The Highly Granular Neutron Detector and Forward Spectator Detectors at the BM@N experiment

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on behalf of the INR RAS team

The 2nd China-Russia Joint Workshop on NICA Facility
12 September 2024, Qingdao, China

Overview

- New neutron detector of the BM@N experiment
  - Physics motivation of measuring the neutrons in heavy-ion collision experiments
  - Detector design
  - Performance studies
  - Construction status
- Forward spectator detectors of the BM@N experiment
  - Detectors tasks & design
  - Performance at the XeCsI physics run

EOS for high baryon density matter

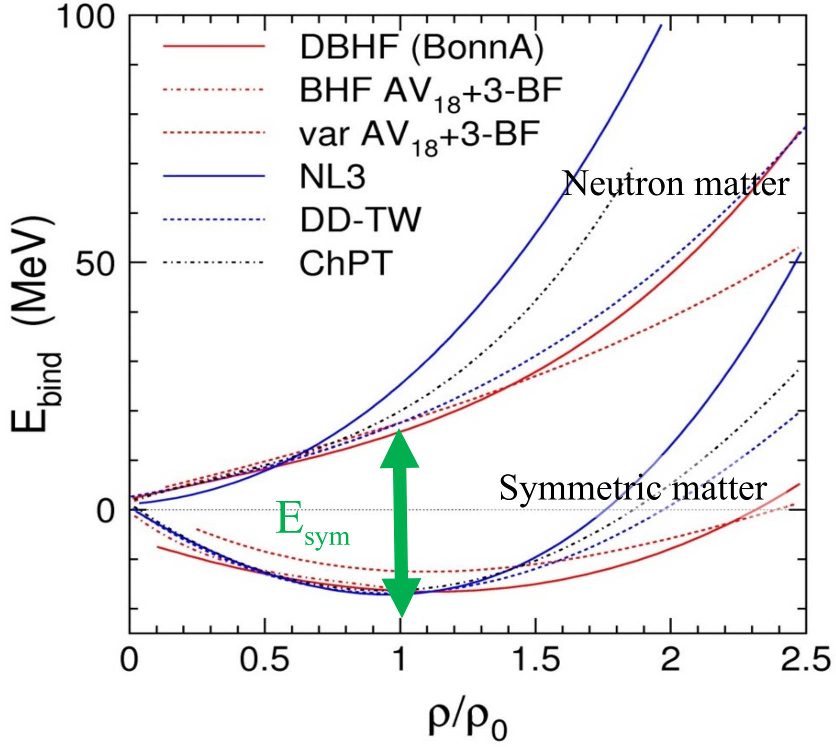
The binding energy per nucleon: $E_A(\rho,\delta) = \boxed{E_A(\rho,0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$

Isospin asymmetry:

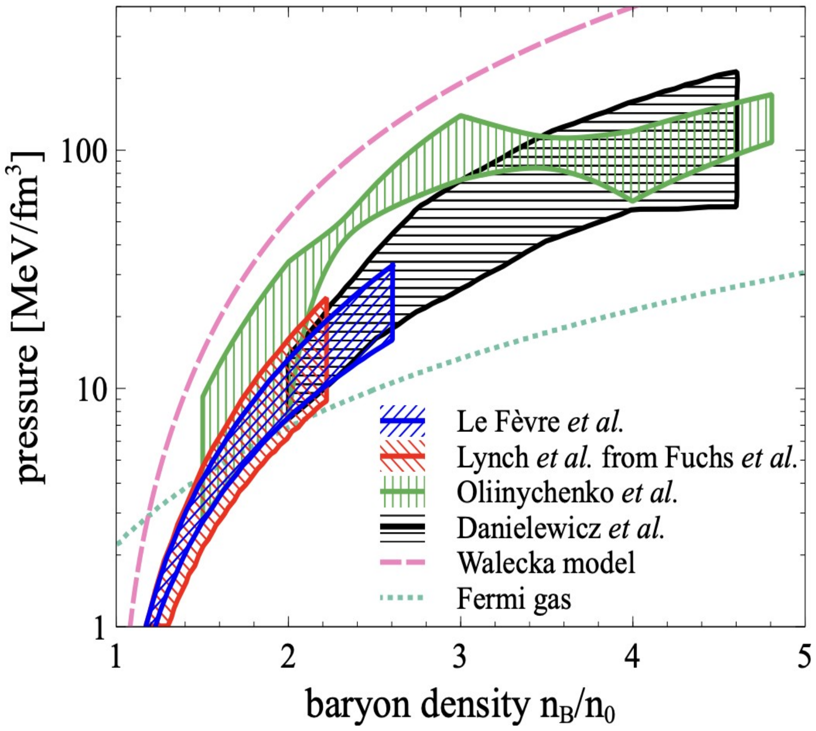
$\delta = (\rho_n - \rho_p)/\rho$

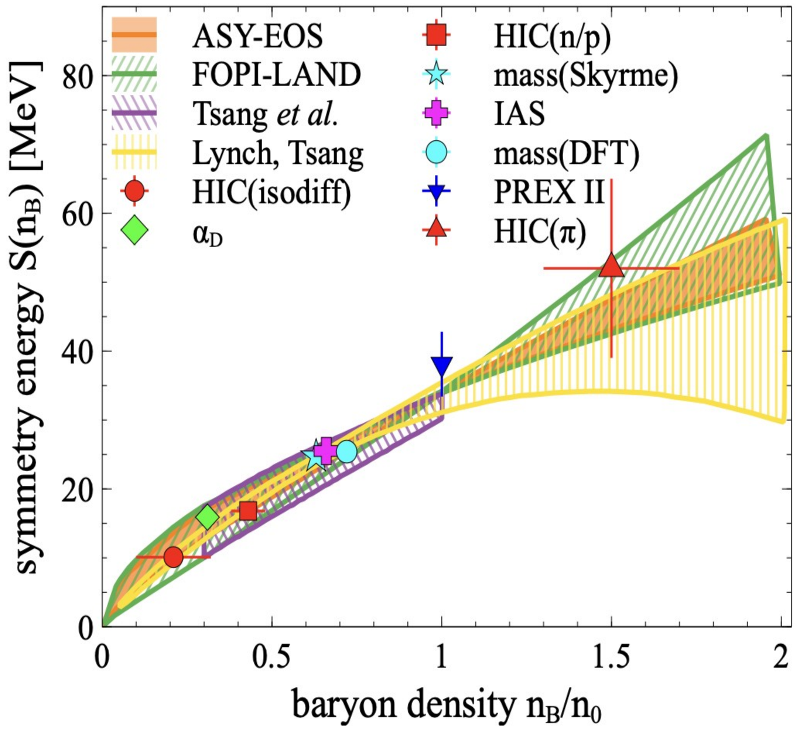
Symmetric matter

Symmetry energy



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





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

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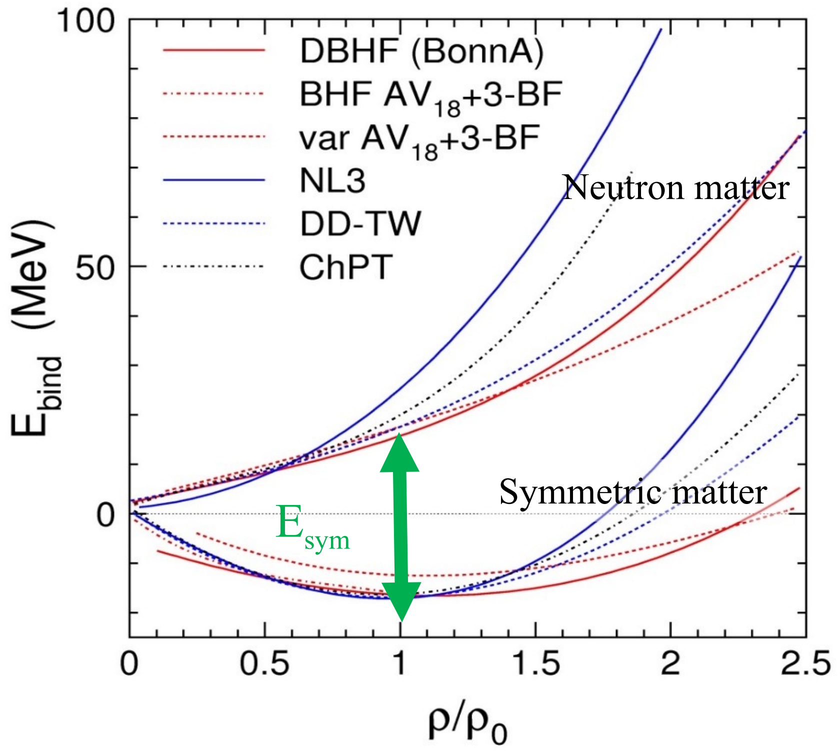


Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

Symmetric matter

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

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

- 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

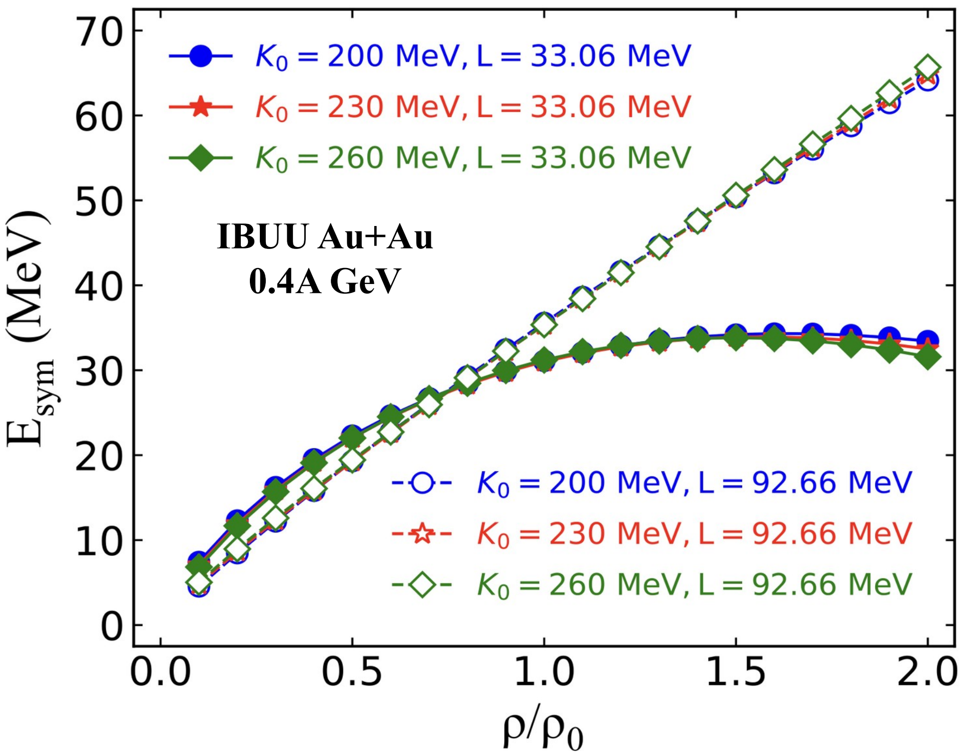
$$L = 3\rho \frac{dE_{sym}(\rho)}{d\rho}$$

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

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



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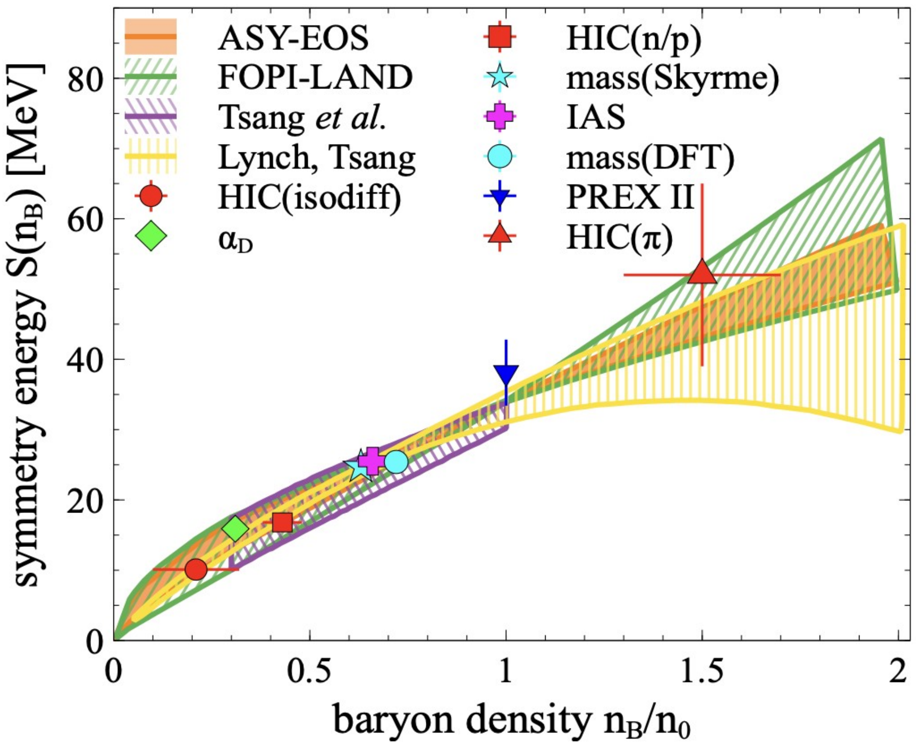
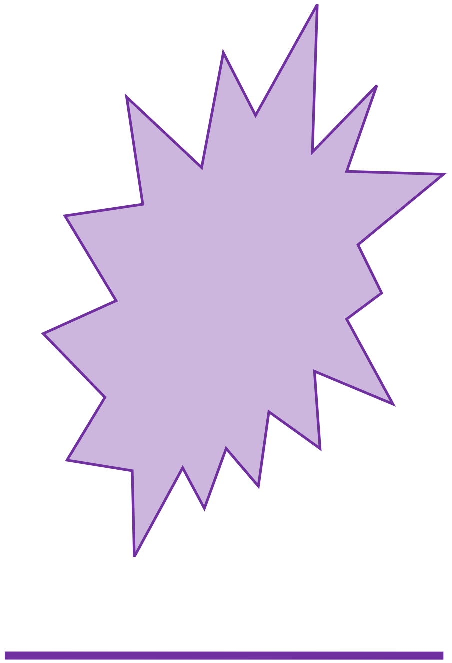




uncovered region above 2 n_B/n_0

- **Nuclotron-NICA density region: $2 < n_B/n_0 < 8$**
- **Symmetry energy E_{sym} has strong density dependence and can be described with its slope**

