Time-over-Threshold Method for the BM@N Highly-Granular Neutron Detector

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on behalf of the INR RAS team

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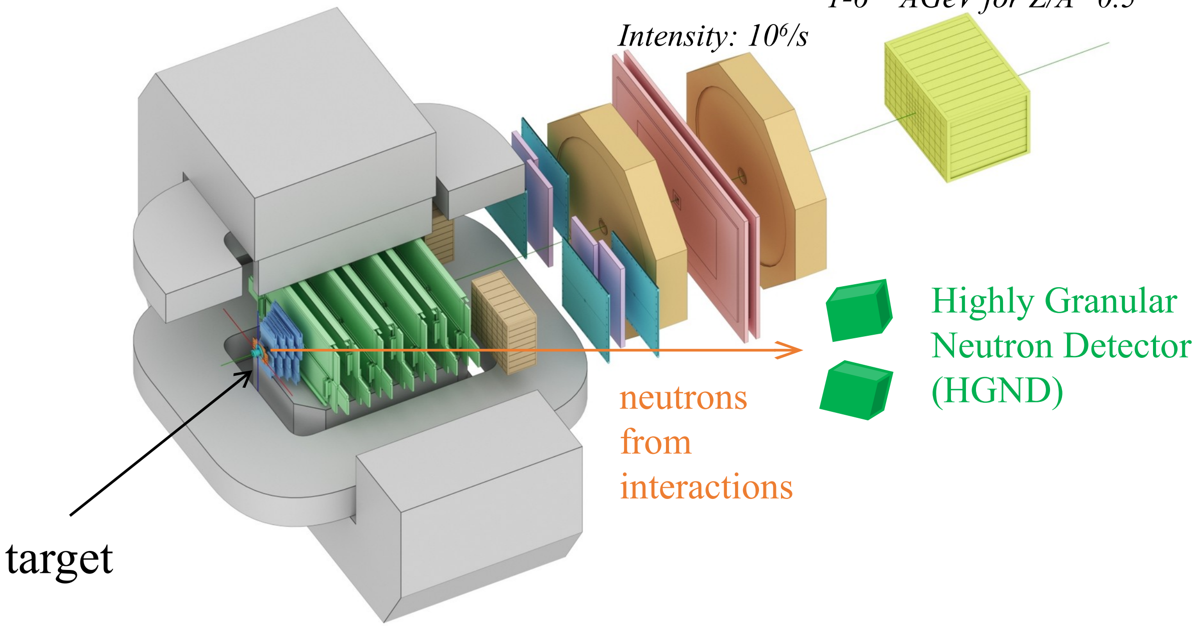
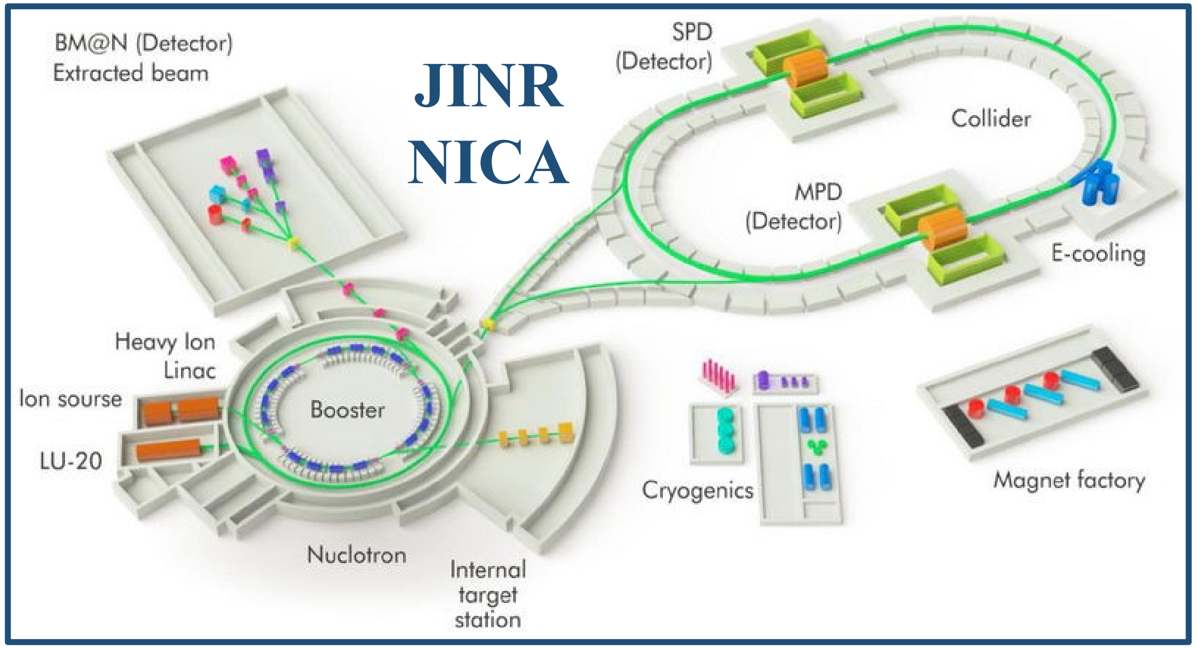
25th of October 2024, Moscow

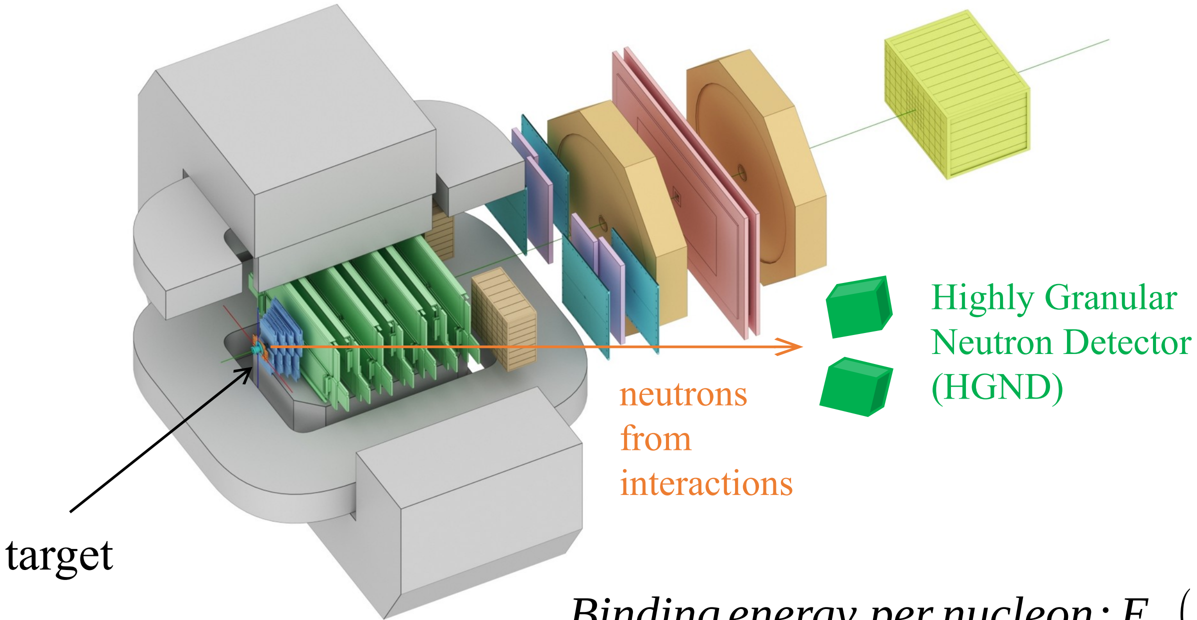
BM@N setup

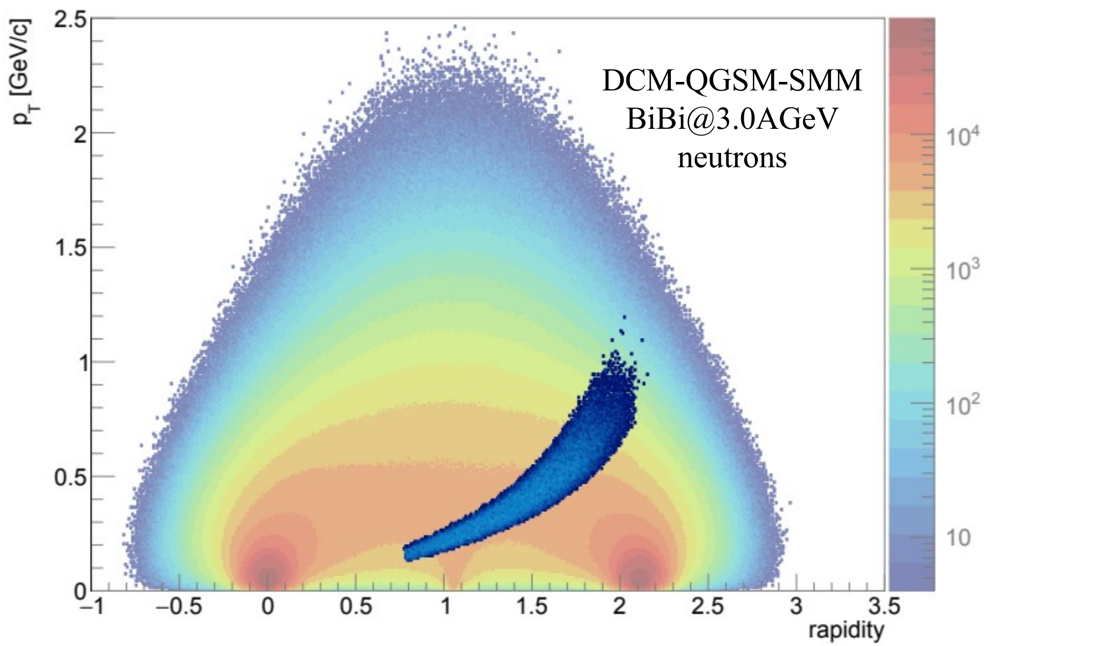
Beams: p to Au
Kinetic energy: 1-4.5 AGeV for Z/A=0.4
1-6 AGeV for Z/A=0.5
Intensity: 10^6/s





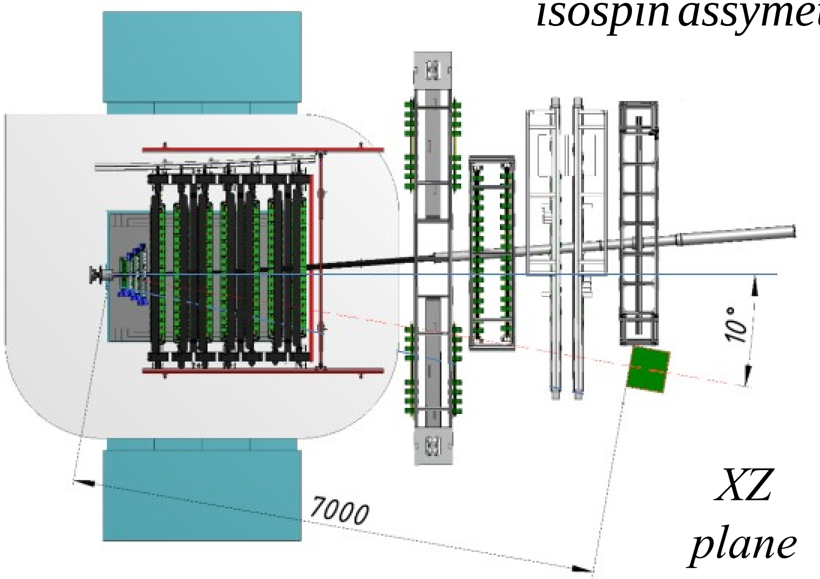
BM@N setup





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

isospin assymetry: $\delta=(\rho_n-\rho_p)/\rho$



XZ plane

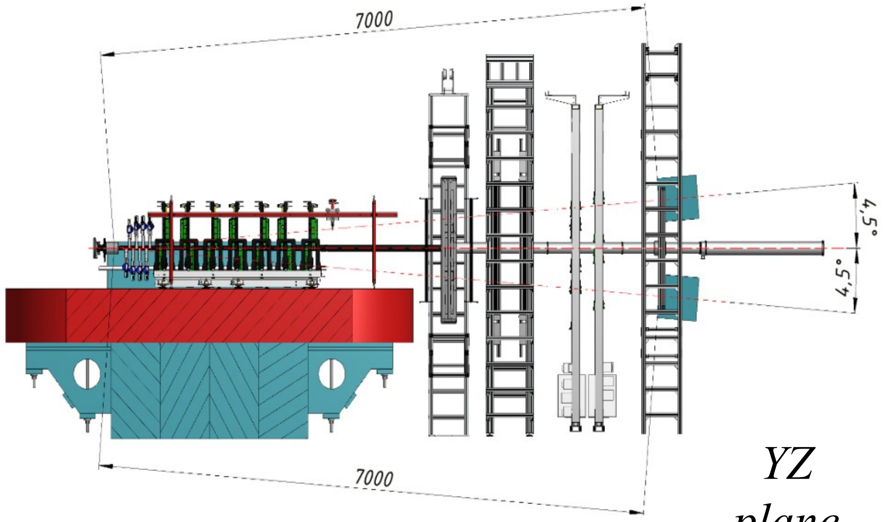
Goal: understanding the symmetry energy in the uncovered region of high baryon densities

