MACHINE LEARNING METHODS FOR EVENT RECONSTRUCTION IN ACCELERATOR NEUTRINO EXPERIMENTS

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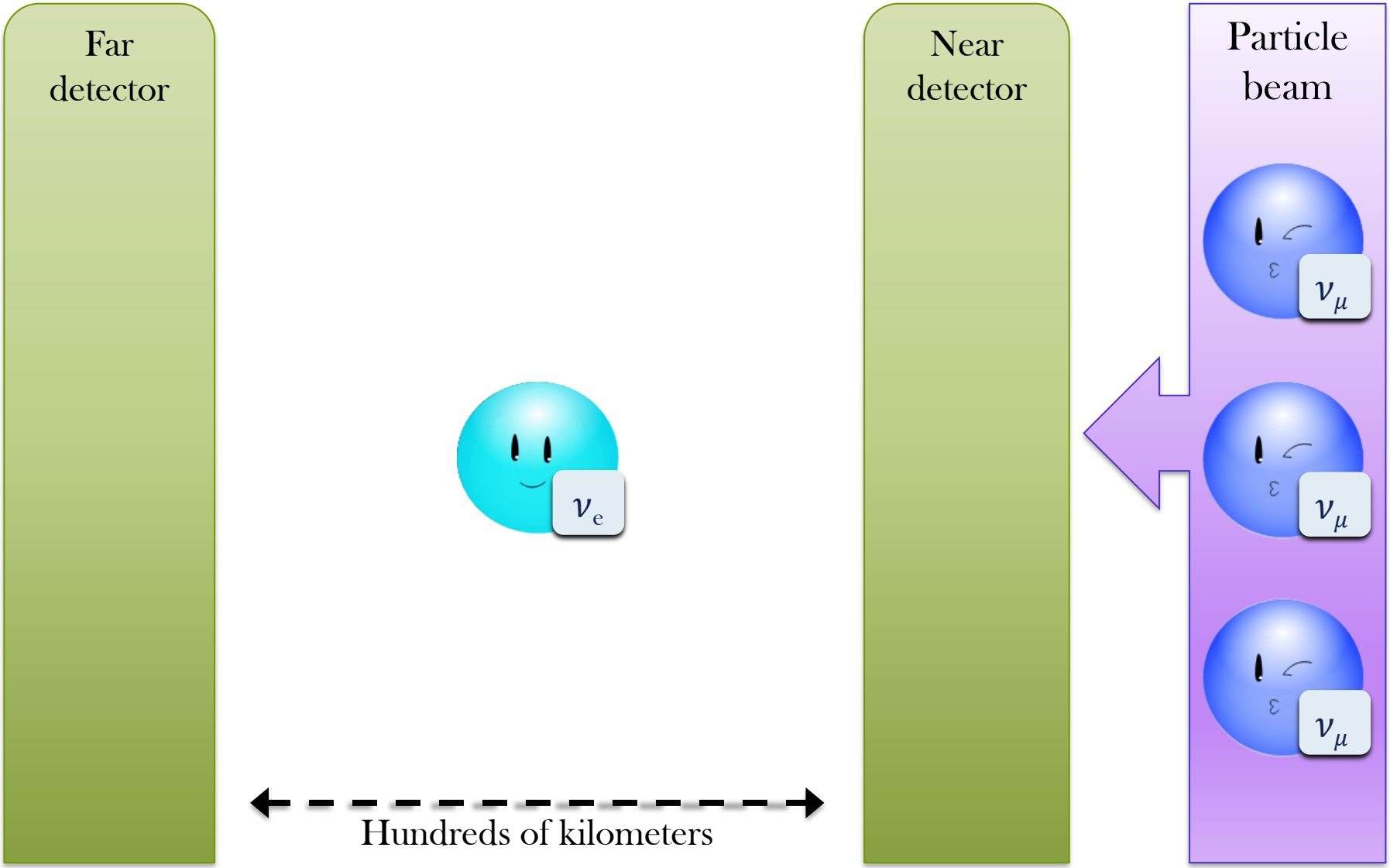
Exploring the Dark Side of the Universe Tools

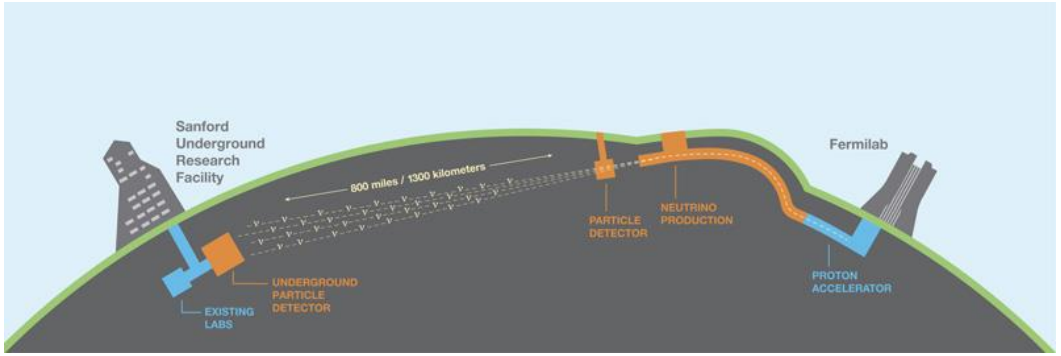
6 June 2024

Neutrino oscillation experiments



DEEP UNDERGROUND NEUTRINO EXPERIMENT

- International neutrino oscillation experiment in the USA.
  - Far detectors located 1300 kilometres away from the source.
- Goal: measuring CP violation.



