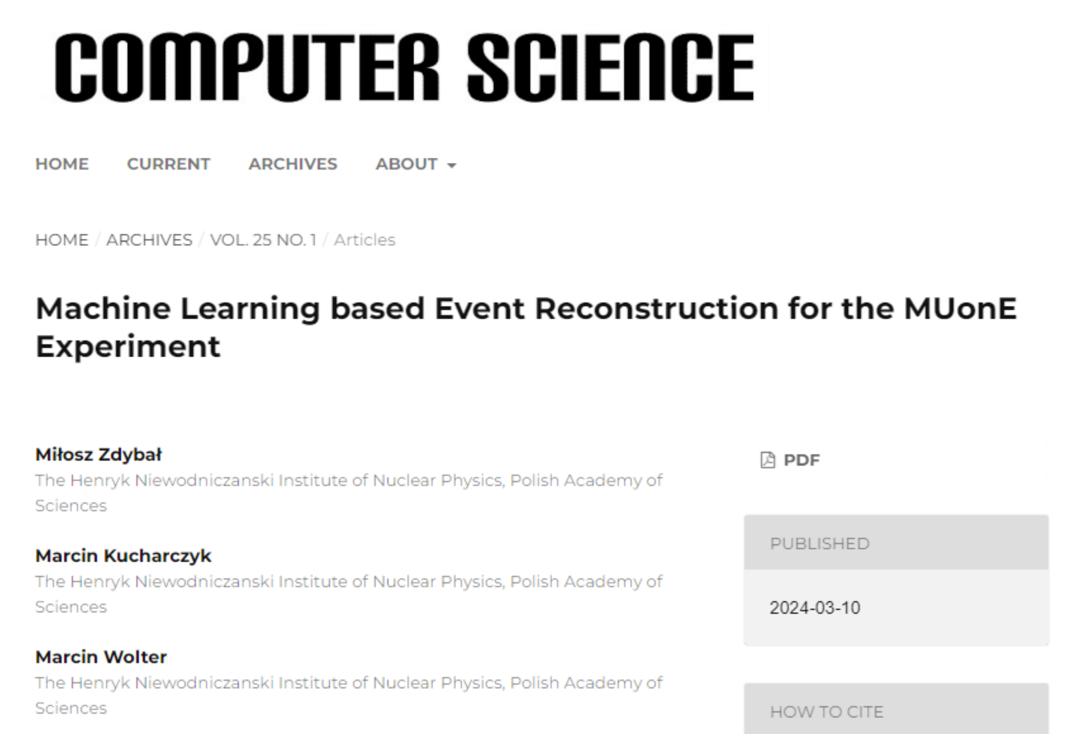
MACHINE LEARNING BASED EVENT RECONSTRUCTION FOR THE MUonE EXPERIMENT

Miłosz Zdybał, NZ17

AS SEEN IN

- Zdybał, M., Kucharczyk, M., & Wolter, M. (2024). Machine Learning based Event Reconstruction for the MUonE Experiment. Computer Science, 25(1)
- https://doi.org/10.7494/csci.2024.25.1.5690



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- https://www.eurekalert.org/news-releases/1038558
- https://press.ifj.edu.pl/news/2024/03/20/

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Sztuczna inteligencja zrekonstruuje drogi cząstek prowadzące ku nowej fizyce

EurekAlert!: [https://www.eurekalert.org/news-releases/1038558]

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Artificial intelligence to reconstruct particle paths leading to new physics

Peer-Reviewed Publication

THE HENRYK NIEWODNICZANSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Cracow, 20 March 2024

Artificial intelligence to reconstruct particle paths leading to new physics

Particles colliding in accelerators produce numerous cascades of secondary particles. The electronics processing the signals avalanching in from the detectors then have a fraction of a second in which to assess whether an event is of sufficient interest to save it for later analysis. In the near future, this demanding task may be carried out using algorithms based on AI, the development of which involves scientists from the Institute of Nuclear Physics of the PAS.

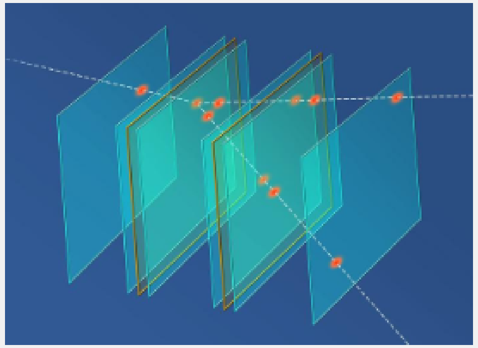

IMAGE:

THE PRINCIPLE OF RECONSTRUCTING THE TRACKS OF SECONDARY PARTICLES BASED ON HITS RECORDED DURING COLLISIONS INSIDE THE

AS SEEN IN

- https://www.chip.pl/2024/03/sztuczna-inteligencja-nieuchwytne-czastki-miony

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Home > Nauka i technika > Sztuczna inteligencja bada nieuchwytne cząstki. Dostrzega coś, co umyk...

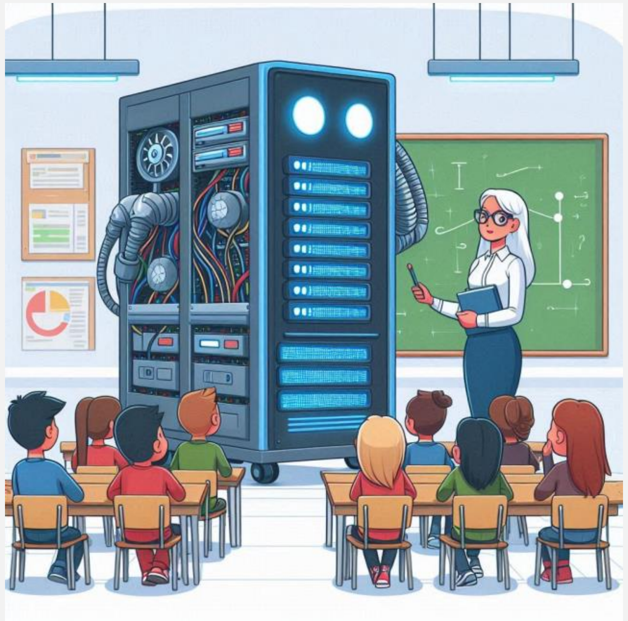
Sztuczna inteligencja bada nieuchwytne cząstki. Dostrzega coś, co umyka naukowcom

Wykorzystanie sztucznej inteligencji nierzadko przynosi świetne rezultaty, które nie zostałyby osiągnięte, gdyby nie pomóc komputerów. A już na pewno nie w tempie, o jakim mowa. Do słuszności takiego podejścia przekonują przedstawiciele Instytutu Fizyki Jądrowej Polskiej Akademii Nauk.

