

MACHINE LEARNING METHODS FOR EVENT RECONSTRUCTION IN ACCELERATOR NEUTRINO EXPERIMENTS

Dr. Saúl Alonso-Monsalve

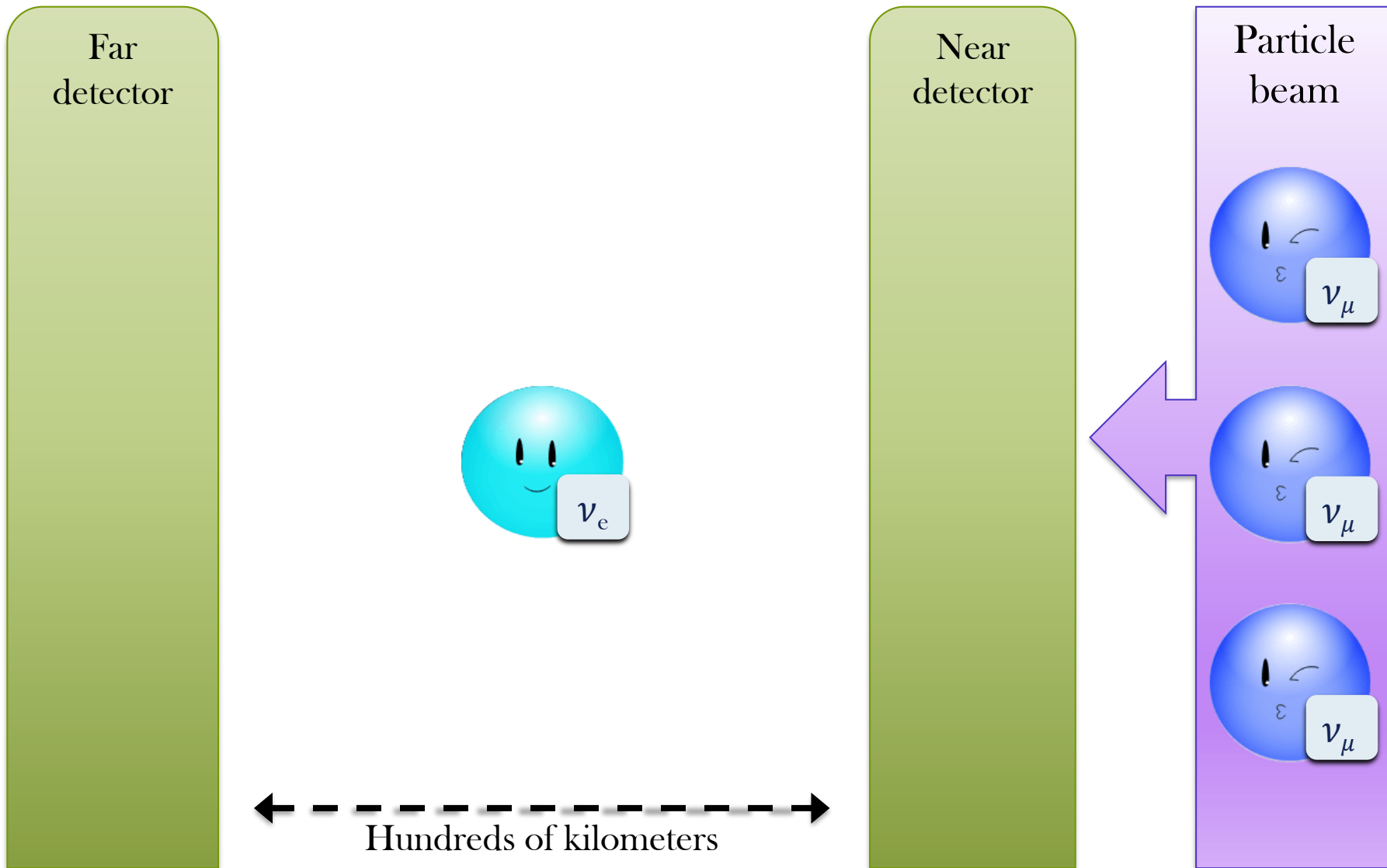
ETH Zürich

salonso@ethz.ch / saul.alonso.monsalve@cern.ch

Exploring the Dark Side of the Universe Tools

6 June 2024

