Highly Granular Time-of-Flight Neutron Detector HGND for the BM@N experiment

Sergey Morozov, INR RAS, Moscow
on behalf of HGND team

The work has been supported by the Russian Scientific Foundation grant № 22-12-00132

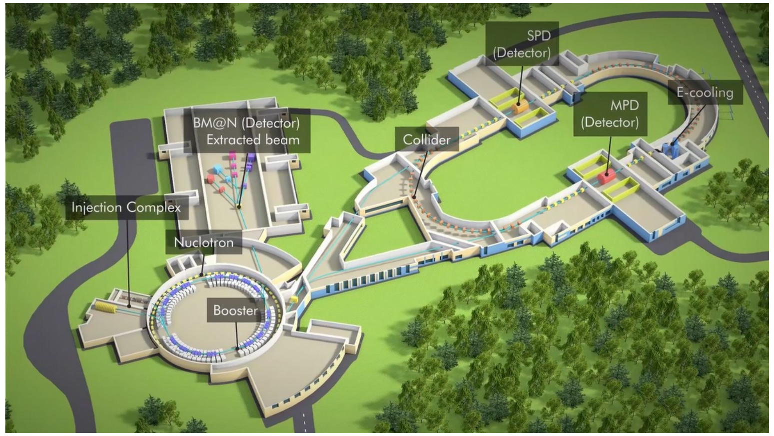
7th international conference on particle physics and astrophysics ICPPA-2024

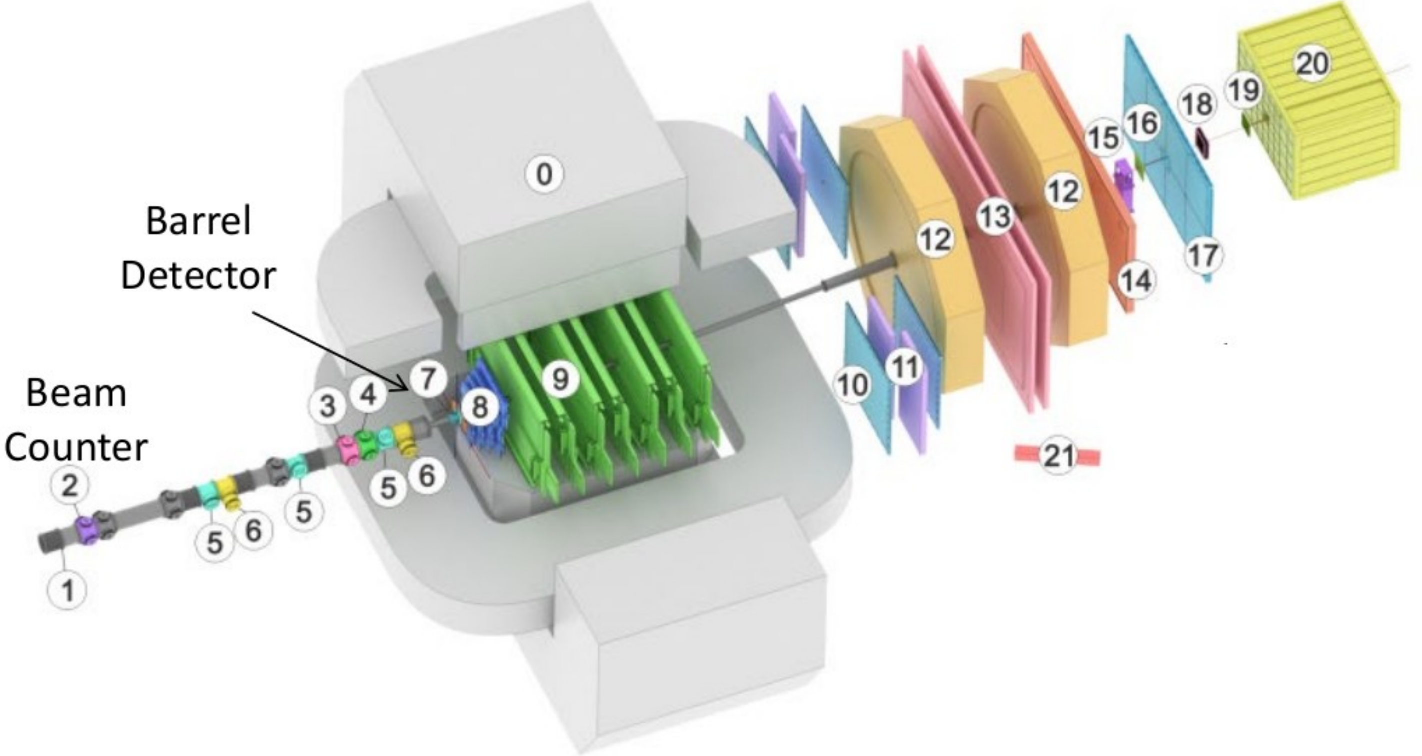
22-25 October 2024, NRNU MEPhI

Outline:

- Physics motivation of measuring the neutrons at the BM@N
- Highly Granular Neutron Detector (HGND) conception
- Performance studies for HGND optimization
- Current status of HGND hardware and electronics development

BM@N – Baryonic Matter At Nuclotron





- ■ Magnet SP-41 (0)
- ■ Vacuum Beam Pipe (1)
- ■ BC1, VC, BC2 (2-4)
- ■ SiBT, SiProf (5, 6)
- ■ Triggers: BD + SiMD (7)
- ■ FSD, GEM (8, 9)
- ■ CSC 1x1 m^2 (10)
- ■ TOF 400 (11)
- ■ DCH (12)
- ■ TOF 700 (13)
- ■ ScWall (14)
- ■ FD (15)
- ■ Small GEM (16)
- ■ CSC 2x1.5 m^2 (17)
- ■ Beam Profilometer (18)
- ■ FQH (19)
- ■ FHCal (20)
- ■ HGN (21)

EOS for high baryon density matter

The binding energy per nucleon: $E_A(\rho,\delta) = \boxed{E_A(\rho,0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$

Isospin asymmetry:

$$\delta = (\rho_n - \rho_p)/\rho$$

Symmetric matter

- Being extensively studied nowadays using observables (flow, meson yields, etc) to explore incomressibility

$$K_0 = 9\rho^2 \frac{d^2E_A}{d\rho^2}$$

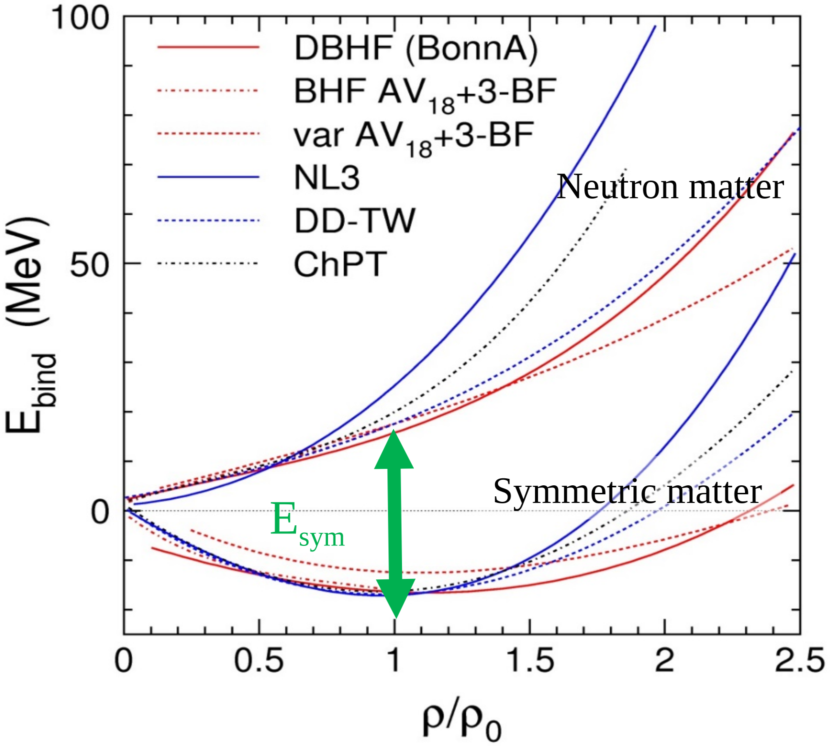
- One of the main sources of uncertainty: discrepancy between experimental data

Symmetry energy

- One of the main parameters to study is the E_{sym} slope

$$L = 3\rho \frac{dE_{sym}(\rho)}{d\rho}$$

- No experimental data for beam energies E_{kin} > 0.4 GeV
- One needs to establish observables sensitive to ***L*** and obtain new experimental data

