Application of the MC-Glauber approach for centrality determination in heavy-ion collisions with the BM@N experiment

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July 14th, 2022
NUCLEUS-2022 Conference

Motivation

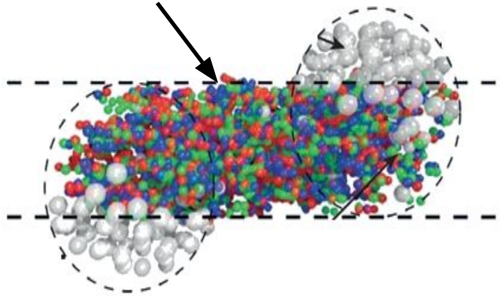
- Evolution of matter produced in heavy-ion collisions depends on its initial geometry

- 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

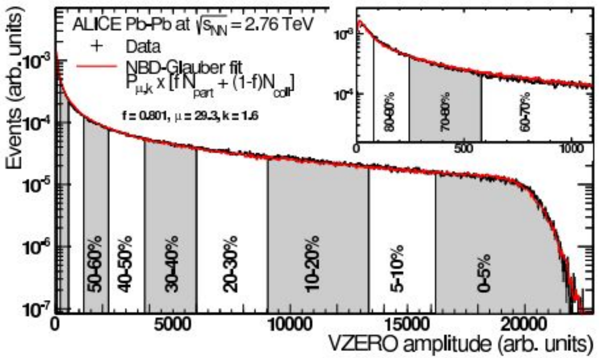
- Centrality class: group of events corresponding to
  a given fraction (%) of the total cross section:

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

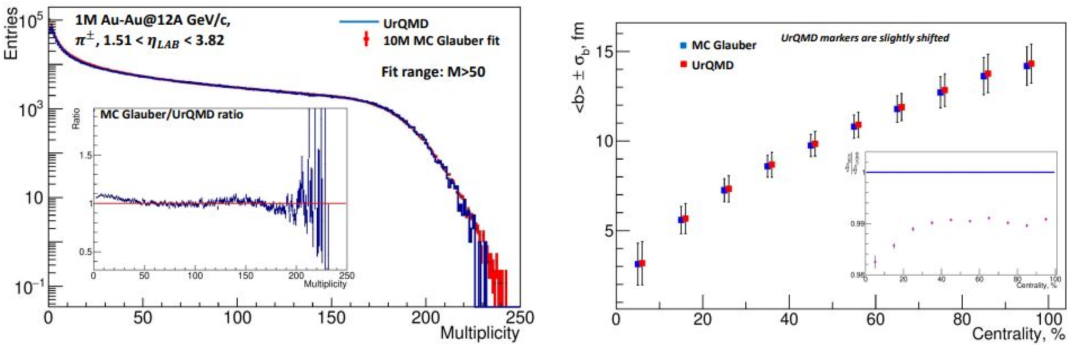


Why this method is important for BM@N

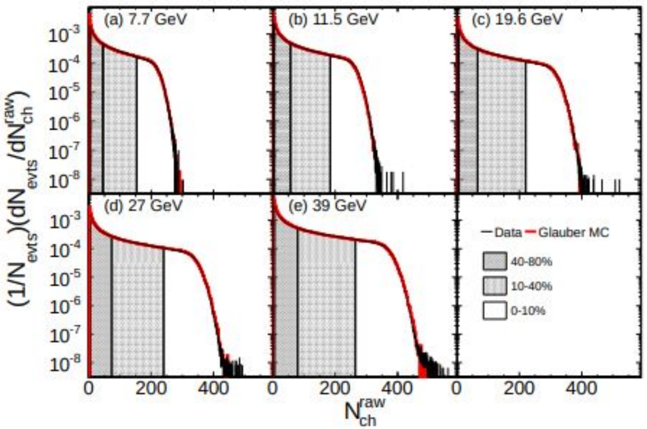
ALICE; Phys.Rev.C 88 (2013) 4, 044909



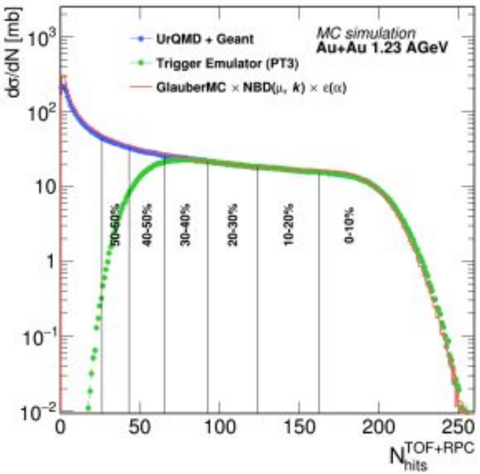
CBM; J.Phys.Conf.Ser. 1690 (2020) 1, 012107



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



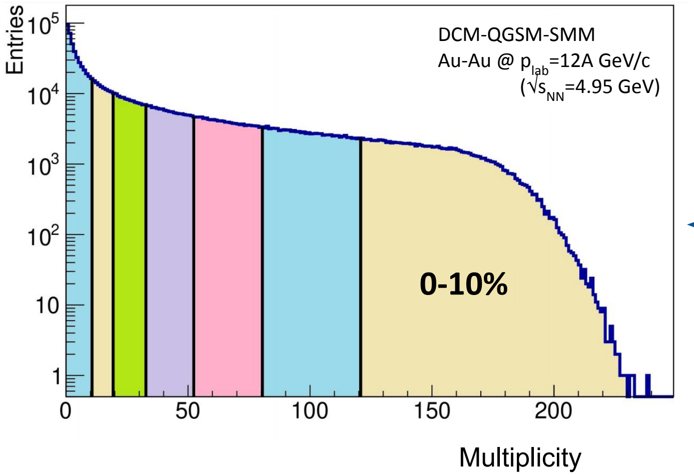
HADES; Eur.Phys.J.A 54 (2018) 5, 85

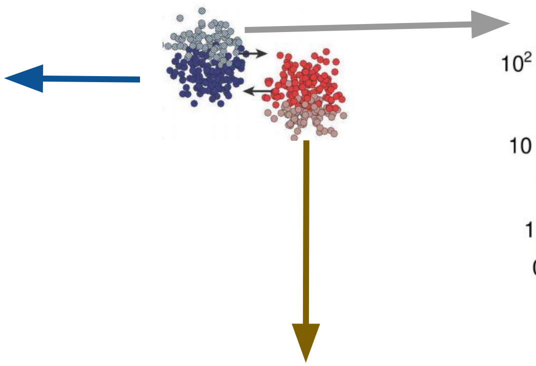


- MC-Glauber x NBD multiplicity fitting procedure is standard method for centrality determination
- BM@N needs this method to compare data in the least experiment dependent way