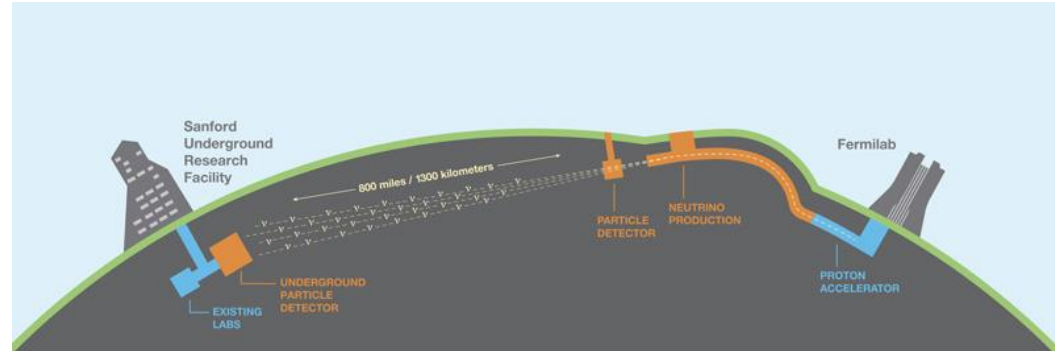
Neutrino oscillation experiments





DEEP UNDERGROUND NEUTRINO EXPERIMENT

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



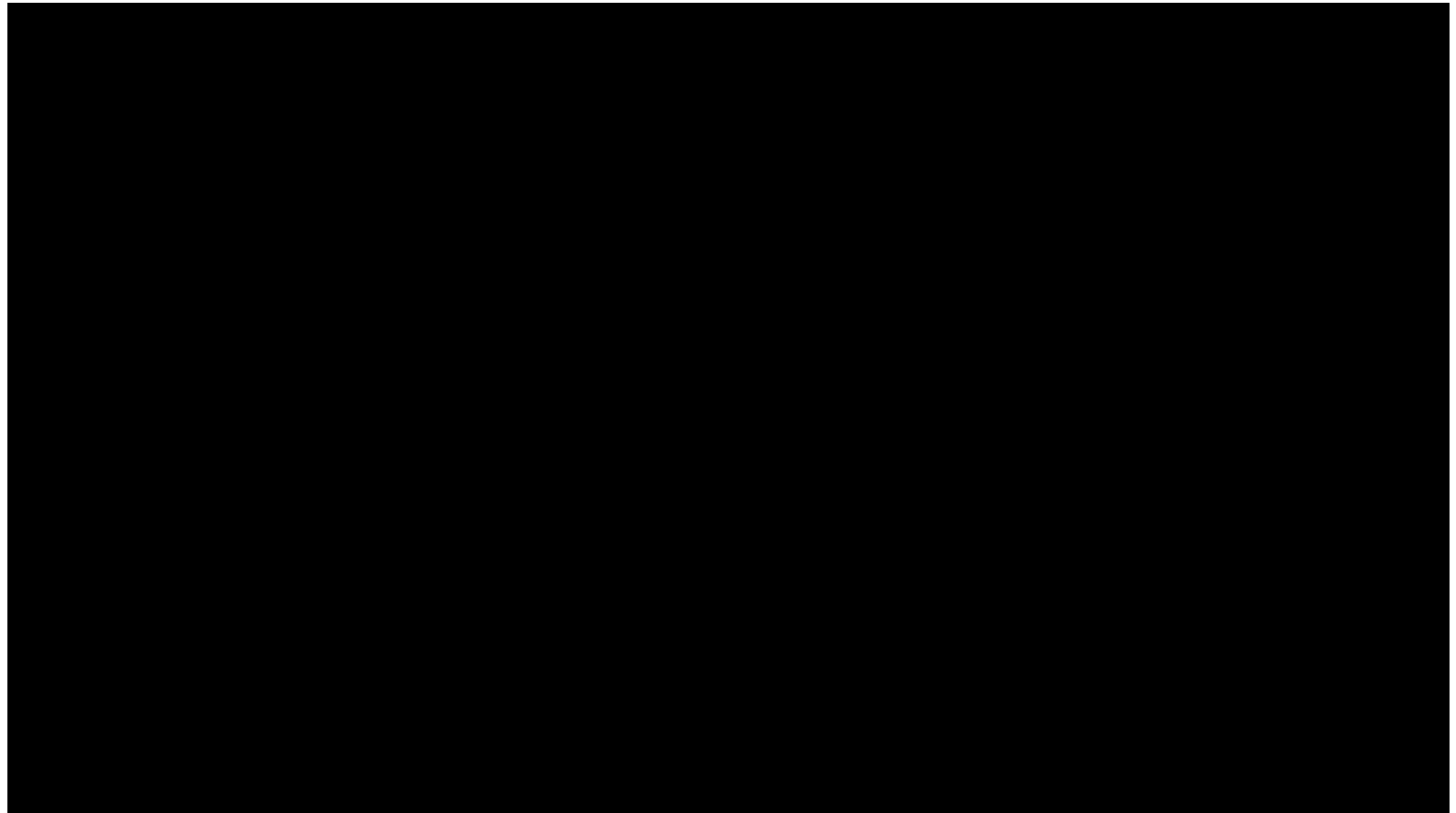
www.dunescience.org/

More than 1000 collaborators from
200 institutions in 30 countries.



