Abstract

Modern experimental physics is often probing for new physics by either finding deviations from predictions on extremely precise measurements, or by looking for a new signal that cannot be explained with existing models. The NA62 experiment at CERN does the former by measuring the ultra-rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. However, due to the layout of the experiment and the high beam energy, there is also an excellent opportunity to search for completely new physics in a hidden sector. Two potential dark matter mediators are of particular interest: axion-like particles (ALPs) and dark photons. The detection of these particles will be direct by assuming visible decay modes, namely ALPs with diphoton decay and dark photons to a dilepton final state. The work done this summer has been devoted to understanding several backgrounds in the hidden sector search at NA62. This document is provided to facilitate future endeavors of similar nature in background analysis.

1. Physics Motivation

The presence of dark matter is widely agreed upon in the physics community. Several important cosmological studies confirm the presence of nonluminous matter with no Standard Model (SM) candidates. Particularly notable support for new particles include galaxy rotation curves higher than predictions from the visible disk, excessive gravitational lensing, and the unexplained offset of the gravitational center of the Bullet Cluster [1]. This motivates models with ‘portals’ to hidden sector particles that interact extremely weakly with visible matter.

The presence of dark matter (at a certain energy scale) could potentially provide insight or solutions to several existing open questions in modern physics, such as the anomalous muon magnetic moment and baryon asymmetry of the universe (BAU). Experiment has then to determine the mass of hidden sector particles as well as the coupling strength to SM particles.

2. Theoretical Background

2.1. Candidates

The prevalence of dark matter over visible matter could suggest that there exists rich physics and possibly many new particles in a hidden sector. At NA62 at CERN, two candidates that act as portals to visible matter are being probed: axion-like particles (ALPs) and dark photons.
Theories involving hidden sector portals are often focused on fifth-order operators, where the coupling would impose an energy scale. As experiment has yet to successfully identify a hidden sector particle, it would seem the particle is either very heavy or extremely weakly interacting. A possibility for this particle could be an ALP, a light pseudo-scalar portal from the SM to a hidden sector [2].

A modified Lagrangian including the pseudo-scalar \( a \) would be

\[
\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}
\]

where there exists a kinetic term and mass term for the ALP, and also a dimension five term including couplings to the electromagnetic field and the ALP [2]. Note that the coupling \( g_{a\gamma} \propto 1/\Lambda \) for \( \Lambda \) some energy, presumably very large. Measuring this coupling would give strong insight to the energy hierarchy of hidden sector interactions.

The other potential candidate in the NA62 search is the dark photon, a possible \( U(1) \) field in a dark sector that could couple to the hypercharge \( U(1)_Y \) of the SM. The corresponding Lagrangian for \( A' \) is then

\[
\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{\epsilon}{2} F^{'\mu\nu} F_{\mu\nu} - \epsilon e \bar{\psi} \gamma_\mu \psi A'^\mu - \frac{1}{2} m_{A'}^2 A'^\mu A'^\mu
\]

where there exists a field-strength term for a dark sector \( U(1) \) field, a kinetic mixing term between the fields, a dilepton-dark photon interaction term, and a mass term [3]. Note that the several interaction terms between DM and SM terms yields many possible production mechanisms.

2.2. Detection

NA62 provides a particularly promising layout (see [4] for layout details) for detecting weakly coupled hidden sector particles. A 400 GeV/c proton beam from the SPS collides with a beryllium target to produce secondaries. The secondary beam propagates another \( \sim 100 \) m until reaching the 60 m fiducial volume [4]. Primary production of some hidden sector particles is to come from slightly downstream of the target in the ‘Target Attenuator eXperimental areas’ (TAX), approximately 1.6 m thick and made of copper. The high-Z material of the TAX along with the highly boosted nature of the incoming particles could produce dark particles within the acceptance of the detector [2].

