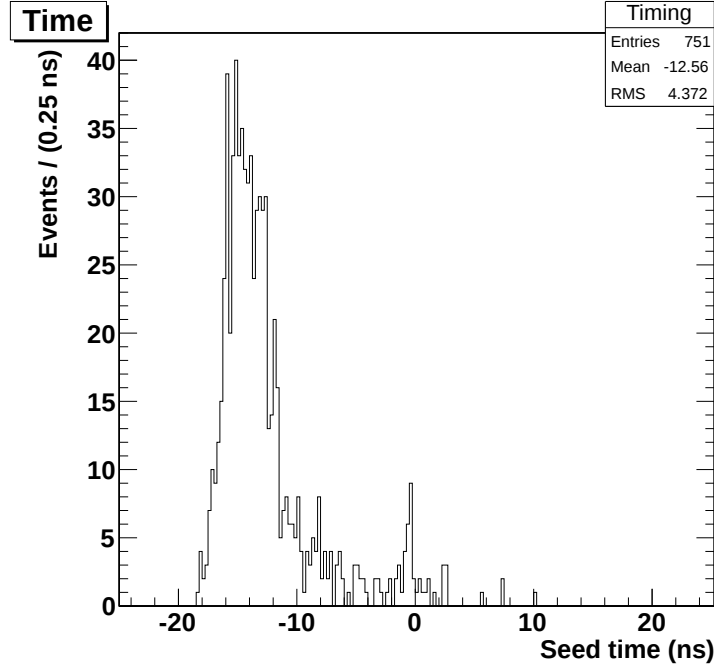


FIGURE 5.6. The timing distribution of photons which fail topological cuts on $\sigma_{i\eta i\eta}$.

ECAL and the HCAL. An event is considered to contain beam halo if it has energy deposited in the HCAL that fulfills the following criteria:

- Has a CaloTower with $E > 1$ GeV in the HE
- The CaloTower is $\Delta\phi < 0.2$ from the cluster in the ECAL barrel
- The energy deposited in the HCAL is located radially in the range $110 \text{ cm} < r < 140 \text{ cm}$ from the beam line
- The sum of the p_T of tracks within a cone of $\Delta R = 0.4$ around the CaloTower is no more than 2 GeV, qualifying the CaloTower as isolated

These requirements, combined with the hadronic activity vetoes limiting jet and track activity that are applied to the signal sample, produce a sample of clearly identifiable beam halo events used to create a beam halo template, shown in terms of $\sigma_{i\eta i\eta}$ in Figure 5.7. The seed time distribution of the beam halo template events shows that the beam halo events correspond to the spike of events centered right before the nominal event time ($t = 0$ ns).

5.5.1.3. Collision event template. A template of photon candidates from collision events is also made. These candidates are termed prompt because the timing of their seed crystals are consistent with collision data. The prompt photons are selected by applying all of the

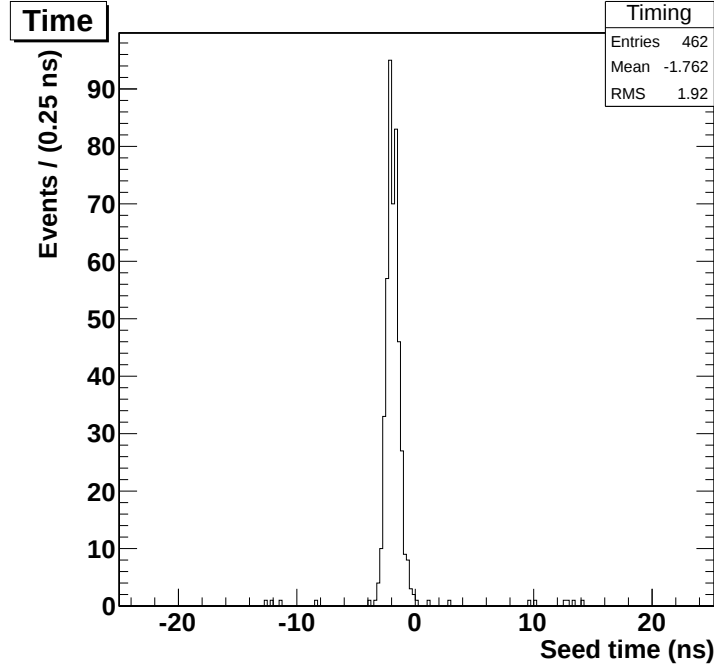


FIGURE 5.7. The timing distribution of photons which are tagged as beam-halo objects using hit information in the HE.

event selection criteria except for the track isolation, which is inverted to require some minimum amount of track activity in the event outside of the vicinity of the photon. The presence of tracks in the event is attributed to collision activity, further indicating that the event is prompt. These requirements produce the prompt event template.

5.5.1.4. *Fraction fitting and background estimate.* Once the different photon populations in the timing distribution are identified, the remaining selection criteria can be applied and the resultant sample can be broken down into its estimated fractions of prompt and background events. The jet and track vetoes are next applied to the sample. At this level of event selection, the cosmic-ray muons (which did not require a template because their distribution is expected to be flat in time) and anomalous signals produce no appreciable contributions to the background, and the signal is primarily composed of prompt collision and beam halo events. The timing requirement does not significantly reduce the beam halo background, but the shower shape proves to be a strong discriminator between beam halo and prompt events. The relationship between the timing distribution and shower shape is shown for the beam halo sample and candidate sample in Figure 5.8. While the timing distributions of beam halo and prompt events are nearly on top of each other, the beam

halo and prompt events form two distinct populations when plotted in $\sigma_{i\eta i\eta}$: the beam halo sample produces a fairly narrow peak around 0.09 while the prompt sample produces a broader distribution peaking around 0.017, as can be seen in Figure 5.9. While there are many beam halo events, only $0.87 \pm 0.43\%$ will pass all of the event selection criteria, including the shower shape requirement of $\sigma_{i\eta i\eta} > 0.013$. Based on these studies, 11.1 ± 5.6 beam halo events are estimated to be in the signal sample.

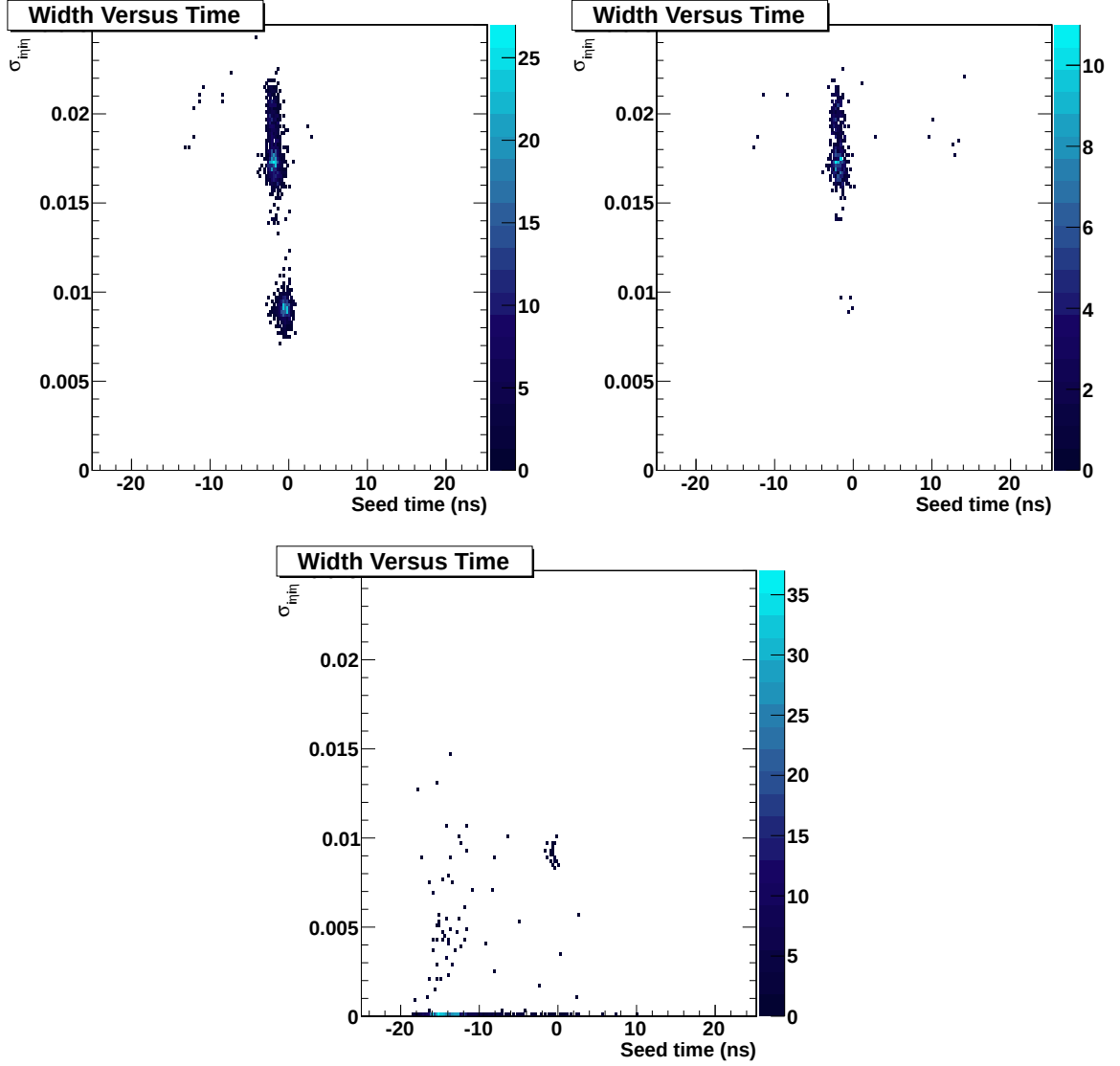


FIGURE 5.8. The relationship between seed time and $\sigma_{i\eta i\eta}$ plotted in 2D for the photon candidate sample (left), beam halo sample (right), and the anomalous signal sample (bottom).

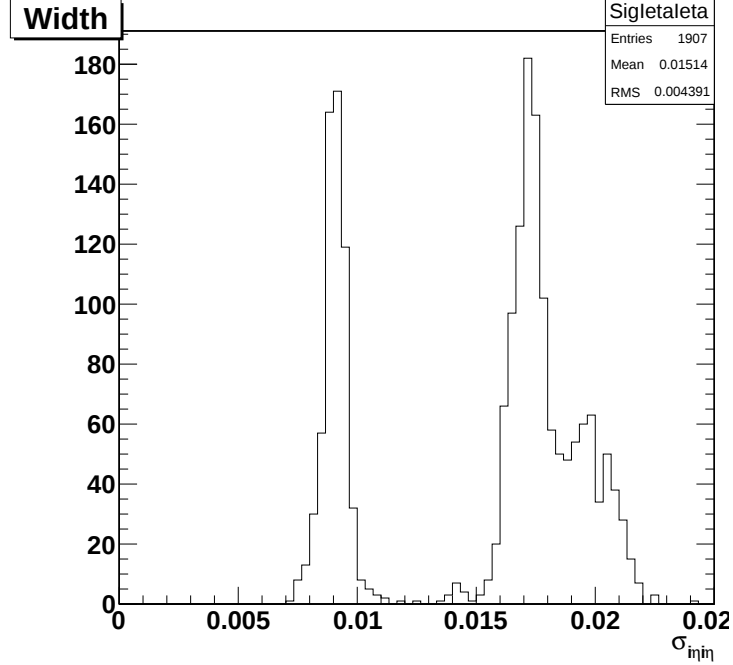


FIGURE 5.9. Histogram of $\sigma_{ii\eta\eta}$ for photons passing all candidate selection criteria, with jet and track vetoes but without shower shape requirements. Note that the $\sigma_{ii\eta\eta}$ cut, set at 0.013, largely removes beam halo events.