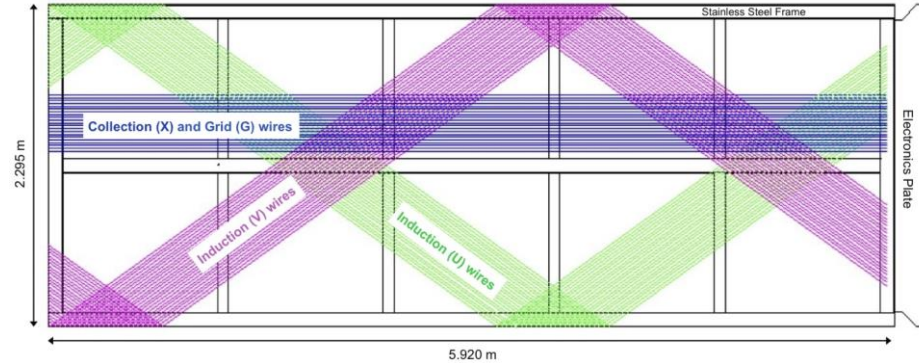
DUNE far detectors

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

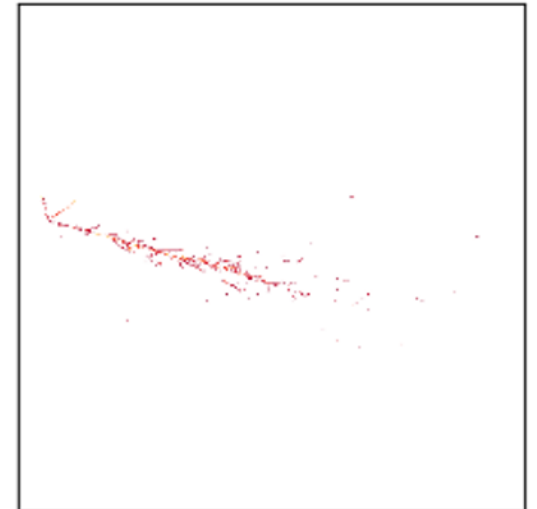
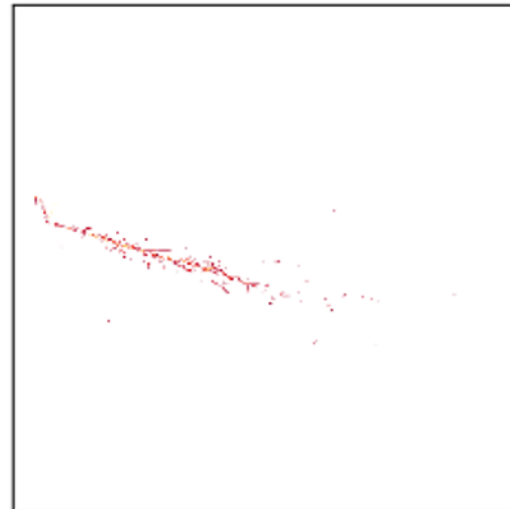
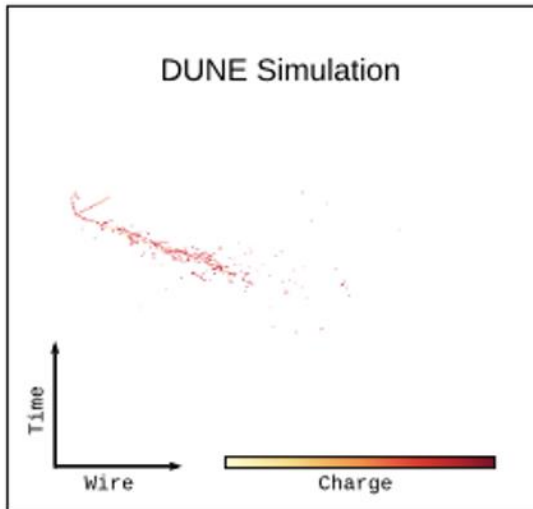


DUNE far detector data

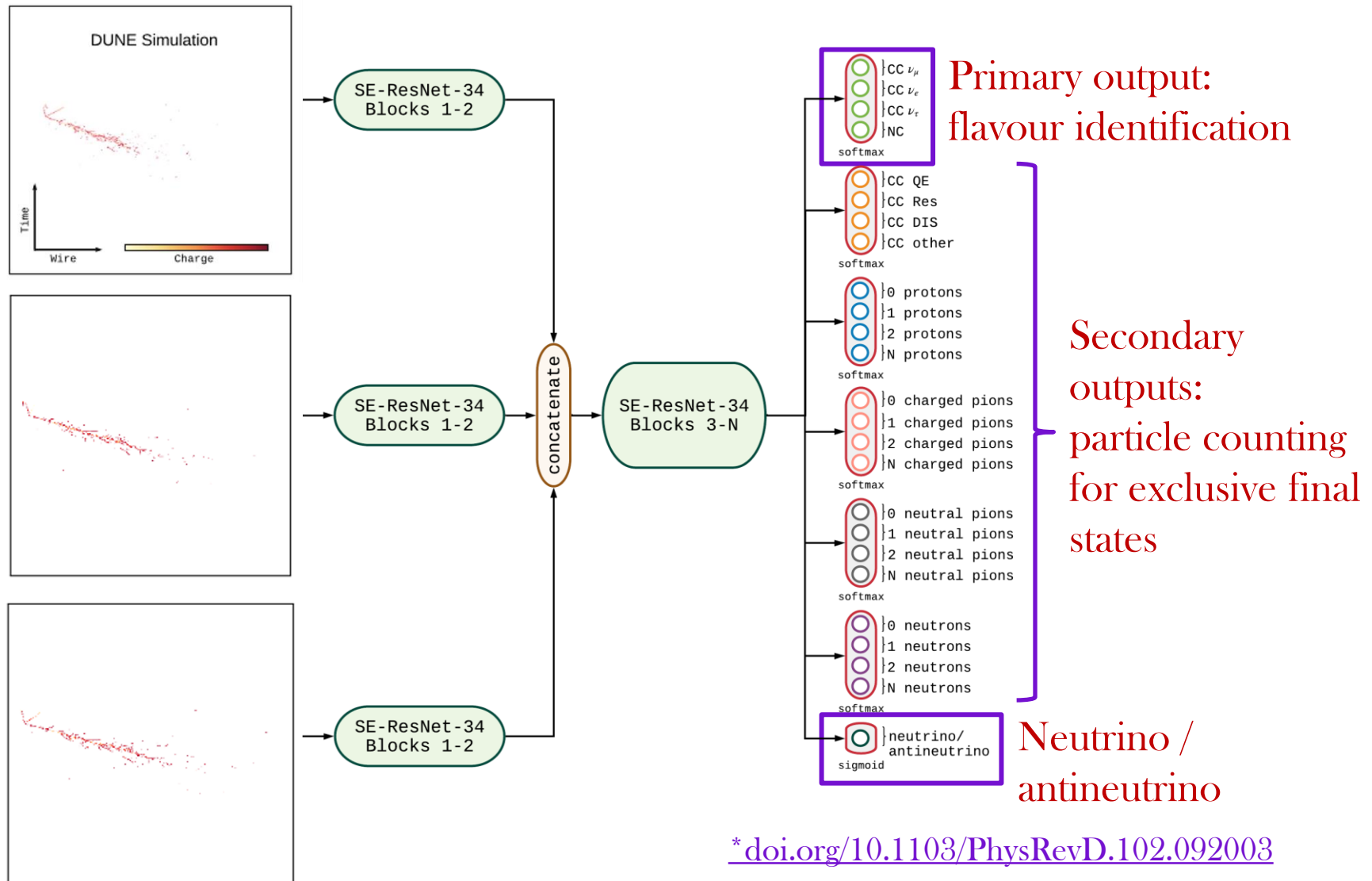
- The Far Detectors contain three wire readout planes.
 - This provides three “images” of each neutrino interaction (500x500 pixels each).
- Official simulated electron neutrino interaction:



doi.org/10.1016/j.nima.2022.167217

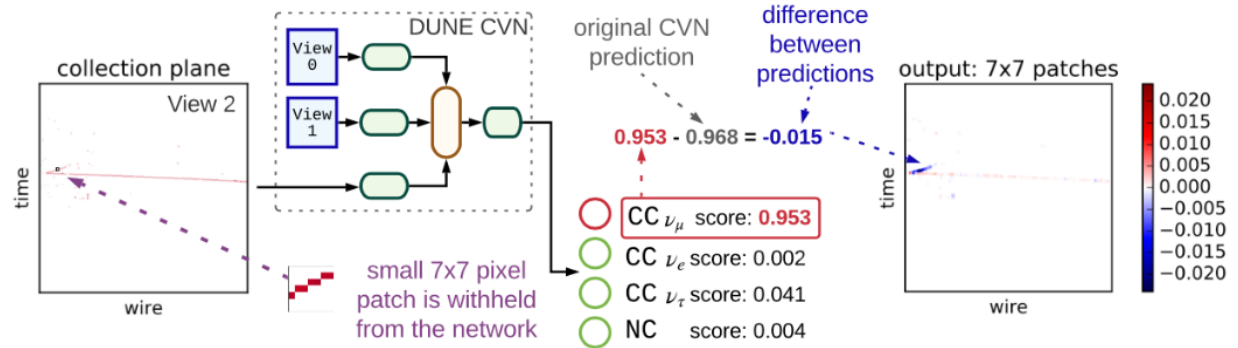


Convolutional neural network in DUNE

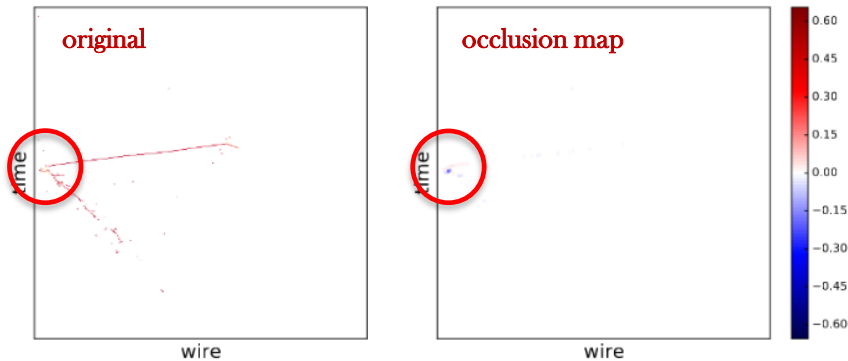


Understanding the CNN

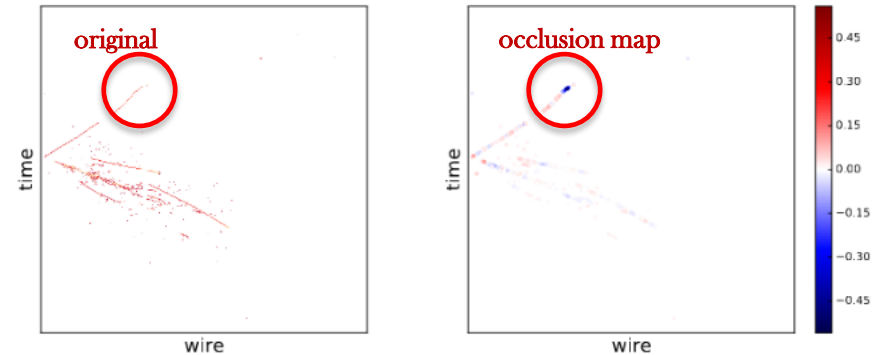
- Occlusion tests:
 - Hide parts of the images and check how the CNN reacts to the changes.



electron neutrino (ν_e)



muon neutrino (ν_μ)