The extended decay volume is imperative to detecting weakly coupled particles. That in combination with the high energy (and therefore large boost of the primary particles) and the sophisticated trigger system of the experiment provide great opportunity for this particular search. Although many direct detection experiments have probed the \( > \text{MeV}/c^2 \) mass range, NA62 would be able to search for particles in the MeV/c^2 - GeV/c^2 mass range with a coupling of \( \epsilon \sim 10^{-5} \) for the dark photon [3] and \( 10^{-6} \) GeV\(^{-1} < g_{a\gamma} < 10^{-2} \) GeV\(^{-1} \) for ALPs [2].

3. Single-Track Reconstruction

The first objective of the summer project was to understand potential backgrounds in the signal region of \( \pi^+\nu\bar{\nu} \) using single-track reconstruction [5]. The `vertexMomentumAnalyzer.cc`
Figure 1: Linear (left) and logarithmic (right) plots of kaon decays for a given $m_{\text{miss}}^2$ region. Region I and II are dominant for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ as the other decay modes are suppressed kinematically [4].

was developed to reproduce existing plots regarding missing mass in the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal region, but also to study the kinematics of muons from the $K^+$ beam.

This analyzer utilizes Extrap.cc files [6] to extrapolate entries in the spectrometer to the LKr and CHOD for missing mass studies, and also to the MUV3 for muon studies. If the track is within acceptance, cuts in timing are applied to confirm an entry in the MUV3. To associate a cluster in the LKr with a track, a cut is made on the maximum distance of the track entering the LKr to the cluster center (< 15 cm). Further cuts on the fractional energy deposition ($E/p$) in the LKr were performed to ensure muon presence rather than electrons or positrons in the MUV3 (Section 3.2).

3.1. Missing Mass Reconstruction

For the positively charged candidates in the spectrometer, mostly the $\pi^+$ or $\mu^+$ momentum is measured. In the rare-kaon decay search, the discriminating variable to identify the $\pi^+ \nu \bar{\nu}$ signal is the missing mass,

$$m_{\text{miss}}^2 \equiv (p_K - p_\pi)^2,$$ (3)

Figure 2: $m_{\text{miss}}^2$ from $K^+ \rightarrow \pi^+ \pi^0$ (left) and $K^+ \rightarrow \mu^+ \nu$ (right). Notice the straight line in the distribution centered about the missing particle’s mass squared; the remainder of the entries must be vetoed to reject background in the signal regions. Data from minimum bias run 3809.r1053.
for \( p_K, p_\pi \) are the four-momenta of the beam \( K^+ \) and the positively charged single track \([4]\). The backgrounds that leak into the signal regions are those that must be vetoed (fig. 1).

Since any positively charged track in the spectrometer could potentially be a \( \pi^+ \) from \( \pi^+ \nu \bar{\nu} \), it is important to study the kinematics of those in acceptance that are not the signal (fig. 2). Rejection for the events in the signal regions of the \( m_{\text{miss}}^2 \) plot can be done by \( \pi/\mu \) separation using calorimeters, photon rejection, and kinematics \([5]\).

![Figure 3: This distribution only includes particles with acceptance in the LKr, CHOD, and MUV3. Cuts on timing and \( E/p \) are used to discriminate the electrons (left, \( E/p > 0.9 \)) from muons (right, \( E/p < 0.2 \)). Note for the muon cut, there is a high population density where the STRAW1 is. It is possible that this is an artifact of the Extrap.cc code and should be investigated.]

3.2. Muon Studies

Dark photon signals are particularly sensitive to muon backgrounds, thus their kinematics must also be closely examined. Muons are identified by the following cuts:

1. A quality cut is imposed on the spectrometer candidate such that the track must have \( \chi^2 < 20 \) and entries in at least STRAW1, 2, and 4.
2. Using the momentum from the spectrometer, track is extrapolated and kept if in acceptance of the LKr, CHOD, and MUV3.
3. Timing coincidence is imposed between the candidates of the spectrometer and CHOD, and the spectrometer and MUV3.
4. Tracks are assigned to clusters in the LKr by cutting on the maximum distance between extrapolated impact point and cluster center to be 15 cm.
5. The \( E/p \) for \( E \) the deposited energy in the LKr, \( p \) the total momentum measured by the spectrometer, is cut \( < 0.2 \).

