Multi-neutron detection based on machine learning

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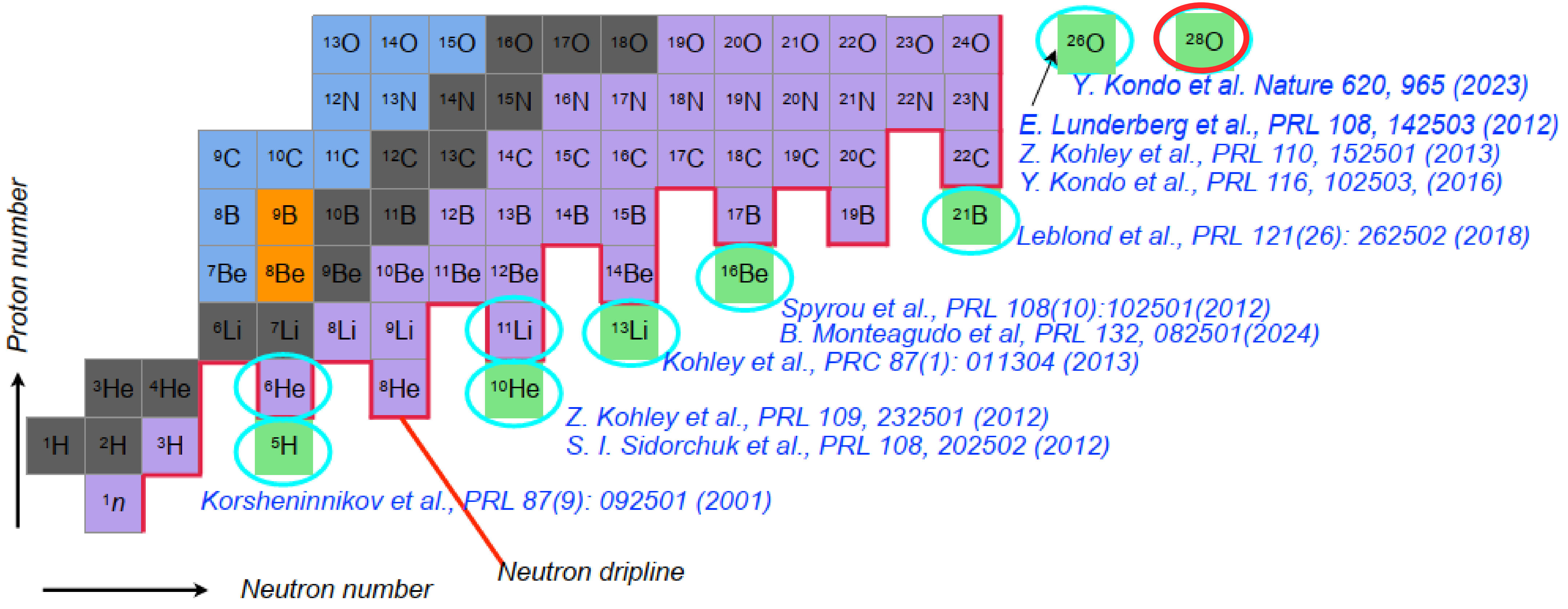
Outline

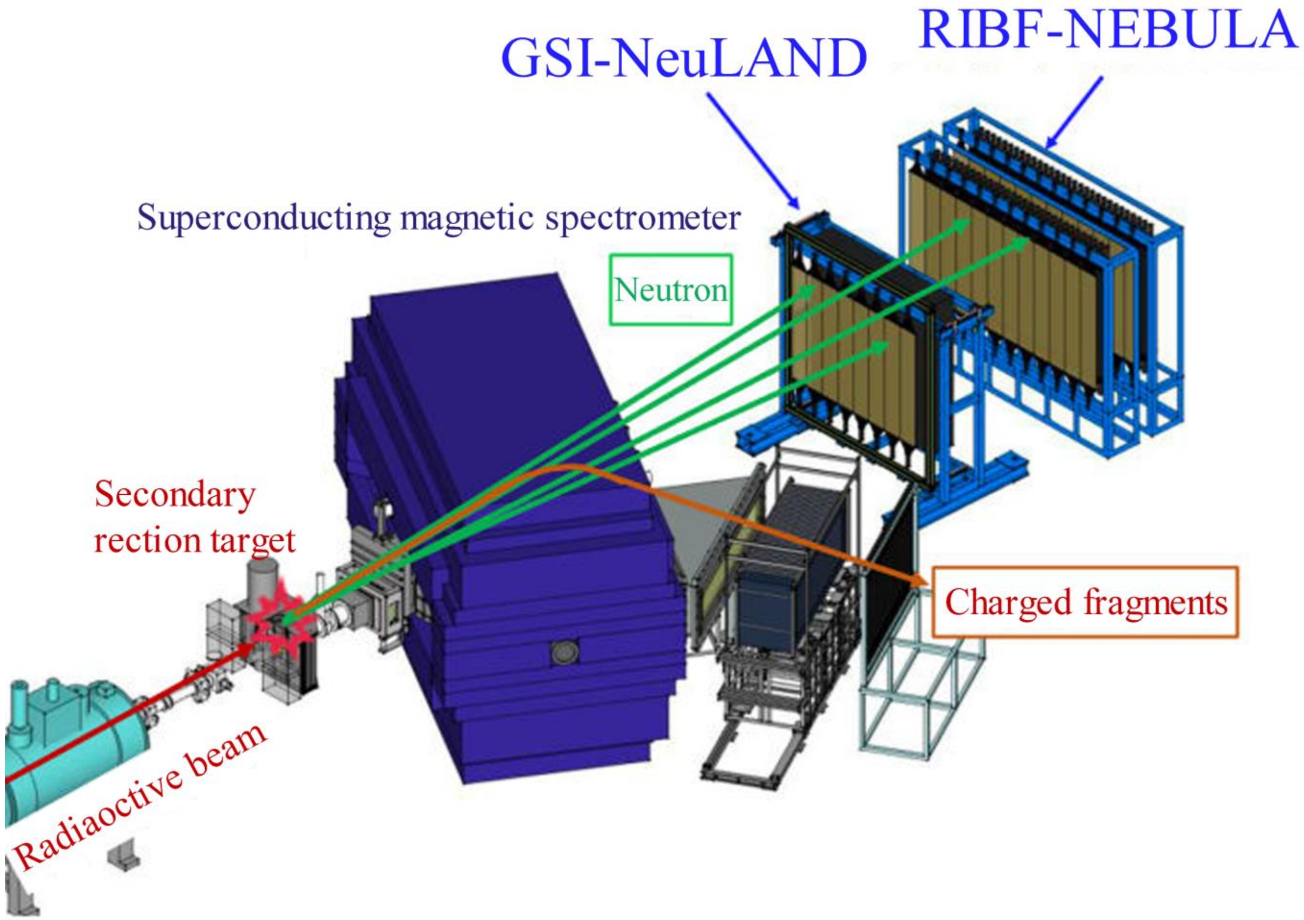
- Background
- Method – exclusion of crosstalk using DNN
- Result – comparing traditional and machine learning algorithms
- Summary

