2017

A Study of the Timing Distribution of Events with a Photon and Large Missing E_T

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A STUDY OF THE TIMING DISTRIBUTION OF EVENTS WITH A PHOTON AND LARGE MISSING E_T

By

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A Thesis submitted to the
Department of Physics
in partial fulfillment of the requirements for graduation with
Honors in the Major

Degree Awarded:
Spring 2017

The members of the Defense Committee approve the thesis of Lara Zygala defended on April 19, 2017.

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Abstract

This thesis describes the analysis of the time distribution of events with a final state consisting of a high-energy photon and large missing transverse energy. This study was done using data collected by the Compact Muon Solenoid experiment at the Large Hadron Collider. The data comes from proton-proton collisions at a center of mass energy of 13 TeV. The data has an integrated luminosity of $12.9 \pm 0.9 fb^{-1}$. Three major contributing factors to the time distribution were hypothesized to be halo events, spike events, and prompt events($Z \rightarrow \mathrm{e}^{-} + \mathrm{e}^{+}$). A template was created for each contribution and the time distribution of each was analyzed and fit to the time distribution of the signal candidate sample. It was found that spike events contributed to $93.94 \pm 3.46\%$ of the candidate sample time distribution, that the prompt events contributed to $6.06 \pm 0.46\%$. of the candidate sample time distribution, and that halo events contributed to $8.64 \times 10^{-11} \pm 0.068\%$ of the candidate sample time distribution.

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1 Introduction

The Standard Model describes all known elementary particles and the mediators for three fundamental forces in nature. It is made up of 2 types of particles, fermions and bosons. A fermion is an elementary particle that has a half-integer intrinsic spin and a boson is an elementary particle that has a full-integer intrinsic spin. The force carriers are bosons and the particles that make up all known matter are fermions. The particles that make up matter are further split into two groups, leptons and quarks. All known matter (Baryonic matter) is made up of these particles.

It is well known, though, that the Standard Model is incomplete. This can be seen in issues such as the hierarchy problem or the lack of unification on the energy levels of the forces. These issues give cause to the search for new theories that would extend the Standard Model. One of the more popular theories for extension of the Standard Model is the Theory of Supersymmetry, which would solve many of the problems that the Standard Model has today.

1.1 Supersymmetry

The Theory of Supersymmetry (SUSY) is a theory that aims to fix some of the problems with the Standard Model by predicting that each particle in the Standard Model has a partner particle. These supersymmetric particles would have the same properties as their partners, except for their intrinisic spin. Particles with a half-integer spin would have a partner with a full-integer spin and particles with a full-integer spin would have a partner with a half-integer spin. So, each fermion would have a boson partner and vice-versa, effectively doubling the particles in the Standard Model.

SUSY also predicts that the supersymmetric particles would have the same mass as their partners, which is known to be impossible. If the supersymmetric particles had the same mass as their partners, they would have already been observed in various experiments. So, if SUSY does exist, then it must be broken.

SUSY is particularly interesting because of the solutions it offers. One reason being that it offers dark matter candidates. Baryonic matter (ordinary matter) makes up less than $\sim 5\%$ of all matter in the universe. The rest of the matter is made up of dark matter ($\sim 24\%$) and dark energy ($\sim 71\%$). Dark matter is called such because it does not interact with electromagnetic radiation nor does it emit it. So dark matter has never been directly observed, but dark matter does interact gravitationally with light and with baryonic matter.

SUSY particles provide a dark matter candidate specifically because these particles would be on the correct mass scale. A supersymmetric model can only provide a dark matter candidate if the R-parity for the interaction is conserved. R-parity is a quantum number that each particle has, where all Standard Model particles have R-parity of +1 while all supersymmetric particles have R-parity of -1. If R-parity is conserved, then the lightest supersymmetric particle cannot decay. This particle would be a dark matter candidate for it could account for the missing mass in the universe.

Another solution that SUSY offers is Grand Unification of the fundamental forces. Grand Unification unifies the three gauge forces: the nuclear strong force, the nuclear weak force, and the electromagnetic force. Currently, the strength of these three forces never unify at high energies in the way that the weak and electromagnetic force do.

The specific model that inspires this analysis contains an off-shell W boson decaying into a chargino ($\chi^{\pm}$) and a neutralino (χ^{0}) with a final state of a long-lived photon and missing transverse energy (MET). The diagram for this interaction can be seen in Figure 1 below. Since this model conserves R-parity, it contains a viable dark matter candidate.

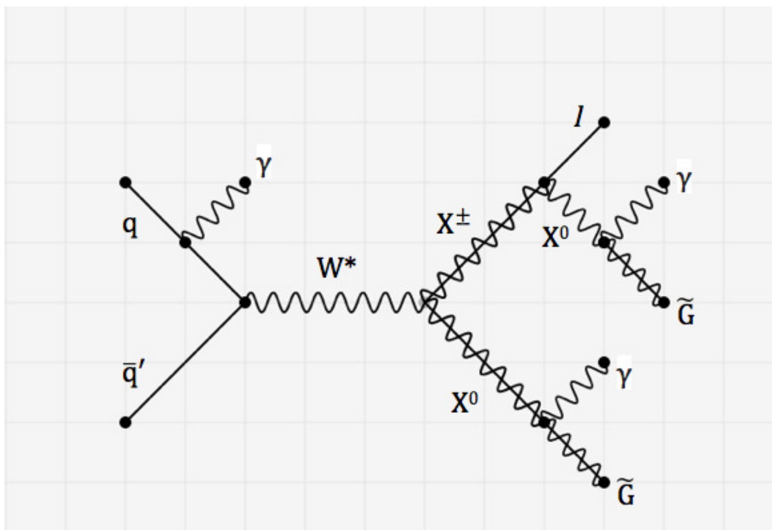

Figure 1: Feynman diagram for supersymmetric model with a final state of a long-lived photon and missing transverse energy.

