The Highly Granular Neutron Detector (HGND) for the BM@N Experiment

Sergey Morozov, INR RAS, Moscow

Supported by RSF grant No. 22-12-00132

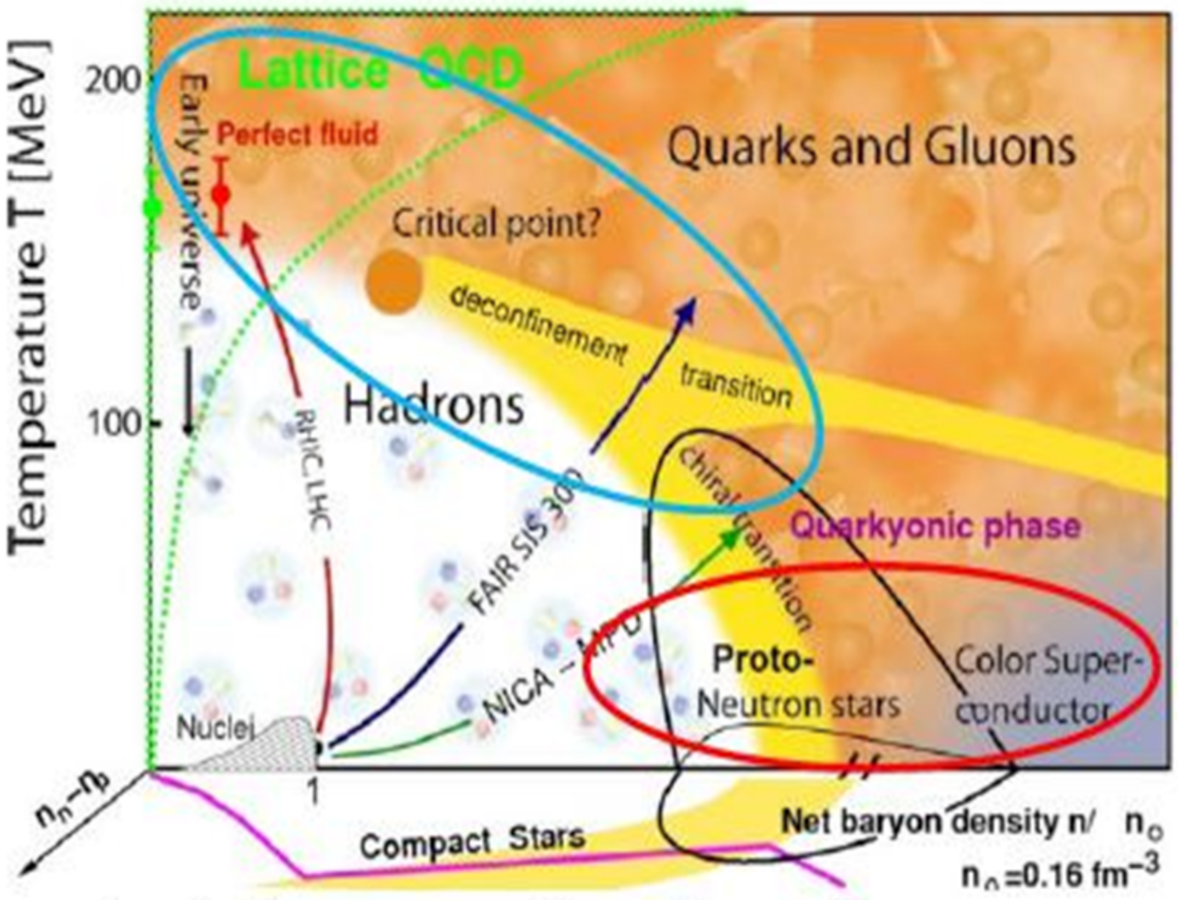
LXXIV International conference Nucleus-2024:
Fundamental problems and applications

1–5 Jul 2024 Dubna, Russia

Outline:

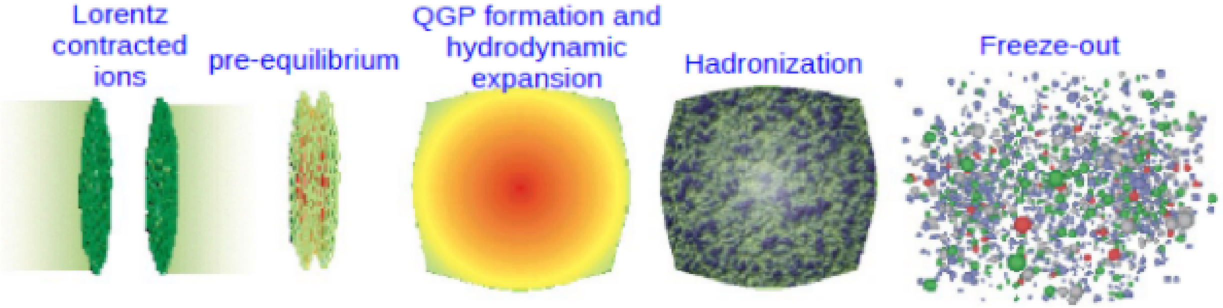
- Physics motivation of measuring the neutrons in heavy-ion collision experiments
- The BM@N experiment and new Highly Granular Neutron Detector (HGND)
- Performance studies for HGND optimization
- Current status of HGND construction

QCD Phase Diagram of the Strongly-Interacting Matter



Top RHIC/LHC: validation of the crossover transition leading to the sQGP

RHIC-BES/NICA/Nuclotron: search for the first-order phase transition and onset of the critical point



Relativistic heavy ion collisions allow us to study different regions of the QCD phase diagram

- **Top RHIC/LHC energies:** access to high T and small μ_B
- **RHIC-BES/SPS/NICA/Nuclotron:** access to different systems and a broad domain of the (T, μ_B)-plane
  - Equation of state (EOS)
  - Speed of sound (c_s)
  - Specific shear viscosity (η/s)
  - Specific bulk viscosity (ζ/s)
  - etc

EOS for high baryon density matter

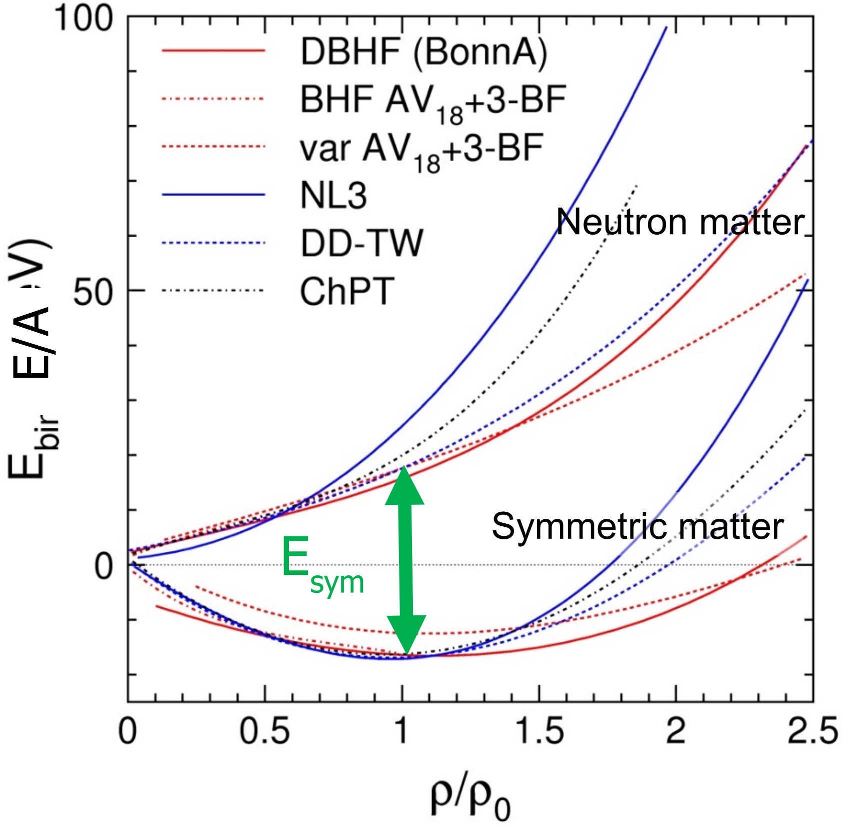
The binding energy per nucleon: $E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

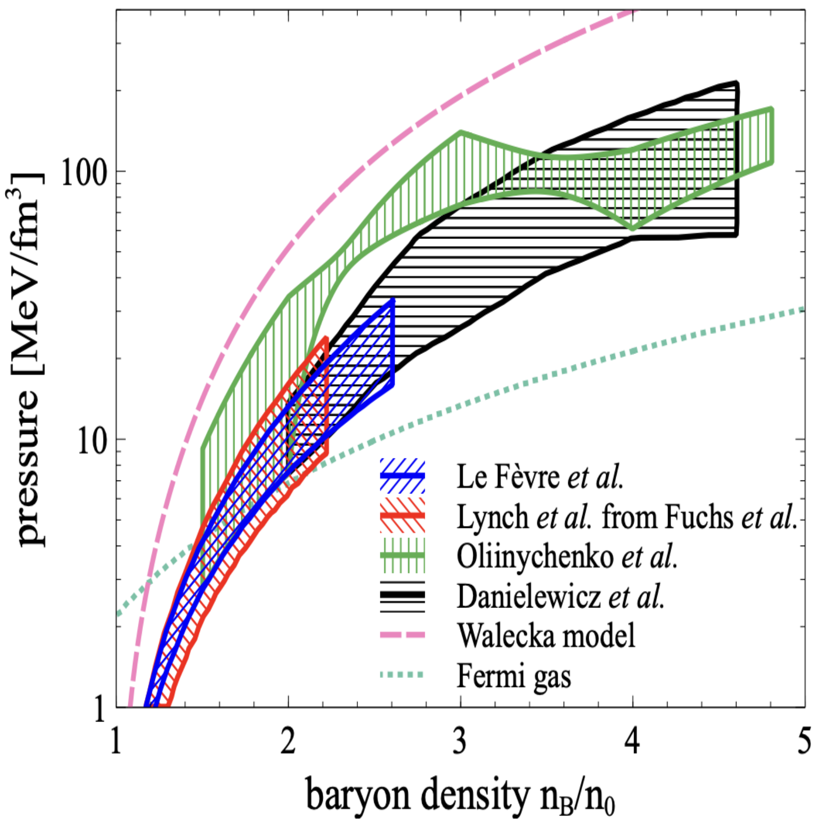
Isospin asymmetry:

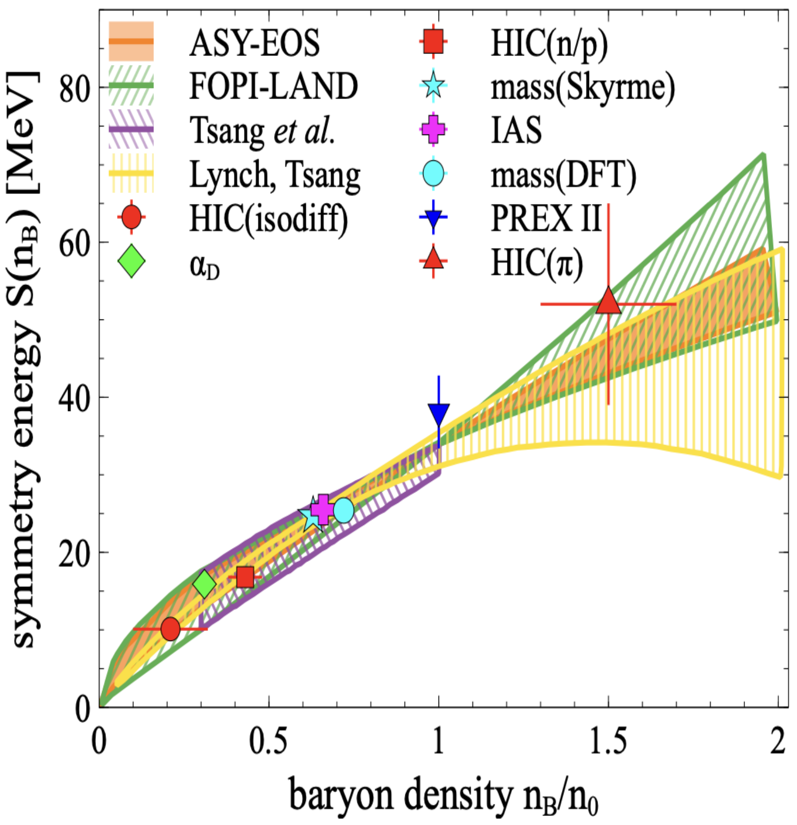
$\delta = (\rho_n - \rho_p)/\rho$

Symmetric matter

Symmetry energy







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

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

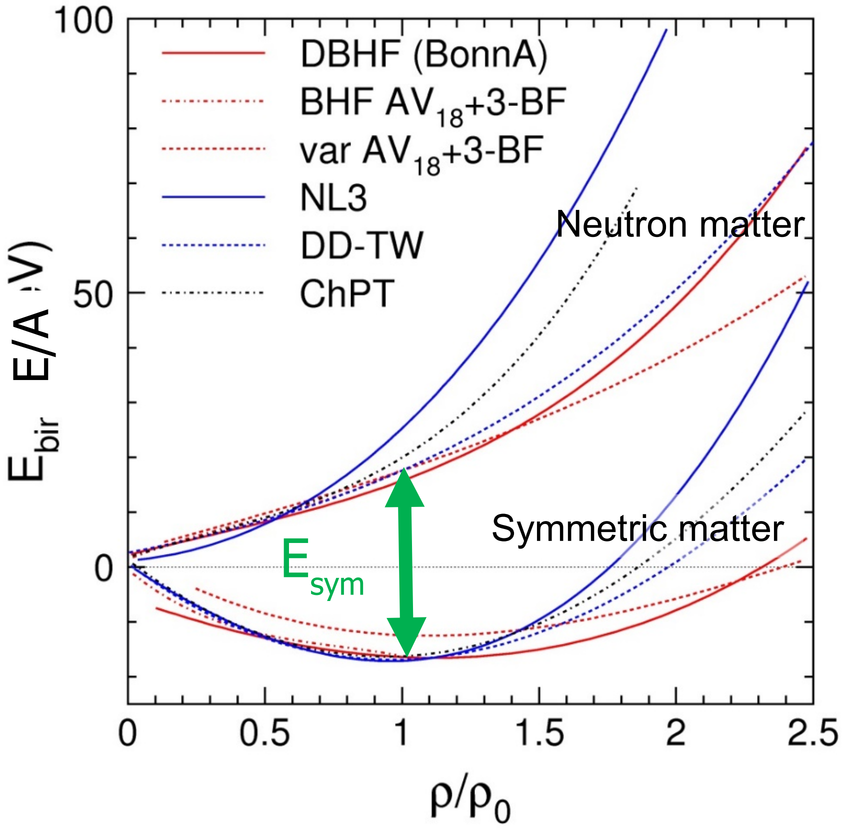
New data is needed to further constrain transport models with hadronic d.o.f.

EOS for high baryon density matter

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

Isospin asymmetry:

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



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

Symmetric matter

- Being extensively studied nowadays
- Using observables (flow, meson yields, etc.) to find incompressibility $K_0 = 9\rho^2 \frac{\partial^2(E_A)}{\partial\rho^2}$
- One of the main sources of uncertainty: discrepancy between experimental data

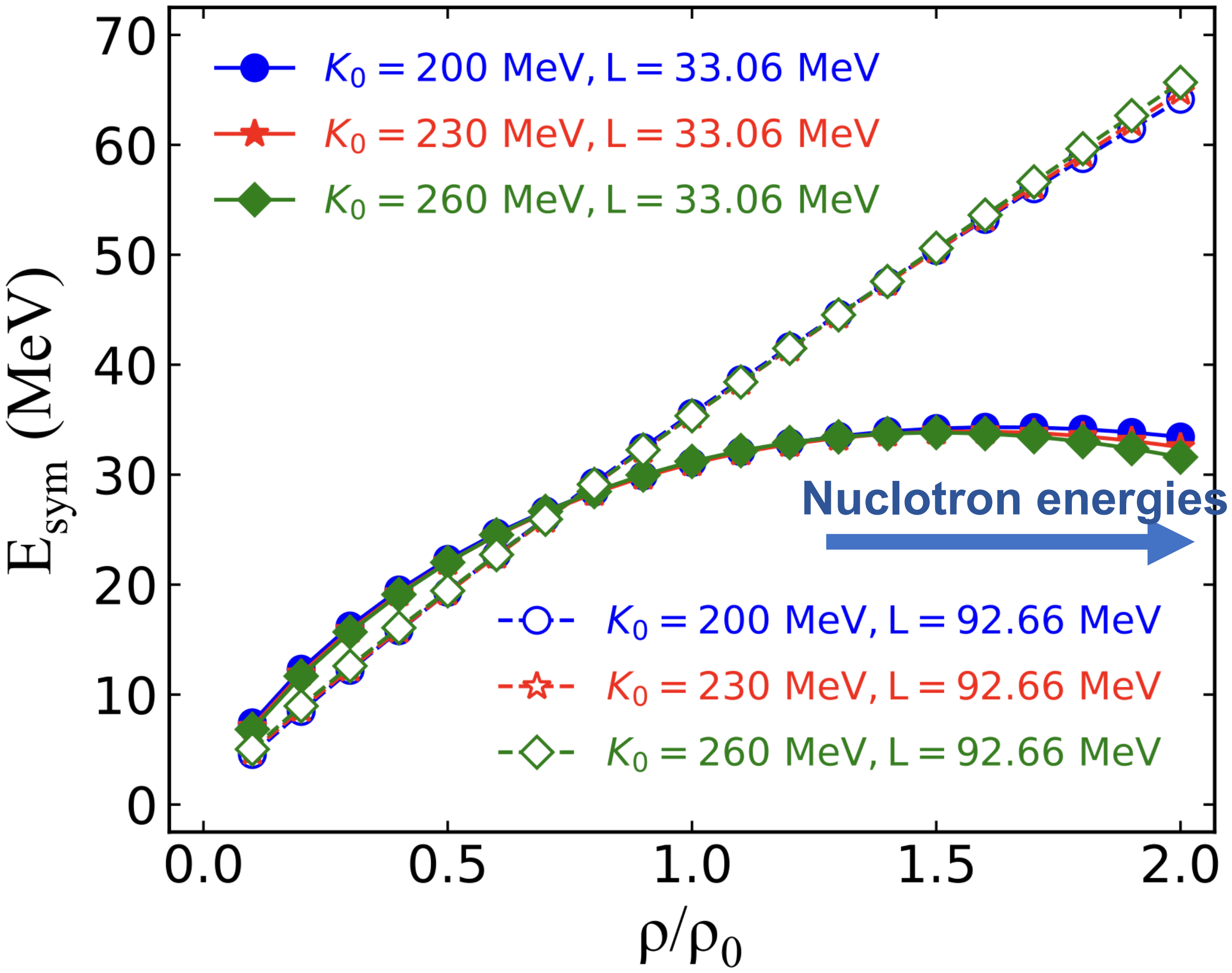
Symmetry energy

- No experimental data for beam energies $\sqrt{s_{NN}}$>0.8 GeV
- One of the main parameter to study is the E_{sym} slope $L = 3\rho\frac{dE_{sym}(\rho)}{d\rho}$
- One needs to establish observables sensitive to L and obtain new experimental data

New data is needed to further constrain transport models with hadronic d.o.f.

Symmetry energy in high-density region

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



- Nuclotron-NICA density region:

$$2 \lesssim n_B/n_0 \lesssim 8$$

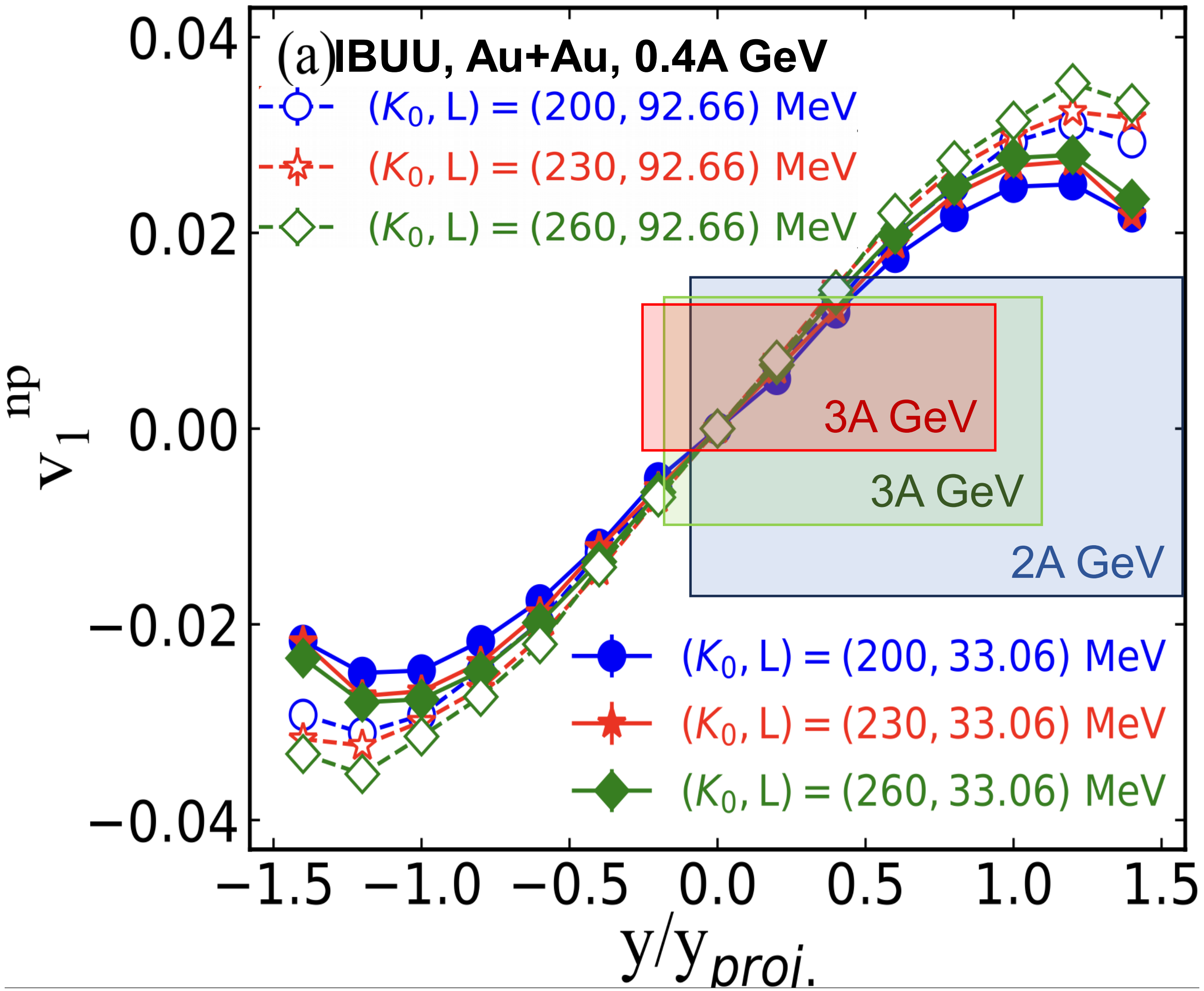
- Symmetry energy E_{sym} has strong density dependence and can be described with its slope L:

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

What observables can we use to extract information about L?

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:

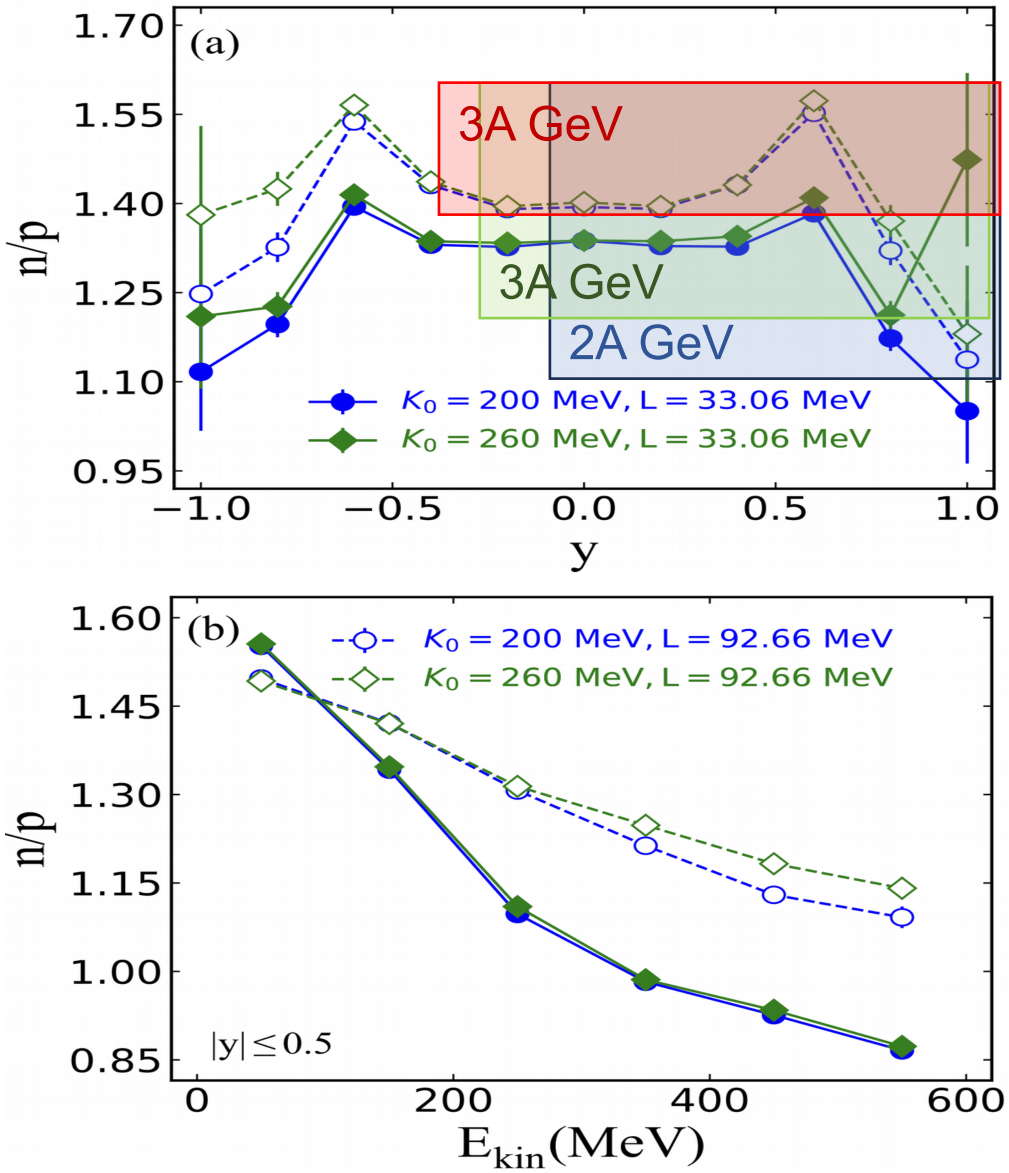
$$v_1^{np} = \frac{N_n(y)}{N(y)}\langle v_1^n(y)\rangle - \frac{N_p(y)}{N(y)}\langle v_1^p(y)\rangle$$

$N_n(y), N_p(y), N(y)$ - 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

Using $dN/dy\,(n,p)$, $dN/dE_{kin}(n,p)$ to study L



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

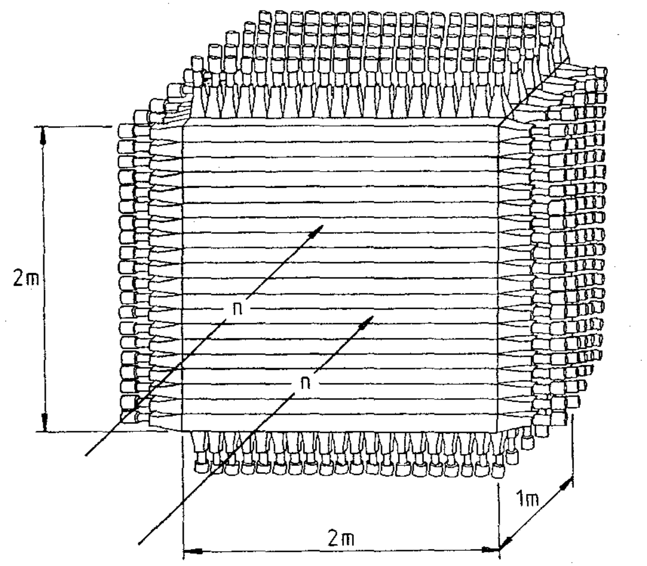
Rapidity and kinetic energy distributions of n/p ratios can be used to study L

- n/p ratios show strong dependence on L and significantly weaker dependence on K_0
- n/p ratios require less statistics than anisotropic flow measurements

Neutron measurements are required in order to extract robust information about symmetry energy

LAND - a TOF neutron spectrometer (constructed in 1990).

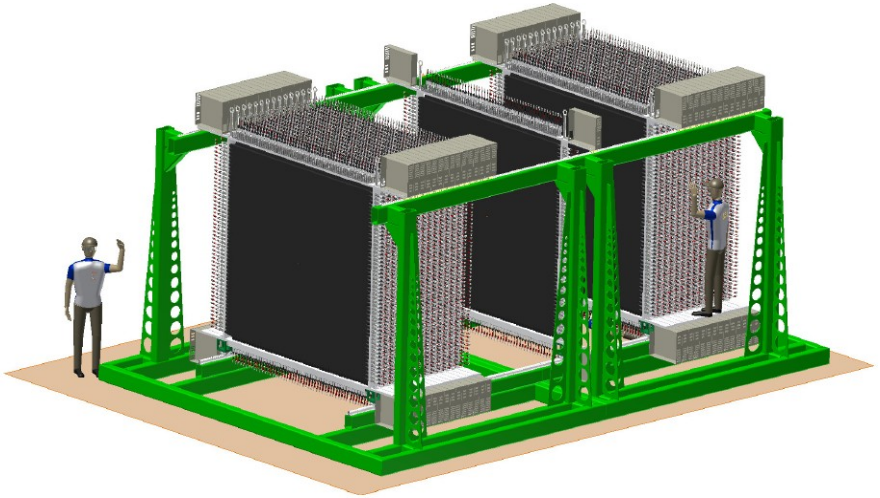
T. Blaich, et al., NIM. A 314 (1992) 136.



