Identification of muon-electron elastic events using Graph Neural Networks for precision measurements

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The MuonE experiment

The Fermilab Muon g-2 Experiment:

- 2023: Measured a 5.0 sigma discrepancy in the muon's anomalous magnetic moment a_μ from the Standard Model prediction [1]
- Conflicting results arise from different methods of calculating the hadronic contribution to a_μ

The MUonE Experiment:

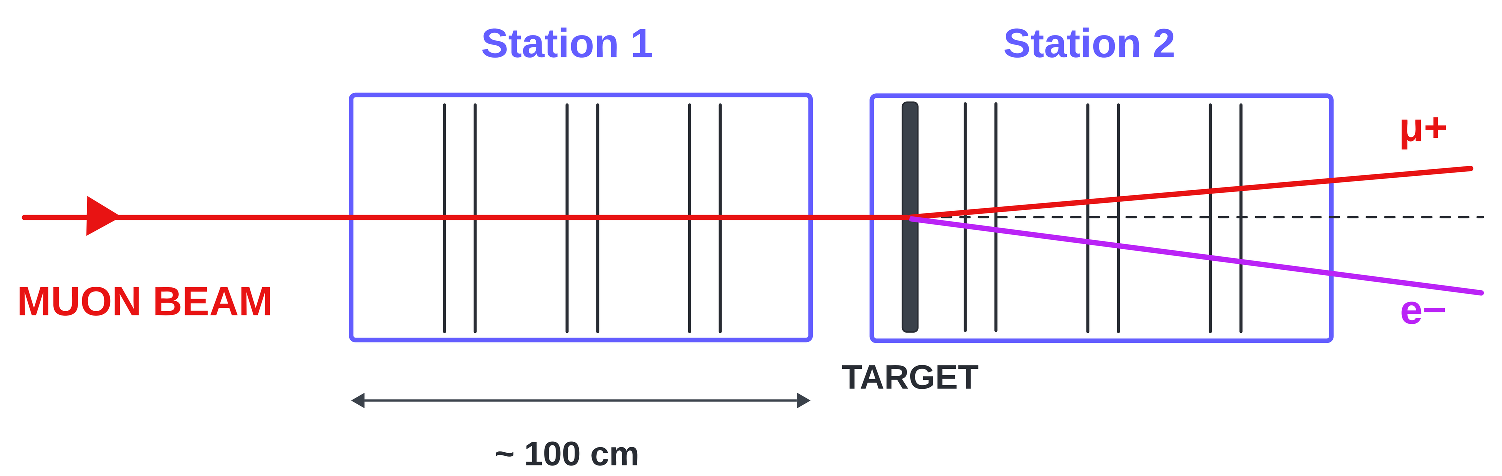
- Aims to measure the leading-order hadronic contribution to a_μ with a new approach [2,3,4]
- Method:
  - Measures the running of the electromagnetic coupling constant in $\mu-e$ elastic scattering

Experimental setup:

- Experiment performed by scattering a high-energy muon beam on the atomic electrons of a low-Z target
- Final setup: 40 tracking stations, electromagnetic calorimeter and muon filter
- Each tracking station consists of 6 CMS Outer Tracker 2S modules to measure the scattering angles of outgoing particles

Simulated setup:

- Monte Carlo simulation geometry used for the analysis consists of 2 tracking stations as basic unit of the experiment, which has been tested in the 2023 test run
- Use of calorimeter or muon filter has not yet been considered

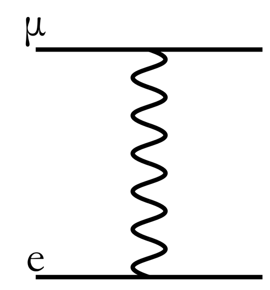


Event classification

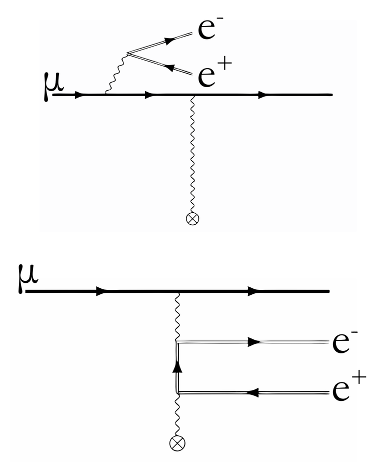
The main source of background is the **electron-positron pair production** (on nuclei and on atomic electrons) [4]:

- $\mu + N \rightarrow \mu + N + e^+ + e^-$
- $\mu + e^- \rightarrow \mu + e^- + e^+ + e^-$
- Contaminates the signal region and mimics the elastic scattering behavior if an electron or a positron leaves the detector acceptance region
- The main goal of the study: develop a method to distinguish between background and signal to improve the precision of the experiment
- Other sources of background (Bremsstrahlung, nuclear interactions) not included at this stage