5.5.2. Data-driven estimates.

5.5.2.1. *Electron-fakes-photon background.* Electrons can be incorrectly reconstructed as photons, since both objects produce similar EM showers in the ECAL, the energy deposited in the pixel detector by the electron fails to be reconstructed into a pixel seed that is associated with the electron ECAL supercluster. Most of the electrons misidentified as photons arise from off-shell $W(e\nu)$ events with kinematic signatures similar to our signal sample. This background is estimated by applying the well-understood efficiency of the pixel seed algorithm to a control sample of $W(e\nu)$ events in the data.

The pixel seed match efficiency, ϵ , has been studied extensively, initially estimated with MC simulated events and later measured and confirmed with $Z(ee)$ events in data [53] to be 0.9940 ± 0.0025 . These studies have also shown that ϵ is constant as a function of p_T . A control sample of $W(e\nu)$ events in the data is created by applying the event selection criteria used in this analysis but requiring a pixel seed instead of vetoing events with them, selecting events with an isolated electron and $\cancel{E}_T$ that are kinematically similar to our candidate events. Dividing the number of events in this $W(e\nu)$ sample by the pixel

match efficiency provides an estimate of the actual number of electron events in the signal sample. The number of events with an electron misidentified as a photon contributing to the background in the signal sample is estimated by weighting the number of electron events by the pixel match inefficiency, given by $(1 - \epsilon)/\epsilon$. The electron p_T distribution, prior to being scaled by the pixel match inefficiency, is shown in Figure 5.10. This approach yields an estimate of 3.52 ± 1.48 electron events in the candidate sample.

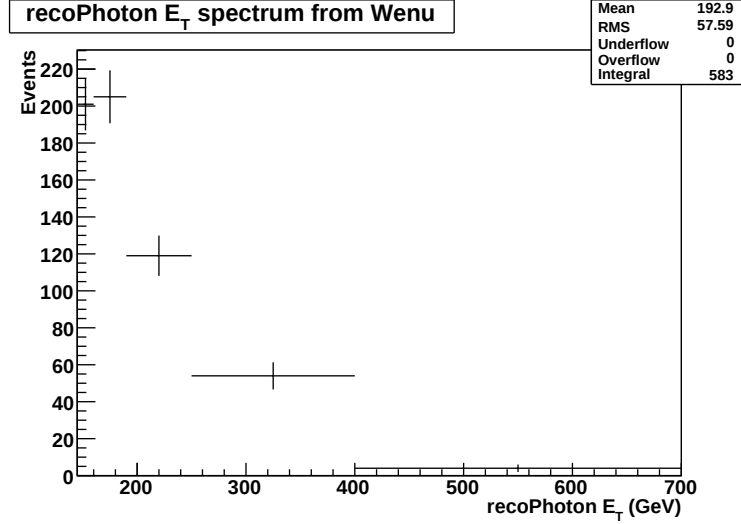


FIGURE 5.10. Electron p_T distribution before weighting by pixel match inefficiency.

5.5.2.2. *Jet-fakes-photon background.* Jets can be misidentified and reconstructed as photons, especially when high- E_T jets decay primarily into isolated π_0 or η particles which produce collimated EM showers in the ECAL. This background contribution from QCD multijet events is estimated from data using the fake ratio method [67]. “Fake” refers to the jets misidentified as photons, which are commonly referred to as “jets faking photons,” or “fake photons.” The fake ratio is the ratio of isolated-to-non-isolated jets that pass some of the photon criteria. In principle, the variation in isolation (and therefore the ratio) should be the same for jets regardless of the jet production mechanism, so the ratio can be measured with one sample of events and applied to another. A control sample of EM-enriched QCD events is used to calculate the fake ratio. The control sample is made of events in the photon dataset that pass loose photon selection criteria like the photon p_T cut, η cut, shower width cut, H/E cut, and have no pixel seed, but have limited $\cancel{E}_T$ ($\cancel{E}_T < 20$ GeV) and no vetoes on jet or track activity. All of the events in the control sample have passed one of the HLT

triggers used for the signal sample, contain a good vertex, and pass the scraping event veto, and the reconstructed photon candidate is required match the HLT trigger object within $\Delta R < 0.2$ so that the control sample reflects what is found in the signal sample. The cuts that define the numerator, the number of events that include a jet that mimics the signature of an isolated photon, are:

- ECAL Isolation $< 4.2 \text{ GeV} + 0.006 \times p_T^\gamma$
- HCAL Isolation $< 2.2 \text{ GeV} + 0.0025 \times p_T^\gamma$
- Track Isolation $< 2.0 \text{ GeV} + 0.001 \times p_T^\gamma$
- $H/E < 0.05$
- $\sigma_{i\eta i\eta} < 0.013$
- no pixel seed

The events in the denominator of the fake ratio include a jet that passes one of the following non-isolation requirements:

- ECAL Isolation $> 4.2 \text{ GeV} + 0.006 \times p_T^\gamma$
- HCAL Isolation $> 2.2 \text{ GeV} + 0.0025 \times p_T^\gamma$
- Track Isolation $> 3.5 \text{ GeV} + 0.001 \times p_T^\gamma$

as well as loose photon selection criteria:

- ECAL Isolation $< \min[5.0 \times (4.2 + 0.006 \times p_T^\gamma), 0.2 \times p_T^\gamma]$
- HCAL Isolation $< \min[5.0 \times (2.2 + 0.0025 \times p_T^\gamma), 0.2 \times p_T^\gamma]$
- Track Isolation $< \min[5.0 \times (3.5 + 0.001 \times p_T^\gamma), 0.2 \times p_T^\gamma]$
- $H/E < 0.05$
- $\sigma_{i\eta i\eta} < 0.013$
- No pixel seed

The events selected in the numerator and denominator are shown in Figure 5.11 as a function of p_T .

The fake ratio aims to estimate the number of jets that are misidentified as photons, but the numerator sample includes a number of photons correctly reconstructed from QCD direct photon production. In order to identify the true fake ratio, the distinction between collimated jets and photons in $\sigma_{i\eta i\eta}$ is used to estimate and remove these events from the numerator. A simulated sample of γ +jet events is used to produce p_T -dependent shower

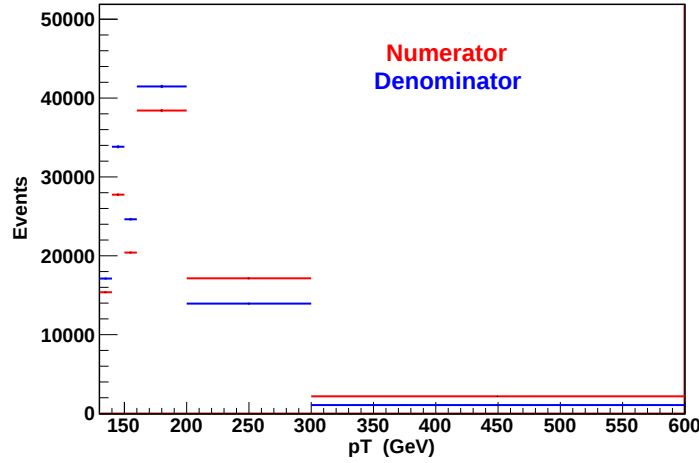


FIGURE 5.11. Events selected in the numerator (red) and denominator (blue) for the fake ratio [65].

width templates for true photons, and a data sample of multijet QCD events is selected by requiring some track p_T depositions within the isolation cone around the event,

$$(2.0 + 0.001 \times p_T) < \text{Track Iso} < (4.0 + 0.001 \times p_T), \quad (5.2)$$

and used to create p_T -dependent shower width templates for jets. The results of the template fitting in data are shown in Figure 5.12 for a selection of p_T bins. These templates are applied to the events in the control sample in order to estimate how many contain direct photon production. The estimates are calculated in the range $\sigma_{i\eta i\eta} < 0.013$ so that it matches the requirements on the numerator and the selection criteria for our signal sample. The corrected fake ratio is shown as a function of p_T in Figure 5.13.

The last step in this process is to apply the corrected fake ratio to a sample of **Photon** dataset events that pass the denominator requirements and more closely resemble the signal sample, passing $\cancel{E}_T > 130$ GeV and the jet and track vetoes as well as $\sigma_{i\eta i\eta} < 0.013$ to minimize the beam halo contamination. The fake ratio is parametrized as a function of p_T :

$$f_{p_T^\gamma} = 0.2551 - 2.406 \times 10^{-3}(p_T^\gamma) + 1.323 \times 10^{-5}(p_T^\gamma)^2 \quad (5.3)$$

This yields an estimate of 11.2 ± 2.8 events in the signal sample with a jet reconstructed as a photon.

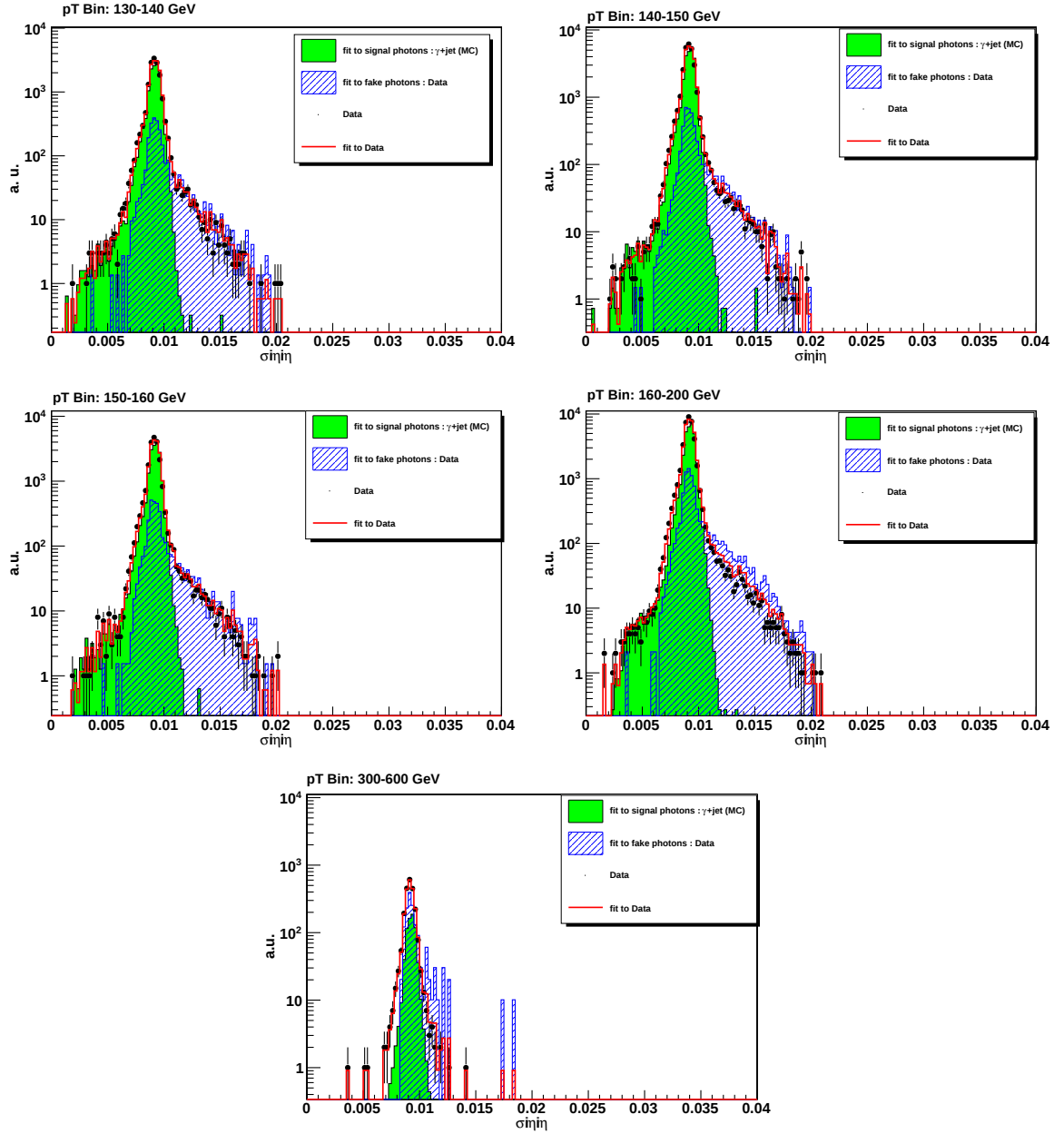


FIGURE 5.12. The $\sigma_{ii\eta\eta}$ template distributions and fits to QCD- and true-photon contributions in p_T bins. The fit to signal photons is filled in green, the fit to fake photons is filled with a blue dashed line, the data points are black and the overall fit to data is in red. [65].