1.2 Long-lived Particles

At the LHC, the proton beams cross every 25 nanoseconds, so there are collisions every 25 ns. When a particle triggers an event, it is marked as arriving at the ECAL at the beginning of the collision. Not every event gets saved and included in the dataset, but since a collision occurs every 25 ns, every object in an event will have their time recorded as being between -12.5 ns and 12.5 ns.

A particle is described as prompt if it arrives at the ECAL at time t = 0. It is described as long-lived, or time-delayed, if it arrives between time t = 0 and time t = 12.5 ns. When a particle arrives between t = 12.5 ns and t = 25 ns, then it is marked as early for the next event.

2 The CMS Detector

The LHC is the largest and most powerful particle collider in the world. The CMS Detector is one of two general purpose detectors situated on the collider ring. It features a four Tesla solenoid and four component detectors to measure the products of collisions. The CMS detector is composed of four main detectors: a muon chamber, a hadronic calorimeter (HCAL), an electromagnetic calorimeter (ECAL), and a silicon tracker.

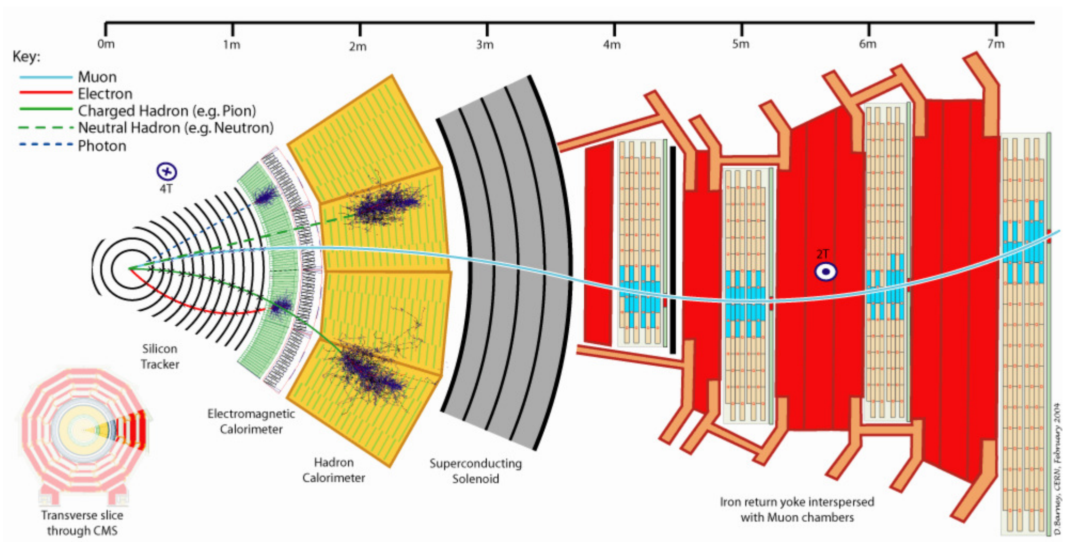

Figure 2: Transverse slice of the CMS Detector [10]

The silicon tracker tracks the motion and trajectory of charged particles. The tracker measures the electrical signals that are produced when the charged particles pass through the layers of the silicon tracker. When they pass through, they deposit ionization energy and produce electron-hole pairs which the the tracker measures with electrodes. The hits in the tracker are formed into tracks which are then used in the reconstruction of particles.

The HCAL is used for the detection of hadronic particles. The material that the HCAL is made out of increases the likelihood of interactions with hadrons. The material used is a mixture of dense absorbers and plastic scinitillors, which are used to measure the energy deposits left by the hadrons.

The ECAL is used for the detection of electromagnetic particles, photons and electrons specifically for the purposes of this analysis. The material used that the ECAL is made out of increases the likelihood of interactions with electromagnetic particles. It is composed of a barrel and two endcaps, which are constructed from lead tungstate crystals. The ECAL is where the data for this analysis comes from.

The lead tungstate crystals in the ECAL are used to measure the energy from electromagnetic objects that interact with them. Specifically, when the electromagnetic particles interact with the crystals they cause scintillation light. This is an emanation of light that occurs within each crystal as the photon interacts with it which is proportional to the energy of the particle. There is a photodetector on the back of each crystal which turn this scintillation light into electric signals.

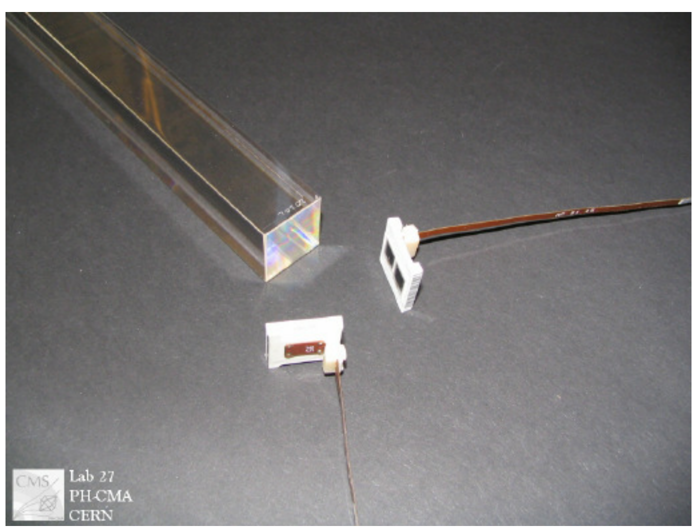

Figure 3: Lead Tungstate Crystal [11]

The ECAL collects data through energy deposits. The CMS detector unifies the energy deposits in the ECAL and the HCAL with the tracks observed in the silicon tracker in order to reconstruct particles. The specific reconstruction methods necessary for this analysis are described in the next section.

3 Data

The data for this analysis comes from the Compact Muon Solenoid (CMS) experiment during the second run of the Large Hadron Collider (LHC). This dataset was collected prior to August 2016. During Run 2, the beams ran at a center-of-mass energy of $\sqrt{s} = 13$ TeV. This dataset has an integrated luminosity of 12.9 ± 0.9 fb^{-1}. In order for the dataset to be useful for this analysis, parts of it must be manually reconstructed.