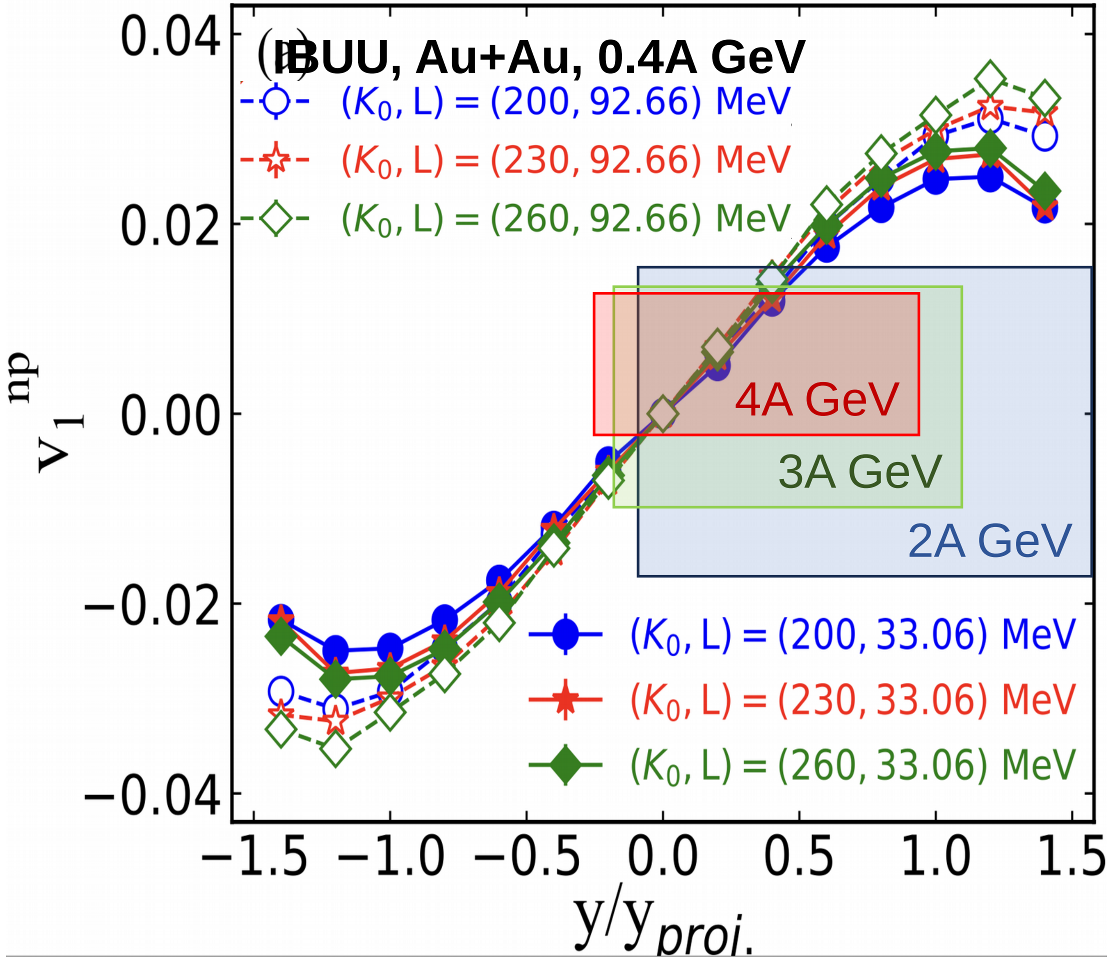


Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

Observables to study symmetry energy

Using v_1^{np} to study L

X.X. Long, G.F. Wei, Phys.Rev.C 109 (2024) 5, 054619



One can define free neutron-proton differential directed flow:

$$v_1^{np} = \frac{N_n(y)}{N(y)}\langle v_1^n(y)\rangle - \frac{N_p(y)}{N(y)}\langle v_1^p(y)\rangle$$

$N_n(y), N_p(y), N(y)$ - total number of neutrons, protons and nucleons respectively

$\langle v_1^n(y)\rangle, \langle v_1^p(y)\rangle$ - flow of neutrons and protons respectively

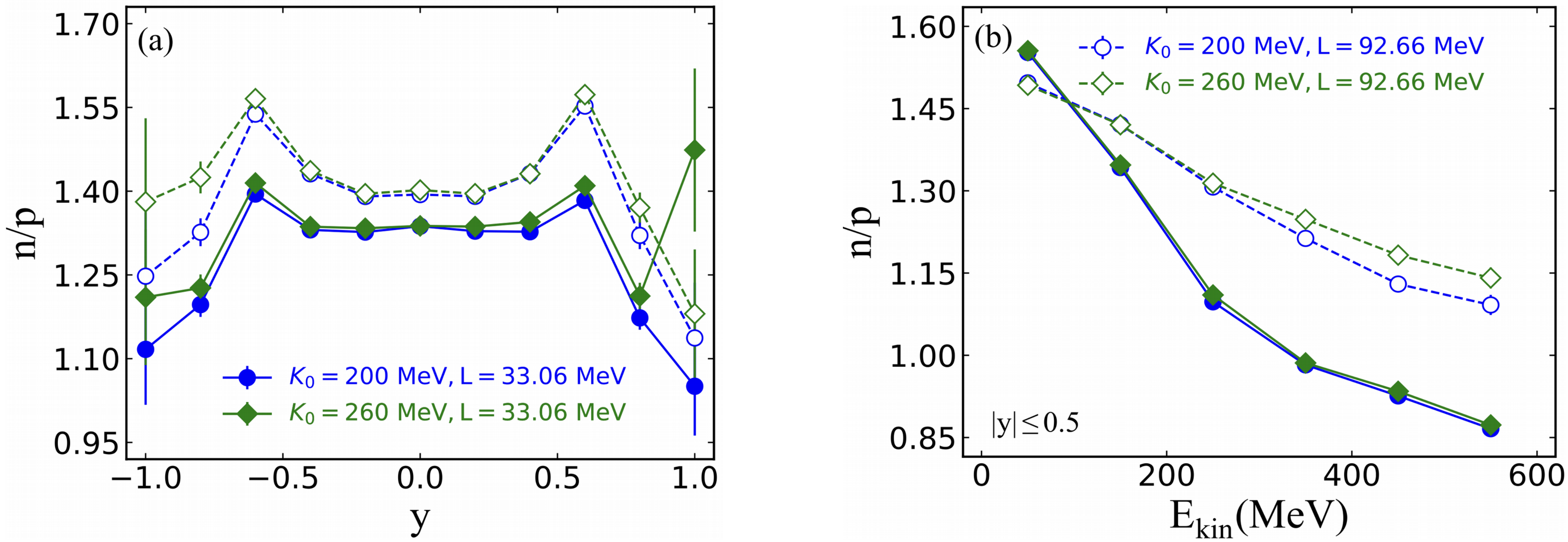
- v_1^{np} sensitive to both K_0 and L which may lead to ambigous interpretation
  - More observables might be necessary for robust study of L

Observables to study symmetry energy

Rapidity and kinetic energy distributions of n/p ratios show strong dependence on ***L*** and weak dependence on $\boldsymbol{K_0}$