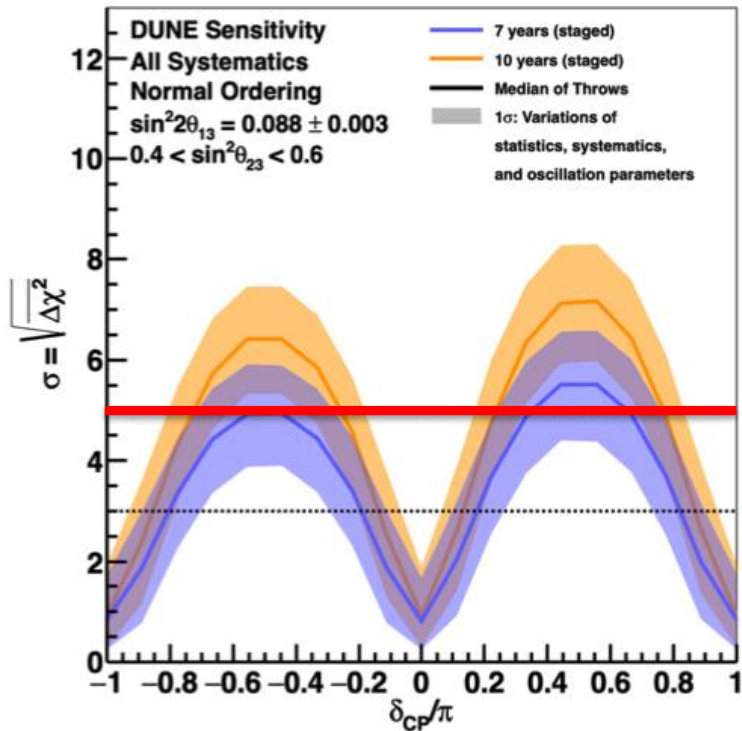


Removing the start of the electron shower reduces the ν_e score, as expected

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

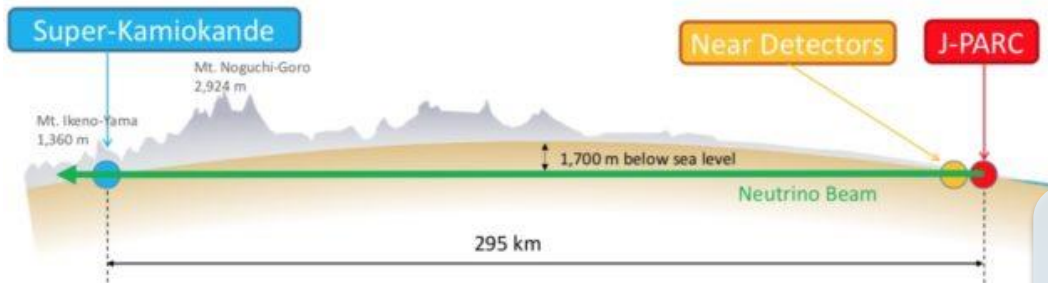
- The flavour identification results are used in the official analysis of DUNE:
 - [arXiv:2002.03005](https://arxiv.org/abs/2002.03005).
 - <https://doi.org/EPJC/S10052-020-08456-Z>.
- Sensitivity to CP violation:



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

T2K

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

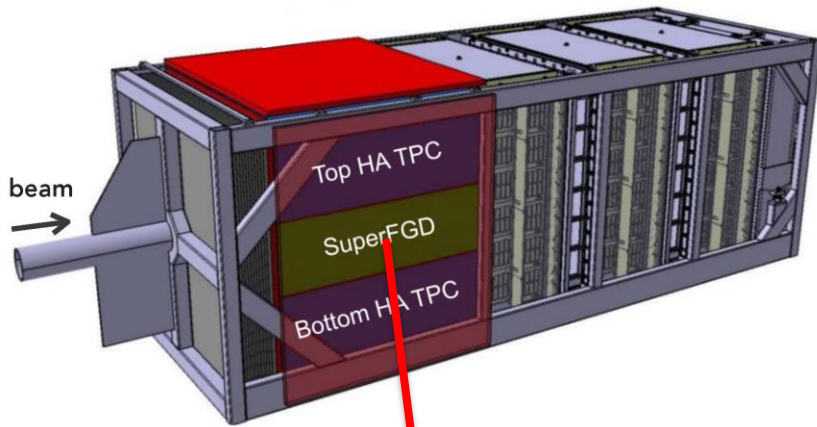


More than 500 collaborators from 80 institutions in 12 countries.

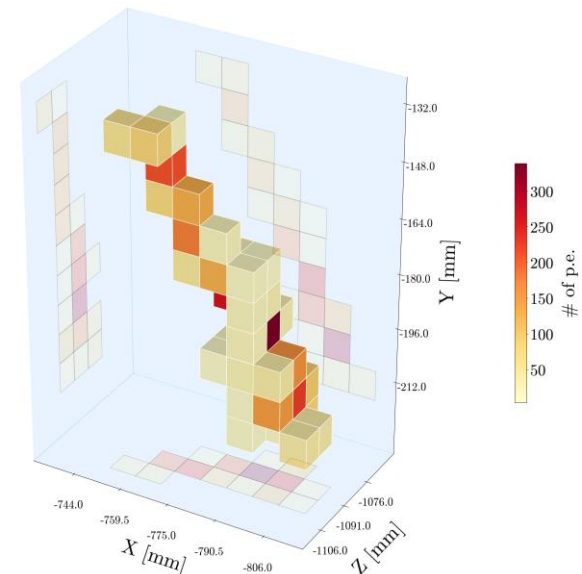
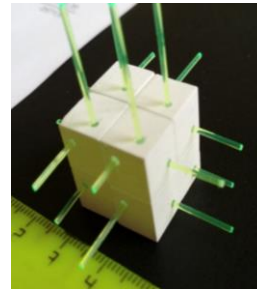
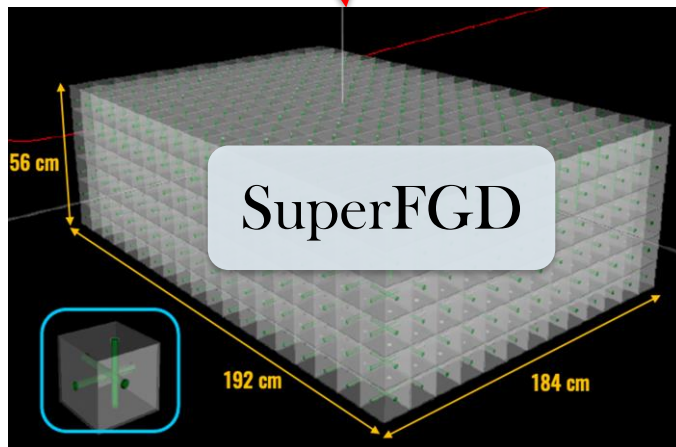
- Far detectors located 300 km away from the near ones.



