# Study of neutron production in nucleus-nucleus collisions

## Addendum to BM@N program

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1. Status of neutron data and neutron spectrometry
2. Aim of neutron measurements
3. Phenomenological picture of neutron emission
4. Project of neutron measurements at BM@N
   - Methods for study of neutron emission in *AA*- collisions
   - Layout of neutron detectors
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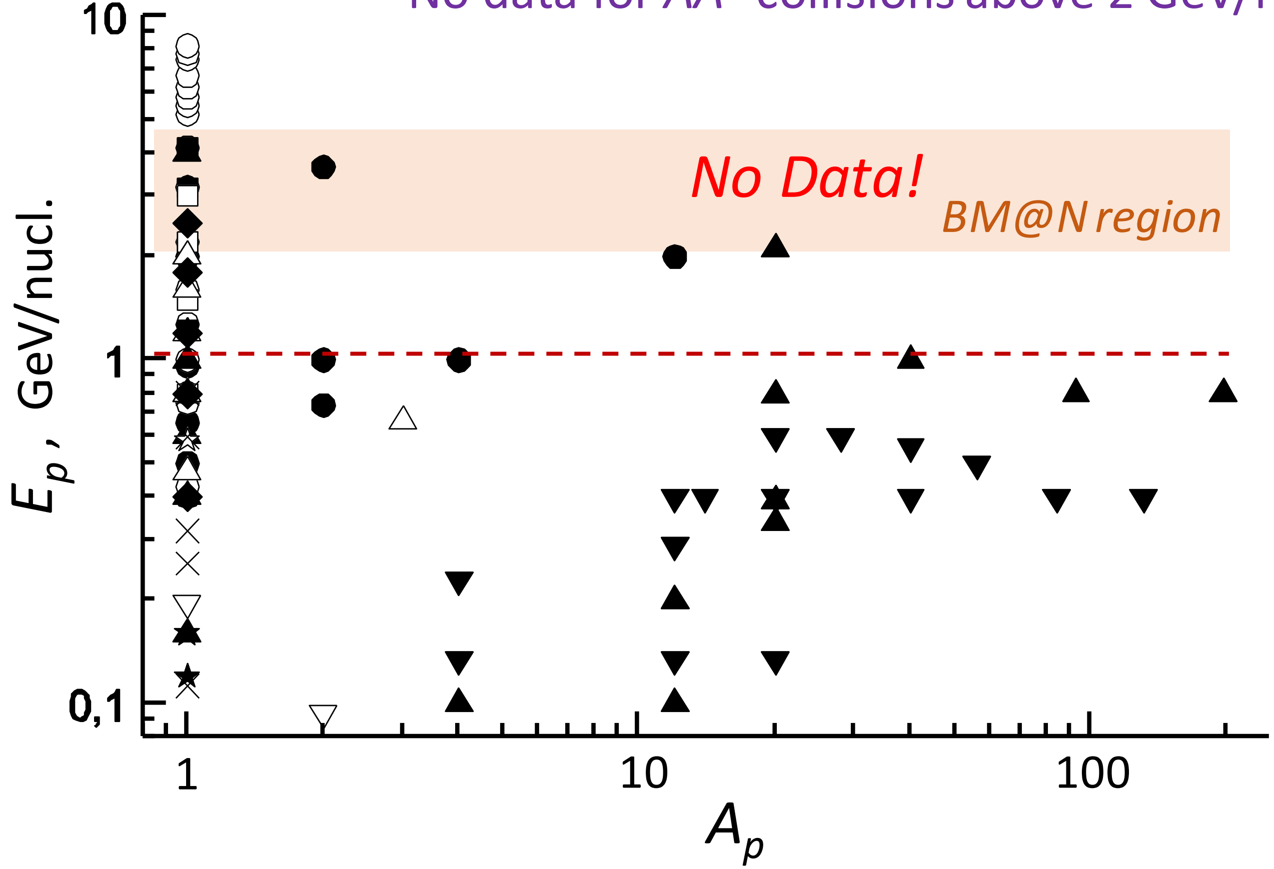
   - Forward neutron detector
   - Neutron Zero-Degree Calorimeter
   - Status of the neutron detectors

# Status of neutron data

- Mainly the data were obtained with proton beam
- Neutron spectra measurements without selection on centrality
- No data for *AA*- collisions above 2 GeV/nucleon



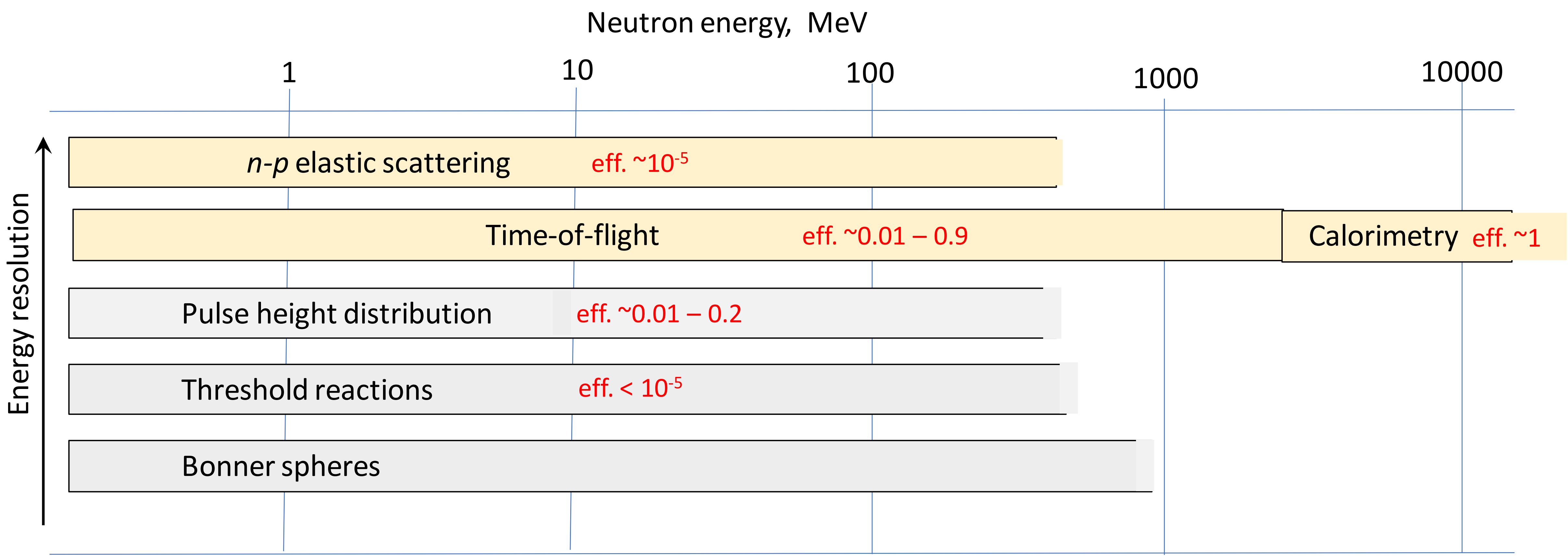

<u>TOF measurements of neutron spectra</u>

*p* + *A* collisions
(LANL, SATURNE, JINR, ITEP, KEK, CERN)

*A* + *A* collisions
(LBNL, JINR, HIMAC, GSI, AGS, CERN)

✓ Neutron spectra were measured with min. bias trigger (no selection on centrality)

# Basic Methods of Neutron Spectrometry




– definite correspondence between energy and measured value

– complicated unfolding procedure with well-known response functions and some a priori information about neutron spectrum is required

# Comparison of energy resolution for HCal and TOF spectrometer

## Calorimeters

Detection efficiency of neutrons above 5 GeV ~ 100%

**Examples**

**SPACAL calorimeter**
Large number of layers Pb / plastic scintillator (20%)
Energy resolution: $a = 0.306$ GeV$^{1/2}$, $b = 0.01$

**E864 calorimeter**
Spaghetti type calorimeter. Array from 58×13 modules, each module 10×10×117 cm Pb/scintillator with ratio Pb : scintillator = 4.55 : 1 (in volume)
Energy resolution: $a = 0.34$ GeV$^{1/2}$, $b = 0.035$
Time resolution: $\sigma_t = 0.4$ ns

**E814 calorimeter**
Layers of U-Cu-scintillator with thickness of 4.2 inter. lengths
Energy resolution: $a = 0.37$ GeV$^{1/2}$, $b \approx 0$

