Centrality determination in heavy-ion collisions with Monte-Carlo sampling procedure for spectators energy

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for the MPD Collaboration

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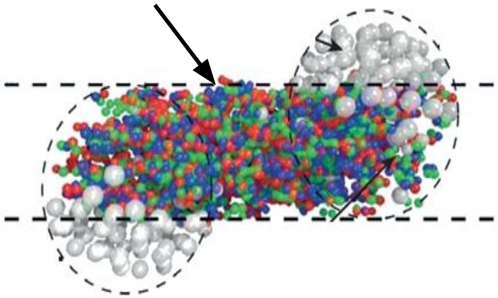
Motivation for centrality determination

- 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



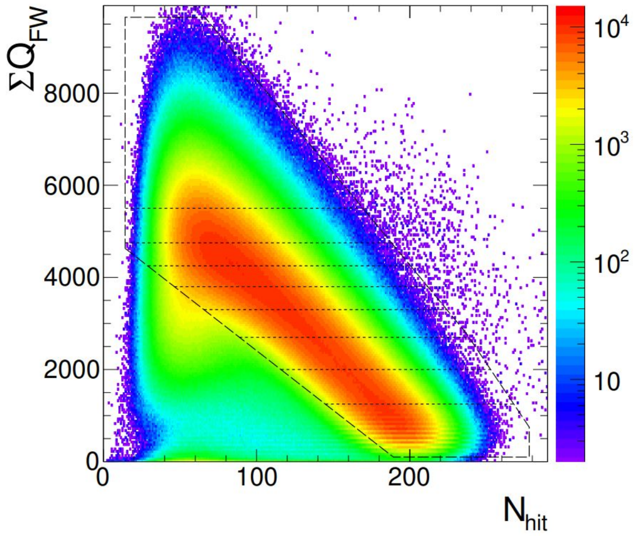
- Centrality class S_1-S_2: group of events corresponding to a given fraction (in %) of the total cross section:

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

Why several alternative centrality estimators

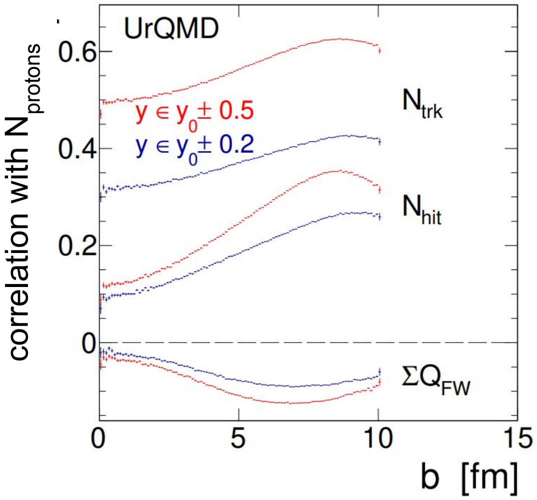
Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

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

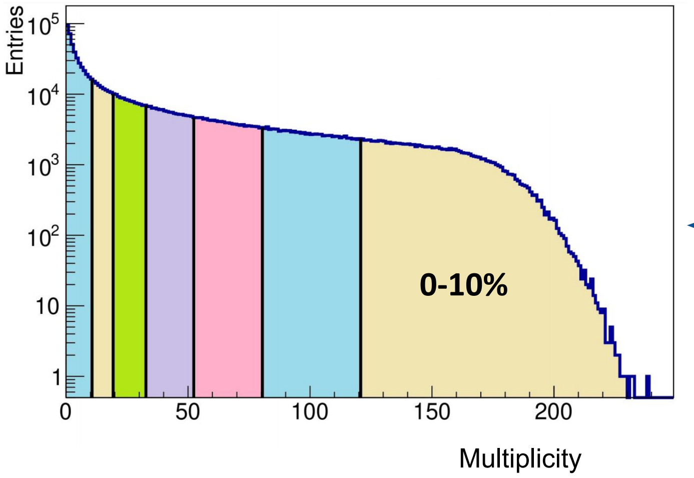


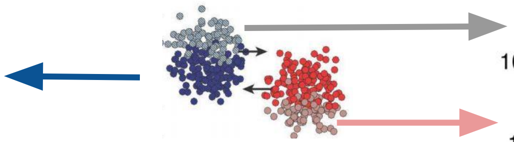
Avoid self-correlation biases when using spectators fragments for centrality estimation

Types of centrality estimators

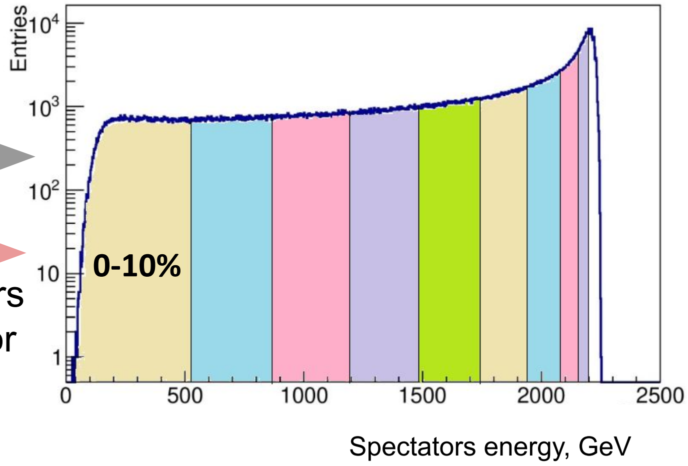
Produced charged particles

Spectators





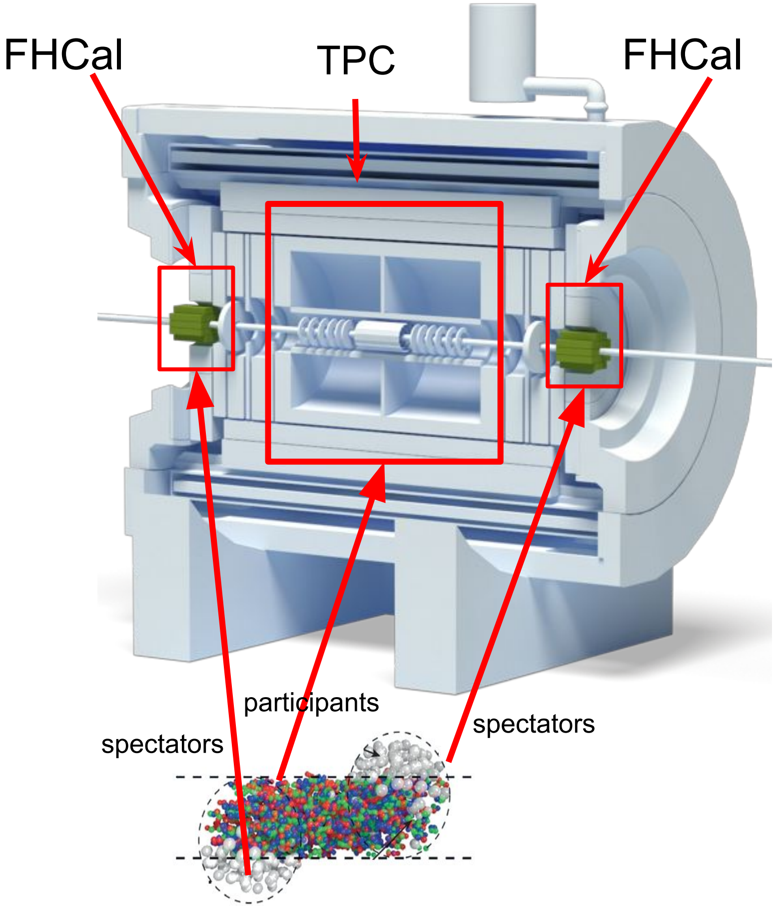
(Target spectators not measured for fixed-target)



