Neutrino Reconstruction with Graph Neural Network on SND@LHC

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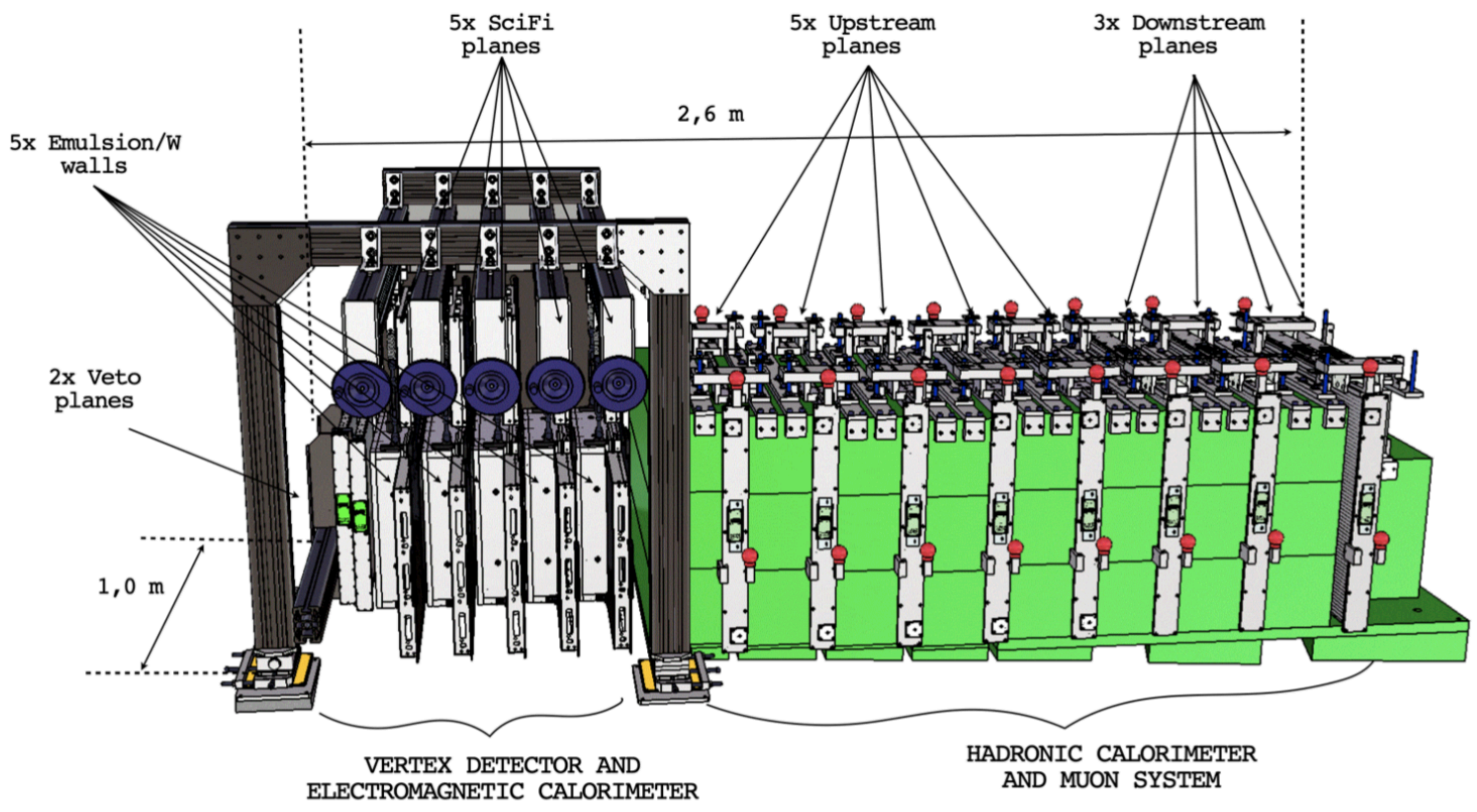
EPFL