Background

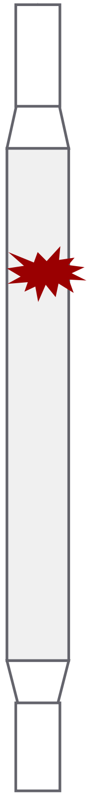


13O 14O 15O 16O 17O 18O 19O 20O 21O 22O 23O 24O
26O
28O
Y. Kondo et al. Nature 620, 965 (2023)
12N 13N 14N 15N 16N 17N 18N 19N 20N 21N 22N 23N
E. Lunderberg et al., PRL 108, 142503 (2012)
Z. Kohley et al., PRL 110, 152501 (2013)
Y. Kondo et al., PRL 116, 102503, (2016)
9C 10C 11C 12C 13C 14C 15C 16C 17C 18C 19C 20C 22C
8B 9B 10B 11B 12B 13B 14B 15B 17B 19B 21B
Leblond et al., PRL 121(26): 262502 (2018)
7Be 8Be 9Be 10Be 11Be 12Be 14Be 16Be
Spyrou et al., PRL 108(10):102501(2012)
B. Monteagudo et al, PRL 132, 082501(2024)
6Li 7Li 8Li 9Li 11Li 13Li
Kohley et al., PRC 87(1): 011304 (2013)
3He 4He 6He 8He 10He
Z. Kohley et al., PRL 109, 232501 (2012)
S. I. Sidorchuk et al., PRL 108, 202502 (2012)
1H 2H 3H 5H
1n
Korsheninnikov et al., PRL 87(9): 092501 (2001)
Proton number
Neutron number
Neutron dripline

Multi-neutron detection experiment



Typical layout of experiment at RIBF, RIKEN.



(x, y, z, TOF, Q)