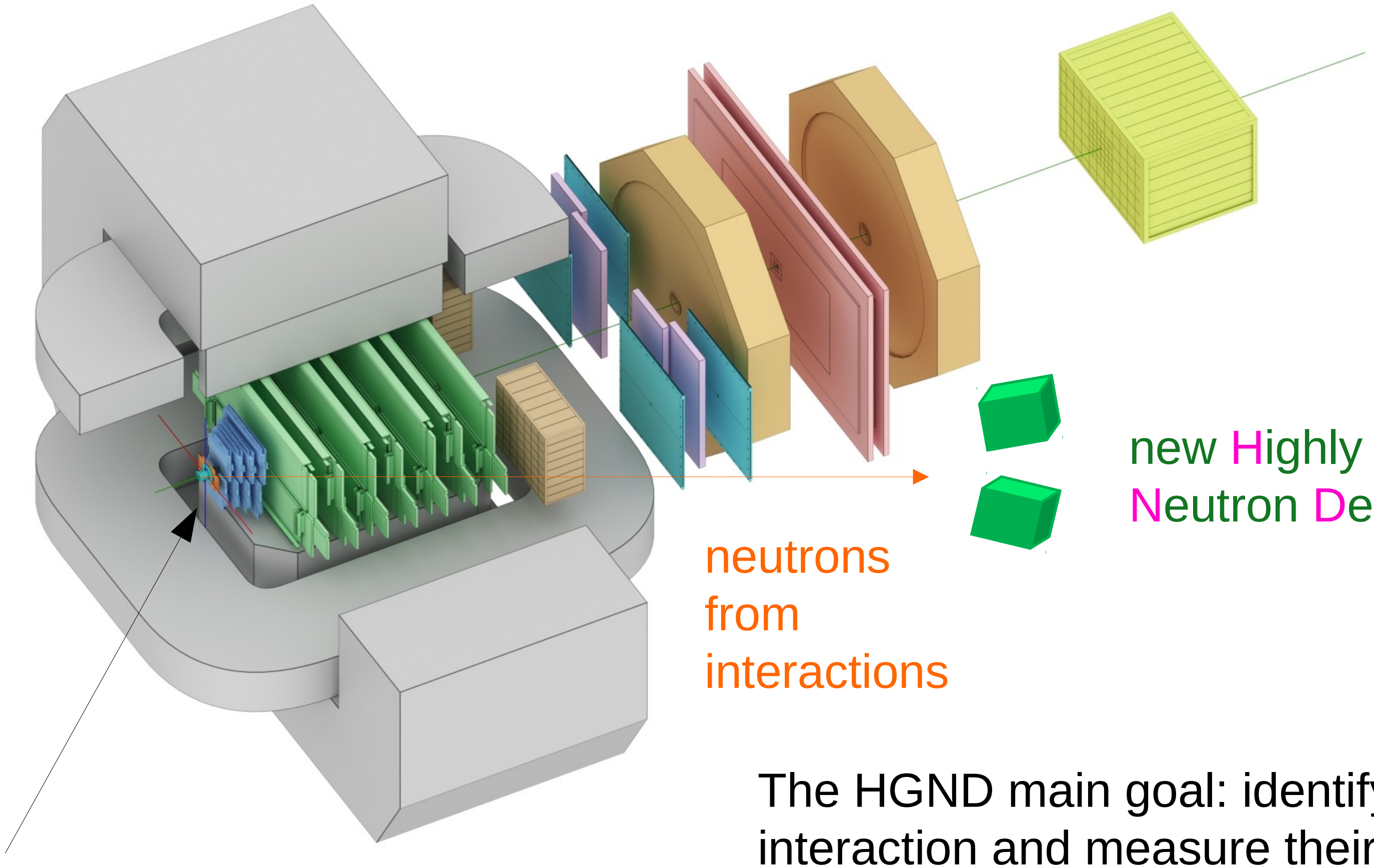
X.X. Long, G.F. Wei, Phys.Rev.C 109 (2024) 5, 054619

IBUU, Au+Au, 0.4A GeV



- n/p ratio requires less statistics than anisotropic flow measurements

New time-of-flight neutron detector for the BM@N experiment is under development and construction now



target

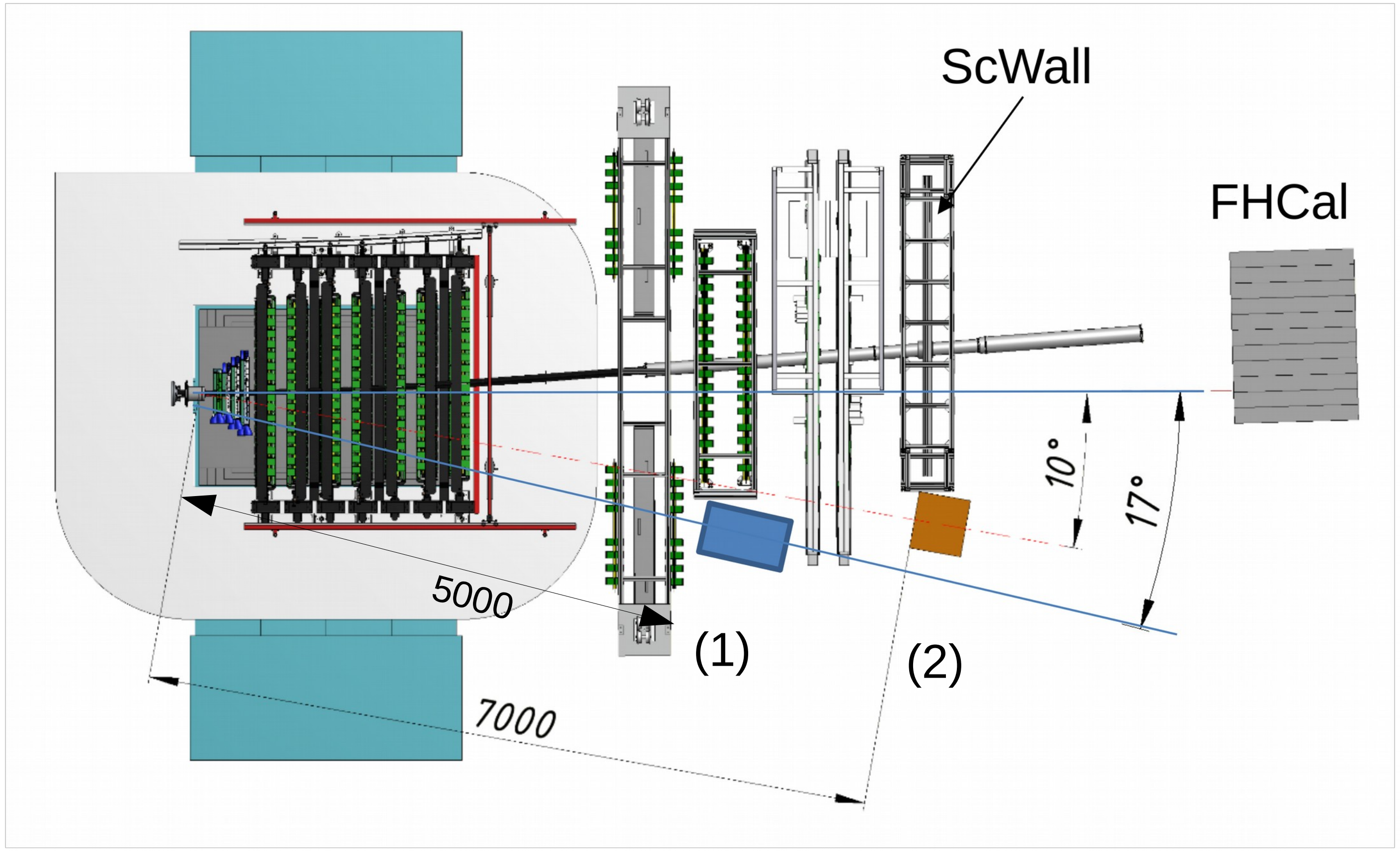
neutrons from interactions

new Highly Granular time-of-flight Neutron Detector (HGND)

The HGND main goal: identify neutrons from interaction and measure their energies

→ to study the symmetry energy of EoS

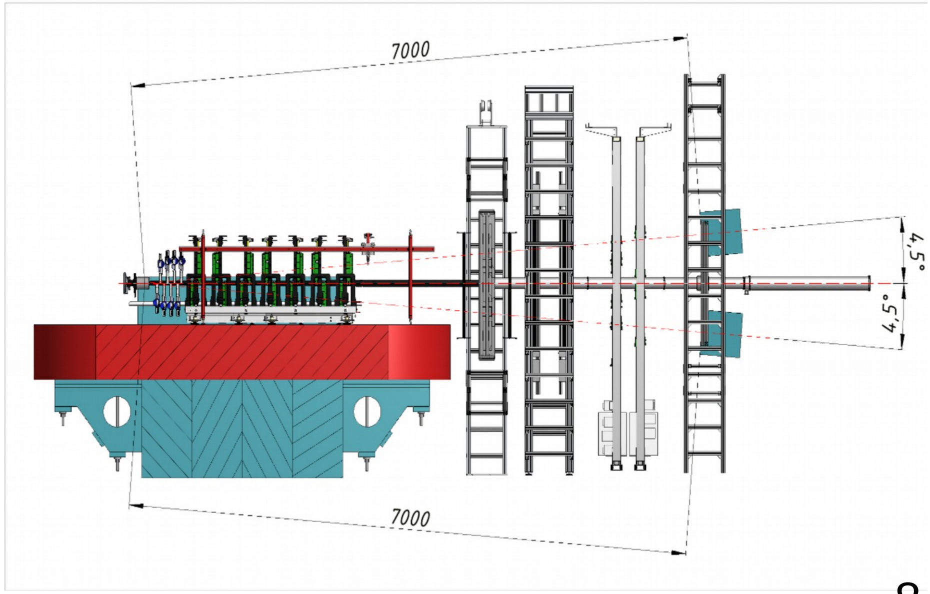
Positioning of the HGND at the BM@N experiment



