Estimators study for centrality determination in the BM@N experiment

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for the BM@N Collaboration

MEPhI

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BM@N Collaboration meeting

Motivation

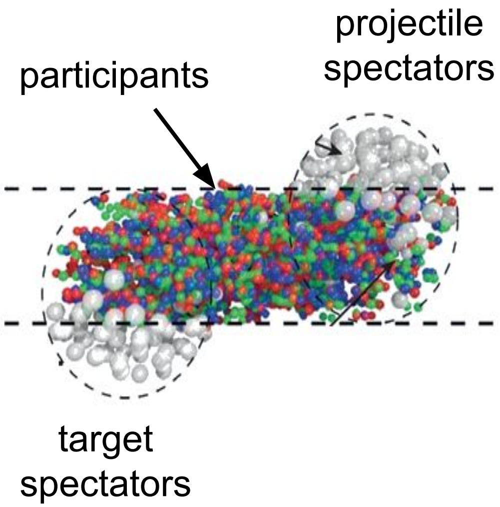
- Evolution of matter produced in heavy-ion collisions depends on its initial geometry

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

  - Glauber model is commonly used to build such connection
  - Model parameters are fixed by minimizing
    the difference between the model and real data distributions

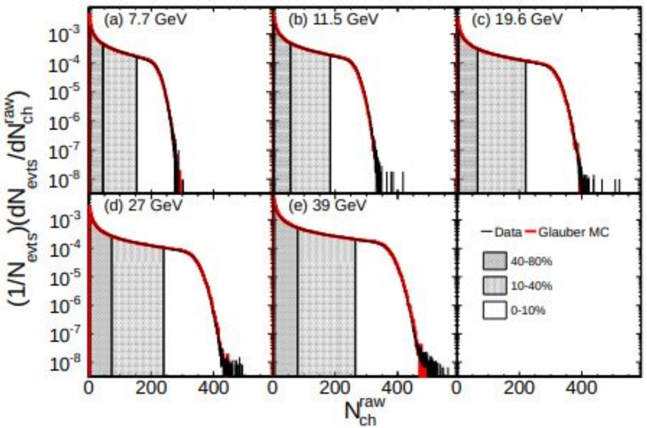
- Centrality class: group of events corresponding to
  a given fraction (%) of the total cross section:

$$C_b = \frac{1}{\sigma_{inel}^{AA}} \int_0^b \frac{d\sigma}{db'} db'$$

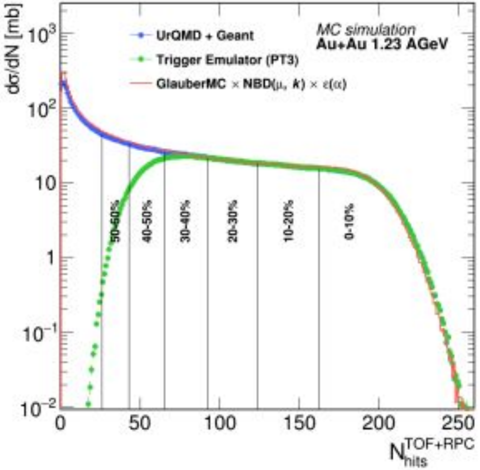


Why several alternative centrality estimators

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

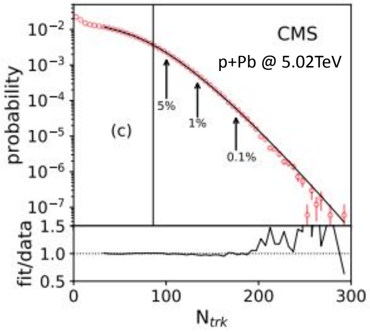


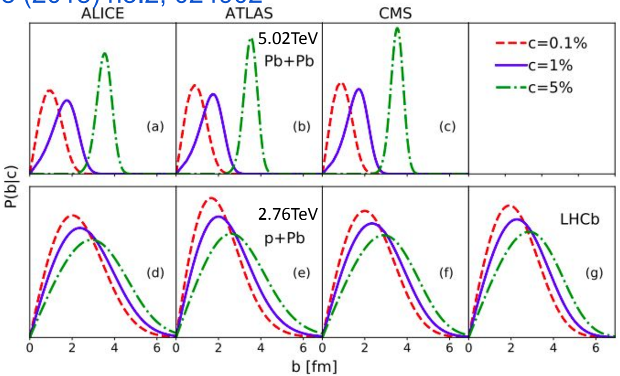
HADES; Eur.Phys.J.A 54 (2018) 5, 85



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

R. Rogly, G. Giacalone and J. Y. Ollitrault,
Phys.Rev. C98 (2018) no.2, 024902



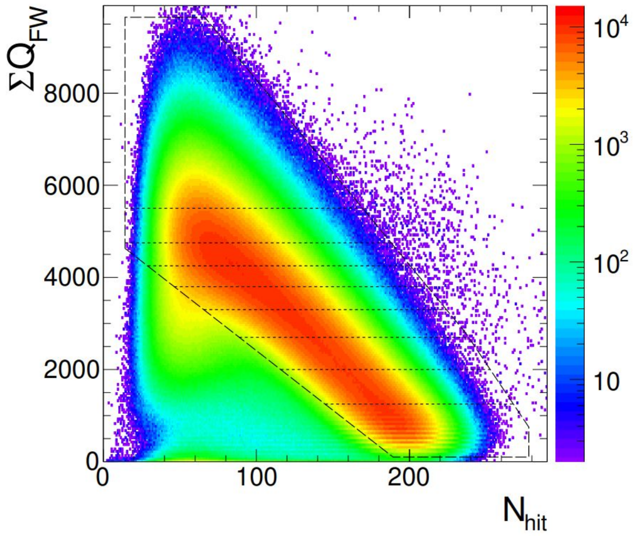


- Innovative Γ-fit method is also being considered for centrality determination based on multiplicity

Why several alternative centrality estimators

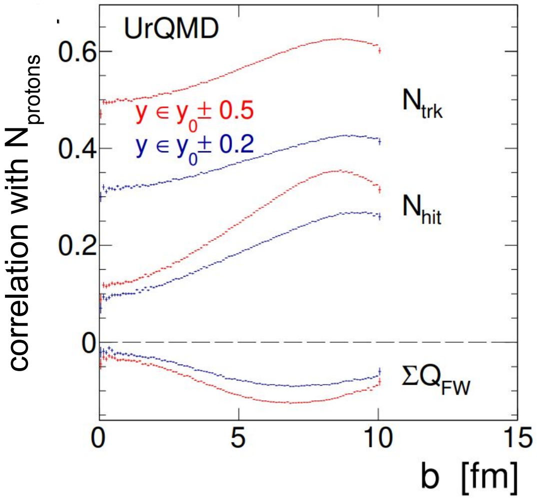
Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

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)

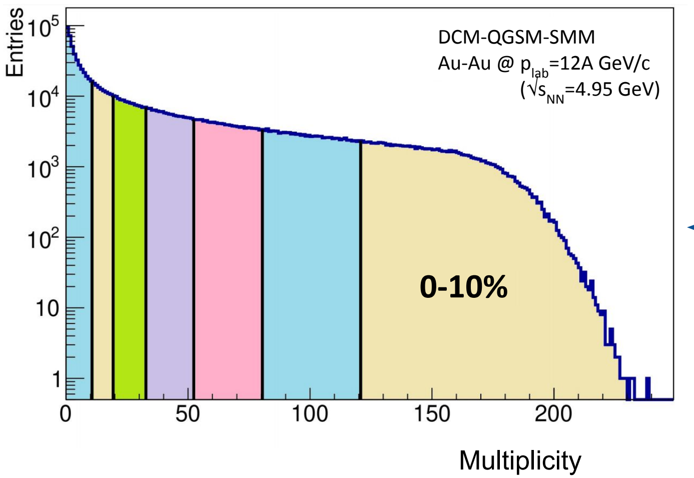
HADES; Phys.Rev.C 102 (2020) 2, 024914

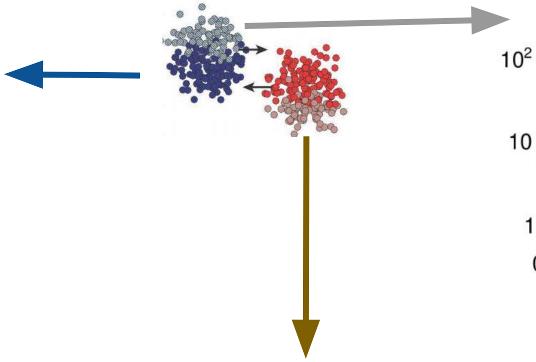


Avoid self-correlation biases when using spectators fragments for centrality estimation

Centrality Estimators in BM@N

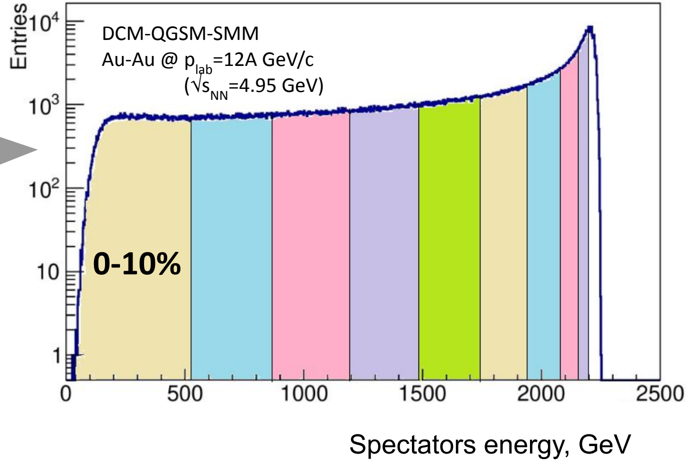
Produced charged particles





Target spectators
(not measured)

