Reconstructing Dark Photons with the DarkQuest Experiment at Fermilab

by

Ellison J. Scheuller

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE IN PHYSICS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2024

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ABSTRACT

The DarkQuest experiment will search for dark photons by looking for their decay into standard model leptons which can be detected. DarkQuest will use the momentum of these standard model leptons to calculate the position or vertex where the dark photons decay. Looking at the vertex positions will show if a dark photon was detected and if it is, physicists will be able to confirm DM predictions and learn a lot about the nature of dark matter which has yet to be detected. We use simulation to study the performance of the vertex reconstruction algorithm that will be used on DarkQuest when it starts taking real data. The vertex is calculated using the vertex reconstruction algorithms which are outlined in this thesis. The performance of the algorithm is then analyzed by looking at the vertex reconstruction efficiency, sensitivity, and displaced dimuon mass resolution.

Thesis supervisor: Philip C. Harris
Title: Associate Professor of Physics

Acknowledgments

I would like to thank Professor Philip Harris for his invaluable teaching, advice, and for sparking my interest in high energy particle physics starting with being a fantastic JLAB instructor to me. I have learned so many lessons from him in experimental physics that will carry into graduate school and for that I am extremely grateful.

I would also like to thank Patrick McCormack for his constant guidance, encouragement, and helping me understand and become passionate about the search for dark matter. His expertise and dedication have been invaluable in overcoming various challenges and achieving the goals of this project.

I would also like to thank Professor Markus Klute for the wonderful CMS research opportunity during my sophomore and junior year, including the summer in Karlsruhe. This was another pivotal time that helped me develop my passion for particle physics.

I am grateful to Fermilab, MIT, and the DarkQuest collaboration for providing the resources, facilities, and opportunities necessary for conducting this research. I am also very grateful to the graduate and undergraduate students who offered me guidance including Noah Paladino, Duc Hoang, Eric Moreno and Dowling Wong.

Finally, I would like to extend my heartfelt appreciation to my family for their love, encouragement, and support throughout my undergraduate studies. Their constant belief in me has been a driving force behind my academic pursuits, and I am deeply grateful for everything they have done for me to get here.

Contents

List of Figures

Chapter 1

Introduction and Background

In order to explain astrophysical observations concerning galaxy formation and dynamics, cosmic microwave background, and the universe's structure and evolution, physicists have theorized that there exists an abundance of dark matter (DM) in the universe. DM is predicted to make up 26.8% of the universe. In contrast, only 5% of the universe is normal matter and the rest of the makeup of the universe is dark energy [1]. Because there is so much evidence supporting the existence of DM [1], particle physicists want to understand its identity and interactions.

As of today, no particle experiment has been able to detect DM using direct detection methods. These methods are searching for particles on the order of 10-1000 GeV [2]. This is considered a large mass as most current DM theories predict DM is made up of Weakly Interacting Massive Particles (WIMP) which are O(100 GeV) [3]. Because the direct detection methods have yet to detect DM, physicists are now also trying to search for DM candidates with masses O(1 GeV) and one of these candidates is the dark photon. The dark photon has a smaller coupling than WIMPs (which have a coupling strength similar to the weak force; hence, the name weakly interacting massive particles), which allows them to produce the right amount of dark matter in the early universe and not have been observed already. The dark photon is now a popular candidate to search for because it is predicted to interact with some Standard Model (SM) particles, all of which have been and can be detected.

Similar to the photon, which is a force-carrying gauge boson of spin 1, the dark photon is predicted to also be a force carrying gauge boson of spin 1 but in the dark sector. In order to understand how physicists look for dark matter, one must start with understanding what particles are currently known and this is outlined in the Standard Model.

1.1 The Standard Model of Particle Physics

The Standard Model (SM), given by Fig. 1.1, is a model of all known elementary particles in particle physics. It describes the electromagnetic, weak, and strong nuclear interactions, which are the basic forces that make up the universe. The model has been successful in explaining a wide range of experimental results and predicting the behavior of particles at the subatomic level, however many new phenomena, including dark matter, can not be explained by the Standard Model.

The Standard Model classifies particles into two main categories: fermions and bosons. Fermions, which include quarks and leptons, are the particles that make up matter. Quarks combine to form protons and neutrons, which make up the nucleus of atoms. Leptons, such as electrons and neutrinos, are involved in various processes, including the structure of atoms and differ from quarks because they do not interact with the strong force. Bosons, on the other hand, are force carriers that mediate the fundamental forces. The bosons include the photon which mediates the electromagnetic force, the W and Z bosons which mediates the weak nuclear force, and the gluons which mediate the strong nuclear force.

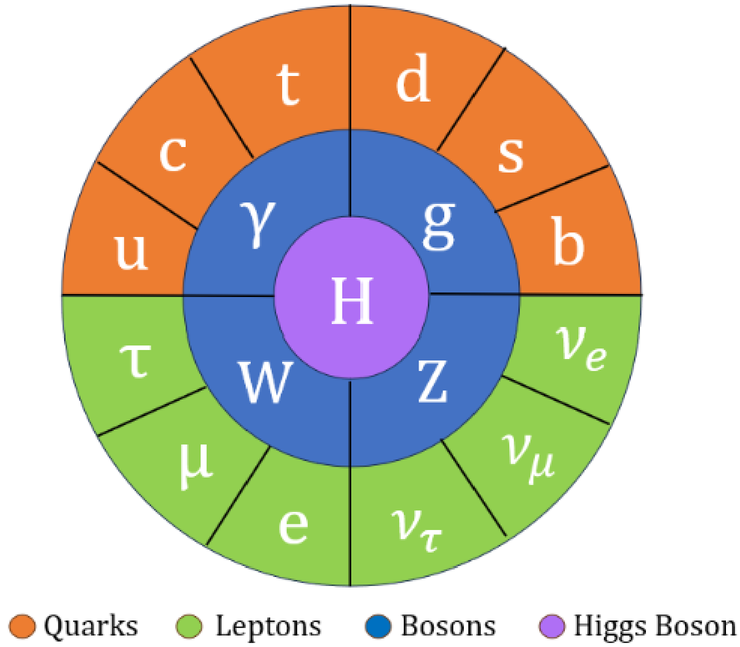

Figure 1.1: The Standard Model of Particle Physics. The particles in the outermost ring are fermions, or particles that make up matter. Orange particles are the quarks which interact with the strong force, and leptons are given by the green particles and do not interact with the strong force. The innermost ring has the bosons which are force carrying particles including the photon which mediates the electromagnetic force, the W and Z bosons which mediate the weak nuclear force, and the gluon which mediates the strong force. The Higgs Boson in the center is a special boson which mediates the field which gives rise to all mass.