How:

- Differential study of n/p ratio

Measure:

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



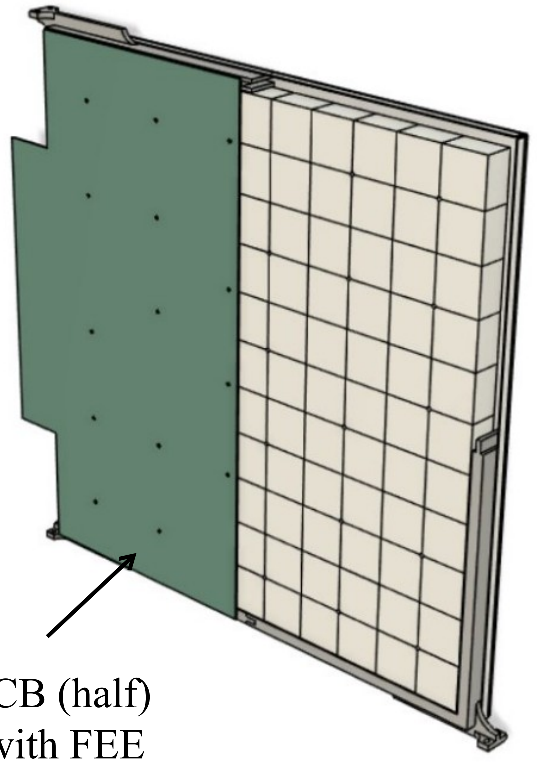
YZ plane

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

Mechanical design

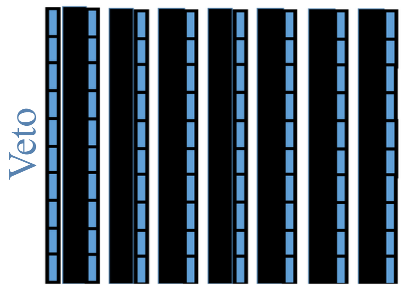
Light-tight and air-cooled assembly of 2 separate arms. Each arm:

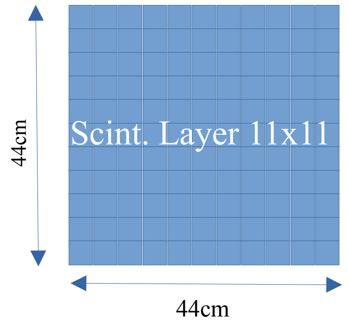
- 1 veto-layer
- 7 Cu absorber layers (3 cm thick)
- 7 sensitive layers:
  - 11x11 matrix of scintillator detectors 4x4x2.5 cm^3
  - surrounded from both sides by PCBs
    - upstream board: LEDs for time calibration
    - downstream board: SiPMs and FEE



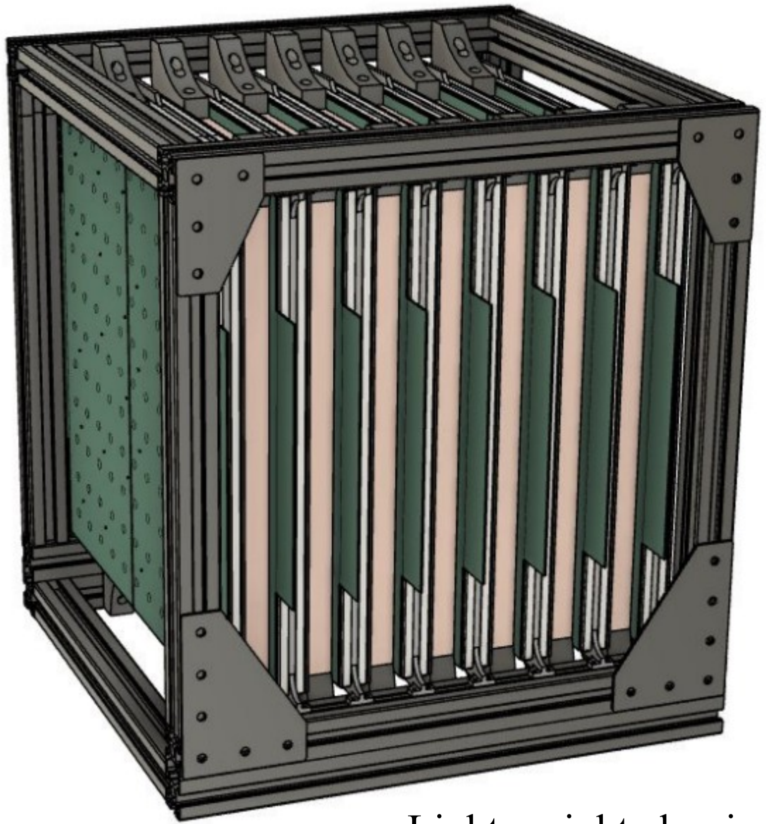
PCB (half) with FEE

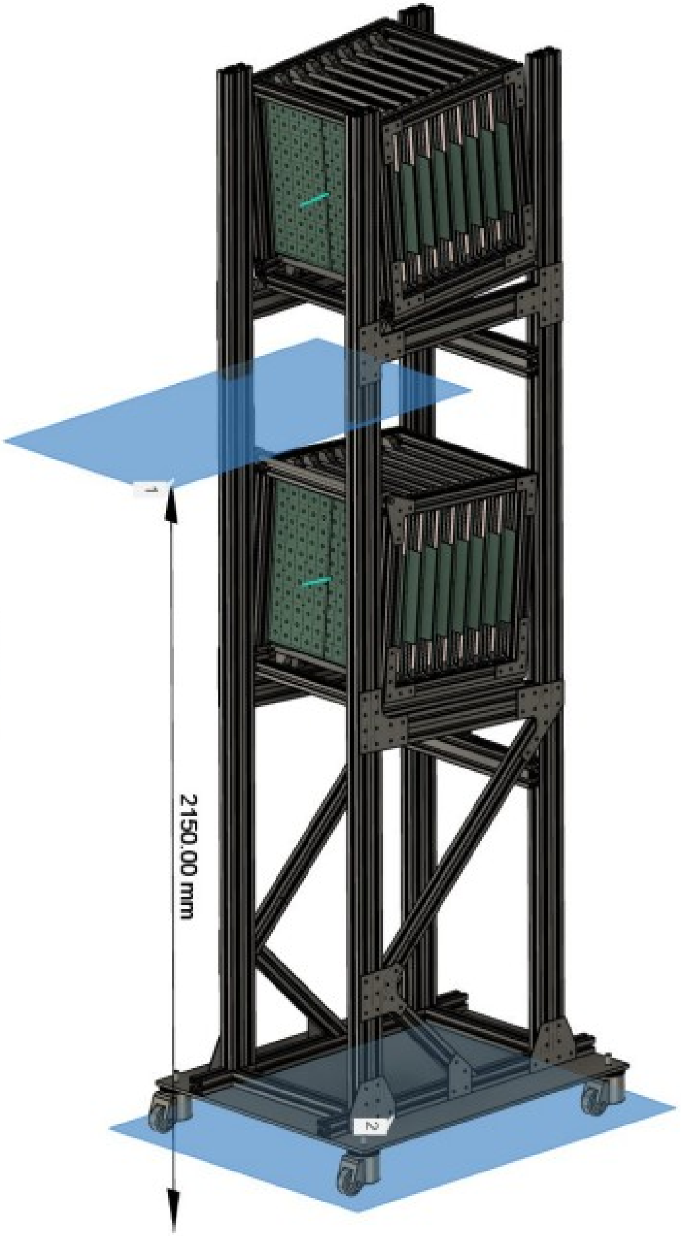
7 layers (Cu/Scint)



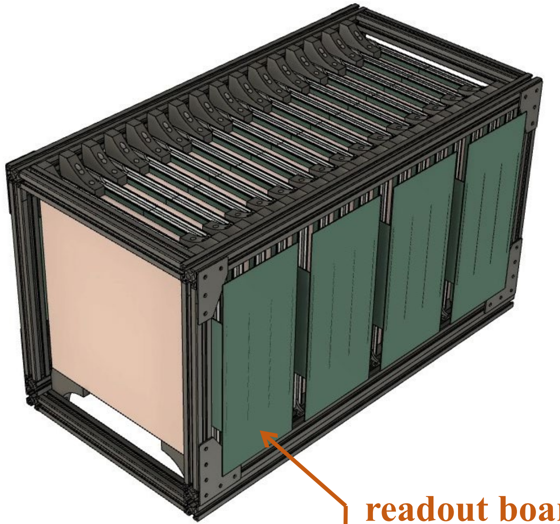


total length ~ 48cm (1.5 λ_{in})

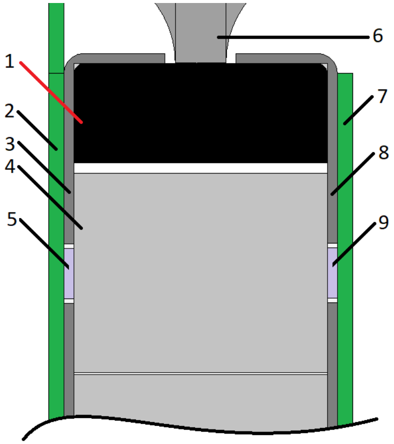




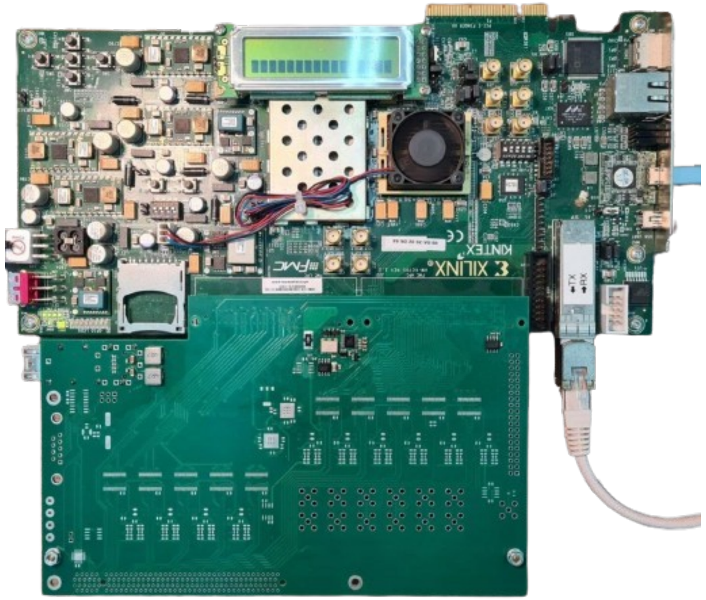
Light-weight aluminum frame



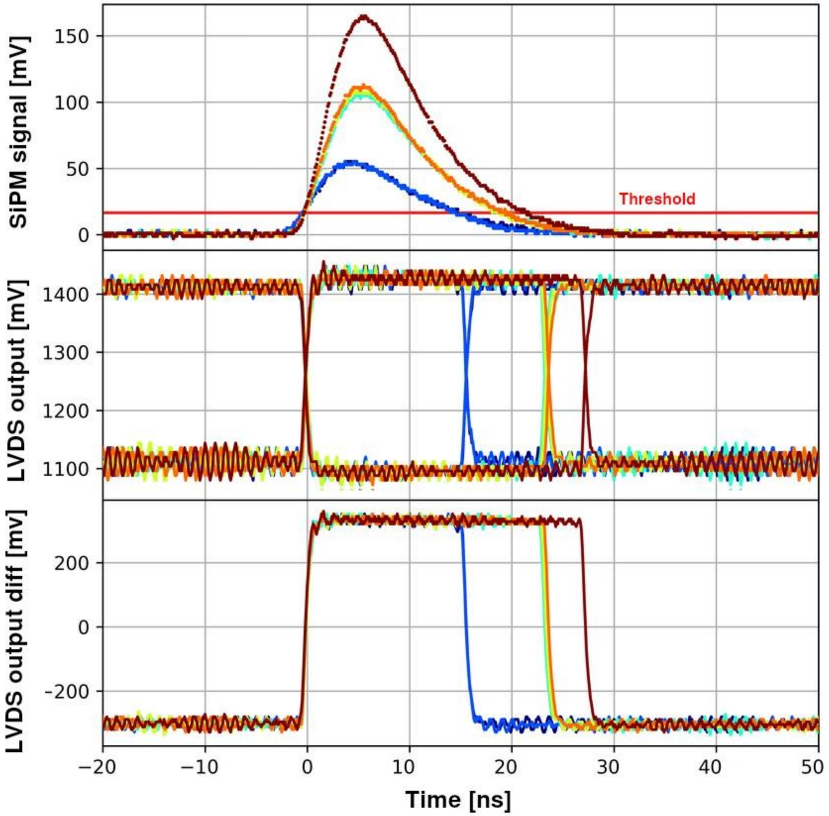
readout board



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 board prototype based on Xilinx Kintex 7 Evaluation Board



