Compact high granularity neutron detector for flow measurements at the BM@N experiment

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OUTLINE

- Neutron detectors in heavy ion experiments for flow measurements

- Proposed structure of neutron detector for the BM@N
  and possible layout of neutron detector in the BM@N cave

- First simulation results of nDet
  - Acceptance, neutron multiplicity, neutron background
  - One neutron efficiency and energy resolution

- Preliminary results of neutron flow simulation

- Summary and outlook

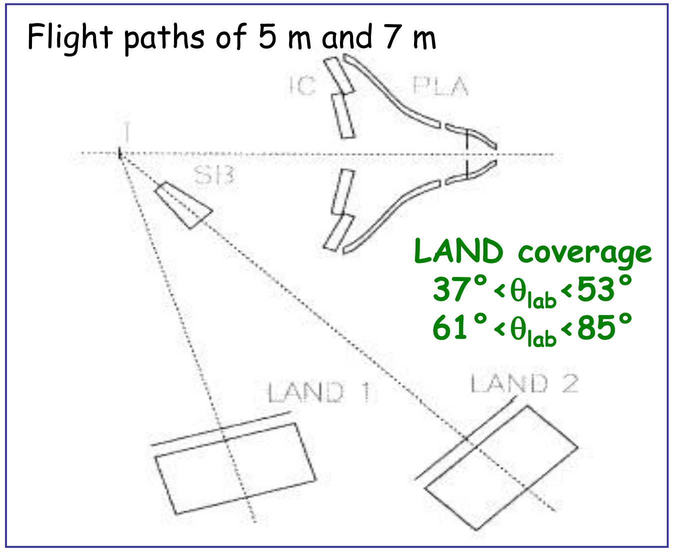
Neutron flow measurements at GSI

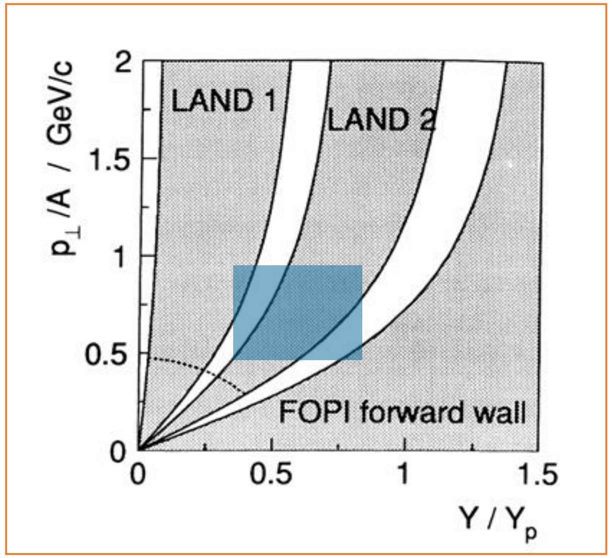
FOPI/LAND

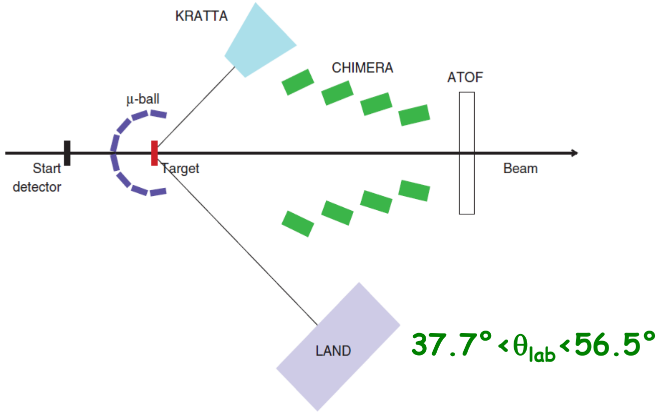
Au+Au, 400 AMeV
Y. Leifels *et al.* Phys. Rev. Lett. 71, 963 (1993)
Au+Au, 400-800 AMeV
D. Lambrecht et al., Z. Phys. A 350, 115-120 (1994)

ASY EOS

Au+Au, 400 AMeV
P .Russotto et al., Physics Letters B 697 (2011) 471–476





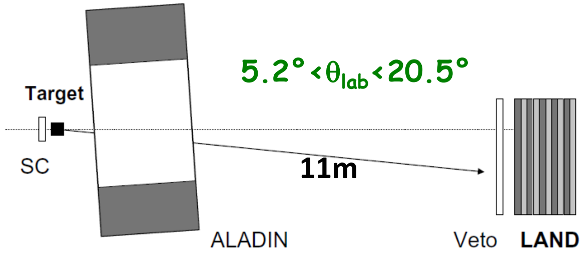


The multiple-hit resolving capability is limited since each neutron induces a spatially extended shower.

At 1 A GeV, **only the first two detector** layers was used for the data analysis separately.

For a single layer the efficiency reduces to, 0.19 and 0.265 for neutron energies of 200 MeV and 1.05 GeV, respectively.

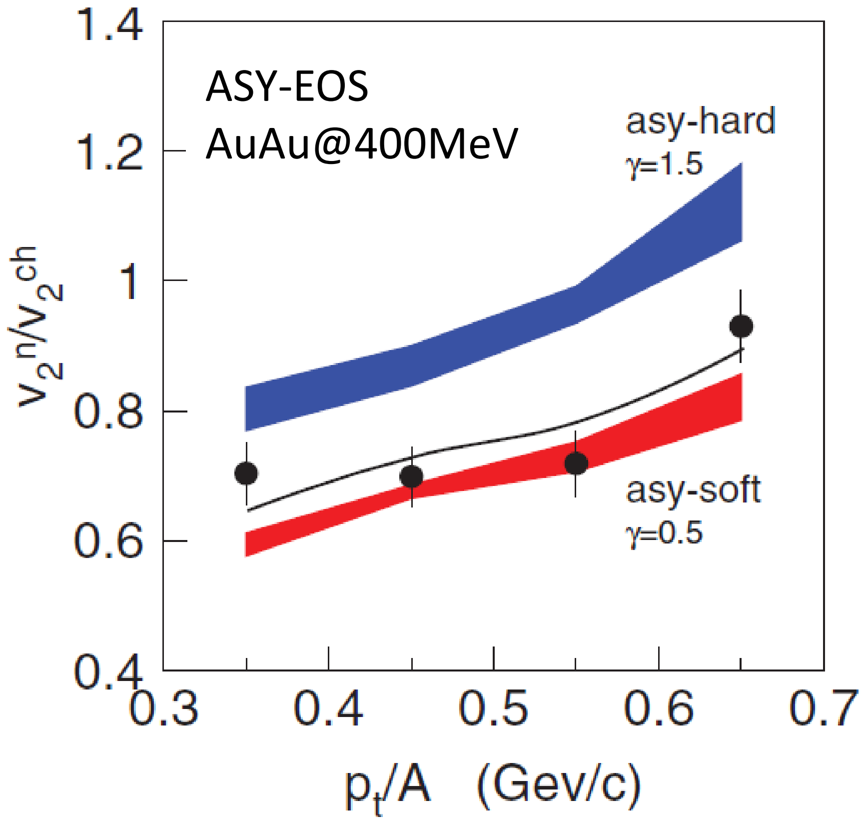
Neutron yields from 1 GeV/nucleon ^{238}U ion beams on Fe target
O. Yordanov, et al., NIM B 240 (2005) 863–870

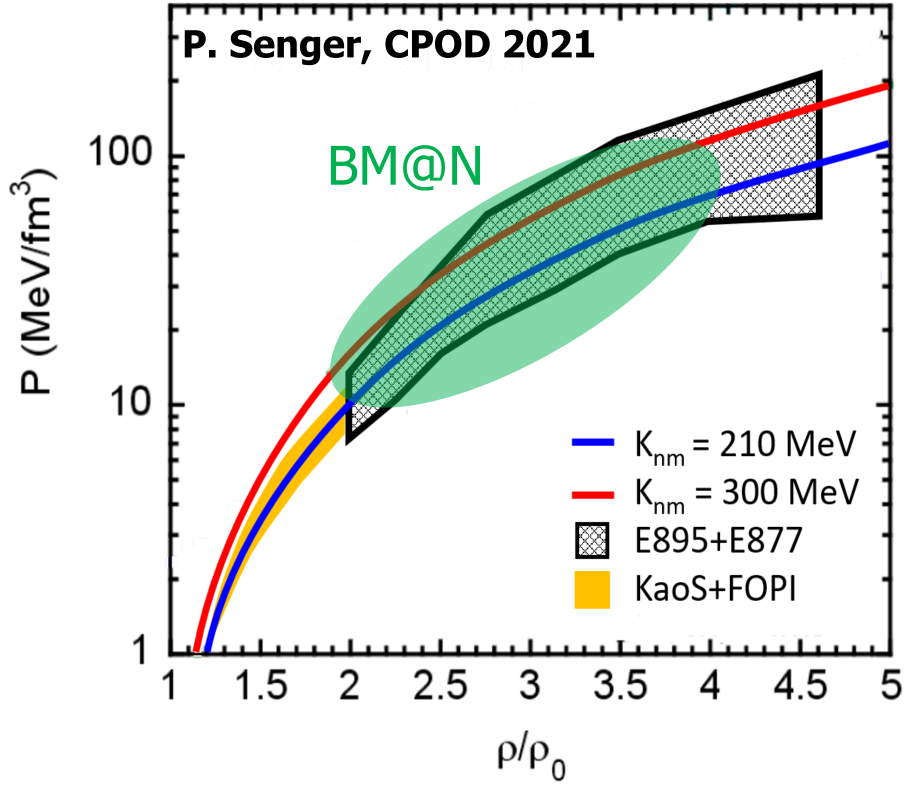


Flow as probe of the high-density EOS

EoS – relation describes the relation between density, pressure, energy, temperature and the isospin asymmetry

The neutron-proton elliptic flow ratio - sensitive probe of the high density behavior of the nuclear symmetry energy

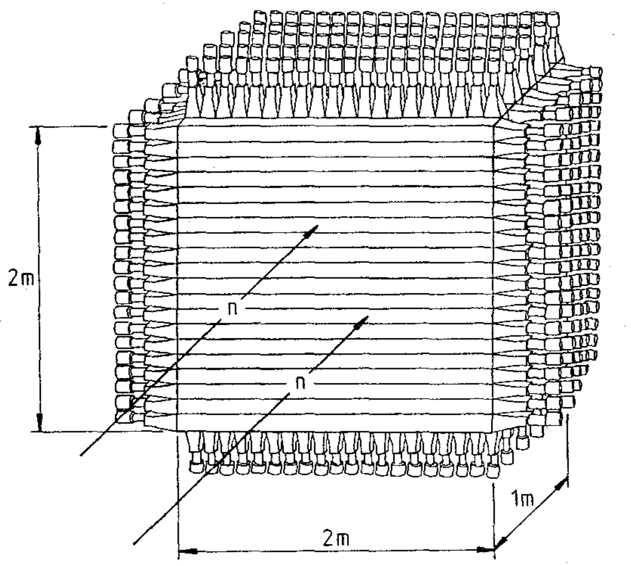




LAND detector

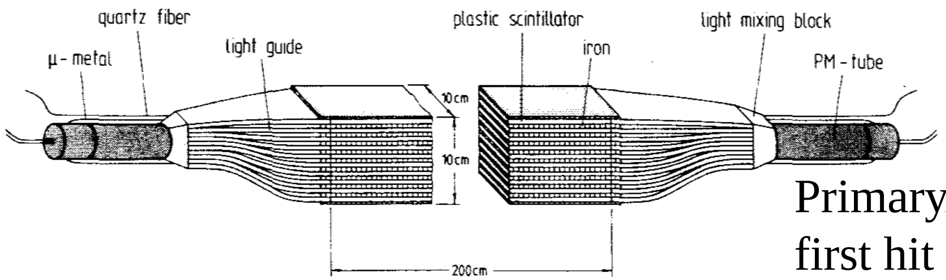
T. Blaich, et al., NIM. A 314 (1992) 136.

(constructed in ~1990)



LAND - a TOF neutron spectrometer with the precise determination of the position and arrival time of identified neutrons.

- 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 plane
- 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
- multi-neutron detection capability
- without 1,2,3H isotopic discriminations



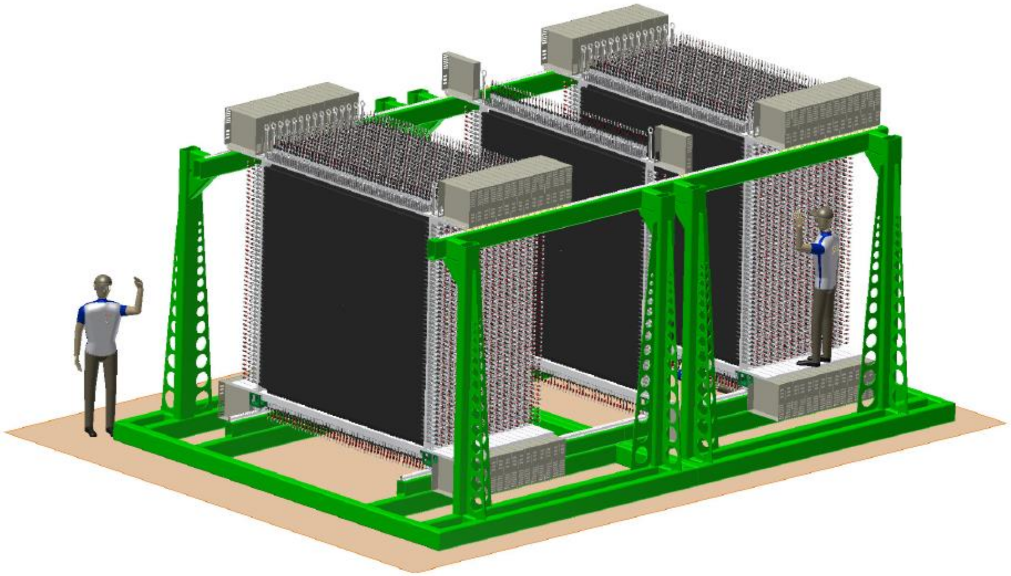
P. Pawłowski et al., ‚Neutron recognition in the LAND detector for large neutron multiplicity, arXiv.org > nucl-ex > arXiv:1203.5608v3

Primary neutron hit recognition is based on an event-by-event identification of the first hit generated by the neutron.
Hit location and time is used to determine the velocity vector of the incident neutron.

For determining the multiplicity of detected neutrons more then one, two calorimetric observables are used: the hit multiplicity N_{hit} and the total visible energy E_{vis}.

NeuLAND

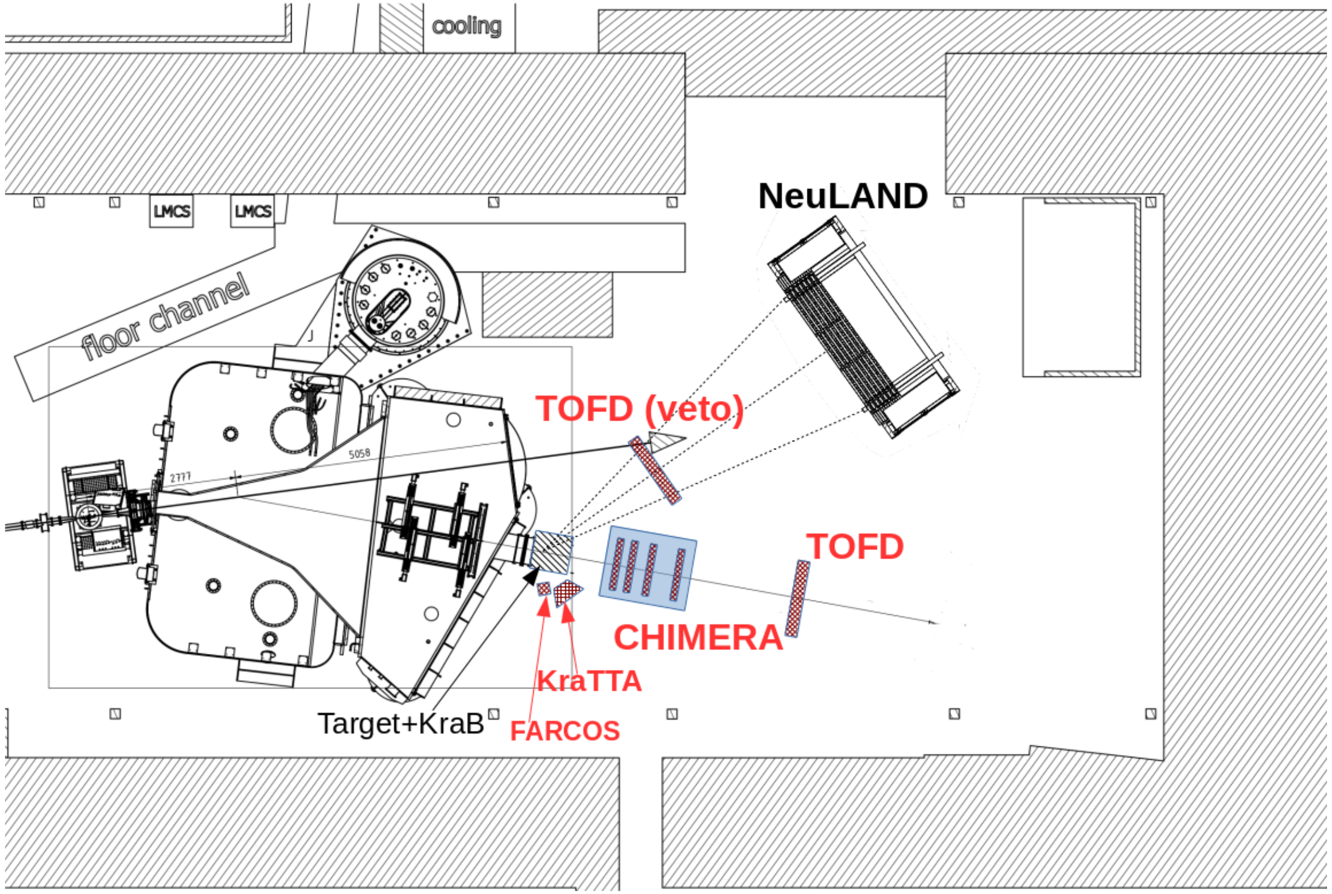
K.Boretzky et al., NIM, A 1014 (2021) 1



- 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
  multi-neutron detection capability

New proposal at GSI:
Symmetry energy at high densities from neutron/proton flow excitation functions
for Au + Au at 250, 400, 600, 1000 AMeV

P.Rissotto et al/.
arXiv:2105.09233v1 [nucl-ex]
May 2021



NeuLAND - start-up version
(120 cm detector depth (12 double planes)),

NeuLAND - 5.8 m away from the target
covering effectively the mid-rapidity regions,
i.e., the polar angles between 33 and 57.

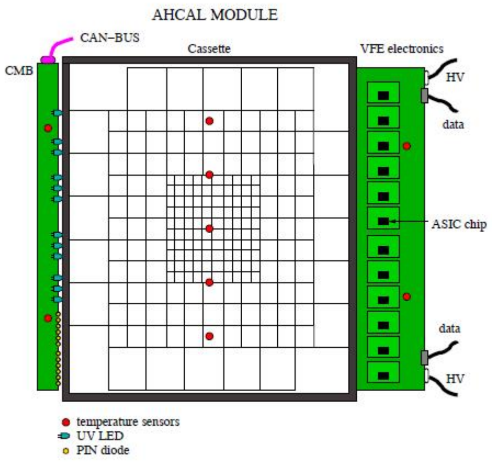
The one neutron interaction probability is about 70% at 400 MeV.

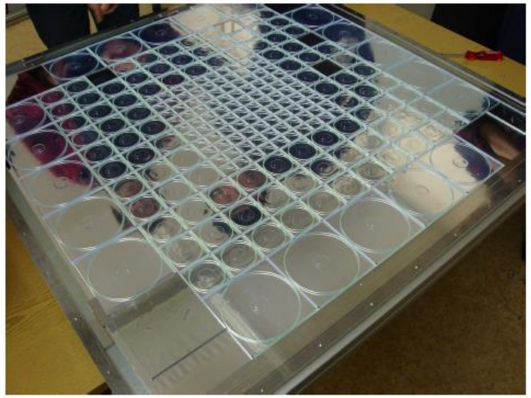
A five-neutron event is recognized with correct neutron multiplicity with a probability of about 20 to 30% for 200 to 1000 MeV neutron energy.

CALICE

M. Chadeeva et all, CALICE collaboration.
JINST 15 (2020) 07, C07014

Prototypes of detectors for jets reconstructions by separating the contributions of charged particles, photon showers and neutral hadron showers.





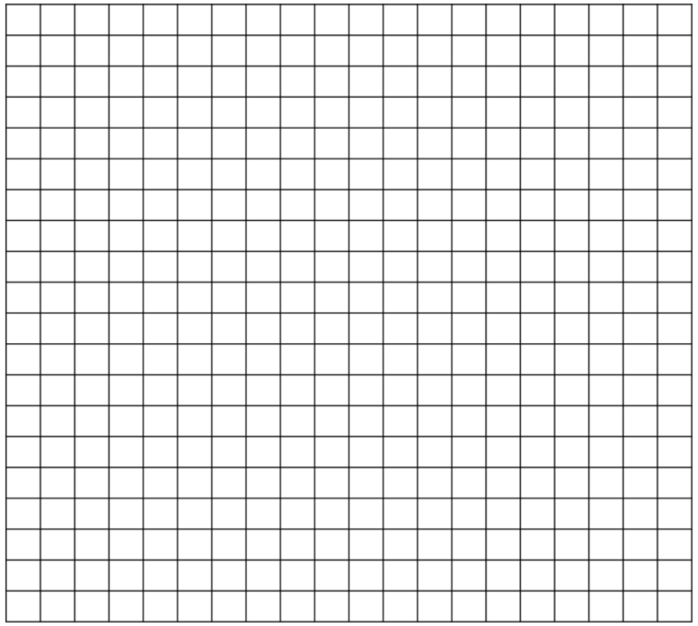
An analog hadron calorimeters prototypes:

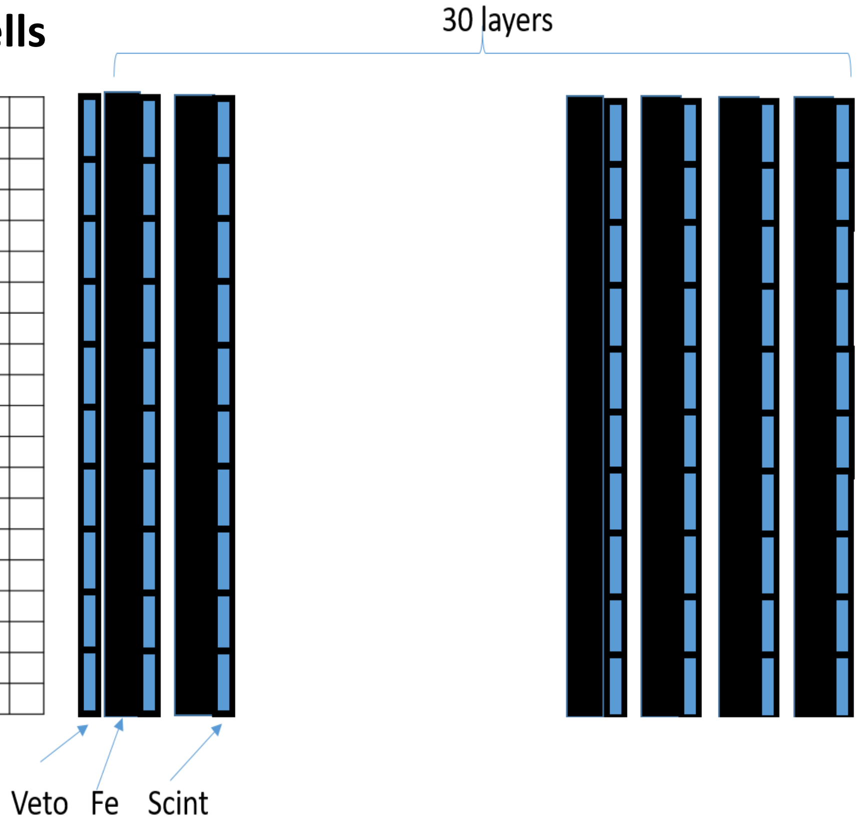
- Fe-AHCal (Fe (20 mm) + Scint.(5 mm)), 38-layer,
  - Transverse size 1x1 m, length -4 λ_I
  - **7608 Scint. Cells** (3 types - 30x30mm, 60 x60 mm and 120x120mm)
  - Scintillator tiles are read out by WLS fibers coupled to SiPMs
- W-AHCal (W(10) mm +Fe (4 mm) + Scint (5mm), 38 layers - 5.6 λ_I

Detailed simulation have shown that a transverse tile dimension of 3 ×3 cm provides optimal two-particle separation.

Proposed structure of nDet for the BM@N

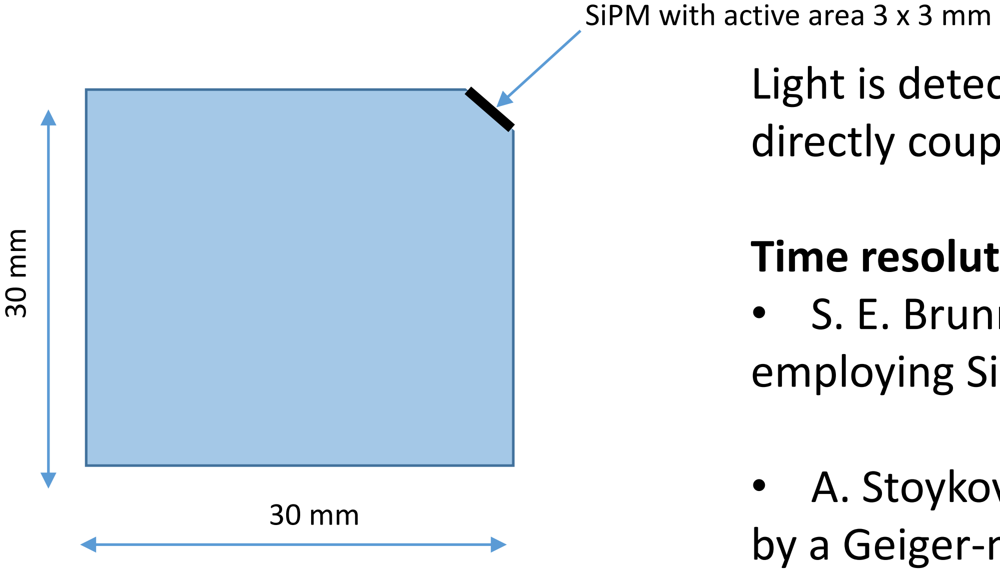
One layer: 20x20 scintillator cells





- **Transverse size - 60 x 60 cm,**
- **30 layers:**
  (Fe 1.6 cm + Sc 0.4 cm + Plastic 0.5 cm)
- **400 scintillator cells per layer, 3x3x0.4 cm^3**
- **Light readout from each cell by one SiPM directly coupled with scintillator**
- **Total number of cells in nDet: 12 400**
- **Total length of nDet – 75 cm (3.2 λ_{in})**

Light readout from nDet cells



Light is detected with fast SiPMs with active area 3x3mm^2
directly coupled with scintillator plate 30x30x4mm^3.

Time resolution 100 ps ?

- S. E. Brunner et al., Time resolution below 100 ps for the SciTil detector of PANDA employing SiPM, arXiv:1312.4153v2 [physics.ins-det], 2014

- A. Stoykov et al., A time-resolution study with a plastic scintillator read out by a Geiger-mode Avalanche Photodiode, arXiv:1107.2545v1 [physics.ins-det], 2011

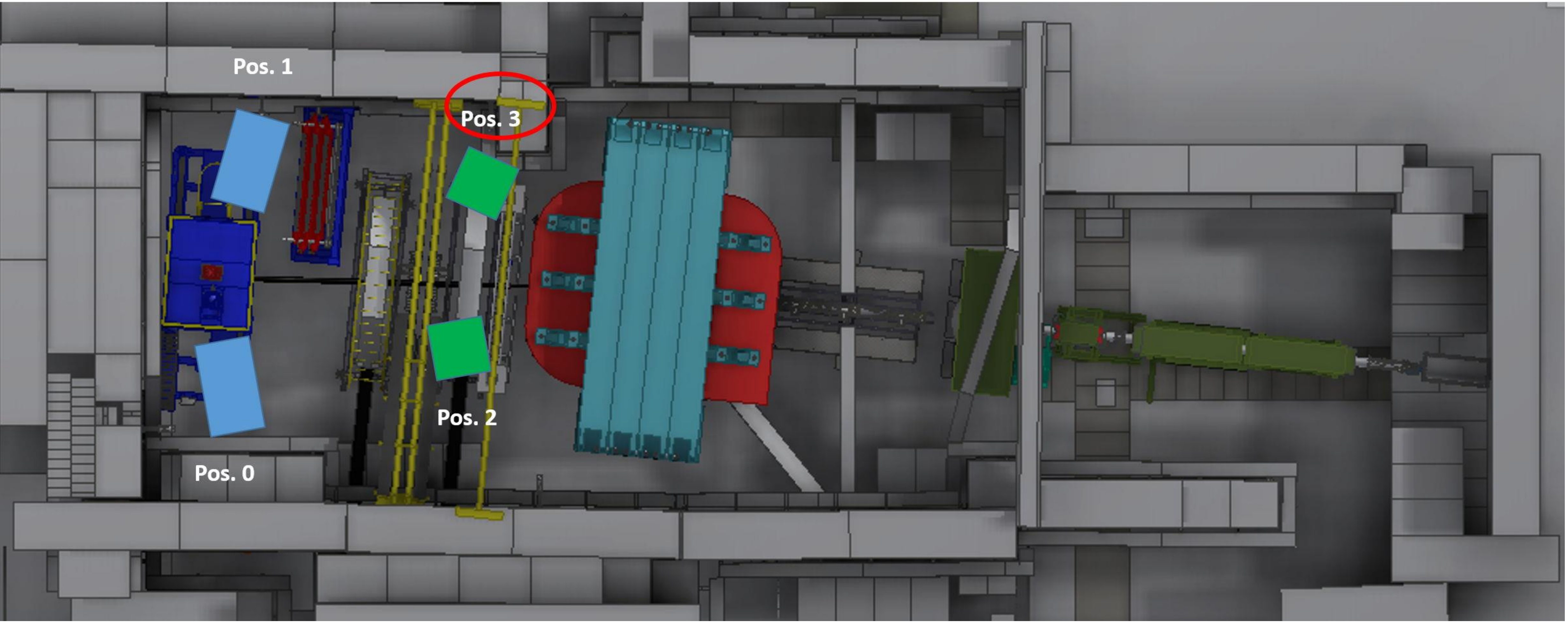
First tests at INR

SenSel photodiode with fast output: -rise time 0.6 nsec
Preliminary result:
Measured time resolution for given scintillator cell
(w/o amplifier) ~ 200 ps.

Optimization of the scintillator material, shape of cell, reflectors, FEE etc. are required.

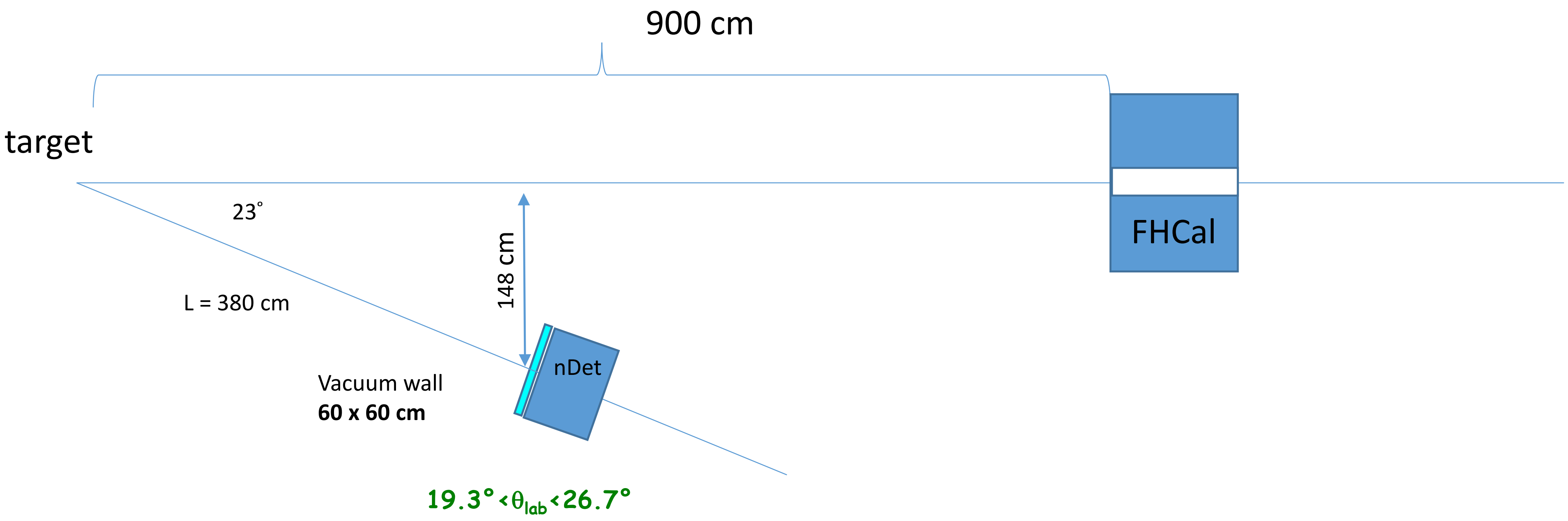
MICROFC-SMA-30035-GEVB
Evaluation Board, MicroFC-30035
SiPM Sensor, 3 x SMA Connectors

Possible positions for neutron detector in the BM@N cave



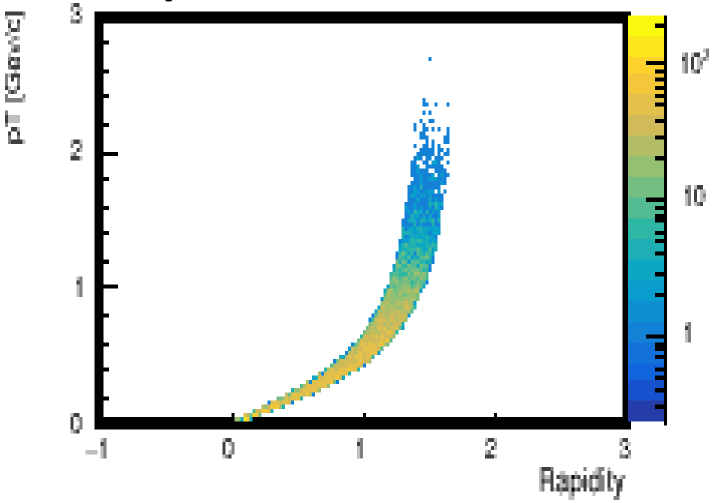
nDet simulation

- Au+Au@3.8A GeV, DCM-SMM (V.Zhezher, G.Musulmanbekov, Dubna, JINR)
- Bmnroot framework: only Magnet SP-41, FHCal and nDet
- GEANT4, Physics list FTFP_BERT 2.0
- Pos. 3: L = 380 cm, 23 deg

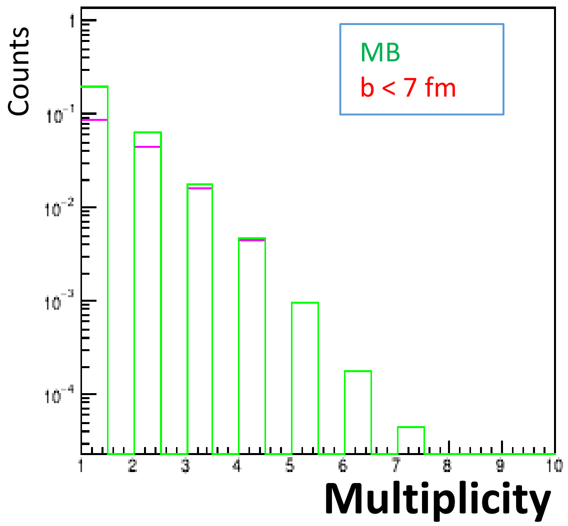


Acceptance of nDet for primary neutrons

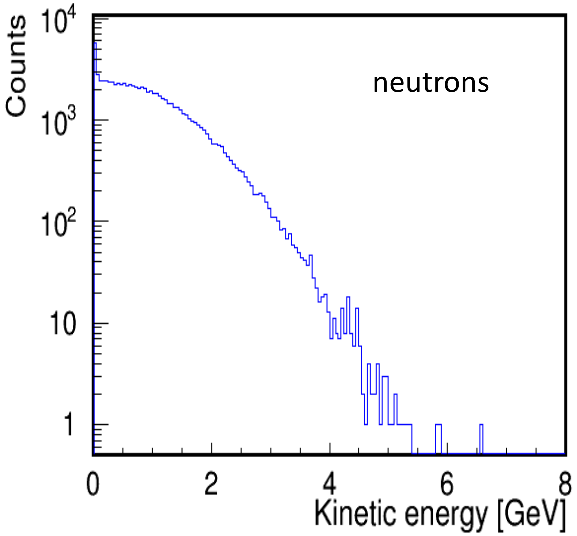
- Au+Au@3.8A GeV, DCM-SMM
- GEANT4, Physics list FTFP_BERT 2.0
- L = 380 cm, 23 deg
- Only nDet in cave, vacuum in cave

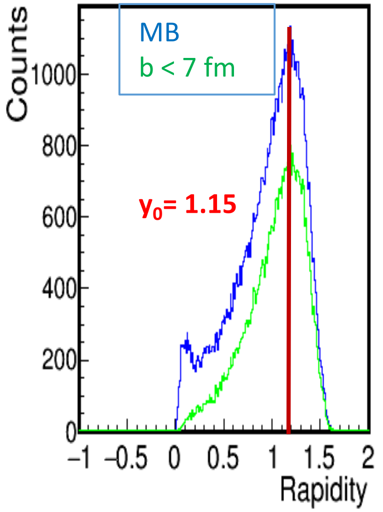


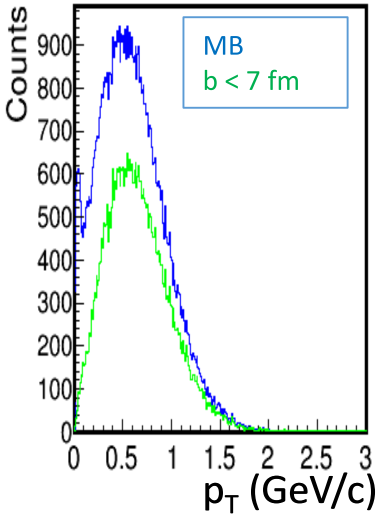
Neutron multiplicity



Neutron energy spectra







Acceptance of nDet

y: [0 - 1.6]
p_T: [0 – 2 GeV/c]

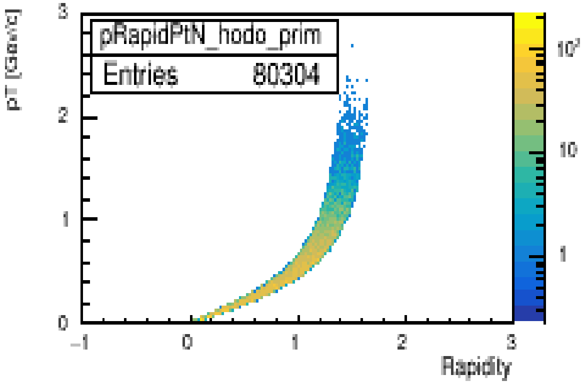
Neutron background in nDet acceptance

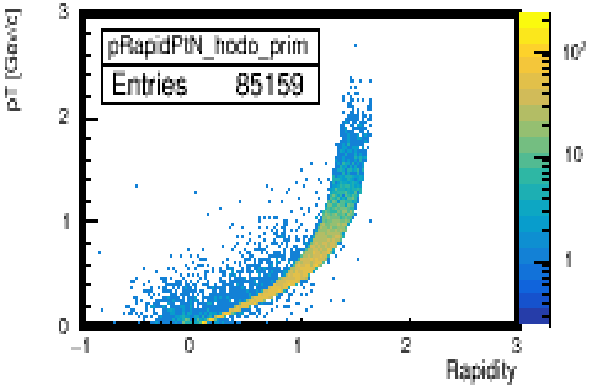
Au+Au@3.8A GeV, DCM-SMM, 200k events

Primary neutrons from target

Vacuum in cave

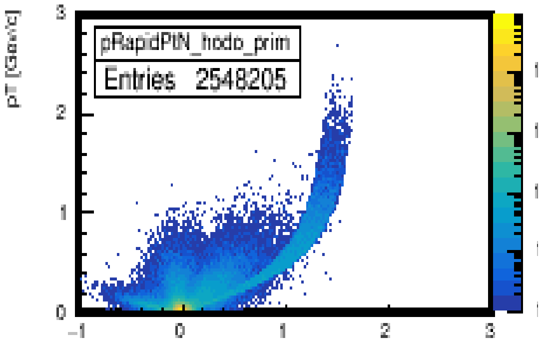
Air in cave

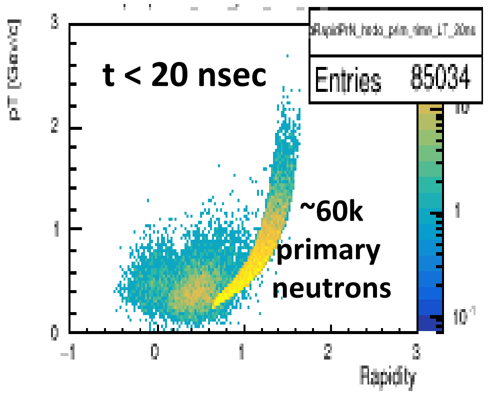




All neutrons

Air in cave + FHCal and Magnet





Estimation of neutron rate in nDet acceptance:

Simulation

60k neutrons per 200k interactions ➡ 0.3 primary neutrons/ev.

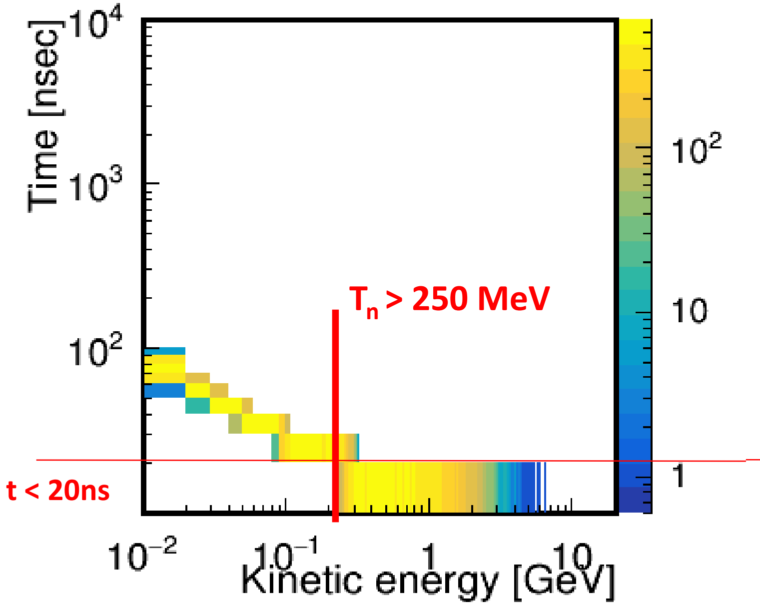
Experiment

Au beam rate – 10^5 1/sec, target – 1% , interaction rate – 1k/sec ➡ 300 neutrons/sec

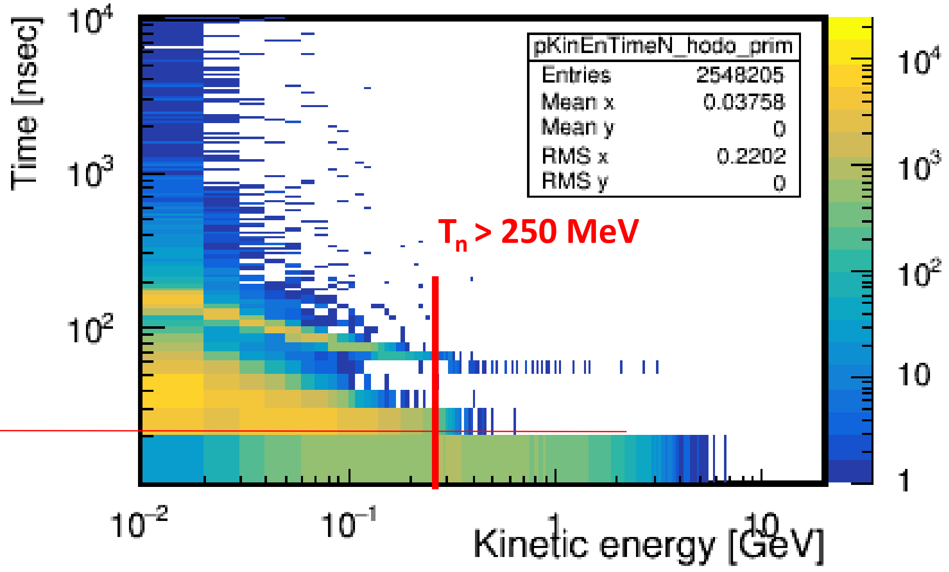
To have statistics 10M neutrons one needs ~ 4 days (w/o taken into account the efficiency)

Neutrons time-of-flight vs kinetic energy

Primary neutrons,
Vacuum in cave



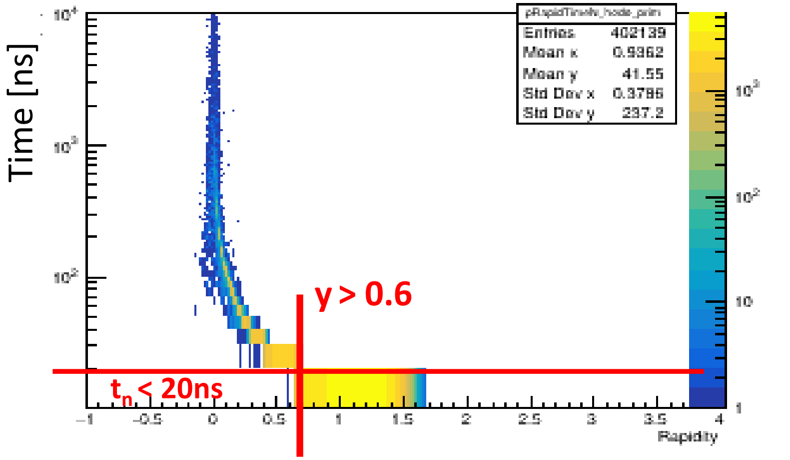
All neutrons
Air + Magnet + FHCal in cave

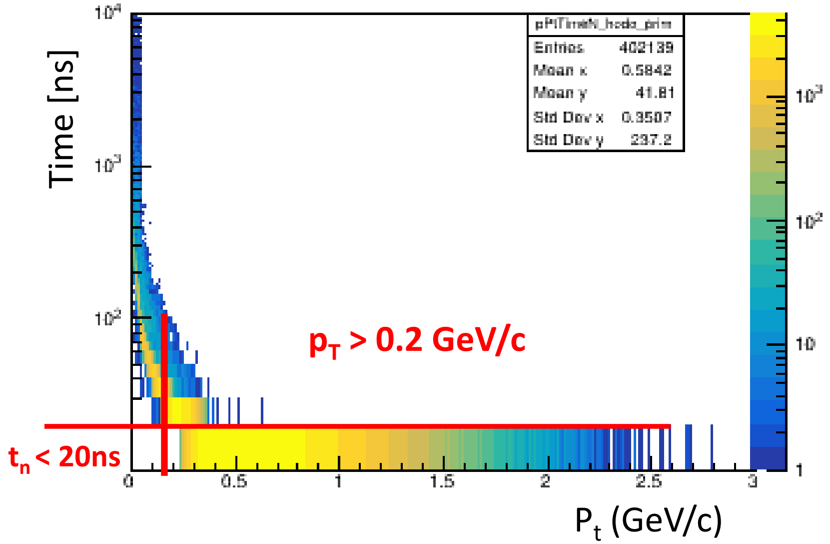


The use cut on neutron TOF < 20 ns leads to cut on neutron energy > 250 MeV.

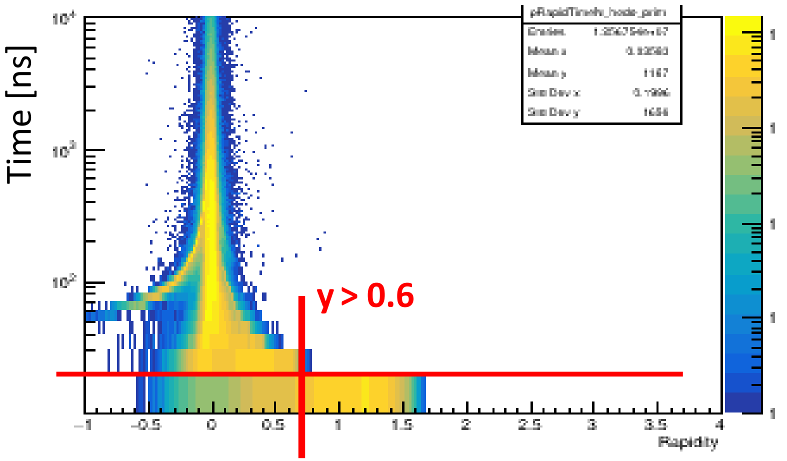
Acceptance of nDet at neutron TOF < 20 ns cut

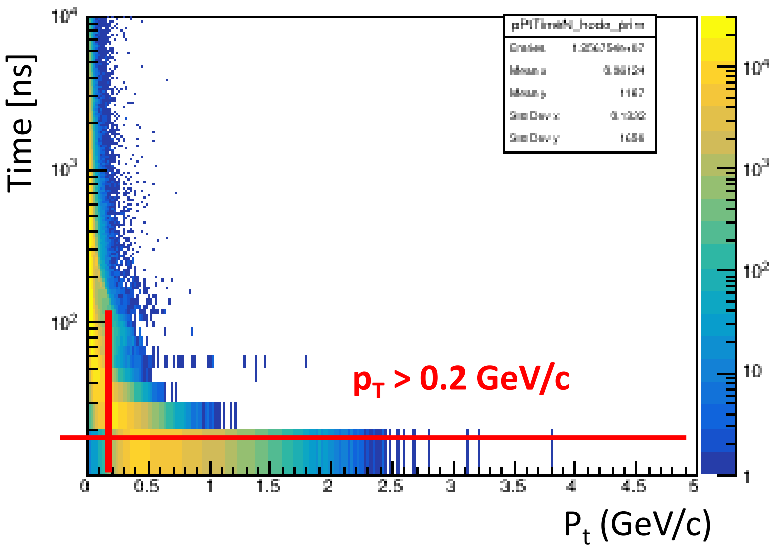
Primary neutrons,
Vacuum in cave





All neutrons
Air + Magnet + FHCal in cave





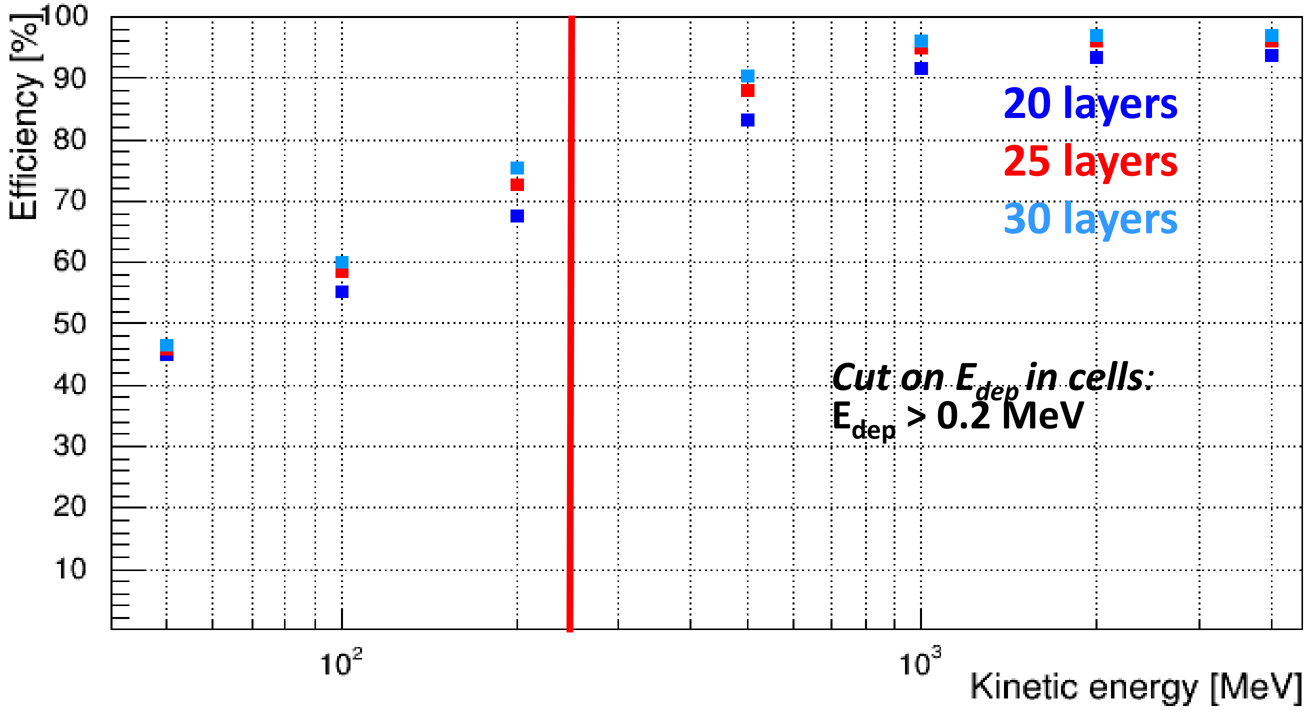
Acceptance at t_n < 20 ns:

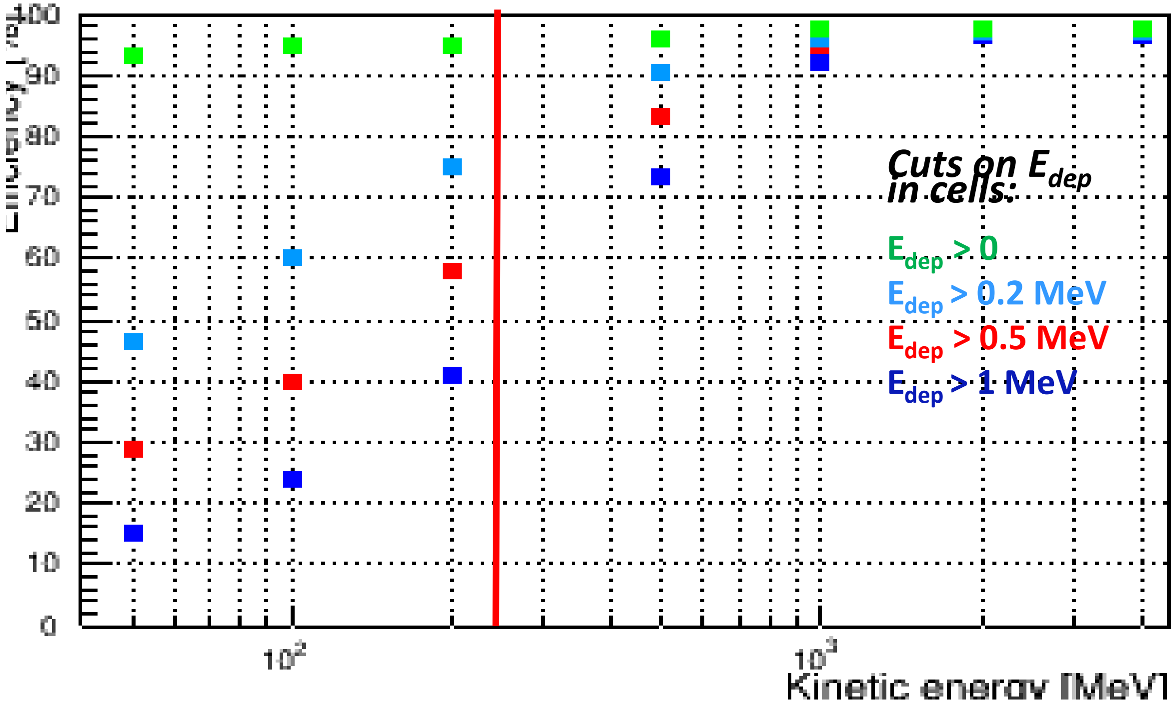
y – [0.6 - 1.6]

p_t – [0.2 – 2.0 GeV/c]

Efficiency of one neutron detection vs kinetic energy and threshold on E_{dep} in cells

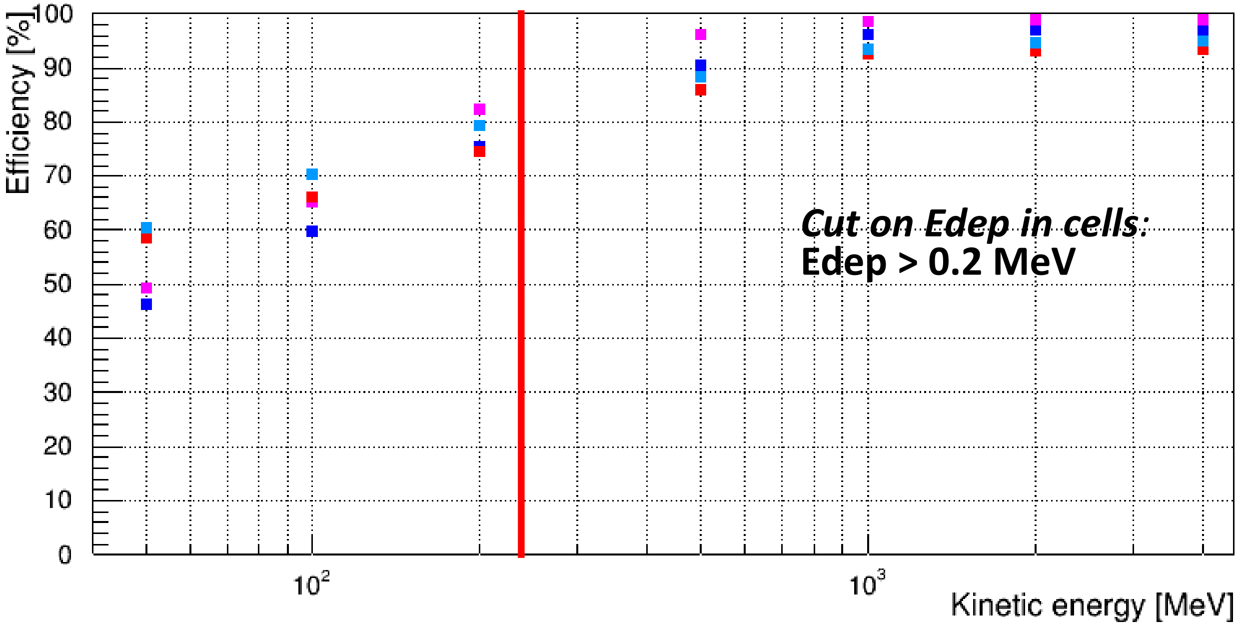
Structure of 1 layer- (Fe 1.6 cm + Sc 0.4 cm + Plastic 0.5 cm)





Efficiency of neutron detection depends rather strong on threshold in scintillator cells for neutron energies below 1 GeV.

Efficiency of one neutron detection vs kinetic energy for different structures of layers



400 cells in one layer with transverse size 60 x 60 cm

30 layers
(Fe 1.6 cm + Sc 0.4 cm + Plastic 0.5 cm)
L= 75 cm (3.2 λ_{in})

30 layers
10 layers of (Fe 0.5 cm + Sc 0.4 cm + Plastic 0.5 cm)
+ 10 layers of (Fe 1 cm + Sc 0.4 cm + Plastic 0.5 cm)
+10 layers of)Fe 2 cm + Sc 0.4 cm + Plastic 0.5 cm)
L = 62 cm (2.4 λ_{int})

30 layers
10 layers of (W 0.5 cm + Sc 0.4 cm + Plastic 0.5 cm)
+ 10 layers of (Fe 1 cm + Sc 0.4 cm + Plastic 0.5 cm)
+ 10 layers of (Fe 2 cm + Sc 0.4 cm + Plastic 0.5 cm)
L = 62 cm (2.95 λ_{int})

25 layers
5 layers of (W 0.5 cm + Sc 0.4 cm + Plastic 0.5 cm)
+ 20 layers of (W 2 cm + Sc 0.4 cm + Plastic 0.5 cm)
L = 65 cm (4.55 λ_{int})

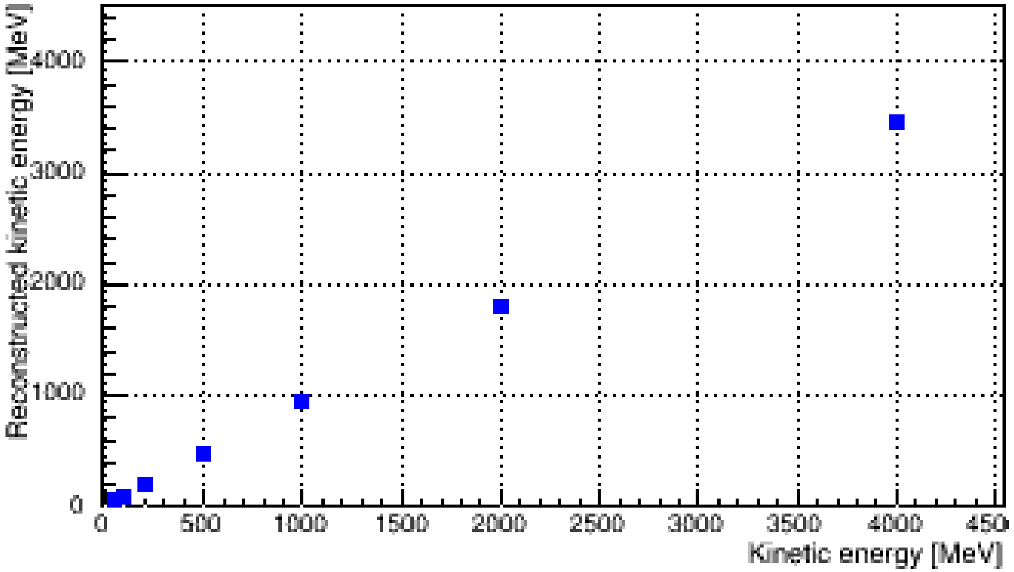
Taking into account the compromise between efficiency and cost, nDet with layers: Fe 1.6 cm + Sc 0.4 cm + Plastic 0.5 cm is considered as more optimal.

Reconstructed neutron kinetic energy

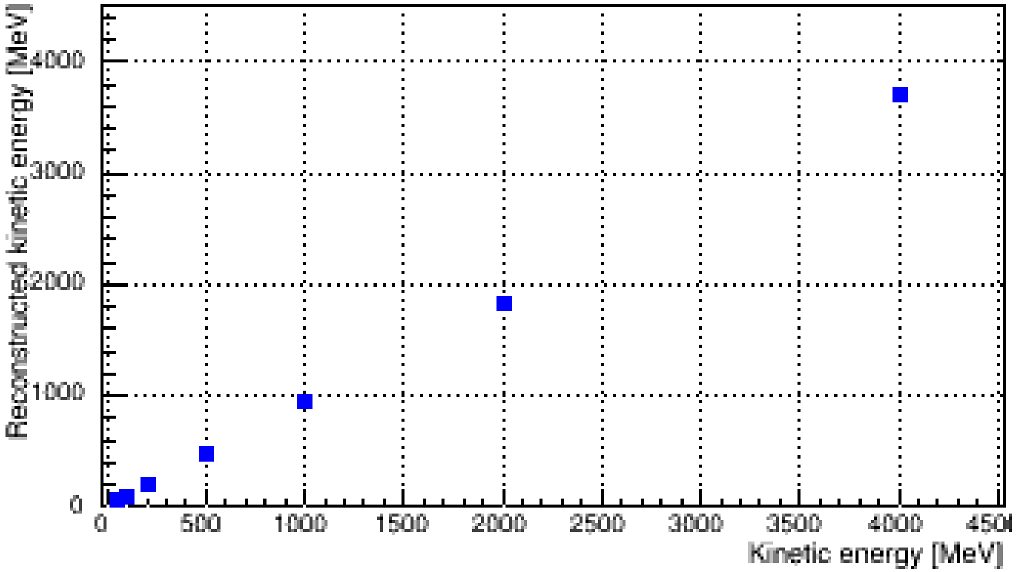
Reconstruction of primary neutrons energy is based on selecting of nDet cells with time–of-flights in time window ± 1 ns wrt cell with minimum TOF and calculating mean neutron kinetic energy for these cells. In addition, cell's TOF were smeared by Gauss distributions with $\sigma_t = 100\ (150\ \text{ps})$.

30 layers of (Fe 1.6 cm + Sc 0.4 cm + Plastic 0.5 cm)

Time resolution of cell 100 ps



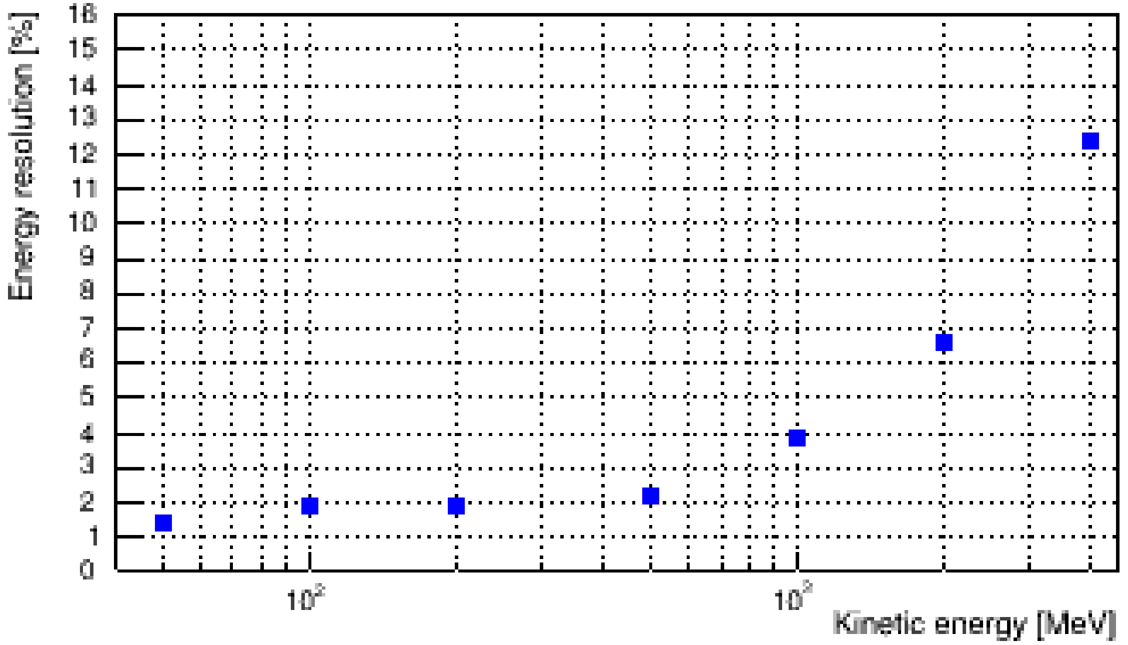
Time resolution of cell 150 ps



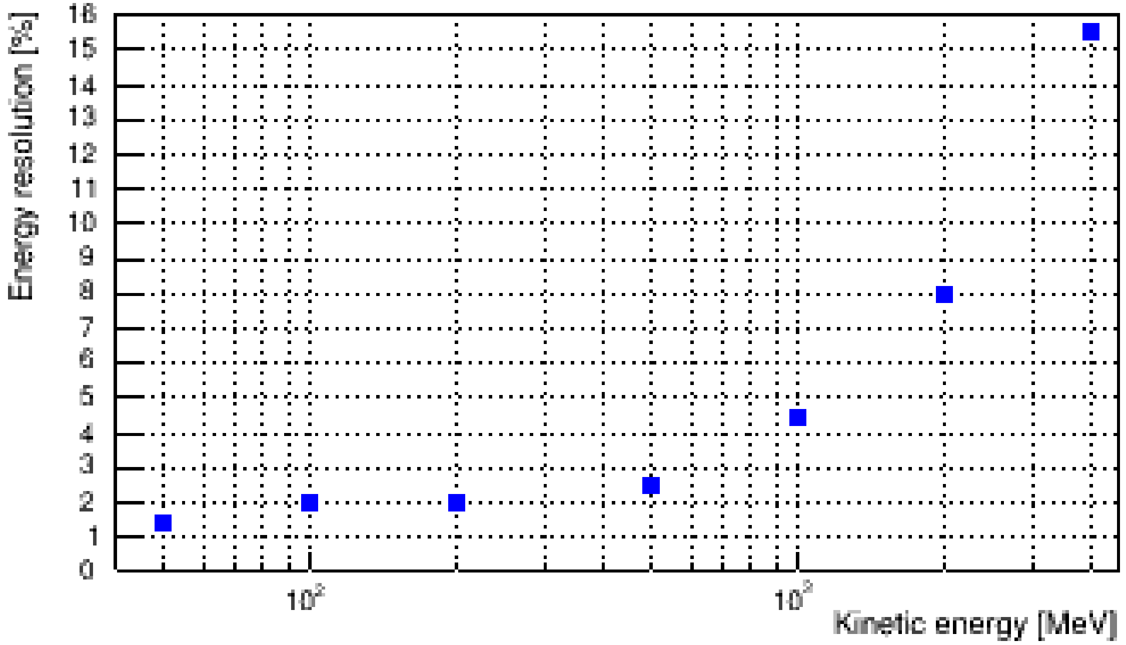
Neutron energy resolution

30 layers of (Fe 1.6 cm + Sc 0.4 cm + Plastic 0.5 cm)

Time resolution of cell 100 ps



Time resolution of cell 150 ps



Simulation of neutron flow

- Au+Au@3.8A GeV, DCM-SMM,
- ~ 10^6 Min. Bias events
- neutrons flow in nDet acceptance and for $t_n < 20$ ns
- Flow is calculated relative reaction plane measured by FHCal (w/o magnetic field) for semicentral events with 3≤b≤7.

$$\frac{dN}{dp_t d_y} = \left(\frac{dN}{dp_t dy}\right) \quad (1 + 2 \underbrace{\sum_{n=1}^{\infty} v_n(p_t, y)\cos(n(\phi - \Psi_{RP}))}_{\text{Describes anisotropic behavior}}$$

