

Mu2e: Modeling Drift of Ionized Particles with ML

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Introduction

The Mu2e experiment searches for charged lepton flavor violation (CLFV) through muon-to-electron conversion in the field of a nucleus. The signal is a monoenergetic electron with an energy of 104.97 MeV. Its momentum is reconstructed with a straw tracker using information from drifting ionized particles. This project analyzes the drift of ionized particles to help improve the momentum reconstruction process.

Background

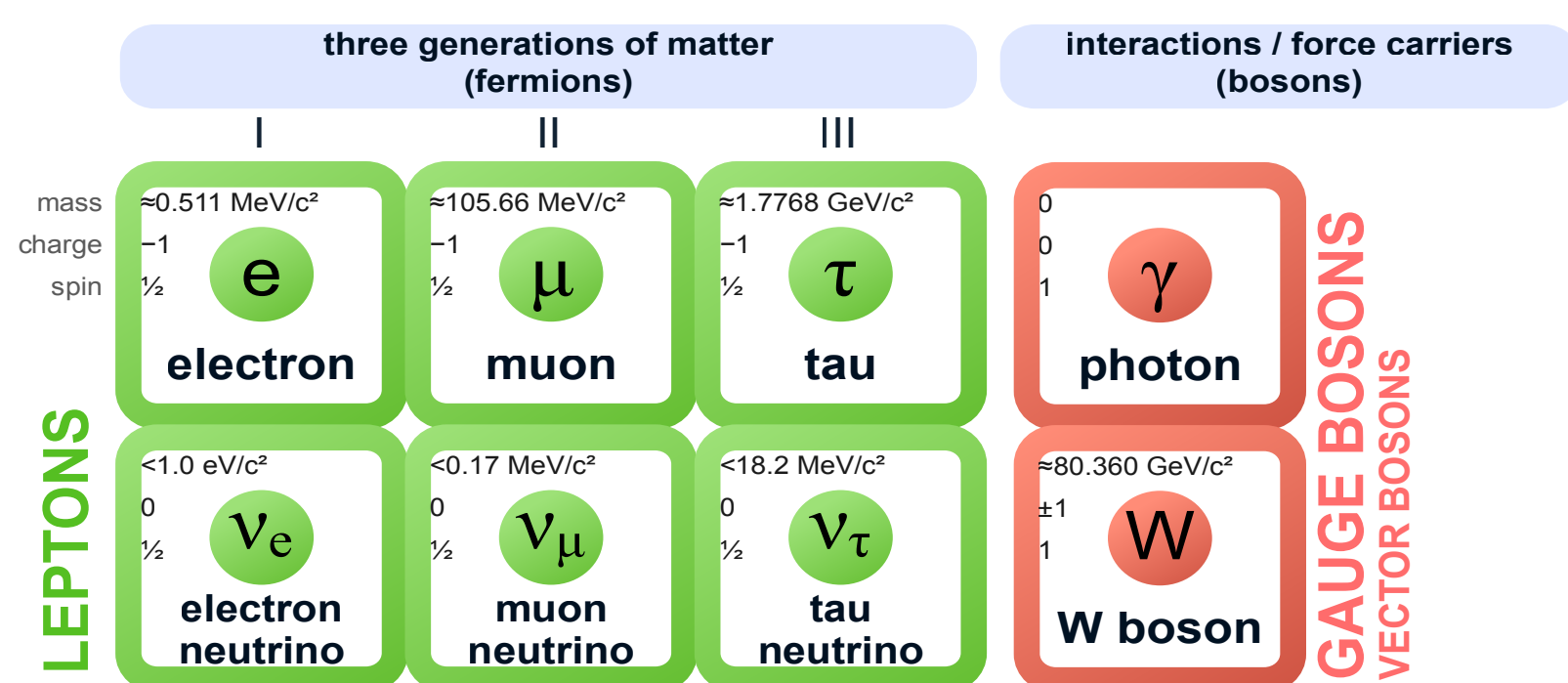


Fig 1. Three generations of charged and neutral leptons, and relevant force carriers for CLFV muon-to-electron conversion¹.