Projectile spectators



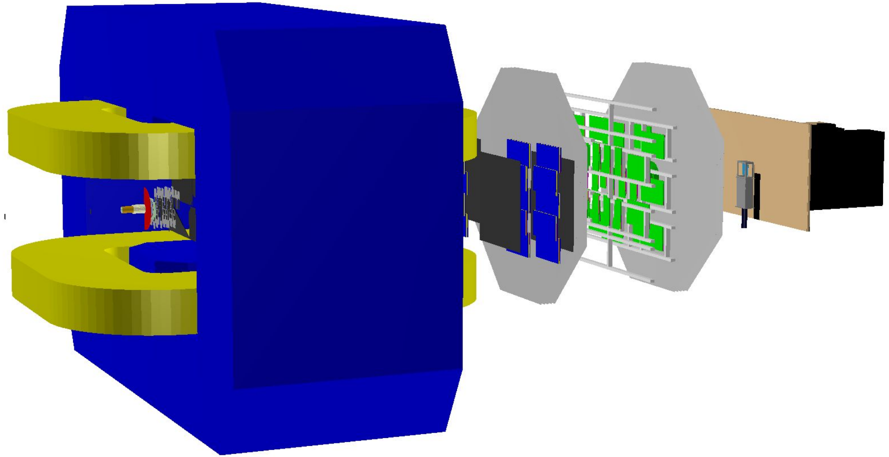
BM@N subsystems for centrality determination

Simulation setup

- DCM-QGSM-SMM

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

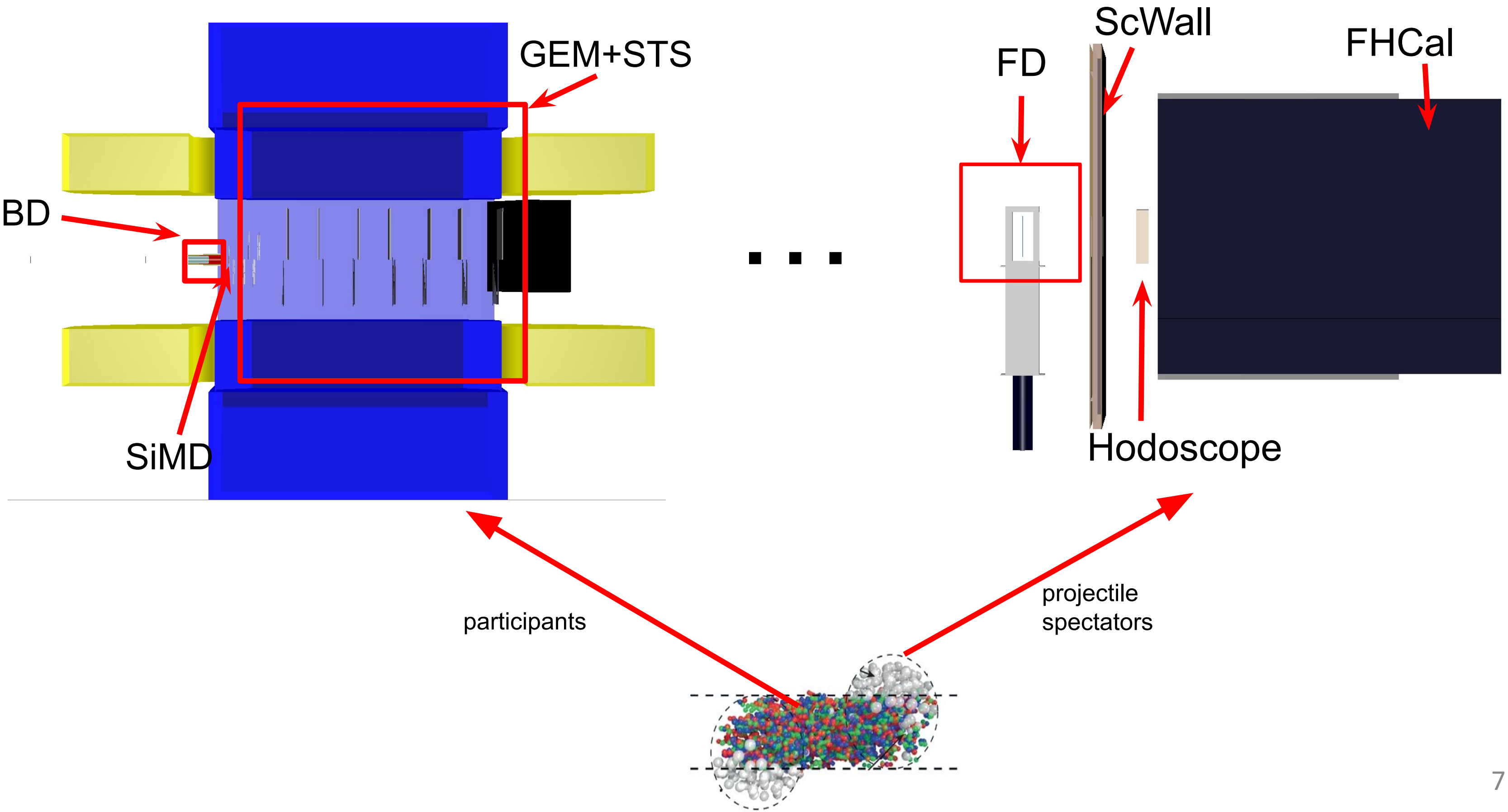
- Xe-Cs @ E_{kin} = 4*A* GeV
- Transport: GEANT4



Subsystems

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

BM@N subsystems for centrality determination

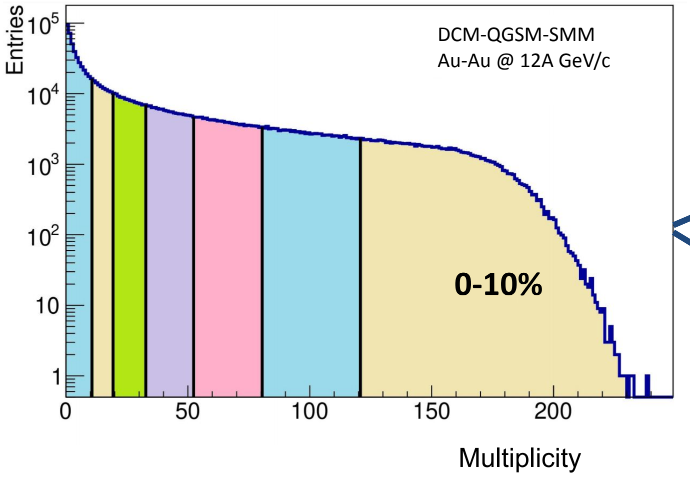


MC-Glauber + NBD fitting procedure

MC-Glauber
multiplicity distribution, dN/dM_{Gl}

Full Monte-Carlo (real data)
multiplicity distribution, $dN/dM_{MC/data}$

Produced charged particles



Extract relation between geometry parameters and multiplicity

Code repository: *https://git.cbm.gsi.de/pwg-c2f/analysis/centrality*

MC-Glauber + NBD fitting procedure

MC-Glauber
multiplicity distribution, dN/dM_{Gl}

Full Monte-Carlo (real data)
multiplicity distribution, $dN/dM_{MC/data}$

MC-Glauber calculations
for a set of fit parameters

Sample N_{part}, N_{coll} from MC-Glauber

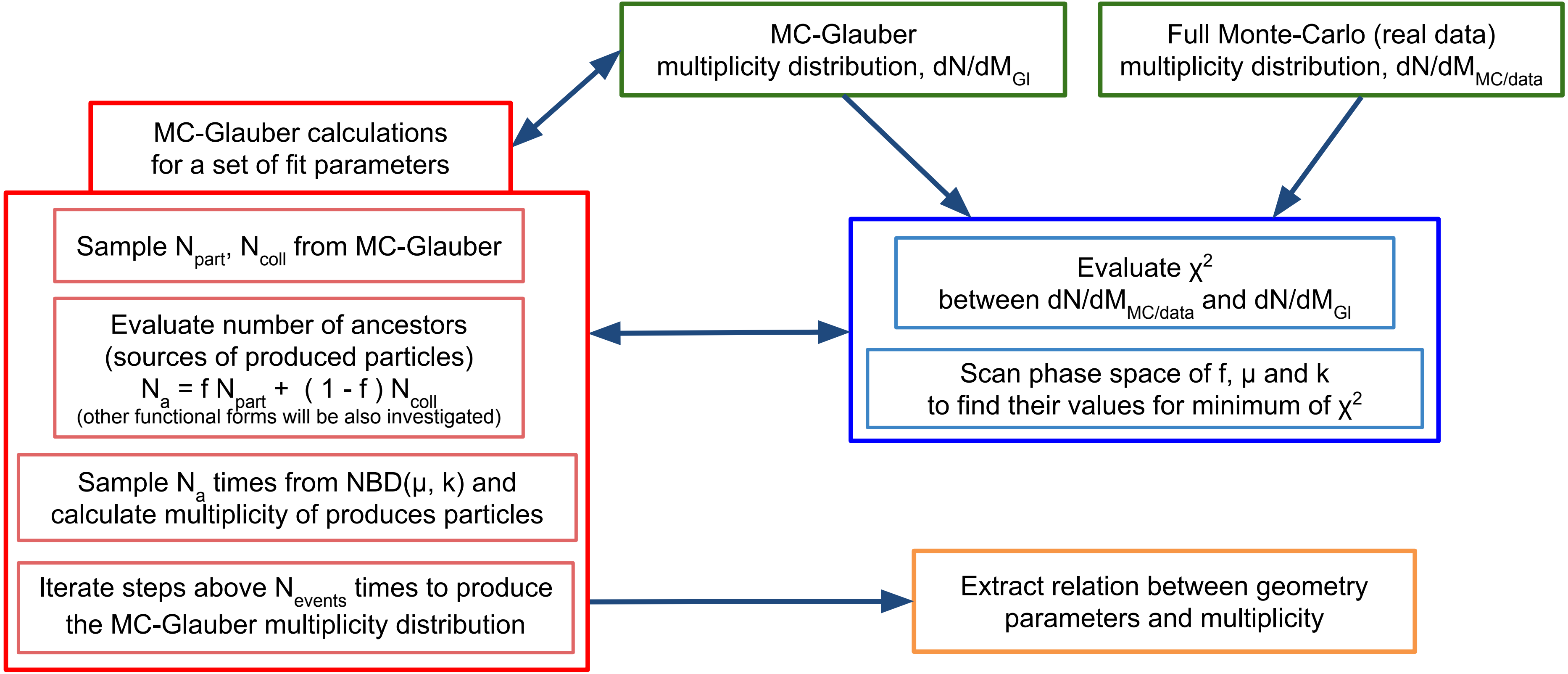
Evaluate number of ancestors
(sources of produced particles)
$N_a = f N_{part} + (1 - f) N_{coll}$
(other functional forms will be also investigated)

Sample N_a times from NBD(μ, k) and
calculate multiplicity of produces particles

Iterate steps above N_{events} times to produce
the MC-Glauber multiplicity distribution

