Reconstructing Neutrino Interactions with Machine Learning

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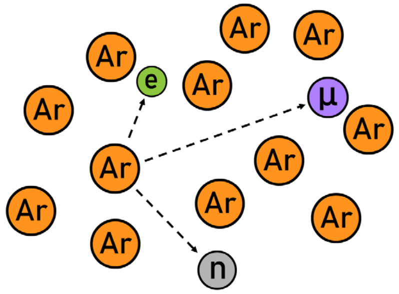
Mentored by Dr. David Caratelli and Chuyue "Michaelia" Fang

UCSB Physics REU 2025

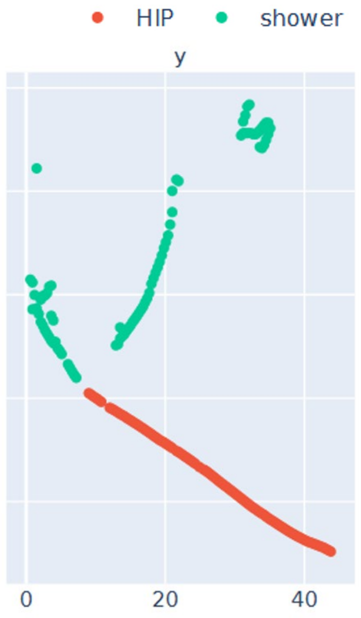
Outline

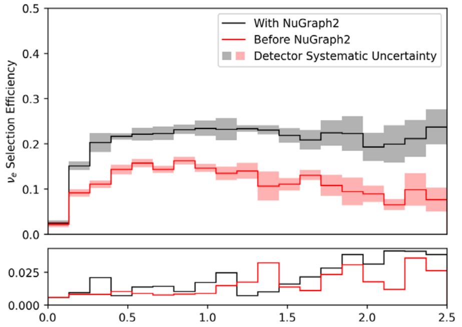
What are neutrinos?



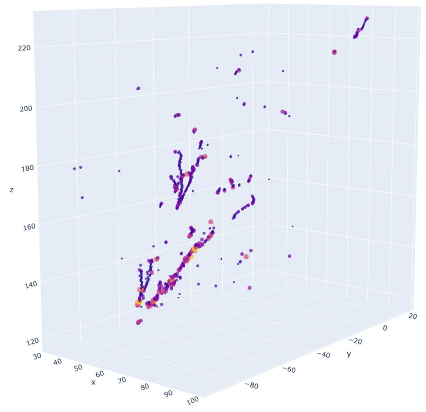
How do we detect them?

What tools do we use to analyze them?





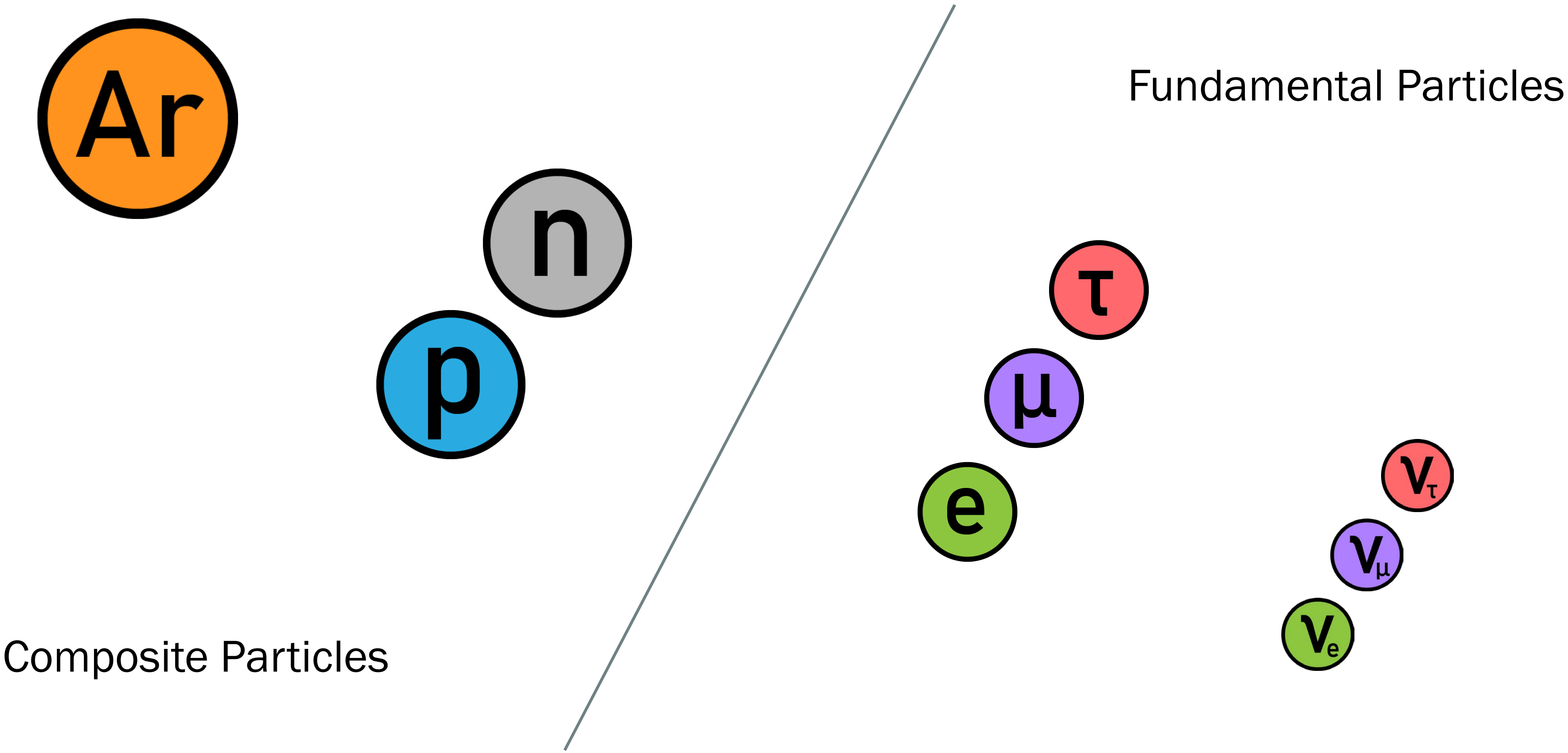
Can we improve these tools?



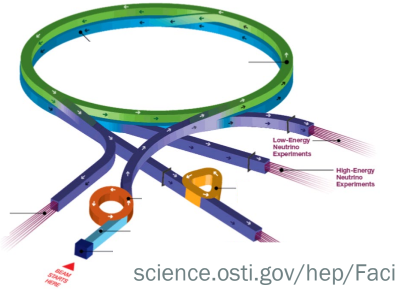
What are Neutrinos?

Mass, Flavor, Oscillations

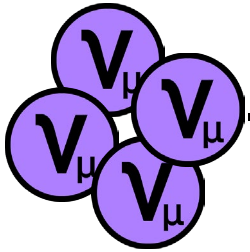
Neutrinos are the lightest massive particles in the Standard Model

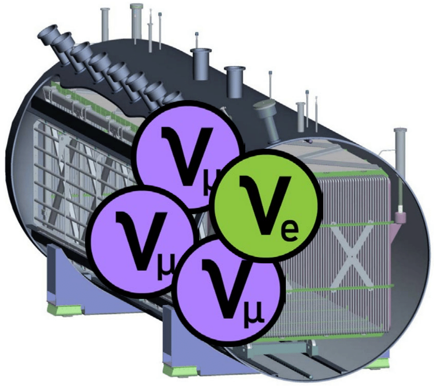


Three flavors of neutrinos oscillate between each other



science.osti.gov/hep/Facilities/User-Facilities/Fermilab-Accelerator-Complex





Booster Neutrino Beam creates trillions of neutrinos

The neutrinos have a chance of being detected as an electron neutrino

MicroBooNE Detector
https://microboone.fnal.gov/images-videos/

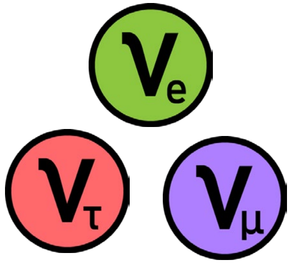
Oscillations require neutrinos to have mass ⟶ The Standard Model is incomplete

Motivation for increased precision in neutrino oscillation measurements

Where do the masses of neutrinos come from?

<< Mass of other particles

Multiple competing theories that predict sterile neutrinos



Sterile = Even fewer interactions

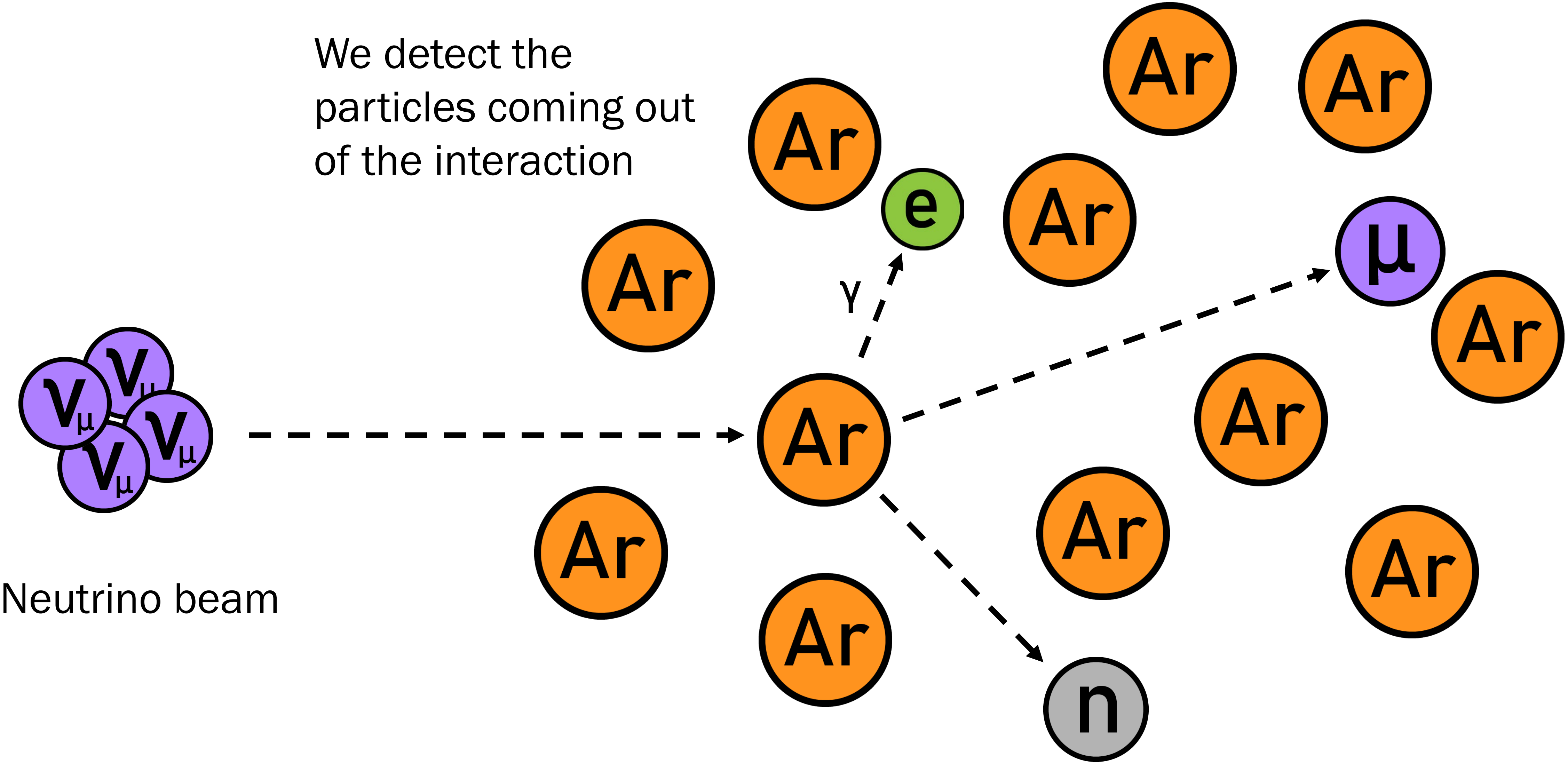
Neutrinos could help explain matter-antimatter asymmetry via CP-violation

