



# RECENT ADVANCEMENTS IN MACHINE LEARNING TECHNIQUES UTILISED BY NOvA

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Alexander Booth, for the NOvA Collaboration

WIN 2025, Brighton

June 10th, 2025

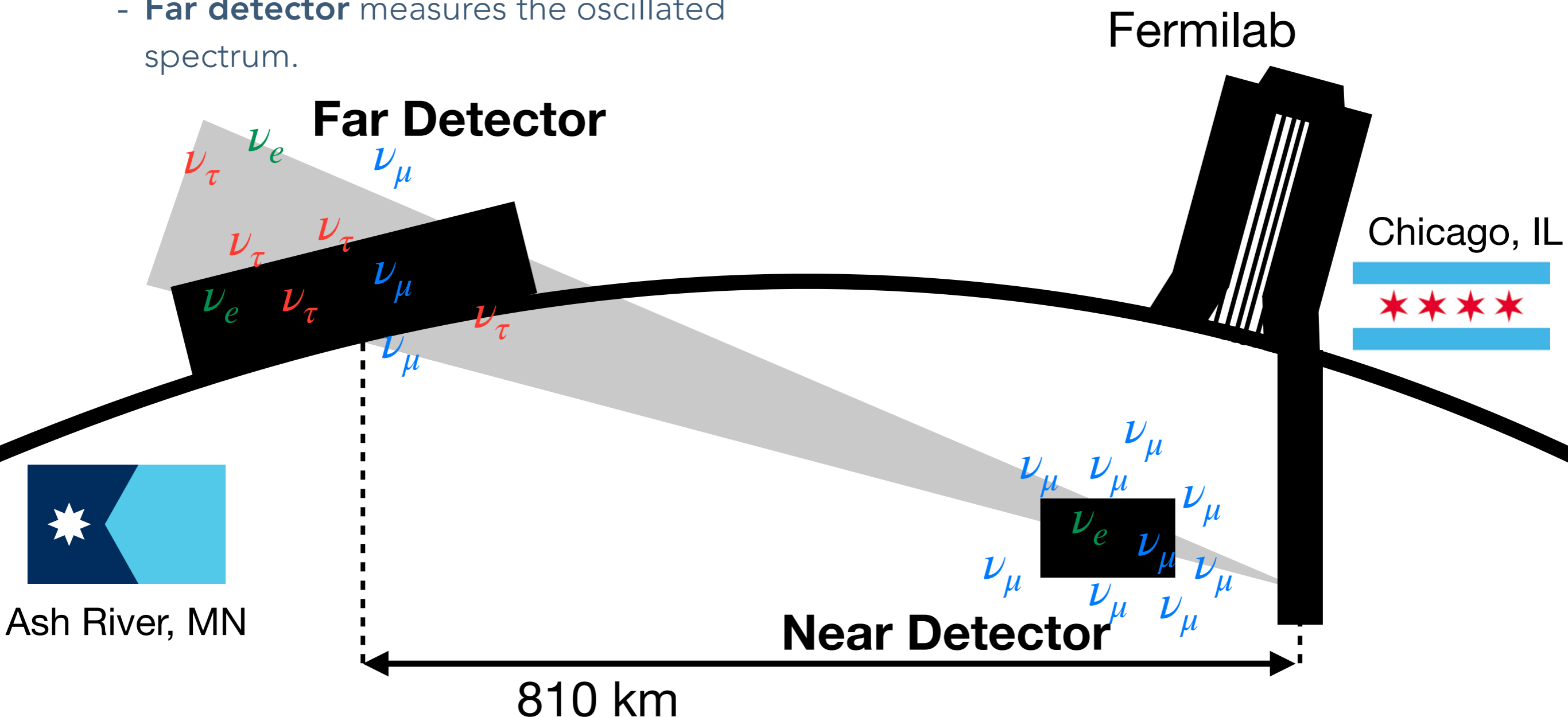
# NOvA in 1 Minute



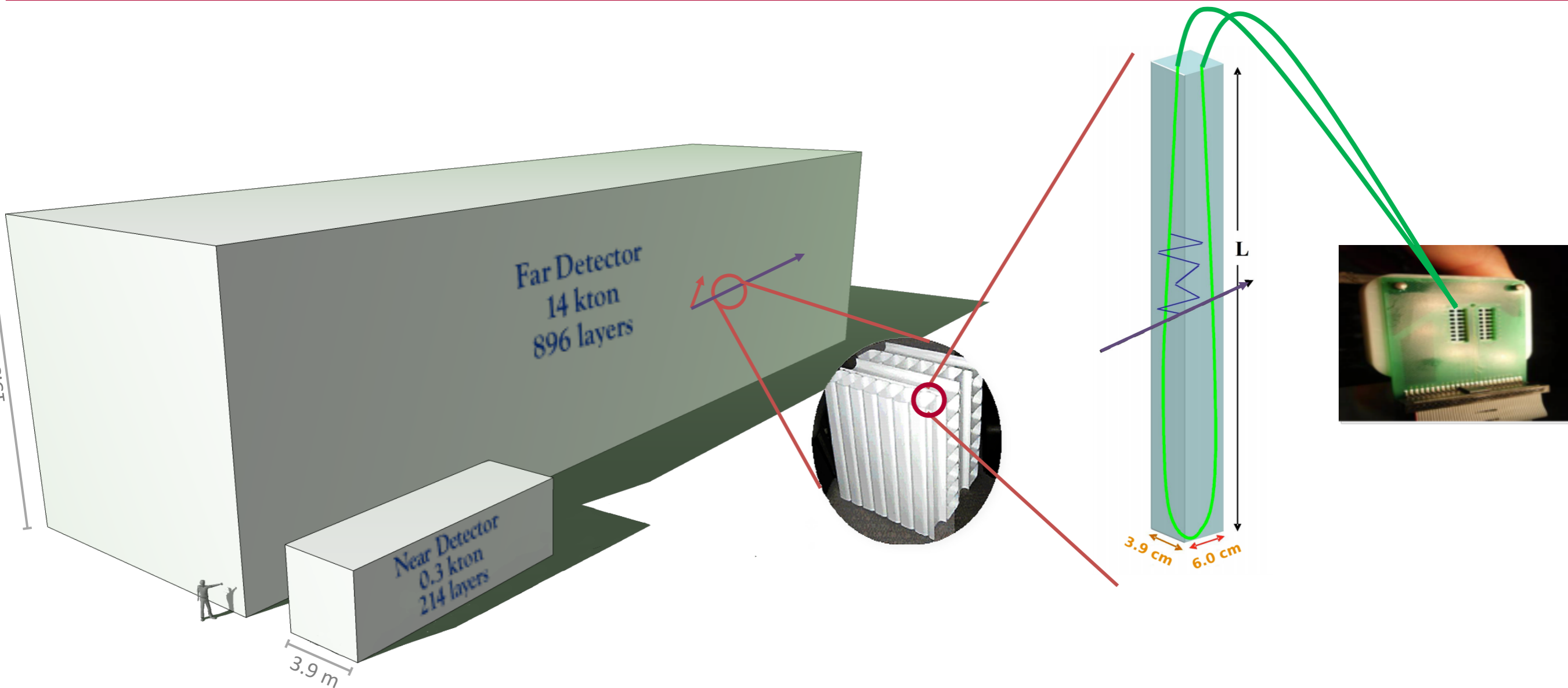
- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab.
  - **Near detector** to measure beam before oscillations.
  - **Far detector** measures the oscillated spectrum.

- **Primary goal is to** study 3-flavour oscillations via:

- $\nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e$
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$



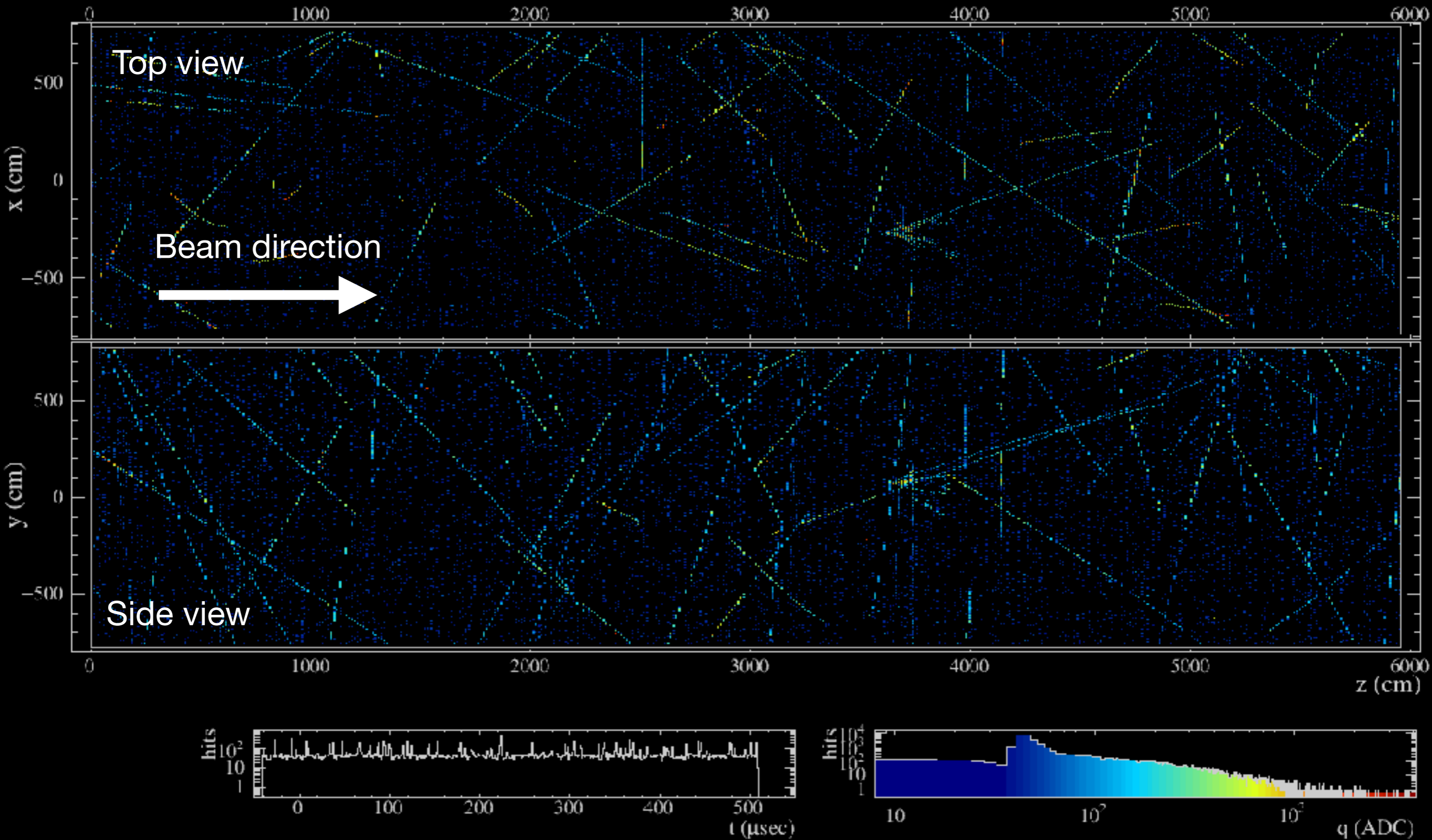
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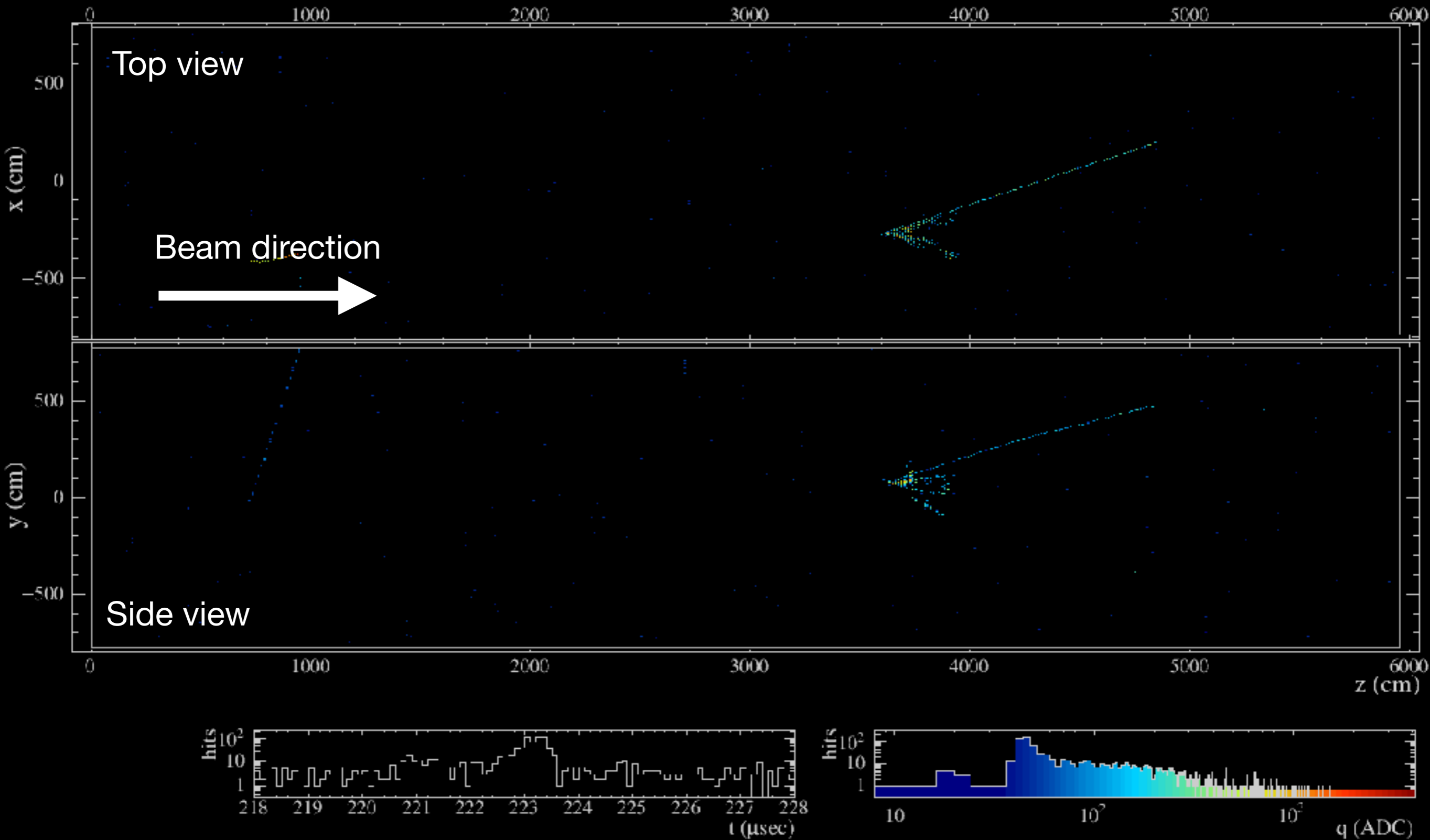


- Both are **large**, (FD 60 m long).
- **Functionally identical**: consist of extruded PVC cells filled with 11 million litres of liquid scintillator.
- Arranged in alternating directions producing **2, 2D views (pixel maps)** for **3D reconstruction**.