momentum of neutrons

momentum of fragments

invariant mass method

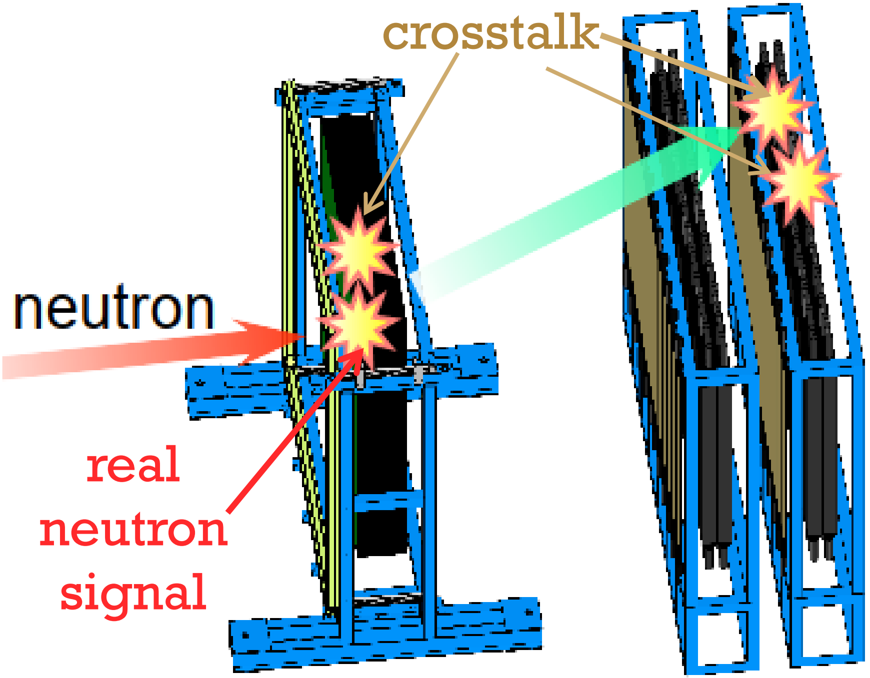
$M^* = \sqrt{(E_i)^2 - (\Sigma P_i)^2}$

$E_{rel} = M^* - \Sigma m_i$

Relative energy E_{rel} spectrum reconstruction

HUANG S, YANG Z, MARQUÉS F, et al. Few-Body Systems, 2021, 62(4): 102

crosstalk



The secondary charged particles
gamma rays
scattered neutrons

⇩

crosstalk

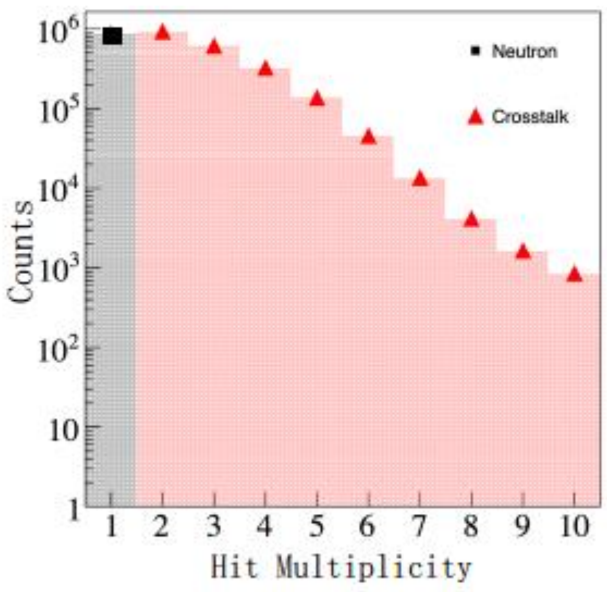
The challenges of multi-neutron detection:

- low detection efficiency of neutrons
- large number of crosstalk signals, real neutron signal will inevitably be excluded

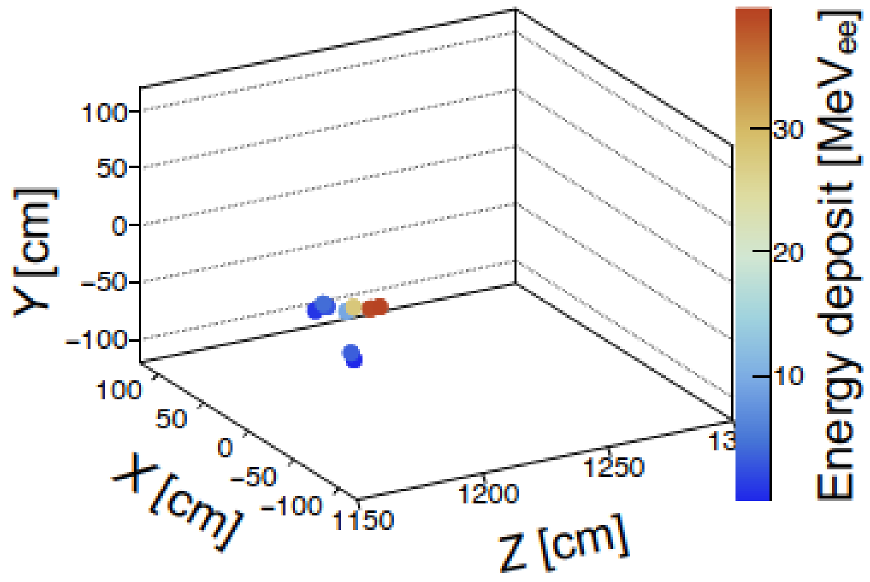
Crosstalk

Data from Geant4 simulation

1n



1n



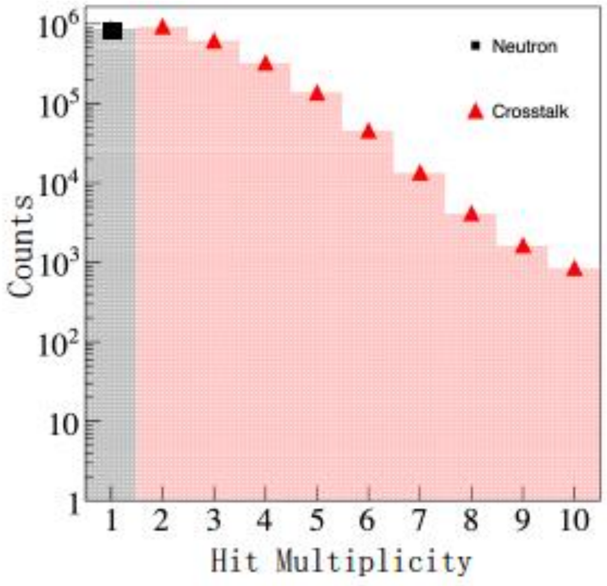
a single neutron can also generate a large number of crosstalk

directly select the first signal?