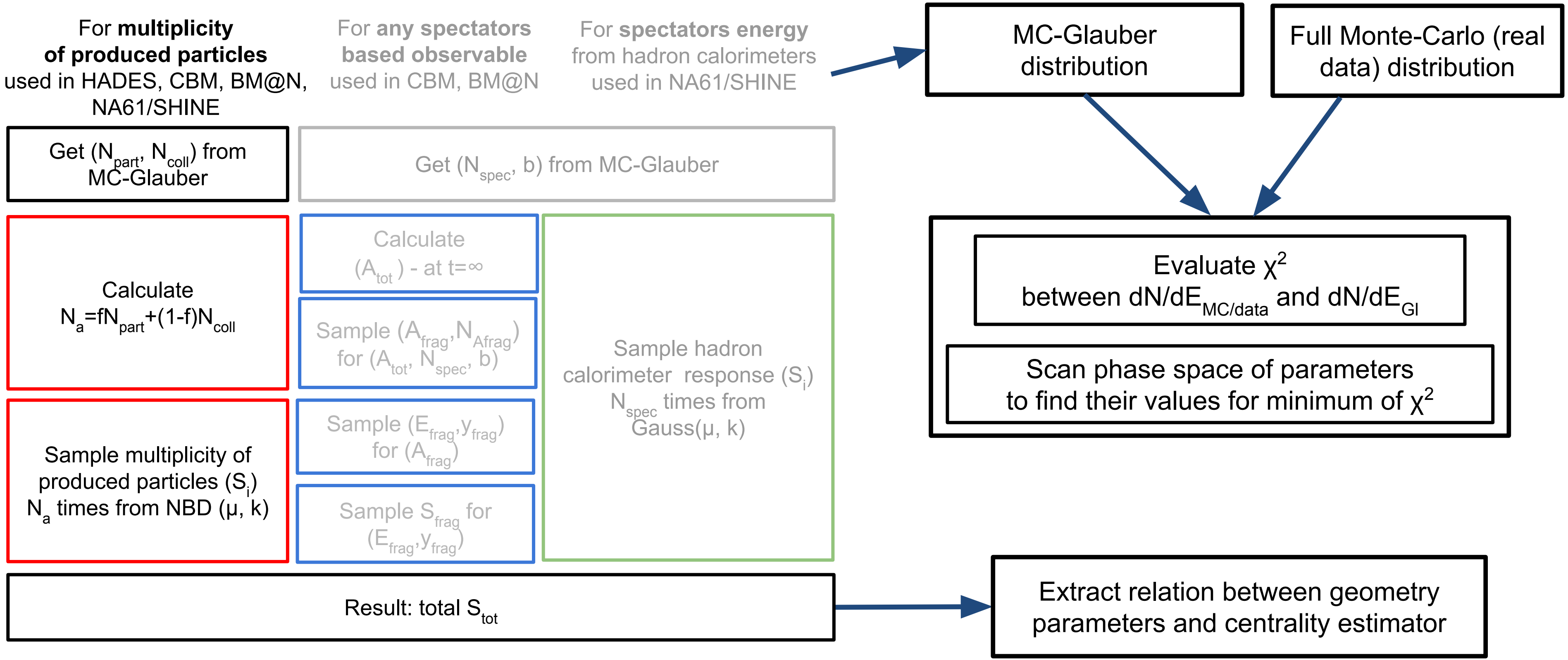
MPD experimental setup

Subsystems for centrality determination

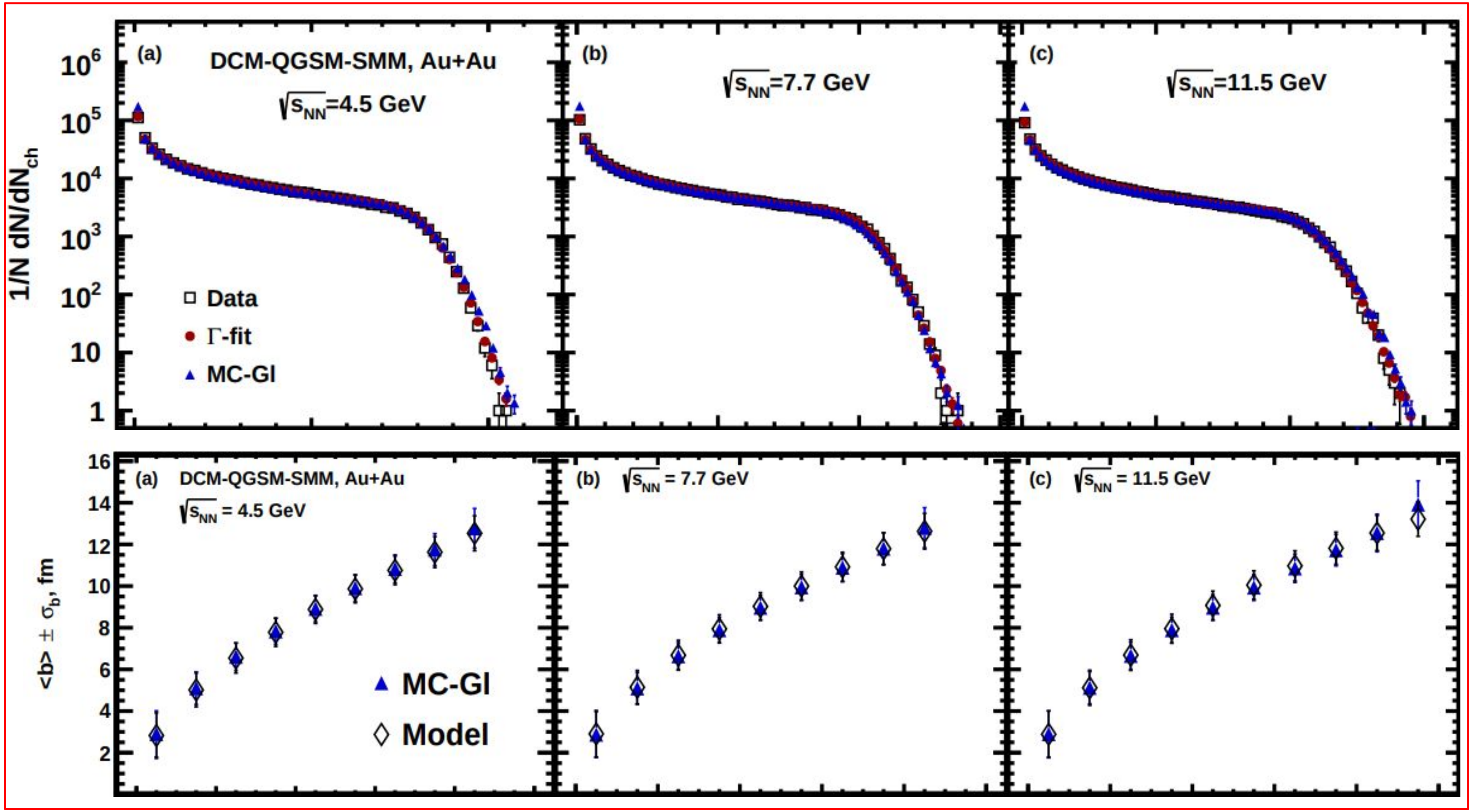
- Produced particles multiplicity: TPC
- Spectators energy: FHCal



