GNN-based neutron reconstruction in the neutron detector at BM@N experiment

V. Bocharnikov[1], D. Derkach[1], F. Ratnikov[1], M. Golubeva[2], F. Guber[2], S. Morozov[2]

[1]HSE University, Moscow, Russia

[2]Institute for Nuclear Research RAS, Moscow, Russia

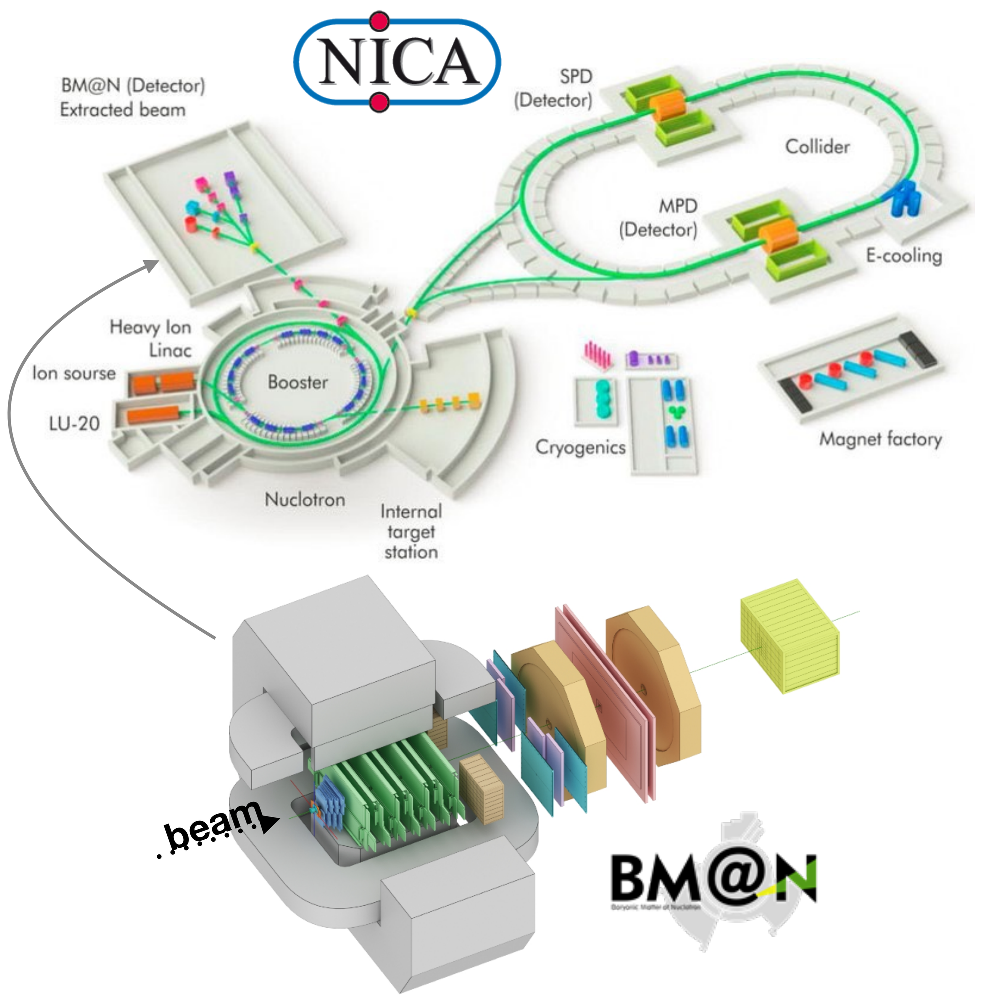
BM@N experiment

Studies of **B**aryonic **M**atter **at** the **N**uclotron (NICA, JINR)