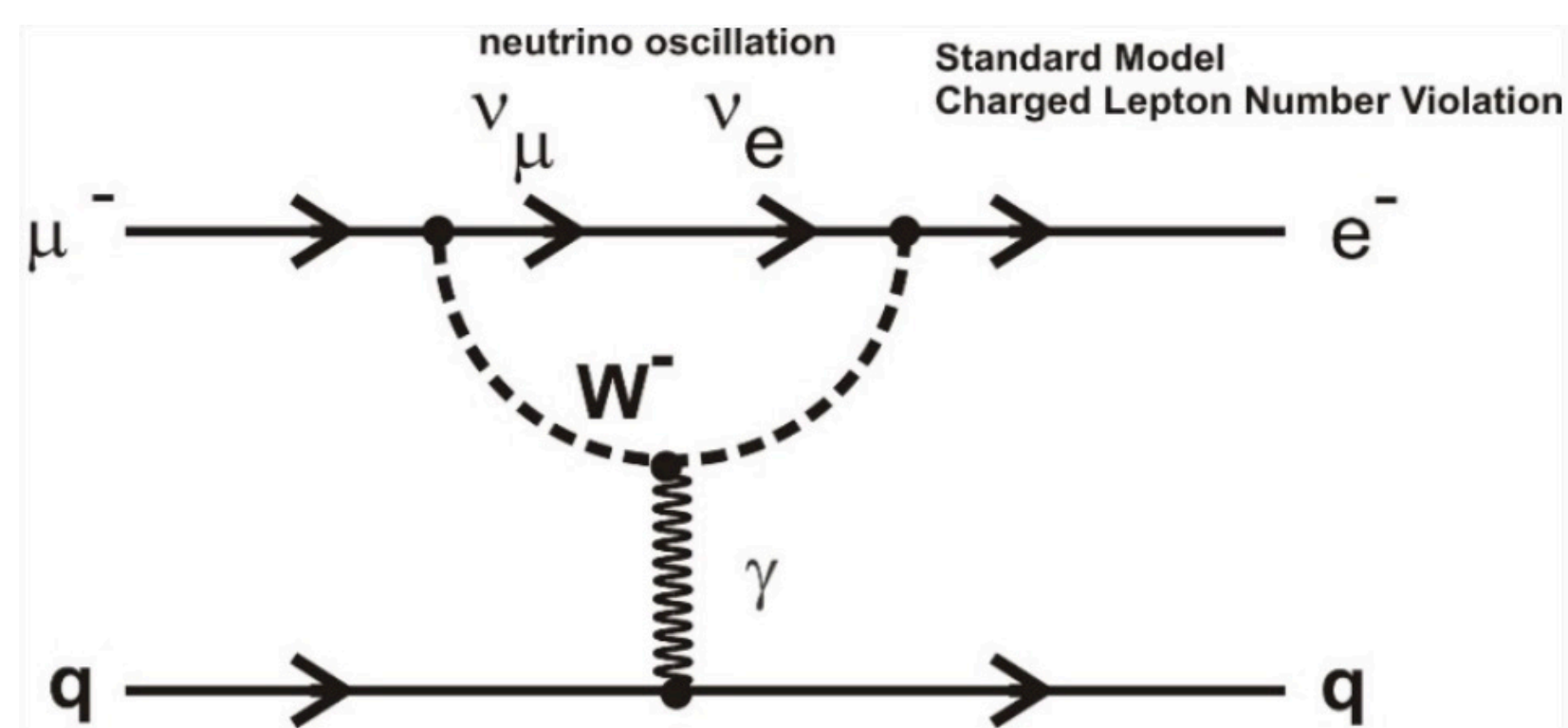


Fig 2. CLFV with neutrino oscillation as described by the Standard Model².