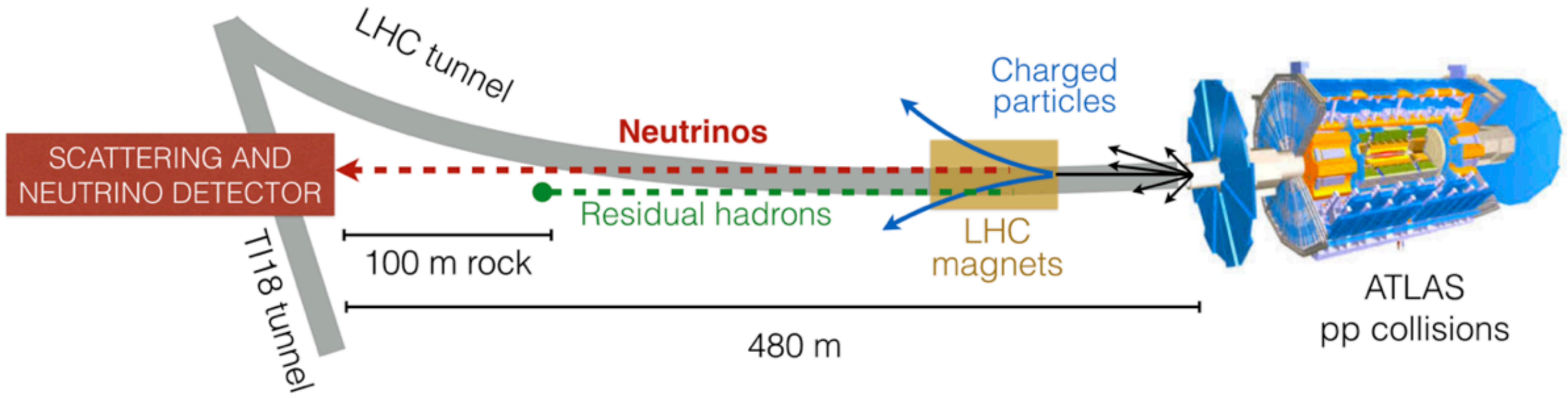
Swiss Institute of Particle Physics

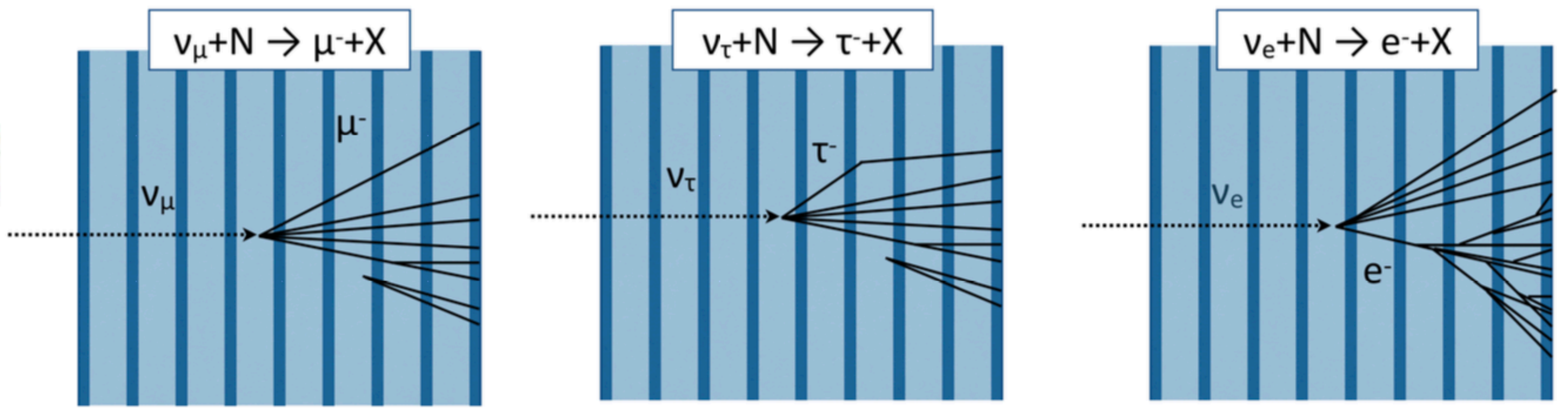
SND LHC
Scattering and Neutrino Detector at the LHC

Introduction

- Physics goals:
  - Neutrino interactions, QCD, flavour, feebly interacting particles
- Physics results:
  - Observation of muon neutrino, currently 32 events observed [Phys. Rev. Lett. 131, 031802]





