SIMULATION AND DATA ANALYSIS OF THE NA64 EXPERIMENT

SUMMER STUDENTS REPORT 2023

BY:

MARCELO VIDAL

ADDLES CASTILLO

ADVISOR:

MIKHAIL KIRSANOV

Contents

Chapter 1

Introduction

The primary goal of the NA64 experiment is the search for unknown particles that may belong to a hypothetical "dark sector". These particles could be dark photons, which would bear a new force between visible matter and dark matter, in addition to gravity, or they could constitute the dark matter itself.

To achieve this goal, NA64 directs a beam of electrons with an energy of 100-150 GeV from the Super Proton Synchrotron (SPS) onto a fixed target. Through collisions between the beam's electrons and the atomic nuclei of the target, researchers aim to detect the "dark sector" particles that would be produced in these interactions. The search involves observing the ordinary particles, such as electrons, that would result from the decay of the unknown "dark sector" particles, or searching for the missing energy that would be carried by the particles not detected by the detector.

In addition to the search for dark photons, NA64 also investigates the existence of axions and axion-like particles, which could resolve mysteries related to the symmetric properties of the strong force or act as mediators of a new force in the universe.

The NA64 team takes advantage of different particle beams from the SPS to conduct additional searches. Using a muon beam, they search for particles that primarily interact with muons, which could provide answers to the enigma of the muon's anomalous magnetic moment. They also use hadronic beams to explore invisible decays of neutral kaons and other mesons, investigating new physics phenomena, as well as searching for mirror dark matter candidates.

This report presents the four fundamental areas of our project: the acquisition of energy and momentum data, the simulation of geometry with iron bars in the electromagnetic calorimeter, the optimization of efficiency in chi2 histograms, and statistical analysis. Our objective has been to enhance and optimize the simulation through the use of the C++ programming language, oriented towards ROOT and Geant4.

Geant4 is a particle event simulation platform developed by international collaborations. This tool allows modeling and studying the passage of particles through matter, including their interaction with the detector and materials. Geant4 uses a detailed description of particle physics, which includes models for nuclear, electromagnetic, and high-energy processes, thereby realistically simulating the behavior of particles in the detector.

On the other hand, ROOT is a data analysis library developed by CERN. ROOT provides a wide range of tools for data analysis and visualization in particle physics and other research areas. It allows handling large data sets and performing fits, histograms, function adjustments, and other statistical analysis procedures.

Chapter 2

Experimental Setup

The NA64 experiment uses the enhanced electron beamline H4 at CERN SPS. The beam is produced by the primary proton beam of 450 GeV with an intensity of up to $5 - 7 \times 10^{12}$ Proton On Target (POT) per SPS spill. Electrons are produced in a primary beryllium target and transported to the detector inside the evacuated light line tuned with an adjustable beam impulse. In the case of NA64, in the invisible decay setup $A' \to invisible$, the beam impulse is set to 100 GeV and is deposited in an electromagnetic calorimeter (ECAL), responsible for activating such decay and evaluating the missing energy in the final state. Therefore, a well-defined initial state is required, along with longitudinal hermeticity to prevent any energy leakage.

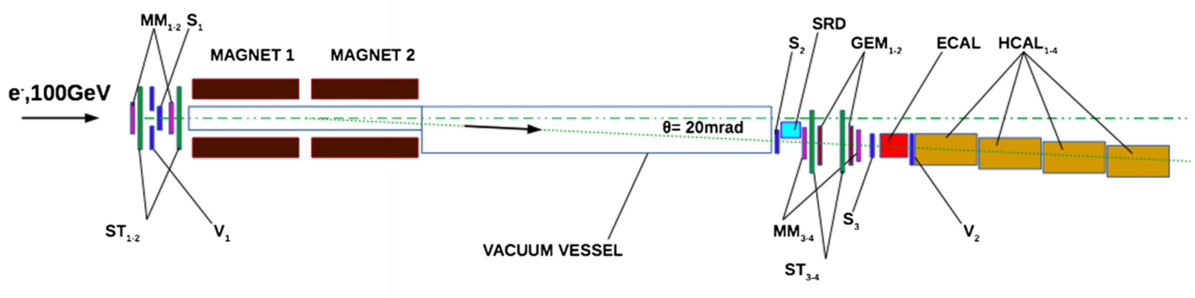

Figure 2.1: Schematic illustration of the NA64 experiment setup for searching $A' \to$ invisible decays produced by the bremsstrahlung interaction $e^- Z \to e^- Z A'$ of 100 GeV e^- incident on the ECAL target