The error on the estimate is calculated by measuring the uncertainty generated by a 1σ variation in several sources and adding them in quadrature. The sources of uncertainty included in the error calculation are: the fit parameters of the fake ratio, the systematics associated with variations in the sideband selection, the bin sizes of the shower shape

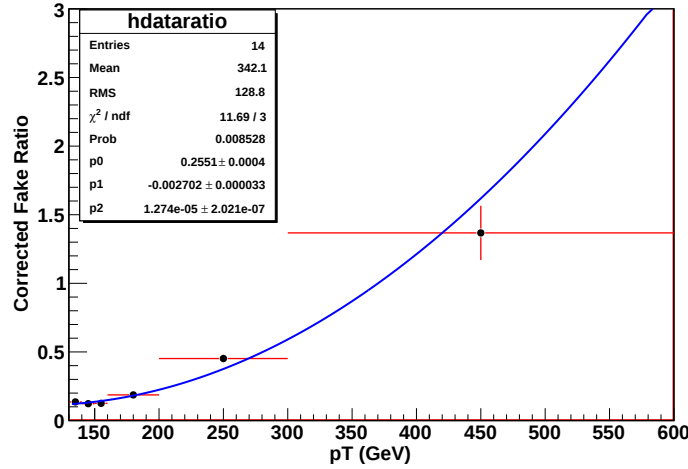


FIGURE 5.13. The corrected fake ratio as a function of p_T .

templates, and the statistical uncertainty from the normalization of the data sample, which is the dominant source of uncertainty in this calculation. In order to calculate the additional uncertainty, the sideband selection criteria and the bin size of the templates were varied. Several parameters were changed to measure the variation of the sideband uncertainty: the sideband width, introducing the constant term of the track isolation into the sideband fit, and requiring the QCD templates to fail the ECAL and HCAL isolation criteria. The template bin sizes were varied by a factor of 0.5 and 2.0. The results of these variations, listed in Tables 5.3 and 5.4, are that the uncertainties on the fraction estimations are more than 3 – 4% in the lowest p_T bins and fall in the range of 6 – 11% for the higher p_T bins. The greatest variation is observed when the ECAL and HCAL isolation criteria is inverted along with the Track isolation, and when MC is used for the shower shape background template instead of data selected from the sideband region. When MC is used for the shower shape background template, the fraction varies by 20%, and when the sideband is varied the fraction varies up to 18% in a single p_T bin. To account for these effects, we assign a conservative systematic uncertainty of 20%.

5.5.3. Simulation-driven estimates. Four of the sources of background are estimated from MC simulated samples. The backgrounds from $W(l\nu)\gamma$, γ +jet, and diphoton events are estimated with MC to measure the Standard Model $Z(\nu\bar{\nu})\gamma$ signal, and the

p_T^γ Bins (GeV)	f_{qcd} $2.0 + 0.001p_T^\gamma >$ track Iso. $< 4.0 + 0.001p_T^\gamma$	f_{qcd} $2.0 > \text{trk Iso} < 4.0$	f_{qcd} $2.0 + 0.001p_T^\gamma >$ track Iso. $< 5.0 + 0.001p_T^\gamma$
130-140	0.151±0.013	0.168±0.014	0.120±0.009
140-150	0.150±0.010	0.169±0.012	0.117±0.007
150-160	0.151±0.013	0.169±0.014	0.117±0.008
160-200	0.202±0.014	0.218±0.014	0.126±0.007
200-300	0.367±0.027	0.406±0.028	0.221±0.024
300-600	0.673±0.094	0.645±0.0957	0.617±0.079

TABLE 5.3. QCD fraction from template fits using different widths for the side-band track isolation requirement [65].

p_T^γ Bins (GeV)	f_{qcd} bin size increased by a factor of 2.0	f_{qcd} bin size reduced by a factor of 0.5	f_{qcd} ECAL and HCAL Iso also flipped for QCD template
130-140	0.144±0.012	0.157±0.013	0.079±0.012
140-150	0.141±0.009	0.154±0.011	0.067±0.006
150-160	0.144±0.012	0.157±0.013	0.062±0.007
160-200	0.162±0.011	0.207±0.014	0.084±0.014
200-300	0.324±0.028	0.397±0.028	0.289±0.028
300-600	0.684±0.097	0.745±0.105	0.489±0.125

TABLE 5.4. QCD fraction from template fits when the bin sizing of the $\sigma_{i\eta i\eta}$ template distributions has been increased by a factor of 2.0, decreased by a factor of 0.5, and when the ECAL and HCAL isolations are flipped for the QCD templates [65].

$Z(\nu\bar{\nu})\gamma$ signal itself is estimated using MC to test for an excess in the channel and set limits on χ -nucleon interactions.

With a cross section of 7.9 nb at the LHC from 7 TeV proton collisions, $W(l\nu)$ has the potential to be one of the largest backgrounds in this analysis. A $W(l\nu)\gamma$ event contributes to the background when the charged lepton isn't reconstructed in the event, which is a separate phenomenon from electrons being misidentified as photons, described in Sec. 5.5.2. A simulated sample of $W\gamma$ events is used to estimate the background contribution and includes photons production through initial state radiation (ISR), final state radiation (FSR) from a lepton, and emission from the W. Most of the $W\gamma$ background for our signal sample comes from ISR events. The FSR contribution is estimated with a high mass ($m_l \geq 200$ GeV) sample of simulated $W(l\nu)$ events from Pythia, it is found to be very small and comes from

very high-mass, off-shell W decays when the radiated photon carries away most of the energy. In order to differentiate between these events and the electrons faking photons and avoid double counting the contribution, the electrons in FSR events are required to have $p_T < 50$ GeV after they radiate the photon; this is a generator-level cut. An estimated 3.0 ± 0.1 $W(l\nu)\gamma$ events are in the signal sample.

Diphoton events can be selected as signal events if one of the photons isn't reconstructed, leading to what appears to be a single-photon event with $\cancel{E}_T$. Using a simulated sample, 0.6 ± 0.3 events in the signal sample are expected to come from diphoton events.

The background contribution from γ +jet events that is studied with the simulated sample is different from the data-driven fake ratio discussed earlier, which provided an estimate for the background events due to a jet reconstructed as a photon. The simulated γ +jet sample is used to study a second background phenomenon: the case when a jet is poorly reconstructed and introduces $\cancel{E}_T$ to an event that has a real photon. To distinguish this background from its fake photon counterpart, simulated events must include a photon candidate that originates from the initial hard scatter. The prediction from the simulated sample is that 0.5 ± 0.2 additional γ +jet events will be part of the background.

The number of events expected to contribute to the background from each of these channels are listed in Table 5.5.

	Vertex	Scraping	Non Cosmics	MET	γ -ID & $p_T^\gamma \& \eta^\gamma $	Track Iso	Jet Veto	Track Veto	HLT	Events in 5.0 fb^{-1}
$W+\gamma$	0.999	0.999	0.591	0.002	8.19e-05	7.62e-05	1.41e-05	1.22e-05	1.22e-05	$4.27^{+1.74}_{-1.16}$
$W \rightarrow e\nu$	0.998	0.998	0.992	0.236	0.0085	0.0069	0.0048	0.0032	0.0032	$0.36^{+0.13}_{-0.10}$
$W \rightarrow \mu\nu$	0.997	0.997	0.116	0.014	0.000	0.000	0.000	0.000	0.000	$0.00^{+0.05}_{-0.0}$
$W \rightarrow \tau\nu$	0.999	0.999	0.780	0.124	0.018	0.015	0.0092	0.0083	0.0083	$0.26^{+0.12}_{-0.08}$
$\gamma\gamma$	0.999	0.999	0.923	0.010	0.0069	0.0066	0.0017	0.0012	0.0012	$0.54^{+0.60}_{-0.27}$
γ +Jet	0.998	0.998	0.750	0.012	0.0060	0.0058	6.20e-07	3.38e-07	3.38e-07	$0.63^{+0.58}_{-0.29}$

TABLE 5.5. The cumulative efficiencies of the background processes after successive analysis cuts. The last column shows the total number of events from each background at 5.0 fb^{-1} .

A sample of $Z(\nu\bar{\nu})\gamma$ events is also simulated to compare against the estimated cross section in data, and to provide a background estimate for a DM signal. Based on a 5.0 fb^{-1}

dataset, 45.3 ± 6.9 $Z(\nu\bar{\nu})\gamma$ events are expected in the signal sample, corresponding to a channel cross section of 59 ± 3.0 fb. This expected cross section is scaled to reflect NLO contributions using a k-factor from BAUR, discussed in the following section.

The uncertainty given for these simulation-based background estimates is calculated taking into account several sources: the theoretical uncertainties on the LO cross section and k-factors; the uncertainty on the scale factor that models data-MC differences in the efficiency; the systematic uncertainties associated with the photon vertex assignment, modeling of pileup, and the accuracy of the energy calibration and resolution for photons, jets, and $\cancel{E}_T$.

A full summary of the background sources and estimated contributions can be found in Table 5.12.

5.5.4. Scaling Simulations for NLO. Monte Carlo generators fall into two categories: parton shower generators and matrix element generators. Parton shower (PS) generators are also known as full event generators because they simulate full hadronization and underlying event information that can be used to simulate events in detectors, but the interactions only include tree-level, or LO, contributions to the cross section. Matrix element (ME) generators perform a more precise matrix element calculation and some are able to run a full NLO calculation for event production and include Born, virtual, and real terms, but the generators do not propagate the event through full hadronization and do not include underlying event information. At the LHC energy scale, NLO contributions become important, so ratios of the NLO-to-LO event contributions, called k-factors, are calculated using ME generators and applied to the PS generator samples. For this analysis, fully hadronized $Z(\nu\bar{\nu})\gamma$ events are produced using the PS generator PYTHIA and the k-factor is formed from the p_T^γ distributions in NLO and LO events produced using the ME generator BAUR. The k-factor is calculated to scale the theoretical prediction for the SM $Z(\nu\bar{\nu})\gamma$ channel cross section generated using PYTHIA. The k-factor that scales the cross section is produced by generating NLO and LO-level $Z(\nu\bar{\nu})\gamma$ events using BAUR with selection criteria to match the PYTHIA samples: $p_T^\gamma > 130$ GeV, $|\eta^\gamma| < 10$, and additional generator-level information listed in Table 5.6.

Parameter	NLO Cut
Photon p_T	130 GeV
Cluster(Z, γ) transverse mass	100 GeV
Soft divergence parameter	0.15
Collinear divergence parameter	0.001
$\Delta R(\gamma, \nu)$	0.7
% Hadronic Energy in a R=0.7 cone around γ	0.15
Factorization scale	$\sqrt{\hat{s}}$
Form Factor scale	1.5 TeV

TABLE 5.6. Generator-level cuts in Baur MC with restrict photon p_T .