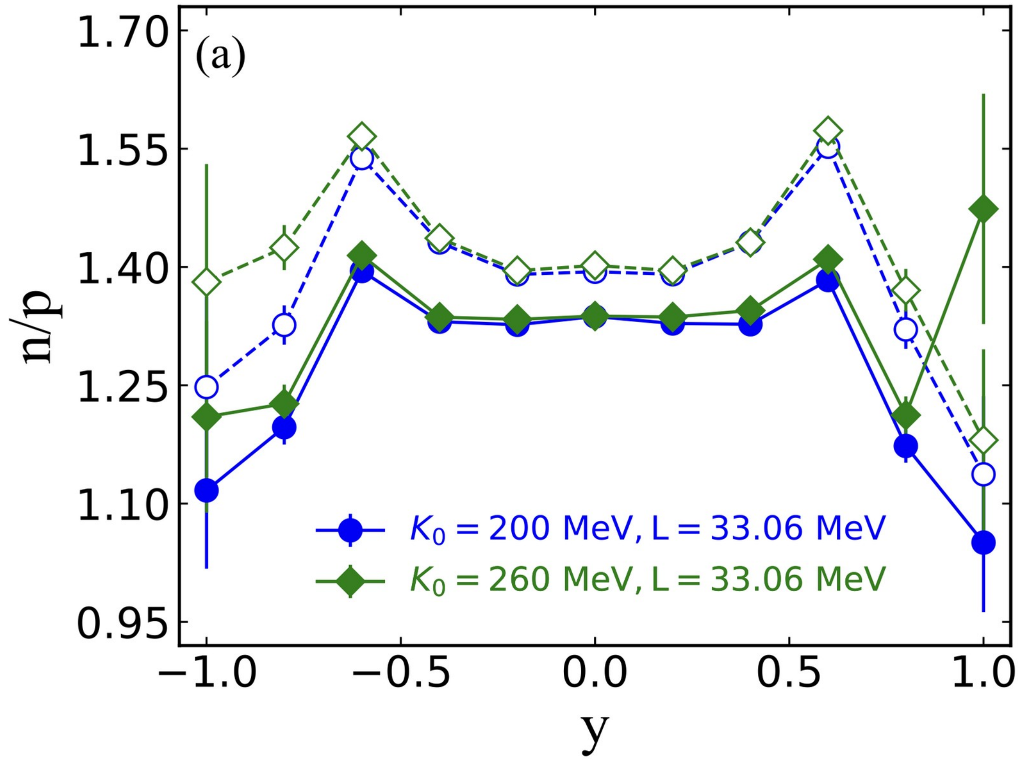
What observables can we use to extract information about ***L***?

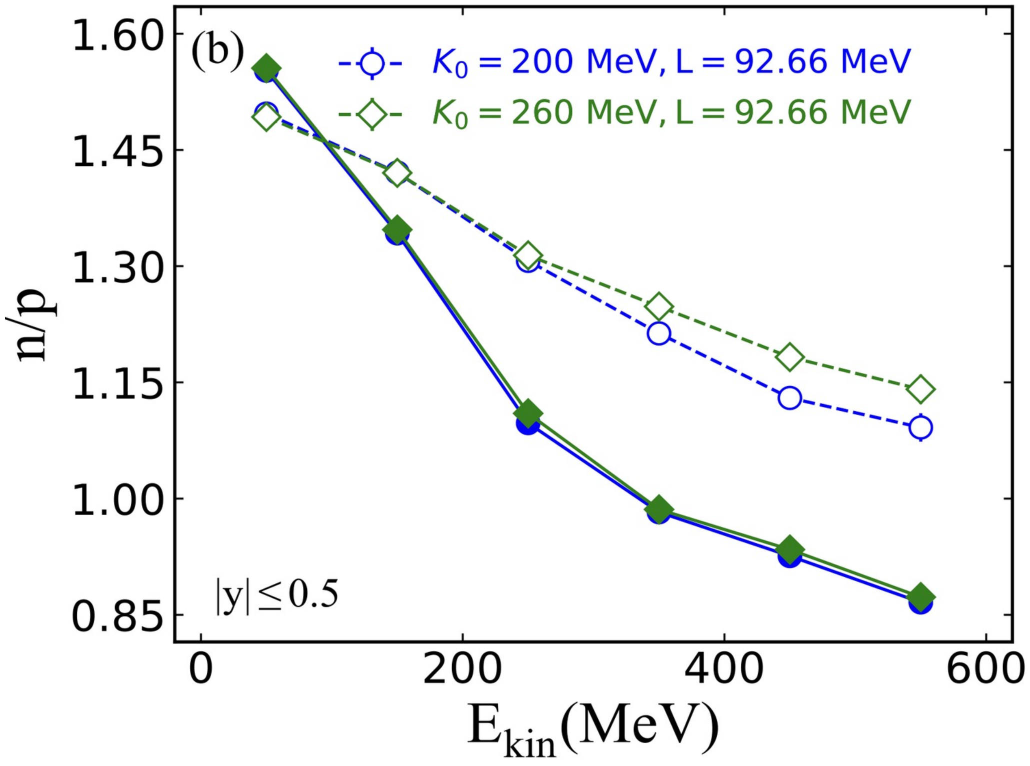
Observables to study symmetry energy

Rapidity and kinetic energy distributions of n/p ratios show strong dependence on ***L*** and weak dependence on ***K_0***

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

IBUU, Au+Au, 0.4A GeV

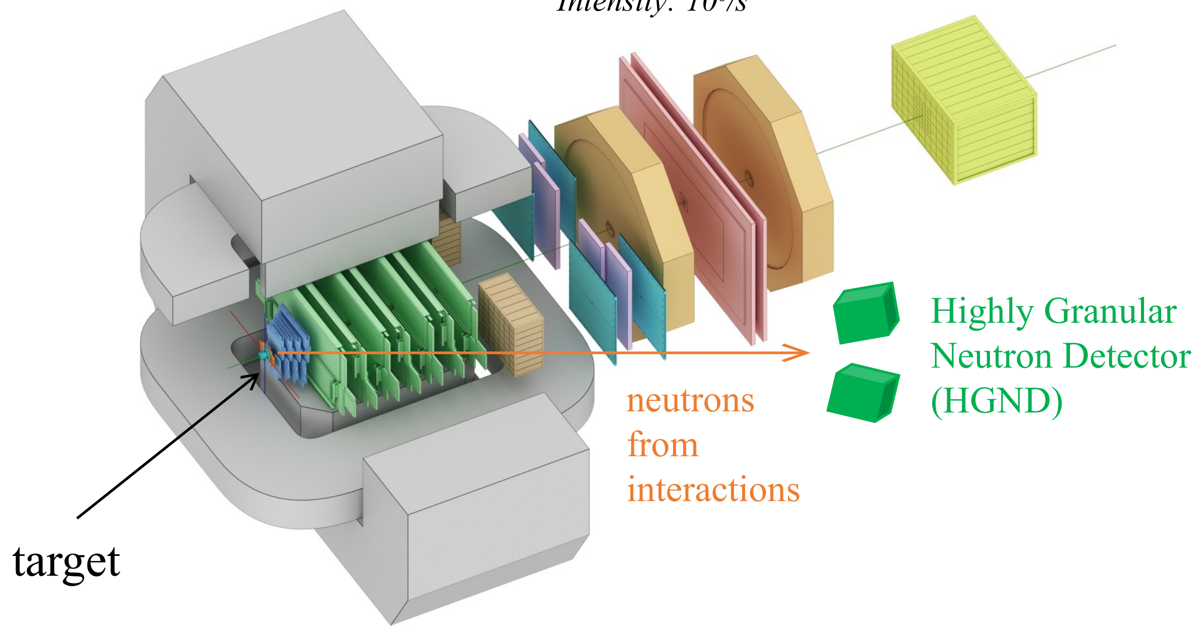


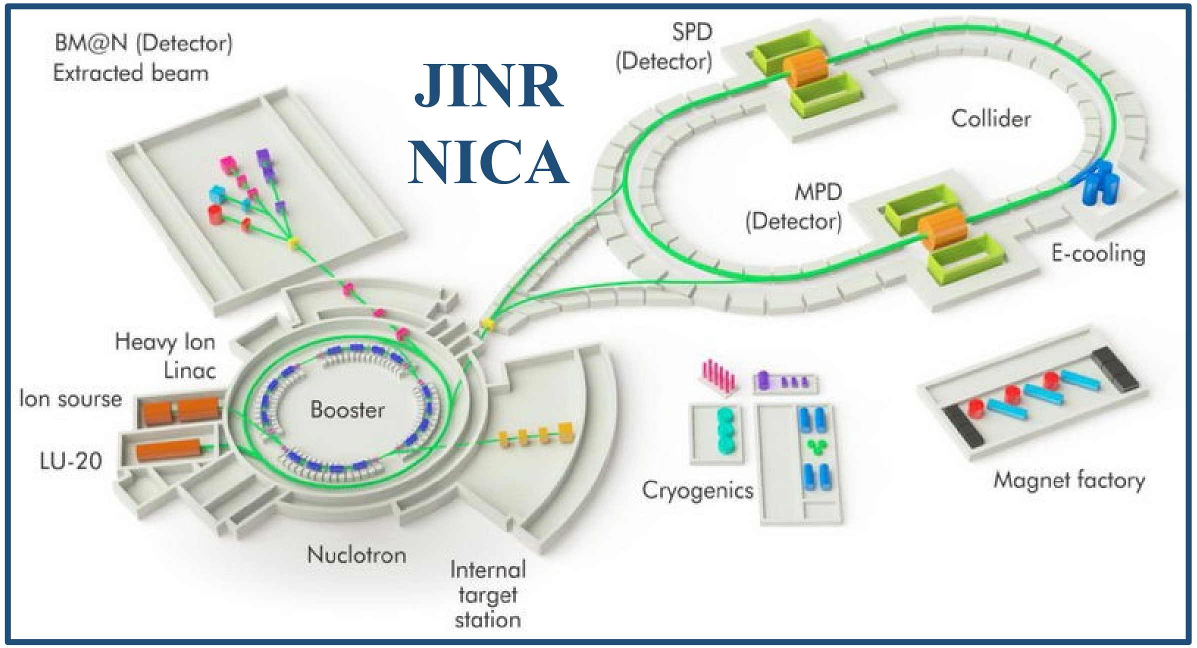


Neutron measurements are required to extract robust information about symmetry energy

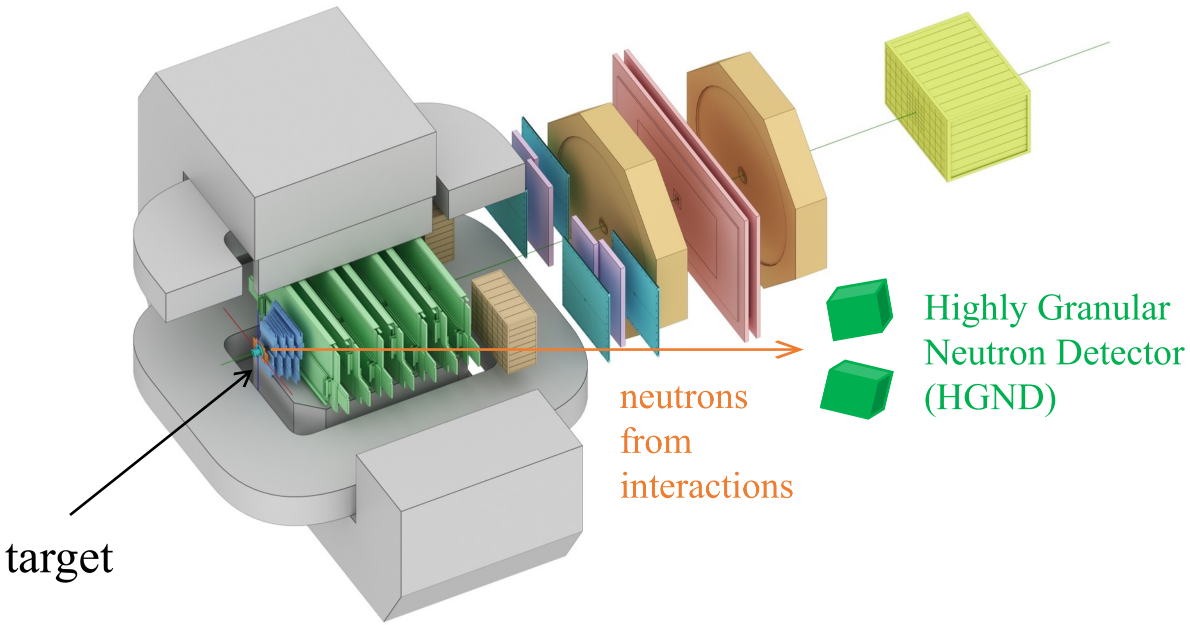
BM@N setup

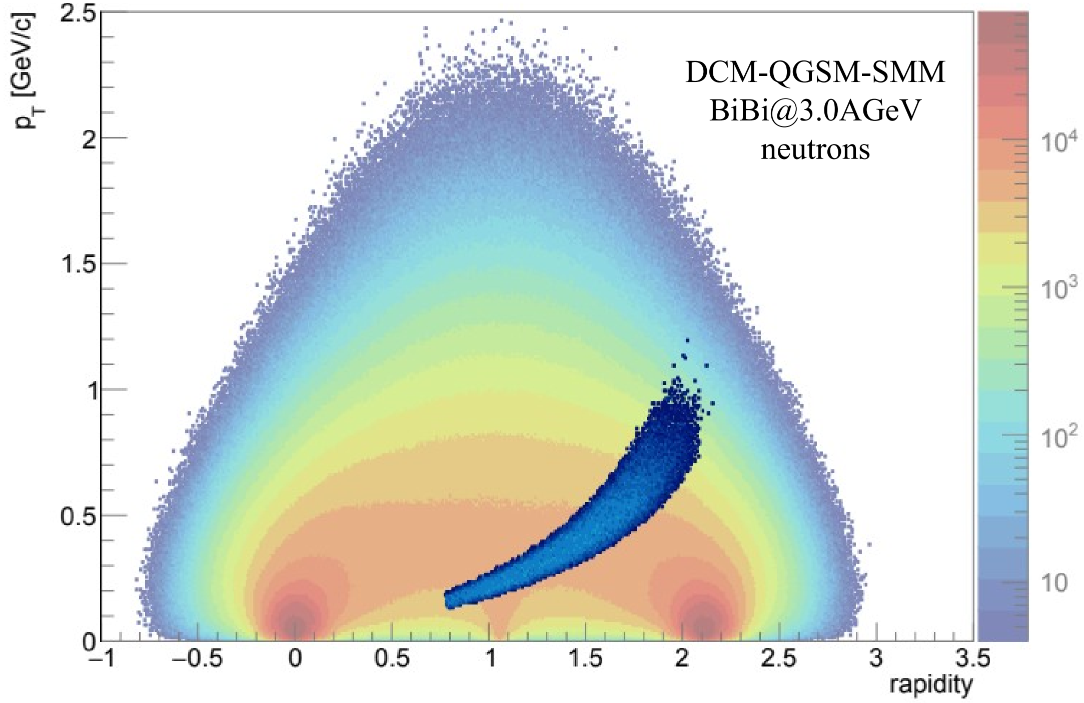
Beams: p to Au
Kinetic energy: 1-4.5 AGeV for Z/A=0.4
1-6 AGeV for Z/A=0.5
Intensity: 10^6/s