A straight forward conservation of four-momenta calculation gives the lower limit of the momentum of a muon from the 75 GeV/c momentum \( K^+ \) beam (\( \sim 37 \) GeV/c). Muons with momenta below this range are more likely produced from the muon halo (fig. 3), although these processes can also produce high momenta muons.

During the kinematic studies of muons in dump mode (Run 4139.r834), an anomalous \( E/p \) distribution was observed; there exists a dip near 0.04 (fig. 4). The three bumps can be distinguished and considered separately (table 1). Further studies show that while the
Figure 4: A dip in $E/p$ distribution at about 0.04 for Run 4139.r834. In other runs the curve is monotonically decreasing.

A narrow peak in the beginning of the distribution correspond mostly to three clusters present in the LKr, the entries in the second bump are primarily due to two cluster depositions (fig. 5). A possible cause of this could be overlapping clusters which are accidentally merged into one. This would artificially inflate the $E$ value while decreasing the number of clusters. One could check this in future studies by either checking the average distance between clusters as a function of $E/p$, or if the shower shape changes noticeably as a function of $E/p$. This peak did not appear in the minimum bias run nor in a lower intensity muon run. The trigger condition for the run is total energy $> 2 \text{ GeV/c}^2$ in the LKr, but in this run there is a ‘hot cell’ in the LKr was constantly reading $30 \text{ GeV/c}^2$. In this analysis, the clusters in the vicinity of the hot cell have been cut, however one should study this run after reprocessing with the hot cell removed.

<table>
<thead>
<tr>
<th>Presumed Particle</th>
<th>$E/p$ Cuts</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>$&lt; 0.02$</td>
<td>179435</td>
</tr>
<tr>
<td>$\mu^+ \mu^-$ hadrons?</td>
<td>$0.02 &lt; E/p &lt; 0.9$</td>
<td>1109580</td>
</tr>
<tr>
<td>$e$</td>
<td>$&gt; 0.9$</td>
<td>3060</td>
</tr>
</tbody>
</table>

Table 1: Rates of particles distinguished by $E/p$ regions from Run 4139.r834. In addition to the $E/p$ cuts, the selected particles also have acceptances in CHOD x LKr x Spectrometer x MUV3. The total number of events in these acceptances is 1294268.

While reconstructing tracks, one must be cognizant of ‘accidental’ vertices where a $\mu^- \mu^+$ crossing occurs by pure coincidence (fig. 6), as a two-muon vertex could give a fake dark photon signal. Muons here are again defined as tracks in time coincidence with the spectrometer and CHOD, LKr, and MUV3. A cut of 0.2 is applied to the $E/p$ value, and the LKr track association distance is again cut at 15 cm. Vertices outside of the fiducial volume can be easily cut, but further kinematic cuts must be used to discriminate accidental vertices from possible signal. As the muon background is of great interest to the dark photon signal, Monte Carlo studies of the muon halo were to be conducted. Future studies will include the output of the HALO program for closed TAX.
4. Background from GTK3 Region

Studies of the backgrounds produced in the final collimator and GTK3 region have three-fold purpose. First and most obvious, particles produced in this region that can decay into $\pi^+$ contribute to the background for the $\pi^+\nu\bar{\nu}$ signal, thus it is in the interest of the experiment to understand and veto these events. Another reason is to develop two-track vertexing methods that can be compared to pre-existing analyses. Similar studies have been done to analyze non-prompt activity from the GTK3 region [5]. Therefore there exists other analyses to cross-check against, potentially rationalizing novel results. Lastly, these particular backgrounds have special relevance to ALP and dark photon detection. As some of these backgrounds have been observed in the muon run as well as MC studies (for both NA62 and the SHiP proposal), they can be used potentially for normalizing detector sensitivity.