www.dunescience.org/

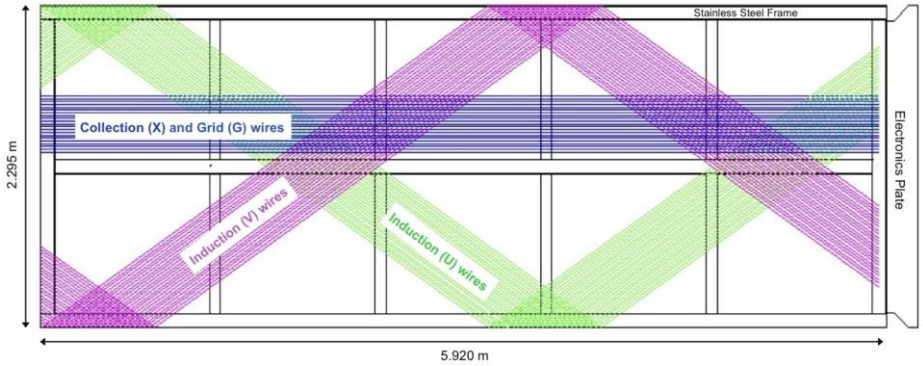
DUNE far detectors

- Technology: Liquid Argon Time Projection Chamber (LArTPC).
  - Provides images of each neutrino interaction.

youtube.com/c/fermilab

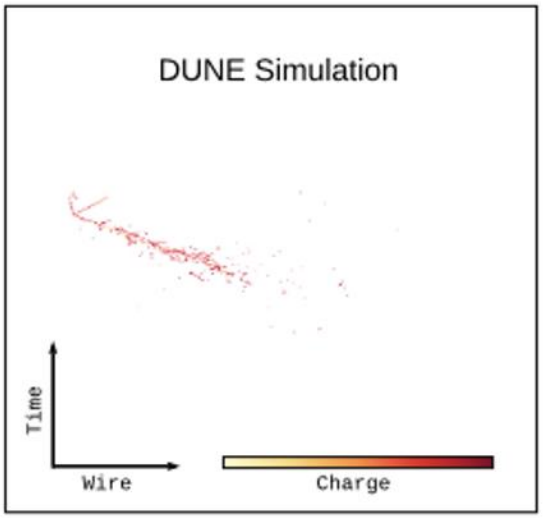
DUNE far detector data

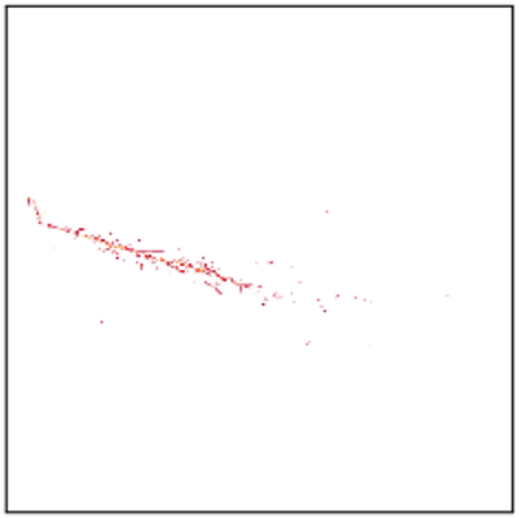
- The Far Detectors contain three wire readout planes.
  - This provides three "images" of each neutrino interaction (500x500 pixels each).

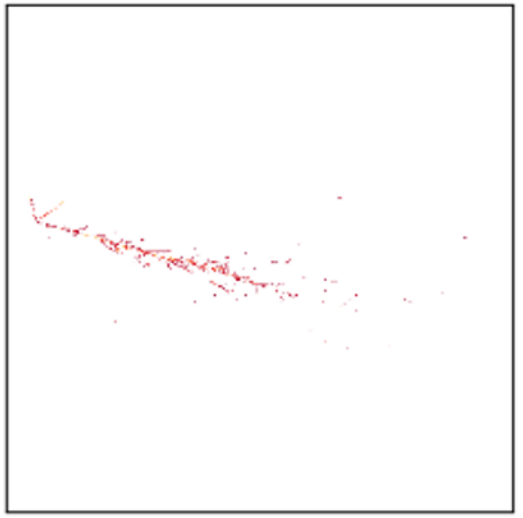


- Official simulated electron neutrino interaction:

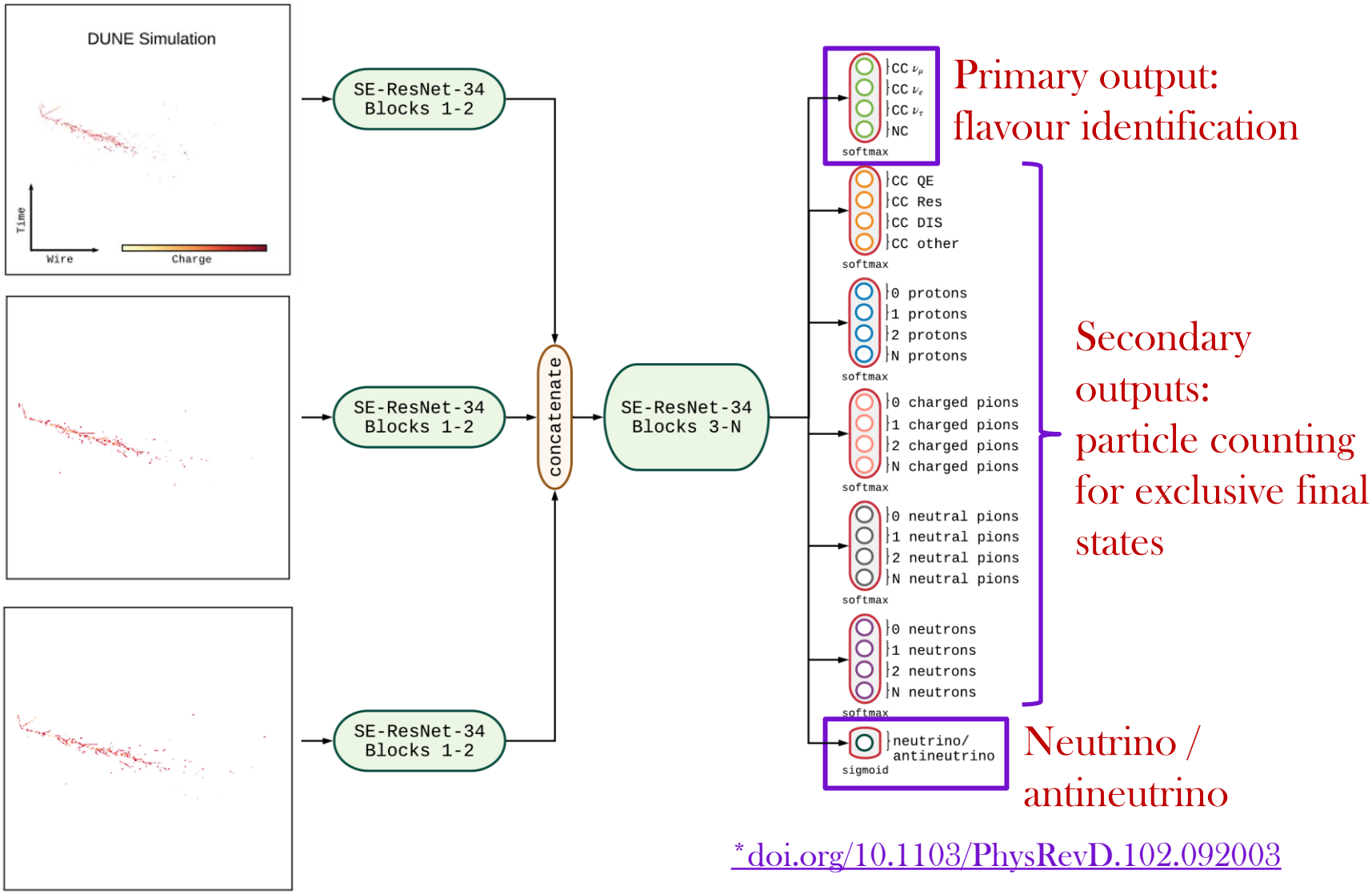
doi.org/10.1016/j.nima.2022.167217







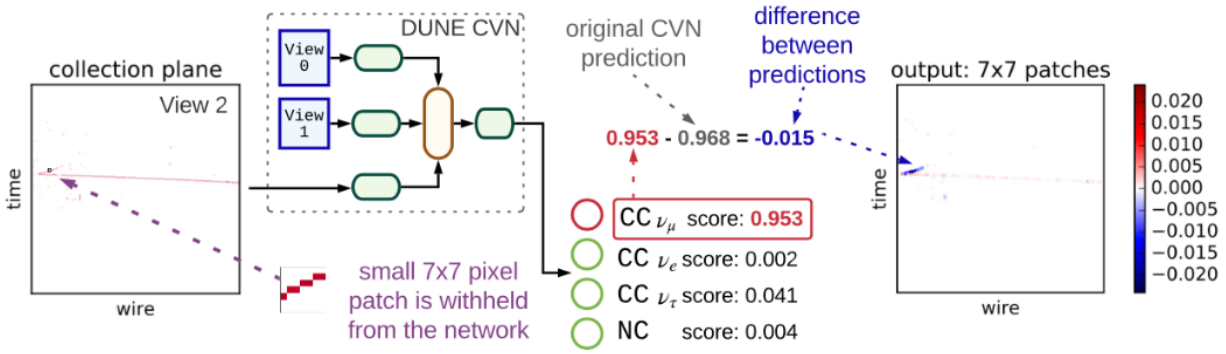
Convolutional neural network in DUNE



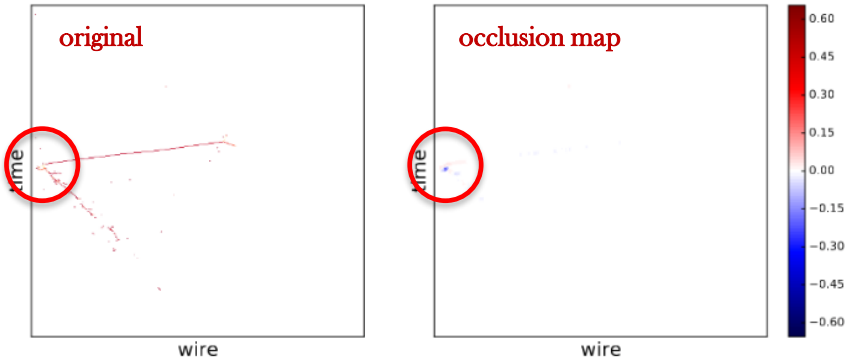
*doi.org/10.1103/PhysRevD.102.092003

Understanding the CNN

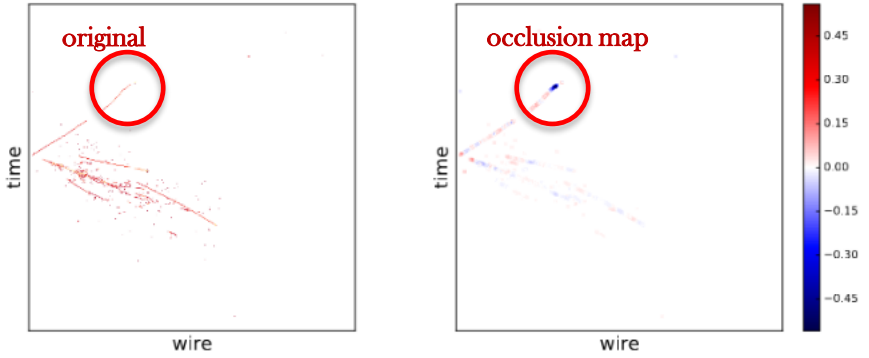
- Occlusion tests:
  - Hide parts of the images and check how the CNN reacts to the changes.



electron neutrino (ν_e)



muon neutrino (ν_μ)