Aleksander Kowal
25.03.2024 | Przeczytasz w 2 minuty

OUTLINE

- Why machine learning?
- What is it?
- How to apply it to the experiment like MUonE?
- How does it compare to the "classical" methods?



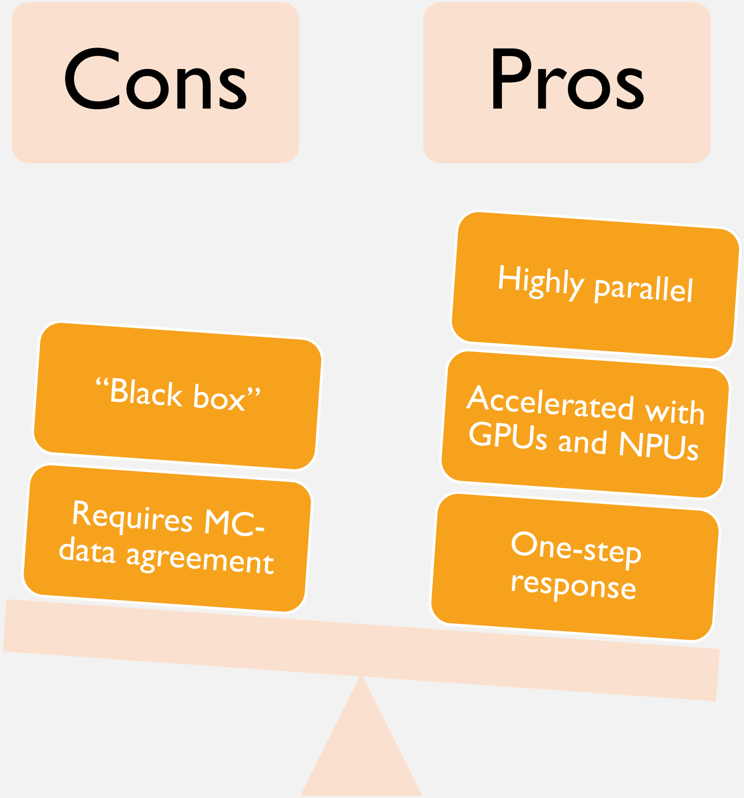
WHY MACHINE LEARNING?

More complicated detectors, extreme luminosities

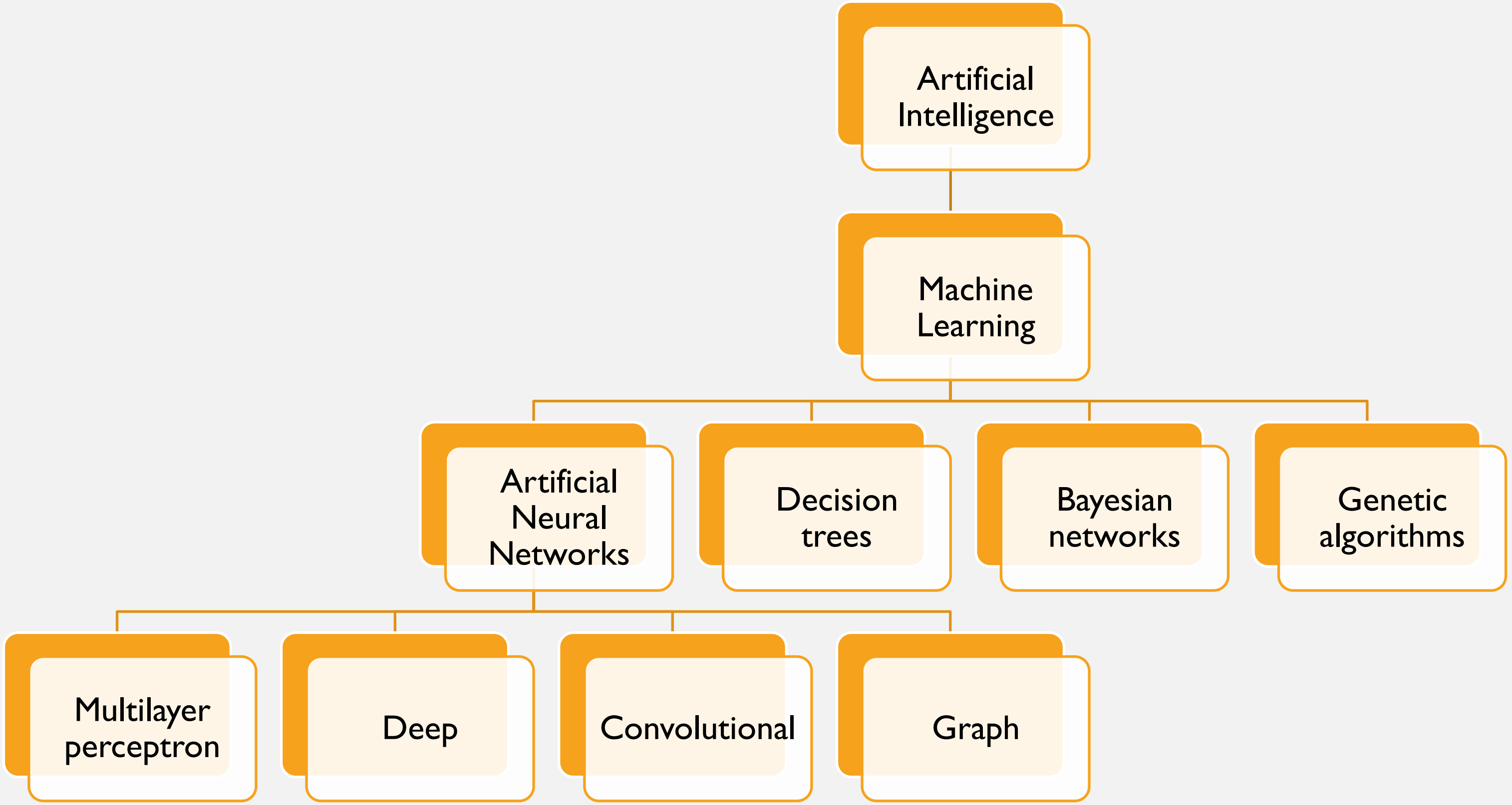
More data to be processes

Stricter time constraints

WHY MACHINE LEARNING?