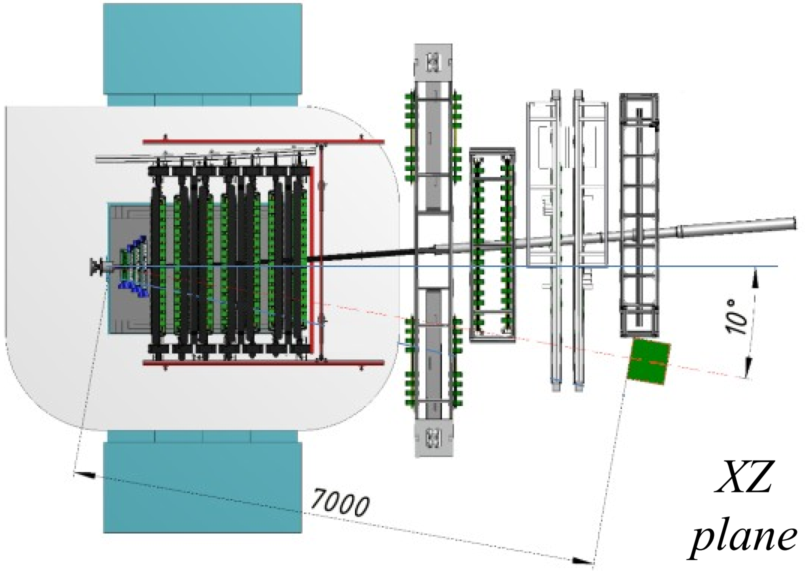




BM@N setup







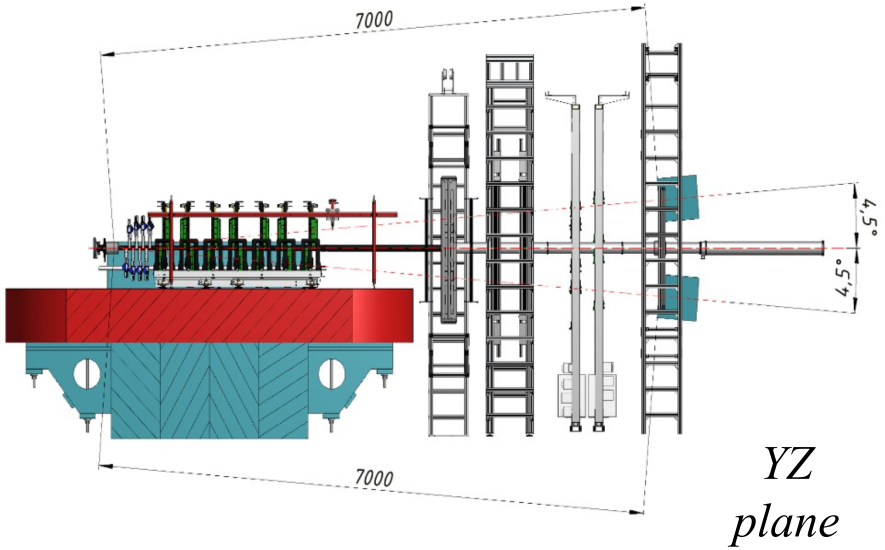
Goal: understanding the symmetry energy in the uncovered region of high baryon densities

How:

- Differential study of n/p ratio

Measure:

- protons — BM@N spectrometer
- neutrons — HGND via their kinetic energy determined by ToF

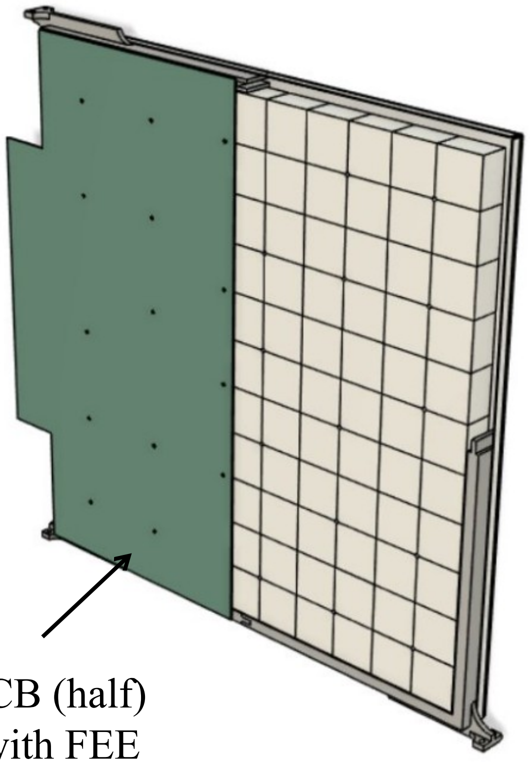


Mechanical design

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

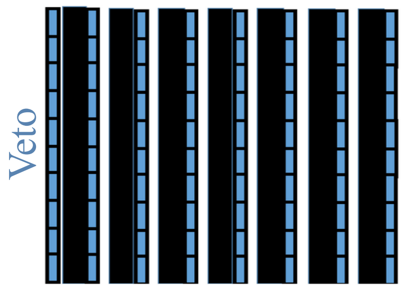
Light-tight and air-cooled assembly. Each arm:

- 1 veto-layer
- 7 Cu absorber layers (3 cm thick)
- 7 sensitive layers:
  - 11x11 matrix of scintillator detectors 4x4x2.5 cm^3
  - surrounded from both sides by PCBs
    - upstream board: LEDs for time calibration
    - downstream board: SiPMs and FEE

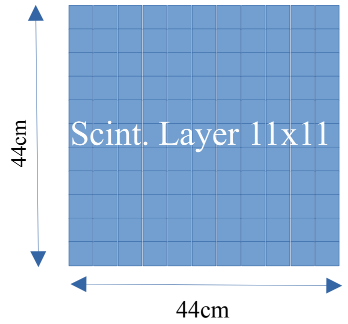


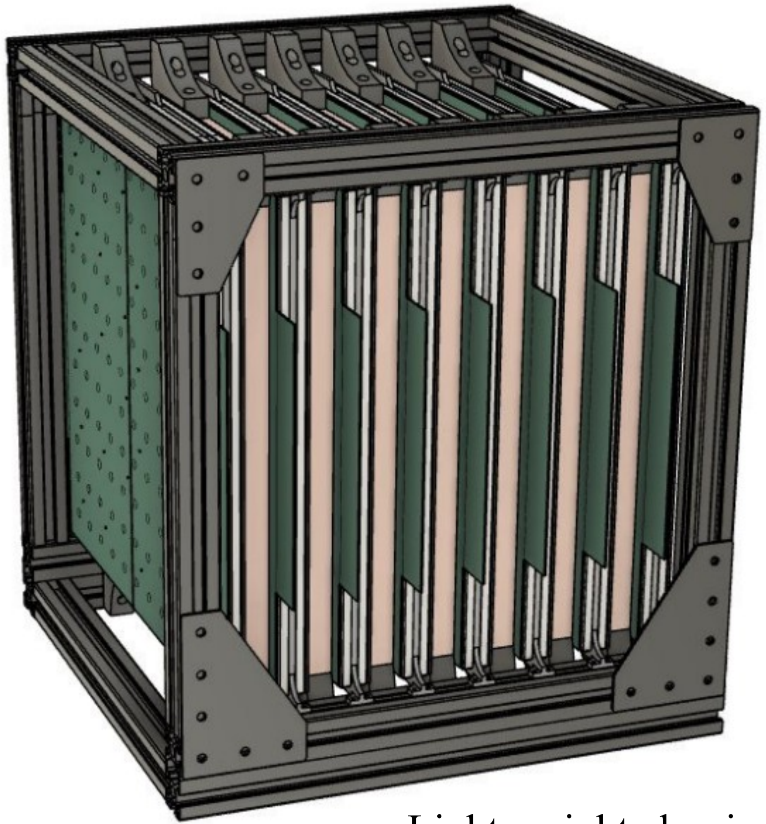
PCB (half) with FEE

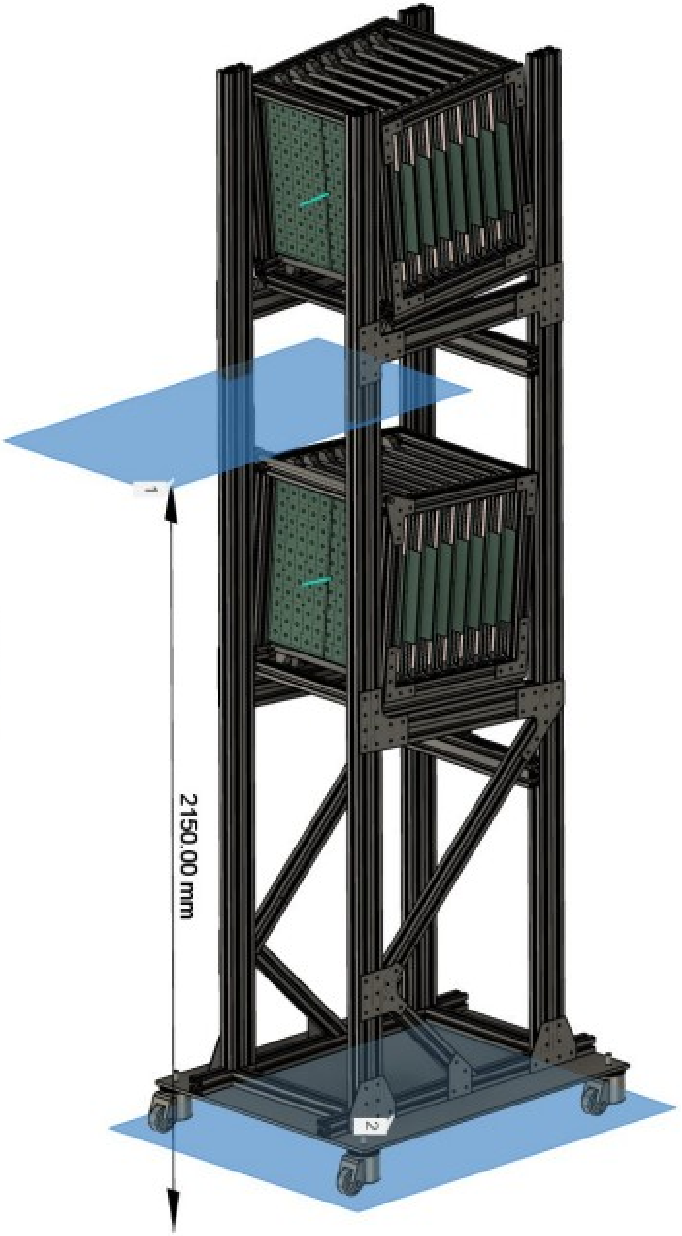
7 layers (Cu/Scint)



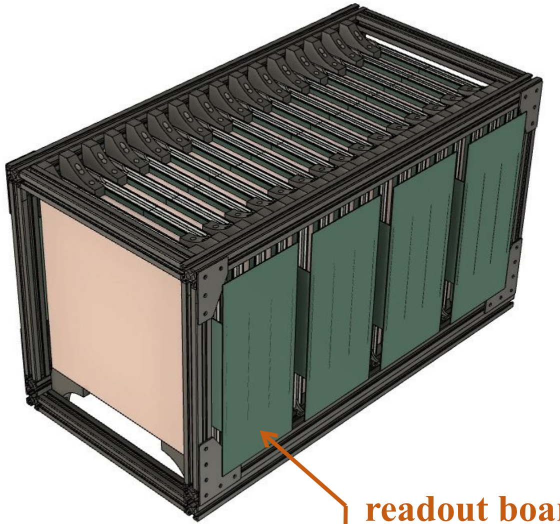
total length ~ 48cm (1.5 λ_{in})