- Lepton number is conserved in muon-to-electron conversion with production of electron and muon flavor neutrinos.
- Standard Model (SM) predicts CLFV $< 10^{-50}$
- Mu2e sensitivity $\sim 10^{-17}$, so CLFV detection would be explained by Beyond SM physics

Mu2e Detector

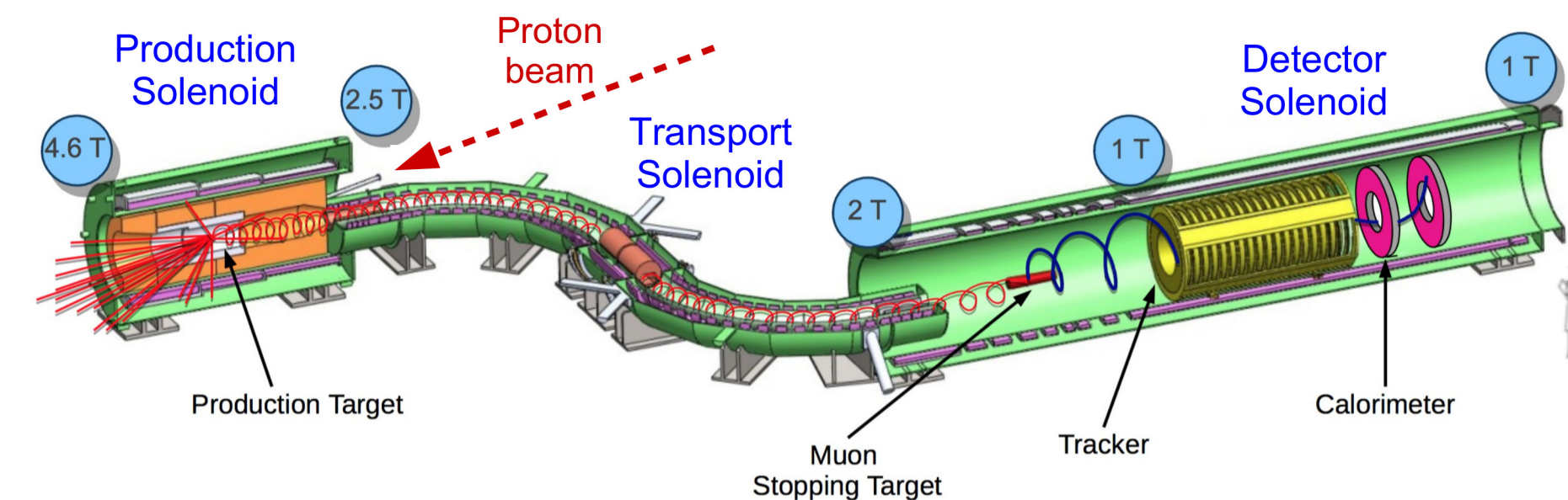


Fig 3. Mu2e detector³

- Fermilab proton beam hits tungsten production target and produces muons
- Muons stop at aluminum target, muonic decay, or convert
- Detector solenoid with gradient field curves tracks of resulting ionizing particles towards straw tracker