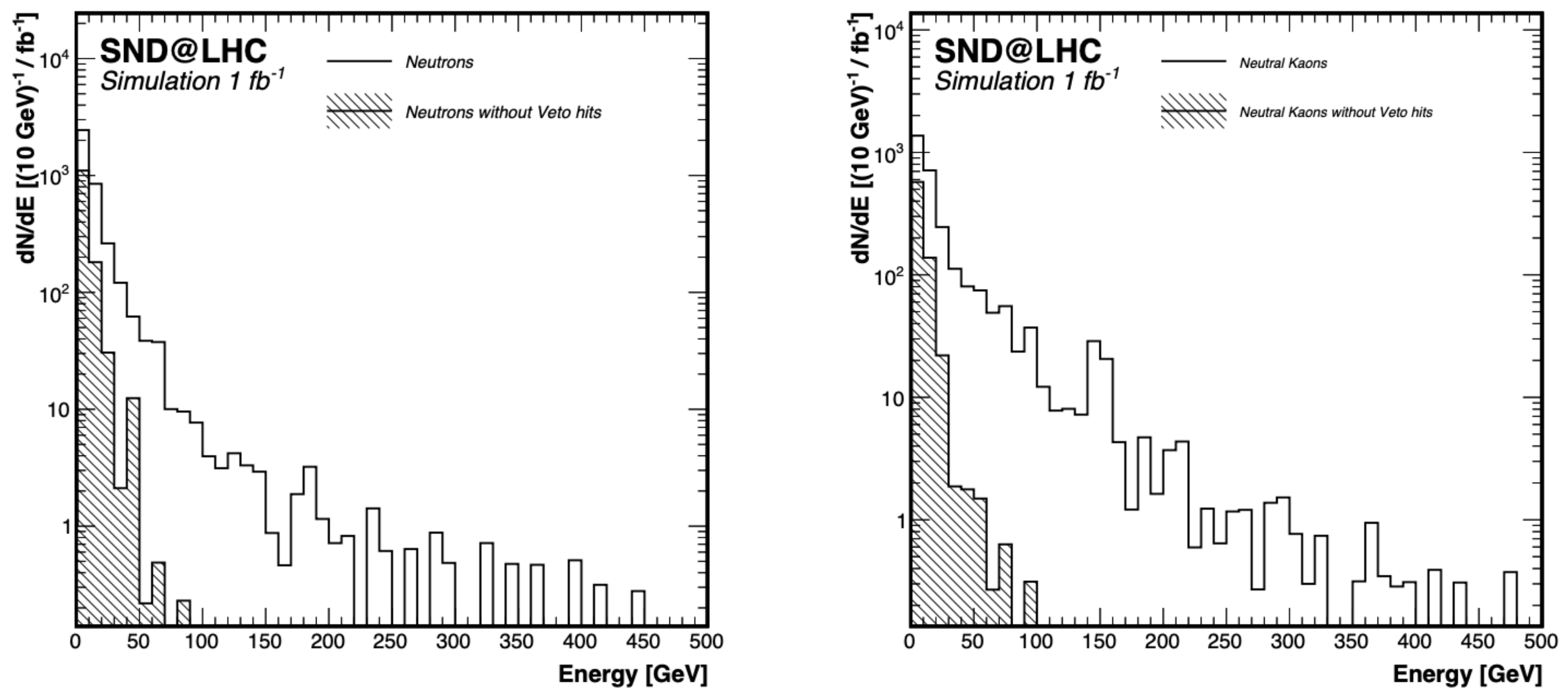


Background and Dataset

- Background
  - Neutral particles, mainly neutrons and Kaons
- Monte Carlo Simulated dataset

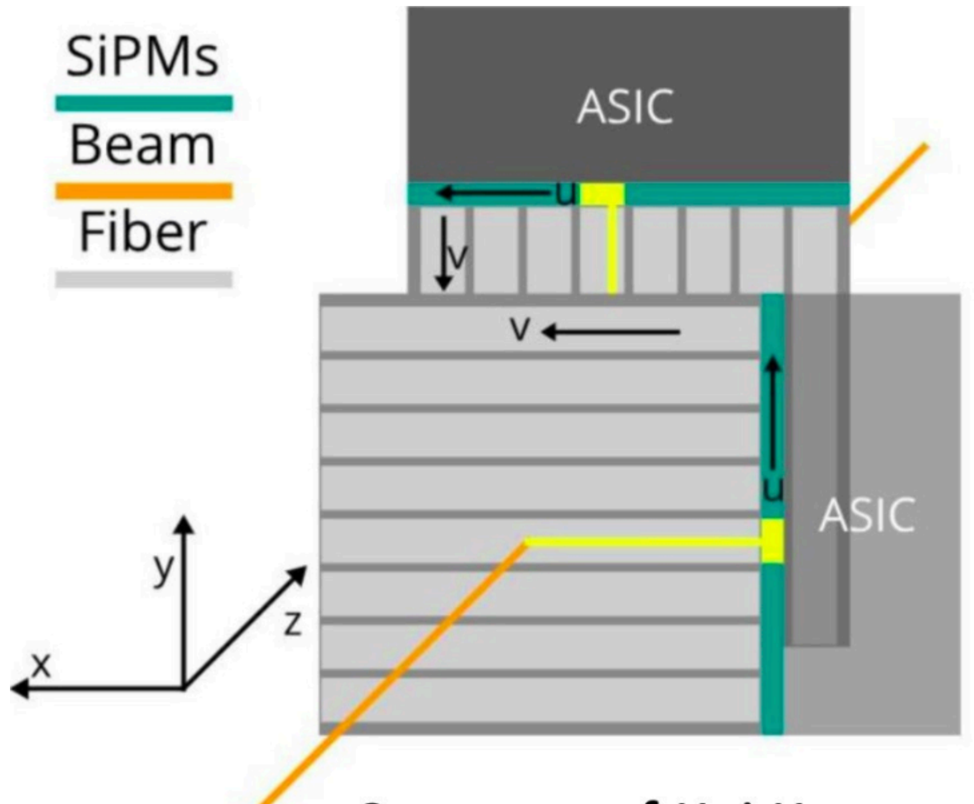
Particle	Count
Neutrinos	3.18E+05
Kaons	2.23E+07
Neutrons	2.43E+07

- Input features (End-to-End)
  - **Hit features**: two end positions, orientation, detector type
  - **Event features**: momentum and position of reconstructed muon track