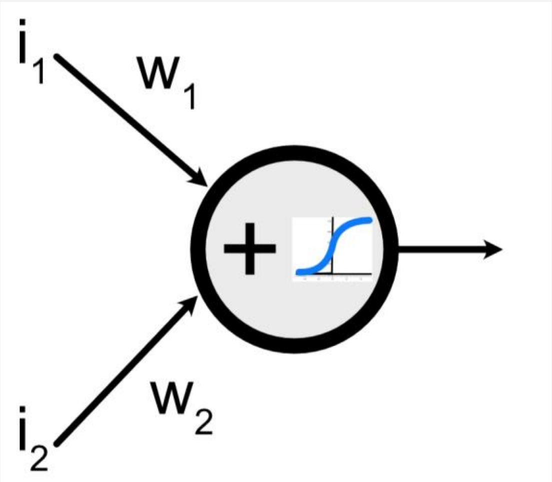


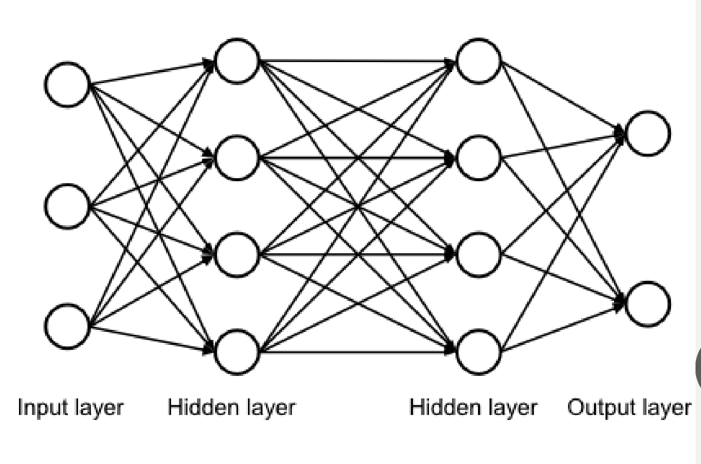
AI, ML, ANN, MLP, CNN, DNN, GNN…



ARTIFICIAL NEURAL NETWORK
ARTIFICIAL NEURONS AND LAYERS

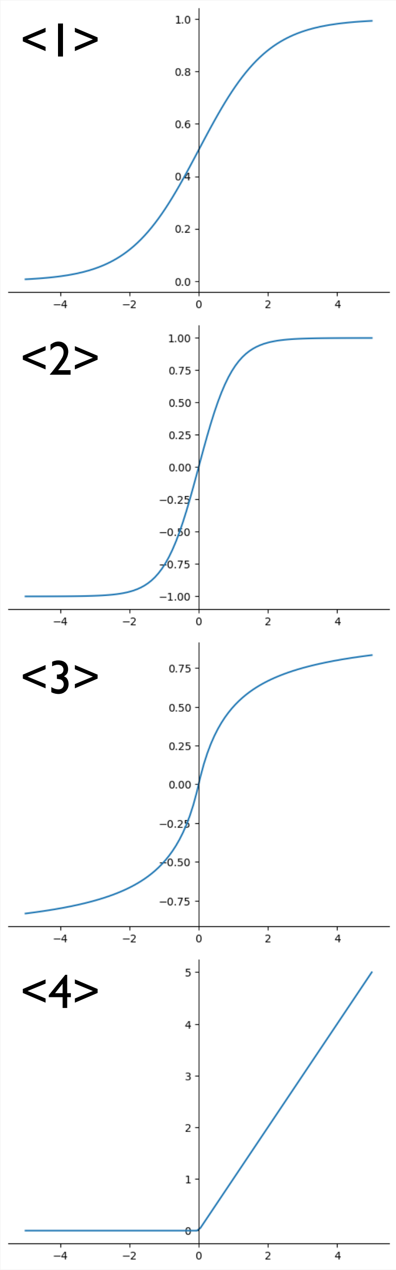
- aka *perceptron*,
- Inspired by biological counterpart,
- Input weighted with trainable parameters and summed,
- Activation function determines the output,
- Organized in layers





ARTIFICIAL NEURAL NETWORK
ACTIVATION FUNCTION

- aka *transfer function*,
- Defines the answer of the neuron for the given input,
- Most popular:
  - Logistic function (sigmoid) <1>,
  - Softmax (sigmoid in multiple dimensions),
  - Hyperbolic tangent <2>,
  - Softsign <3>,
  - Rectified Linear Unit (ReLU) <4> and variants.

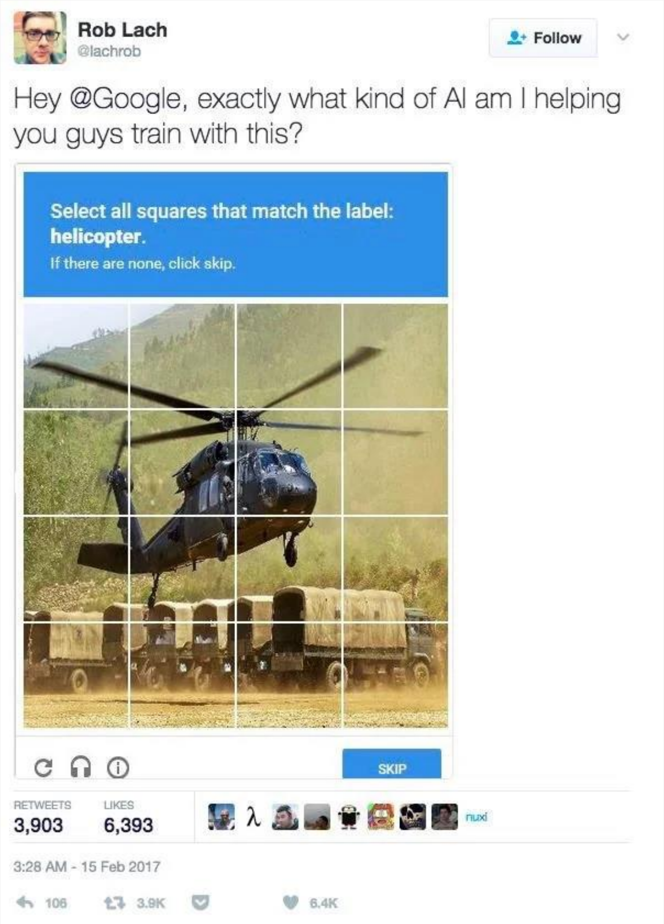


ARTIFICIAL NEURAL NETWORK
TRAINING

- Generalize the model, so it can perform a task using data not seen before,
- Supervised training:
  - Uses *training dataset* (labelled data, ground truth),
  - Responses compared with the labels by the *loss function* (cost function),
- Unsupervised training:
  - No labelled dataset,
  - Network expected to find patterns in the data,
- Reinforcement training:
  - Agents are scored for their actions,
  - Can be used in situation where there is no mathematical model of the problem.