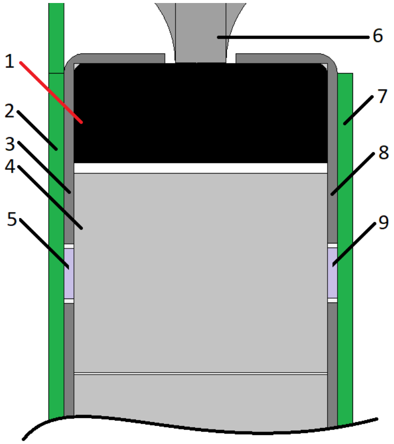




Light-weight aluminum frame



readout 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

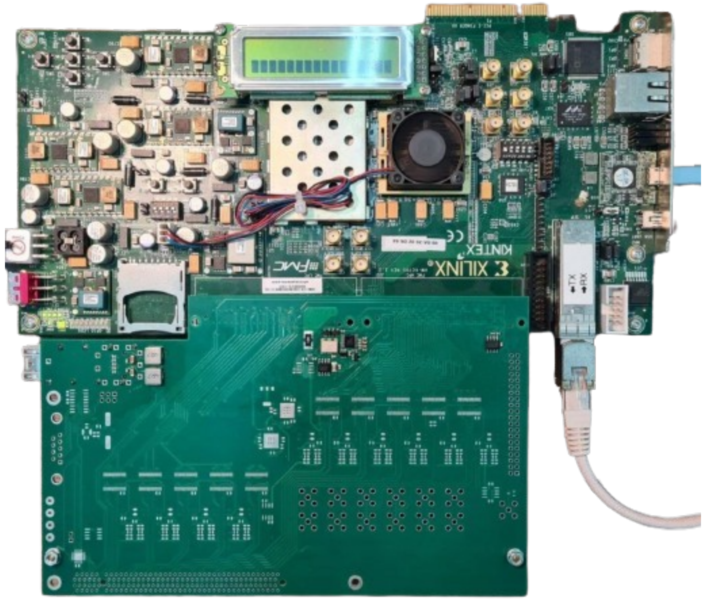
Readout scheme

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

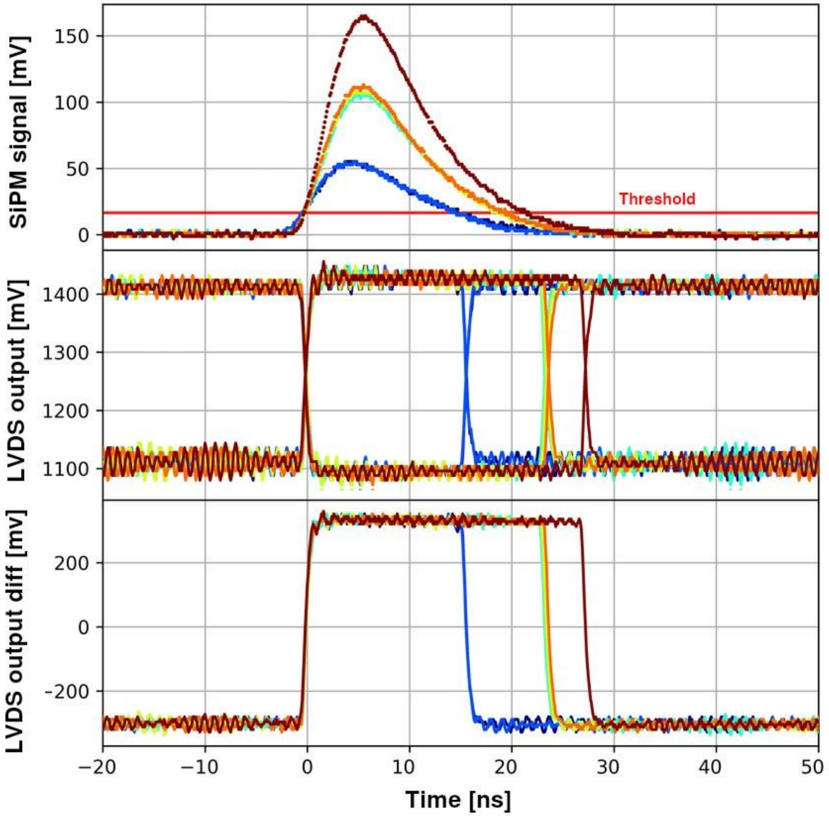
= Response time + ToT

Per channel

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



Readout board prototype based on Xilinx Kintex 7 Evaluation Board



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

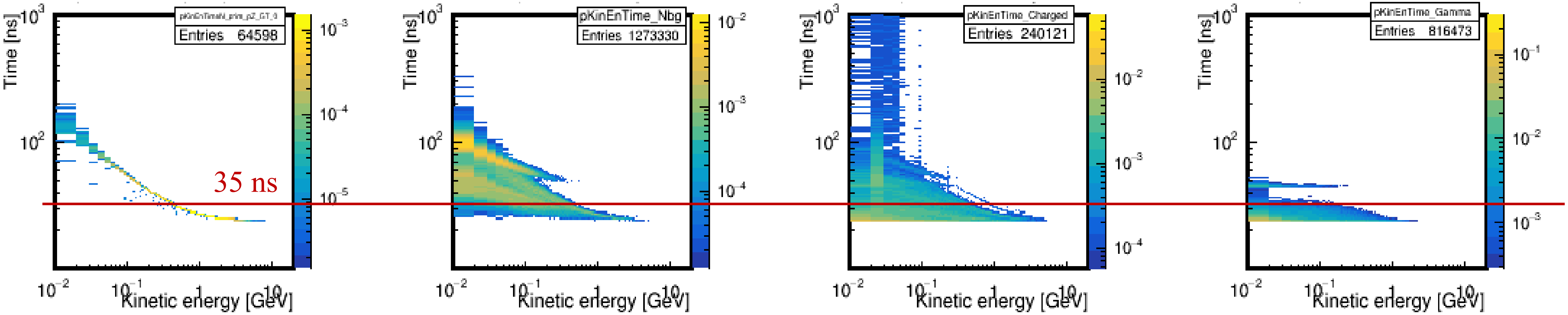
- Active area 6×6 mm^2
- Pixel size15×15 μm^2
- Total pixels: 160 000
- PDE: 45%
- Gain: $4*10^5$

Discussing the ToF cut

BiBi@3AGeV
DCM-QGSM-SMM
200k minbias

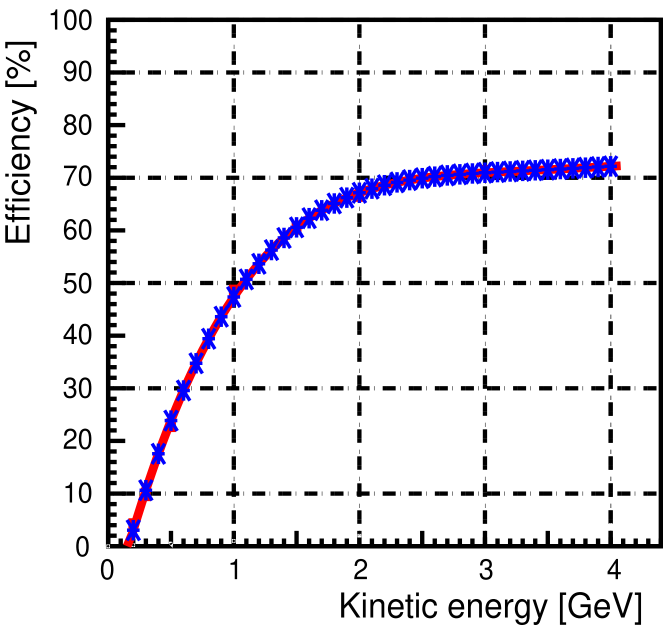
At HGND entrance — All HGND surfaces

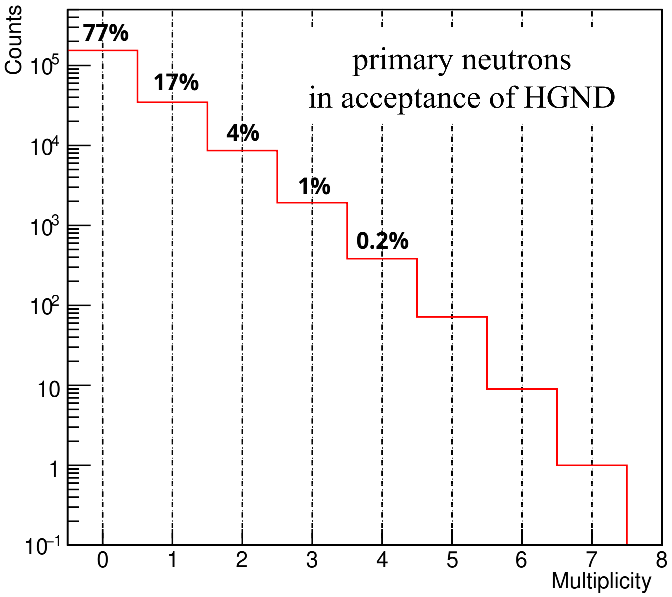
Primary neutrons — Bg neutrons — Charged particles — Gamma

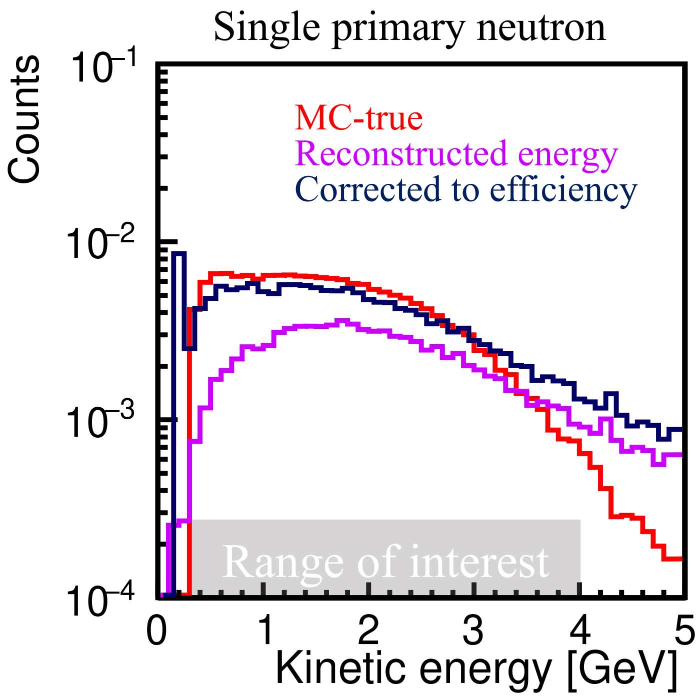


Selecting ToF < 35 ns rejects:

background neutrons - 77%
gamma - 15%
primary neutrons - 8%
Measuring the primary neutrons with energies **≳300MeV**







BiBi@3AGeV
DCM-QGSM-SMM
200k minbias

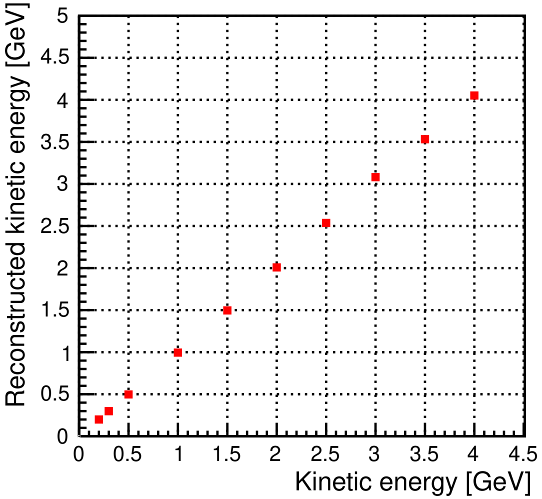
$$Efficiency = \frac{N_{events\ with\ hits}}{N_{events}}$$

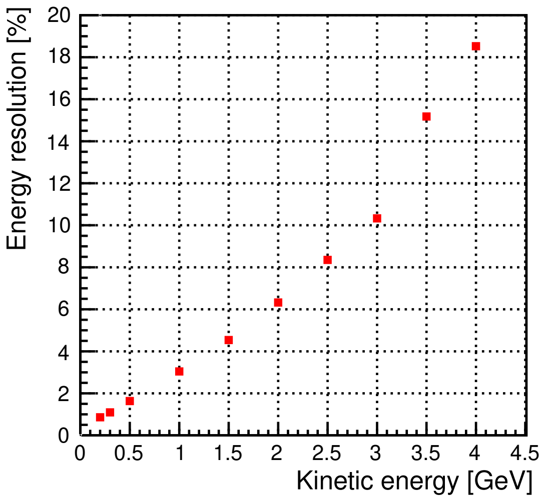
Hit selection: ≥2 hits with signal > 3 MeV (~0.5 MIP)

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%

1 month of the BM@N run ~ **$1.2*10^9$** *single* primary neutrons with kinetic energy > 300 MeV can be collected
Upper limit: **$1.5 * 10^9$** neutrons (additional multi-neutron event recognition is required).

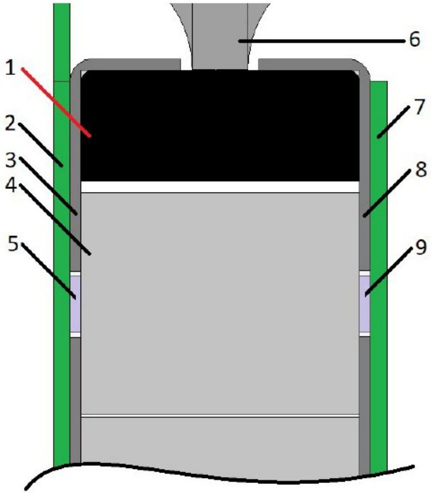




Methods of neutrons energy reconstruction in multi-neutron events are currently under development.

Construction status

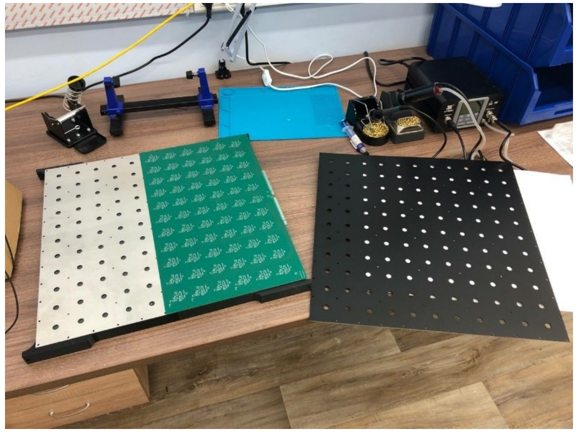
Structure of active layer



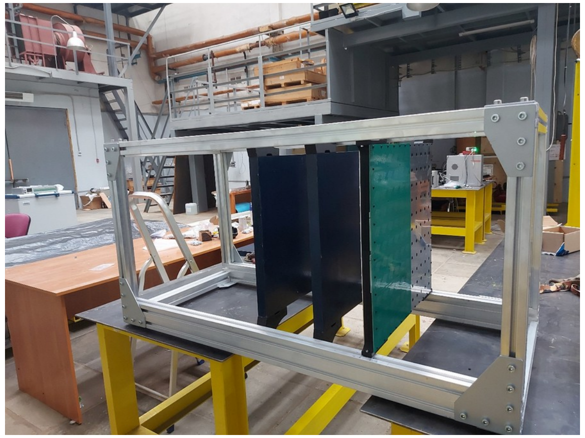
1 – the frame of layer case
2 – SiPM PCB
3&8 – aluminum plates
4 – scintillator
5 – SiPM
6 – layer support bracket
7 – LED PCB
9 – LED

scintillator layer assembled

active layer PCB positioning



The HGND mock-up assembled at INR



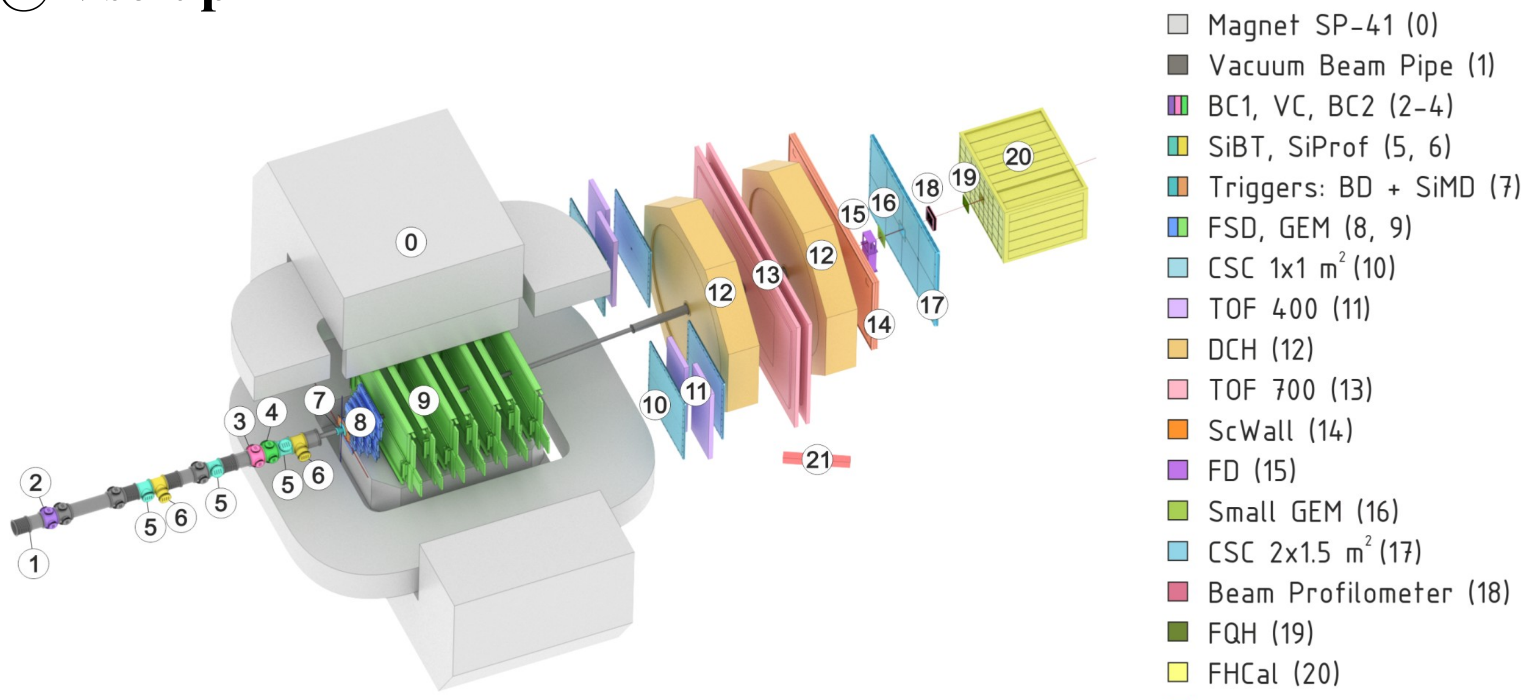
- **Scintillator Cells**: All ~2,000 cells (40x40x25 mm³) have been built.
- **PCB**: Design is finalized and production is underway.
- **Readout board**: The FPGA-based TDC readout board is under active development.
- **Prototype:** First mock-up prototype with scintillator layer assembled; beam test preparations completed.
- **Timeframe:** To be commissioned by the end of 2025.