The backgrounds of interest are produced primarily by inelastic scattering by the secondary beam (fig. 7): $K_S^0 \rightarrow \pi^+\pi^-$, $K_L^0 \rightarrow \pi^+\pi^-\pi^0$, $\Lambda \rightarrow p^+\pi^-$, and $\bar{\Lambda} \rightarrow p^-\pi^+$. These backgrounds were studied in the MC, a minimum bias run (Run 3809.r1053), and muon mode (Run 4139.r834).
4.1. Monte Carlo Studies

The first attempt to understand these backgrounds, $K^0$s in particular, was done using the TURTLE beam MC. The output, however, seemed inconsistent with the generation of $K^0$ superpositions in Geant4. While Geant4 was theoretically designed to immediately assign a $K^0$ to either $K^0_S$ or $K^0_L$ with fifty-percent probability, there was a clear dominance of $K^0_S$ production over $K^0_L$ by a factor of 3 (fig. 7).

Figure 7: Comparison of $K^0_S$ and $K^0_L$ production in the z-position (left) and production process (right). The MC Sample was produced with $10^4$ events in the TURTLE beamline using the k12hika+ gtk1 run card, which simulates the beamline up to GTK1. $K^0_S$ particles are over produced in comparison to the $K^0_L$.

Other curious behavior was observed when using the TURTLE beam. When TURTLE simulated CEDAR but not the GTK, $K^0_S$, $K^0_L$ were produced. However, when TURTLE also simulated the GTK, they were not. In the case that $K^0_S$ were generated, a majority of their end processes were ‘transportation’ (exiting the simulation volume), which is a very unphysical result as their life time is on the order of centimeters. Some investigations of the MC output shows possible regeneration of $K^0_S$, but the cause of these results must be studied further.

Figure 8: Production processes of $K^0_S$ and $K^0_L$ from using the GPS. The ratio of $K^0_L : K^0_S$ is now $\sim 1.08 : 1$, which is a much more physically reasonable production rate than for the TURTLE beam.
Instead of using the TURTLE beam, the MC studies were instead conducted using the General Particle Source (GPS) Geant4 option which produced a nearly 1 : 1 ratio of $K^0_S$ to $K^0_L$ (fig. 8). The beam was set as $K^+$ with a Gaussian momentum distribution about 75 GeV/c with $\sigma = 1$ GeV/c. The cross section of the beam is a rectangle centered about the beampipe with a width of $\Delta x = 60\text{mm}$ and $\Delta y = 30\text{mm}$, and the beam originates at 100 m as given in the 2016 detector and beam summary [8]. This is the beam used to simulate and reconstruct events with $K^0_S$, $K^0_L$, $\Lambda$, and $\bar{\Lambda}$.

4.1.1. Geant 4 Modification

Running on statistics high enough to produce a reasonable sample proved extremely time- and memory-consuming. The run time of the MC was largely dependent on how many detectors were included; it was an order of magnitude slower with sensitive detectors placed than without them. To improve run time in this regard, the only subdetector physically placed in the simulation was the GTK.

In batch mode, subdetectors can be placed using

\[ /\text{Detector}/\text{EnableSubDetector} \text{ DetectorName} \]  

as a command in the macro, otherwise by default they are disabled. Since the particles of interest are those produced in the last GTK, the geometric object is necessary, but not the detector output.

To disable the sensitive detector in Geant4, one must go into

\[ /\text{PATH/TO/GIT/NA62MC/GigaTracker/src/GigaTrackerDetector.cc} \]  

and comment out the line of code

\[ //\text{SDman->AddNewDetector(GTKSD);} \]  

which will place the GTK when enabled, but no ‘data’ will be collected.