Signal



Pair production



FairMUonE simulation software

- Software developed for the MuonE experiment, based on the FairRoot [5] framework
- Provides a detailed simulation of processes involved in the experiment using the GEANT4 package [6]
- Includes MESMER (Muon Electron Scattering with Multiple Electromagnetic Radiation) Monte Carlo event generator [7], for simulating signal and primary background events
- Integrates the geometry of the experimental setup, including beam position, tracking system, calorimeter, and other components
- Supports complete event reconstruction for the experiment

Graph Neural Network

Graph Neural Networks (GNNs):

- Well-suited for event classification
- Effectively model complex relationships in graph-structured data

Graph Representation:

- Vertices: particle hit positions detected by the tracking system
- Edges: relationships between these hits

Ground Truth Labels:

- Assigned based on interaction types:
  - Signal interactions ($\mu-e$ elastic scattering)
  - Background interaction (e^+e^- pair production)

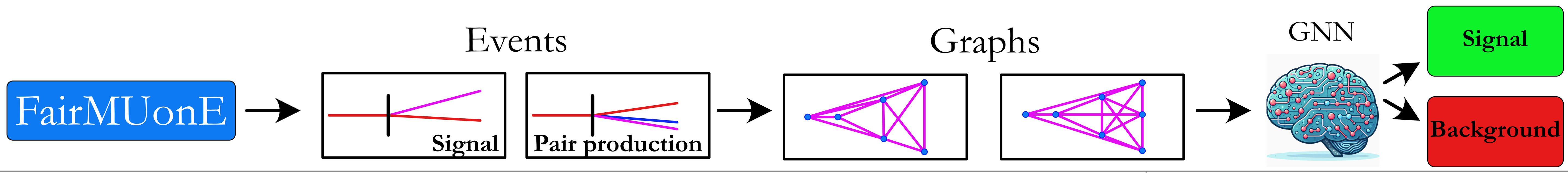
Event Treatment:

- Each event treated as a complete graph
- Utilizes all detected hits and their interrelationships

Network Architecture:

- Based on PointNet++ (PyTorch implementation) [8]:
  - Originally developed for segmentation and classification tasks in point clouds
  - Treats hit positions as points in space, analogous to point cloud representations

This approach uses the strengths of GNNs to efficiently classify events based on hit positions, eliminating the need for additional track information.



Results

Events production:

- Signal: muon-electron elastic scattering events generated with MESMER at Leading-Order and passing a loose preselection
- Background: e^+e^- pair-production events extracted from GEANT4 Minimum Bias simulation

FairMUonE reconstruction tools used to validate the network output.

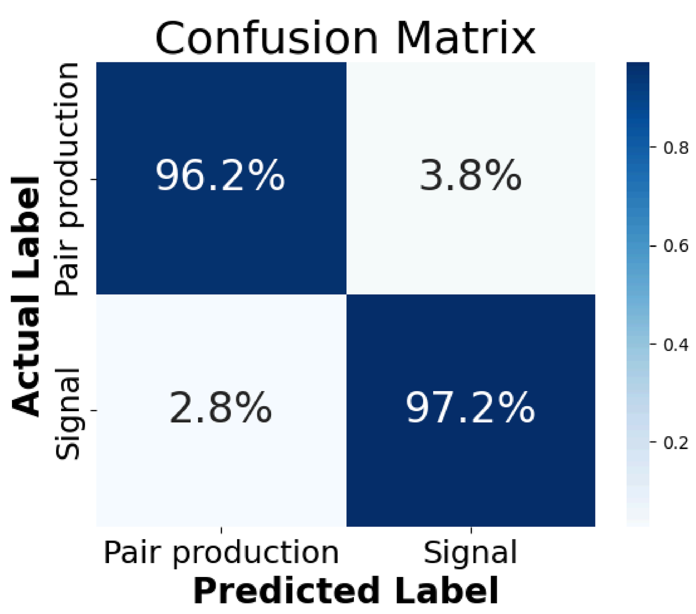
Datasets:

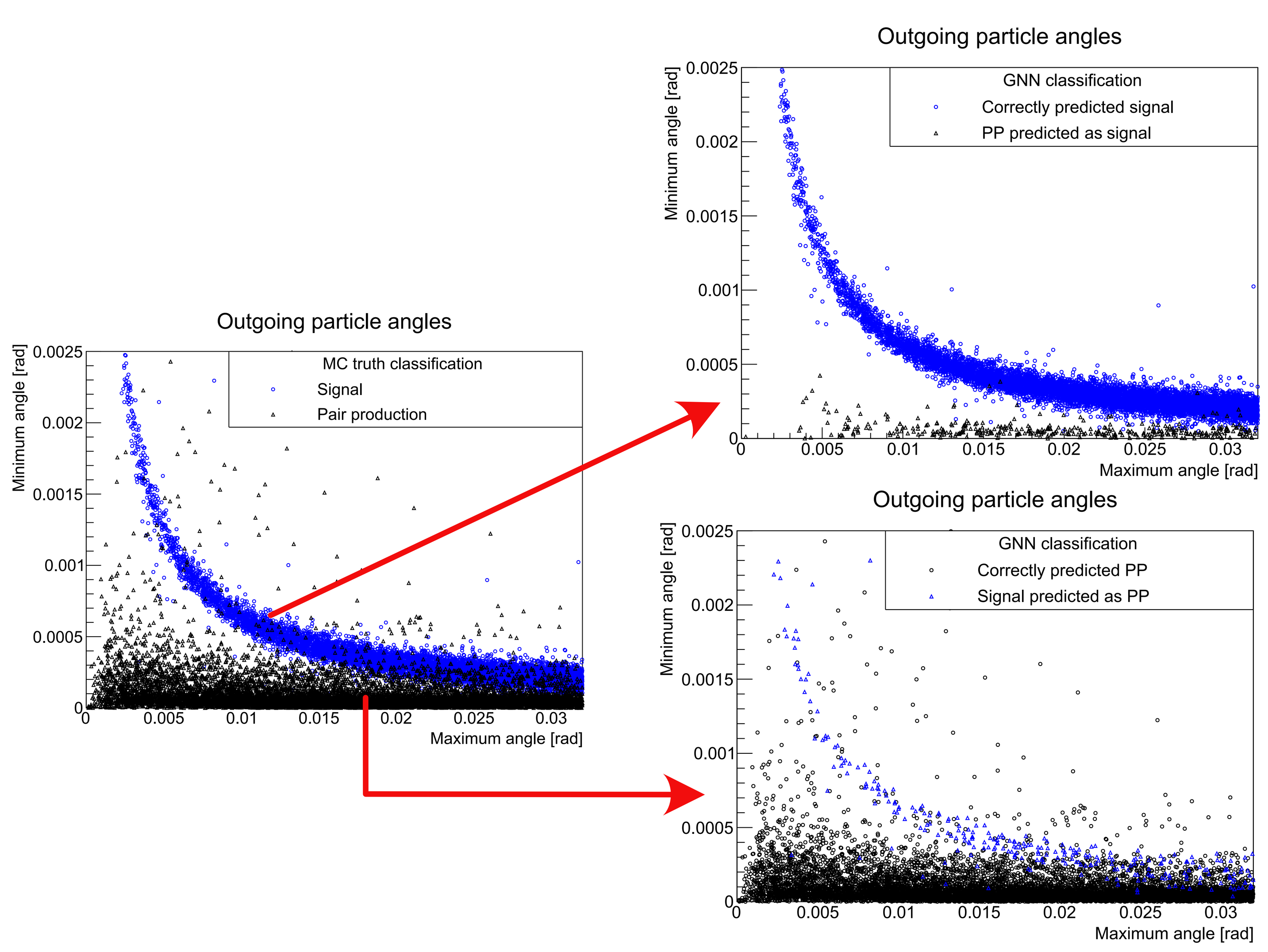
- Training: 58088 events
- Testing: 19458 events
- 50/50 signal to pair production

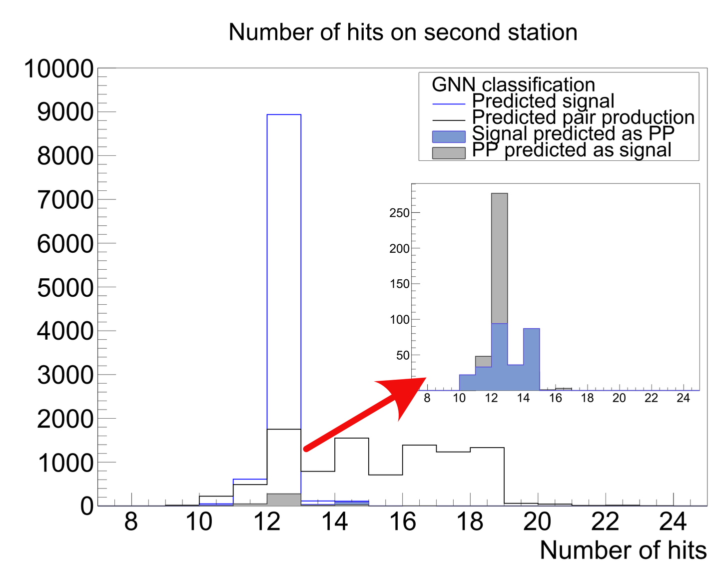
Network parameters:

- Number of layers: 5
- Layer size: 70
- Loss function: focal loss

Overall accuracy: 96.7%







Misidentification occurs mostly when pair production events result in 12 hits instead of more. This happens when one outgoing particle exits the detector's acceptance area.

Conclusions

- Machine learning techniques can serve as valuable tools to resolve critical signal vs background ambiguities online, before full analysis is performed
- This pilot version is focused on two types of interactions: $\mu-e$ elastic scattering (signal) and e^+e^- pair production (background)
- Initial results show the potential of GNN-based solution, although further studies and optimizations are needed
- Network response mainly driven by event hit multiplicity
- With higher statistics it is expected that the network would use more features and further improve

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