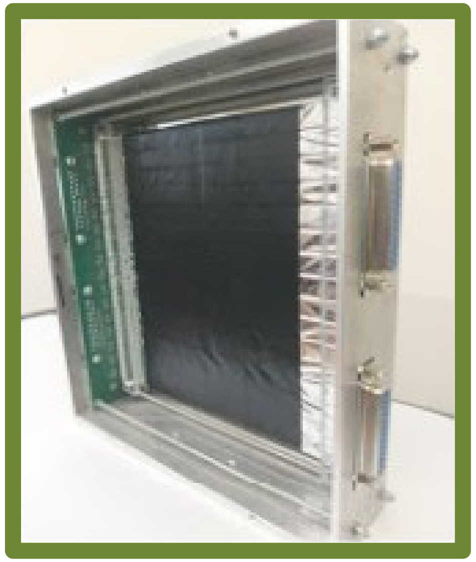
Forward detectors of the BM@N setup

- **FHCal (F**orward **H**adron **Cal**orimeter)
- **FQH** (**F**orward **Q**uarz **H**odoscope)

Tasks:

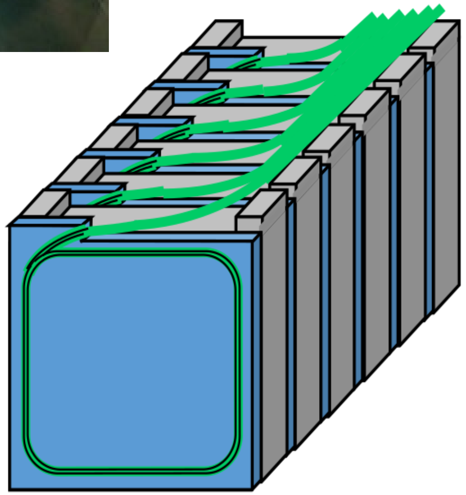
- centrality determination
- reaction plane orientation
(see report by M.Mamaev)





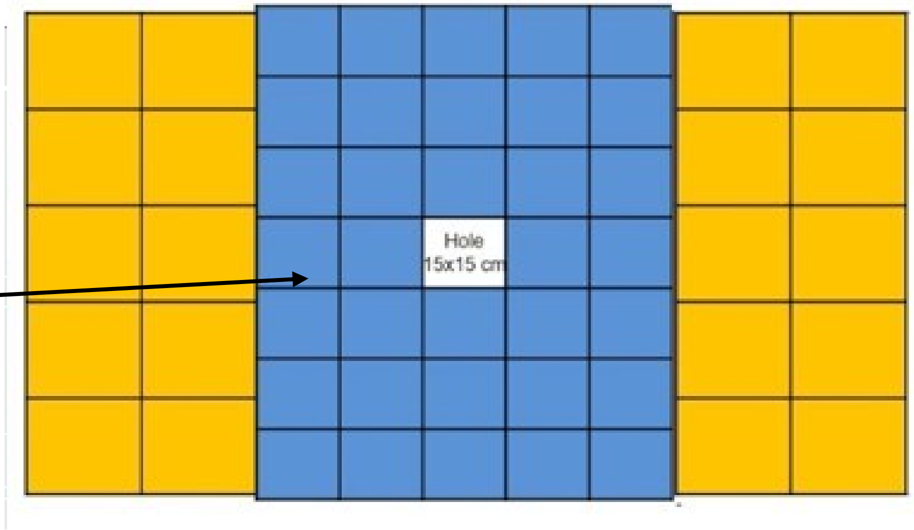
FHCal (Forward Hadron Calorimeter)

module production

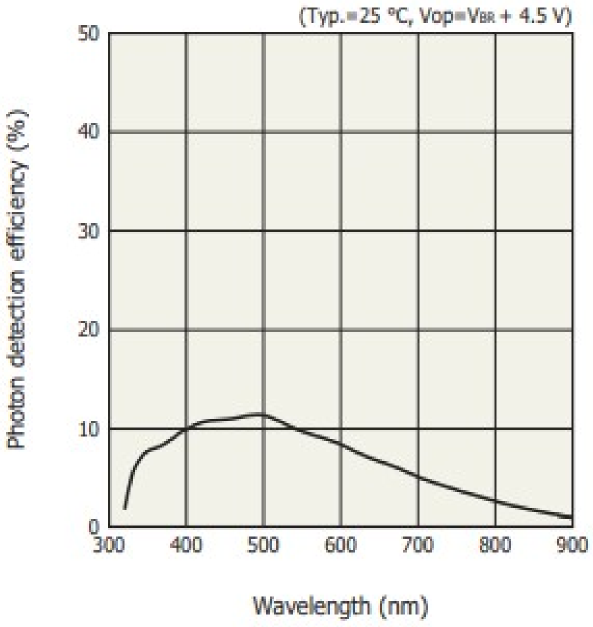


one section

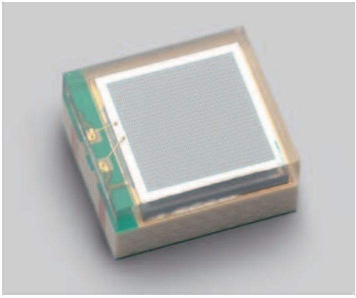
- 34 inner modules 15x15 cm^2 – 42 Pb/scint samples (16mm Pb + 4mm Scint)
- 20 outer modules 20x20 cm^2 – 60 Pb/scint samples (16mm Pb + 4mm Scint)
- Length of small module ~ 4 λ_{int}
  Length of large module ~ 5.6 λ_{int}
- Light collection – 6 WLS fibers from each 6 conseq. scint tiles (one section) combined to one optical connector at the end of module
- Light readout:
  7 MPPCs per small module
  10 MPPCs per large module
- Weight of small module – 200kg
  Weight of large module – 500kg



BM@N FHCal



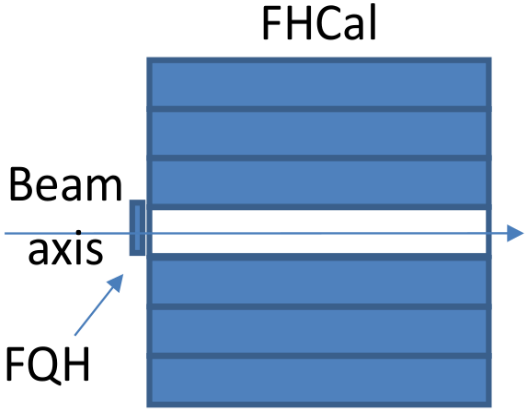
Hamamatsu MPPC S12572-010P
3*3mm^2
Number of pixels: 90000
Gain: 1.35*10^5
PDE: 12%

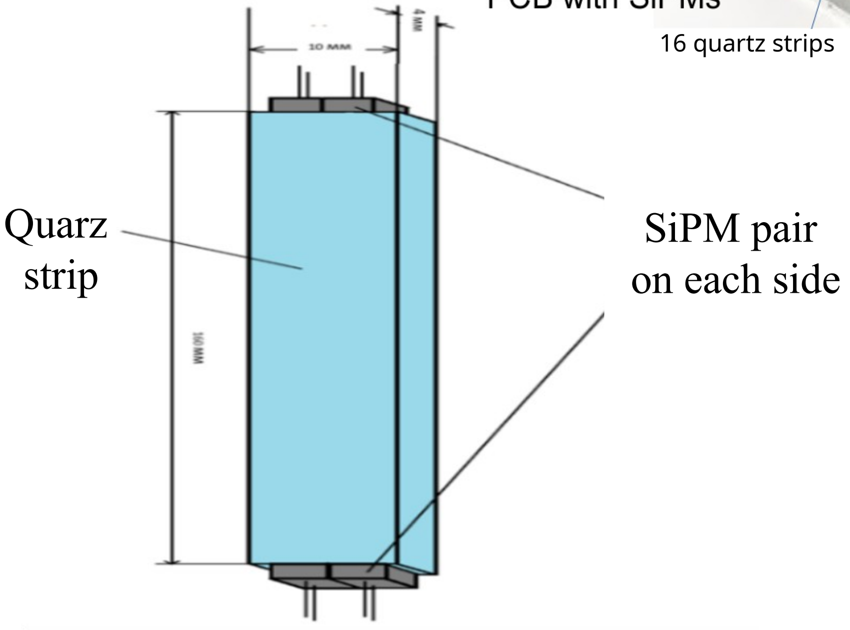


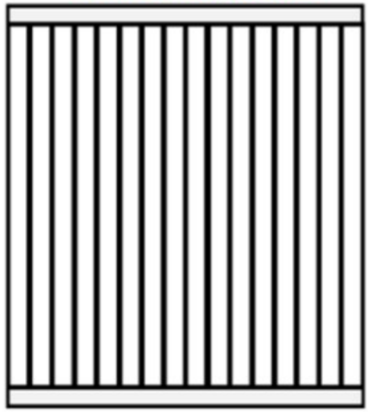
FQH (Forward Quarz Hodoscope)

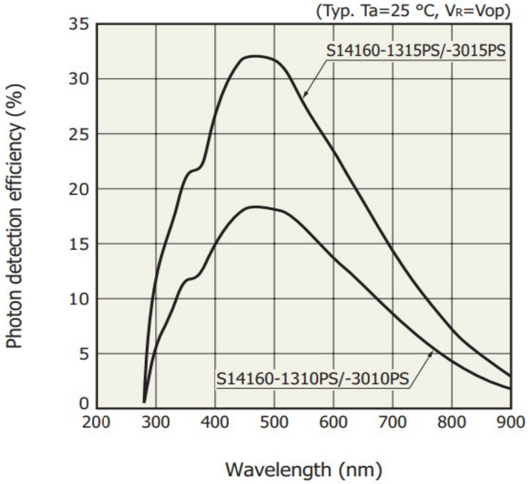
measurement of fragments charge in the FHCal beam hole – very forward rapidity region (for event centrality determination)

- 16 strips 160*10*4 mm^3 with mylar reflector
- cover beamhole 15*15cm^2
- light readout from both edges of each strip
- 2 MPPCs connected in parallel on each side
- each MPPC pair is read with gains x1 and x4

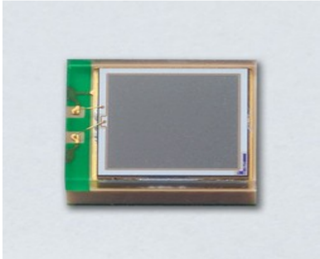




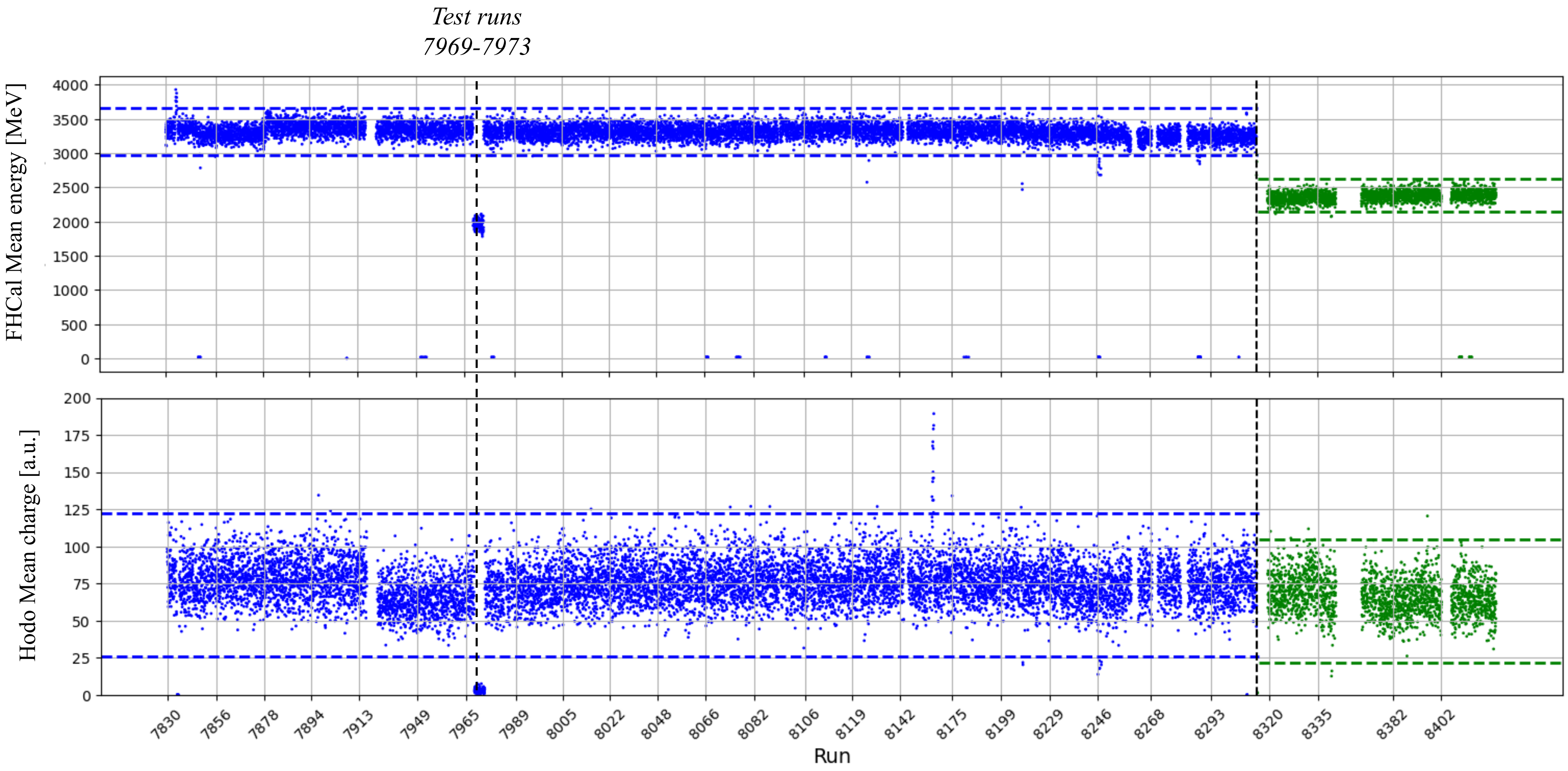




Hamamatsu MPPC S14160-3015PS 3*3mm^2
Number of pixels: 39984
Gain: 3.6*10^5
PDE: 32%