Another cut to be made is the explicit rejection of particles while saving tracks. This is done in

\[ /\text{PATH/TO/GIT/NA62MC/src/MCTruthTrackingAction.cc} \]  

To improve the efficiency of the MC, the \texttt{MCTruthTrackingAction.cc} in \texttt{PATH/TO/GIT/NA62MC/src} was modified to only store the particles relevant to the study. The macro should have been able to make these cuts without needing to edit the MC executable, but the logic structure of \texttt{MCTruthTrackingAction.cc} permitted ‘cut’ particles to be saved.

The developed method (fig. 9) should be used with caution, as cutting production particles will also cut their output, even if they are explicitly to be saved. For instance, not saving $K^+$ could lead to no saved $K^0_S$.

4.1.2. Acceptances & Rates

To evaluate the accuracy of the Geant4 simulation, the first step is to compare well-studied detection rates in the NA62 data. As no detectors were included in the MC output, all acceptance checks were done by geometrically extrapolating the particle’s track using initial
Figure 9: Modifications done to the Geant4 executable to bias the selection of particles. In this case, the selected particles are $K_0^S$, $\Lambda$, $\bar{\Lambda}$ from the beam $K^+$. The decay products of these short lived particles are also saved ($\pi^-$, $\pi^+$, $p^+$, $p^-$). Insert at line 200 in the `trackToBeStored(G4Track*)` method.

and final position as well as initial and final momentum. A more recent version of this analyzer uses `Extrap.cc` method [6]. To best compare detection rates, the structure of the vertexing method (Section 4.2) was implemented here.

The analysis for the $K_0^S$ background is as follows:

1. Loop over all the particles to find $K_0^S$ produced from the beam particles. Save their IDs.
2. Loop over all the particles to find a $\pi^-$ with a parent ID of the $K_0^S$.
3. Extrapolate position of particle at STRAW1, 2, and 4 to check acceptances (matching a quality condition in the data vertexing).
4. Find $\pi^+$ with the same parent ID to find the other daughter of $K_0^S$.
5. Apply the same acceptance cuts to the $\pi^+$.

The methodology generalizes easily to find $\Lambda$, $\bar{\Lambda}$ particles. Instead of identifying $\pi^+\pi^-$ daughters, we find $\Lambda \rightarrow p^+\pi^-$ and $\bar{\Lambda} \rightarrow \pi^+p^-$. Each background particle has its own analyzer:
The results are from a $10^9 K^+$ run (table 2). Unfortunately, the Geant4 output was simulated in such a way that the (anti) protons did not save the (anti) lambdas’ parent ID. Thus all the Λ studies on the large data set are empty. However, taken on smaller samples, some lambdas were observed.

The relevant check for $\pi^+\nu\bar{\nu}$ analysis would be to check the $m^2_{miss}$ from the positive tracks in acceptance. For the $K^0_S$ study, several kinematic cuts are placed to find what events are within signal region.

- Momentum of $\pi^+$, $\pi^-$ is between 5 GeV/c and 90 GeV/c (spectrometer acceptance)
- Momentum of $\pi^+$ is between 15 GeV/c and 35 GeV/c for the RICH identification
- $m^2_{mass}$ for the beam $K^+$ to accepted $\pi^+$ is within the two signal regions, Region I within [0, 0.01] GeV$^2$/c$^4$ and Region II within [0.026, 0.068] GeV$^2$/c$^4$

<table>
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<tr>
<th>Particles in Acceptance</th>
<th>Momentum Cuts</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neither Required</td>
<td>None</td>
<td>492540</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>5 GeV/c &lt; $p_\pm$ &lt; 90 GeV/c</td>
<td>1021</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>15 GeV/c &lt; $p_\pm$ &lt; 35 GeV/c $m^2_{miss} \in ([0, 0.01] \text{ or } [0.026, 0.068])$ GeV$^2$/c$^4$</td>
<td>153</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>5 GeV/c &lt; $p_\pm$ &lt; 90 GeV/c</td>
<td>16209</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>15 GeV/c &lt; $p_\pm$ &lt; 35 GeV/c $m^2_{miss} \in ([0, 0.01] \text{ or } [0.026, 0.068])$ GeV$^2$/c$^4$</td>
<td>2791</td>
</tr>
</tbody>
</table>

