Methods for centrality determination in heavy-ion collisions

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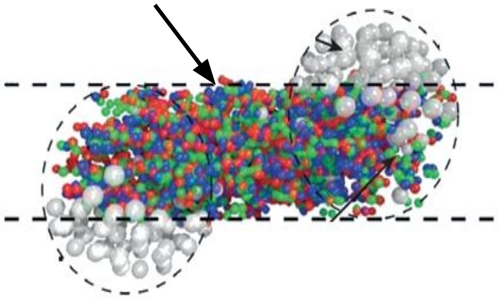
Motivation for centrality determination

- Evolution of matter produced in heavy-ion collisions depends on its initial geometry

- **Goal of centrality determination**:
  map (on average) the collision geometry parameters
  to experimental observables (centrality estimators)

- Centrality class S_1-S_2: group of events corresponding to a given fraction (in %) of the total cross section:

$$C_S = \frac{1}{\sigma_{inel}^{AA}} \int_{S_1}^{S_2} \frac{d\sigma}{dS} dS$$

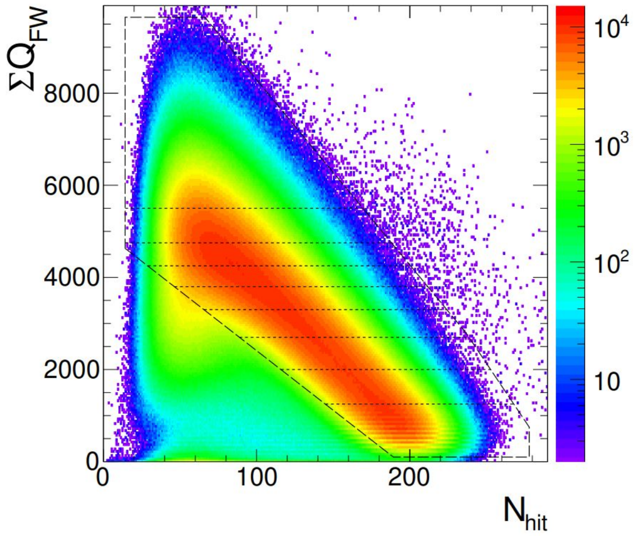


Why several alternative centrality estimators

Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

A number of produced protons is stronger correlated with the number of produced particles (track & RPC+TOF hits) than with the total charge of spectator fragments (FW)

HADES; Phys.Rev.C 102 (2020) 2, 024914



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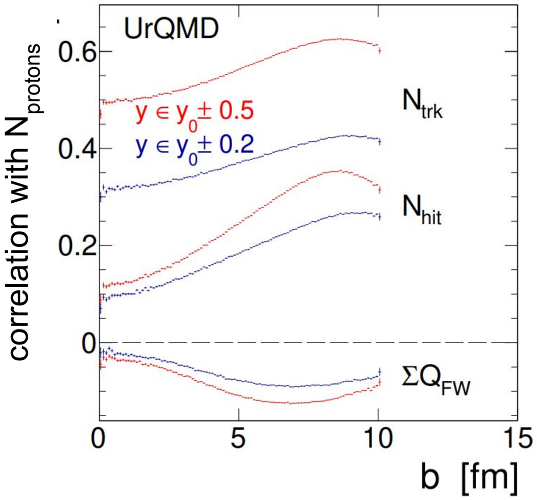
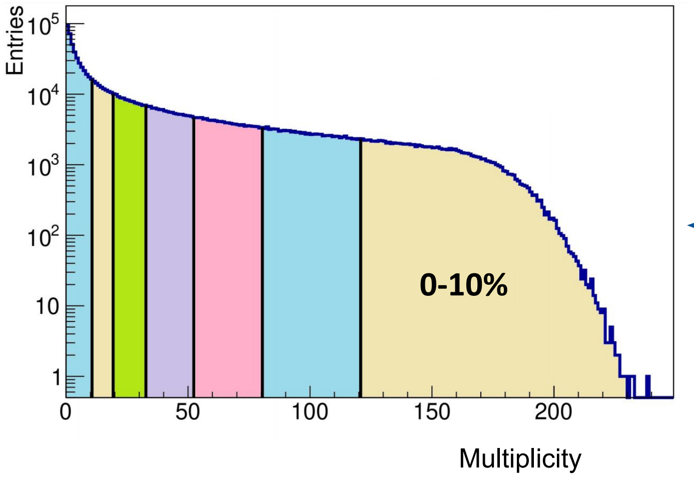


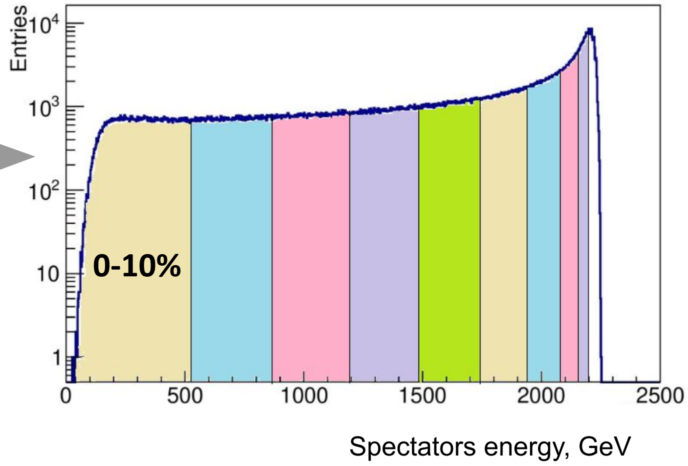
Avoid self-correlation biases when using spectators fragments for centrality estimation

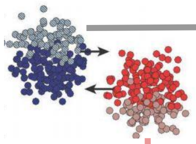
Types of centrality estimators

Produced charged particles



Spectators





(Target spectators not measured for fixed-target)

Overview of centrality determination methods

Method type	MC-Glauber based	Model independent (e.g. Γ-fit method) see talk by D. Idrisov	Based on ML
Used in	STAR, ALICE, HADES, CBM, MPD, etc.	ALICE, CMS, ATLAS J. Y. Ollitrault et al. Phys.Rev. C 98 (2018) 024902	Becoming popular Fupeng L. et al. J.Phys.G 47 (2020) 11, 115104
Advantages	Commonly used, well established procedure	Universality due to model independence	The most modern and fast methods
Disadvantages	MC-Glauber model provides non-realistic N_{part} simulations at low energies M. O. Kuttan et al. e-Print: 2303.07919 [hep-ph]	In strong connection with σ_{inel} which dependence on energy is not well studied at low energies (same problem for MC-Glauber based methods)	There no way to control the physicality of the methods

NA61/SHINE experimental setup

Data samples:

- Pb-Pb @ p_{beam} = 13A GeV/c
- data from 2016 physics run

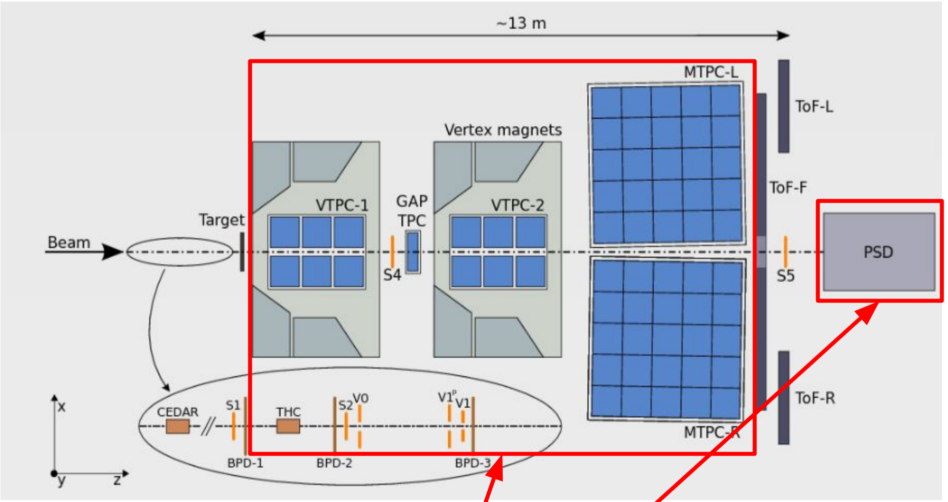
E.Kashirin et al. J. Phys. Conf. Ser. 2020, 1690, 012127

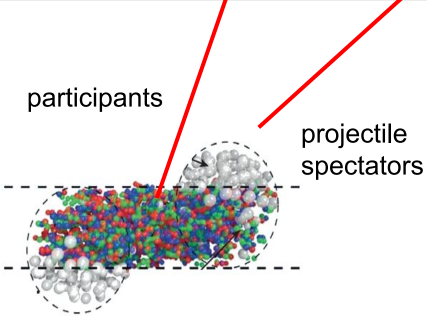
- DCM-QGSM-SMM x Geant4

M.Baznat et al. PPNL 17 (2020) 3, 303

Subsystems

- Multiplicity: TPCs
- Spectators energy: PSD





Centrality determination based on Monte-Carlo sampling

For **multiplicity of produced particles** used in HADES, CBM, BM@N, NA61/SHINE

Get (N_{part}, N_{coll}) from MC-Glauber

Calculate $N_a = fN_{part} + (1-f)N_{coll}$

Sample multiplicity of produced particles (S_i) N_a times from NBD (μ, k)

For **spectators energy** from hadron calorimeters tested based on NA61/SHINE results

Get (N_{spec}, b) from MC-Glauber

Calculate total mass of fragments $A_{tot} = A^{1-f} N_{spec}^{\ f}$ (based on the results of DCM-QGSM-SMM model)

Sample hadron calorimeter response (S_i) A_{tot} times from Gauss(μ, k)

Mixing of produced particles contribution based on Monte-Carlo events

Result: total S_{tot}

MC-Glauber distribution

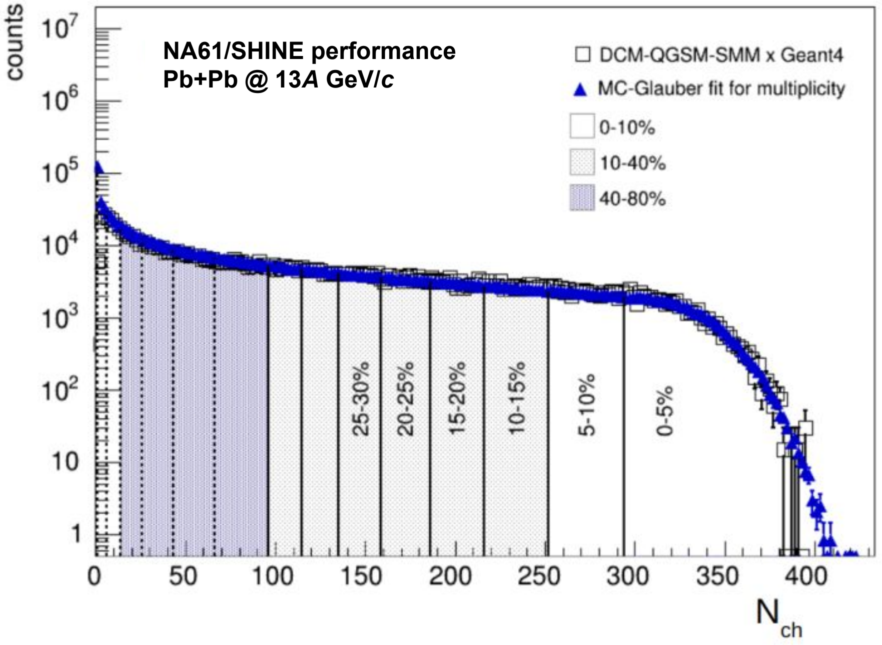
Full Monte-Carlo (real data) distribution

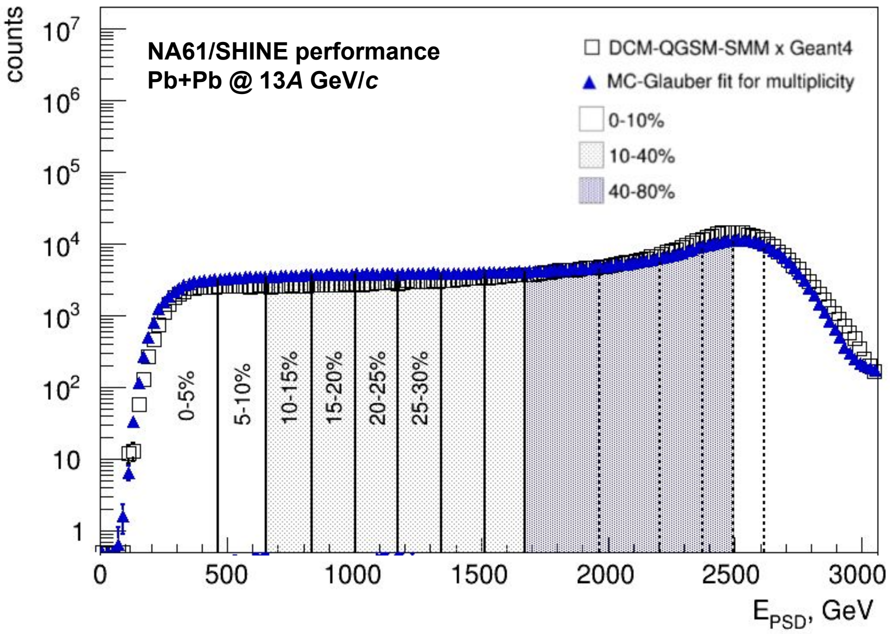
Evaluate χ^2 between $dN/dE_{MC/data}$ and dN/dE_{Gl}

Scan phase space of parameters to find their values for minimum of χ^2

Extract relation between geometry parameters and centrality estimator

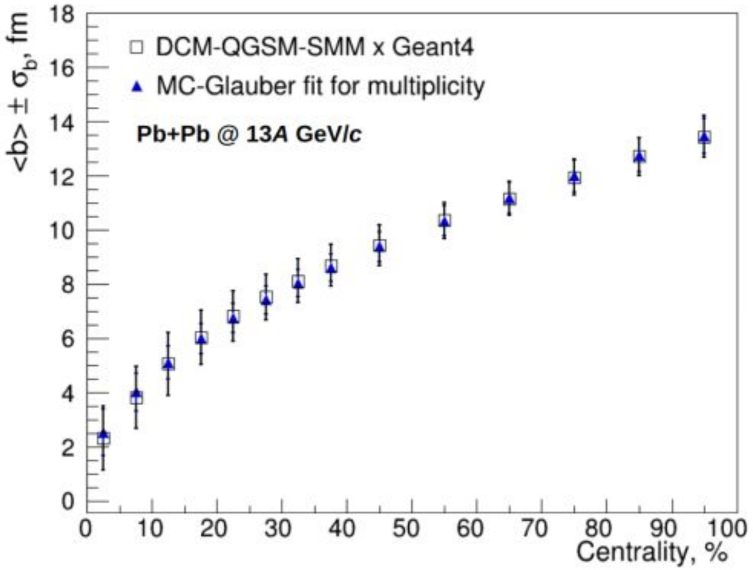
Results of the fit

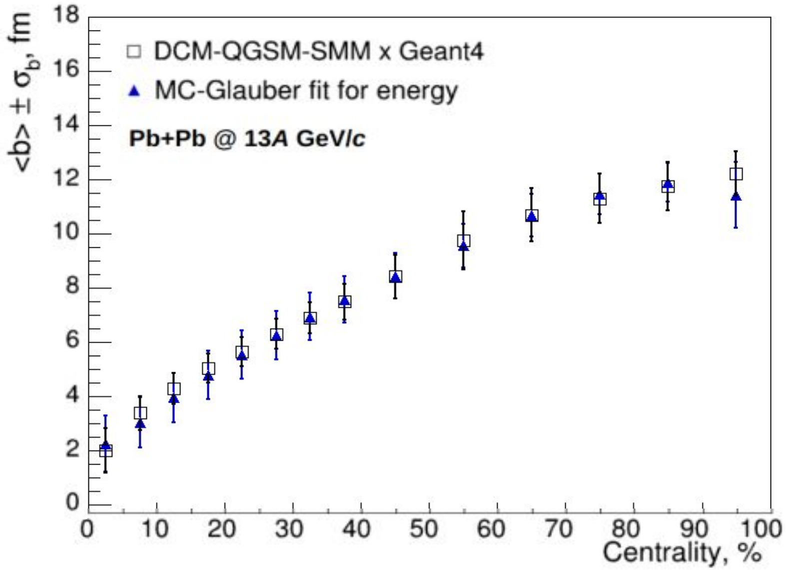




- Fit for multiplicity is good
- The procedure for spectators now better fits the most central events
- There is imbalance between the central and peripheral events which should be improved with more realistic mixing of produced particles in central events

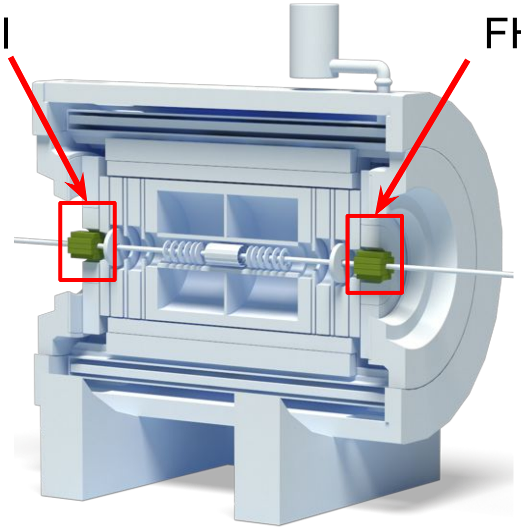
Comparison with model and between methods



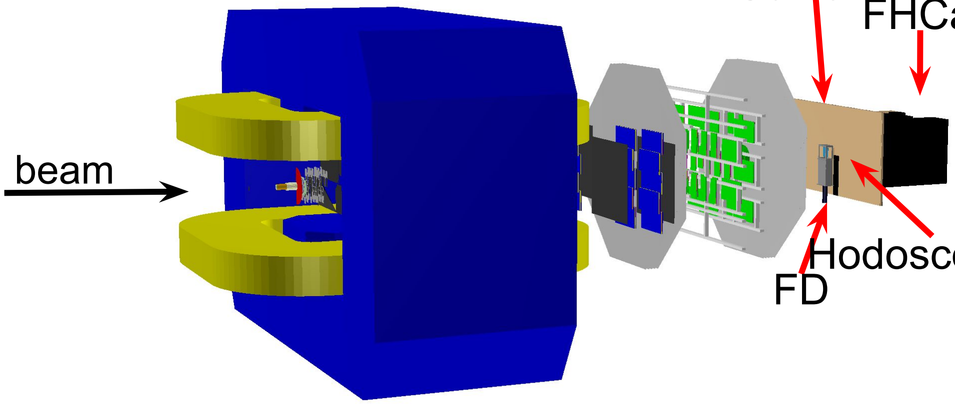


- Centrality classes determined separately using the multiplicity of produced particles and spectators both reproduce ones from DCM-QGSM-SMM model reconstructed events
- Width of energy based centrality classes is larger due to the different shapes of two-dimensional distributions of impact parameters and corresponding centrality estimators
- Impact of this effect should be considered during further work

Proposed methods at NICA experiments



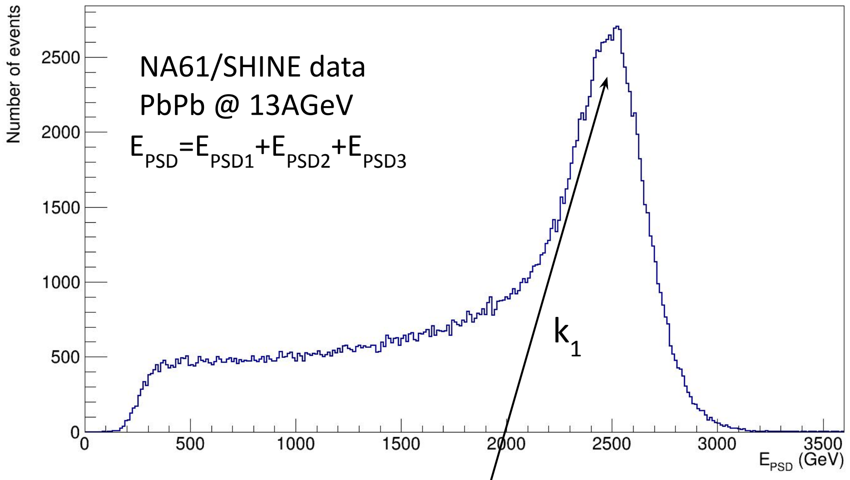
MPD at NICA

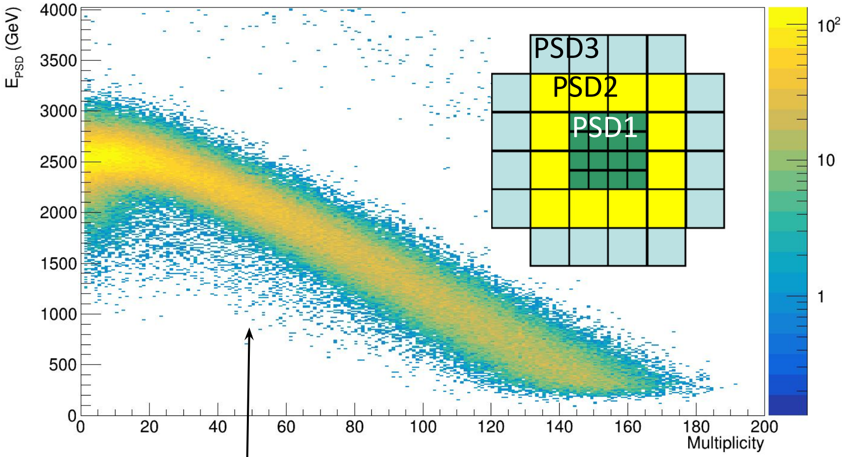


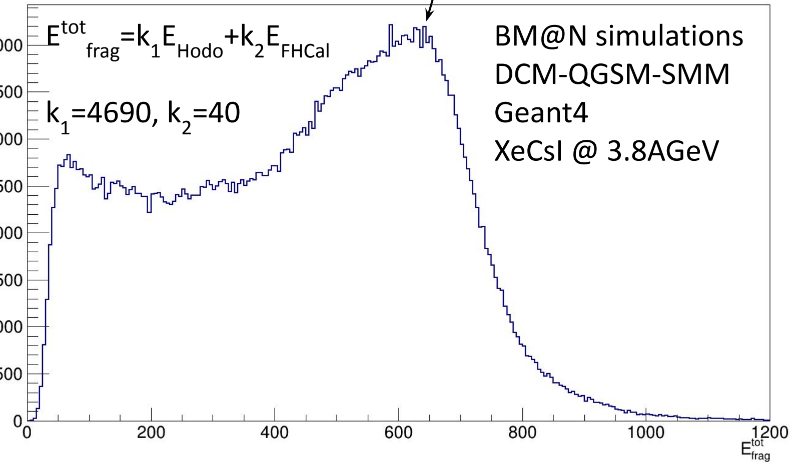
BM@N at Nuclotron

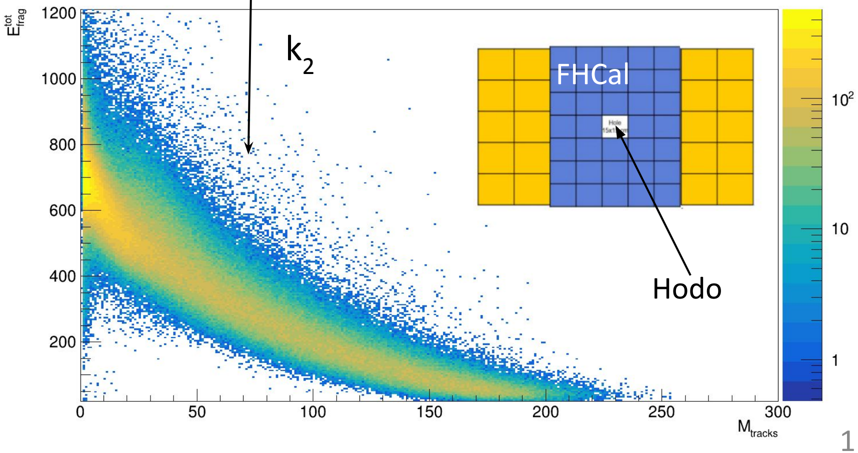
- Proposed methods can be used at MPD and BM@N experiments
- Effect due to beam hole should be taken into account
- Similar procedures can be developed for charge and multiplicity of spectators

Possibilities of spectators fragments as estimators

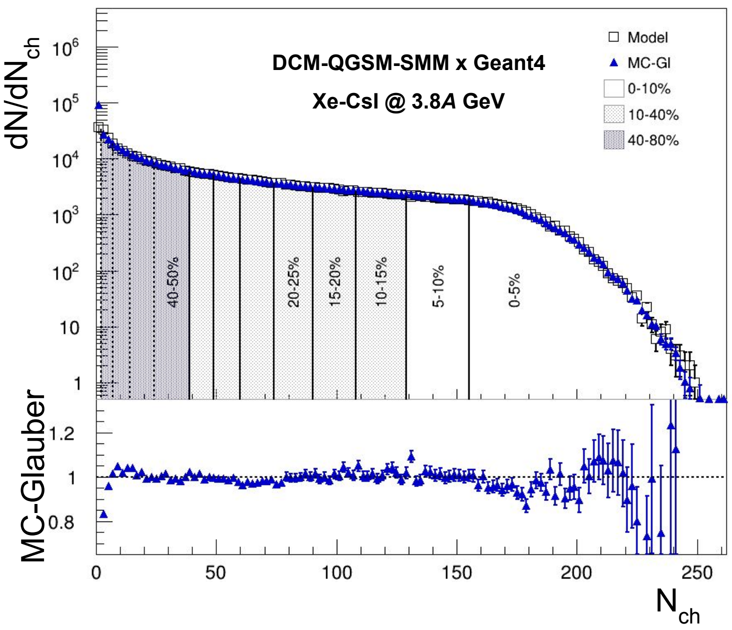


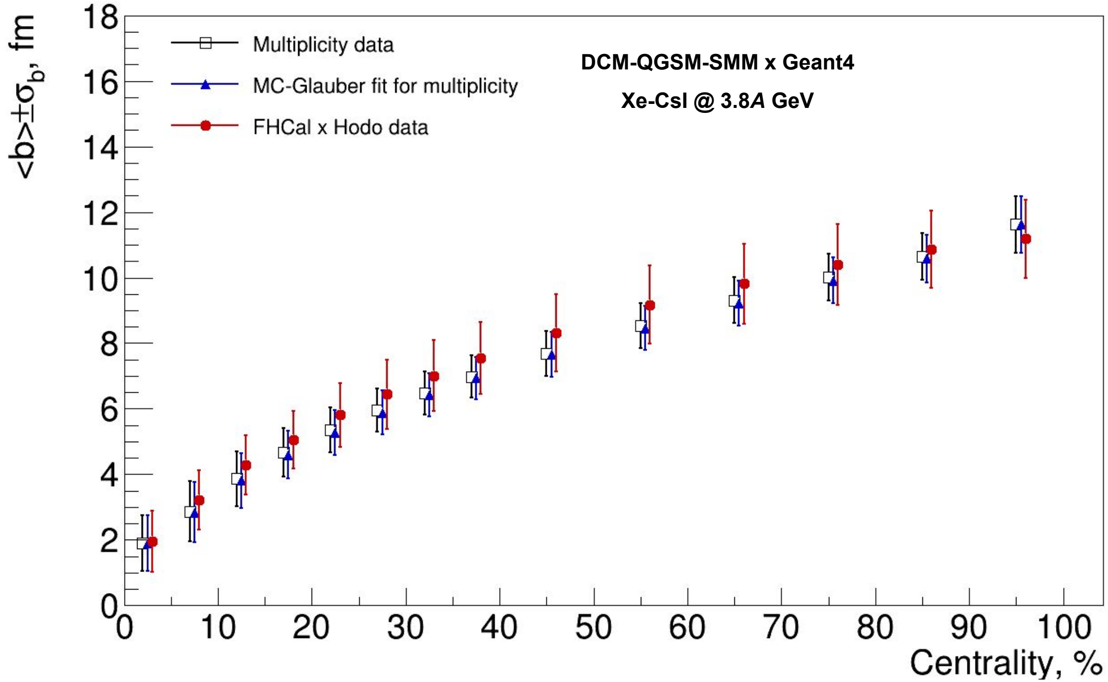






Comparison of different estimators and methods





- Impact parameter distributions in different centrality classes are similar for different centrality estimators
- These distributions for spectators energy is wider because of the width of b and energy correlation

Summary

- Centrality determination procedure based on multiplicity of produced particles is ready to use
- Centrality determination procedure based on MC sampling of spectators fragments is proposed
- Both procedures were tested based on the results of NA61/SHINE experiment
- Prospects of using the procedures for BM@N and MPD experiments are estimated

Work in progress

- Finalize developed procedure based on the energy of spectators
- Apply proposed procedures for centrality determination at BM@N and MPD
- Compare centrality classes determined with different centrality estimators in event-by-event analysis

Backup

MC Glauber model

MC Glauber model provides a description of the initial state of a heavy-ion collision

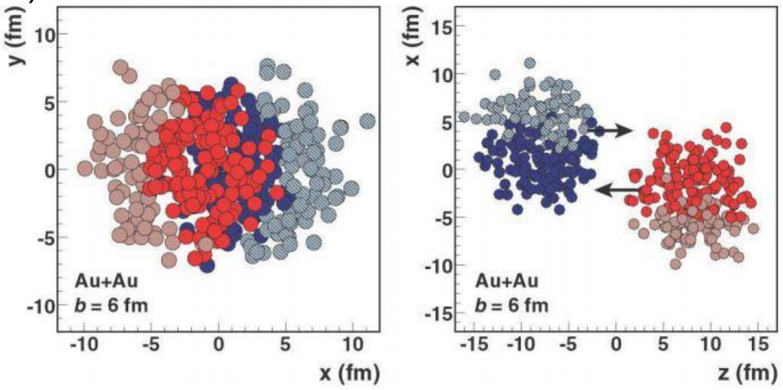
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

Main model parameters

- Colliding nuclei
- Inelastic nucleon-nucleon cross section (σ^{NN}_{inel}) (depends on collision energy)
- Nuclear charge densities (Wood-Saxon distribution)

$$\rho(r) = \rho_0 \cdot \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}$$

Glauber Modeling in High Energy Nuclear Collisions: ARNPS57:205-243,2007



Geometry parameters

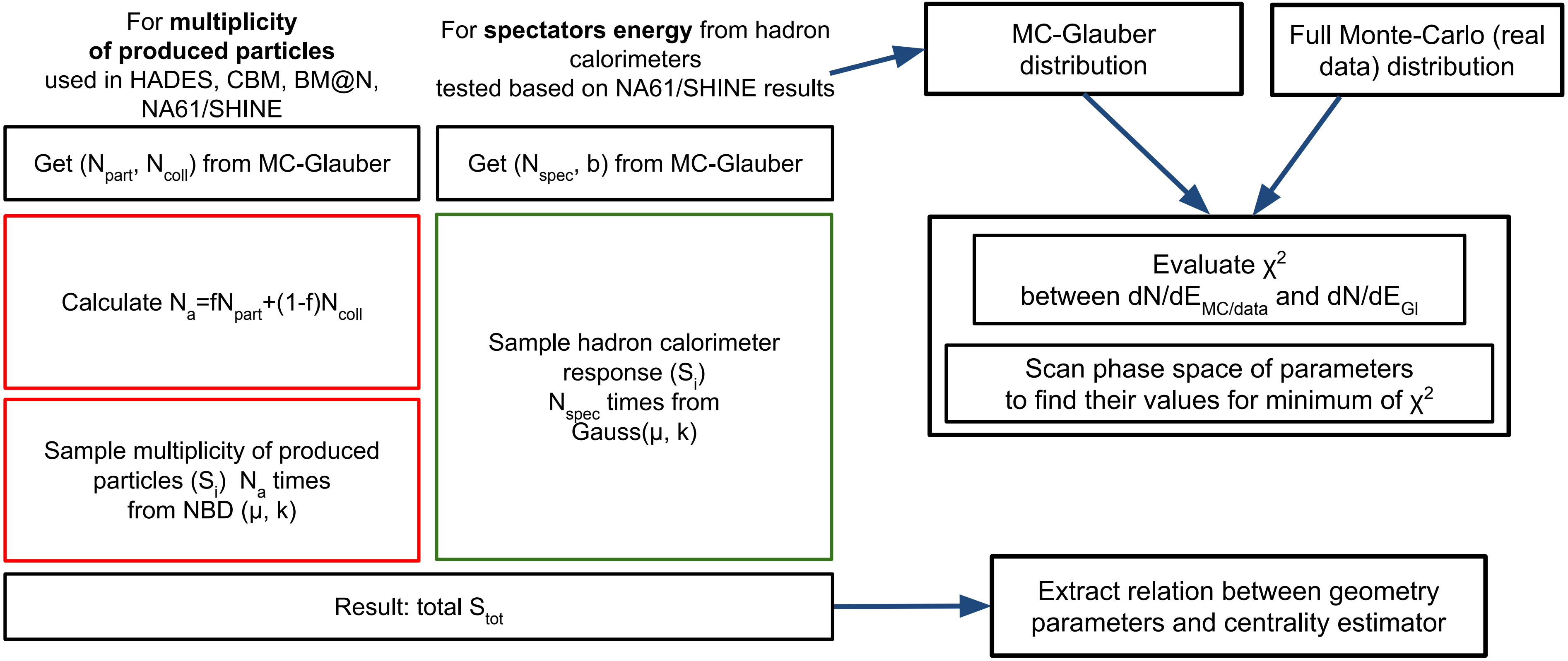
b – impact parameter

N_{part} – number of nucleons participating in the collision

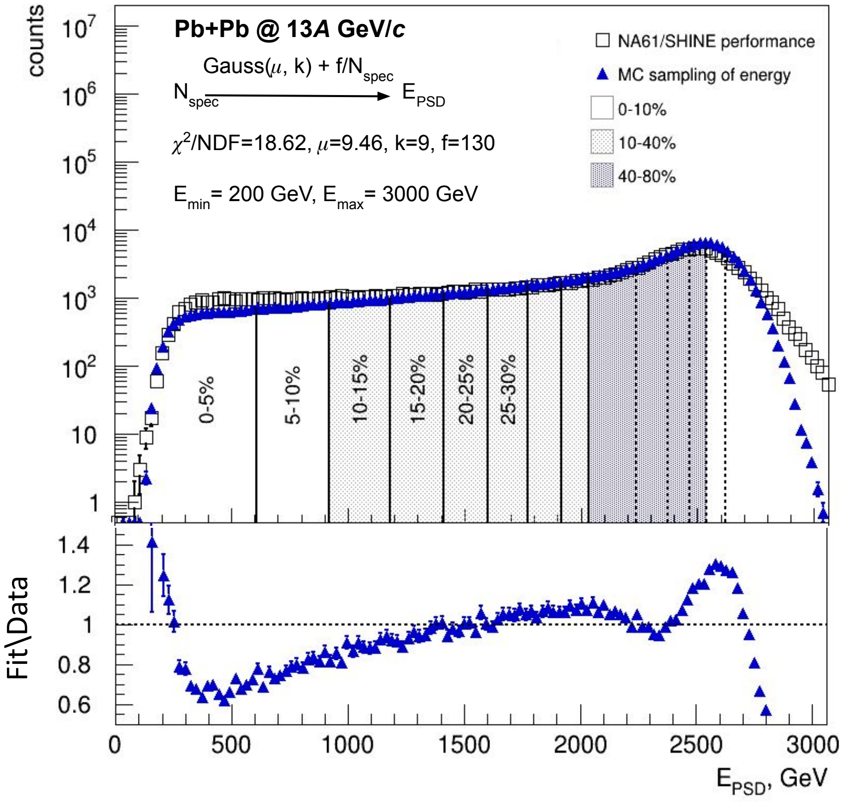
N_{spec} – number of spectator nucleons in the collision

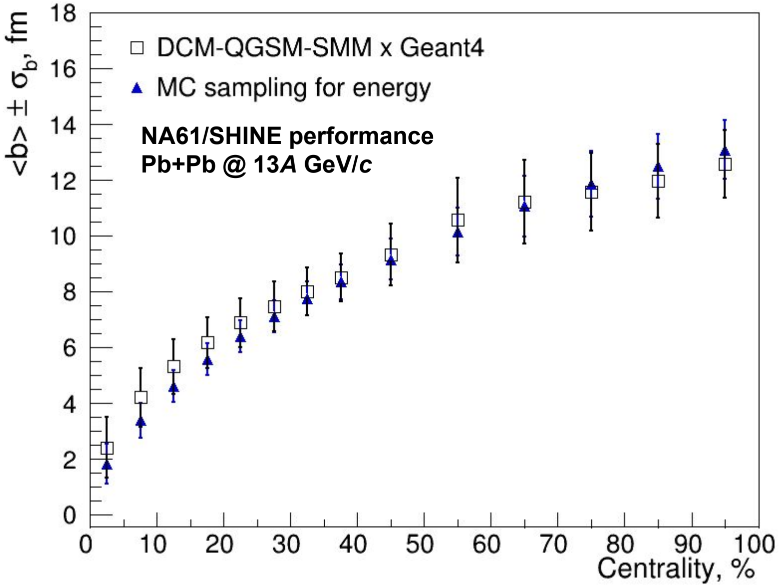
N_{coll} – number of binary NN collisions

Centrality determination based on Monte-Carlo sampling



Simplified MC sampling for hadron calorimeters

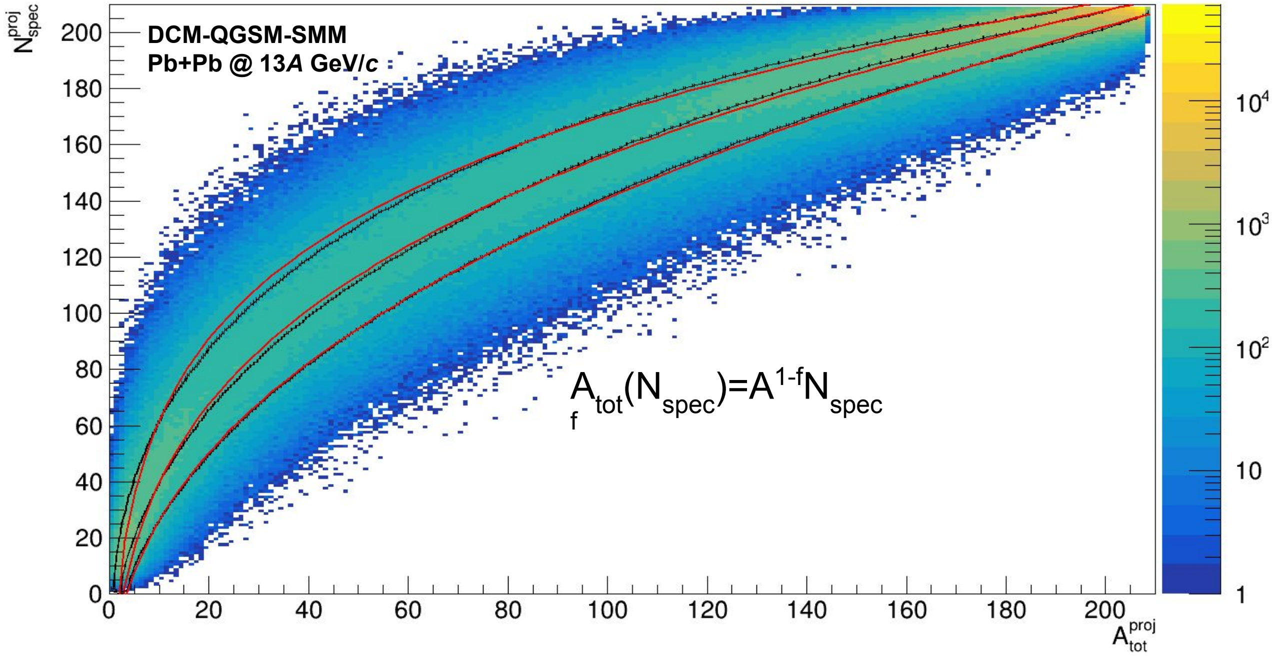




- Gauss distribution can not reproduce the energy distribution in the most central collisions
- Sampling of the most central events should've been improved

see for more details Segal I. Particles. 2023; 6(2):568-579.

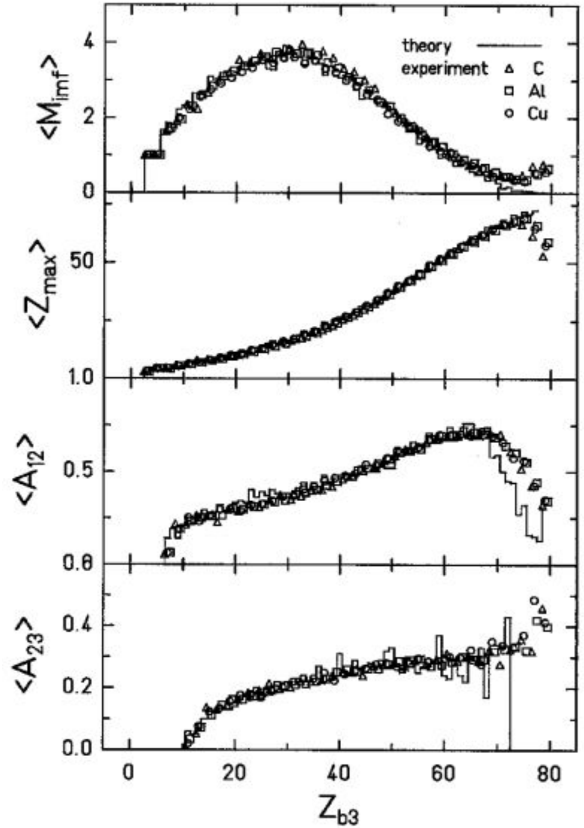
Transition from the number of spectators to the total mass of all produced fragments $A_{tot}(N_{spec})$



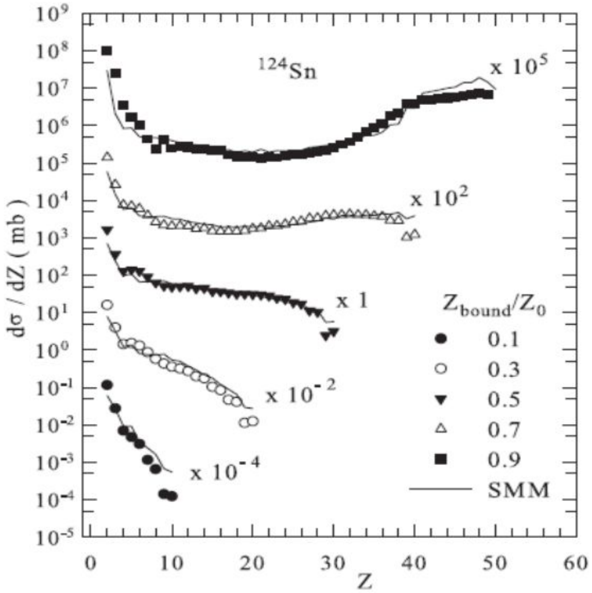
- Based on the results from DCM-QGSM-SMM model total mass of spectators fragments is not equal to N_{spec}

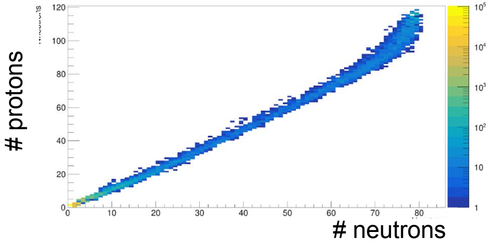
SMM description of the ALADIN's fragmentation data

A.S. Botvina et al. NPA 584 (1995) 737

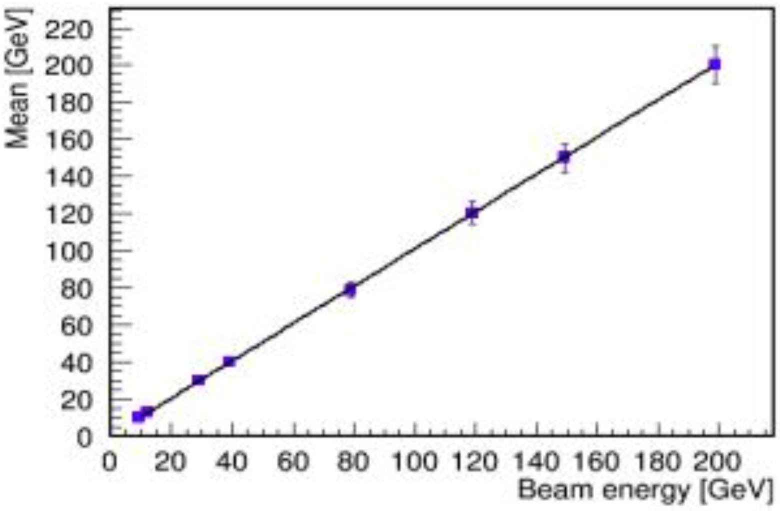


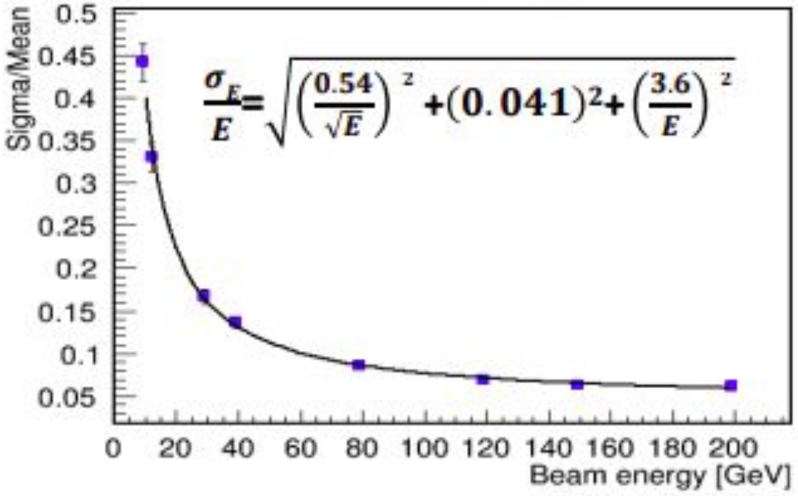
R.Ogul et al. PRC 83, 024608 (2011)





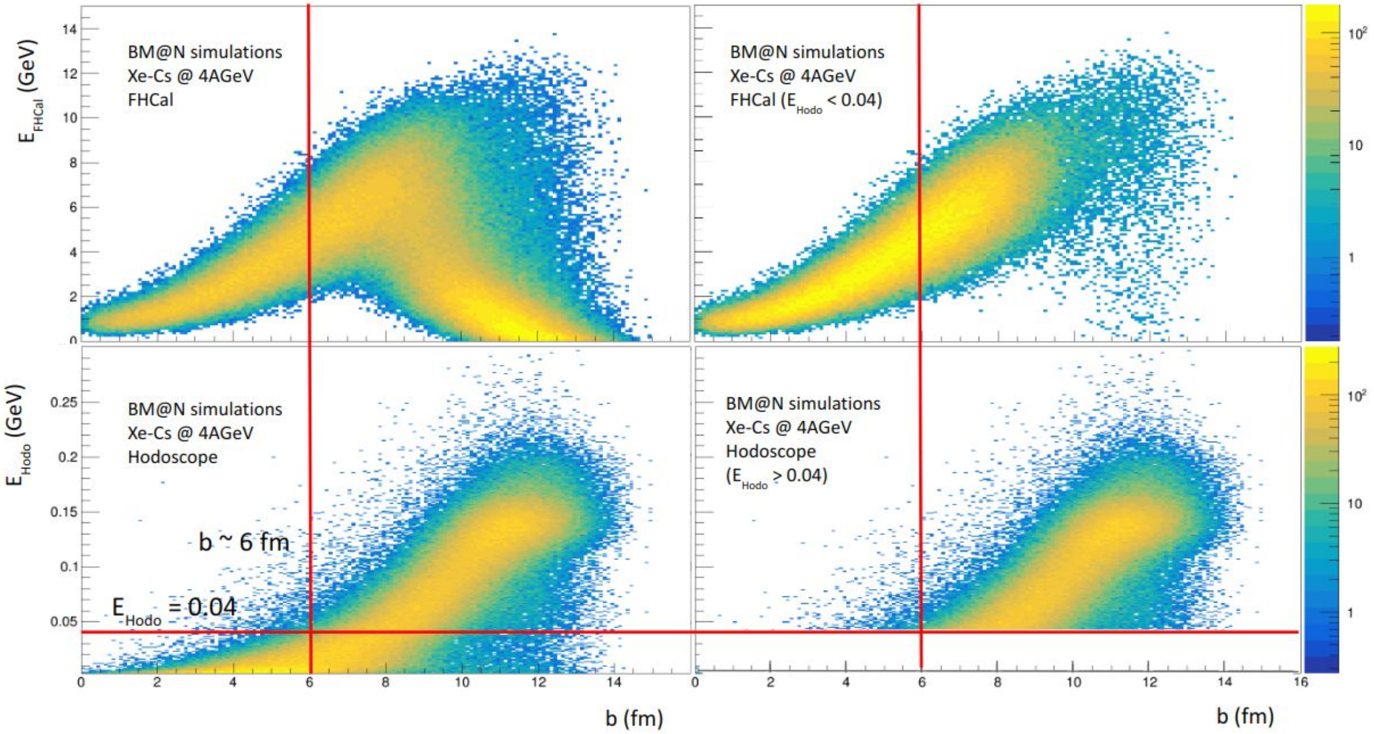
Respond of FHCal detector





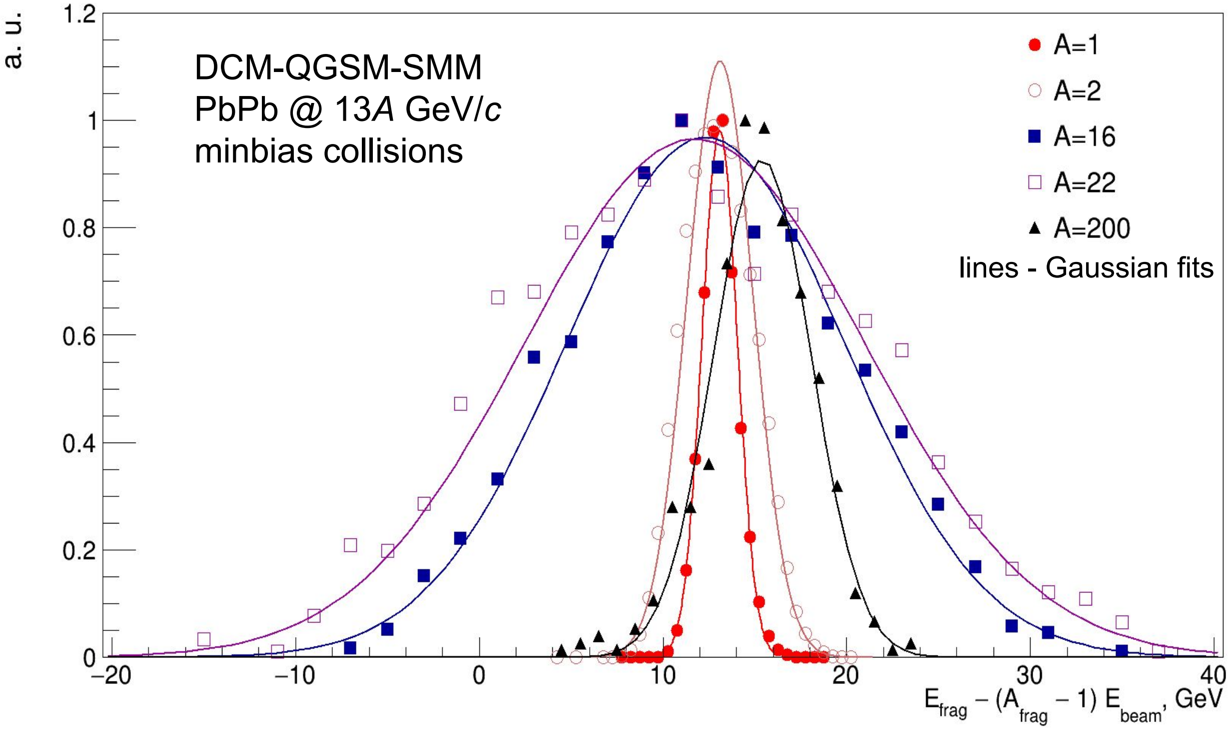
- Mean of signal has linear dependency with beam energy

Possibilities of spectators fragments as estimators



- Physical threshold of switching between estimators could be Hodoscope signal E_{Hodo} = 0.04 (corresponding to b ~ 6 fm)
- FHCal energy distribution improved and has more linear correlation with impact parameter (for range E_{Hodo} < 0.04)
- There is good correlation between Hodoscope charge and impact parameter (for range E_{Hodo} > 0.04)

Gaussian approximation for fragments energy

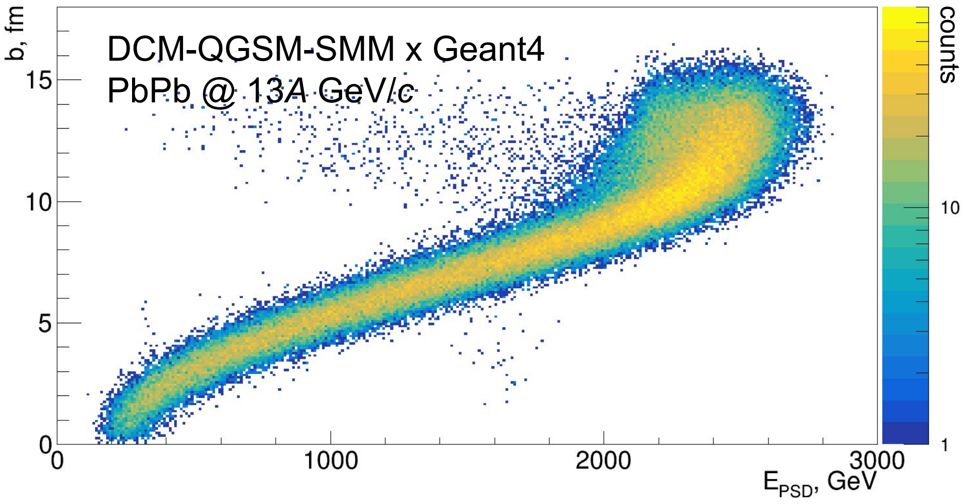


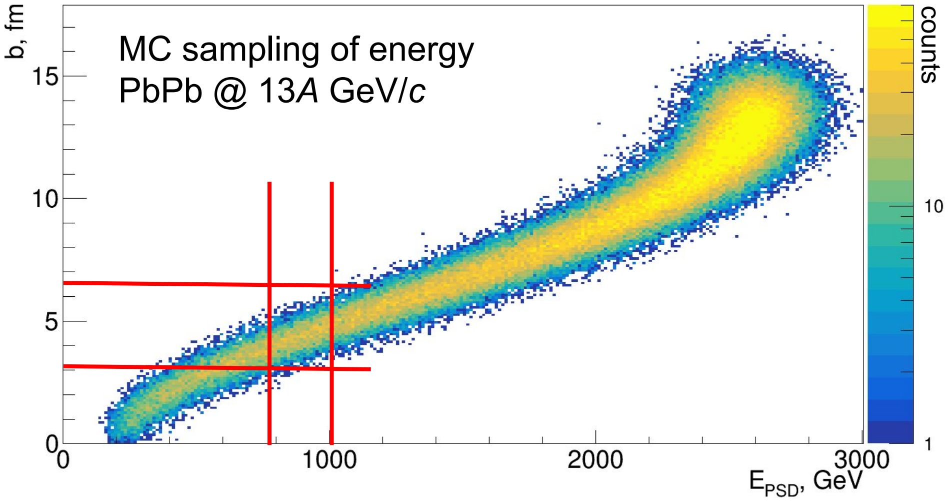
- Distribution of mass numbers of spectators fragments could be fitted by Gauss distribution
- Mean values equal to product of beam energy and fragment's mass
- Total spectators energy distribution is also Gauss:

$$P(E_{tot};\mu_{tot},k_{tot}) \approx \prod_{i=1}^{N_{frag}} P(E^i_{frag};\mu^i_{frag},k^i_{frag}) \approx \prod_{j=1}^{N_{spec}} P(E^j_{spec};\mu_{spec},k_{spec})$$

- Measured energy distribution follows convolution of two Gauss distributions (sum of fragments energy and detector response)

Simplified MC sampling for hadron calorimeters





Segal I. Particles. 2023; 6(2):568-579.

- Shapes of energy and impact parameter distributions are similar
- Width of distribution for energy is larger than for multiplicity
- Possible decrease of width will be study