- total volume 2.0x2.0x1 m^3
  200 modules (plastic scint/Fe bars 200x10x10 cm^3
- 10 mutually perpendicular planes with 20 bars in each,
- two PMT for each bar readout (400 readout channels)
- $\sigma_t \approx 250$ ps,
- $\sigma_{x,y,z} \leq 3$ cm
- one-neutron efficiency > 80% for energies > 400 MeV
- without 1,2,3H isotopic discriminations

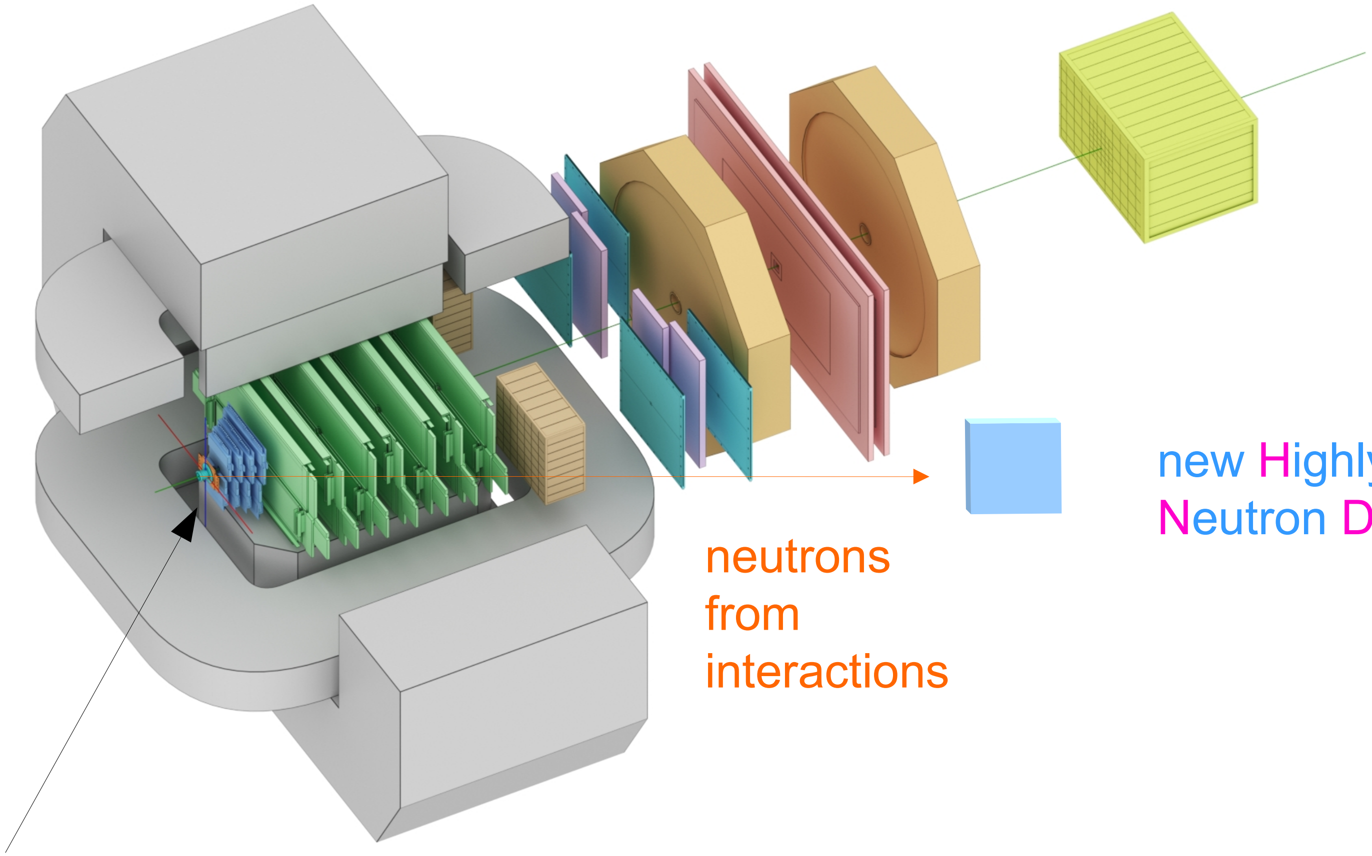
NeuLAND

K.Boretzky et al., NIM, A 1014 (2021) 1



- total volume 2.5x2.5x3 m^3
  3000 modules (plastic scintillator bars (w/o Fe) 250x5x5 cm^3
- 30 double planes mutually perpendicular with 100 bars each
- two PMT for each bar readout (6000 readout channels)
- $\sigma_t \leq 150$ ps
- $\sigma_{x,y,z} \leq 1.5$ cm
- one-neutron efficiency ~95% for energies 200-1000 MeV,

New proposed time-of-flight neutron detector for the BM@N experiment



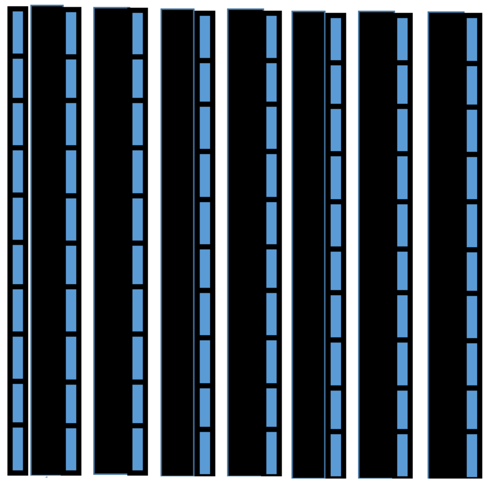
New detector of neutrons allows to measure at first time the energy range of neutrons 0.5 – 4 GeV in heavy-ion collisions

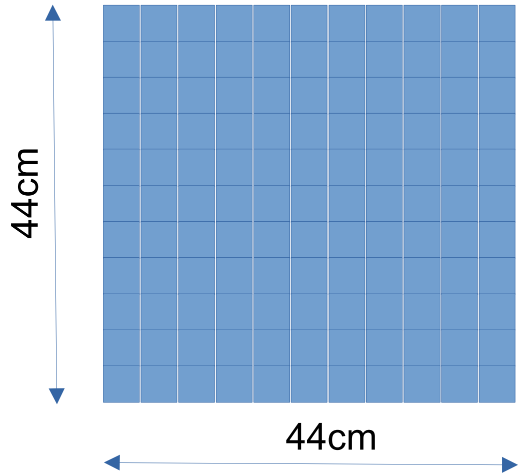
new Highly Granular time-of-flight Neutron Detector (HGND)

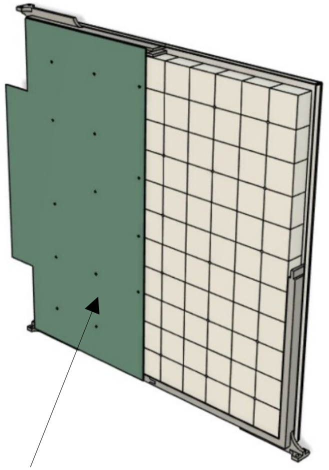
target

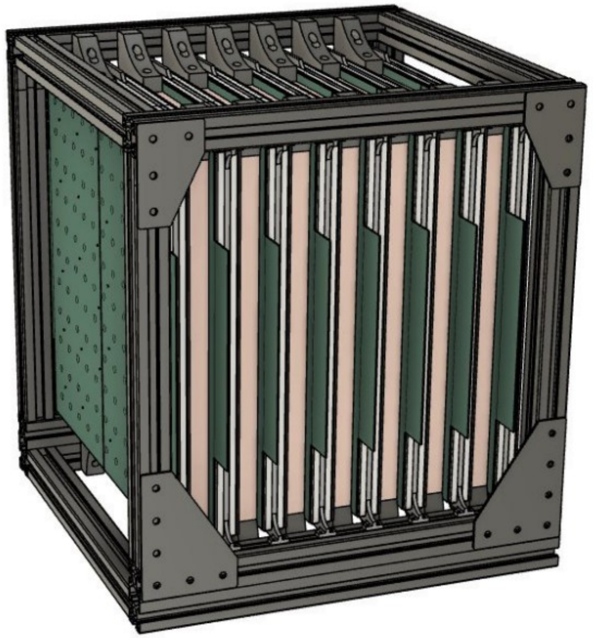
- proton flow can be measured with particle identification at magnet spectrometer
- to measure neutron flow new neutron detector is needed to be developed and constructed

Conception of neutron detector for the BM@N (neutron energies 0.3 – 4 GeV): High Granular Neutron time-of-flight Detector (HGND) with SiPM readout



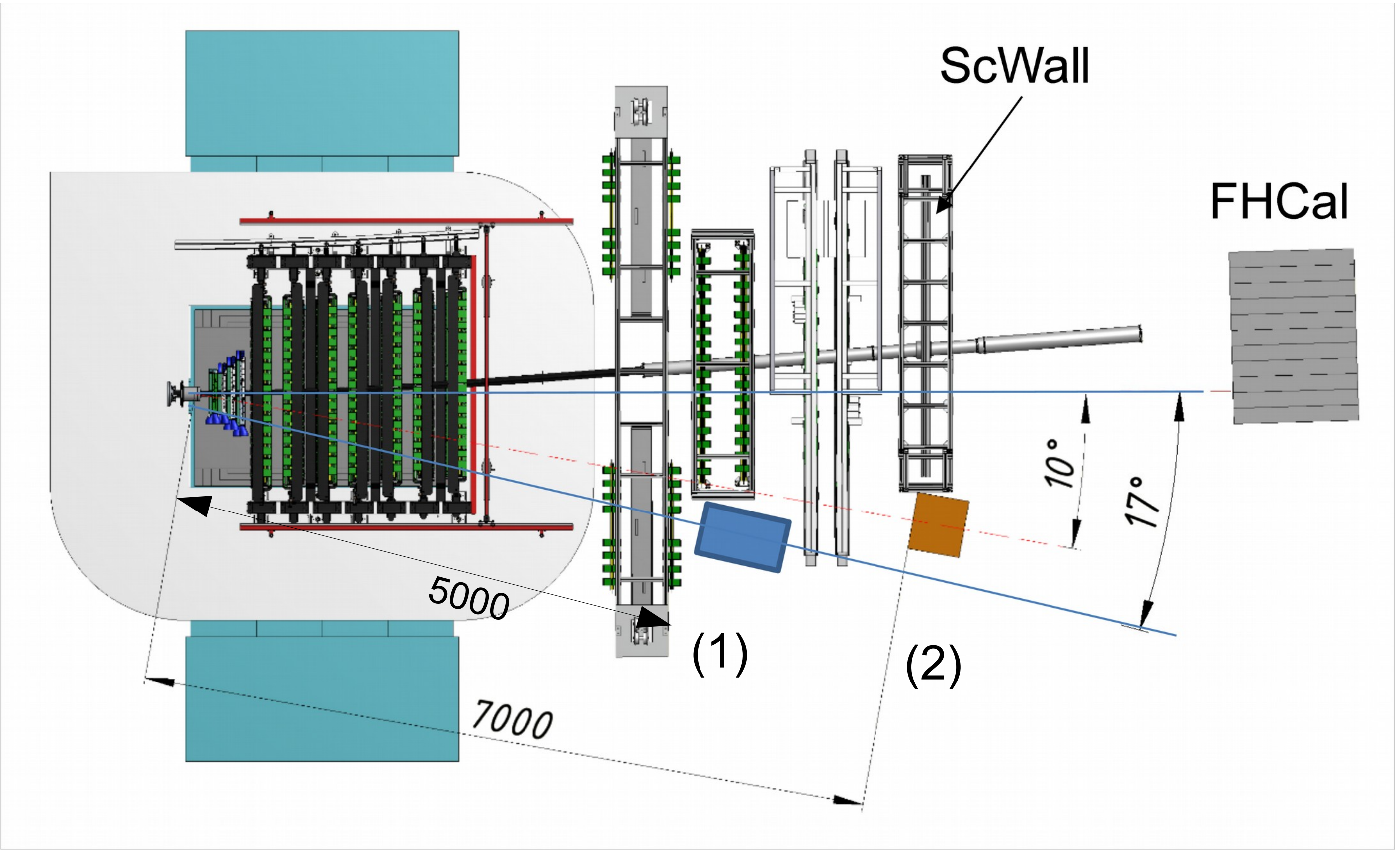






- **transverse size of one layer: 44 x 44 cm^2,**
- **number of layers: 7 with absorber + 1 Veto,**
- **structure of layer: 3 cm Cu (absorber) + 2.5cm Scint. + 0.5cm (SiPM+FEE)**
- **size of scintillation detectors (cells): 4x4x2.5 cm^3, 121 cells in each layer**
- **light readout: one SiPM with sensitive are 6 x 6 mm^2 per cell (EQR-15), measured time res. ~ 120ps**
- **total length of one HGND half-detector: ~ 48 cm (~1.5 λ_{in})**