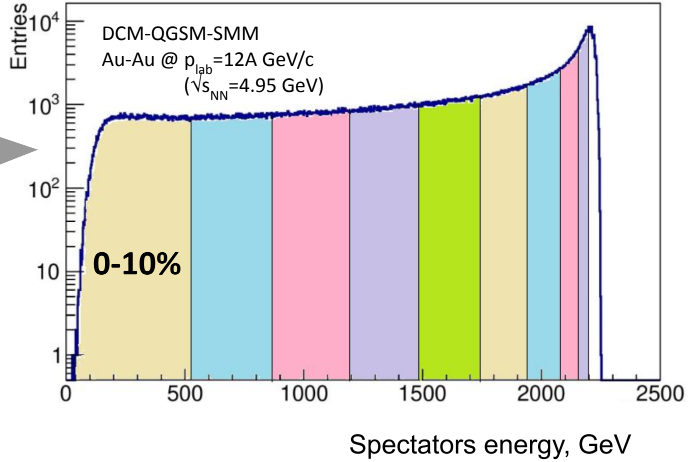
Centrality Estimators in BM@N

Produced charged particles





Projectile spectators



Target spectators
(not measured)

* these plots are illustrative only and do not directly refer to BM@N

BM@N subsystems for centrality determination

Simulation setup

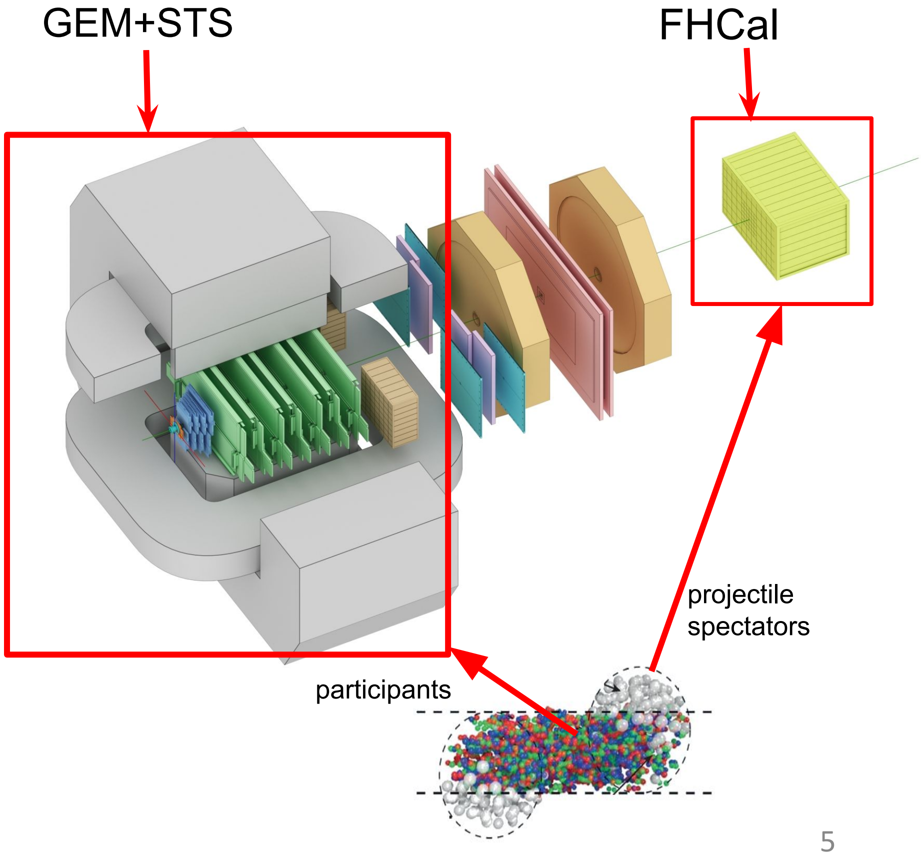
- DCM-QGSM-SMM

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

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

Subsystems

- Multiplicity: Tracking system GEM+STS
- Spectators energy: FHCal



MC Glauber model

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

- Main ideas:
  - Independent straight line trajectories of the nucleons
  - A nucleus-nucleus collision is treated as a sequence of independent binary nucleon-nucleon collisions
  - Position of nucleons in individual collision are sampled using Monte-Carlo simulation

Main configuration parameters:

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

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

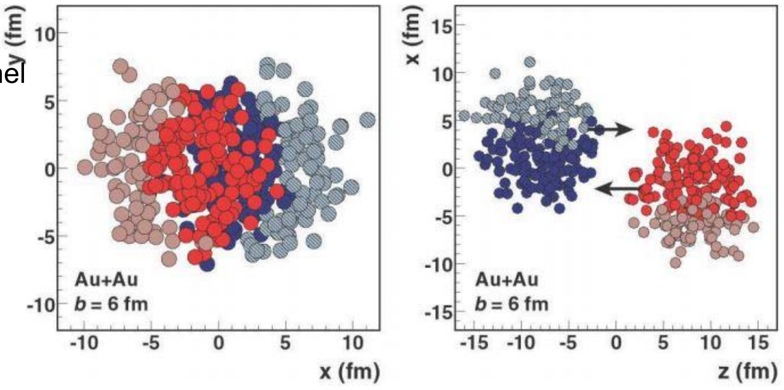
Geometry parameters:

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



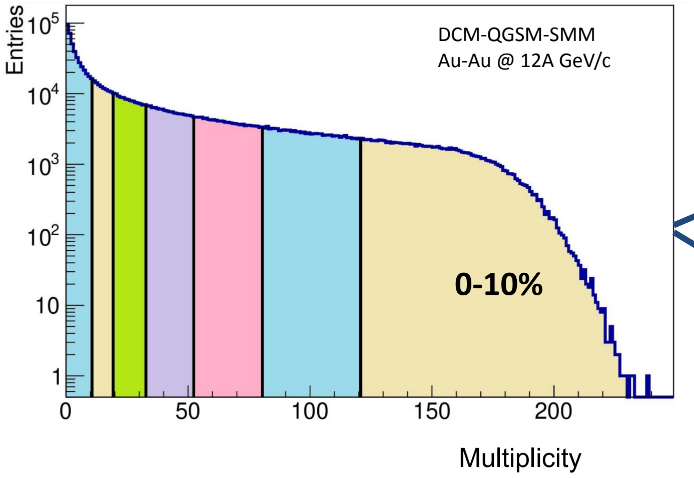
Glauber Modeling in High Energy Nuclear Collisions: Ann.Rev.Nucl.Part.Sci.57:205-243,2007

