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Detecting the Phi Meson with CLAS12

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ABSTRACT

Analysis and detection of the phi ($\phi(1020)$) vector meson from exclusive electroproduction decay into Kaons have been performed. Studying exclusive ϕ electroproduction is an ideal channel for quantifying the gluonic properties of the nucleon. This detection used the CEBAF Large Acceptance Spectrometer (CLAS12) at Thomas Jefferson National Accelerator Facility (JLab) with a 10.6 GeV longitudinally polarized electron beam and an unpolarized hydrogen target. Using the detected final state particles phase space, x_B, Q^2, W, and by developing specialized exclusivity cuts as well as several additional cuts, events containing the production of a $\phi(1020)$ meson were able to be extracted. Additionally, a unified wagon has been developed that uses these measurements and cuts to perform advanced real-time visualization of the data processing and eventually will be applied to detect and identify events that contain the phi vector meson across all applicable data-sets with CLAS12 at JLab.

Detecting the ϕ Meson with CLAS12

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Detecting the ϕ Meson with CLAS12

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Chapter 1

Introduction

In the field of physics, there are still many unanswered questions. One such question is understanding the structure of the nucleon. The nucleon makes up an atom's nucleus, the protons and neutrons. There are many questions about the properties of the nucleon, such as how is the spin and momentum distributed inside of the nucleon? To answer these questions, a system must be developed to probe the inner workings of such a small object. One such probe works by using high-energy electrons and imparting their energy into the nucleon. This process, known as deep inelastic scattering, allows for the nucleons to produce numerous particles due to the inelastic energy transfer between the beam and the target. By characterizing these resulting particles, the internal structure of the nucleon can be better mapped out.

One facility that probes the nucleon is Thomas Jefferson National Accelerator Facility (JLab). At JLab, the Continuous Electron Beam Accelerator Facility (CEBAF) can produce polarized electron beams at up to 12 GeV. These electron beams can be shot at different types of targets and, using the CEBAF Large Acceptance

Spectrometer (CLAS12), the shower of particles due to the deep inelastic scattering can be detected.

Deeply virtual meson production (DVMP) can result from the scattering of a polarized electron beam off of an unpolarized proton target such as H_2. One such example, and the primary point of investigation in this thesis, is the $\phi(1020)$ vector meson. Unfortunately, it is not possible to directly measure the phi meson as its mean lifetime is on the order of 10^{-22} seconds. However, it has detectable decay products. Roughly 48% of decays will result in a kaon plus (K^+) and a kaon minus (K^-). These kaons can then be detected using the CLAS12 Cherenkov counters, calorimeters, and reconstructed track information. This will allow for the characterization of the reaction chain of $ep \rightarrow ep\phi_{1020} \rightarrow epK^+K^-$, where the phi meson can be detected and, eventually, the beam spin asymmetry (BSA) can be characterized.

To detect the phi meson, an extensive selection of cuts must be performed to reduce the background signal and identify events that are candidates for phi production. A brief overview of these cuts will be presented alongside a more in-depth analysis of the exclusivity cuts used, and the resulting phi mass peak from the cuts. All of the data shown was collected from the RGA Fall 2018 to Spring 2019 session and stored in skim8. Moreover, this project was done in conjunction with the data preservation of the recent University of Connecticut graduate Dr. Brandon Clary's Ph.D. dissertation *Exclusive Phi Production Beam Spin Asymmetry Measurements with CLAS12* [1]. As such, results from this project are cross-referenced and compared to his work as a figure of merit.

1.1 Outline and Goals of the Thesis

Within this thesis, we hope to present to you a new procedure for the detection of the phi vector meson at Jefferson National Lab. Namely, this procedure takes advantage of the computing capabilities at JLab and creates a streamlined process to implement a workflow capable of extracting events that result in the exclusive electroproduction of the phi meson.

This required using the GRAPES and CLARA environments to develop what is called a "wagon", a singular class capable of performing the numerous cuts necessary to identify candidate events. Moreover, the development of the wagon required the creation of new particle identification classes that were precise. These new classes demanded that the new code be written with minimal time and space complexity for rapid deployment and analysis of datasets.

A discussion of the computational requirements will be done alongside the advantages of this method. Then, the analysis of the phi meson and the necessary cuts to detect it in CLAS12 with the wagon will be presented, and finally, these results will be compared to the procedure originally developed by Dr. Clary.

Chapter 2

Development of Wagon

One of the primary goals of this thesis was the development of the unified "wagon". The UConn group as well as other groups at Jefferson Lab use wagons for the skimming of datasets and identification of events containing certain particles. Using the built in services CLARA and GRAPES, we are able to develop a singular platform that has all of the necessary cuts built into it. Thus, in later workflows, one could easily import the wagon and have access to the cuts necessary to perform further measurements with the phi meson.

2.1 Grapes Code

Initially, our goal was to identically reproduce a selection of cuts originally created by Dr. Brandon Clary, a recent Ph.D. graduate from our lab at UConn. This required that we document and analyze the programs developed by Dr. Clary which were originally written in Groovy and Python. However, these programs required significant

manual intervention and modification for each type of input. As mentioned before, our goal was to streamline the process such that any individual could easily detect the phi meson, the wagon would serve this purpose and improve upon previous codes.

The wagon was written in Java with an emphasis on being data efficient and computationally fast. Running independently of other analysis codes, GRAPES at JLab would be able to process the wagon as well as the input parameter files and, finally, the input events. GRAPES would run the wagon on these inputs and give an output of HIPO files containing all of the phi candidate events, and a ROOT file with the pertinent histograms for further analysis of the phi meson, such as beam asymmetry calculations.

An example of an input CLARA file and an input YAML can be seen in listings 2.1 and 2.2.

LISTING 2.1: Input CLARA file for GRAPES in order for the system to process the DVPhiWagon.java wagon. The CLARA file requires the initialization of relevant parameter files, input files, and output directories.

```
#--------------------------------------------
# Configuration script to run trains
#--------------------------------------------
set servicesFile phiwagon_inb.yaml
set fileList   files_inb.txt
set inputDir   /cache/clas12/rg-a/production/recon/fall2018/torus-1/pass1
    ↪ /v0/dst/train/skim8/
set outputDir  output/inb
set threads    16
#------------
run local
```

LISTING 2.2: Input parameter YAML file for the DVPhiWagon.java service. This file creates the definitions and configuration parameters required for the wagons and services.

```
io-services:
```

```
    reader:
      class: org.jlab.jnp.grapes.io.HipoFrameReader
      name: HipoFrameReader
    writer:
      class: org.jlab.jnp.grapes.io.HipoFrameWriter
      name: HipoFrameWriter

services:
    - class: org.jlab.jnp.grapes.services.DVPhiWagon
        name: DVPhi

configuration:
    services:
        DVPhi:
            id: 2
            beamEnergy: 10.604
            field_type: "inb"
            json_cuts: "/work/clas12/psimmerl/wagon/phi_cuts.json"

mime-types:
    - binary/data-hipo-frame
```

Looking at listing 2.1, we can see that several items are defined. First is the services file which defines the parameters for the wagon. Next is the file list, where we select what file from the input directory we wish to perform the analysis on. The finally we have the output directory where our final event list contains the phi candidates, and the number of multiprocessor threads we want to run the analysis over.

In listing 2.2, we are able to see the parameters for GRAPES to pass to our wagon. We define our input-output services which read the input HIPO files and writes our phi candidate HIPO, and we call our wagon itself, DVPhi. In configuration, the parameters for the cuts are passed along to the DVPhi wagon. These parameters are explored further in the next section.