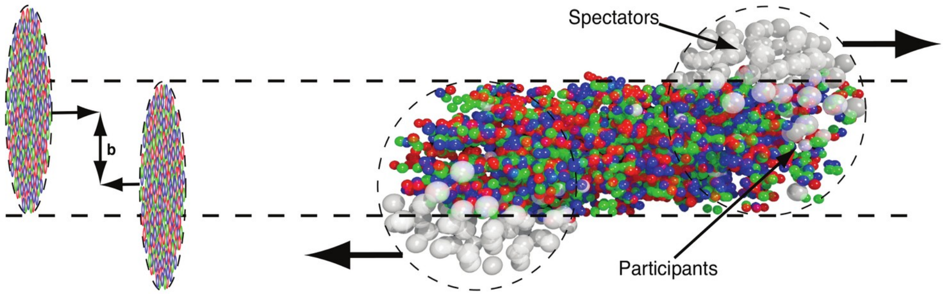
Forward detectors in experimental run XeCsI 3.8A GeV and 3.0A GeV

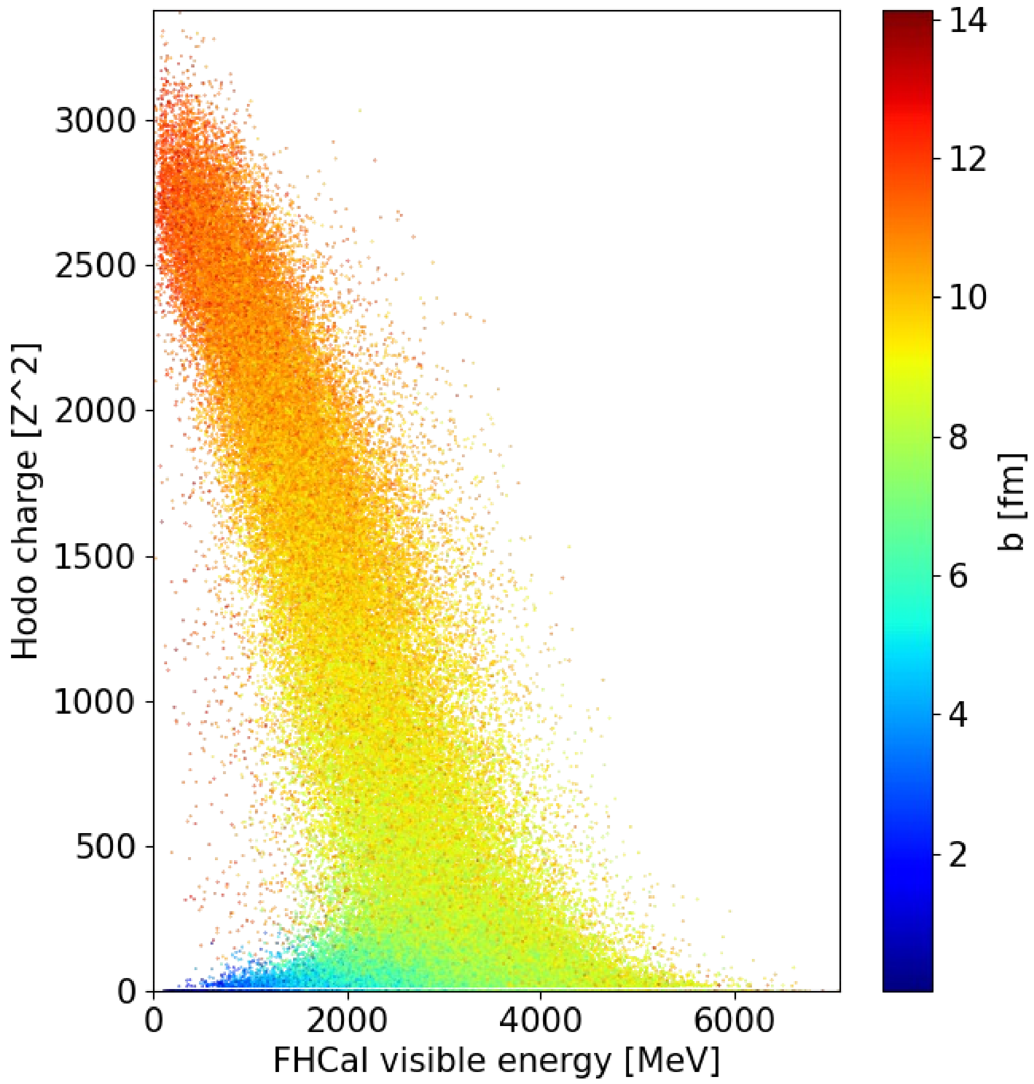


- Forward detectors exhibited stable operation throughout BM@N Experimental Run in 2022-2023.
- Two collision energies were measured
- Almost all statistics fall within 5σ borders, otherwise marked problematic

Event centrality: FQH&FHCal correlation

*XeCsI@**3.8A GeV**. DCM-QGSM-SMM 250k minbias*

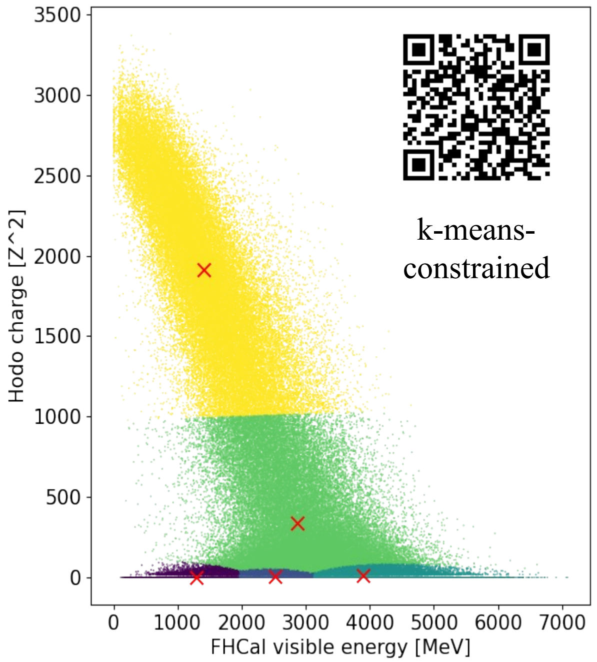


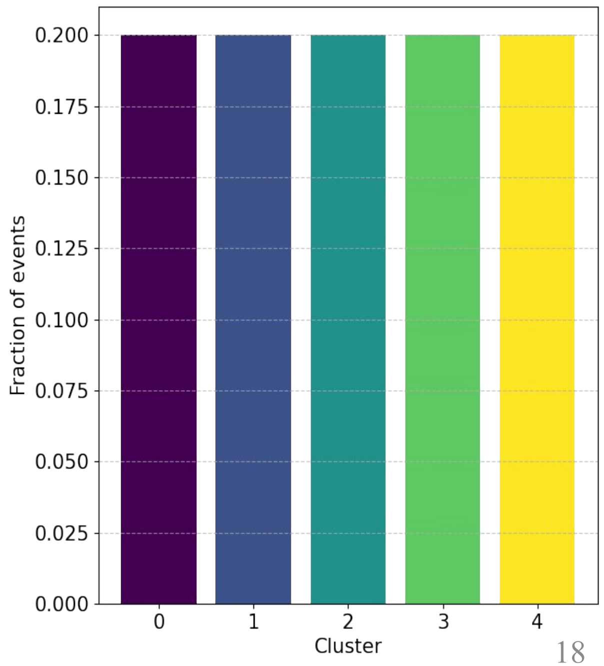


$$c(b) = \frac{\int_0^b \frac{d\sigma}{db'}db'}{\int_0^\infty \frac{d\sigma}{db'}db'} = \frac{1}{\sigma_{A-A}} \int_0^b \frac{d\sigma}{db'}db'$$

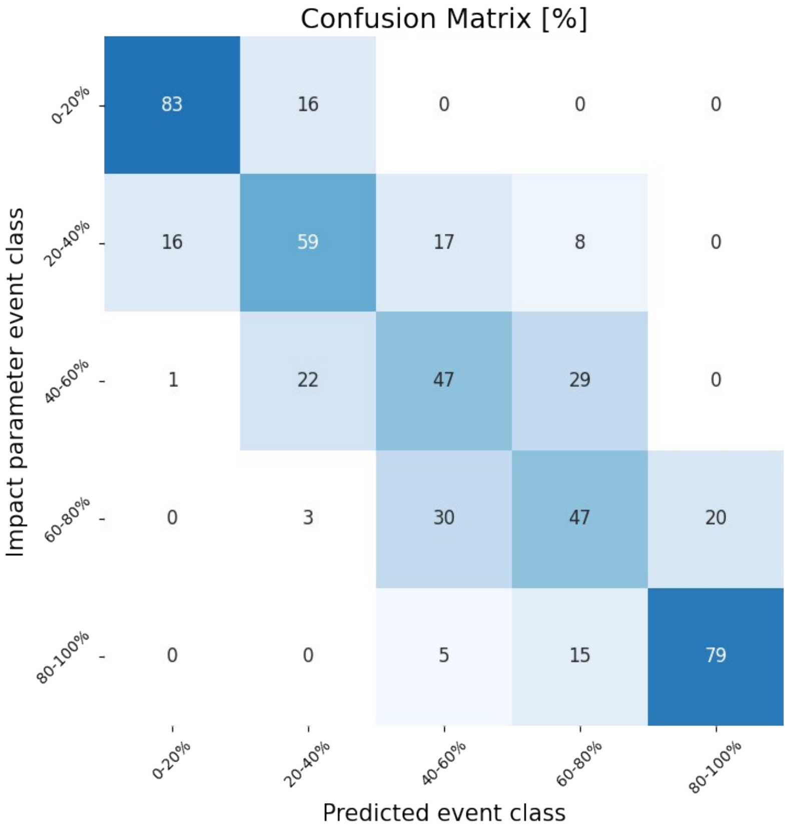
The impact parameter b is not a measurable quantity, therefore experimental observables are used to determine centrality.

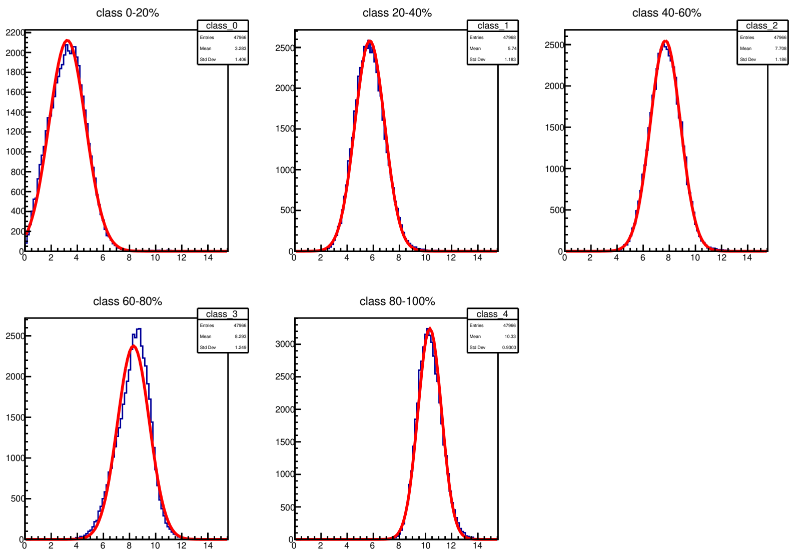
Event class as <u>clusterization</u> task: $c \approx \frac{1}{\sigma_{A-A}} \int_{\mathbf{X}\in\mathbf{\Omega_k}} \frac{d\sigma}{d\mathbf{X}} d\mathbf{X}$