SUPERVISED LEARNING

- Labelled dataset:
  - Expected output value assigned to each input,
  - Used for training and testing,
- Loss function:
  - Grades every response from the network,
  - Results used to optimize the model,
- Optimization:
  - Backpropagation algorithm.

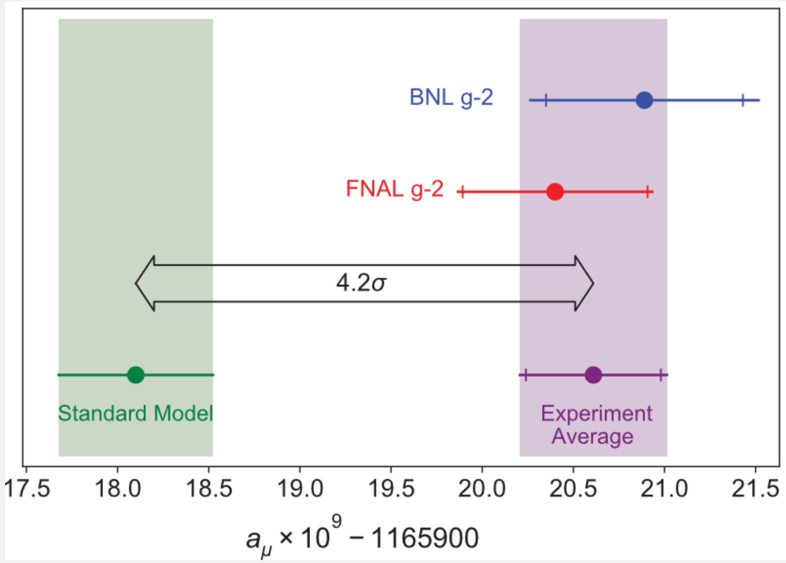


BACKPROPAGATION AND OPTIMIZATION

- Backpropagation for feedforward neural networks:
  - Estimation of the gradient of the loss function with respect to the weights,
  - Term often used to refer to the learning algorithm,
- Optimizer:
  - Utilizes calculated gradient (e.g. stochastic gradient descent),
  - Adjusts values of the weights to minimize the value of the loss function.

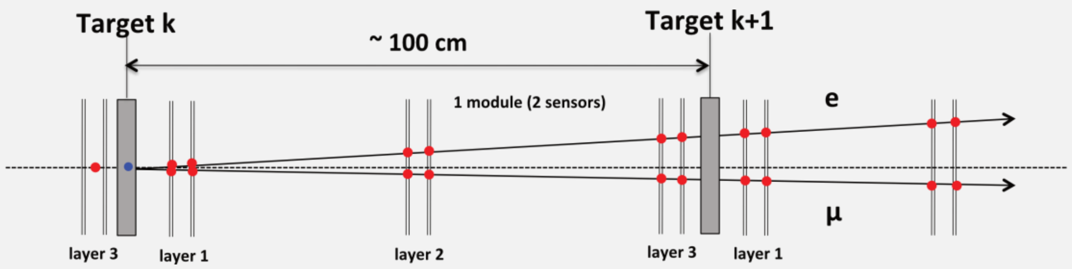
THE MUonE EXPERIMENT

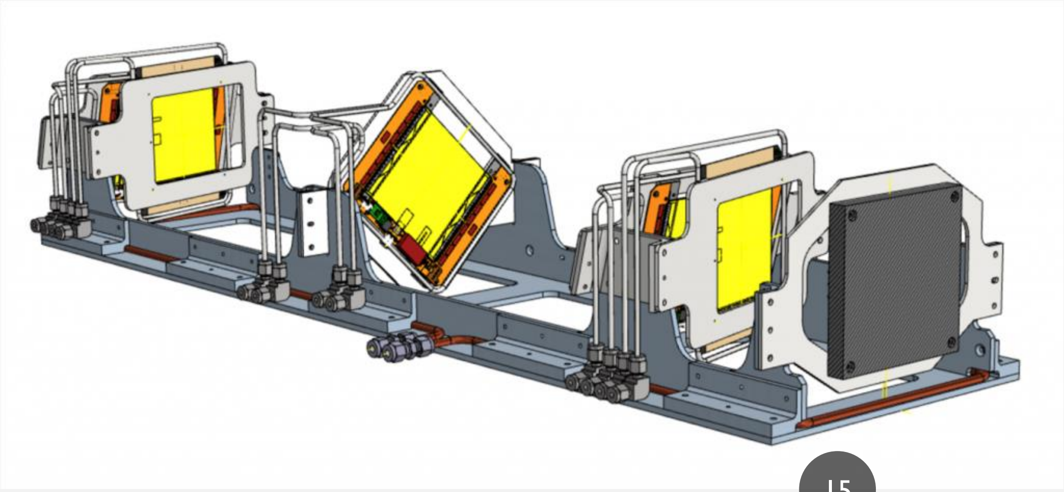
- Looking for signs of the New Physics in determination of the leading hadronic contribution to the muon anomalous magnetic moment α_μ ,
- Elastic scattering of muons on the atomic electrons in the target,
- Previous measurements of α_μ deviate from Standard Model by 4.2σ
- Chance to improve the significance to 7σ by lowering the theoretical error coming from the hadronic vacuum polarization $\alpha_\mu^{HVP,LO}$



MUonE DETECTOR

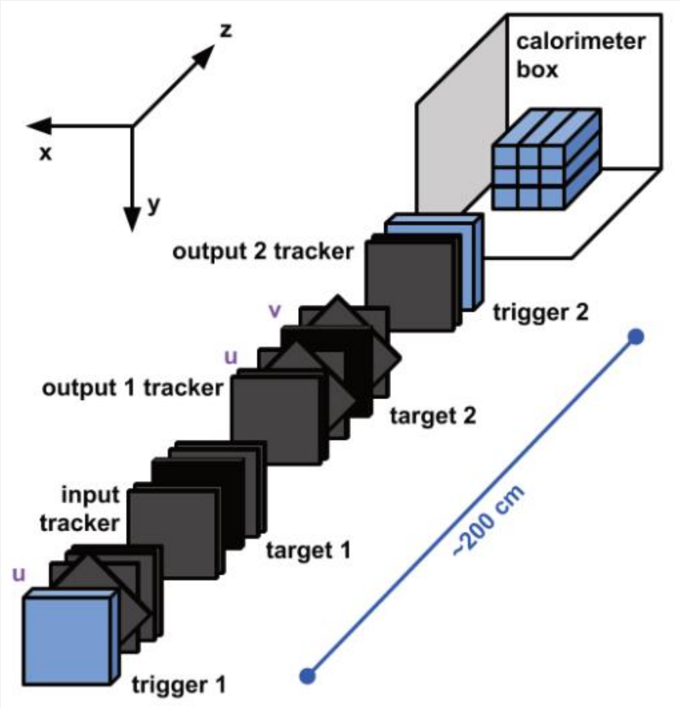
- Will operate at a high energy muon beam at CERN SPS,
- Beryllium or carbon target,
- Pair of outgoing muon and electron will pass through the set of tracking stations with silicon strip sensors,
- Measured coordinates:
  - *z* along the beam axis,
  - *x* or *y* (alternatively) in the plane perpendicular to the beam axis,
  - *u* or *v* (*stereo layers*) – like *x* and *y*, but rotated ±45°.
- 40 stations followed by the calorimeter and muon chamber.