1) previous proposed 16 layer (1 veto + 15 active Scint./absorber) HGND detector configuration in position (1) at 17 deg shows limited rapidity range for neutrons

2) in order to extend neutron rapidity range the new position (2) has been found at 10 deg but the distance is 7m from target now, resulting in lost of acceptance

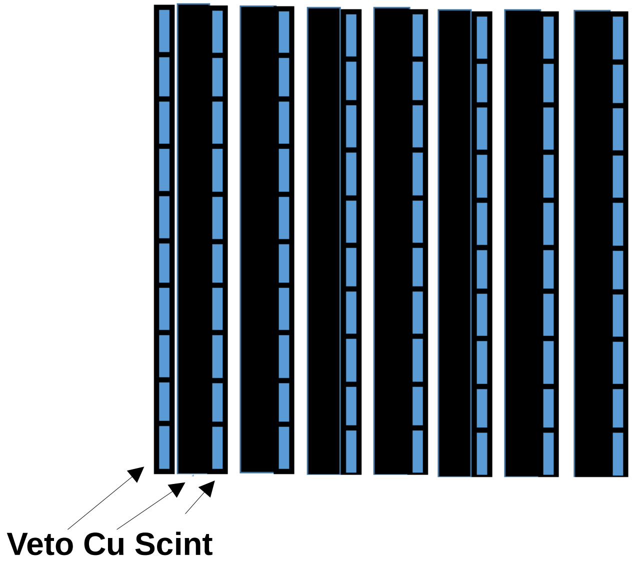
3) in order to keep the acceptance for neutrons the new system has been checked: two 8 layers (1 veto + 7 active Scint./absorber) detectors



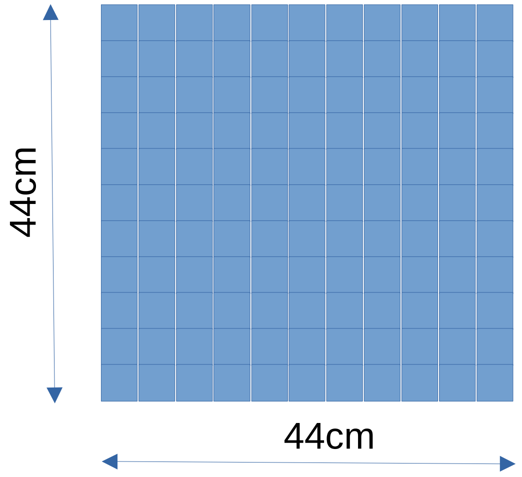
F. Guber, et al., Instrum. Exp. Tech. №3 (2024)

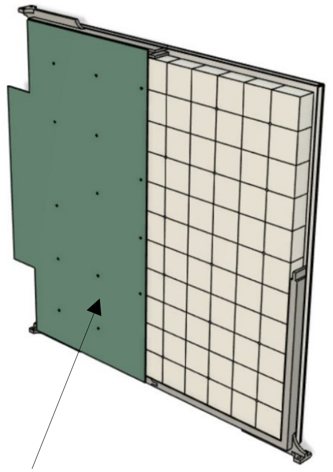
Highly Granular Neutron time-of-flight Detector (HGND) with SiPM readout

1 Veto + 7 Cu/Scint layers



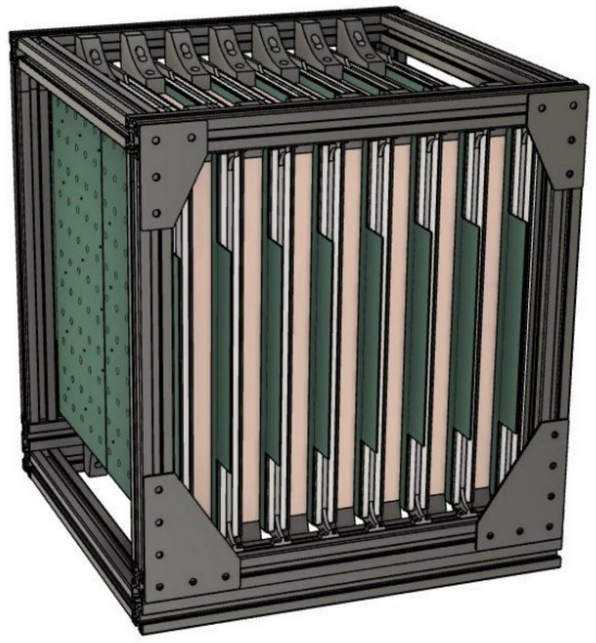
Structure of Scint. layer: array of 11x11 scintillator cells 4 x 4 cm^2





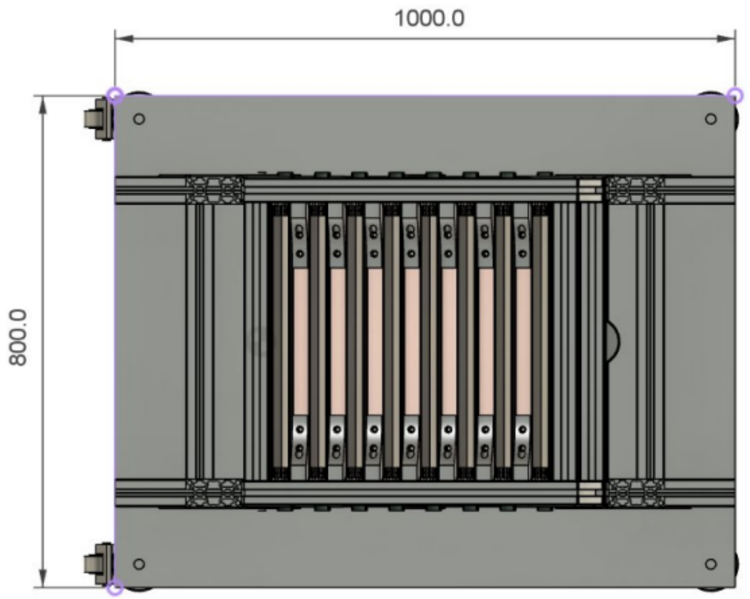
PCB (half) with Front-End-Electronics (FEE) components

