Predicting COMPASS/AMBER Acceptance with Neural Networks

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1 Introduction

1.1 COMPASS/AMBER

The COMPASS experiment, short for "Common Muon and Proton Apparatus for Structure and Spectroscopy," is a cutting-edge particle physics experiment conducted at CERN, the European Organization for Nuclear Research, in Geneva, Switzerland. COMPASS is a collaborative endeavor involving scientists and researchers from institutions around the world. This experiment is dedicated to unraveling the mysteries of the subatomic world by probing the structure and properties of hadrons, which are particles composed of fundamental constituents called quarks and held together by the strong nuclear force. COMPASS achieves this by utilizing a high-energy polarized muon beam, making it unique in its precision measurements of hadron physics and spin properties. With its sophisticated array of detectors, including spectrometers and tracking chambers, COMPASS captures and analyzes particles produced during high-energy collisions, providing valuable insights into the internal structure of nucleons like protons and neutrons. Additionally, COMPASS explores the production of exotic hadrons, expanding our understanding of the strong force interactions and the fundamental constituents of matter. The data generated by the COMPASS experiment contributes significantly to advancing our knowledge of the building blocks of the universe and the forces that govern them, furthering our understanding of the intricacies of particle physics.

2 Data Origin and Preprocessing

Data Origin: Generation and Reconstruction

The data used for the analysis presented in this paper was generated using a LEPTO generator, a dedicated generator for deep inelastic scattering (DIS) processes. Beyond that, the full simulation of the COMPASS spectrometer was done using the GEANT4 programme. The data was then reconstructed using the COMPASS reconstruction software. With this process, two files were generated for each type of events (Hadrons and Inclusive), one with the Monte Carlo (MC) data, and another with the reconstructed data. The goal with this data is to check if it is possible to predict the acceptance of the COMPASS/AMBER using a Neural Network, since the GEANT4 simulation is very time consuming, aproximately 30 seconds per event. That might not seem like a lot, but when you have millions of events, it becomes a problem. Therefore, one could use a Neural Network to habe a better idea of how changed parameters affect the data/MC agreement, and then only run the GEANT4 simulation for the events that are more likely to be accepted.

Data Variables

The data used for the analysis of the Inclusive events has 11 variables:

Variable	**Description**
X_b	$Bjorken_x$
Y	Virtual Photon Energy Fraction of the initial momentum
Q^2	Four-momentum transfer
$Trig$	Trigger
PV_z	X-Position of interaction vertex in the target
PV_x	Y-Position of interaction vertex in the target
PV_y	Z-Position of interaction vertex in the target
Mom_{mu}	Incoming beam momentum
Mom_{mup}	Outgoing muon momentum
$d_x d_z mup$	Angle of Muon
$d_y d_z mup$	Angle of Muon

While the data used for the analysis of the Hadrons events has 16 variables:

Variable	**Description**
X_b	$Bjorken_x$
Y	Virtual Photon Energy Fraction of the initial momentum
Z	Fraction of hadron energy to the virtual photon energy
Q^2	Four-momentum transfer
$Trig$	Trigger
PV_z	X-Position of interaction vertex in the target
PV_x	Y-Position of interaction vertex in the target
PV_y	Z-Position of interaction vertex in the target
Mom_{mu}	Incoming beam momentum
Mom_{mup}	Outgoing muon momentum
$d_x d_z mup$	Angle of Muon
$d_y d_z mup$	Angle of Muon
q	Hadron Charge
mom	Momentum of Hadron
$d_x d_z$	Angle of Hadron
$d_y d_z$	Angle of Hadron

As mentioned before, for each type of events, we have a file with the Monte Carlo data and another with the reconstructed data. Since the goal is to find a way to predict the acceptance of the COMPASS/AMBER, we created a new variable, called "Accepted", which is 1 if the event was accepted and 0 if it was rejected. Therefore, for the data with the Monte Carlo information, we added a column with the value 1 for all the events, and for the data with the reconstructed information, we added a column with the value 0. It's important to refer that the number of events for each of the files is different, since the Monte Carlo data has more events than the reconstructed data. Hence, we had to balance the data for the training and testing of the Neural Network, which will be explained in the section.