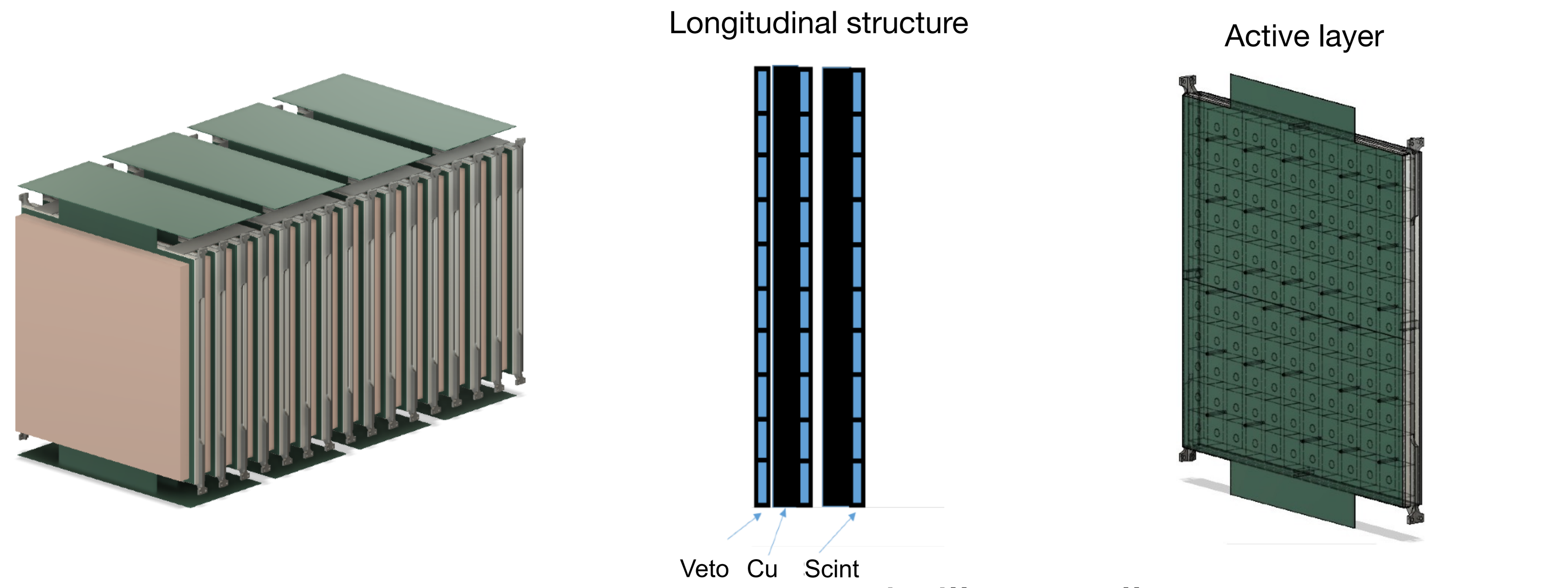
- Fixed target experiment
- Heavy-ion beam with energies up to 4.5 GeV/nucleon

➡ investigate the equation-of-state (EOS) of dense nuclear matter which plays a central role for the dynamics of core collapse supernovae and for the stability of neutron stars.

- **neutron azimuthal flow** - new tool for EOS studies



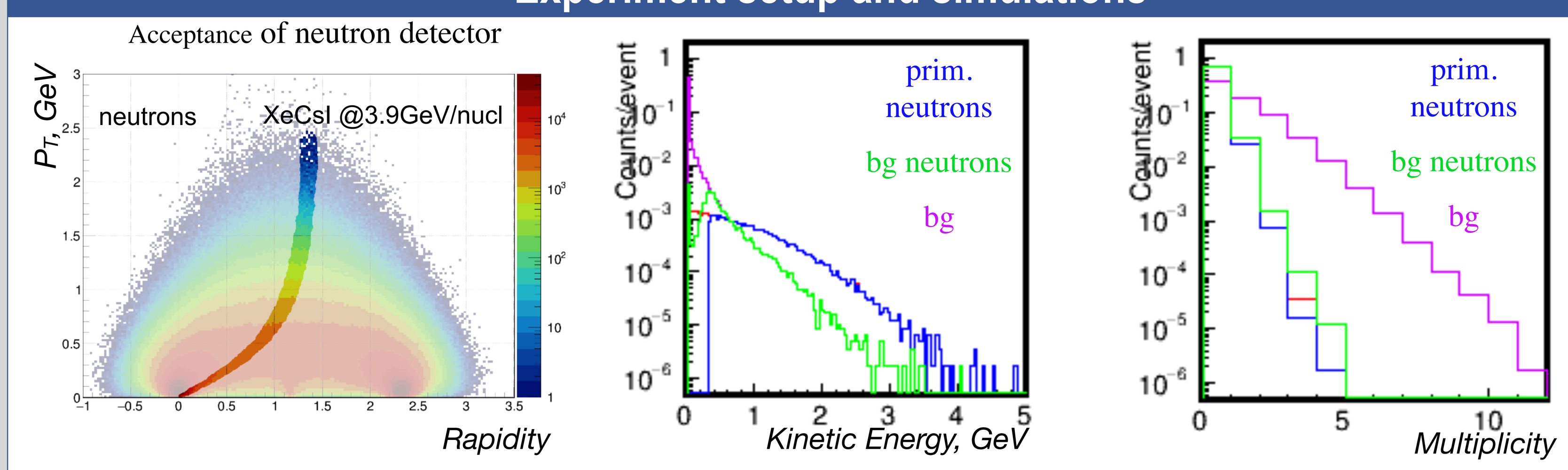
Highly granular time-of-flight neutron detector (HGN)