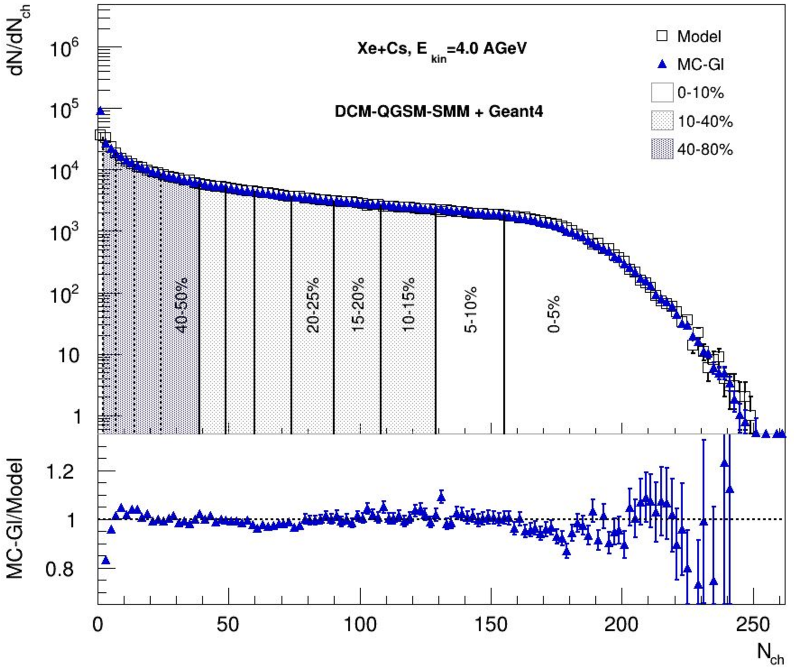
Extract relation between geometry
parameters and multiplicity

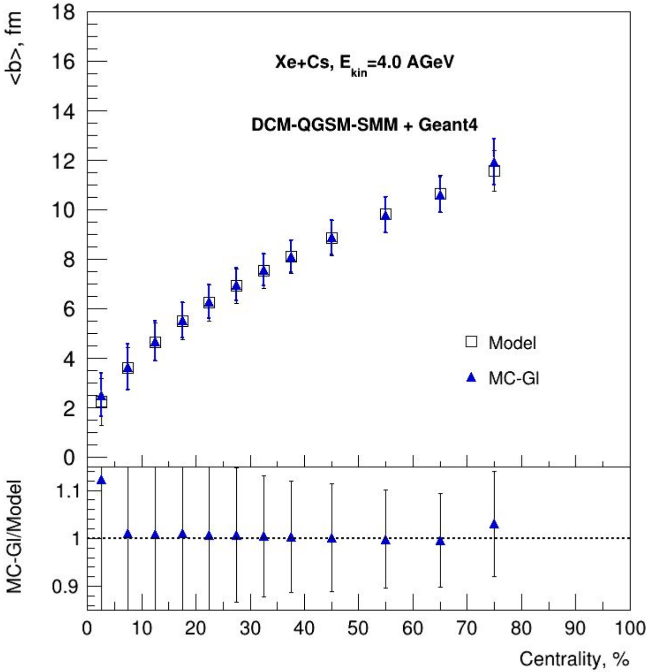
MC-Glauber + NBD fitting procedure



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

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

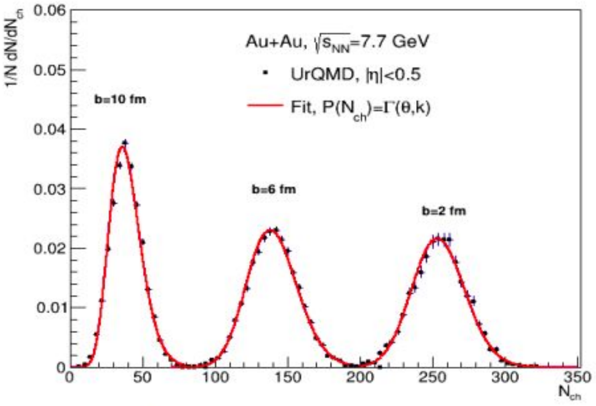
- Fit result is good
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM

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

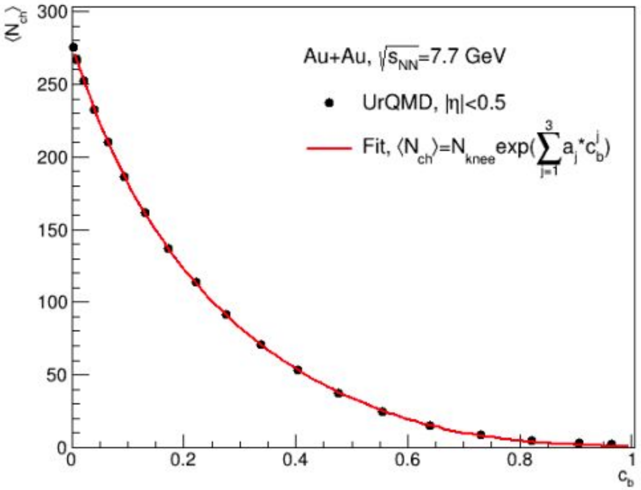
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

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

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

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

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

Five fit parameters N_{knee}, θ, a_j

Reconstruction of b

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

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

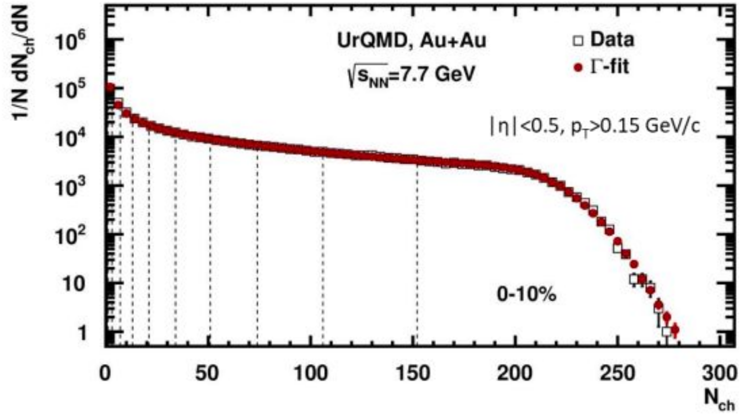
- Find probability of *b* for fixed range of N_{ch} using Bayes' theorem:

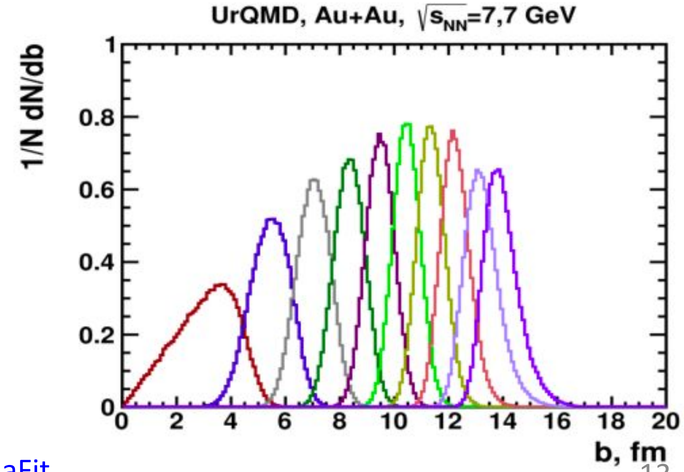
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(b|N_{ch})dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$

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

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

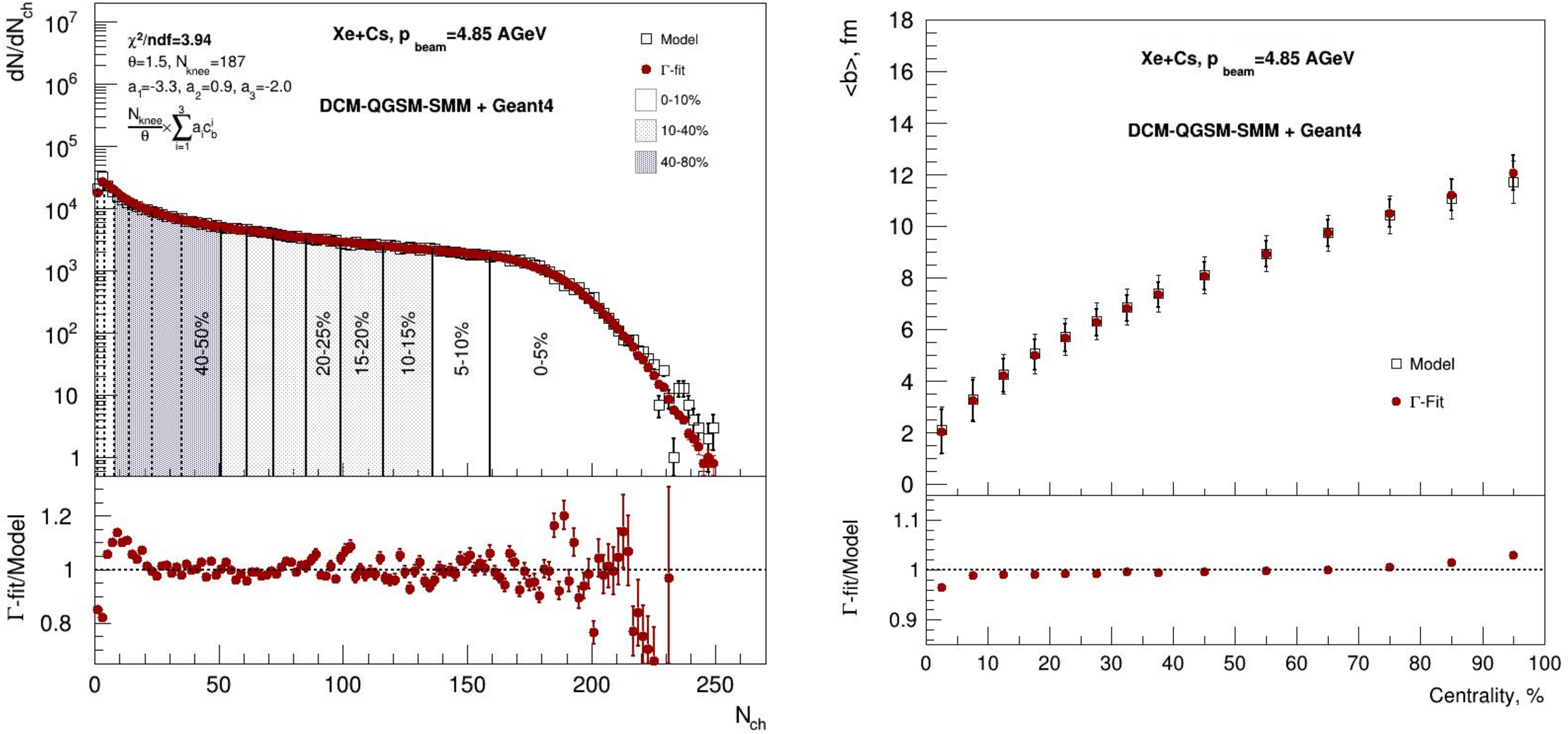
–Construct $P(b|N_{ch})$ using Bayes' theorem with parameters from the fit