Neutrino Detection in LArTPC

Ionization Charge, Showers vs. Tracks, Charge Collection

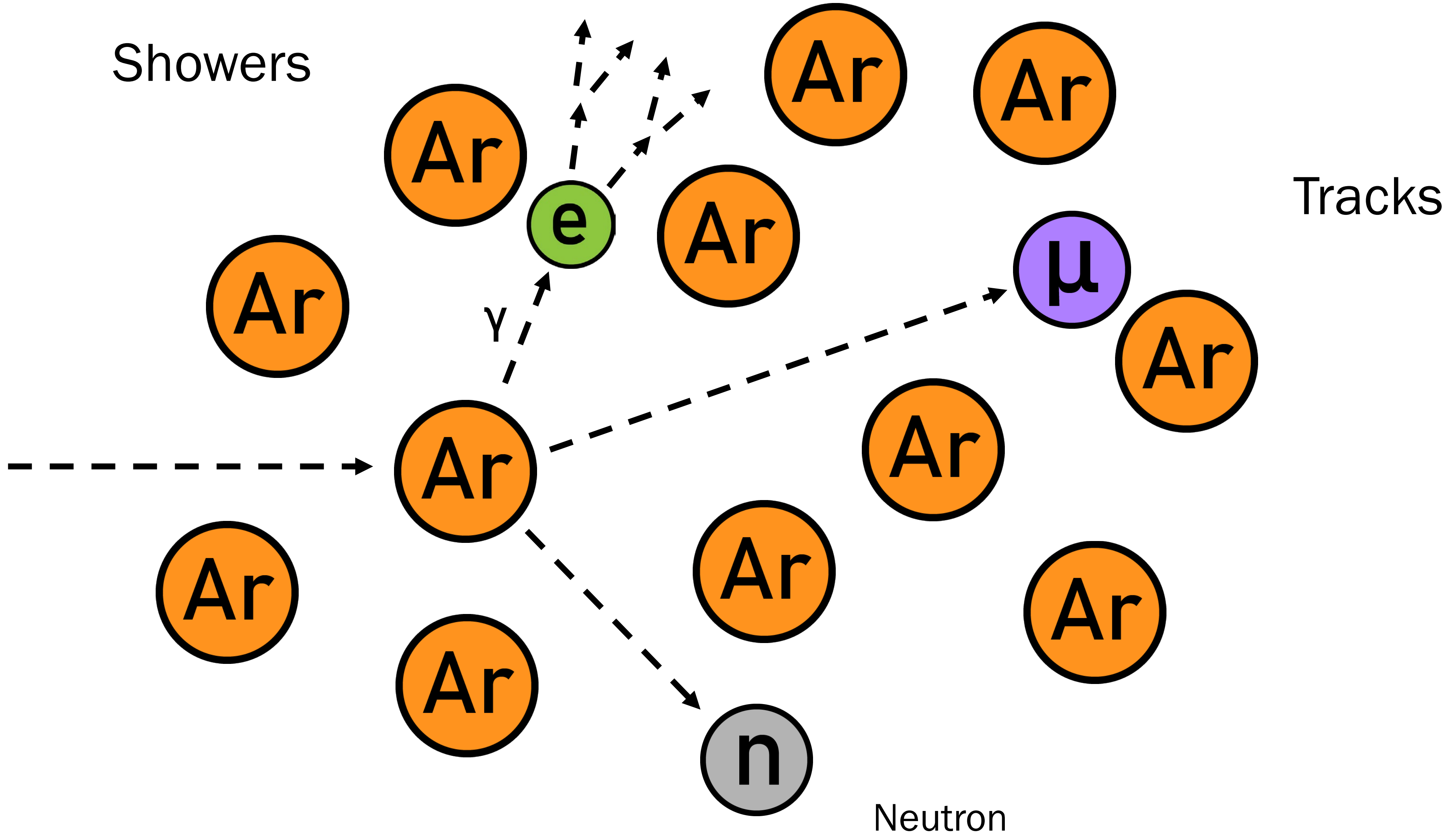
Liquid Argon Time Projection Chambers (LArTPC)

We detect the particles coming out of the interaction

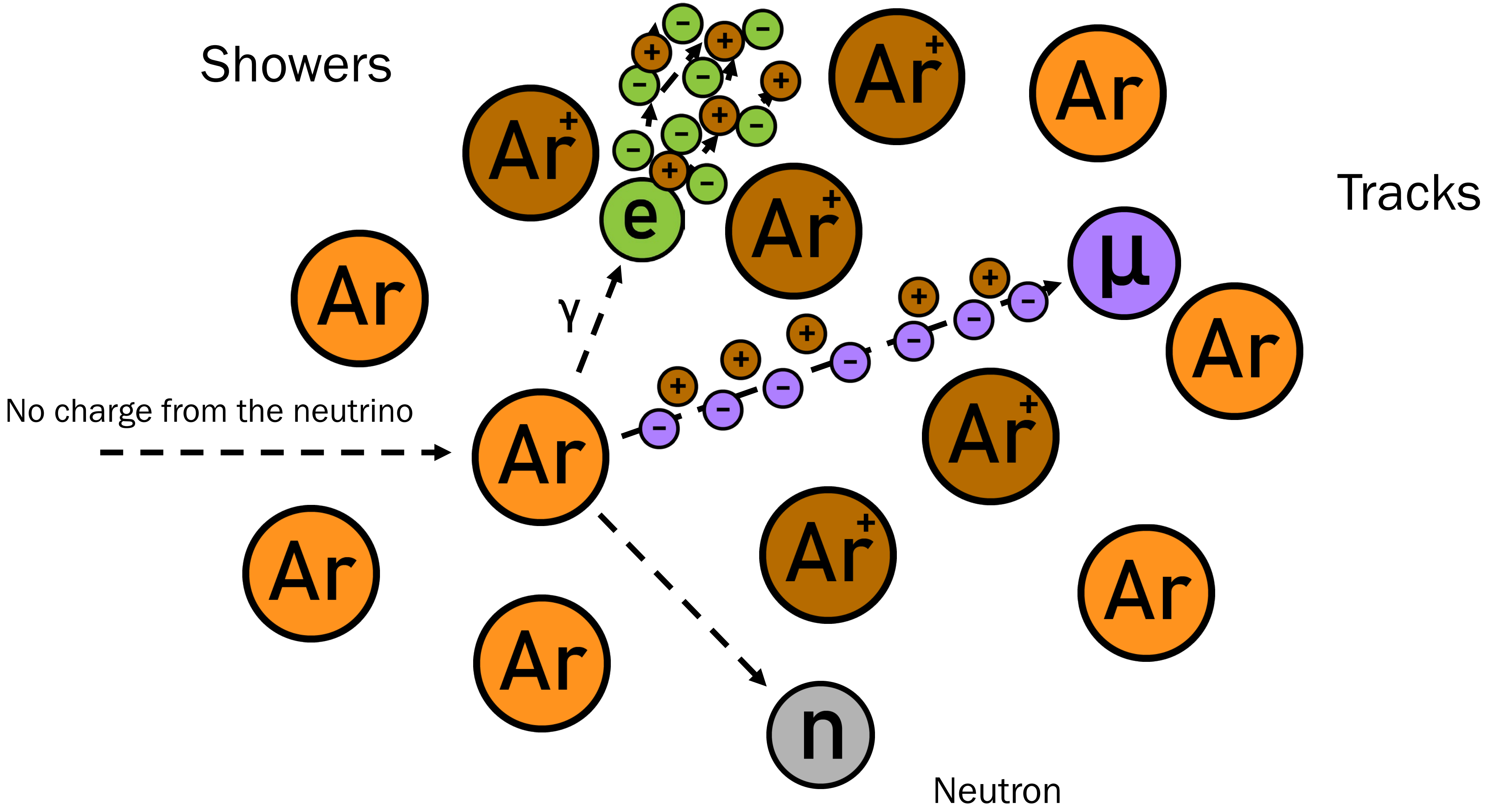


Neutrino beam

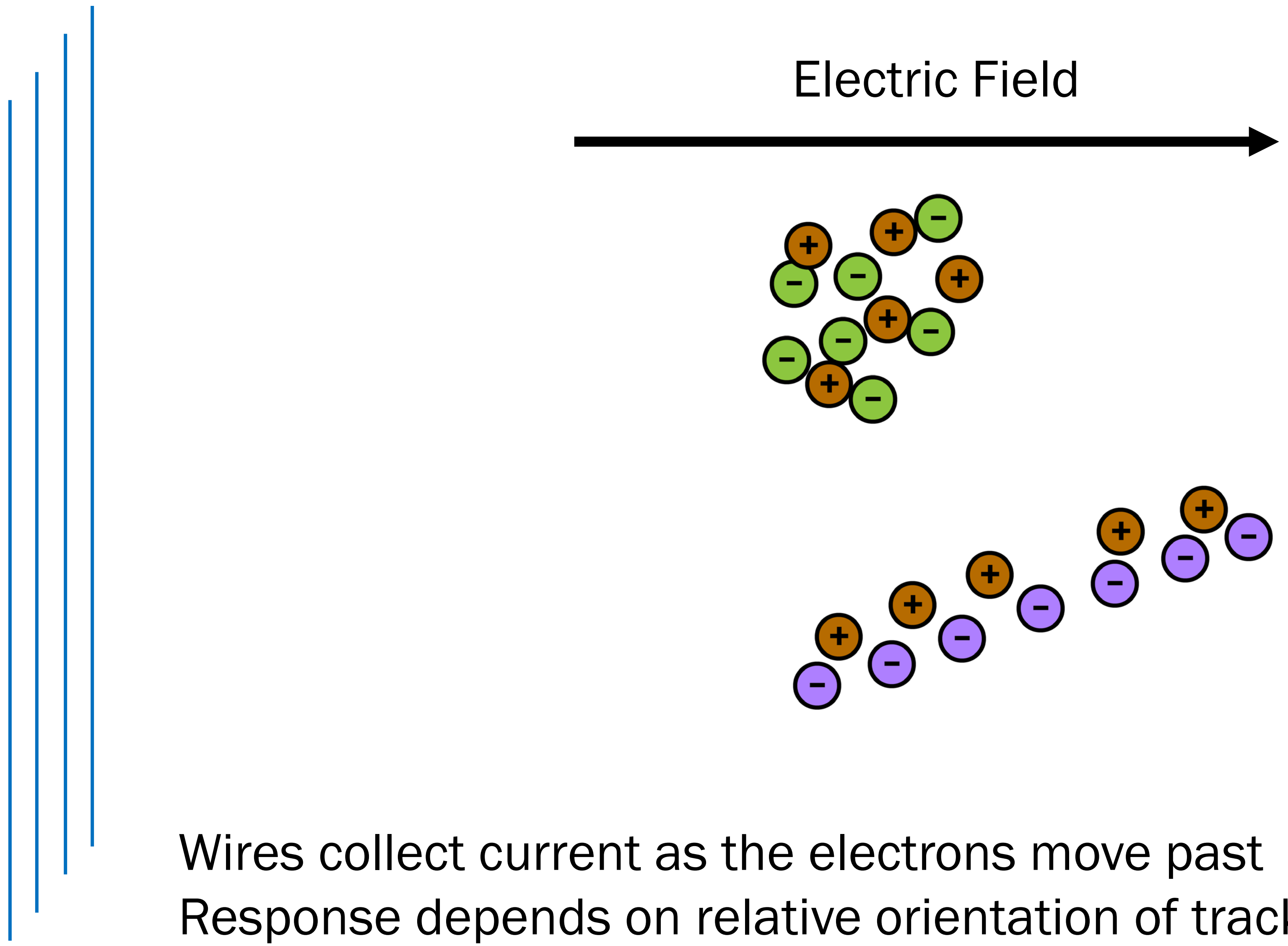
Different particles leave different charge signatures