The Standard Model associates a particle for three of the four fundamental forces but it does not include a description of gravity, and it leaves some questions unanswered, such as the nature of dark matter. Because theory demands dark matter particles to be long lived, to hold the universe together (cannot be slippery and pass through like photons and neutrinos), and dark matter particles cannot absorb or emit light, dark matter cannot be found on the standard model. Because of this, physicists are working on extending the Standard Model to a dark sector to describe the nature of dark matter.

1.2 Dark Matter Candidates

There are many theories to describe the identity and interactions of dark matter. Two leading theories which investigate the large and small ends of the mass scale for particles include Weakly Interacting Massive Particle (WIMP) Theory which postulates massive O(100 GeV) dark matter and QCD Axion Theory which predicts light dark matter.

1.2.1 WIMP Theory

The Weakly Interacting Massive Particle (WIMP) theory comes from the idea of particles, both DM and SM particles, being in thermal equilibrium in the early universe. In the early universe temperatures were extremely high and particle-antiparticle pairs from both dark and normal (SM) matter were constantly being created and annihilated. As the universe expanded and cooled, these processes became less frequent. WIMP theory suggests that at some point, a population of WIMPs froze out of thermal equilibrium [2] due to their weak interactions, leading them to be cold compared to the thermal bath, a property dark matter is predicted to have today. If the annihilation of WIMPs was similar to the expansion of the universe when the WIMPs decoupled from equilibrium, their predicated density today would be approximately consistent with the observed dark matter density.

The thermal WIMP scenario explains why the dark matter observed today has a similar density across large cosmological scales [4]. By knowing what density this theory predicts, physicists can predict that WIMPs would be on the order of 100 GeV in mass, which is about one hundred times heavier than a proton. This idea of massive and weakly interacting (very spread out and undetected) particles gives WIMP Theory its name.

1.2.2 Quantum Chormodynamics Axion Theory

Another theory, which described dark matter as light, is the theoretical particle called a QCD axion. Quantum Chromodynamics (QCD) axions are hypothetical elementary particles proposed as a solution to the strong CP problem in particle physics. The strong CP problem arises within the framework of the Standard Model of particle physics, particularly in the QCD sector [5], which describes the strong force responsible for holding quarks together to form protons, neutrons, and other hadrons.

The strong CP problem revolves around a term in the QCD Lagrangian that violates the combined symmetries of charge conjugation (C) and parity (P). This term involves a dimensionless parameter called θ [5], and its presence could lead to an observable electric dipole moment for the neutron, which is not experimentally observed. The absence of this observable dipole moment is puzzling, and the strong CP problem seeks an explanation for why the θ term is extremely small or effectively zero.

The QCD axion is motivated by Quantum Chromodynamics which gives three charges characterized by colors (RGB) rather than positive and negative. The basic idea in QFT is to introduce a new pseudo-scalar field, the axion field, which couples to the QCD Lagrangian in such a way that it dynamically suppresses the term. The axion field is characterized by a vacuum expectation value that minimizes the energy associated with the QCD Lagrangian [5].

The dynamics of the axion field result in a potential that is minimized when the theta term goes to zero, solving the strong CP problem. The QCD axion, and axion like-particles (these particles when compared to QCD axions have a mass and coupling to the SM that are independent of each other [6]) are proposed to be a candidate for dark matter because the axions are an addition to the Lagrangian of the Standard Model and can help describe some of the properties and phenomena observed astrophysically for dark matter. The QCD axion theory predicts dark matter to be very light and an axion like-particle (ALP) that mediates the electromagnetic force via the dark sector.

ALPs can interact with SM particles via a wide variety of dimension-five couplings. For DarkQuest, we consider only the possibility of their coupling to photons via the operator

$$\mathcal{L}^{\text{eff}}_{\text{gauge}} = \frac{a}{4\pi v_a}\left(g_{agg}G^{a\mu\nu}\tilde{G}^{a}_{\mu\nu} + g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aZ\gamma}Z_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aWW}W^{+\mu\nu}\tilde{W}^{-}_{\mu\nu}\right)$$

(1.1)

where the effective couplings $g_{aV_1V_2}$ are actually form-factors, i.e., functions of $\frac{m_{V_1}}{m_a}$ and $\frac{m_{V_2}}{m_a}$. [7].

1.3 Dark Photon Theory

The dark photon (A') is a well-motivated mediator particle that couples to SM electromagnetic currents with a suppressed electromagnetic charge ϵe with $\epsilon << 1$ and e is the electric charge. The dark photon (A') can be weakly coupled to existing SM particles through the kinetic mixing term:

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta_{\text{w}}} {A'}_{\mu\nu}B^{\mu\nu} \tag{1.2}$$

Dark photons are produced at DarkQuest from the collisions of the high-energy protons with nuclei in the iron dump via the decay of SM mesons (pions, eta, ...), and the Bremsstrahlung and Drell-Yan processes [6]. The dark photon decays back to SM