As it was previously mentioned, the NLO events are generated using the CTEQ66 PDF and the LO events are generated with the CTEQ6L1 PDF. The k-factor is produced by dividing the normalized p_T^γ spectrum of the NLO events by the normalized p_T^γ spectrum of the LO events, and the resulting k-factor is 1.56 and nearly flat in p_T . The plots of the generator-level p_T^γ spectrum for LO and NLO events, scaled by the event count and cross section, as well as the k-factor as a function of p_T , is shown in Figure 5.14. An additional k-factor is calculated, this time by generating BAUR events with selection criteria to match the signal sample: $p_T^\gamma > 145$ GeV, $|\eta^\gamma| < 1.4442$, $\cancel{E}_T > 130$ GeV, $|\eta^\nu| < 5$, and $|\eta^{jet}| < 3$. This gives us an idea of what kind of distribution of NLO events we should expect to pass our cuts and add to our data sample. The more constrained samples produce a k-factor of 1.19, as shown in Figure 5.15. The PYTHIA sample is scaled to reflect NLO contributions by calculating an acceptance term from the ratio of these k-factors, $1.19/1.56 = 0.76$, and multiplying the signal acceptance by that value.

Additional LO and NLO samples produced with requirements similar to the signal sample are used to test the sensitivity of the k-factor to the choice of PDF, factorization scale, and renormalization scale. The uncertainty from the PDF on the BAUR simulations are calculated according to the standard method described in Section 5.6, providing an uncertainty of ± 0.05 . The PDF uncertainty and k-factors are broken down bin-by-bin in Table 5.7.

To test the sensitivity of the samples to the choice of factorization scale, new events are generated with kinematic requirements similar to the signal sample and a factorization scale of $\frac{1}{2}\hat{s}$ and $2\hat{p}_T$ which produce k-factors of 1.10 and 1.15, respectively, indicating that

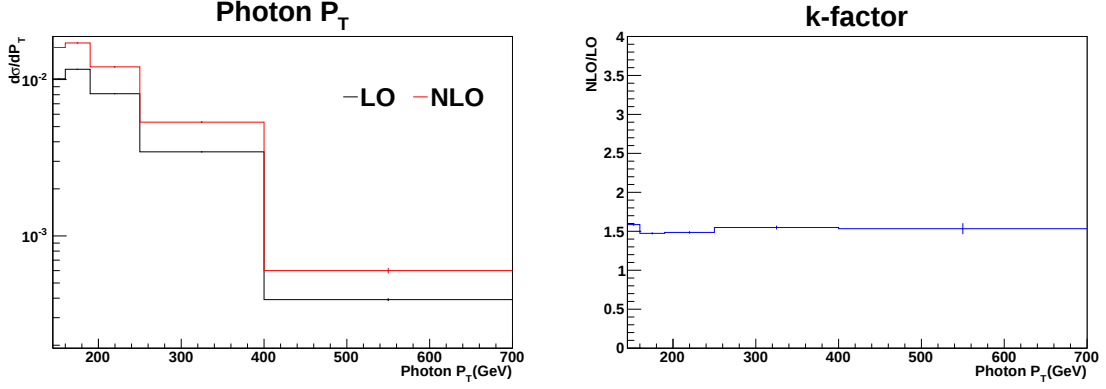


FIGURE 5.14. (left) The generator level p_T spectrum for both LO and NLO events, scaled by event count and cross section. (Right) The k-factor produced by the two p_T spectra. The events were generated with $p_T > 130$ GeV to match the generator-level PYTHIA requirements. The k-factor is 1.56.

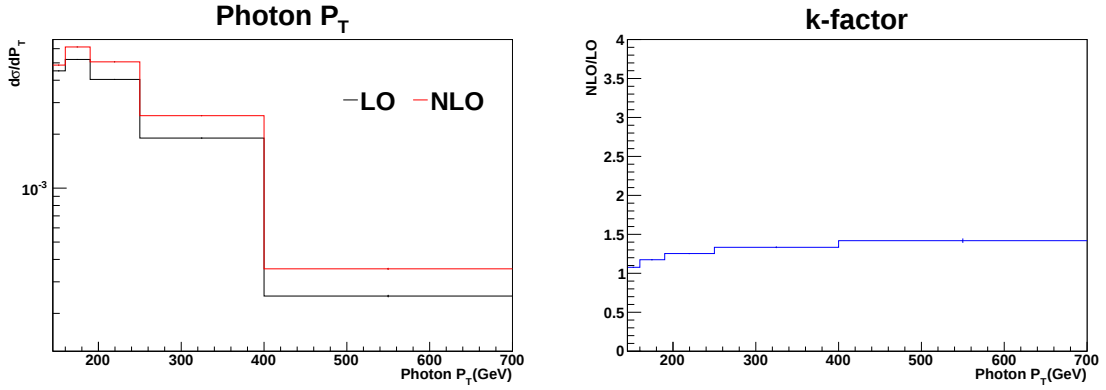


FIGURE 5.15. (left) The generator level p_T spectrum for both LO and NLO events, scaled by event count and cross section. (Right) The k-factor calculated with LO and NLO events generated by Baur with $p_T^\gamma > 145$ GeV in the barrel region and $\cancel{E}_T > 130$ GeV. The overall k-factor is 1.19.

p_T bin (GeV)	k-factor	uncertainty from PDF
145 - 160	1.08	± 0.18
160 - 190	1.17	± 0.14
190 - 250	1.25	± 0.23
250 - 400	1.33	± 0.24
400 - 700	1.42	± 0.65

TABLE 5.7. The k-factors as a function of p_T . Also listed are uncertainties due to choice of PDF.

the choice of factorization scale introduces an error of ± 0.05 to the k-factor. Additionally, to test the sensitivity of the k-factor to the renormalization scale, α_S is varied by 10% and the corresponding change measured in the k-factor is ± 0.02 .

The acceptance of the signal is also scaled to reflect NLO-level contributions. A ratio of k-factors is produced using the k-factor generated with signal selection criteria described in the previous paragraph and a k-factor from events generated with $p_T^\gamma > 130$ GeV and no other cuts to illustrate full acceptance. To calculate the full acceptance k-factor, 852,235 NLO events and 552048 LO events are generated, and the normalized NLO p_T^γ spectra is divided by that of the LO events. The resulting k-factor is 1.56 and the acceptance ratio, $A_{\text{NLO/LO}}$, is 0.76 ± 0.02 , where the error is statistical.

5.6. Acceptance and Systematic Uncertainties

The measurement of the cross section for $Z(\nu\bar{\nu})\gamma$ events, which is also used to set limits on the production of dark matter, is calculated as:

$$\sigma \times \text{BR} = \frac{N_{\text{data}} - N_{\text{bkg}}}{A \times \epsilon \times \mathcal{L}} \quad (5.4)$$

where N_{data} is the number of events found in data, N_{bkg} is the predicted number of background events, A is the geometric and kinematic acceptance of the selection criteria, ϵ is the selection efficiency for the signal, and $\mathcal{L}$ is the integrated luminosity. The term $A \times \epsilon$ is actually broken down into two calculations, estimating $A \times \epsilon_{MC}$ from simulated events and then multiplying it by a scale factor, ρ , to correct for the difference in efficiency between the simulated and real events. The systematic uncertainties that contribute to $A \times \epsilon_{MC}$ are from the choice of PDF [58, 68, 69], the selection of the primary vertex for the photon, how the pileup is modeled, and the energy calibration and resolution for photons [56], jets [70], and $\cancel{E}_T$ [51].

5.6.1. PDF uncertainty. The parton distribution function (PDF) used by MC events simulators introduces some theoretical uncertainty into the cross section estimation. The MC samples are produced with PYTHIA using the LO CTEQ6L1 [58] PDF and the generated LO cross section for $Z(\nu\bar{\nu})\gamma$ is then scaled to reflect NLO effects by a k-factor obtained with BAUR MC, which uses the LO CTEQ61 NLO CTEQ66 PDF. The uncertainty due to the choice of PDF is calculated according to the PDF4LHC guidelines [68] and the procedures established by the CMS EWK group [71], where the simulations are rerun with different PDFs produced by varying the defining eigenvectors, and the results are compared. The observed error on the acceptance due to the choice of PDF is $\pm 2.4\%$.

5.6.2. Vertex uncertainty. As it was discussed in Section 5.4, there is a chance the photon candidate is assigned the wrong vertex, which can affect the calculation of E_T (and the corresponding $\cancel{E}_T$ in the event). A control sample of $W(e\nu)$ events from data is used to study the likelihood of incorrectly assigning an EM object to a vertex, and the resulting effect on the energy. Since electrons deposit energy in the tracker, the EM cluster in the ECAL can be matched to the vertex with more precision. In this study, the track corresponding to the electron is excluded from the event information and the sum of the squares of the track p_T is calculated for each vertex in the event, which is the standard method used to identify the primary vertex in the event. In 38% of the events, the primary vertex selected by this method is not the one associated with the electron when the electron track information is taken into consideration. The E_T of the electron in the ECAL is recalculated for these mismatched events, shown in Figure 5.16, and when it is compared to the electron E_T in the ECAL calculated from the correct primary vertex, the choice of primary vertex is shown to introduce a 2% uncertainty to the photon transverse energy resolution, which is included in the overall calculation of the acceptance.

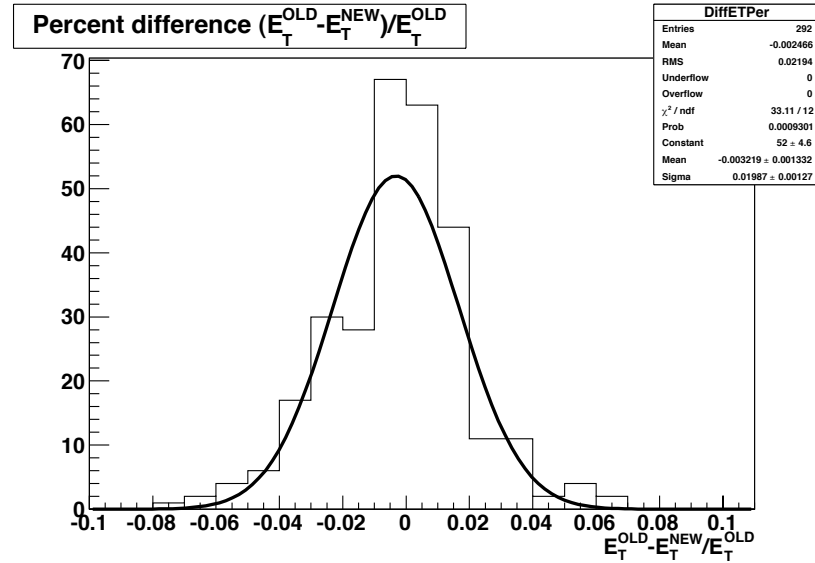


FIGURE 5.16. Event selection showing data points along with the contributions from various processes in photon p_T for the full data set [65].

5.6.3. Pileup modeling. The additional inelastic proton-proton interactions that result in multiple possible events (and primary vertices) per collision are referred to as pileup interactions, or simply pileup. The number of pileup interactions is proportional to the

instantaneous luminosity of the collider and the bunch spacing, and the excess information in the event can affect the reconstruction efficiency. To study the effects of pileup, the simulated events of interest in this analysis are combined with a sample of minimum bias interactions (events collected by a scaled inclusive trigger, largely comprising low p_T , soft events). However, this is not enough to create a complete model of the effects of pileup; the signal integration time for some of the CMS subdetectors is long enough to include information from out-of-time pileup interactions, as well. To take this into account, a 3D re-weighting procedure is used which takes into account the presence of pileup interactions in bunch crossings within ± 50 ns of each interaction of interest. This re-weighting method is the standard suggested procedure for 2011 data and MC, and the approach and official tools are described in more detail in Ref. [72]. A good agreement is found between data and simulation by using the Deterministic Annealing primary vertex reconstruction algorithm to reconstruct primary vertices, with an accompanying systematic error of $\pm 2.4\%$ that contributes to the acceptance uncertainty.