- Total length: **~1m** (~3 λ_{in})
- Transverse size: **44x44 cm²**
- 16 layers: *3 cm Cu (absorber) + 2.5cm Scintillator + 0.5cm PCB*
- *11x11 scintillator cell grid*

- scintillator cells:
  - size: 4x4x2.5 cm³,
  - total number of cells: 1936
  - light readout: SiPM,
  - expected time resolution: ~150 ps

Experiment setup and simulations



- Neutron detector is located at **27° to the beam** axis at **~6m from the target**
- DCM-SMM event generator + Geant4
- Neutron rate in acceptance ~2.6*10⁷ n / month
- Reconstruction goal: identify neutrons and reconstruct energy on event basis
- Particle multiplicity ≈1 => **event classification approach**

Observables per hit:

- $(x,y,z)_{hit}$
- E_{dep} (>3 MeV)
- $T_{hit}+\mathcal{N}(0,\sigma = 150ps)$

Dataset

Table 1. 600K simulated reactions. Number of events in the detector

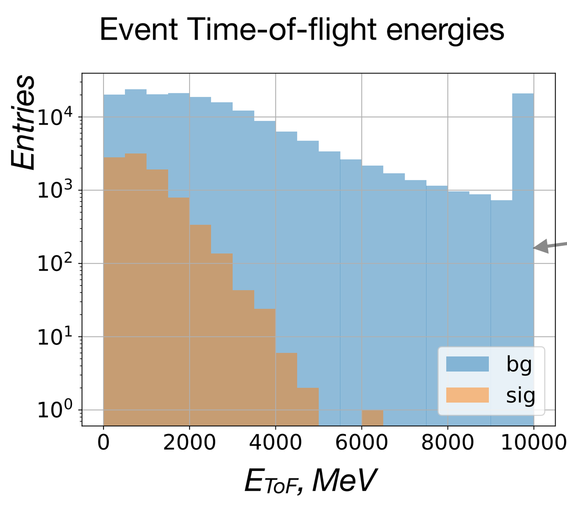
	E_{dep} in acceptance	n in acceptance	signal
N_{events}	206K	~25K	~9K

Signal event selection:

- Single neutron,
- E_{kin} > 100 MeV,
- Angle to detector axis < 10°
- $\delta(E_{ToF})$ < 40%
- ~36% neutrons selected

Time-of-flight (ToF) energy for *n* hypothesis:

$$E_{ToF} = m_n\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$



Distribution of E_{ToF} has visible separation power however it is our **target variable** and it depends on simulations - possible **source of bias**