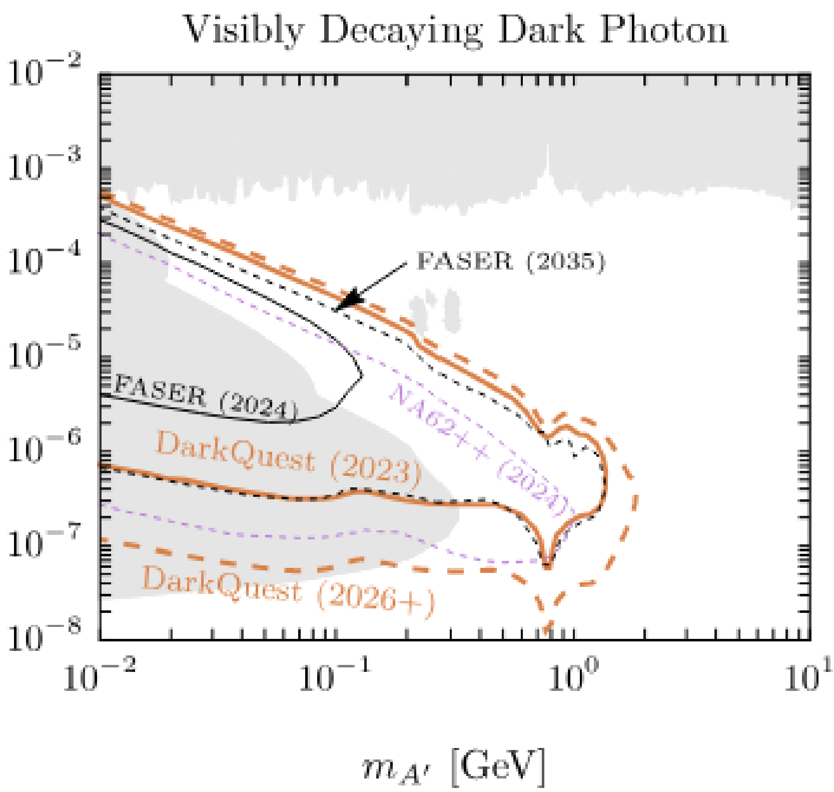

Figure 1.2: The search scope of the DarkQuest experiment.

particles and its branching ratio to electrons and muons is of $O(10\%)$ [8]. The reach of DarkQuest for dark photons is given in figure 1.2.

1.4 Methods to Search for a Dark Photon

There are many ways to search for dark matter, and thus varying kinds of experiments which search for dark matter via annihilation, scattering and production. Searching for dark matter via production involves observation of dark matter particles in particle colliders or fixed target experiments. Unlike scattering or annihilation searches, which rely on existing dark matter populations, the production approach aims to create dark matter particles in controlled environments. WIMPS, QCD Axions and ALPs can be searched for using production experiments. The DM candidate being studied depends on the energy and intensity levels of the experiment. To achieve high energy and search for WIMPs, one must use a colliding beam experiment like the Large Hadron Collider (LHC). To achieve high intensity and search for ALPs and dark photons, one must use a fixed target experiment like DarkQuest.

1.4.1 Fixed Target Experiments

A fixed-target experiment is characterized by a stationary target material placed in the path of a single, accelerated beam of particles. Unlike colliding beam experiments, where two beams collide with each other, fixed target experiments involve the interaction between accelerated particles and a static target. This setup is particularly useful for studying specific characteristics of the target material, exploring particle-nucleus interactions, and investigating the internal structure of particles. Fixed-target experiments have been instrumental in numerous discoveries in particle physics, offering a simpler and cheaper experimental setup compared to colliding beam experiments and also achieving high intensity (many events of proton collisions because the protons are almost guaranteed to collide with the fixed target) compared to colliding beam experiments which achieve high energy because of conservation of momentum for smashing accelerated protons together. Because of this high intensity, fixed target experiments are used to search for the dark photon.

1.4.2 Visible Signatures

The current fixed target experiments searching for dark photons are split into two categories. Some experiments, like DarkQuest, search for visible signatures (decay back to SM particles) and others, such as Light Dark Matter eXperiment (LDMX), look for

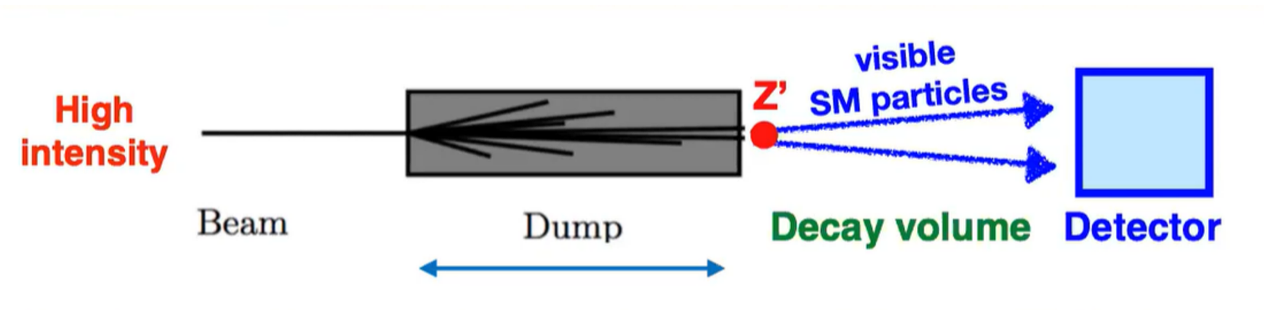

Figure 1.3: Layout of a high intensity fixed target beam dump experiment searching for visible signatures (SM particles) produced by dark photons. The beam dump allows dark matter particles such as the dark photon to pass through while filtering out the SM particles. After the dark matter particles (given by Z' pass through the beam dump they decay to SM particles and can be detected.

invisible signatures (decay back to DM). If the mass of the dark photon is lighter than twice the mass of any other DM particle, the decays in DM are kinematically forbidden and the dark photon can only decay to SM particles [9]. These are called visible decay or visible signatures. The lifetime of a visible decay is given by:

$$c\tau = \frac{1}{\Gamma} = \frac{3}{N_{\text{eff}} m_{A'} \alpha \epsilon^2} \approx \frac{80\mu m}{N_{\text{eff}}} \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100MeV}{m_{A'}}\right) \tag{1.3}$$

where N_{eff} is the number of available decay channels, $c\tau$ is the impact parameter for the detection of displaced vertices due to dark photon decay, which is estimated to be around 80 μm for dark photons of mass O(100 MeV). ϵ is the coupling of the particle which is described by the interactions between fields, and $m_{A'}$ is the mass of the dark photon. Using this lifetime, physicists can design fixed target experiments to search for these visible signatures knowing when the dark photon will decay to SM particles. They can place beam dumps (which filter out SM particles from dark photons) strategically knowing how long the dark photon exists from collision to decay. A visual is provided in figure 1.2 which illustrates a high intensity beam dump experiment which searches for visible signatures. This is precisely what DarkQuest aims to do and the experiment will be described in more detail in the next chapter.