3.1 Reconstruction

It is impossible to know with 100% certainty that a particle has been observed in the CMS detector. The detector merely provides energy deposits in the calorimeters and hits in the silicon tracker which are used to reconstruct particles. The energy deposits are used to create clusters and the hits are used to create tracks. This information is then used to for particle hypotheses.

3.1.1 Electromagnetic Shower Shape Tomography

The electromagnetic shower shape of an electromagnetic object is necessary in reconstructing and identifying the particle. The shower shape allows for the tomography of the electromagnetic shower to be studied. The tomography of the shower shape is the average energy distribution for the particle objects in the shower.

To find and plot the tomography of the shower shape of an electromagnetic shower in the ECAL, first the seed crystal of the electromagnetic object must be found. The seed crystal of an electromagnetic object is the crystal that has the largest energy deposit of all the crystals associated with the object. Then, the energy deposit in each of the neighboring crystals, as well as the seed crystal, for each electromagnetic object in the event is recorded. The energy deposit for each crystal has their location plotted relative to the highest energy electromagnetic object. So, the seed crystal for each electromagnetic object is plotted at η = 0 and $\phi = 0$. [2]

3.1.2 Shower Shape Width ($\sigma_{i\eta i\eta}$ and $\sigma_{i\phi i\phi}$)

$\sigma_{i\eta i\eta}$ is defined as the variance in the η direction for a cluster in the ECAL. The width of an electromagnetic shower in η is used to differentiate between candidates and jets of hadrons. Jets tend to have a larger $\sigma_{i\eta i\eta}$ due to the fact that they are wider and more spread in eta than a candidate object would be. [2]

$\sigma_{i\phi i\phi}$ is defined as the variance in the ϕ direction for a cluster in the ECAL. The width of the shower shape in both η and ϕ is required to determine whether an event can be categorized as a spike event. $\sigma_{i\phi i\phi}$ is needed, beyond $\sigma_{i\eta i\eta}$, because the electromagnetic object can have a small spread in phi, as well as η, in order to be categorized as a spike.

3.1.3 Separation

In order to ensure that one electromagnetic particle has not been misidentified as two particles, or vice versa, we must ensure that the electromagnetic object is sufficiently separated from other the objects. This is done by performing a calculation based on the position of both electromagnetic objects.

In the prompt template, two electron objects are searched for. In order to ensure that two separate electron objects are being observed, both objects are required to have an angular separation (ΔR) greater than 0.7. ΔR for an object can be calculated using the following:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \tag{1}$$

$$\Delta\phi = \phi_1 - \phi_2 \tag{2}$$

$$\Delta\eta = \eta_1 - \eta_2 \tag{3}$$

Where η_1 and ϕ_1 are the η and ϕ of the first particle and η_2 and ϕ_2 are the η and ϕ of the second particle

3.1.4 Isolation

In order to ensure that particle candidates have not originated from jets of hadrons, three separate isolation criteria are required for candidates: Charged Hadron Isolation, Neutral Hadron Isolation, and Photon Isolation. These criteria require that a candidate object not be in close proximity with any other object. These cuts are based on the p_T sums of the event.

These isolation cuts ensure that a candidate particle object have their energy deposits in the the calorimeters be sufficiently isolated from other energy deposits in both the ECAL and the HCAL. The calculations create a cone around the candidate object, beginning at the vertex and extending out to the HCAL.

Each of these isolation cuts has a ρ correction applied to it. ρ is the measure of the average energy density for each event. The p_T sum in each isolation cone is corrected by multiplying ρ and an effective area, which varies with the position η in the barrel, and subtracting it from the isolation value. This is done in order to reduce pile-up energy for each particle in the detector. [1]

3.1.5 H/E

The ratio of the energy deposited in the HCAL to the ECAL (H/E) is used to ensure that no charged or neutral hadrons have been included in the candidate sample. H/E is measured as the ratio of the energy deposited in the HCAL to the energy deposited in the ECAL at the position of the center of the electromagnetic shower. Since photons interact solely with the ECAL and deposit the majority of their energy there, their H/E value would look distinct from a charged or a neutral hadron. This is due to the fact that charged hadrons interact with both the ECAL and the HCAL and neutral hadrons interact with only the HCAL.

3.1.6 Time Signature

The time at which energy is deposited into a crystal is saved for each crystal. So, in order to determine the time signature for a particular electromagnetic particle, the seed crystal for the electromagnetic particle object must first be found. Once the seed crystal has been identified, the time signature from that crystal can then be applied as the time signature for the electromagnetic object.

Since the proton beams intersect every 25 ns, an event occurs every 25 ns. Whether that event gets saved is determined by the triggers, but every event that is included in this dataset occurs on a 25 ns crossing. So, the time signature for any object can range from -12.5 ns to 12.5 ns.

4 Candidate Sample

The candidate sample for this analysis will be made up of events that have a final state of a high-energy photon and sufficiently large missing transverse energy, along with other selection criteria. To ensure that only events that are interesting to this search are analyzed, the entire dataset is forced to pass a series of selection criteria, which will be described in the following section. Once the candidate sample has been collected, the time signature for each high energy photon is recorded. The resulting time distribution is what will be used for analysis.

In order to determine whether an event can be considered a candidate for signal for this analysis, a series of selection cuts were applied.

4.1 Selection

For a photon to be considered a candidate in this analysis, the event must pass the following criteria. The cuts made were based on the criteria for a medium photon selection as described for the Photon ID for Run 2.

1) The photon must have a transverse momentum of at least 175 GeV. This allows us to assume that the photon either triggered the event period (and thus would be a prompt photon) or was a decay product of a neutralino or chargino.

2) The missing transverse energy of the event must be of about the same threshold as the photon E_T requirement. So, the MET of the event must be at least 175 GeV.

3) The photon must be located in the barrel of the ECAL, thus the pseudorapidity of

the photon must be $|\eta| < 1.44$.

4) The photon must pass the Pixel Seed Veto in order to ensure that a photon has indeed been identified as opposed to an electron object.

5) The photon must have a shower shape width of at least $\sigma_{i\eta i\eta}< 0.01$.