5.6.4. Energy scale of physics objects. The photon energy scale is taken from the $V\gamma$ analysis measurement, applying a Crystal-Ball fitting to the photon candidates in $Z(\mu\bar{\mu})\gamma$ FSR events [73]. Based on that measurement, the photon energy scale uncertainty is estimated to be $\pm 1.5\%$ with a systematic error of $+4.2\%$ and -4.3% . The $\cancel{E}_T$ scale uncertainty is taken to be 5% , which is a conservative estimate derived from the 2010 data [51], while the $\cancel{E}_T$ resolution uncertainty is taken to be 10% , which corresponds to the difference between the simulated prediction and the measured resolution in the data. The jet energy scale uncertainties are obtained using the 2011V2 official Jet Energy Correction tools [70], and the jet energy resolution is scaled up by 10% according to the stretching method [74].

The estimated value of $A \times \epsilon_{MC}$ for the SM channel $Z(\nu\bar{\nu})\gamma$ is 0.223 ± 0.001 . The systematic errors on the various components of the $A \times \epsilon_{MC}$ calculation are given in Table 5.8.

5.6.5. Scale factor. The simulation-derived $A \times \epsilon_{MC}$ term is multiplied by a scale factor, ρ , to account for the differences in efficiency between data and simulation. The calculated ρ of 0.90 ± 0.11 includes studies of the trigger, photon reconstruction, uniformity of cluster timing, and vetoes.

Source	Sys error in $A \times \epsilon_{MC}$ [%]
Photon scale	+4.2 -4.3
$\cancel{E}_T$ scale	+1.6 -3.1
$\cancel{E}_T$ resolution	± 0.03
jet energy scale	+0.85 -0.79
jet resolution	± 0.2
Photon vertex	± 0.3
Pile-up	± 2.4
PDFs	± 2.4
Total	+5.7 -6.3

TABLE 5.8. Systematic uncertainties on $A \times \epsilon_{MC}$ calculated for $Z(\nu\bar{\nu})\gamma$.

The HLT is determined to be essentially 100% efficient for our selection criteria in data and simulation events. A study of the efficiency of the HLT for our selection criteria was discussed earlier in Sec. 5.3. A 2% uncertainty is assigned to the trigger, though, based on efficiency studies of the L1SingleEG20 trigger that seeds the HLT used in this analysis.

The photon reconstruction efficiency is measured using the standard tag-and-probe tool on $Z \rightarrow ee$ events, since photon identification requirements have similar efficiencies for photons and electrons and $Z \rightarrow ee$ events are well defined and provide a clean data sample for testing. In the tag-and-probe method, tight photon requirements are placed on one electron candidate. This candidate, called the “tag”, must pass the trigger, have an associated track, and pass high quality photon requirements. Looser requirements are placed on the second candidate, called the “probe”, which is reconstructed only as a track or a supercluster. Two invariant mass distributions are made from the pair, one for the case where the probe passes the photon identification criteria and one for the case when the probe fails the photon criteria, and both distributions are fit to the Z peak with the QCD background subtracted. The efficiency of the photon identification criteria is calculated from the two distributions, once for data using the $Z \rightarrow ee$ sample and once for simulated events as well, as shown in Figure 5.17. The ratio of efficiencies between MC and data provides a scale factor of 0.96 ± 0.02 .

The crystals within an EM cluster must have consistent intraccluster timing to remove spike events, as discussed in Sec. 5.4. The photon clusters in simulated events always have consistent timing among crystals, and the efficiency of the LICTD cut is tested in data with a sample of $Z \rightarrow ee$ candidates. Both electron candidates must pass the regular candidate

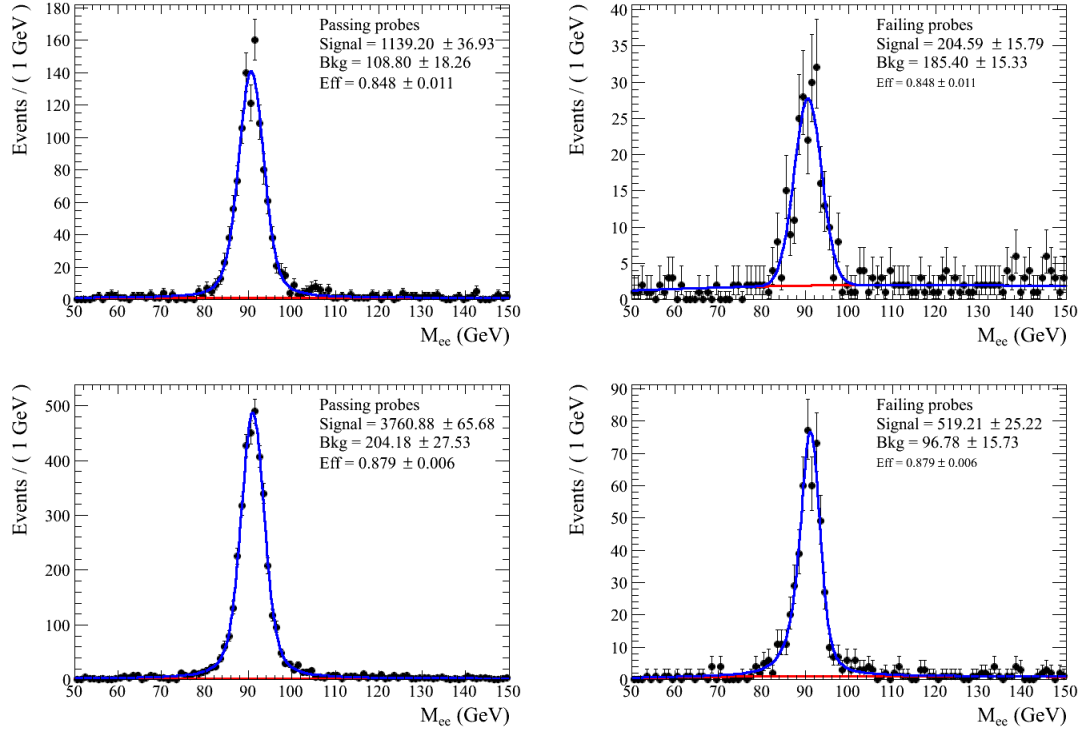


FIGURE 5.17. Invariant mass distribution and fits for tag and probe method applied to data (above) and MC (below).

selection, but are required to have a pixel seed, and both must pass the LICTD cut. The efficiency of the LICTD cut is measured to be 0.983 ± 0.009 using the $Z \rightarrow ee$ candidate sample. This result is cross-checked using a data sample of $W \rightarrow e\nu$ candidates and good agreement is found between the two samples.

Three vetoes are studied to see how they scale in data and MC: the reconstructed cosmic muon veto, the veto on jets with $p_T > 40$ GeV within $|\eta| < 3.0$, and veto on tracks with $p_T > 20$ GeV that are greater than $\Delta R = 0.04$ away from the photon candidate. The efficiencies of the jet and track vetoes are correlated since they both remove events with jet activity, so their joint efficiency is studied. The jet and track veto and cosmic muon veto efficiencies are measured in a sample of known $W \rightarrow e\nu$ events in data and a simulated sample to compare the efficiency of the vetoes. The $W \rightarrow e\nu$ candidates must pass all of the event selection criteria with the exception that the electron candidate must have a pixel seed. Table 5.9 shows the numerator and denominator used to calculate the veto efficiencies, which are listed in Table 5.10.

Cut Set	$W_{e\nu}$ MC	$W_{e\nu}$ Data	$Z(\nu\bar{\nu})\gamma$ MC	Cand Data
Numerator for N-1 Eff.	48	583	938	73
Denominator CosMu Eff.	54	653	995	121
Denominator Trk+Jet Eff.	107	1198	1344	218

TABLE 5.9. Number of candidates that pass vetoes.

Efficiency	$W_{e\nu}$ MC	$W_{e\nu}$ Data	$Z(\nu\bar{\nu})\gamma$ MC	Cand. Data
CosMu Eff.	0.90 ± 0.17	0.89 ± 0.05	0.94 ± 0.04	0.60 ± 0.09
Trk+Jet Eff.	0.45 ± 0.07	0.49 ± 0.02	0.70 ± 0.03	0.33 ± 0.05

TABLE 5.10. N-1 efficiencies of the jet-and-track veto and the cosmic muon veto.

The difference jet-and-track veto efficiencies in $W_{e\nu}$ and $Z(\nu\bar{\nu})\gamma$ events is not unreasonable since the W is probably recoiling off of a jet while the $Z(\nu\bar{\nu})\gamma$ event is already balanced. This means we would expect a jet veto to eliminate more events in a W sample compared to a $Z(\nu\bar{\nu})\gamma$ sample. Additional studies of the jet-and-track veto using production samples more similar to $Z(\nu\bar{\nu})\gamma$ could yield a better estimate of the jet-and-track veto efficiency for this analysis. The cosmic muon efficiency matched in the $W_{e\nu}$ data and simulations even though cosmic muons aren't part of the simulated sample because the cosmic muon bremsstrahlung events were already selected against by requiring a pixel seed for the photon in the event. This same reason explains why the $Z(\nu\bar{\nu})\gamma$ MC and candidates do not have matching cosmic muon veto efficiencies, since monophoton candidates do not have the additional tracker information and are more susceptible to cosmic muon event contamination.

The larger $Z \rightarrow ee$ data sample is used to compare the results of the jet-and-track veto efficiencies, and to test the inefficiency of only using the cosmic muon veto. The candidate events are selected from the **Photon** dataset and must have two electron objects that both pass the tight photon criteria with $p_T > 30$ GeV and have a pixel seed. The invariant mass of the $Z \rightarrow ee$ candidates is shown in Figure 5.18 for events that pass the track-and-jet vetoes in black and events that additionally pass the cosmic muon veto in red. The efficiencies measured for the jet and track-vetoes in these samples agree within their uncertainties, so the scale factor is set to unity and assigned a systematic uncertainty of ± 0.10 . The efficiency measured for the cosmic-muon veto is 89.9% in data and 94.3% in MC, producing a scale factor of 0.95 ± 0.01 .

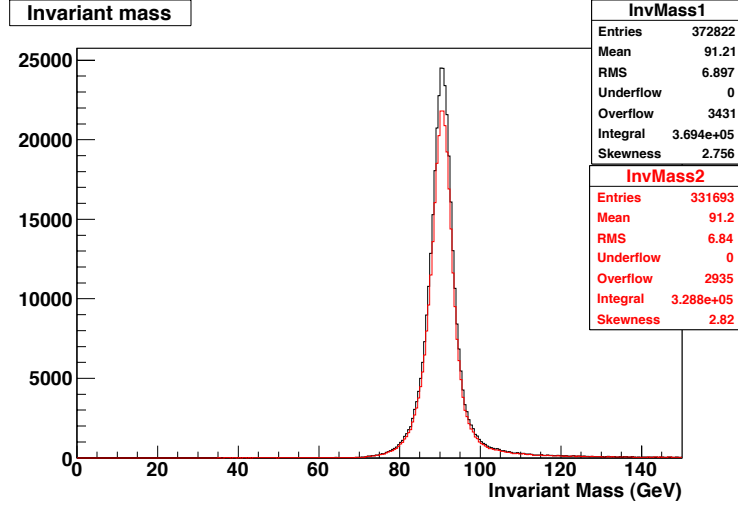


FIGURE 5.18. The invariant mass for $Z \rightarrow ee$ events that pass jet and track vetoes (black), and for those also passing CosmicMuon veto (red) [65].

The contributions to the scale factor ρ are listed in Table 5.11.

Source	Estimate for ρ
Trigger	1.00 ± 0.02
LICTD	0.983 ± 0.009
Photon Efficiency	0.96 ± 0.02
Jet and track veto	1.00 ± 0.10
Cosmic muons veto	0.95 ± 0.01
Total	0.90 ± 0.11

TABLE 5.11. The difference in the efficiencies for selection criteria in data and simulation.