Chapter 2

DarkQuest Experiment

2.1 Overview

Fermilab currently has an experiment called SpinQuest designed to analyze the makeup of nucleon. The proposed DarkQuest experiment will extend the detector capability of SpinQuest to have the full sensitivity to dark sector searches [6] with the addition of an electromagnetic calorimeter (EMCal) which will detect electrons - a possible decay product from a dark photon. DarkQuest will have a much shorter timescale than a lot of current dark photon detection experiments, be cost effective and also reach farther into untested parameter space with the possibility of finding a dark photon. The experimental apparatus is given in Fig. 2.1.

Dark photon samples are produced at DarkQuest from the incoming high-energy proton collisions from the beam dump. Because a dark photon is in the lightest hidden sector state, it can only decay back to SM leptons, physicists can look at displaced electron and muon decays to reconstruct the dark photons [6]. When the proton beam enters the detector, a thick iron beam dump/magnet (FMag) bends and stops most of the SM particles produced by particle-iron-interactions except for a dark photon,

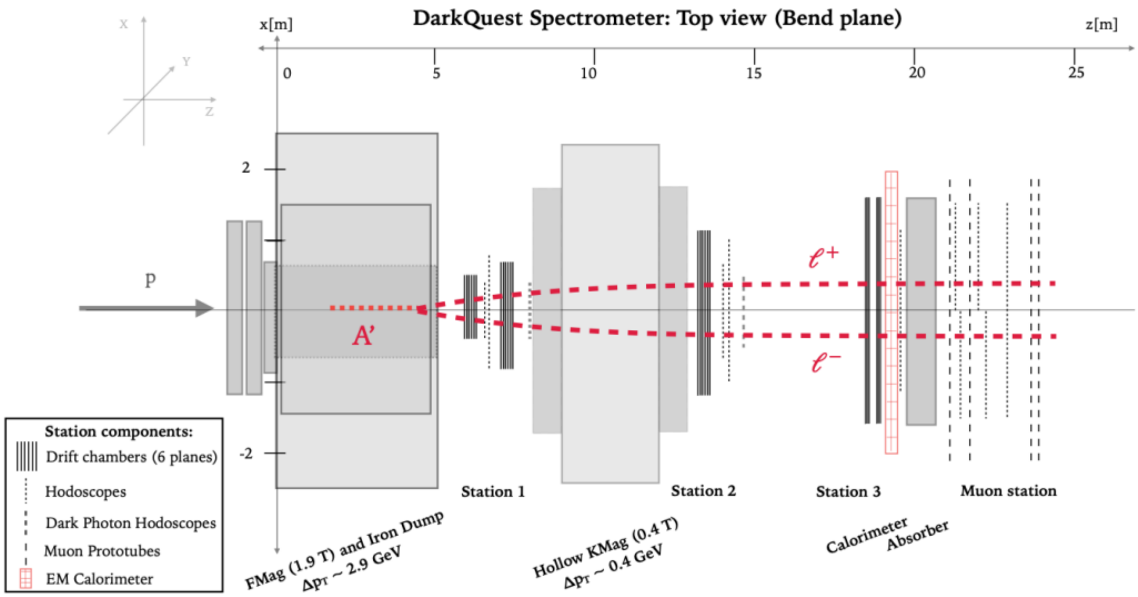

Figure 2.1: This figure is taken from [6] and is identical to their figure 1. Pictured is the overhead view of the DarkQuest detector. The high energy proton beam given by p enters the focusing magnet (FMag) which is 5m long. The open-aperture magnet (KMag) sweeps away soft SM radiation, the drift chambers are used for tracking, and hodoscopes are used for triggering and particle identification. An absorber is placed upstream the muon prototube station. The red bar is the proposed electromagnetic calorimeter (EMCal) to extend the detection capability to electrons, pions and photons. The red lines show an example of how a dark photon is produced either in the FMAg or after, and decays into dileptons given by (l +, l). The dileptons hit each of the stations and the information is used to reconstruct the vertex.

which interacts only weakly with normal matter, as predicted by WIMP theories [6]. This particle can travel a significant distance from the creation point before decaying into a pair of leptons conventionally referred to as dileptons. The dileptons hit each of the stations, seen in Fig. 1, and the information is used to reconstruct the vertex at which the dark photon decayed.

2.2 Dipole Magnets

The beam dump for the DarkQuest experiment is a 5 meter long piece of magnetized iron adjacent to the proton beam target. Because it is a magnet made of iron we call it the FMAG. The FMag acts a beam dump as well as redirects soft radiation away from the detector. Consequently, only the highest energy or neutral particles are allowed through. The FMAG generates a magnetic field of 1.8 Tesla, achieved through a current of 2000 A at 25 V.

There is also a second magnet placed farther from the proton beam target called the KMag which ensures proper momentum reconstruction.

2.3 Tracking Stations

There are four tracking stations: station 1-3 and the muon station as seen in figure 2.1. Each station is equipped with scintillator hodoscopes for the trigger system. The first three tracking stations are equipped with drift chambers to facilitate high-resolution tracking, while the fourth station utilizes proportional tube modules to track incoming muons.

The first two tracking stations employ two planes of scintillator oriented perpendicularly to measure position along both the x and y axes (with the z-axis considered to be into the plane of the detectors). The scintillator strips comprising these planes overlap by approximately 2-3 mm. Preceding the fourth tracking station is a 1 meter iron wall, designed to filter out particles that are not muons.

Chapter 3

Vertex Reconstruction

3.1 Reconstruction Algorithm

The position where the dark photon decays into dileptons is defined as the vertex. If the vertex is relatively far away from the start of the FMag, it can be a unique signal to identify dark sector particles (called the displaced vertex) because the FMag filters out SM particles. Therefore, we are developing algorithms to reconstruct vertex positions using the dilepton station hit information.