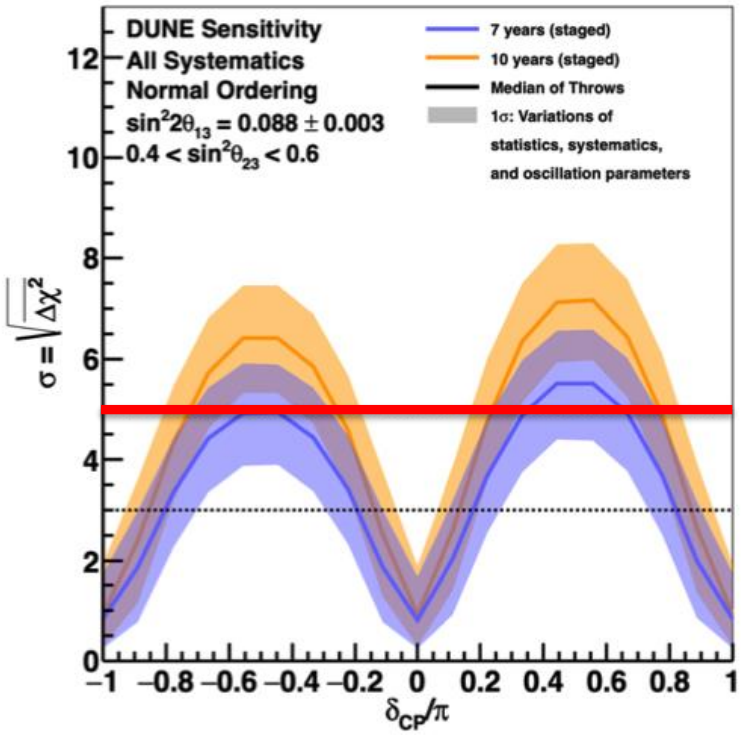
Removing the start of the electron shower reduces the νe score, as expected

The CVN finds the vertex a bit ambiguous, but it is using the end point of the muon to gain a handle on the event type.

Results

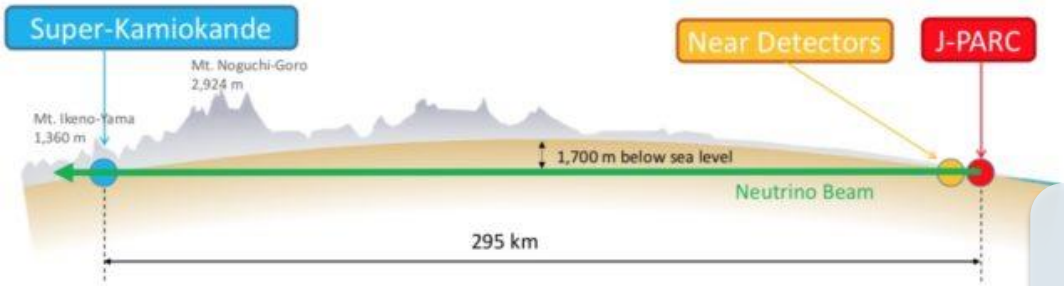
- The flavour identification results are used in the official analysis of DUNE:
  - arXiv:2002.03005.
  - https://doi.org/EPJC/S10052-020-08456-Z.

- Sensitivity to CP violation:



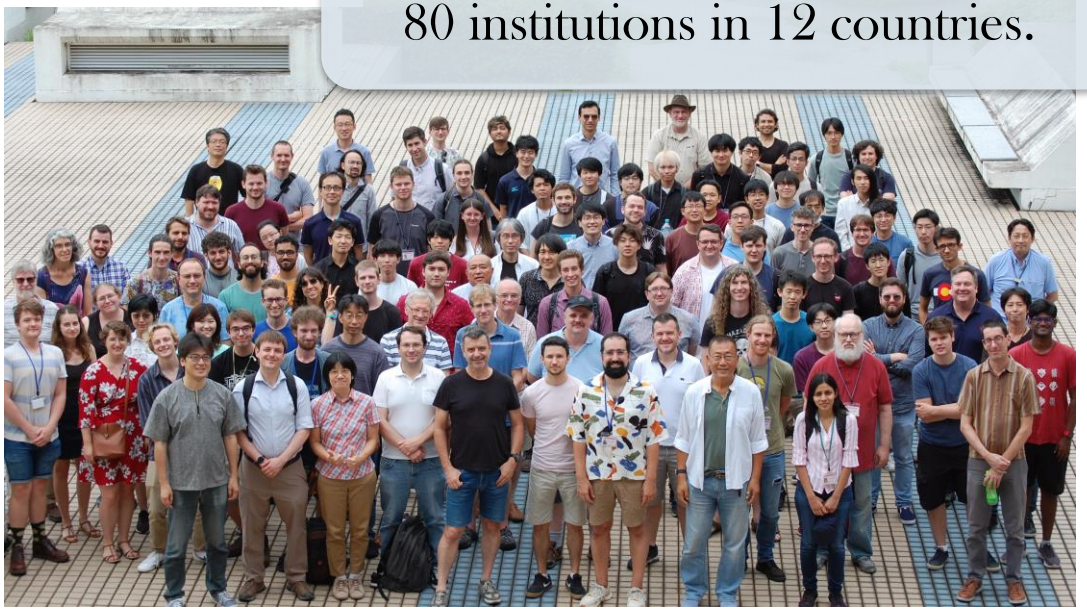
- 5σ after seven years of data collection.
- A milestone for the experiment!
- Made possible thanks to the convolutional neural network.

- T2K (Tokai to Kamioka) is an international neutrino oscillation experiment located in Japan.

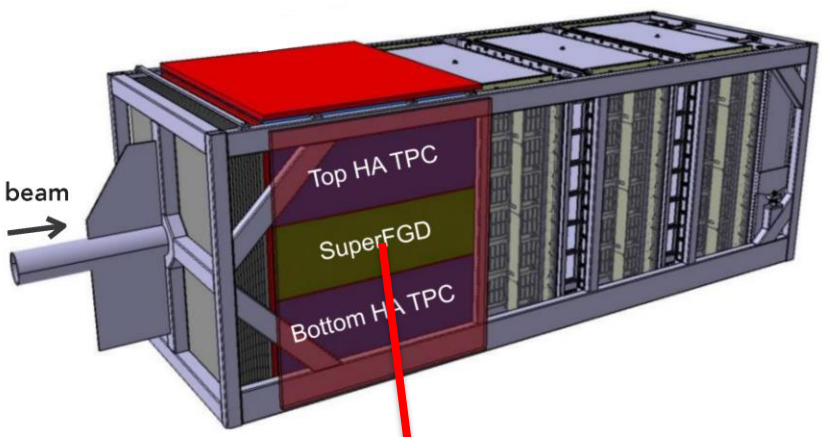


- Far detectors located 300 km away from the near ones.