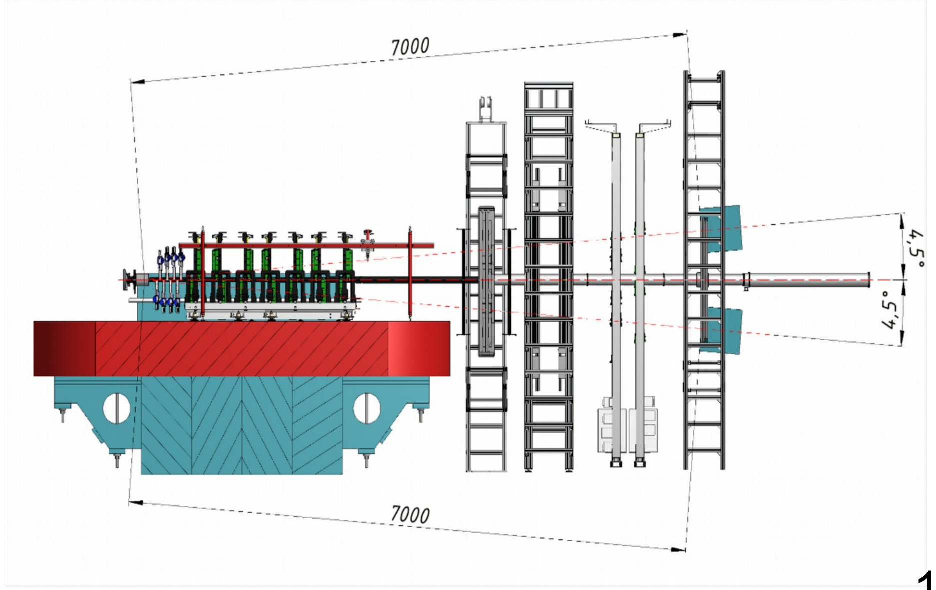
Positioning of the time-of-flight neutron detector at the BM@N experiment



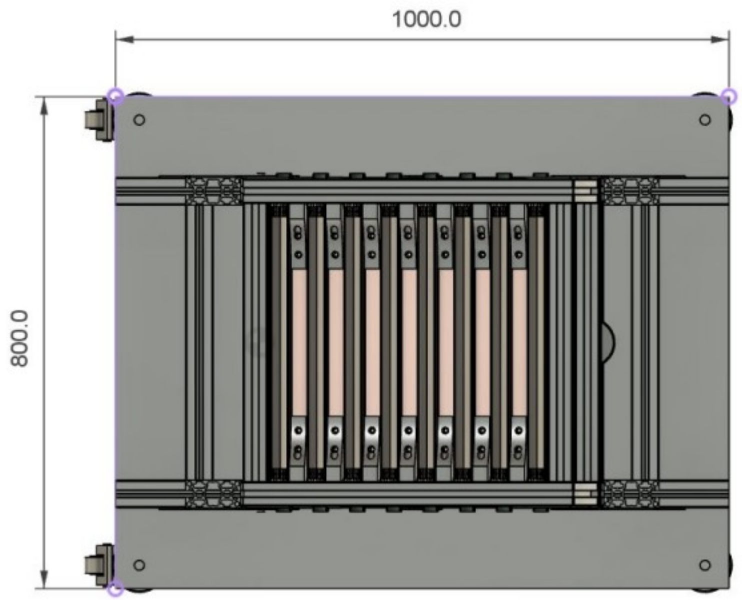
1) previous proposed 16 layer (1 veto + 15 active Scint./absorber) HGND detector configuration in position (1) at 17 deg shows limited rapidity range for neutrons

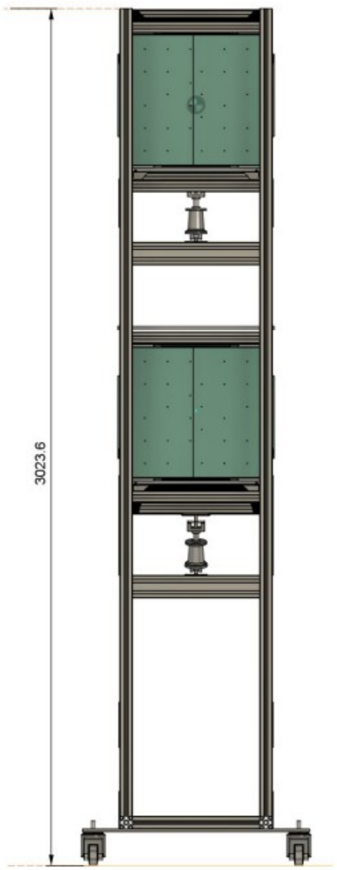
2) in order to extend neutron rapidity range the new position (2) has been found at 10 deg but the distance is 7m from target now, resulting in lost of acceptance

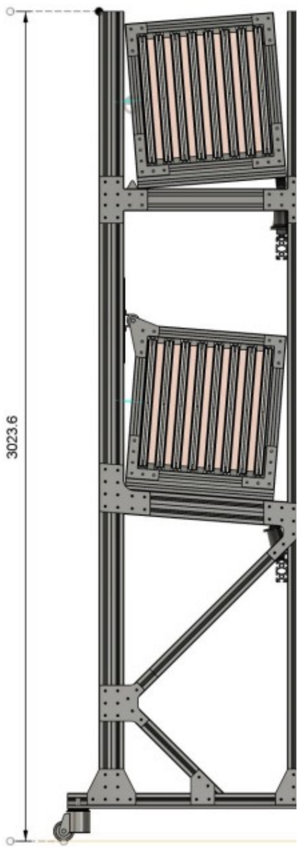
3) in order to keep the acceptance for neutrons the new system has been checked: two 8 layers (1 veto + 7 active Scint./absorber) detectors