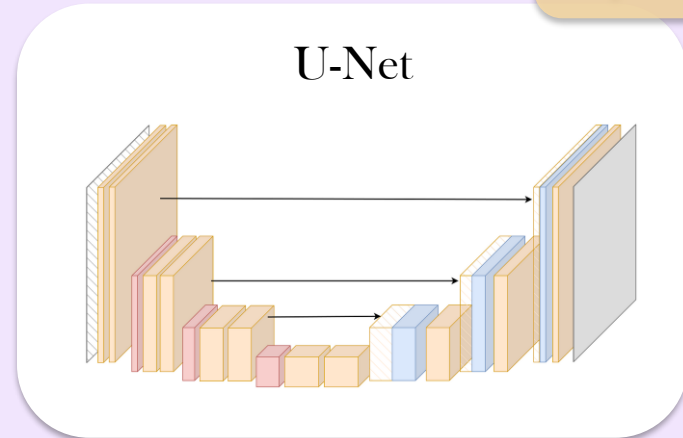
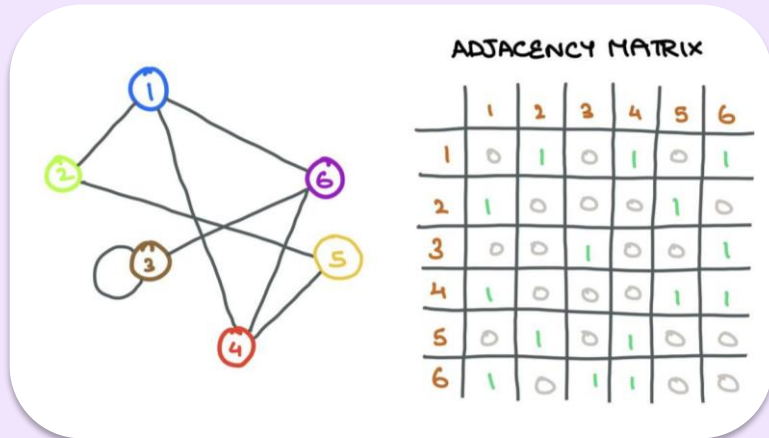
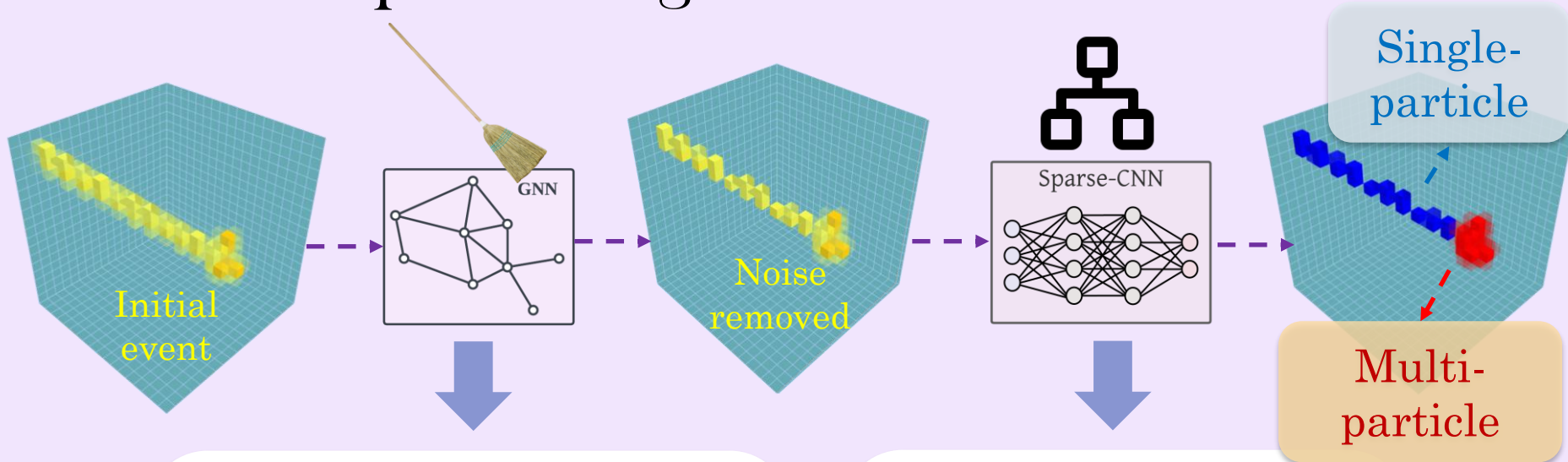
Near Detector (ND280)



- 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 $1 \times 1 \times 1 \text{ cm}^3$ in size.



Deep learning in the near detector



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

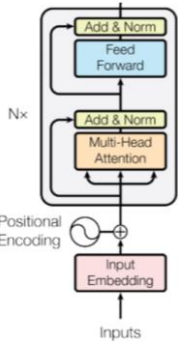
~95% accuracy!

[*doi/10.1103/PhysRevD.103.032005](https://doi.org/10.1103/PhysRevD.103.032005)

Deep learning in the near detector

[*nature.com/articles/s42005-023-01239-4](https://www.nature.com/articles/s42005-023-01239-4)

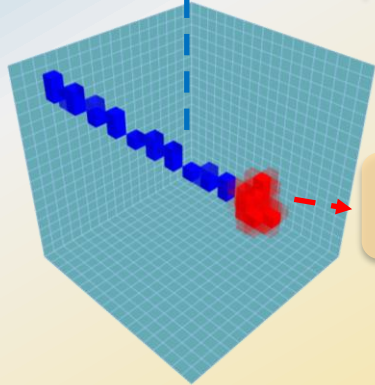
Transformer encoder



Improved resolution by 35%.