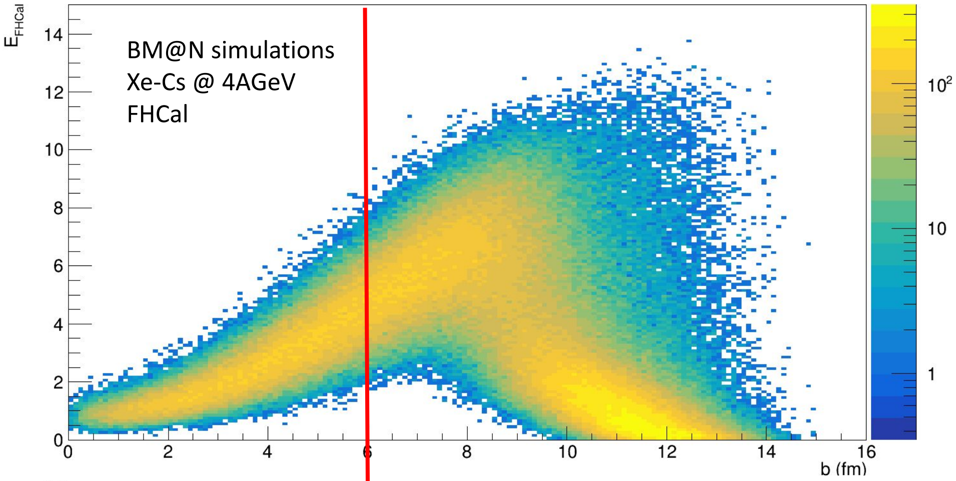
R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902
Implementation for MPD and BM@N by D. Idrisov: https://github.com/Dim23/GammaFit

MC-Glauber Γ-fit result Xe-Cs @ 4.0 AGeV

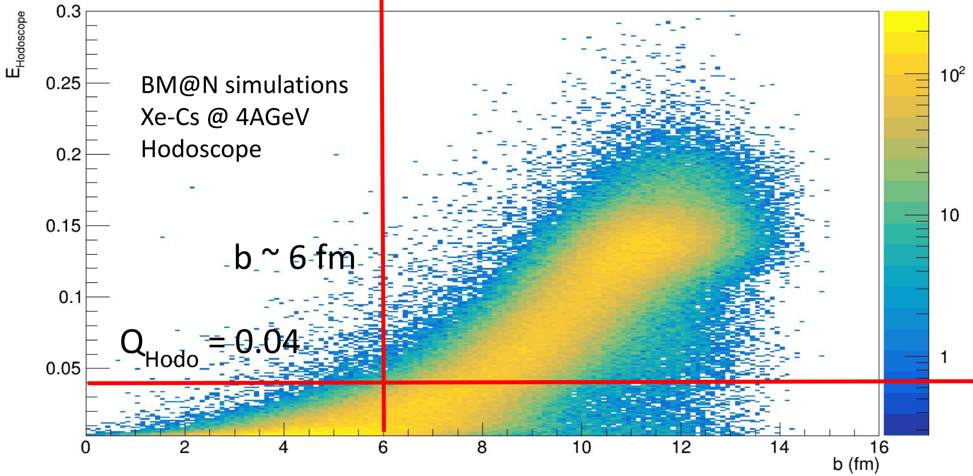


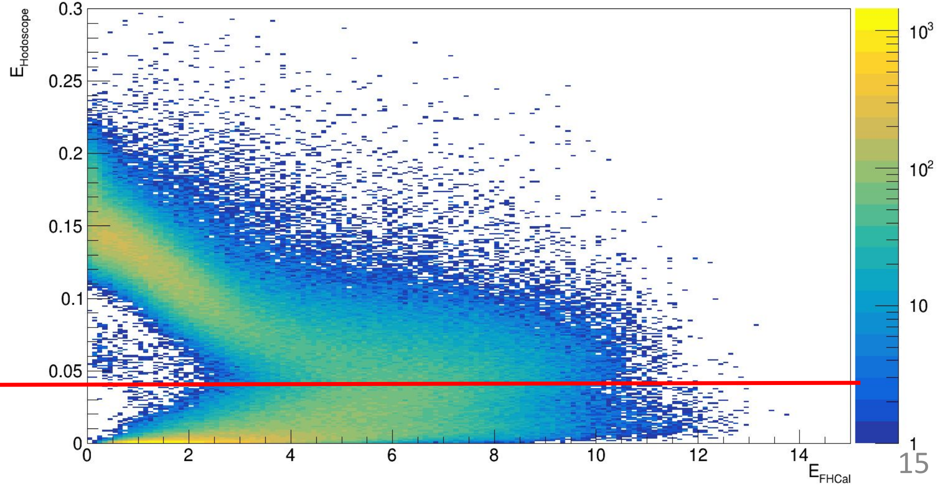
- Fit result is good
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM

Possibilities of spectators fragments as estimators

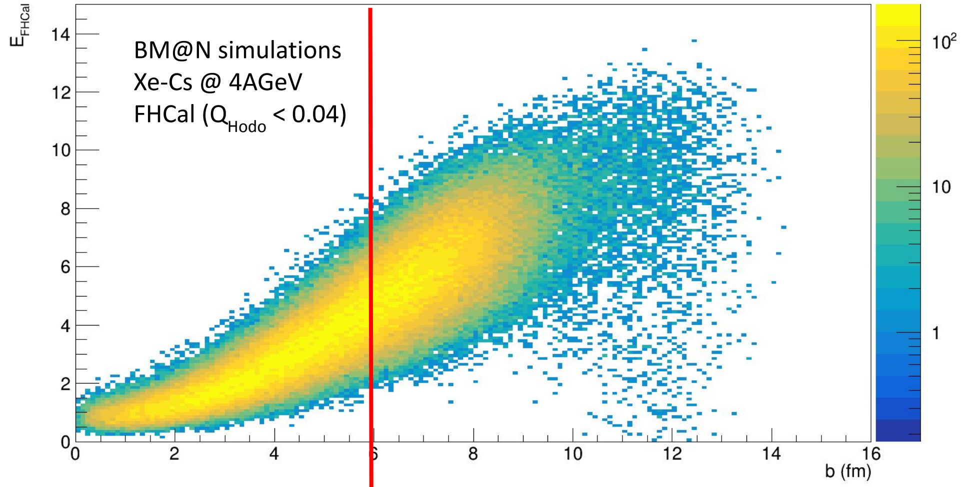


- FHCal energy and Hodoscope charge distributions have partial correlation with impact parameter
- For example, impact parameter at 6 fm might be used as threshold for simulations
- Corresponding physical threshold could be Hodoscope signal Q_{Hodo} = 0.04