Table 2: Rates of acceptances of $K^0_S \rightarrow \pi^+\pi^-$ The kinematics of the $\pi^+$ were studied for single track and two track acceptance to check possible background in the $\pi^+\nu\bar{\nu}$ signal. The momentum cuts are for first the spectrometer, then the RICH for $\pi$ discrimination. For acceptance, not only does this require geometric acceptance into the spectrometer, but also within the momentum cuts. This was done over a $10^9 K^+$ MC sample.

There are several notable things about the missing mass squared plots (fig. 10, 11). The first is that there is a sharp cut-off of vertices at 102.4 m. This is an artifact of the Geant4 simulation. The GTK3 is placed at 102.4 m, and the beam is generated at 100 m with a cross section specified to fit within the acceptance of the GTK3. Thus this is the first region where inelastic scattering could happen. Another feature of this plot is the general density between 100 m - 110 m. A possible veto for $K^0_S$ events could then be a z-vertex cut.

As the beam produced is actually a mix of $K^+$, $p^+$, and $\pi^+$, it is relevant to check the production of $K^0_S$ from all of these particles. Thus far $\pi^+$ has been checked. For $2.5 \times 10^7$ events, only 1 $K^0_S \rightarrow \pi^+\pi^-$ was in acceptance. These results indicate the $K^0_S$ background from $\pi^+$ will be at least an order of magnitude suppressed from the $K^+$ background.

4.1.3. ALP Background

A similar study on MC data would be useful for estimating backgrounds for ALP with diphoton detection. Many muons from the halo will be present in the dump mode of the
Figure 10: Missing mass $m_{\text{miss}}^2 = (p_K - p_\pi)^2$ where $p_K$ is the four-momentum of the beam $K^+$ for that event, and $p_\pi$ is $K_S^0$ decay daughter $\pi^+$. For these events only $\pi^+$ is within acceptance ($\pi^-$ is either not in the geometric acceptance or not within the spectrometer momentum cuts). The regions highlighted by the red box are the regions of $\pi^+\nu\bar{\nu}$ signal.

Figure 11: Same plot as fig. 10, but requiring both $\pi^+$, $\pi^-$ in geometric and kinematic acceptance.

experiment run. From MC runs, $\eta$ and $\pi^0$ particles have been observed. As both of these particles can decay into $2\gamma$, the kinematics and rates of these processes should be taken into account.

The MC analyzer for this study is the `muonBgd.cc` analyzer, which checks for $\eta \rightarrow \gamma\gamma$ and $\pi^0 \rightarrow \gamma\gamma$ and the $\gamma$ acceptance into the LKr. The MC output to analyzer was generated by a $\mu^+$ beam with the same profile as the $K^+$ beam. However, the production of $\eta$ and $\pi^0$ is very small with these beam settings. In a $2.5 \times 10^7 \mu^+$ run, only 10 $\pi^0 \rightarrow \gamma\gamma$ and 1 $\eta \rightarrow \gamma\gamma$. This could demonstrate that the sensitive region of the GTK3 is too thin to interact with the $\mu^+$. For a more informative study about the background from muons, one should use the HALO program. The anticipated region of interaction is the electronics around the sensitive region of the GTK3.

4.2. Data

Two approaches were taken to reconstruction vertices of two oppositely charged tracks: geometric vertexing and least square fitting (LSF).
4.2.1. Geometric Vertexing

The primary tool in this reconstruction is the `Extrap.cc` method [6]. Positively charged tracks in the spectrometer are matched with negatively charged tracks by geometrically tracing back along their momentum to find the CDA of the two. The same decay products are assumed as in the MC simulation. An additional process, $K_0^L \rightarrow \pi^+\pi^-\pi^0$, is considered\(^1\).