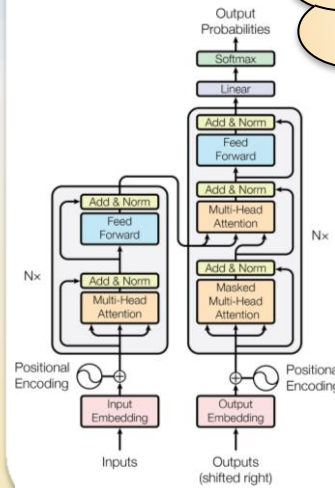
Fitted trajectory

Single-particle



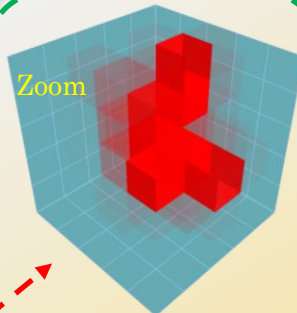
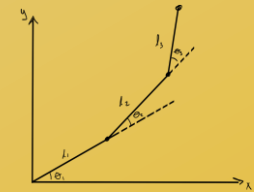
Multi-particle

Transformer

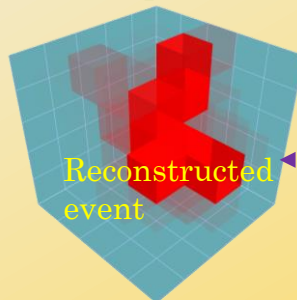


Automatically decomposes the event!

Reconstructed kinematics of each particle.

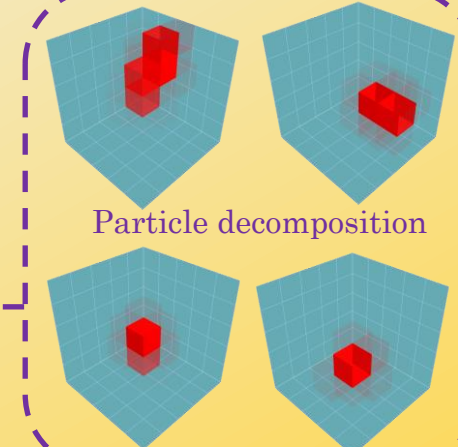


Verify the decomposition

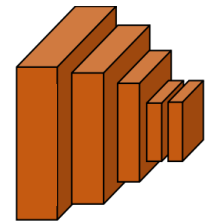


Reconstructed event

Particle decomposition




Generative model



[*nature.com/articles/s42005-024-01669-8](https://www.nature.com/articles/s42005-024-01669-8)

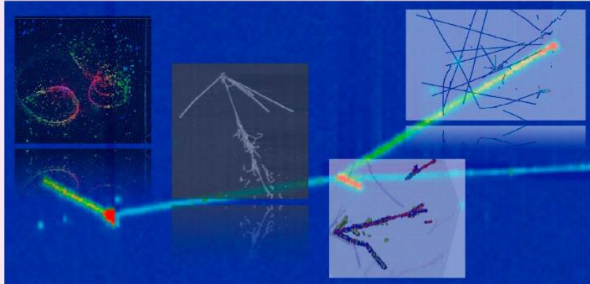
Neutrino Physics and Machine Learning (NPML) Workshop

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

ETH zürich  **Universität Zürich**¹⁷⁸⁴ Department of Physics


Neutrino Physics and Machine Learning Workshop 2024

June 25 - 26, 2024, ETH Zurich, Höggerberg (HCI J4)



Local Committee
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DPHYS

AI image generator (Bing)

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



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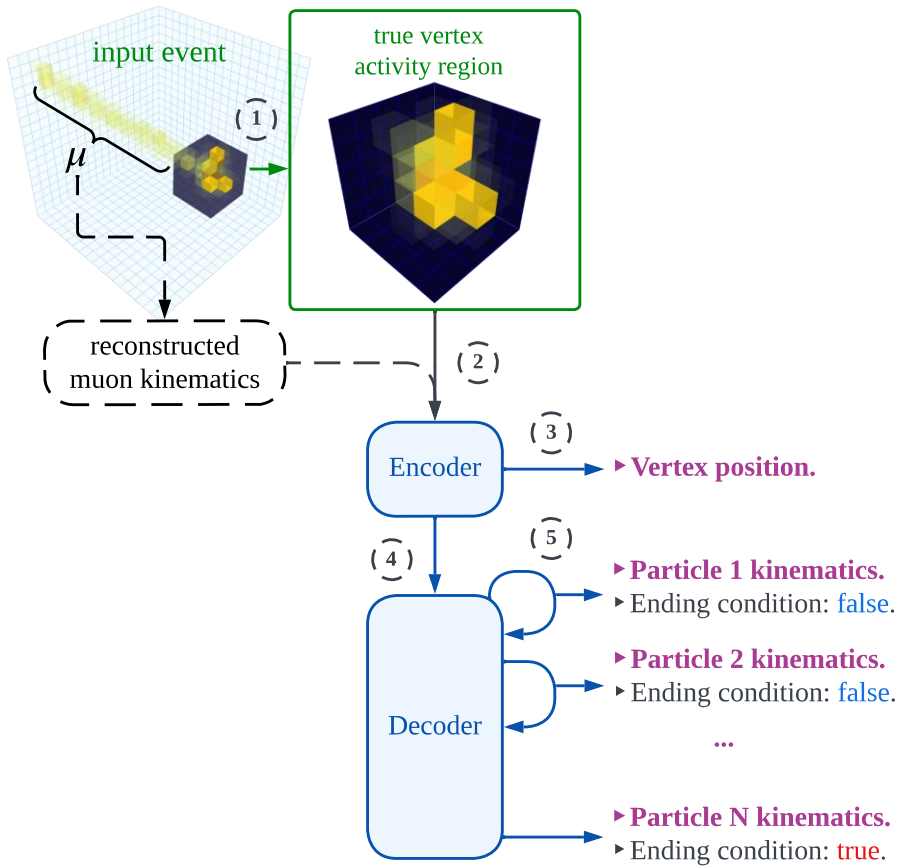
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Deep-learning approach