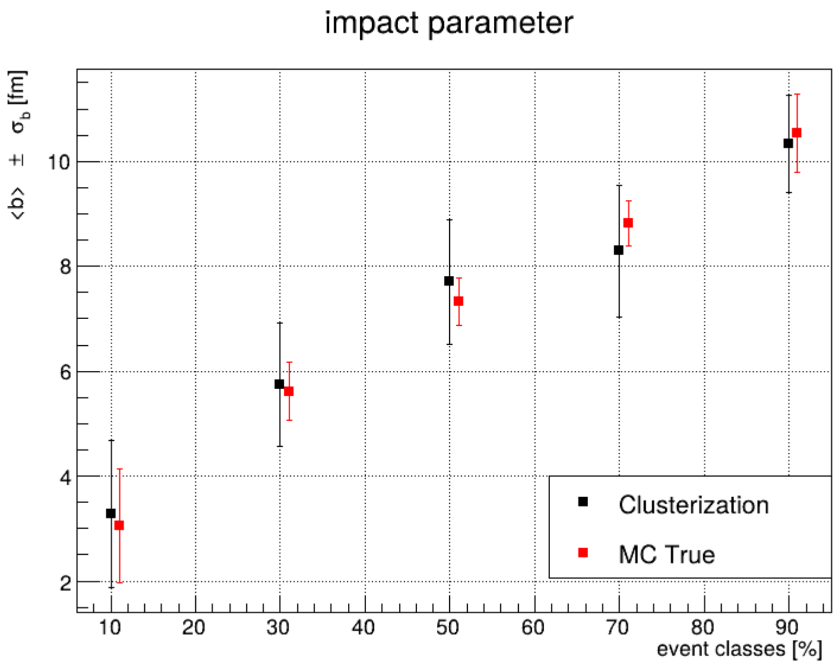




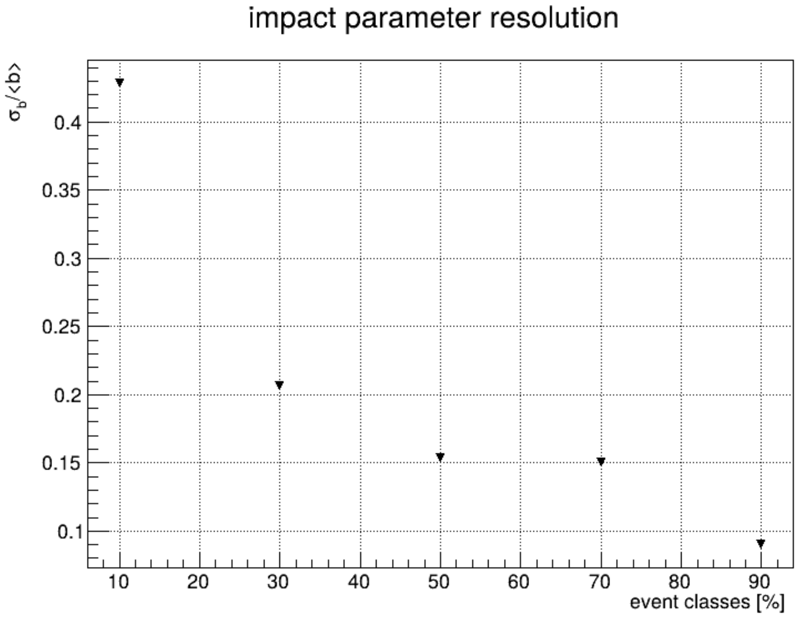
Event characterisation: Cluster information from simulation







*XeCsI@**3.8A GeV**. DCM-QGSM-SMM 250k minbias*



Bayesian inversion is upcoming to determine centrality in experimental data

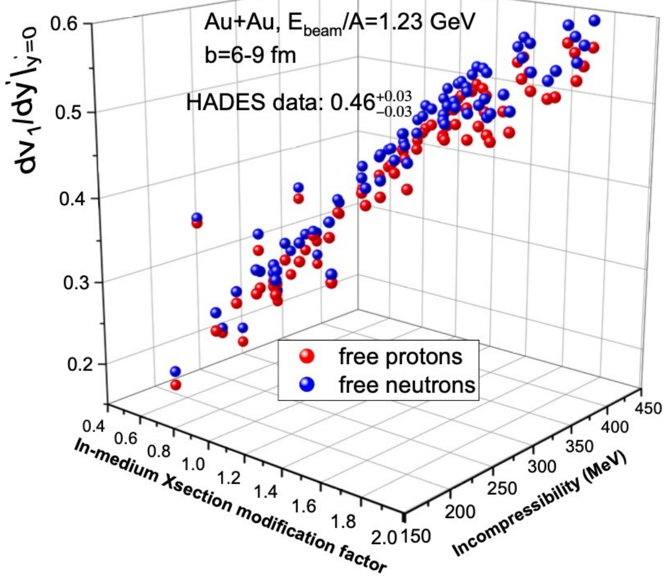
Conclusions

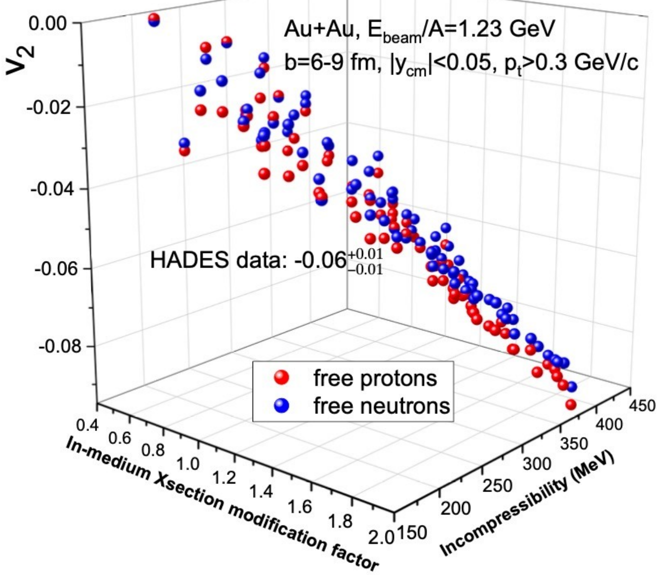
- New Highly-Granular Neutron Detector is a perspective detector for the BM@N experiment aimed to explore the symmetry energy in the high baryon density region
- Construction status:
  - Scintillator Cells: All ~2,000 cells (40x40x25 mm^3) have been built.
  - PCB: Design is finalized and production is underway.
  - Readout board: The FPGA-based TDC readout board is under active development.
  - Prototype: First mock-up prototype with scintillator layer assembled; beam test preparations completed.
  - Timeframe: To be commissioned by the end of 2025.
- Forward spectator detectors are designed for the BM@N experiment to estimate centrality and reaction plane
- They were used for the first time in physics run at BM@N and have demonstrated stable work throughout the whole experimental session

Thank you for your attention!

BACKUP

Collective flow as sensitive probe to the EOS

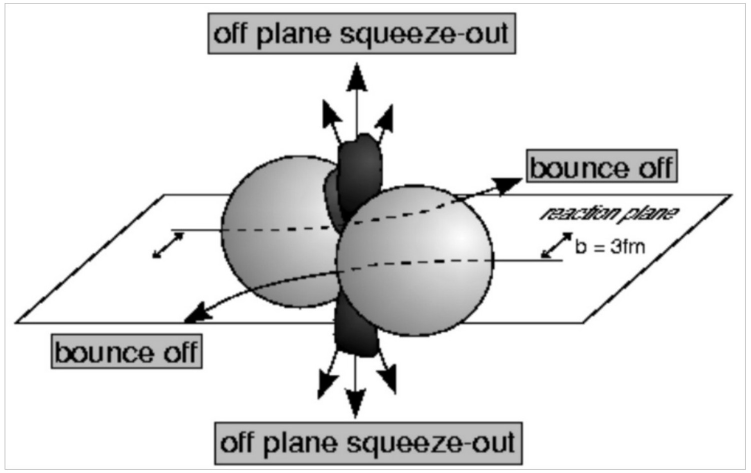




Incompressibility parameter $K_0(\rho)$:

Specifies the behavior of EOS in the given baryon densities

Models with flexible EOS for different (K_0, ρ) are required



$$\frac{dN}{d\varphi} \propto 1+2\sum_{n=1} v_n \cos\left[n\left(\varphi-\Psi_{RP}\right)\right], v_n=\left\langle \cos\left[n\left(\varphi-\Psi_{RP}\right)\right]\right\rangle$$

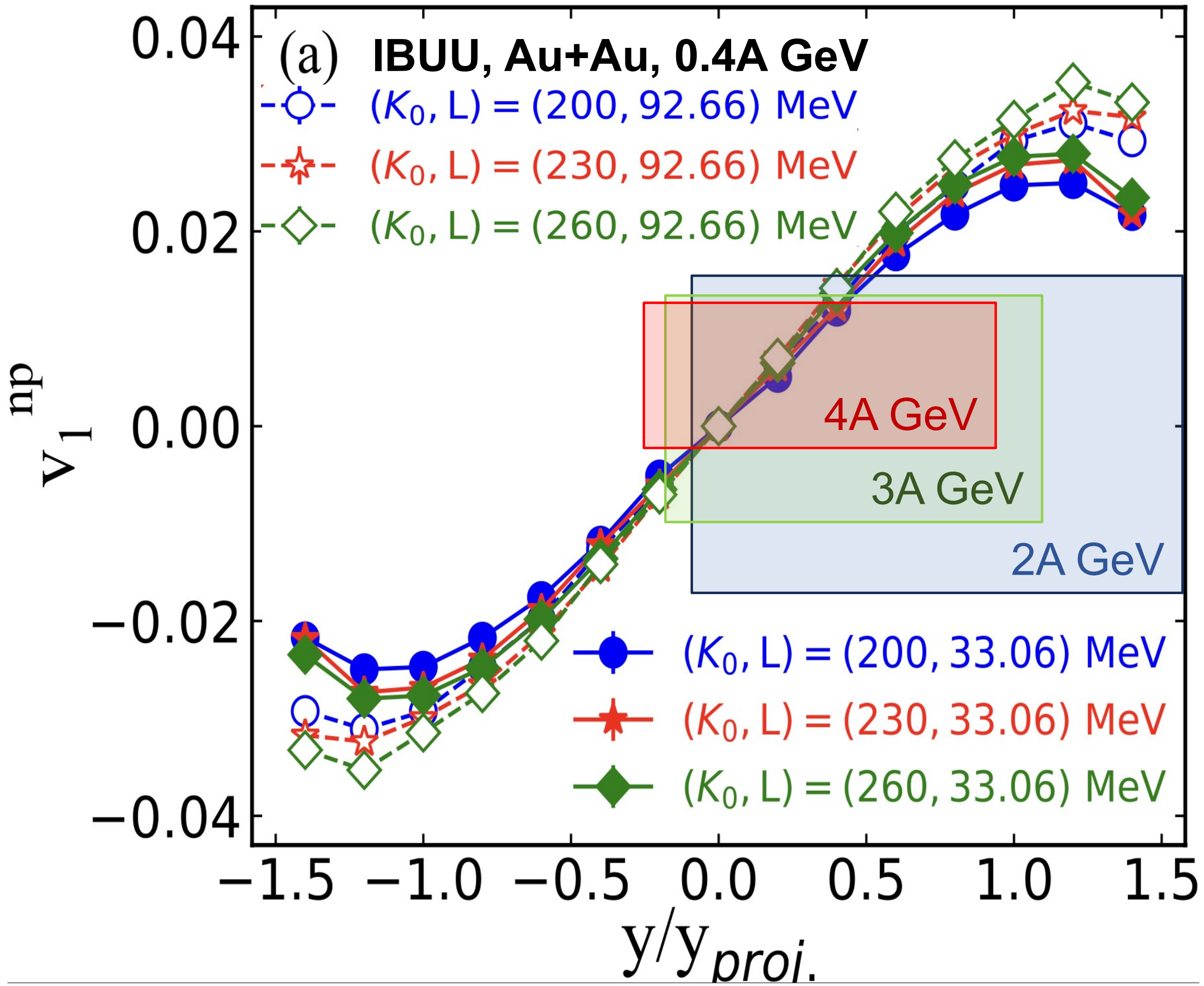
Collective flow is sensitive to:

- Compressibility of the created in the collision matter
- Time of the interaction between the matter within the overlap region and spectators

How to measure the collective flow?

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

P.Russotto, Phys.Rev.C 94, 034608 (2016)