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://github.com/IlyaSegal/NICA*

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

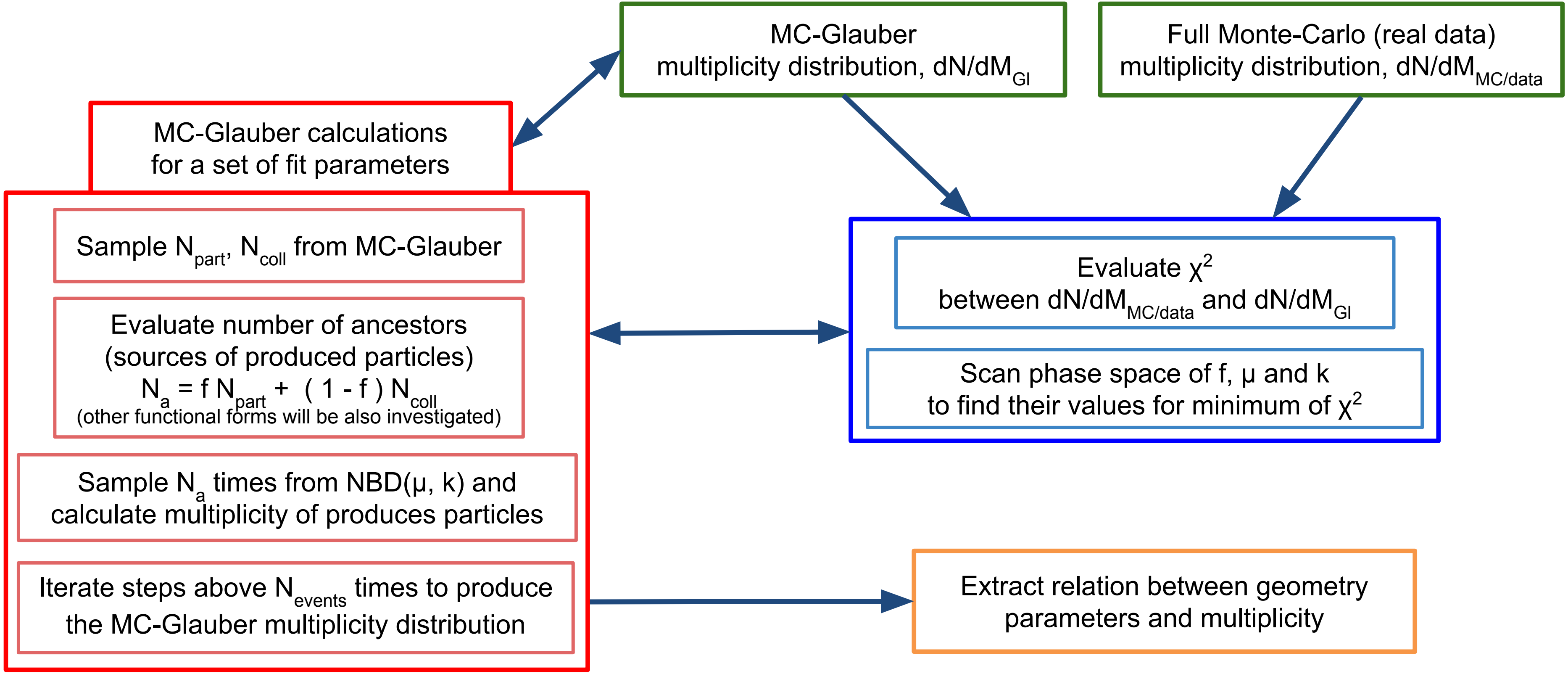
Evaluate number of ancestors
(sources of produced particles)
$N_a = f N_{part} + (1 - f) N_{coll}$
(other functional forms will be also investigated)

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

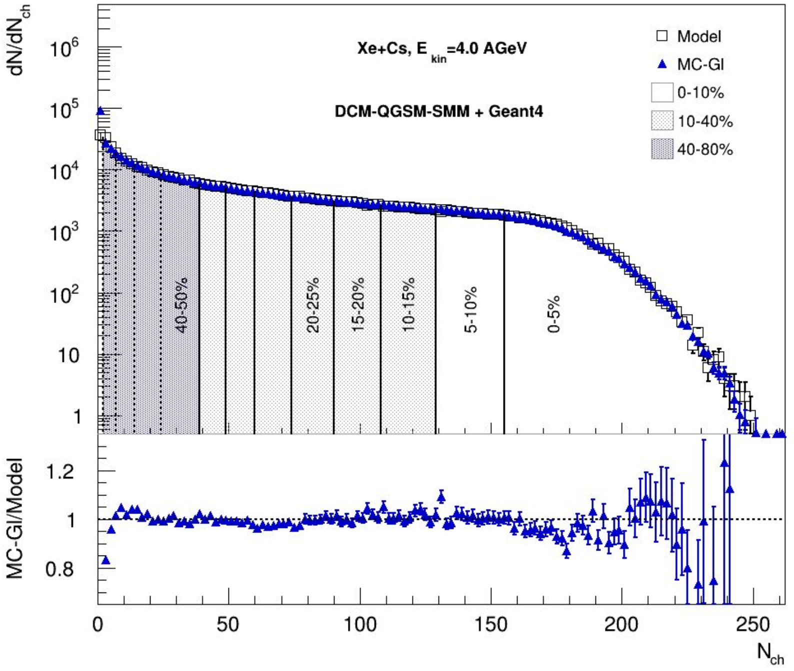
Iterate steps above N_{events} times to produce
the MC-Glauber multiplicity distribution