5.6.6. Luminosity. The integrated luminosity is measured offline and provides a measurement of the amount of data collected by the CMS detector. Luminosity measurements were initially made with the HF, but problems arose: the HF response function for the instantaneous luminosity is non-linear; HF has an afterglow effect where the energy from one bunch crossing will create a response in the next bunch crossings; and there is a slow gain drift. An alternative technique to measure the luminosity has been developed that uses information from the pixel detector and is called the Pixel Cluster Counting Method [75]. This technique takes advantage of the fact that the pixel detectors are very highly segmented and it is highly unlikely that a single pixel will be traversed by multiple tracks. A Van der Meer scan determines the size of the cross section of the beams at their point

of collision. That information is combined with the rate of pixel cluster hits per bunch crossing, which is linearly related to the number of collisions per bunch crossing, to provide a measurement of the luminosity. The technique is discussed in detail elsewhere [75], and results in a luminosity measurement of 5.0 fb^{-1} with a low 2.2% systematic uncertainty.

5.7. Standard Model Results

The selection criteria for this analysis is applied to the data collected in 2011, and 73 events are observed in 5.0 fb^{-1} of data. This matches very well with the expected signal of 75.1 ± 9.5 events, which is broken down by the contribution from each source in Table 5.12. The p_T spectrum of the full combination of the candidate events and selected backgrounds can be seen in Figure 5.19, and the $\cancel{E}_T$ spectrum of the candidates can be seen in Figure 5.20.

Source	Estimate
Jet Fakes Photon (data)	11.2 ± 2.8
Electron Fakes Photon (data)	3.5 ± 1.5
Beam Halo (data)	11.1 ± 5.6
$W\gamma$ (MC)	3.0 ± 1.0
Diphoton (MC)	0.6 ± 0.3
γ +jet (MC)	0.5 ± 0.3
Total Bkg to $Z(\nu\bar{\nu})\gamma$	29.8 ± 6.8
$Z(\nu\bar{\nu})\gamma$ Signal (MC)	45.3 ± 6.9
Expected Events (SM)	75.1 ± 9.5
Observed Events	73

TABLE 5.12. Summary of estimated backgrounds for 5 fb^{-1} of data collected in 2011.

The cross section for the SM signal is measured based on the formula in Eq. 5.4 and compared to the theoretical prediction. The observed number of events, N_{data} , is 73 and the number of estimated background events, N_{bkg} , is 29.8 ± 6.8 . The $A \times \epsilon$ term, calculated as $A \times \epsilon_{\text{MC}} \times \rho \times A_{\text{NLO/LO}}$, is estimated to be 0.153 ± 0.020 . The systematic uncertainty on the measured integrated luminosity, discussed in the last section, is 2.2% [75]. The resulting measured cross section for $Z(\nu\bar{\nu})\gamma$ is $57 \pm 11(\text{stat.}) \pm 12(\text{sys.}) \pm 2.0 \text{ fb}$, which is in good agreement with the theoretical NLO prediction of $59 \pm 3(\text{stat.}) \text{ fb}$ [76].

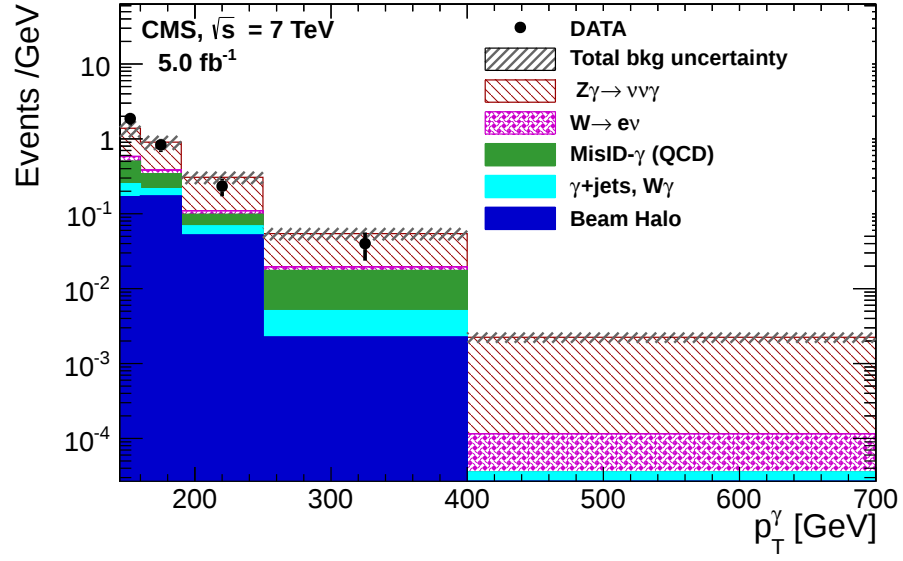


FIGURE 5.19. Final event selection showing data points along with the contributions from various processes in terms of photon p_T . The shaded bands denote the background uncertainty.

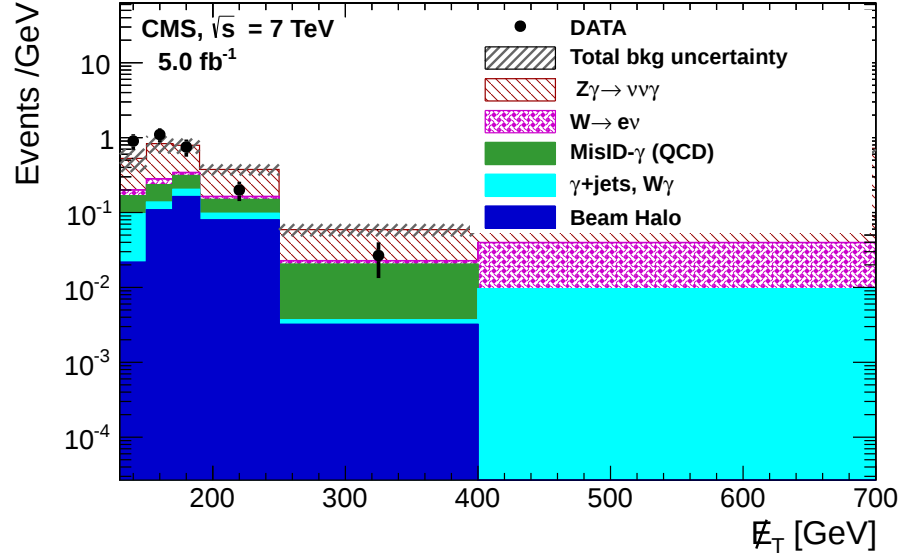


FIGURE 5.20. Final event selection showing data points along with the contributions from various processes in terms of event E_T . The shaded bands denote the background uncertainty.

CHAPTER 6

Limits on Dark Matter

The good agreement between the signal sample and the SM prediction is used to set limits on the dark matter production cross sections. The limits on dark matter production are set as a function of the dark matter candidate mass, M_χ , for the scenarios with SI and SD interaction terms. These limits are converted into lower limits on the cutoff scale Λ , which are used to also derive upper limits on the χ –nucleon cross sections.

Samples of events including the pair production of dark matter are generated with MADGRAPH 4 and fully simulated with PYTHIA 6 for both the SI and SD cases using a software package from Ref. [34]. These samples are generated for a range of dark matter candidate masses ($M_\chi = 1, 10, 100, 200, 500$, and 1000 GeV) with $p_T^\gamma > 125$ GeV, $|\eta^\gamma| < 1.5$, and Λ set to 10 TeV, and the production cross section is assumed to scale with Λ^{-4} . The cross sections for DM pair production for various masses and additional requirements of $E_T > 125$ GeV and $|\eta| < 1.5$ are given in Table 6.1 for both cases of vector and axial-vector operators. The monophoton selection criteria are applied to the DM simulated events, and

Dark Matter Mass [GeV]	Theoretical Cross Section [fb]	
	Vector	Axial-Vector
1	1.530×10^{-4}	1.542×10^{-4}
10	1.525×10^{-4}	1.520×10^{-4}
100	1.489×10^{-4}	1.312×10^{-4}
200	1.296×10^{-4}	9.335×10^{-5}
500	5.222×10^{-5}	2.254×10^{-5}
1000	5.127×10^{-6}	1.220×10^{-6}

TABLE 6.1. The theoretical cross sections for DM pair production, taken from simulation, for the vector and axial-vector models as a function of the dark matter candidate mass, given the requirements $E_T > 125$ GeV and $|\eta| < 1.5$.

the systematic uncertainties are calculated in a similar way. Across the range of masses, the contributions to the systematic uncertainty are as follows: 1.7% statistical error, 2.3% photon p_T error, 1.2% Jet Energy Correction error, 0.5% $\cancel{E}_T$ error, and 2.4% pileup error.

Table 6.2 provides the $A \times \epsilon_{MC}$ values for the different candidate mass values, which are all scaled by the same $\rho = 0.90 \pm 0.11$ term. Overall, the estimated value of $A \times \epsilon_{MC}$ for the range $M_\chi = 1 - 1000$ GeV is between 30.5%–31.0% for vector and 29.2%–31.4% for axial-vector couplings.

Dark Matter Mass [GeV]	Acc. $\times \epsilon_{MC}$	
	Vector	Axial Vector
1	0.305	0.292
10	0.305	0.310
100	0.306	0.314
200	0.305	0.311
500	0.320	0.319
1000	0.310	0.314

TABLE 6.2. The $A \times \epsilon_{MC}$ of the monophoton event selection applied to simulated samples of vector and axial-vector dark matter pair production.

The modified frequentist CL_s technique [77] is the statistical test used to place limits on DM model parameters. Statistical tests set rules that reject or reinforce a given hypothesis for a distribution of data. Frequentist statistical methods define probability as the frequency of the outcome of a repeatable experiment, they aren't used to define limits and confidence levels rather than probabilities for a hypothesis or a parameter. In this situation, the sample of data has been collected by the CMS experiment and limits are placed on the hypothesis that, for a range of DM candidate particle masses, DM production interactions should increase the number of events found in the monophoton channel. The CL_s technique is used because it is designed specifically for searches for new signal processes in cases of low sensitivity. The modified CL_s technique is a standard method available in the CMSSW RooStatsCl95 package and described in more detail by the Particle Data Group [77]. To give a brief overview, the CL_s method is used to calculate limits on BSM cross sections at a specified confidence level (CL) based on incompatibilities between data, SM predictions, and BSM predictions compared to a standard error rate α . CL_s is defined as $CL_s = p_\mu / (1 - p_{\text{not}})$, where μ is defined to be proportional to the DM production cross section, p_μ is the probability that the incompatibilities between the data and DM prediction are due to error, and p_{not} is the probability of the SM-only hypothesis. Limits are placed on DM production cross sections that yield $CL_s < \alpha$. The standard practice for exotic signature searches at the collider is to calculate their results with an error rate of $\alpha = 5\%$. However,

the standard practice among direct detection dark matter experiments is to quote results calculated with an error rate of $\alpha = 10\%$. In this case, the results are calculated twice, once at a $1 - \alpha = 95\%$ CL and once at a $1 - \alpha = 90\%$ CL to be comparable to direct detection results.

Upper limits are placed on the DM pair production cross section for both vector and axial-vector models. Using the assumption that the cross section scales as $1/\Lambda^4$, the upper limits on the cross section are converted into corresponding lower limits on the cutoff scale Λ for the model. Both limits are reported in Table 6.3 at a 90% CL and Table 6.4 at a 95% CL.

Dark Matter Mass [GeV]	90% CL Upper Limits			
	Vector		Axial-Vector	
	σ [fb]	Λ [GeV]	σ [fb]	Λ [GeV]
1	14.3 (14.7)	572 (568)	14.9 (15.4)	565 (561)
10	14.3 (14.7)	571 (567)	14.1 (14.5)	573 (569)
100	15.4 (15.3)	558 (558)	13.9 (14.3)	554 (550)
200	14.3 (14.7)	549 (545)	14.0 (14.5)	508 (504)
500	13.6 (14.0)	442 (439)	13.7 (14.1)	358 (356)
1000	14.1 (14.5)	246 (244)	13.9 (14.3)	172 (171)

TABLE 6.3. Observed (expected) 90% CL upper limits on the DM production cross section and 90% CL lower limits on the cutoff scale Λ for the vector and axial-vector operators as a function of the DM matter mass M_χ .