The displaced vertex reconstruction is modified from the SpinQuest E-1039 vertex reconstruction code, which is based on the Kalman Filter [6]. The vertex reconstruction algorithm works as follows:

1. *Preparing all possible dimuon candidates.* Valid reconstructed tracks with positive and negative charges are looped separately in this step, and all possible pairs of tracks are formed and saved in the dimuon candidate collection.

2. *Initial estimation of the vertex position.* After the track reconstruction, the point of the closest approach to the beam pipe (z-axis) is calculated, and this is referred to as the vertex of one track. For one dimuon candidate, the average of the two

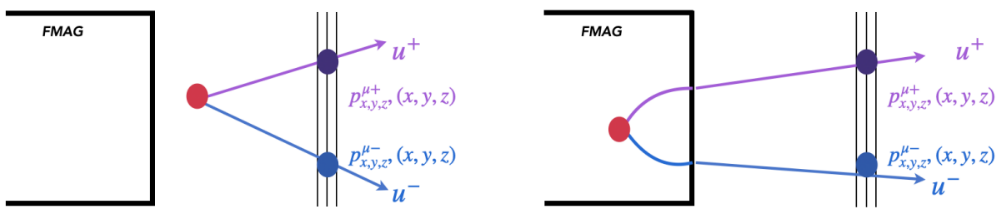

Figure 3.1: Picture of the vertex reconstruction of two dileptons (u^+, u^-) hitting station 1 with their associated momentum vectors. This figure is taken from [6] and is identical to their figure 24. Pictured left is when the decay happens after A' travels through the FMag whereas the right scenario shows the decay within the FMag. The FMag distorts the shape of the tracks.

track vertices is used as one initial estimation of the dimuon vertex position. In addition, each track is swum from station 1 to upstream. In the gap between the downstream side of FMag and station 1, the swimming is done by projecting the track linearly, since the magnet effect in this region is small. The point with the smallest distance between the two tracks during this swimming process serves as the 2nd estimation of the dimuon vertex position. The swimming is then done in the region between the dump and FMag, taking into account the FMag effects. The point with the smallest distance between the two tracks here serves as the 3rd estimation of the dimuon vertex position.

3. *Vertex fit.* For one initial estimation of one vertex pair candidate, the Kalman Filter is running with the two associated tracks. The resulting vertex with the smallest χ^2 among all the initial estimations will be the vertex of the corresponding dimuon pair.

There is a possibility that the $A' \to \ell^+\ell^-$ decay happens within the FMag rather than after (which is ideal). Figure 3.1 shows the two possibilities and what happens to the tracks. If the A' decays after the FMag, the effects from the FMag are small

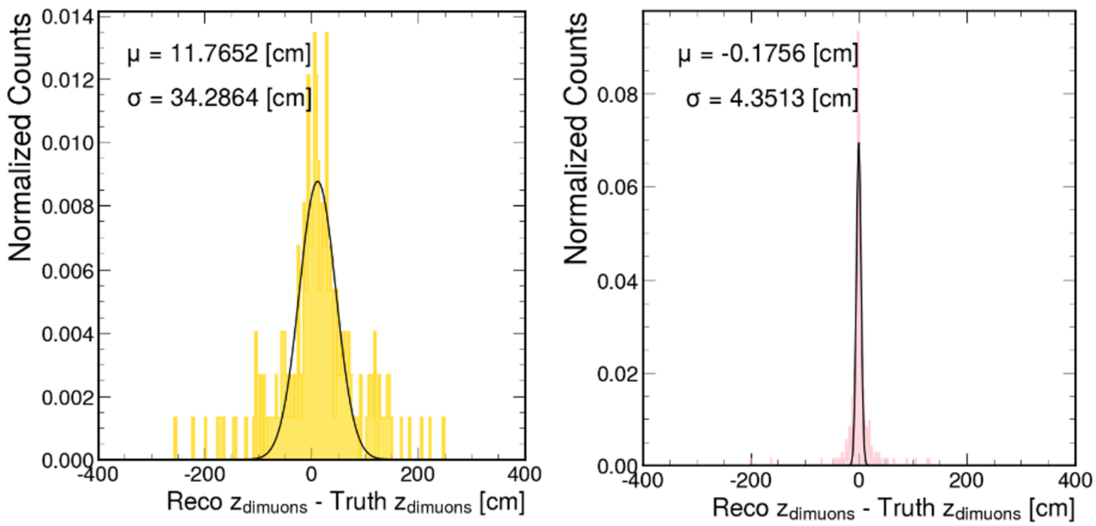

Figure 3.2: Vertex resolution in cm constructed within the FMag (left) and outside the FMag (right). The sample used for these plots was an $A' \to \mu\mu$ decay with an A' mass of 0.85 GeV. There is much better resolution for events constructed outside the FMAg with a much smaller spread.

and the track upstream propagation is linear. Because of this, the track and vertex momentum resolutions are better. If the A' decays within the FMag, the track upstream propagation is distorted by the effects of the FMag and the track and vertex resolutions are much worse making the reconstructions worse. This can be seen in figure 3.2 which uses simulated A' samples run through the vertex reconstruction algorithm to calculate vertex resolution in different positions of the FMag.

After the vertex fit is performed, and a vertex is obtained, there is a regression that gives the mass and momentum parameters. Using the results that come out of this recontruction flow we can analyze the performance of the algorithm to see if it is ready to be used on the experiment or what needs to change.

3.2 A' Reconstruction Possible Failures

Before we dive into measuring the reconstruction efficiencies, we need to understand the A' reconstruction possible failures to sufficiently analyze the efficiency. The main possible failures are given below:

1. *Leptons go out of acceptance.* If a lepton goes out of acceptance, this information is impossible to recover.

2. *Reconstruction of single leptons fail by lost hits.* Approximately 6% of hits are lost at SpinQuest relative to perfect acceptance because of an inefficiency of the detectors due to a few effects. This information is also impossible to recover.

