MC Glauber based centrality determination with spectator fragments in the CBM experiment

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for the CBM Collaboration

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Introduction

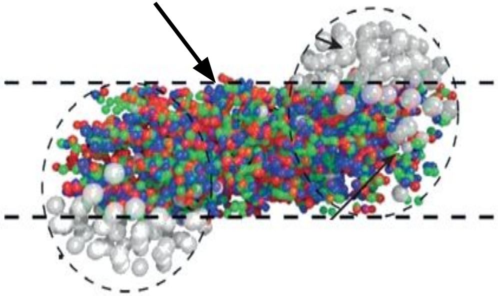
- Evolution of matter produced in heavy-ion collisions depends on its initial geometry

- 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:

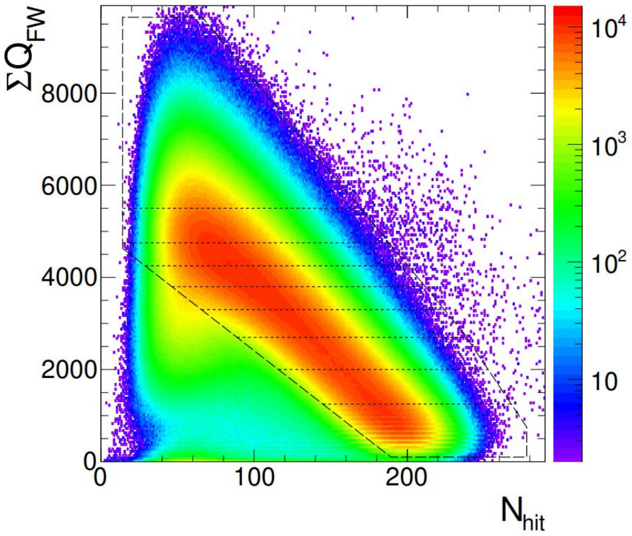
$$C_b = \frac{1}{\sigma_{inel}^{AA}} \int_0^b \frac{d\sigma}{db'} db'$$



Why estimating centrality with spectators

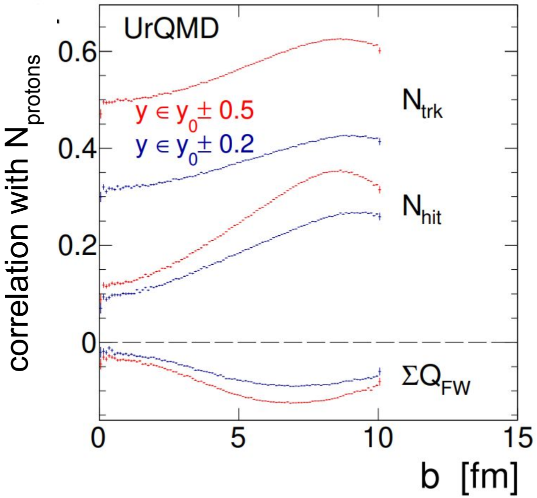
Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