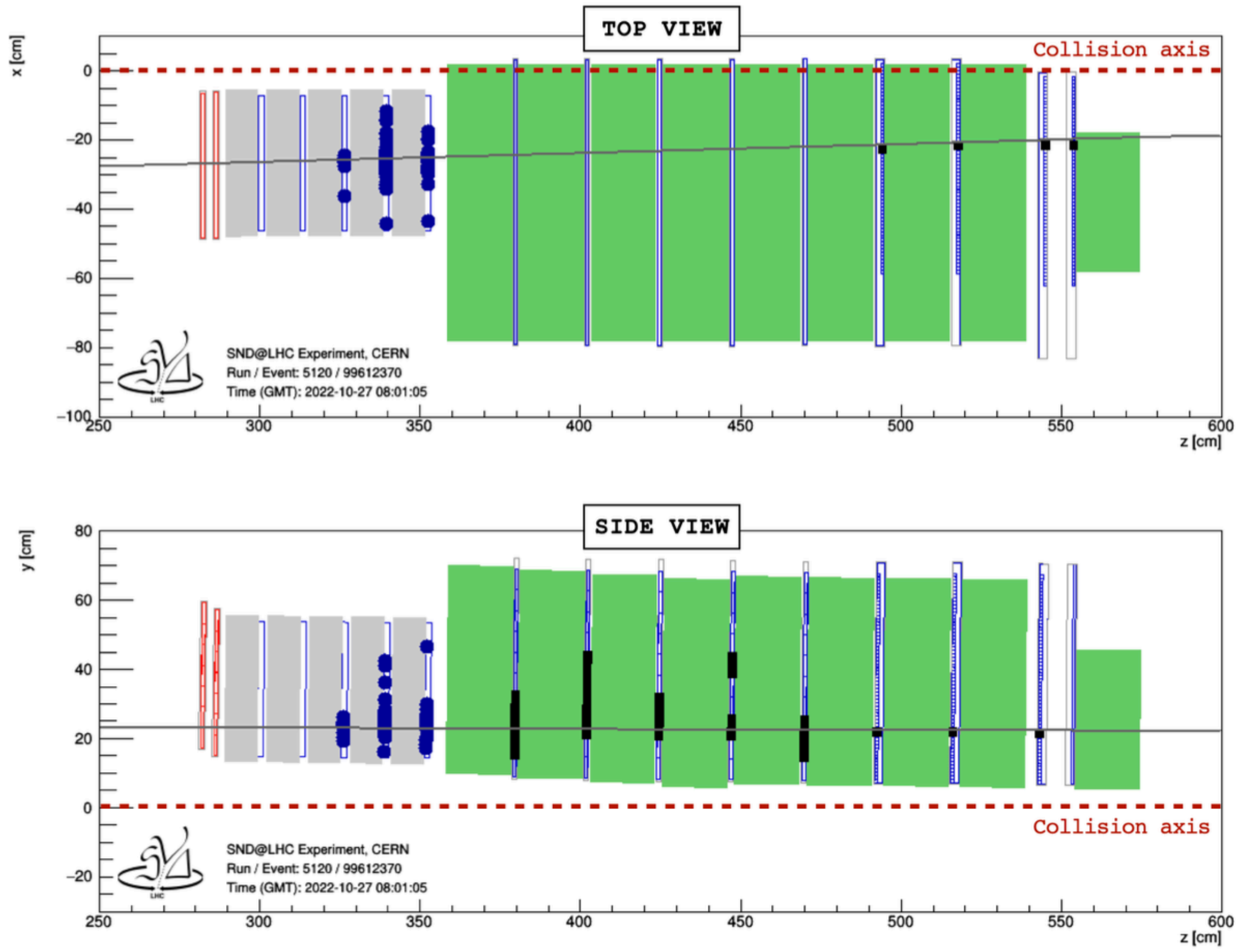


(a) *Neutrons* (b) *Neutral Kaons*

Energy spectra of different neutral particles interacting within the detector target including (blank) and excluding (shaded) Veto activity as function of their energy for neutrons (left) and Kaons (right)