Conclusions

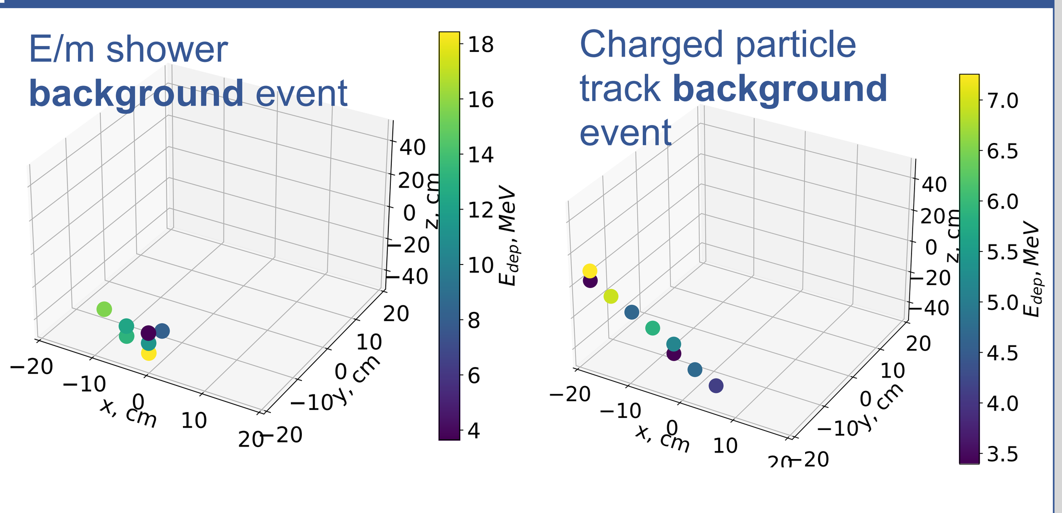
- Event structure-based **GNN compared with BDT** which performs well in various event classification problems in HEP
  - BDT learns feature distributions
  - GNN learns event structures
- **Similar performance using** target feature E_{ToF}
- **Excluding E_{ToF}** variable increases significance of event topologies for events with N_{hits}>1 => **slight increase of GNN performance** compared to BDT
- Possible limit of GNN performance:
  - Large fraction of single hit events and irregular event signatures for given dataset

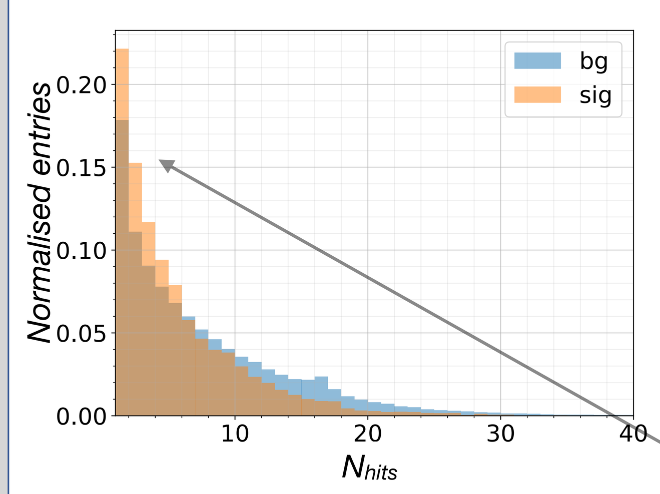
  ➡ GNN can be more beneficial at higher energies and higher detector granularities

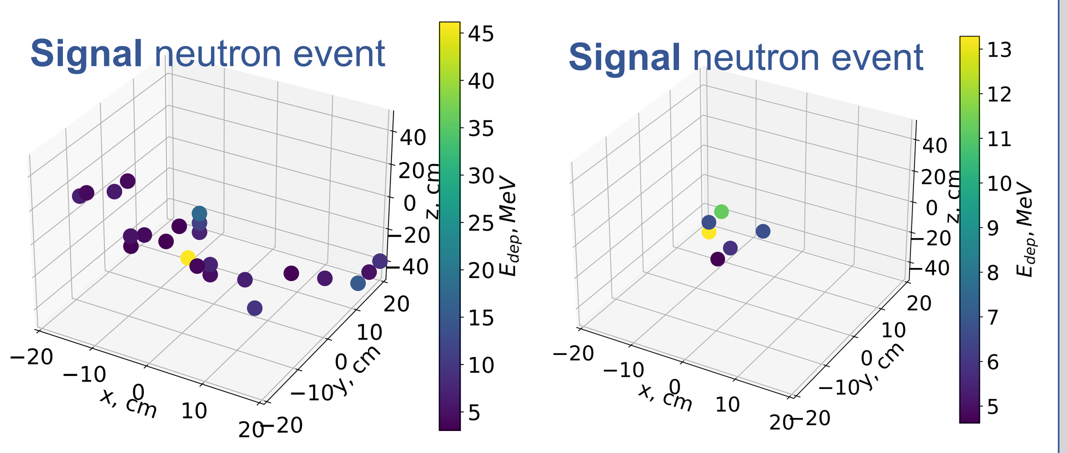
Imaging capabilities of the HGN detector

