Measurements of spectators with Forward Hadron Calorimeter in MPD/NICA experiment

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RFBR grant tasks

Detector's tasks:

- Software for FHCal readout.
- FHCal signal processing.
- FHCal modules characterization.
- Development of energy calibration.
- FHCal minimum bias trigger.
- Detector Control System.

Simulation tasks:

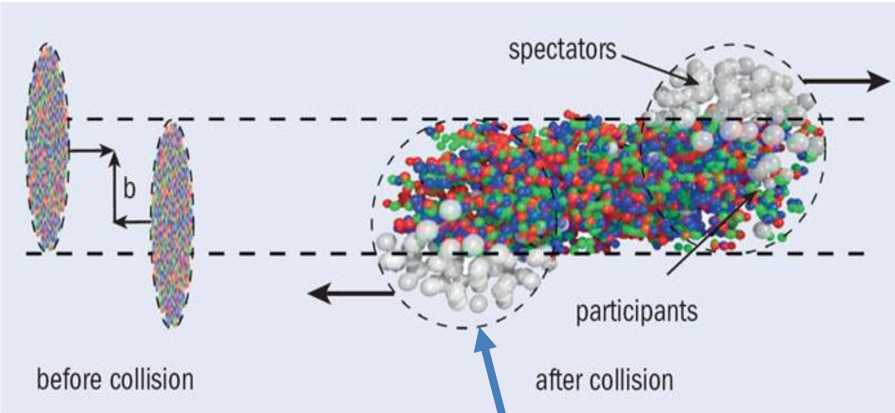
- Simulation for study of spectator's matter.
- Geometry of ion collisions:
  event plane,
  centrality.
- Properties of spectators:
  energy depositions,
  scattering angles.

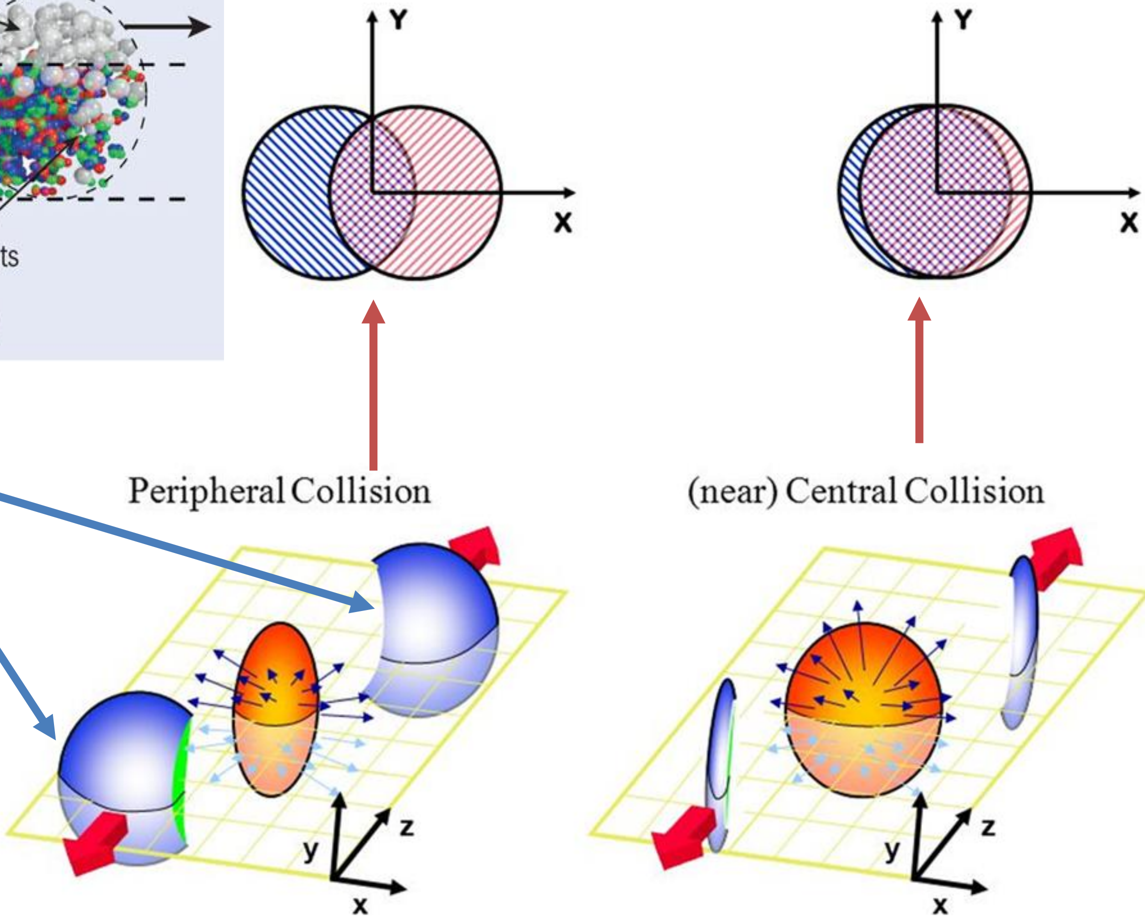
All tasks are associated with the FHCal performance.

FHCal is unique detector dedicated for the measurements of spectators at MPD/NICA

Spectators in ion collisions

Spectators – non-interacting nuclear fragments.





spectators

Reaction plane:
plane of ***b*** and ***Z*** (beam).

Free spectators – protons and neutrons.
Bound spectators - A>1.

- **Spectators are effective tool in the measurements of centrality and the reaction plane of collisions.**
- **Spectators in simulations are dependent on the fragmentation models.**
- **Can spectators be an additional probe of the fireball?**

Detector’s tasks:

- Software for FHCal readout.
- FHCal signal processing.
- FHCal modules characterization.
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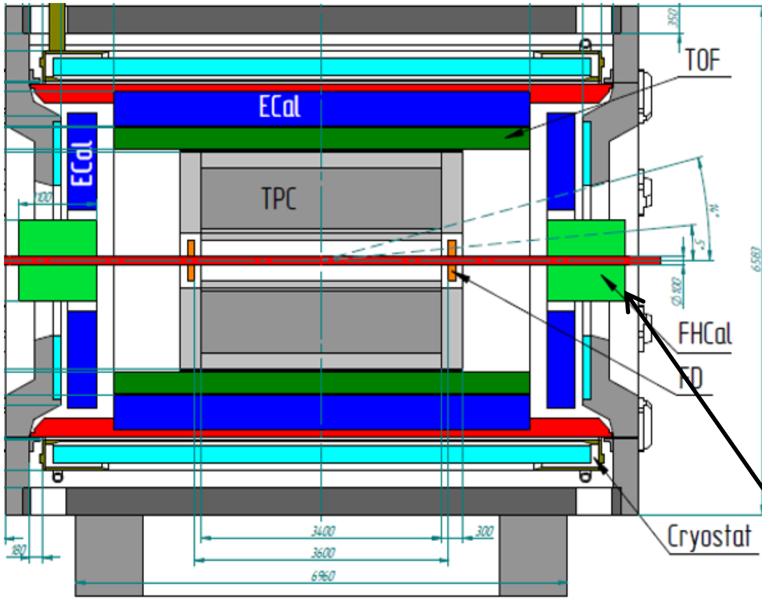
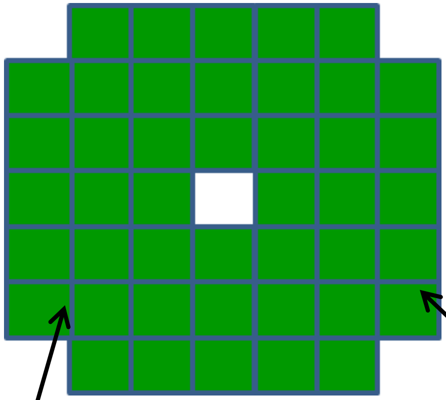
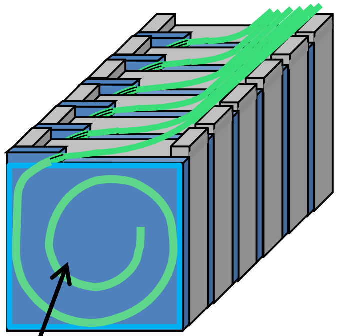
FHCal as a dedicated detector of spectators in MPD