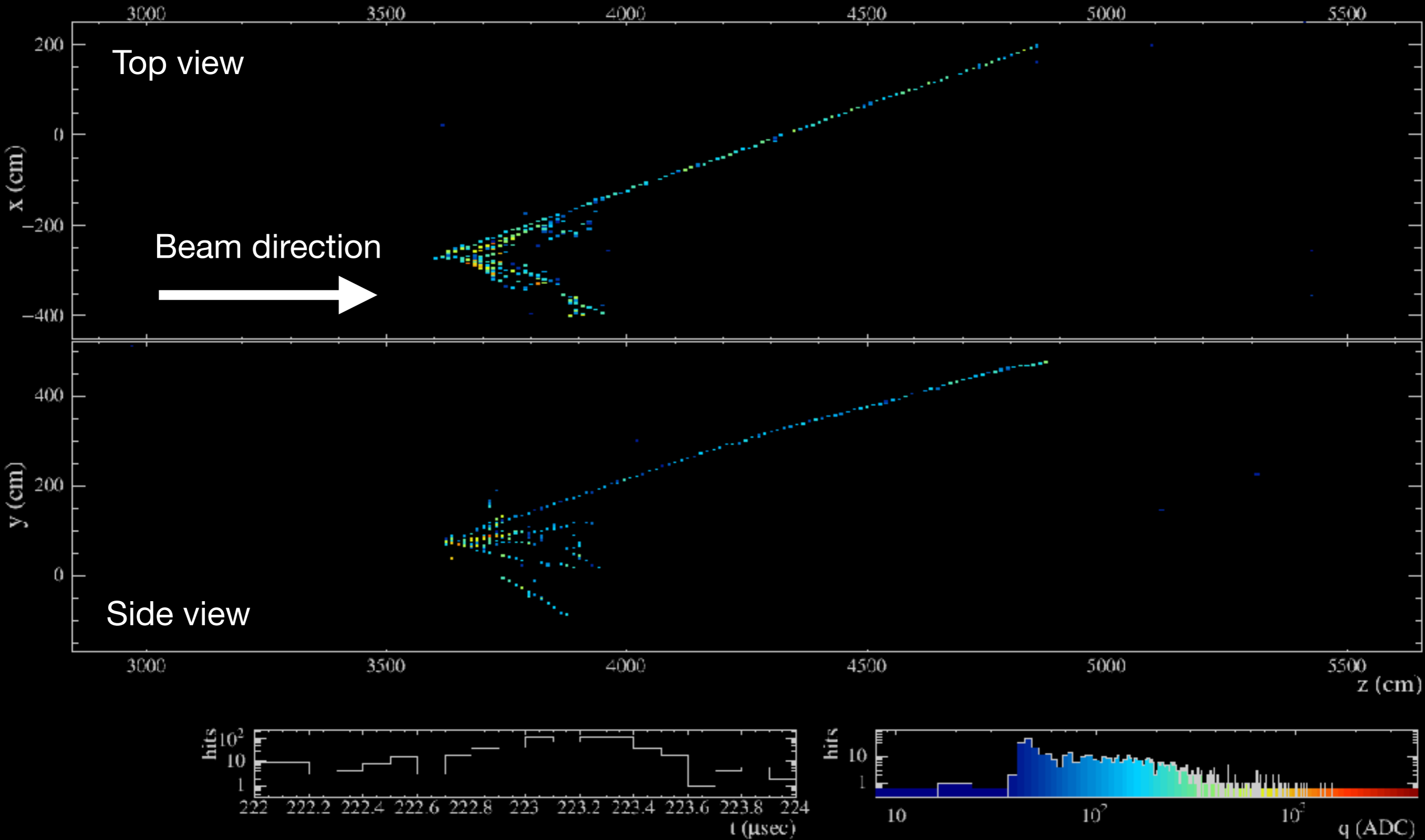


# 550 $\mu$ s Readout Window

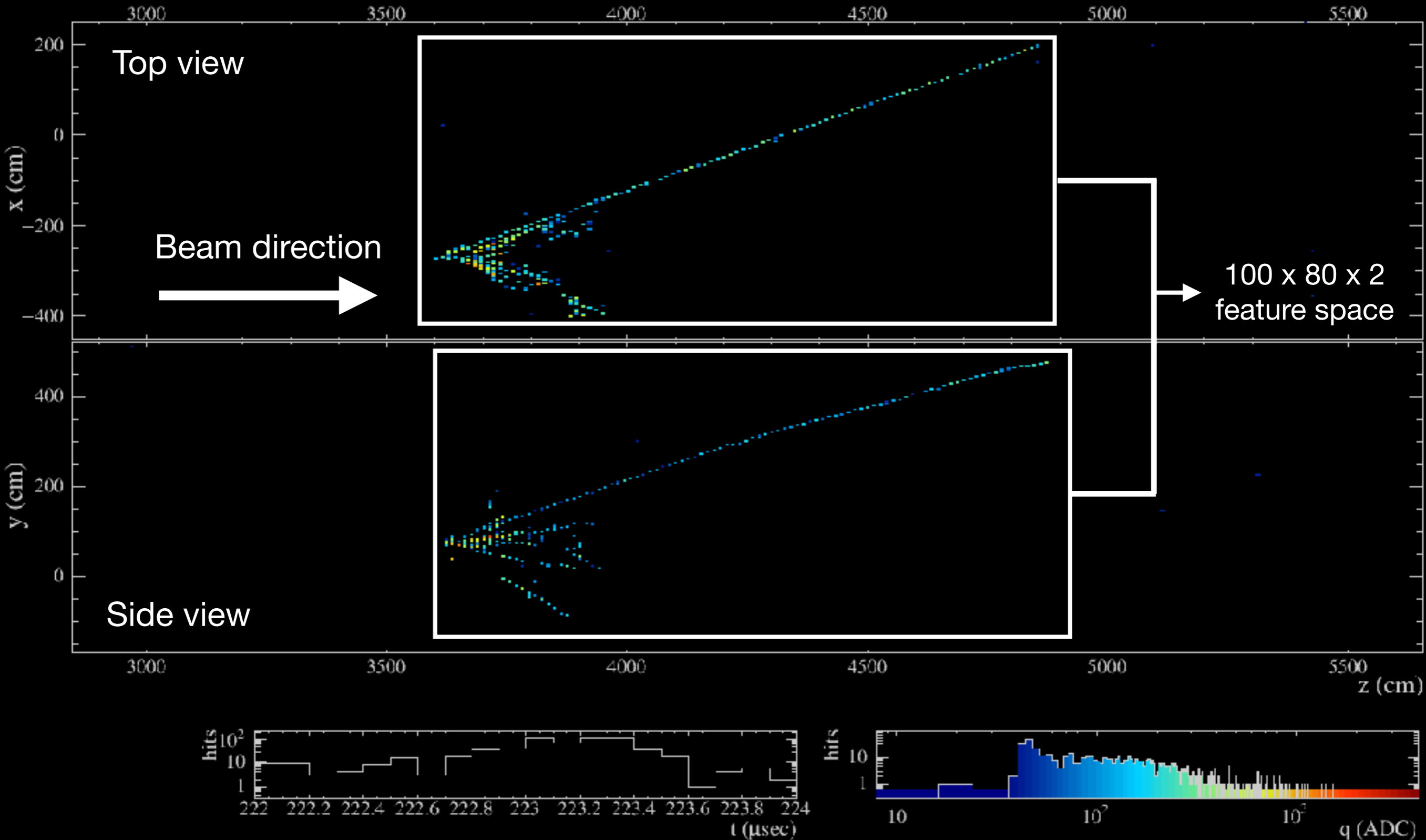


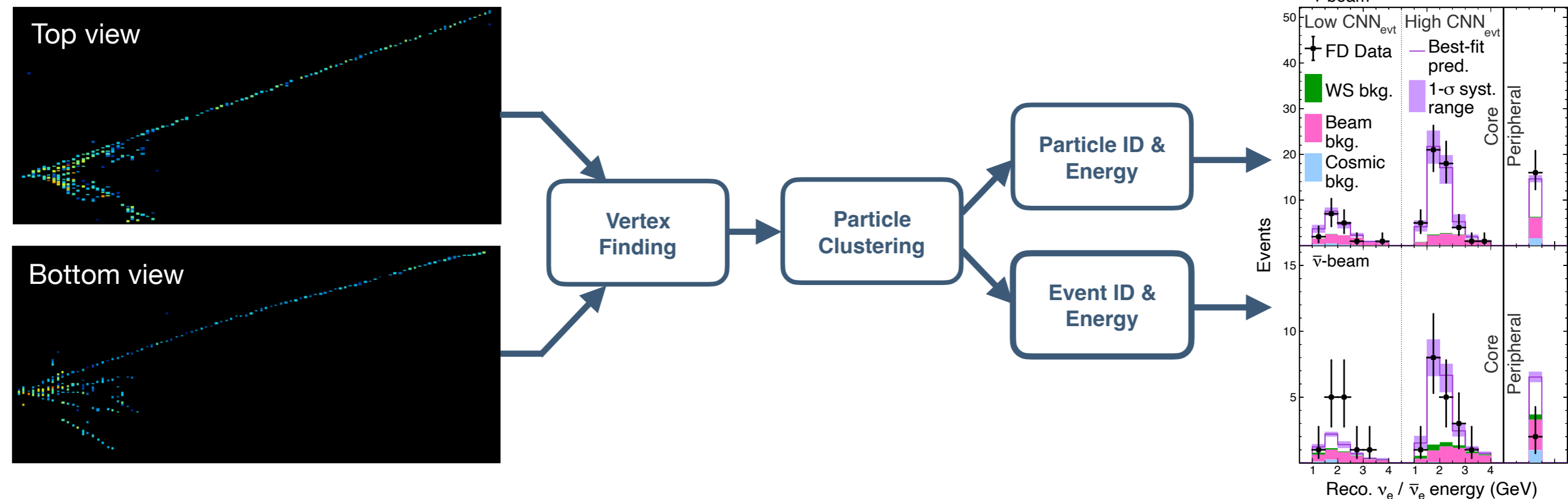


# Slice by Time $\rightarrow$ Slice Spatially $\rightarrow$ Pixel Maps



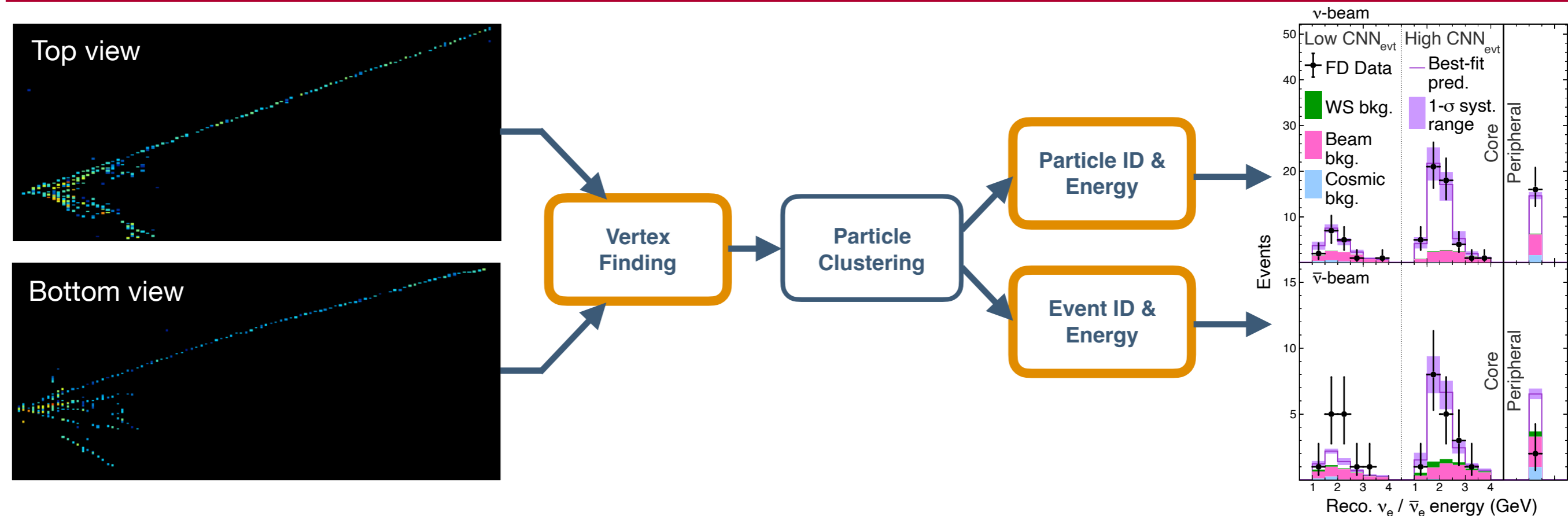
# Slice by Time $\rightarrow$ Slice Spatially $\rightarrow$ Pixel Maps





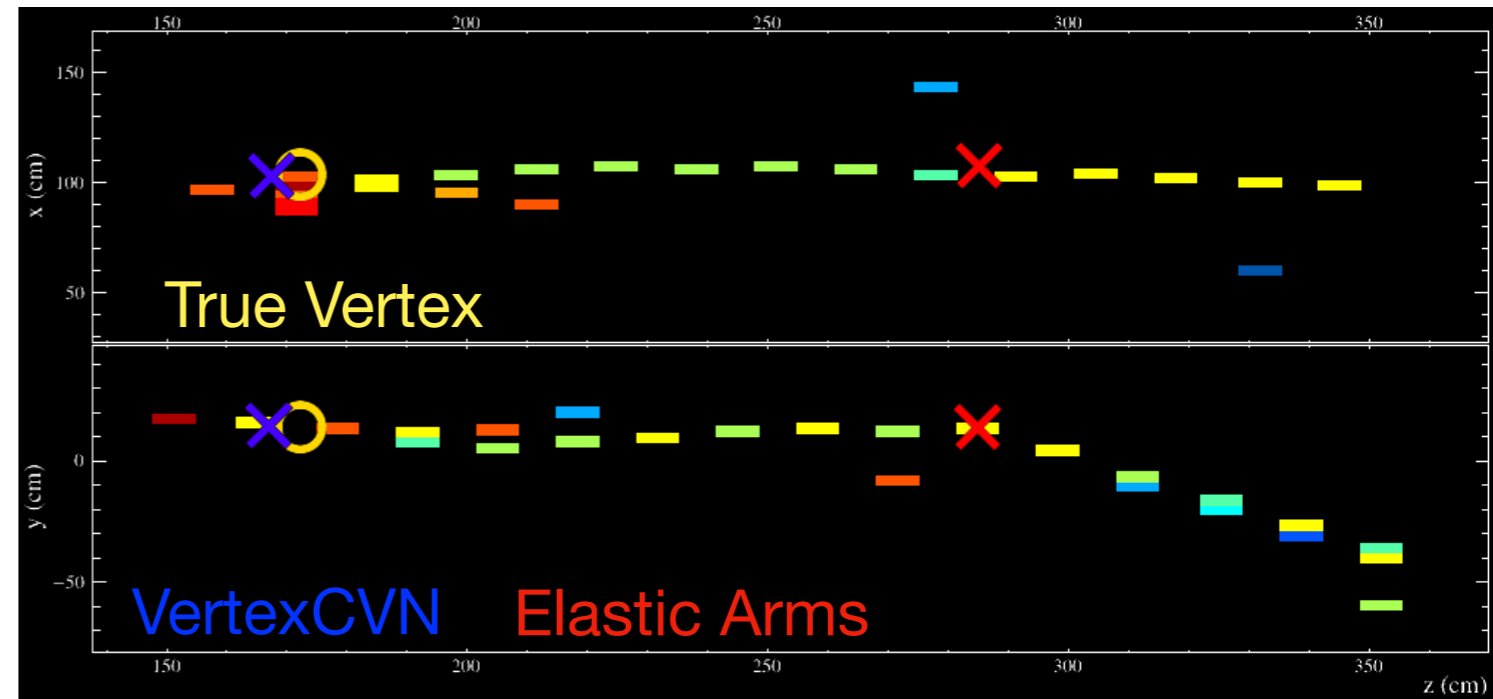
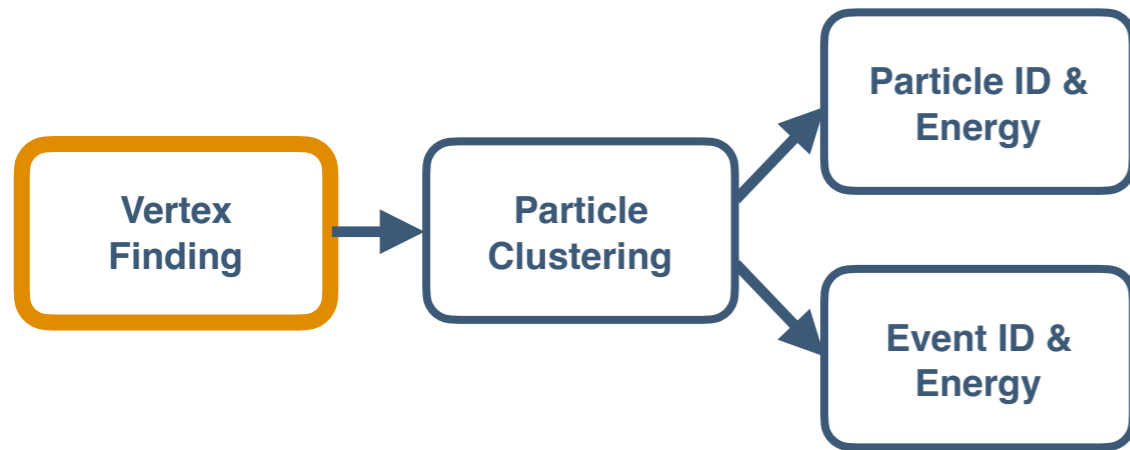
- NOvA uses a variety of algorithms to reconstruct physics information.
- Machine learning contributes significantly to the reconstruction chain, replacing “traditional” kinematics-based algorithms in some places.
  - ▶ Neutrino Event Reconstruction Using CNNs: *JINST 11, P09001 (2016)*.
  - ▶ Particle Identification Using CNNs: *Phys.Rev.D 100, 073005 (2019)*.
  - ▶ Neutrino and Lepton Energy Estimation Using CNNs: *Phys.Rev.D 99, 012011 (2019)*.