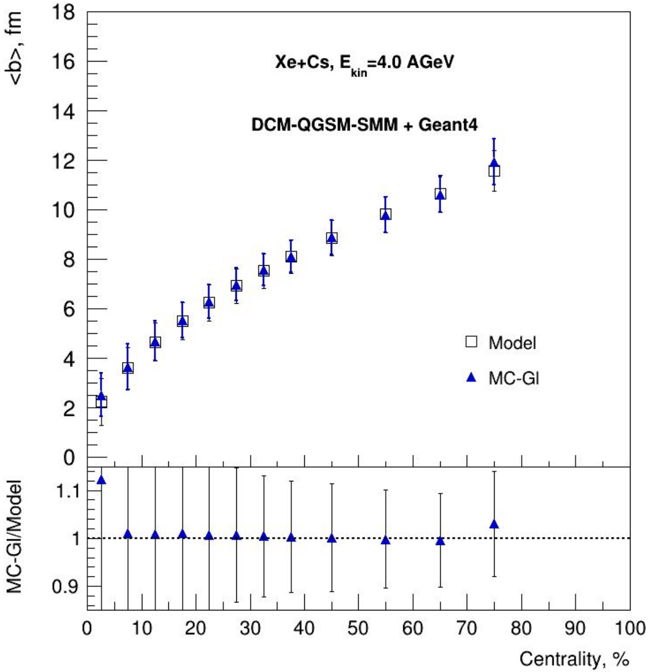
Extract relation between geometry
parameters and multiplicity

MC-Glauber + NBD fitting procedure



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

Summary

- MC Glauber and multiplicity fitting procedure is developed for BM@N
- Relation between impact parameter and centrality classes is extracted
- Software implementation of the procedure is ready and also used also in MPD (see tomorrow talk about centrality in MPD)

Work in progress

- Apply this procedure for data of run8 session
- Develop centrality determination procedure based on spectators energy and MC Glauber model (for details also see tomorrow talk about centrality in MPD)

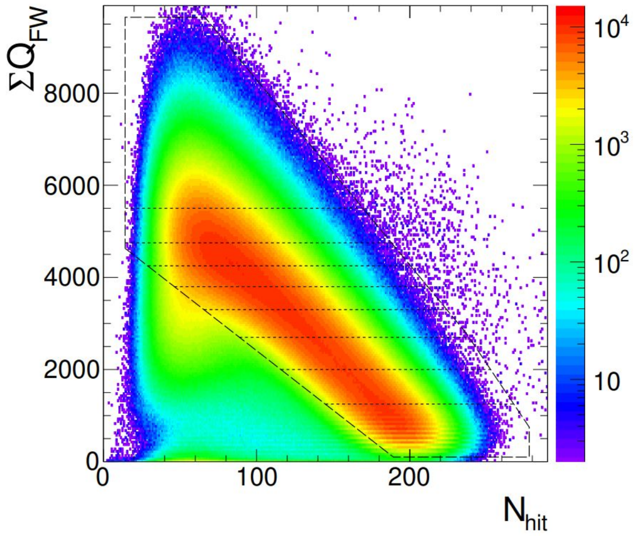
This work is supported by:
the RFBR grant No. 18-02-40086,
the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013)

Backup

Why several alternative centrality estimators

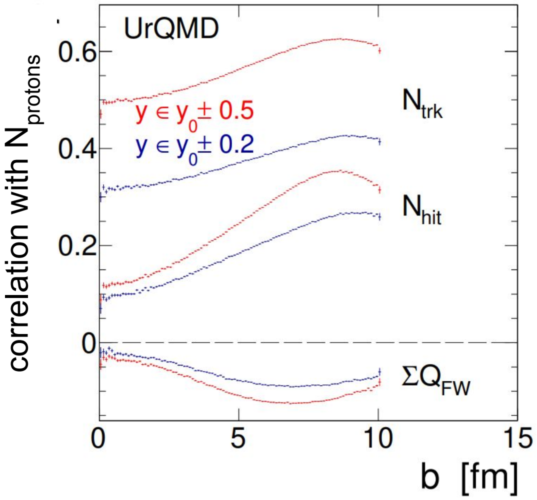
Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

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)

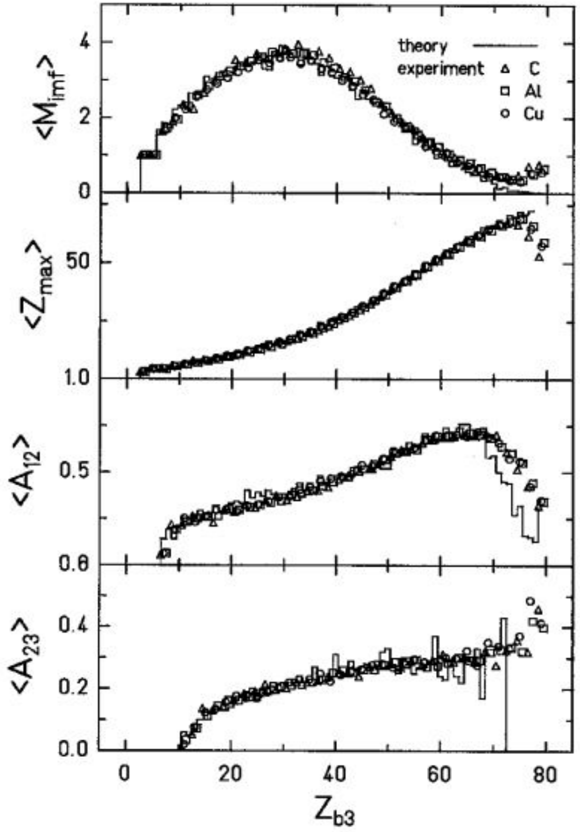
HADES; Phys.Rev.C 102 (2020) 2, 024914



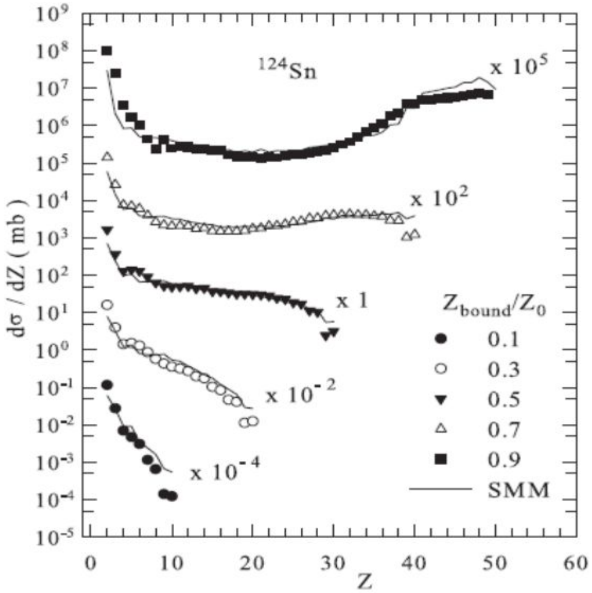
Avoid self-correlation biases when using spectators fragments for centrality estimation