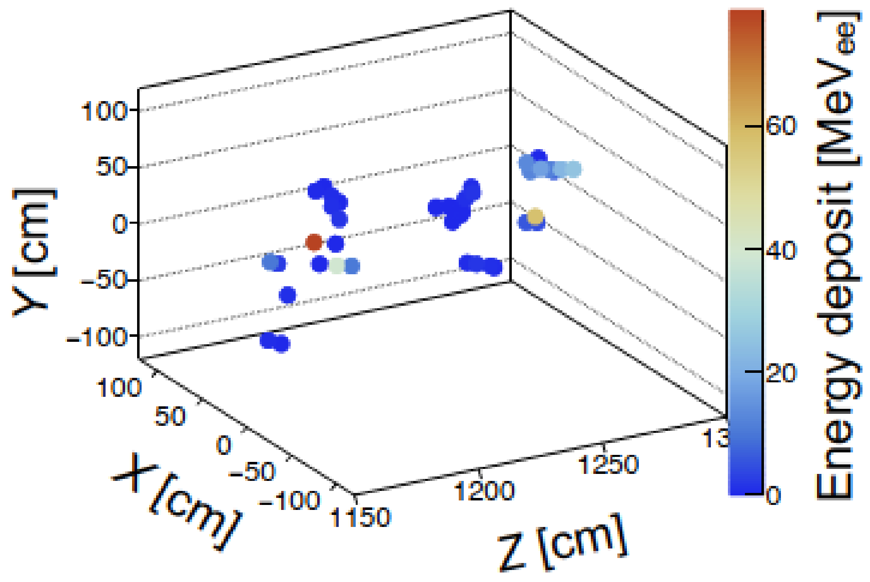
Crosstalk

Data from Geant4 simulation

1n



4n



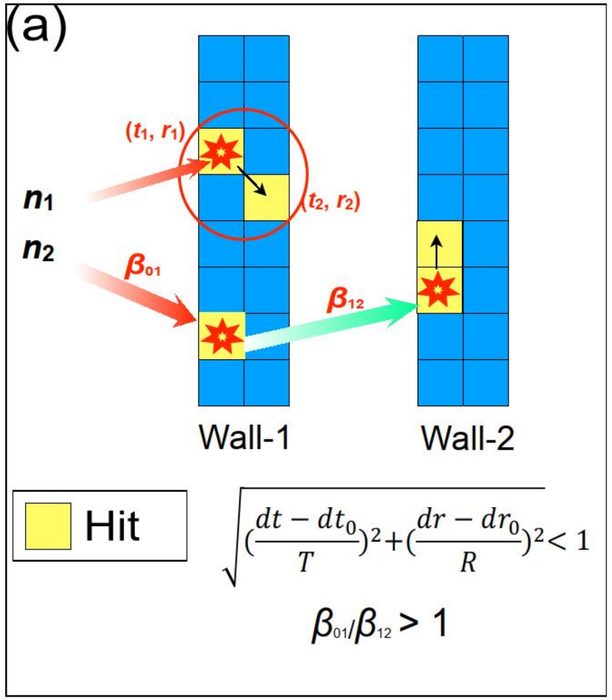
a single neutron can also generate a large number of crosstalk

directly select the first signal?

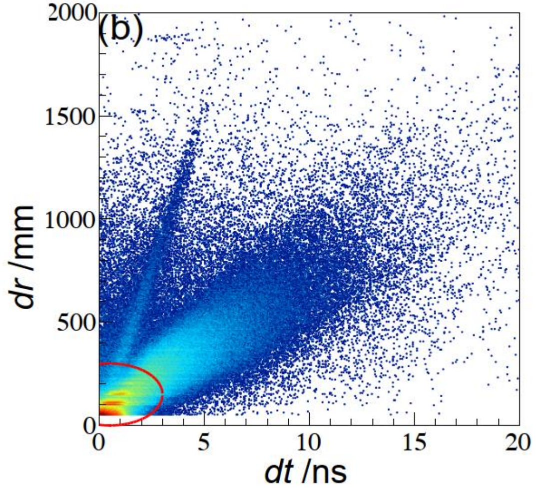
not applicable to the case of multiple neutron events, timing of signals is very complicated

Traditional algorithm

high crosstalk rejection

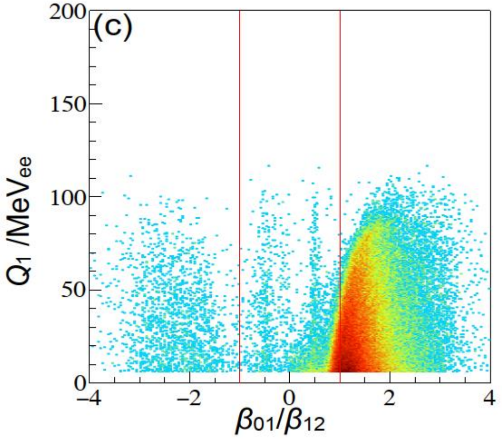


1n



Crosstalk signals can be divided into two types

The first type
caused by the secondary particles near
the initial signal of the neutron detectors
time and space correlation



The second type
generated by reaction of scattered neutrons
velocity should decrease compared to incident neutrons.
kinematic condition

Kondo et al., Nuclear Instruments and Methods in Physics Research Section B 463: 173-178 (2020)
S. W. Huang et al., Few-Body Systems 62(4): 1-7 (2021)

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Machine learning

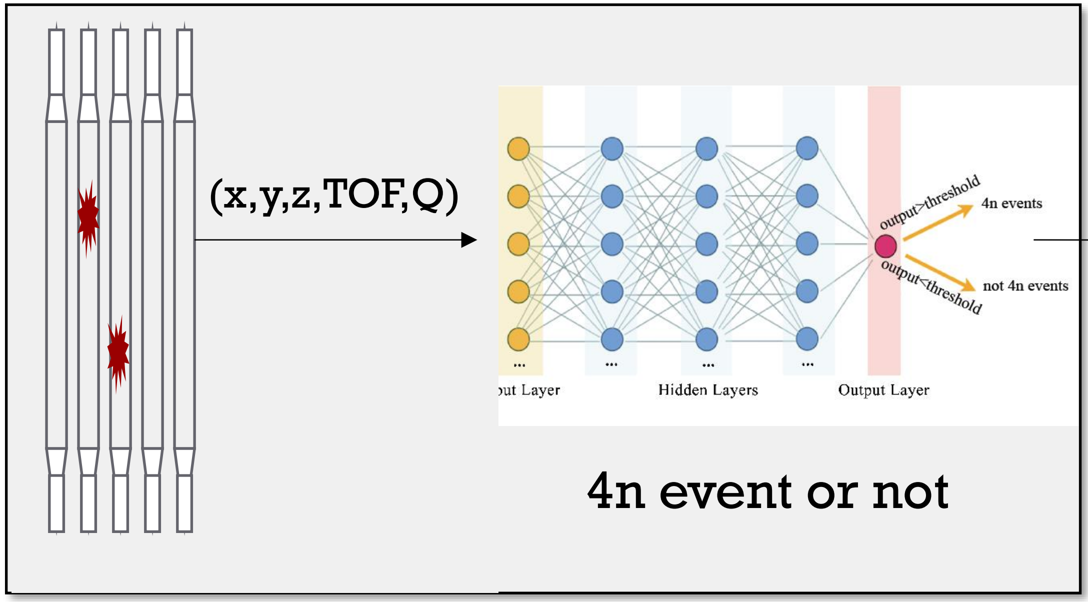
- **predicting fission fragment yield distribution.** WANG Z A, PEI J, LIU Y, QIANG Y., PRL 123: 122501 (2019)
- **predicting nuclear mass.** Niu Z M, Liang H Z., PRC 06(2): L021303 (2022)
- **predicting ground state energy.** Knöll et al., PLB 839: 137781 (2023)
- **particle identification in plastic scintillators.**
  Doucet et al., Nucl. Instrum. Methods Phys. Res., Sect. A 954, 161201 (2020)
- **particle identification in AT-TPC tracks.**
  Kuchera et al., Nucl. Instrum. Methods Phys. Res., Sect. A 940: 156-167 (2019)