Courtesy of Kai Kang



Display of one ν_μ CC candidate

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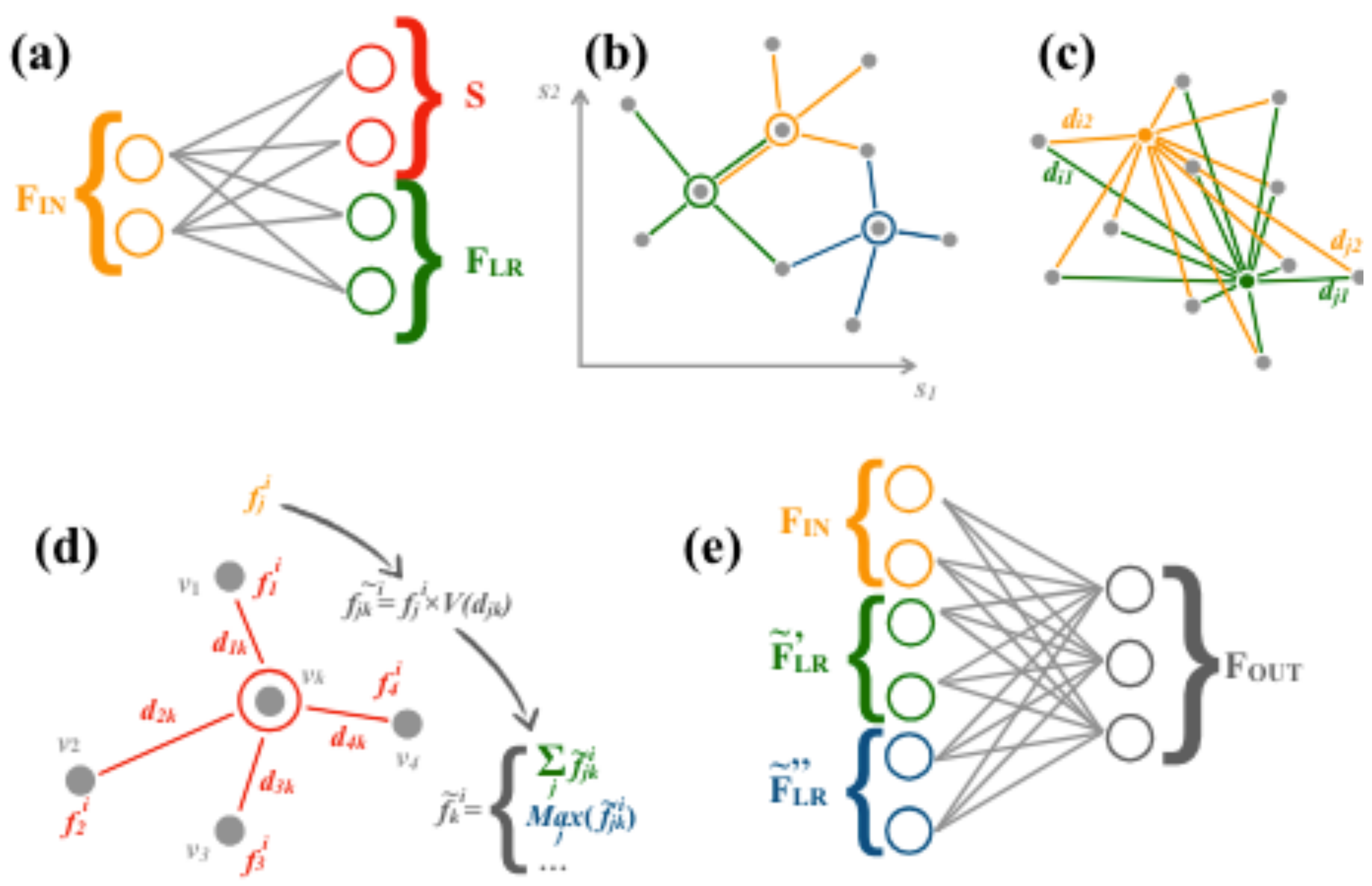
Model

- GravNet, a graph neural networks to deal with irregular-geometry detectors in the context of particle reconstruction.
- Loss function: Cross Entropy Loss Function
- Updates of the original GravNet architecture:
  - Graph net layer structure
  - Different aggregation methods
  - Global feature encoder
  - Transformer, attention mechanism (GeoAttention)