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

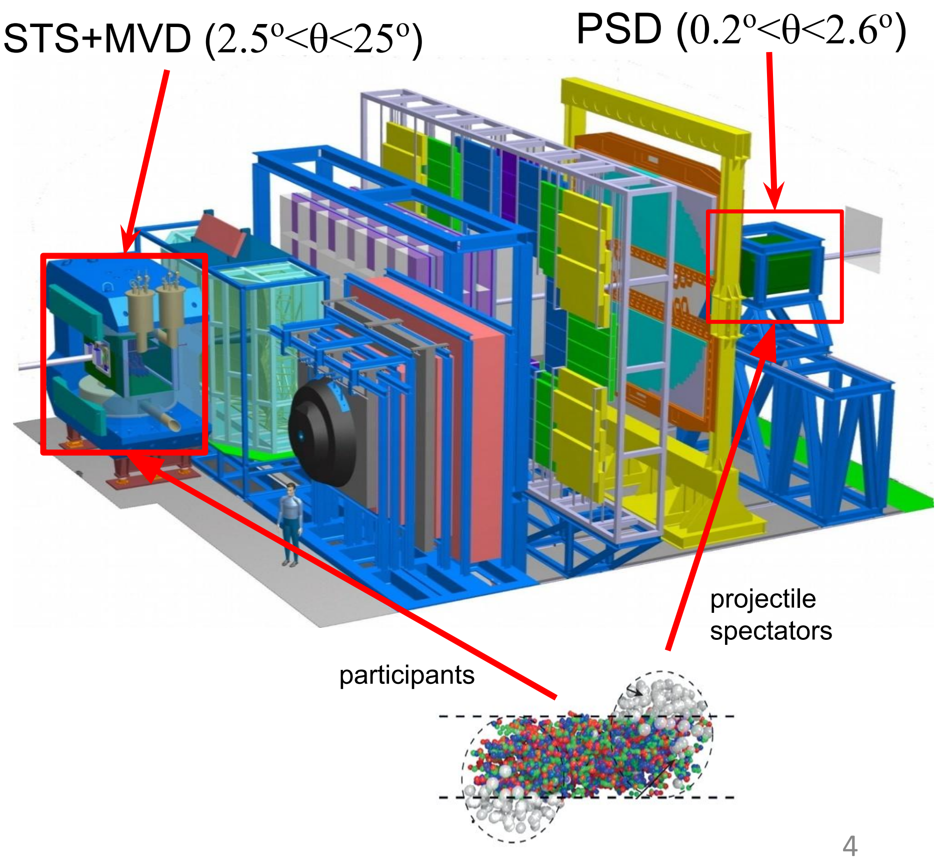
CBM subsystems for centrality determination

Simulation setup

- UrQMD (multiplicity)
  DCM-QGSM-SMM (fragments)
  M.Baznat et al. PPNL 17 (2020) 3, 303
- Au-Au @ p_{beam} = 12*A* GeV/*c*
- Transport: GEANT4

Subsystems

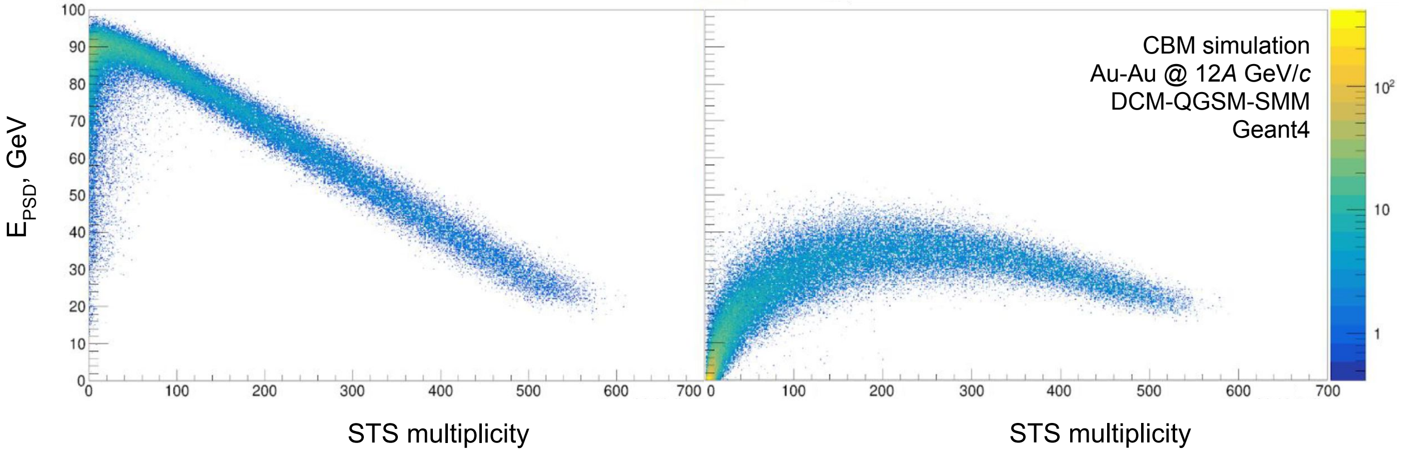
- Tracking system: MVD+STS
- Projectile spectators fragments: PSD