Dark Matter Mass [GeV]	95% CL Upper Limits			
	Vector		Axial-Vector	
	σ [fb]	Λ [GeV]	σ [fb]	Λ [GeV]
1	17.6 (19.0)	543 (533)	18.4 (20.0)	537 (526)
10	17.6 (19.0)	543 (532)	17.3 (18.8)	545 (533)
100	17.5 (19.0)	540 (529)	17.1 (18.6)	527 (516)
200	17.6 (19.0)	521 (511)	17.2 (18.7)	482 (472)
500	16.7 (18.2)	420 (412)	16.8 (18.3)	340 (333)
1000	17.3 (18.8)	233 (229)	17.1 (18.6)	163 (160)

TABLE 6.4. Observed (expected) 95% CL upper limits on the DM production cross section and 95% CL lower limits on the cutoff scale Λ for the vector and axial-vector operators as a function of the DM matter mass M_χ .

The DM model referenced in this study provides a way to connect the t -channel χ -nucleon elastic scattering to the s -channel pair production mechanism by relating the

χ -nucleon cross section to the interaction parameter Λ :

$$\sigma_{\text{SI}} = \frac{9}{\pi} \left(\frac{\mu}{\Lambda^2} \right)^2 \quad \text{and} \quad \sigma_{\text{SD}} = \frac{0.33}{\pi} \left(\frac{\mu}{\Lambda^2} \right)^2 \quad (6.1)$$

where μ is the reduced mass of the DM candidate and the proton. By substituting in the upper limits for the interaction parameter Λ , this relationship produces lower limits on the χ -nucleon cross section, which allows comparisons to be drawn between the CMS results and direct detection experiments. The results presented here are valid for mediator masses larger than the limits on Λ , assuming unity for the couplings g_χ and g_q . The CMS monophoton limits are displayed in Figure 6.1 as a function of the DM candidate mass, along with the results from several contemporary experiments.

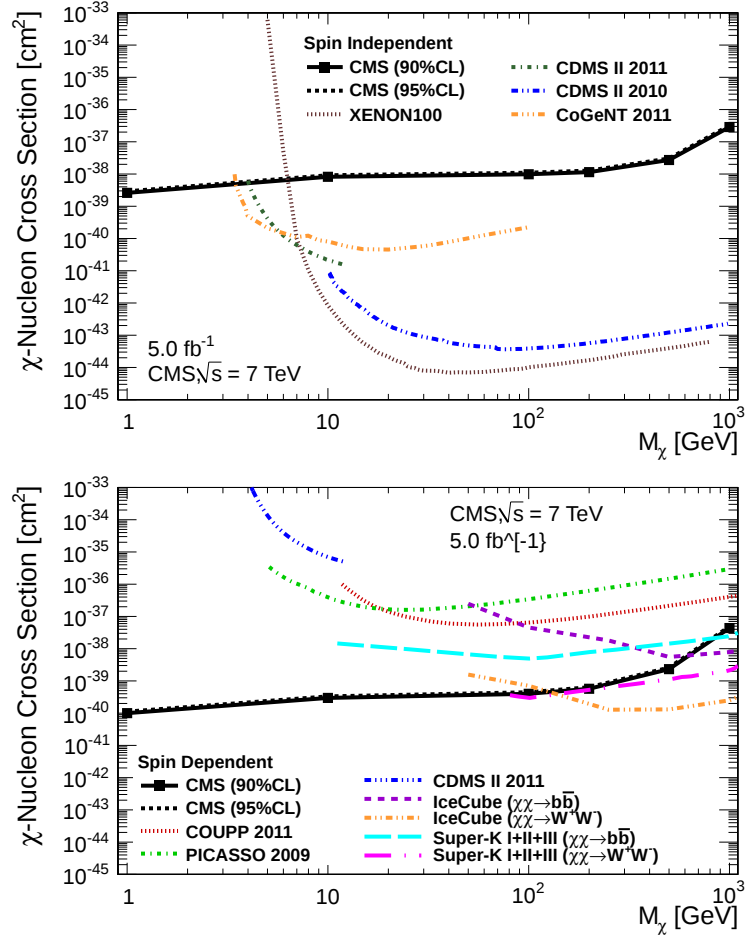


FIGURE 6.1. The 90% upper limits on the χ -nucleon cross section as a function of M_χ for spin-independent (top) and spin-dependent (bottom) scattering. The limits from other selected experiments are also shown [78, 79, 80, 81, 82, 83, 84, 85, 86].

Based on the models for the production of DM particles set forth by Harnik et. al., 90% CL upper limits of $13.6 - 15.4$ fb and 95% CL upper limits of $16.7 - 18.4$ fb were set on χ production in the $\gamma + \cancel{E}_T$ final state [67]. At the time of publication, these provided the most sensitive upper limits for spin-dependent χ -nucleon scattering for χ masses between 1 and 100 GeV. For the spin-dependent case, this study excluded previously inaccessible χ masses below about 3.5 GeV for a χ -nucleon cross section greater than about 3 fb at a 90% CL [67].

CHAPTER 7

Conclusions

A search was performed for an excess of $Z(\nu\bar{\nu})\gamma$ events in 5.0 fb^{-1} of data from CMS. This study provided the first dark search matter results from the LHC and set significant upper limits on the vector and axial-vector contributions to χ -nucleon scattering cross section. The methods outlined by the model-independent theory of dark matter that are employed in this analysis allow these CMS results to be interpreted in a complementary way to searches for both elastic χ -nucleon scattering and $\chi\bar{\chi}$ annihilation.

Shortly after the approval of this result, the dark matter search in the monojet channel at CMS was also approved, setting stronger upper limits on the χ -nucleon cross section. However, while the monophoton channel is less sensitive to DM, it probes a different set of DM-SM couplings [34] than the monojet channel; if an excess is observed in either channel, a comparison between the two would be helpful to determine if the excess was related to DM production. CMS has the potential to contribute a great deal to the field of dark matter studies as the collisions become more energetic and the data rapidly accumulates.

Looking beyond dark matter, the stability of the SM $Z(\nu\bar{\nu})\gamma$ channel and the range of BSM predictions that include a high- p_T photon and $\cancel{E}_T$ still make the monophoton channel a promising way to test for new physics. This same initial search was interpreted in terms of a model for extra dimensions, and the scope of the study is currently being extended to set limits on anomalous trilinear gauge couplings. While this analysis was being conducted, another analysis group at CMS independently measured the number of monophoton events and interpreted their results in terms of a search for supersymmetry. The monophoton channel will continue to be relevant to a number of searches in the future at the LHC.

Work is already underway to improve the event identification and background discrimination techniques for future monophoton analyses. Studies are being done to create a more robust definition of the jet events and further reduce the significant jet-faking-photon background contribution. Currently, the LHC is producing collisions at $\sqrt{s} = 8\text{ TeV}$, which

means pileup has increased. As a result, the efficiency of the vertex identification and the jet- and track-vetoes are being tested in this new environment. Finally, the recent Higgs-like discovery showed what might be a slight excess in the photonic decay channel [17], which makes photon identification and background discrimination all the more important as many turn their attention to Higgs studies. It is an exciting time to be studying single-photon signatures, and it is an exciting time in physics in general.

APPENDIX A

Fraction Fit Estimate Closure Test

The estimation of the background contribution from jets misidentified as photons, discussed in Section 5.5.2.2, is significantly affected by the correction made to the fake ratio to account for the direct photon production in the QCD sample. Since this is the largest source of background in the analysis, a test is performed to validate the method of identifying the separate contributions from direct production photons and jets misidentified as photons using the shower shape variable. This test is performed using mixed simulation samples, labeled a “data” in Table A.1 with a known ratio of QCD and γ +jet events to see how accurately the sample compositions are identified.

The validation test is run in the p_T range of 120-160 GeV. The simulated samples are combined in a ratio of $10^3:1$, which reflects the QCD:(γ +jet) cross section ratio, for the given p_T range, and analysis is run using the $\sigma_{i\eta i\eta}$ templates developed for that momentum range. The same event selection criteria is applied to the simulation sample, except for the data-cleaning requirements to remove spikes, scraping events, and beam halo contamination. The photon templates used here to estimate the real photon contribution are also the same templates used for the data-driven estimate in the analysis, and the simulated samples are from the Summer11 production. The number of events in each sample that are used to form the various templates is listed in Table A.1.

$\sigma_{i\eta i\eta}$ Template	QCD (MC) (entries)	$\gamma + jet$ (MC) (entries)	Total (entries)
data	335	1225	1560
QCD	155	20	175
γ +jet	-	68736	68736
Events used	550619	5400	566019

TABLE A.1. The events identified by the templates for fraction fitting. [65]

Table A.2 presents the results of the test, which are consistent with the original study within the uncertainty range of the fit, which is about 3%. The fit distribution is shown in

Figure A.1, with the separate contributions from QCD and the photon fraction identified. Despite the disproportionate number of events used to form the templates, the fit provide an accurate determination of the the composition.

	Fake Data Composition (fraction)	Fraction Fit Result (fraction)
QCD	0.215	0.236 ± 0.035
Real Photons	0.785	0.763 ± 0.038

TABLE A.2. Results from the fraction fit and comparison with the known composition of fake data.

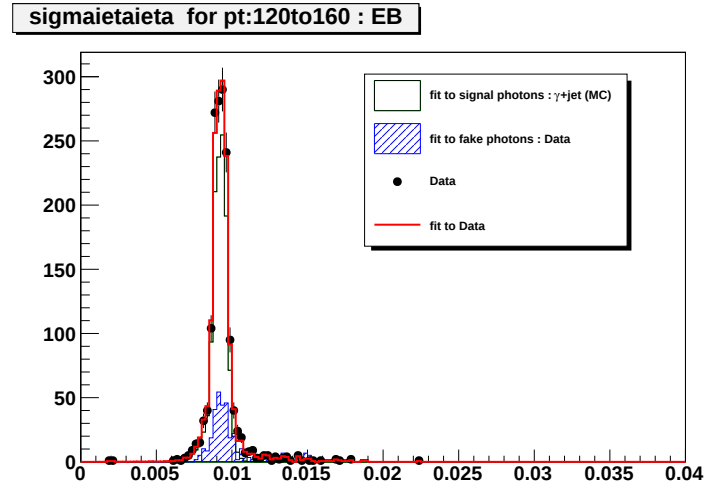


FIGURE A.1. Template shapes formed using QCD and photon+jet simulations [65].

A second fit test is performed in the same range with the same templates and event selection criteria, but this time with a very different fraction of QCD and γ +jet events: 55.9% of the sample is QCD and the fraction of real photons is set to 44.1%. In this case, the fraction fit estimate is 0.408 ± 0.062 for QCD and 0.592 ± 0.059 for the real photon contribution. These results are also consistent with the true composition of the sample, within the uncertainty of the fit, despite the very different composition. The results of these two tests indicates that the fraction fitting method accurately subtracts the direct photon component of the QCD sample within the uncertainties of the fit.

APPENDIX B

Veto Efficiencies with $Z(ee)\gamma$

It was mentioned in Section 5.6.5 that the veto efficiency of $W(e\nu)$ is very different from the veto efficiency observed for $Z(\nu\bar{\nu})\gamma$. To address this issue, an additional cross check is performed with $Z(ee)\gamma$ production, testing the veto efficiency in a sample of data events and a simulated sample and comparing the results. The same selection criteria are applied to the data and simulation samples:

- Every event must have at least two reconstructed photon objects in either the EB or EE with an associated pixel seed and $E_T > 30$ GeV. These are the electron candidates in the event, and they must pass the same selection criteria as the photon candidates in the event selection, including the track, H/E, and isolation requirements.
- At least one photon object must be reconstructed in the barrel region, and must pass the same photon selection criteria as our candidate sample.
- All three electromagnetic objects must be separated from each other by $\Delta R > 0.8$.