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

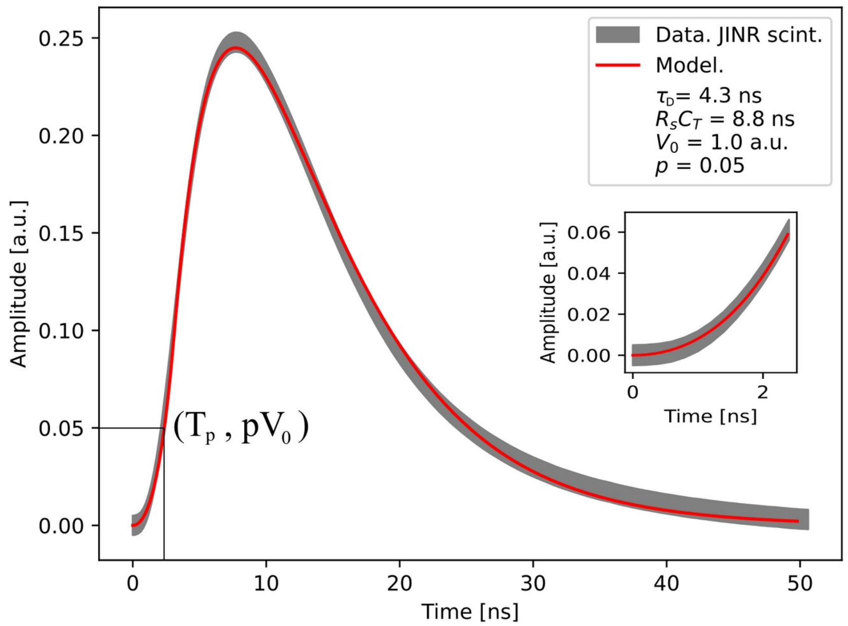
- Dynamic range: 0.5-7 MIP
- Time resolution: 135 ps
- Amplitude resolution: < 20% (reconstructed from ToT)

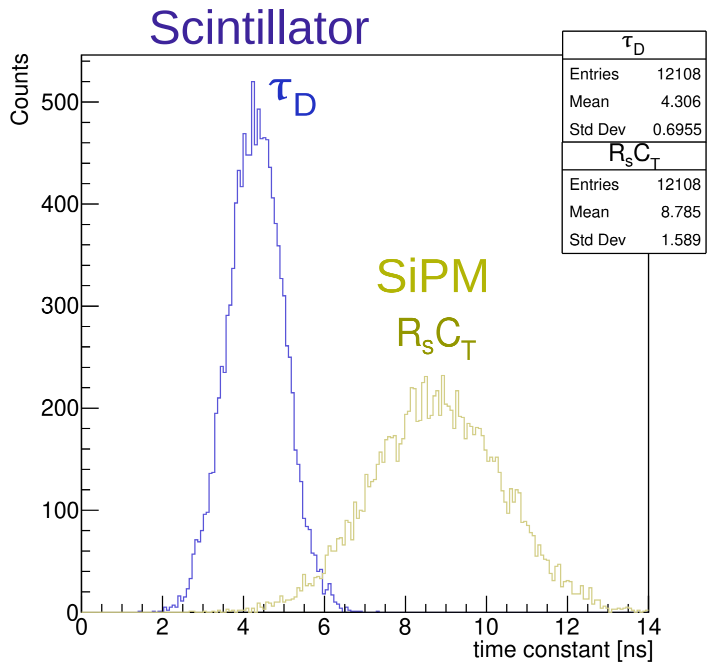
F. Guber, et al., Instrum. Exp. Tech. 66 (2023) 4, 553-557.
D. Finogeev, et al., Nucl. Instrum. Meth. A 1059 (2024) 168952.

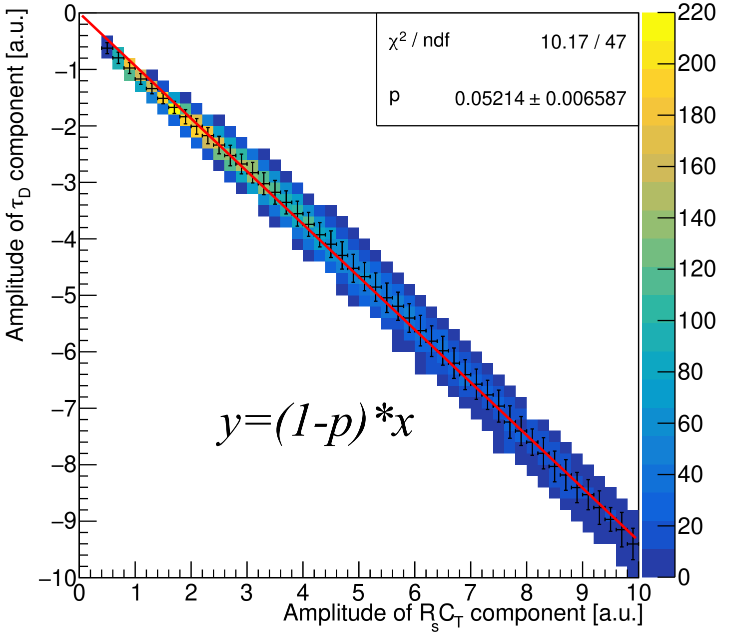
SiPM: Beijing NDL EQR15 11-6060D-S
- Active area 6×6 mm^2
- Pixel size15×15 μm^2
- Total pixels: 160 000
- PDE: 45%
- Gain: $4*10^5$

Analytical description of light signals captured by SiPM

CAEN DT5742 5GHz sampling rate





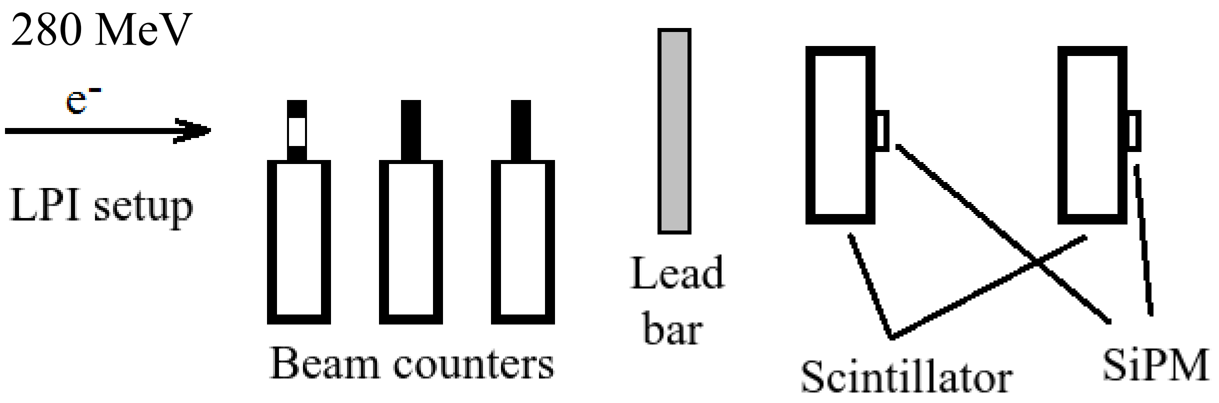


N. Karpushkin, et al., Nucl. Instrum. Meth. A 1068 (2024) 169739.

$$V_0 \equiv \frac{\eta q G N^0_{ph} R_s}{R_s C_T - \tau_D} \qquad T_p = \frac{2e-1}{e-1}\,\frac{p R_s C_T \tau_D}{R_s C_T(1-p) - \tau_D}$$

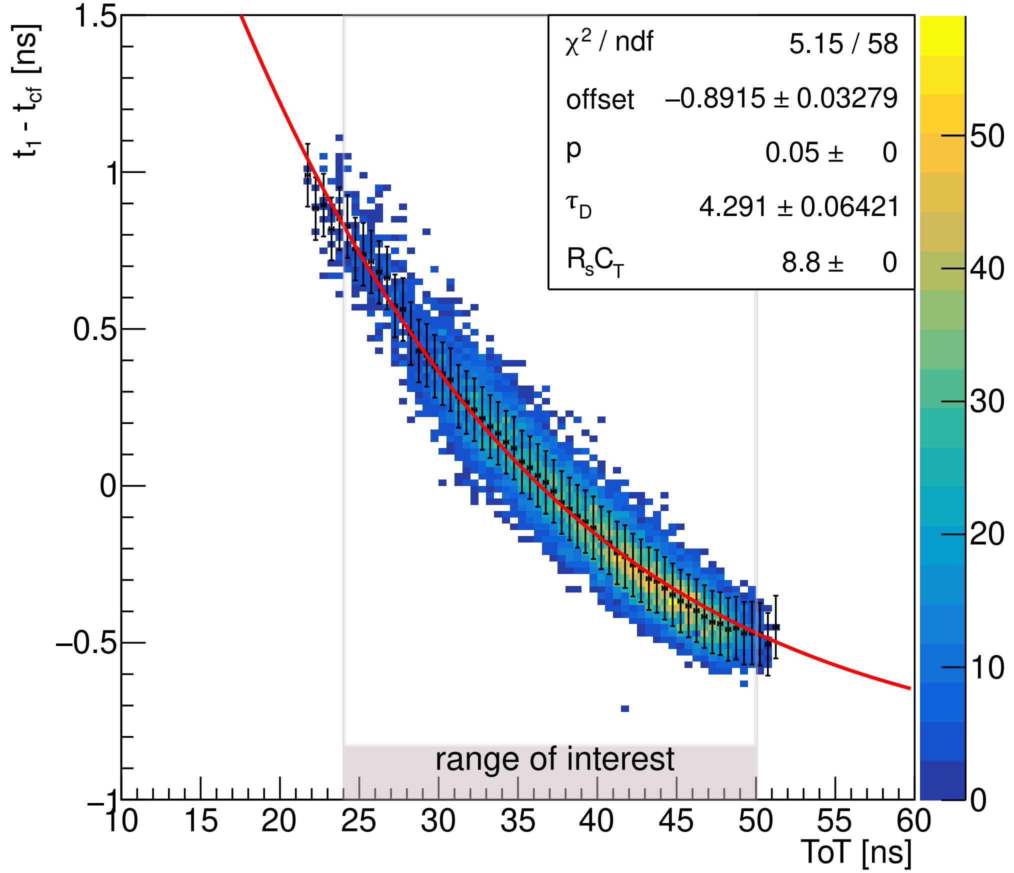
$$V(t) = \begin{cases} \frac{pV_0}{e-1}\frac{t}{T_p}\left(e^{\frac{t}{T_p}} - 1\right) & \text{if } 0 \le t < T_p \\ V_0\left(e^{-\frac{t-T_p}{R_sC_T}} - (1-p)e^{-\frac{t-T_p}{\tau_D}}\right) & \text{if } t \ge T_p \end{cases}$$