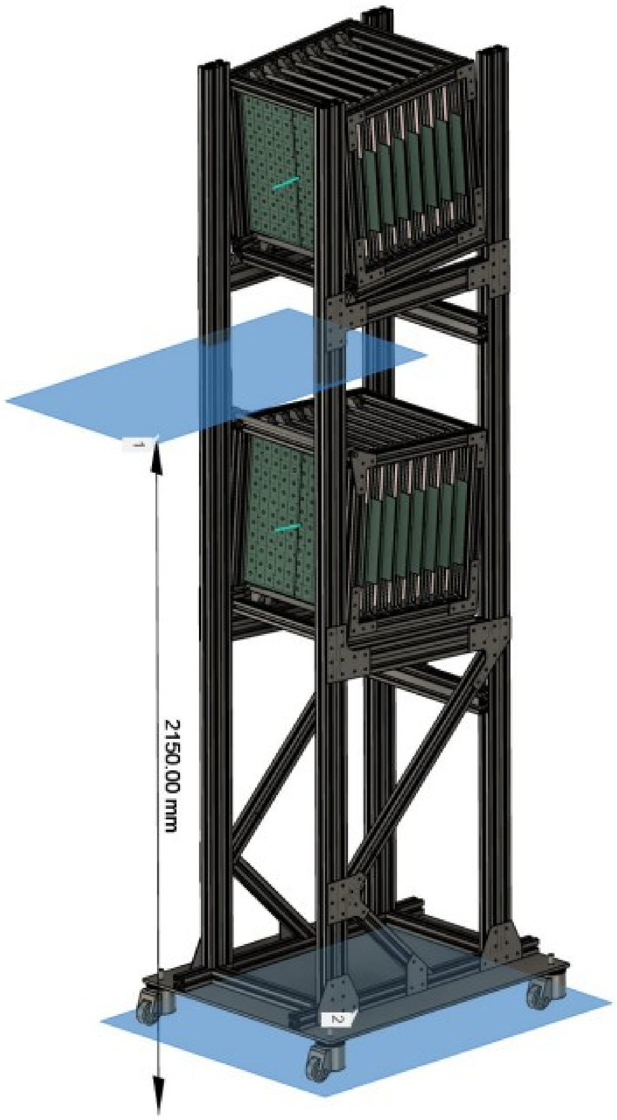


HGND support structure









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

Total weight: ~800 kg

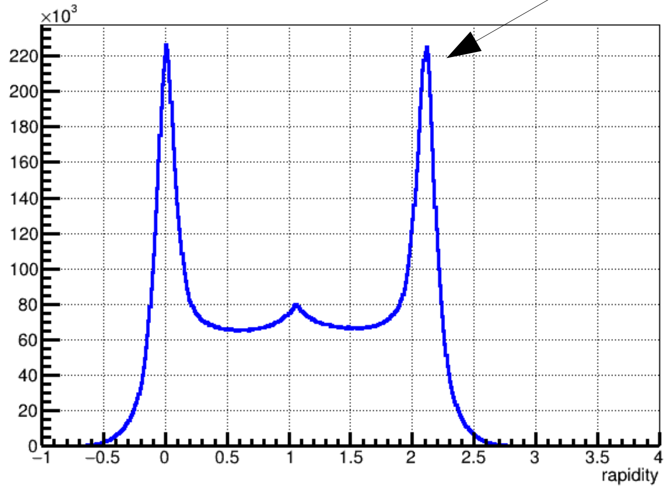
BiBi@3A GeV

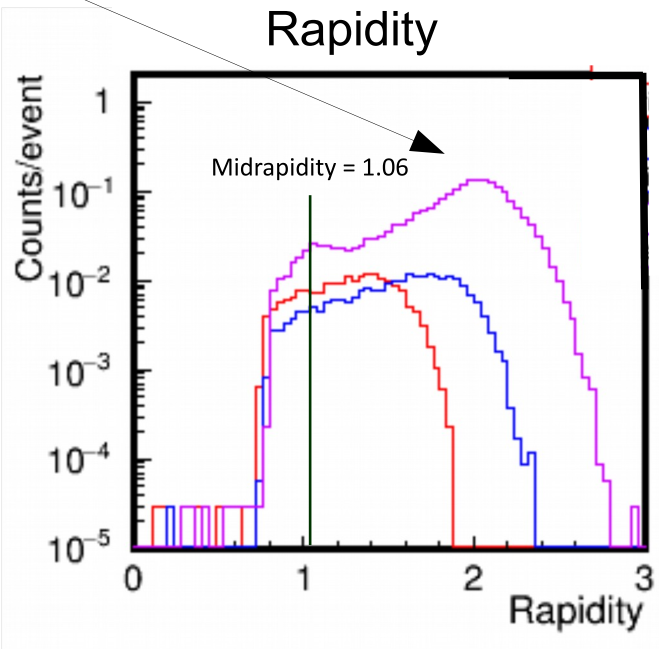
DCM-QGSM-SMM

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

projectile spectator neutrons

neutron rapidity distribution

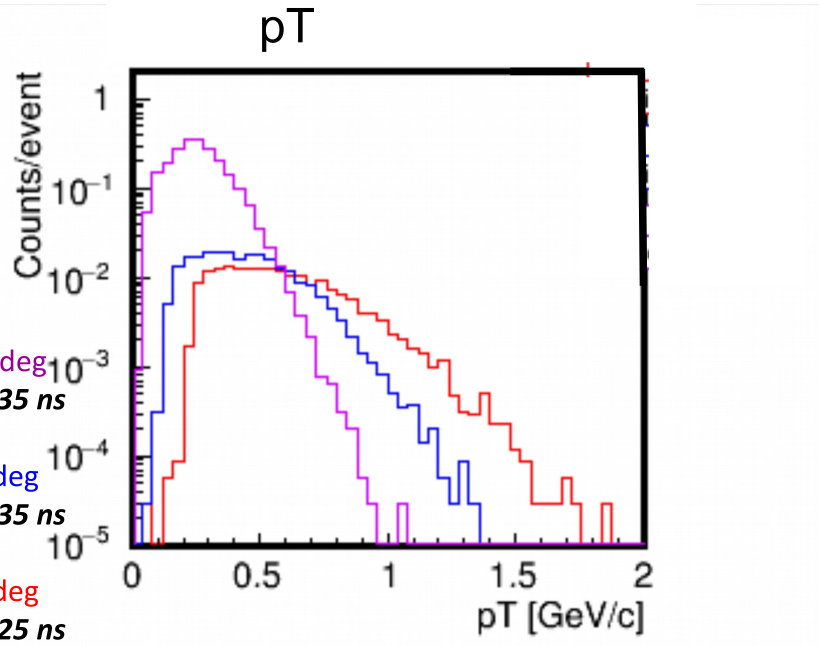




700cm -4.7deg
timeCut < 35 ns

700cm -10deg
timeCut < 35 ns

500cm -17deg
timeCut < 25 ns

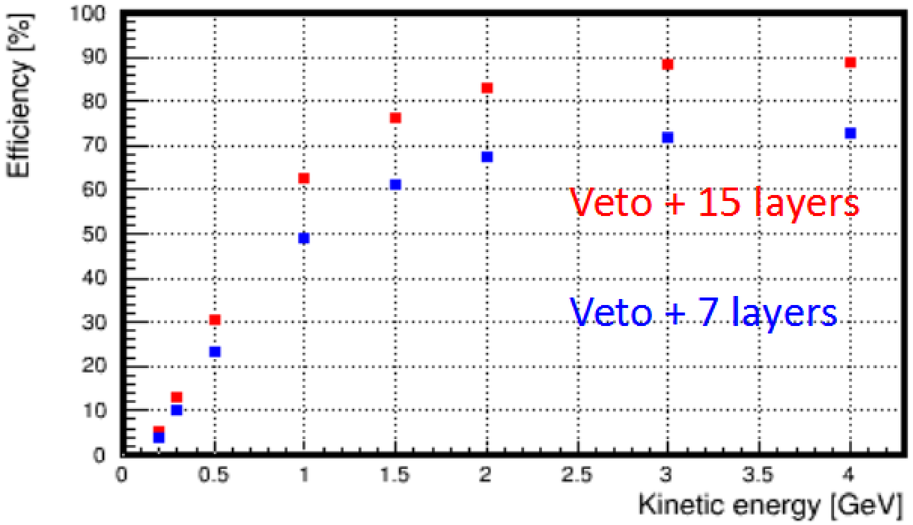


BiBi@3A GeV

DCM-QGSM-SMM

Comparison of neutron detection efficiency for the HGND with 7 and 15 active layers

Single neutrons with 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

Reconstruction of neutron energy performs with the ToF of the fastest hit in HGND cell.

Neutron detection efficiency ratio (HGND with 7 layers / HGND with 15 layers):

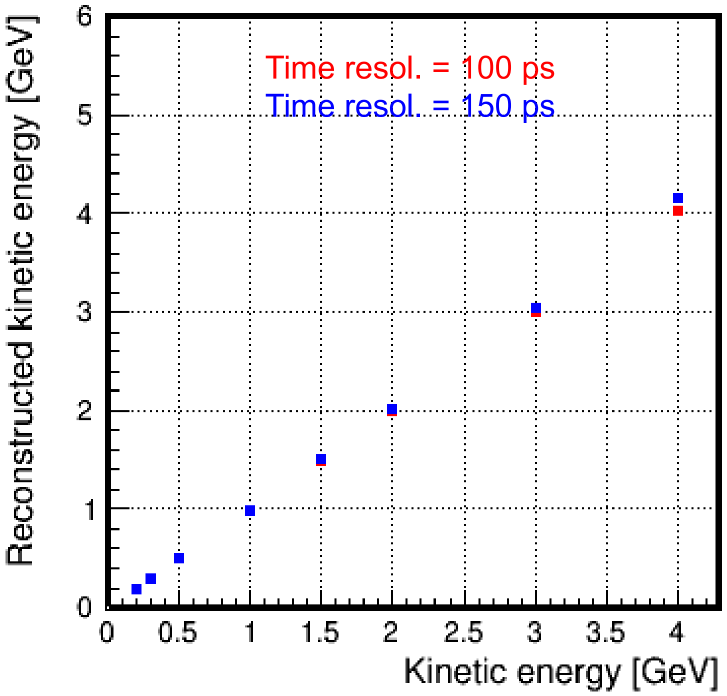
0.7 at 500 MeV
0.79 at 1GeV
0.81 at 4GeV

BiBi@3A GeV

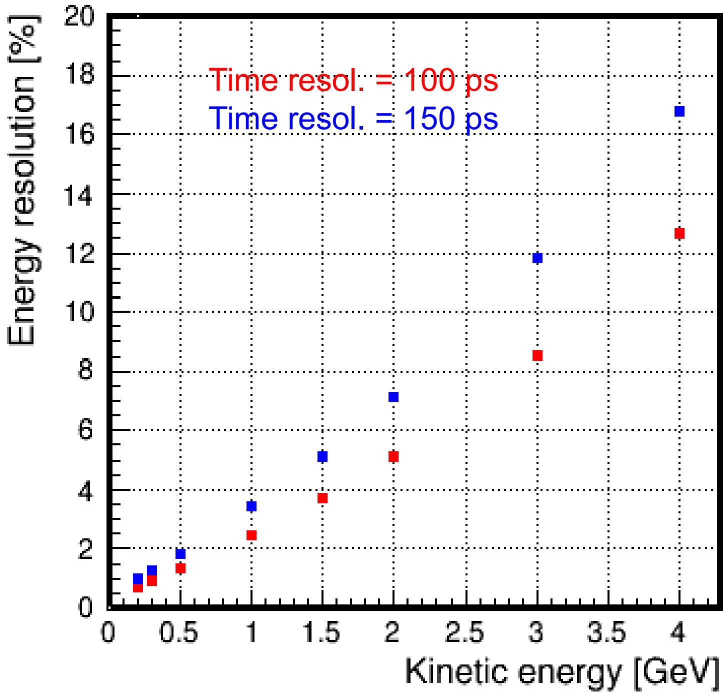
DCM-QGSM-SMM

Reconstruction of neutron kinetic energy and energy resolution

Reconstructed kinetic energy



Reconstructed energy resolution



Experimentally measured time resolution of the HGND scintillation cell ~ 120ps [link]

BiBi@3A GeV

DCM-QGSM-SMM

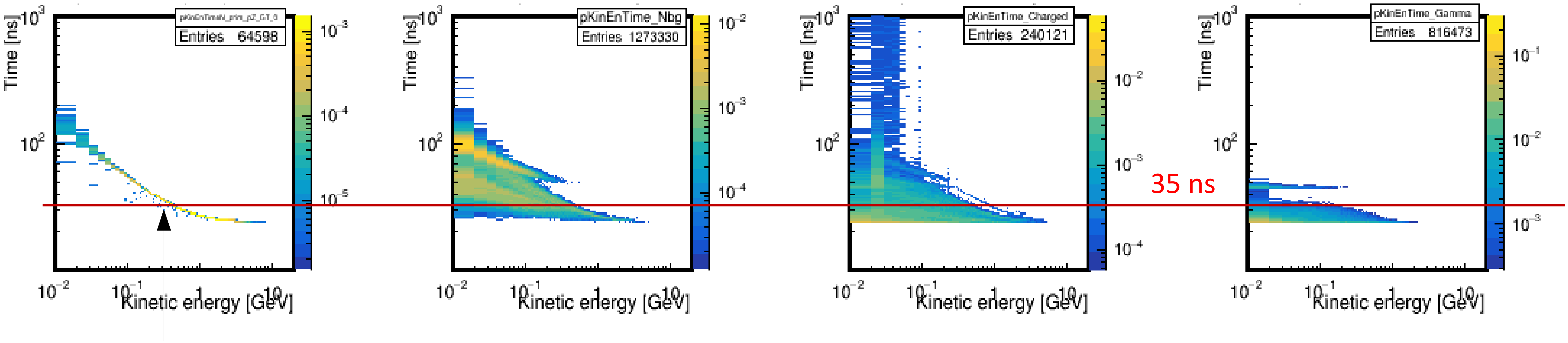
ToF vs kinetic energy of different type of particles the HGND is at 700cm, 10 deg from beam axis