TOF spectrometer with $\sigma_t = 0.1$ ns

$\sigma_E/E$ (%)

| | $E$ = 1 GeV | $E$ = 5 GeV |
|---|---|---|
| $L$ = 2.5 m | 7.9 | 58 |
| $L$ = 5 m | 4 | 30 |
| $L$ = 10 m | 2 | 15 |

Calorimeters

$\sigma_E/E$ (%)

| | $E$ = 1 GeV | $E$ = 5 GeV | $E$ = 10 GeV |
|---|---|---|---|
| SPACAL | 31.6 | 14.7 | 10.7 |
| E864 | 37.5 | 18.7 | 14.2 |
| E814 | 37 | 16.5 | 11.7 |

# TOF spectrometers with organic scintillators

| Accelerator | Detector (cm) | Efficiency | Path (m) | $\sigma_t$ (ns/m) | *n/γ* | Type* | Status |
|---|---|---|---|---|---|---|---|
| LAMPF/LANL | BC418 D5.08x5.08, D5.08x2.5<br>BC501 D25.4×5.1, D30.5×20.3<br>NE213 D10.2×10.2 | Exp./Calc.<br>Calc.<br>Calc. | 29 - 50 | 0.034 - 0.02 | No<br>Yes<br>Yes | **SC** | *Active* |
| SATURNE / Saclay | NE213 D12.7x5.1<br>NE213 D16x20 | Exp./Calc. | 8.5 | 0.24<br>0.18 | Yes<br>Yes | **SC** | |
| Synchrophasotron / JINR | Stilbene D4x1<br>Stilbene D5x5<br>Plast. scintill. D12x20 | Exp.<br>Exp./Calc.<br>Exp. | 0.5 - 0.7<br>0.7 - 1.2<br>1.5 - 2 | 0.8<br>0.7 - 0.4<br>0.3 - 0.25 | Yes<br>Yes<br>No | **OG** | |
| Synchrotron / ITEP | Plast. scintill. D20x20 | Exp./Calc. | 1.5 | 0.3 | No | **OG** | |
| Synchrotron / ITEP | Liquid scintill. D12.7x15.2<br>NE110 20x20x11.5 | Calc. | 2, 3 | 0.3, 0.2 | Yes<br>No | **OG** | |
| PS / KEK | NE213 D5.08x5.08,<br>D12.7x12.7 | Exp./Calc. | 0.6 - 0.9<br>1 - 1.5 | 0.8 - 0.6<br>0.5 - 0.3 | Yes<br>Yes | **OG** | *Active* |
| HIMAC/NIRS | NE213 D12.7x12.7 | Exp./Calc. | 3 - 5 | 0.3 - 0.2 | Yes | **OG** | *Active* |
| Cyclotron / iThemba LABS | NE213 D5.08x10.16 | Exp./Calc. | 8 | 0.13 | Yes | **SC** | *Active* |

**SC** – shielding and collimators, fixed angles **OG** – open geometry

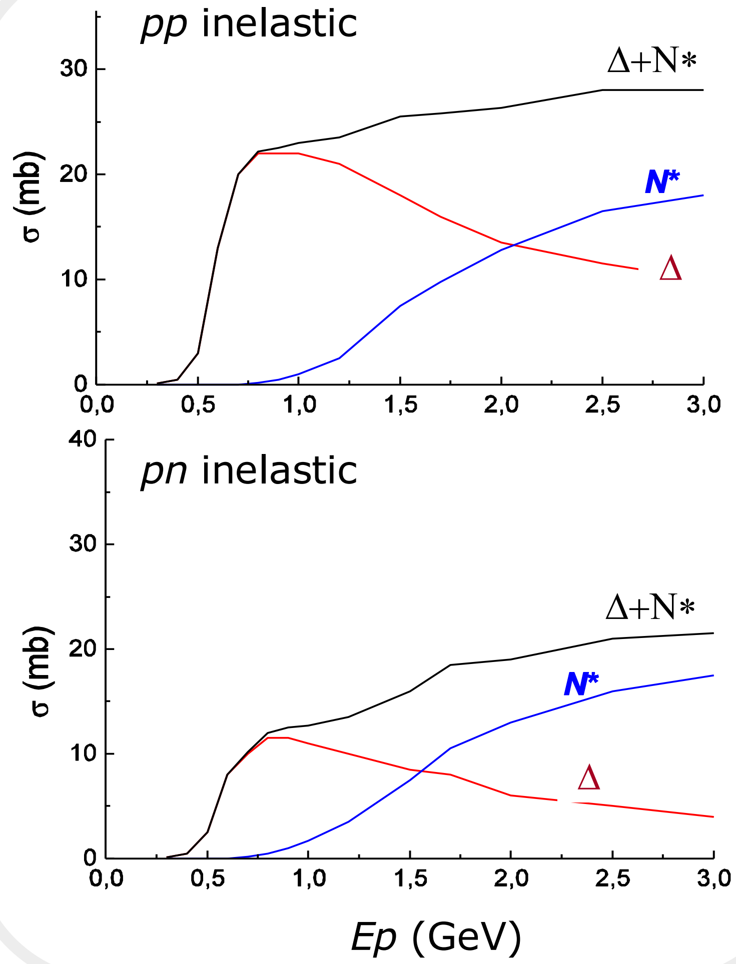
# Aim of neutron measurements

- ✓ Neutron production double differential cross sections
- ✓ Neutron multiplicity distribution
- ✓ Neutron production dependence on centrality of *AA*- collisions
- ✓ Neutron production dependence on size of colliding nuclei
- ✓ Contribution of different stages of nuclear system decay to neutron production
- ✓ Estimation of temperature and velocity of neutron sources
- ✓ Estimation of neutron collective flow as a function of centrality and reaction plane

These results will be unique and very useful for development of theoretical models and codes.

# Phenomenological picture of neutron emission

## Nucleus – nucleus collisions and neutron emission at BM@N energies




Wave length of nucleon:

*1000 MeV* → *λ ~ 0.7 fm*
*100 MeV* → *λ ~ 2.7 fm*
*10 MeV* → *λ ~ 9 fm*

In energy region > 0.7 GeV the free path length of nucleon in nuclear matter $\lambda_I \sim 1$ fm and heavy nucleus becomes very thick target.

⇩

*AA*- collisions at BM@N energies characterized by

- Formation of hot and dense baryonic matter in participant region
- High excitation of target and beam nuclear spectators

⇩

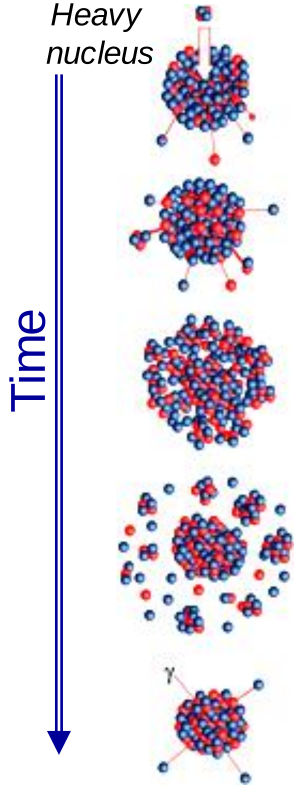
High multiplicity of emitted neutrons at all stages of nuclear system decay

# Phenomenological picture of neutron emission

## Stages and sources of neutron emission in collisions of light-mass nuclei with heavy nuclei

*Light projectile (H,He,C)*

*Heavy nucleus*




First collisions of projectile and target nucleons
*Source 1 (CC&PC)* → ***n***, *p*, $\pi$