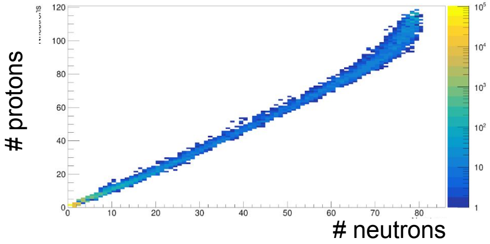
SMM description of the ALADIN's fragmentation data

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

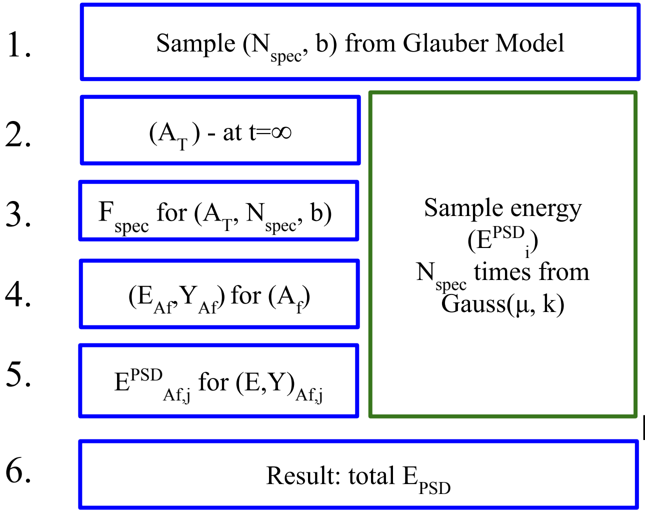


R.Ogul et al. PRC 83, 024608 (2011)





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 $A_{tot} = N^1_A A^1_{frag} + N^2_A A^2_{frag} + \ldots N^{NU}_A A^{NU}_{frag}$

MC-Glauber+Spectators fitting procedure

MC-Glauber
energy distribution, dN/dE_{Gl}

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

General idea

replace sampling of

MC-Glauber **x** NBD multiplicity

with

MC-Glauber **x** fragments energy

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 energy

MC-Glauber+Spectators fitting procedure

Full procedure

- Sample number of spectator nucleons ($N_{spec,Gl}$) and impact parameter (b) from Glauber Model
- Sample number of bound spectator nucleons ΣA_{Frag} according to fragmentation model from number of free spectator nucleons in MC-Glauber $N_{spec,Gl}$
- Sample a mass number distribution of fragments, $A_{Frag}(\Sigma A_{Frag}, b)$
- Sample energy & rapidity distribution of fragments $(E,Y)_{Frag}\{A_{frag}, E_{lab}\}$
- Calculate detector response, $E_{FHCal}\{(E,Y)_{Frag}\}$
- Iterate steps above N_{events} times to produce the MC-Glauber energy distribution

MC-Glauber energy distribution, dN/dE_{Gl}

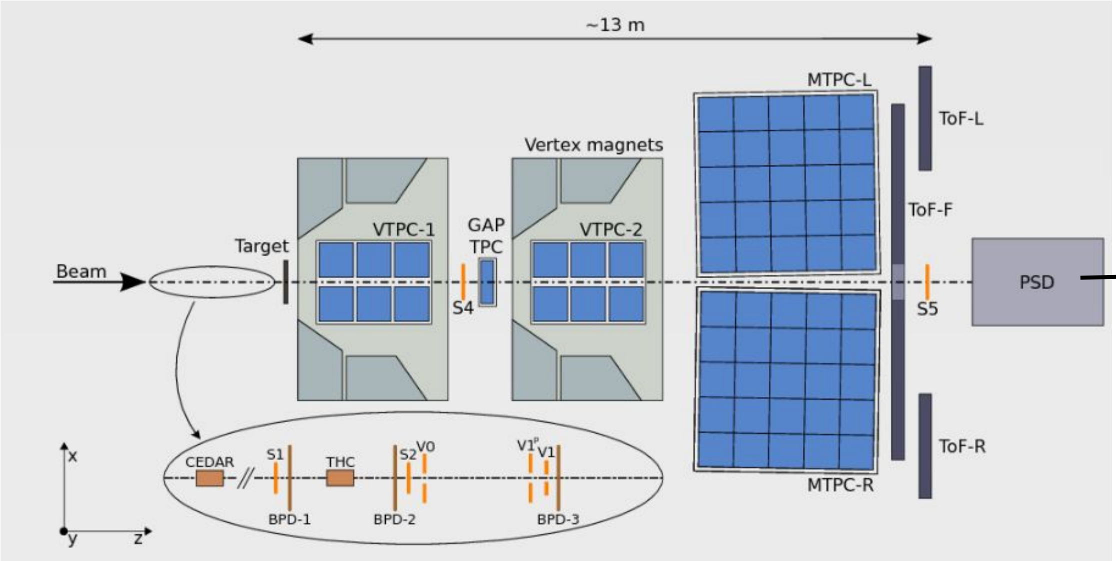
Full Monte-Carlo (real data) energy distribution, $dN/dE_{MC/data}$

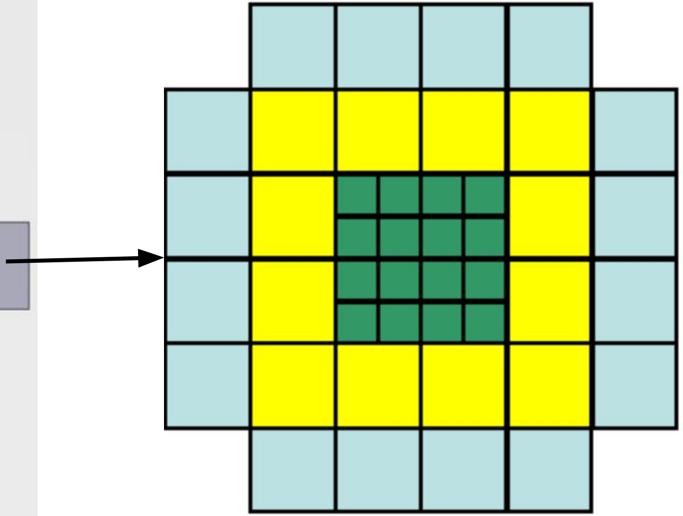
Evaluate χ^2 between $dN/dE_{MC/data}$ and dN/dE_{Gl}