DATASET

- Simulation based on Test Run 2018 configuration,
- ~132 000 events,
- 2D hits: z + measured value,
- Ground truth:
  - Track parameters:
    - Slope,
    - Intercept,
  - Particle type.

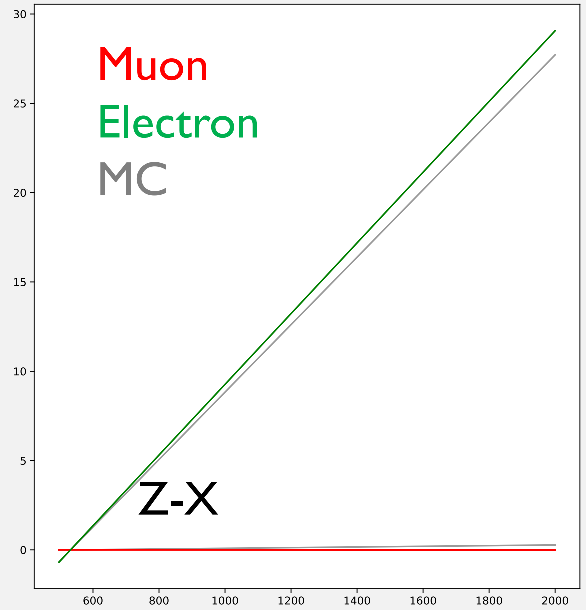


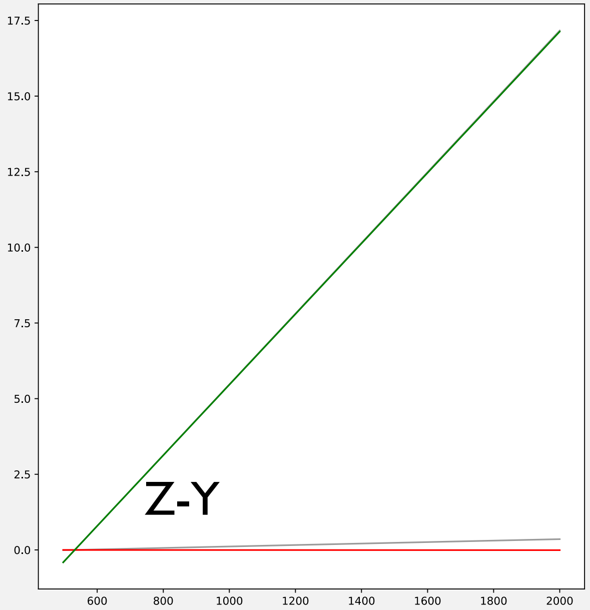
THE NETWORK

- Multi Layer Perceptron (MLP):
  - PyTorch,
  - Deep neural network: 4 linear layers, 1000 neurons each,
  - Activation function: ReLU,
  - Loss function: MSELoss (Mean Square Error Loss).
- Input: 2D hit coordinates,
- Output: slopes and intercepts of two 3D tracks.

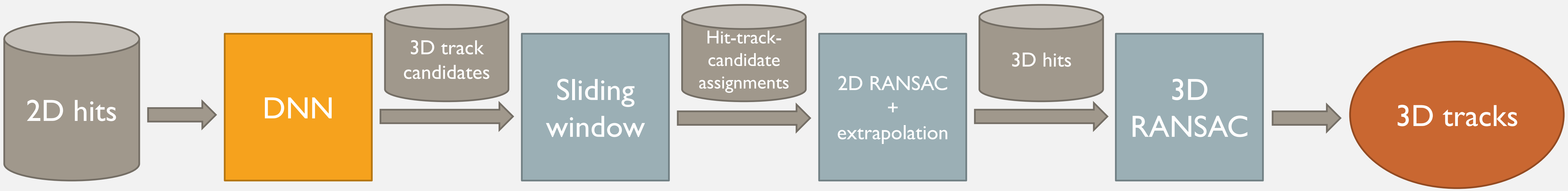
FIRST RESULTS

- Promising, but experiment requires high precision,
- Response from the network may be used as a part of the algorithm.





RECONSTRUCTION ALGORITHM



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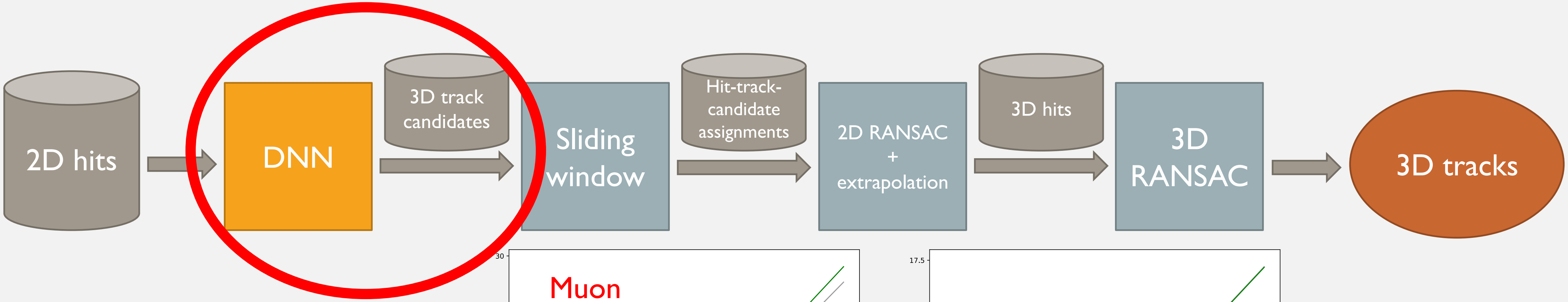