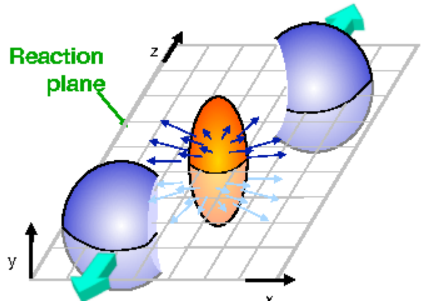
FHCal

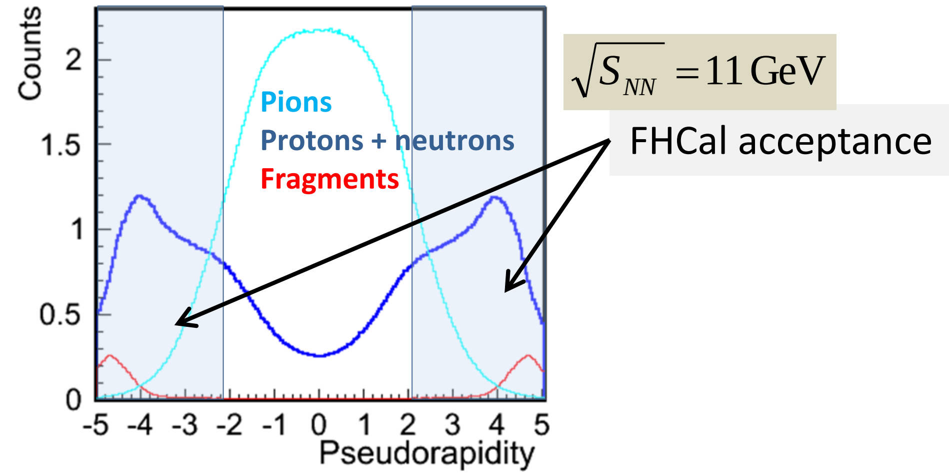
FHCal modules

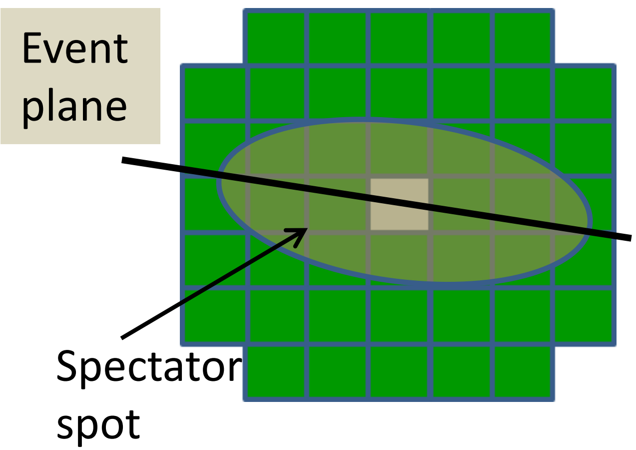
- <u>Two arms of hadron calorimeter</u> at opposite sides in forward regions.
- At the distance 3.2 meters from the interaction point.
- Available acceptance corresponds to pseudorapidity $2.0<\eta<5.0$

- FHCAL consists of 2x44 modules.
- ~1x1 m^2 each part.
- Beam hole 15x15 cm^2.
- Lead/scintillator sampling calorimeter.
- Longitudinal segmentation;
- Light readout- WLS-fibers;
- 7 sections/photodetectors in each module.

FHCal features



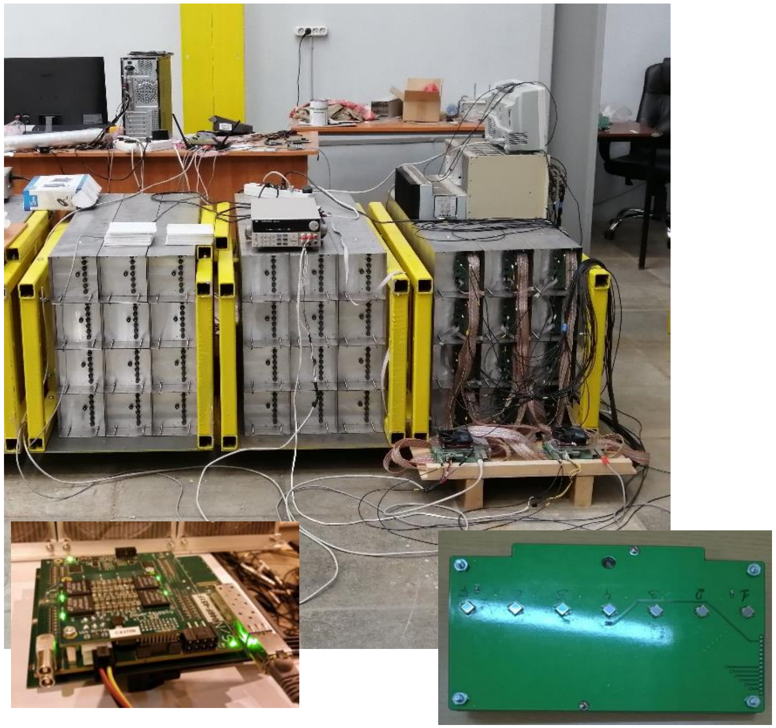




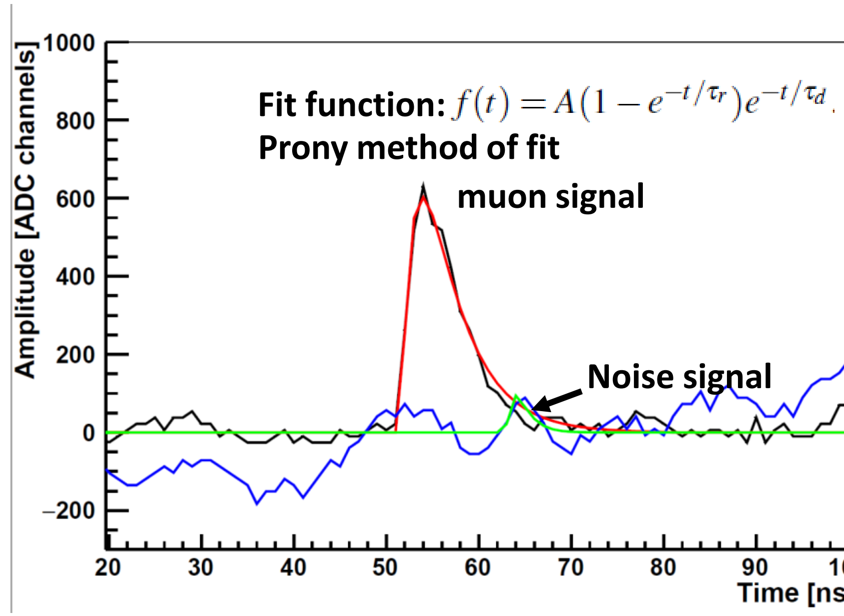
- ✓ **FHCal detects the energy of spectators;**
- ✓ **FHCal detects the space distribution of the spectators;**
- ✓ **FHCal detects the produced particles in forward region.**

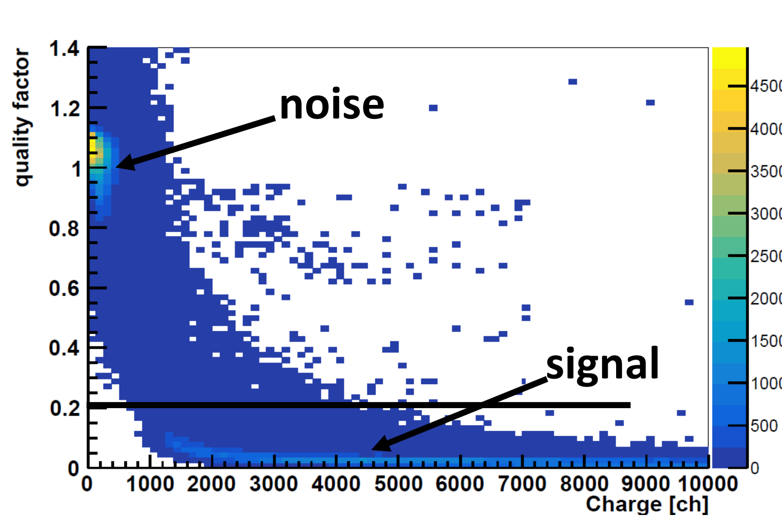
- **Since FHCal has a beam hole, most of the <u>bound spectators</u> leak in this hole.**
- **Mainly, <u>free spectators</u> (protons and neutrons) deposit energy in FHCal.**

FHCal signal processing



Shape of digitized signal.





The readout electronics:
FPGA based 64 channel ADC64 board, 62.5MS/s (AFI Electronics, JINR).

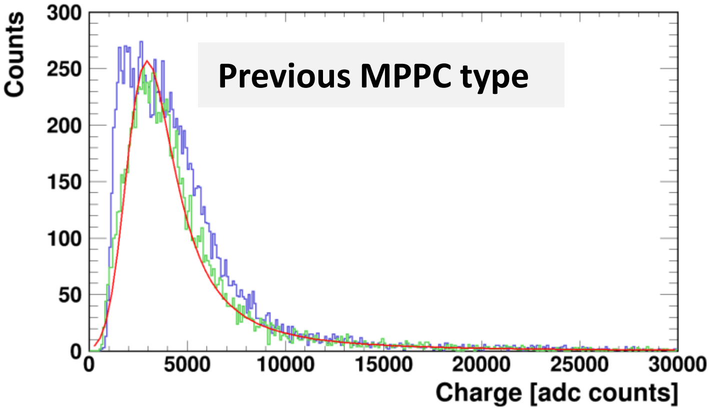
MPPC: new type S14160-3010PS
size – 3x3 mm^2;
pixel -10x10 μm^2;
PDE~18%.

Fit of waveforms and suppression of noises allow the identification of low (~MeV) signals.