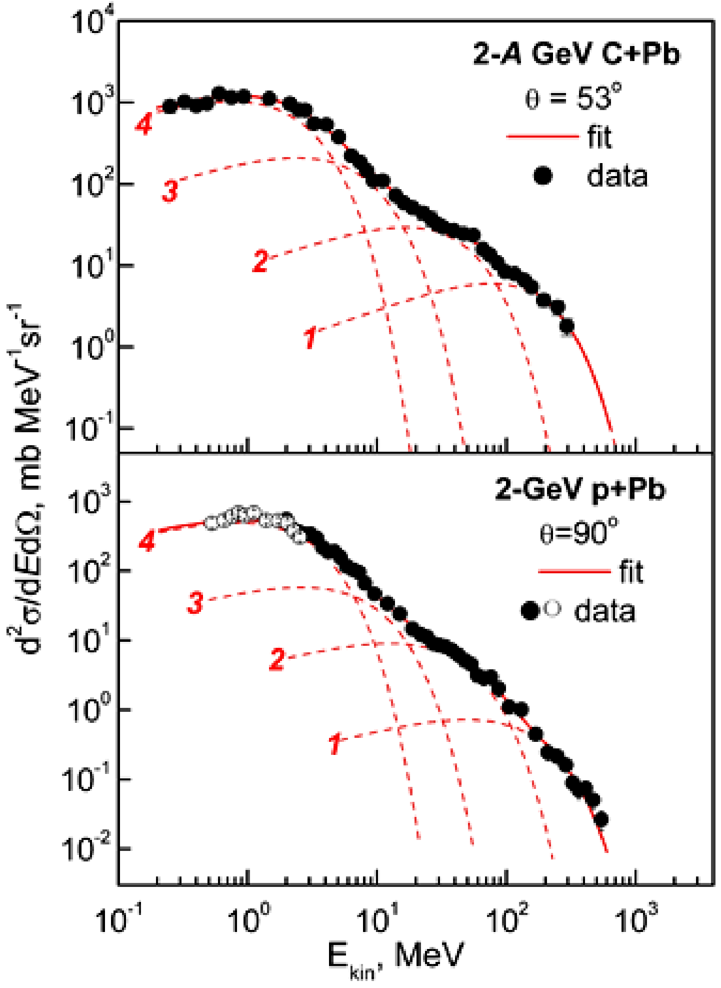
Hot non-equilibrium stage
*Source 2 (CC)* → ***n*** and LCP

*Stage of expansion and thermalization*

Freeze-out stage (fragmentation)
*Source 3 (CC)* → ***n***, LCP and IMF

De-excitation of fragments by evaporation
*Source 4 (CC&PC)* → ***n***

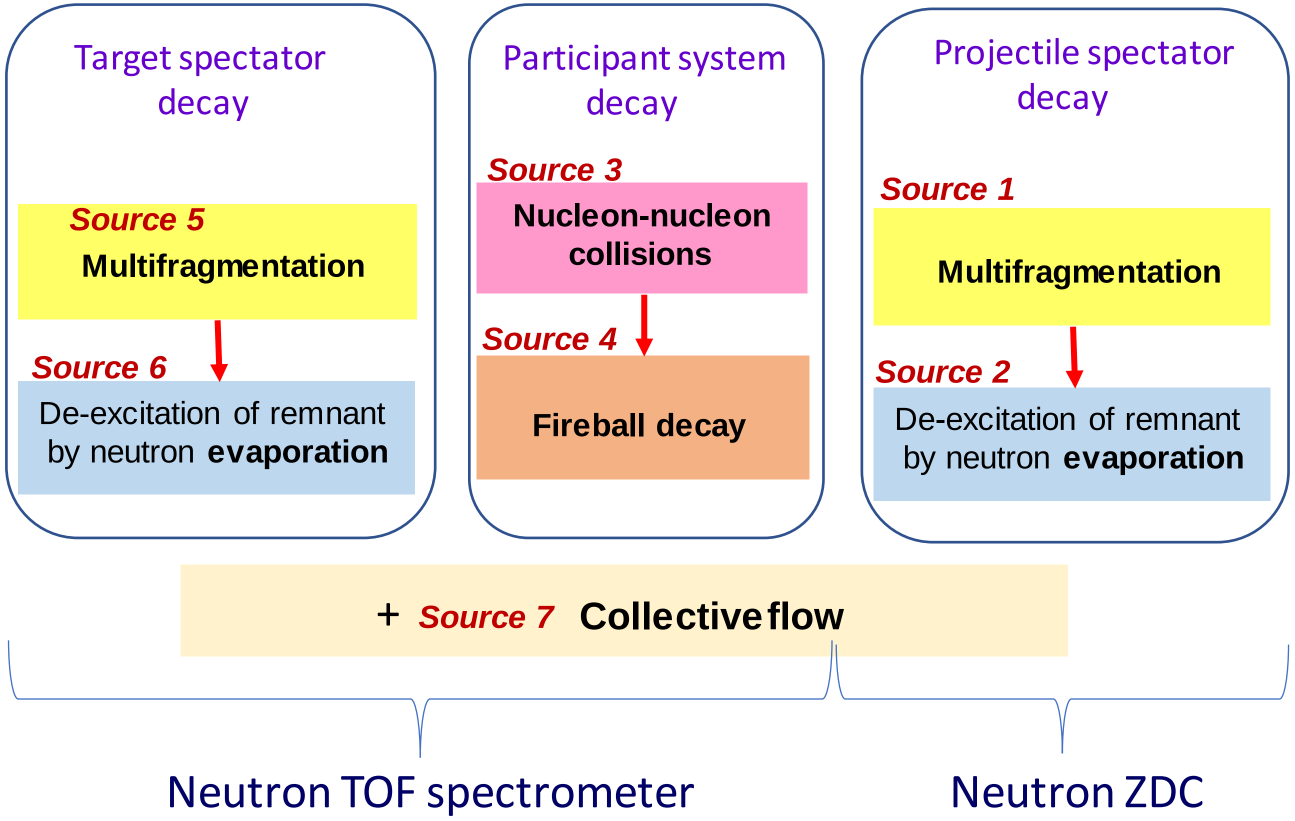
**Emitted particles**



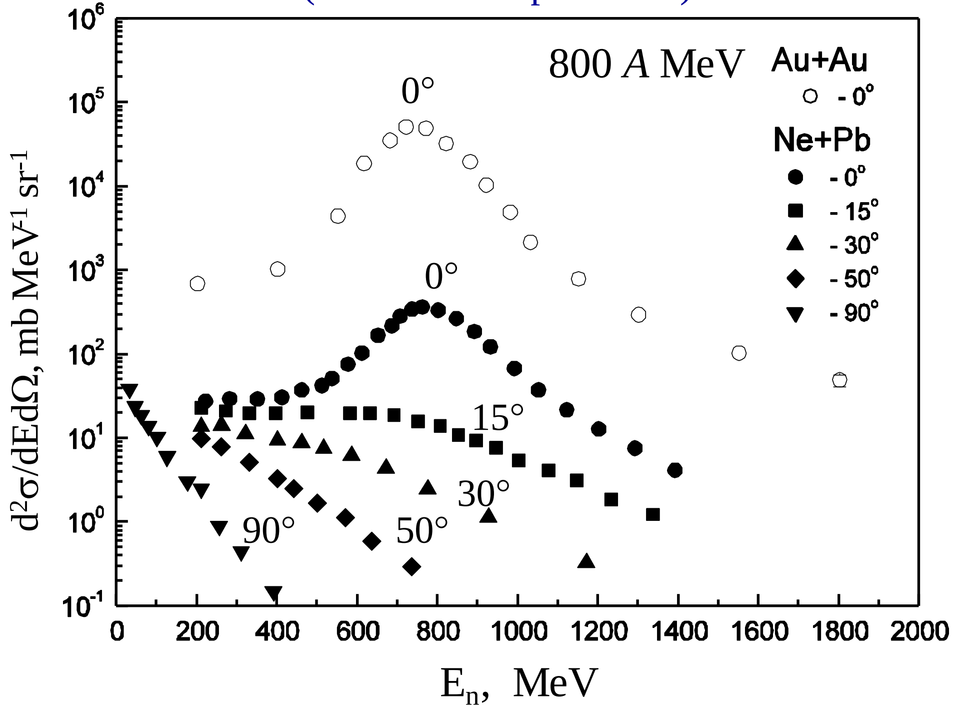

*CC – Central collisions, PC – Peripheral Collisions*

# Phenomenological picture of neutron emission

## Neutron emission in collisions of heavy nuclei




Example of neutron energy spectra
(BEVALAC experiments)