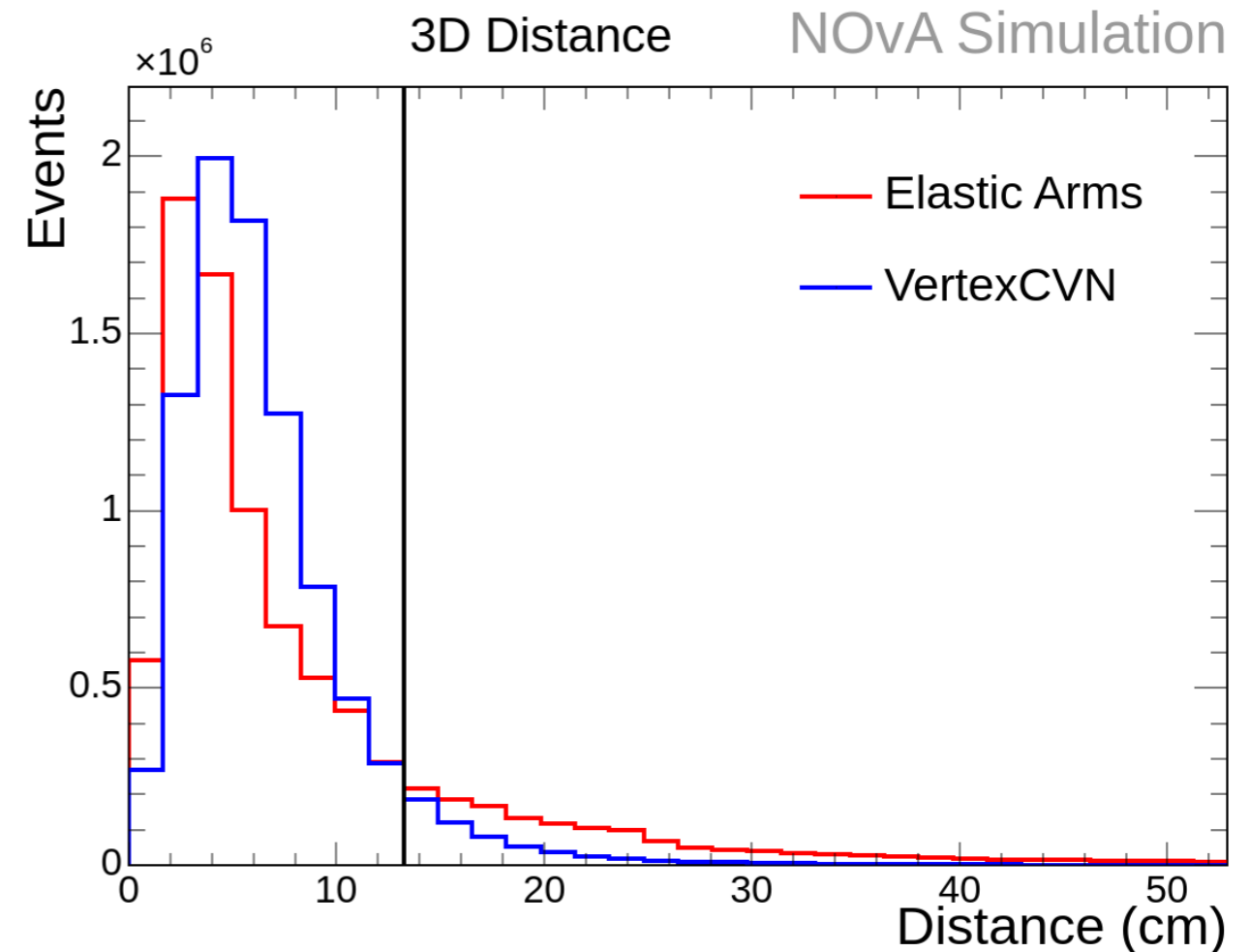
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- Recent focus on extending to vertex finding (**VertexCVN**) and improving **interpretability** (**TransformerCVN**) of machine learning techniques.

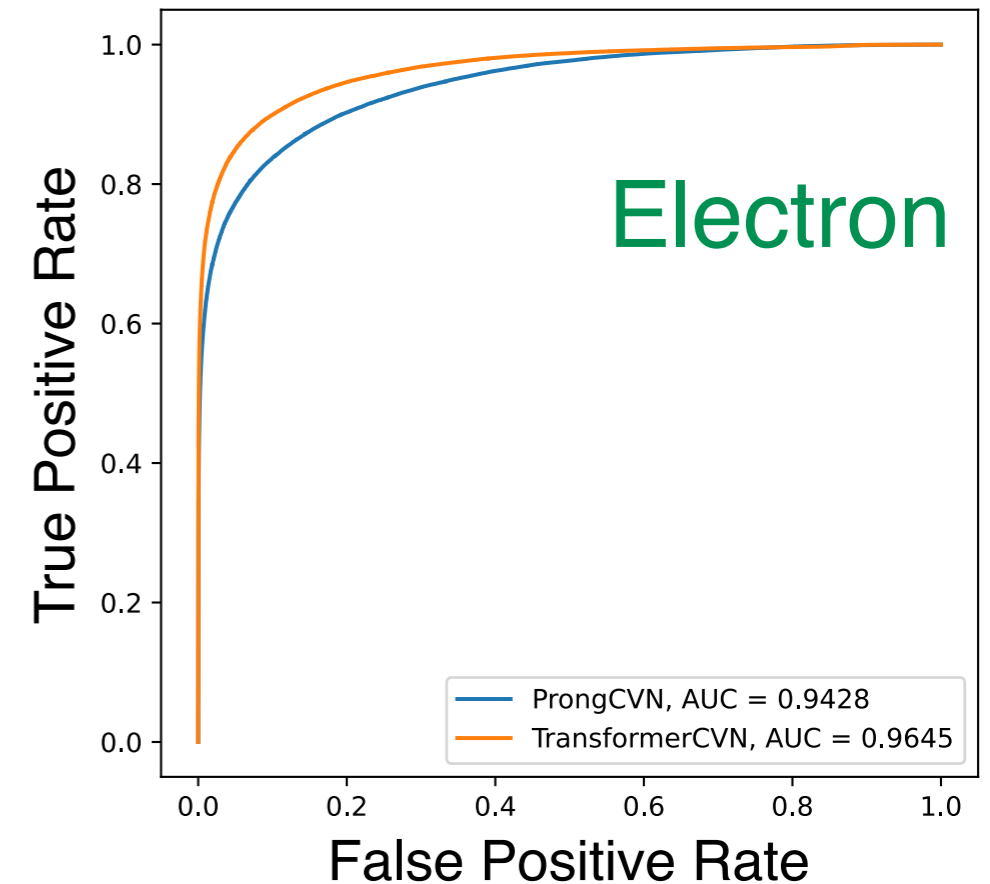
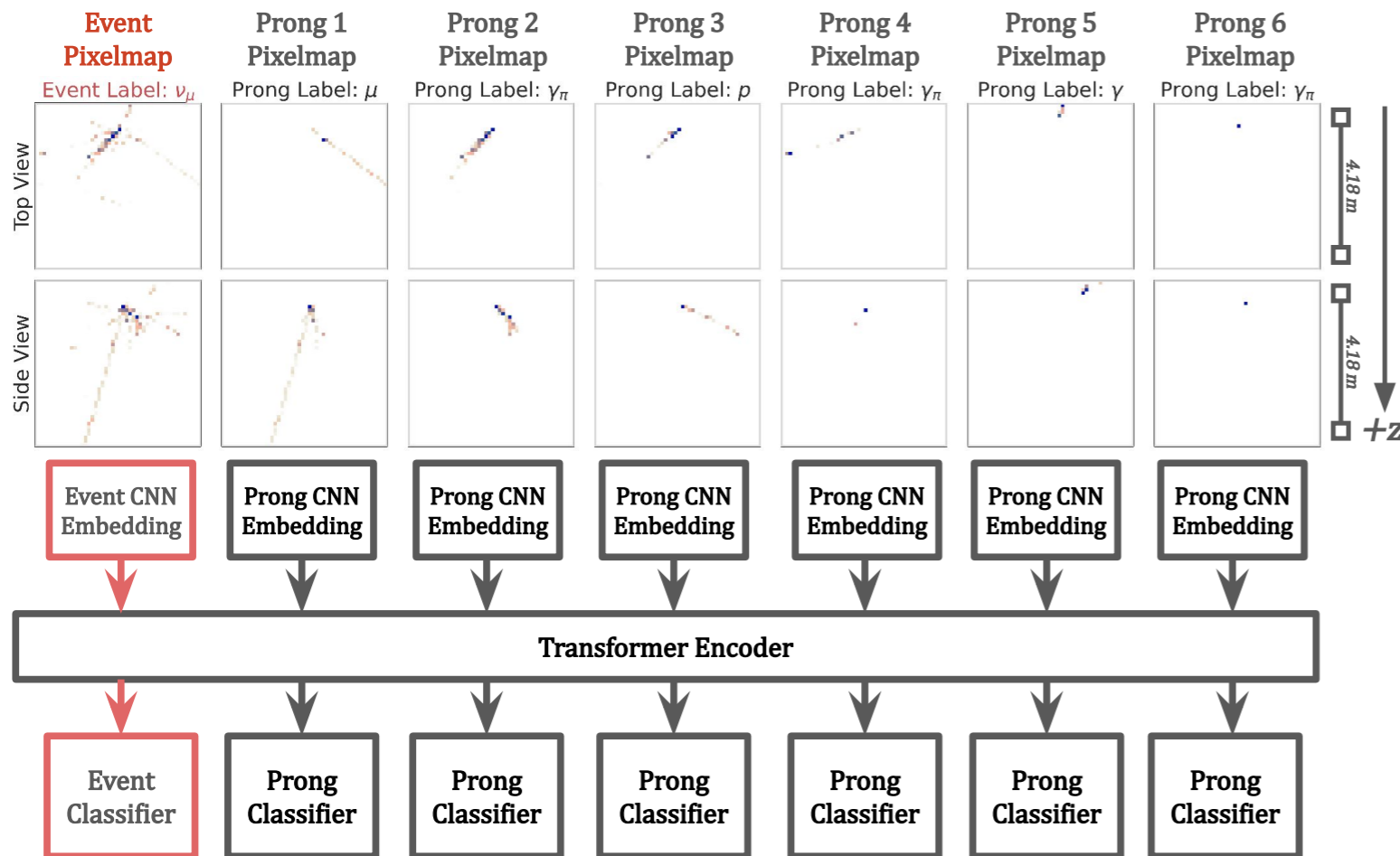




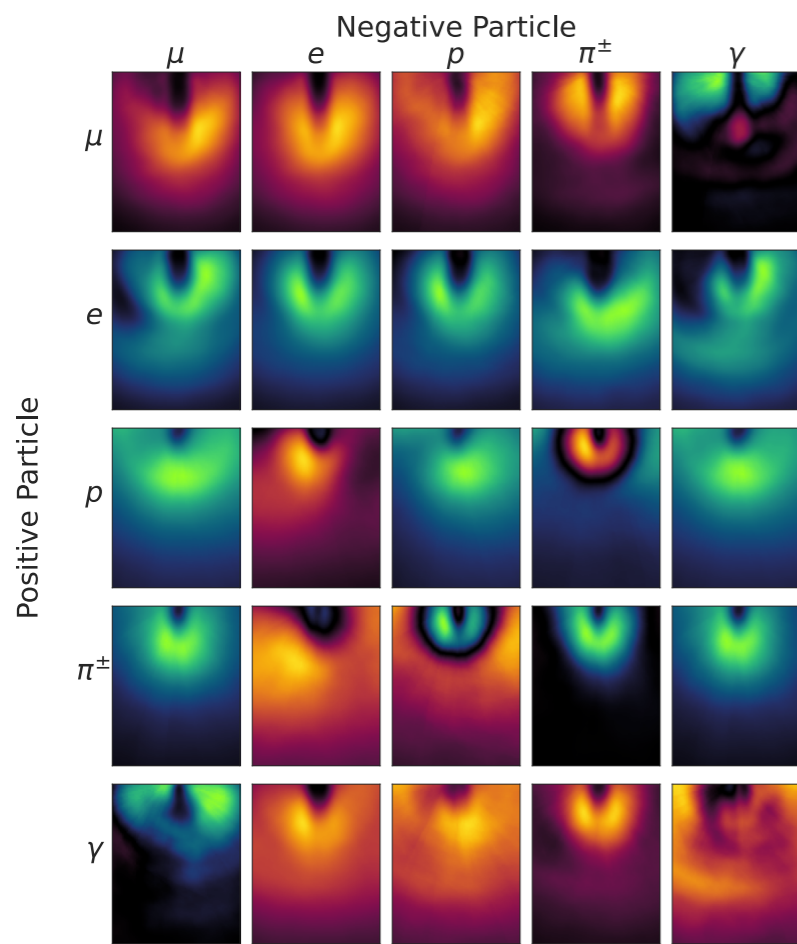
- **Vertexing:** estimate the position of the neutrino interaction with the detector medium.
- Improved vertex finding means improved downstream reconstruction.
- Apply machine learning to address several known failure modes of NOvA existing algorithm "Elastic Arms".
  - **Forward failure** - tendency for main prong to be split in two.
  - **Backward failure** - tendency for multiple, small prongs to be combined into one.

- Uses same CNN architecture as NOvA's event-level classifier (modified MobileNetv2, arXiv:1801.04381) to predict a single 3D position.
- Training samples with **beam modes combined** but **separated** for **Near** (~18 million) and **Far** (~26 million events) detector.
- VertexCVN is **more precise** than Elastic Arms but slightly **less accurate**.

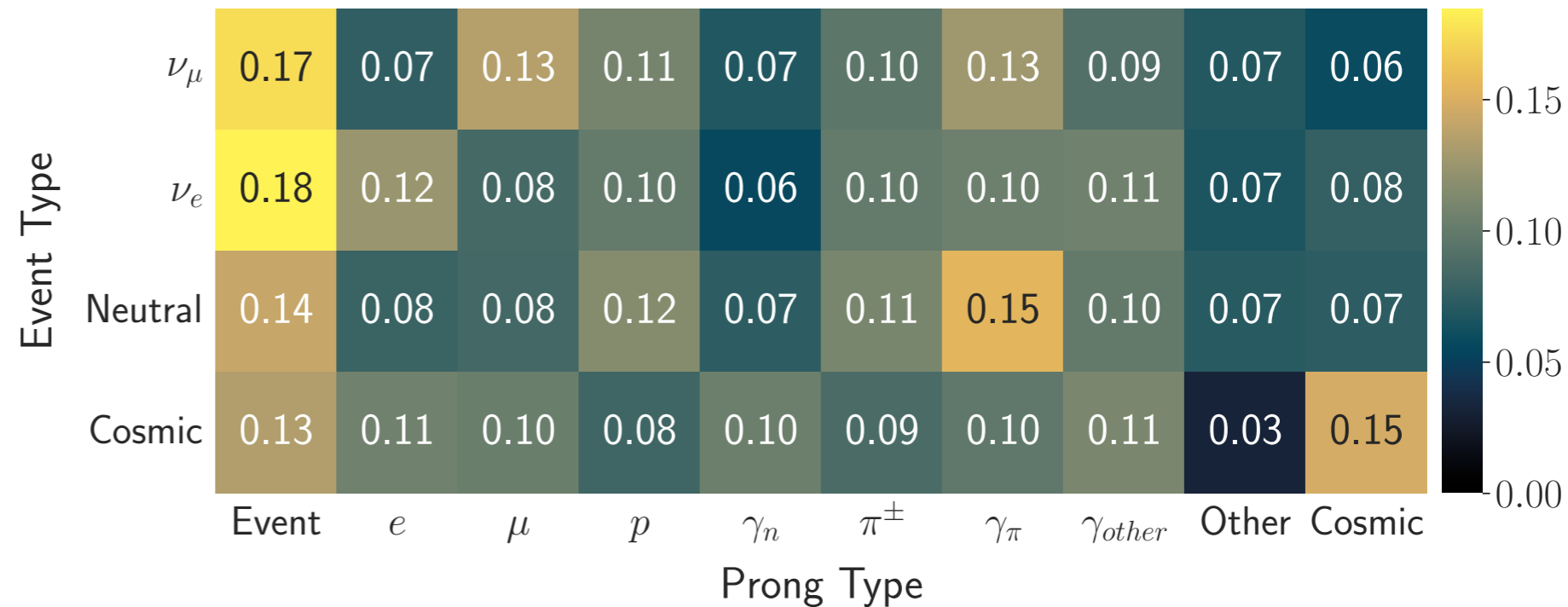




- **CNN + Transformer** → Network that combines **spacial learning** of **convolutions** with **contextual learning** enabled by **attention**.
- Joint approach to PID that **simultaneously classifies** each **event** and every **individual particle's** identity.
- Gives improvement in **performance** but also **interpretability**.