Different particles leave different charge signatures

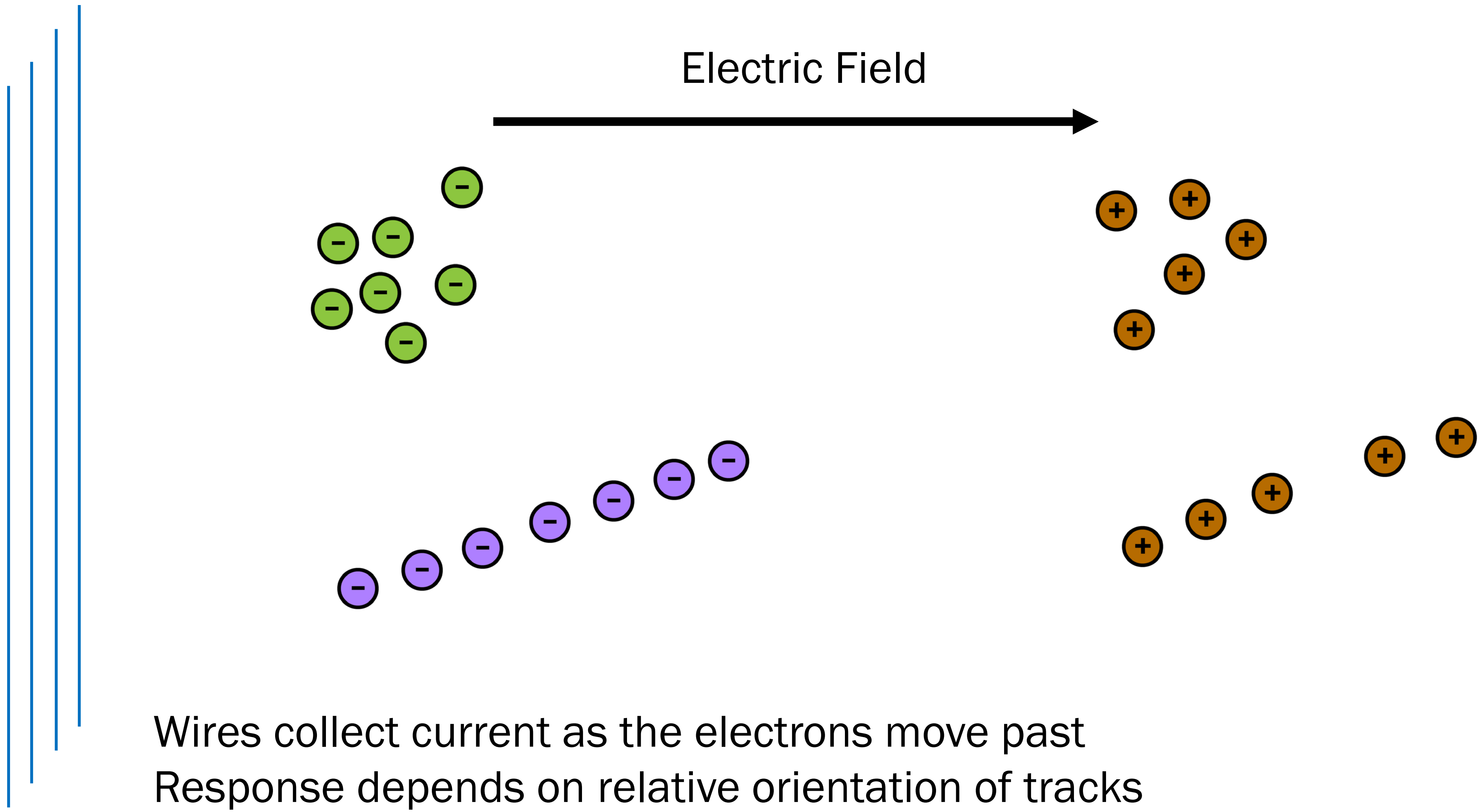


We separate the charges with an electric field



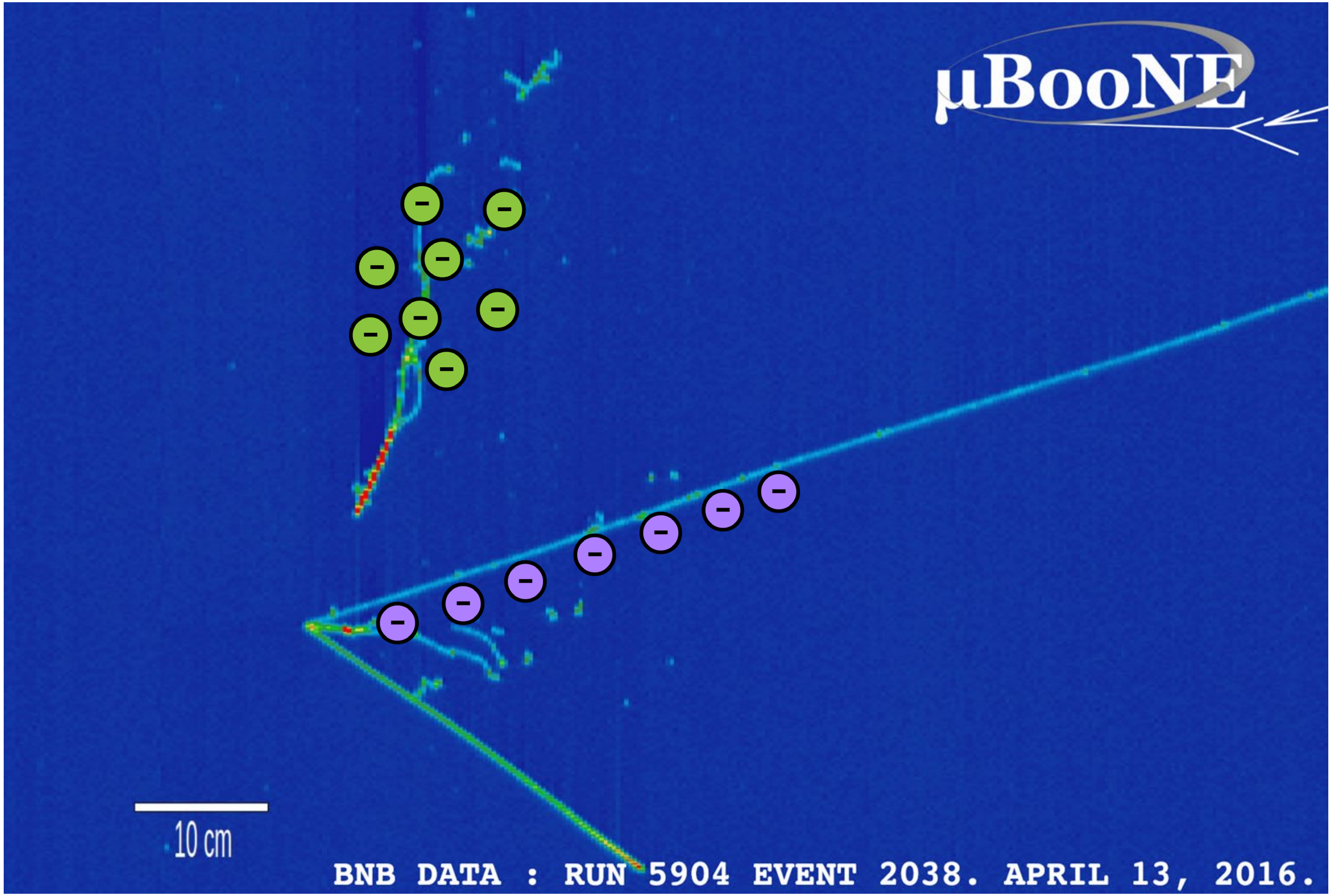
Wires collect current as the electrons move past
Response depends on relative orientation of tracks

We separate the charges with an electric field



Wires collect current as the electrons move past
Response depends on relative orientation of tracks

The detector creates images of charge and time



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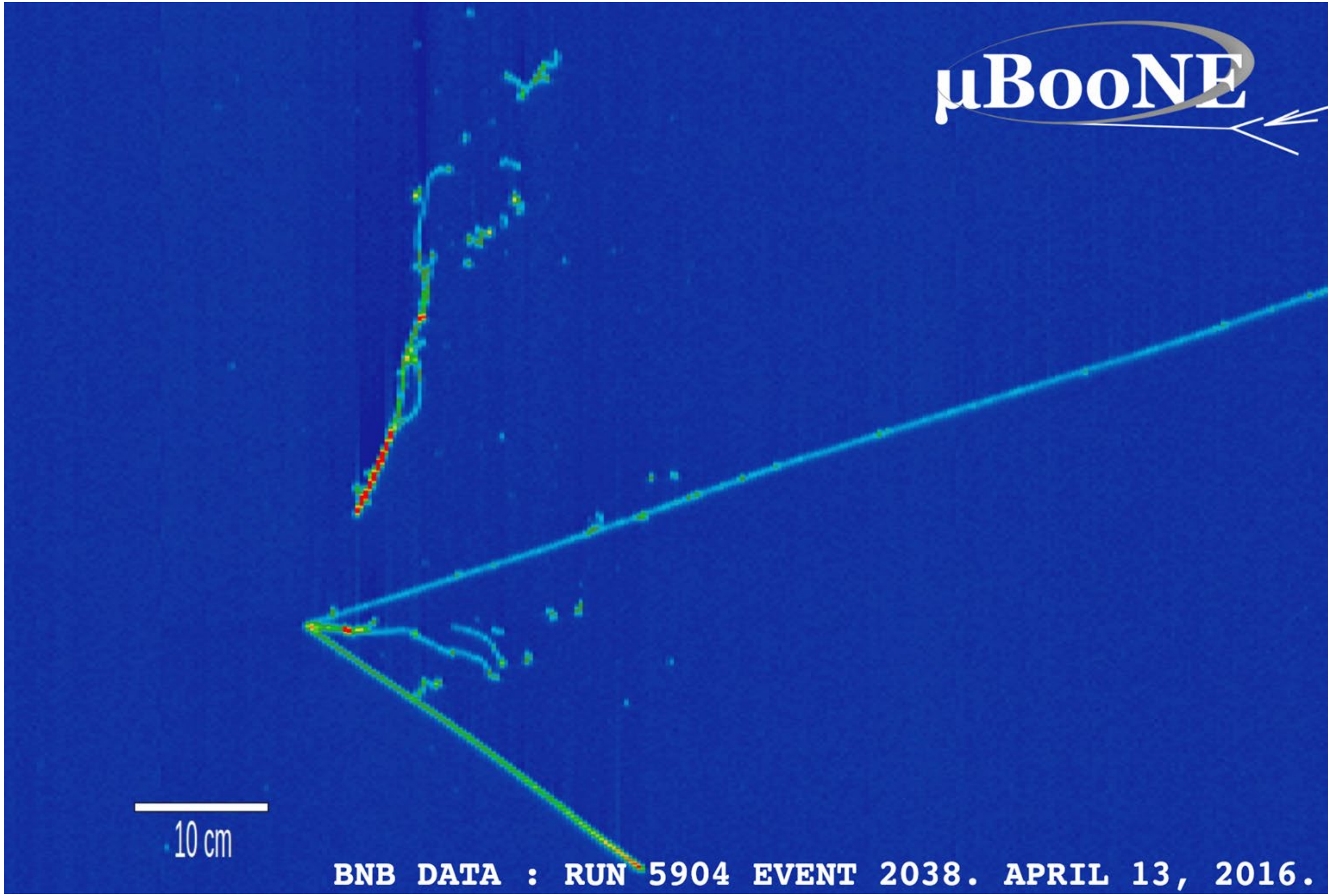
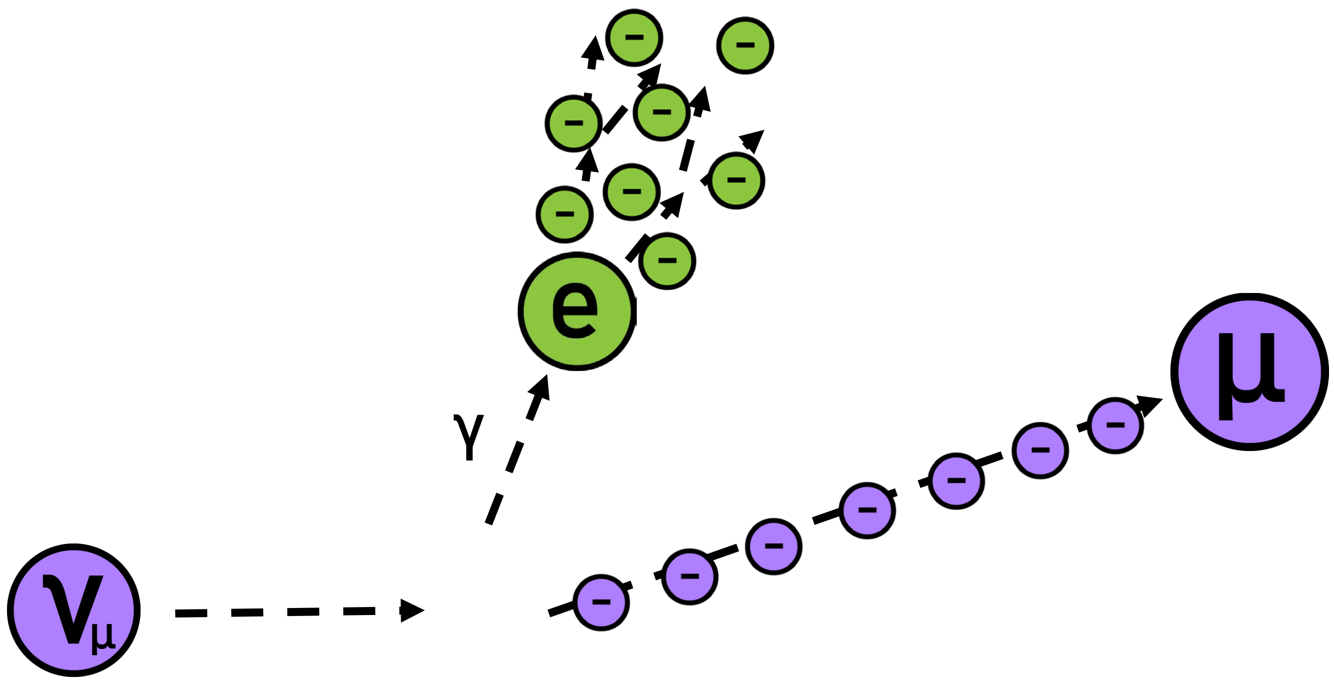


Reconstruction with NuGraph2

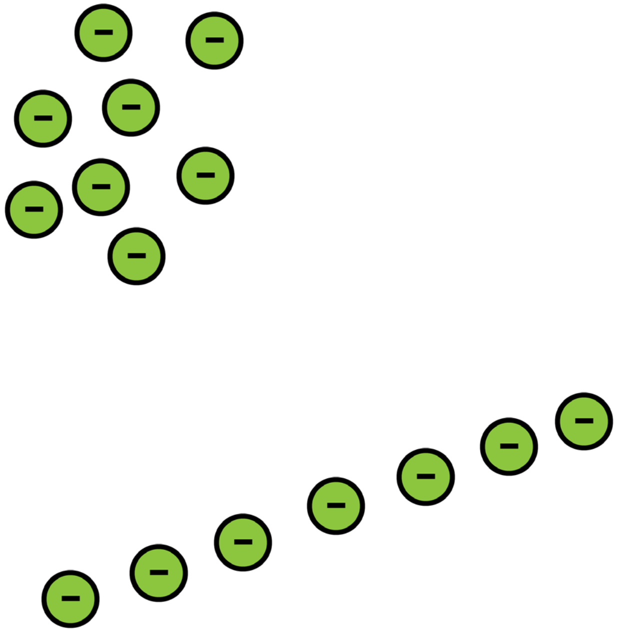
Application of Machine Learning

Reconstruction algorithms predict what occurred



In simulations we know the truth about the source of each charge deposit…

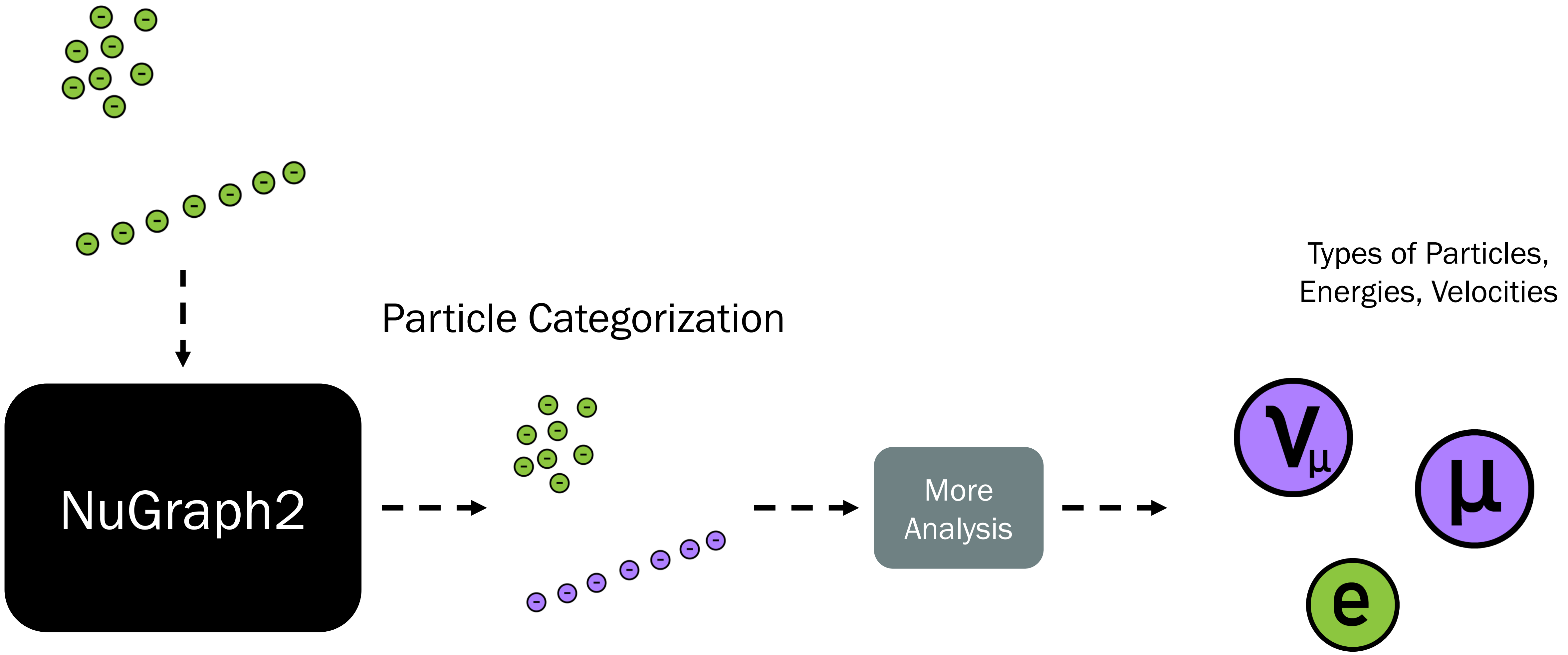
Reconstruction algorithms predict what occurred