2.2 Dynamic Cut Variables

One of the advantages of using the wagon is the ease of definition for the global parameters on which we want to cut the candidate phi events around. In previous scripts, these parameters were hard-coded such that if these variables needed to be changed, the code itself would need to be rewritten and recompiled. This was fixed by developing an input format based on JSON.

Futhermore, when the cuts are first occurring, the statistics surrounding the variables are not known to high detail. For example, a cut around the mass of all the particles excluding the proton may not know the precision the detector system provided. However, after running the cuts and fitting a gaussian to the profile, the free parameters, mean and variance, for the proton's mass's are known. These can then be back-propagated into the analysis code, previously via rewriting the script, now by using a JSON parser and modifying the parameter.

The significant part about this is that there are 62 free parameters (31×2 for inbending and outbending field settings) in the wagon. Resetting the parameters by hand was a lengthy time consuming process and prone to error.

2.3 PID Cuts

Another important addition was the inclusion and improvement of particle identification (PID) cuts. The original codes included PID cuts that were designed around guaranteeing that the detected electrons, protons, kaon pluses, kaon minuses were proper candidate particles. The goal here was to document the PID cuts from Dr. Clary and include them into the UConn Maven repository so they could be used for

further analysis.

These codes were rewritten into Java from Groovy for increased data efficiency and decreased computational cost. They were also improved to properly account for the multiplicity in the DC sectors in the DC fiducial cuts, as well as removing other bugs which proved to have little effect on the final state particles.

It also allowed for dynamic parameterization of the cuts such that it is easier to create the proper diagnostic modifications on the PID cuts without needing to rewrite variables by hand. Moreover, the PID cuts were coded such that the strictness of the cut level can be modified to change how many candidate particles are allowed to pass through.

2.4 Jupyter Notebook

Furthermore, the wagon allows for real-time data visualization of the events that are being processed. As the event histograms are written to the ROOT histogram files, one could read the files and see the event-by-event cuts on the final state particles and determine if the process is going ideally. Occasionally the system may malfunction due to some unforeseen error so by allowing for real-time visualization, errors can be caught early.

Moreover, it allows for debugging code to be easier since the program can be started and watched over runtime instead of requiring completion, which could take over a day. For example in figure 2.1, the Jupyter Notebook is parsing the ROOT file and outputting some of the histograms.

Figure 2.1 allows us to see how the wagon is performing it's cuts. In this specific

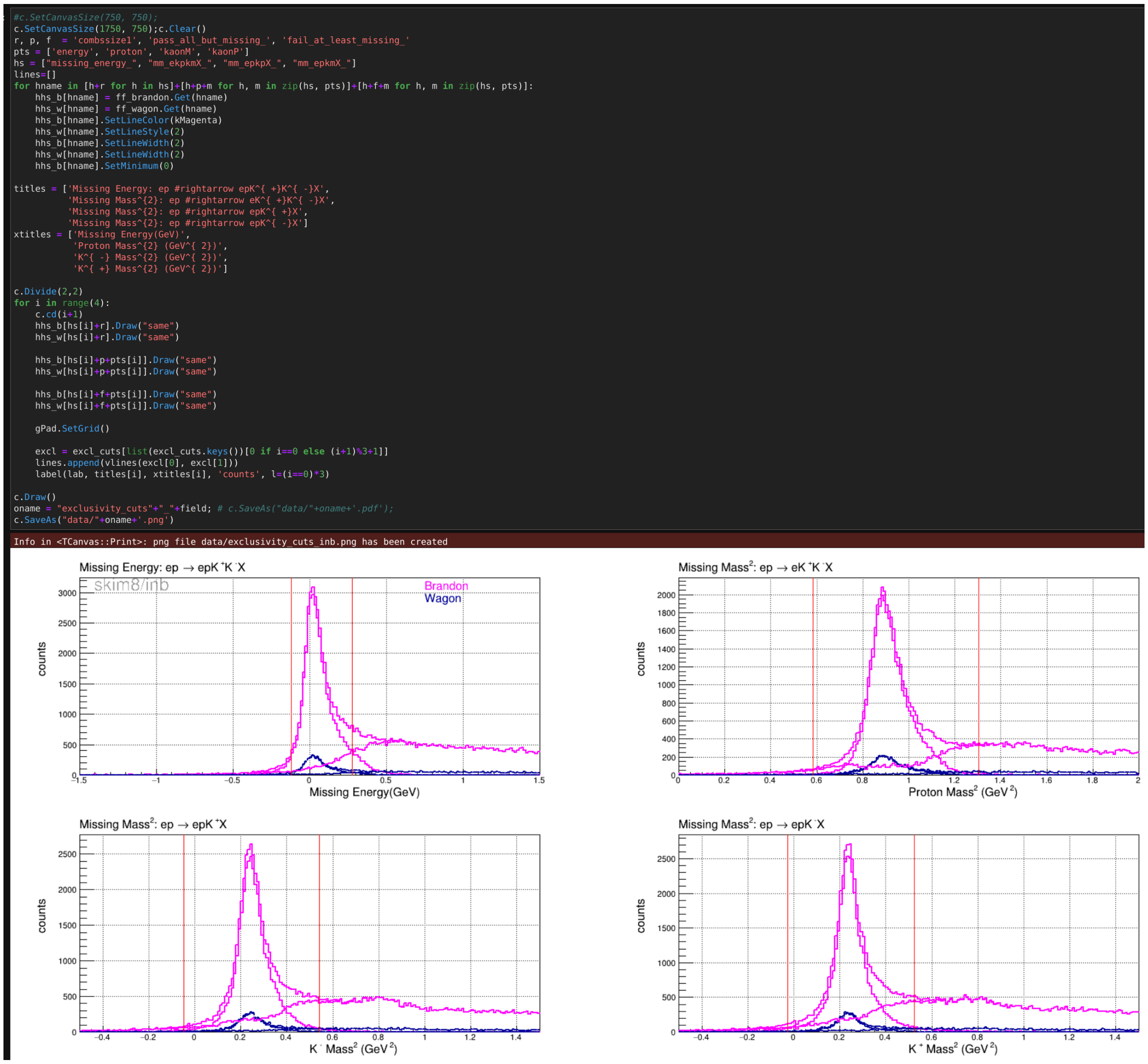


FIGURE 2.1: Snapshot of the diagnostic procedure using the Jupyter Notebook. In purple, the results for the original code are plotted, in blue the new results are being displayed in real-time.

case, we are comparing the results to the previous results from Dr. Brandon Clary's code. We can see the wagon is producing a histogram with similar parameters as the original and can be assumed to be working properly.

Chapter 3

Processing Events

Using the aforementioned wagon to process the events from CLAS12, we were able to develop an extensive selection of cuts. These cuts allowed us to reduce the background signal and identify events that are candidates for the electroproduction of the phi vector meson. These events could then be recorded into their own HIPO skim file for further analysis such as beam spin asymmetry calculations. All of the data shown is collected from the RGA Fall 2018 to Spring 2019 session and stored in skim8.

3.1 General Data Processing Order

For this detection, twenty-two individual cuts were made on the data to identify events that were candidates for the exclusive phi electroproduction. A flowchart of the wagon's logic and the subsequent cuts can be found in figure 3.1.