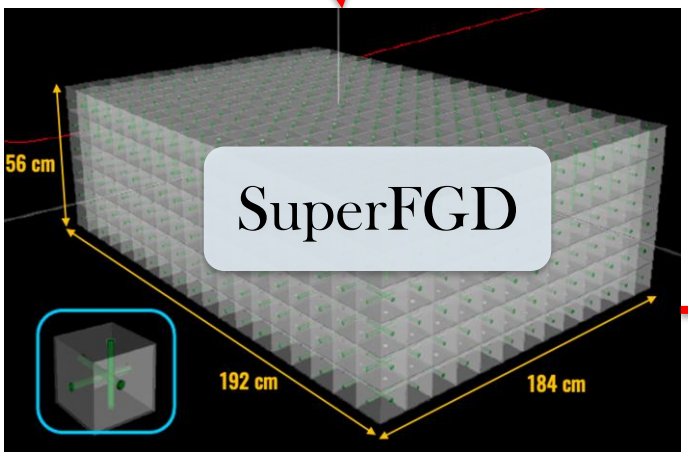
More than 500 collaborators from 80 institutions in 12 countries.

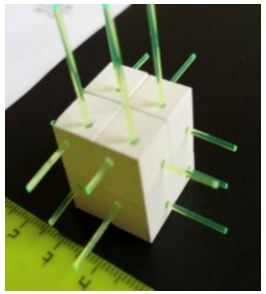


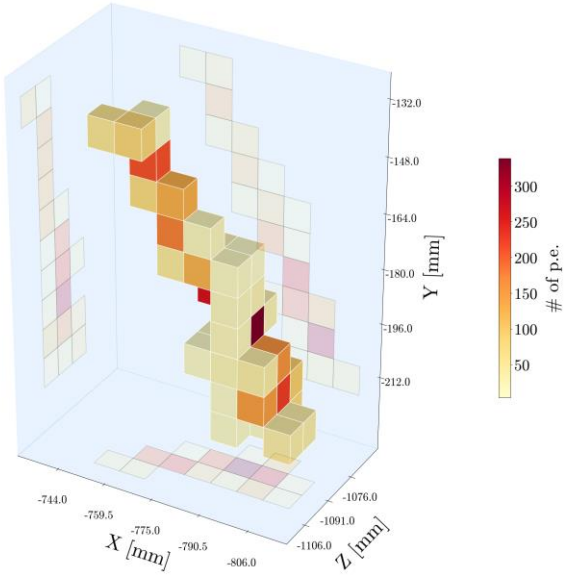
Near Detector (ND280)



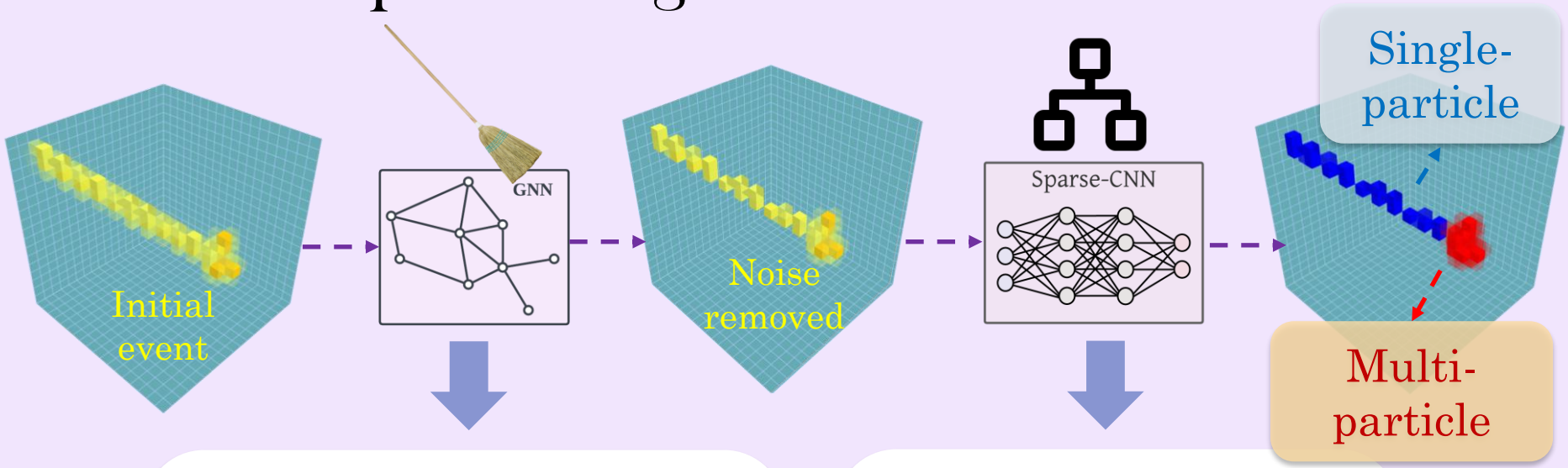
- The nearby detector ND280 of the T2K (and HyperK) experiment measures neutrino interactions before oscillations occur.
- A key component is the SuperFGD, comprised of optically isolated plastic scintillator cubes measuring 1x1x1 cm^3 in size.