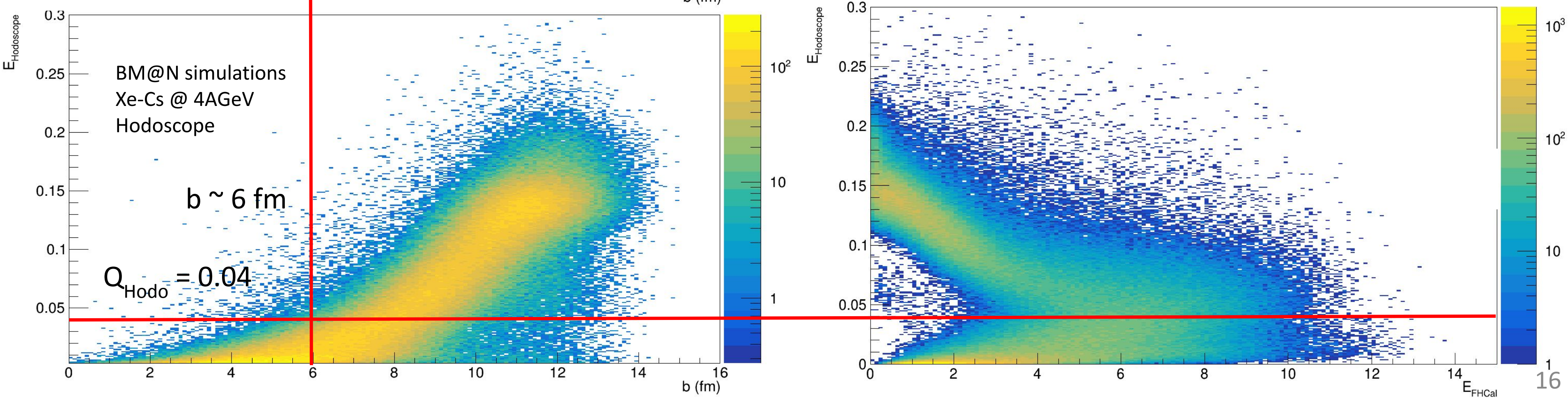


Possibilities of spectators fragments as estimators

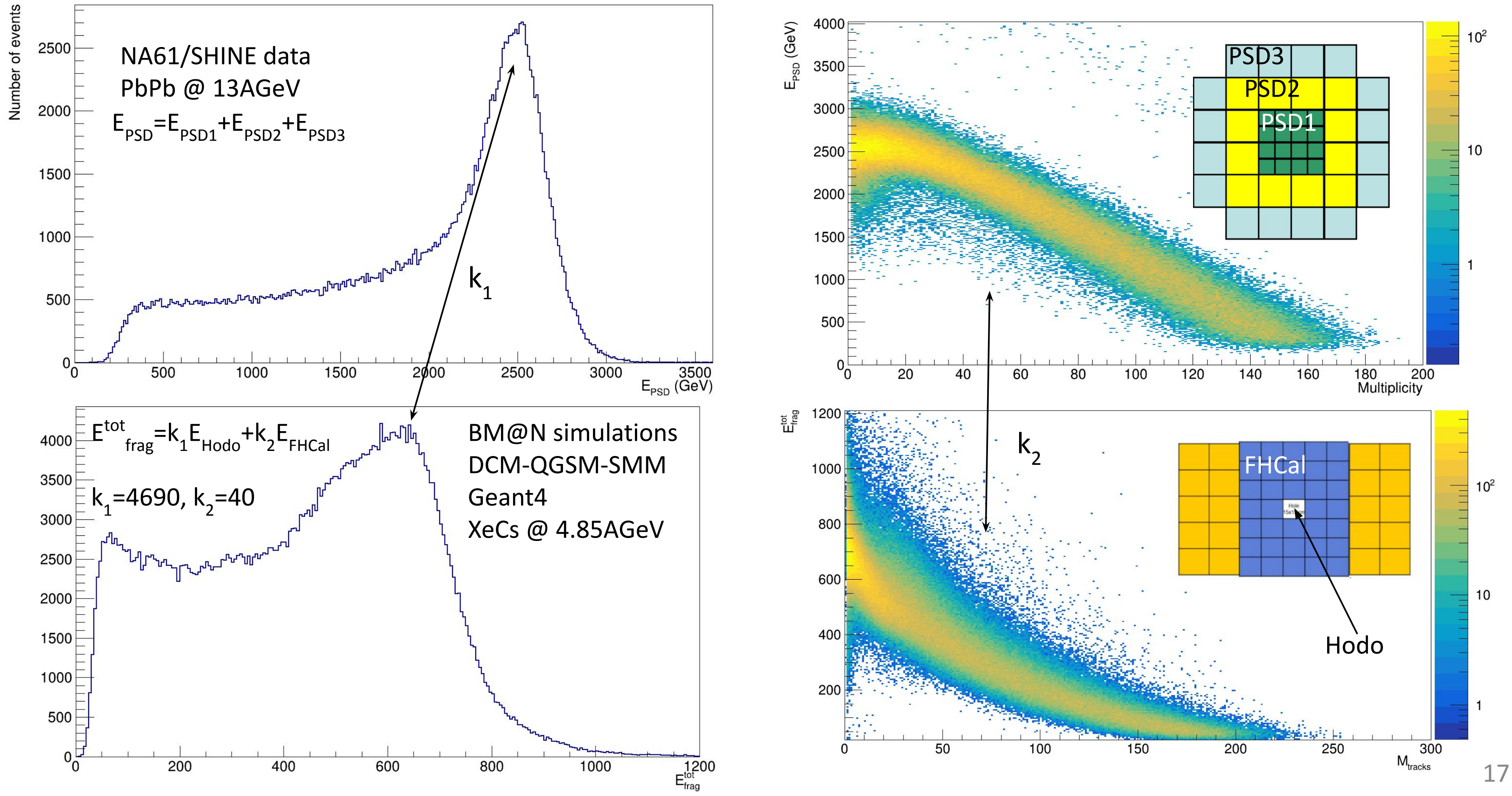


- FHCal energy distribution improved and has more linear correlation with impact parameter (for range $Q_{Hodo} < 0.04$)

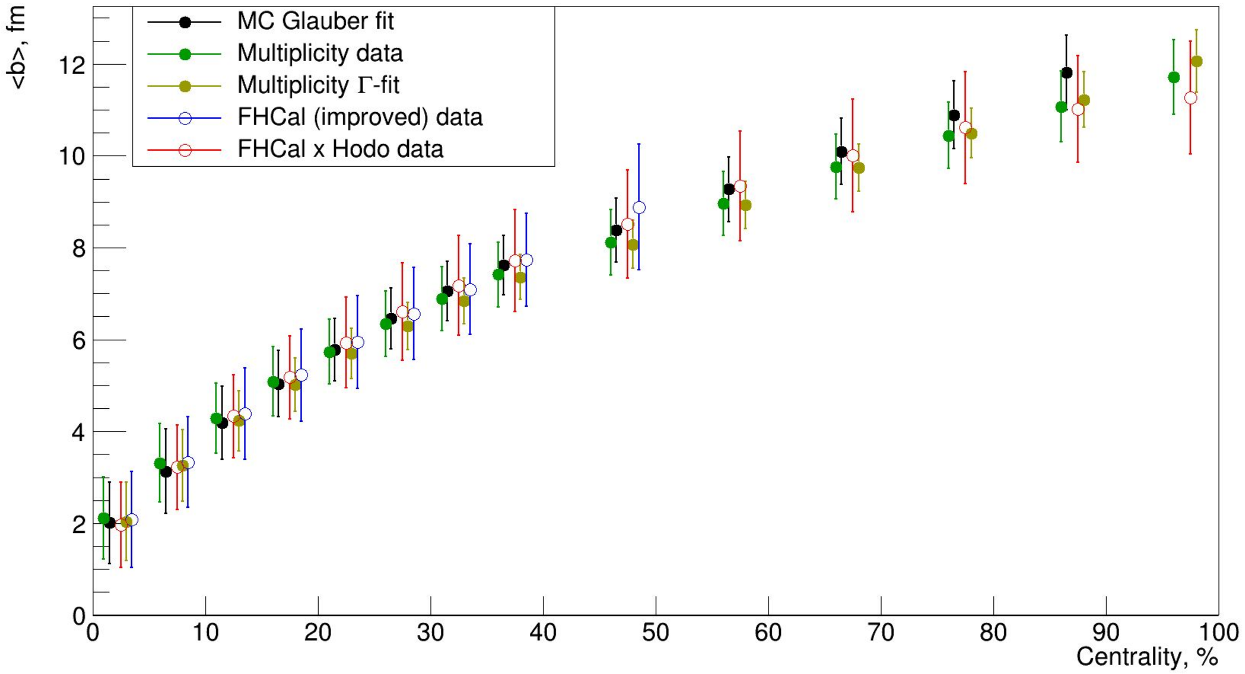
- There is good correlation between Hodoscope charge and impact parameter (for range $Q_{Hodo} > 0.04$)



Possibilities of spectators fragments as estimators



Comparison of different estimators and methods



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

Summary

- MC Glauber and inverse bayesian fitting procedures are developed for multiplicity
- Relation between impact parameter and centrality classes is extracted
- Software implementation of the procedure is ready and also used in MPD

- Possibilities of using of forward detectors for centrality determination was studied
- Main tasks was detected: improvement of the width of impact parameter and energy distributions, validation of FHCal x Hodoscope energy distribution

Work in progress

- Apply centrality determination procedures based on multiplicity
  for simulations of lower energies collisions
- Continue work on preparing of centrality determination procedure based on spectators energy

Backup

MC Glauber model

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

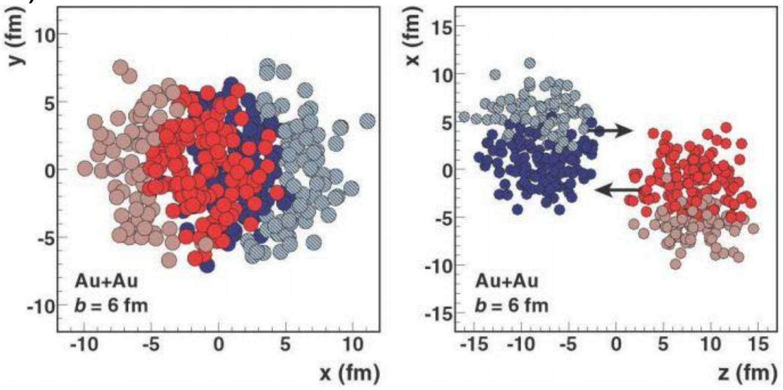
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

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

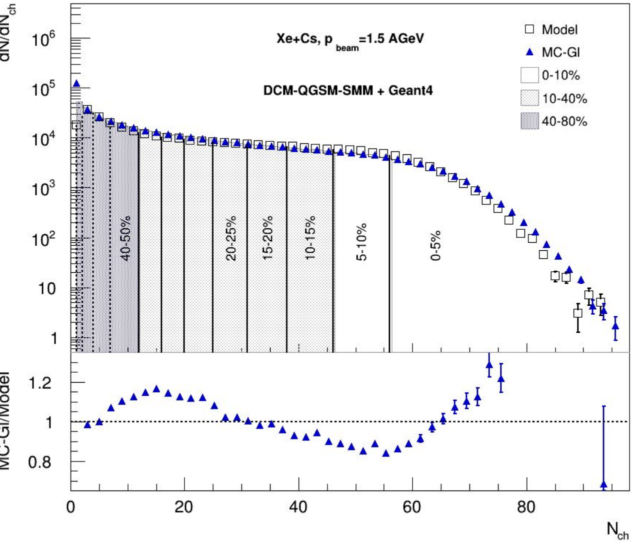
b – impact parameter

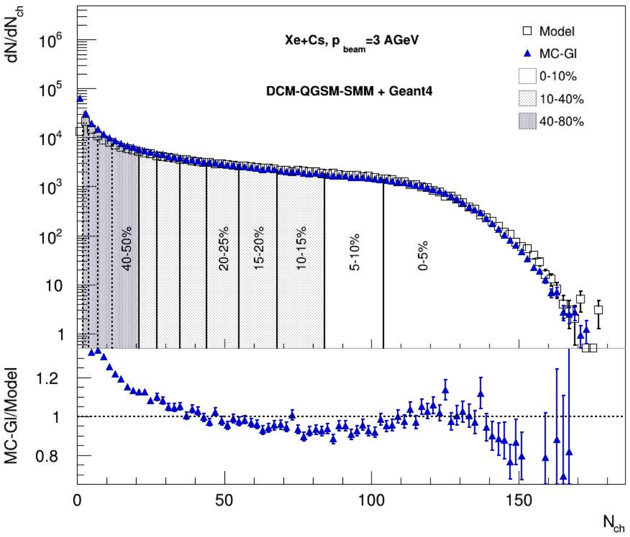
N_{part} – number of nucleons participating in the collision