3. *Reconstruction of single leptons fail by algorithm failure.* This can happen from resolution effects if the position is mismeasured by extrapolating tracklets between stations. This failure would be something we can improve in the algorithm and quantify the efficiency.

4. *Vertex Reconstruction fails by algorithm inefficiencies.* This can happen because within the FMag it is hard to do vertexing, we do backwards extrapolation, the swimming back isn't perfect, there are magnetic field effects hard to account for, etc. This failure would also be something we can improve in the algorithm and quantify the efficiency.

5. *Vertex reconstruction fails by poor extraction of single lepton kinematics.* This can happen if we measured the tracks of the individual particles wrong. This failure would also be something we can improve in the algorithm and quantify the efficiency.

Now that an overview of the vertex reconstruction algorithm and the possible A' reconstruction failures, we will now analyze the capabilities of the current code by analyzing the reconstruction efficiency.

Chapter 4

Reconstruction Software Performance Analysis

4.1 Dimuon and Dielectron Efficiency

To investigate the vertex reconstruction algorithms and quantify their performance, we look at the vertex reconstruction efficiency. In order to do this, we need to isolate the vertex reconstruction efficiency from the other A' reconstruction possible failures. We use simulated data with ten thousand events to test the vertex reconstruction algorithms. We run the algorithm with six different generated data sets, each with a different dark photon mass. The overall flow of this will be:

1. *Check what fraction of leptons have a reconstructed track.* This is done in order to understand the individual tracking efficiency.

2. *Quantify reconstructable tracks.* Reconstructable tracks are defined as both leptons are within detector acceptance at station 3. We look at this in order to quantify the leptons going out of acceptance (information is impossible to recover).

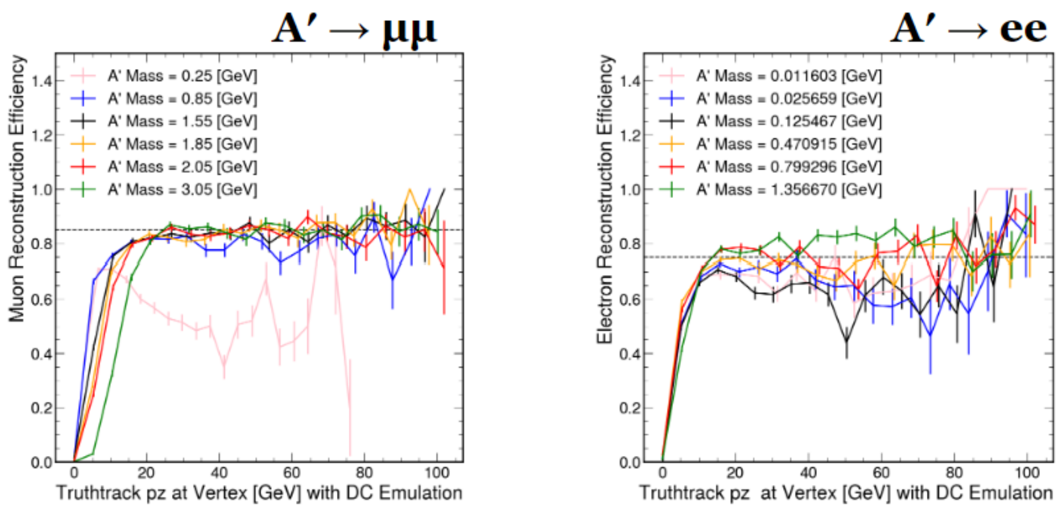

Figure 4.1: Individual Lepton Reconstruction Efficiency plotted over truthtrack pz at vertex in [GeV] for 6 different A' masses. On the right shows a $A' \rightarrow \mu\mu$ decay and the left shows a $A' \rightarrow ee$ decay.

3. *Find the fraction of events with two matched tracks.* The inefficiences come from tracks going out of acceptance, tracking failure due to missing hits, and tracking algorithm inefficiencies.

4. *Check the A' recontruction efficiency.*This is calculated by taking the number of events with a reconstructed dimuon over the total number of events. Every effect from the A' reconstruction possible failures are uncorrected for in this measure of efficiency.

5. *Vertex reconstruction fails by poor extraction of single lepton kinematics.* Because the fraction of events with two matched tracks is uncorrected for all A' reconstruction possible failures not including the vertex reconstruction efficiency component, we can isolate the vertex efficiency component by dividing A' reconstruction efficiency over fraction of events with two matched tracks.

The individual lepton reconstruction efficiency given in figure 4.1. The efficiency is around 80%-90% for dimuons and around 70-80% for dielectrons. We notice that

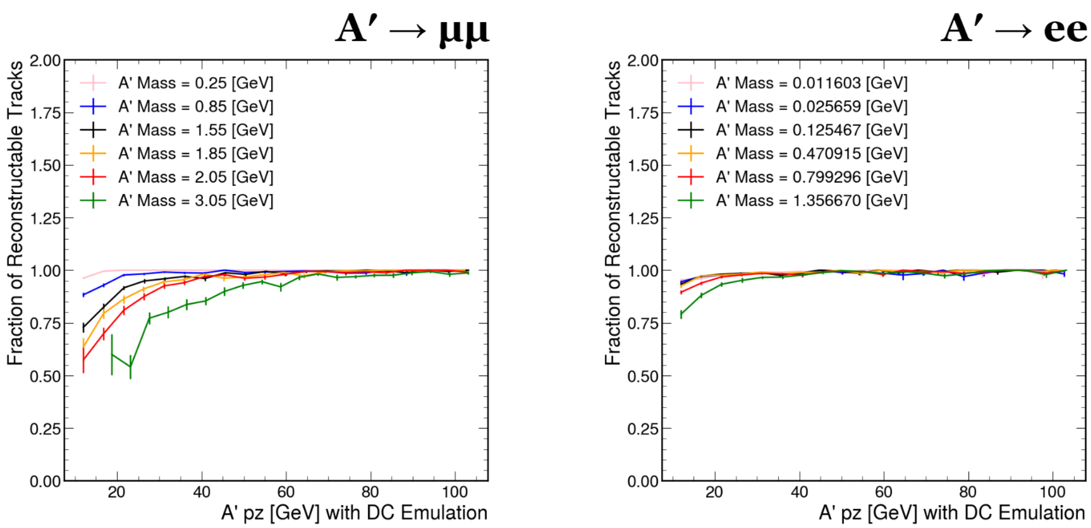

Figure 4.2: Reconstructable tracks plotted over A' pz in [GeV] for 6 different A' masses. On the right shows a $A' \to \mu\mu$ decay and the left shows a $A' \to ee$ decay.

the efficiency does not depend on the A' mass as we would expect. The low mass distortions could be track hit ambiguity from collinear tracks. These results agree with previous studies [6].