6) The photon must have H/E < 0.05.

7) The photon must have a ρ-corrected charged hadron isolation less than 1.37.

8) The photon must have a ρ-corrected neutral hadron isolation less than $1.06 + 0.014 * P_{T_{photon}} + 0.000019 * P^2_{T_{photon}}$.

9) The photon must have a ρ-corrected photon isolation less than $0.28 + 0.0053 * P_{T_{photon}}$.

10) The event must pass the Beam Halo Veto in order to minimize background.

11) The photon must have a shower shape width and length of at least $\sigma_{i\eta i\eta}> 0.0001$ and $\sigma_{i\phi i\phi}> 0.0001$ in order to select against spikes.

Only the events that passed this criteria were chosen to be included in the candidate sample and the high energy photon that was identified in each candidate event had their time signature recorded.

4.2 Timing

The time that each candidate photon arrived at the ECAL was found by using the process described in Section 3.1.6. The distribution of the time (t) that each of the high energy photons of the candidate sample of events arrived at the ECAL can be seen in Figure 4 below.

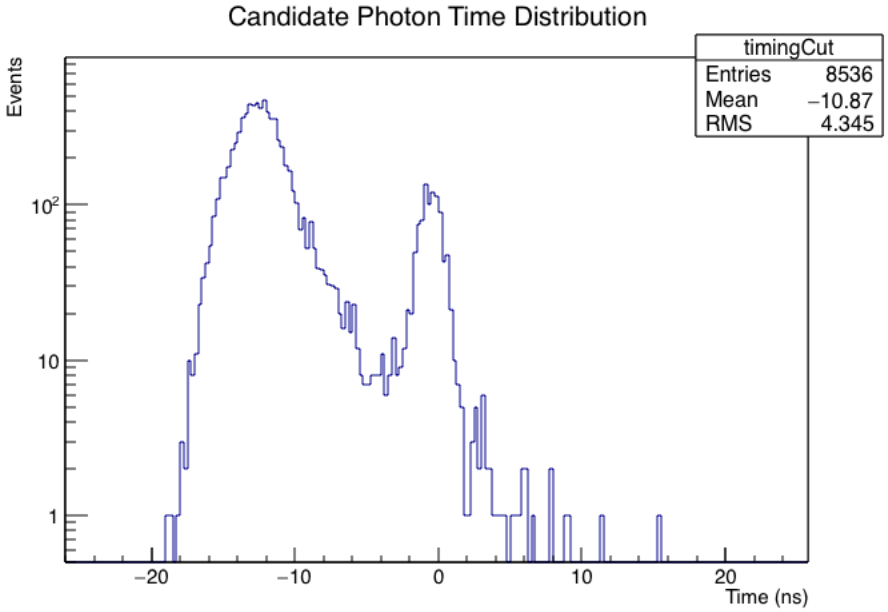

Figure 4: The timing distribution for the photons that passed the selection criteria.

Clearly, this distribution is not only made up of the time signature of long-lived photons. In order to determine the exact makeup of this distribution, the time distributions from each of the templates must be analyzed. The largest three factors that are thought to provide the makeup for this distribution are prompt events, early events, and out-of-time (beam halo) events. The three templates used for this analysis embody each of these proposed factors.

5 Templates

In order to deconstruct the time distribution for the candidate sample, three separate templates were created: one prompt template, one out of time template, and one early template. These three time templates are hypothesized to be the three largest factors that are included in the time distribution of the signal candidate sample. The time distribution from each of these templates will give a clear and generic model of their respective time signature. By fitting the time distribution of each template to the time distribution of the candidate sample, the contributing factors to the time distribution of the signal candidate sample can be understood.

5.1 Prompt Template: $Z \rightarrow \mathrm{e}^{-} + \mathrm{e}^{+}$

The prompt timing template comes from the decay of the Z boson into an electron and a positron. This decay has been observed to occur with a prompt time-signature. When this particular interaction occurs, the higher energy electromagnetic decay product will certainly be the particle that triggered the event. So, the time distribution of the high energy electron or positron should peak at t = 0, which will make this distribution ideal for modeling a prompt time distribution.

5.1.1 Selection

For an event to be considered as a candidate for the prompt template, each event was required to pass the following criteria.

1) The lead electron must have a transverse momentum of at least 175 GeV and the trail electron a transverse momentum of at least 10 GeV.

2) Each electron object must be located in the barrel, thus the pseudorapidity must be $|\eta| < 1.44$.

3) Each electron must have a Pixel Seed Match in order to ensure that an electron object has indeed been identified.

4) Both electron objects must be sufficiently separated from each other, thus they must have a $\Delta R > 0.7$.

5) Each electron object must have a shower shape width of at least $\sigma_{i\eta i\eta}$< 0.01.

6) Each electron must have $H/E < 0.05$.

7) Each electron must have a ρ-corrected charged hadron isolation less than 1.37.

8) Each electron must have a ρ-corrected neutral hadron isolation less than $1.06 + 0.014 * P_{T_{electron}} + 0.000019 * P^2_{T_{electron}}$.

9) Each electron must have a ρ-corrected photon isolation less than $0.28+0.0053*P_{T_{electron}}$.

Once the events that passed these requirements were collected, the invariant mass of both electron objects was calculated in order to determine whether they were in fact decay products of a Z boson. The peak in Figure 5 is clearly at about 90 GeV, so the only the events within that peak were chosen to be included in the prompt sample of events.