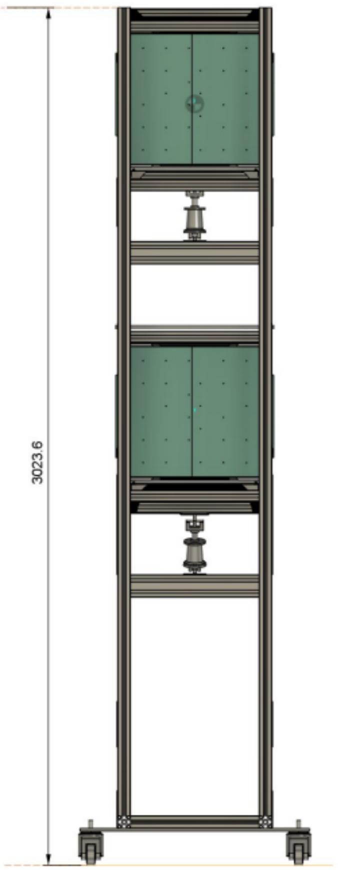
3D view of HGND module

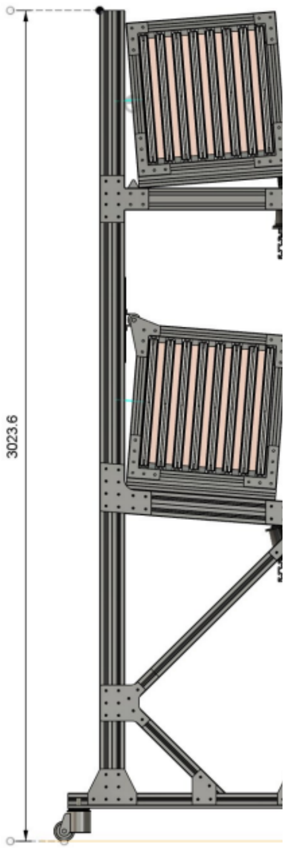


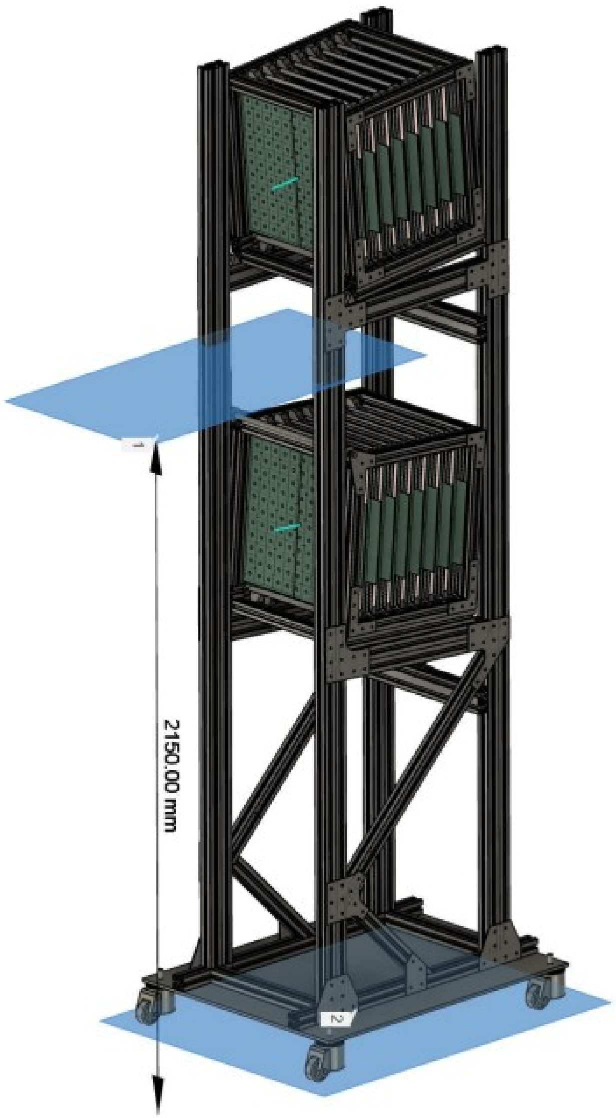
- **transverse size of one layer: 44 x 44 cm^2,**
- **number of layers: 7 with absorber + 1 Veto,**
- **structure of layer: 3 cm Cu (absorber) + 2.5cm Scint. + 0.5cm (SiPM+FEE)**
- **size of scintillation detectors (cells): 4x4x2.5 cm^3, 121 cells in each layer**
- **light readout: one SiPM with sensitive are 6 x 6 mm^2 per cell (EQR-15), measured time res. ~ 130ps**
- **total length of one HGND half-detector: ~ 48 cm (~1.5 λ_{in})**

HGND support structure







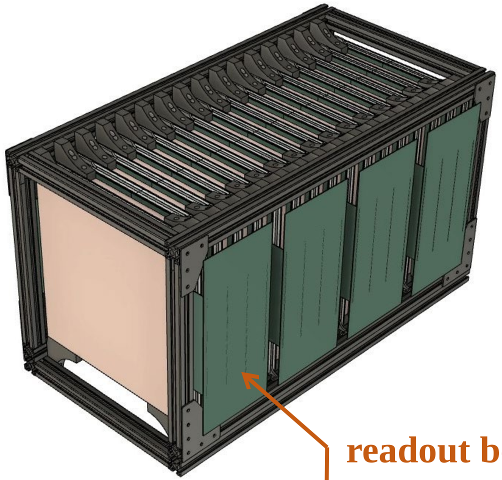


Support structure allow for:
- lateral movement of the detector
- height and angle adjustment
- adjustment of the distance between blocks

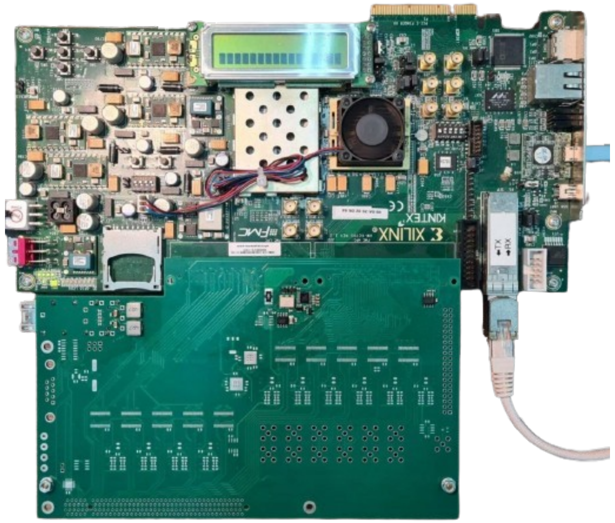
Total weight: ~800 kg

See presentation of A. Makhnev (today, 18:35) for details..

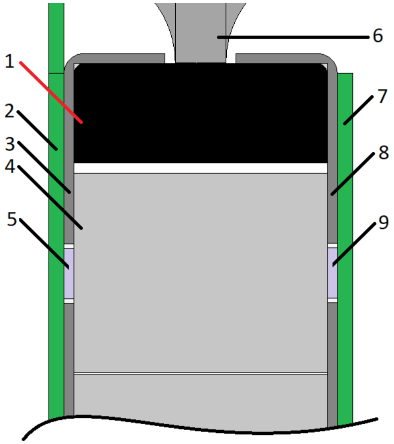
The HGND for the BM@N experiment



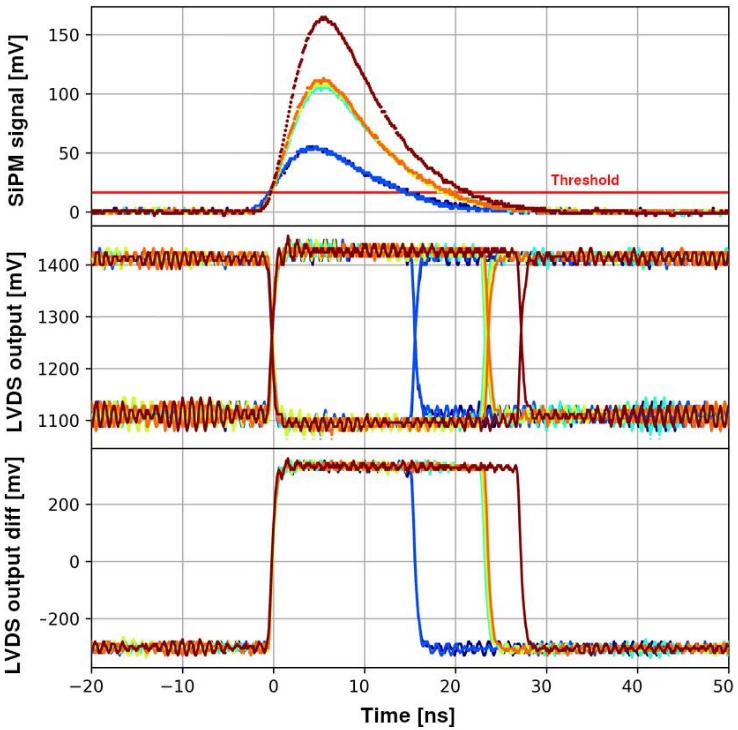
readout board



Readout board prototype based on Xilinx Kintex 7 Evaluation Board



1 – the frame of layer case
2 – SiPM PCB
3&8 – aluminum plates for both sides of the frame case with cutouts for SiPMs and LEDs
4 – scintillator
5 – SiPM
6 – layer support bracket
7 – LED PCB
9 – LED



Readout scheme

1. Plastic scintillator light flash
2. SiPM EQR15 11-6060D-S
3. High-speed comparator with differential LVDS output
4. FPGA-based TDC

= Response time + ToT

Per channel

- Dynamic range: 0.5-7 MIP
- Time resolution: 130 ps
- Amplitude resolution: < 20% (reconstructed from ToT)

F. Guber, et al., Instrum. Exp. Tech. 66 (2023) 4, 553-557.

D. Finogeev, et al., Nucl. Instrum. Meth. A 1059 (2024) 168952.

N. Karpushkin, et al., Nucl. Instrum. Meth. A 1068 (2024) 169739.

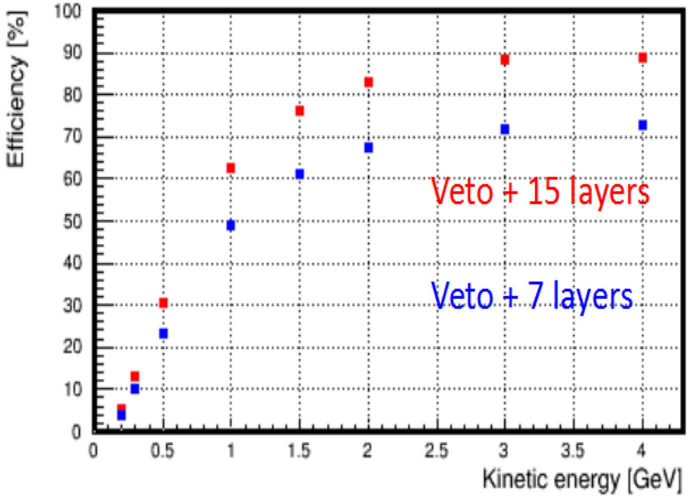
SiPM: Beijing NDL EQR15 11-6060D-S
- Active area 6×6 mm^2
- Pixel size15×15 μm^2
- Total pixels: 160 000
- PDE: 45%
- Gain: $4*10^5$

See presentation of D. Finogeev (today 18:45) for details..