The invisible mode configuration used for the CERN data acquisition in 2018 is presented in Figure 2.1. After the primary e^- enters the setup, its impulse is accurately measured with a magnetic spectrometer. It provides an integrated field of ~ 7 Tm generated by two dipolar magnets placed in series along the primary beam axis. The particle's entry angle into the magnet is defined by two Micromegas trackers (MM) placed within the 5m space between the beam entrance and the entrance of the first magnet. Between the two MMs, in a space of about 2m, are a scintillator (S_1), a V_1 counter and 2 Strawtubes ($St_{1\text{-}2}$). This ensures a correct definition of the beam and rejects particles with a high beam divergence that could be a potential source of background. The two magnets are followed by a 10.2m long vacuum tube maintained at 10^{-3} mbar placed immediately afterwards with a total length of 10.2m. The vacuum minimizes the interaction of particles during their journey to the target. This is important to suppress the emission of secondary particles before the primaries reach the target.

After the vacuum tube, a space of ~ 4.5m contains the last detectors before the target. A second set of two scintillators ($S_{2\text{-}3}$) completes the triggering system. In the arc contained between the original beam and the bent beam, a synchrotron radiation detector (SRD) is placed, emitted in the upstream magnetic field. On the other side of the beam (see Figure 2.1), two additional MMs

($MM_{3\text{-}4}$), 2 Strawtubes ($St_{3\text{-}4}$), and 2 four-gas electron multipliers (GEM) are placed along the beam direction to complete the momentum reconstruction by detecting the electron's displacement after passing through the magnetic field. After this region, the primary electron strikes the active target (ECAL). The ECAL is composed of 36 modules arranged in a 6×6 matrix. Each module has a Pb-Sc structure with 150 layers for a total of $40X_0$. Due to its transverse segmentation, the ECAL allows a higher background rejection using a shower profile analysis to distinguish between an em shower and a hadronic one. To ensure total hermeticity, a high-efficiency VETO and a large hadronic calorimeter (HCAL) are placed after the ECAL target. The VETO consists of three separate scintillators stacked together resulting in a thickness of 5cm. The HCAL, located immediately afterwards, consists of four modules of $\simeq 7\lambda_{int}$ (nuclear interaction length) each. Each module is integrated into a 3×3 matrix of a single sandwich-type Fe-Sc array. The role of the HCAL is to detect the particles (hadrons, neutrals, and muons) that penetrate the ECAL to ensure energy hermeticity.

Chapter 3

Tasks

3.1 Reconstruction of the Incident Particle Momentum Using Straw Tube Tracker (STRAW)

During the course of the first project, an analysis of the simulation code used by the NA64 experiment was carried out, which uses the GEANT4 software. In this analysis, the NA64SD.cc code was modified in order to process the hits recorded in the STRAW (Straw Tube Tracker) type detectors. In this way, the deviation angle between the $STRAW_{1,2}$ and $STRAW_{3,4}$ detectors is calculated, thus allowing the reconstruction of the incident particle's momentum. The main objective is to obtain an accurate estimate of the particle's momentum based on the data collected by the mentioned detectors.