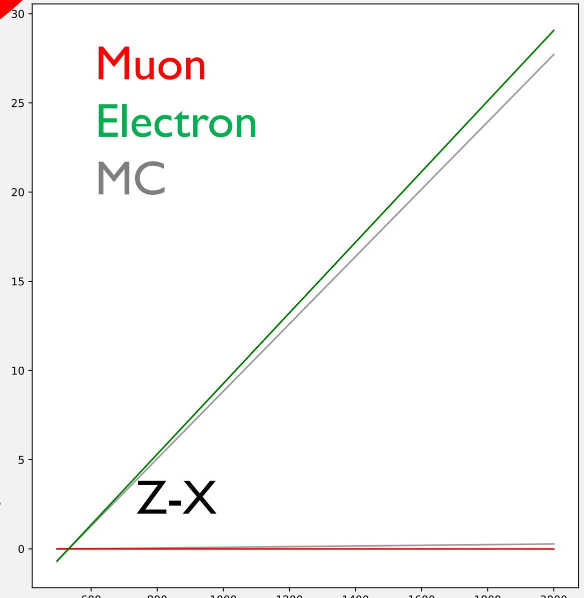

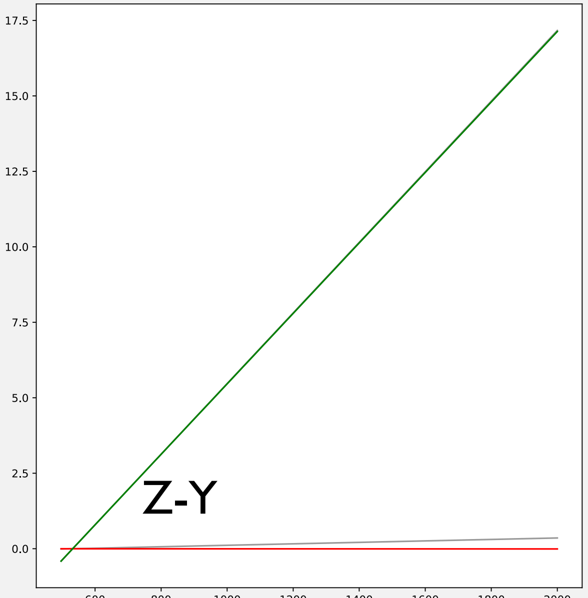

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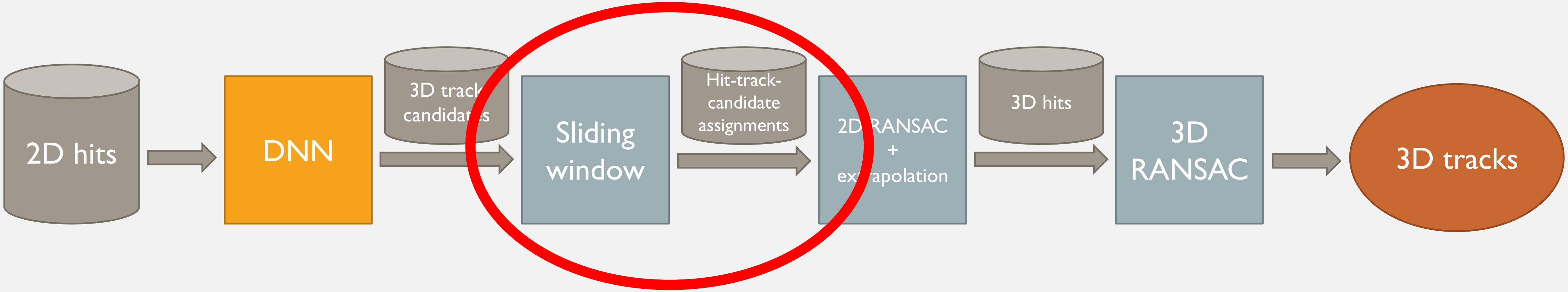