Single neutrons detection efficiency for different kinetic energies on the HGND surface

Efficiency = 1 – Nevents without selected hits in HGND / Nevents

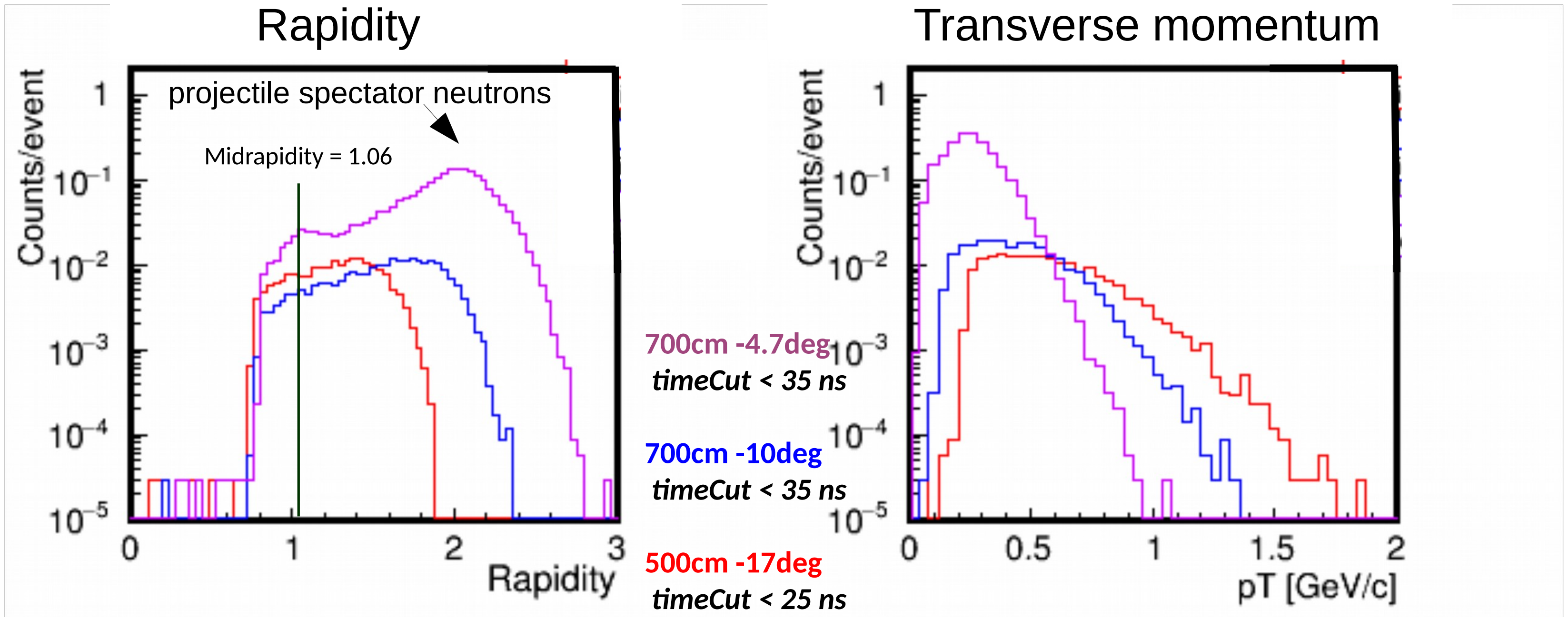
Hit selection: minimum 2 hits
with > 3 MeV (~1/2 MIP) signal



Comparison of primary neutrons rapidity and pT distributions on the HGND entrance surface for different positions of the HGND

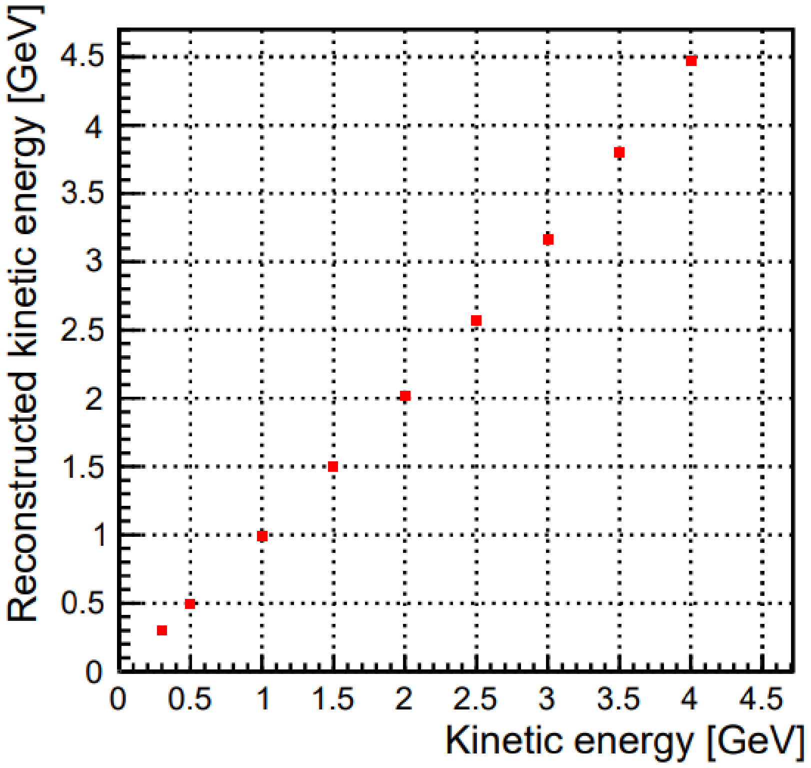
BiBi@3A GeV

DCM-QGSM-SMM

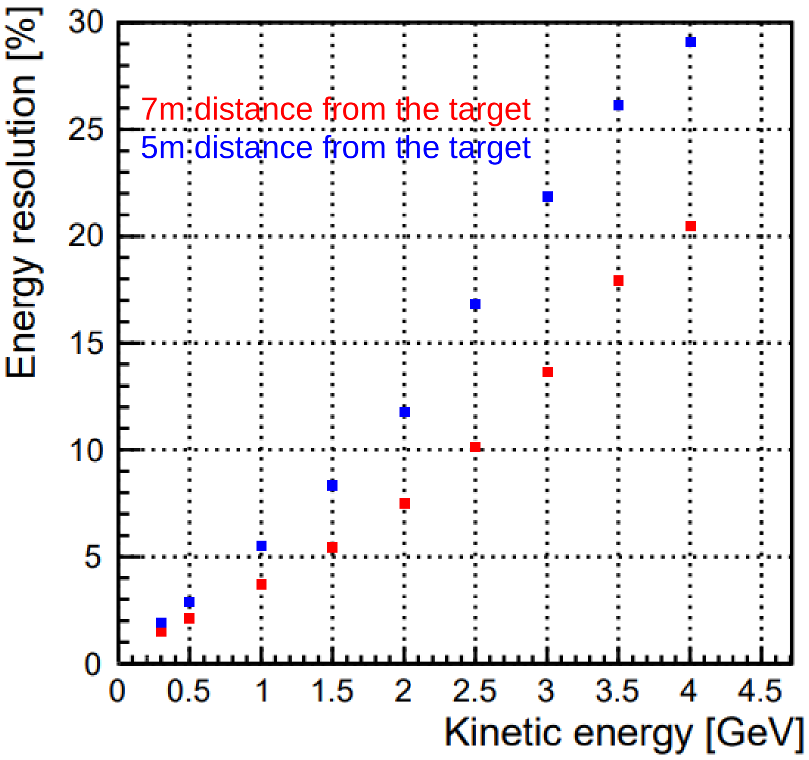


Reconstruction of neutron kinetic energy and energy resolution

Reconstructed kinetic energy



Reconstructed energy resolution



Experimentally measured time resolution of the HGND scintillation cell ~ 130ps has been applied