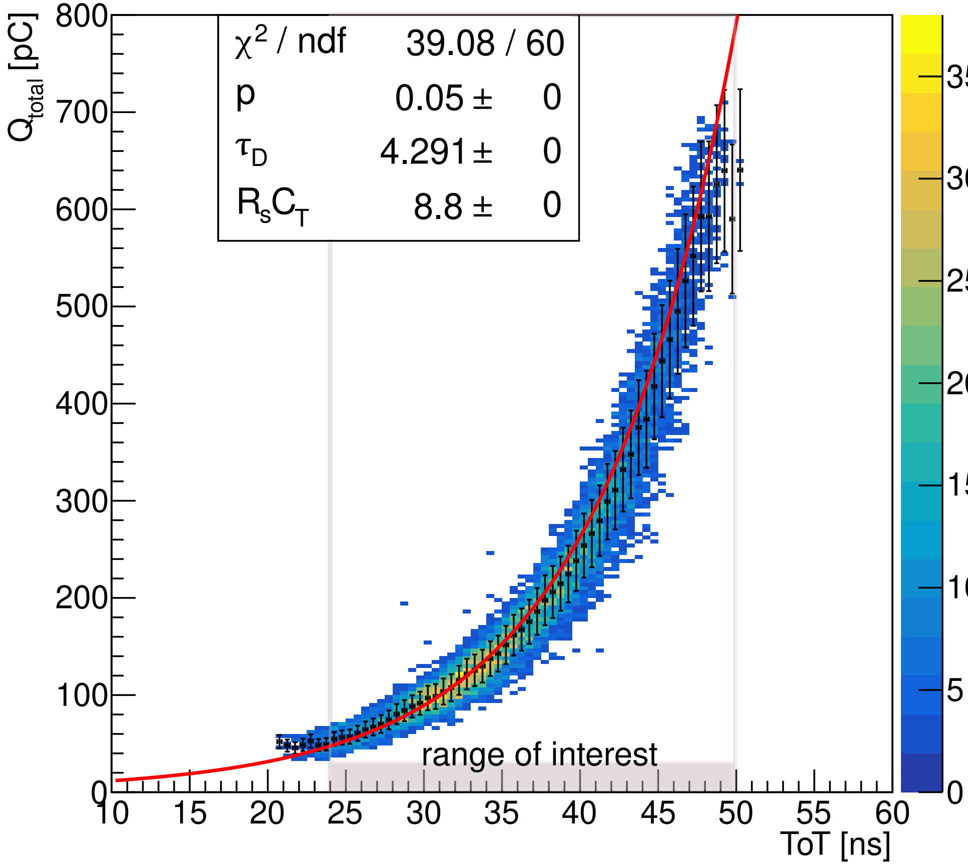
free parameters: τ_D, R_sC_T, p



$$t_1 \approx 2R_sC_TW_0\left(\frac{T_p}{2R_sC_T}\sqrt{\frac{e-1}{p}e^{\frac{T_p-ToT}{2R_sC_T}}}\right) \qquad ToT \equiv t_2 - t_1$$

$$Q_{total} = \frac{\theta}{R_s}\left(\frac{pT_p}{2(e-1)} + R_sC_T - \tau_D(1-p)\right)e^{\frac{ToT+t_1-T_p}{R_sC_T}}$$





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

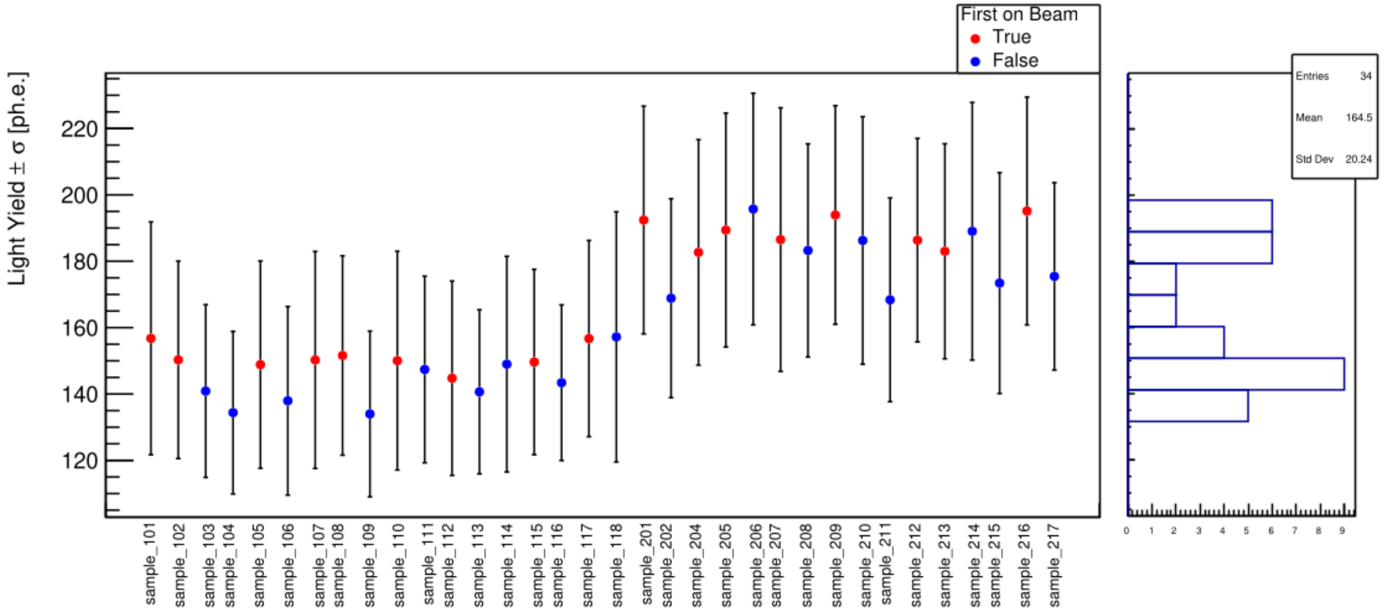
Purpose:

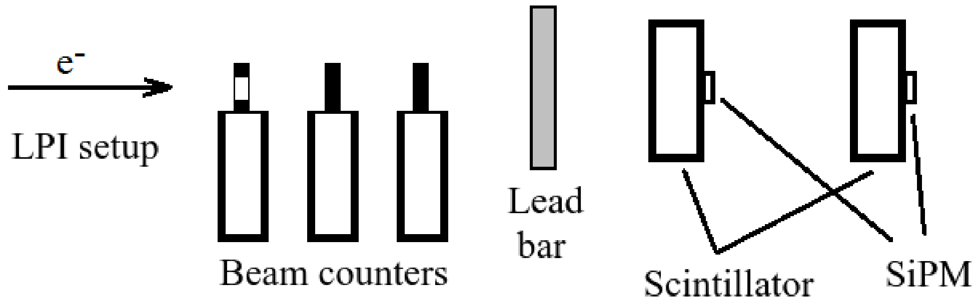
- Perform slewing correction based on physical principles

By-product:

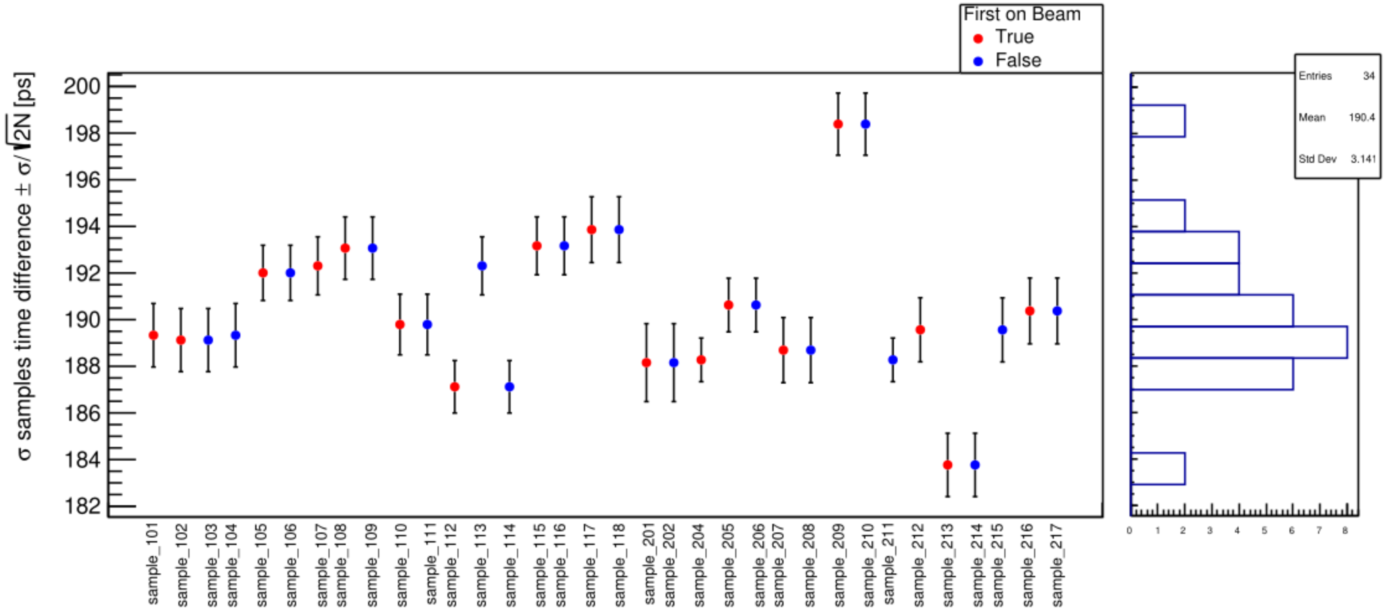
- Ideal: obtain τ_D , R_sC_T , p from tdc:tot slewing correction fit and reconstruct signal charge
- Reality: tdc:tot correlation shows low sensitivity to p and R_sC_T, therefore these parameters are fixed at their average values

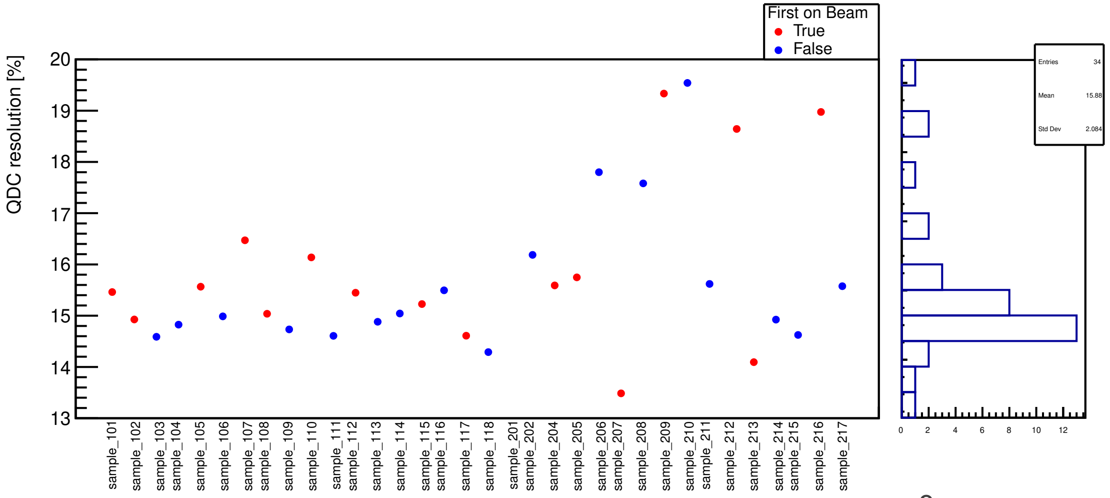
34 scintillator samples from 2 production series were tested at 280-MeV electron beam at LPI.