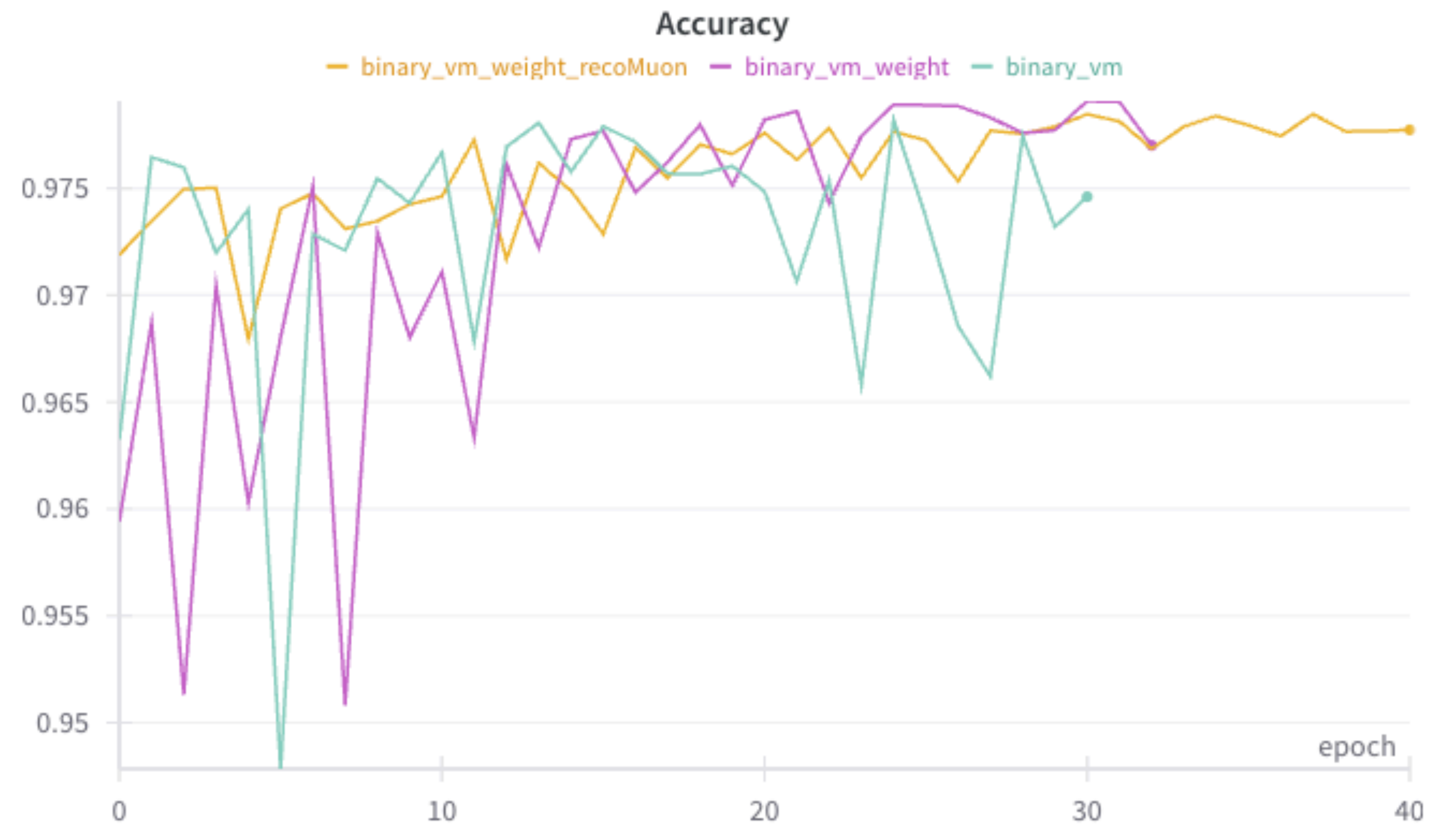
Pictorial representation of the data flow across the GravNet layers.

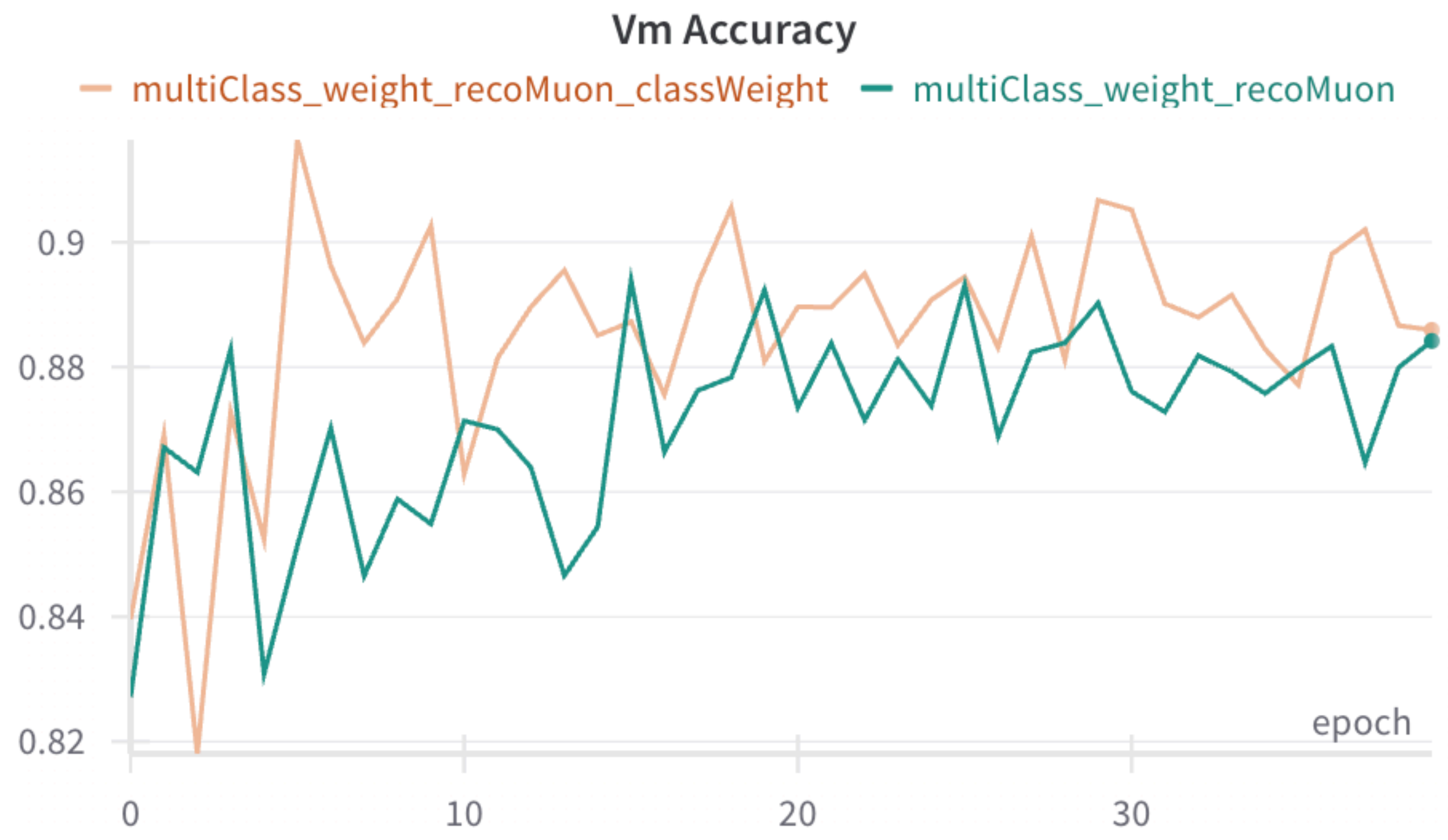
Index	Name	Type	Params
1	feature_encoder	Sequential	9.2 K
2	grav_convs	ModuleList	33.4 K
3	global_feature_encoder	Sequential	168
4	output_network	Sequential	638