# Project of neutron measurements at BM@N

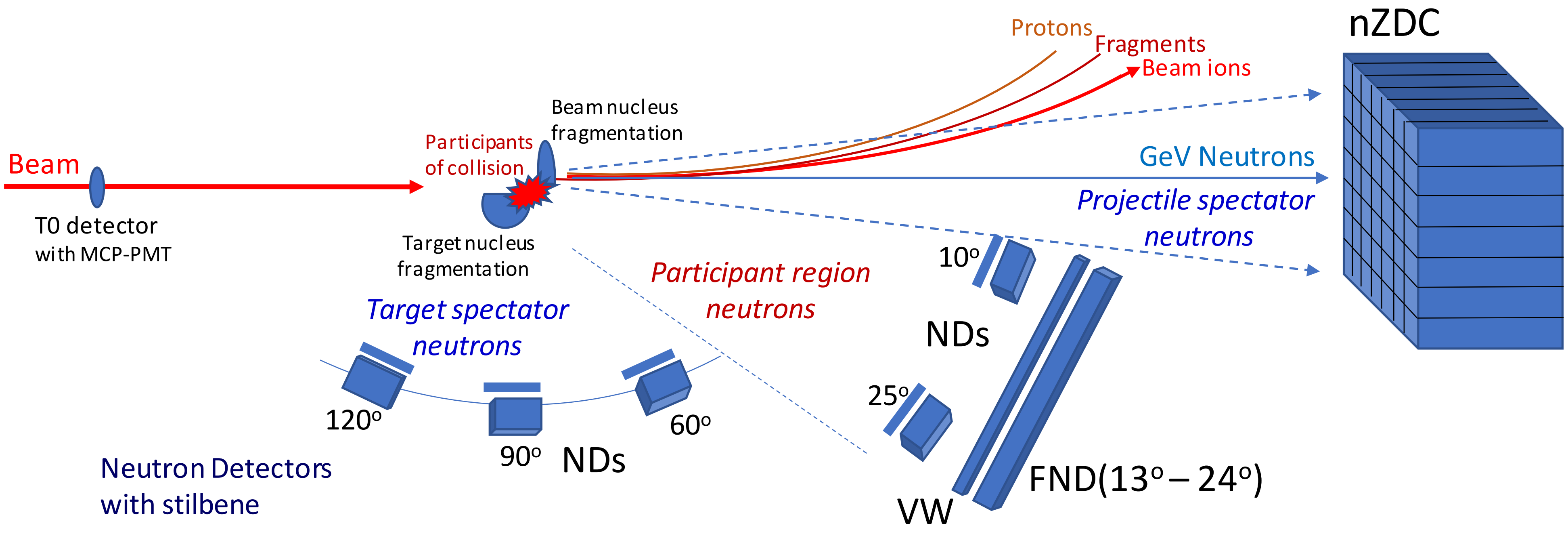
## Methods for study of neutron emission in *AA*- collisions

| Decayed system | Main Stages / sources | Kinematics | Method | Detectors* | Energy range |
|---|---|---|---|---|---|
| Target spectator | Fragmentation<br>Evaporation | Near isotropic emission | TOF with $\sigma_t$ < 100 ps and 40 cm flight path | ND | 0.5 < E < 200 MeV |
| Hot source (participant region) | Inter-nuclear cascade<br>Decay of hot fireball | Forward angle emission | TOF with $\sigma_t$ < 100 ps and 3 m flight path | ND / FND | 100MeV< E <3GeV |
| Beam spectator | Fragmentation<br>Evaporation | Zero-degree emission | Hadron calorimeter | nZDC | > 3 GeV |

- ND – neutron detectors with stilbene crystals and SiPM readout
  FND – forward neutron detector
  nZDC – neutron zero-degree calorimeter

# Project of neutron measurements at BM@N

## Layout of neutron detectors




*TOF neutron spectrometer*

$\sigma_t$ < 100 ps for high-energy neutrons

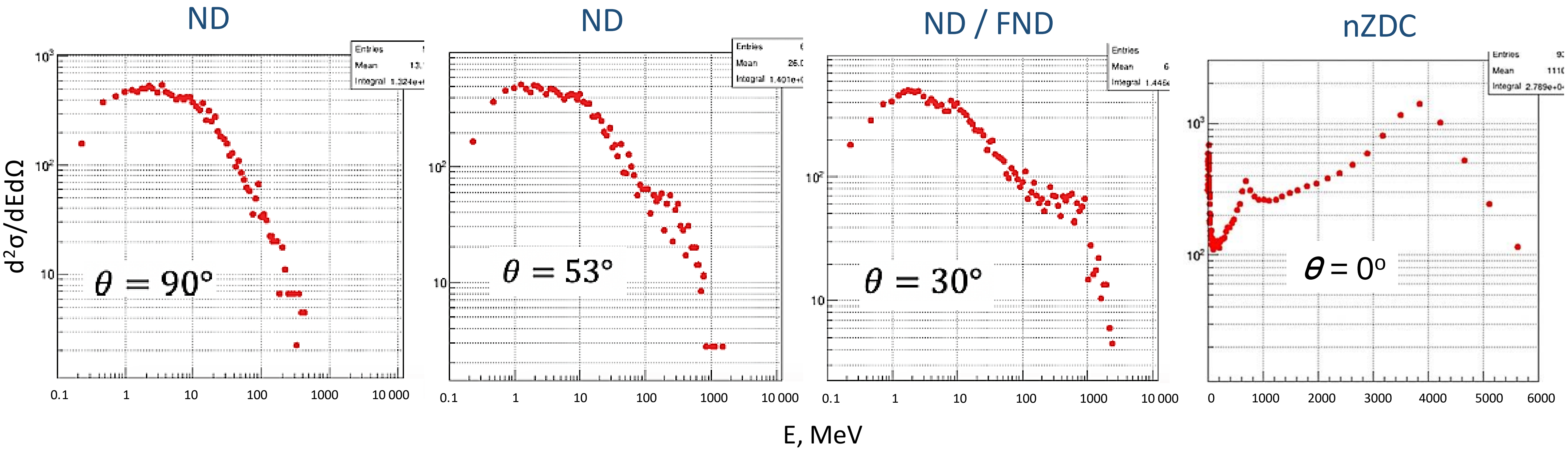
nZDC – neutron zero-degree calorimeter
FND – forward neutron detector
ND – neutron detector with stilbene
VW – veto wall

# Project of neutron measurements at BM@N

## Neutron energy spectra

DCM-QGSM simulation
*N. Lashmanov*

Au + Au , 4.2 *A* GeV

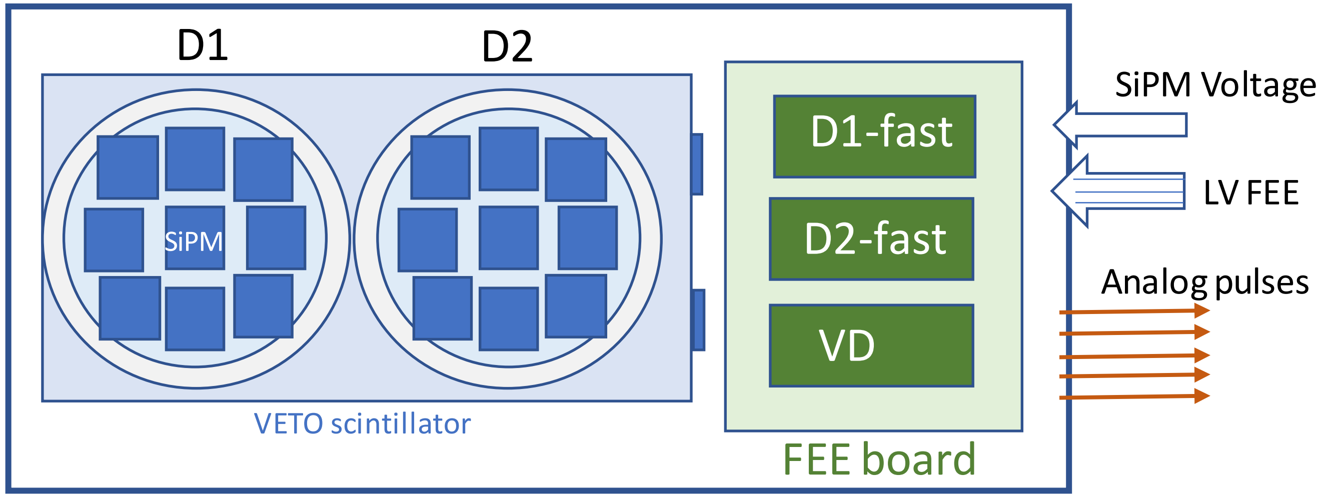


# NEUTRON DETECTORS with STILBENE (ND)

Detector with 2 stilbene crystals 1”diam. x 1”
from Inrad Optics (USA) and SiPM readout

*Why stilbene?*

Stilbene provides *n*/γ pulse shape discrimination
with large suppression of background




Veto scintillator 80x40x5 mm
20 SiPMs 6 x 6 $mm^2$ J-ser. SensL
DAQ electronics: TQDC modules (5 ch. per detector)

Stilbene crystal from Inrad Optics (USA)
10 units are available for detector production

# NEUTRON DETECTORS with STILBENE (ND)

## Estimation of event statistics

**Experimental conditions**

Au + Au collisions at 4.2 *A* GeV

- TOF path: L = 40 cm
- Beam intensity: $I = 10^5$ *ion/s*
- Probability of interaction in target: $P = 0.01$
- ND efficiency: $\varepsilon = 0.15$ (*2-5 MeV*)