In simulations we know the truth about the source of each charge deposit…

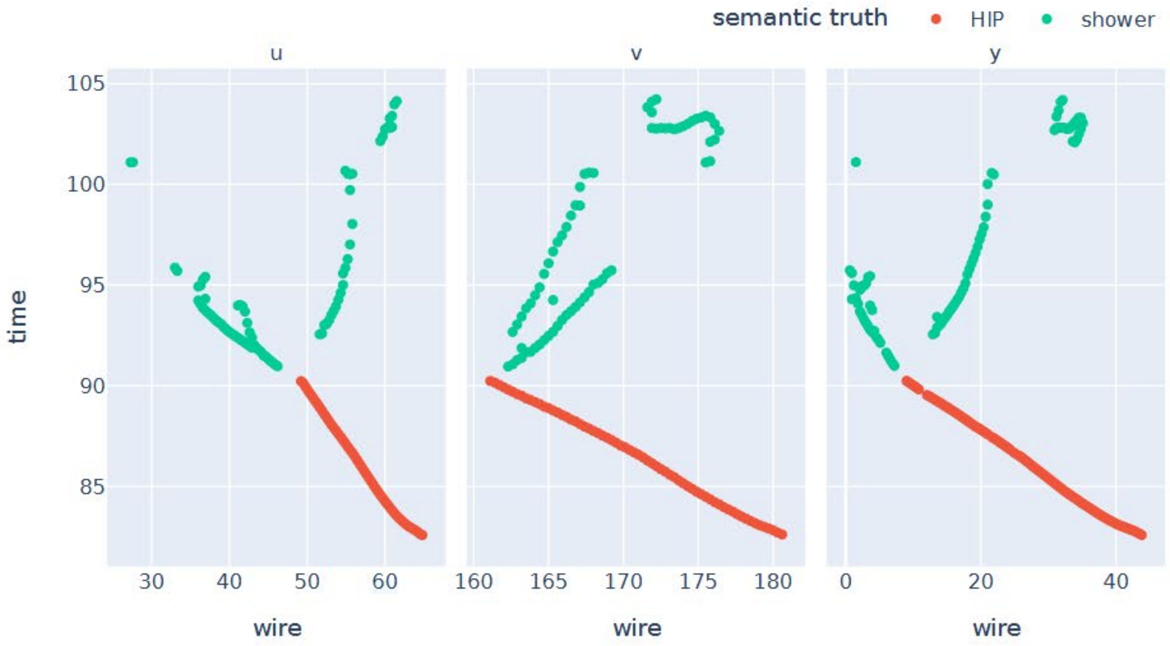
But not on real data

Neural networks play a crucial role in reconstruction

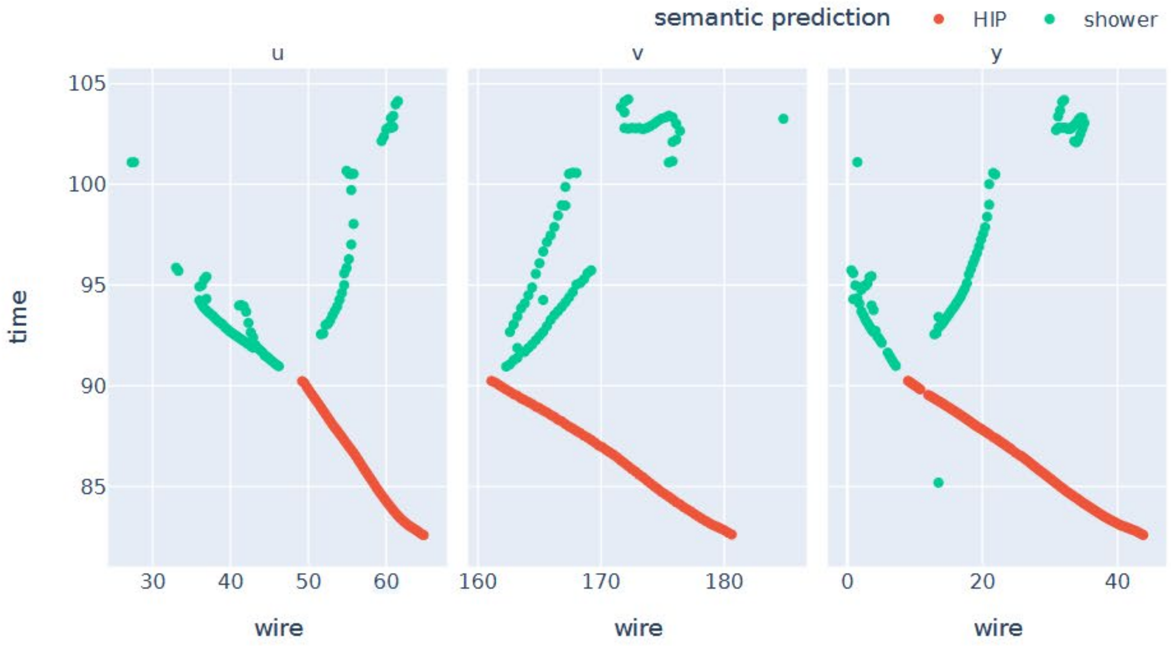


NuGraph2 particle identification performs at 95%

Simulation Truth



NuGraph2 Prediction



These look very similar!

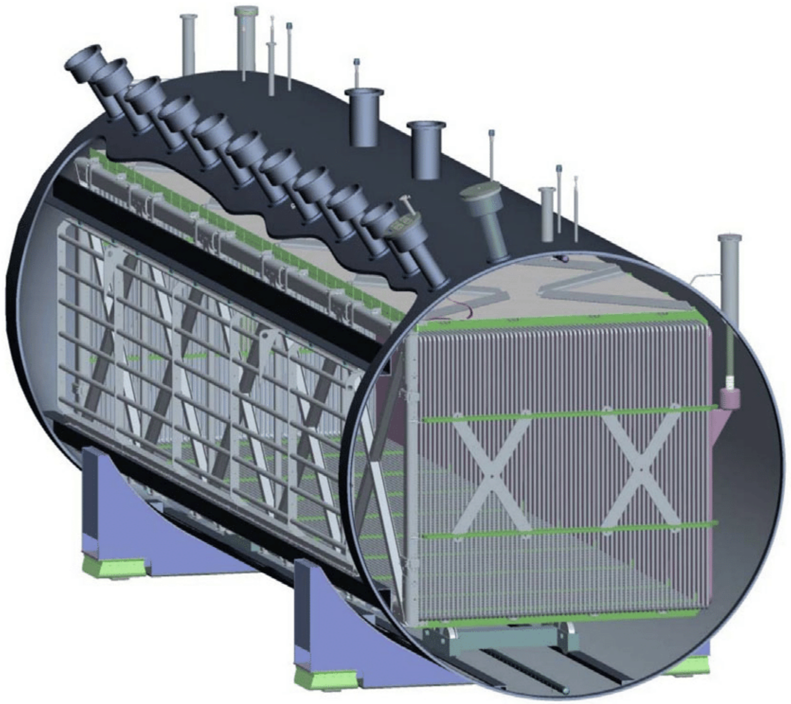
Hewes, V. et al. (2024). Graph Neural Network for Neutrino Physics Event Reconstruction. *Physical Review D*, *110*(3), 032008.
https://doi.org/10.1103/PhysRevD.110.032008

Detector Modeling Uncertainties

Wire Modifications, ν_e Selection Efficiency

How sensitive is NuGraph2 to the uncertainties in real data?

Modify simulated data to create more realistic data samples



Central Value

Detector Systematic Uncertainties

↔

Change the wire current waveforms

Detector Variations

Abratenko, P., An, R., Anthony, J. *et al.* Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data. *Eur. Phys. J. C* **82**, 454 (2022). https://doi.org/10.1140/epjc/s10052-022-10270-8

https://microboone.fnal.gov/images-videos/

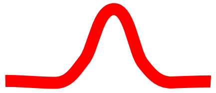
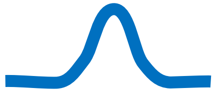
Wire modifications

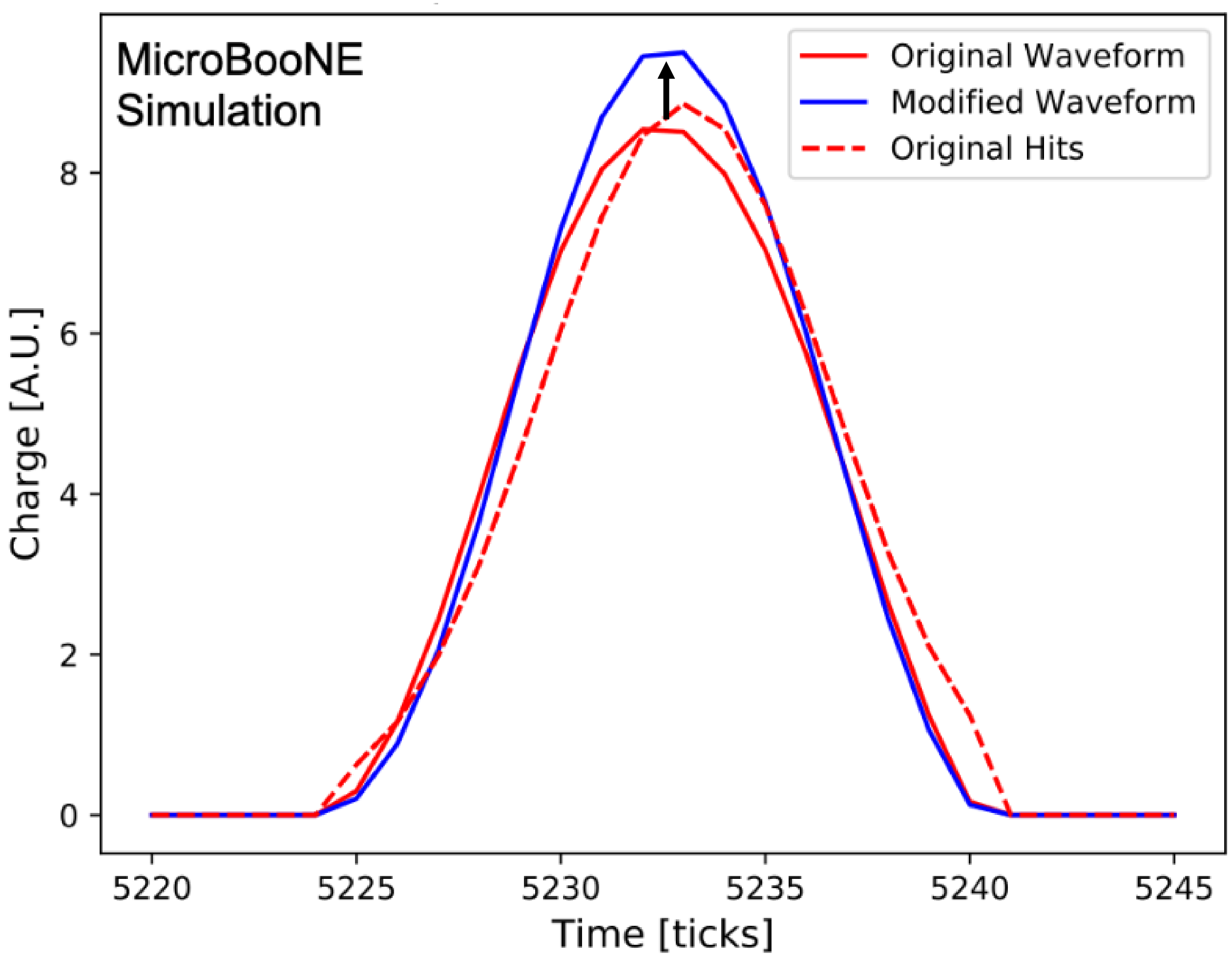
5 Variables

- Track positions (X, YZ)
- Track angles w.r.t. wire planes (θ_{XZ}, θ_{YZ})
- Charge scaling ($\frac{dE}{dx}$)

Width and charge of waveforms changed to align with experimental data

Ex: Scale X

f( , X) → 



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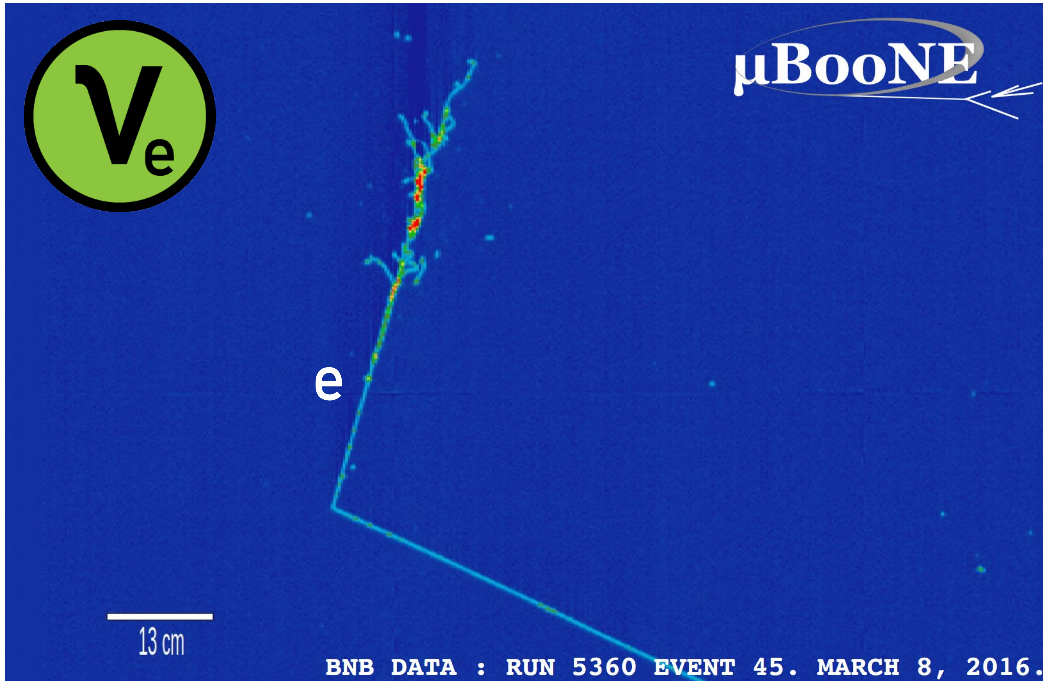
NuGraph2 is particularly good at picking out electron neutrinos