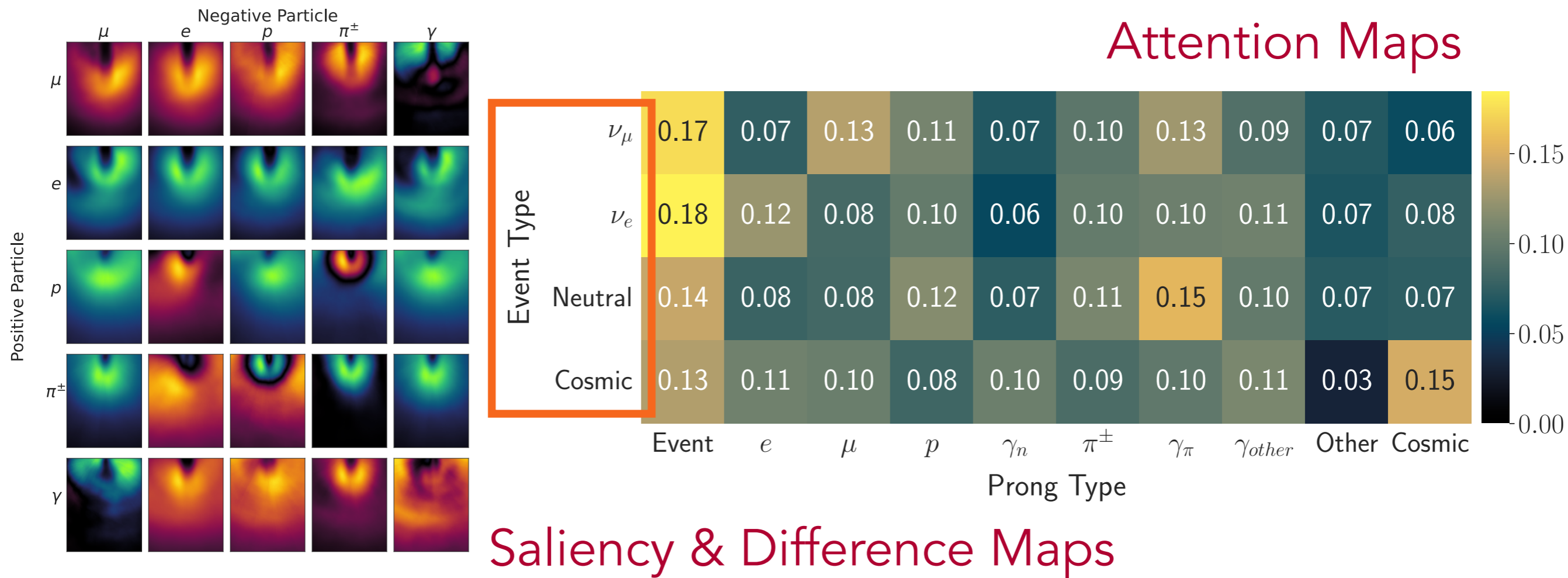


## Attention Maps

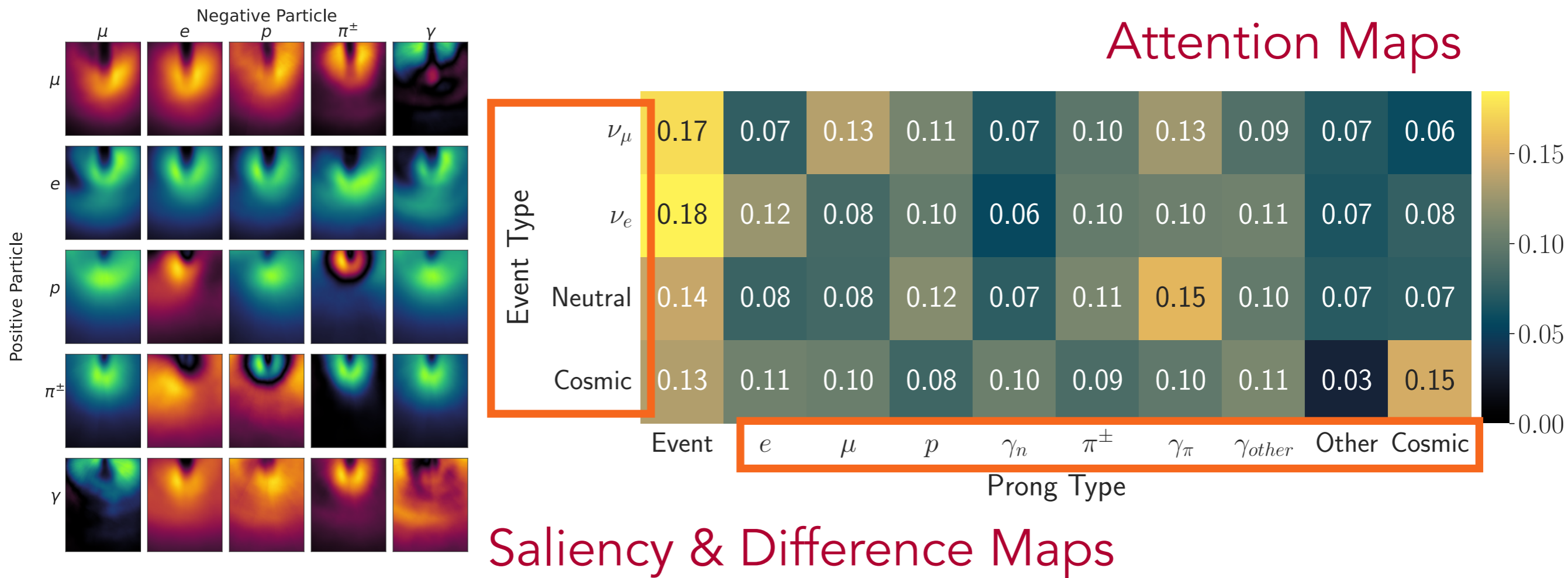


## Saliency & Difference Maps

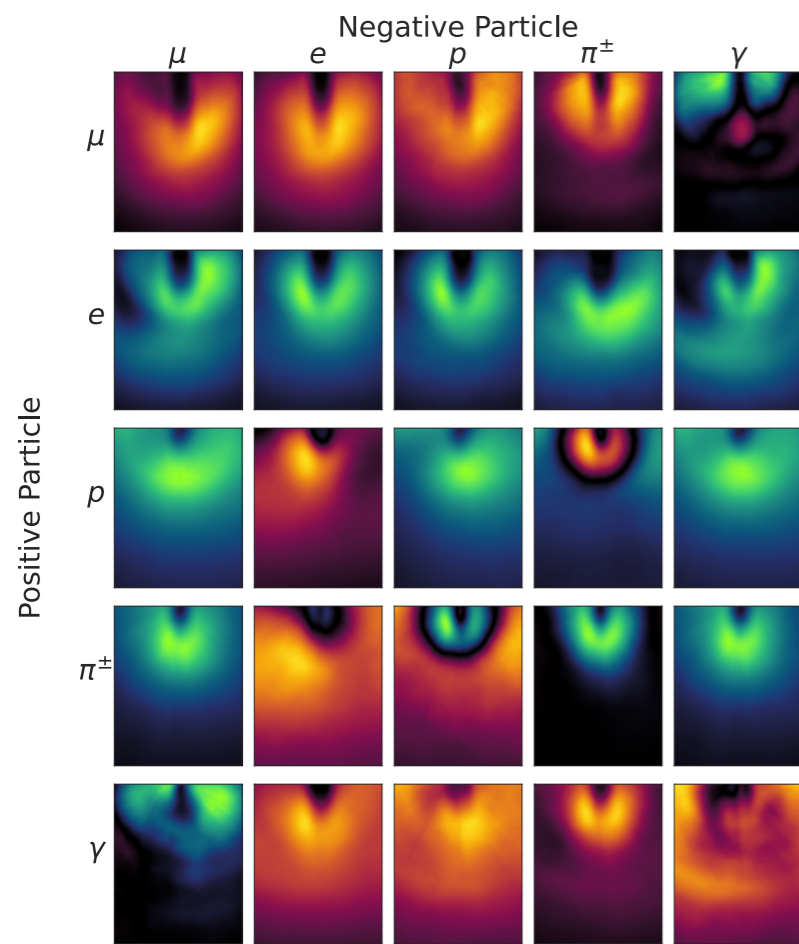
- **Attention** describes the relative importance of each input to the output → how the network makes a decision.
  - ▶ Build an understanding of the relationship between different particles and event types.
- **Saliency** is the derivative of the network output with respect to the **pixel** input → understand which regions the transformer focusses on to make a decision.



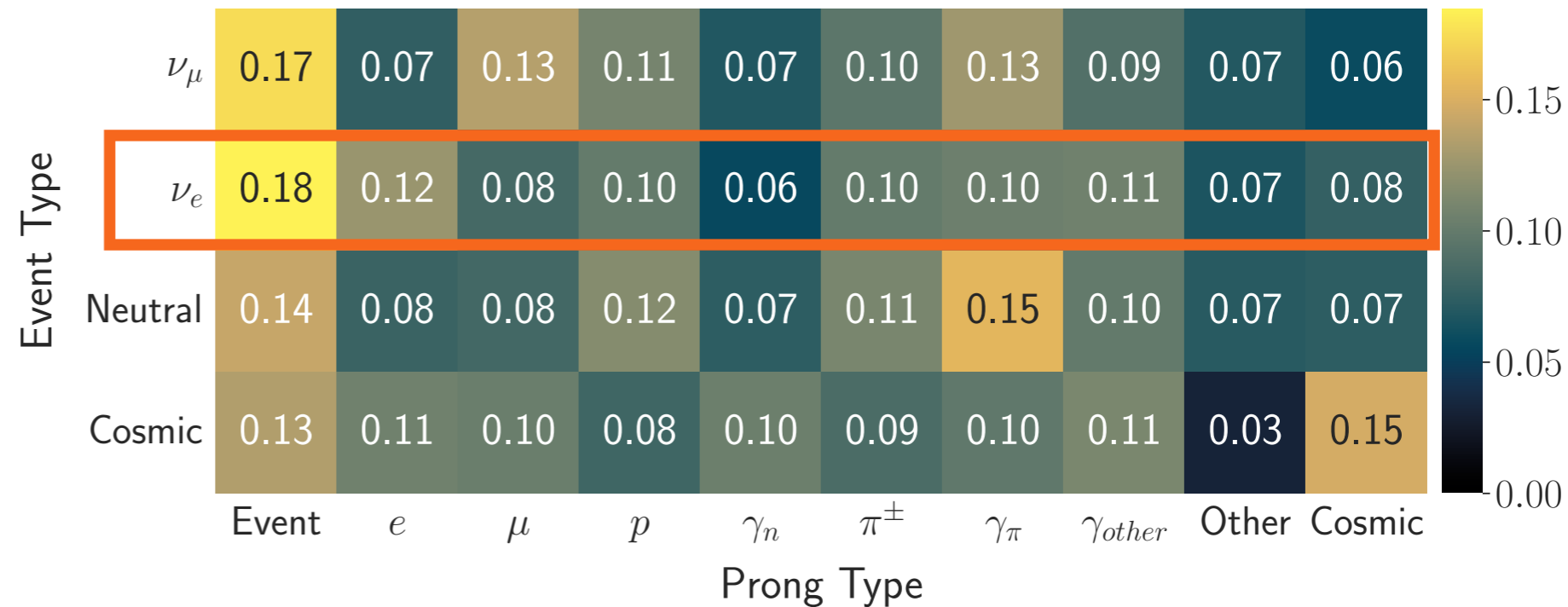
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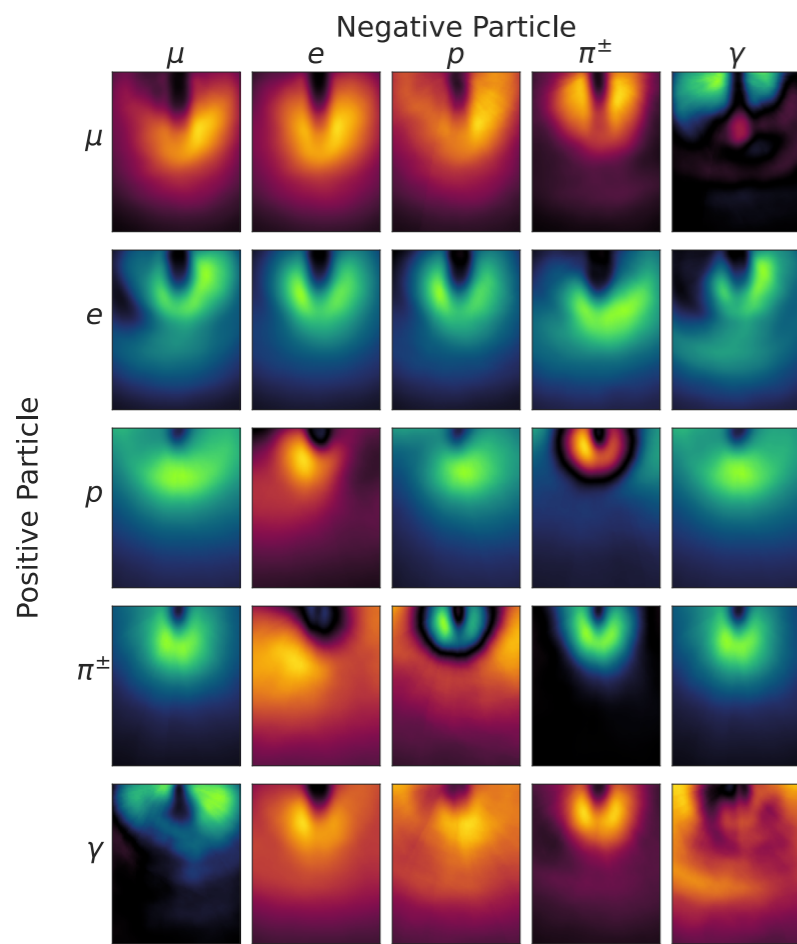


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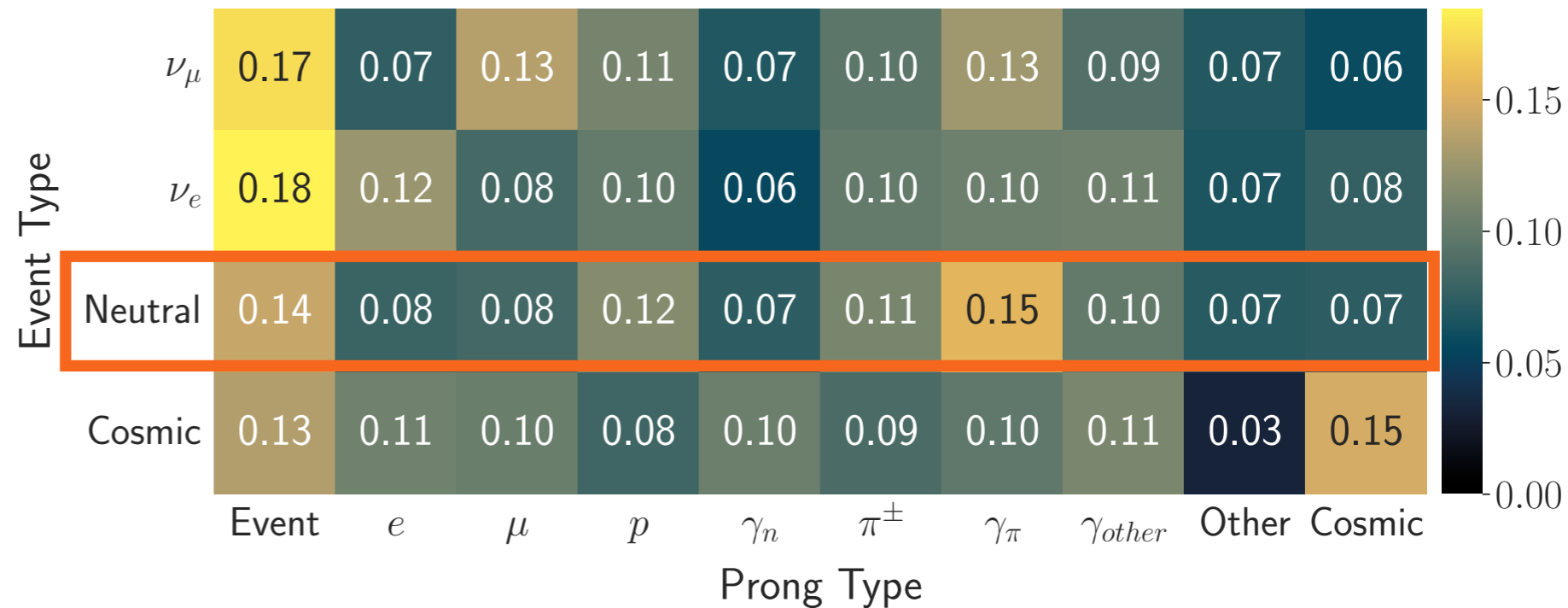