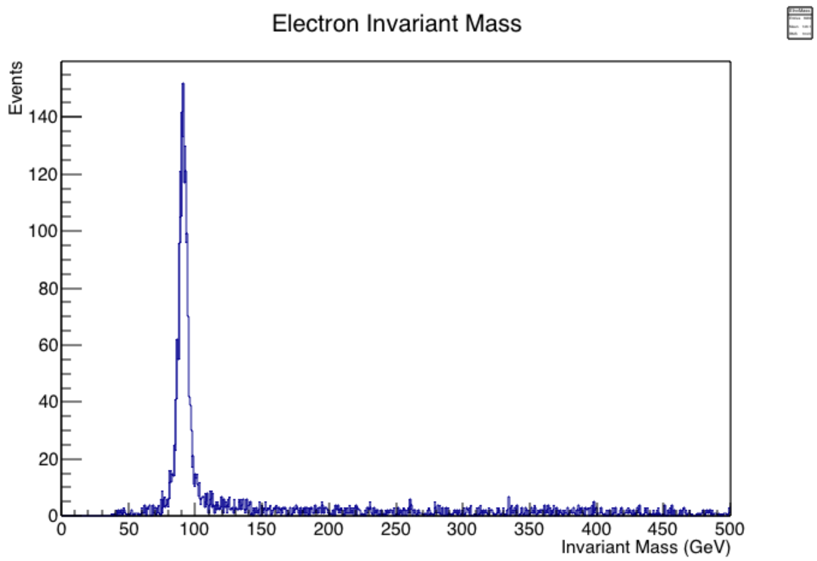

Figure 5: The invariant mass of both electron objects.

5.1.2 Timing

Once both electron objects have been identified, the higher energy of the two has its time signature recorded. The distribution can be seen in Figure 6, it is clearly centered around 0 ns. So, this sample provides a good model for a prompt time distribution.

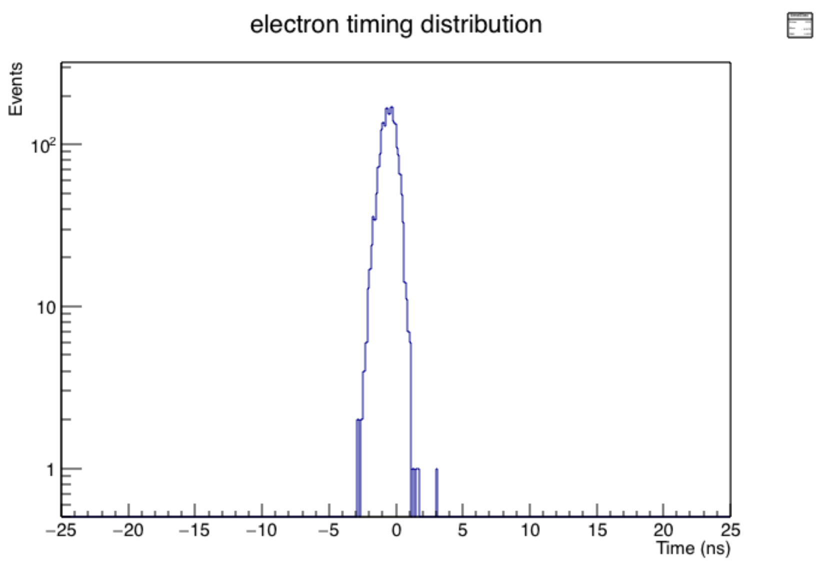

Figure 6: The time distribution for the prompt template candidates.

5.2 Out of Time Template: Beam Halo

Beam halo occurs during the beam focusing process [6]. Muons will then travel parallel to the beam and interact with the ECAL both before interactions trigger ($t < 0$ ns) and after when a particle is considered long-lived ($t > 12.5$ ns). Thus, the time distribution for beam halo events would be an ideal model of an out-of-time time distributions.

5.2.1 Selection

For an event to be considered as a candidate for a halo event, the events were required to pass the following criteria.

1) The event must fail the Beam Halo Veto in order to confirm that a halo event has been selected.

2) The photon must have a transverse momentum of at least 175 GeV.

3) The MET of the event must be at least 175 GeV.

4) The photon must be located in the barrel of the ECAL, thus the pseudorapidity of the photon must be $|\eta| < 1.44$.

5) The photon must pass the Pixel Seed Veto in order to ensure that a photon has indeed been identified.

6) The photon must have $H/E < 0.05$.

7) The photon must have a ρ-corrected charged hadron isolation less than 1.37.

8) The photon must have a ρ-corrected neutral hadron isolation less than $1.06 + 0.014 * P_{T_{photon}} + 0.000019 * P^2_{T_{photon}}$.

9) The photon must have a ρ-corrected photon isolation less than $0.28 + 0.0053 * P_{T_{photon}}$.

The way that a particle that triggers a halo event travels through the detector would cause the electromagnetic shower to be spread in eta, the way that the shower shape of the halo sample in Figure 7 is spread. This ensures that the sample are in fact candidate halo events.

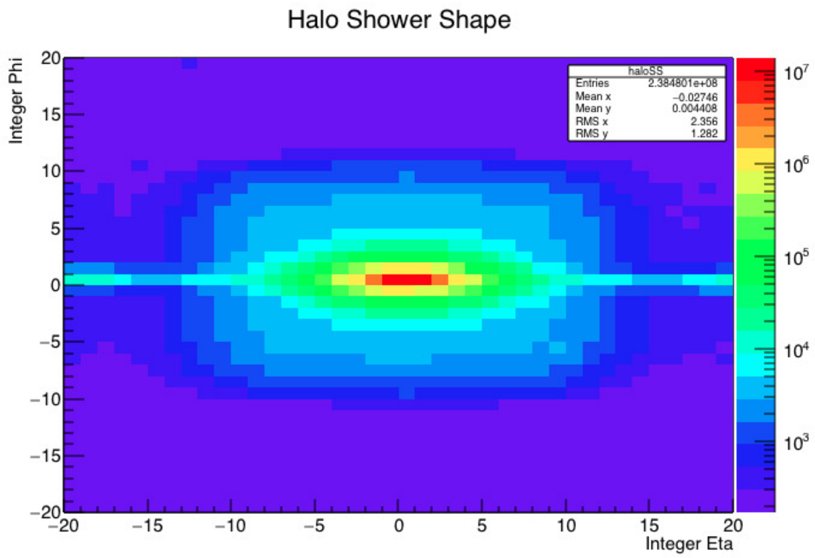

Figure 7: Shower shape of the halo event candidates.