In figure 3.1, we see first that the HIPO files are input into the processing wagon. The wagon's first set of cuts is identifying that the event contains at least one electron

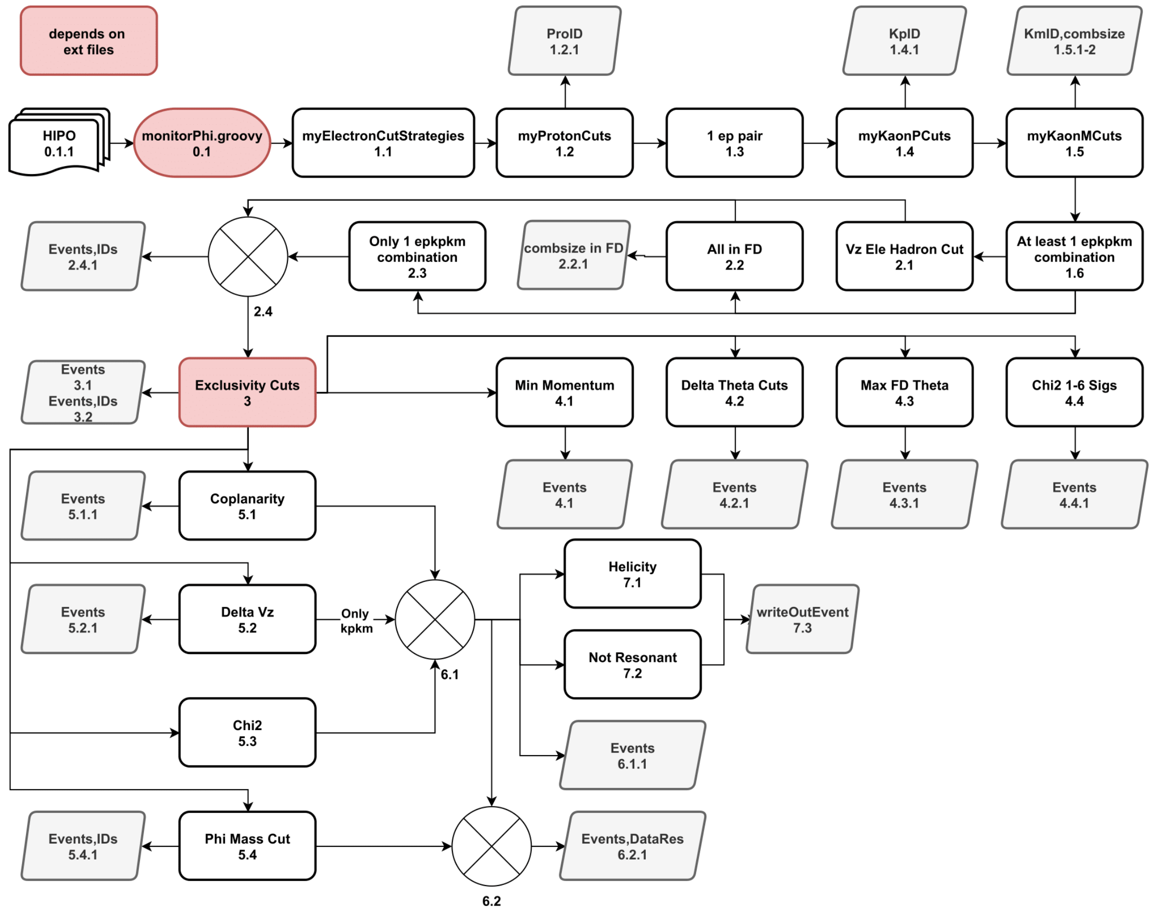


FIGURE 3.1: Flowchart of the cuts used to detect the phi vector meson in CLAS12. Red boxes indicate that these cuts or programs rely on dynamic external files and grey slanted parallelograms are where histograms or events are written.

and at least one proton using the event IDs and more specifically the PID cuts which we created and deployed to the UConn Maven repository. Events that do not contain electrons and protons are immediately discarded. We then require that the detected particles only contain one electron and one proton. Following this step, we do the same for the kaon plus and the kaon minus.

Next, three more cuts are done simultaneously. The first cut is requiring all events to be in the forward detector (FD), this is for consistency as we want all events to

have the same calibrated values. We then require that the events must contain only one set of electron, proton, kaon plus, and kaon minus as our end state particles should consist of only these four. We also require that the reconstructed path of each particle originates from within ±3cm of the same z coordinate as the electron; this parameter is dynamic and imported from our JSON file. This is to make sure all the detected particles are from the same scattering event.

Following these cuts, we perform exclusivity cuts which are explained further below as well as coplanarity, a z coordinate cut again, as well as a phi-mass cut. These are the pertinent cuts to detect the phi vector meson

3.2 Particle Identification

The particle identification cuts were imported from the UConn Maven repository and tailored for the data analysis procedure. This allows for a class level abstraction of the particle candidates for easy development and deployment of the analysis. The use of these PID cuts in the DVPhiWagon can be seen in listing 3.1. Each of the particles is first identified using the built in PID property from the HIPO file where the particle type was predetermined using its characteristics. We can then pipe this into our modified Candidate class for each of the particles which contains the latent variables needed to determine and identify our input particles.

Listing 3.1: Use of the PID cuts in the DVPhiWagon, each particle creates a static call to the relevant particle candidate class to determine whether the detected particle is a correct candidate for this analysis.

```
import uconn.utils.pid.brandon.ElectronCandidate;
import uconn.utils.pid.brandon.ProtonCandidate;
import uconn.utils.pid.brandon.KaonCandidate;
```

```

...

for(int ipart=0; ipart<recPart.getRows(); ipart++) {
    int pid = recPart.getInt("pid", ipart);
    if (pid==11) {
        ElectronCandidate eCand = ElectronCandidate.getElectronCandidate(ipart, recPart, calPart, ccPart, trajPart);
        if (field_type.contains("inb")) eCand.setINBENDING();
        else eCand.setOUTBENDING();
        if(eCand.iselectron()) ieles.add(ipart);
    }
    else if(pid==2212) {
        ProtonCandidate pCand = ProtonCandidate.getProtonCandidate(ipart, recPart, trajPart);
        if(pCand.isproton()) ips.add(ipart);
    }
    else if(pid==321) {
        KaonCandidate kpCand = KaonCandidate.getKaonCandidate(ipart, recPart, trajPart);
        if(kpCand.iskp()) ikps.add(ipart);
    }
    else if(pid==-321) {
        KaonCandidate kmCand = KaonCandidate.getKaonCandidate(ipart, recPart, trajPart);
        if(kmCand.iskm()) ikms.add(ipart);
    }
}
```

3.2.1 Forward Detector

As mentioned earlier, identifying particles coming from the forward detector as compared to the central detector was essential for calibration purposes. We wanted to make sure there was as little variation in our datasets that we required that each of the input particles be detected in the forward region. The cut for this can be seen in listing 3.2 where we require the electron to be the first electron detected, and each of

the other particles be in the status region corresponding to the forward detector.

LISTING 3.2: Cut on the particles requiring them to be in the forward detector. The electron will always be in the forward detector so we require it to be the first detected particle. The other particles must have a status identifying them to be in the forward region.

```
boolean el_fd = recPart.getShort("status", iele) < 0;
boolean pr_fd = recPart.getShort("status", ip) >= 2000 && recPart.getShort("status", ip) < 4000;
boolean kp_fd = recPart.getShort("status", ikp) >= 2000 && recPart.getShort("status", ikp) < 4000;
boolean km_fd = recPart.getShort("status", ikm) >= 2000 && recPart.getShort("status", ikm) < 4000;
boolean all_in_fd = el_fd && pr_fd && kp_fd && km_fd;
```

3.3 Exclusivity Cuts

The most important set of cuts used in this analysis were the exclusivity cuts. Here we wanted to make sure that the particles being identified were the only particles in that reaction, i.e. the only particles that resulted from the inelastic scattering between the electron and the proton were epK^+K^- and not epK^+K^-X where X is another particle or set of particles.