LPI test March 2024 averaged results		
Measurement	Average in center	Gradient
Light Yield	151 or 179 p.e.	-43 p.e./cm
Time resolution	135 ps	+16 ps/cm
Charge resolution	<20 %	0 %/cm



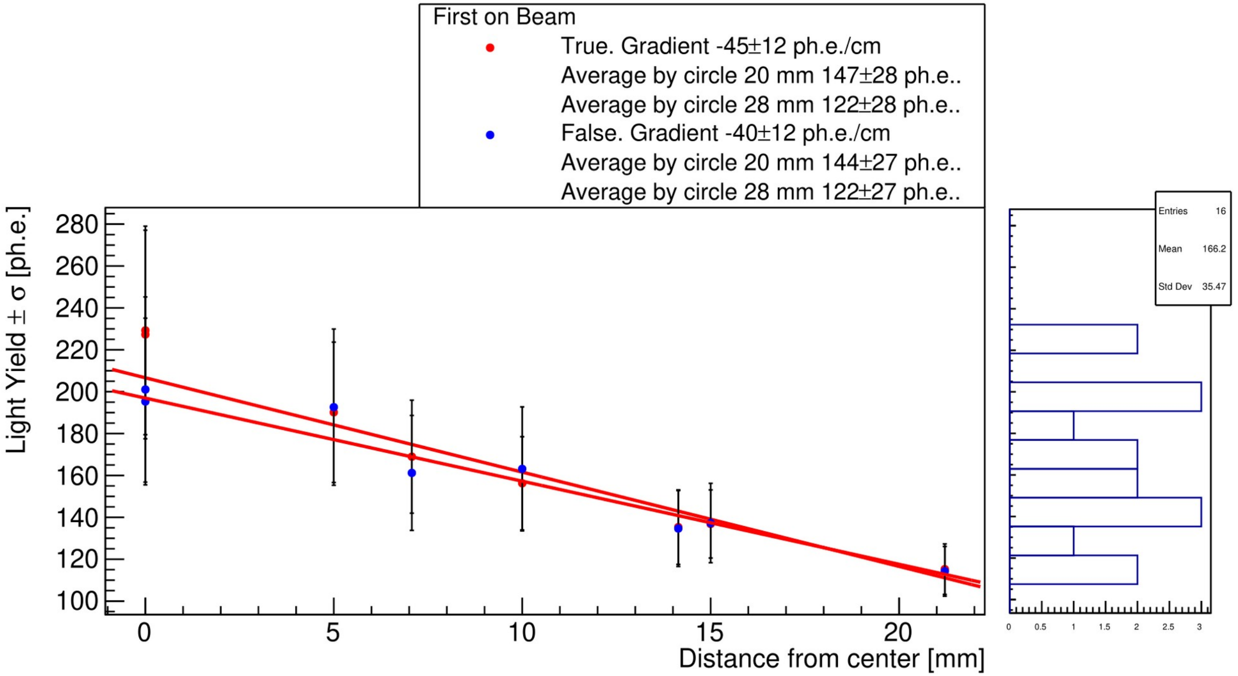


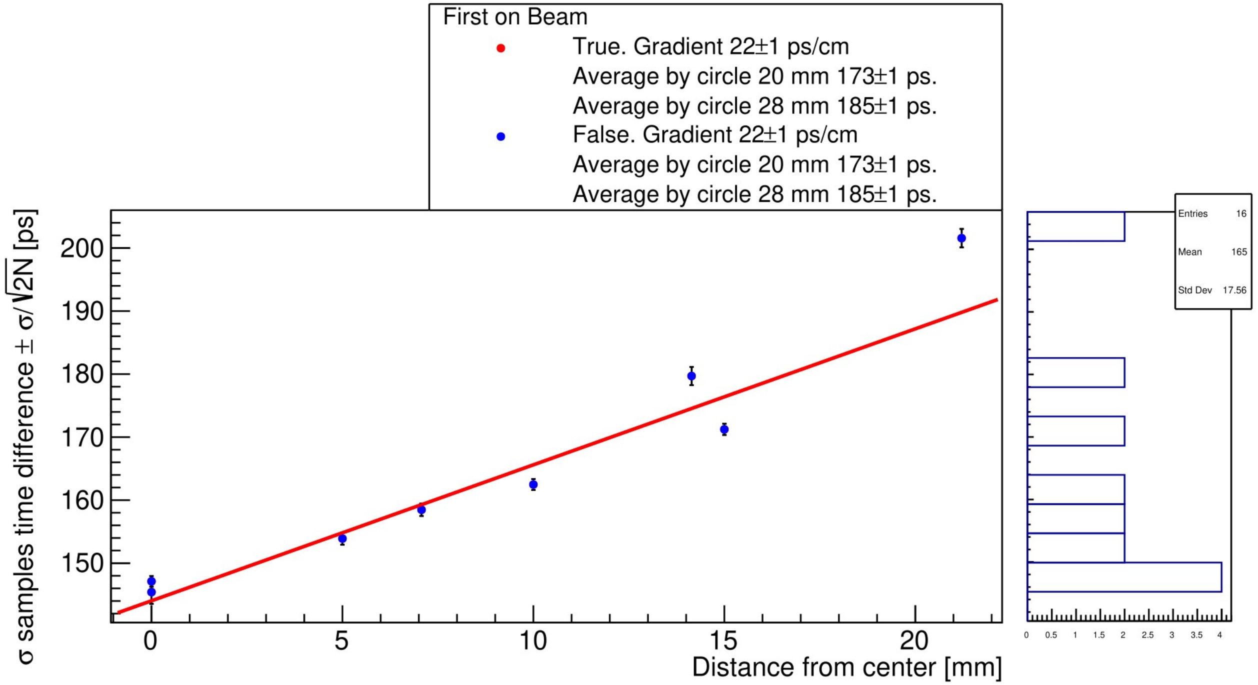
Conclusions

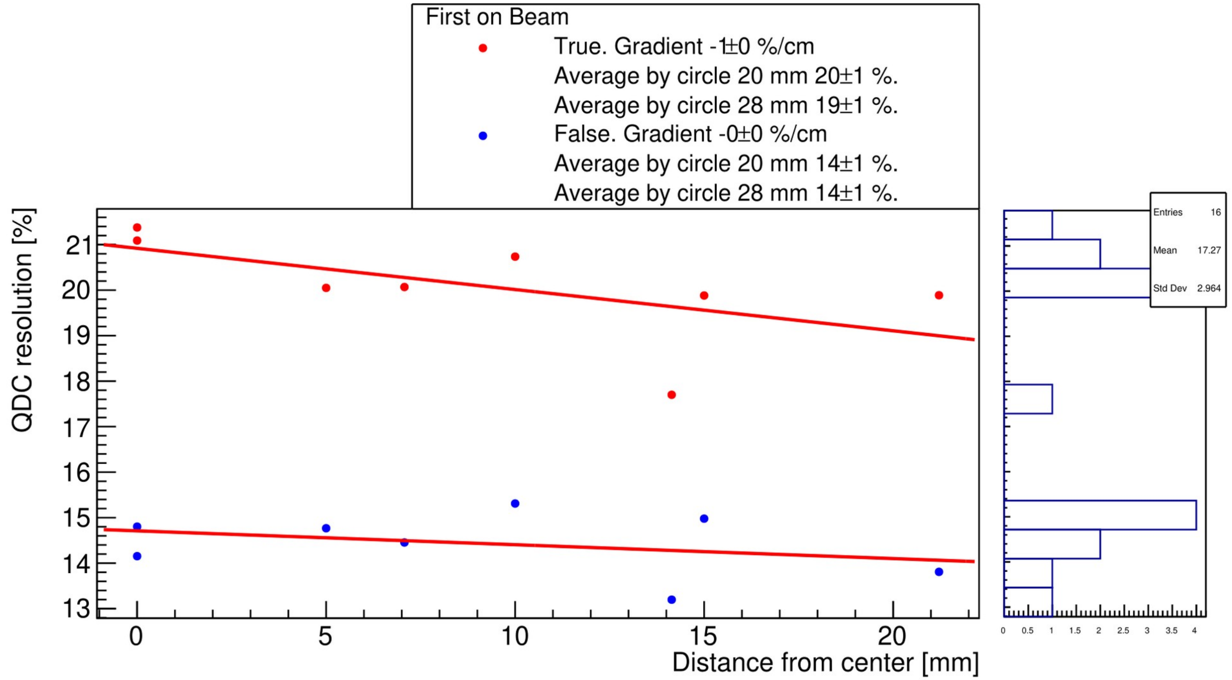
- New Highly-Granular Neutron Detector is a perspective detector for the BM@N experiment aimed to explore the symmetry energy in the high baryon density region
- The electronics are tuned so as not to distort the smooth physical behavior of detector elements.
- Analytical description of signal shape is developed,
  allowing physically based description of tdc:ToT slewing correction and signal charge reconstruction
  - Average time resolution achieved: 135 ps
  - Average charge resolution achieved: <20%

Thank you for your attention!

BACKUP







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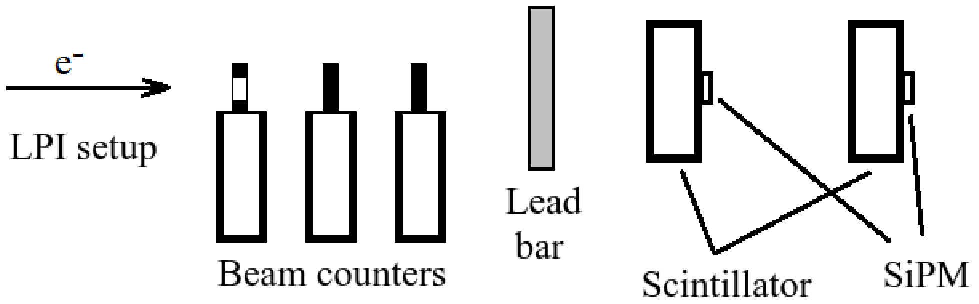


EOS for high baryon density matter

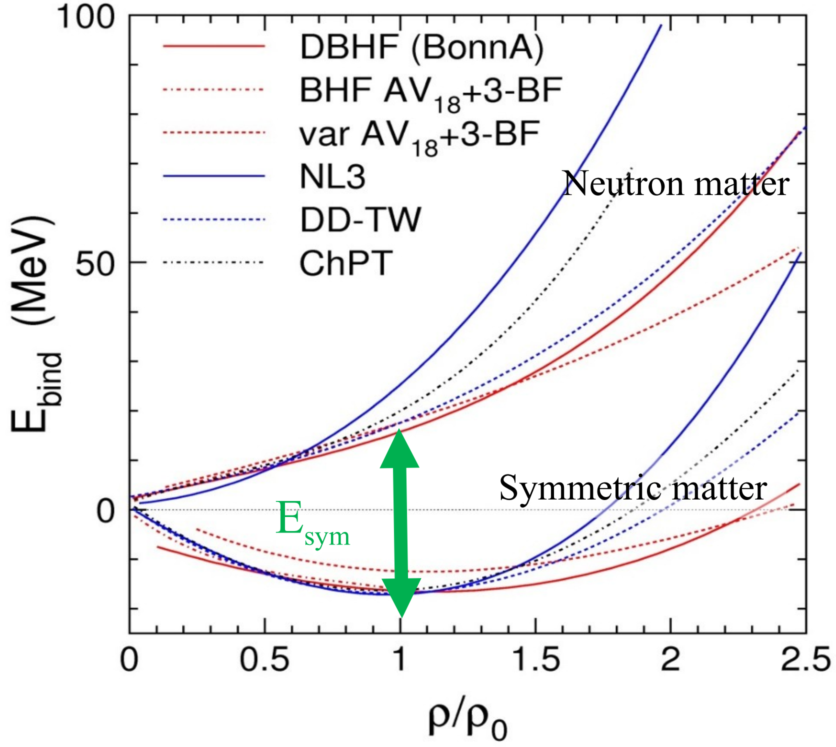
The binding energy per nucleon: $E_A(\rho, \delta) = \boxed{E_A(\rho, 0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$

Isospin asymmetry:

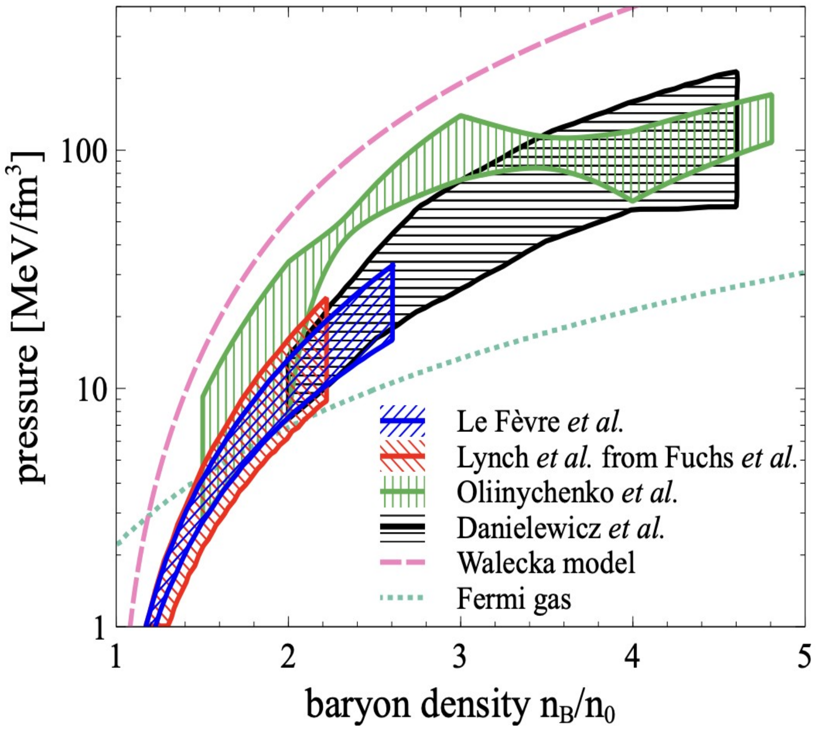
$\delta = (\rho_n - \rho_p)/\rho$

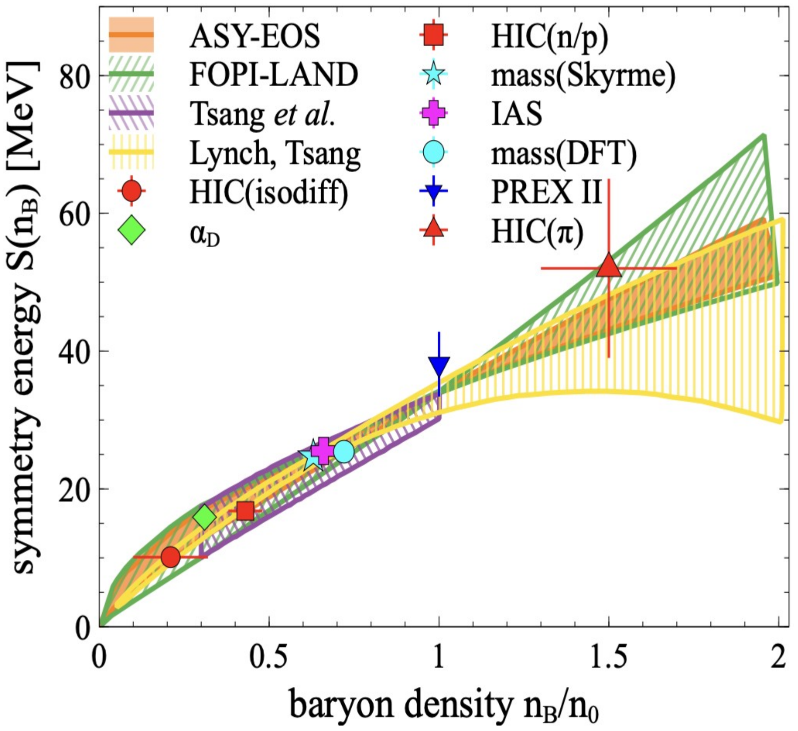
Symmetric matter

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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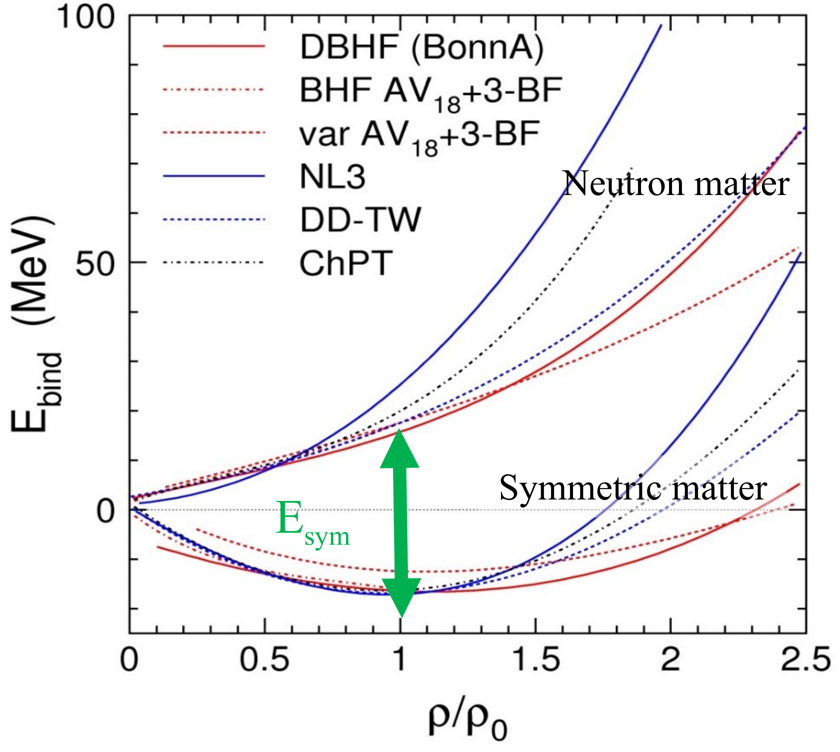
Symmetry energy



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

- 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

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

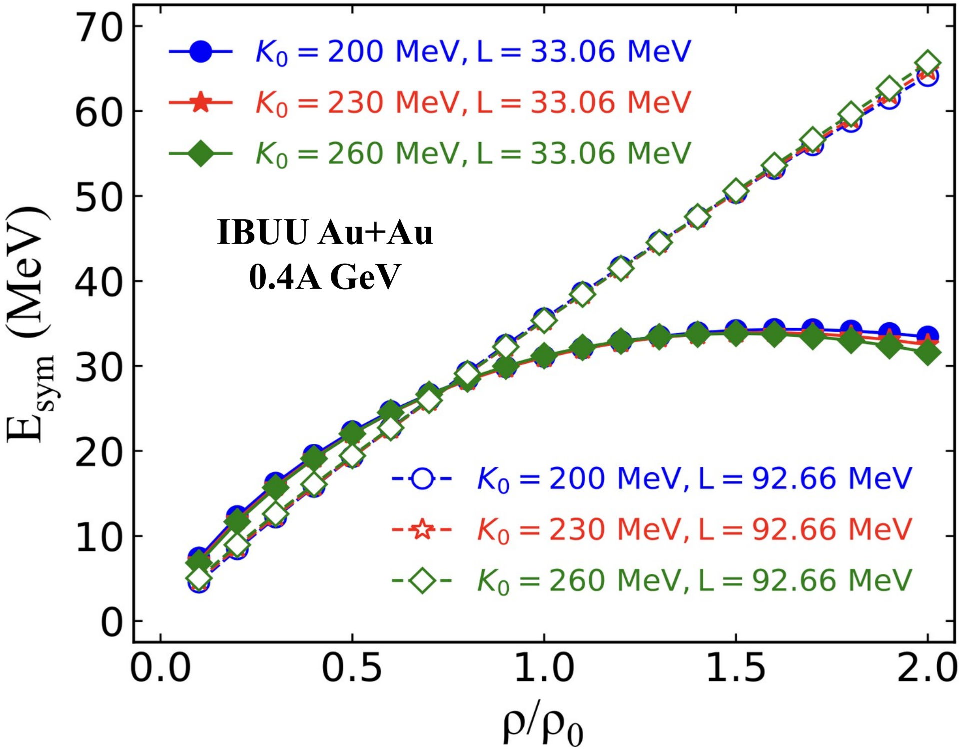
$$L = 3\rho \frac{dE_{sym}(\rho)}{d\rho}$$

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

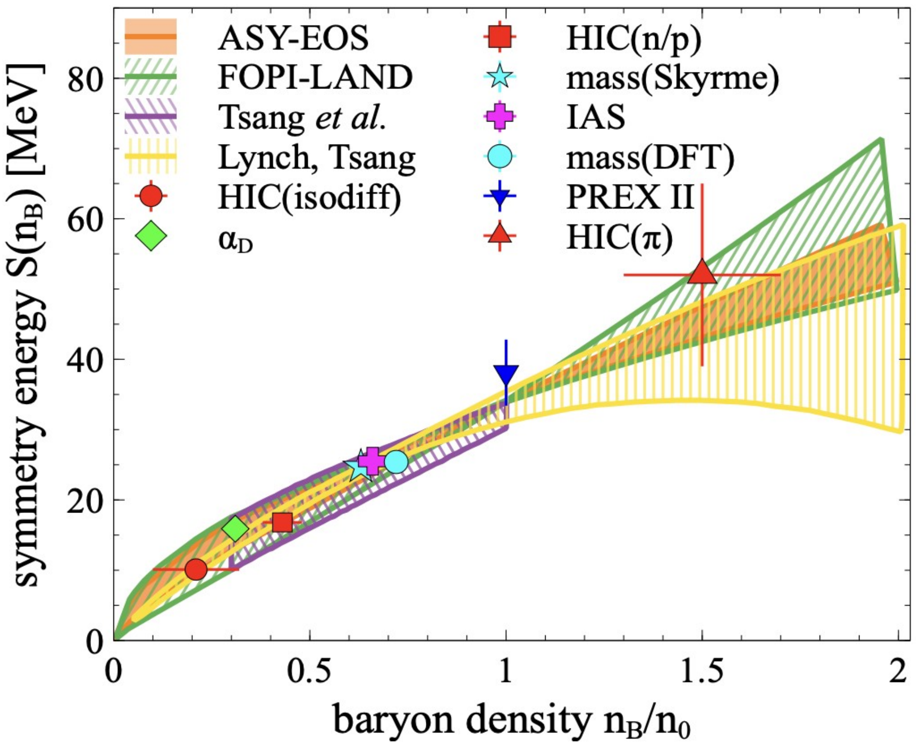
New data is needed to further constrain transport models with hadronic d.o.f.

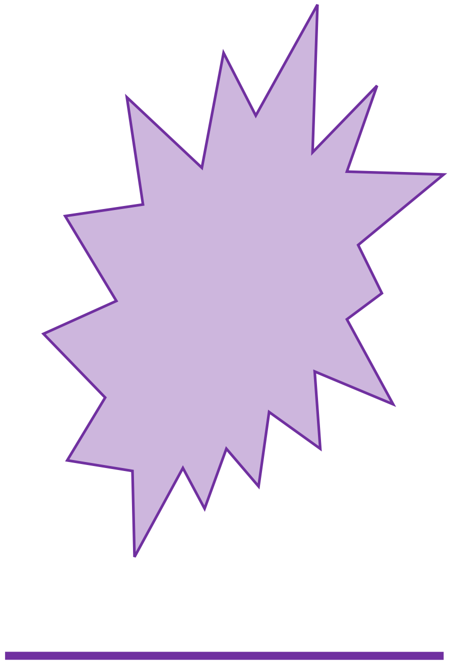
Symmetry energy in high-density region

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



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





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**

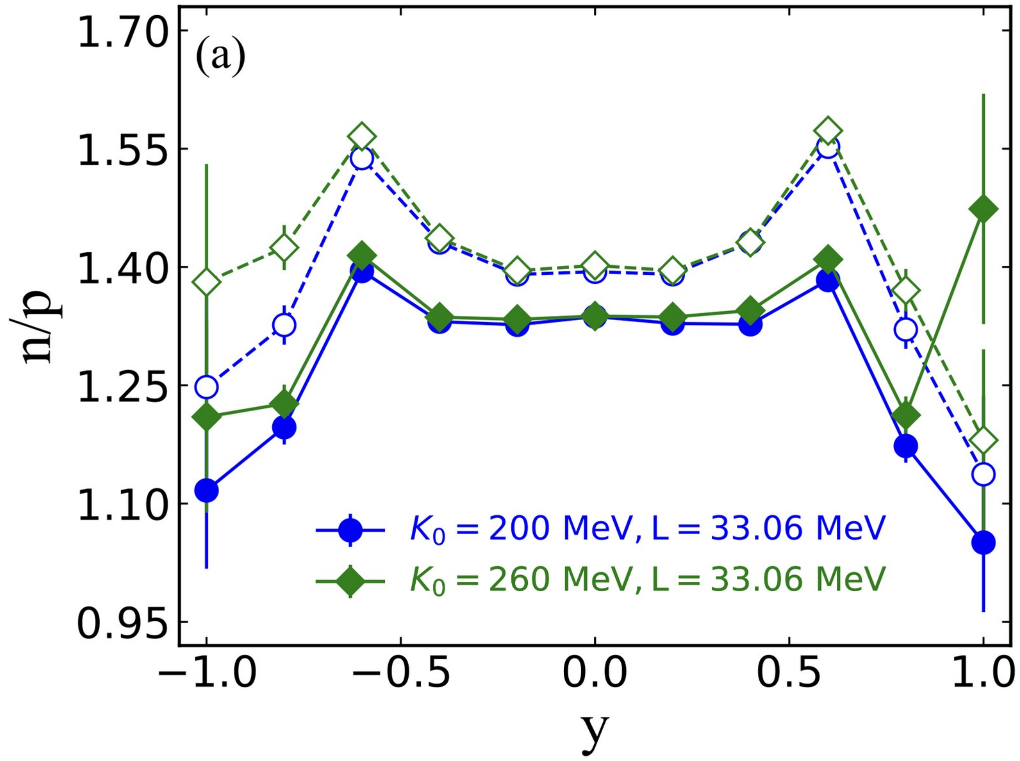
What observables can we use to extract information about ***L***?

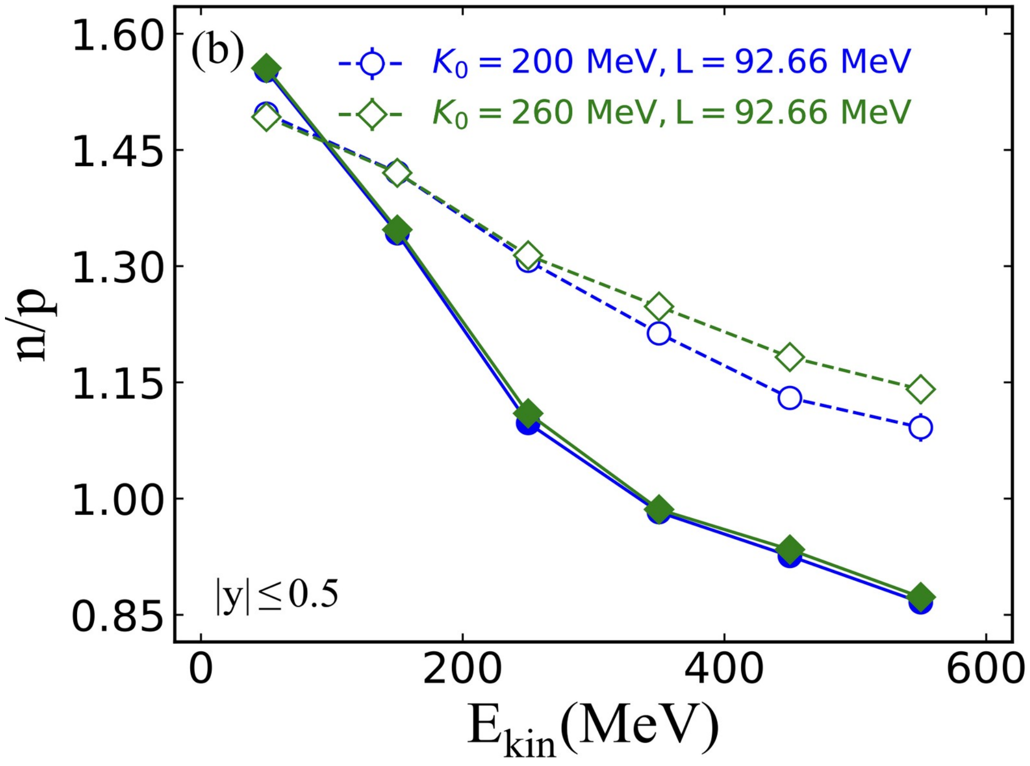
Observables to study symmetry energy

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

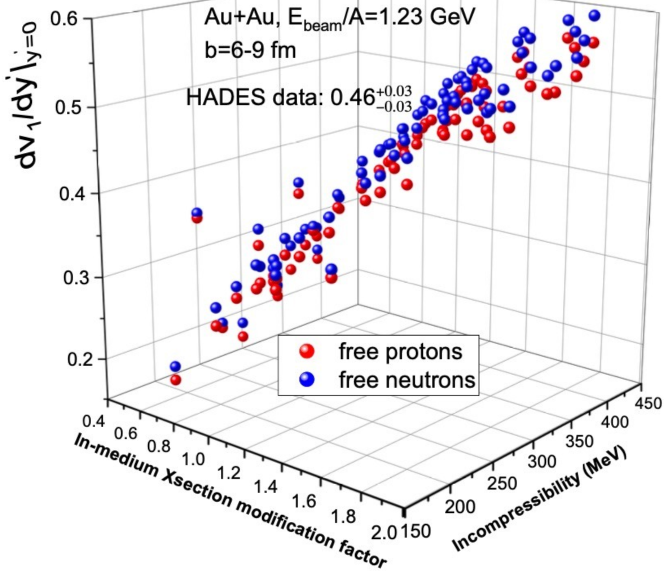
IBUU, Au+Au, 0.4A GeV





Neutron measurements are required to extract robust information about symmetry energy

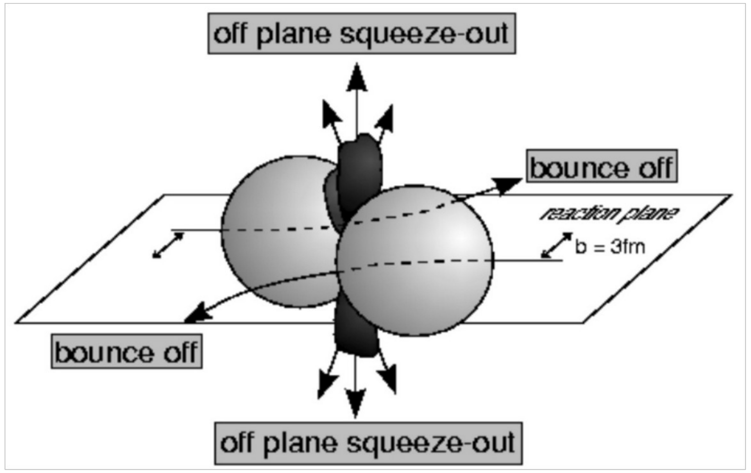
Collective flow as sensitive probe to the EOS



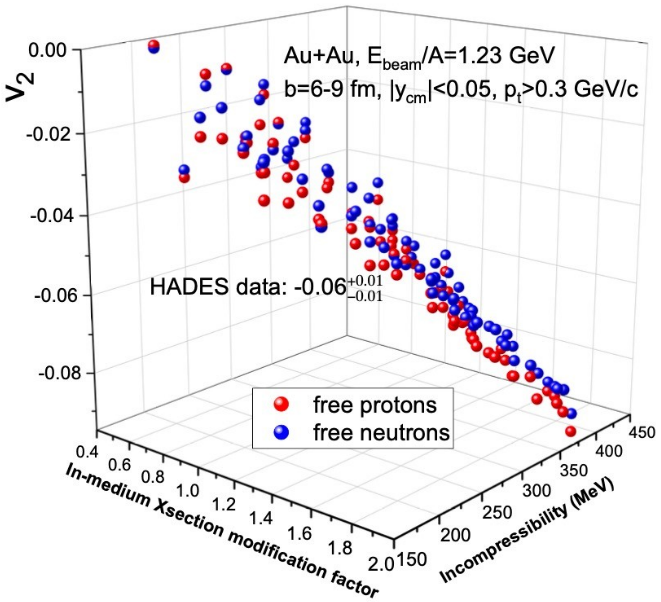
Incompressibility parameter $K_0(\rho)$:

Specifies the behavior of EOS in the given baryon densities

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



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



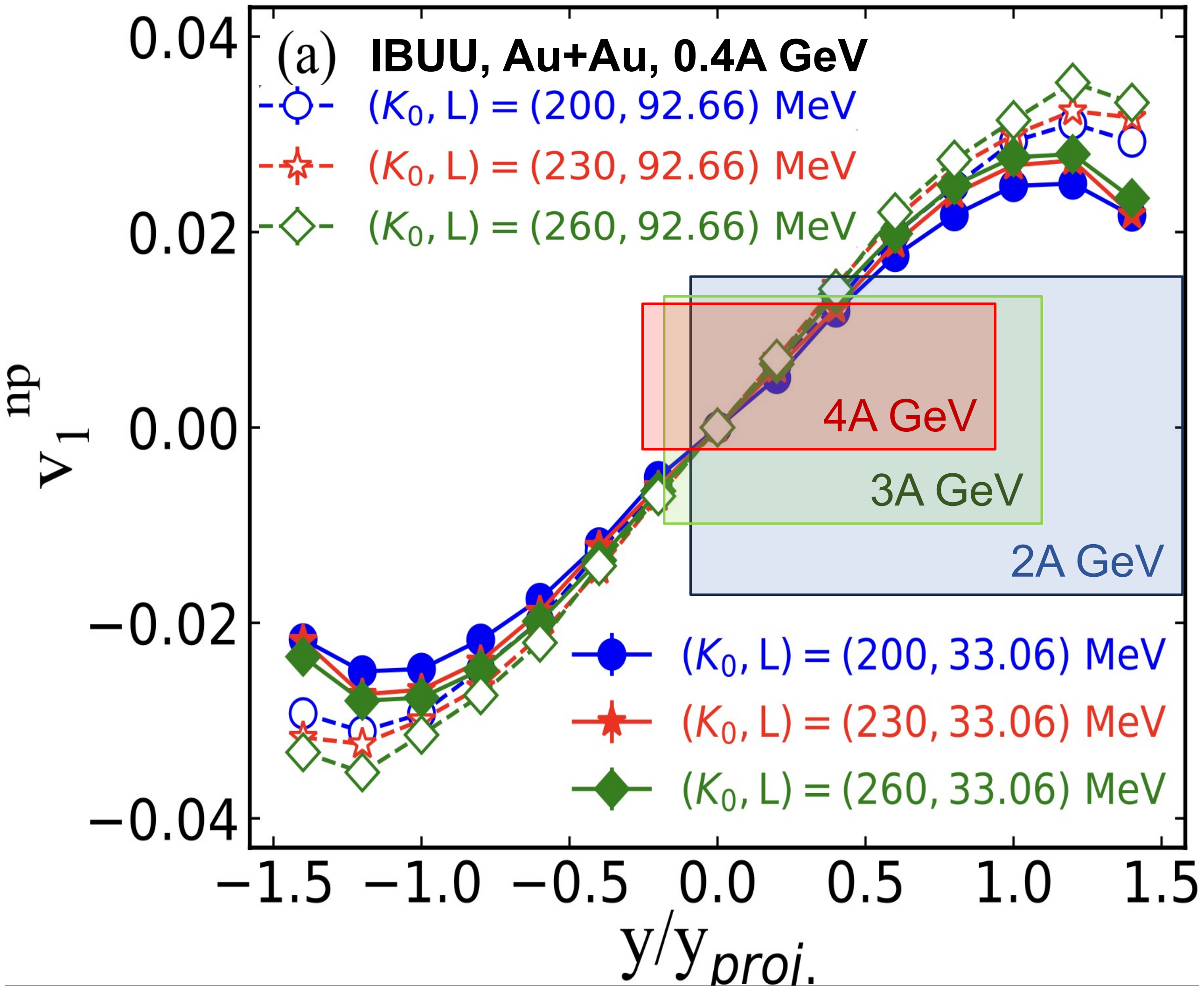
Collective flow is sensitive to:

- 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)

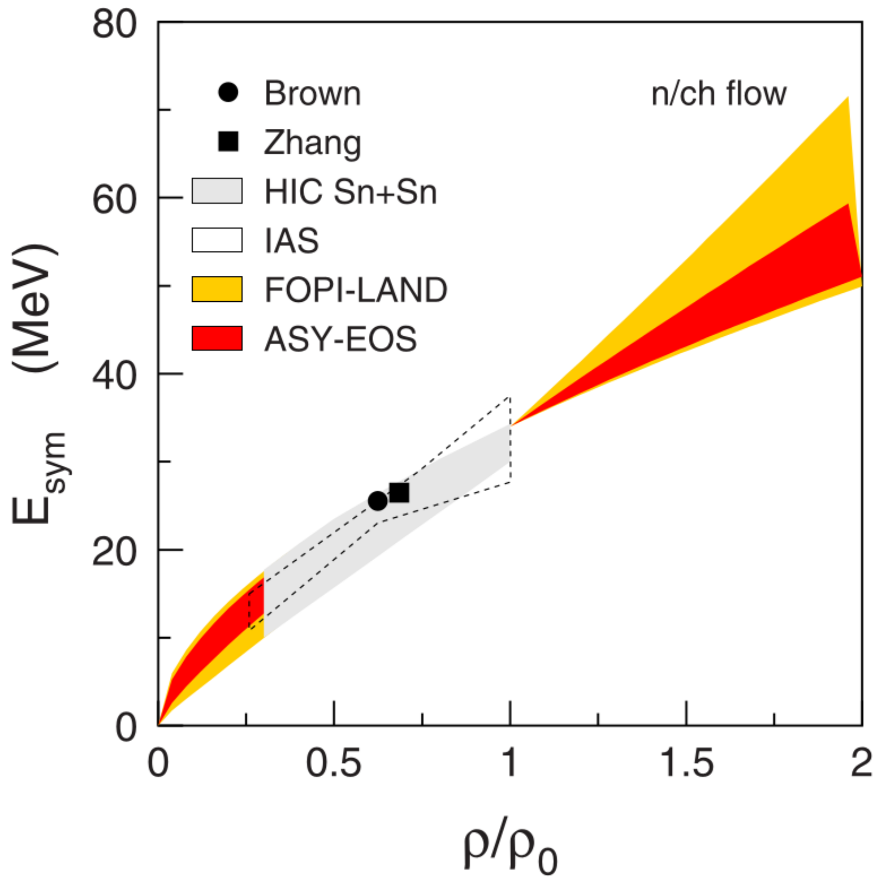
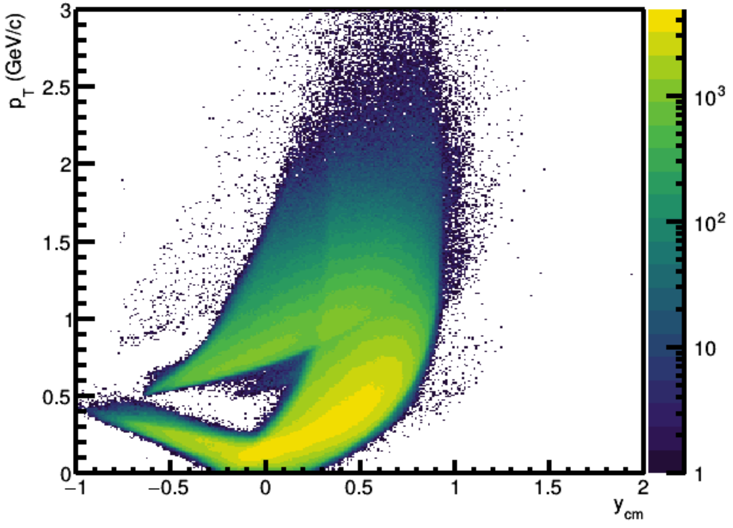