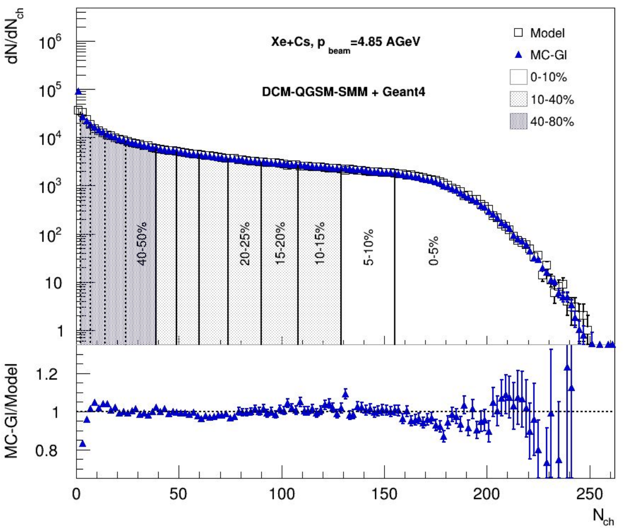
N_{spec} – number of spectator nucleons in the collision

N_{coll} – number of binary NN collisions

Result of the fitting

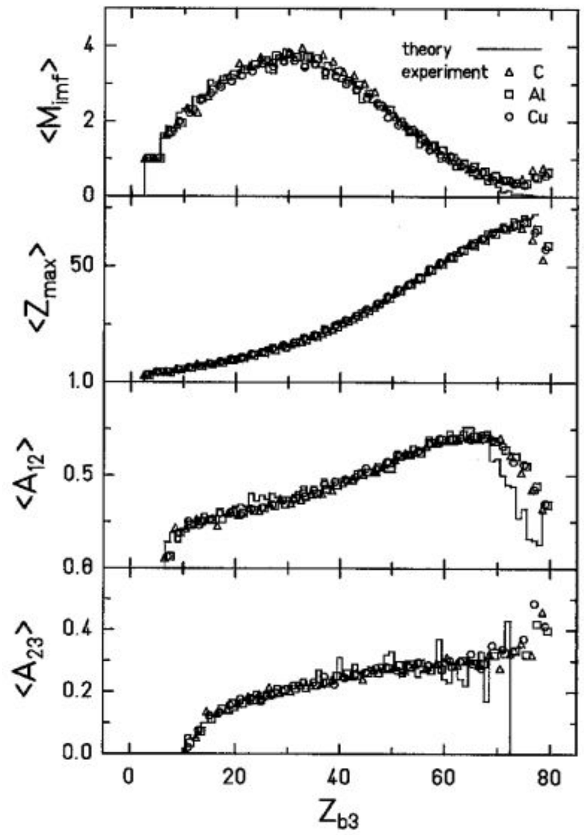




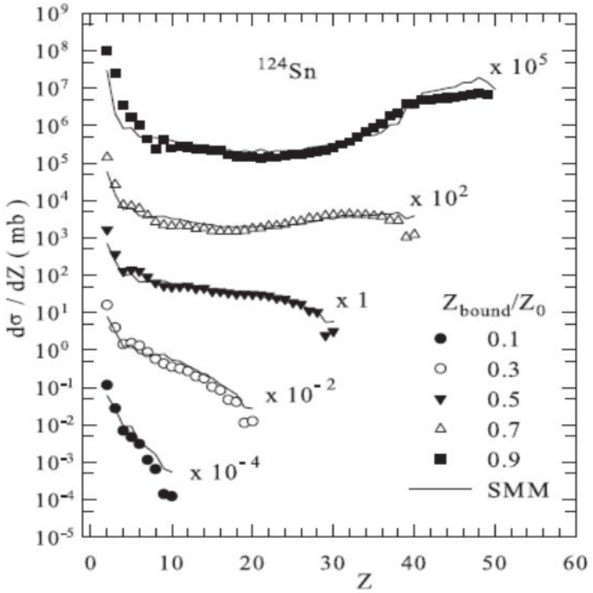


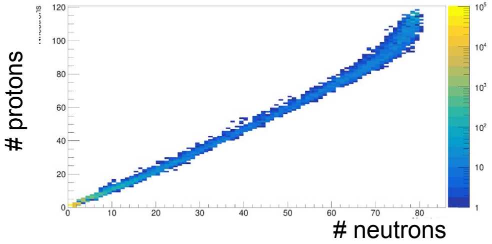
SMM description of the ALADIN's fragmentation data

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

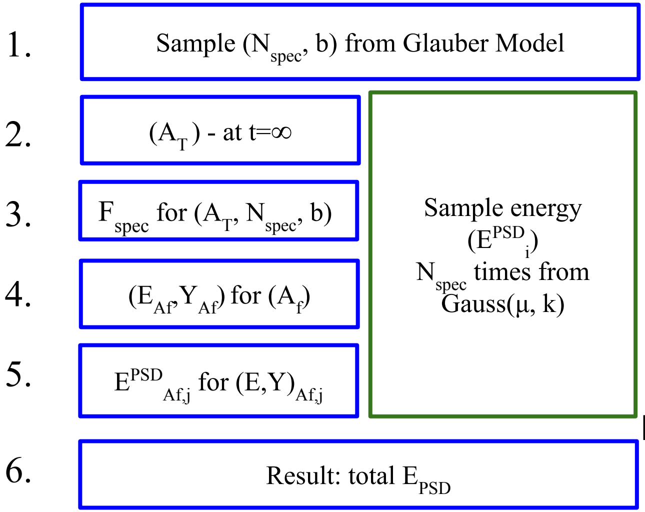


R.Ogul et al. PRC 83, 024608 (2011)





Mass number of fragments sampling for given event: new procedure



1. Fill set of 2D probability distribution of A_{frag} and N_A for each set of (A_{tot},N_{spec},b)
2. Reset all pairs $(A_{frag}, N_A)_i$, N_U=0
3. Generated pair $(A_{frag}, N_A)_i$,

   if:

   a. A_{frag} already among existing pairs from (1, N_U-1), then skip

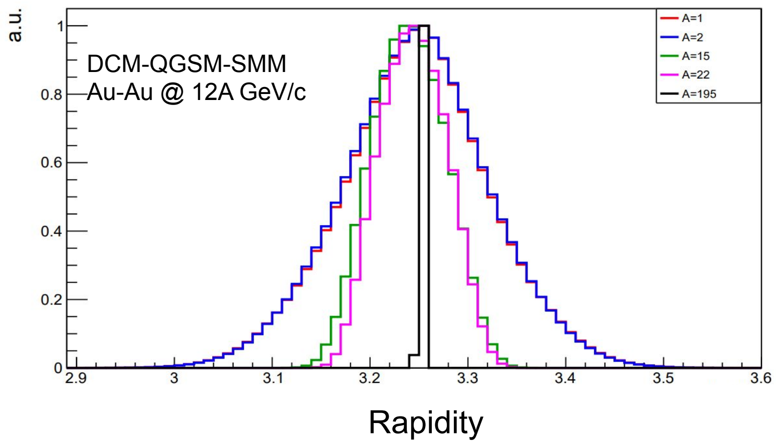
   b. $(\Sigma_{i=(1,NU)} N^i_A A^i_{frag}) > A_{tot}$ then go to step 2

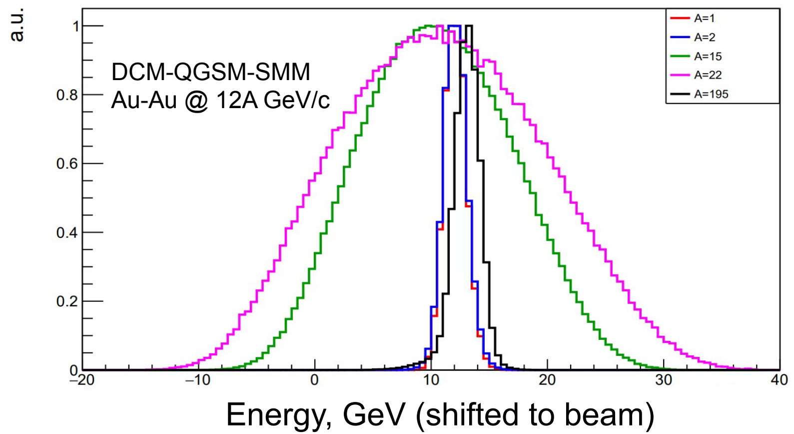
   else:

   Add $(A_{frag}, N_A)_i$ to the list of pairs, increment $N_U = N_U + 1$

Result: a set of N_U pairs (A_{frag}, N_A) with $A_{tot} = N^1_A A^1_{frag} + N^2_A A^2_{frag} + \ldots N^{NU}_A A^{NU}_{frag}$

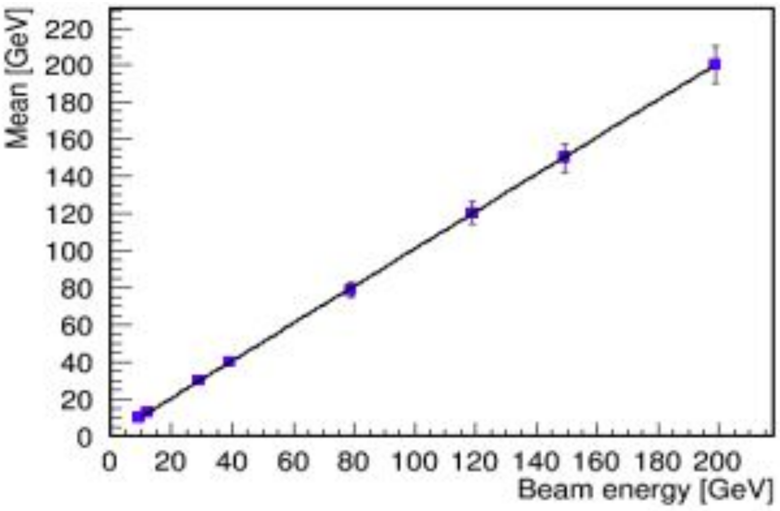
Population of fragments with energy and rapidity