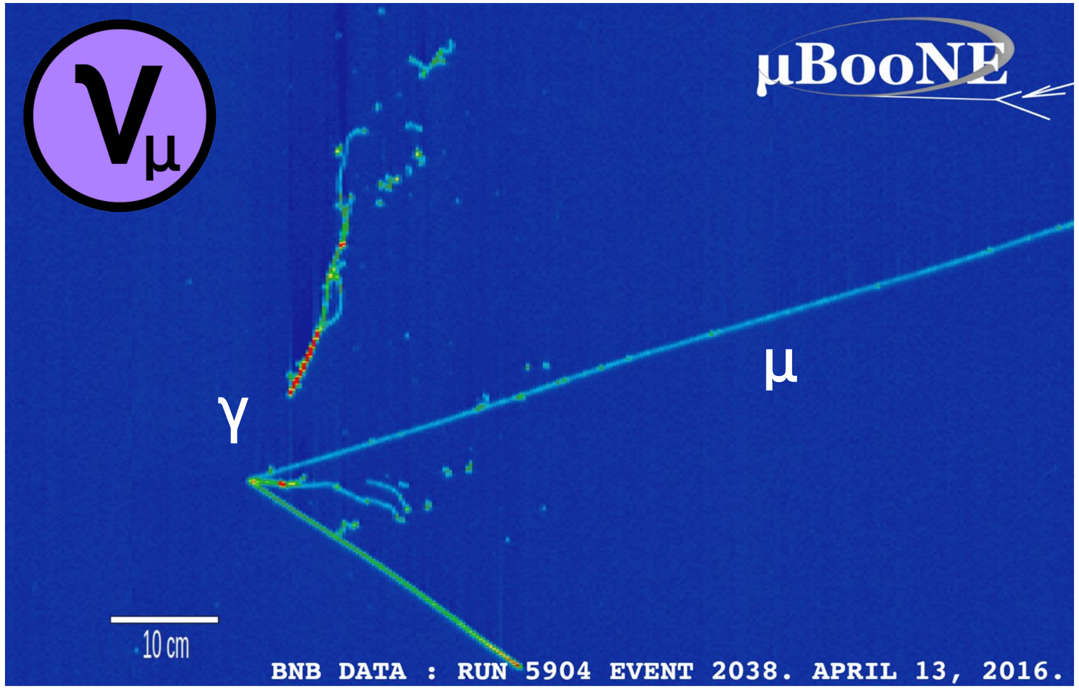
Apply a series of selection criteria

Looking for an electron shower

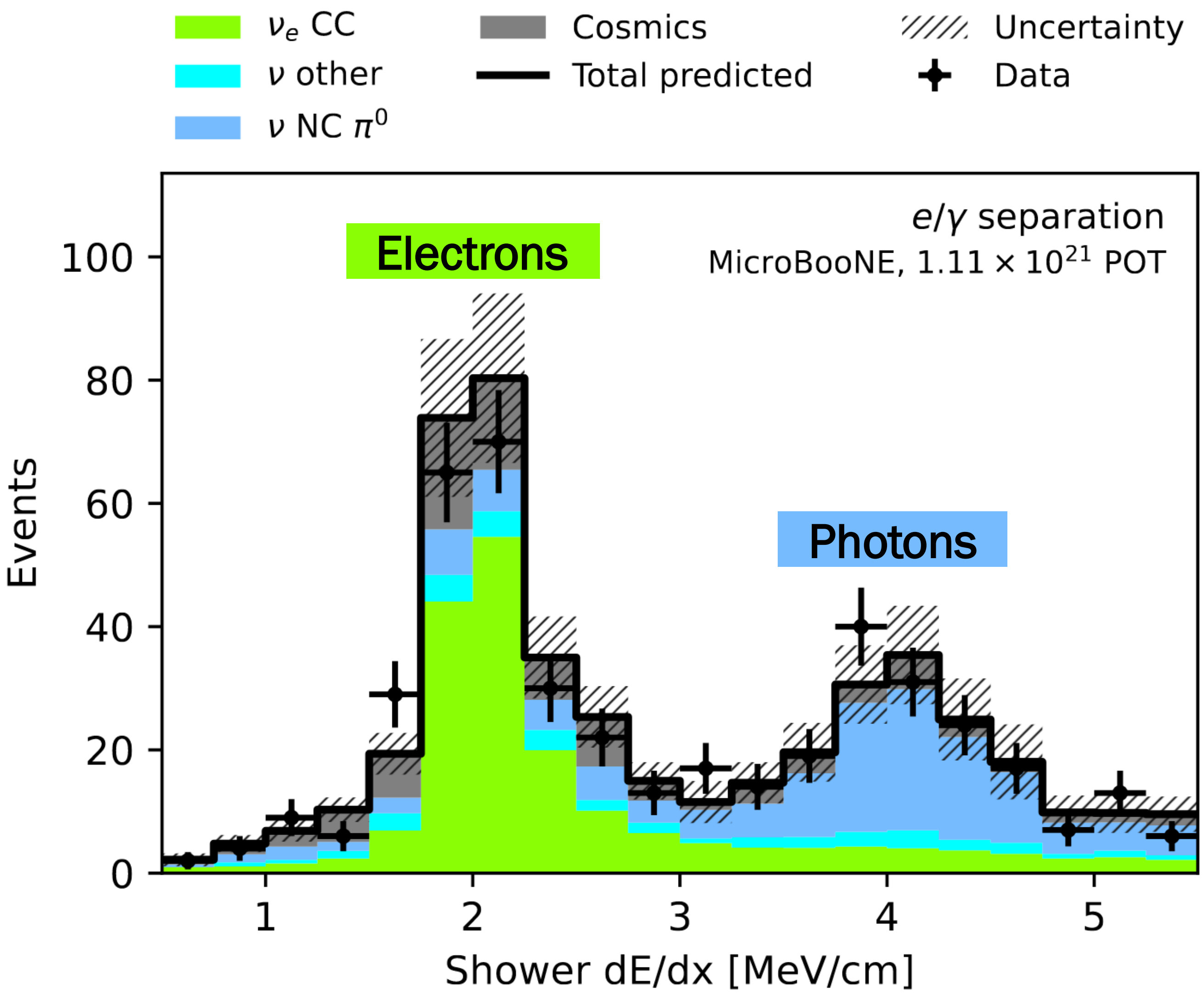
Electron neutrinos create electrons



Muon neutrinos create muons (and photons)



Example Cut: Distinguishing electrons and photons with shower $\frac{dE}{dx}$

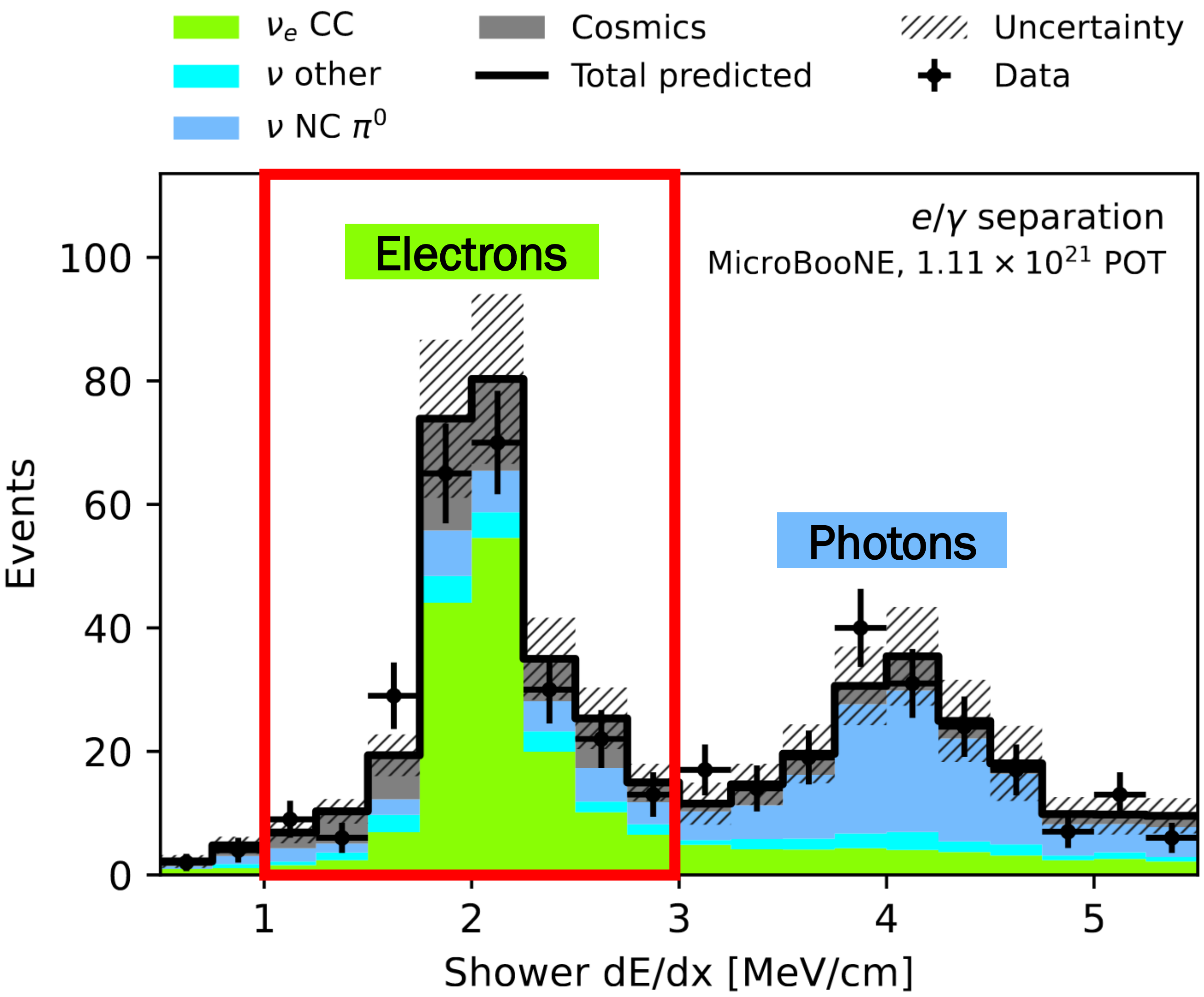


Photon showers peak at double the energy of electron showers

MicroBooNE Collaboration (2024). *Search for an Anomalous Production of Charged-Current v_e Interactions Without Visible Pions Across Multiple Kinematic Observables in MicroBooNE* (No. arXiv:2412.14407). arXiv. https://doi.org/10.48550/arXiv.2412.14407

Example Cut: Distinguishing electrons and photons with shower $\frac{dE}{dx}$

$$1 < \frac{dE}{dx} < 3$$



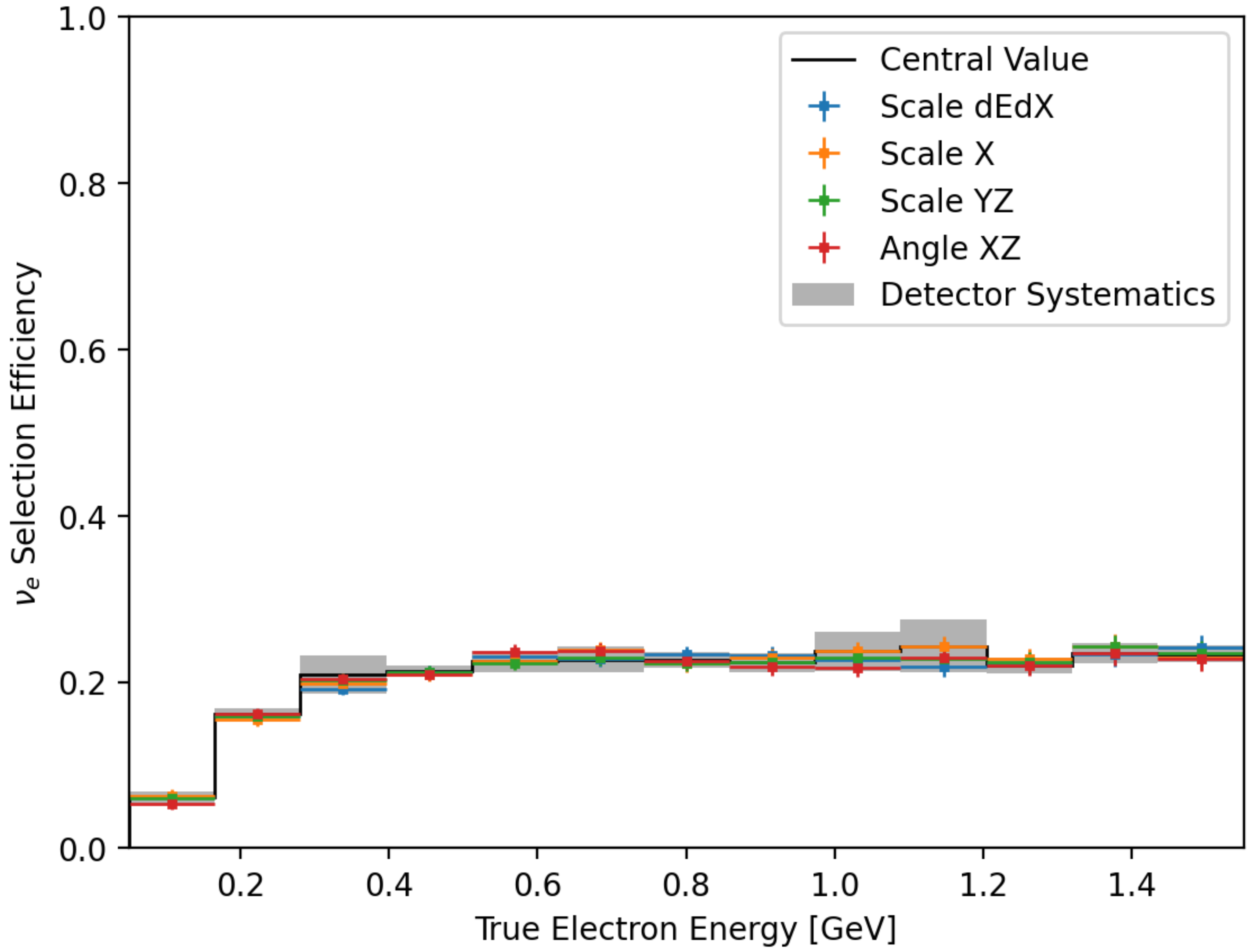
Balance between selection efficiency and selection purity