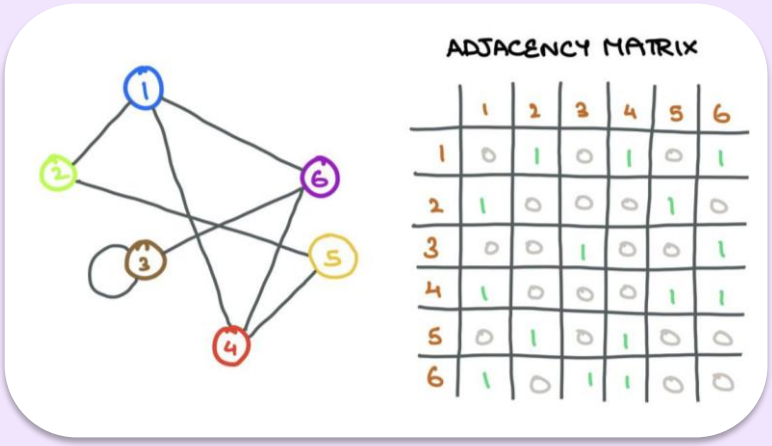






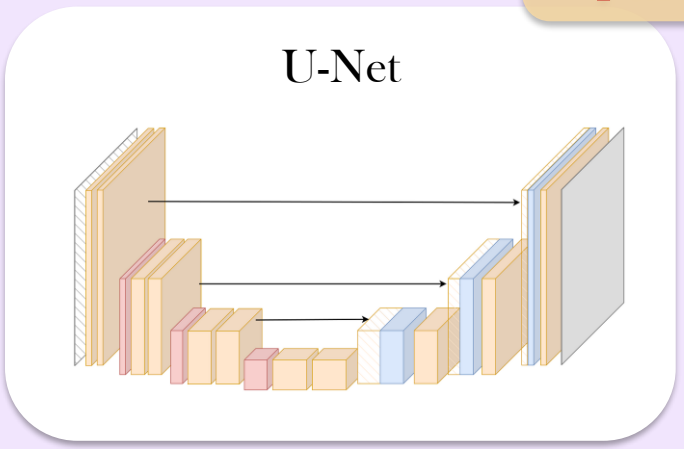
Deep learning in the near detector





90% of the noise is eliminated without harming the signal.

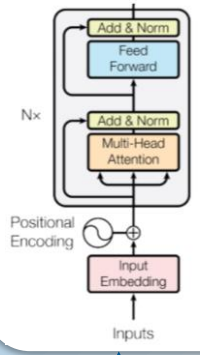
*doi/10.1103/PhysRevD.103.032005



~95% accuracy!

Deep learning in the near detector

Transformer encoder

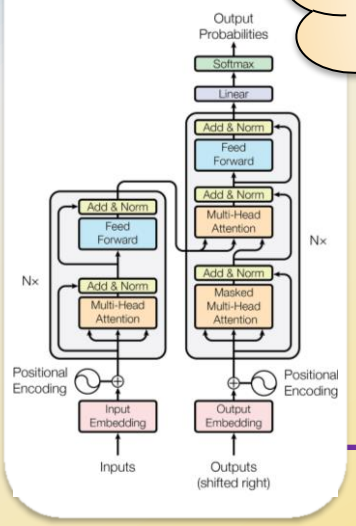


*nature.com/articles/s42005-023-01239-4

Improved resolution by 35%.

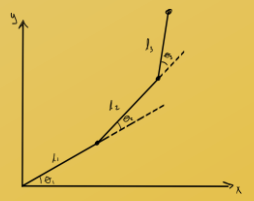
Fitted trajectory

Transformer

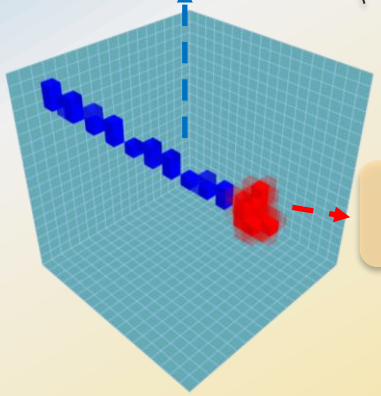


Automatically decomposes the event!

Reconstructed kinematics of each particle.