The analyzer used was `bgdVertex.cc`. The general methodology is the same for vertexing $\Lambda$, $K_0^S$, only different masses are assumed in the daughter particle reconstruction. For $K_0^S$, one must also include the $\pi^0 \rightarrow \gamma\gamma$ as two clusters in the calorimeter. The reconstruction of the $\pi^0$ could definitely use improvement. Currently for the z-position of the vertex is calculated by a conservation of 4-momenta of the two gammas. To a good approximation, we expect

$$z_{\text{decay}} \approx \frac{d \sqrt{E_1 E_2}}{m_{\pi}} \quad (8)$$

where $d$ is the distance between clusters in the calorimeter, $E_{1,2}$ are the energies of the clusters, and $m_{\pi}$ is the mass of the $\pi^0$. The $x$, $y$ coordinates of the vertex are determined by a center of energy weighting in the plane of the calorimeter:

$$\vec{\rho} = \frac{1}{E_1 + E_2} ((E_1 x_1 + E_2 x_2) \hat{x} + (E_1 y_1 + E_2 y_2) \hat{y}) \quad (9)$$

where $x_i$, $y_i$ the coordinates of the $i$ cluster in the calorimeter. Selection of the events are done by putting cuts on the $\chi^2$ value of the track reconstruction and the two track fit, the invariant mass of the reconstructed parent particle, and for $K_0^L$, distance between the $\pi^\pm$ and $\pi^0$ vertex. This method does not account for the TRIM5 magnet, whereas the LSF method does. Comparisons of these two will follow.

![Figure 12: Discriminating $K_0^S$ from background in Run 3809 with the LSF vertexing tool. A clear peak at the mass of $K_0^S$ appears at $\sim 497.6$ GeV/c\(^2\). A majority of the $K_0^S$ decay near 102m, the GTK3, which suggests this is where they are produced as the lifetime is so short.](image)

\(^1\)From a back of the envelope calculation, $K_0^L$ detection should be incredibly rare. Assuming an energy near 60 GeV/c, $\gamma \sim 120$. For a mean lifetime of about $\tau \approx 5 \times 10^{-8}$, this equates to an average decay length of $\sim 1$km. Compared to the fiducial decay volume of about 60m, not many should be in acceptance.
4.2.2. LSF Vertexing

This analyzer uses the least squares fitting tool *MultipleLinesCDA.cc* developed by Minucci, et al. [9]. While this method works on many track reconstruction, we are implementing it for two charged tracks.

Before any vertexing, the first step of this method is to determine if it is a ‘good track’ or not. The requirements are:

- The event is in acceptance of at least STRAW1, 2, and 4.
- No hits in common with another track, and
- Reconstruction $\chi^2$ of spectrometer track

Tracks that meet these requirements are then sorted similarly to the geometric vertexing tool. First, positive tracks in the spectrometer are selected then paired with negative tracks. If the CDA of the two tracks in the fit is $< 15 \text{ mm}$ (as in the geometric vertexing), then the reconstruction is accepted. We are assuming the same decay channels. For $K_L^0$ reconstruction, the same approach is used to include the $\pi^0 \rightarrow \gamma\gamma$ as in the geometric method.

4.3. LSF vs. Geometric Vertexing

The LSF is in general a more sophisticated track reconstruction tool that accounts for more of the subtleties of particle propagation. For instance, the LSF method implements the effects of the TRIM5 when reconstructing the tracks. The 90 MeV/c kick in $\hat{x}$ provided by the TRIM5 magnet [9] is considered in the LSF vertexing, whereas it is only considered to redefine the $K^+$ nominal beam for the missing mass study in the geometric method. The inclusion of the TRIM5 in the LSF method is obvious by the extrapolated position of the reconstructed tracks in the GTK3 sensitive region (fig. 14).