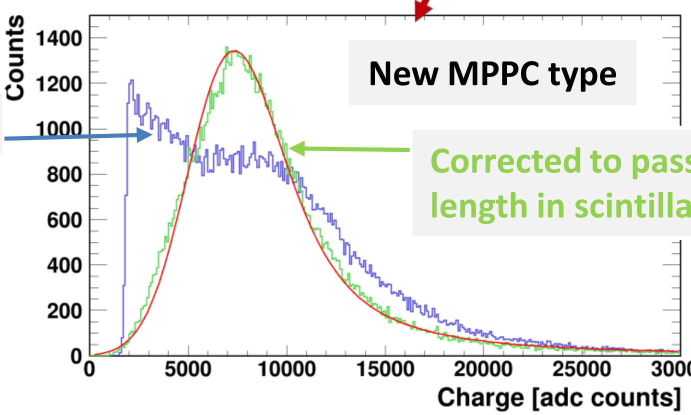
FHCal modules characterization with cosmic muons

- Tasks:
- Tests of different SiPM's;
- Tests of FEE;
- Development of methods of the energy calibration;
- Control of the light yield of the modules;
- Determination of energy threshold for the FHCal trigger.

Response of FHCal modules with different types of MPPC to cosmic muons .



Raw spectrum

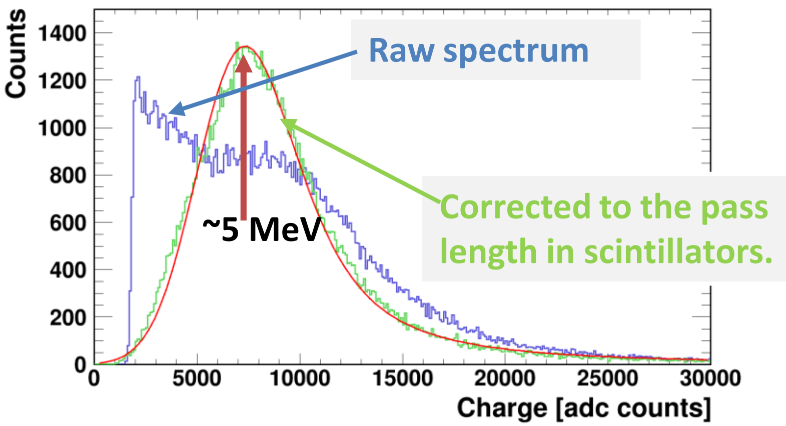


Corrected to pass length in scintillators.

MPPC: S12572-010P
pixel -10x10 μm^2;
PDE~12%;
G~10^5.

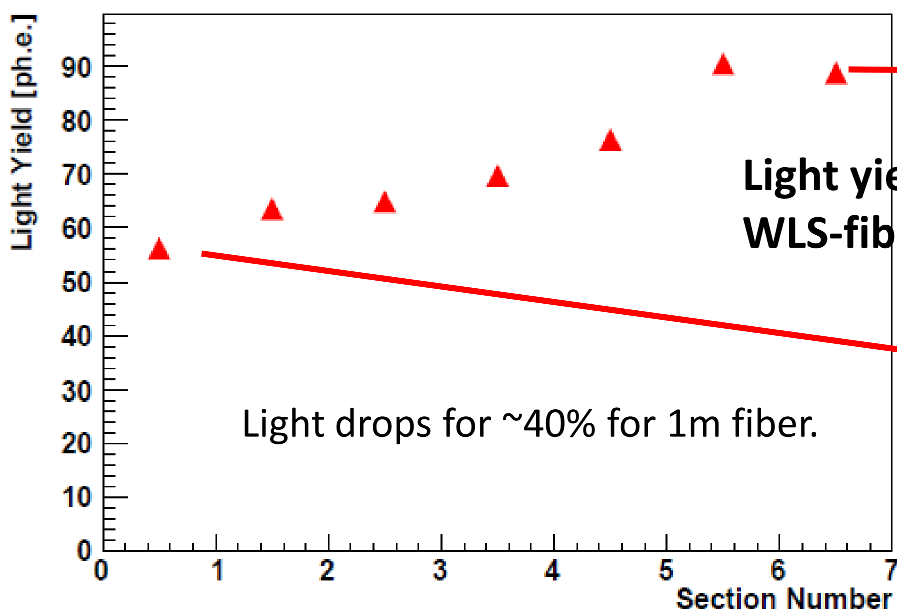
MPPC: S14160-3010PS
pixel -10x10 μm^2;
PDE~18%;
G~1.8×10^5.

Energy calibration and light yield of FHCal modules



- Clear amplitude spectra from cosmic muons allow the energy calibration in self-triggering mode (without external muon trigger).
- Energy deposition was corrected to the muon pass length in the scintillators (tracking of muons in FHCal longitudinal sections).

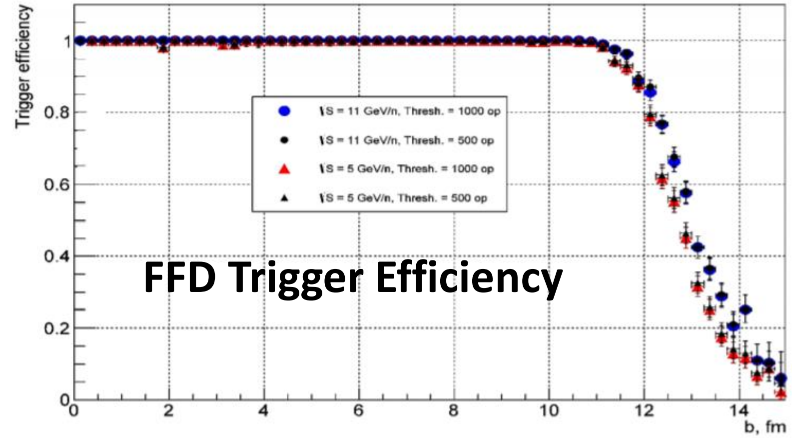
Average light yield for MIP's in longitudinal sections.



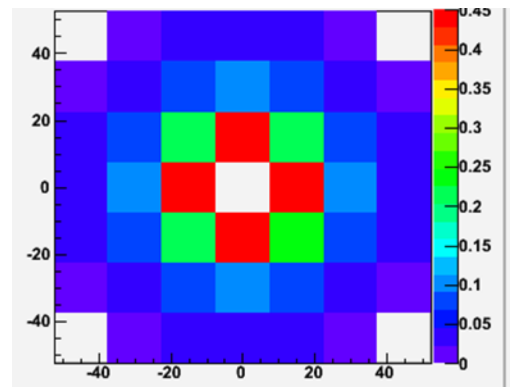
Light yield depends on WLS-fiber length.

FHCal in trigger

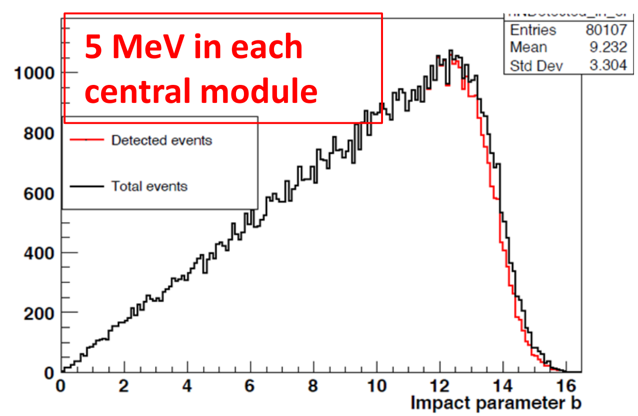
- **Problem: FFD trigger efficiency drops for peripheral collisions.**
- **Is it possible to arrange minimum bias trigger?**



- **FHCal detects the energies practically from all events, including the most peripheral ones.**
- **In peripheral collisions the energies are mainly deposited in central modules.**

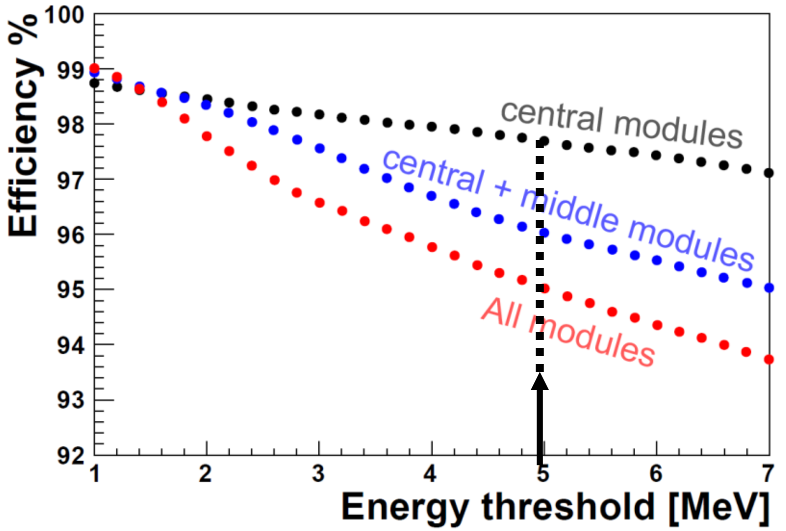


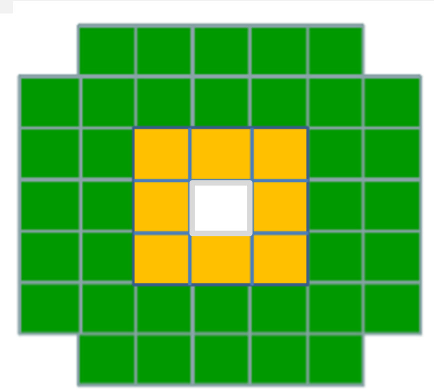
- **Detected events – if the energy deposition in each central module exceeds 5 MeV.**



FHCal in trigger - 2

Dependence of trigger efficiency on the energy threshold and on the number of modules.