Centrality determination based on Monte-Carlo sampling



Standard MC sampling for produced particles

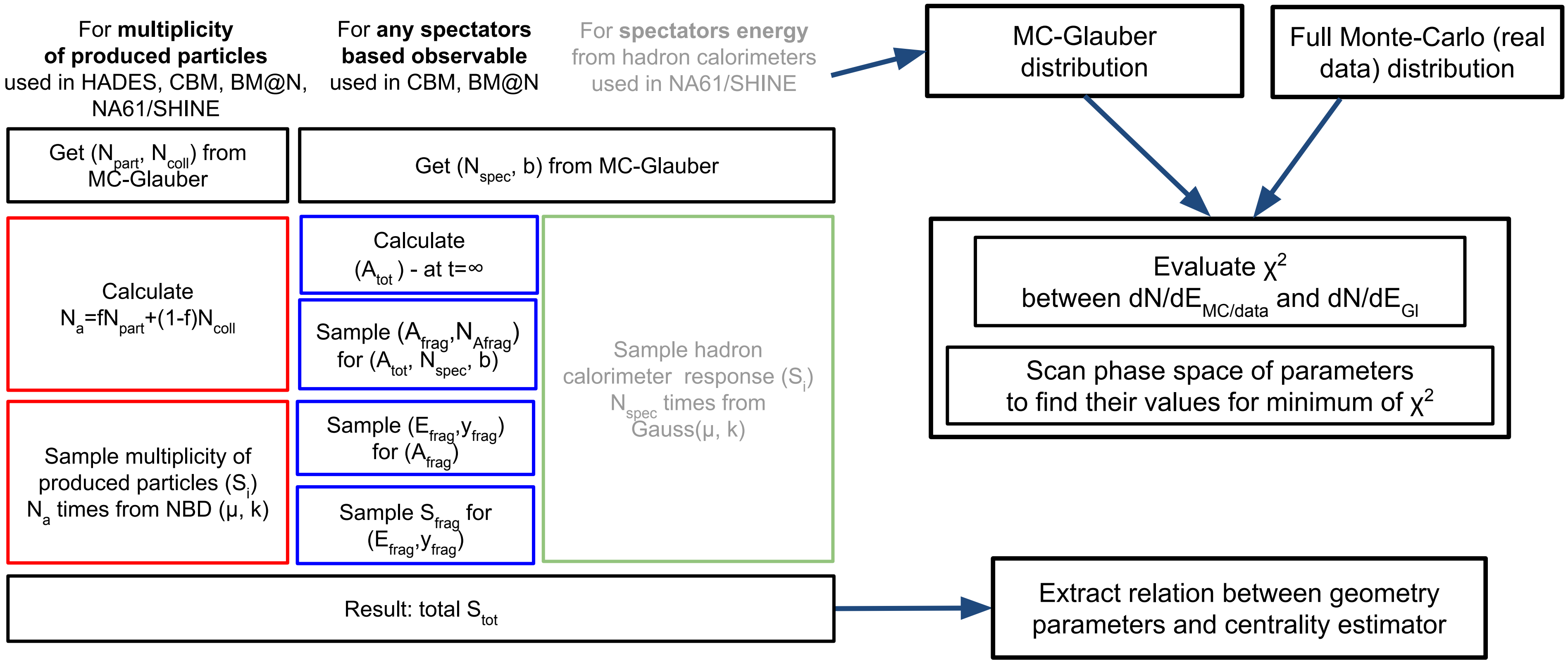


D.Idrisov et al. Moscow Univ.Phys.Bull. 77 (2022) 2, 206-207

Implementation for MPD: https://github.com/FlowNICA/CentralityFramework

- Standard procedure based on multiplicity is implemented
- It was tested for Monte-Carlo
- Possibilities of improvement of this procedure under investigation

Centrality determination based on Monte-Carlo sampling



NA61/SHINE experimental setup

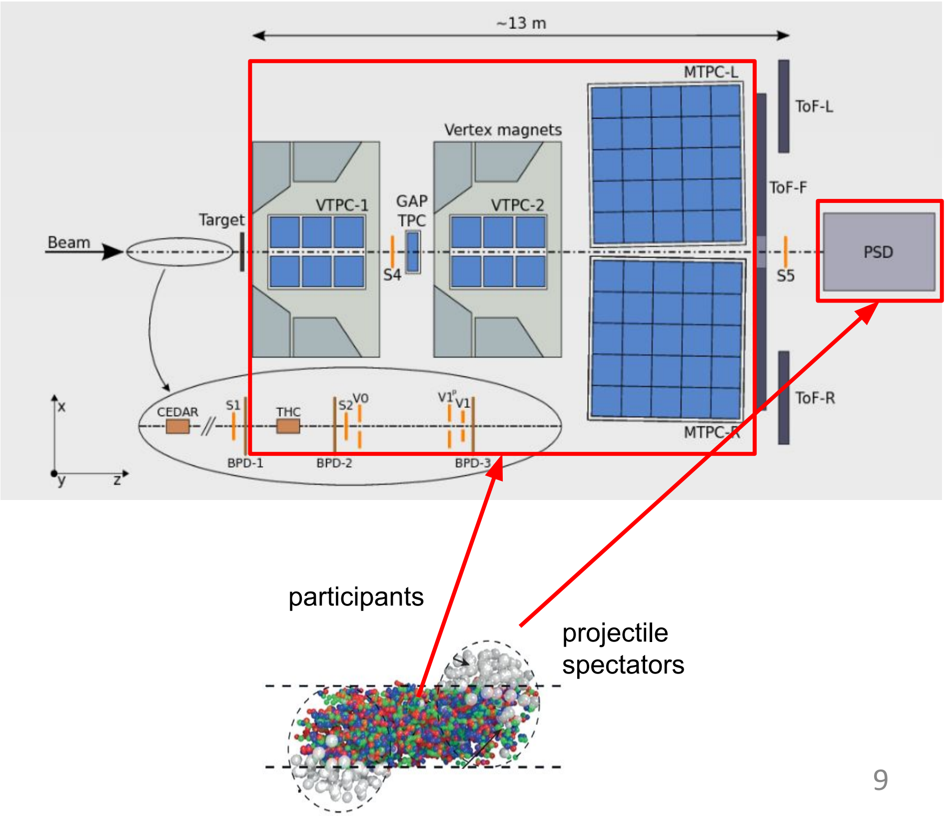
Data samples:

- Pb-Pb @ p_{beam} = 13A GeV/c
- data from 2016 physics run
- DCM-QGSM-SMM x Geant4

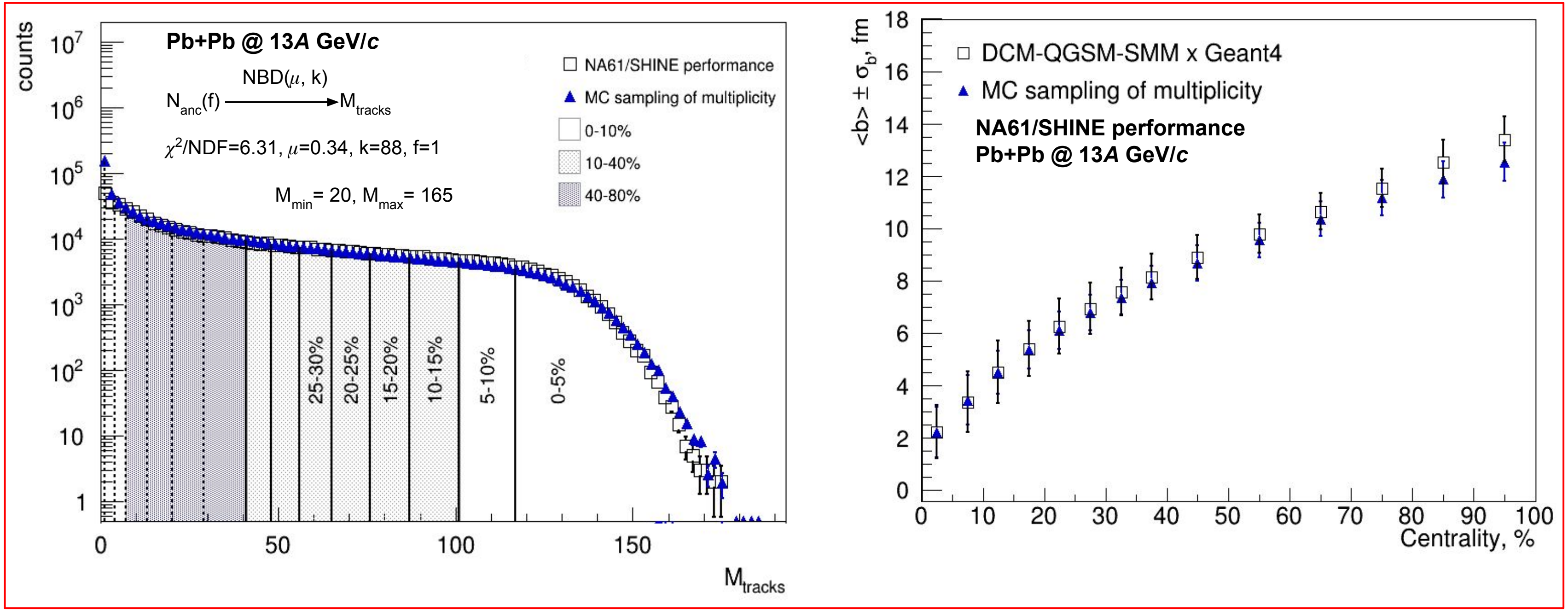
  M.Baznat et al. PPNL 17 (2020) 3, 303

Subsystems

- Multiplicity: TPCs (p_T>0.05, η<3.5)
- Spectators energy: PSD

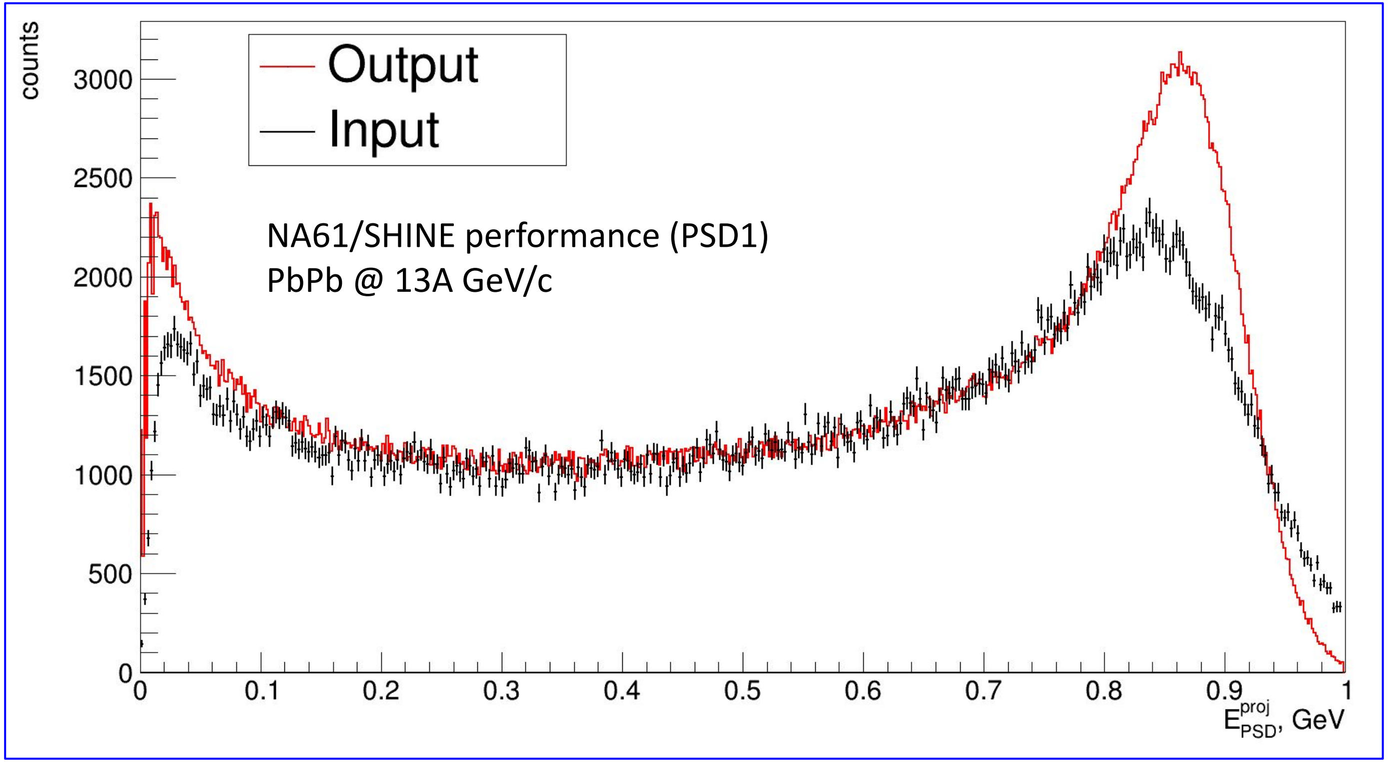


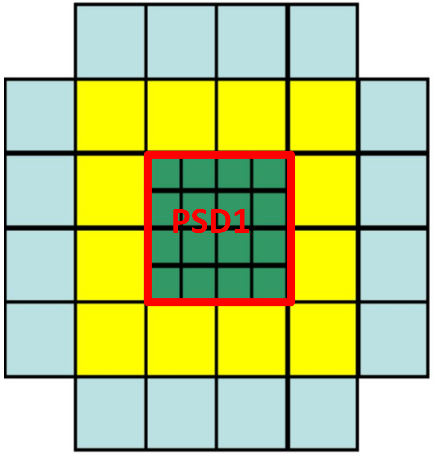
Standard MC sampling for produced particles