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

Extract relation between geometry parameters and energy

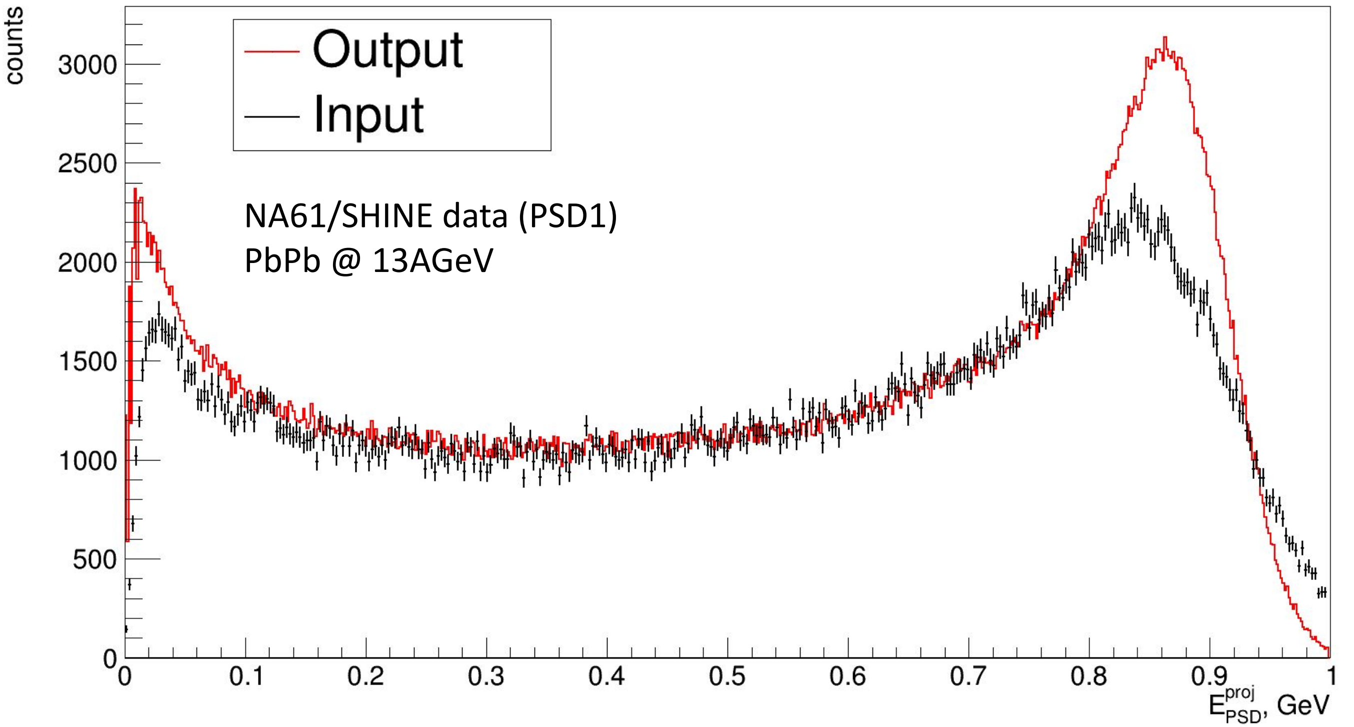
NA61/SHINE experimental setup

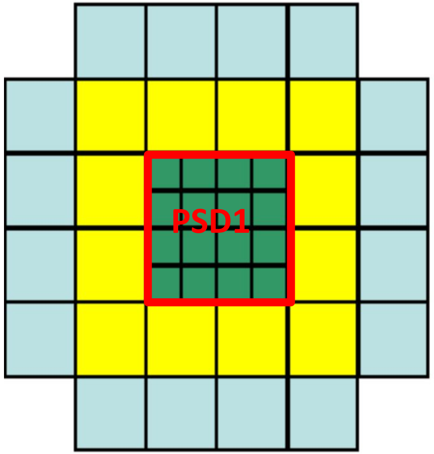




PSD detector layout

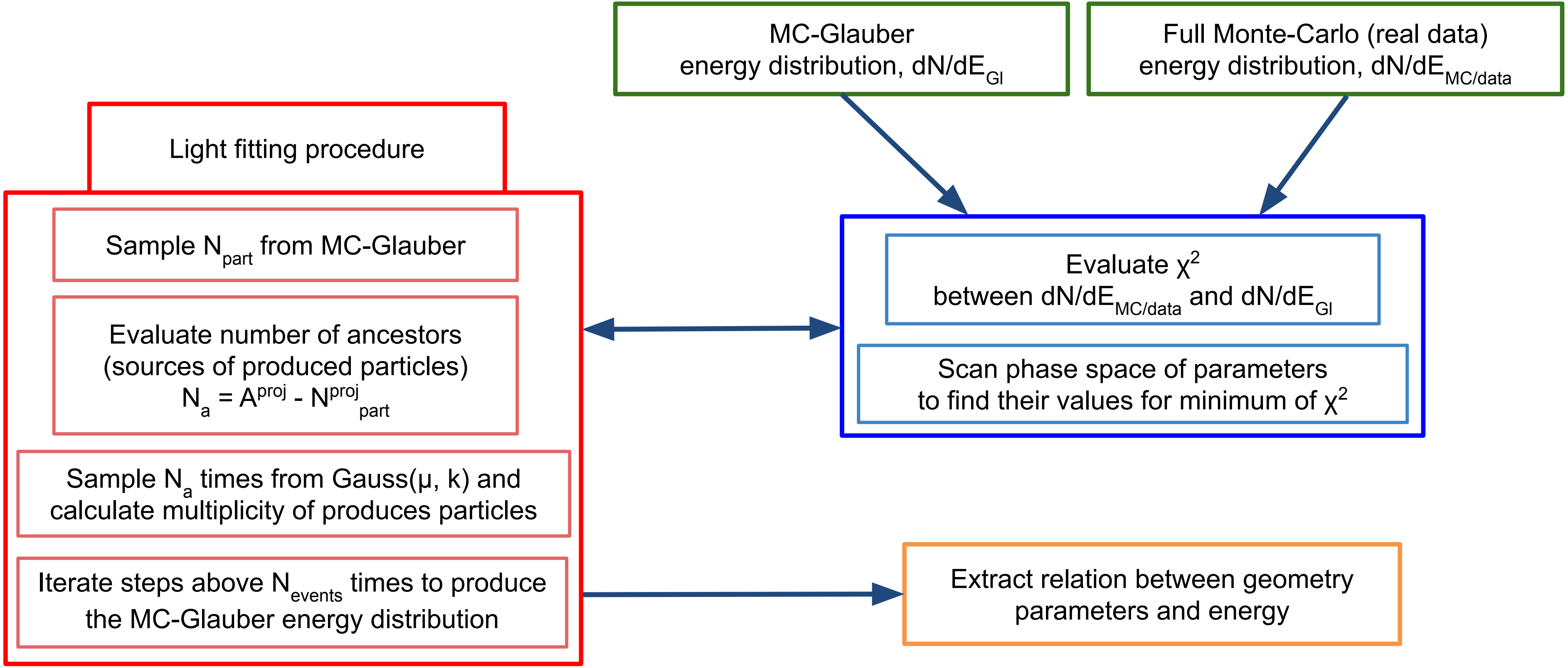
Full mode procedure (example for NA61)