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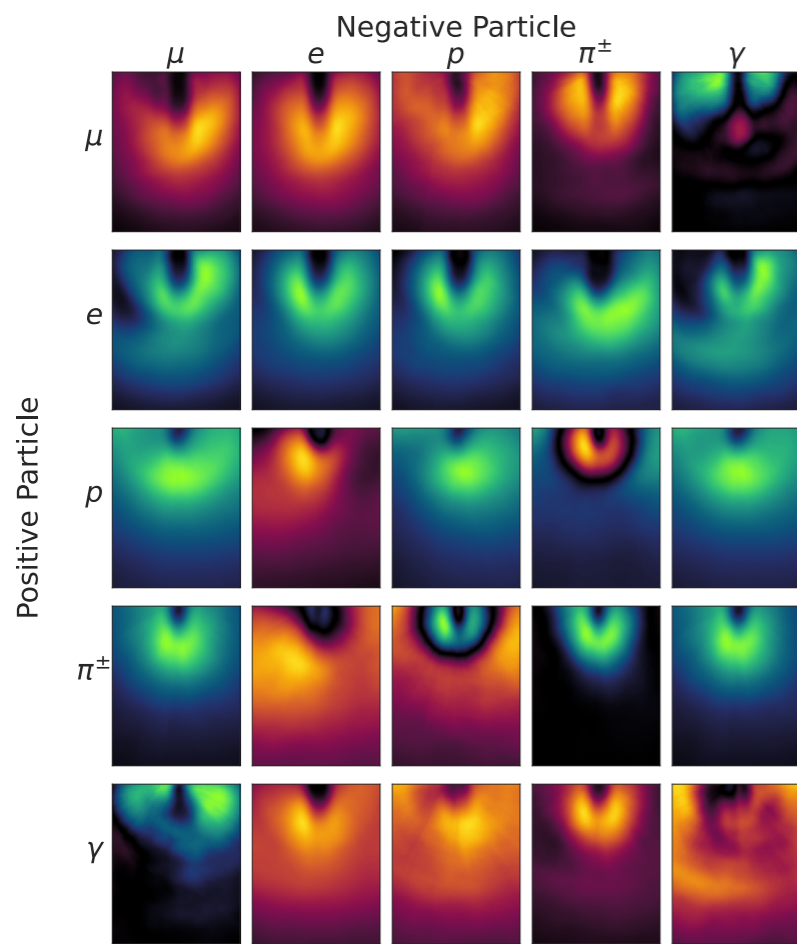


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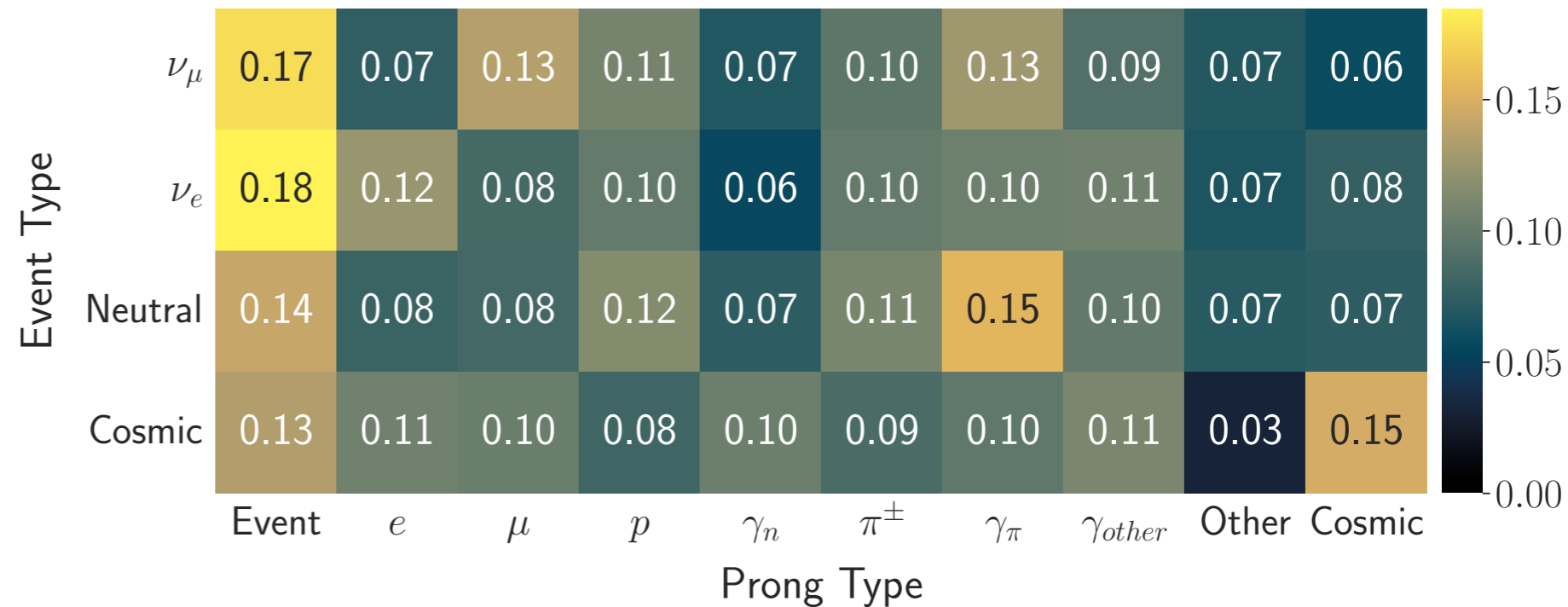


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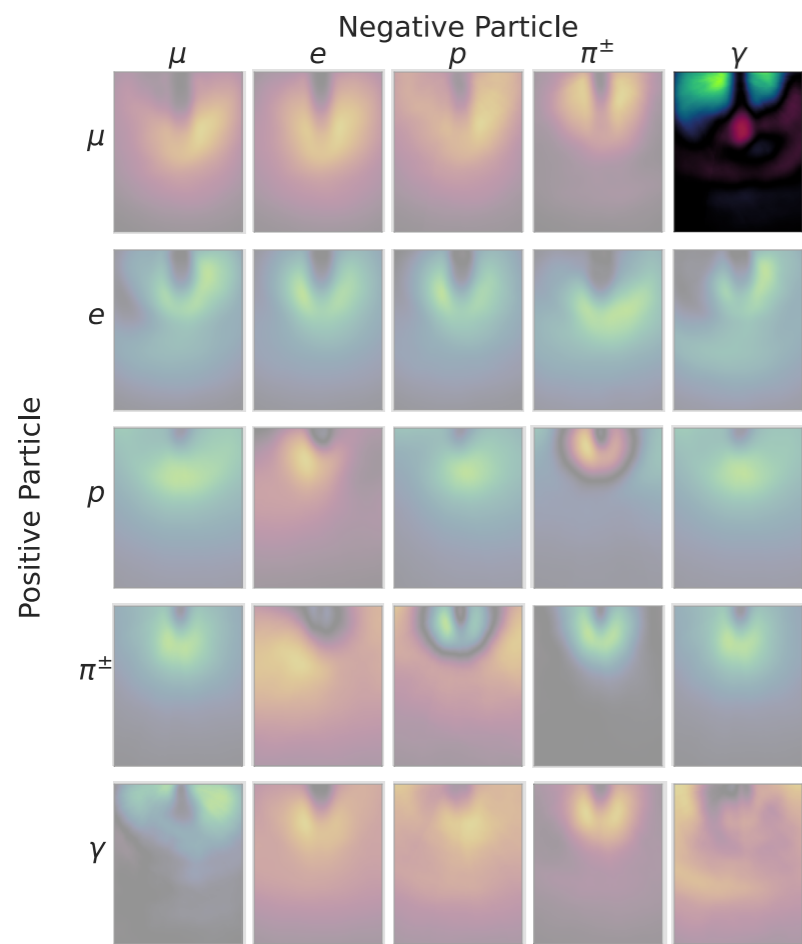


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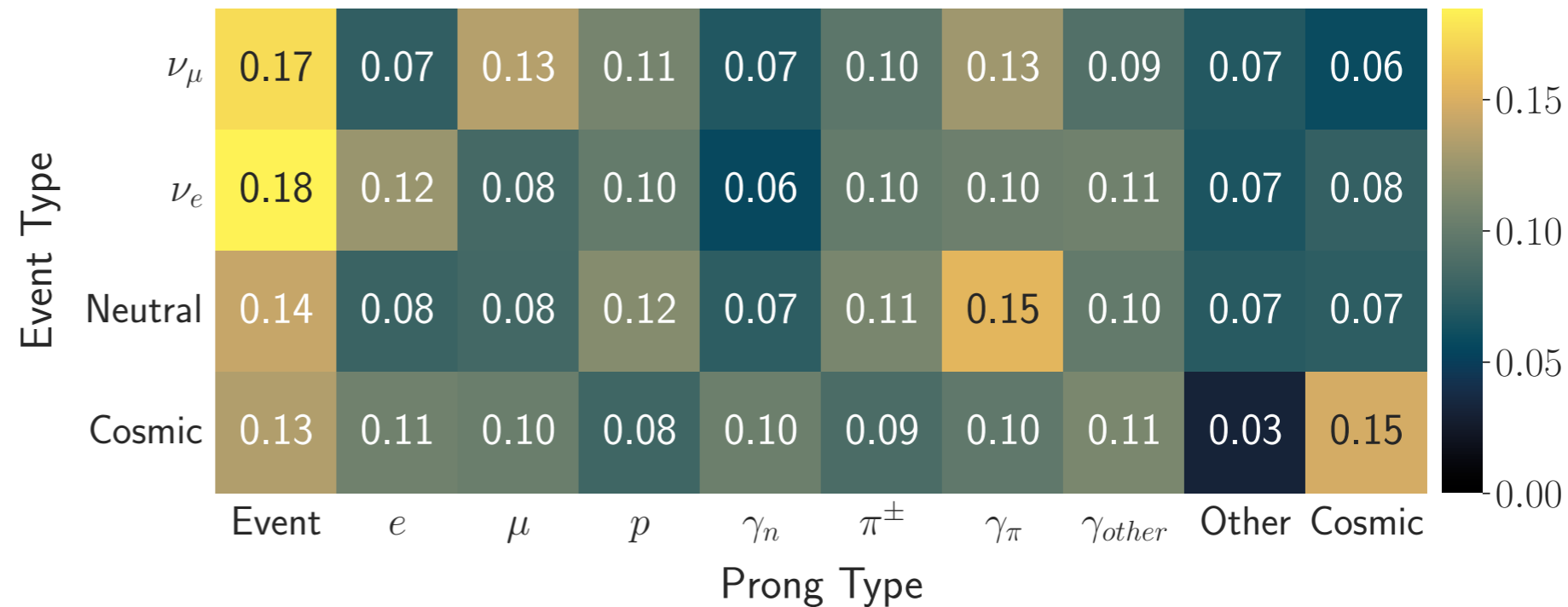


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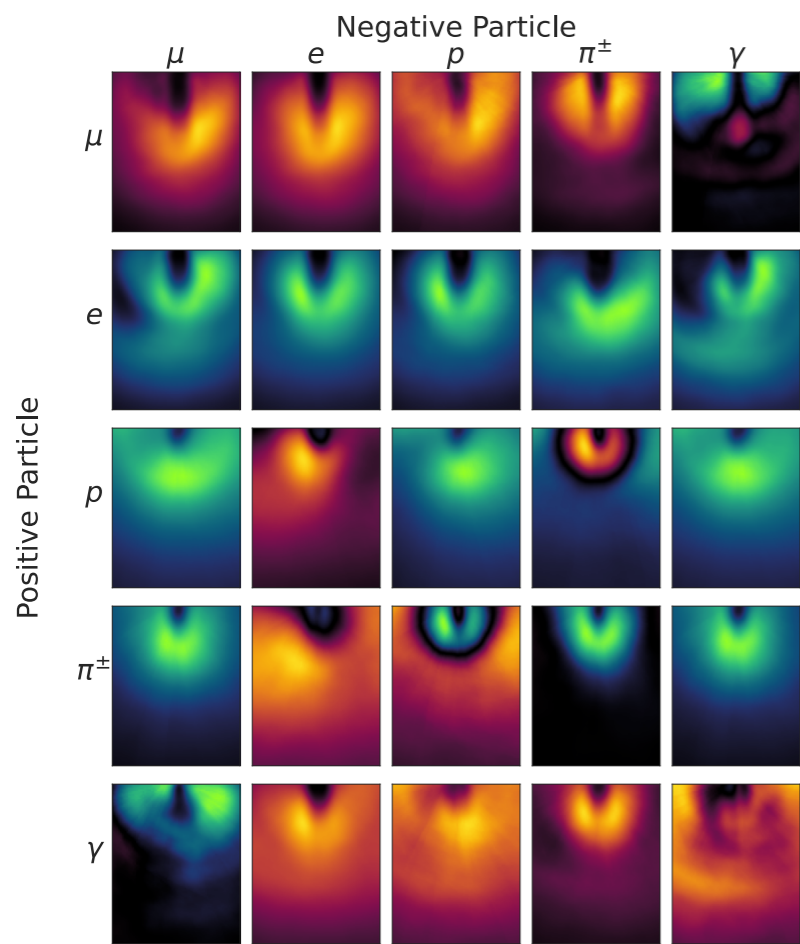


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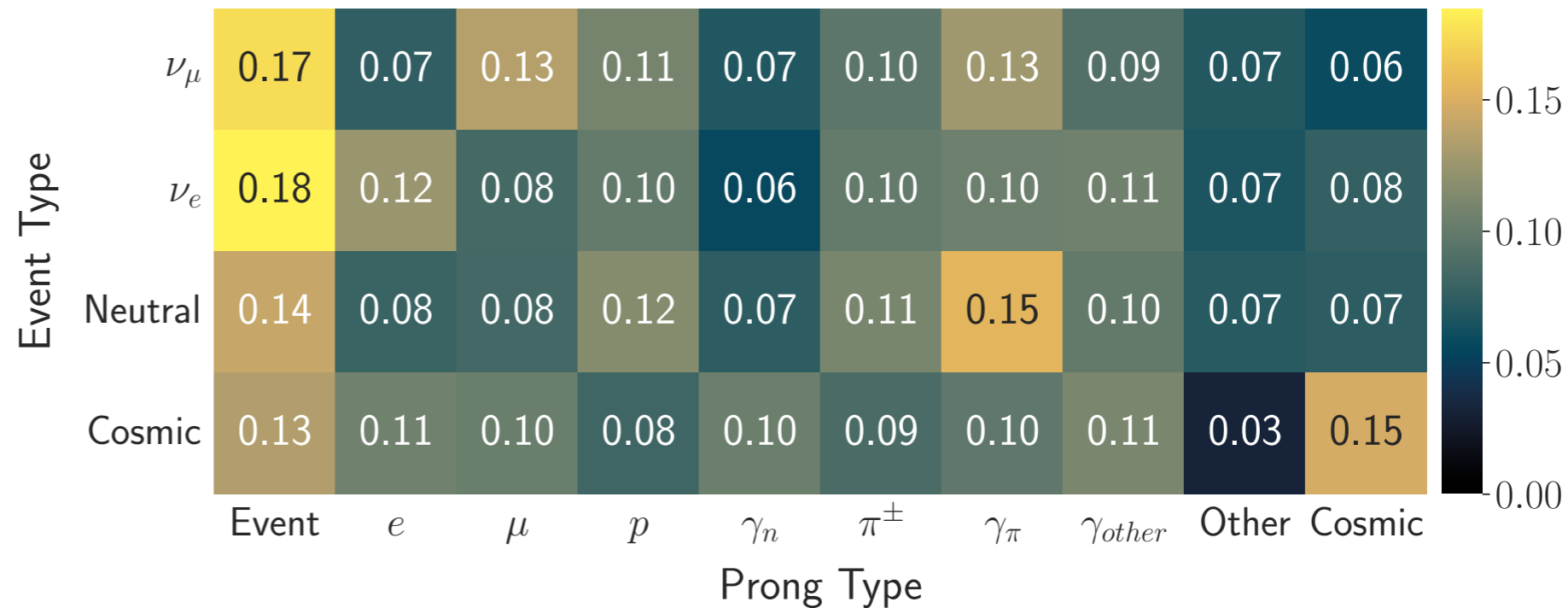


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- NOvA has been using machine learning techniques across its physics program for several years.
- Recent efforts have been focussed on low level reconstruction and improving the interpretability of the machine learning techniques that we use.
  - ▶ CNN-based vertex finder.
  - ▶ Attention and saliency metrics through TransformerCVN.
- ML group continues to be very active! Transformer-based energy estimator and raw-hit level panoptic segmentation coming soon.