⇨

Number of neutrons detected with ND per hour

16500 (60º)
10400 (90º)
8500 (120º)

**Statistics of neutron events per detector for 20-hour run:** $N_n$ **= 330 000 ev (60º)**
**208 000 ev (90º)**
**170 000 ev (120º)**

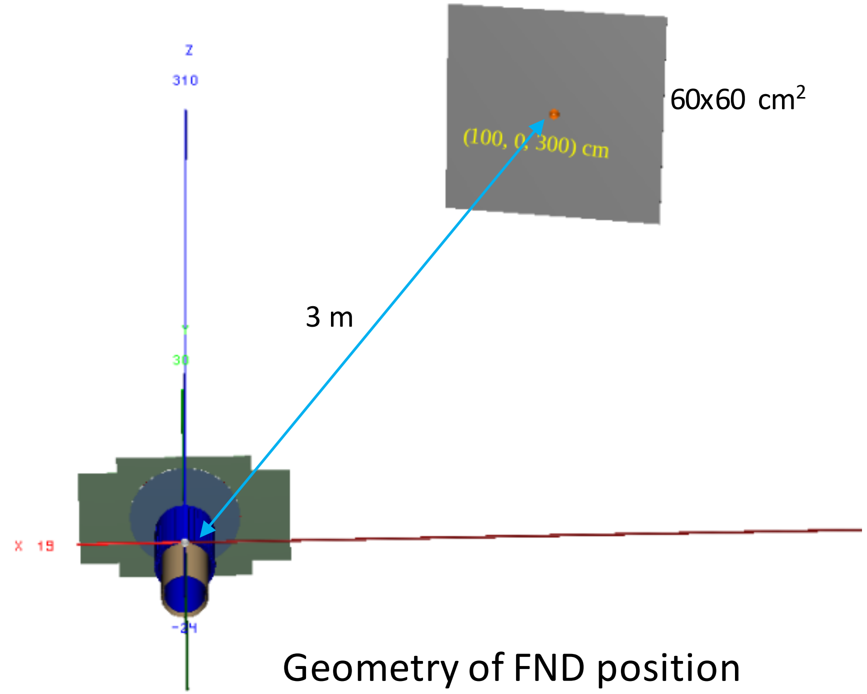
# Forward Neutron Detector (FND)

Au + Au collisions at 4.2 *A* GeV
FND active area: 60x60 $cm^2$
Number of collisions: 10000
FND efficiency: 0.04

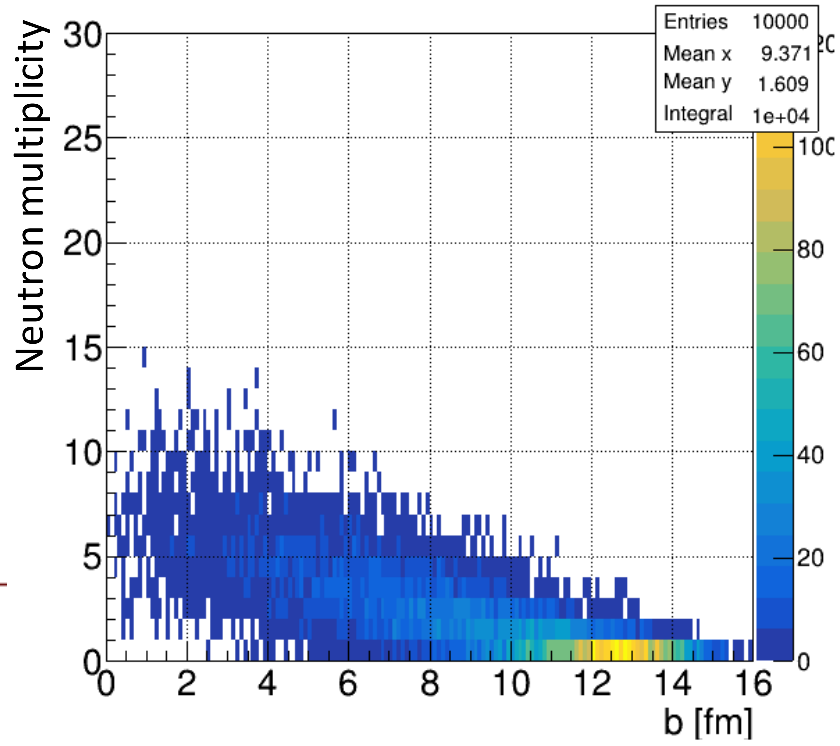
⇨ 16092 neutrons to FND acceptance or 644 detected neutrons

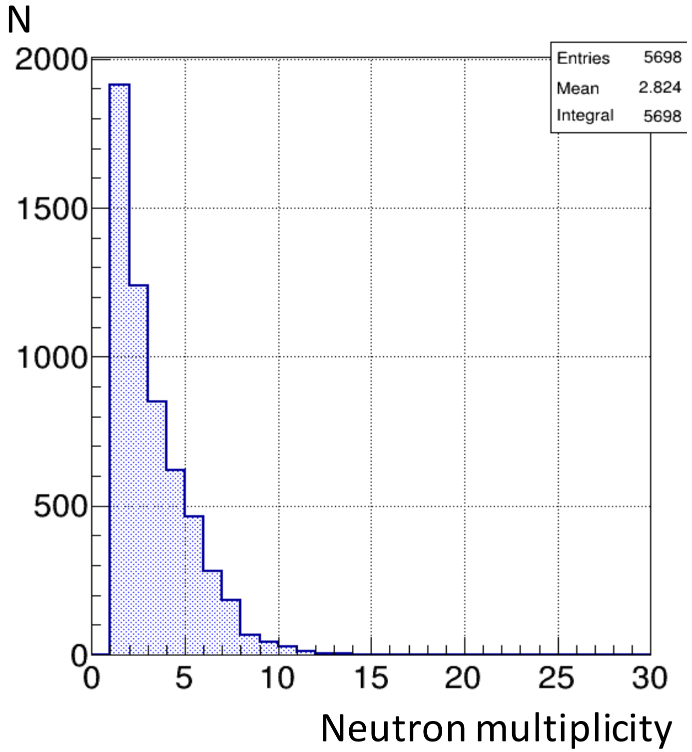
⇨ I = $10^5$ ion/s
1% target
**$N_n$ = 232 000 ev/hour**