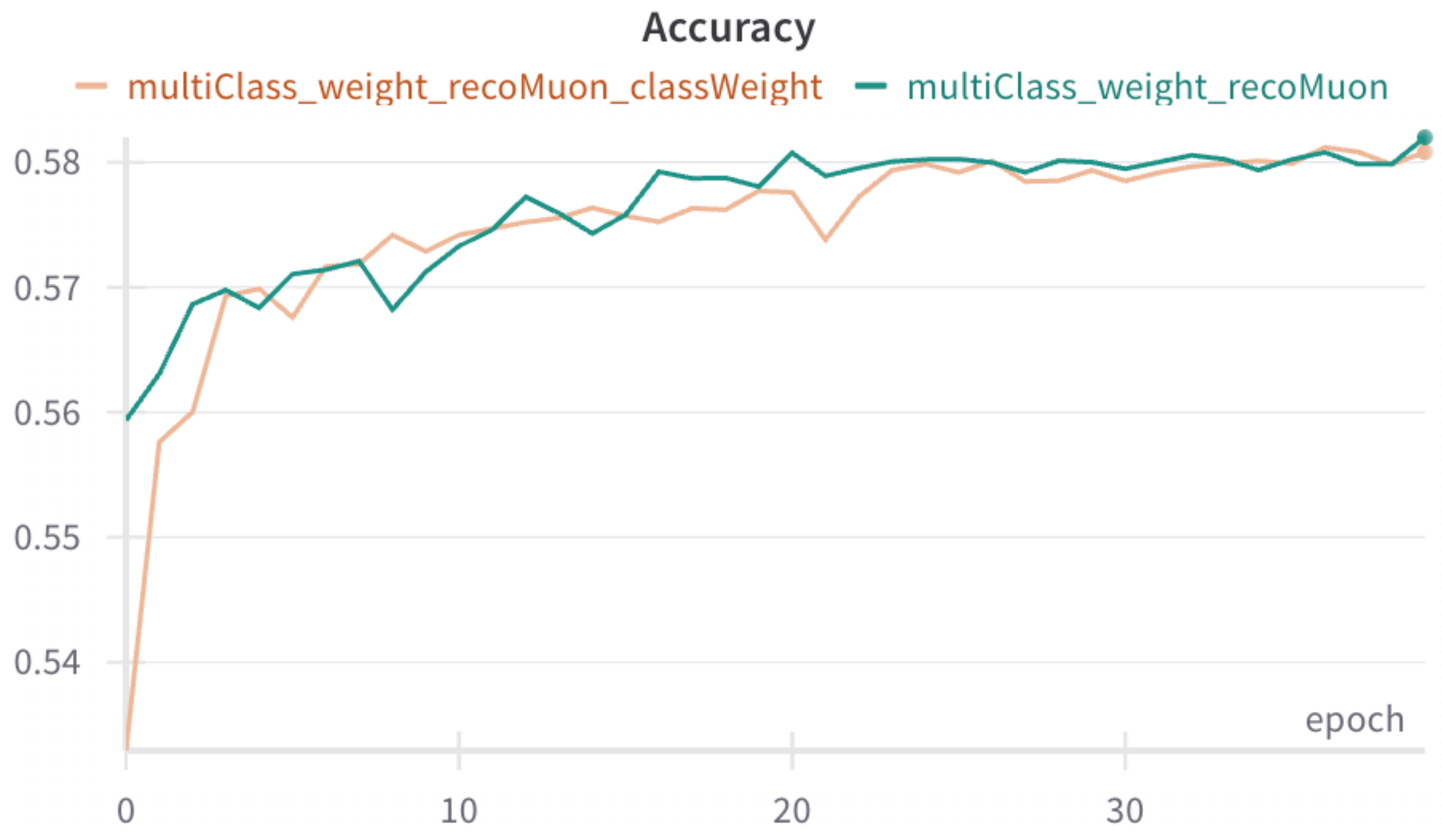
The total trainable parameters are listed as 43.3 K.