The reconstructable tracks given in figure 4.2 show that at high pz nearly all of the tracks are reconstructed. Low momentum particles we expect to be harder to reconstruct. There is also trend with A' mass such that lower masses result in less reconstructable tracks.

To find the vertex reconstruction efficiency we follow steps 3-5 given above. To find the efficiency we divide the A' reconstruction efficiency by the fraction of events with two matched tracks. This is given in figure 4.3. The number of events with a reconstructed dimuon is the same as the number of events with a reconstructed vertex because a dimuon can only be reconstructed if there was a vertex (point of decay). This is a good way to investigate the vertex reconstruction efficiency because it is looking at how many vertices were reconstructed out of all the events which results in two tracks (filter out failures due to things outside the algorithms control such as missing

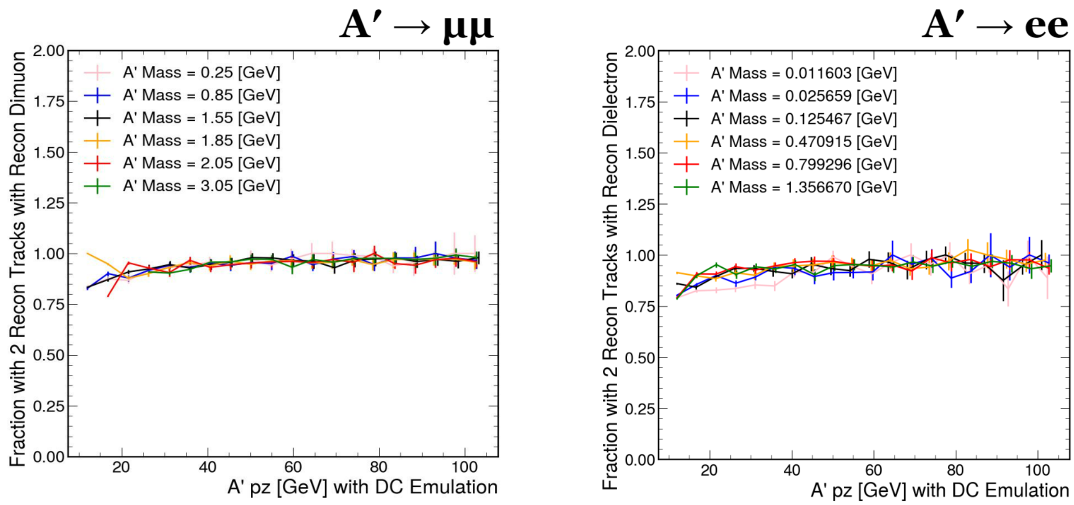

Figure 4.3: A Reconstruction Efficiency over Fraction of Events with 2 Matched Tracks plotted over A' pz in [GeV] for 6 different A' masses. On the right shows a $A' \rightarrow \mu\mu$ decay and the left shows a $A' \rightarrow ee$ decay.

hits and leptons not in the acceptance for the detector). We calculate the number of events with a reconstructed dimuon by counting how many vertices the algorithm reconstructed. We then calculate the number of events with 2 reconstructed tracks by using the tracking algorithms but not selecting events which resulted in a vertex. As seen in Fig. 4.3, the vertex reconstruction efficiency is approximately 90%-95% for the six dark photon masses which indicates the vertex reconstruction algorithms do not need significant modifications at the moment. We can see in figure 4.3 that events with low dark photon momentum slightly diverge from the trend but this is because if the momentum is low, it is much harder to reconstruct the tracks.

4.2 Sensitivity

Another interesting aspect to analyze is the sensitivity concerning the A' mass and coupling. Across all simulated samples encompassing various A' mass and coupling values within the DarkQuest search scope, we calculated both the A' reconstruction

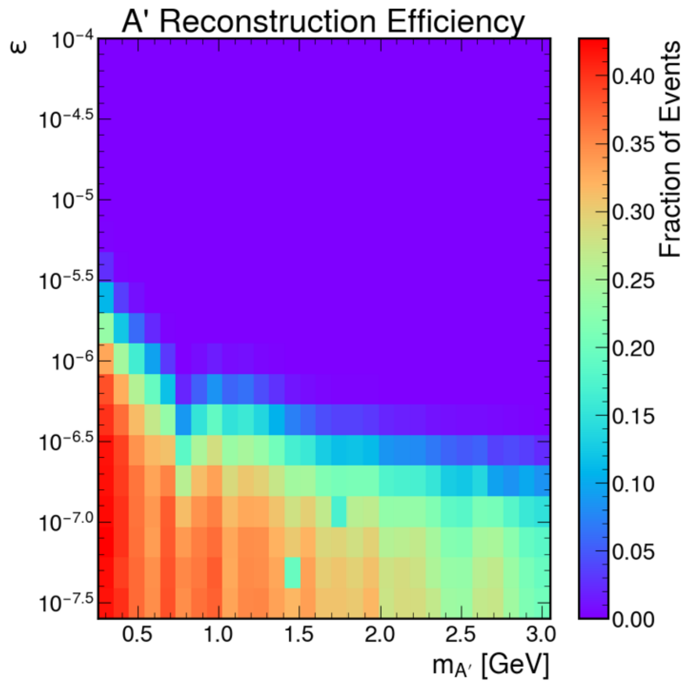

Figure 4.4: A' reconstruction efficiency in $A' \to \mu^+\mu^-$ decays (between 5-6m - after the FMag) in different A' masses and couplings.

efficiency (as depicted in Figure 4.4) and the fraction of events with reconstructable tracks (as illustrated in Figure 4.5). These plots serve to find the dark photon parameters for which the DarkQuest experiment is more likely to reconstruct a track and a dimuon. Consequently, they plots provide the search scope of DarkQuest, identifying potential regions where a dark photon could exist and the likelihood of reconstructing such events.