DCM-QGSM simulation
*N. Lashmanov*

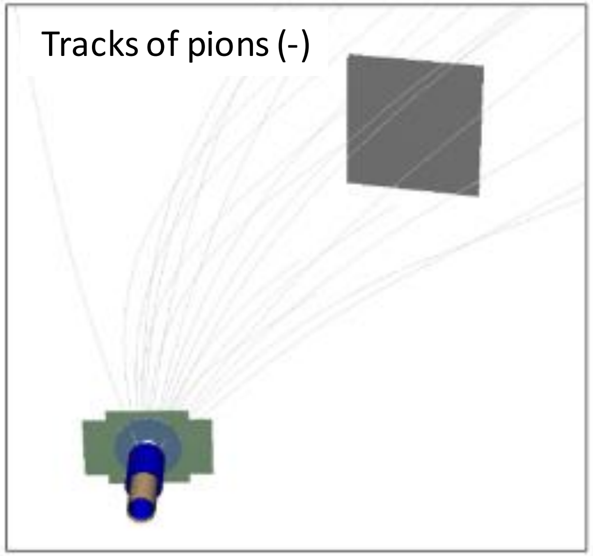


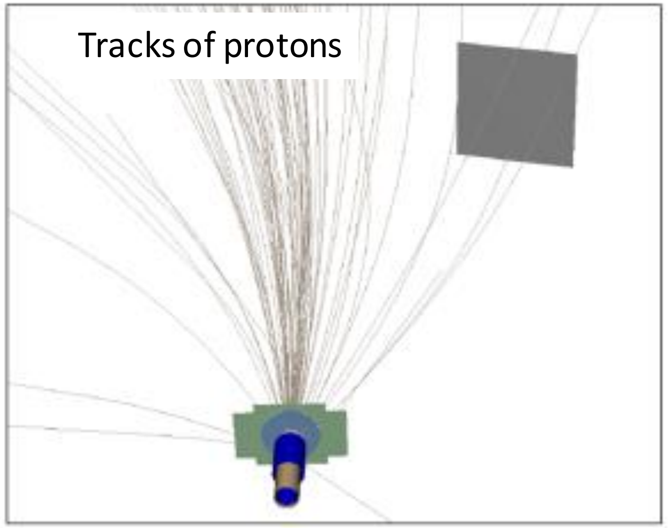

Geometry of FND position



# Forward Neutron Detector (FND)

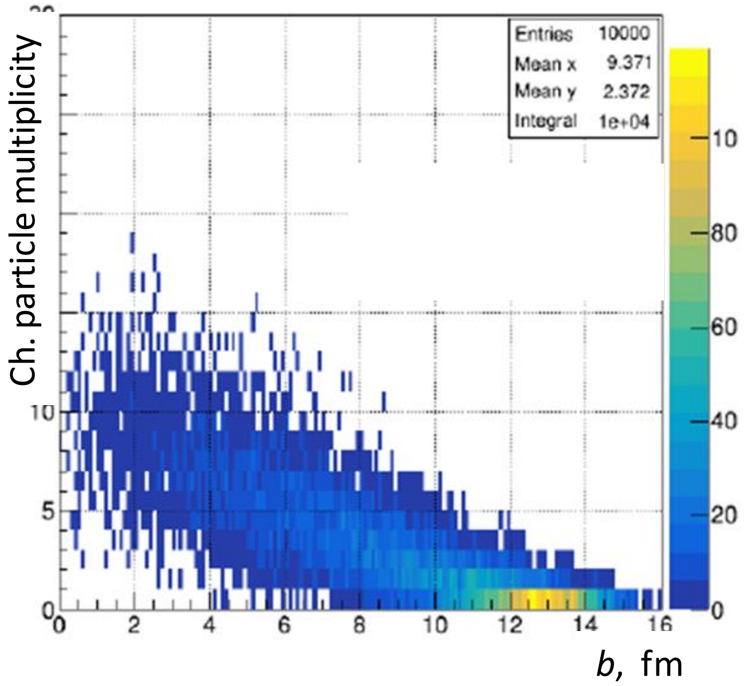


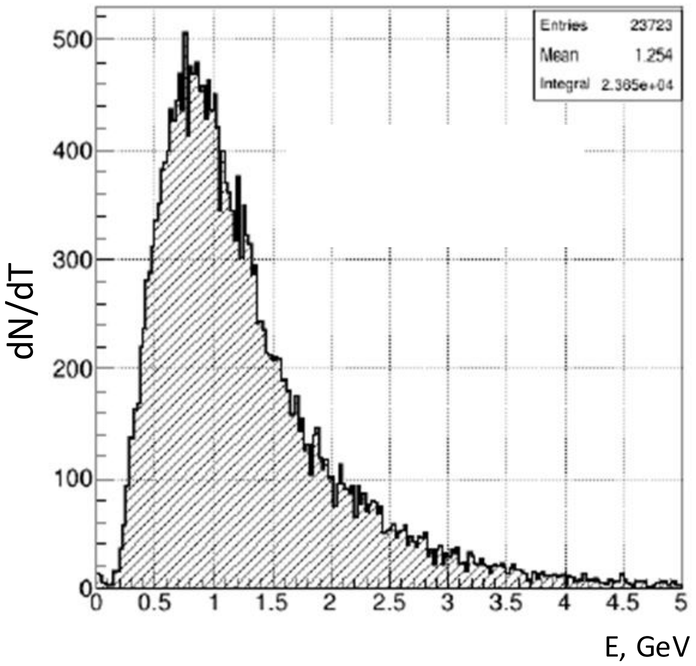



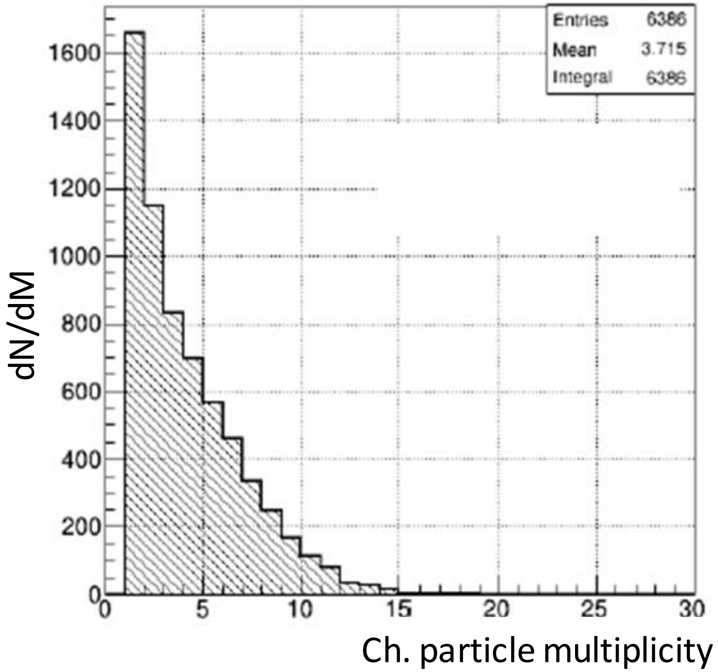

## Ch. particle background to FND

DCM-QGSM simulation
*N. Lashmanov*

Au + Au collisions at 4.2 *A* GeV
FND active area: 60x60 $cm^2$
Number of collisions: 10000



# Forward Neutron Detector (FND)

## Energy resolution of FND

For flight path of 3 m and $\sigma_t$ = 100 ps

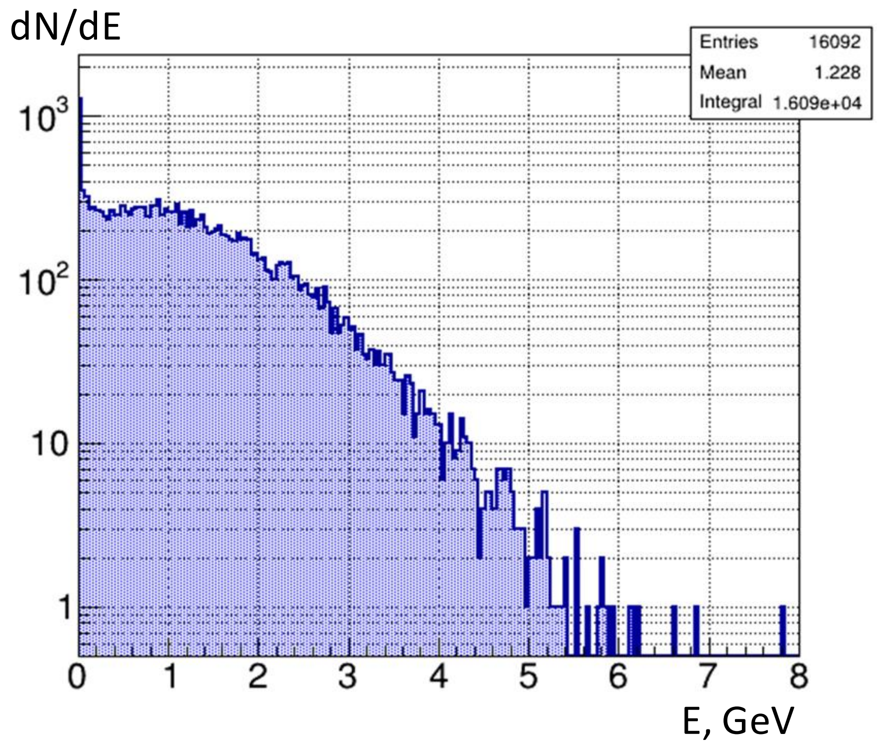
| Ekin (MeV) | γ | β | σE/E (%) |
|---|---|---|---|
| 50 | 1.053 | 0.313 | 0.69 |
| 100 | 1.106 | 0.427 | 1.00 |
| 250 | 1.266 | 0.613 | 1.77 |
| 500 | 1.532 | 0.758 | 3.00 |
| 1000 | 2.064 | 0.875 | 5.58 |
| 2000 | 3.13 | 0.948 | 12.4 |

$\sigma_E/E = \gamma(\gamma+1)[(\sigma_L/L)^2 + (\sigma_t/t)^2]^{1/2} \approx \gamma(\gamma+1)[\beta\sigma_t/(L/c)]$