Keras

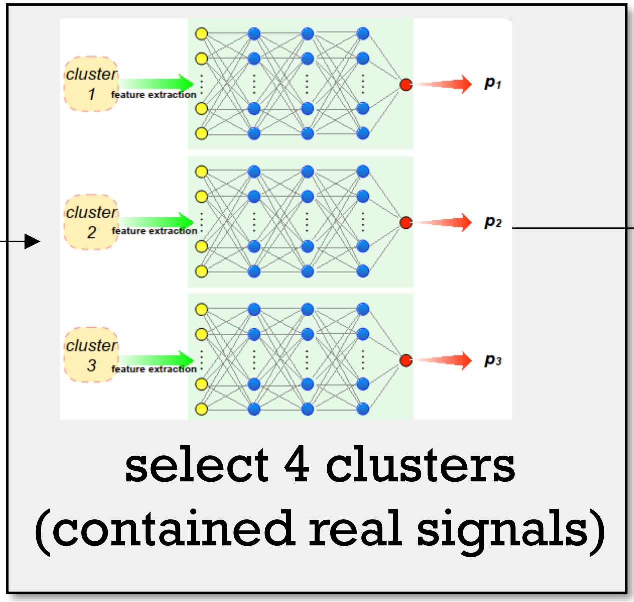
TensorFlow

C.A. Douma et al, Nucl. Instrum. Methods Phys. Res., Sect. A 990, 164951 (2020)

Deep Neural Network

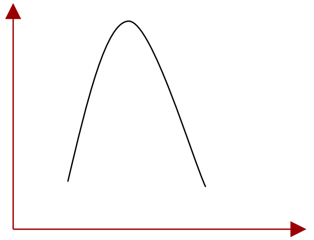


step1



step 2

selected signals
reconstruct energy spectrum



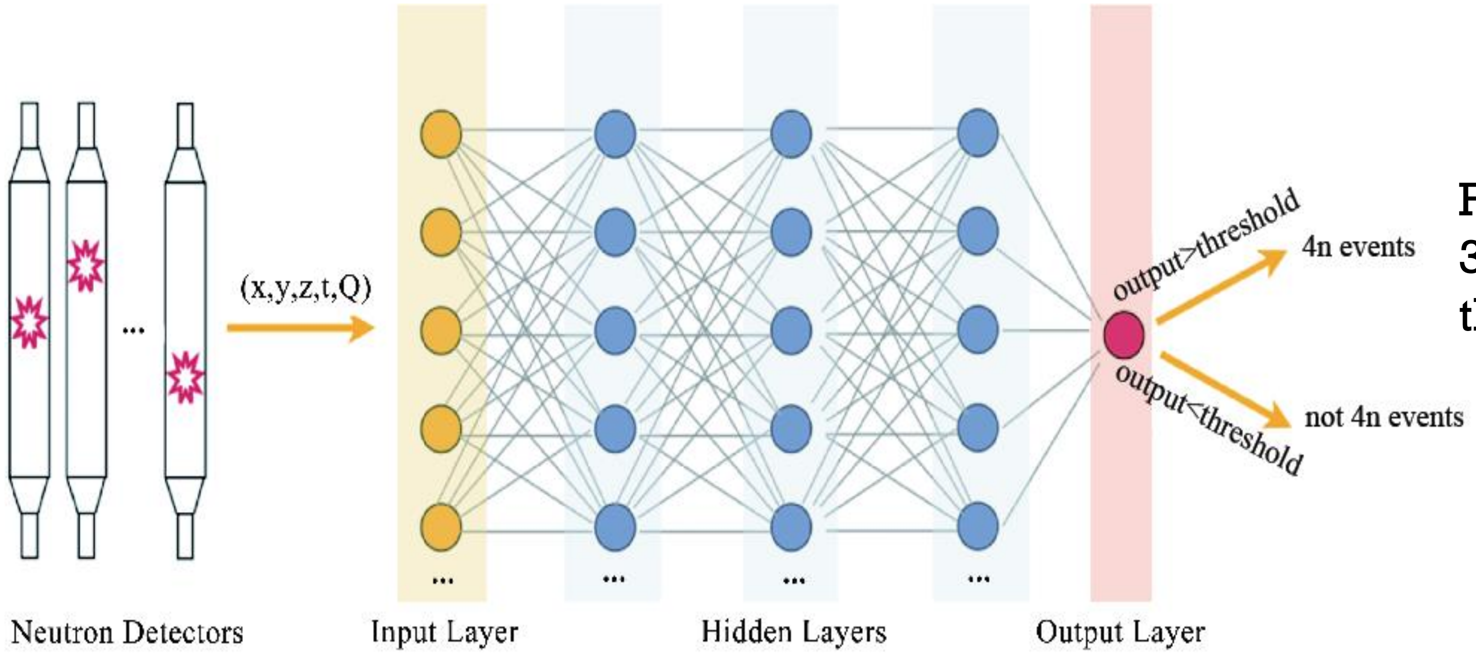
Two-step deep neural network (DNN).