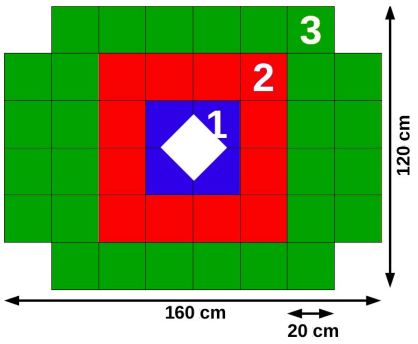
Charged hadron multiplicity vs. spectator's energy

PSD without a hole

PSD with 20 cm hole



Projectile Spectator Detector transverse layout



Challenge: Loss of fragments in the PSD beam hole distorts anticorrelation between the PSD energy and STS multiplicity (and impact parameter)

MC Glauber model

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

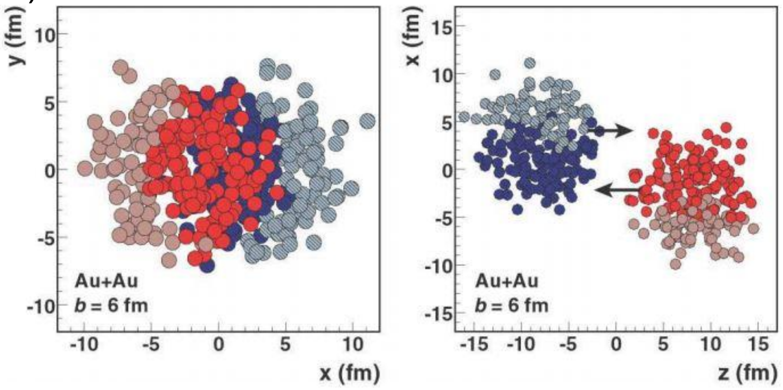
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

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

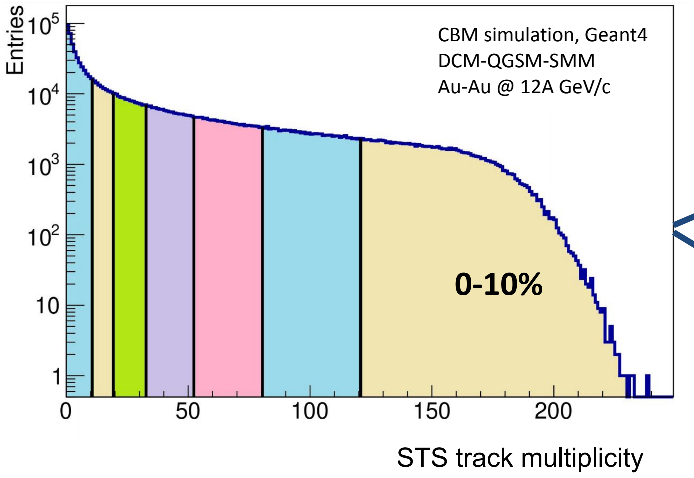
N_{coll} – number of binary NN collisions

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)