Time cut (time<35 ns)
rejects at nDet entrance:

primary neutrons - 8%
background neutrons - 77%
gamma - 15%

At nDet entrance | Around all nDet surfaces

Primary neutrons | Bg neutrons | Charged particles | Gamma



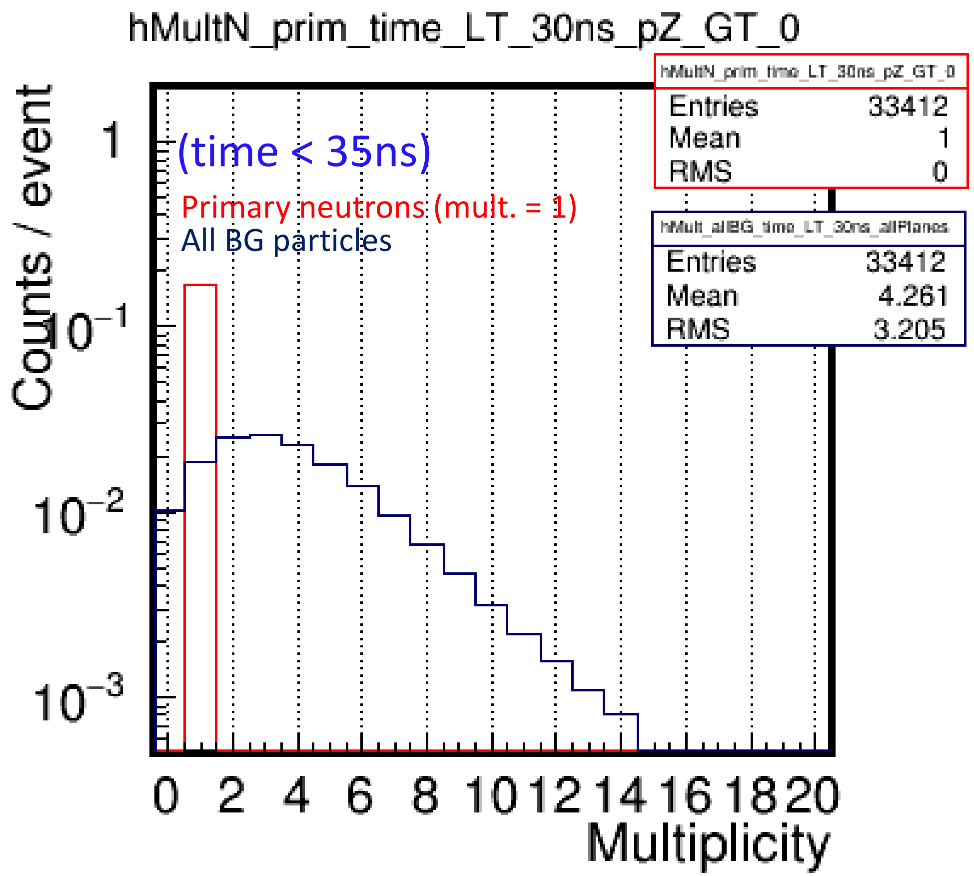
start measuring the energy from ~300MeV

BiBi@3A GeV

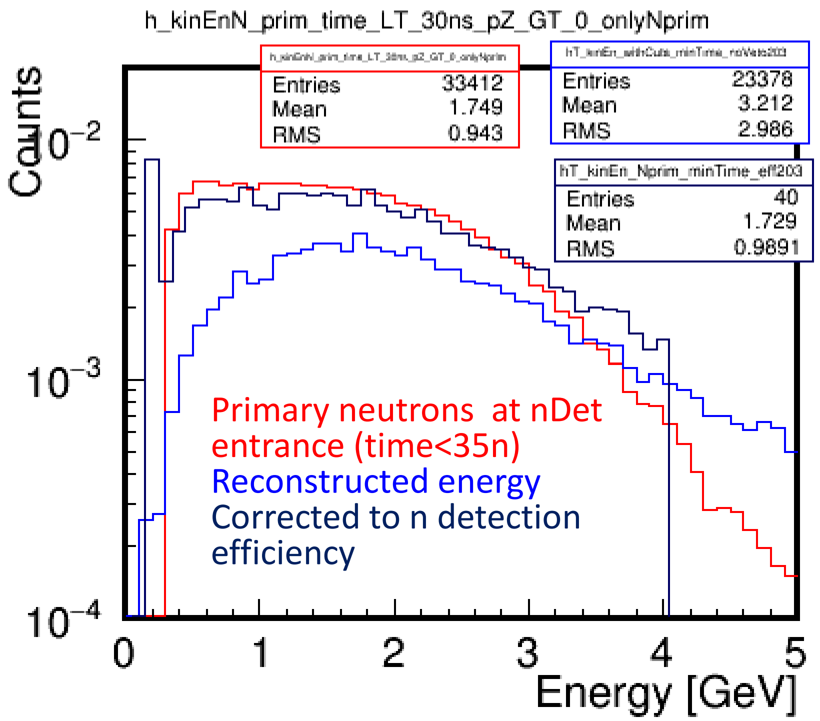
DCM-QGSM-SMM

Multiplicity of neutrons

Events with only 1 primary neutron at nDet entrance (time < 35ns)
Background at all nDet planes (time < 35ns)



1 Primary neutron



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

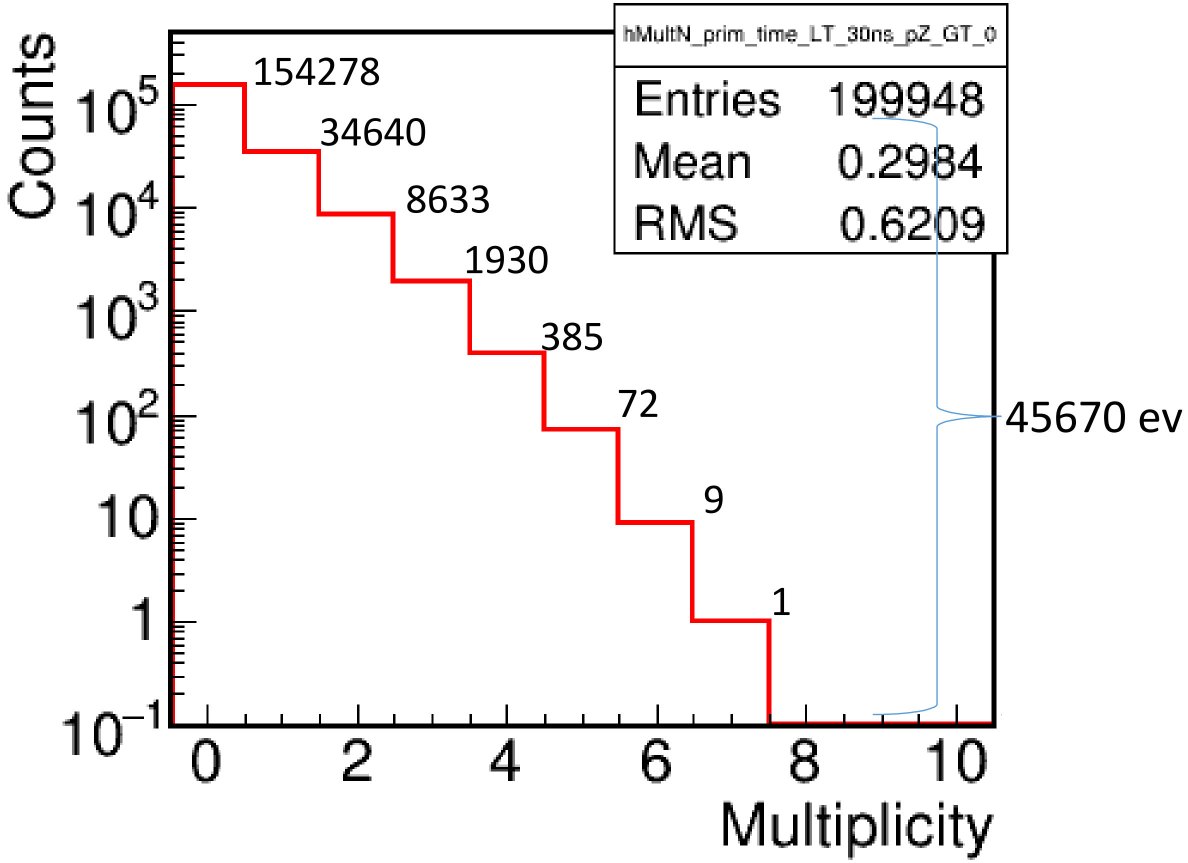
Neutron energy reconstruction for events with more than 1 neutron in events requires development of more sophisticated methods of energy reconstruction.

BiBi@3A GeV

DCM-QGSM-SMM

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

number of registered primary neutrons at the HGND



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

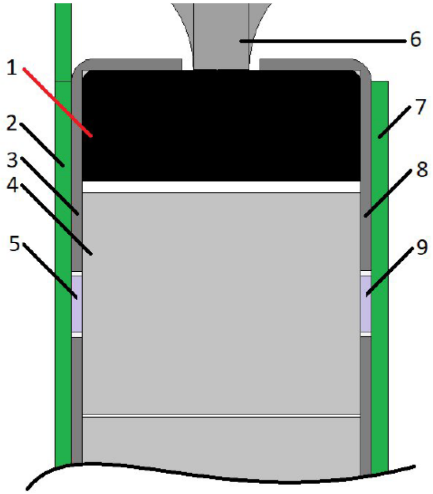
Target interaction length - 2%,
Mean primary neutron yield:
0.17 (single) - 0.23 (all) neutron / interaction
Mean efficiency of the HGND detector - 50%

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).