Straw Tracker

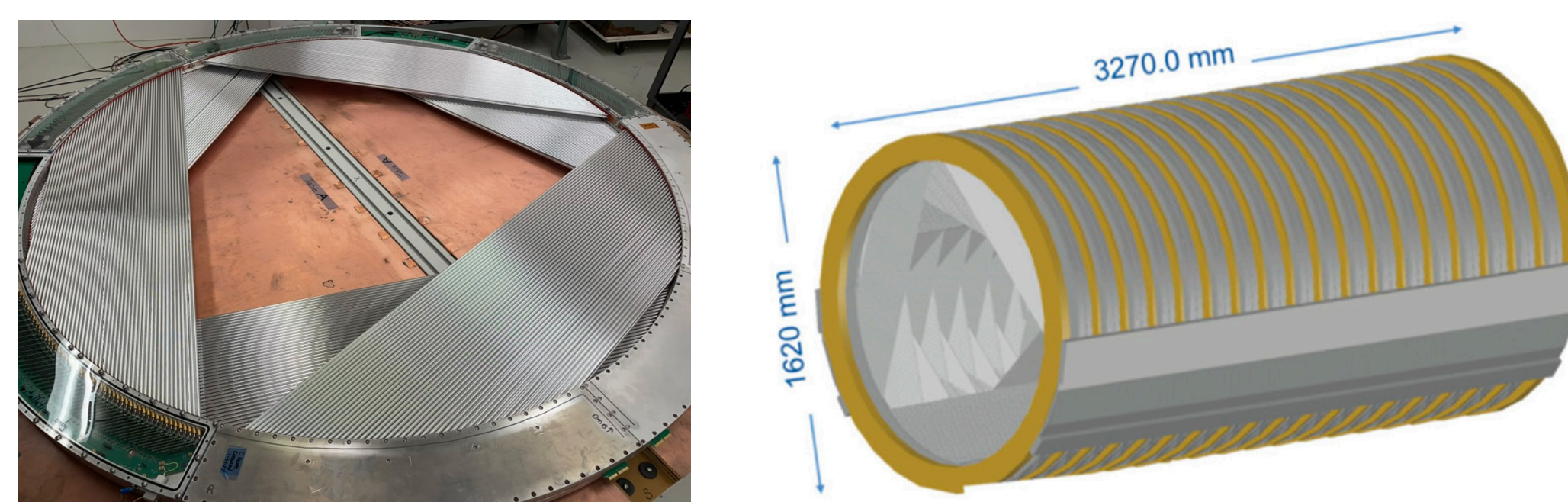


Fig 4. A straw tracker plane at Fermilab and fully assembled straw tracker detector⁴.

- 96 straws/panel, 6 panels/plane, 36 planes for total of 21,000 straws
- Panels stacked and offset to localize path of high energy particle through the tracker

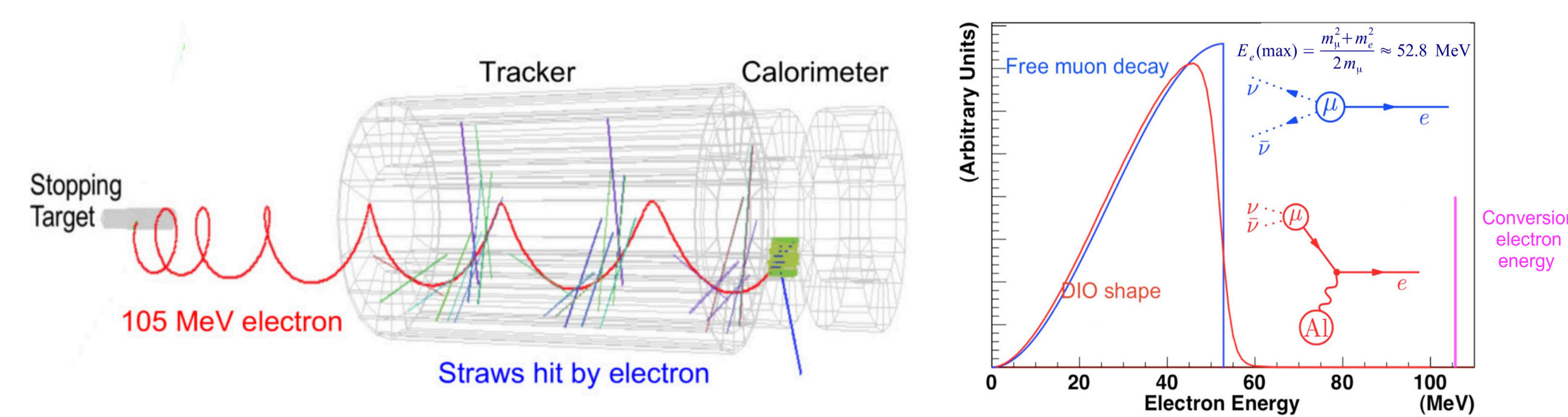


Fig 5. Path of high energy particle through the straw tracker; Energy spectrums of free muon decay, decay-in-orbit, and monoenergetic conversion electron².

- Particles produced from stopping target pass through straws
- Interaction ionizes ArCO₂ gas in straws
- Ionized particles drift to wire inside straws and produce signals

Modeling Drift with ML

A deep neural net (DNN) machine learning model is trained in the task of multi-variable regression on simulated input data to construct a predictive model for the drift of ionized particles.