MicroBooNE Collaboration (2024). *Search for an Anomalous Production of Charged-Current v_e Interactions Without Visible Pions Across Multiple Kinematic Observables in MicroBooNE* (No. arXiv:2412.14407). arXiv. https://doi.org/10.48550/arXiv.2412.14407

Selection efficiency also varies due to detector systematic uncertainties

Selection efficiency:
The proportion of target events that are successfully selected

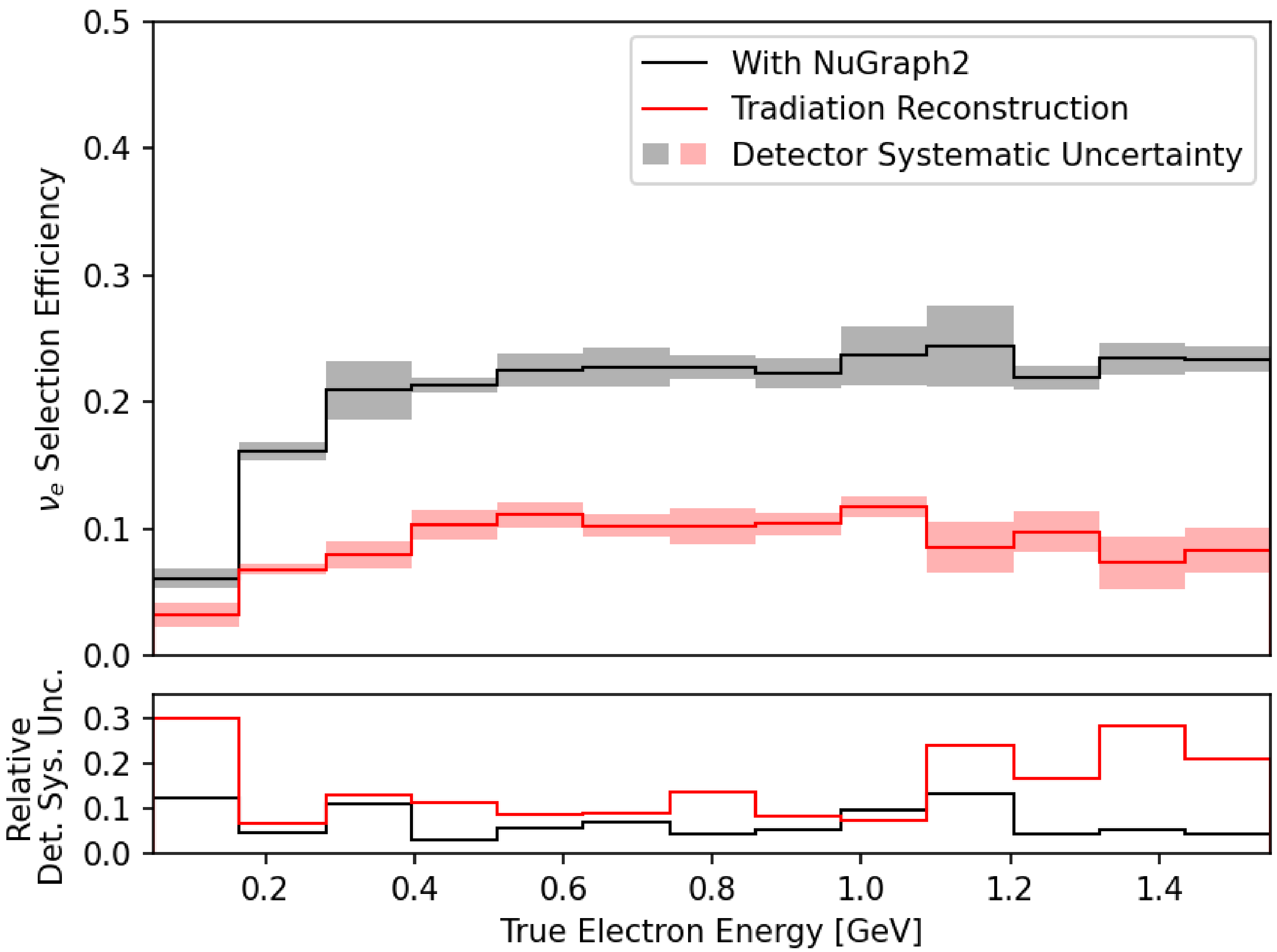
Detector Systematic Uncertainty:
The expected error in the measurement due to mismodeling in the detector simulations



Colors represent different detector variations

Total selection efficiency is 21%

Comparison with analysis before NuGraph2 implementation



Improved selection efficiency

Comparable detector modeling uncertainty

η-π^0 Separation with Machine Learning

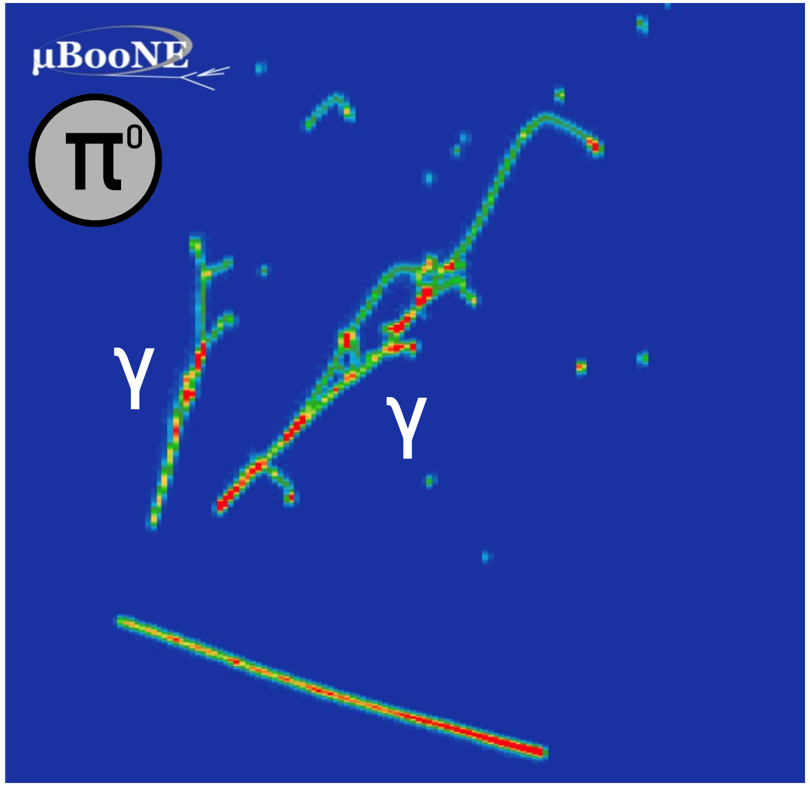
Two Photon Decay, Initial Training

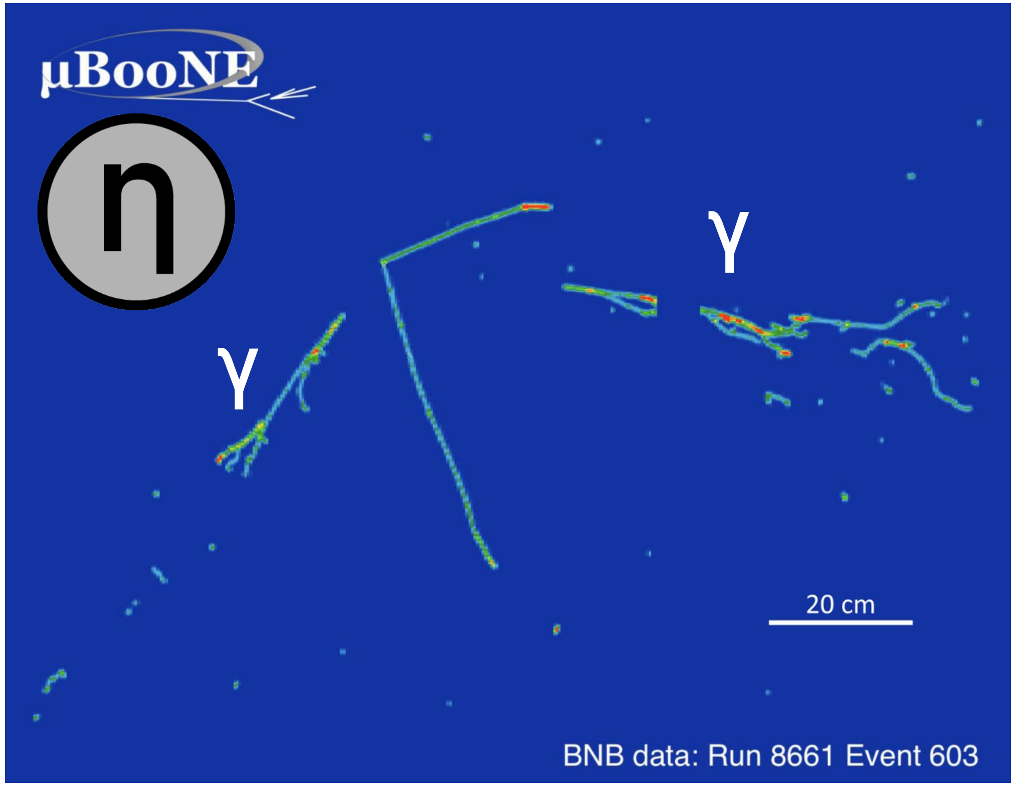
η and π^0 particles both can decay into two photons

Both neutral particles that decay very quickly inside the detector

Current selection efficiency of η is 13.6%

$$M_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\theta_{\gamma\gamma})}$$

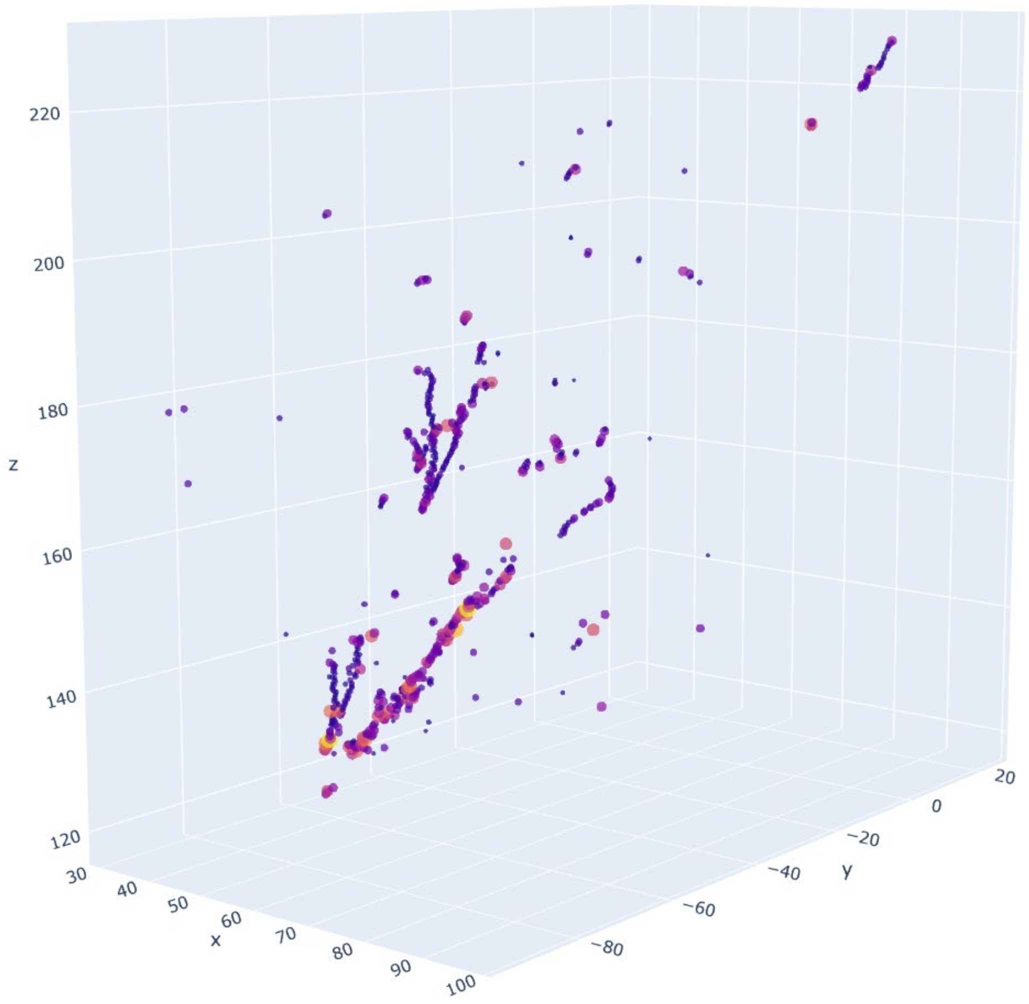




P. Abratenko et al. (MicroBooNE Collaboration), First measurement of η meson production in neutrino interactions on argon with MicroBooNE, Phys. Rev. Lett. 132, 151801 (2024). https://link.aps.org/doi/10.1103/PhysRevLett.132.151801