decomposing transformer

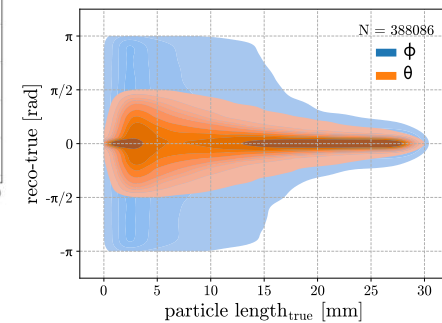
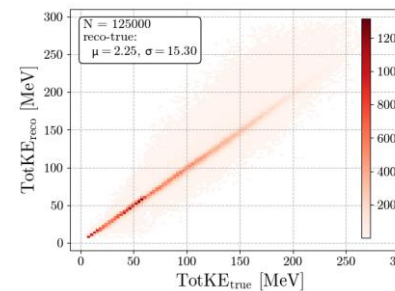
particle features (type and kinematics)

- **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.

precision [%] N=125000 recall [%]

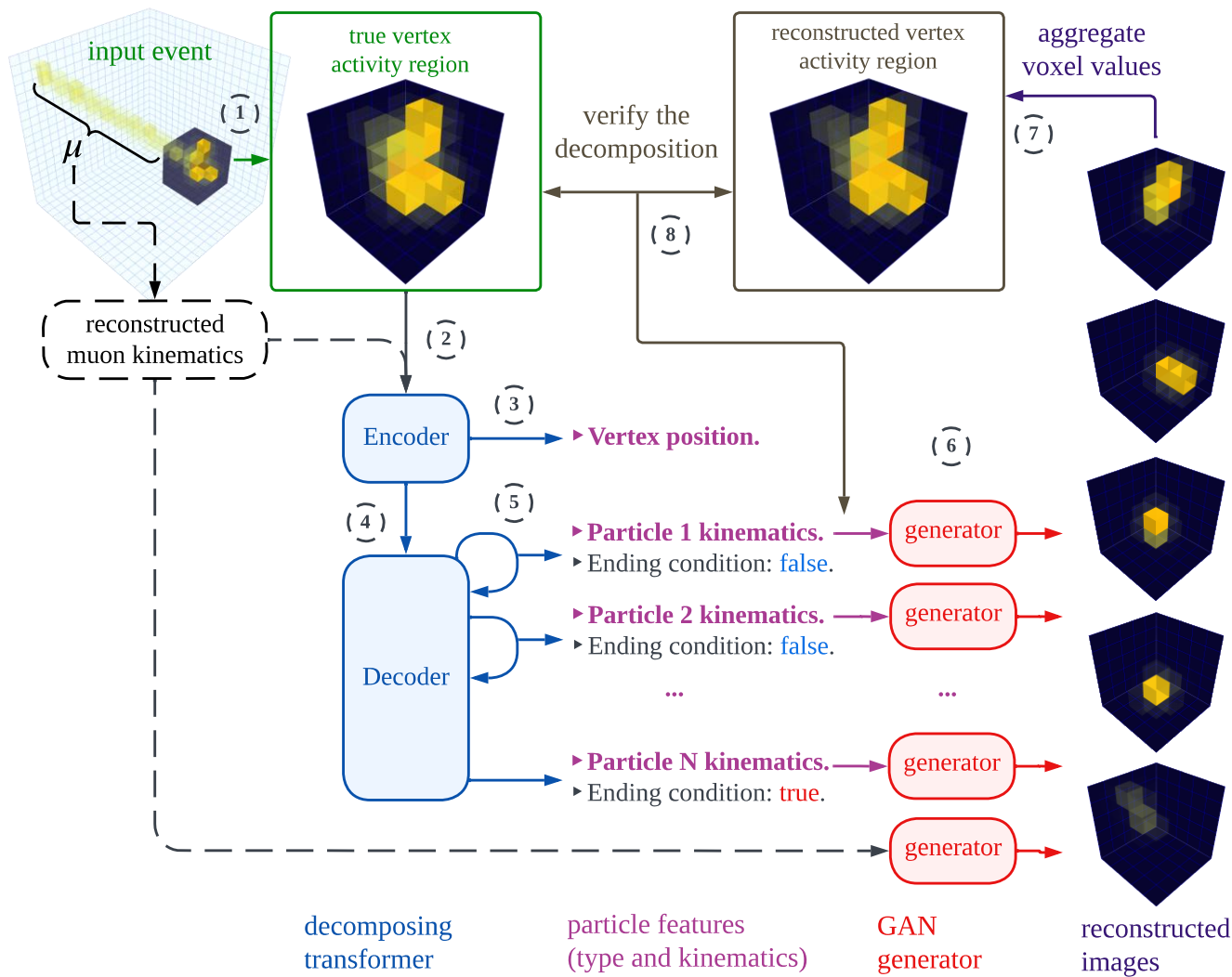
num. particles _{reco}	1	2	3	4	5	1	2	3	4	5
1	94.59	11.47	0.62	0.02	0.01	88.65	10.75	0.58	0.02	0.01
2	5.33	76.56	18.95	2.02	0.17	5.18	74.31	18.39	1.96	0.16
3	0.09	11.49	64.47	25.92	4.71	0.08	10.77	60.43	24.30	4.42
4	0.00	0.47	14.47	57.50	35.11	0.00	0.43	13.46	53.46	32.64
5	0.00	0.05	1.19	14.72	60.35	0.00	0.06	1.56	19.29	79.08

num. particles_{true}



- **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*).