To do this, we took the input lorentz vectors for the beam and target, where the beam is a 10.604 GeV (parameterized in our YAML) electron beam and the target is a stationary proton target, summed them together and subtracted out all of the final particles except one which was permuted over. We would then look at the missing mass from this subtraction and see if it corresponds to the mass of the missing particle. This can be seen in equations 3.1, 3.2, 3.3, and 3.4. In equation 3.1, we look at the

missing energy as that should be conserved thus be approximately zero.

$$ep \to e'p'K^+K^-X \tag{3.1}$$

$$ep \to e'K^+K^-X \tag{3.2}$$

$$ep \to e'p'K^-X \tag{3.3}$$

$$ep \to e'p'K^+X \tag{3.4}$$

The resulting missing mass and missing energy distributions for these permutations can be seen in figure 3.2. In this figure, we see a histogram of each missing particle's distribution and the background signal associated with these particles which we want to remove.

Once we fit these histograms with the gaussian to find the missing particles characteristics, we then need to rerun the wagon with these values such that the background signals are removed. This is easy to do with the dynamic JSON input file. The code snippet used to remove the background is shown in listing 3.3 and the distributions after the removal signal can be seen in figure 3.3.

Listing 3.3: Extraction of the missing particles parameters using the JSON file parsed by excl_cuts and used to perform the exclusivity cuts.

```
double epkpkmXe_low = (double)((List)excl_cuts.get("epkpkmxe")).get(0);
double epkpkmXe_high = (double)((List)excl_cuts.get("epkpkmxe")).get(1);
double ekpkmX_low = (double)((List)excl_cuts.get("ekpkmX")).get(0);
double ekpkmX_high = (double)((List)excl_cuts.get("ekpkmX")).get(1);
double epkmX_low = (double)((List)excl_cuts.get("epkmX")).get(0);
double epkmX_high = (double)((List)excl_cuts.get("epkmX")).get(1);
double epkpX_low = (double)((List)excl_cuts.get("epkpX")).get(0);
double epkpX_high = (double)((List)excl_cuts.get("epkpX")).get(1);

boolean pass_epkpkmXe = epkpkmX.e() > epkpkmXe_low && epkpkmX.e() <
```

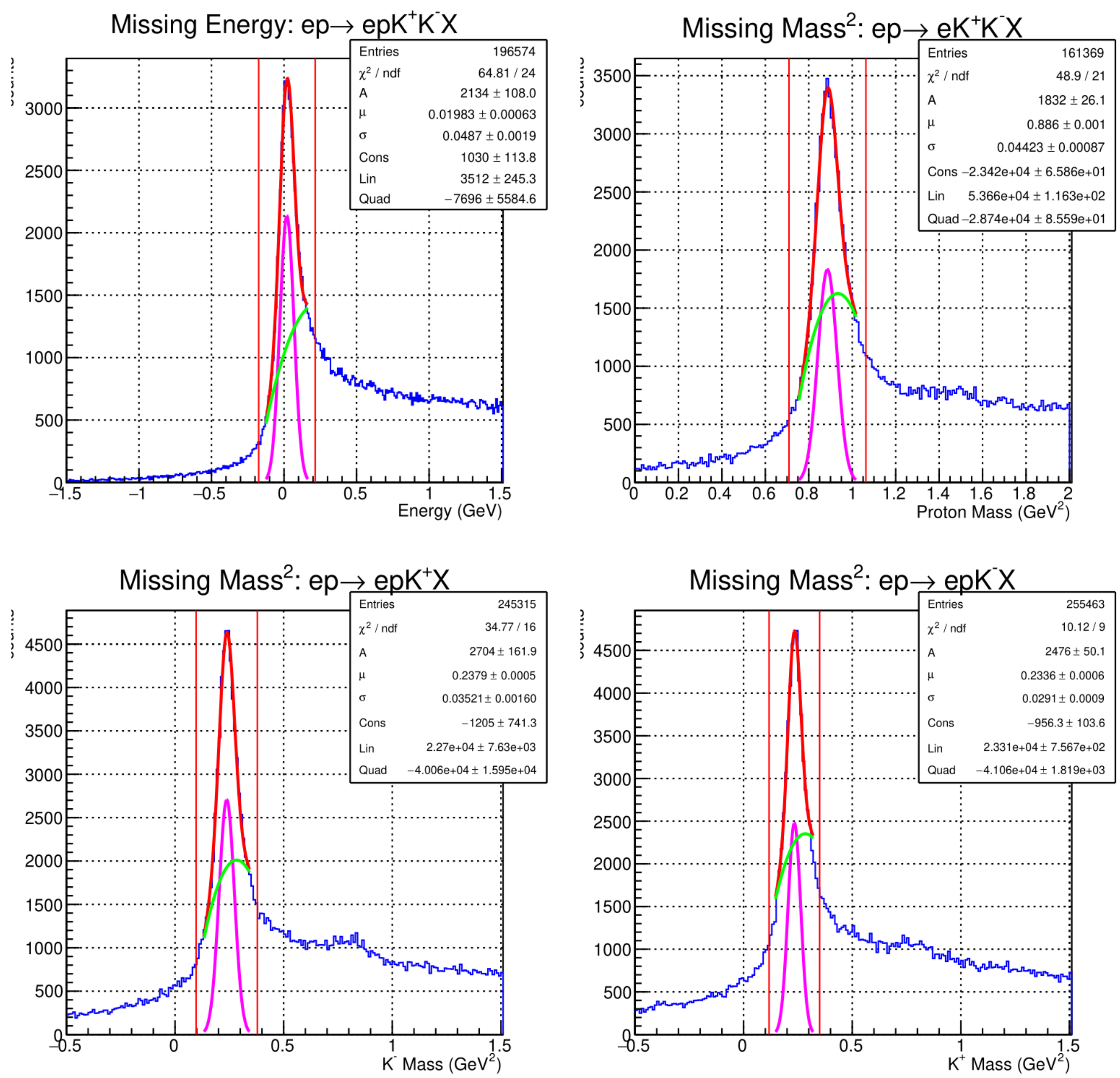


FIGURE 3.2: Missing mass and energy distributions for each of the final state particles. These distributions are fit with a gaussian plus quadratic background to extract the mean and variance of the missing particles mass/energy.

```
    ↪ epkpkmXe_high;
boolean pass_ekpkmX = ekpkmX.mass2() > ekpkmX_low && ekpkmX.mass2() <
    ↪ ekpkmX_high;
boolean pass_epkmX = epkmX.mass2() > epkmX_low && epkmX.mass2() <
    ↪ epkmX_high;
boolean pass_epkpX = epkpX.mass2() > epkpX_low && epkpX.mass2() <
```

```
↪ epkpX_high;
```

One thing to note from listing 3.3 is the dynamic inclusion of the phiwagon.json file originally defined in listing 2.2. This allows for fast, automated cuts by linking together the parameters of the wagon with analysis outputs.

By performing these four cuts, our wagon helps to assure that these events are the result of an exclusive reaction and there are no other particles that are either from secondary interactions or cosmic background.