- Standard procedure based on the multiplicity of produced particles is also applicable for NA61
- Determined centrality classes is being used in physics analysis

Full MC sampling for spectators

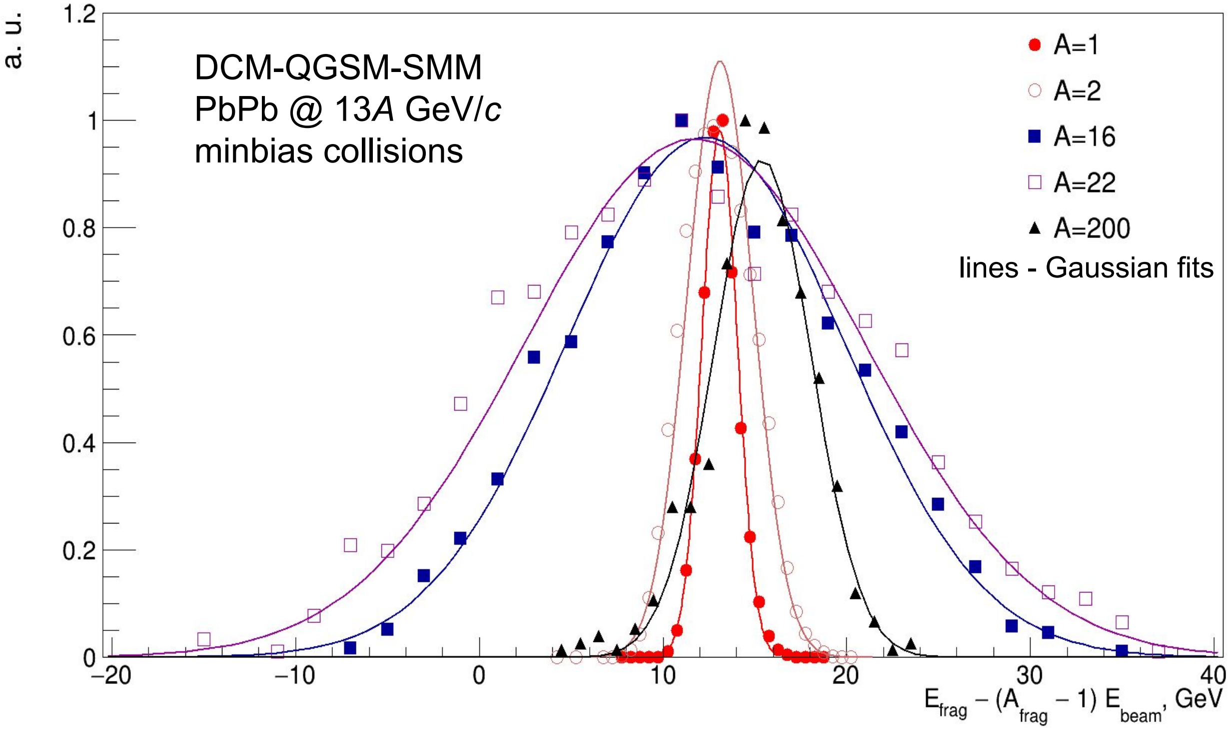




PSD detector layout

- Scaling along both X and Y axis is applied
- Form of energy distribution is reproducible