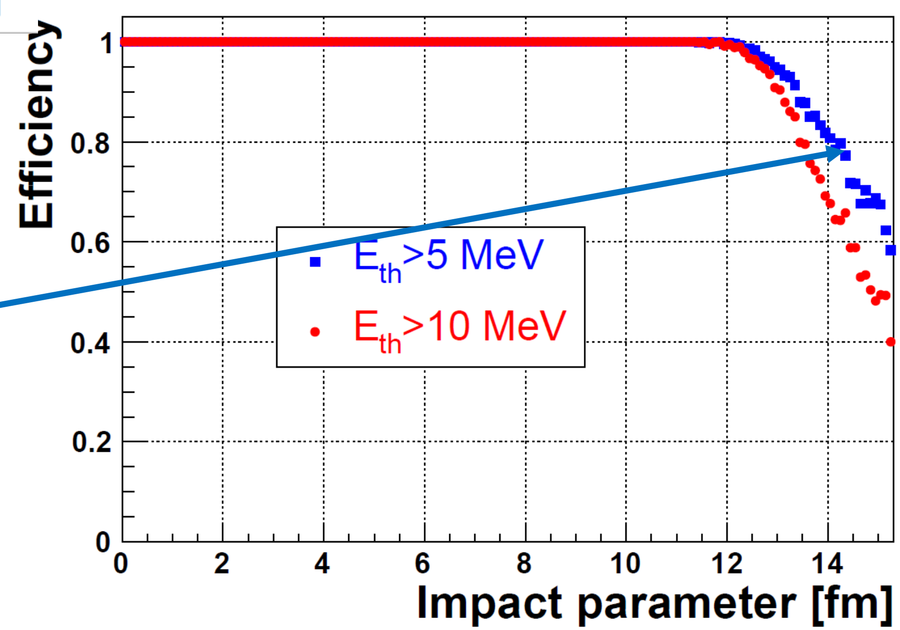




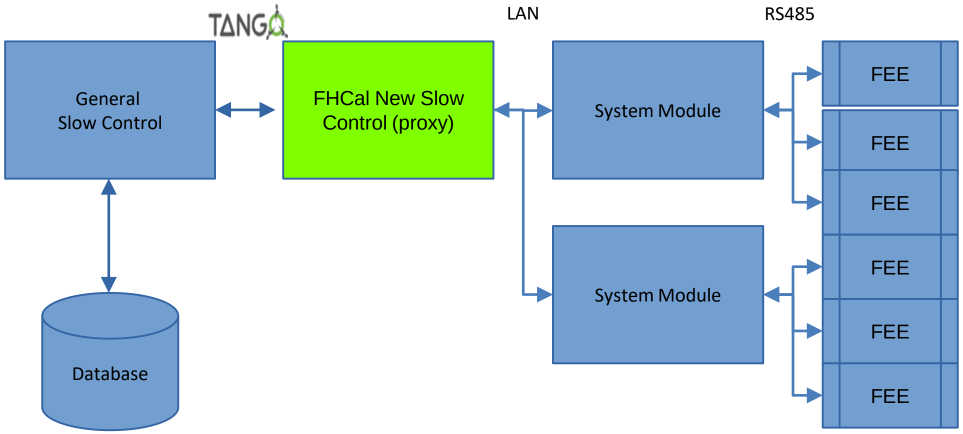
5 MeV is rather reasonable threshold for a single FHCal module with new photodiodes.

Total trigger efficiency ~97.7%.

Events with energy deposition in each central module > 5 MeV.

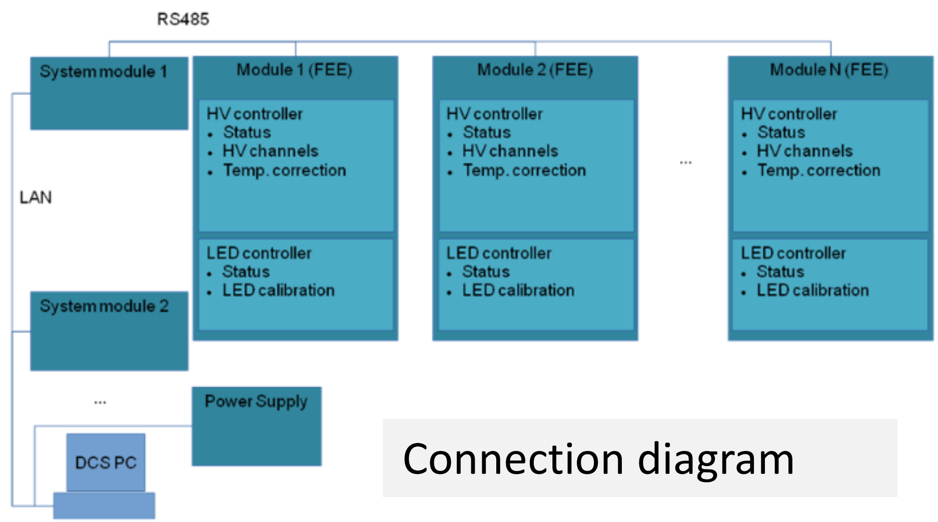


Detector Control System for FHCal



DCS Tasks:

- **Control of HV at photodetectors (MPPC's);**
- **Temperature control of photodetectors;**
- **Compensation of temperature drift of MPPC gain;**
- **Monitoring of MPPC gain with stabilized light source.**



Connection diagram

Software:

- Test version (full functionality) is **ready**.
- New (advanced) python version **in development.**
  - Provide TANGO bindings
  - Faster operation with multiple System Modules

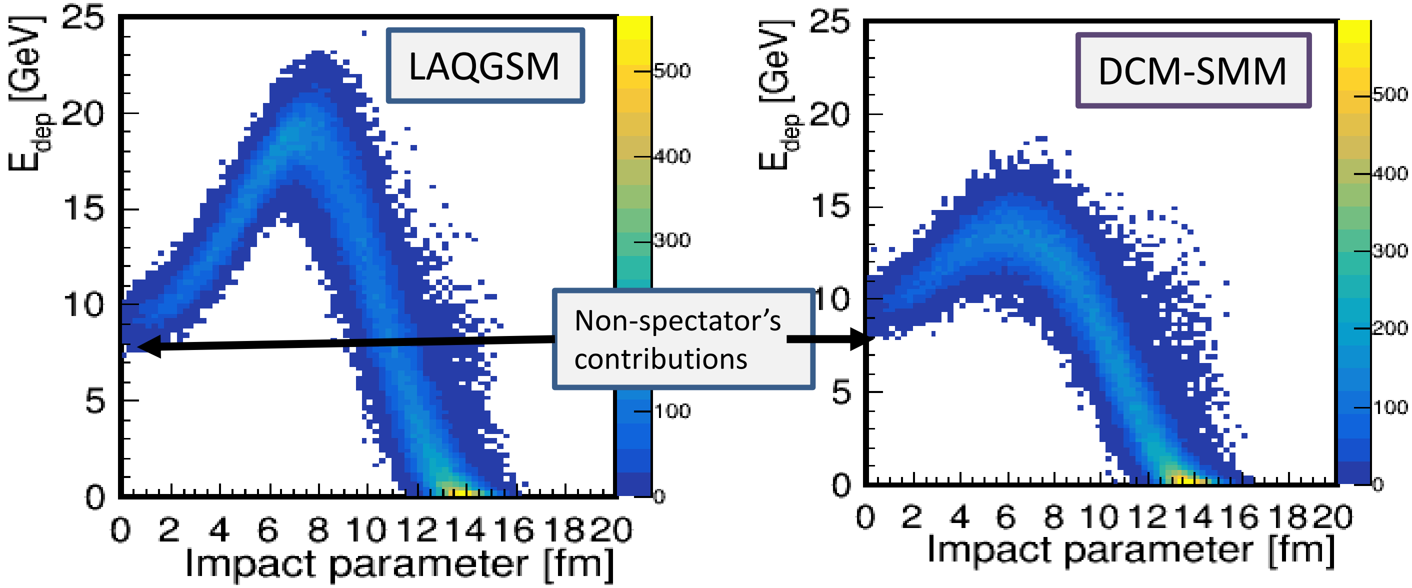
Simulation tasks:

- Simulation for study of spectator's matter.
- Geometry of ion collisions:
  event plane,
  centrality.
- Properties of spectators:
  energy depositions,
  scattering angles.

Fragmentation models/generators

Depending on fragmentation model, simulated energy deposition in FHCal can be quite different.

$\sqrt{S_{NN}} = 11\,\text{GeV}$



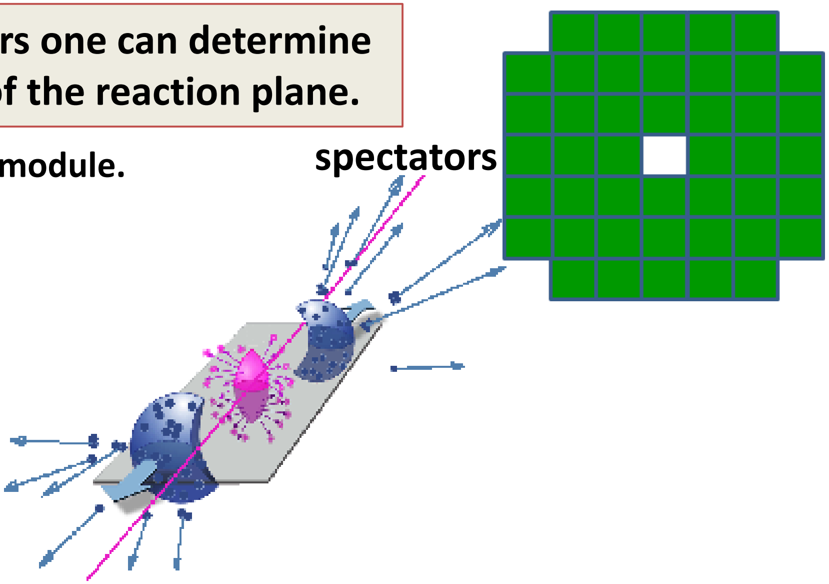
LAQGSM: S. G. Mashnik, K. K. Gudima, R. E. Prael, A. J. Sierk, M. I. Baznat, N. V. Mokhov, CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes, arxiv:0805.0751 [nucl-th] (2008)

For DCM-SMM, the maximum energy deposition in FHCal is about 30% less due to the larger number of intermediate mass fragments (effect of beam hole).

DCM-SMM: M. Baznat, A. Botvina, G. Musulmanbekov, V. Toneev & V. Zhezher Monte-Carlo Generator of Heavy Ion Collisions DCM-SMM, *Phys. Part. Nuclei Lett.* 17, 303–324 (2020). https://doi.org/10.1134/S1547477120030024

Reconstruction of the event plane with spectators

From energy and space distribution of spectators one can determine the <u>event plane</u> as an experimental estimate of the reaction plane.



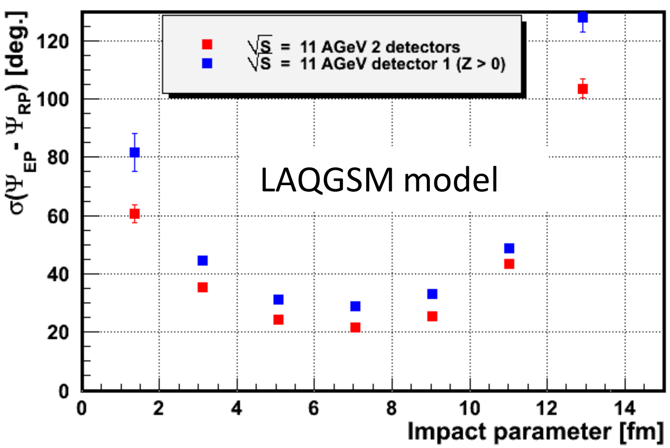
E_i, (x_i, y_i) – energy and coordinates of *i*-module.

$$\sin(\varphi_i) = \frac{y_i}{\sqrt{x_i^2 + y_i^2}} \qquad \cos(\varphi_i) = \frac{x_i}{\sqrt{x_i^2 + y_i^2}}$$

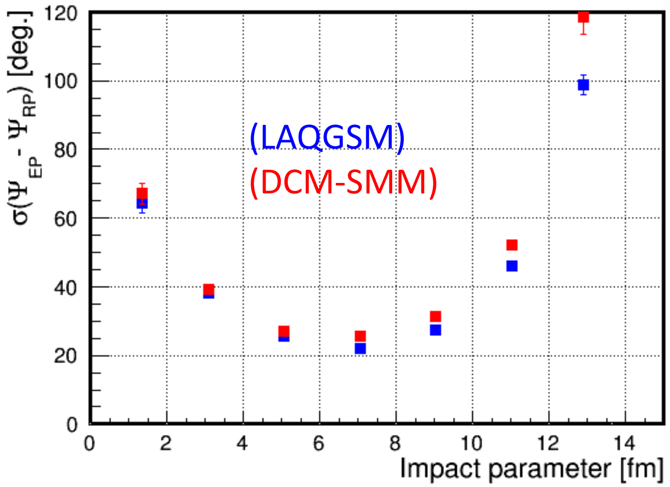
Event plane in first FHCal part: $$\Psi_{1,EP} = acrtg \frac{\sum E_i \sin(\varphi_i)}{\sum E_i \cos(\varphi_i)}$$

Event plane in both FHCal parts: $$\Psi_{EP} = \Psi_{1,EP} + (\Psi_{2,EP} + \pi)$$

Resolution: difference between true reaction plane and reconstructed event plane.



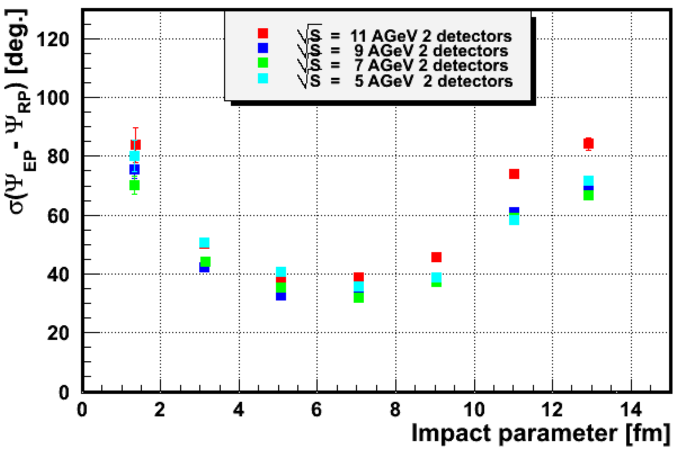
$\sqrt{S_{NN}} = 11\,\mathrm{GeV}$



Detection of all types of the spectators (protons, neutrons) for both colliding nuclei would ensure the outstanding ~20^0 angular resolution of the event plane!

Resolution of the event plane for only charged particles

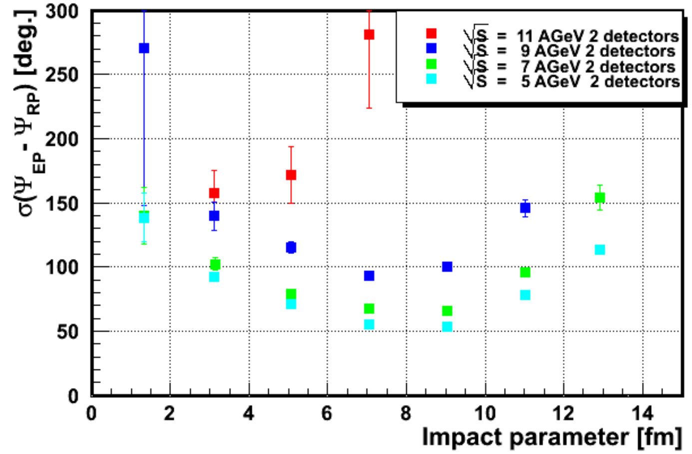
Only charged spectators (protons and fragments)



$$\vec{Q}=\sum_{i=1}^{Nsp} w_i \frac{\vec{r}_i}{|\vec{r}_i|}$$

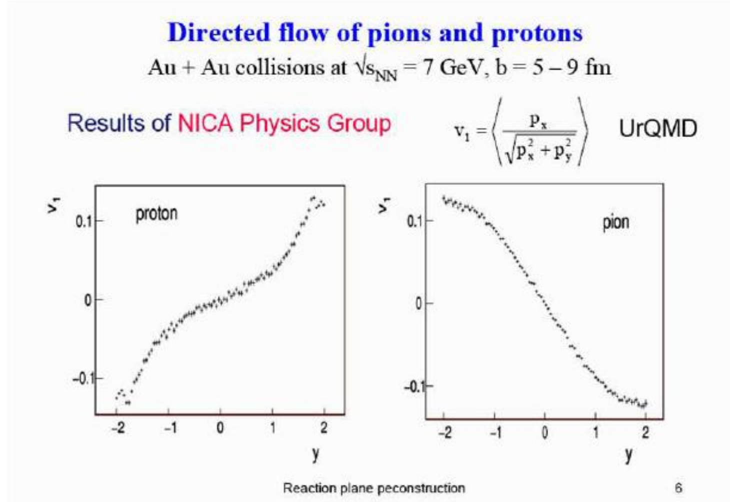
Weight w_i=1.

All charged particles (including pions)



- **The best resolution of event plane is about 30⁰-40⁰ in case of <u>charged spectators</u> only.**
- **For all charged particles (including pions) the resolution is 60⁰ and larger.**
- **It is a factor of 3 and more worse comparing to FHCal option.**

The resolution degradation is due to the fact that protons and pions have an opposite signs of v_1 flow.

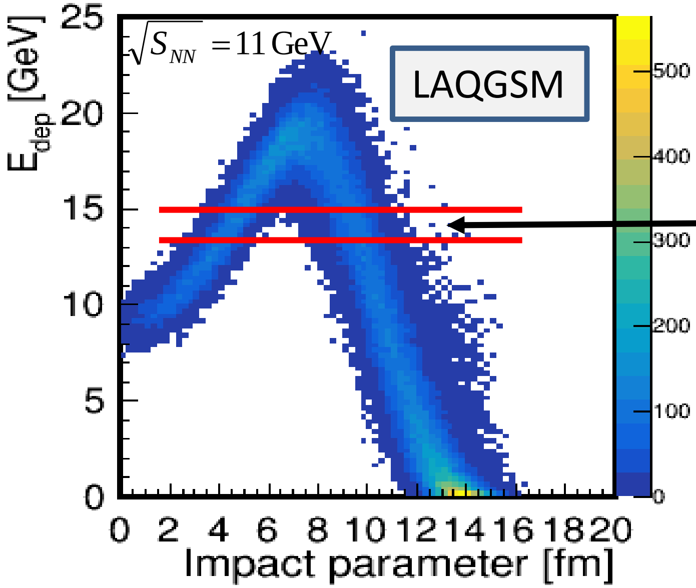


Impact of pion multiplicity at the event plane resolution is very strong. The contribution of pion energy in calorimeter is less significant.

Hadron calorimeter is the best option!

Centrality: problem due to the beam hole

- For hermetical calorimeter the energy deposition of spectators has monotonic dependence on impact parameter.
  - It is not true in real situation.



Bound fragments have small transverse (Fermi) momentum and leak into beam hole.

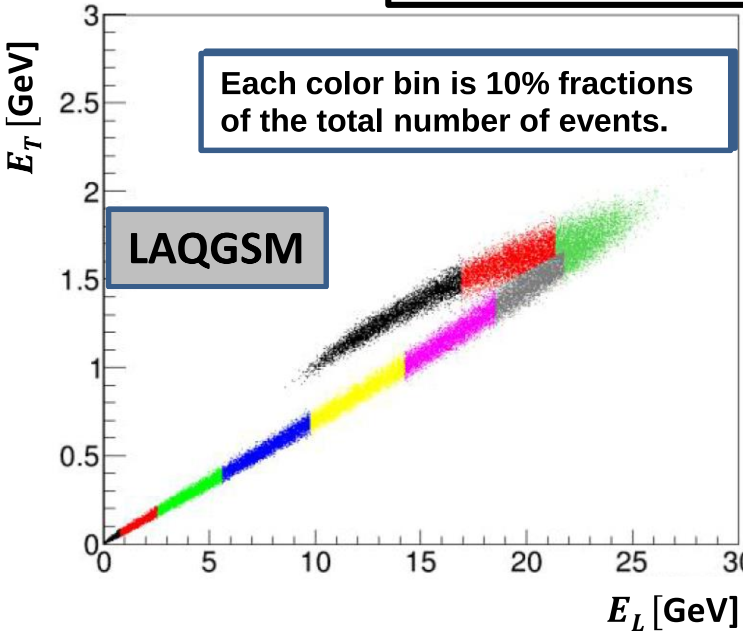
Energy deposition in FHCal can not resolve the central and peripheral events.

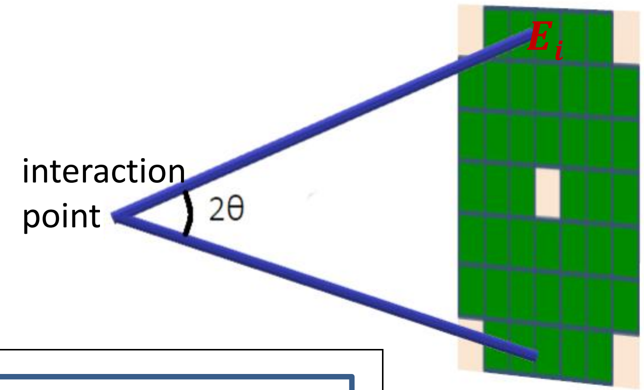
- New observables are needful to resolve ambiguity in energy deposition of the central and peripheral events.
- The space information about the spectator hit points can be used additionally to the detected energy.
- One can construct a few such observables.

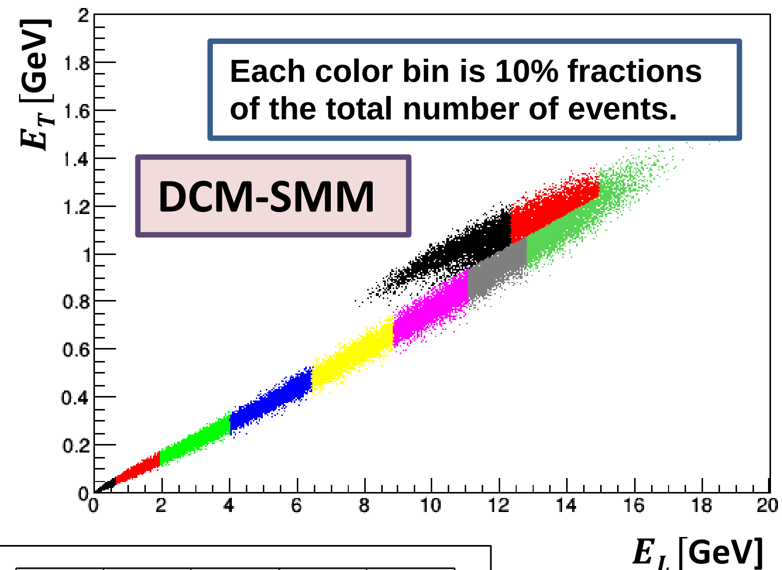
(E_T, E_L) observables in FHCal for the centrality measurement

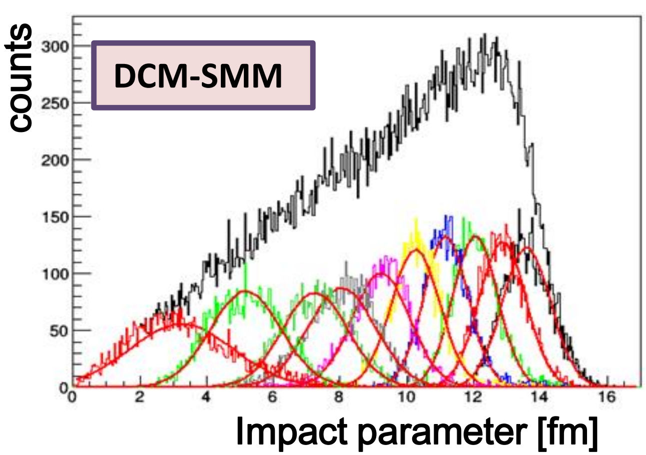
Transverse energy: $E_T = \sum E_i \sin\theta_i$

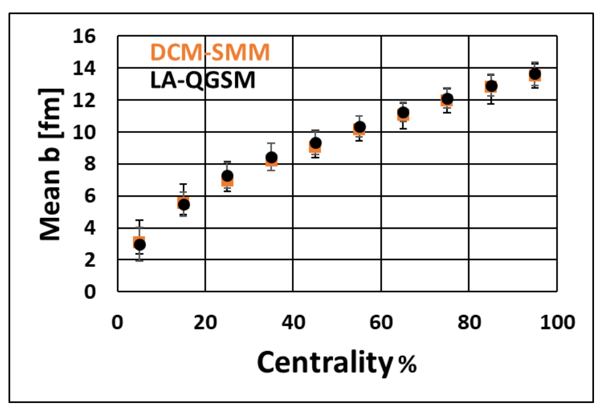
Longitudinal energy: $E_L = \sum E_i \cos\theta_i$









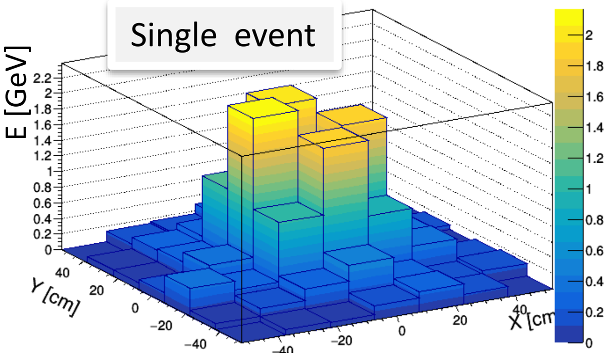


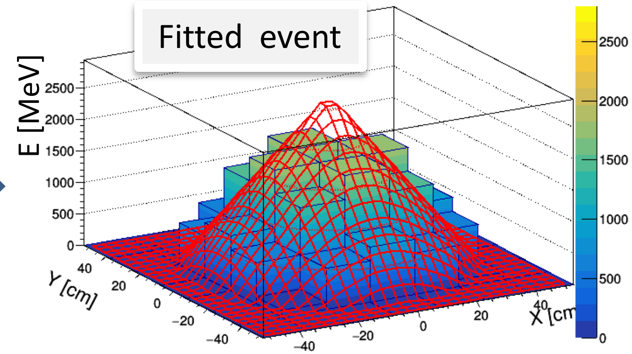
For DCM-SMM model the identification of central events is not suitable.
New approaches are needed!

Centrality: 2D-fit of energy distributions (linear approach)

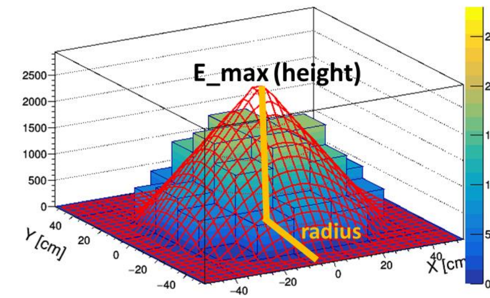
- In this method the space energy distribution in FHCal modules is used.
- The histogram is fitted by a symmetrical cone (linear approximation).
- Weight of each bin is proportional of the energy deposited in corresponding FHCal module.

Energy distribution in FHCal modules

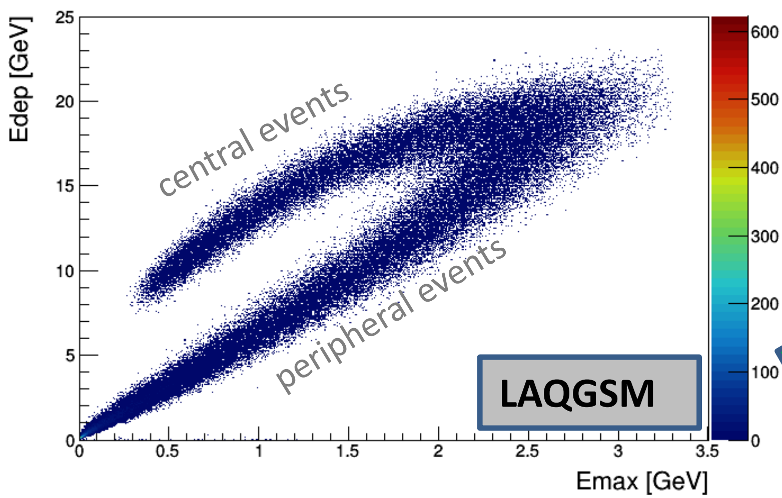




Initially we have experimental energy deposition E_{dep} in FHCal.



Energy deposition vs maximum energy in FHCal center



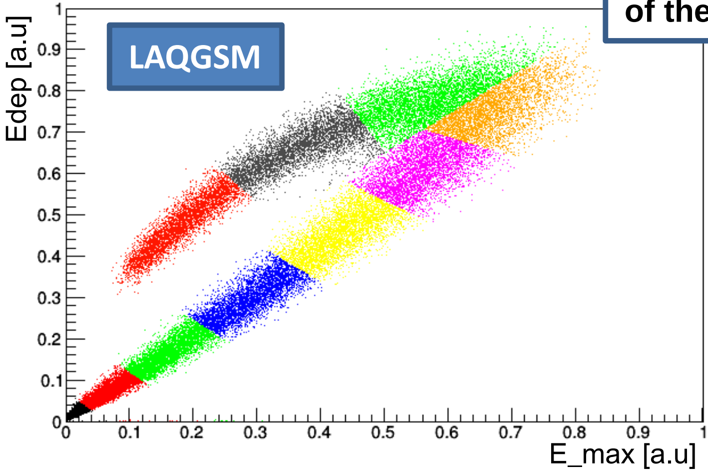
After linear fit we have:

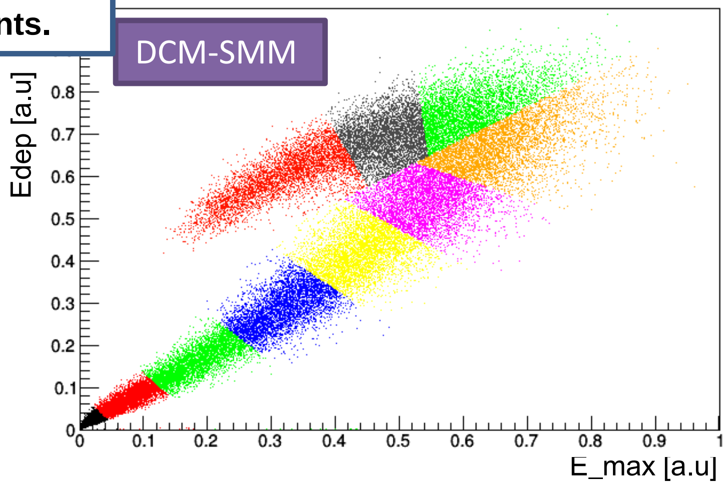
- ***E_{fit}*** **is reconstructed energy (volume of cone);**
- ***E_{max}*** **– maximum energy in central bin (in FHCal hole);**
- ***Radius*** **is defined by the scattering angle of spectators.**

This correlation can be used for the centrality determination.

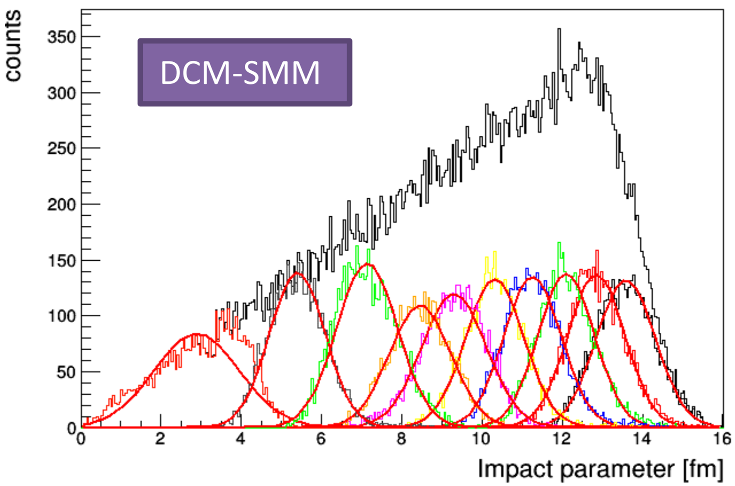
Centrality resolution for E_{dep} vs E_{max}

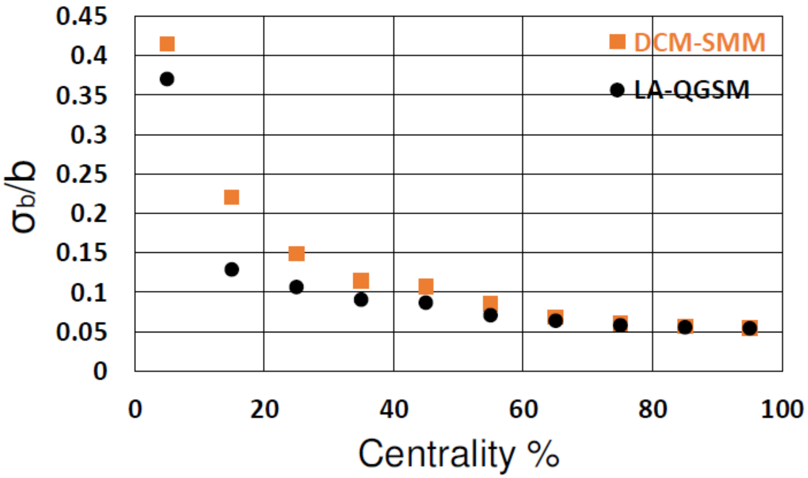
Each color bin is 10% fractions of the total number of events.





Energy deposition vs maximum energy in FHCal center

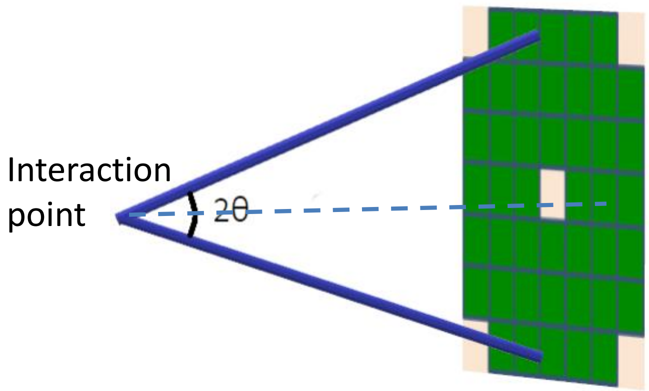


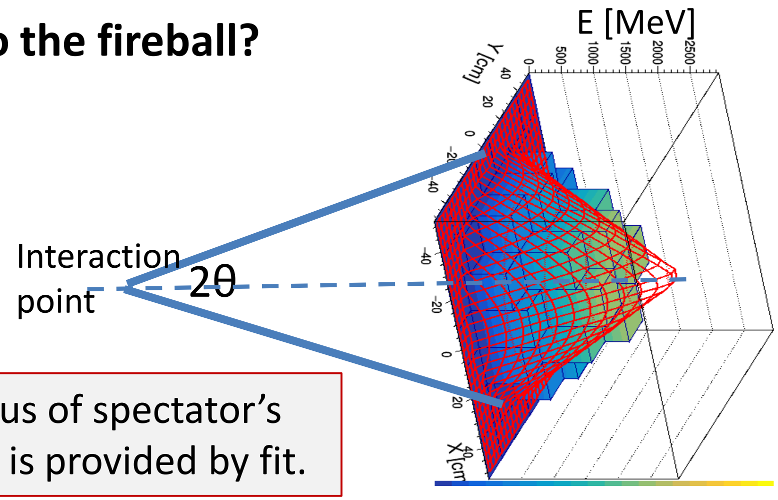


The accuracy of centrality determination depends on fragmentation model. Real data can be quite different!

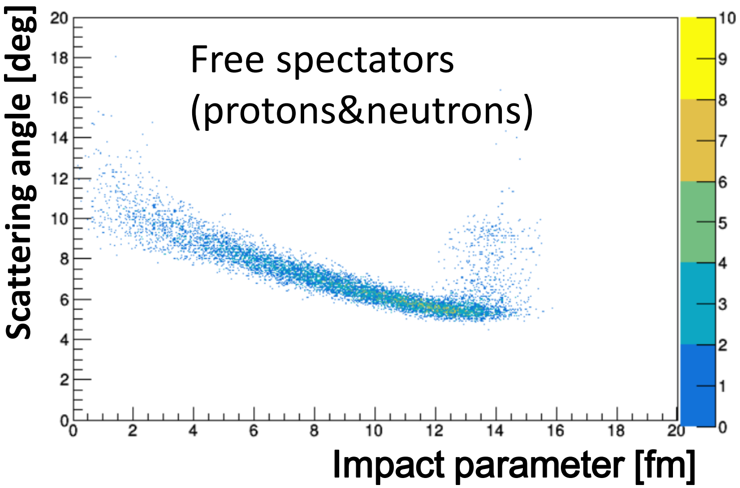
Scattering angles of spectators

Can spectator's scattering angle be sensitive to the fireball?

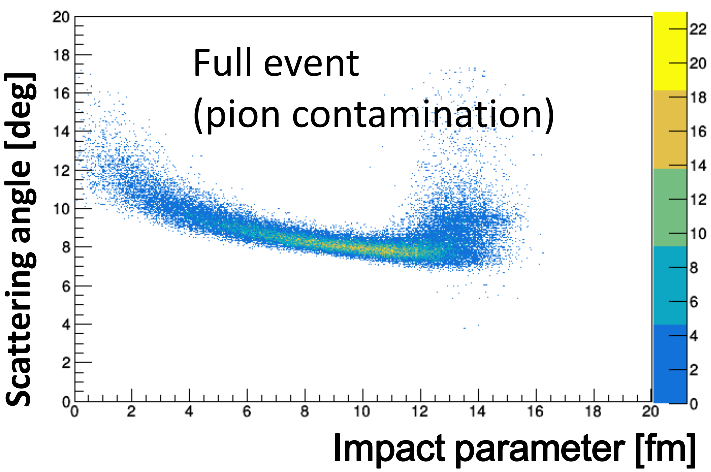




Radius of spectator's spot is provided by fit.



LA-QGSM model



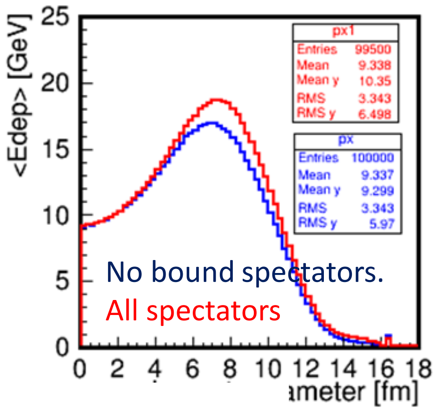
According to the models, the size of the spectator's spot (scattering angle) depends on the impact parameter. It reflects the spectator's transverse momenta obtained from fireball.

Can it be used to probe the fireball properties?

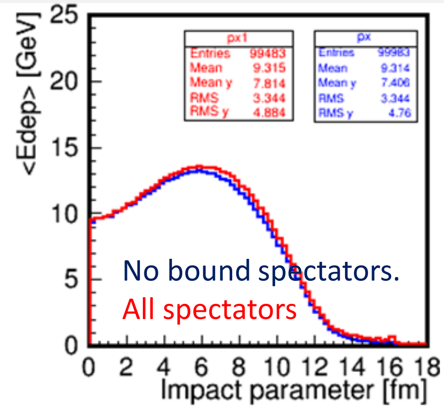
Energy of spectators as a probe of fragmentation model

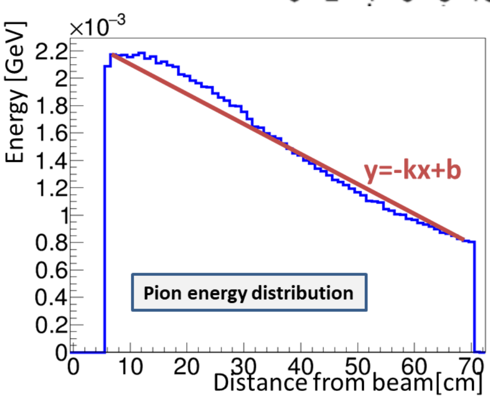
Energy depositions in FHCal strongly depend on the composition of the free and bound spectators. Most of bound spectators escape in beam hole, while free spectators deposit energy in FHCal.

LAQGSM



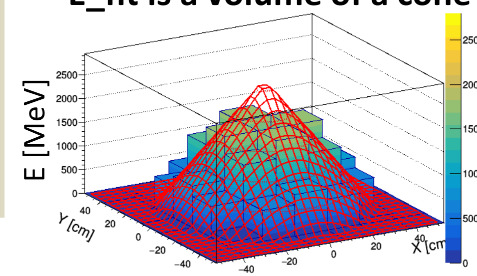
DCM-SMM



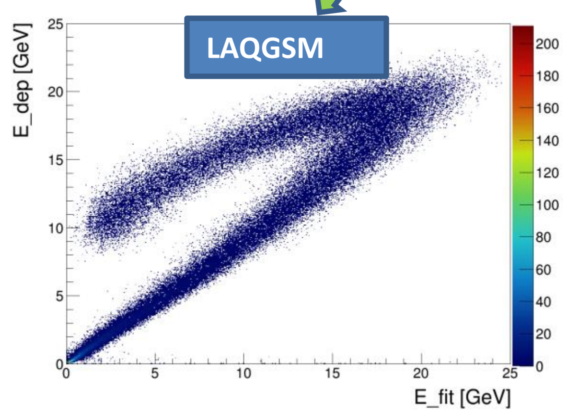


Subtracting the pion energy contribution from the FHCal full energy one can obtain the energy of spectators which is dependent on the fragmentation model.

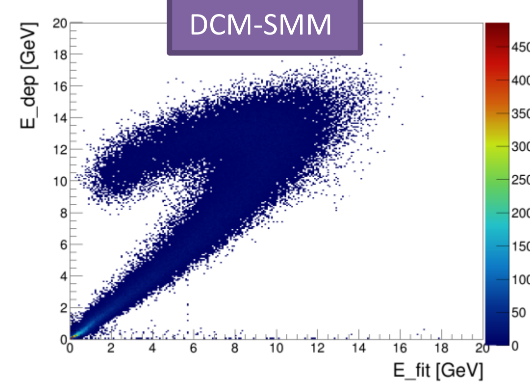
E_fit is a volume of a cone



LAQGSM



DCM-SMM



Present status:

- ✓ FHCal readout software;
- ✓ FHCal signal processing;
- ✓ Characterization of the FHCal modules;
- ✓ Calibration with cosmic muons;

In progress:

- ➢ FHCal DCS development;
- ➢ Observables for the centrality measurements with spectators;
- ➢ Characterization of the spectators properties.

Future plans:

- Further development of FHCal readout (different options with analog cables);
- Development of FHCal minimum bias trigger (analog adders, tests with cosmic muons);
- Integration of FHCal to MPD setup (cabling, cooling, mechanical support);
- FHCal DCS development;
- Implementation of FHCal calibration procedure;
- Further development of methods for collision centrality determination;
- Comparison of the centrality classes for two approaches (multiplicities and spectators);
- Characterization of the spectator’s properties;
- Simulations with different fragmentation models.

Publication activity

- A. Ivashkin, D. Finogeev, M. Golubeva et al., **Compact segmented hadron calorimeter for detection of low energy spectators at MPD/NICA facility**, **Nuclear Inst. and Methods** in Physics Research, A (2019), https://doi.org/10.1016/j.nima.2019.05.081.

- Nikolay Karpushkin, Fedor Guber and Alexander Ivashkin, **Application of the Prony least squares method for fitting signal waveforms measured by sampling ADC, AIP Conference Proceedings 2163**, 030006 (2019); https://doi.org/10.1063/1.5130092

- Alexander O. Strizhak and Alexander P. Ivashkin, **Test of modules for Forward Hadron Calorimeter at MPD/NICA facility, AIP Conference Proceedings 2163**, 030013 (2019); https://doi.org/10.1063/1.5130099

- A. Ivashkin, D. Finogeev, M. Golubeva et al., **Determination of geometry of heavy ion collisions with forward hadron calorimeter (FHCal) at MPD/NICA, EPJ Web of Conferences 204**, 0 (2019); https://doi.org/10.1051/epjconf /201920407002

- A. Ivashkin, M. Golubeva, F.Guber et al., **Amplitude parameters of modules for hadron calorimeter at MPD/NICA, Journal of Instrumentation**, Volume 15, June 2020 https://doi.org/10.1088/1748-0221/15/06/C06044

2 papers in Q1.

Reports at 7 international conferences.

Thank you!

Centrality 5% bins.