BiBi@3A GeV

DCM-QGSM-SMM

ToF vs kinetic energy of different type of particles at the HGND 700cm, 10 deg -4.5 deg

At nDet entrance

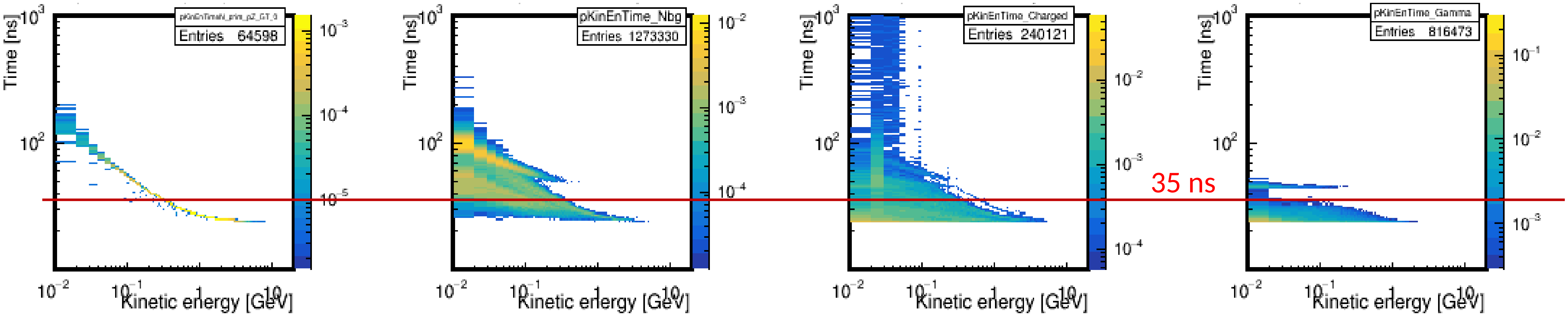
Around all nDet surfaces

Primary neutrons

Bg neutrons

Charged particles

Gamma



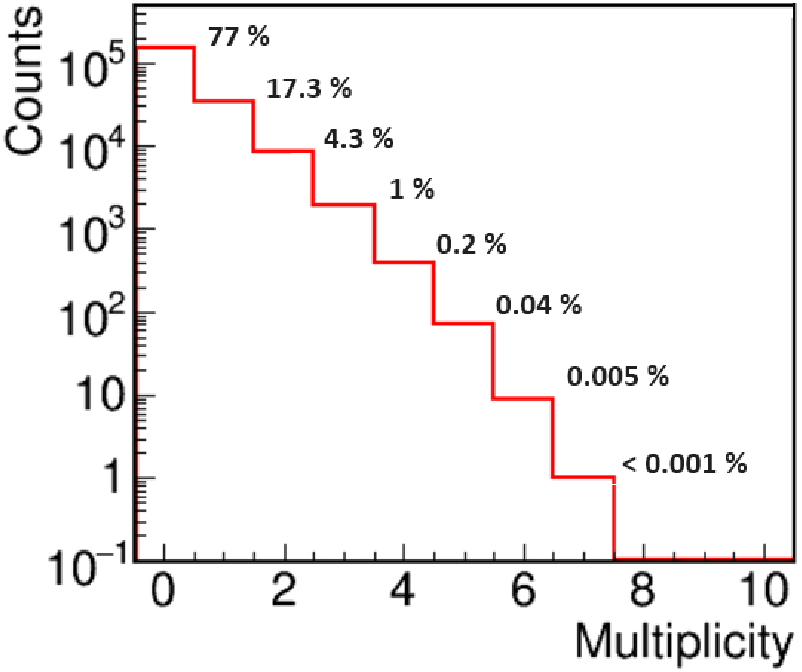
Selecting ToF < 35 ns rejects:

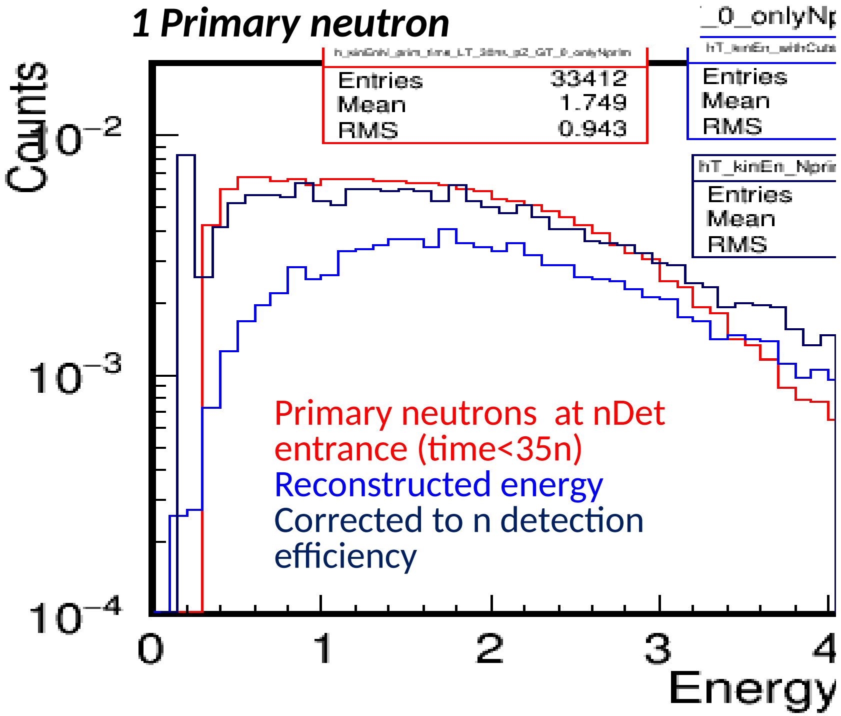
background neutrons - 77%
primary neutrons - 8%
Measuring the primary neutrons with energies $\gtrsim$**300MeV**

number of registered primary neutrons at the HGND

BiBi@3A GeV

DCM-QGSM-SMM





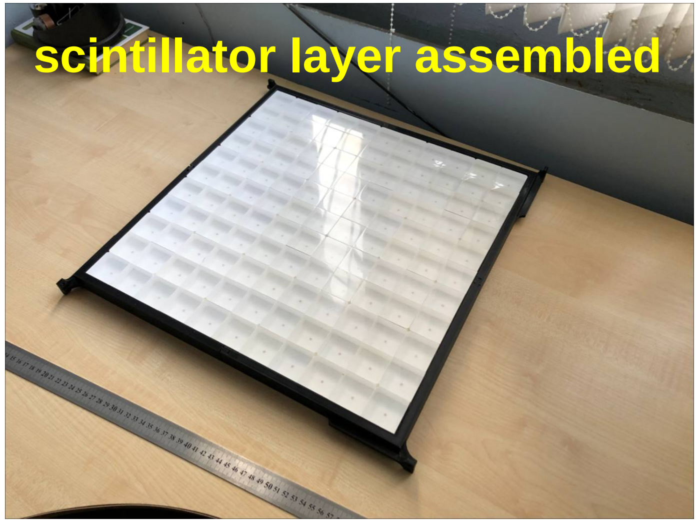
During **1 month** of the BM@N run ~ **$1.2*10^9$** *single* primary neutrons with kinetic energy > 300 MeV can be collected with 2 x HGNDs

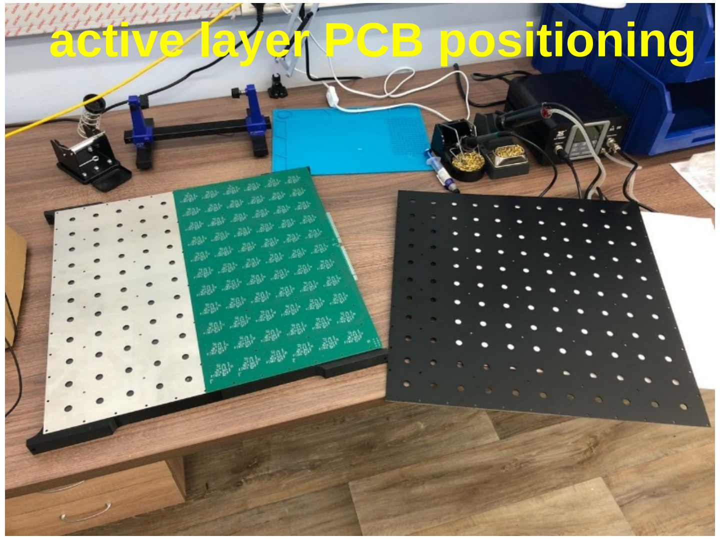
Upper limit is **$1.5 * 10^9$** neutrons (additional multi-neutron event recognition is required).