Training Variables

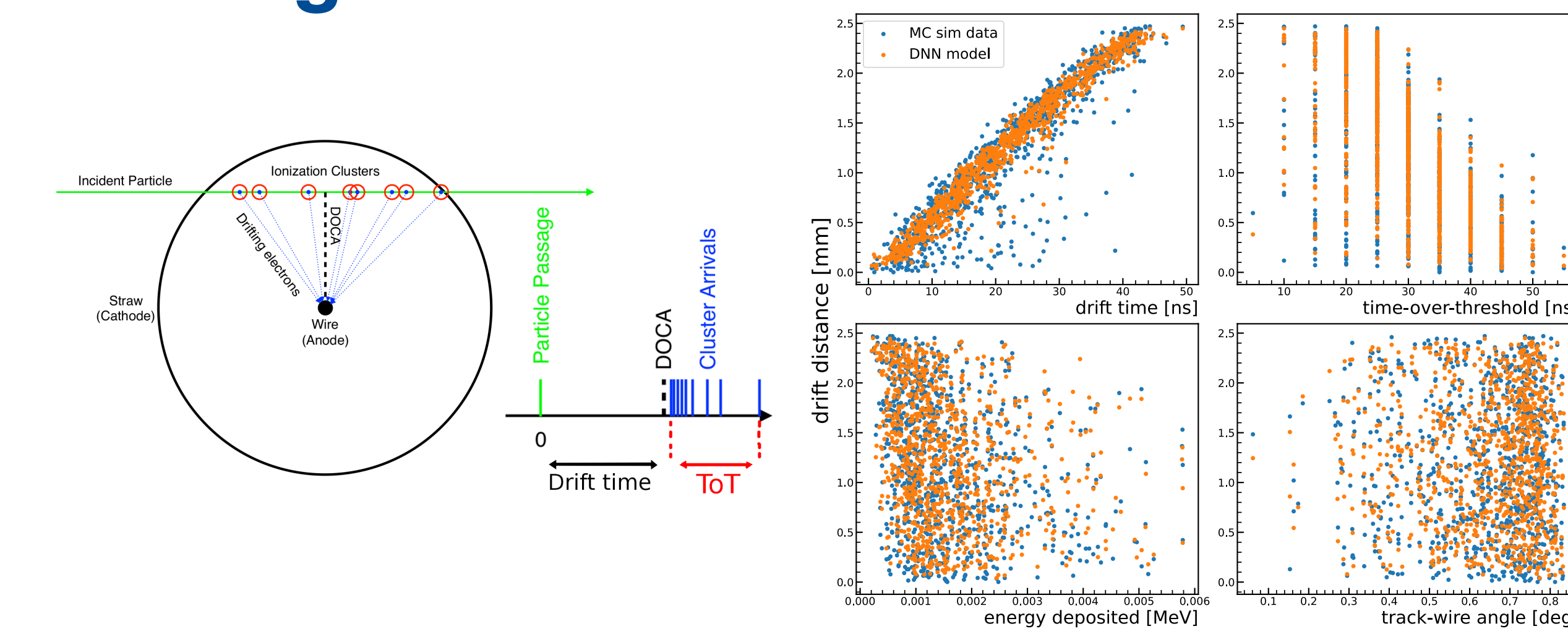


Fig 6. Cross section of straw showing drift of ionized particles²; plots showing correlation between selected input variables and drift distance.

- Drift time
- Time-over-threshold
- Energy deposited
- Angle between straw and track
- Lorentz angle