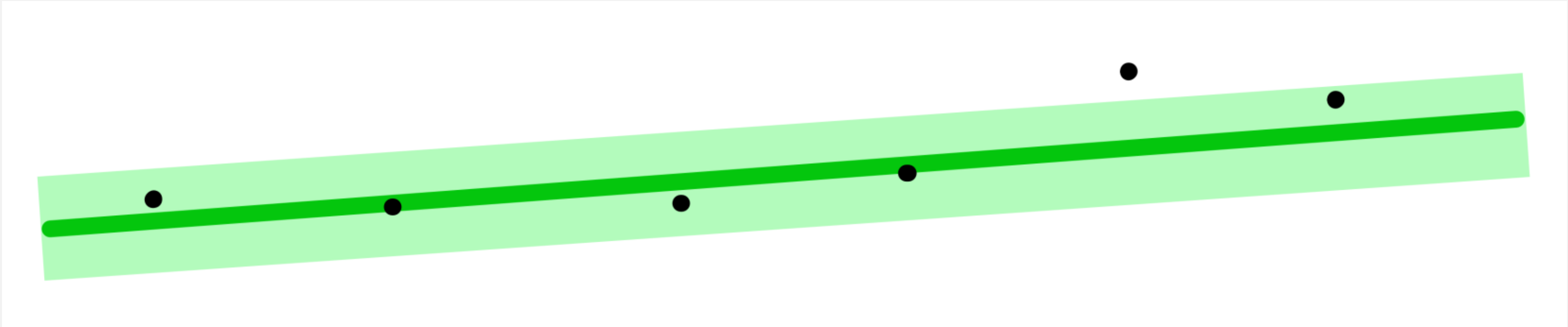

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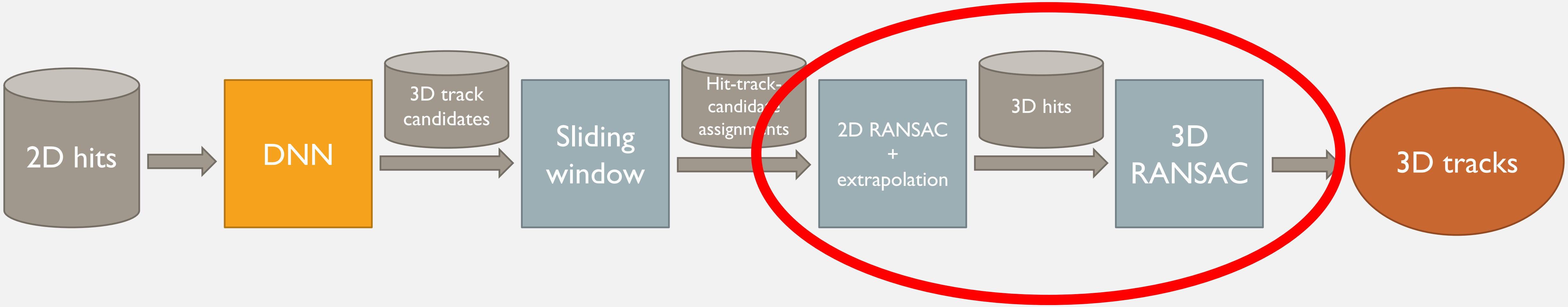
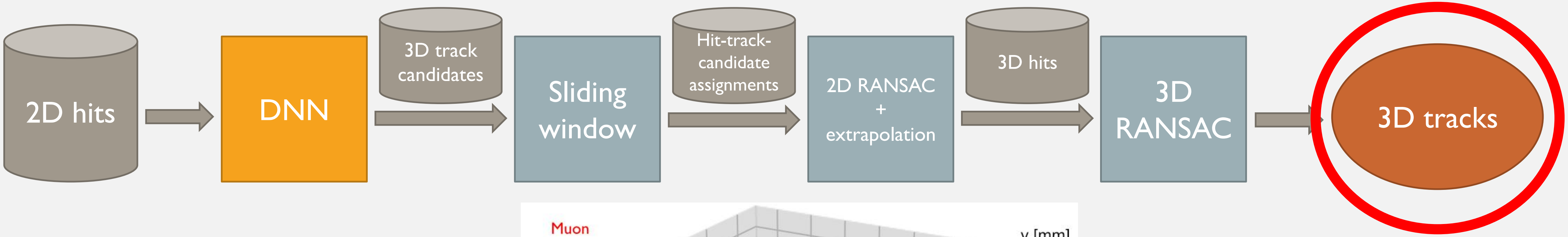
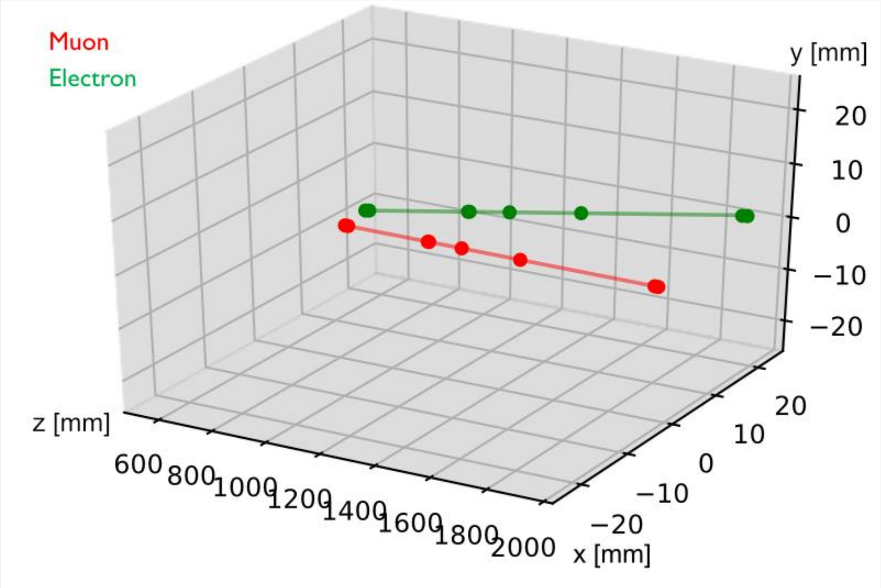


- RANSAC:
  - **RAN**dom **SA**mple **C**onsensus,
  - Robust linear fit algorithm not sensible to outliers.

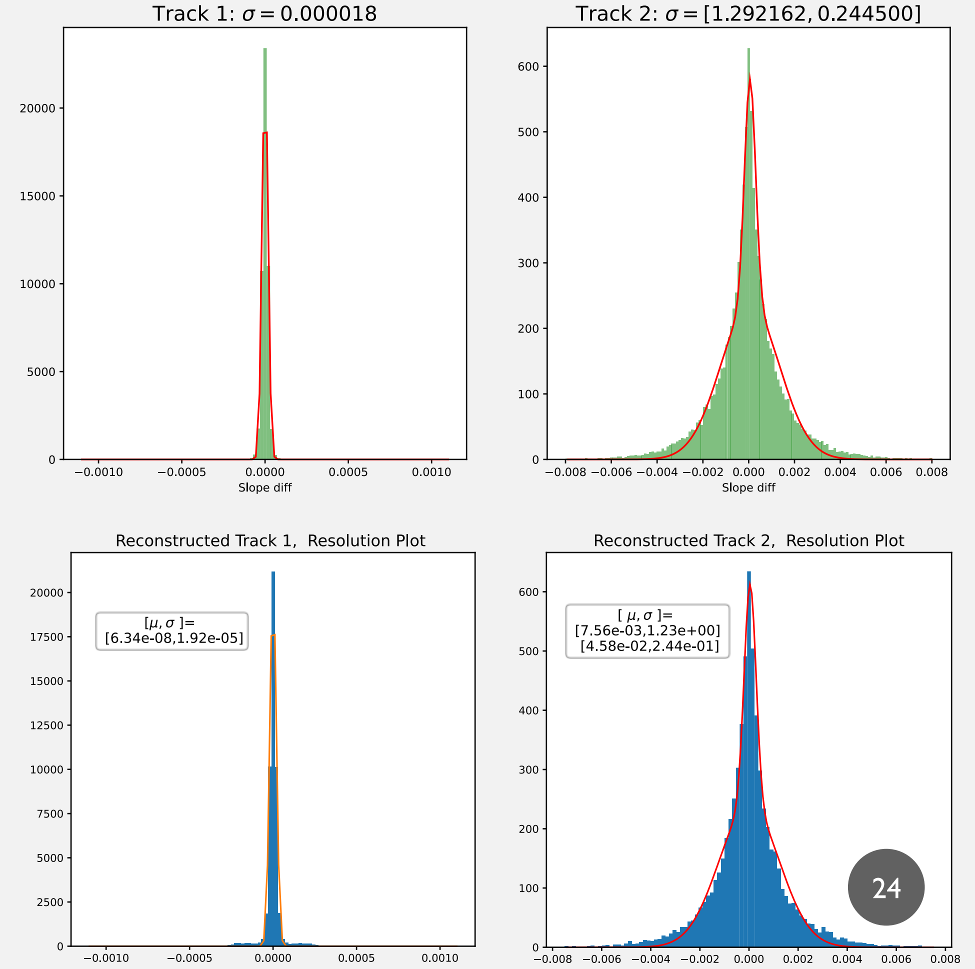
RECONSTRUCTION ALGORITHM





RESULTS

- Track 1: muon, Track 2: electron
- Top: ML-based algorithm
- Bottom: "conventional" reconstruction