Gaussian approximation for fragments energy

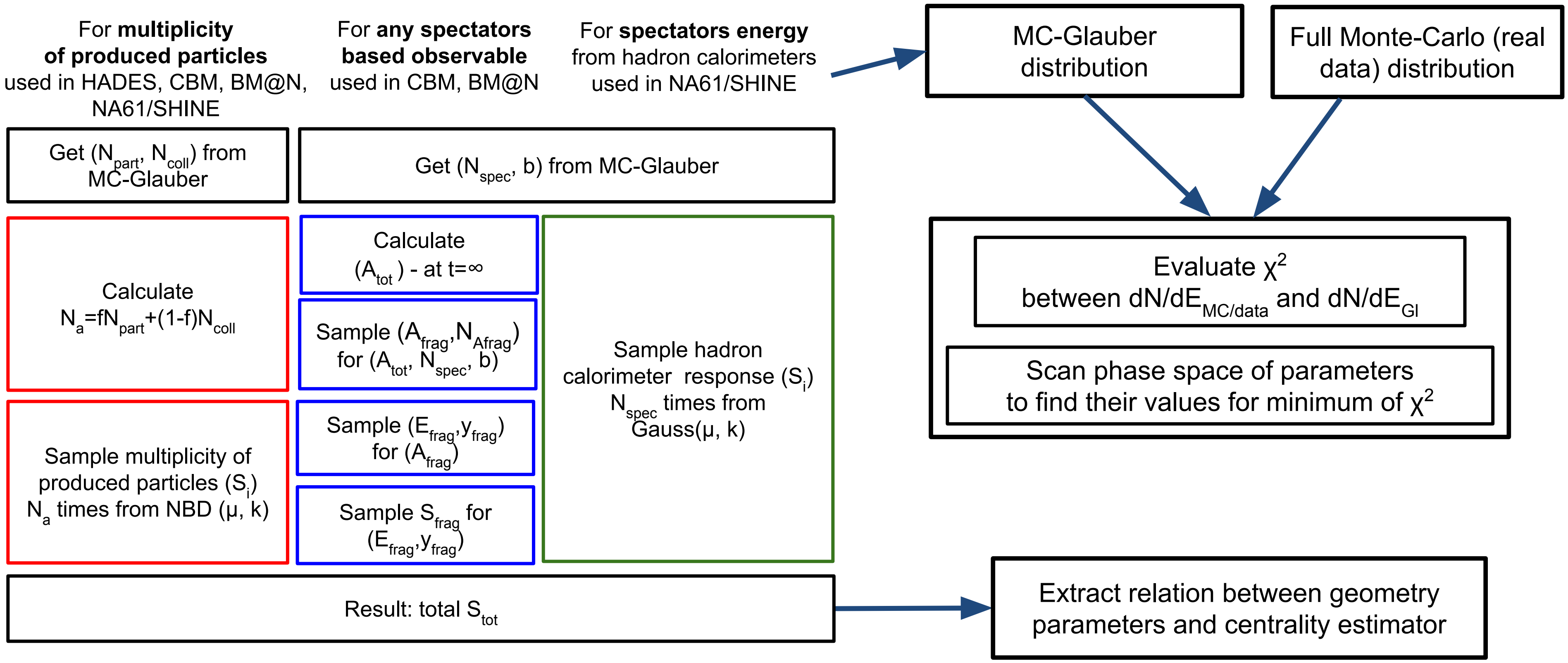


- Distribution of mass numbers of spectators fragments could be fitted by Gauss distribution
- Mean values equal to product of beam energy and fragment's mass
- Total spectators energy distribution is also Gauss:

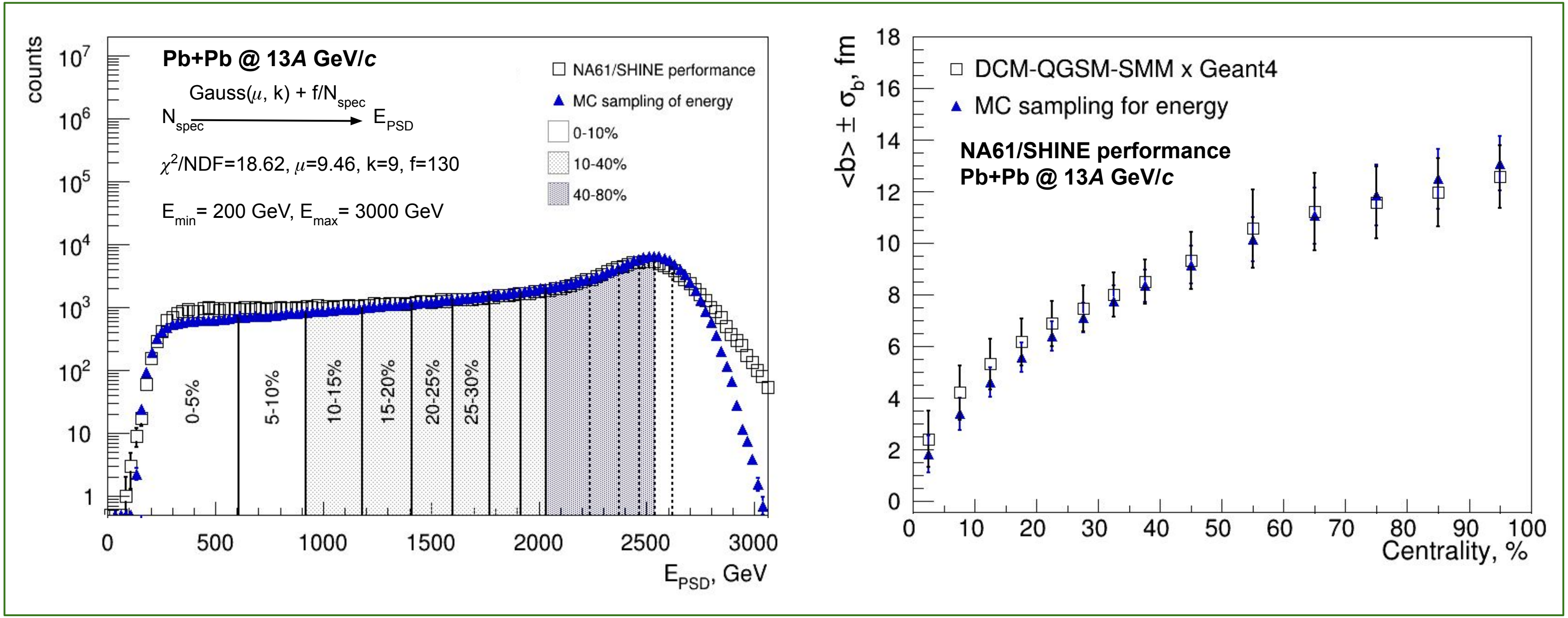
$$P(E_{tot}; \mu_{tot}, k_{tot}) \approx \prod_{i=1}^{N_{frag}} P(E^i_{frag}; \mu^i_{frag}, k^i_{frag}) \approx \prod_{j=1}^{N_{spec}} P(E^j_{spec}; \mu_{spec}, k_{spec})$$