5.2.2 Timing

The time distribution for beam halo events is taken from the time signature of the highest energy photon object from each event. Unlike the signal candidate sample, the photon was not required to pass a $\sigma_{i\eta i\eta}$ cut. Once the sample had been collected, a $\sigma_{i\eta i\eta} < 0.018$ cut was applied, the timing distribution of which can be seen in Figure 9. This process removed about 150,000 events from the sample, leaving a sample of about 13,000 events. This was done in order to remove the possibility of hadronic jets being included in the sample. Another shower width cut was applied to the sample with $\sigma_{i\eta i\eta} < 0.015$, but this removed about 160,000 events, leaving a sample of about 300 events. So, the time distribution of candidate halo events with $\sigma_{i\eta i\eta} < 0.018$ will be the distribution used for the out-of-time template.

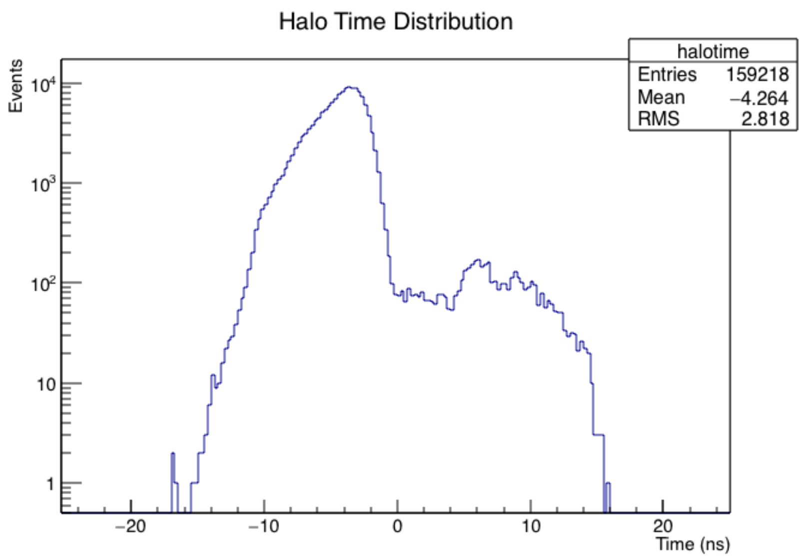

Figure 8: Time Distribution of candidate halo events.

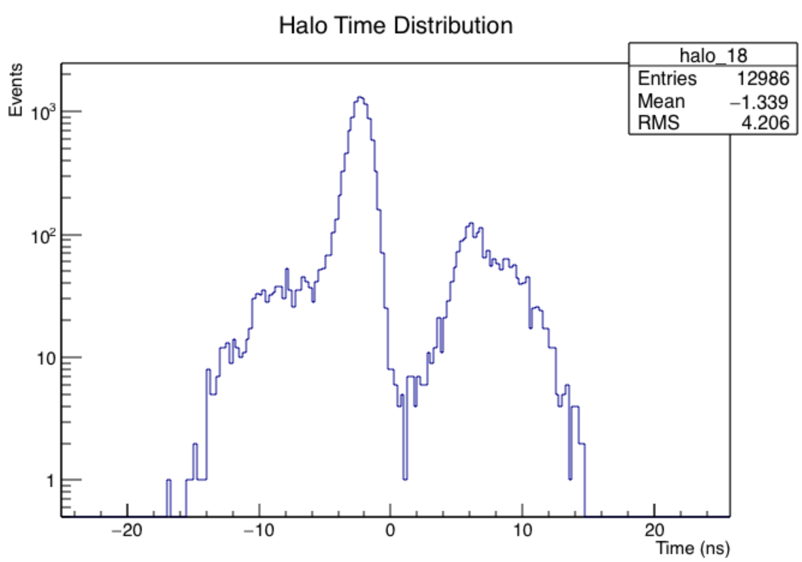

Figure 9: Time Distribution of candidate halo events with $\sigma_{i\eta i\eta}$< 0.018.

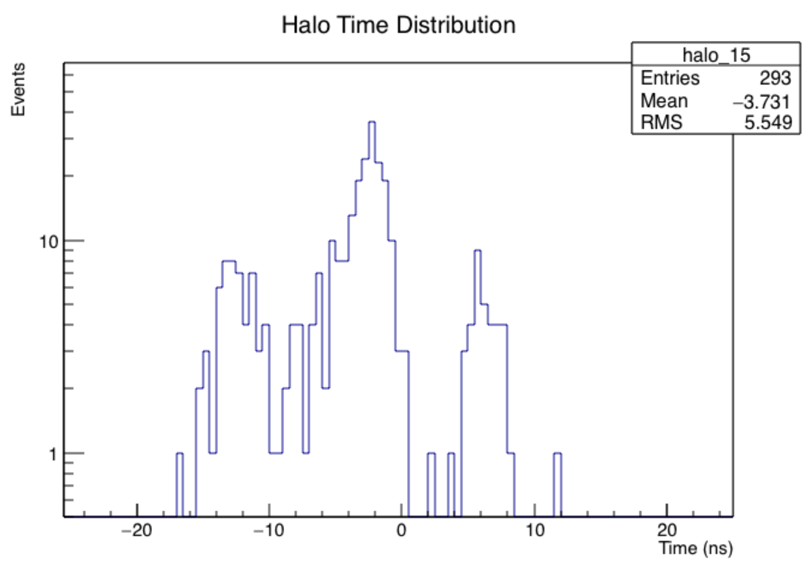

Figure 10: Time Distribution of candidate halo events with $\sigma_{i\eta i\eta}$< 0.015.

5.3 Early Template: Spike Events

Spike events occur when a particle interacts directly with the avalanche photodiodes of the lead tungstate crystals of the ECAL, rather than the crystals themselves. These crystals will then have a significantly larger energy deposit than the neighboring crystals, which is unusual in the ECAL.

5.3.1 Selection

The sample for the early template will consist of those events that were vetoed from the candidate sample for being flagged as spike events. As such, for an event to be added to the spike sample, it must have a high energy photon and a sufficient amount of MET, both at the same threshold required of the signal candidate sample. The difference though, is that either the shower shape width or length must be less than 0.0001, whcih is outlined in item 11 below. Each event is must pass the following requirements in order to be added to the spike template sample.