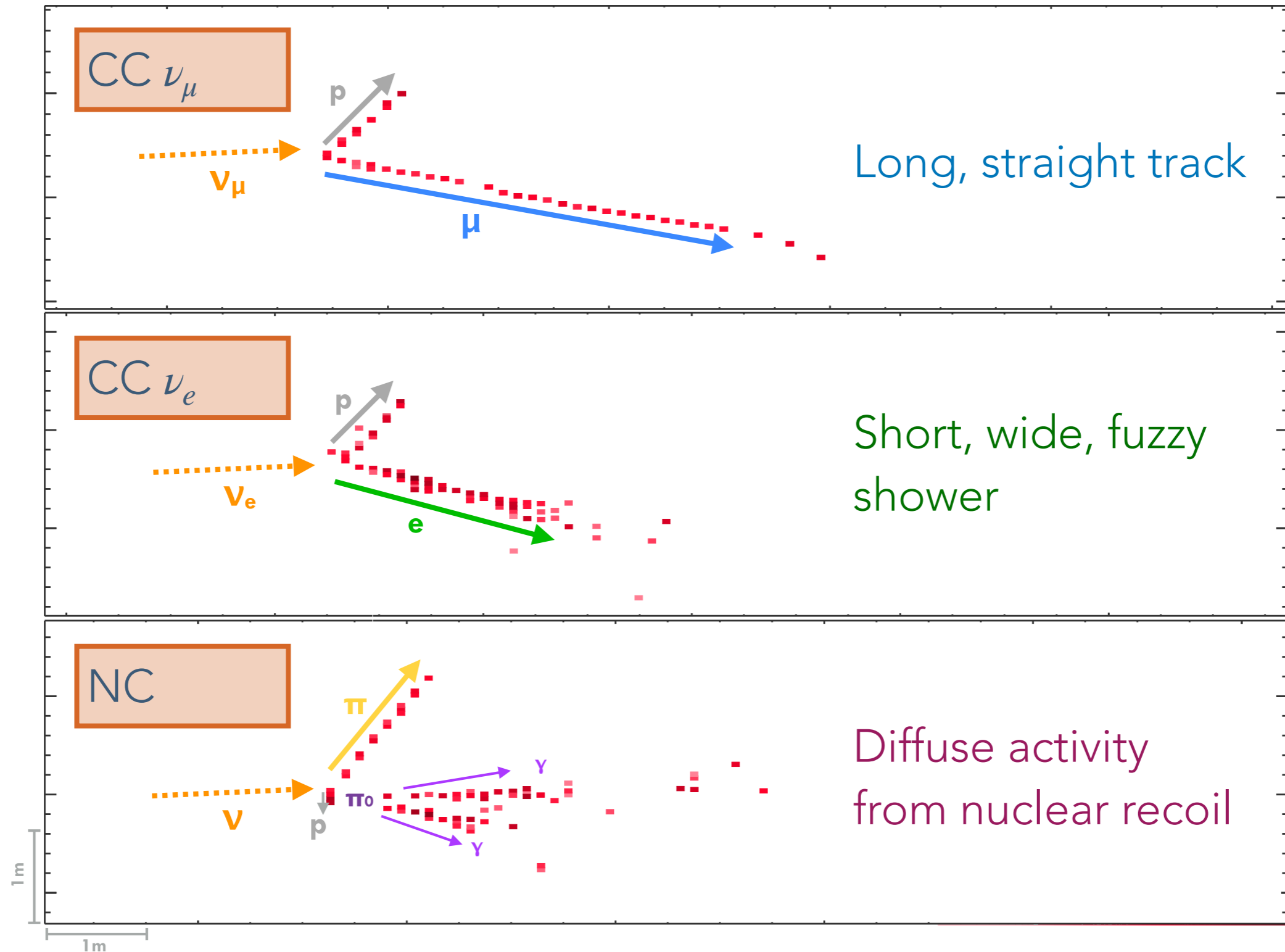


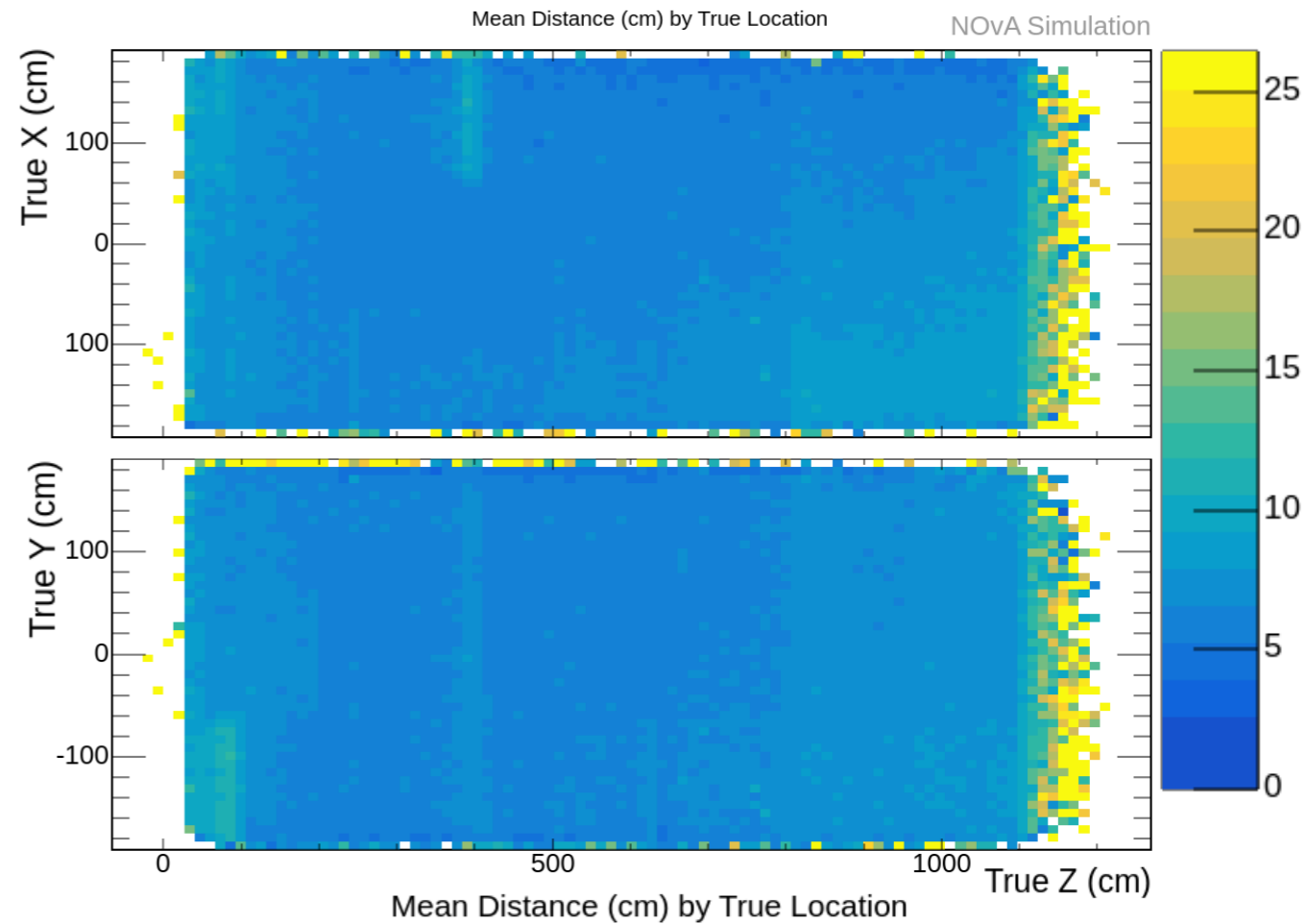
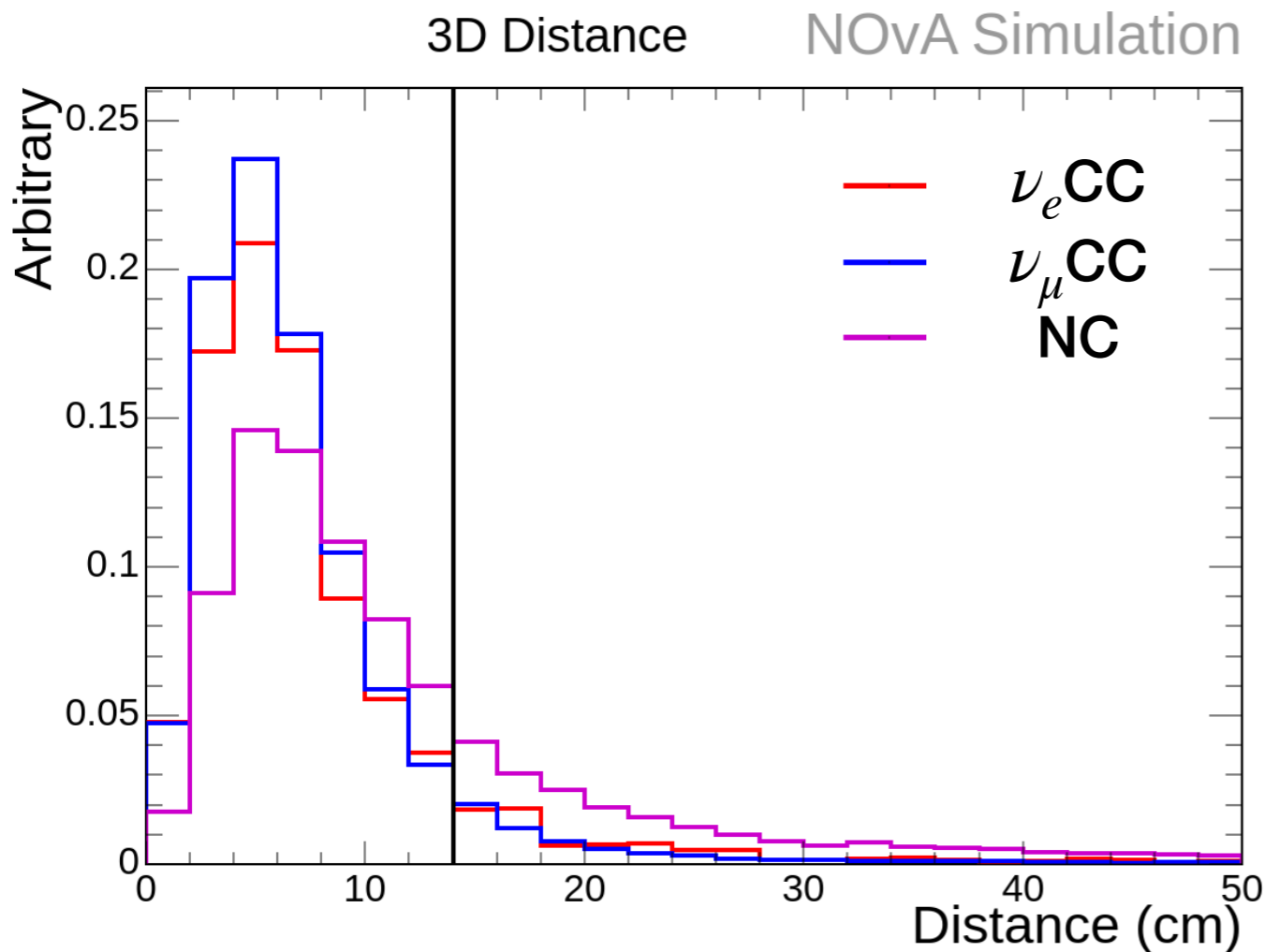
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# Back-up

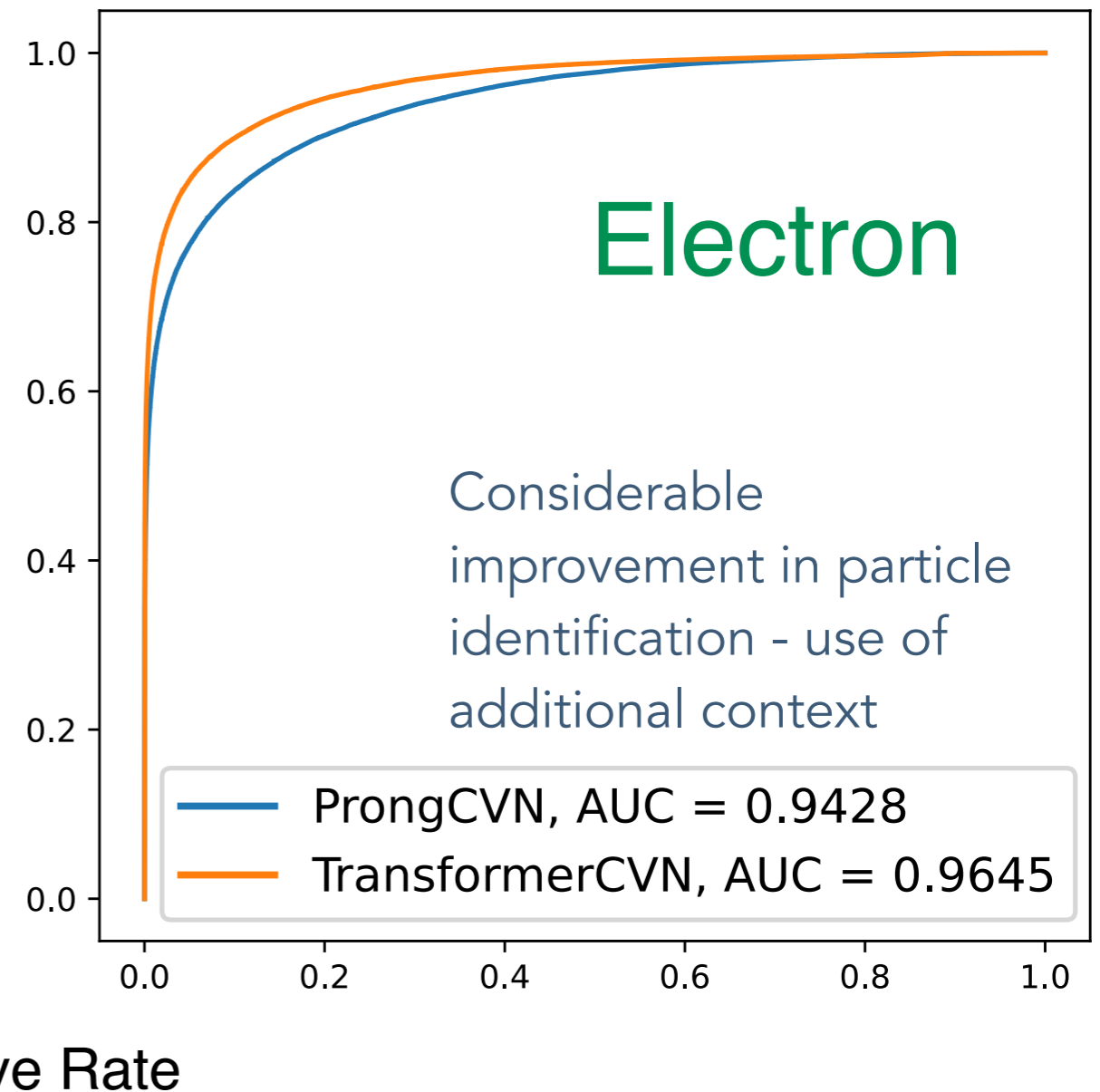
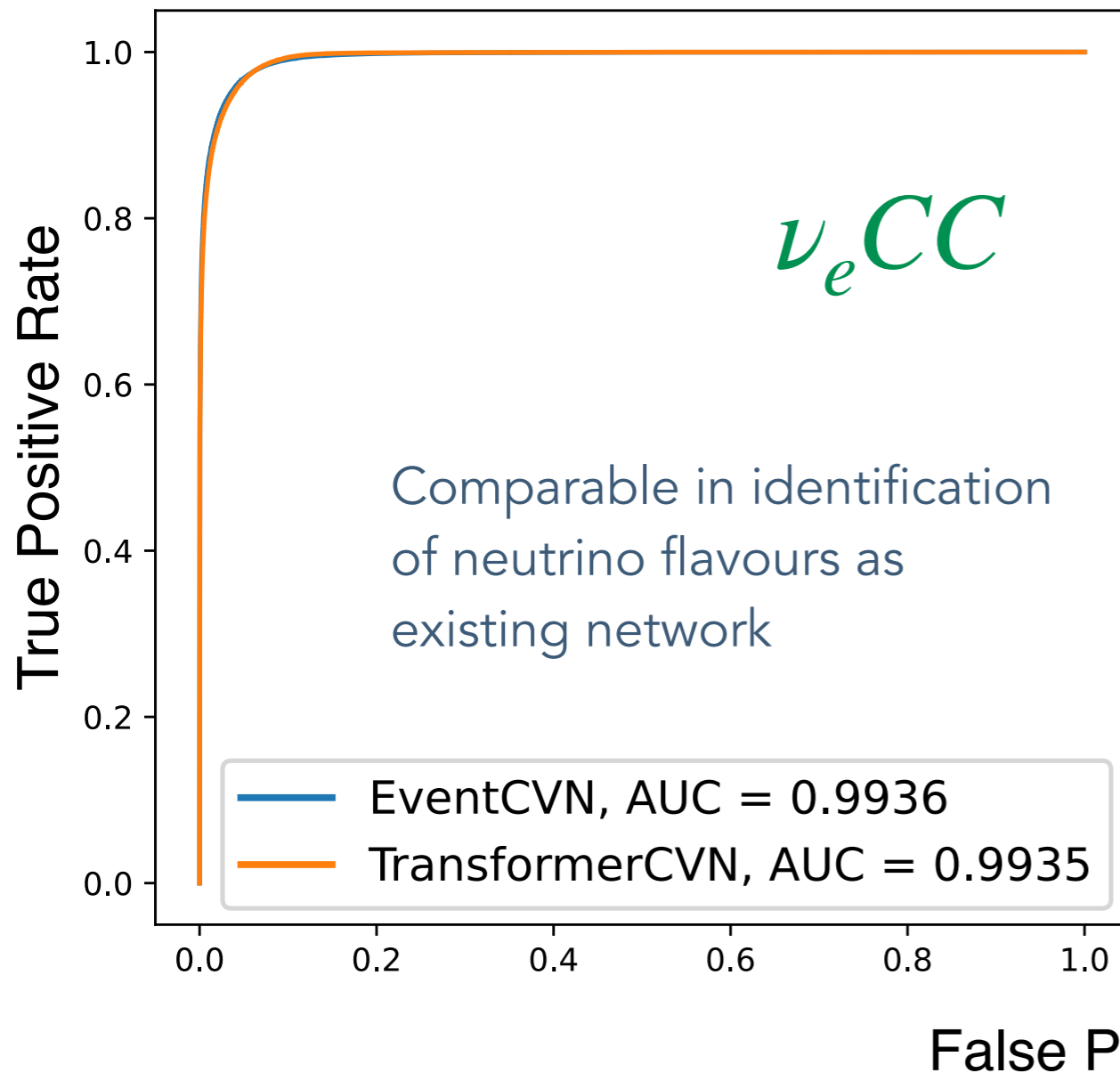
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# Identifying Neutrinos