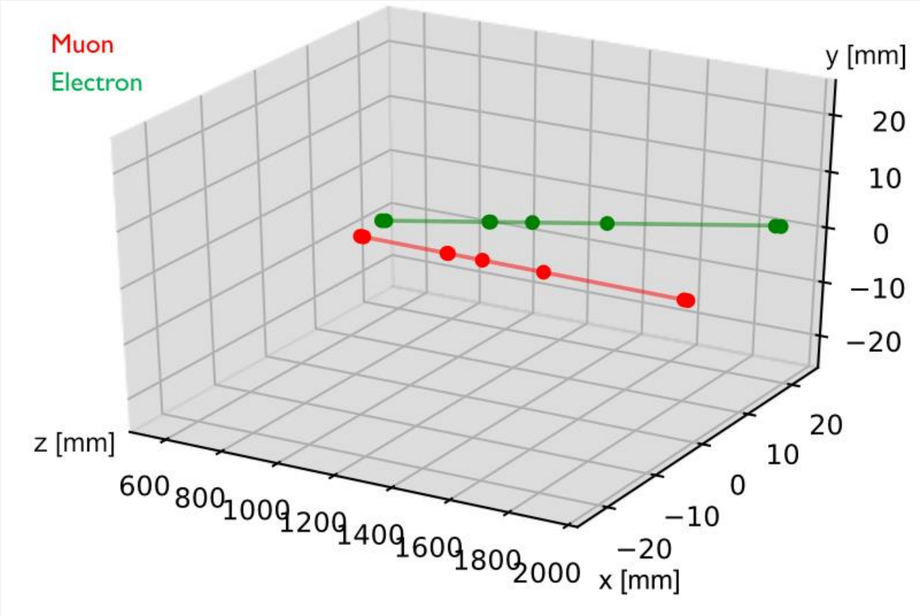


Resolution:

Particle	ML-based	Conventional
Muon	σ = 0.000018 mrad	σ = 0.000019 mrad
Electron	σ_1 = 1.290 mrad, σ_2 = 0.245 mrad	σ_1 = 1.230 mrad, σ_2 = 0.244 mrad

RESULTS

- Track reconstruction efficiency:
  - Track slope difference vs MC under 1×10^{-2}



Efficiency:

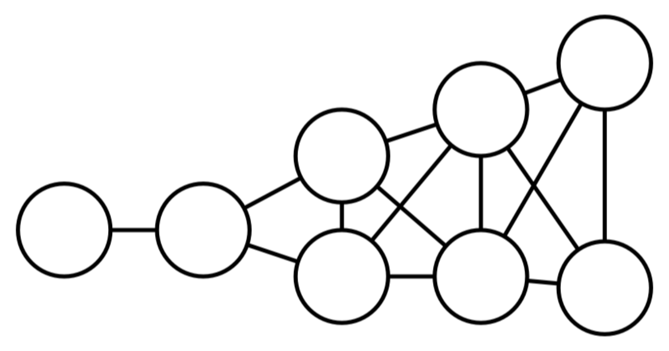
Particle	DNN-based	Classical
Muon	100%	99.98%
Electron	99.66%	99.38%

CONCLUSIONS

- Machine learning potential for HEP:
  - Good at finding patterns in big datasets,
  - Fast response (no iterations),
  - Highly parallel,
- Practical application:
  - ML-based track reconstruction for dataset representing MUonE Test Run,
  - Results on par with the classical method,
- Potential to use also for different tasks in the experiment.

CURRENT/FUTURE WORKS

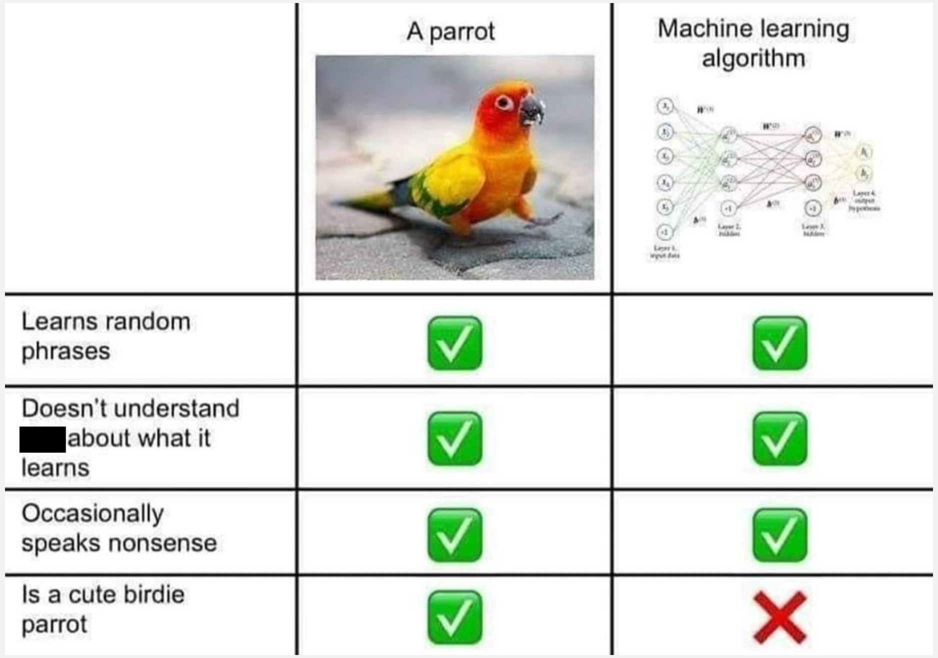
- Graph neural networks (GNN):
  - Growing popularity in HEP,
  - Events represented as graphs:
    - Nodes – hits,
    - Edges – track segments, connections,
  - Flexible at handling missing or additional hits (noise, background),
  - Can perform different tasks:
    - Track reconstruction,
    - Particle identification, track identification,
    - Software alignment.



ML FOR MUonE @ IFJ

- GPU-workstation dedicated to the machine learning for MUonE founded by NCN grant OPUS 2022/45/B/ST2/00318,
- Coordination of the machine learning working group in the experiment.

Q&A



	A parrot	Machine learning algorithm
Learns random phrases	✅	✅
Doesn't understand [redacted] about what it learns	✅	✅
Occasionally speaks nonsense	✅	✅
Is a cute birdie parrot	✅	❌