1) The photon must have a transverse momentum of at least 175 GeV.

2) So, the MET of the event must be at least 175 GeV.

3) The photon must be located in the barrel of the ECAL, thus the pseudorapidity of the photon must be $|\eta| < 1.44$.

4) The photon must pass the Pixel Seed Veto in order to ensure that a photon has indeed been identified.

5) The photon must have a shower shape width of at least $\sigma_{i\eta i\eta}< 0.01$.

6) The photon must have $H/E < 0.0102$.

7) The photon must have a ρ-corrected charged hadron isolation less than 1.37.

8) The photon must have a ρ-corrected neutral hadron isolation less than $1.06 + 0.014 * P_{T_{photon}} + 0.000019 * P^2_{T_{photon}}$.

9) The photon must have a ρ-corrected photon isolation less than $0.28 + 0.0053 * P_{T_{photon}}$.

10) The event must pass the Beam Halo Veto in order to minimize background.

11) The photon must have a shower shape width and length of at least $\sigma_{i\eta i\eta} > 0.0001$ OR $\sigma_{i\phi i\phi} > 0.0001$ in order to ensure that a spike event has been selected. This requirement

Since the photon object in a spike event usually only interacts with a single crystal, the electromagnetic shower shape for the event would have a significantly higher energy dump in the position of the seed crystal than in any other surrounding crystal. This is clearly shown in Figure 11, the center crystal has an energy deposit of about 2 orders of magnitude higher than the surrounding crystals.

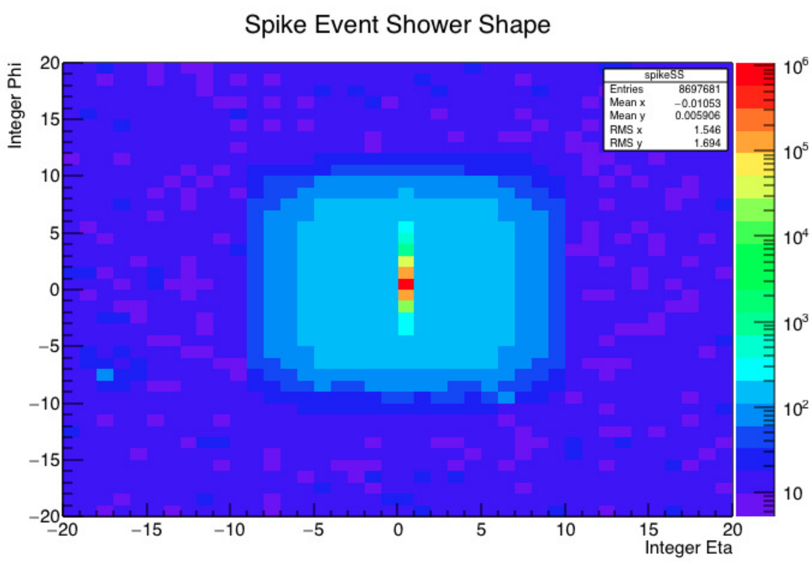

Figure 11: Shower Shape of candidate spike events.

5.3.2 Timing

The time distribution for spike events is taken from the seed crystal for the high energy photon that was required in the event. This crystal should be the crystal whose APDs were directly interacted with. Since this interaction would occur prior to an the event being triggered, the time signature would be early ($t < 0$). This can be seen in Figure 12, the distribution clearly peaks at about -12.5 ns. So, this sample provides a good model for an early time distribution.

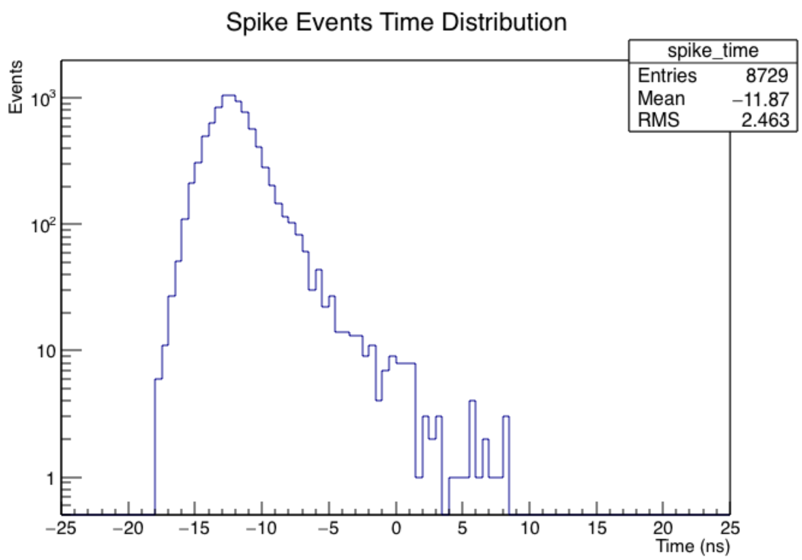

Figure 12: Time Distribution of candidate spike events.

6 Results

Each of the templates time distributions were fractionally fit to the candidate sample time distribution so that the contributions of the three templates to the candidate sample time distribution could be determined. The early template contributed to $93.94 \pm 3.5\%$ of the candidate sample time distribution. The prompt template contributed to $6.06 \pm 0.46\%$. of the candidate sample time distribution. The out-of-time template contributed to $8.64 \times 10^{-11} \pm 0.068\%$ of the candidate sample time distribution.

In the interval of t = 0 ns and t = 12.5 ns, 280 candidates were observed where 173 candidates were expected according to the fit templates. In the interval of t = 1 ns and t = 12.5 ns, 73 candidates were observed where 22 candidates were expected according to the fit templates.