Correlation between Variables

In order to check if there is any correlation between the variables, we plotted the correlation matrix for the Inclusive and Hadrons events. This is important because if there is a high correlation between two variables, it means that they are redundant, and therefore, one of them can be removed, which simplifies the training of the Neural Network, reduces the number of parameters (reducing the training time) and avoids overfitting. The results are shown in the figures below:

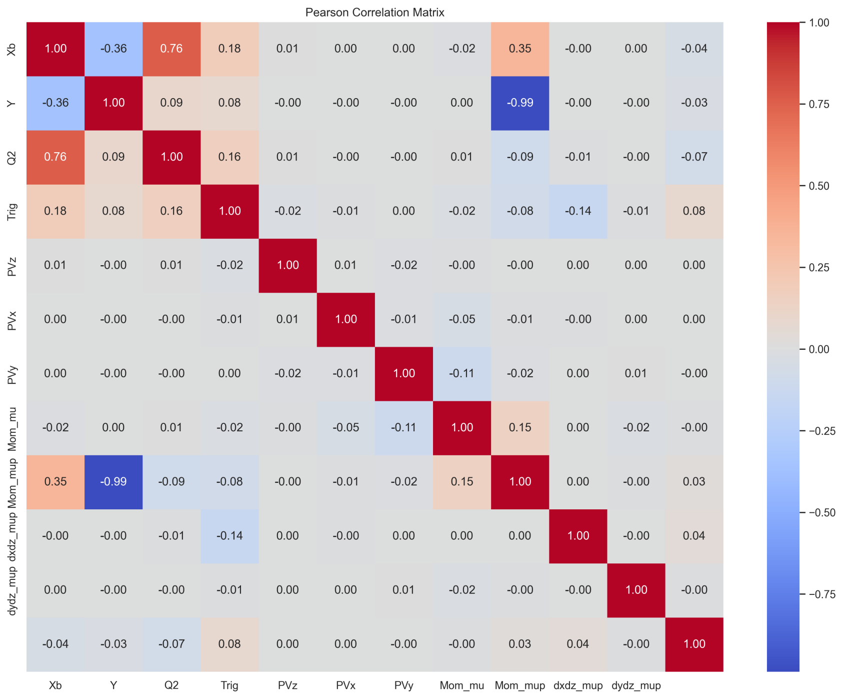
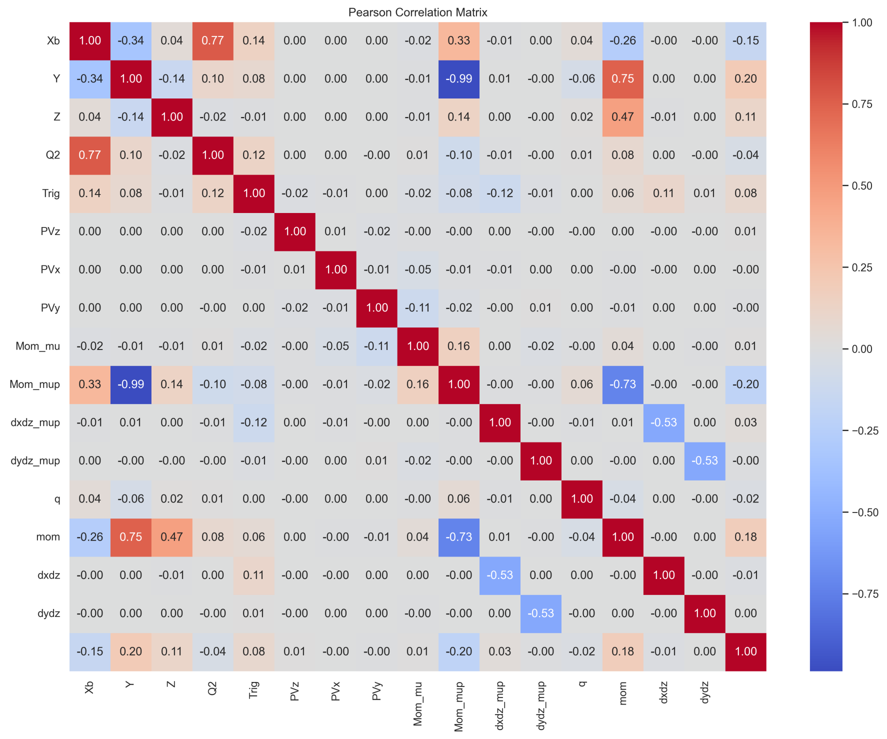