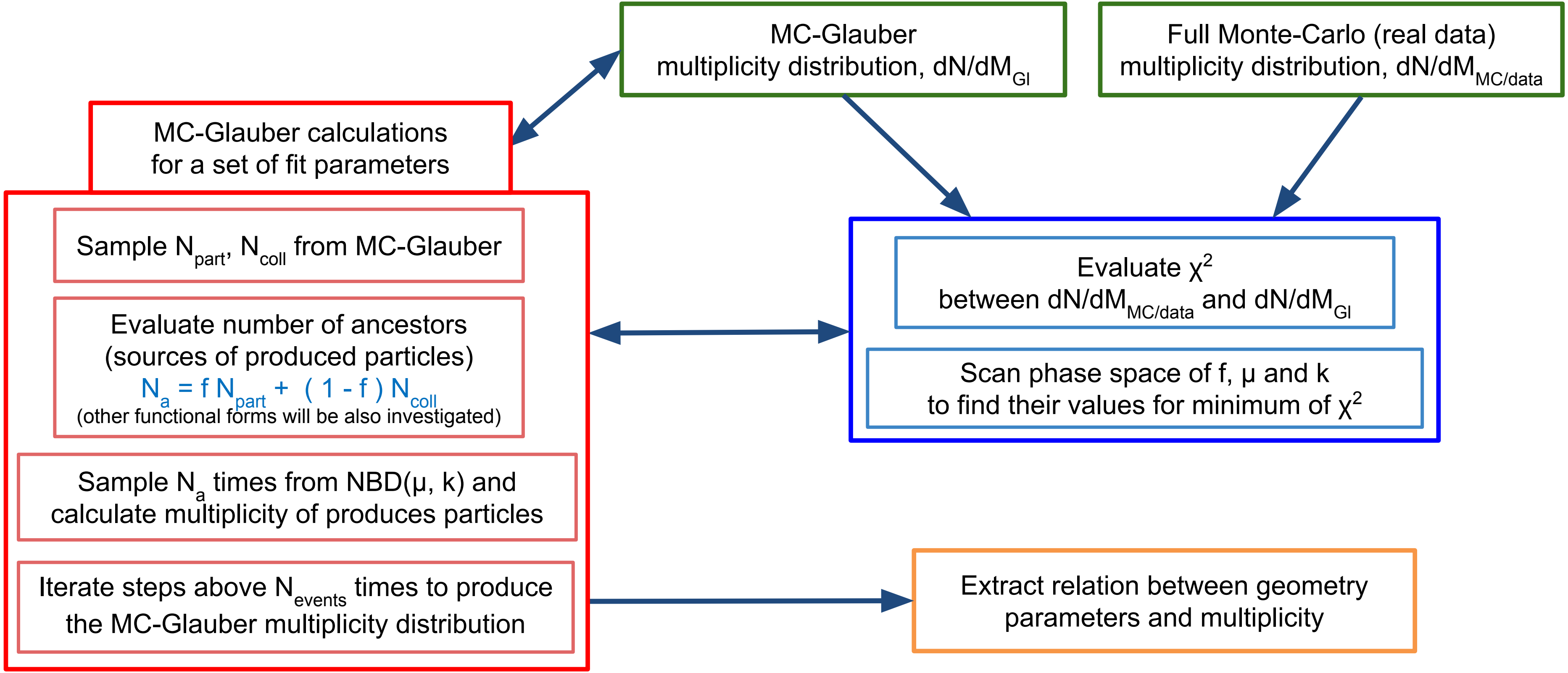
Sample N_a times from NBD(μ, k) and
calculate multiplicity of produces particles

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

Extract relation between geometry
parameters and multiplicity

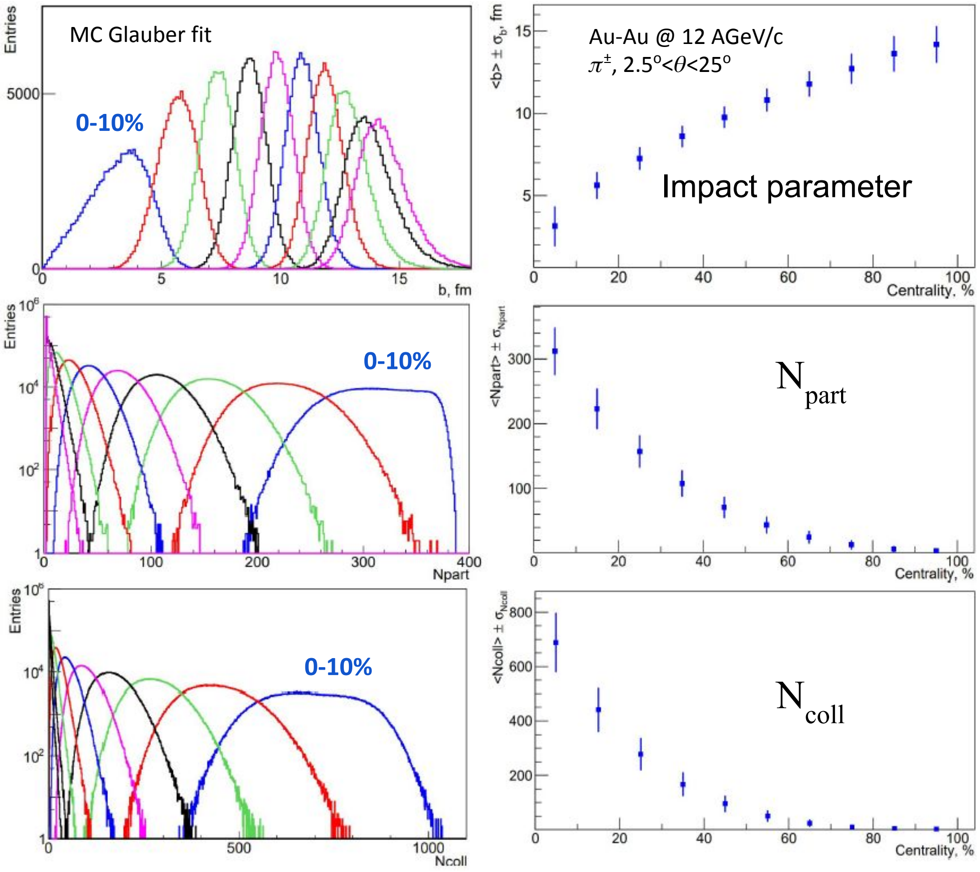
Code repository: *https://git.cbm.gsi.de/pwg-c2f/analysis/centrality*