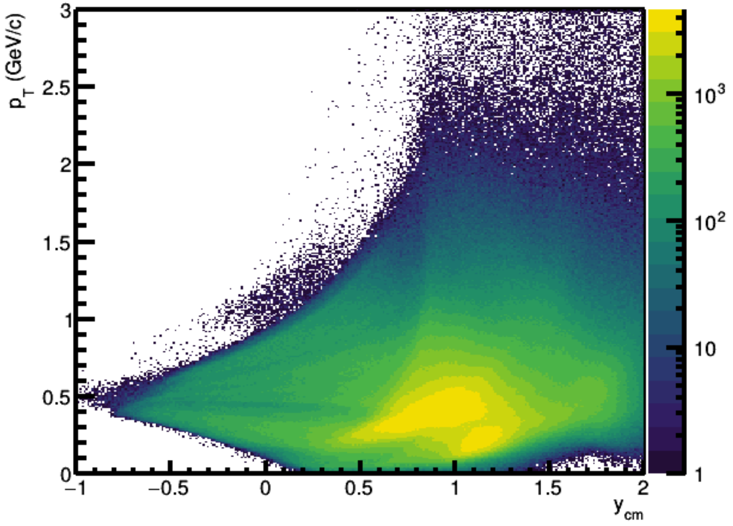
FIG. 18. Constraints deduced for the density dependence of the symmetry energy from the present data in comparison with the FOPI-LAND result of Ref. [5] as a function of the reduced density ρ/ρ_0. The low-density results of Refs. [78–81] as reported in Ref. [82] are given by the symbols, the gray area (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

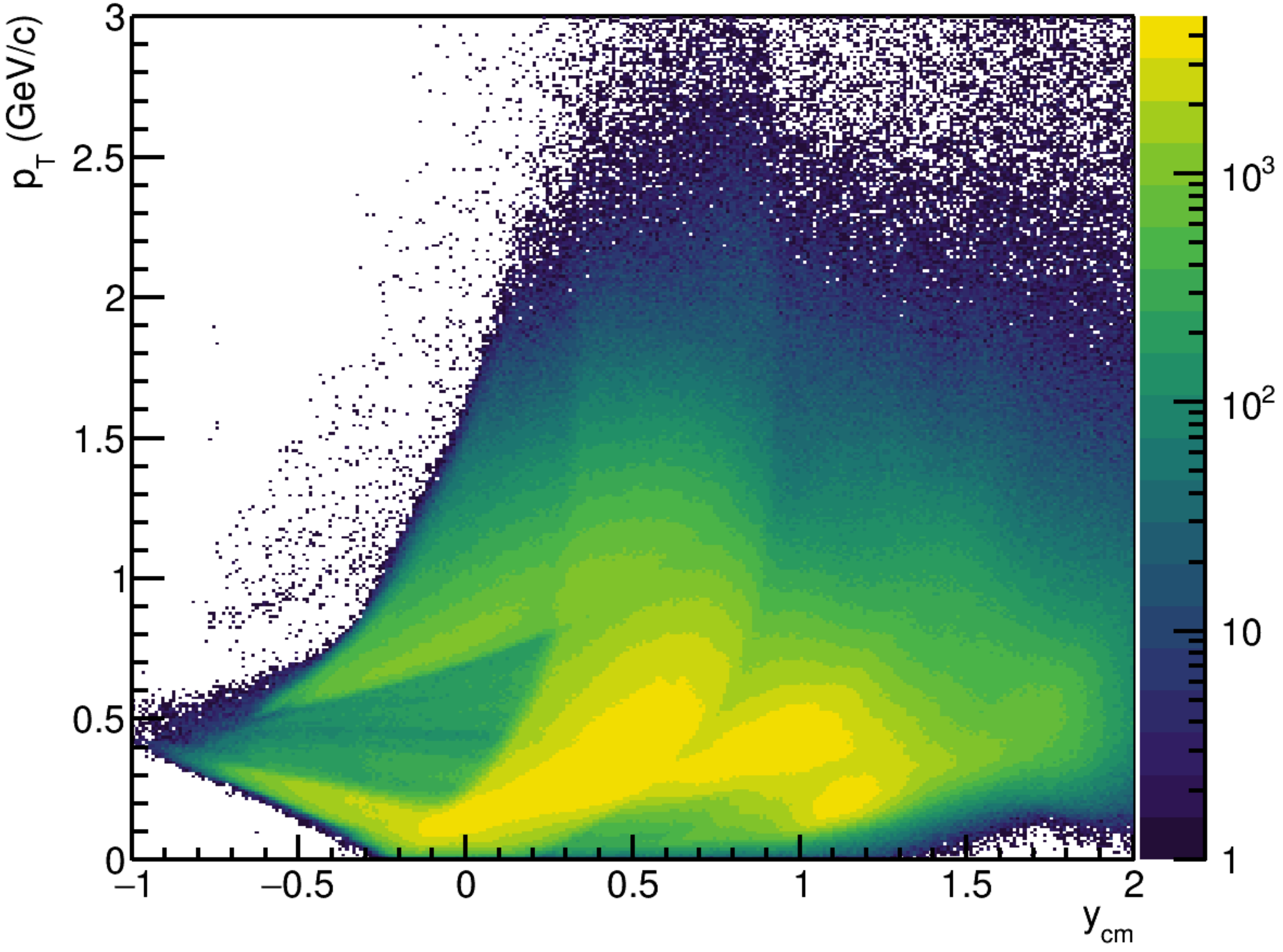
TOF-400



TOF-700



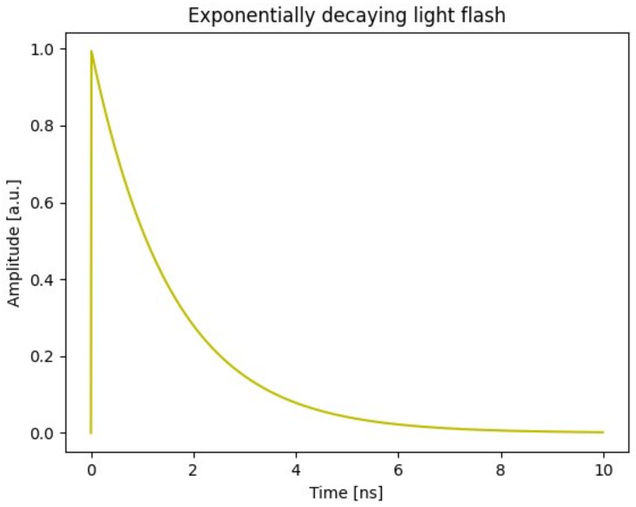
Combined



Alalytical description of light signals captured by SiPM: main behavior

$$N_{ph}^{scint}(t) \approx N_{ph}^{0} e^{-t/\tau_D}$$

N_{ph}^{0} – normalization factor, τ_D – light decay constant.



Solution 1 – Proccess as convolution of photoelectron current $I_{discharge}$ with SiPM impulse response function $g(t)$

$$I_{discharge} = -q\eta G \frac{dN_{ph}^{scint}}{dt} \qquad g(t) = \frac{1}{R_s C_T} e^{-t/R_s C_T}$$

η – PDE, q – electron charge, G – SiPM gain, R_s – load resistance + low intrinsic SiPM resistance, C_T – total SiPM capacitance.

$$V(t) = R_s (I_{discharge} * g)(t) = \frac{\eta q G N_{ph}^{0}}{C_T \tau_D} \int_0^t e^{-\frac{x}{\tau_D}} e^{-\frac{t-x}{R_s C_T}} dx = \frac{\eta q G N_{ph}^{0} R_s}{R_s C_T - \tau_D} \left(e^{-t/R_s C_T} - e^{-t/\tau_D} \right). \tag{1}$$

Solution 2 – Proccess as differential equation

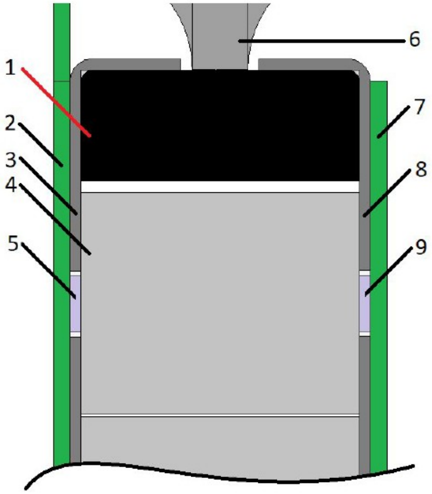
$$\frac{dQ}{dt} = I_{recharge} - I_{discharge} \qquad V_{bias} - R_s I_{recharge} = \frac{Q}{C_T}.$$

$$V(t) = R_s I_{recharge} = \frac{\eta q G N_{ph}^{0} R_s}{R_s C_T - \tau_D} \left(e^{-t/R_s C_T} - e^{-t/\tau_D} \right). \tag{2}$$

Construction status

LPI test March 2024 averaged results	
Measurement	Average over **20mm circle**
Light Yield	94 or 122 p.e.
Time resolution	156 ps = $\frac{\int(135+1.6*r)*2pi\ rdr}{pi\ r^2}$
Charge resolution	<20 %

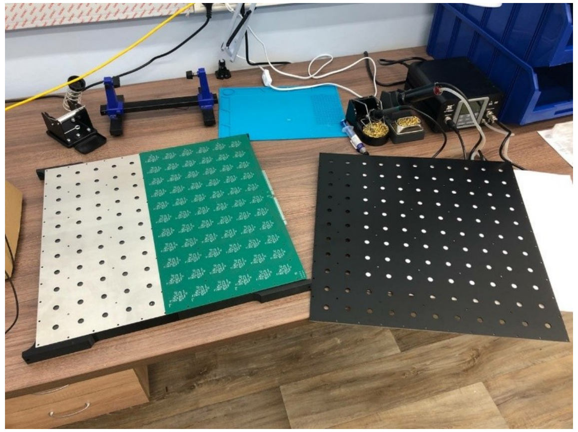
Structure of active layer



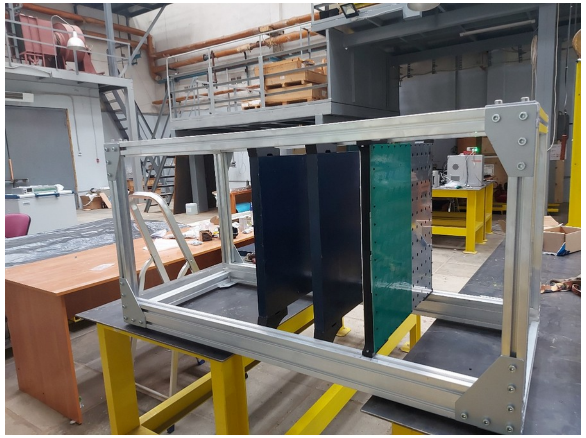
1 – the frame of layer case
2 – SiPM PCB
3&8 – aluminum plates
4 – scintillator
5 – SiPM
6 – layer support bracket
7 – LED PCB
9 – LED

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.