Figure 1: Correlation Matrix for the Inclusive Events



	Xb	Y	Z	Q2	Trig	PVz	PVx	PVy	Mom_mu	Mom_mup	dxdz_mup	dydz_mup	q	mom	dxdz	dydz	
Xb	1.00	-0.34	0.04	0.77	0.14	0.00	0.00	0.00	-0.02	0.33	-0.01	0.00	0.04	-0.26	-0.00	-0.00	-0.15
Y	-0.34	1.00	-0.14	0.10	0.08	0.00	0.00	0.00	-0.01	-0.99	0.01	-0.00	-0.06	0.75	0.00	0.00	0.20
Z	0.04	-0.14	1.00	-0.02	-0.01	0.00	0.00	0.00	-0.01	0.14	0.00	-0.00	0.02	0.47	-0.01	0.00	0.11
Q2	0.77	0.10	-0.02	1.00	0.12	0.00	0.00	-0.00	0.01	-0.10	-0.01	-0.00	0.01	0.08	0.00	-0.00	-0.04
Trig	0.14	0.08	-0.01	0.12	1.00	-0.02	-0.01	0.00	-0.02	-0.08	-0.12	-0.01	0.00	0.06	0.11	0.01	0.08
PVz	0.00	0.00	0.00	0.00	-0.02	1.00	0.01	-0.02	-0.00	-0.00	0.00	-0.00	-0.00	0.00	-0.00	-0.00	0.01
PVx	0.00	0.00	0.00	0.00	-0.01	0.01	1.00	-0.01	-0.05	-0.01	-0.01	0.00	0.00	-0.00	-0.00	0.00	-0.00
PVy	0.00	0.00	0.00	-0.00	0.00	-0.02	-0.01	1.00	-0.11	-0.02	-0.00	0.01	0.00	-0.01	0.00	0.00	-0.00
Mom_mu	-0.02	-0.01	-0.01	0.01	-0.02	-0.00	-0.05	-0.11	1.00	0.16	0.00	-0.02	-0.00	0.04	0.00	-0.00	0.01
Mom_mup	0.33	-0.99	0.14	-0.10	-0.08	-0.00	-0.01	-0.02	0.16	1.00	-0.00	-0.00	0.06	-0.73	-0.00	-0.00	-0.20
dxdz_mup	-0.01	0.01	0.00	-0.01	-0.12	0.00	-0.01	-0.00	0.00	-0.00	1.00	-0.00	-0.01	0.01	-0.53	0.00	0.03
dydz_mup	0.00	-0.00	-0.00	-0.00	-0.01	-0.00	0.00	0.01	-0.02	-0.00	-0.00	1.00	0.00	-0.00	0.00	-0.53	-0.00
q	0.04	-0.06	0.02	0.01	0.00	-0.00	0.00	0.00	-0.00	0.06	-0.01	0.00	1.00	-0.04	0.00	-0.00	-0.02
mom	-0.26	0.75	0.47	0.08	0.06	0.00	-0.00	-0.01	0.04	-0.73	0.01	-0.00	-0.04	1.00	-0.00	0.00	0.18
dxdz	-0.00	0.00	-0.01	0.00	0.11	-0.00	-0.00	0.00	0.00	-0.00	-0.53	0.00	0.00	-0.00	1.00	-0.00	-0.01
dydz	-0.00	0.00	0.00	-0.00	0.01	-0.00	0.00	0.00	-0.00	-0.00	0.00	-0.53	-0.00	0.00	-0.00	1.00	0.00
	-0.15	0.20	0.11	-0.04	0.08	0.01	-0.00	-0.00	0.01	-0.20	0.03	-0.00	-0.02	0.18	-0.01	0.00	1.00