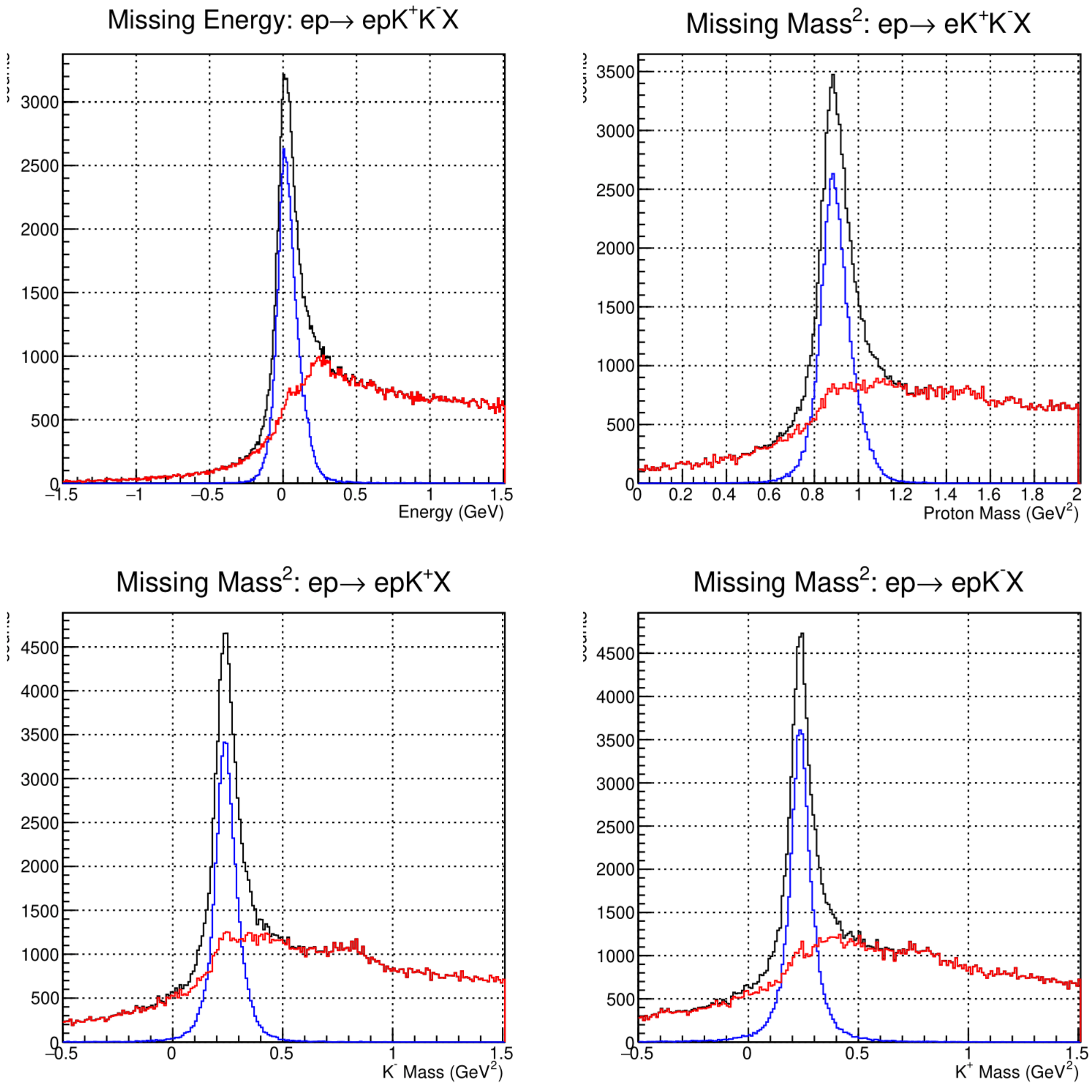


FIGURE 3.3: Missing mass and energy distributions post processing with the exclusivity cuts. The black curve represents the raw data, the red shows the background events that did not pass the cut, and the blue line are the events where the mass is within the missing mass range.

3.4 Vertex Cuts

An additional cut which we also applied to the datasets was identifying whether or not the two kaons originated from the same point. Since the kaons are a direct by-

product of the decay of the phi meson, they should in theory originate from the same coordinates. To identify if the kaons are from the same event, we applied a cut on the difference between the two kaon's z-coordinates. By fitting a gaussian with a quadratic background to the difference in z vertex, we could then back-propagate the parameters into our wagon and remove events where the kaons are not of the same origin. See figure 3.4 for the histograms showing this difference in z coordinate and it's respective fit.

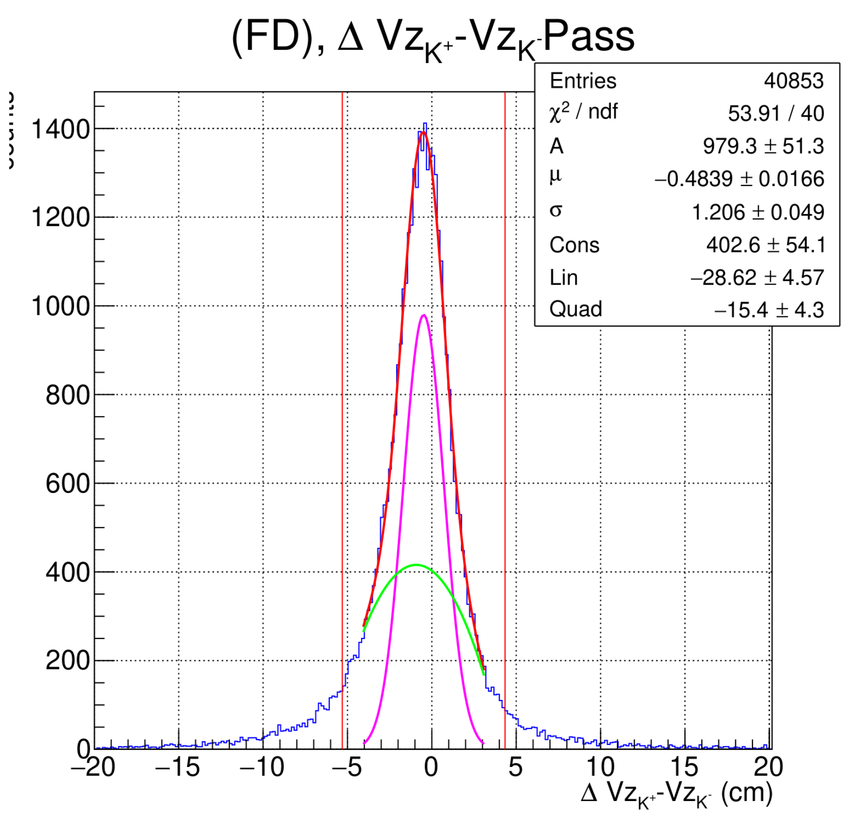


FIGURE 3.4: Difference between the K^+ and K^- z vertices along with the gaussian fit with a quadratic background to characterize the origin point.

After applying this vertex cuts and all the previous cuts, the total change in the distribution of the invariant mass for $K^+ + K^-$, which shows the peak identifying

events as phi candidates is quite dramatic. Many of the background events were removed by the exclusivity cuts. See figure 3.5 for the invariant mass distribution post these cuts.