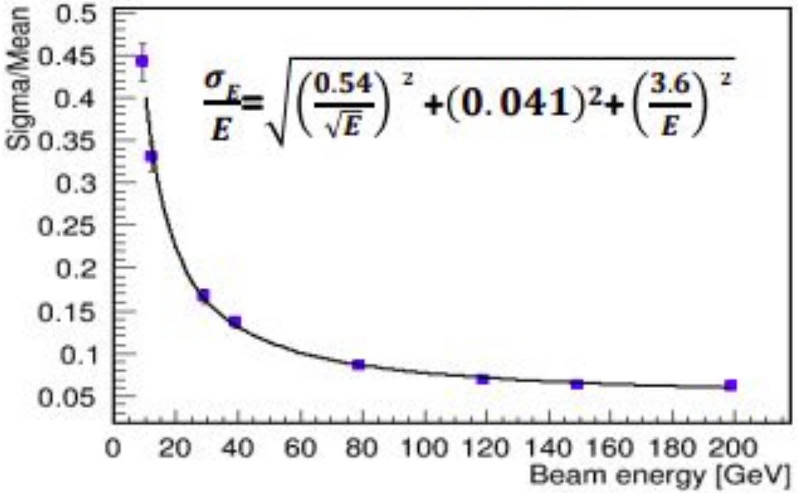




- Energy and rapidity distributions have different shapes for different fragment mass
- Shapes are used as input for sampling energy & rapidity values for each fragment

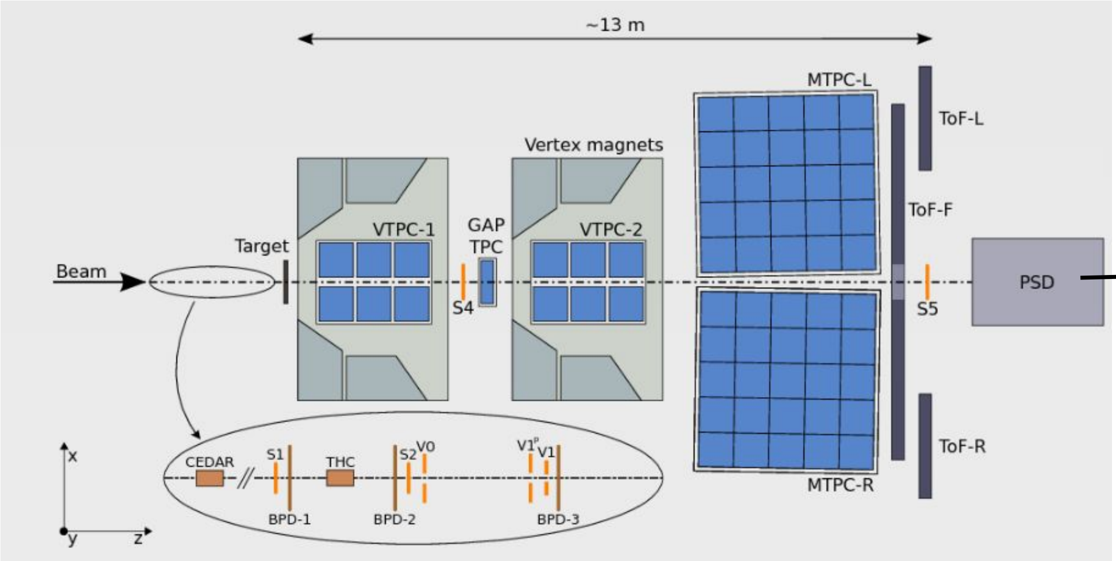
Respond of FHCal detector

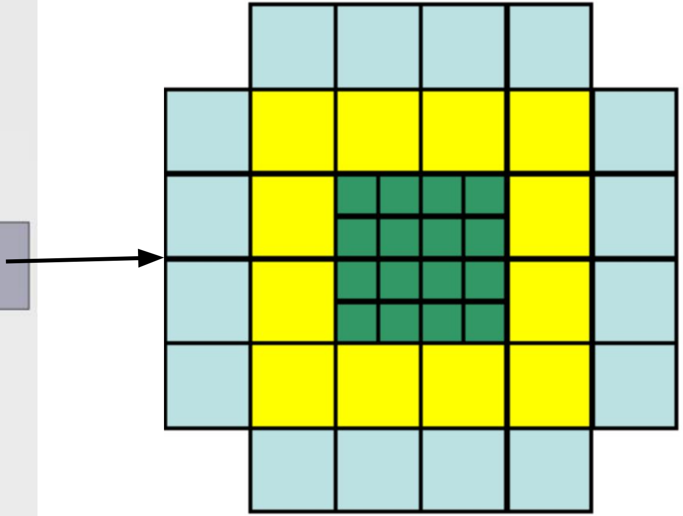




- Mean of signal has linear dependency with beam energy

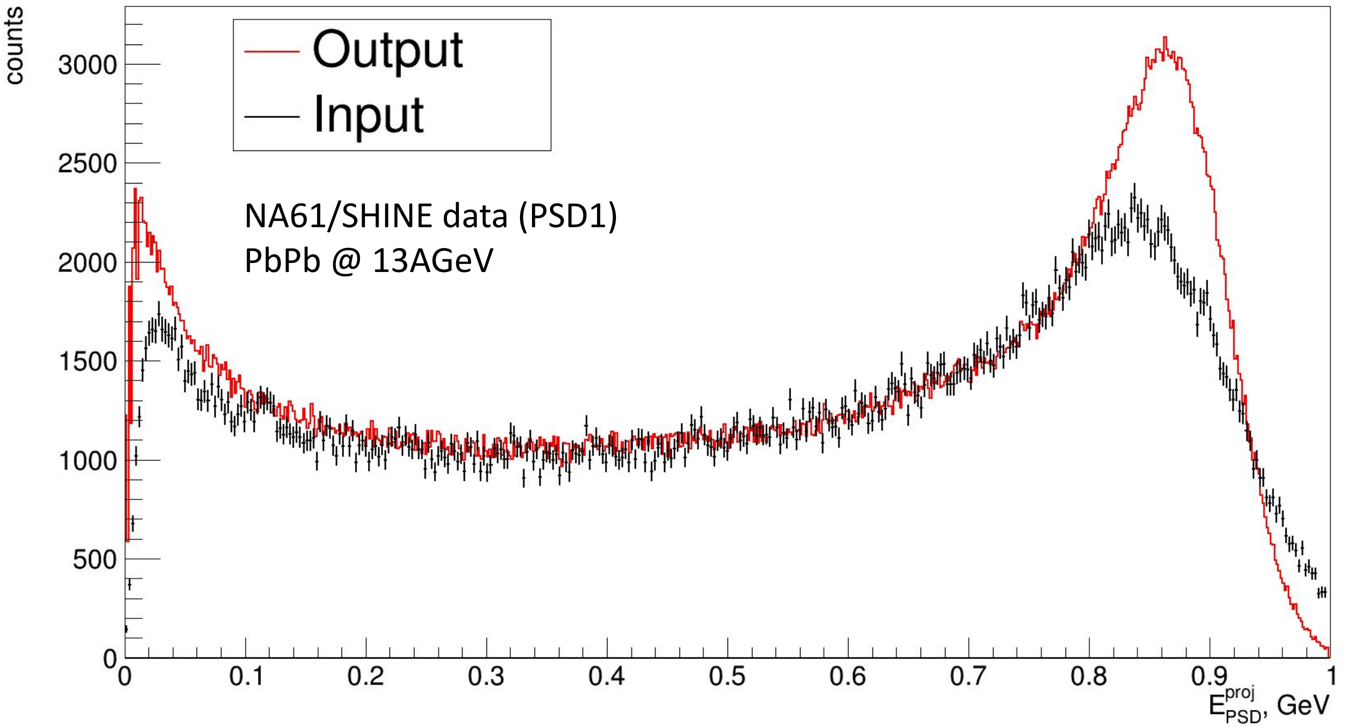
NA61/SHINE experimental setup

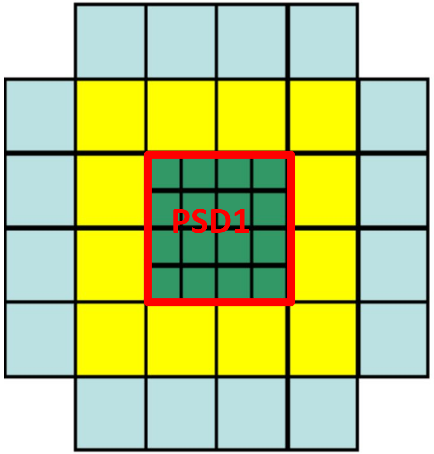




PSD detector layout

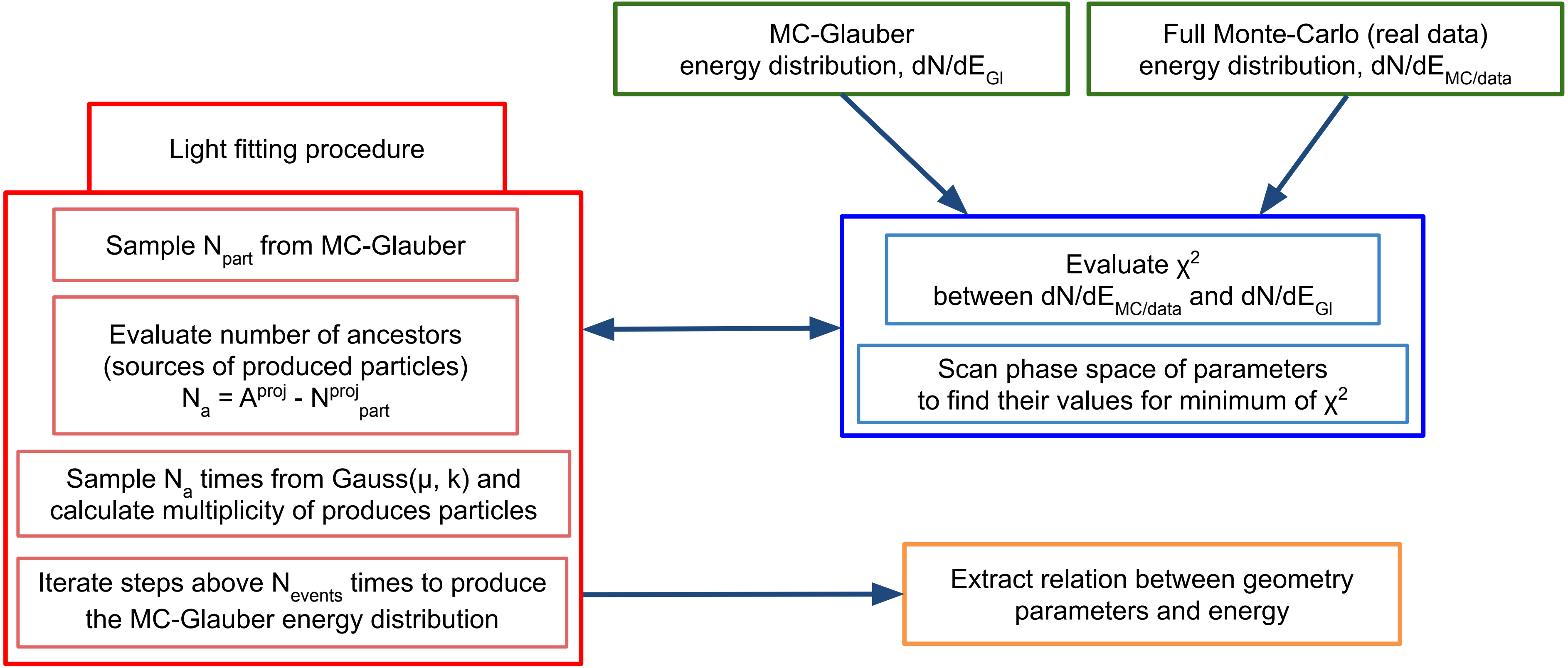
Full mode procedure (example for NA61)