Once the sample is selected, the jet and track vetoes are applied and the efficiency is calculated for events binned by photon E_T . While the efficiency isn't expected to be the same as the monophoton sample, it should be similar; $Z(\nu\bar{\nu})\gamma$ events and $Z(ee)\gamma$ events should have a similarly balanced final state without the recoil problems of $W(e\nu)$ events. The efficiency measured in data is reported in Figure B.1 as a function of the photon E_T , and the corresponding efficiency in the simulated sample is shown in Figure B.2. The ratio of the efficiencies measured in data and simulation, shown in Figure B.3, is consistent with a flat distribution and is well within the systematic uncertainty assigned to the veto efficiency in the simulated events.

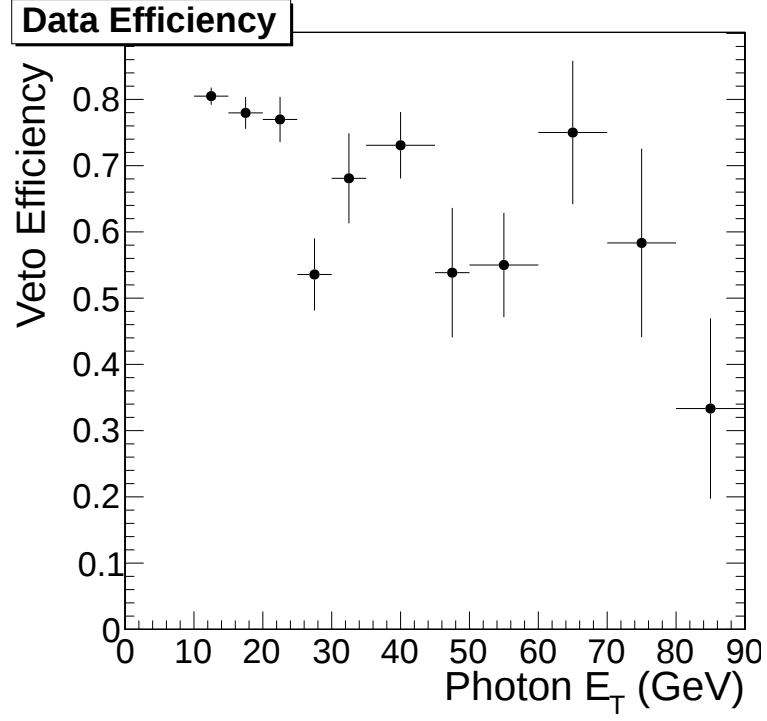


FIGURE B.1. The jet-and-track veto efficiency measured for a sample of $Z(ee)\gamma$ data events as a function of photon E_T [65].

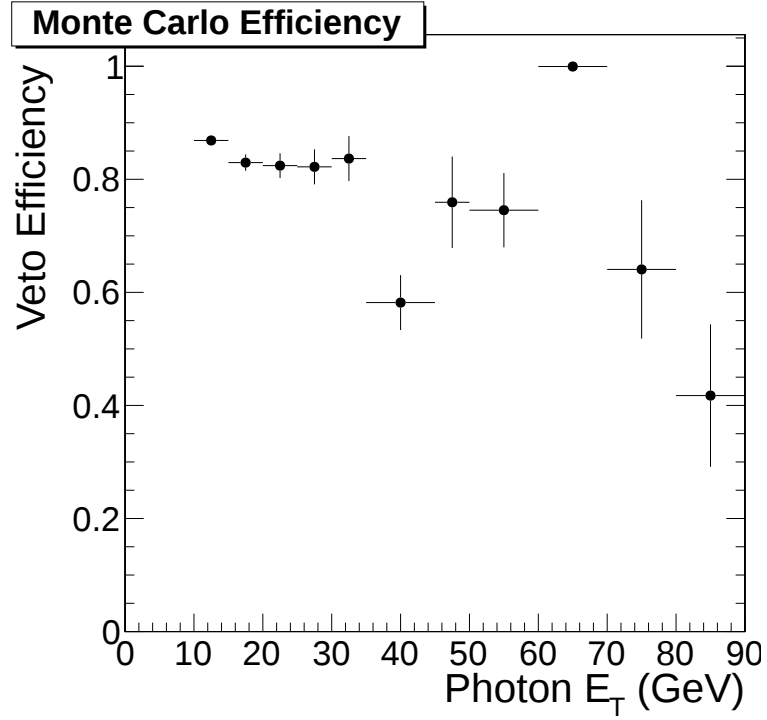


FIGURE B.2. The jet-and-track veto efficiency measured for a sample of $Z(ee)\gamma$ Monte Carlo events as a function of photon E_T .

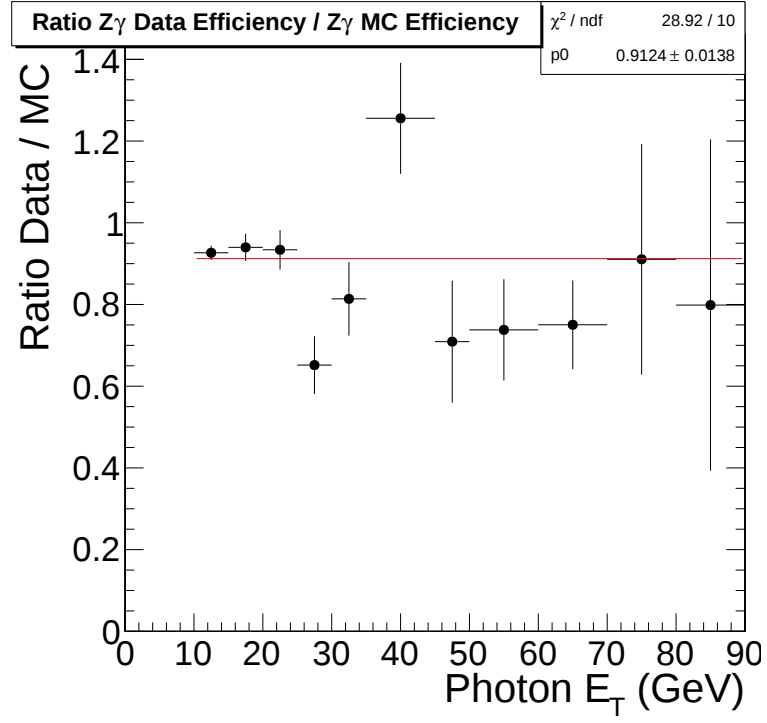


FIGURE B.3. The ratio of data efficiency for $Z(ee)\gamma$ to Monte Carlo efficiency as a function of photon E_T .

APPENDIX C

Baur MCFM Comparison

A short comparison study is done for the two matrix element generators **BAUR** and **MCFM**. Both generators are used in this analysis to scale simulated samples in order to reflect NLO contributions: **BAUR** is used to scale the $Z(\nu\bar{\nu}\gamma)$ **PYTHIA** sample and **MCFM** is used to scale the $W(l\nu)$ **MADGRAPH** samples. To compare the two generators, both produced new $Z(\nu\bar{\nu})\gamma$ events at LO and at NLO criteria with similar generator-level criteria. The events were produced with $p_T^\gamma > 130$ GeV, no $\cancel{E}_T$ cut, and no η constraints. The photons and neutrinos were required to be separated by $dR = 0.7$ and the fraction of hadronic energy surrounding the photon in a cone of $R = 0.7$ had to be no more than 0.15. Both generators used PDF cteq66 for NLO production and cteq6L1 for LO production, and both employed a factorization scale of $\sqrt{M^2 + (p_T^\gamma)^2}$.

The production cross sections and resulting k-factors for the **BAUR** and **MCFM** events are listed in Table C.1.

Generator	LO (fb)	NLO (fb)	k-factor
BAUR	35.57 ± 0.66	56.9 ± 2.22	1.60
MCFM	37.51 ± 0.02	64.5 ± 0.04	1.77

TABLE C.1. Generated cross sections and k-factors for NLO and LO $Z(\nu\bar{\nu})\gamma$.

The errors quoted in Table C.1 are only statistical. The LO events produced by **MCFM** and **BAUR** have similar cross sections with a difference that would fall within range of the uncertainties from the PDF and factorization scale, but the NLO cross sections are notably different. To compare the NLO acceptance terms from **MCFM** and **BAUR**, additional samples are produced with kinematic cuts resembling our signal sample: $p_T^\gamma > 145$ GeV, $\cancel{E}_T > 130$ GeV, and $|\eta| < 1.4442$. The cross sections of the signal-like event samples generated k-factors of 1.45 for **MCFM** and 1.19 for **BAUR**, respectively, which would lead to acceptance terms of $1.45/1.77 = 0.82$ for **MCFM** and $1.19/1.60 = 0.76$ for **BAUR**. The difference in the acceptance term translates to a difference in the calculated cross section for $Z(\nu\bar{\nu})\gamma$ of about

5 fb, with a **MCFM**-scaled cross section of $57 \pm 11(\text{stat}) \pm 12(\text{sys}) \pm 1(\text{lumi})$, and a **BAUR**-scaled cross section of $52 \pm 10(\text{stat}) \pm 10(\text{sys}) \pm 1(\text{lumi})$. Some explanations for the differences have been discussed. While both generators produce events with NLO cross sections, **BAUR** includes next-to-leading-log corrections while **MCFM** does not, and the two generators deal with singularities differently, **MCFM** employing dipole subtraction and **BAUR** including user-controllable soft and collinear cutoff parameters. Further studies are underway.

At the generator level, the photon p_T and $\cancel{E}_T$ distributions match well between the two simulations at leading and next-to-leading order, edespite the difference in the reported cross section. The jet p_T distributions, however, shown in Figure C.1, do not match at very low p_T values, which is not yet understood.

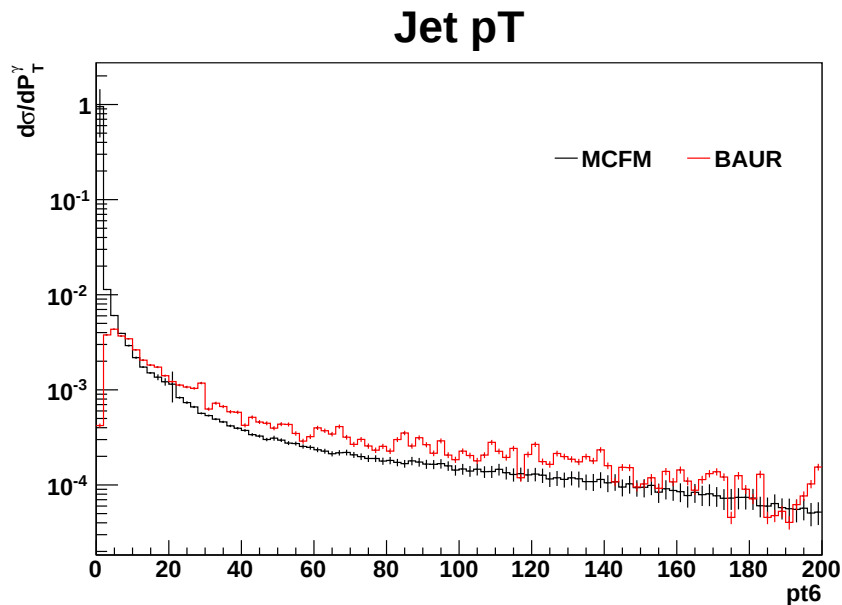


FIGURE C.1. Generator-level normalized NLO jet p_T distribution for **BAUR** and **MCFM**.

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