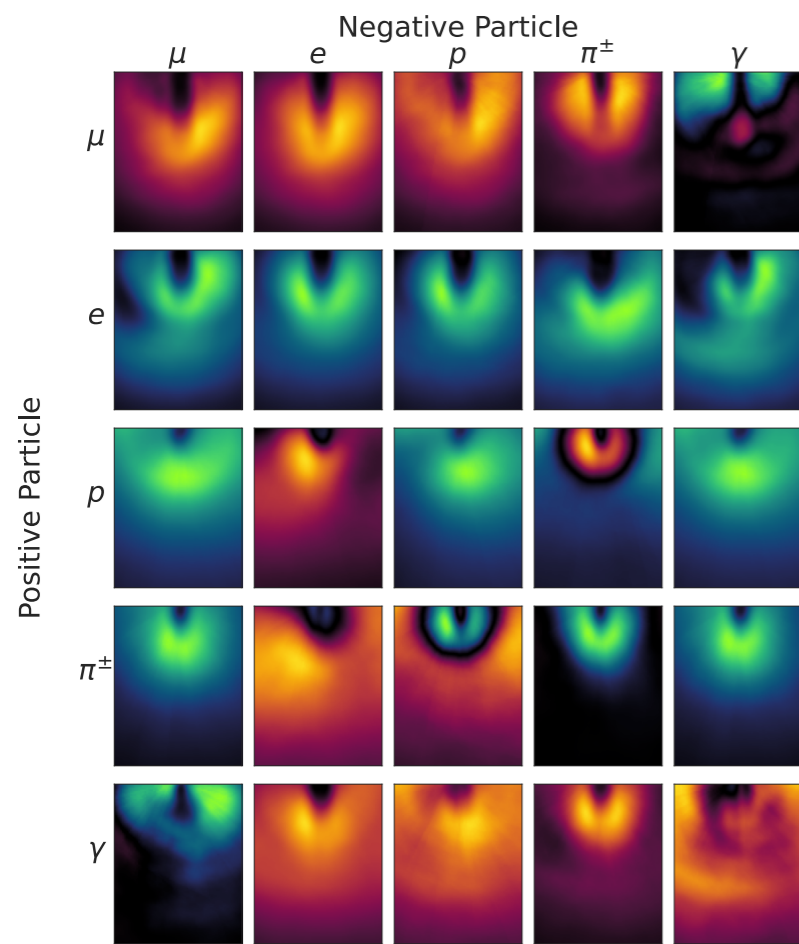


- Relative performance has been studied for different neutrino interaction types - least performant on NC
- Largely insensitive to the true vertex position.

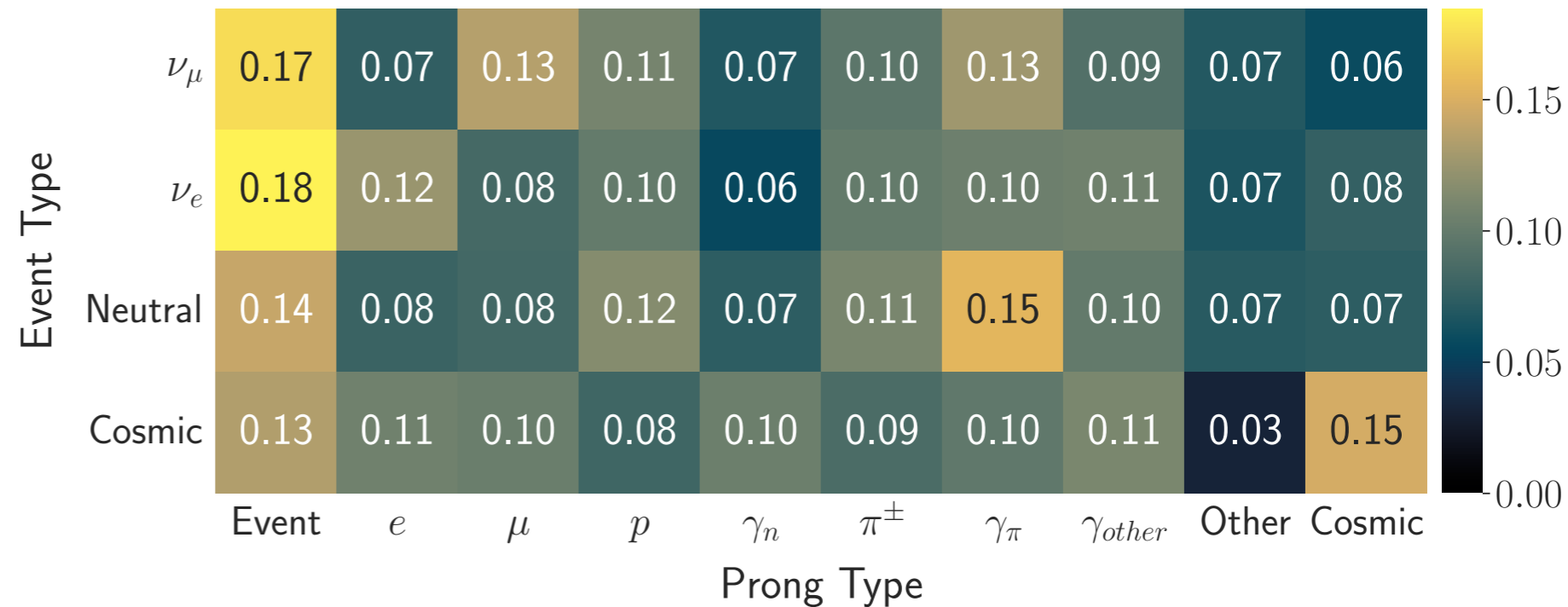


Classifies events with **90% accuracy** and improves identification of individual particles by **6%**.



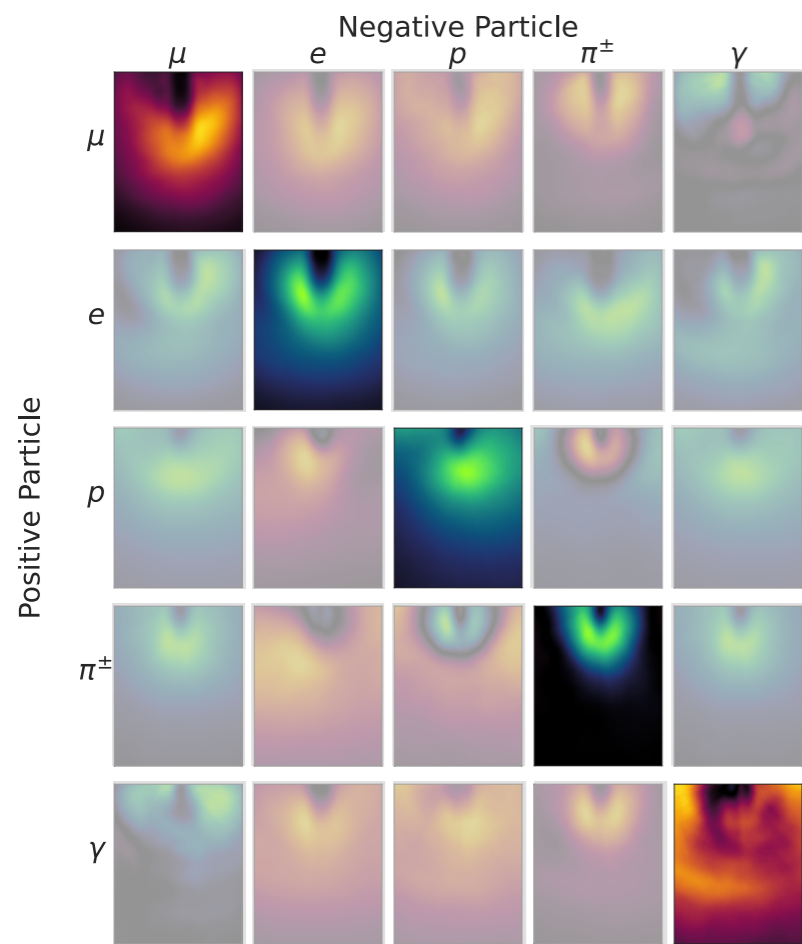


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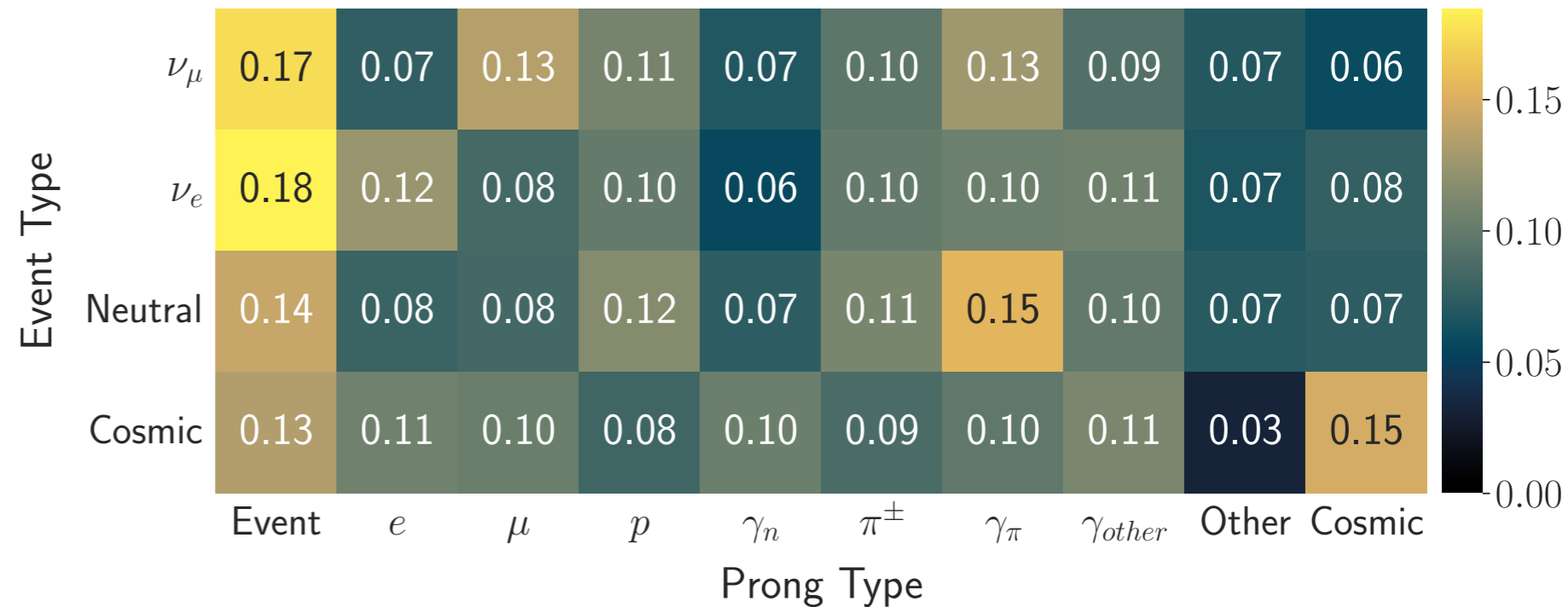


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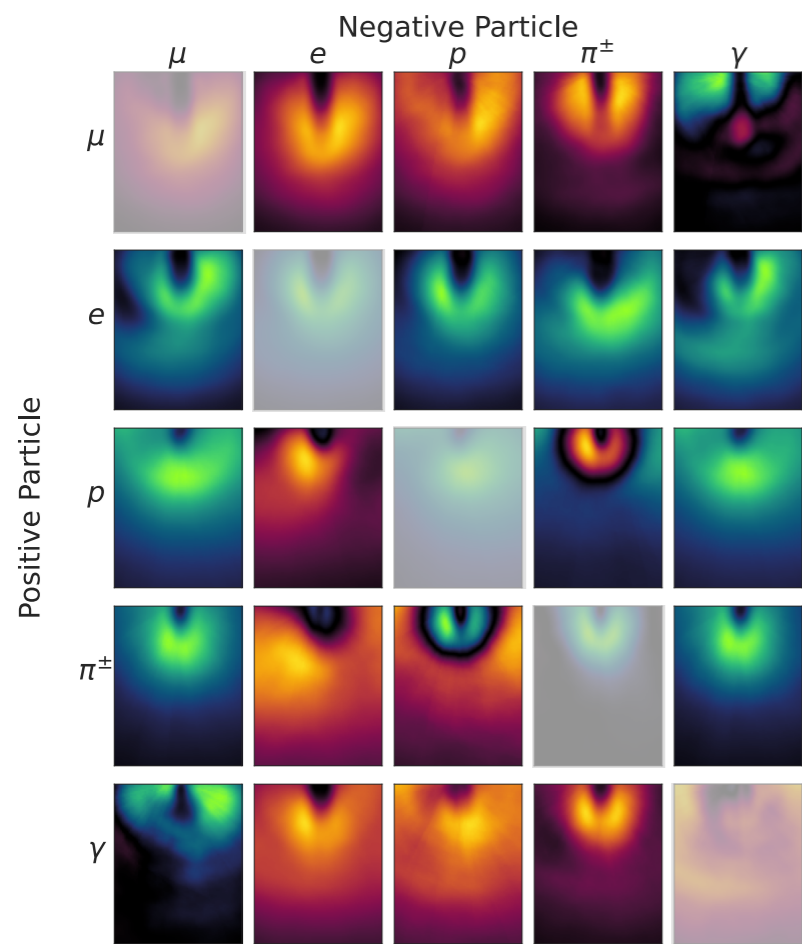


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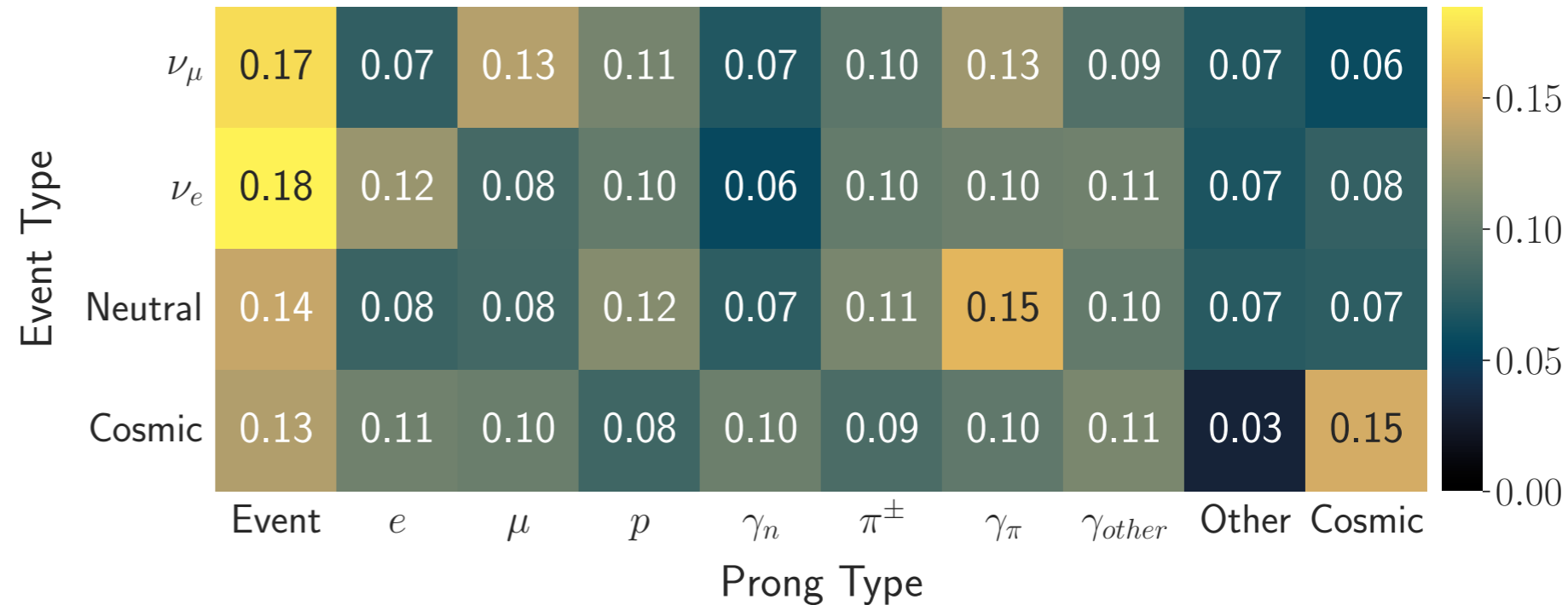