The PointNeXt model takes in 3D space points as input

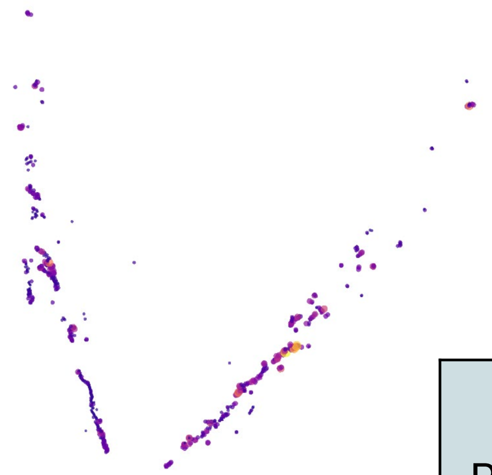
Charge from reconstructed showers



Complex matrix function with thousands of parameters

Scalar output from 0 (π^0) to 1 (η)

Initial training results



π^0 predicted as π^0

Actual Particle Class	Predicted Particle Class	
	π^0	η
π^0	61%	39%
η	31%	69%

π^0 predicted as η

η predicted as π^0

η predicted as η

Acknowledgements

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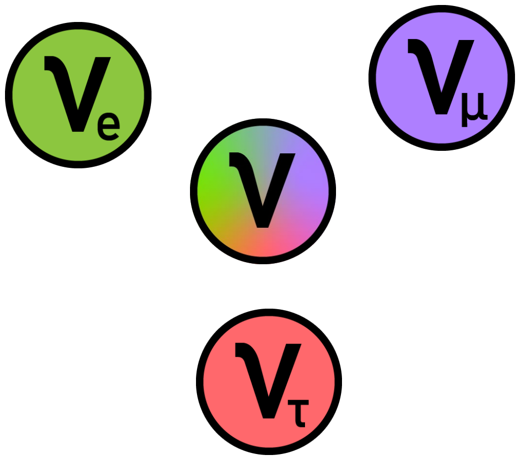
- Professor: Dr. David Caratelli
- Grad Mentor: Chuyue “Michaelia” Fang
- REU Director: Prof. Sathya Guruswamy
- All of the other members of the UCSB neutrino physics group
- The work of the MicroBooNE Collaboration

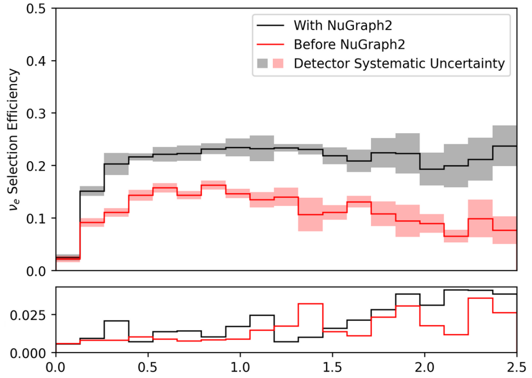
This work is supported by NSF REU grant PHY-2349677

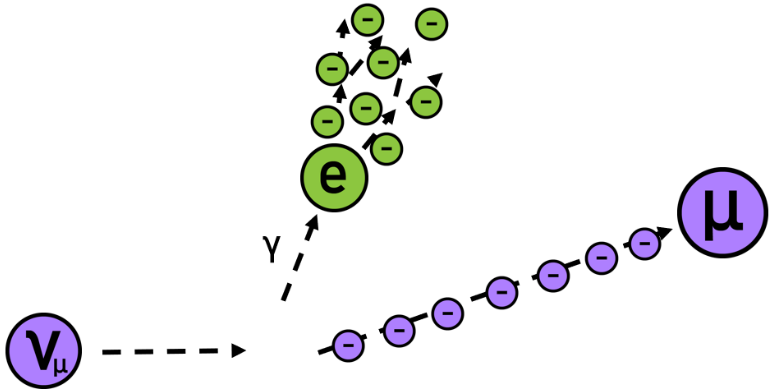
Summary

Neutrino Physics

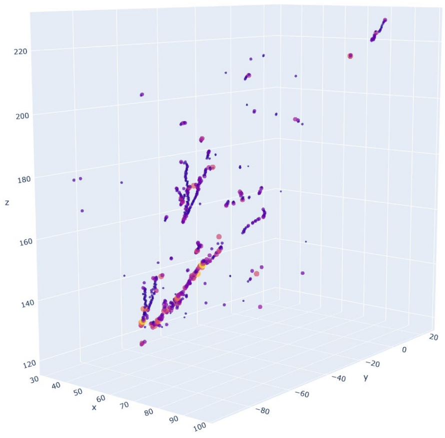


Detector Variation





Event Reconstruction

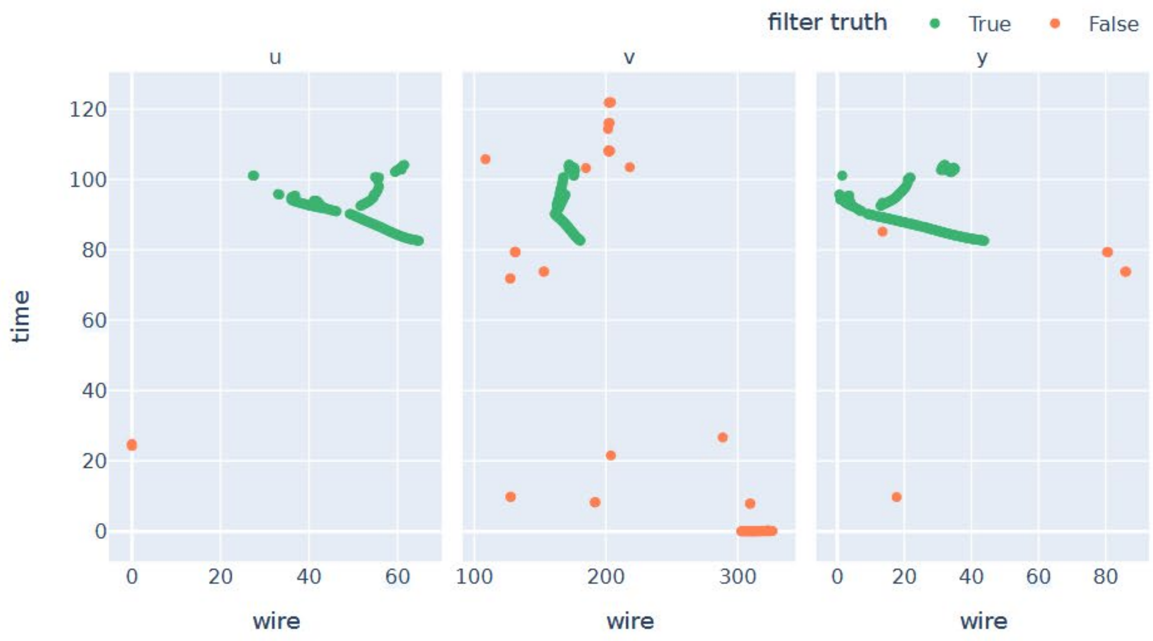


η-π^0 Separation

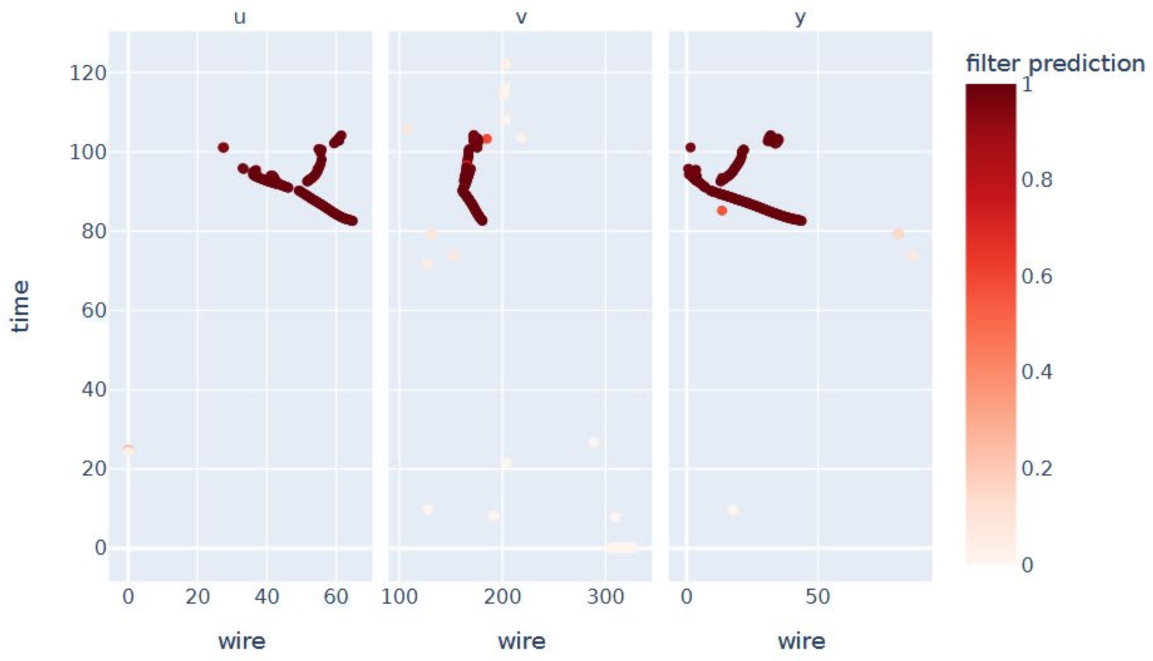
Backup Slides

NuGraph2 cosmic filtering performs at 98%

Simulation Truth



NuGraph2 Prediction



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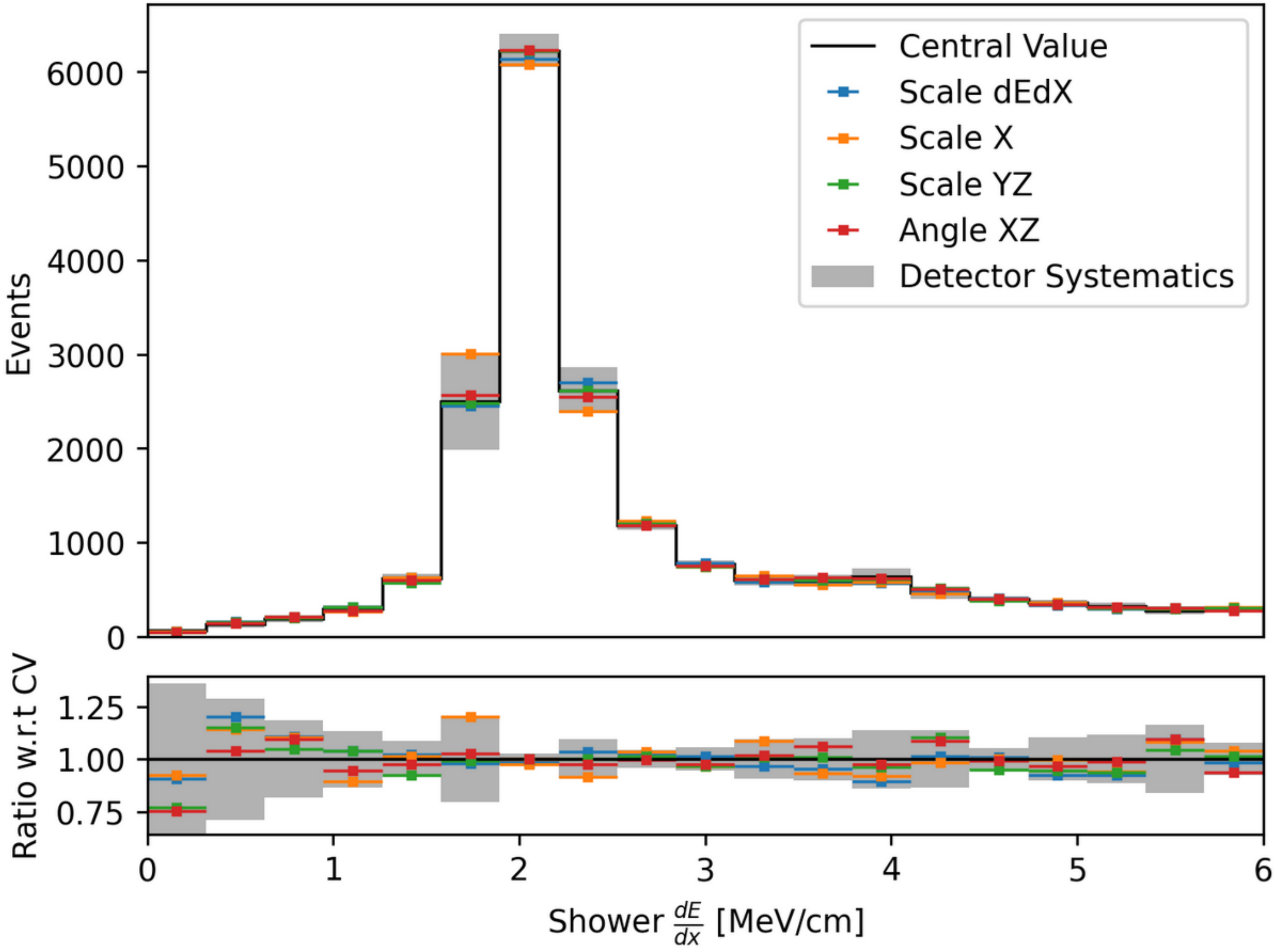
https://doi.org/10.1103/PhysRevD.110.032008