Training

- **Weight**
  - Normalised $w = \frac{Interaction\ Rate}{Number\ of\ Training\ Event}$
- **Event features** (reconstructed muon track)
- **Multi-class training**







Training Evaluation

- Compare the expected background yield with the Cut-base Method. [Phys. Rev. Lett. 131, 031802]
- Cut-base method Vm selection performance:
  - Signal efficiency: 2.7%
  - Signal yield: 4.2, background yield: 0.086

TABLE I. Number of events passing the selection cuts in the data and signal simulation.

	Data	Signal simulation
All	8.4×10^9	157
Fiducial volume	4.9×10^5	11.9
One muonlike track	17	6.1
Large SciFi activity	13	5.1
Large hadronic activity	12	4.7
Low muon system activity	8	4.2

Energy [GeV]	Int. Rate	Generated	Passed cuts	Efficiency	Yield
(5, 10)	4.62×10^4	2.12×10^6	0	0	0
(10, 20)	7.59×10^3	2.05×10^6	1	4.88×10^{-7}	3.70×10^{-3}
(20, 30)	1.18×10^3	7.54×10^5	3	3.98×10^{-6}	4.69×10^{-3}
(30, 40)	5.30×10^2	7.41×10^5	5	6.75×10^{-6}	3.58×10^{-3}
(40, 50)	4.66×10^2	7.37×10^4	1	1.36×10^{-5}	6.33×10^{-3}
(50, 60)	2.60×10^1	3.35×10^5	4	1.19×10^{-5}	3.10×10^{-4}
(60, 70)	1.80×10^1	3.33×10^5	13	3.91×10^{-5}	7.10×10^{-4}
(70, 80)	8.48	3.24×10^5	14	4.32×10^{-5}	3.66×10^{-4}
(80, 90)	8.48	1.17×10^5	5	4.26×10^{-5}	3.61×10^{-4}
(90, 100)	0	3.22×10^5	15	4.66×10^{-5}	0
(100, 150)	0	3.07×10^5	15	4.88×10^{-5}	0
(150, 200)	0.	2.98×10^5	23	7.71×10^{-5}	0
Tot. (5, 200)	5.61×10^4	7.77×10^6	99	3.58×10^{-7}	2.00×10^{-2}

Table 6: Expected background yield due to neutrons, with the QGSP_BERT_HP_PEN GEANT4 physics list.

Energy [GeV]	Int. Rate	Generated	Passed cuts	Efficiency	Yield
(5, 10)	2.51×10^4	2.14×10^6	0	0	0
(10, 20)	5.72×10^3	2.09×10^6	7	3.34×10^{-6}	1.91×10^{-2}
(20, 30)	8.53×10^2	7.49×10^5	2	2.67×10^{-6}	2.28×10^{-3}
(30, 40)	1.10×10^2	7.53×10^5	8	1.06×10^{-5}	1.17×10^{-3}
(40, 50)	9.38×10^1	7.43×10^5	13	1.75×10^{-5}	1.64×10^{-3}
(50, 60)	6.48×10^1	3.41×10^5	12	3.52×10^{-5}	2.28×10^{-3}
(60, 70)	9.90×10^0	3.34×10^5	7	2.09×10^{-5}	2.07×10^{-4}
(70, 80)	2.32×10^1	3.35×10^5	7	2.09×10^{-5}	4.84×10^{-4}
(80, 90)	1.15×10^1	3.17×10^5	15	4.73×10^{-5}	5.44×10^{-4}
(90, 100)	1.15×10^1	3.30×10^5	12	3.64×10^{-5}	4.19×10^{-4}
(100, 150)	0	3.23×10^5	21	6.50×10^{-5}	0
(150, 200)	0	3.12×10^5	16	5.12×10^{-5}	0
Tot. (5, 200)	3.20×10^4	8.77×10^6	120	8.78×10^{-7}	2.81×10^{-2}

Table 8: Expected background yield due to neutral kaons, with the QGSP_BERT_HP_PEN GEANT4 physics list.

Preliminary results

- Weight and recoMuon information improve the performance
- Current best model (multi-class) ν_μ selection results
  - Signal efficiency: 10%
  - Signal yield: 15.7, with background yield: 0.0143
- Current best model (multi-class) ν_e selection results
  - Signal efficiency: 10%
  - Signal yield: 5.0, with background yield: 0.00418
- Results need to be validated, and it's purely on simulation data.

Summary and Next Step

- Summary
  - We have promising results from an End-to-End GNN model
  - Current GNN approach is better than CNN approach
- Next Step
  - Need to consider muon background due to veto inefficiency
  - More input features can be implemented (e.g. hit time information)
  - Try to study and implement different model features
  - More work on dataset (e.g. larger dataset, splits, understand difference between MC simulation data and real data)
  - Including emulsion data