- Neutron energy in events with only one primary neutron can be correctly reconstructed by determining fastest time in the HGND cells.

- Neutron energy reconstruction for events with more than 1 neutron in events requires development of more sophisticated methods of energy reconstruction.

Status and steps of the HGND construction


scintillator layer assembled


active layer PCB positioning


The HGND support frame assembled for tests at INR


copper absorber layers delivered fron JINR


The HGND mock-up assembled at INR

Conclusions:

- new HGND detector has been proposed for the BM@N experiment at Nuclotron
- the performance study of the 2-arms HGND is done based on BiBi 3A GeV simulations
- neutron resonstruction algorythms (cluster, ML) is under development (A. Shabanov, V. Bocharnikov)
- construction of the HGND is ongoing (see presentation of A. Makhnev)
- FPGA based tdc electronics is under development now (see presentation of D. Finogeev)

Outlook:

- the HGND is planned to be ready next year (2025)

Members of HGND development group:

INR RAS: D. Finogeev, M. Golubeva, F. Guber, A. Izvestnyy, N. Karpuskin, A. Makhnev, S. Morozov, P. Parfenov,
I. Pshenichnov, S. Savenkov, D. Serebryakov, A. Shabanov, A. Svetlichnyi, V.Volkov, A. Zubankov
JINR: S. Afanasiev, D. Sakulin, E. Sukhov, V. Ustivov,
Kurchatov Institute NRC: P. Alexeev, A. Martemianov, A. Stavinsky, G. Taer, N. Zhigareva
HSE: V. Bocharnikov, F. Ratnikov

Thank you for your attention!

Backup

Measurements of time resolution of scintillation detectors (scint + SiPM)

F.Guber et.al., Instruments and Experimental Techniques, 2023, Vol. 66, No. 4, pp. 553–557
(JINR + Hamamatsu, SensL photodetectors)
F.Guber et.al., arXiv:2309.03614v1 [hep-ex] 7 Sep 2023 (JINR, EJ230 scint. + EQR photodetector)

Photodetector:
EQR15 11-6060D-S
(sensitive area - 6x6 mm^2, 15mkm pixel pitch, 160 000 pixels, PDE - 45%, gain - 4x10^5)

Test results on e-beam at LPI

Scintillator:

1) JINR produced (40x40x25mm^3), 1.5% paraterphenyl and 0.01% POPOP) with light time decay of 3.9 ± 0.7 ns → σ ~117 ps, N ph.el. = 158 ± 9

2) EJ230 with light time decay of 2.8 ± 0.5 ns → σ ~ 74 ps, N ph.el. = 292 ± 2

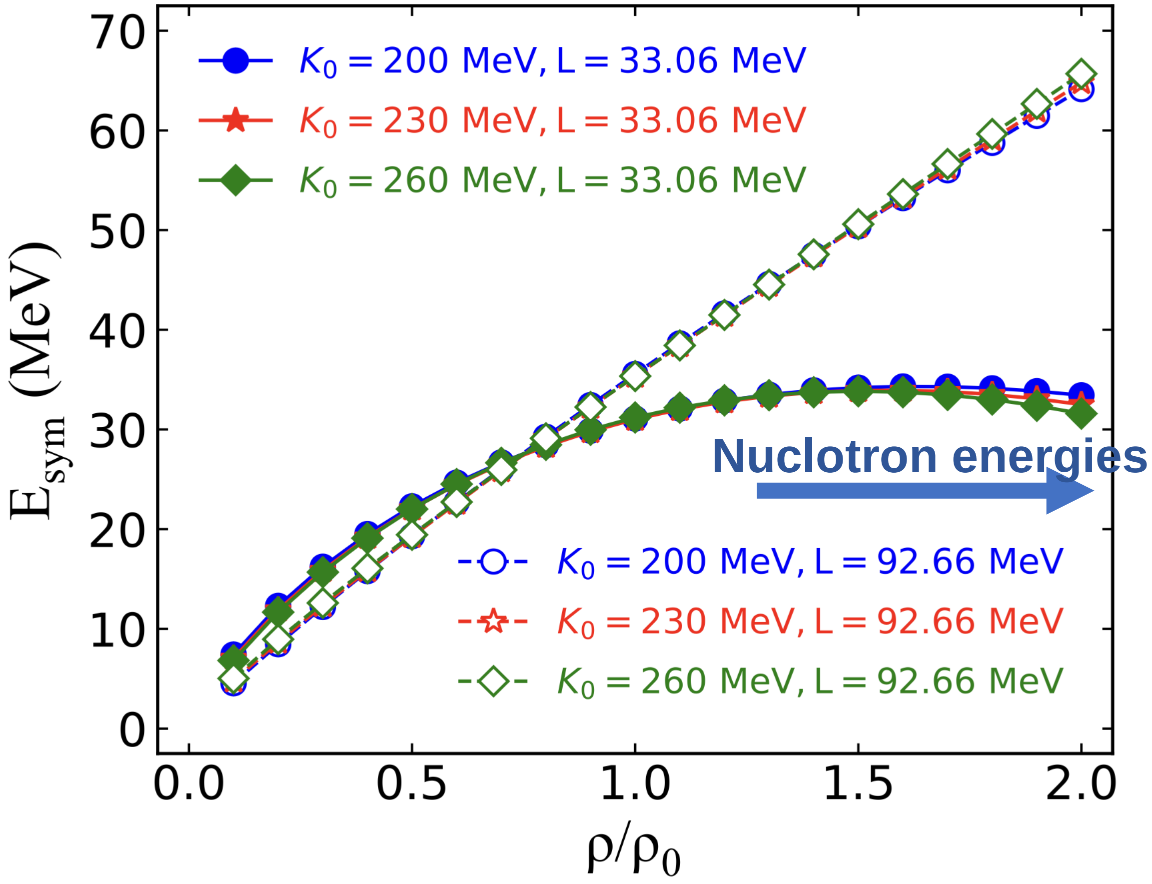
FEE: LMH6629MF preamp (20 dB gain, bandwidth of 600 MHz at a 3 dB level, and noise of <2.2 nV/√Hz) + rapid discriminator (ADCMP553) with a fixed threshold.

Readout: CAEN DT5742

JINR scintillators will be used for the HGN detector because they are available and significantly cheaper than EJ230.

Symmetry energy in high-density region

X.X. Long, G.F. Wei, Phys.Rev.C 109 (2024) 5, 054619



- Nuclotron-NICA density region:
  $$2 \lesssim n_B/n_0 \lesssim 8$$
- Symmetry energy E_{sym} has strong density dependence and can be described with its slope L:
  $$L = 3\rho \frac{dE_{sym}(\rho)}{d\rho}$$

What observables can we use to extract information about *L*?

BiBi@3A GeV

DCM-QGSM-SMM

Estimation of primary neutrons count rate at BiBi@3 AGeV run

Beam rate - 10^6 per spill,
Duty factor of the beam - 50%
Efficiency of accelerator operation – 70%

Target interaction length - 2%,
Mean primary neutron yield:
  0.17 (single) - 0.23 (all) neutron / interaction
Mean efficiency of the HGND detector - 50%

During **1 month** of the BM@N run ~ **$1.2*10^9$** *single* primary neutrons with kinetic energy > 300 MeV can be collected with 2 x HGNDs

Upper limit is **$1.5 * 10^9$** neutrons (additional multi-neutron event recognition is required).

nDet:
780 cm, 44x44 cm, 121 mods, 4x4 cm, 100000 ev., **w/o magnetic field, 45.8 cm**
PLA 0.2cm + **Veto** 2.5 cm + PCB 0.2cm + PLA 0.2cm +
7 layers (**Cu** 3 cm + PLA 0.2cm + **Sc** 2.5 cm + PCB 0.2cm + PLA 0.2cm)
Time cut in nDet: time < **55** nsec (in simulations)
Vac. in cave, **BOX generator, neutrons huge spot, multiplicity=1**

Neutrons reconstructed kinetic energy (**Cu absorbers**)

Kinetic energy is reconstructed with hit ***with min Time***
With Veto

Corrected module geometry

Edep > 3 MeV in cells
>1 hit in nDet
Time resol 150 ps

Neutrons kinetic energy [GeV]: