Methods for centrality determination in heavy-ion collisions with the BM@N experiment

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for the BM@N Collaboration

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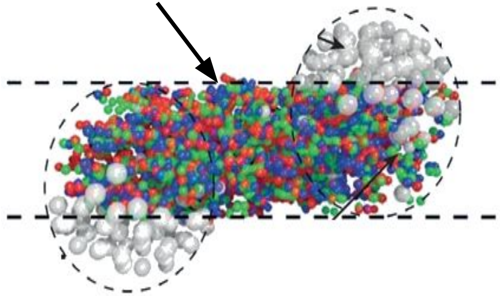
Motivation for centrality determination

- 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)

  - Monte-Carlo sampling based on output of Glauber model
    is commonly used to build such connection



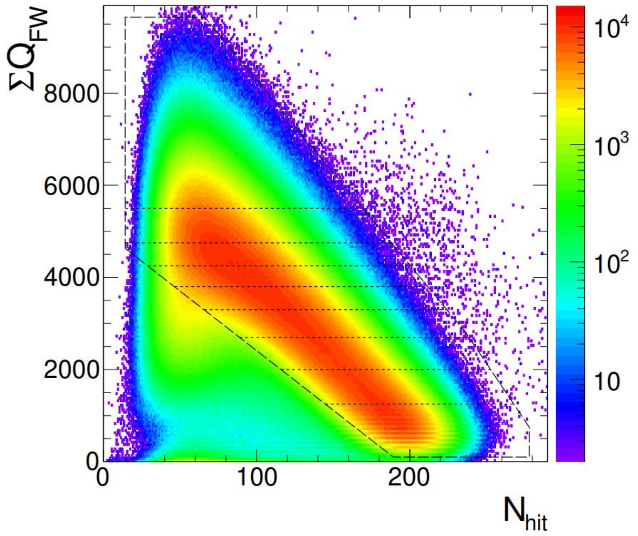
- Centrality class S_1-S_2: group of events corresponding to a given fraction (in %) of the total cross section:

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

Why several alternative centrality estimators

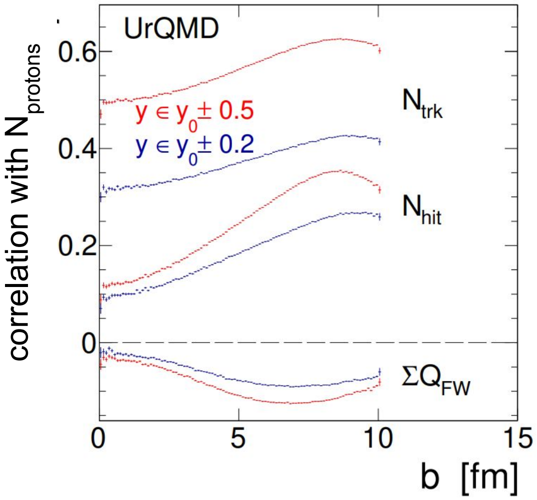
Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

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



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)

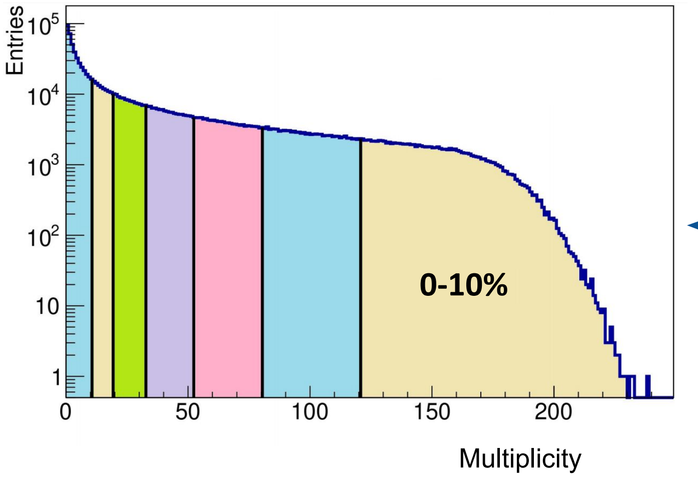
HADES; Phys.Rev.C 102 (2020) 2, 024914

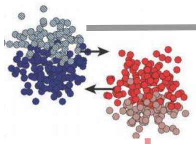


Avoid self-correlation biases when using spectators fragments for centrality estimation

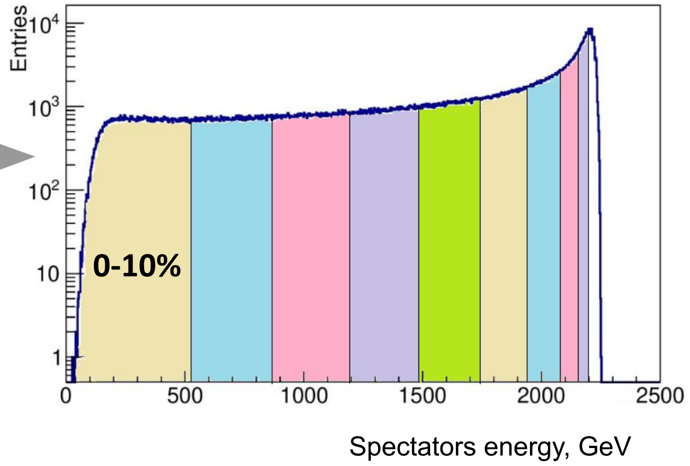
Types of centrality estimators

Produced charged particles





Spectators



(Target spectators not measured for fixed-target)

BM@N subsystems for centrality determination

Simulation setup

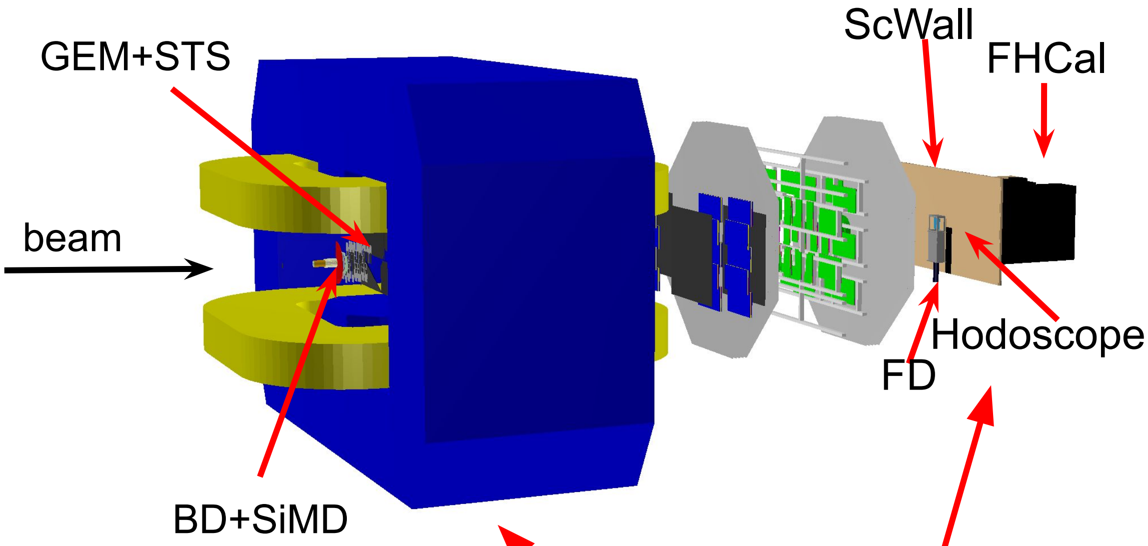
- DCM-QGSM-SMM

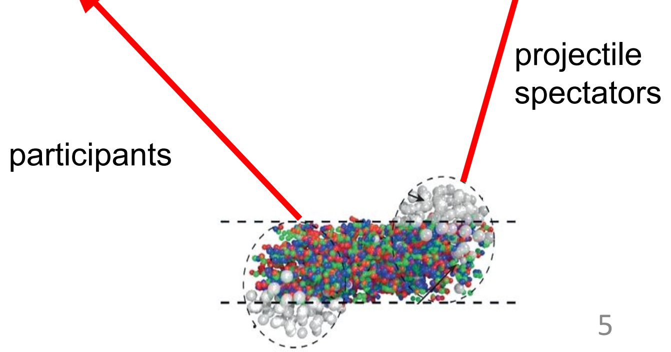
  M.Baznat et al. PPNL 17 (2020) 3, 303

- Xe-Cs @ 4*A* GeV
- Transport: GEANT4

Subsystems

- Participants: **Tracking system GEM+STS**, BD, SiMD
- Spectators: **FHCal, Hodoscope**, ScWall, FD





Overview of centrality determination methods

Method type	MC-Glauber based	Model independent (e.g. Γ-fit method)	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

Centrality determination based on Monte-Carlo sampling of produced particles

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)

Result: total S_{tot}

MC-Glauber distribution

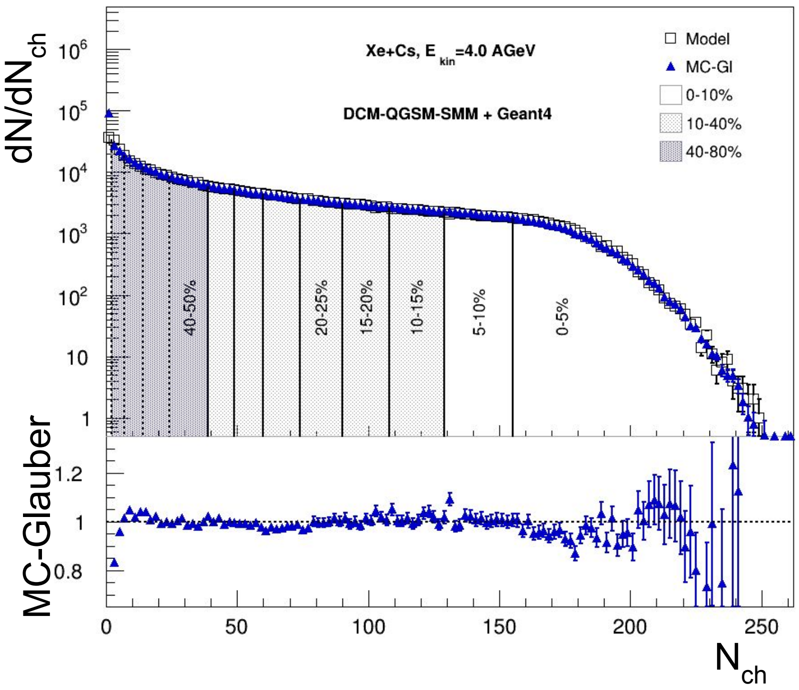
Full Monte-Carlo (real data) distribution

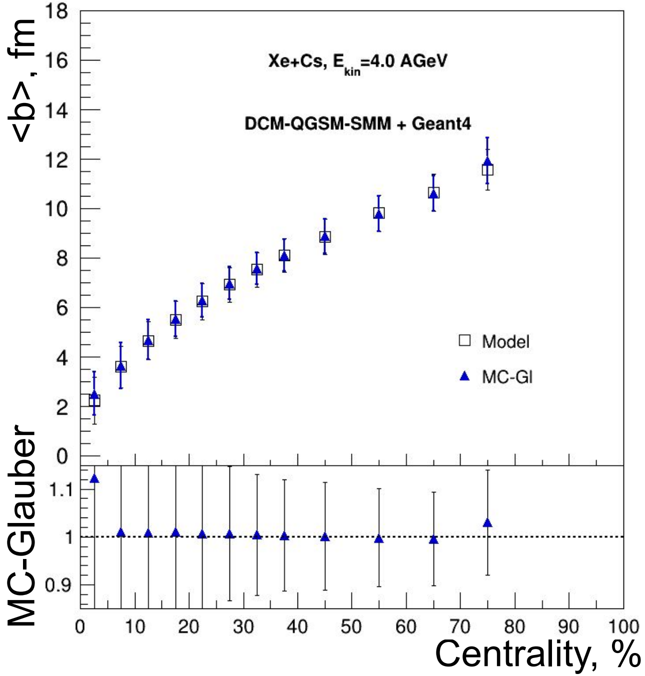
Evaluate χ^2 between $dN/dE_{MC/data}$ and dN/dE_{Gl}

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

Extract relation between geometry parameters and centrality estimator

MC-Glauber fit result Xe-Cs @ 4.0 AGeV





χ^2=1.31±0.07;
f=0.9,
μ=0.786293,
k=1;
MinFitBin=10,
MaxFitBin=250

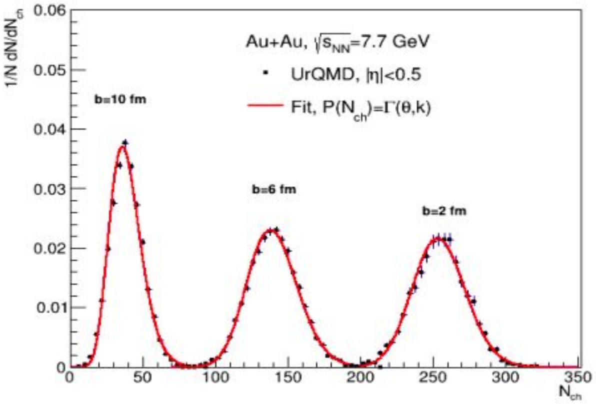
- Fit result is good
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM

The Bayesian inversion method (Γ-fit): main assumptions

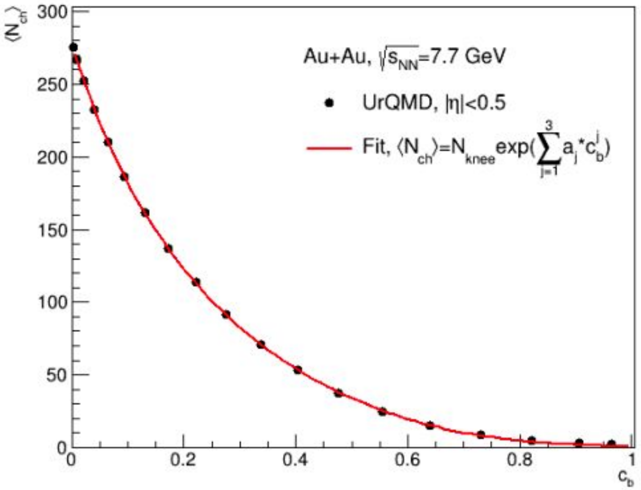
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

$$P(N_{ch}|c_b) = \frac{1}{\Gamma(k(c_b))\theta^k} N_{ch}^{k(c_b)-1} e^{-n/\theta}$$

$$c_b = \int_0^b P(b')db' \simeq \frac{\pi b^2}{\sigma_{inel}}$$ – centrality based on impact parameter



The results of fitting the multiplicity distribution for a fixed impact parameter



The dependence of the average value of multiplicity on centrality and the results of its fit

$$\frac{\sigma^2}{\langle N_{ch}\rangle} = \theta \simeq const$$

$$\langle N_{ch}\rangle = N_{knee}\exp\left(\sum_{j=1}^{3} a_j c_b^j\right)$$, $k = \frac{\langle N_{ch}\rangle}{\theta}$

Five fit parameters N_{knee}, θ, a_j

Reconstruction of b

- Normalized multiplicity distribution $P(N_{ch})$

$$P(N_{ch}) = \int_0^1 P(N_{ch}|c_b)dc_b$$

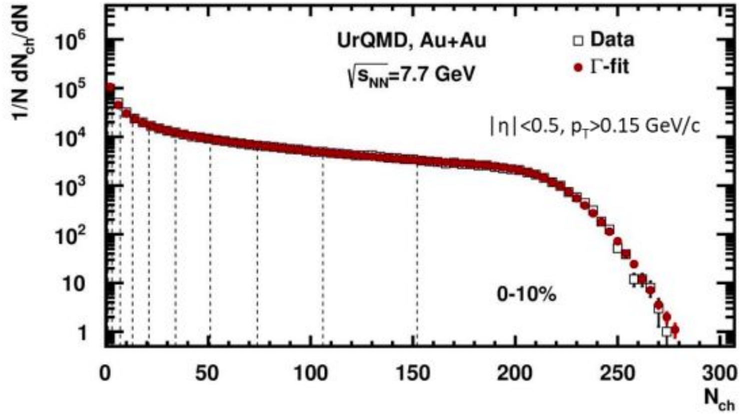
- Find probability of *b* for fixed range of N_{ch} using Bayes' theorem:

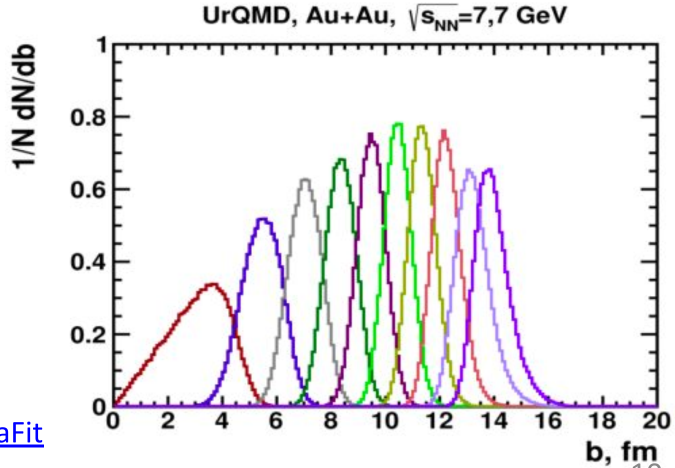
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(b|N_{ch})dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$

- **The Bayesian inversion method consists of 2 steps:**

–Fit normalized multiplicity distribution with $P(N_{ch})$

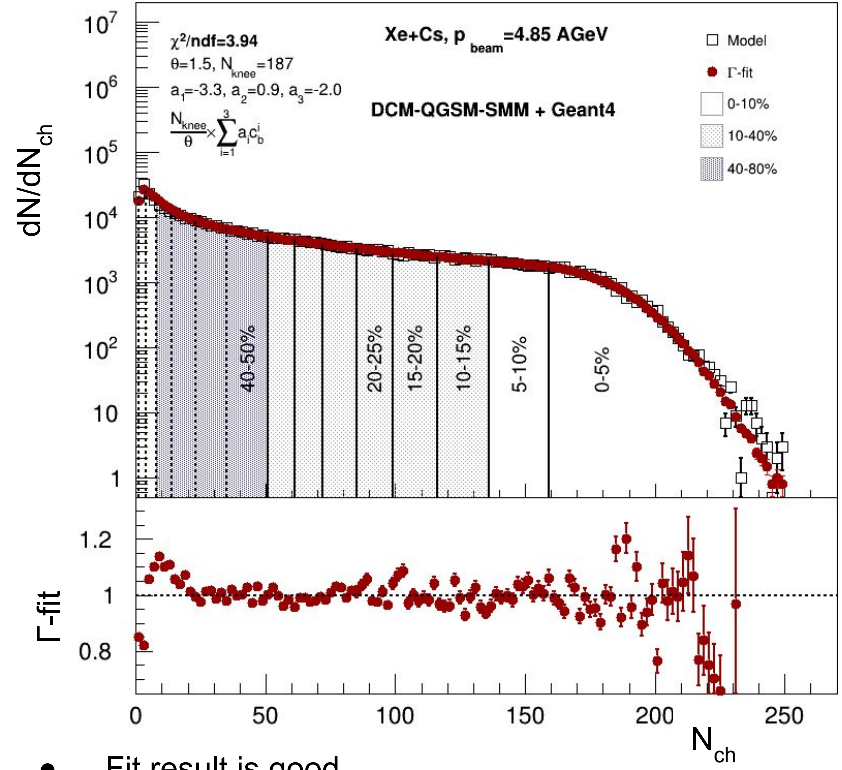
–Construct $P(b|N_{ch})$ using Bayes' theorem with parameters from the fit

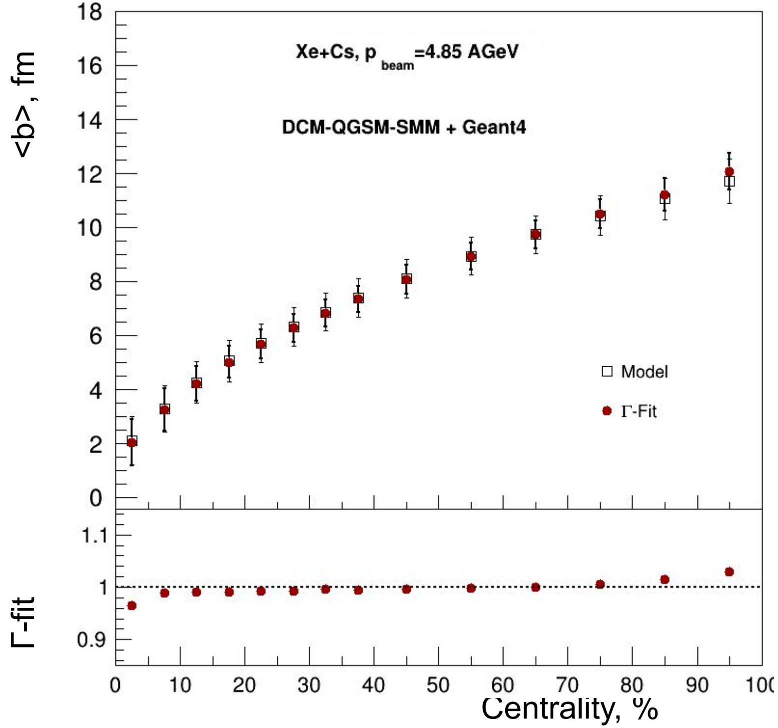




R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902
Implementation for MPD and BM@N by D. Idrisov: https://github.com/Dim23/GammaFit
Example of application in MPD: **P. Parfenov et al., Particles 4 (2021) 2, 275-287**

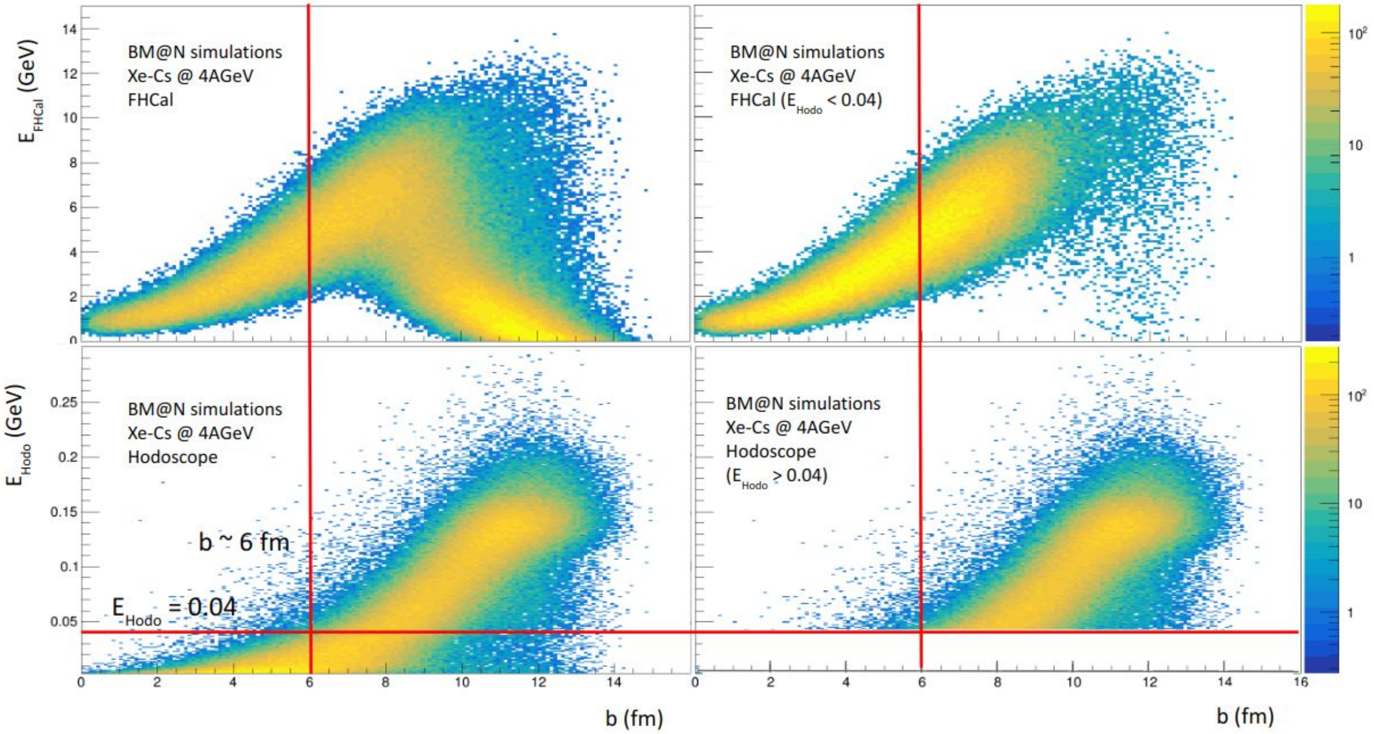
Γ-fit result Xe-Cs @ 4.0 AGeV





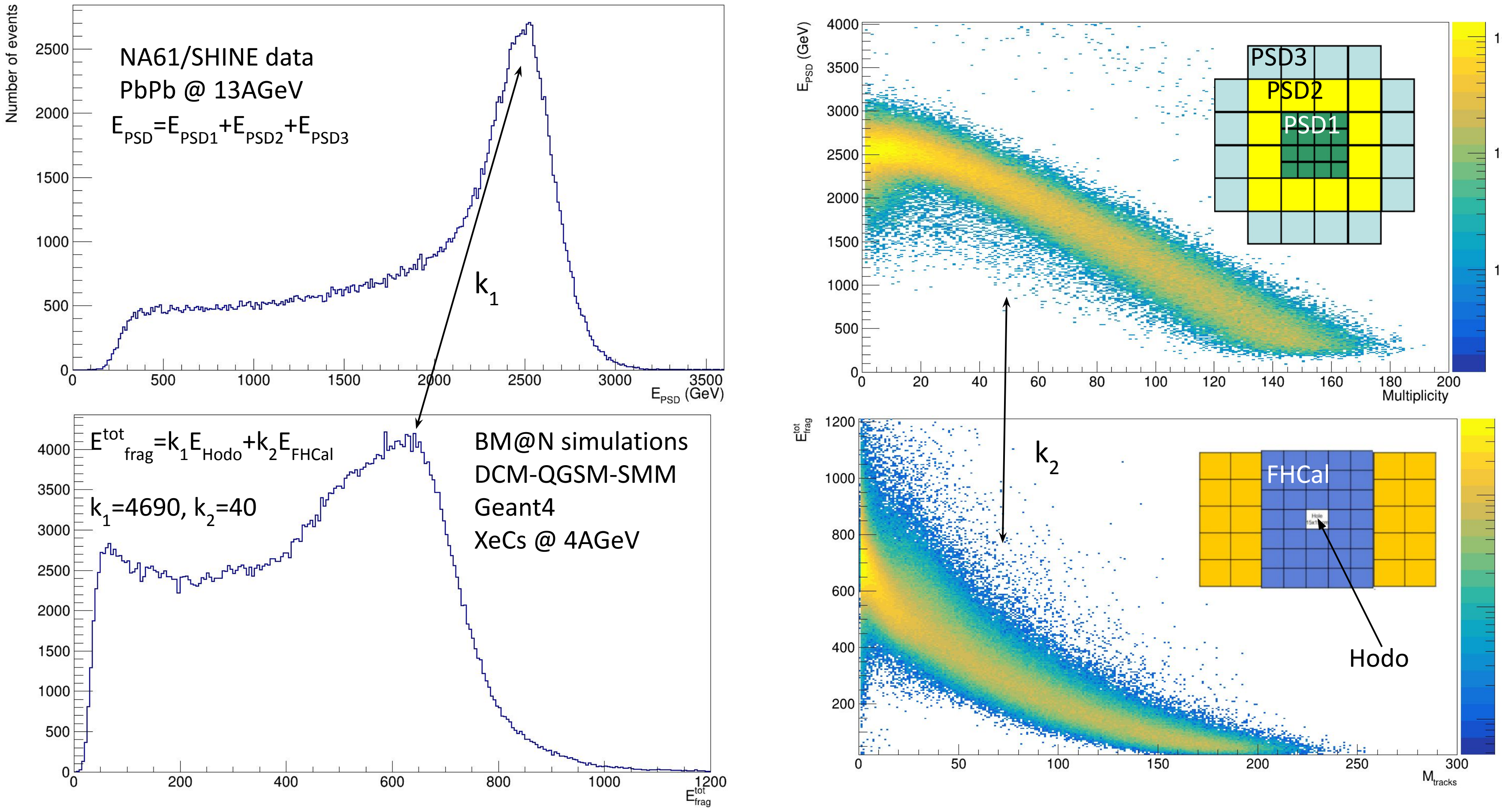
- Fit result is good
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM
- Γ-fit method also could be used for centrality determination based on spectators energy

Possibilities of spectators fragments as estimators

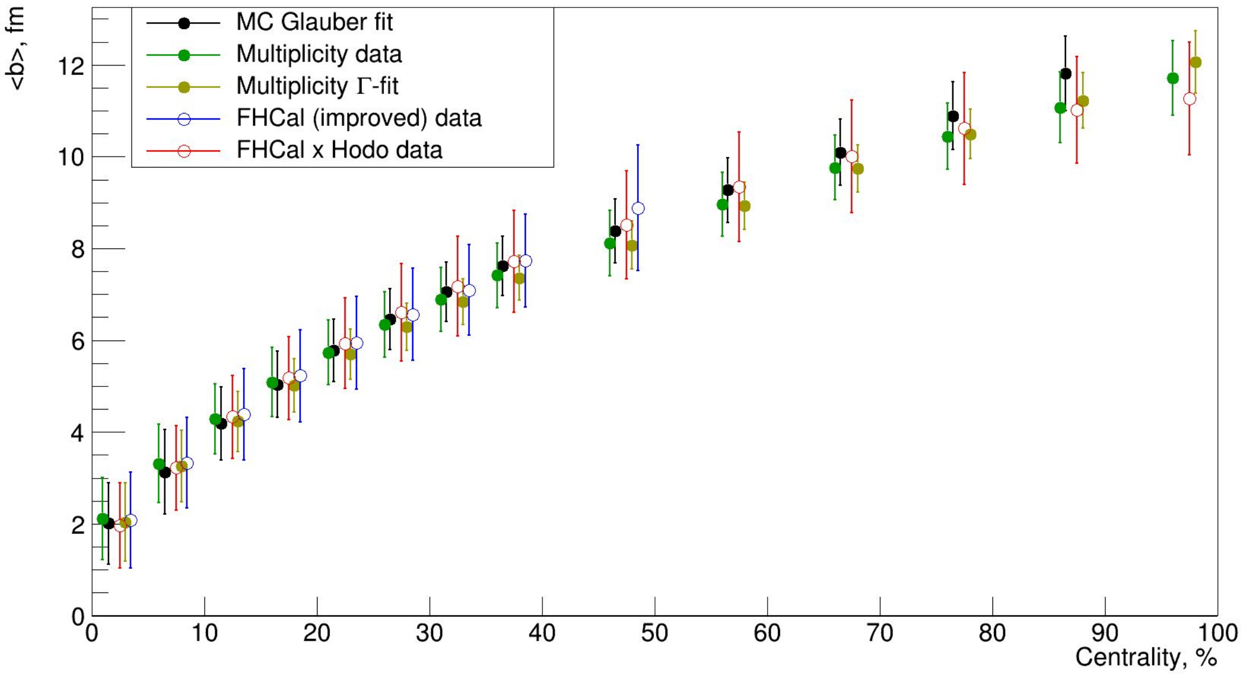


- Physical threshold of switching between estimators could be Hodoscope signal E_{Hodo} = 0.04 (corresponding to b ~ 6 fm)
- FHCal energy distribution improved and has more linear correlation with impact parameter (for range E_{Hodo} < 0.04)
- There is good correlation between Hodoscope charge and impact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

Possibilities of spectators fragments as estimators



Comparison of different estimators and methods



from talk at ICPPA-2022

proceedings submitted
to Physics of Atomic Nuclei

- 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

- Software implementation of MC-Glauber and Γ-fit based fitting procedures for multiplicity are used for BM@N
- Relation between impact parameter and centrality classes is extracted

- Combination of forward detectors can be used to avoid effects due to the beam hole in FHCal
- Results are tuned on the spectator production implemented in the DCM-QGSM-SMM model

Work in progress

- Investigate applicability of the Glauber model for centrality determination at low energies
- Consider using of Γ-fit method for spectators energy
- Apply all procedures for BM@N run8 data

Backup

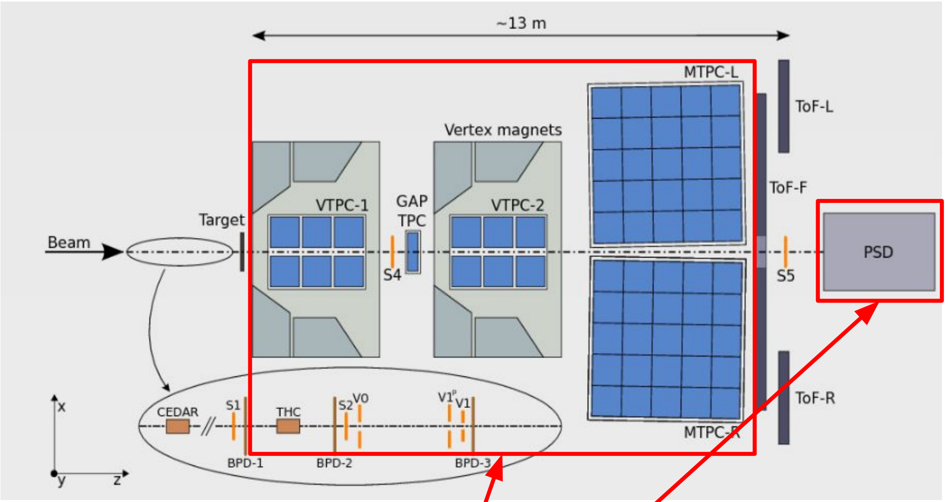
NA61/SHINE experimental setup

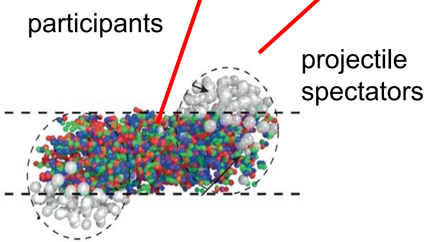
Data samples:

- Pb-Pb @ p_{beam} = 13A GeV/c
- data from 2016 physics run
- DCM-QGSM-SMM x Geant4
  M.Baznat et al. PPNL 17 (2020) 3, 303

Subsystems

- Multiplicity: TPCs (p_T>0.05, η<3.5)
- 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 used in NA61/SHINE

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

Sample hadron calorimeter response (S_i) N_{spec} times from Gauss(μ, k)

Result: total S_{tot}

MC-Glauber distribution

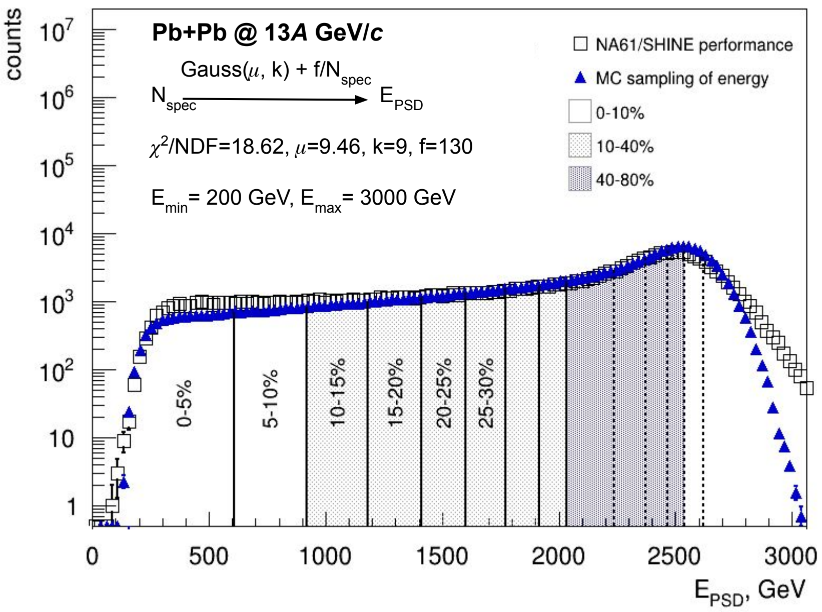
Full Monte-Carlo (real data) distribution

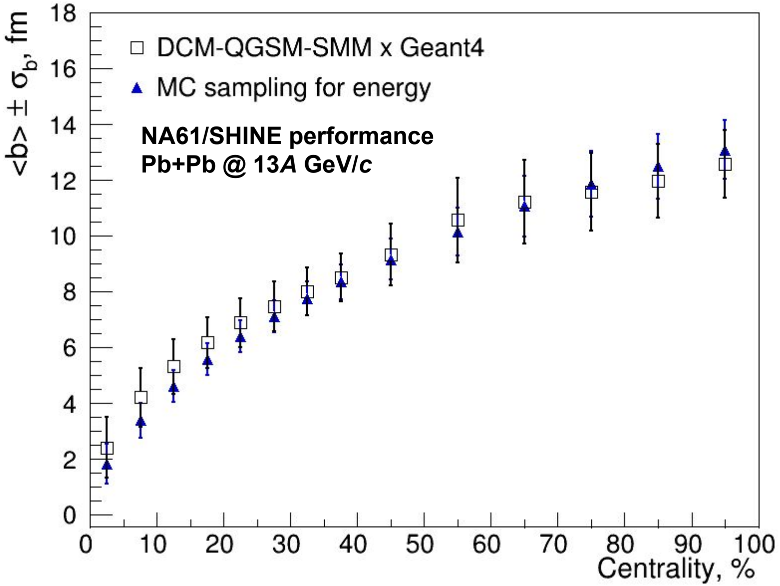
Evaluate χ^2 between $dN/dE_{MC/data}$ and dN/dE_{Gl}

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

Extract relation between geometry parameters and centrality estimator

Simplified MC sampling for hadron calorimeters

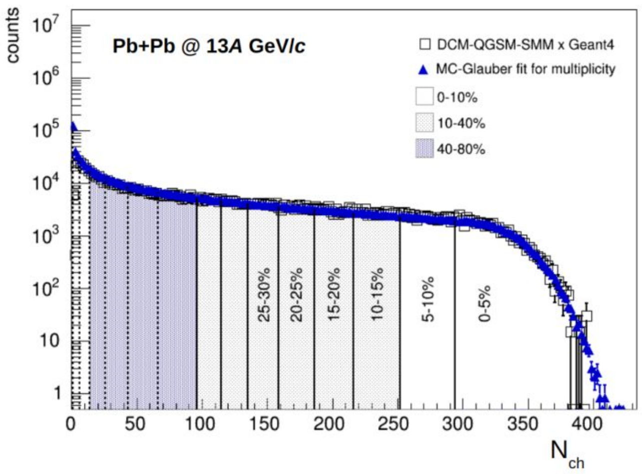


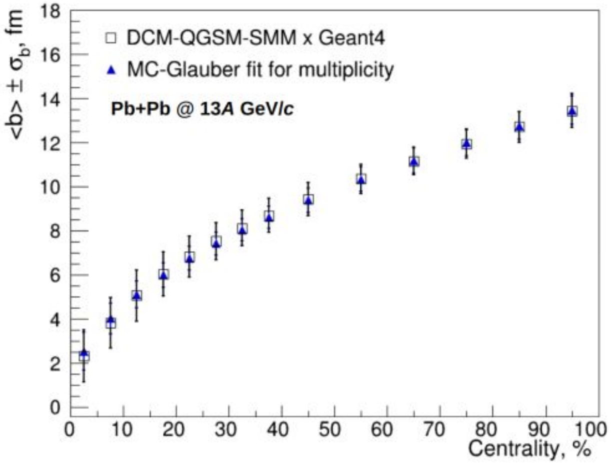


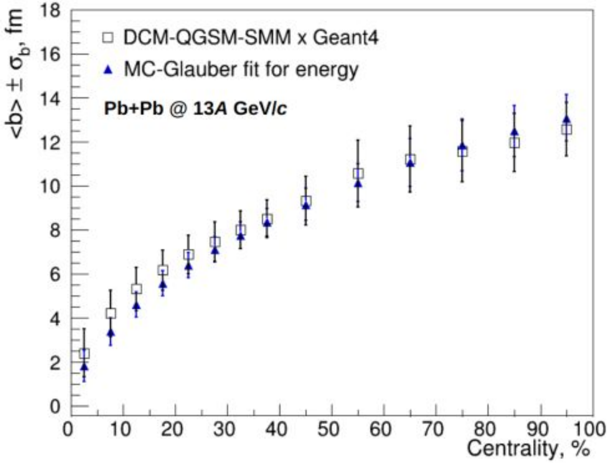
see for more details Segal I. Particles. 2023; 6(2):568-579.

- Gauss distribution can not reproduce energy distribution in the most central collisions
- Possible improvements are now under investigation

Comparison with standard MC-Glauber x NBD method







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

- Centrality classes determined separately using the multiplicity of produced particles and spectators are slightly different
- This is 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

MC Glauber model

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

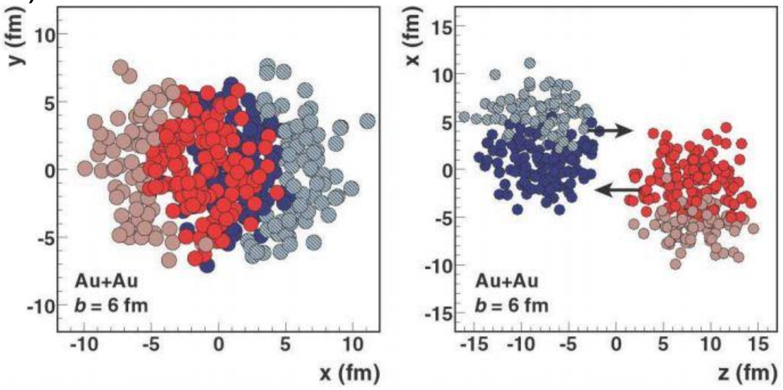
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

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

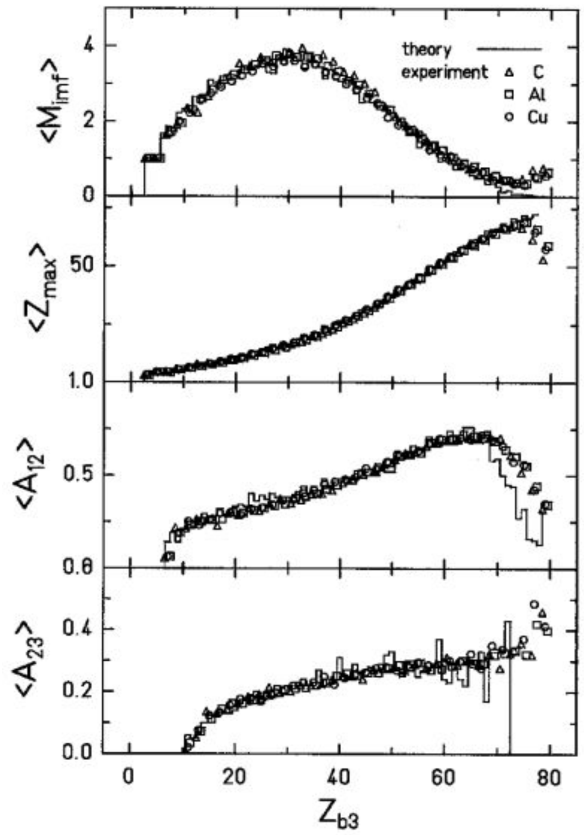
N_{part} – number of nucleons participating in the collision

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

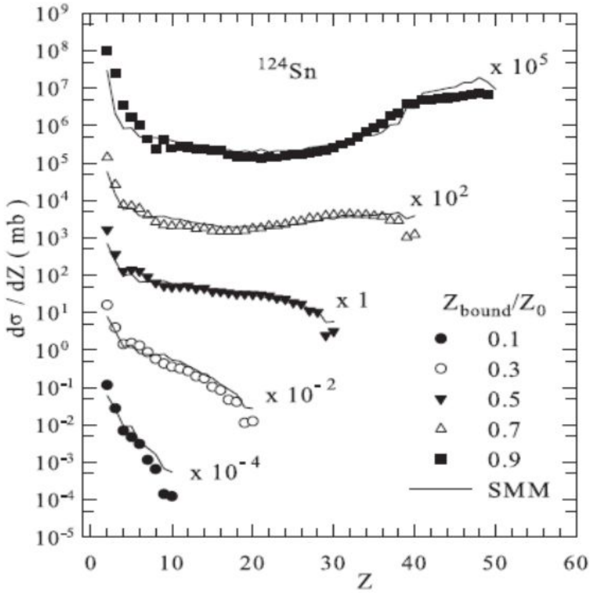
N_{coll} – number of binary NN collisions

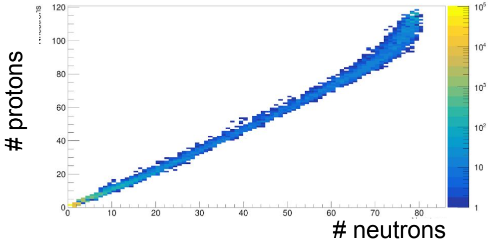
SMM description of the ALADIN's fragmentation data

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

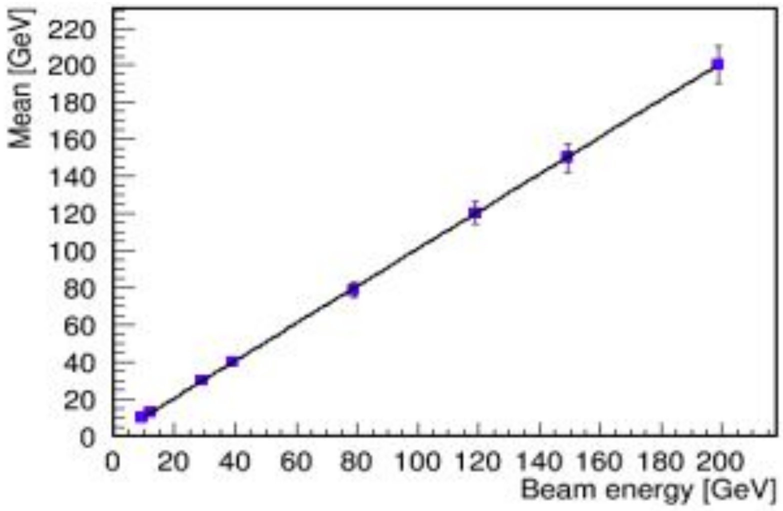


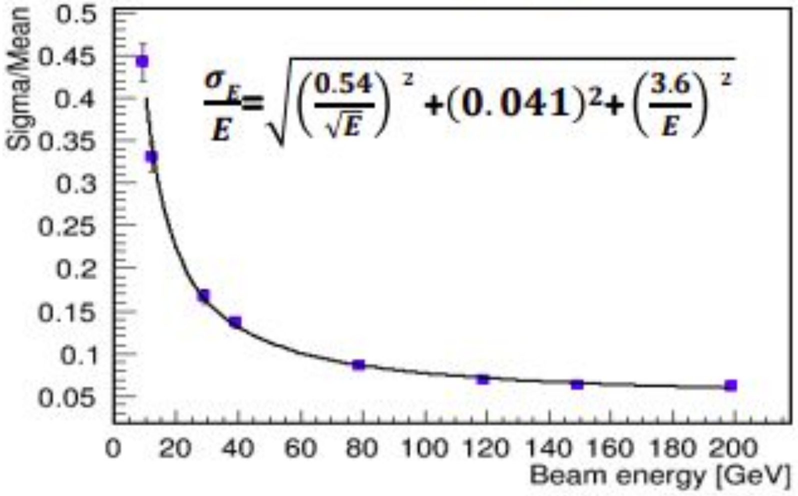
R.Ogul et al. PRC 83, 024608 (2011)





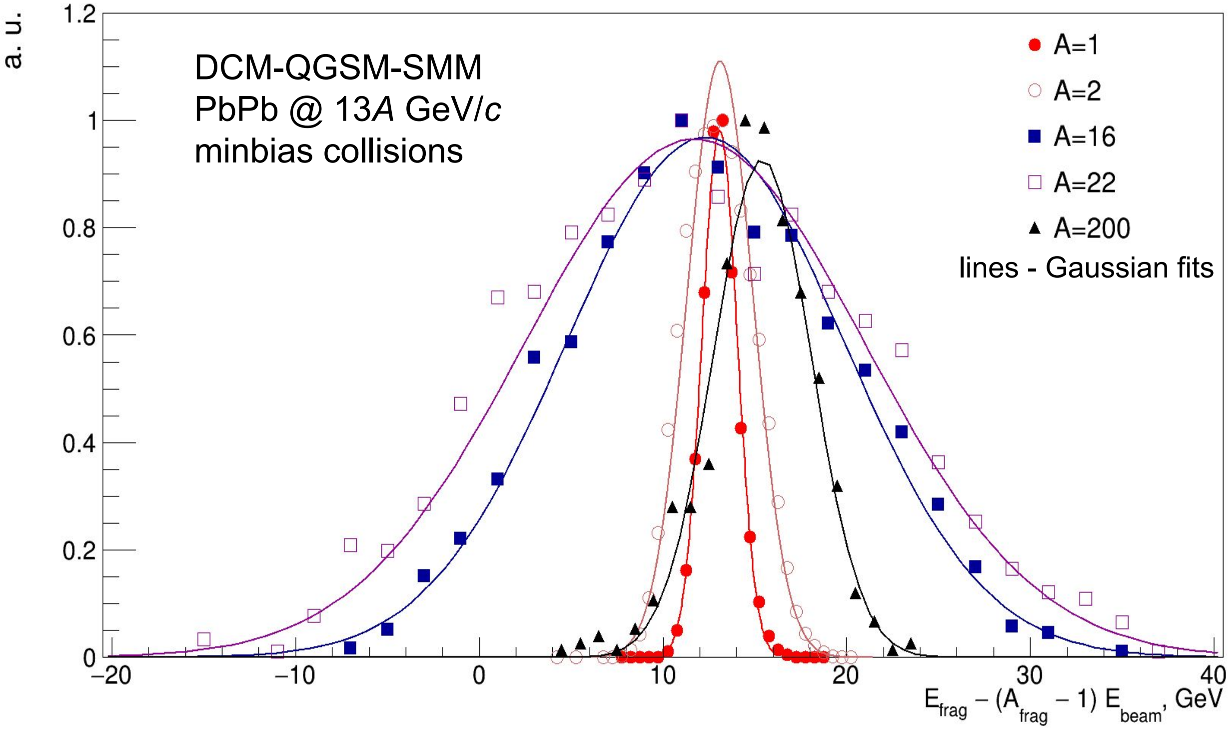
Respond of FHCal detector





- Mean of signal has linear dependency with beam energy

Gaussian approximation for fragments energy

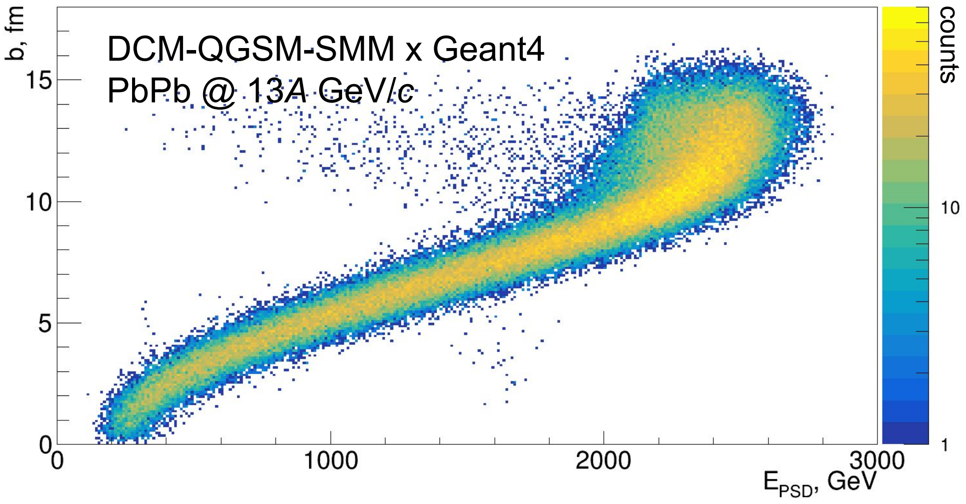


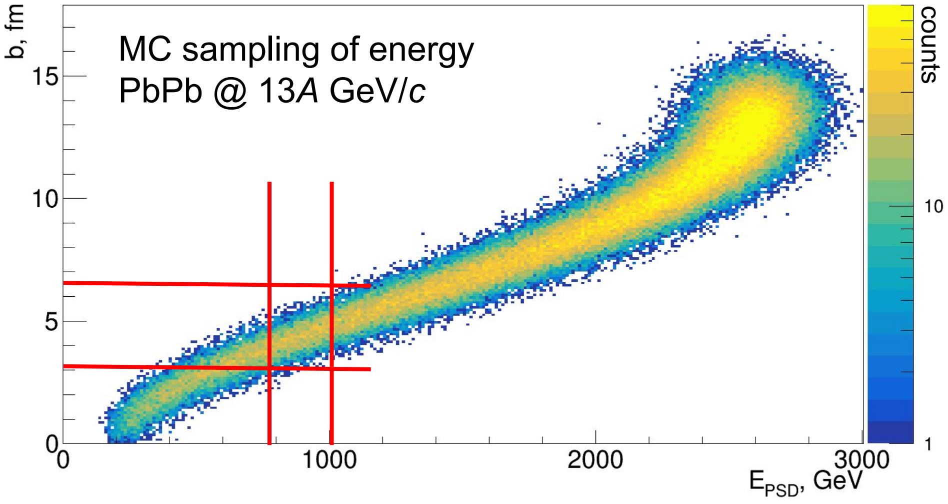
- Distribution of mass numbers of spectators fragments could be fitted by Gauss distribution
- Mean values equal to product of beam energy and fragment's mass
- Total spectators energy distribution is also Gauss:

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

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

Simplified MC sampling for hadron calorimeters

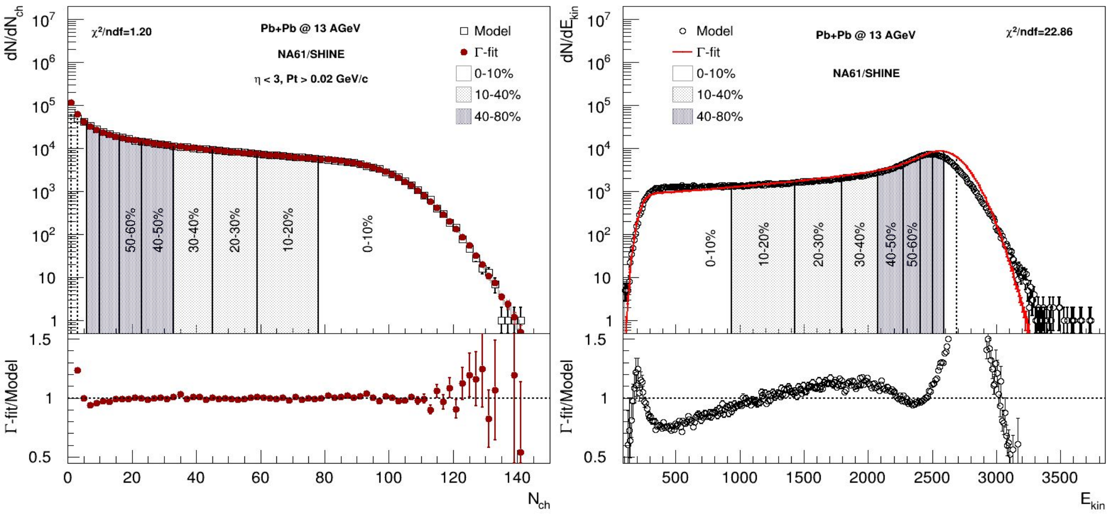


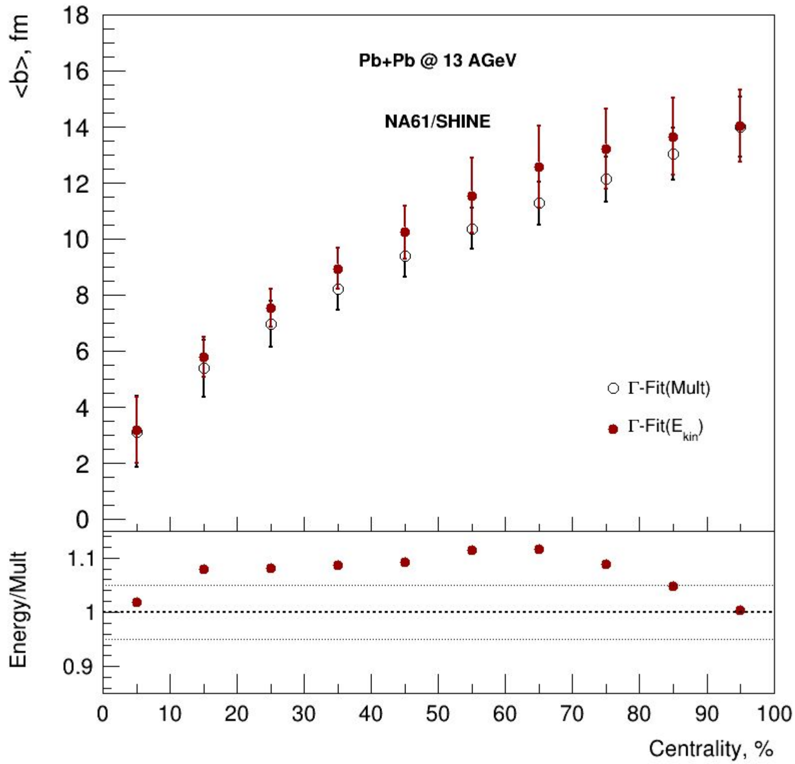


Segal I. Particles. 2023; 6(2):568-579.

- 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

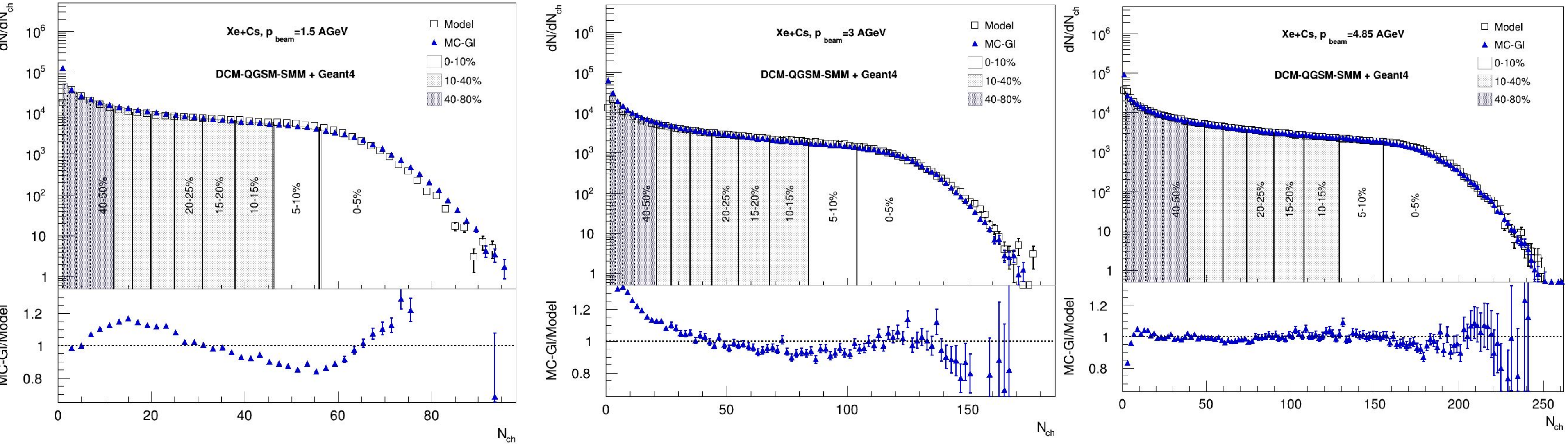
Centrality determination using inverse Bayes approaches





- Centrality determination based on spectator energy using inverse Bayes approach is being developed and tested on model (UrQMD, DCM-QGSM-SMM) and NA61/SHINE data
- Application of centrality determination based on spectator energy using MC-Glauber and inverse Bayes approaches is in progress
- Possible improvements are under investigation

Result of the fitting



NBD at different values of k