Status of the HGND construction

Structure of active layer



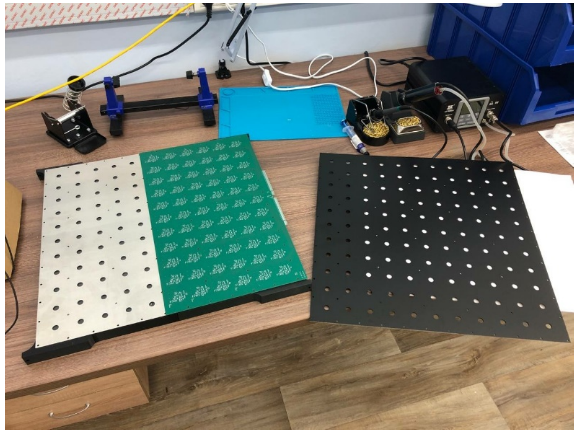
1) plastic frame (3D printed)
2) PCB with photodetectors

3,8) aluminium covering

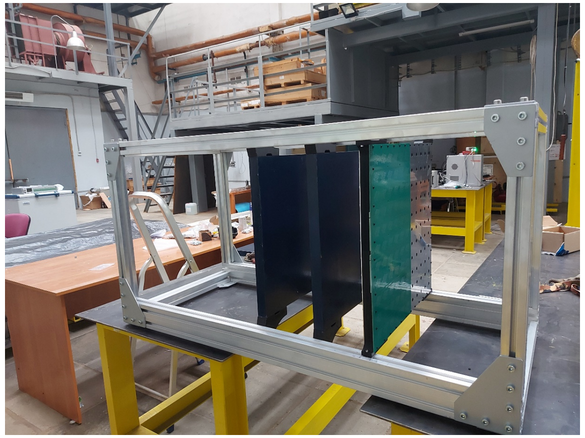
4) scintillator
5) photodetector
6) holding part
7) PCB with LED
9) LED

scintillator layer assembled

active layer PCB positioning



The HGND mock-up
assembled at INR



- all scintillator cells 40x40x25 mm3 (~ 2000 pcs) have been constructed

- first mock-up prototype with scintillator layer has been assembled and prepared for beam tests

Status of FPGA based electronics development see in D.Finogeev presentation

Conclusions:

- 2-arms HGND detector system is proposed (7m from the target position and 10 deg angle)
- the response of the 2-arms HGND was studied (BiBi 3 AGeV)
- mechanics of HGND mock up was assembled at INR and will be used for tests

Outlook:

- the HGND mock-up will be ready to test at the BM@N in Fall 2024
- neutron detection algorithms are still under discussions (cluster method, ML etc.)

Special thanks for all members of HGND development group:

S. Afanasiev, D. Sakulin, V. Ustivov, E. Sukhov (JINR)
A. Stavinsky, A. Martemianov, P. Alexeev, N. Zhigareva, G. Taer (NRCKI, ??)
I. Pshenichnov, A. Svetlichnyy (INR RAS)
F. Ratnikov, V. Bocharnikov (HSE)

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

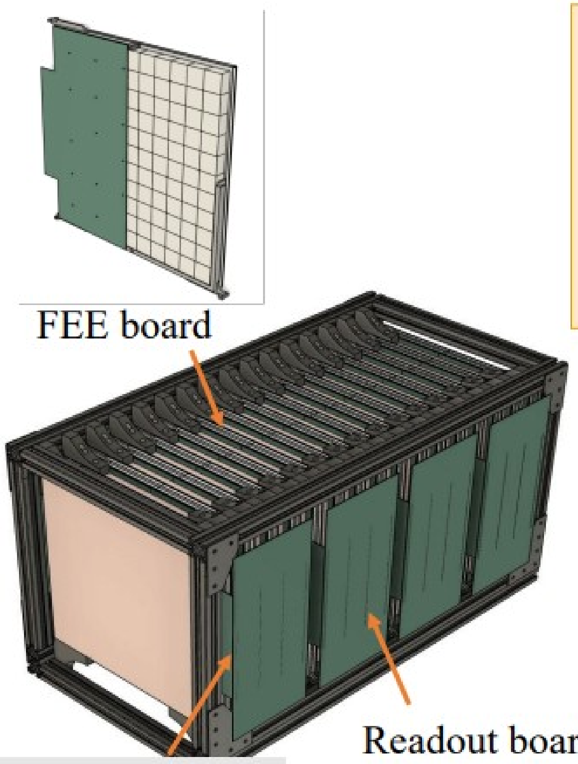
FEE: LMH6629MF preamp (20 dB gain, bandwidth of 600 MHz at a 3 dB level, and noise of <2.2 nV/√Hz) + rapid discriminator (ADCMP553) with a fixed threshold.

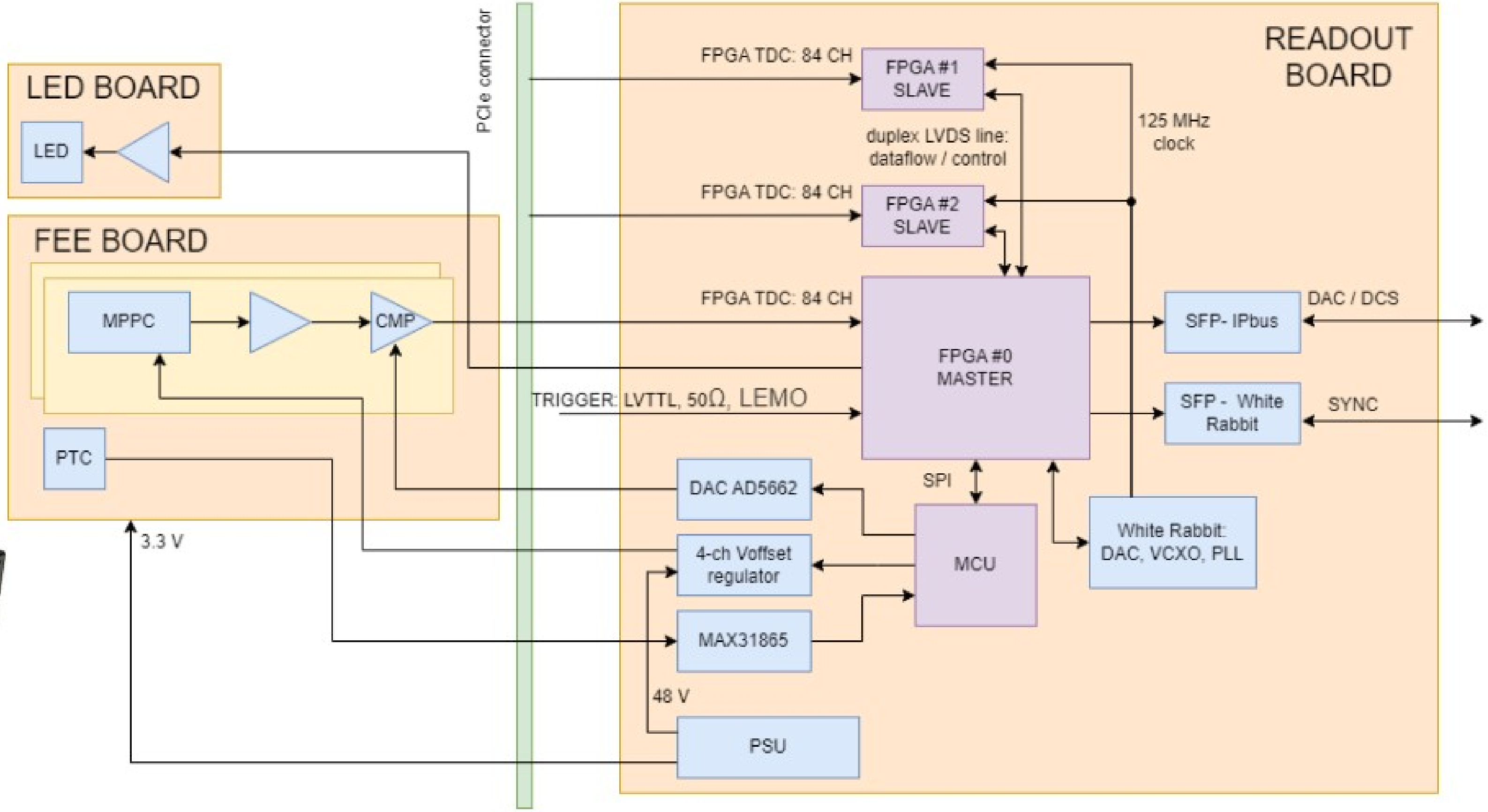
Readout: CAEN DT5742

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

FEE & readout architecture

- 16 layers with scintillation matrix 11X11
- 16 LED boards
- 32 FEE boards
- 8 Readout boards
- 3 FPGA per board
- 84 channels per FPGA
- 2000 channels in total

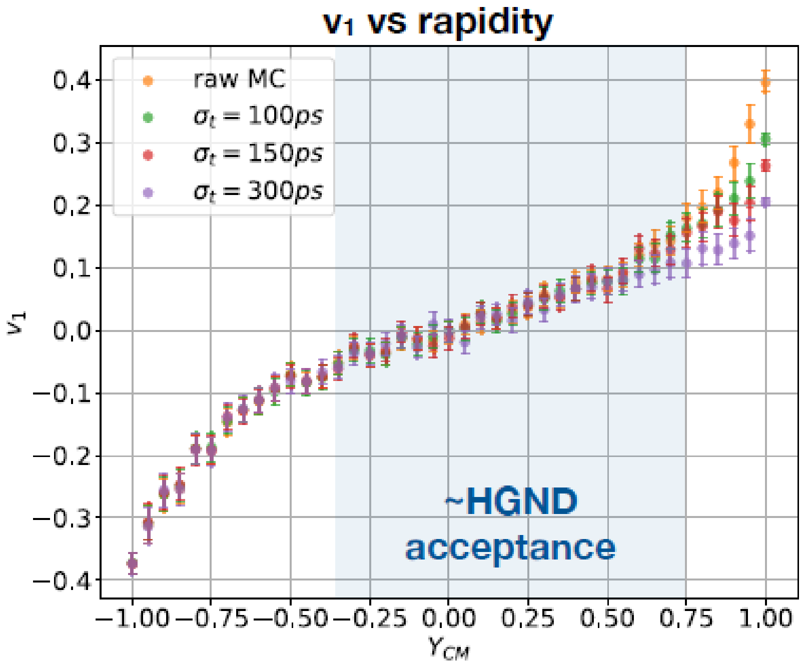




3

Presentation of D. Finogeev

Time resolution and neutron flow measurements (based on V. Bocharnikov slides on 11th BM@N CM)



Influence of HGND time resolution on flow coefficients

- Data source: all primary neutrons from initial DCM-QGSM-SMM Bi+Bi @ 3 AGeV reaction
  - MC truth information
  - Y_{CM} and P_T are converted to time at distance of 5.72m along **p** and recalculated after time smearing
- v_1 vs Y_{CM} selection criteria:
  - $E_{kin} > 0.5$ GeV
  - Impact parameter ∈ (6, 9) fm
  - $p_T \in (1., 1.5)$ GeV
- v_2 vs Pt selection criteria:
  - $E_{kin} > 0.5$ GeV
  - Impact parameter ∈ (6, 9) fm
  - Rapidity in c.m. ∈ (-0.2, 0.2)

p_T and rapidity cuts are on distorted values)

Time resolution effect gets noticeable only at forward rapidities