$E_k = m_0c^2(\gamma-1)$

$\gamma = 1 + E_k/m_0c^2$

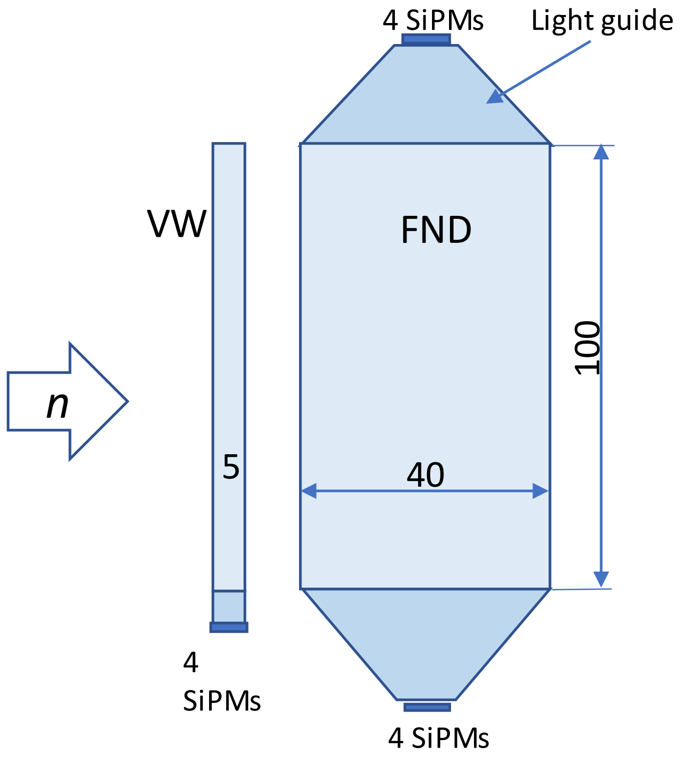
DCM-QGSM simulation
*N. Lashmanov*

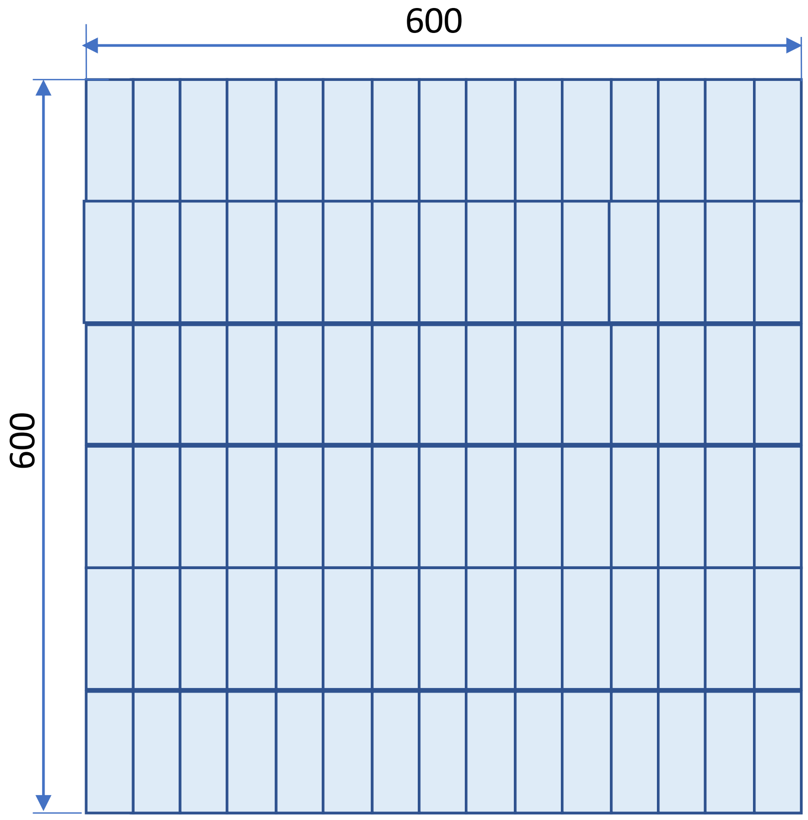



Energy spectrum of neutrons in FND acceptance for Au + Au collisions at 4.2 *A* GeV

# Forward Neutron Detector (FND)

## Project of multichannel FND




SiPM – SensL J-ser. 6x6 $mm^2$

VW – Veto Wall
FND – Neutron Detector

FND – 90 scintillation tiles 100x40x40 mm BC-408
VW – 90 scintillation tiles 100x40x5 mm BC-408

Number of readout channels: 270

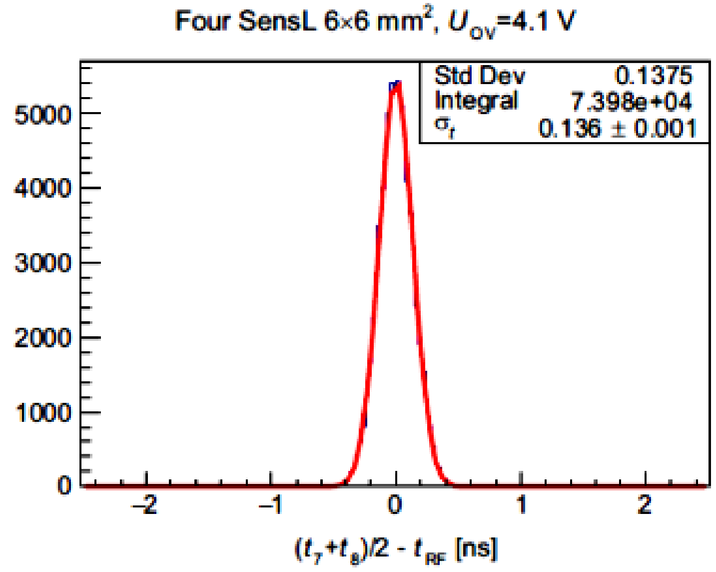
# Study with prototypes – experience of GSI group

For detection of 200–1000 MeV neutrons, the NeuLAND neutron time-of-flight detector at FAIR uses 3000 monolithic scintillator bars of 270 x 5 x 5 $cm^3$ size made of a fast plastic. Each bar is read out on the two long ends, and the needed time resolution is $\sigma_t$ < 150 ps.

| Producer and type | $A$ ($mm^2$) |
|---|---|
| Ketek PM1150 | 1 × 1 |
| Ketek PM3350 | 3 × 3 |
| Excelitas C30742-33 | 3 × 3 |
| SensL C-series | 6 × 6 |
| FBK NUV | 6 × 6 |

Arrays of four 6 x 6 $mm^2$ SiPMs each were built and studied

| Scintillator size in $mm^3$ | SiPM ($mm^2$) | Simulation | | Experiment | |
|---|---|---|---|---|---|
| | | $n_{FP}^{sim}$ | $\sigma_t^{sim}$ | $n_{FP}^{exp}$ | $\sigma_t^{exp}$ |
| 100 × 42 × 11 | 1 × 1 | 20 | 370 | 10 | 340 |
| | 3 × 3 | 270 | 140 | 40 | 170 |
| | 6 × 6 | 980 | 60 | 150 | 94 |
| 100 × 11 × 42 | 1 × 1 | 35 | 280 | 21 | 270 |
| | 3 × 3 | 300 | 130 | 160 | 150 |
| | 6 × 6 | 1160 | 67 | ≥ 280 | 72 |
| 2700 × 50 × 50 | 1 × 1 | 7 | 1300 | 4 | 870 |
| | 3 × 3 | 64 | 420 | 24 | 400 |
| | 6 × 6 | 250 | 230 | ≥ 125 | 240 |
| | Four 6 × 6 | 860 | 124 | | 135 |