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

Centrality determination based on Monte-Carlo sampling

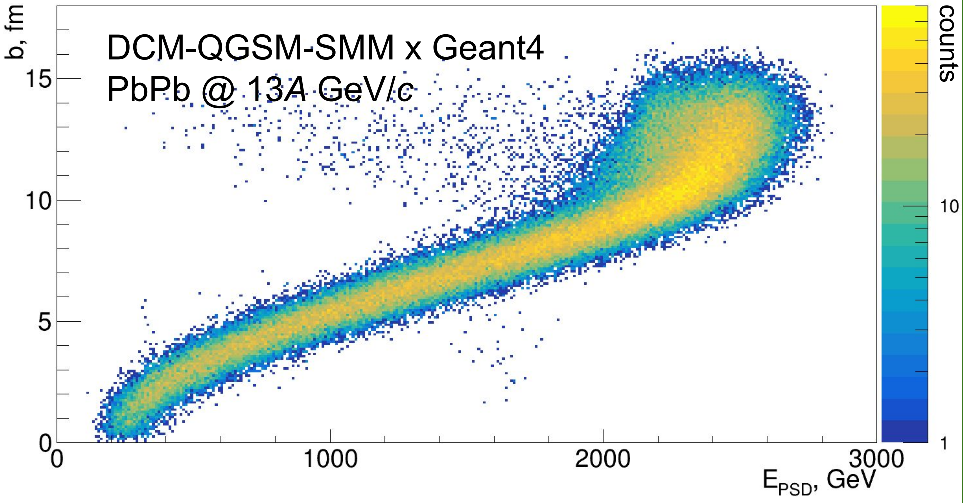


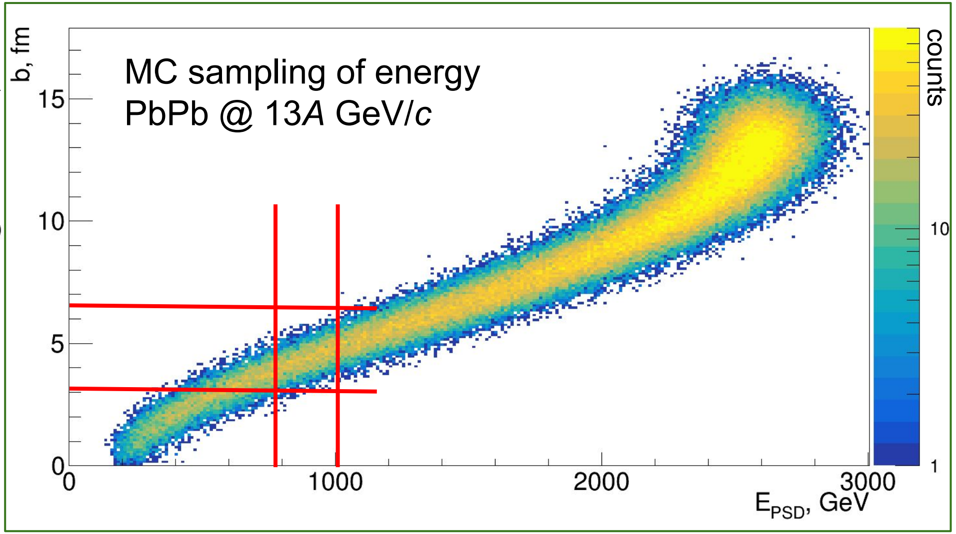
Simplified MC sampling for hadron calorimeters



- Simplified procedure for spectators energy is tested on NA61 data
- Gauss distribution can not reproduce energy distribution in the most central collisions
- Possible improvements are now under investigation

Simplified MC sampling for hadron calorimeters





- 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

Summary

- Software implementation of MC Glauber and multiplicity based fitting procedure is used for MPD
- Relation between impact parameter and centrality classes is extracted

- Centrality determination procedure based on MC sampling of spectators energy is developed and tested based on NA61/SHINE data
- Results are tuned on the spectator production implemented in the DCM-QGSM-SMM model
- Simplified procedure for hadron calorimeters based on Gauss distribution is also proposed

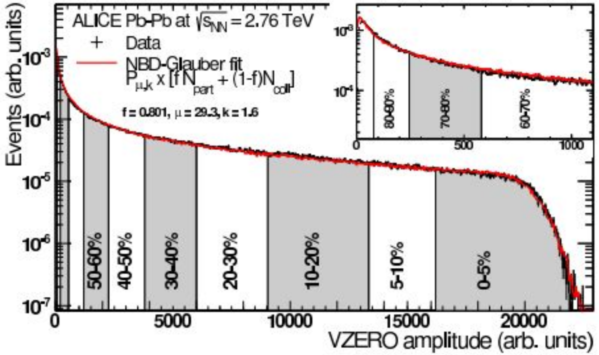
Work in progress

- Investigate the effect on centrality determination due to the fragment loss in beam hole of the MPD FHCal
- Introduce detailed parametrization for steps of centrality determination procedure and improve current parametrization
- Apply this procedure for MPD FHCal simulations

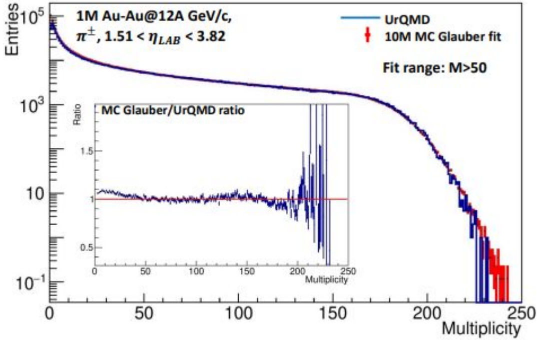
Backup

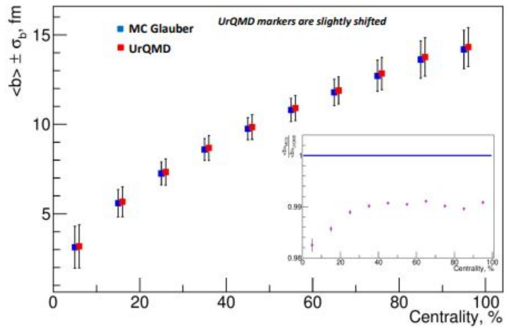
Why several alternative centrality estimators

ALICE; Phys.Rev.C 88 (2013) 4, 044909

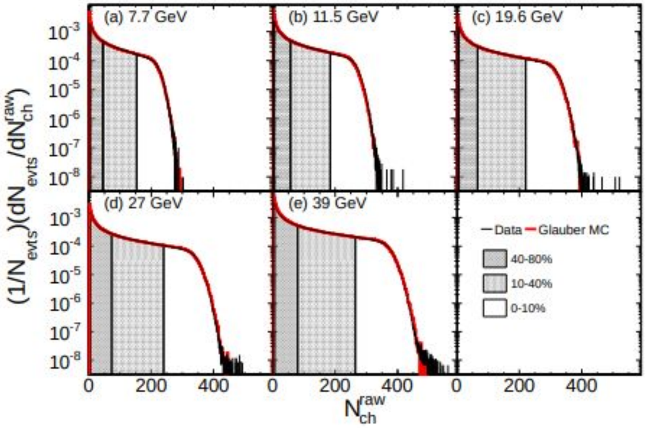


CBM; J.Phys.Conf.Ser. 1690 (2020) 1, 012107

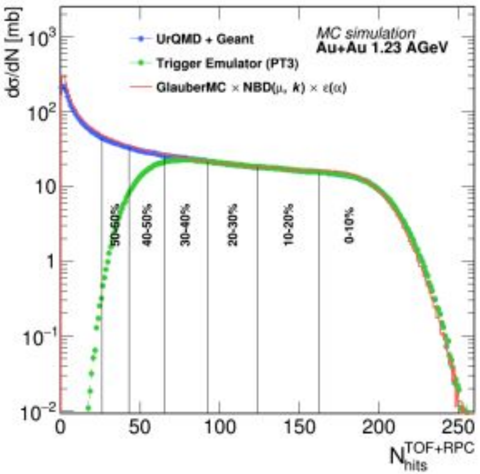




STAR; Phys.Rev.C 86 (2012) 054908



HADES; Eur.Phys.J.A 54 (2018) 5, 85



- MC-Glauber x NBD multiplicity fitting procedure is standard method for centrality determination
- MPD needs this method to compare data in the least experiment dependent way