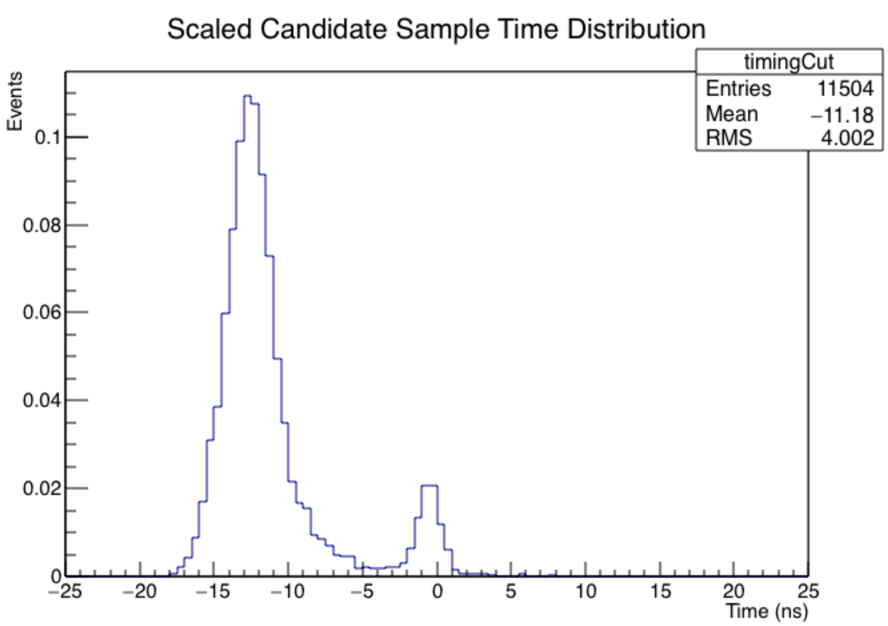

Figure 13: Scaled Time Distribution of the candidate sample.

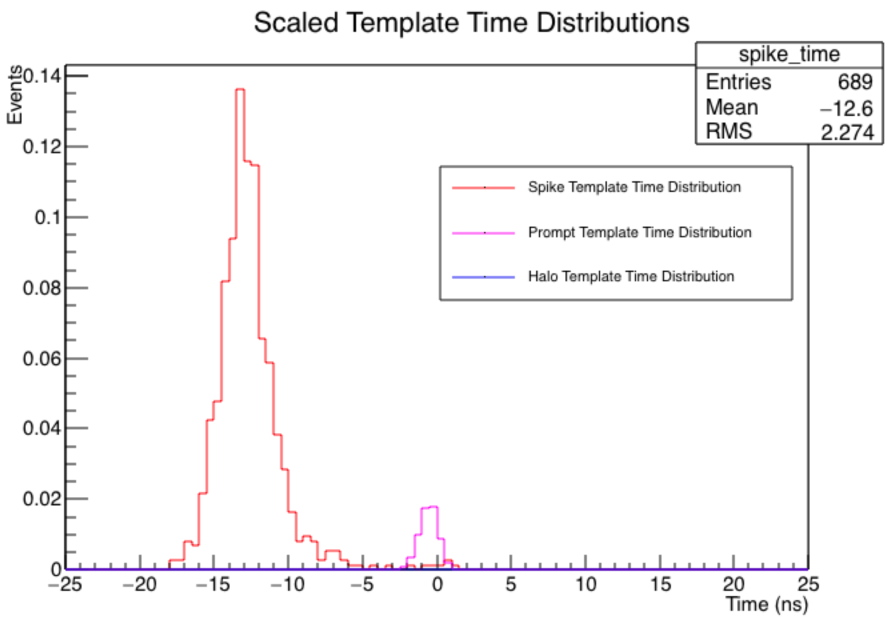

Figure 14: Scaled Time Distributions of all three templates.

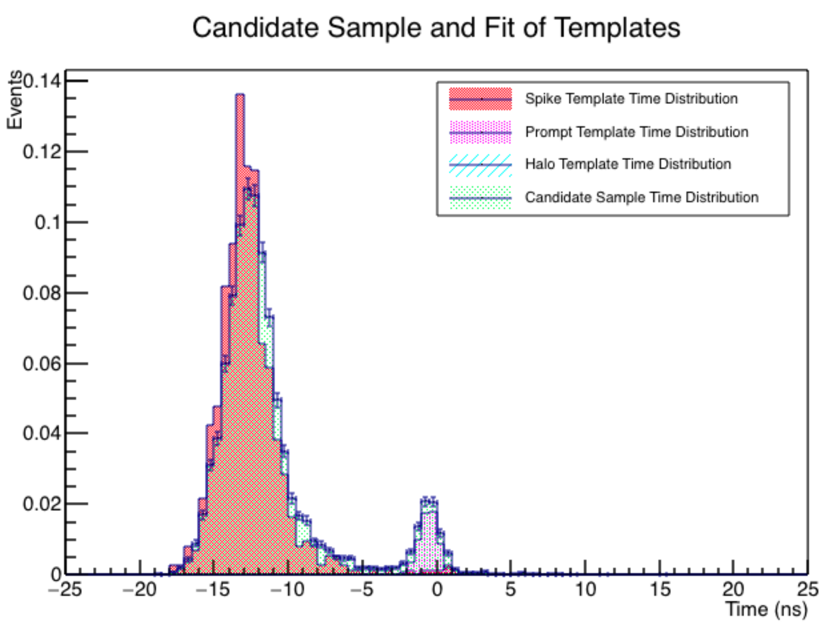

Figure 15: Template Time Distributions scaled to their respective contribution percentage plotted against the candidate sample time distribution.

7 Conclusion

The purpose of this study was to determine the largest contributors to the timing distribution of photons coming from events with a final state of a high-energy photon and large missing transverse energy. Three different time templates were hypothesized to be the largest contributors: a prompt template, an out-of-time template, and an early template. The early template was determined to contribute to $93.94 \pm 3.5\%$ of the candidate sample time distribution, while the early template contributed to $6.06 \pm 0.46\%$, and the out-of-time template contributed to $8.64 \times 10^{-11} \pm 0.068\%$.

An excess of photon candidates has clearly been observed in the late timing region. The next step for this study would be to determine whether there are other contributors to the candidate sample timing distribution, such as Cosmic Rays. The behavior and characteristics of these excess photons can also be studied as a continuation of this study.

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