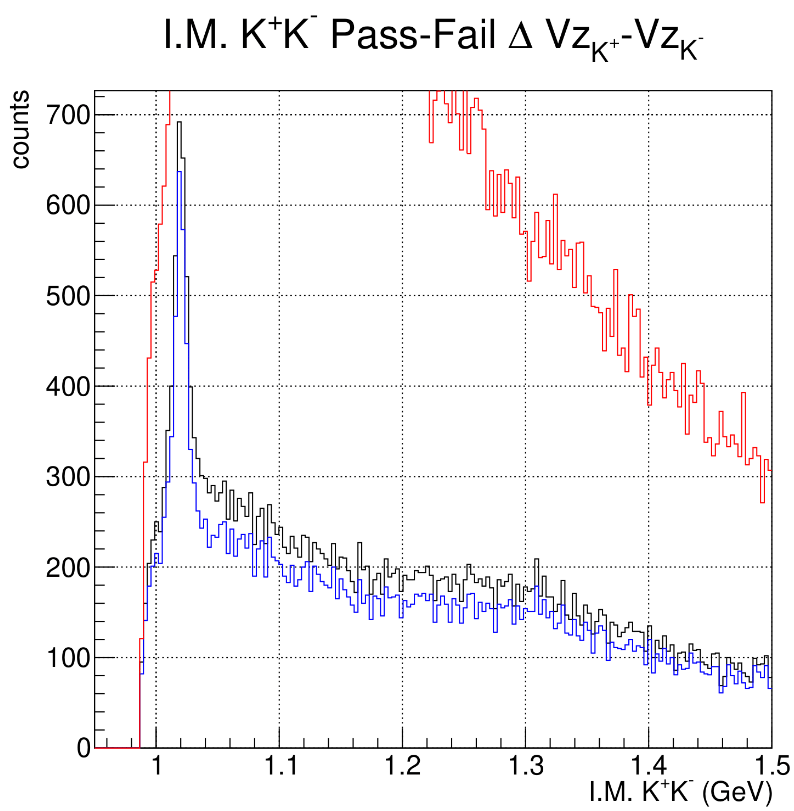


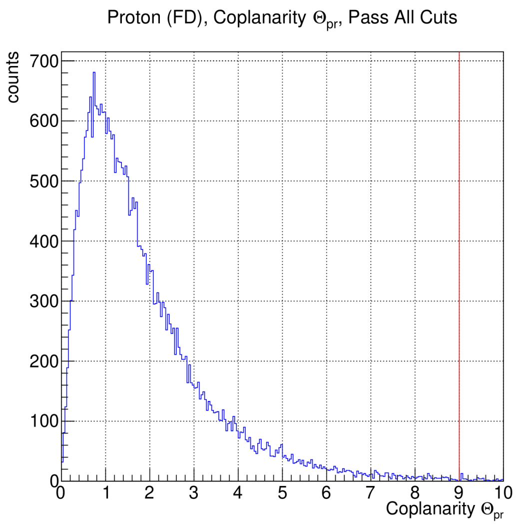
FIGURE 3.5: Invariant mass of the kaon plus and kaon minus, the blue curve represents events that have passed all previous cuts, black is the set of events that the vertex cuts were applied to (post all previous cuts, pre vertex cut) and the red line are the events that have failed all cuts up to this point. The sharp peak at 1.02 GeV represents events that are from phi decays.

3.5 Coplanarity Cuts

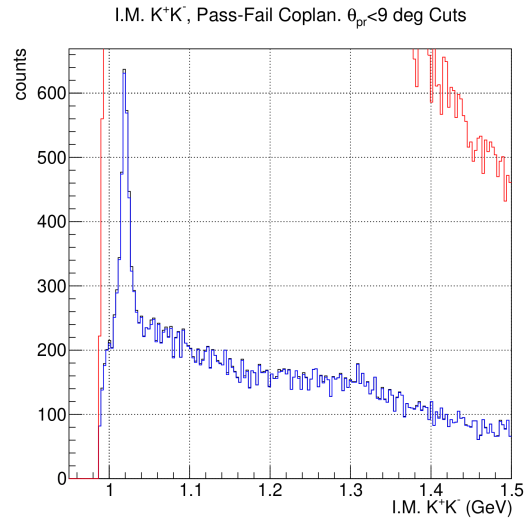
The final set of kinematic cuts on the input particles that the wagon applied to our candidate events was the coplanarity cuts, an extension of the exclusivity cuts. In the coplanarity cuts, we wanted our detected particles path to be close to the path predicted by the missing particle Lorentz vectors, specifically, we wanted them to be with 9° of each other. See equation 3.5 for an example of the coplanarity cut, where we use the three-vector form of the Lorentz vectors momenta. To get the equation for kaons, simply swap them with the proton.

$$\theta = \arccos \frac{eK^+K^-X \cdot p}{|eK^+K^-X||p|} < 9^\circ \tag{3.5}$$

Equation 3.5 can be applied to the proton, kaon plus, and kaon minus where a cut is performed on each particle. See figures 3.6a, 3.7a, and 3.8a for the coplanarity distribution and figures 3.6b, 3.7b, and 3.8b for their corresponding invariant mass distributions.

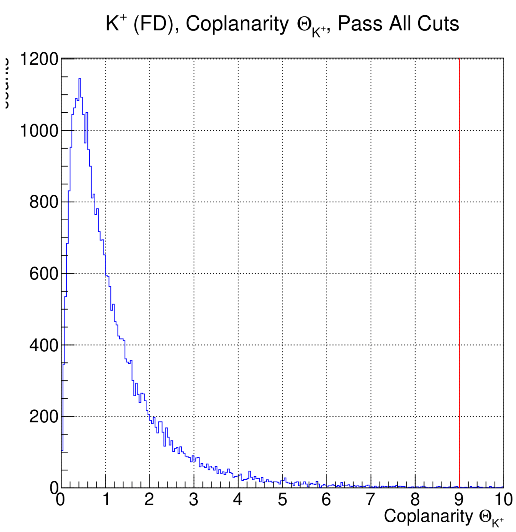


(A) Coplanarity of the proton with 9° cut marked by the red line.

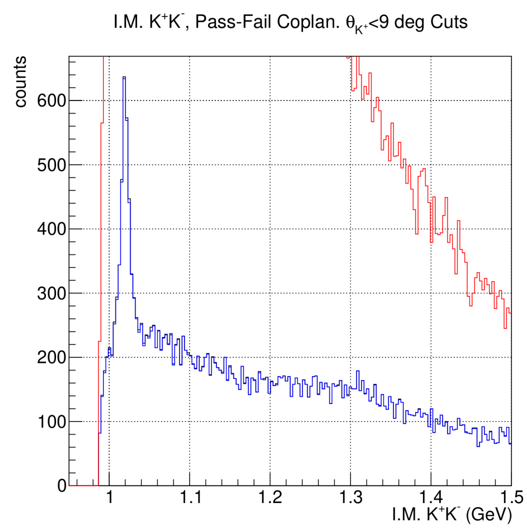


(B) Resulting invariant mass of kaon plus and kaon minus from the proton coplanarity cut and all previous cuts.

FIGURE 3.6: Coplanarity cut between the missing proton, eK^+K^-X, and the detected proton.

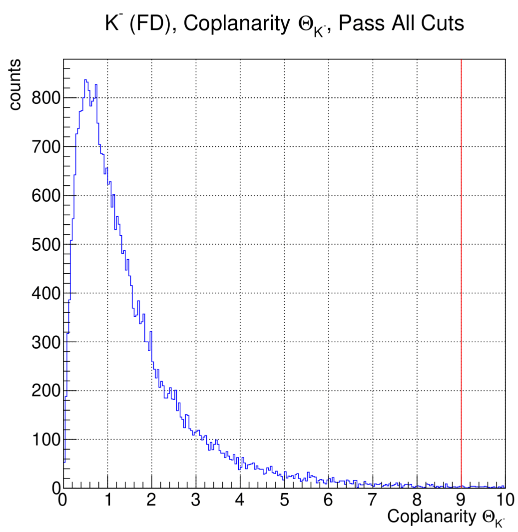


(A) Coplanarity of the kaon plus with 9° cut marked by the red line.

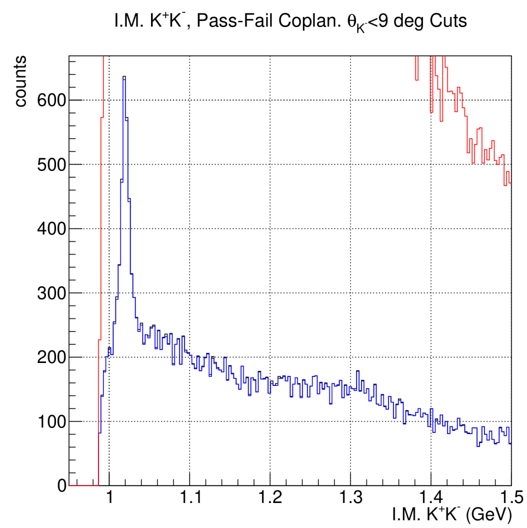


(B) Resulting invariant mass of kaon plus and kaon minus from the kaon plus coplanarity cut and all previous cuts.