(1) Neutron multiplicity determination

(2) Neutron selection

Training/validation set (1million events) + test set from Geant4 simulation

Machine learning algorithm – step 1

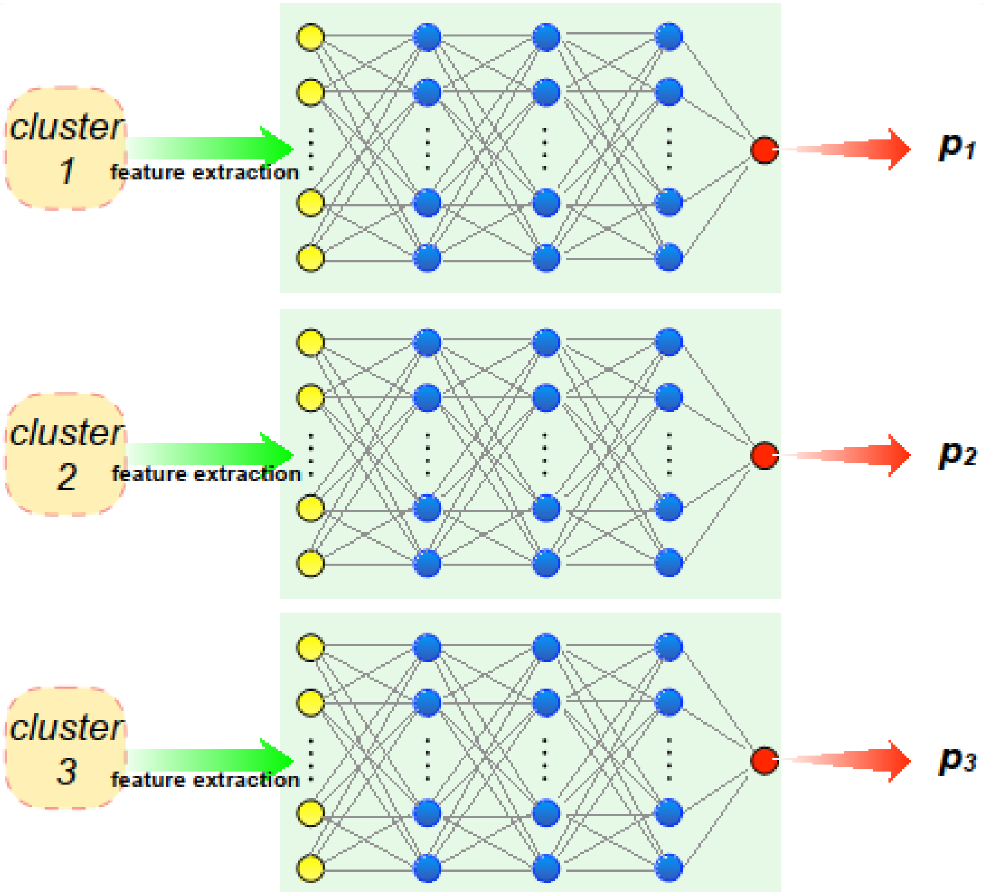


The principle of first step DNN

Fully-Connected DNN
3 hidden layers (1024, 256, 128neurons)
threshold= 0.5

Input: Information recorded by the neutron detector (X,Y,Z,TOF,Q...)
Output: value between 0 (not 4n) and 1 (4n)

Machine learning algorithm – step 2



The principle of second step DNN

14 input layer features
12 hidden layers(200 neurons per layer)

Training Set: Number of reacted neutron equals object neutron
Feature: information of a single cluster (X,Y, Z,TOF,Q...)
Label: 0 or 1 (i.e. whether the cluster contains real signal)

To pick out the cluster where the real neutron is, each cluster is fed into the model and the predicted value p is obtained. Sort all the output value to select them.

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Result: 2n channel

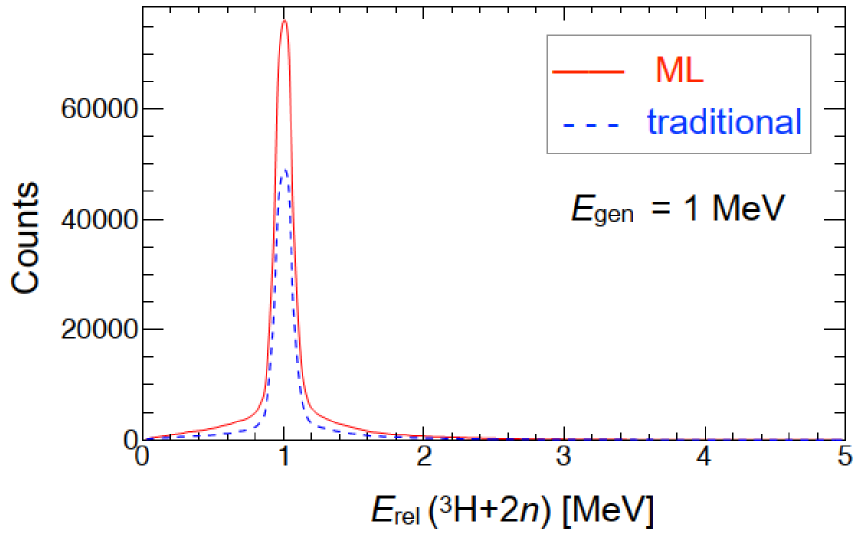
Define:

crosstalk exclusion rate r_1

$$r_1 = \frac{eliminated\ crosstalk\ events}{initial\ crosstalk\ events}$$

multi n misclassification rate r_2

$$r_2 = \frac{misclassified\ as\ 2n\ events}{total\ 2n\ events}$$

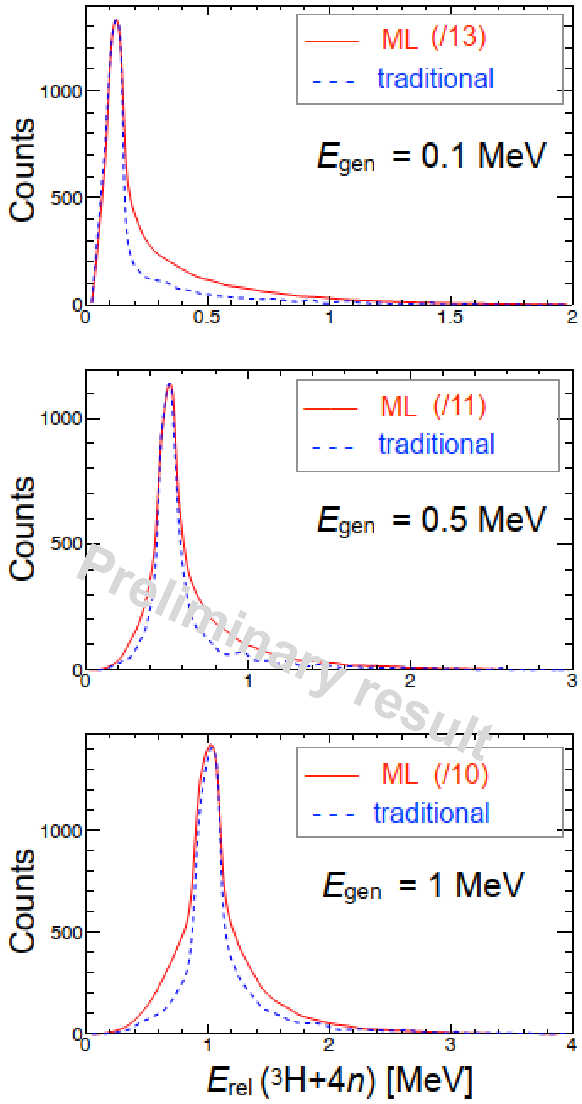


$$M^* = \sqrt{(E_i)^2 - (\Sigma P_i)^2}$$
$$E_{rel} = M^* - \Sigma m_i$$

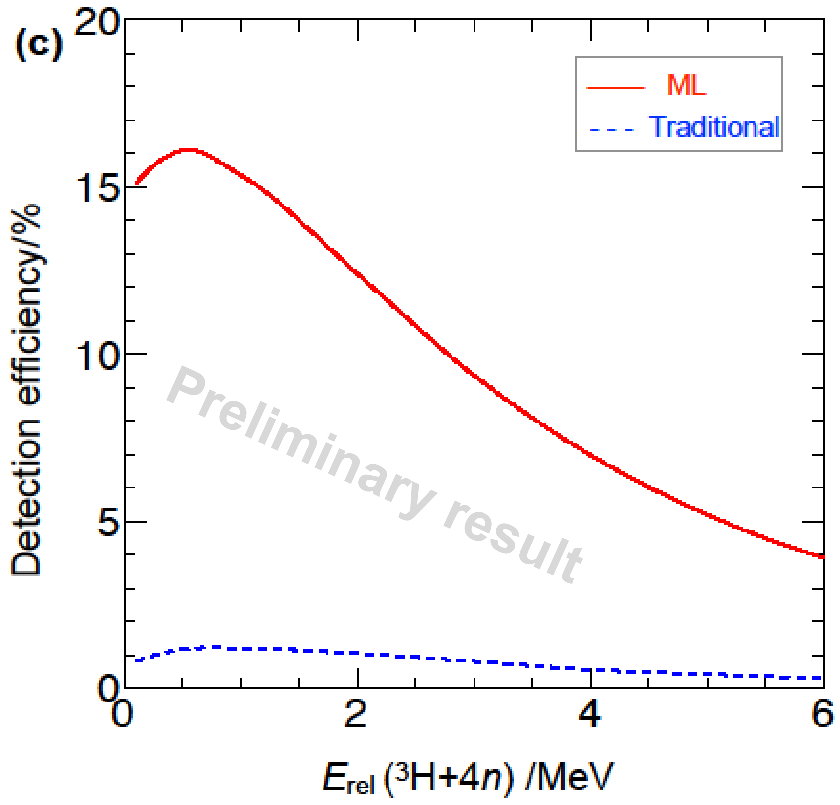
/%	r_1	r_2
traditional	98.43	3.83
ML	99.40	1.33