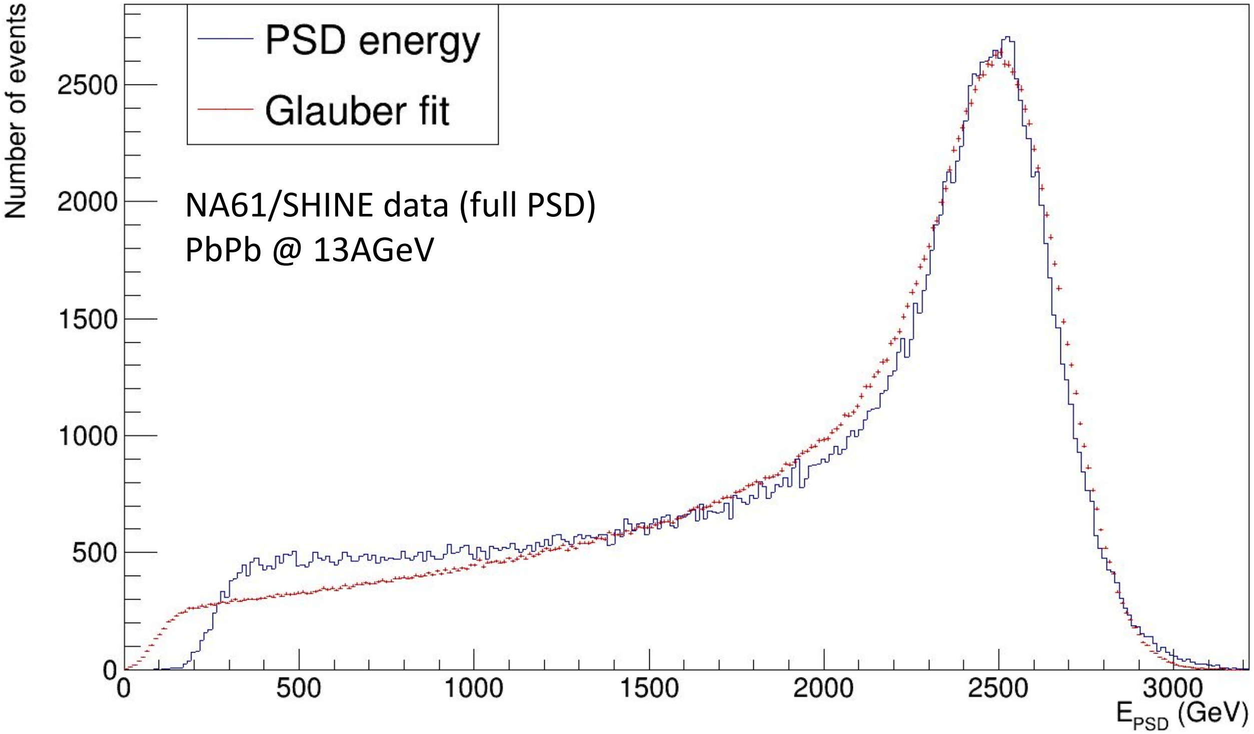


- Scaling along both X and Y axis is applied
- Form of energy distribution is reproducible

MC-Glauber+Spectators fitting procedure



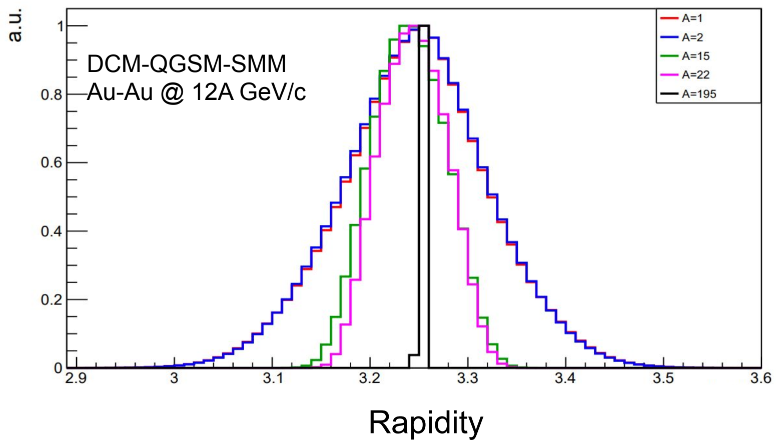
Light mode procedure fit (example for NA61)

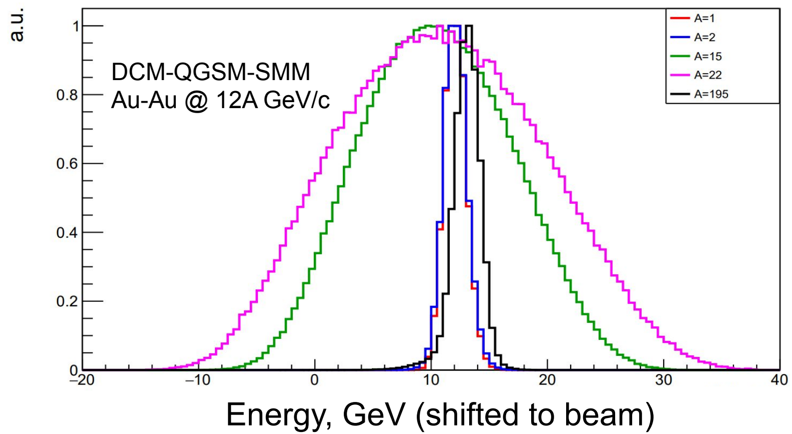


χ^2=18.1891±0.365028;
μ=12.4943,
k=8.9;
MinFitBin=17 (200 GeV),
MaxFitBin=250 (3000 GeV)