MC-Glauber + NBD fitting procedure



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

Centrality determination using STS multiplicity



MC-Glauber configuration:

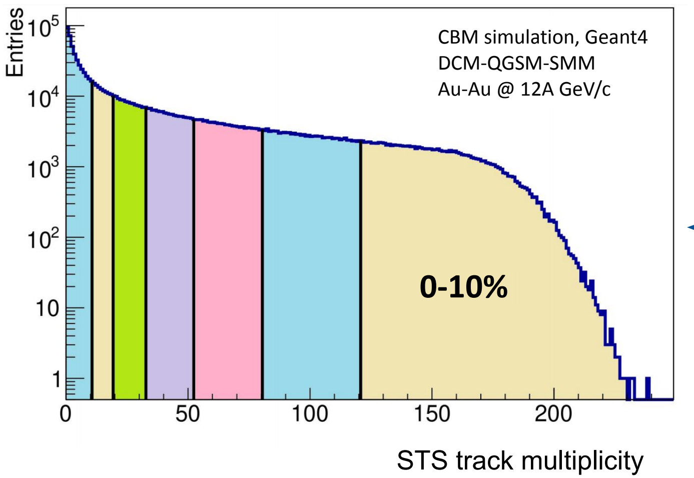
- Au-Au @ 12*A* GeV/*c*
- σ^{NN}_{inel} = 30 mb
- R = 6.38 fm, a = 0.535 fm, w = 0

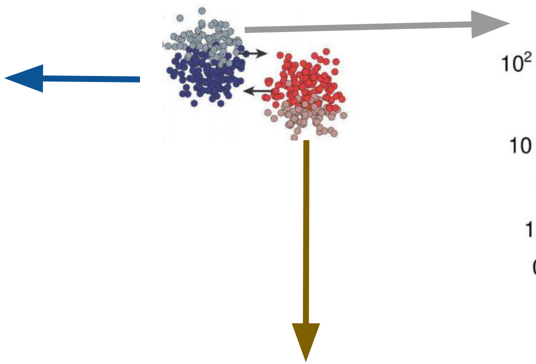
Mapping centrality (multiplicity) classes with geometry parameters:

b - Impact parameter
N_{part} - number of participants
N_{coll} - number of binary collisions