There are two improvements immediately evident in the LSF method over the geometric method. First, the distribution is less dispersive on for the LSF method. The geometry at 102.4 m (GTK3) is more clearly identified as the geometric vertexing method has a large spread. Second, the number of vertices found for LSF is nearly a factor of 2 higher than that of the
Figure 14: Population of tracks in acceptance of the GTK3 (Run 3809, LSF vertexing). The noticeable spread in the x-direction is due to the 1.2 mrad kick delivered by the TRIM5 magnet which is accounted for in LSF vertexing.

Figure 15: Momentum of parent particle vs. z position of decay. In the LSF vertex method (left), the distribution is less disperse and more populated than in the geometric vertexing method (right). By including the TRIM5 magnet [9], it would seem that the reconstruction is more accurate and precise.

generic method (fig. 15). The consideration of the TRIM5 therefore noticeably reduces the CDA between two oppositely charged tracks.

4.4. Data vs. MC

As it would be an extremely valuable tool to simulate backgrounds accurately in Geant4, an important first physics check is to compare the rates of production. Consider the $K_S^0$ (fig. 16). From the LSF method, there are about $196 \pm 5$ $K_S^0$ identified in Run3809.r1053. To find the rate of $K_S^0$ per $K^+$, the number of $K^+$ is calculated as

$$792 \frac{burst}{run} \times 750 \ MHz \times 3 \frac{seconds}{burst} \times 6.6% \times 0.3% \approx 3.524 \times 10^8 K^+/run$$ (10)
Figure 16: Reconstruction of vertices with two oppositely charged tracks using the LSF method assuming $K^0_S \rightarrow \pi^+ \pi^-$. The momentum vs. $z$ vertex is on the left, whereas the projection of missing mass is on the right. A clear peak emerges at $m_{\text{miss}} = 0.497$ GeV/c$^2$, the mass of the $K^0_S$.

where 6.6% is the percent of beam particles that are $K^+$, and 0.3% was the intensity of the run. Thus the calculated rate for $\#(K^0_S) / \#(K^+) = 5.56 \times 10^{-7}$.

Comparing this to the MC, from a $10^9$ sample of $K^+$ particles, the prediction is 556 $K^0_S$ with decay daughters in acceptance. The number from Geant4 was actually 154. This is an order one difference and should be studied further. Perhaps future studies could involve production of all the beam particles in the correct ratios to compare the full beam production.

5. Conclusions

The studies done this summer have been particularly revealing for the $K^0_S$ background in the $\pi^+\nu\bar{\nu}$ signal and two track vertexing methods. To a first order prediction from the MC, the rate of $\pi^+$ single track accepted events from $K^0_S$ in the signal region for $m_{\text{miss}}^2$ is

$$\#(\pi^+_\text{accept}) / \#(K^+) = 2.791 \times 10^{-6}.$$  \hspace{1cm} (11)

As these events are so tightly constrained to the GTK3 area (fig. 10), a veto to consider would be to cut $z$ position of production before 110 m. To get a closer estimate on what the total rate of $\pi^+$ from $K^0_S$ in acceptance from the beam, one should simulate in MC the other hadrons in the secondary beam.

The other particularly notable result from the LSF v. geometric vertexing study of non-prompt activity from the GTK3. Clearly the inclusion of the TRIM5 kick makes a significant difference in quality of the track reconstruction. As ALPs and dark photons are predicted to be produced in the TAX, a $z$-vertex position rejection could be a significant tool in vetoing backgrounds.

6. Acknowledgments

I would like to thank first and foremost Babette Döbrich and Tommaso Spadaro for all of the advisement and collaboration provided this summer. I would also like to thank the NSF and the University of Michigan for funding this amazing learning experience. Furthermore, thank you to Cornell University professors Jim Alexander and Peter Wittich for their recommendations and guidance.