From the analysis of these plots, we see the following trend: the experiment reconstructs more tracks and dimuons for smaller coupling and A' mass values. This observation helps us understand the experiment's sensitivity and its capability to detect potential dark photon signatures for certain dark photon masses and coupling. These predictions line up with the theory of where a dark photon could exist in parameter space and identify where in parameter space DarkQuest is able to search.

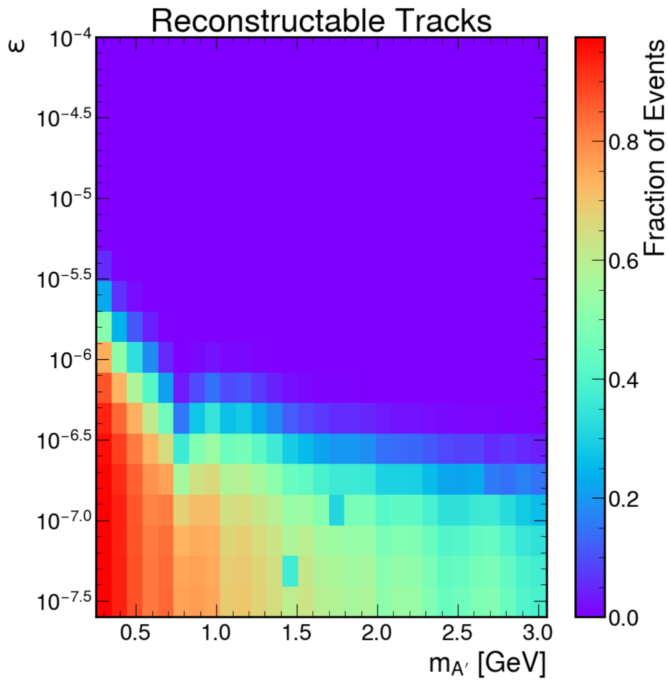

Figure 4.5: Reconstructable tracks in $A' \to \mu^+\mu^-$ decays (between 5-6m - after the FMag) in different A' masses and couplings.

4.3 Displaced Dimuon Mass Resolution

We also investigated the displaced dimuon mass resolution given in figure 6.6. Displaced dimuon mass is analyzed in order to identify if a dark photon decayed and therefore we want to be precise with the mass measurement. We calculated the mass resolution for six different masses and were able to recover a resolution on the order of 10^{-2} GeV which is very good. This is close to the ideal drift chamber resolution and we will have fairly accurate measurements of the displaced dimuon mass. We also analyzed how the mass resolution changes over increments of the FMag, and similarly to the vertex resolution above, we saw that the mass resolution is a lot better if the event is reconstructed after the FMag.

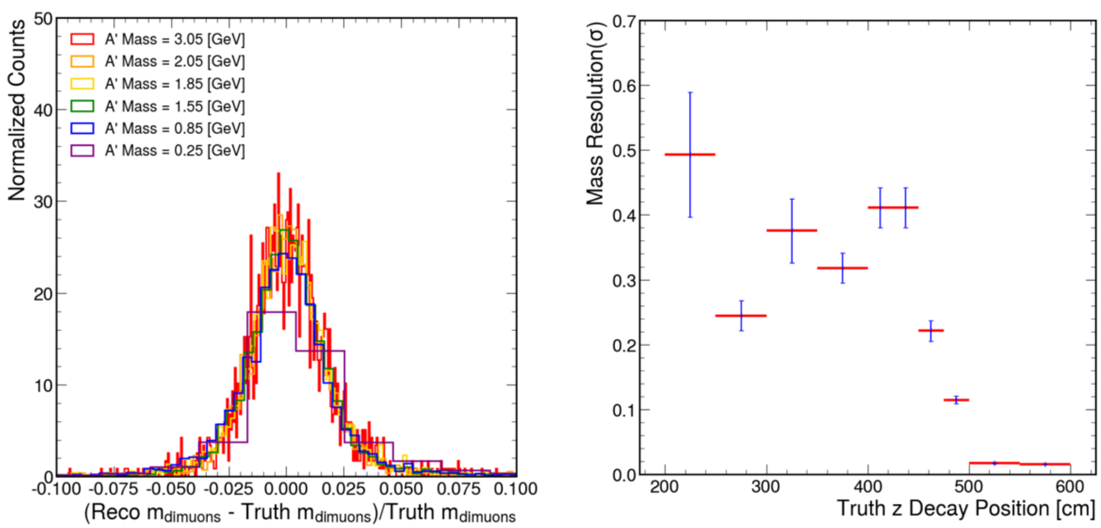

Figure 4.6: Mass resolution for different A' masses (left) and mass resolution in increments over the FMAG (right) with an A' mass of 0.85 GeV.

Chapter 5

Conclusion

The vertex reconstruction efficiency, sensitivity and displaced dimuon mass resolution show that the vertex reconstruction code is performing well and quantify the efficiencies for when the code is used on real data. This information will be used on the real DarkQuest experimental data in 2026 to calculate the errors in the vertex positioning for each event measured by station information and predict where the vertices are found. These numbers will be improved when other parts of the project such as the particle identification and drift chamber emulation gets updated, but we are pleased with the trends of these results as they are what we would expect. This is the first end to end study of dark photon efficiency for SpinQuest and DarkQuest and it shows we will be able to fully reconstruct and identify displaced dimuons and dielectrons and be sensitive to dark photons in unexplored regions. In 2026, when the vertex positions are calculated, physicists will be able to use this to understand if a dark photon has been detected. This would be ground breaking as dark matter has yet to be found and would help physicists understand the nature of DM and finally answer questions about its identity and interactions.

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