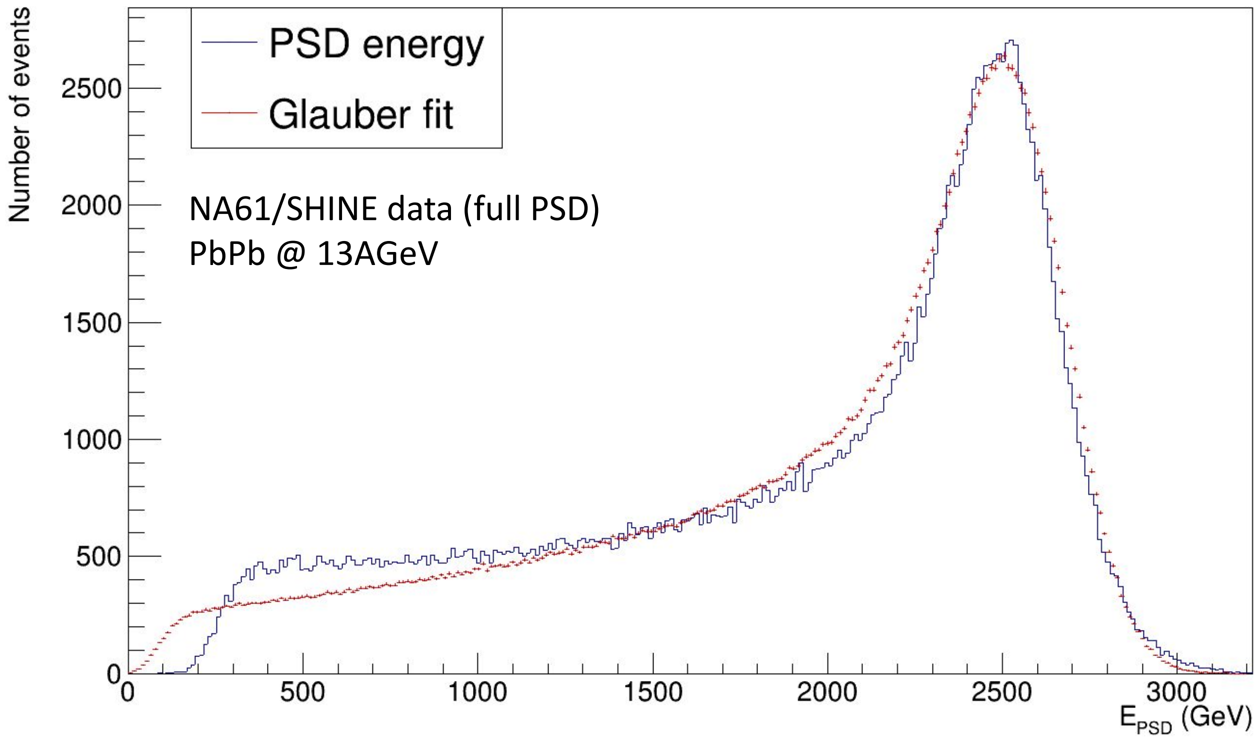


- Scaling along both X and Y axis is applied
- Form of energy distribution is reproducible

MC-Glauber+Spectators fitting procedure



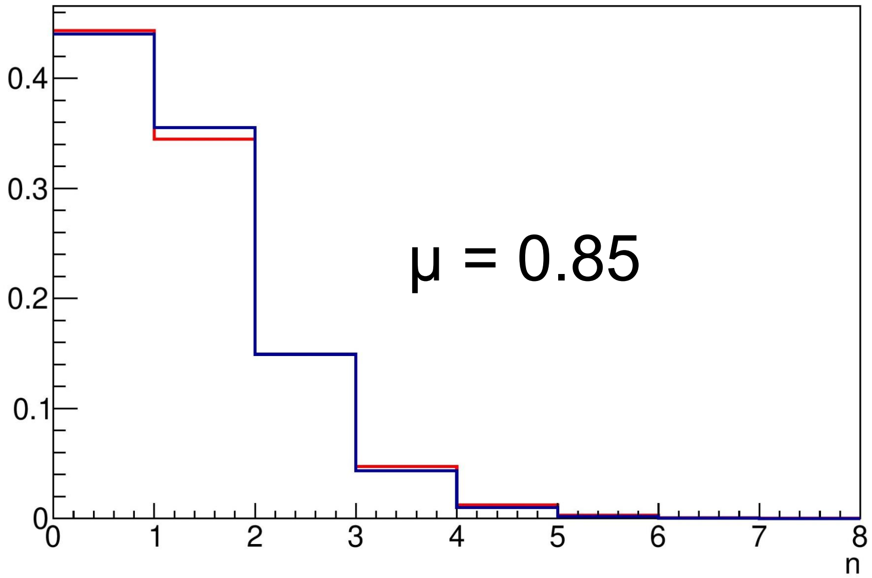
Light mode procedure fit (example for NA61)

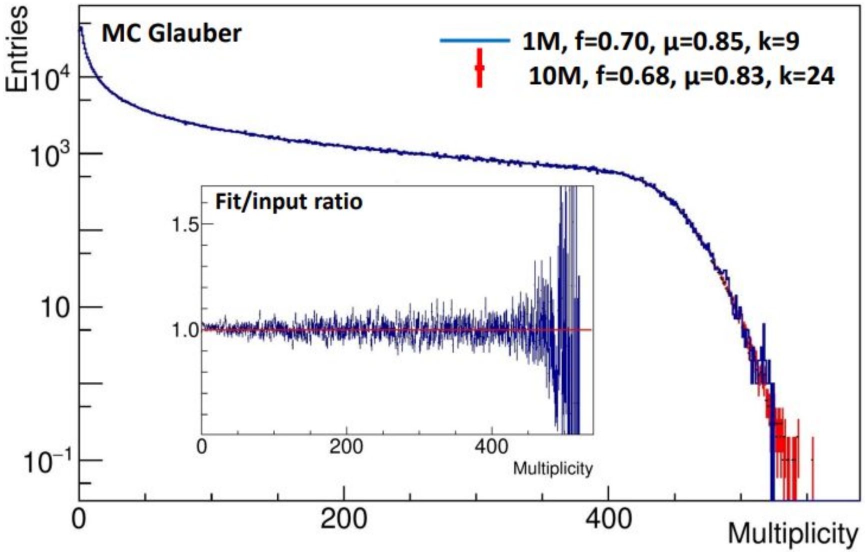


χ^2=18.1891±0.365028;
μ=12.4943,
k=8.9;
MinFitBin=17 (200 GeV),
MaxFitBin=250 (3000 GeV)

- Produced particles affect form of full PSD distribution
- Light mode maybe needs some additional parameters

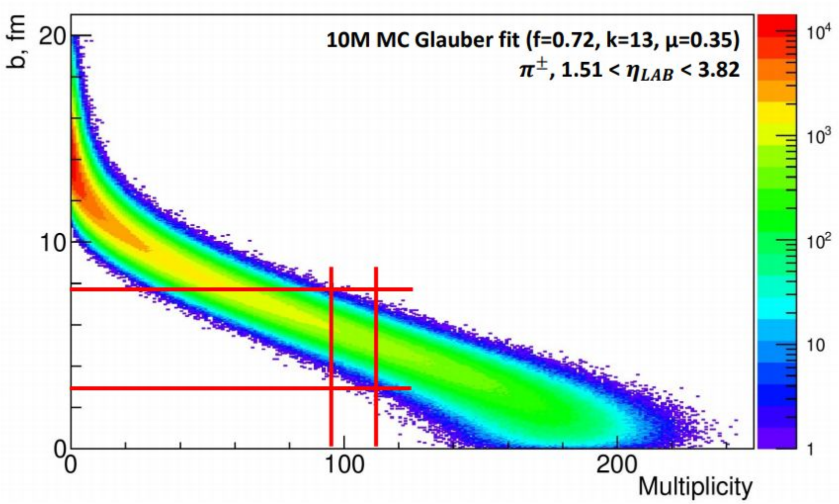
NBD at different values of k

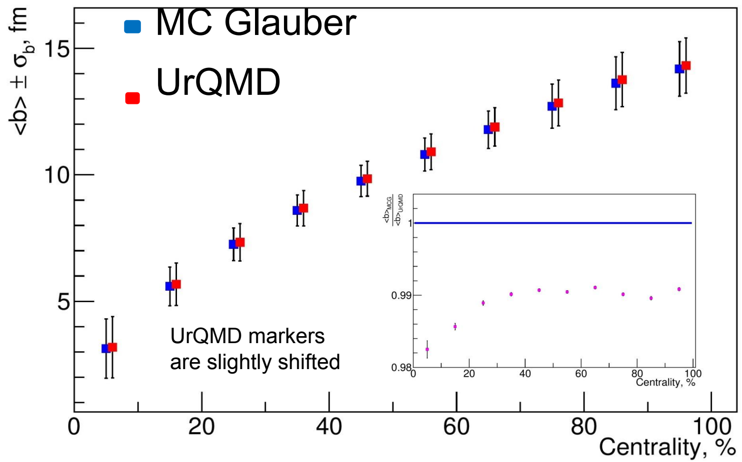




MC Glauber fit results are in good agreement with simulated input

Centrality determination using STS multiplicity





Distribution provides connection between
centrality class (multiplicity range, M ± ΔM) and impact parameter range ($b \pm \sigma_b$)