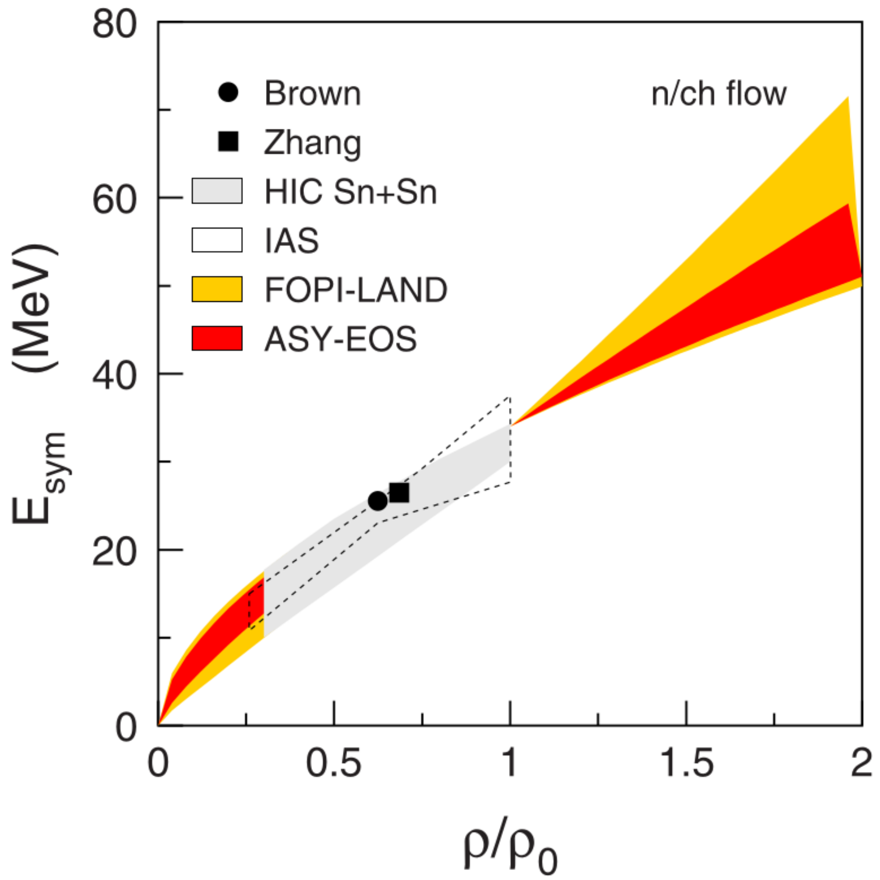
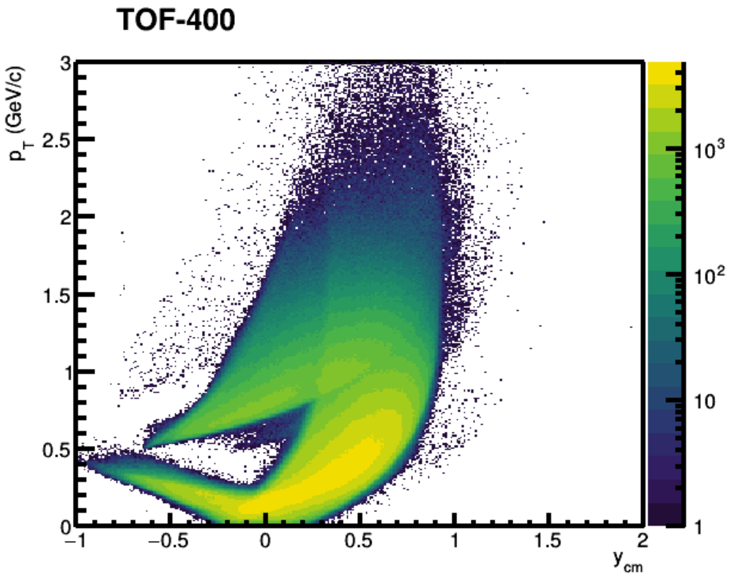
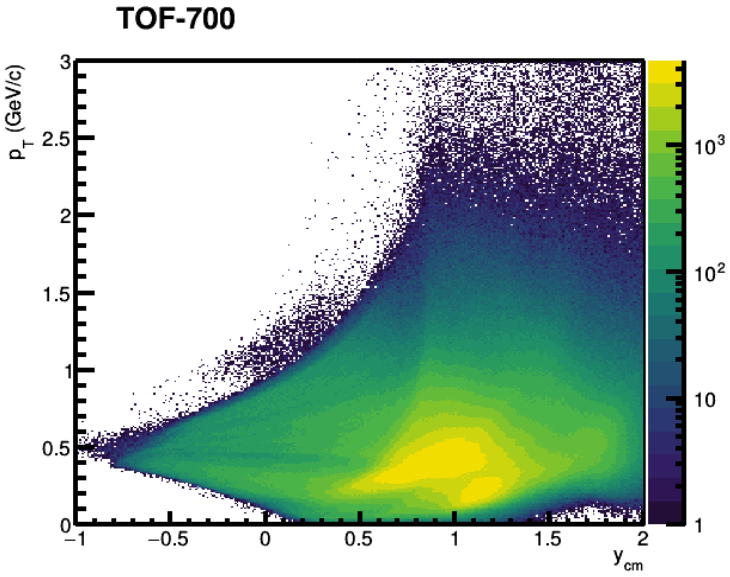
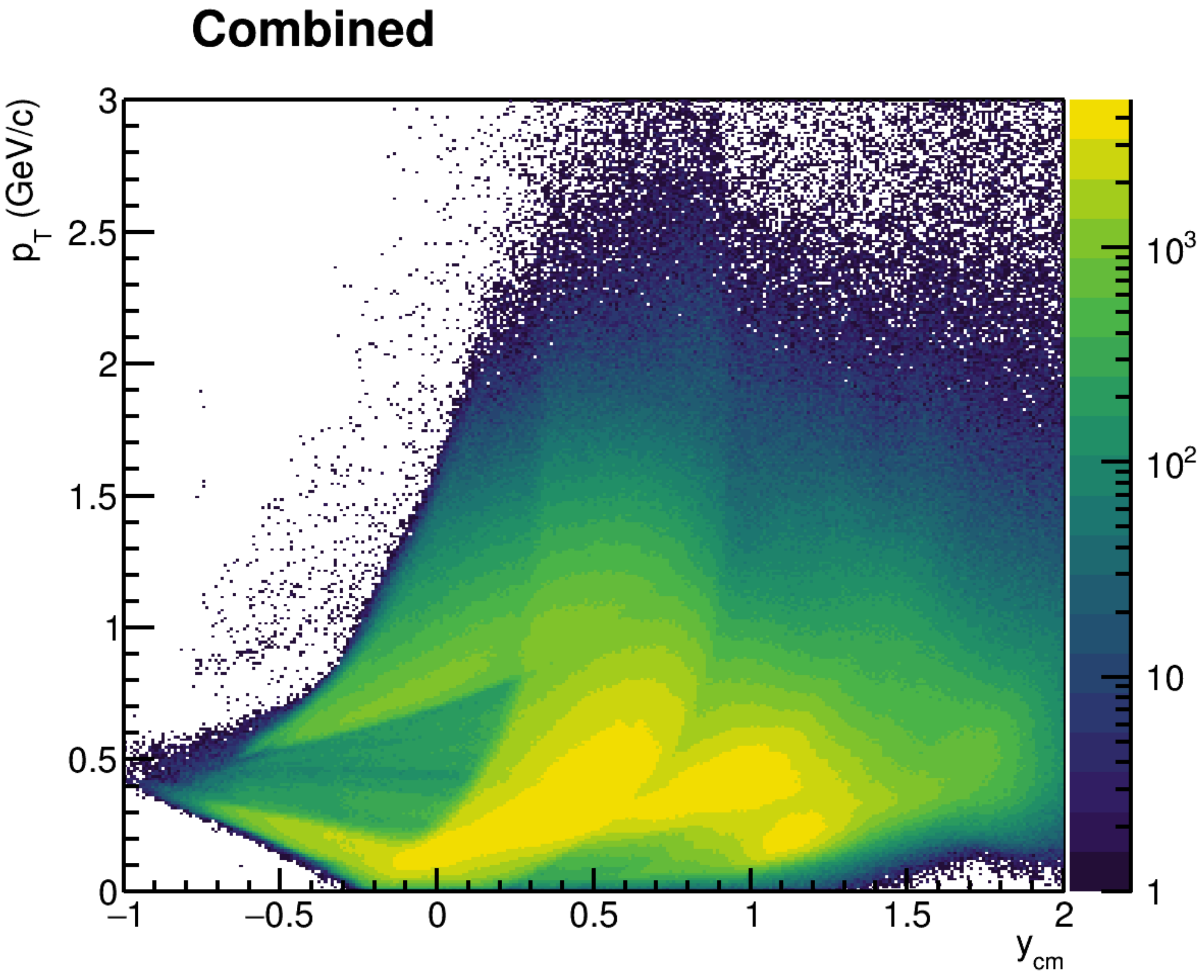


FIG. 18. Constraints deduced for the density dependence of the symmetry energy from the present data in comparison with the FOPI-LAND result of Ref. [5] as a function of the reduced density ρ/ρ_0. The low-density results of Refs. [78–81] as reported in Ref. [82] are given by the symbols, the gray area (HIC), and the dashed contour (IAS). For clarity, the FOPI-LAND and ASY-EOS results are not displayed in the interval $0.3 < \rho/\rho_0 < 1.0$.

Proton p_T-y acceptance

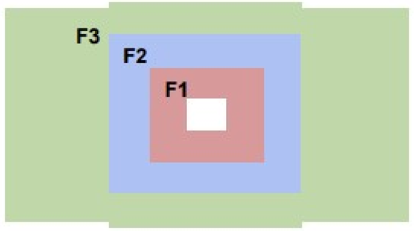




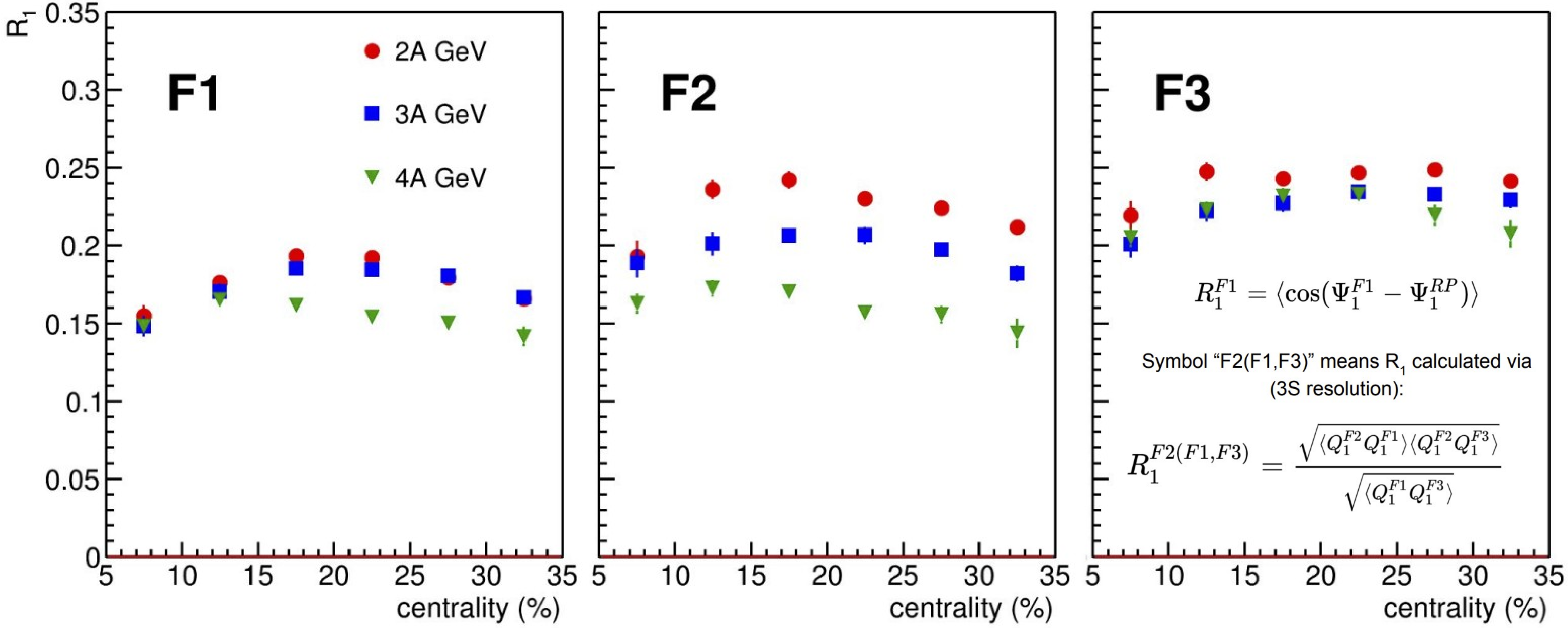


By M.Mamaev

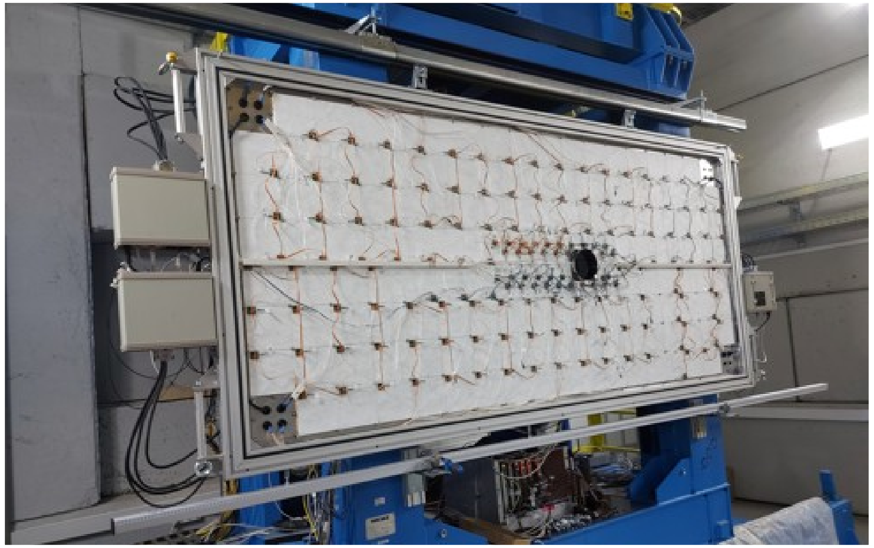
Performance study: R1



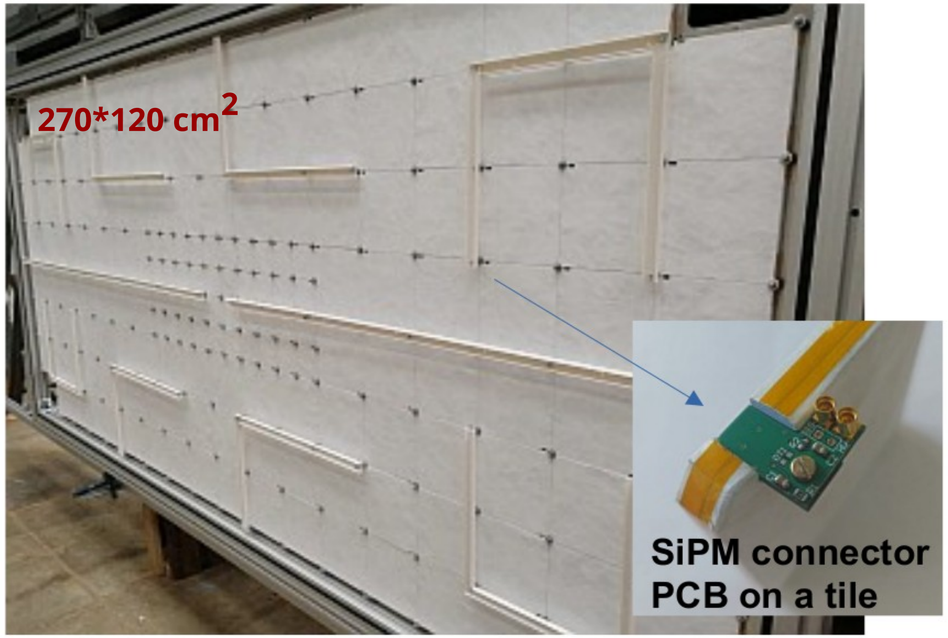
DCMQGSM-SMM

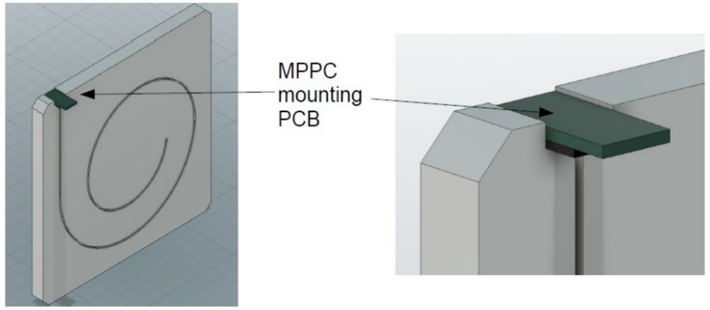


ScWall (Scintillation Wall)

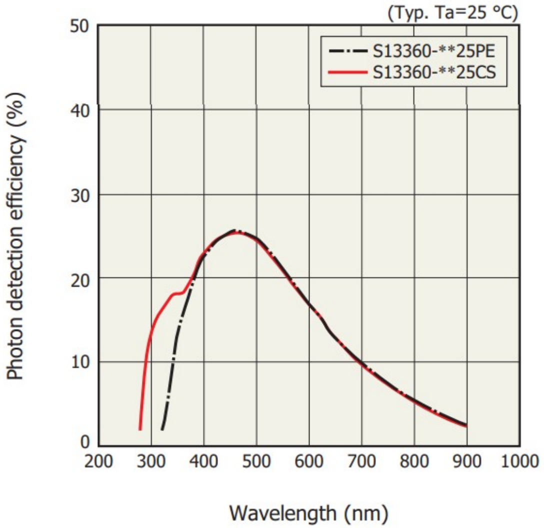


- 36 small inner cells 7.5*7.5*1 cm^3 + 138 big outer cells 15*15*1 cm^3
- light yield for MIP signal – small cells 55 p.e.±2.4%; big cells 32 p.e.± 6%.
- beam hole for heavy fragments
- covered with a light-shielding aluminum plate
- light collection by WLS fibers
- light readout with SiPM mounted on the PCB at each scint. cell





light collection from tiles



Hamamatsu MPPC S13360-1325CS 1.3*1.3mm^2
Number of pixels: 2668
Gain: 7*10^5
PDE: 25%

ScWall Z^2 distributions