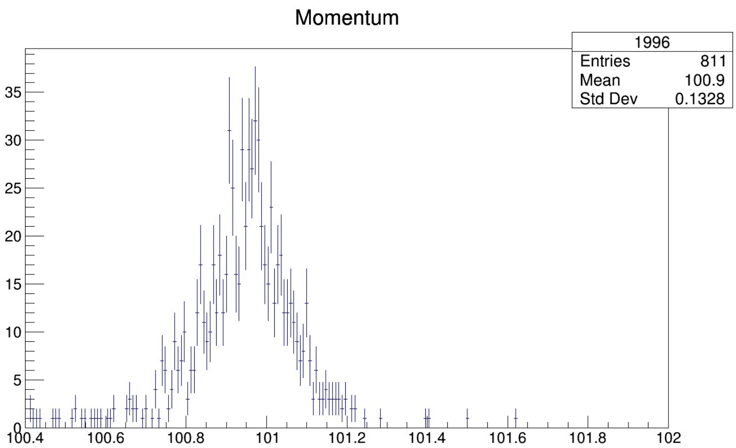

Figure 3.1: Reconstruction of the incident e^{-} momentum

3.2 Optimization of the Electromagnetic Calorimeter (ECAL) Geometry in the NA64 Experiment

The ECAL geometry simulation focused on modifying a specific part of the detector, where circular iron holes were added to each corner of the calorimeter. The position of the holes was determined symmetrically in relation to the center of the ECAL, so they were at a distance equal to half the diagonal of a calorimeter cell. This allowed to observe how these holes affected the energy deposited by the particles in the detector. The results showed a decrease in the deposited energy as the hole radius increased, demonstrating the influence of the ECAL geometry on energy measurements.

It is important to note that this simulation represents only a part of the complete ECAL, which consists of multiple layers and modules. To obtain an accurate representation of the actual detector used in the NA64 experiment, the complete geometry of the ECAL was replicated using techniques provided by the Geant4 library. The replication allowed to build the complete ECAL with all its cells and modules, ensuring that the simulation was as close as possible to the experimental conditions.

The optimization of the ECAL geometry simulation allowed to improve the precision of the measurements. By simulating different geometry configurations and iron holes, valuable information was obtained on how these changes affect the efficiency of the detector and energy measurements.

3.3 Cut in chi2 in function of ECAL

A modification is made to the existing fixed cut in the Chi2 data, transforming it into a variable cut as a function of ECAL energy. The dependence on ECAL energy allows for the removal of high Chi2 values, which are usually associated with low ECAL energy values. These values, resulting from fluctuations in the experiment data, do not significantly contribute to the analysis.

To determine the cut function, the ROOT software was used to fit the electromagnetic calorimeter energy histogram exponentially. This procedure provided the necessary constants to predict the function's behavior. With these constants, a function was created that increases the Chi2 cut as ECAL values decrease.

3.4 Statistical Analysis Using the Combine Program

In the final stage of the research, the Combine software was used with the purpose of finding the minimum expected average limit of the HCALCut. This process involved varying this value 18 times, ranging from 0.2 to 3.0, in order to determine the corresponding value.

However, through this exhaustive analysis, it was found that the minimum value obtained corresponded to 0.8, a result clearly evidenced in Figure 3.2.

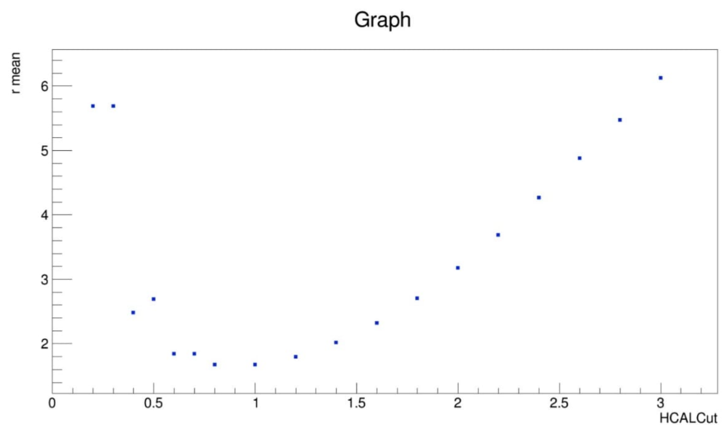

Figure 3.2: Recorded magnitudes for the HCALCut, along with its corresponding average value.

Chapter 4

Conclusions

In summary, all aspects of the project were successfully carried out. The analysis and modification of the NA64 experiment simulation code allowed for the effective reconstruction of the incident particle's momentum using STRAW detectors. In addition, a detailed optimization of the ECAL geometry was carried out, which facilitated greater precision in energy measurements and a better understanding of how geometry affects detector efficiency.

A successful implementation of a modification to the existing fixed cut in Chi2 data was carried out, transforming it into a variable cut depending on ECAL energy, resulting in a more accurate analysis. Finally, the Combine software was used to conduct a statistical analysis that determined the minimum expected average limit of the HCALCut.

Therefore, the objectives of this project can be considered achieved, having contributed valuable observations and results to the experimental physics community.