FIGURE 3.7: Coplanarity cut between the missing proton, epK^-X, and the detected kaon plus.



(A) Coplanarity of the kaon minus with 9° cut marked by the red line.



(B) Resulting invariant mass of kaon plus and kaon minus from the kaon minus coplanarity cut and all previous cuts.

FIGURE 3.8: Coplanarity cut between the missing kaon minus, epK^+X, and the detected kaon minus.

3.6 Removal of Lambda Resonances

While all these cuts have worked to identify exclusive scattering between the electron beam and the proton target, there is still an issue of background signal from particles that have shared the decay products. Namely, lambda resonances λ_{1520} and λ_{1800}. See figure 3.9 to see the crossover from lambda and phi.

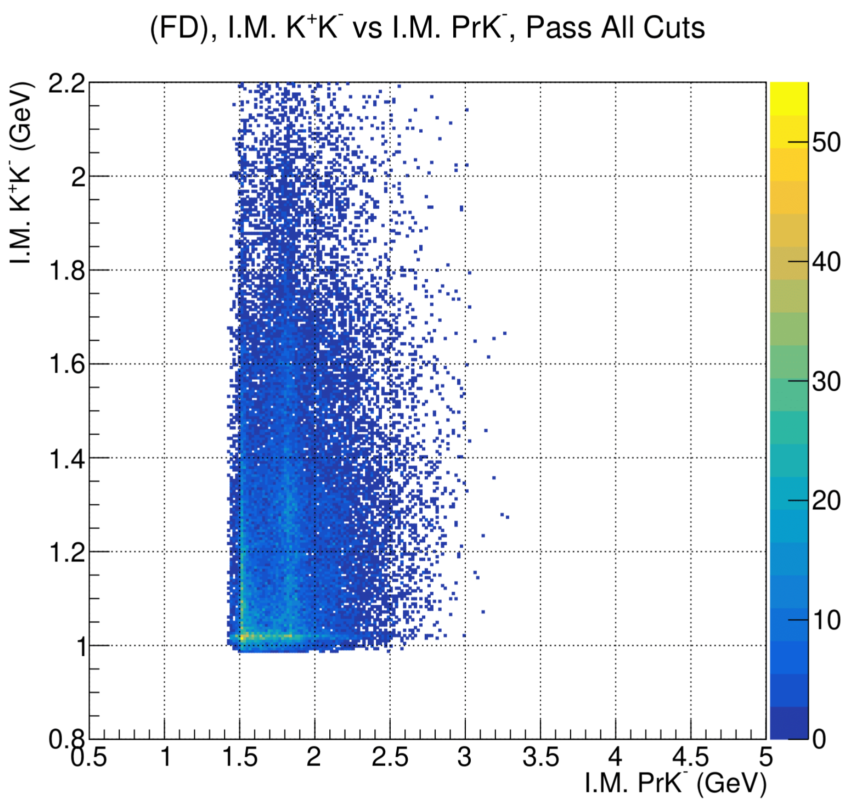


Figure 3.9: Plot of the invariant mass of kaon plus and kaon minus vs the invariant mass of the proton and kaon minus. There is a clear peak in the K^+K^- resonance at the phi mass however it crosses over signals that could be the result of the decay of a lambda baryon in PrK^-.

This shows that a new cut is needed to remove the extra background signal from the lambda resonances. To remove this signal, our wagon simply removes all events

that are in a potential lambda resonance. This can be seen in figure 3.10 where we choose events that are outside of 1.5 GeV to 1.58 GeV and 1.78 GeV to 1.9 GeV. These values are hard coded into the wagon as often there were not enough statistics to make an accurate prediction of where the lambda resonances are, even with strict regularization on the parameters.

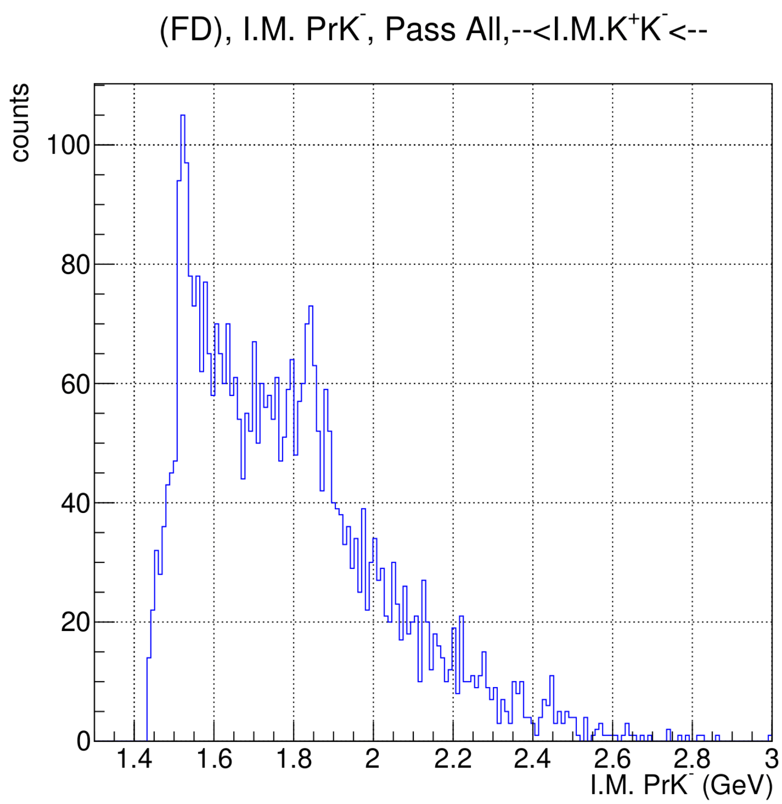


FIGURE 3.10: Invariant mass distribution of the proton and kaon minus before the removal of lambda resonances.

3.7 Phi Meson Signal

After completing all of these cuts on particle identification, number of particles, detector, missing mass, vertex, coplanarity, and outside of shared resonances, we were able to identify the final set of phi candidates and fit a gaussian to it to extract these events. See figure 3.11 for the gaussian fit to the phi candidate events.

Once these events are extracted, we were able to compare the results of our wagon to those that Dr. Clary originally selected. This comparison can be seen in figure 3.12 where the final histogram showing the phi peak in the kaon decay products is shown.

As seen by 3.12, the wagon performs at the same level as the cuts originally proposed by Dr. Clary in his Ph.D. dissertation. Furthermore, the final set of events are identical when observed at an event-by-event basis.