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

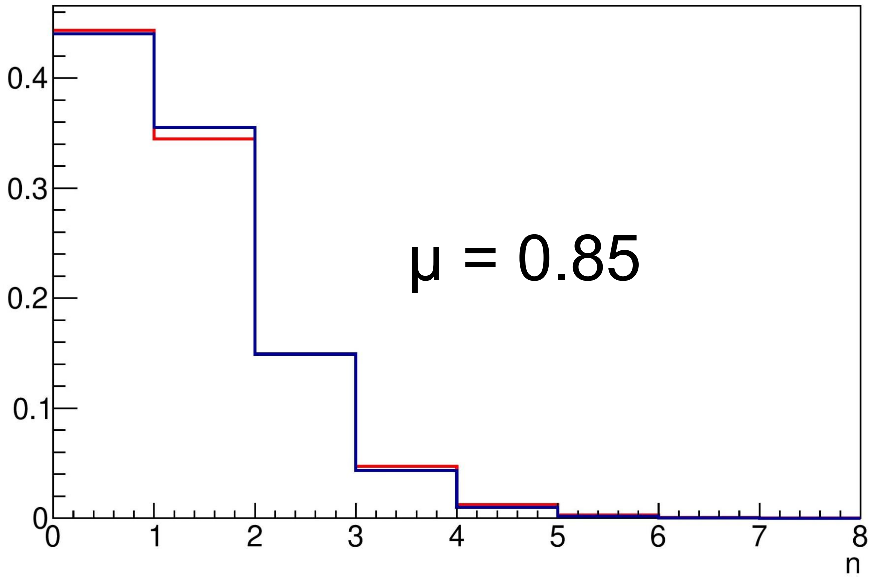
Population of fragments with energy and rapidity

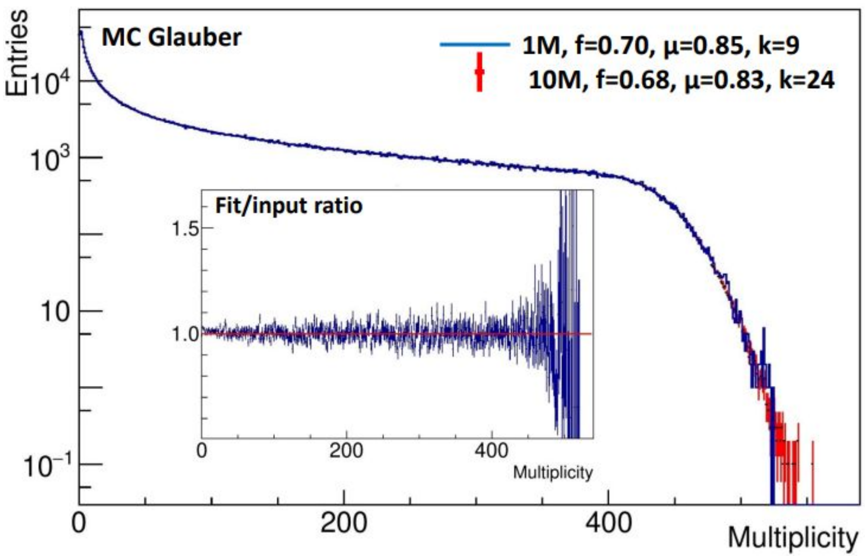




- Energy and rapidity distributions have different shapes for different fragment mass
- Shapes are used as input for sampling energy & rapidity values for each fragment

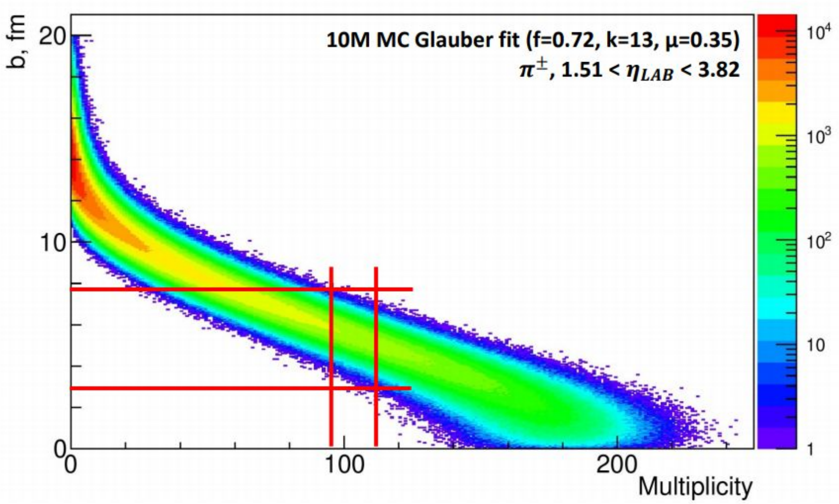
NBD at different values of k

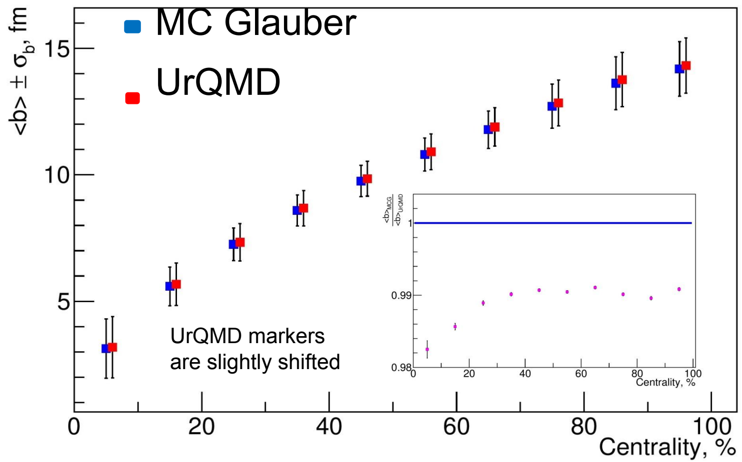




MC Glauber fit results are in good agreement with simulated input

Centrality determination using STS multiplicity





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