Event type signatures:

- **tracks** of charged particles
- compact **electromagnetic showers**
- sparse and irregular **hadronic showers**
  - no upstream track for neutral hadrons







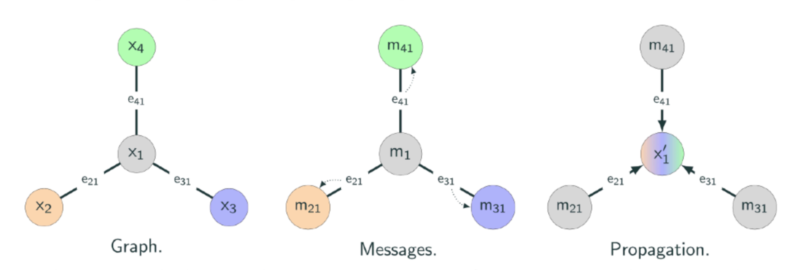
Significant fraction of single hit events

Classification models

Event structure model

Graph neural network (GNN)

- (x,y,z), E_{dep}, T_{hit} (after first hit) + E_{ToF} (optional)
- Fully connected hit graphs
- 2 GraphSage layers with 32 hidden channels -> Self-attention pooling layer -> MLP
- BCE loss function



J. Gilmer *et al.*, "Neural message passing for quantum chemistry," 2017.

PyG

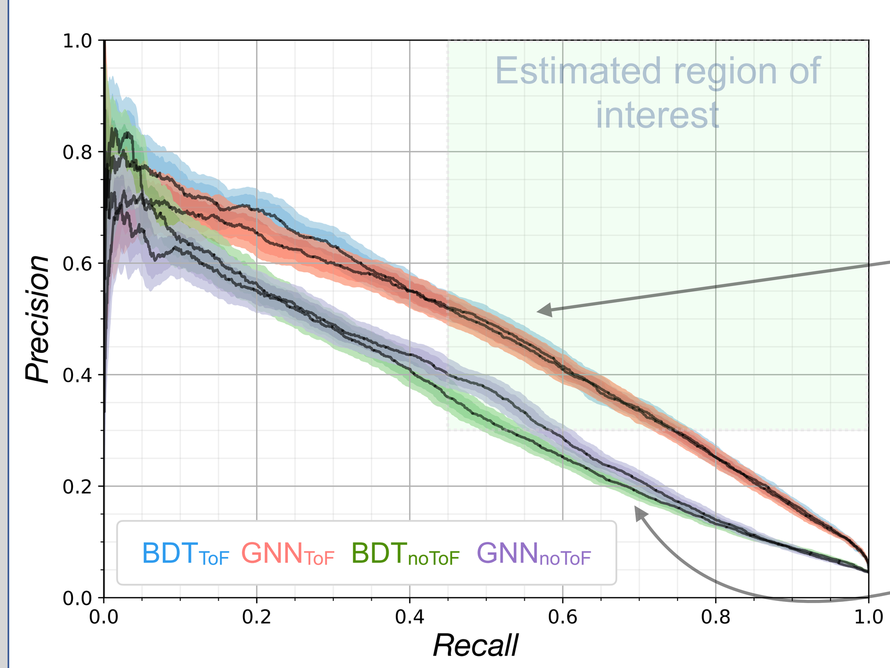
VS.

First principle model

Boosted Decision Tree (BDT) model with ***first-principle* feature set** based on global event properties and parameters of most informative hits.

CatBoost

Results



2 sets of GNN and BDT **models:**

1. Using **E_{ToF}** feature for classification
   - Biased to the parameters of simulations
2. **No time-of-arrival** information is used
   - Less dependent on simulation

$$Precision = \frac{TP}{TP+RP}$$

$$Recall = \frac{TP}{TP+FN}$$

Region of interest:

~ Precision threshold - exclude flat neutron flow hypothesis

~ Recall threshold - covers most of neutron E_{kin} spectrum

MMU package for PR-uncertainties