v_1 : quantifies directed flow

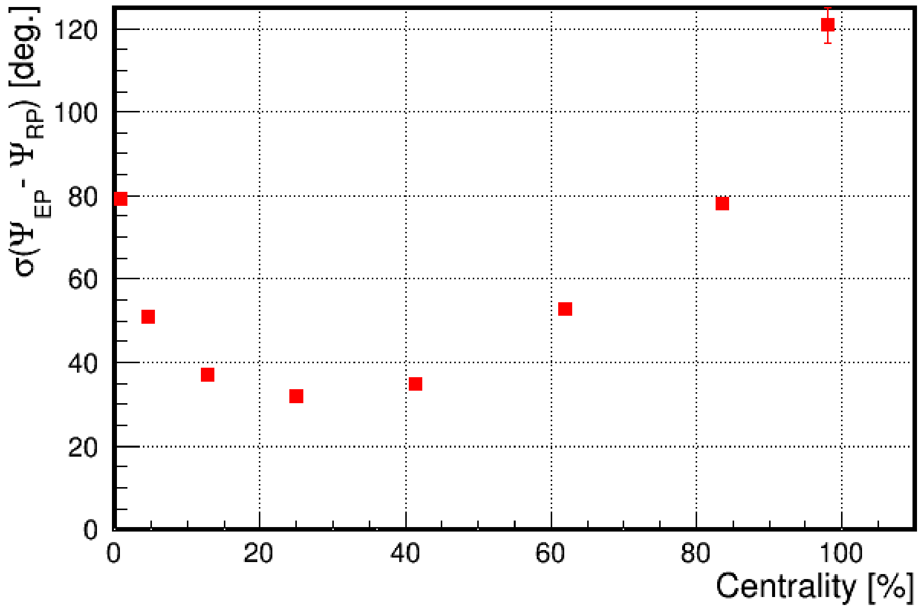
v_2 : quantifies elliptic flow

v_3 : quantifies triangular flow

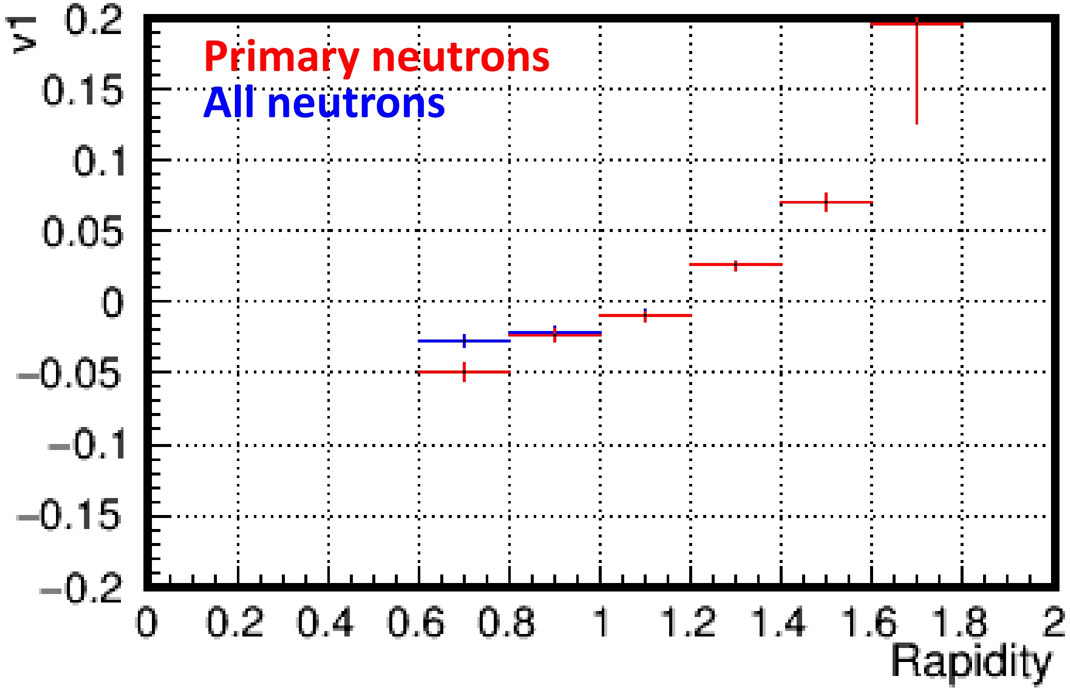
Calculating mean directly :

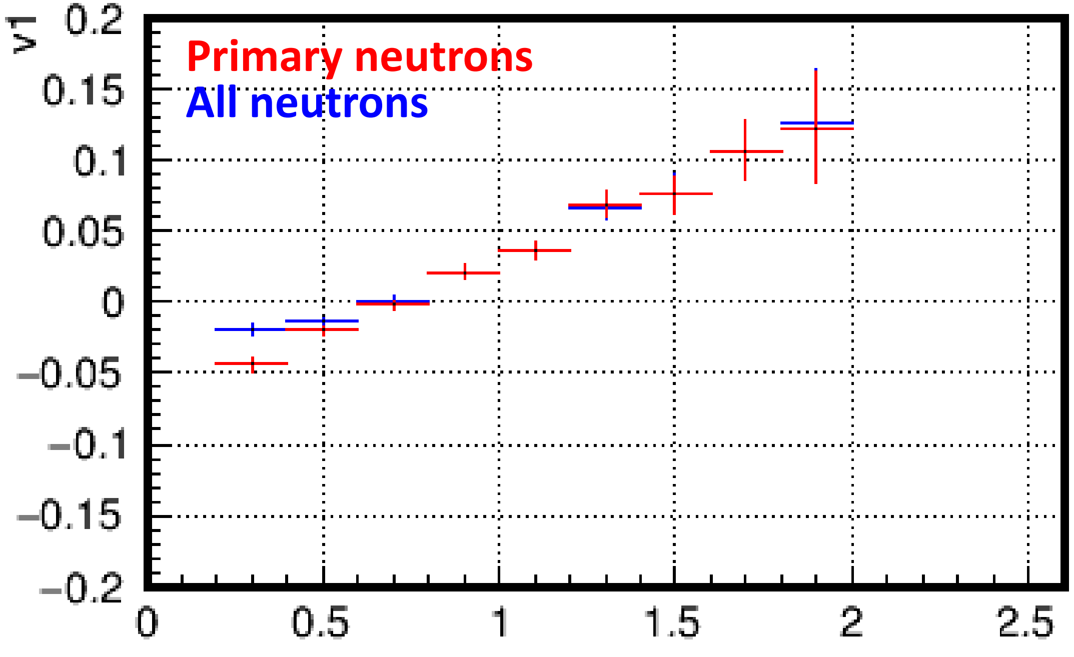
$$\boxed{v_n = \langle \cos(n(\phi - \Psi_{RP})) \rangle}$$

FHCal reaction plane resolution



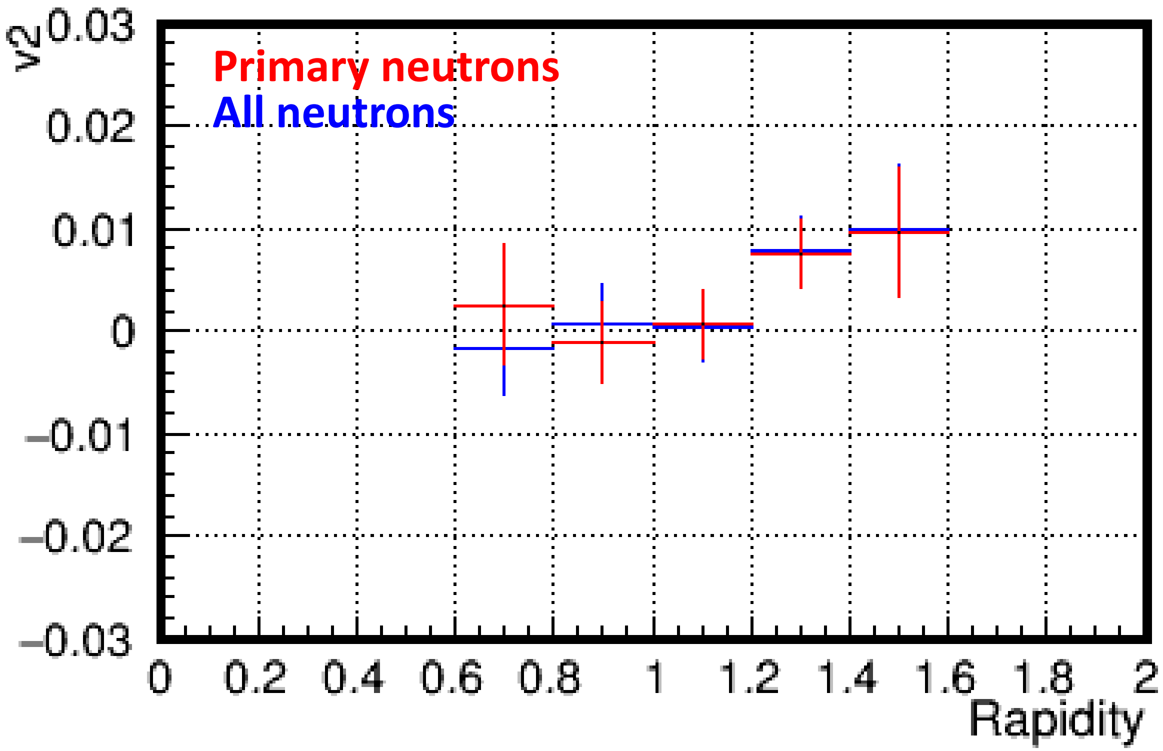
Preliminary results for V_1

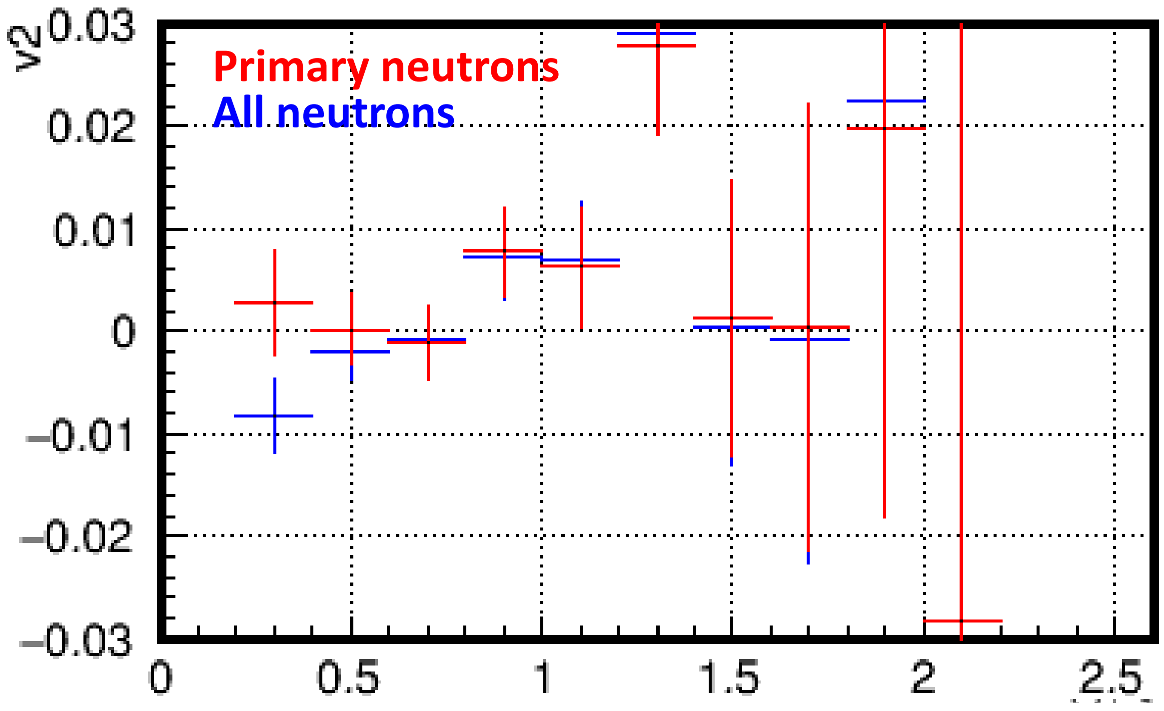




P_T (GeV/c)

Preliminary results for V_2





P_T (GeV/c)

Summary

- **High granularity TOF neutron detector consisted of Fe-Scint layers to measure neutron flow for neutron energy in the range 0.25 – 4 GeV at the BM@N has been proposed. SiPM directly coupled with scintillator cell is proposed to measure the light yield.**

- **Significant neutron background is expected and method of its rejection is proposed.**

- **Efficiency and energy resolution of one neutron has been estimated. The efficiency is more than 95% at neutron kinetic energy > 1 GeV.**

- **The energy resolution is about 2% at neutron energies up to 1 GeV and increased up to 12% at E_n = 4 GeV with cell time of flight resolution about 100 ps.**

- **Preliminary results of neutron flow have been shown.**

Outlook

- Reconstruction algorithm for events with neutron multiplicity >1

- Gamma background rejection

- Time resolution of scintillator cell

- Readout electronics - Integrated electronics or TRB3, NeuLAND,…?

- Neutron detector prototype design and study its response at the BM@N with neutrons from dp reaction.

Thank you for attention