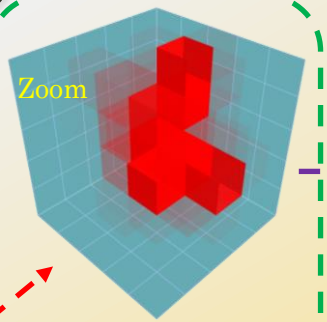


Single-particle

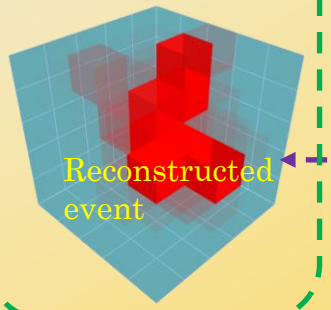


Multi-particle

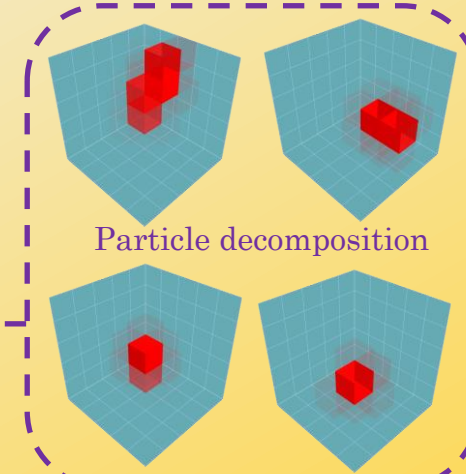
Zoom



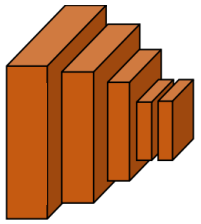
Verify the decomposition



+



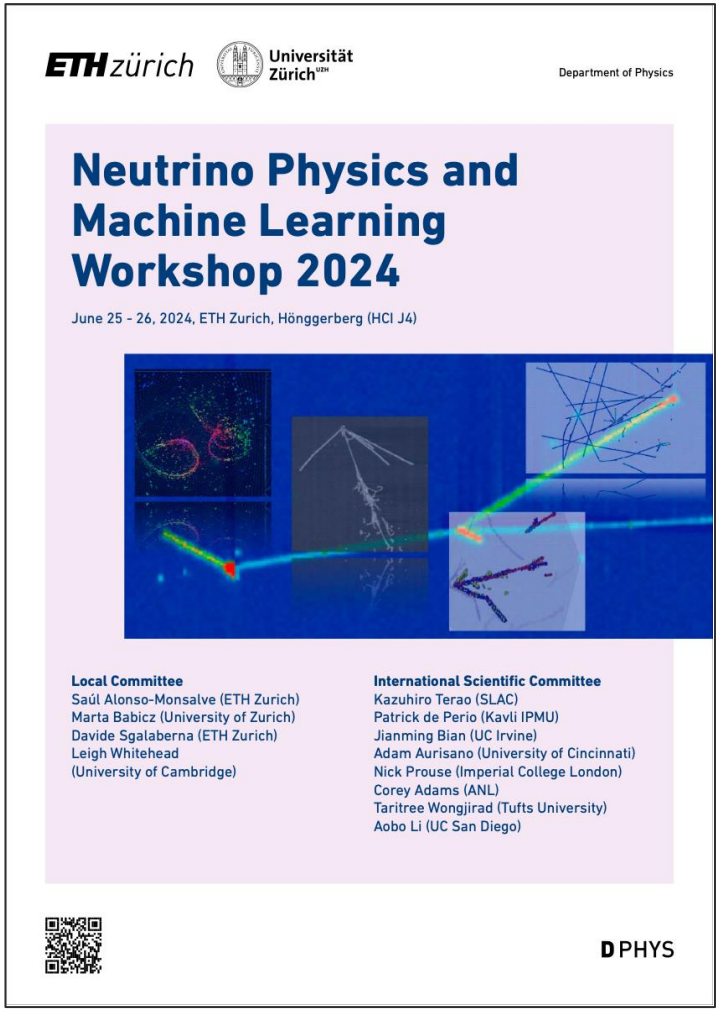
Generative model



*nature.com/articles/s42005-024-01669-8

Neutrino Physics and Machine Learning (NPML) Workshop

- International workshop, 24-28 June, 2024.
- Participants from more than 50 institutions!
- ETH Zürich, Hönggerberg campus.
- indico.phys.ethz.ch/e/npml2024.
- 51 talks + poster session.



AI image generator (Bing)

- Prompt: "AI and Dark Side of the Universe in Nantes, France."

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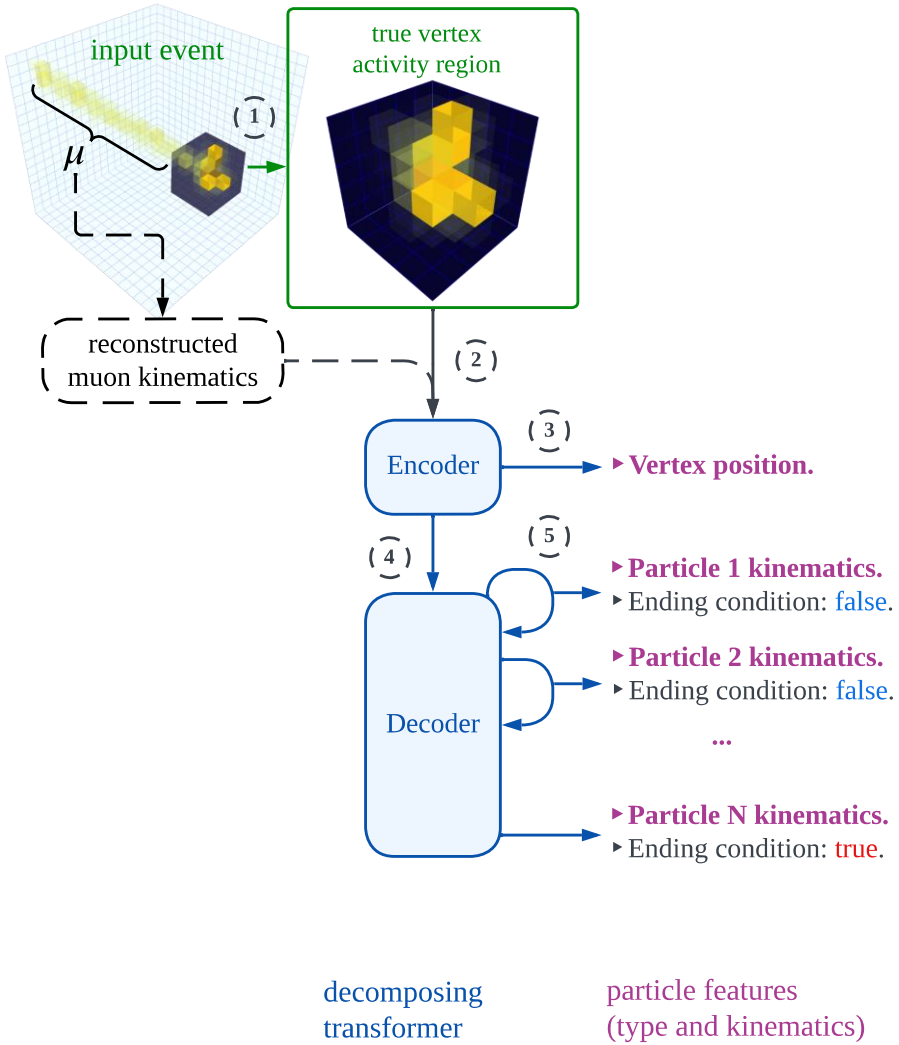
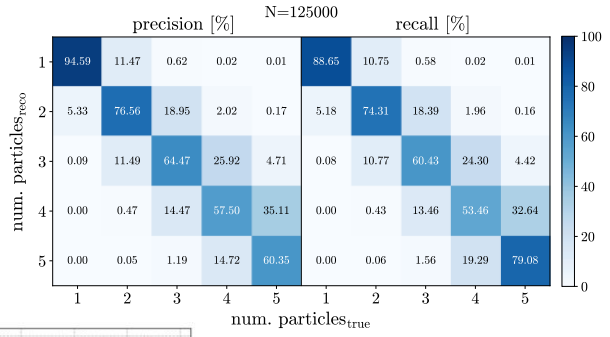
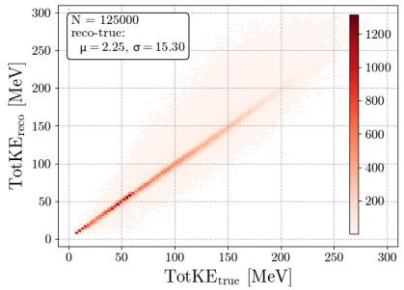
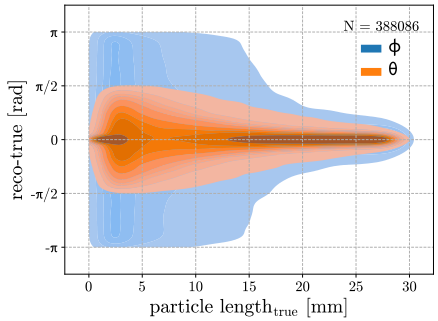
Deep-learning approach



- **Event config: 1 muon, 1-5 protons.**
  - 70% accuracy in reconstructing the correct number of particles.
    - >98% assuming a ±1 error.
  - ~2 mm vertex resolution.
  - Good reconstruction of kinematics.