E_{rel} peak position
Detection efficiency
Energy resolution

Result： 4n efficiency

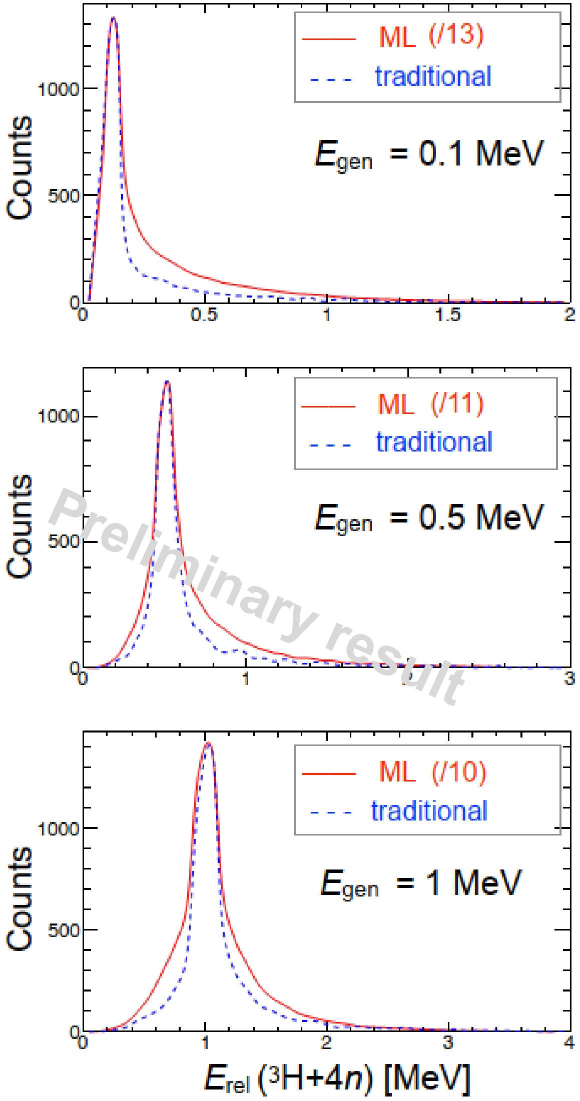


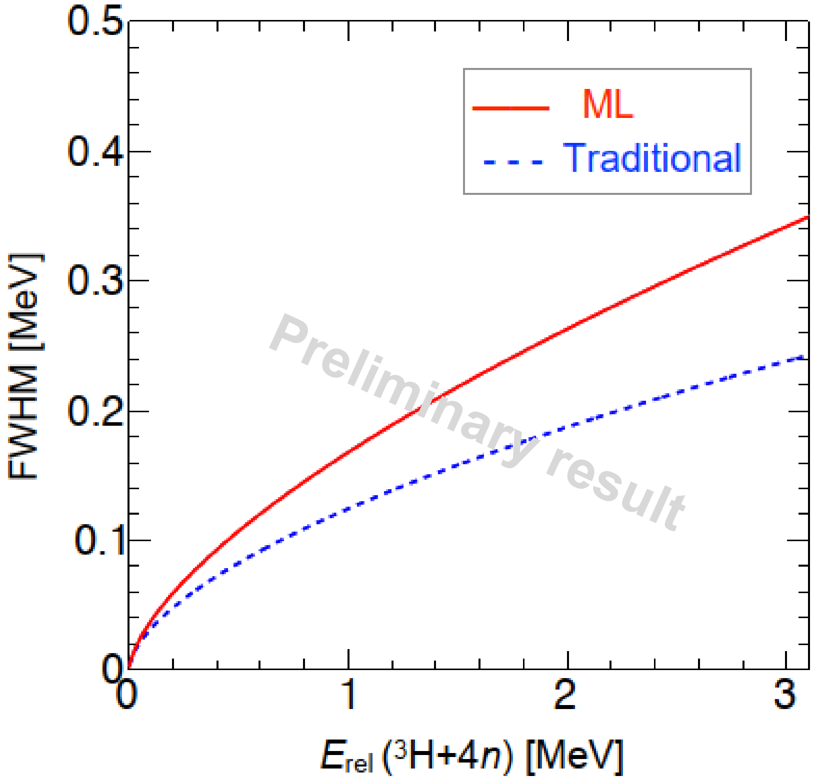
/%	r_1	r_2
traditional	99.53	18.34
ML	99.69	13.75



Machine learning algorithm improves the efficiency significantly

Result：4n resolution

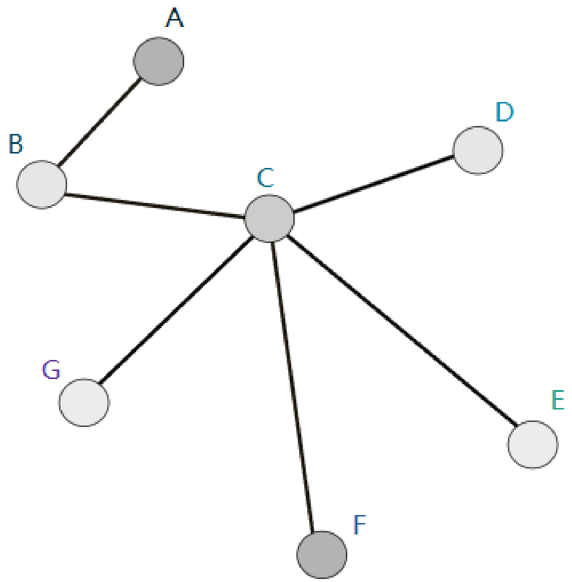




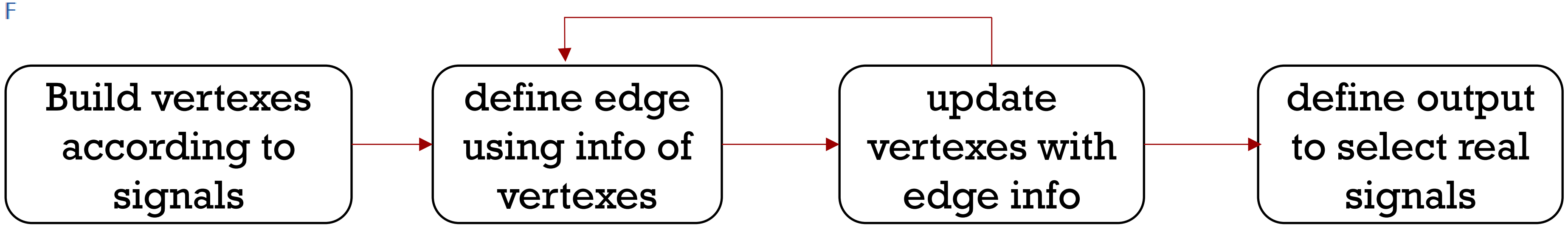
Energy resolution of ML algorithm will be slightly worse

GNN (in progress)

correlation between different clusters of signals （missing in DNN）



- vertex: represent the information of each detector
- edge: information about correlation of two signals (such as β)
- adapted from Particle-net in high energy physics



Huilin Qu et al., Phys. Rev. D 101: 056019 (2020)

Summary

A neural network-based multi-neutron identification algorithm is developed, which significantly improves the four-neutron efficiency (>10 times) compared with the traditional algorithm.

We are now trying to use graph neural network (GNN) and other methods to develop multi-neutron identification algorithm, hoping to further improve the results by introducing correlations between clusters.

We will continue to explore and optimize algorithms for the high-efficiency and high-resolution multi-neutron spectrometer under construction, and apply them to multi-neutron detection.