Figure 2: Correlation Matrix for the Hadron Events

As seen in the figures above, there is a high correlation between Y and Mom_{mup}, with a pearson correlation coefficient of -0.99 for both types of events. Therefore, one of them can be removed from the training of the Neural Network. Since Mom_{mup} and Y have the same correlation coefficient, we decided to remove Mom_{mup} from the training of the Neural Network, since from the physics point of view, Y is more important than Mom_{mup}, since it is the variable that gives us the virtual photon energy fraction of the initial momentum.

Weighting

As mentioned before, the number of events for each of the files is different, since the Monte Carlo data has more events than the reconstructed data. Hence, we had to balance the data for the training and testing of the Neural Network. This was done by weighting the events, so that the number of events assigned to the training and testing set data as the same proportion of accepted and rejected events as the original data. Avoiding that when we split 80% of the data for training and 20% for testing, we would have a different proportion of accepted and rejected events in the training and testing set data. The weighting was done by calculating the ratio between the number of accepted and rejected events in the original data, and then multiplying the number of events.

Neural Network Models

Models Architecture, Hyperparameters and Metrics

For the Neural Networks models we used the PyTorch framework, which is an open source machine learning library based on the Torch library, used for applications such as computer vision and natural language processing. For the models architecture, two different models were used, one with 3 hidden layers, two

GELU activation functions and two dropout layers, and another with 6 hidden layers, 5 GELU activation functions and 3 dropout layers. The choice of the number of hidden layers and the number of neurons in each layer was done by trial and error, and the same applies to the choice of the dropout rate. The GELU activation function was chosen because it is the one that gave the best results, and the same applies to the choice of the optimizer, which was the Adam optimizer. These two models were chosen because they are the ones that gave the best results and also because there was the need to see the difference between a not so deep model and a deeper model. The hyperparameters used for the training of the models were the following:

- Learning Rate: 0.01
- Epochs: 10
- Batch Size: 1

For the loss function, we used the Binary Cross Entropy Loss, which is the most common loss function used for binary classification problems. Despite the fact that this set of data might be familiar with a binary classification problem, since we are trying to predict if an event will be accepted or rejected, we are not doing a binary classification problem, since we are not trying to classify the events, but rather predict the acceptance of the COMPASS/AMBER. Therefore, there was no need to round the output of the Neural Network to 0 or 1, since the output of the Neural Network is a number between 0 and 1, which represents the probability of the event being accepted. During the training of the models, we printed the accuracy and the loss as metrics to evaluate part of the performance of the models. But since the accuracy and loss are not the best metrics to evaluate the performance of the models in this type of problems, the chi-squared test was used to evaluate the performance of the models. The chi-squared test is a statistical hypothesis test that is used to evaluate how well a set of data fits a model. In this case, the model is the Neural Network, and the data is the data used for the training and testing of the Neural Network. For this particular case, the chi-squared was applied to a 2D histogram, where the x_axis is the X variable and the y_axis is the Y variable. The chi-squared used was defined as:

$$\chi^2 = \sum_{i=1}^{N} \frac{(\frac{r}{g} - A_{nn})^2}{err} \tag{1}$$

where O_i is the observed value and E_i is the expected value. The expected value is the value that the model predicts, and the observed value is the value that the data has.

Training, Testing and Results

3 Conclusion