Model Resolution

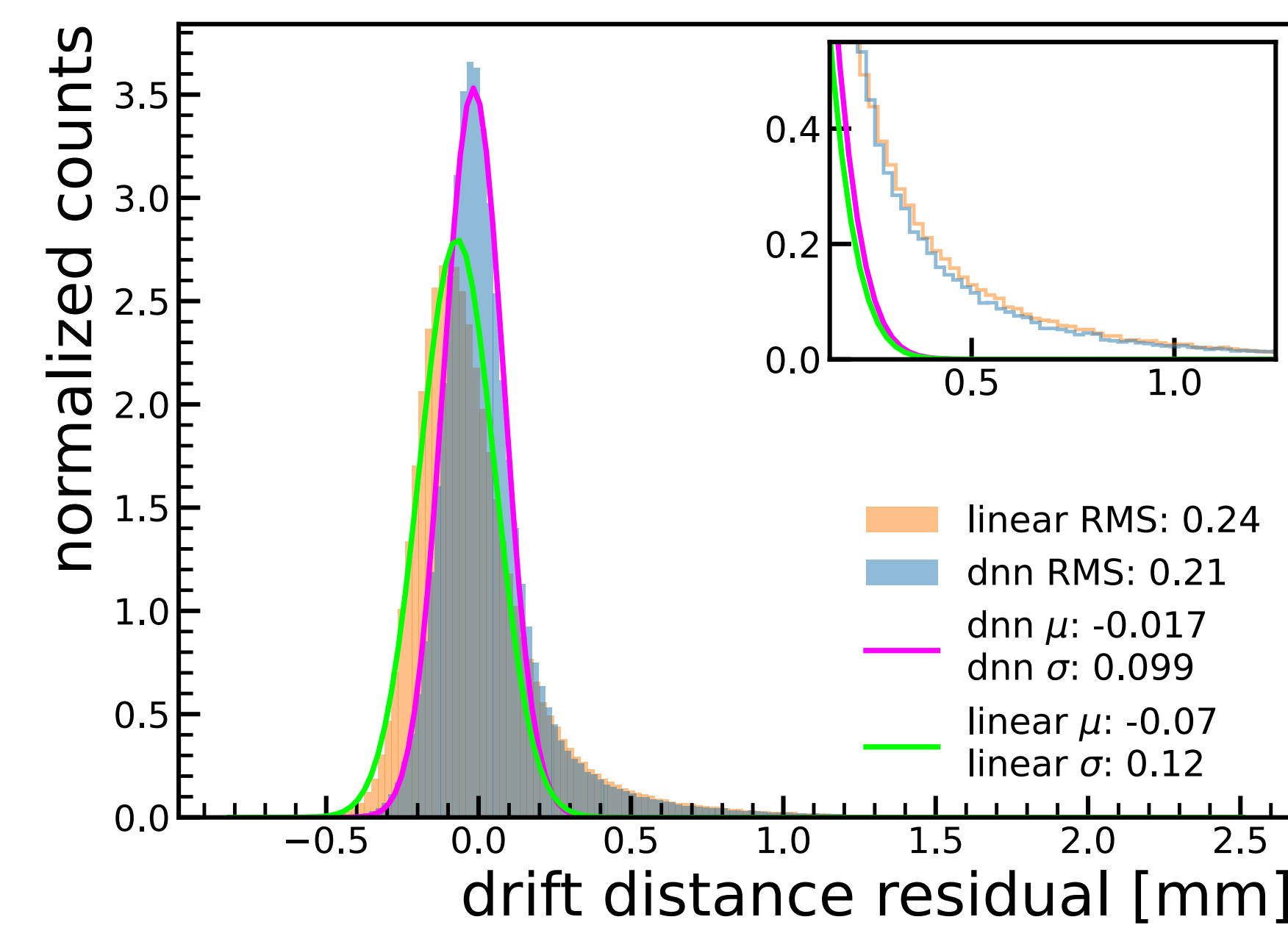


Fig 7. Drift residual from multi-variable DNN model and single-variable linear model

The trained model shows a 20% improvement in resolution over the reference linear model.

Acknowledgements and References

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¹ Custom svg created by Cushman.
² Search in Aluminum, Universe 2023, 9, 54, <https://doi.org/10.3390/universe9010054>
³ Miyashita T. The mu2e experiment. In: Presentation at 51st Annual Fermilab Users Meeting (2018). Available online at: <https://indico.fnal.gov/event/16332/session/5/contribution/17/material/slides/0.pdf>
⁴ Mu2e Collaboration: Mu2e Run 1 Sensitivity Projections for the Neutrinoless $\mu \rightarrow e$ Conversion



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