MC Glauber model

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

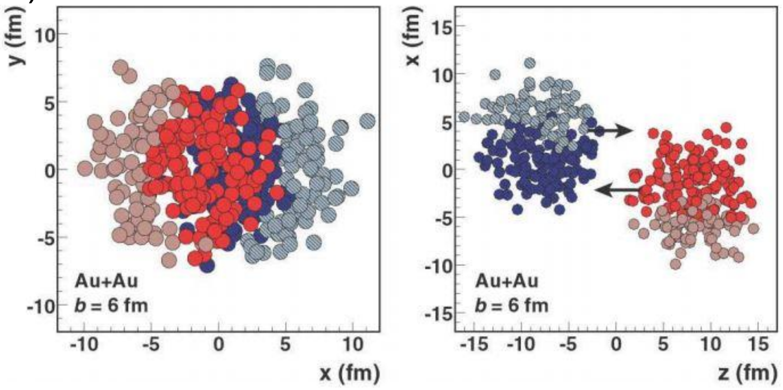
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

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

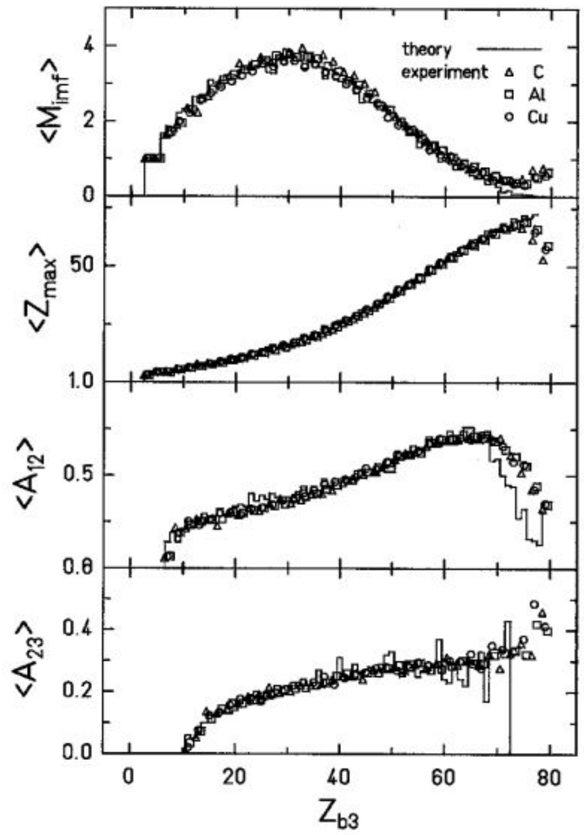
N_{part} – number of nucleons participating in the collision

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

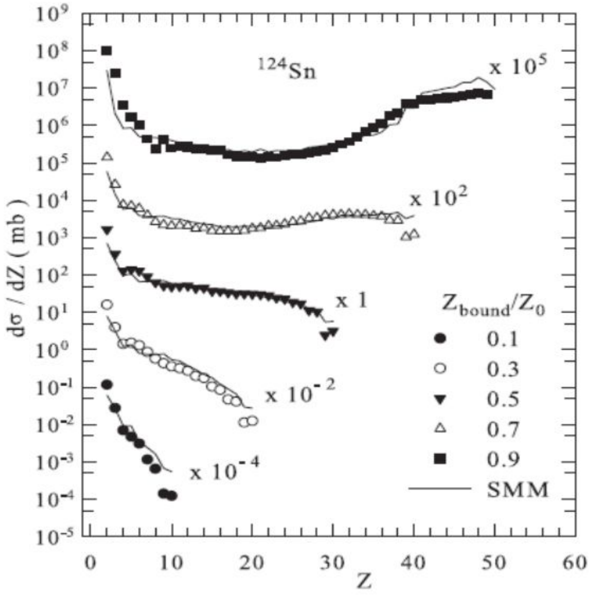
N_{coll} – number of binary NN collisions

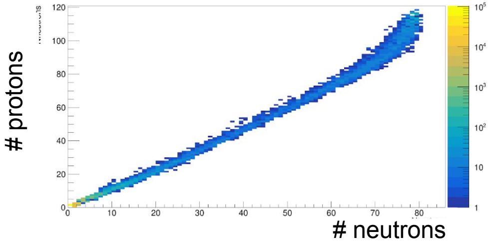
SMM description of the ALADIN's fragmentation data

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

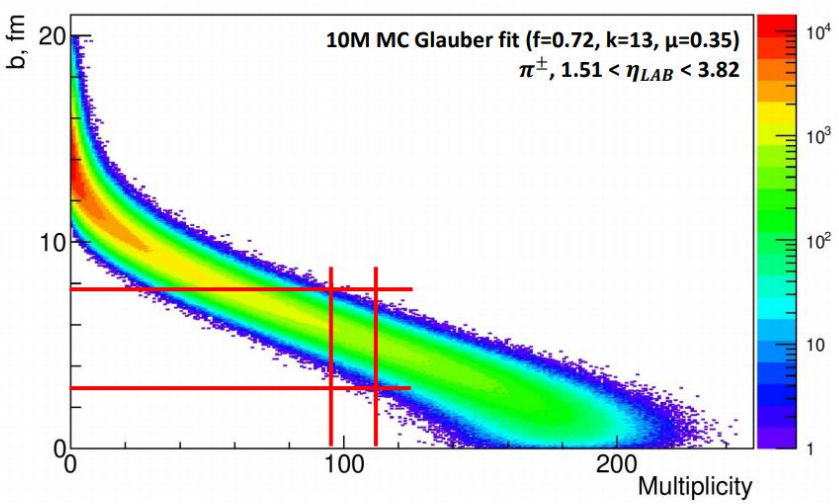


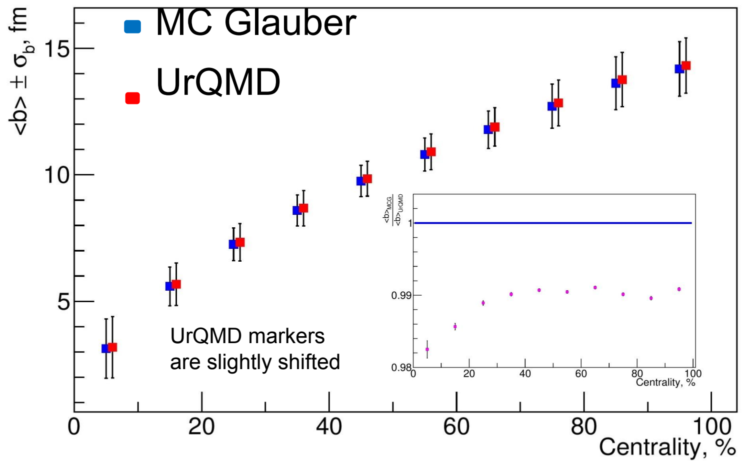
R.Ogul et al. PRC 83, 024608 (2011)





Centrality determination using STS multiplicity





Distribution provides connection between centrality class (multiplicity range, M ± ΔM) and impact parameter range (b ± σ_b)