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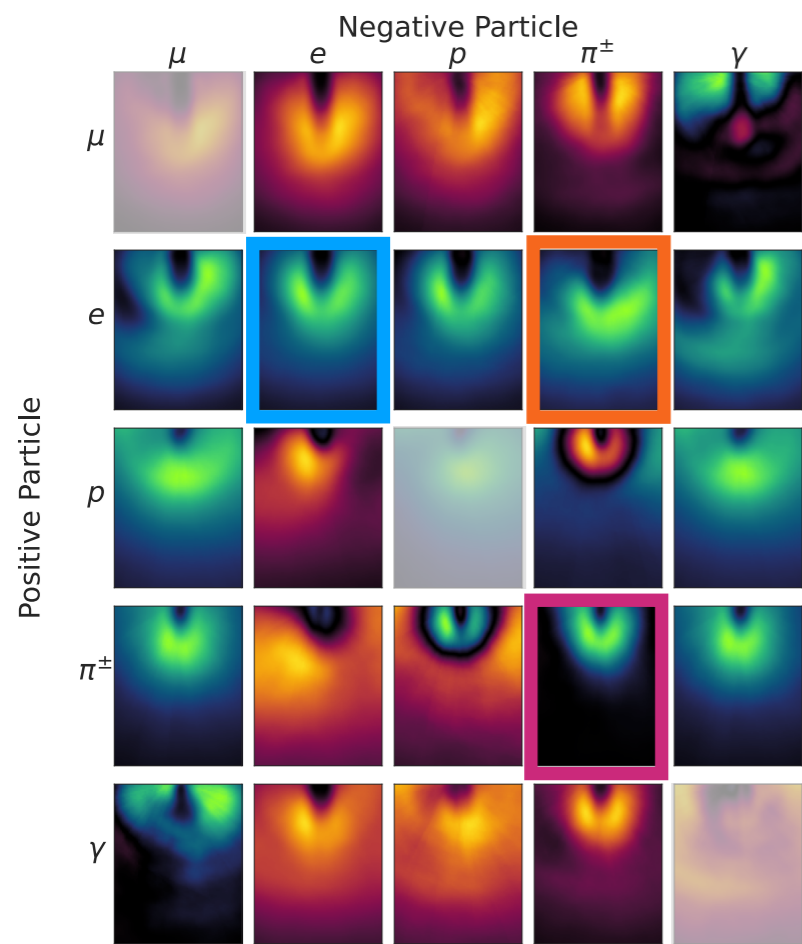


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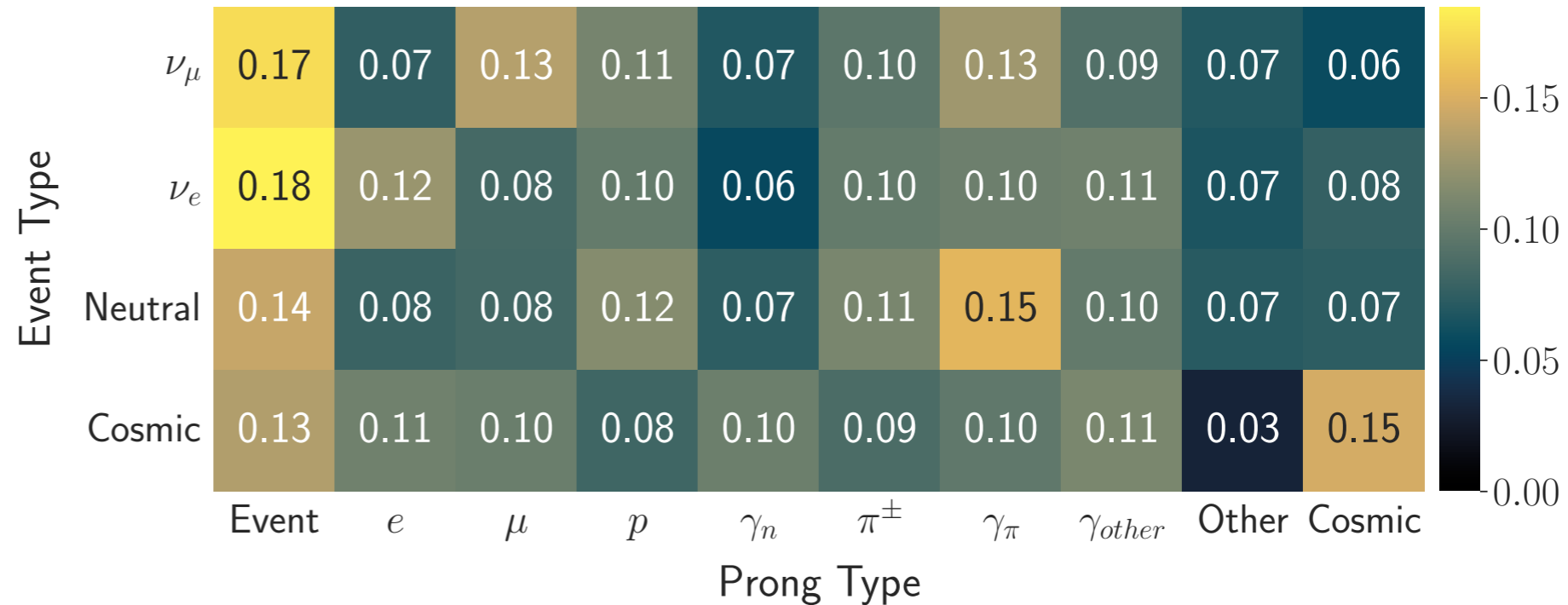
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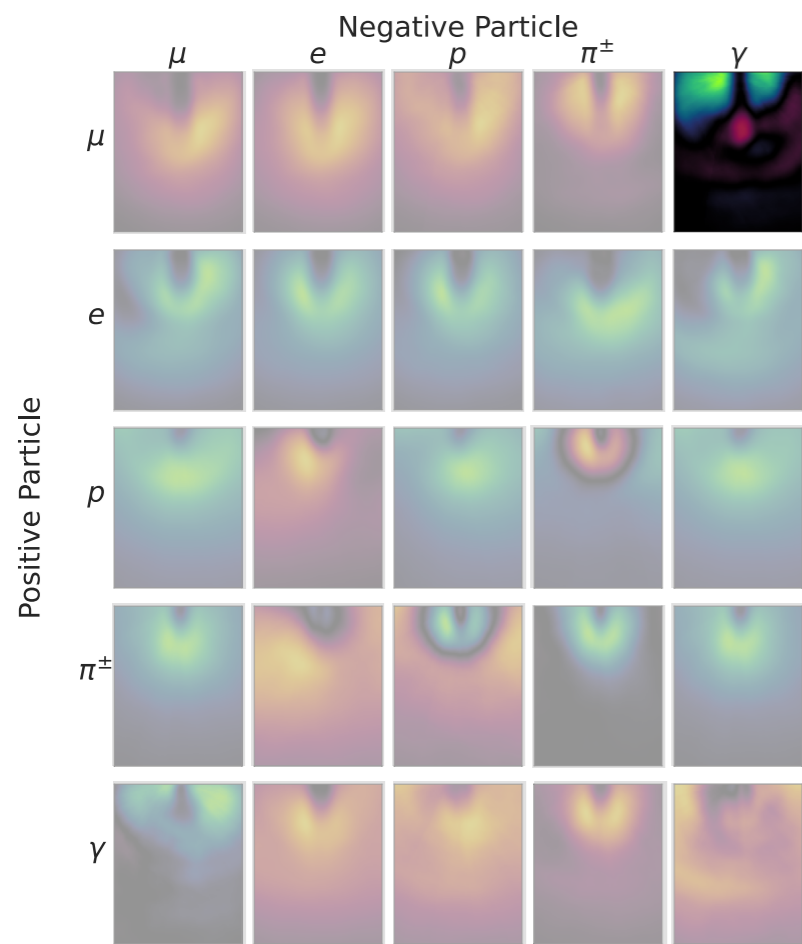
$$\text{Orange Box} = \text{Blue Box} - \text{Pink Box}$$

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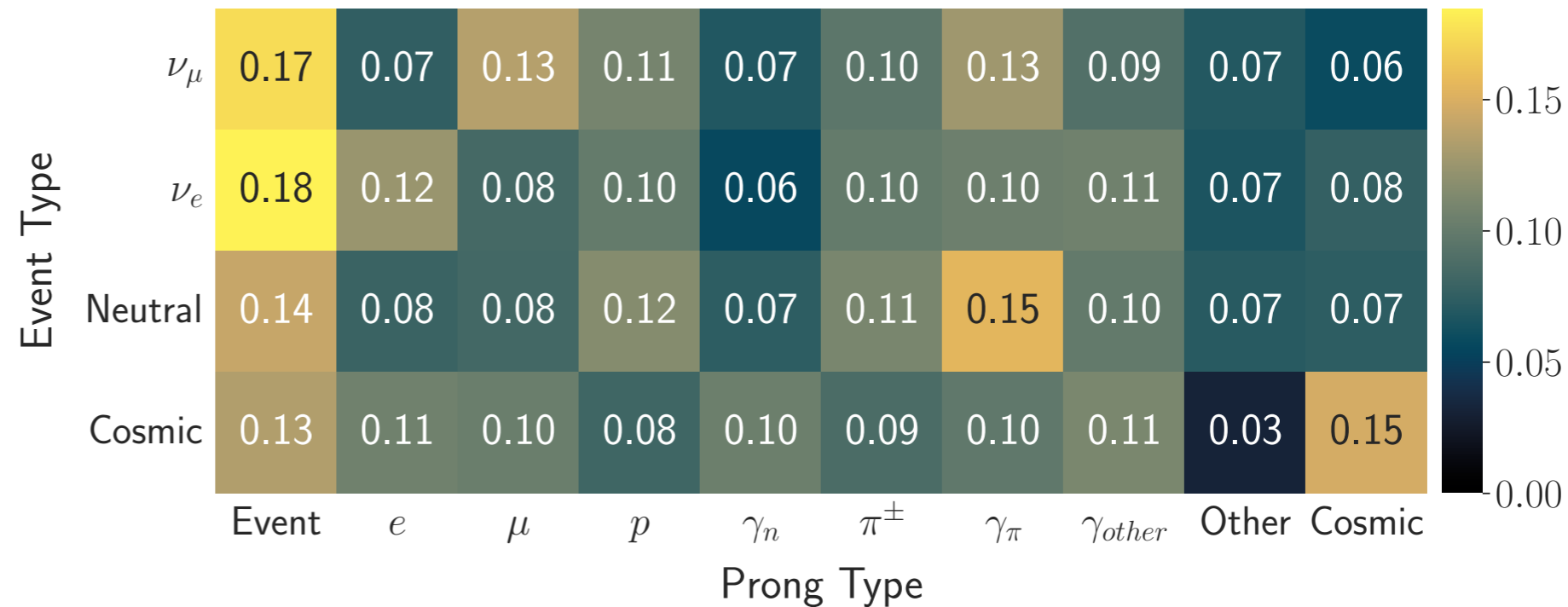


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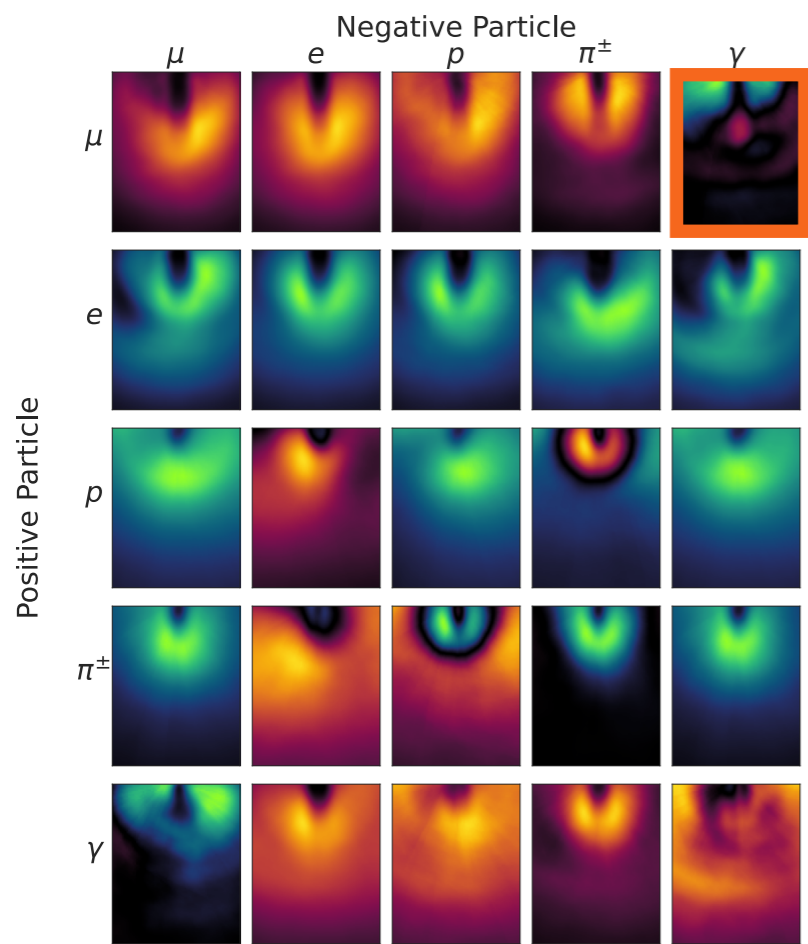


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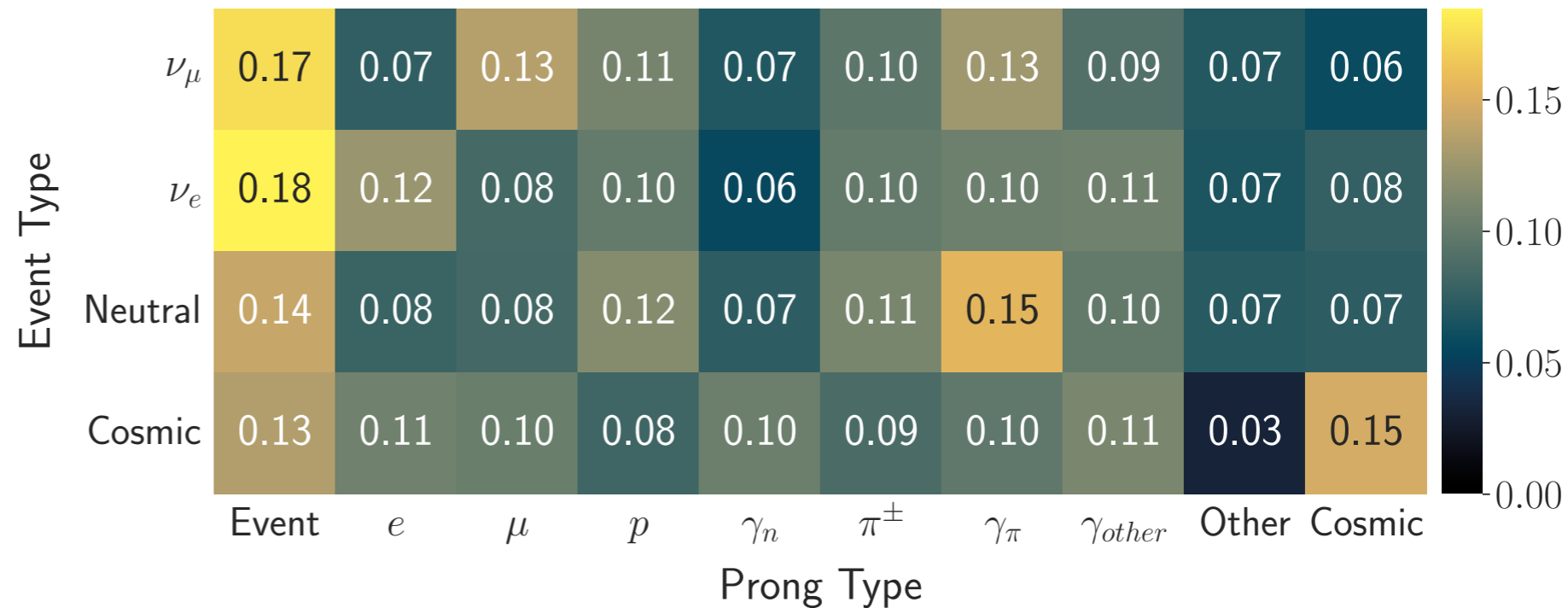


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