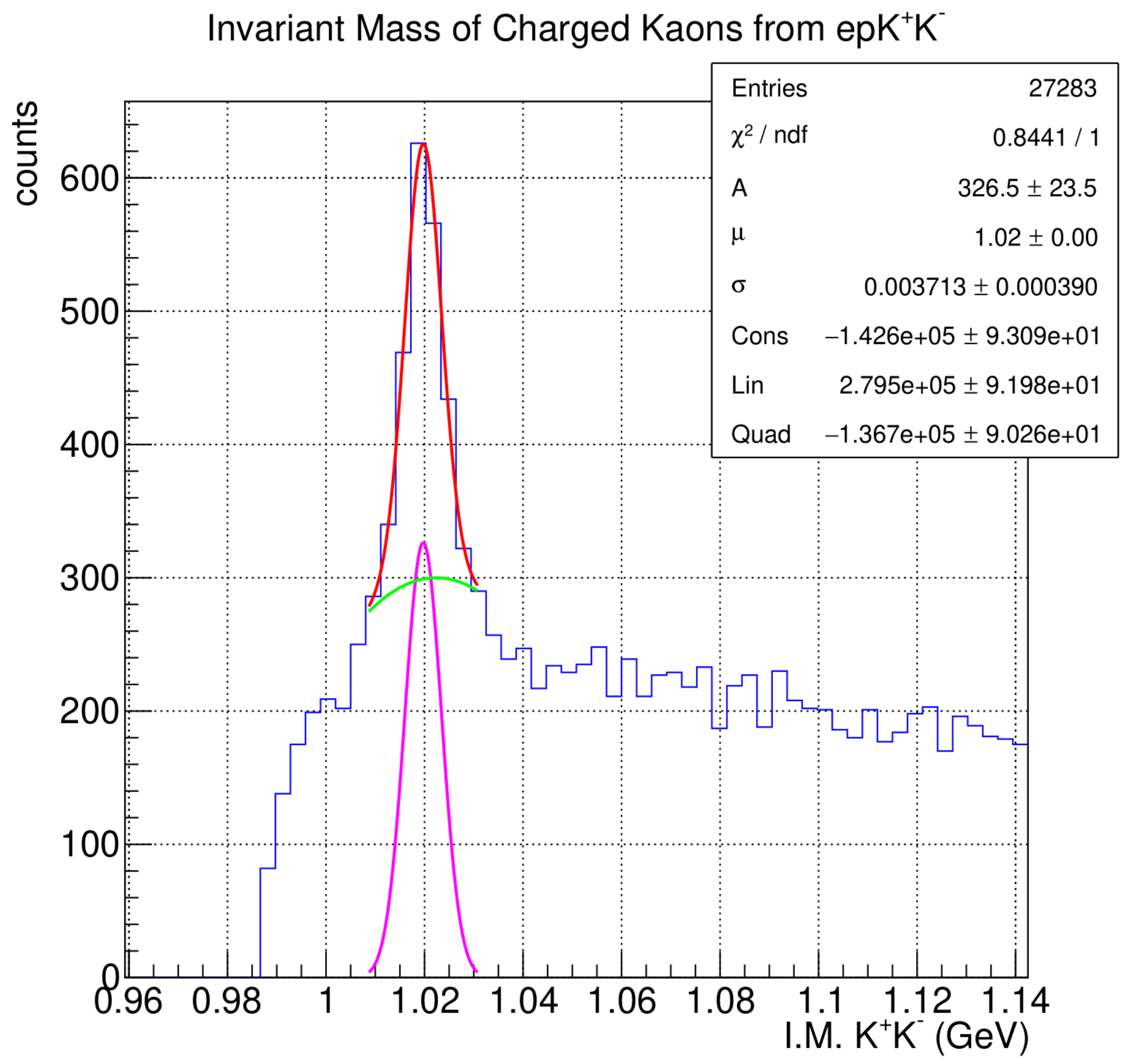


FIGURE 3.11: Histogram of the invariant mass of the kaon plus and kaon minus with a gaussian fit with a quadratic background at the decay mass of the phi meson.

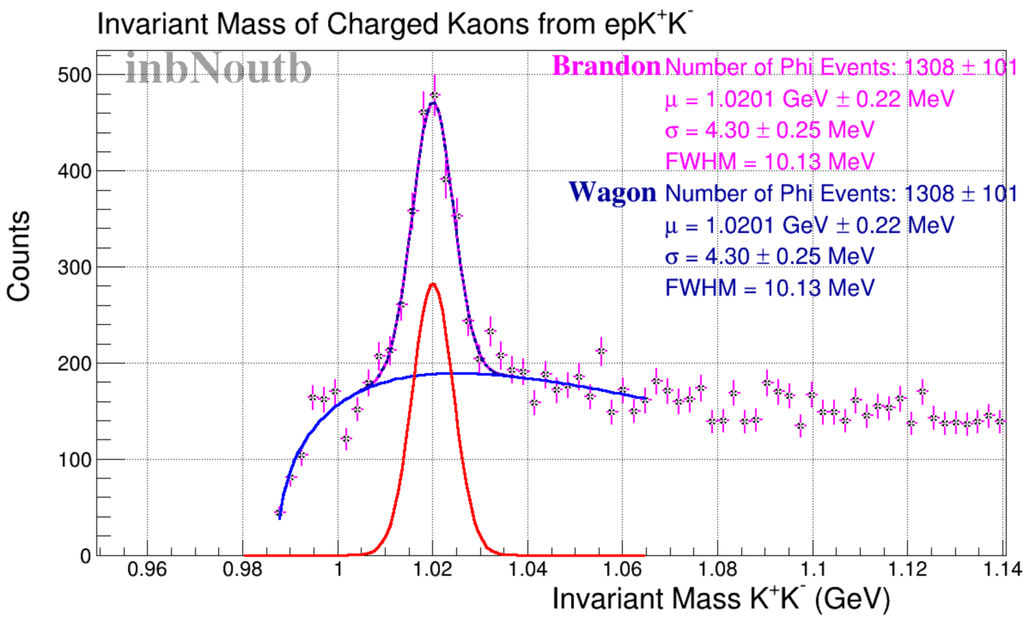


FIGURE 3.12: Histograms showing the events selected by the wagon and by Dr. Clary. The purple lines and scatter points are Dr. Clary's, the blue line and points are those extracted by the wagon. The solid blue and purple line is the radiative background fit, the solid red lines are the gaussian fits, the dashed lines are these fits combined.

Chapter 4

Conclusion

Detecting the phi meson in CLAS12 is a relatively recent development and essential for understanding the nucleus. By the same token, studying the exclusive electroproduction is an ideal channel for quantifying the gluonic properties of the nucleon. Creating a physics-based analysis procedure allowed us to develop a wide selection of cuts that used the phi mesons most common decay products, K^+ and K^-, to detect the exclusive electroproduction of the short lived phi meson at Jefferson National Lab.

Working backwards from the kaon's characteristics, we were able to develop a wagon that can be easily used and deployed in workflows that require the detection of the phi meson. Moreover, this wagon has many useful features that allow for easier development and qualification of future projects such as dynamically typed variable definition, improved memory allocation, and dedicated classes for the identification of input particle candidates.

This wagon was able to reproduce the results of previous codes in a fraction of

the time, requiring both fewer CPU cores and less preallocated memory. By using the results from Dr. Brandon Clary, we were able to preserve the analysis of the phi meson and improve upon the procedure by removing legacy code and adding improved PID and tailored cuts to the type of event.

4.1 Moving Forward

Using the experience and knowledge from the preservation, the UConn group should be able to implement the wagon on future analysis of the phi meson. With wagons, the workflow is streamlined and it is easier to produce further analyses of beam spin asymmetry such as those performed in Dr. Clary's dissertation. Furthermore, the creation of a Maven repository where particle identification codes can be locally stored yet globally accessed allows for easier development of further procedures.

Developing a wagon for the detection of the phi meson proved to be fruitful as it is now easier to classify phi meson events. In the future, other particle classifications using wagons need to be developed and deployed for an improved workflow. Ultimately, this will help us further our understanding of the nucleon and lead to discoveries about the structure of the matter.

Bibliography

[1] B. Clary, "Exclusive phi production beam spin asymmetry measurements with clas12," Ph.D. dissertation, 2020. [Online]. Available: https://opencommons.uconn.edu/dissertations/2634