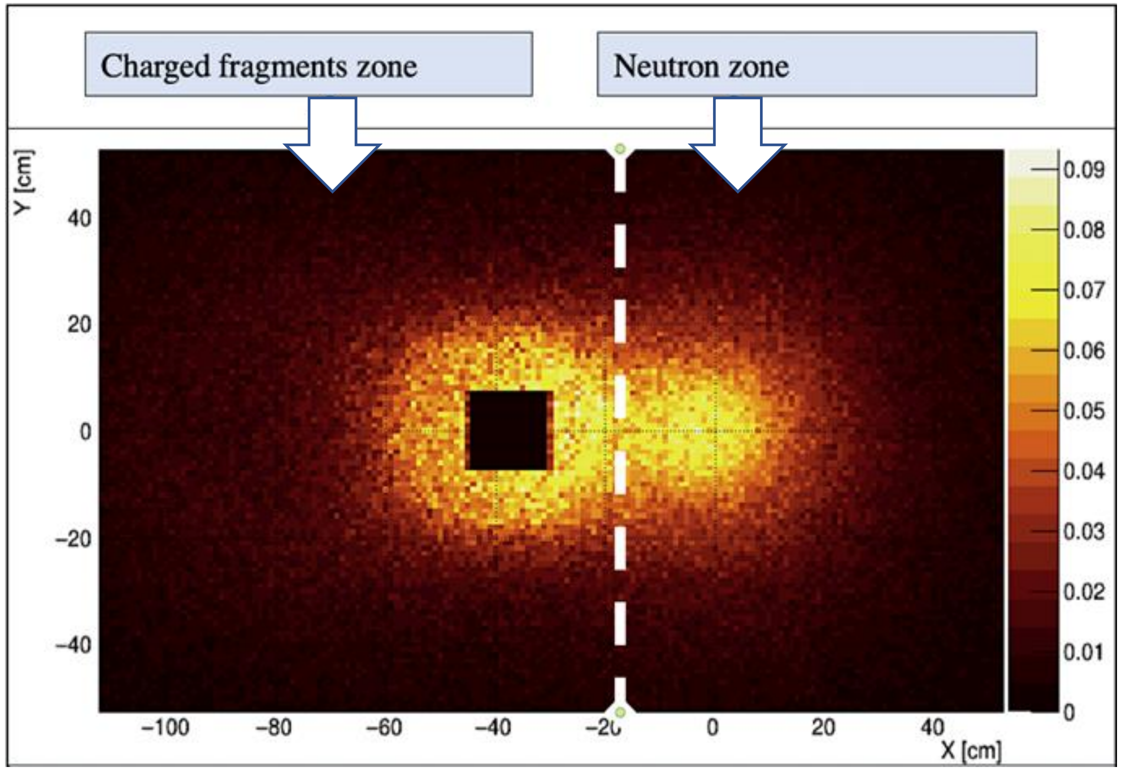

Scintillator bar of 270 x 5 x 5 $cm^3$ with 4- SiPMs arrays:
99% efficiency and $\sigma_t$ = 136 ps

T. P. Reinhardt et al. *Silicon photomultiplier readout of a monolithic 270x5x5 $cm^3$ plastic scintillator bar for time of flight applications*, NIMA 816 (2016) 16–24

# Neutron Zero-Degree Calorimeter (nZDC)

DCM-QGSM simulation
*N. Lashmanov*

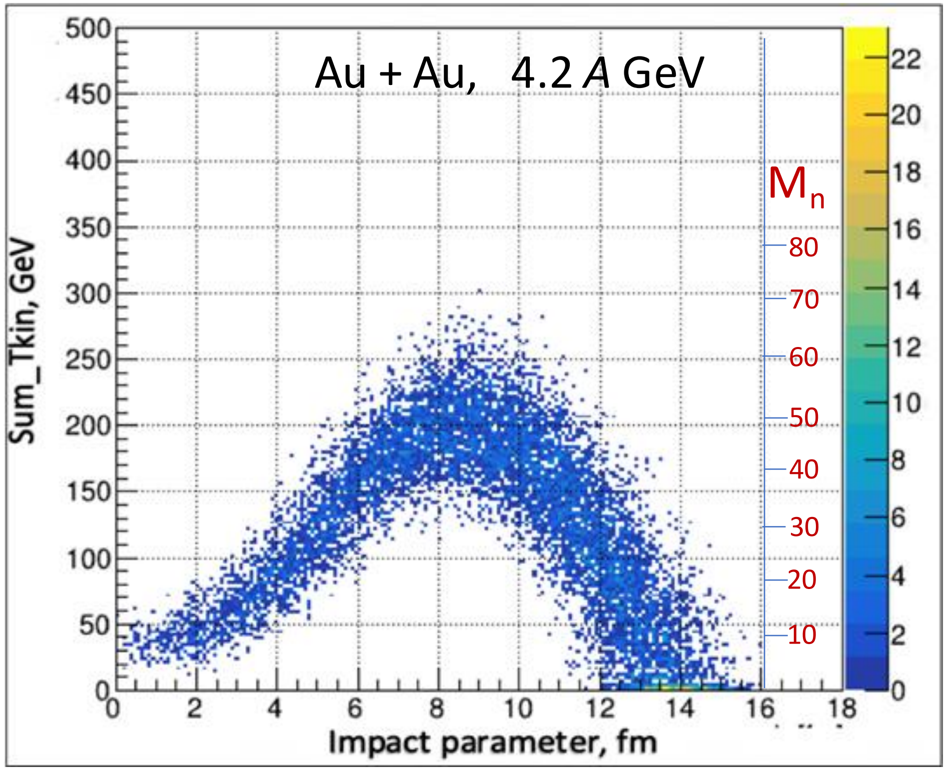
nZDC is the BM@N hadron calorimeter
It detects neutrons of beam spectator for each collision




Incoming energy of fragments in FHCal

## nZDC aim

- Neutron multiplicity from beam spectator decay
- Determination of reaction plane?



# Neutron Zero-Degree Calorimeter (nZDC)

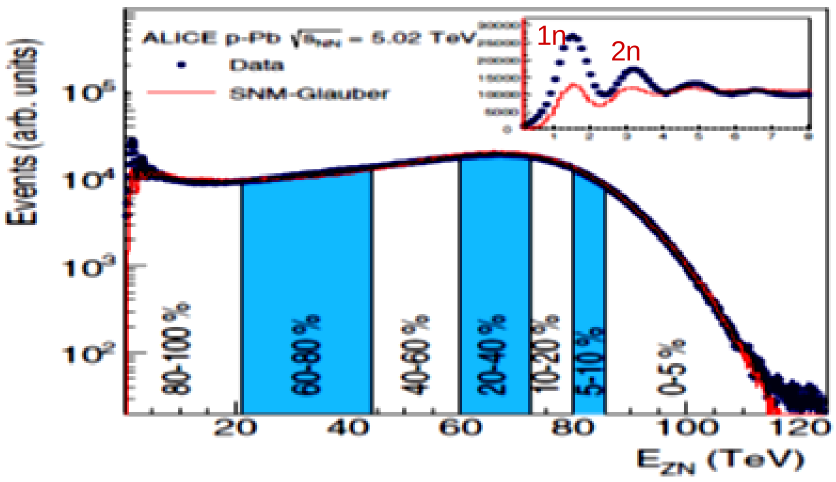
*Example of ALICE nZDC*

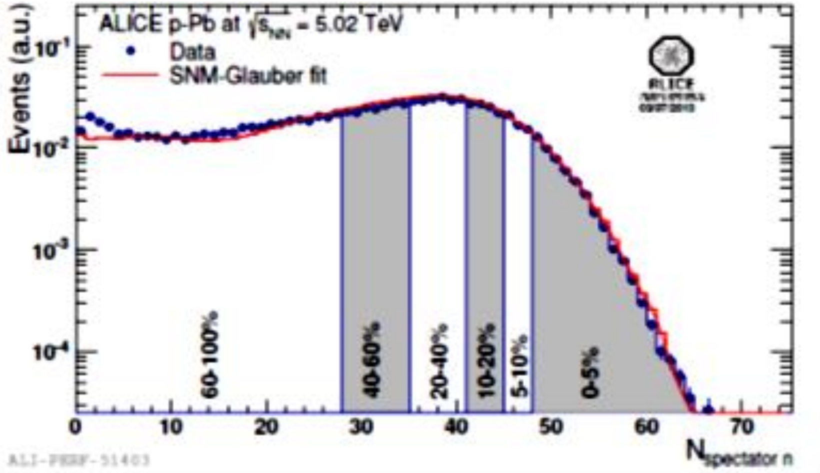
**Determination of reaction plane with nZDC**

In semi-central Au + Au collisions the nZDC response corresponds to 25 – 70 neutrons or 100 – 280 GeV.
Topic for study → Can it be used for determination of reaction plane?

**Calibration of nZDC**

A possible procedure is to study neutron response of nZDC with beam trigger in *AA*- collisions at 4 *A* GeV.
In very peripheral *AA*- collisions the excitation of giant resonance in a target and a projectile nuclei has large cross section. In the last case it decays with emission of 1 – 3 neutrons of beam energy to nZDC. Energy calibration of nZDC is based on observation of these peaks at 4, 8 and 12 GeV.





C. Oppedisano, Nucl. Phys. A932 (2014) 399.
J. Adam et al., Phys. Rev. C91 (2015) 064905.

# Status of the neutron detectors

**nZDC** - available FHCal
It has to be moved to cover 50-cm area around zero-degree position.

**ND with stilbene crystals** - 20 crystals and SiPMs are available for production of 10 neutron detectors.
The detectors will be produced in 2022.
4 modules of TQDC are required for data taking.

**FND** - scintillators, SiPMs, light guides, readout electronics have to be purchased.
The FND project might be realized for period of 2022 – 2024 (JINR, INR).