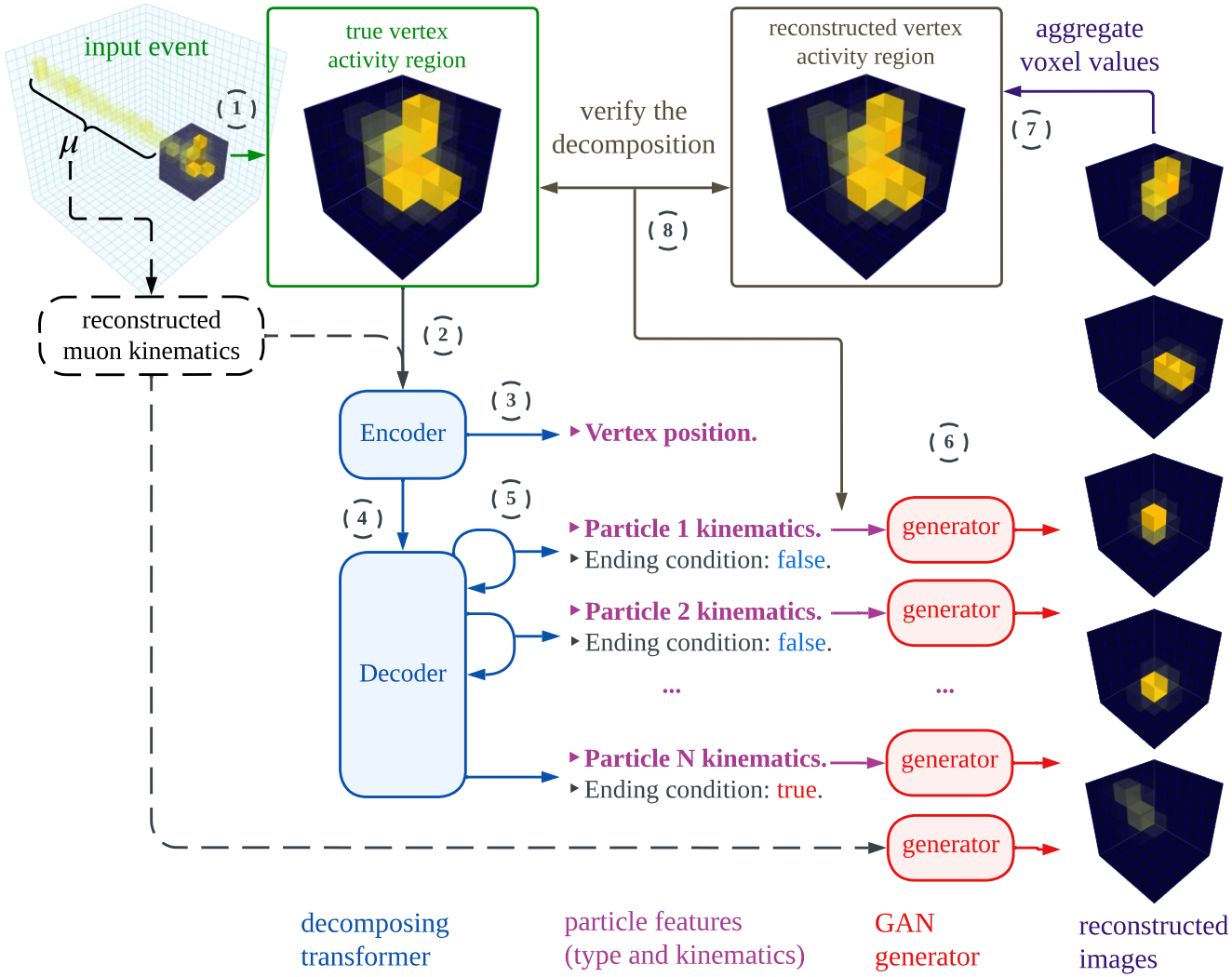






- **Also tested configurations with nuclear clusters (deuterium, tritium)!**

Deep-learning approach



- The generator (GAN) is fully differentiable.
  - Run a gradient-descent minimiser to optimise the particle kinematics further.

Comparison with standard method

- Statistically independent neutrino sample for testing (NEUT).
- **Visible energy (VisE)**: reconstructed energy in MeV.
- **Standard method**: considers a single proton responsible for all VisE in the vertex-activity region.
- **VisE resolution**: $(VisE_{true} - VisE_{reco})\ VisE_{true}^{-1}$

true protons	events	reco protons [%]	VisE resolution (RMS) [%]					
			VA region			entire event		
		transformer	std. method	trans.	trans.+GAN	std. method	trans.	trans.+GAN
1	36505	100.00	33.06±0.25	27.41±0.14	26.36±0.19	2.77±0.01	2.38±0.02	1.34±0.01
2	3520	89.35	22.44±0.32	16.60±0.28	13.05±0.22	3.79±0.05	2.19±0.04	1.66±0.03
3	370	65.13	19.18±0.56	11.06±0.57	8.41±0.43	4.98±0.17	2.42±0.13	1.83±0.10
4	49	65.30	20.61±1.32	11.35±1.35	9.34±1.14	6.06±0.50	2.91±0.35	2.32±0.29

- Absolute improvements in VisE resolution up to 12% in the VA region, and 4% for entire events.
- Impact to reduce associated systematic errors and avoid model dependence.

https://arxiv.org/abs/2310.19695 *(Accepted for publication in Comm. Physics).*