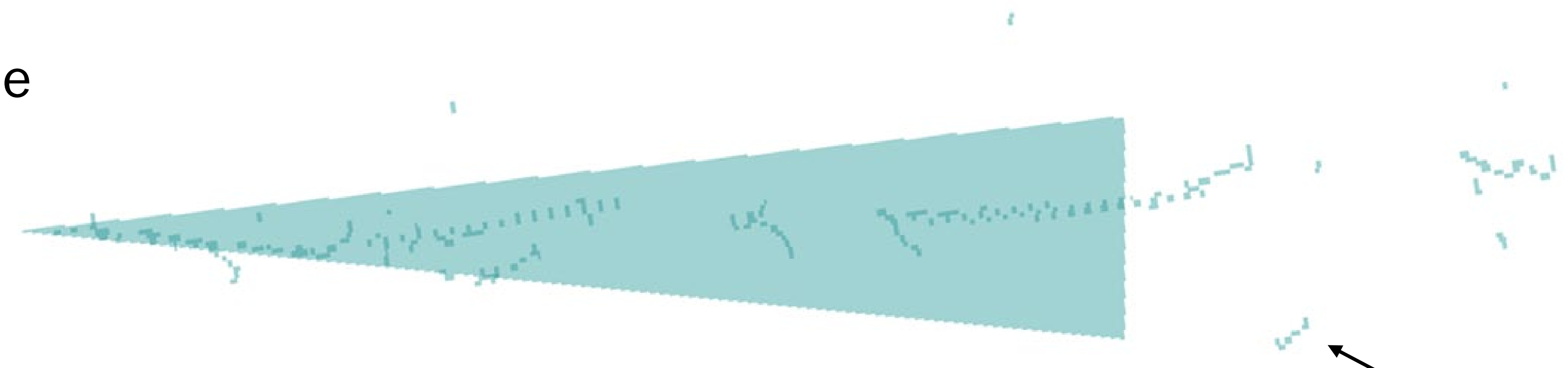
Effect of detector systematic uncertainties on shower $\frac{dE}{dx}$

Simulation data from just ν_e events



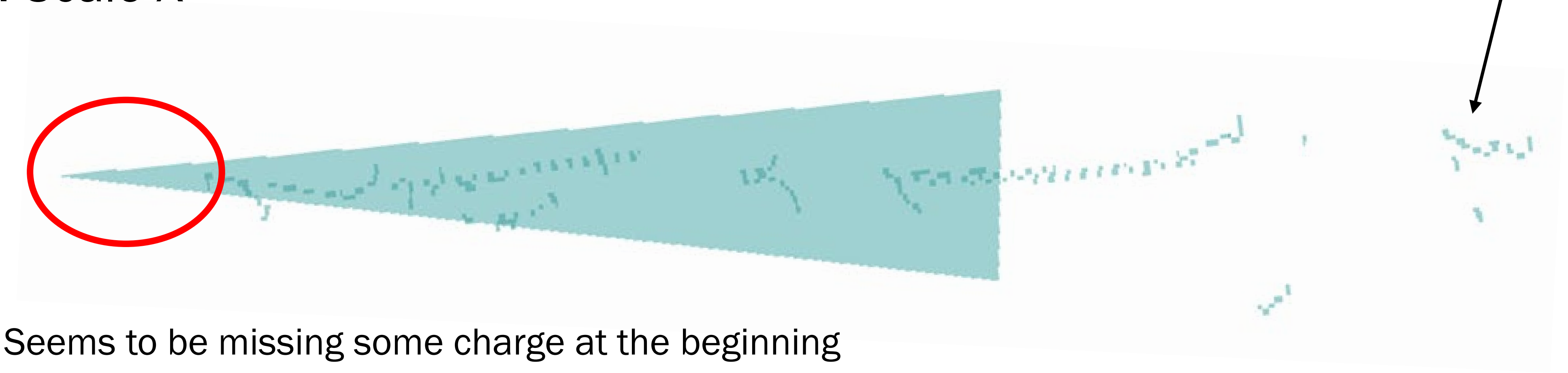
Zoomed and rotated view of electron shower in run 7008, event 22297

Central Value



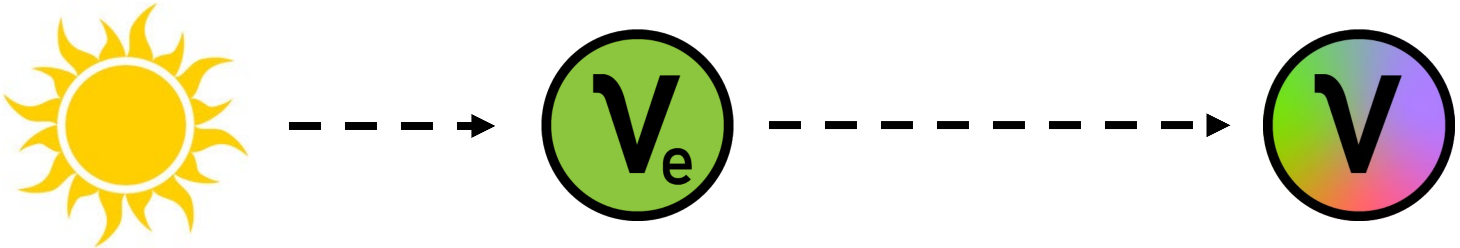
Charge Hits

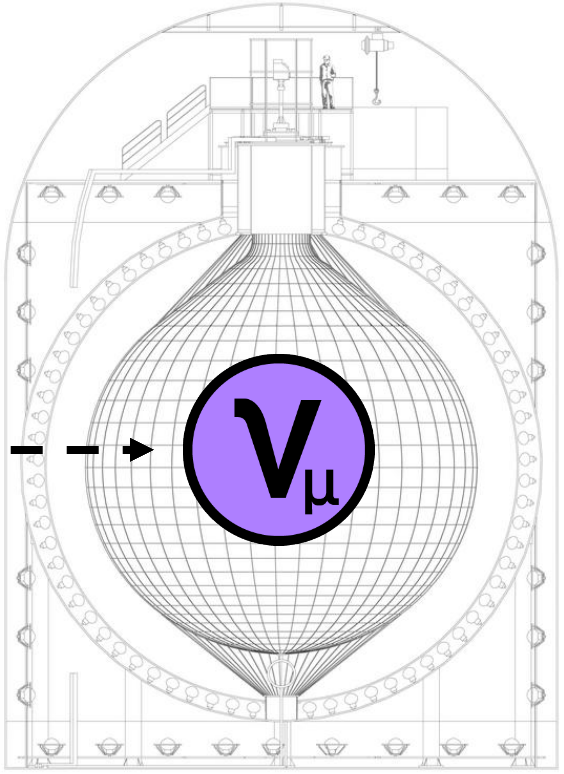
Wire Mod. Scale X



Seems to be missing some charge at the beginning

Three flavors of neutrinos oscillation between each other



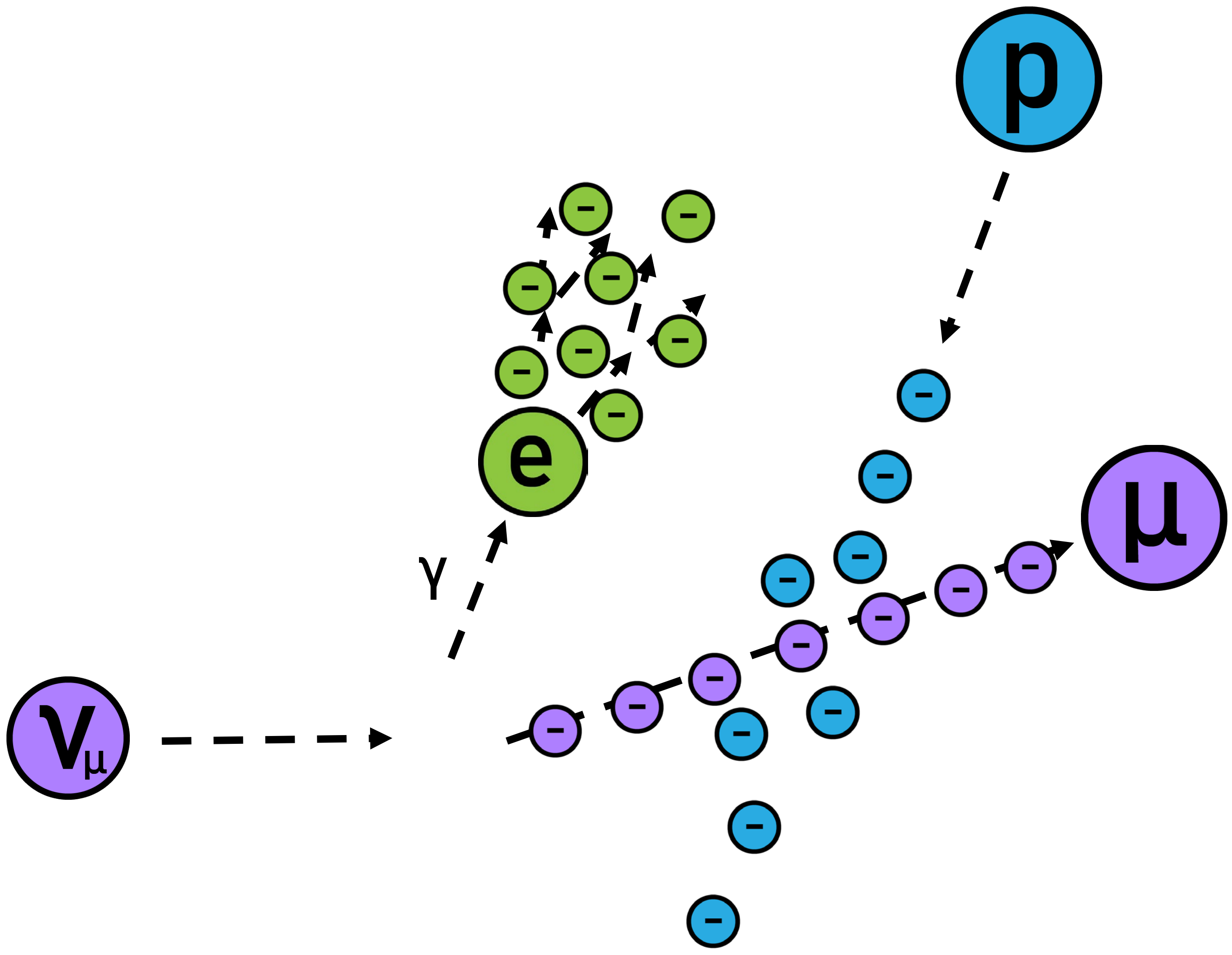


Fusion in sun creates
electron neutrinos

The neutrinos have a
chance of being detected
as a muon neutrino

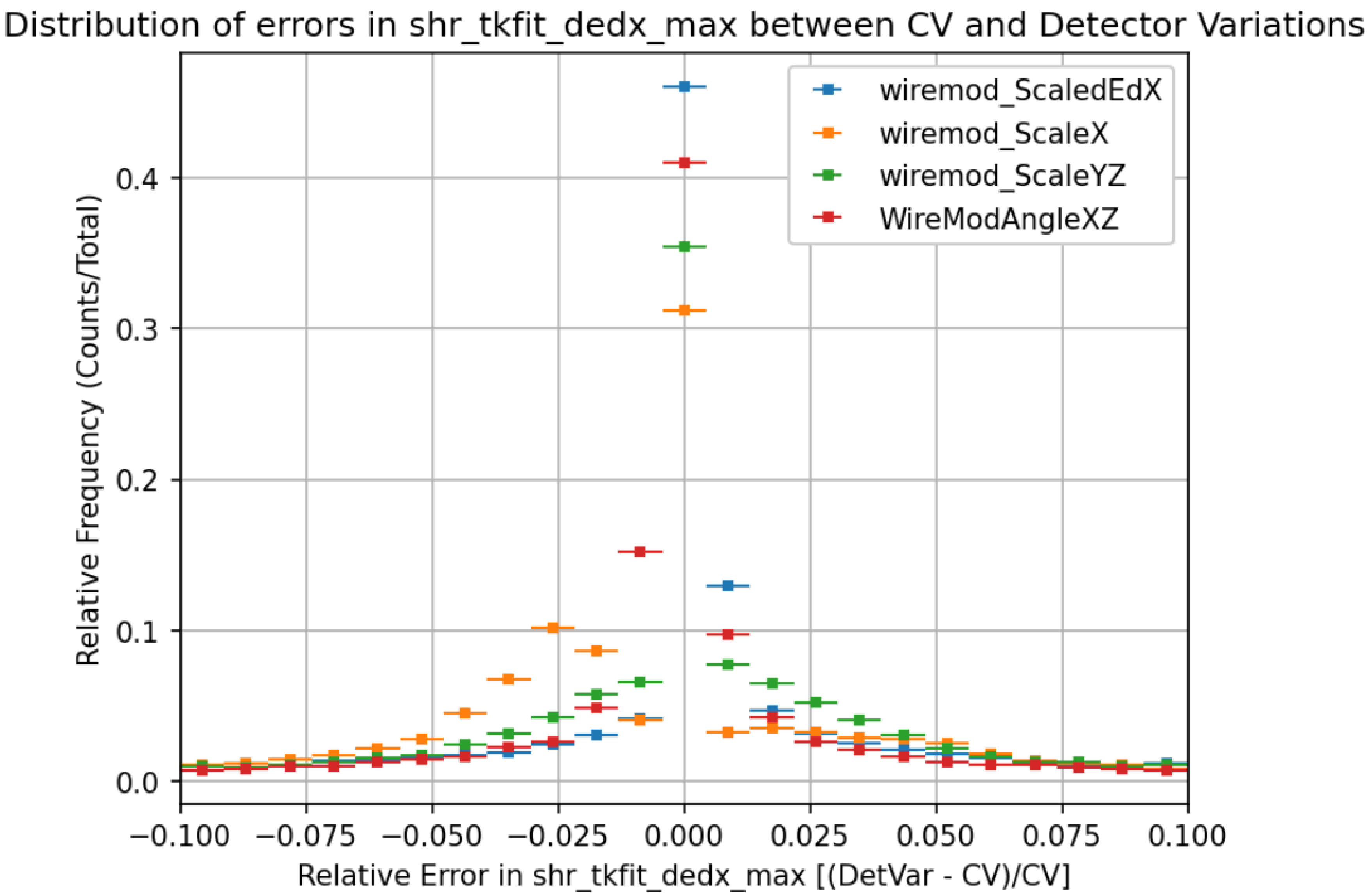
KamLAND Detector
http://kamland.stanford.edu/

Cosmic rays can be mistaken as neutrinos



In simulations we know the truth about the source of each charge deposit...

The energy seems to be reduced in one of the variations



Changes in measured $\frac{dE}{dx}$ with detector variation

$$1 < \frac{dE}{dx} < 3$$