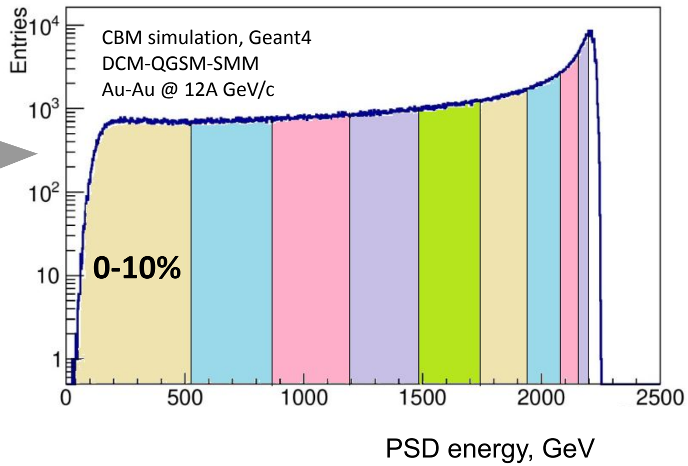
Centrality Estimators in CBM

Produced charged particles



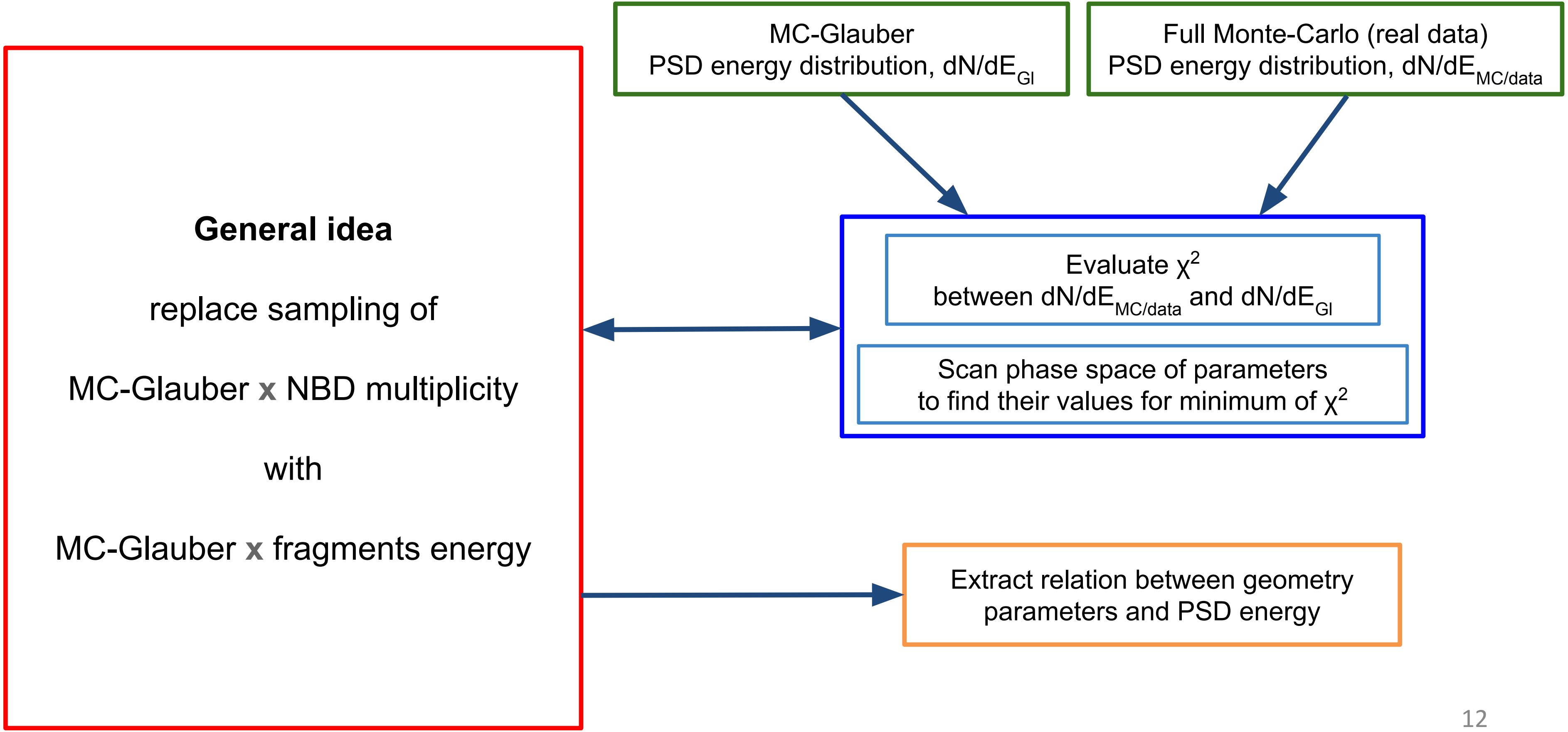


Projectile spectators

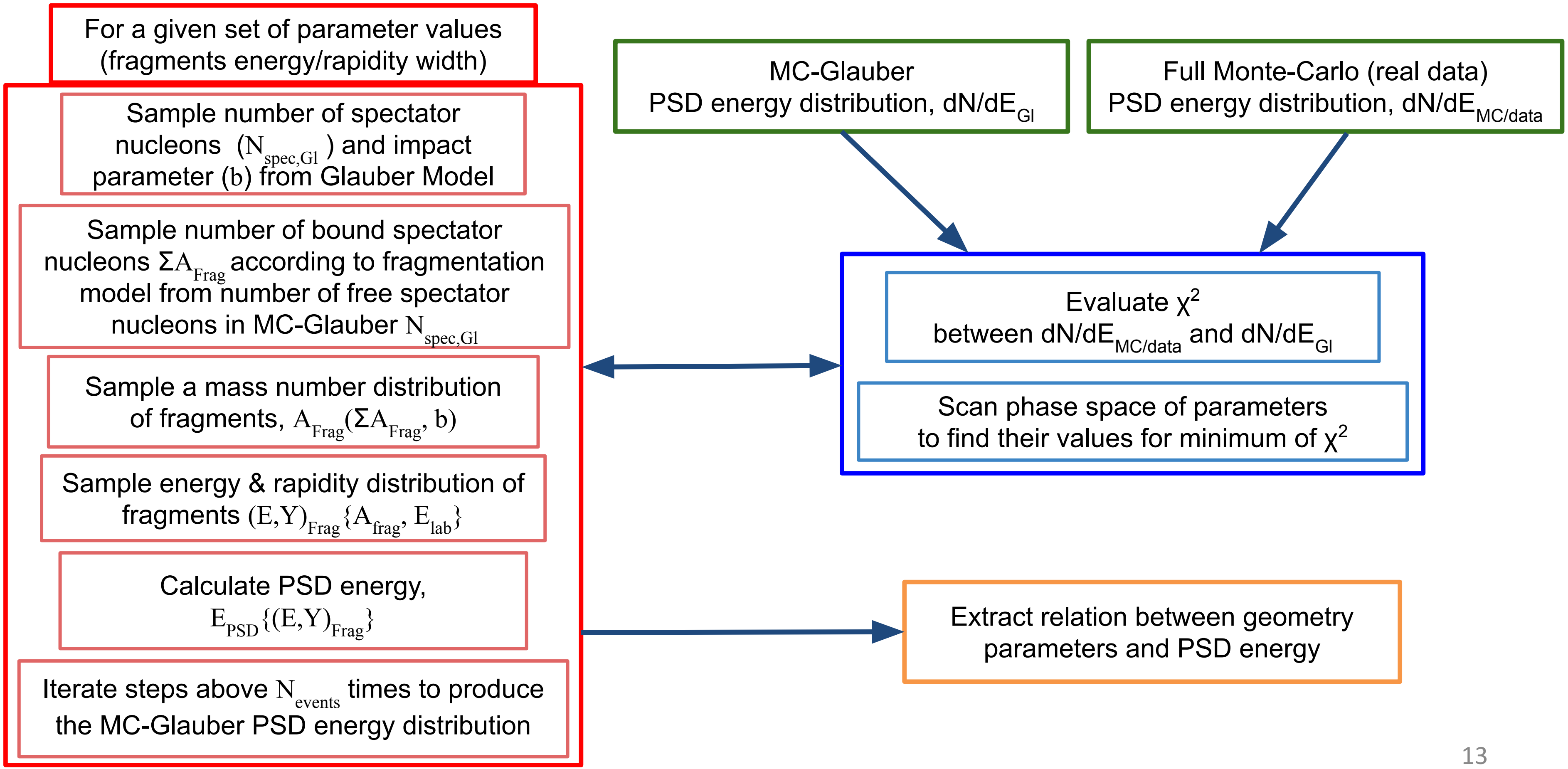


Target spectators
(not measured)

MC-Glauber+Spectators fitting procedure



MC-Glauber+Spectators fitting procedure



Fragment's mass number vs. Impact parameter distribution

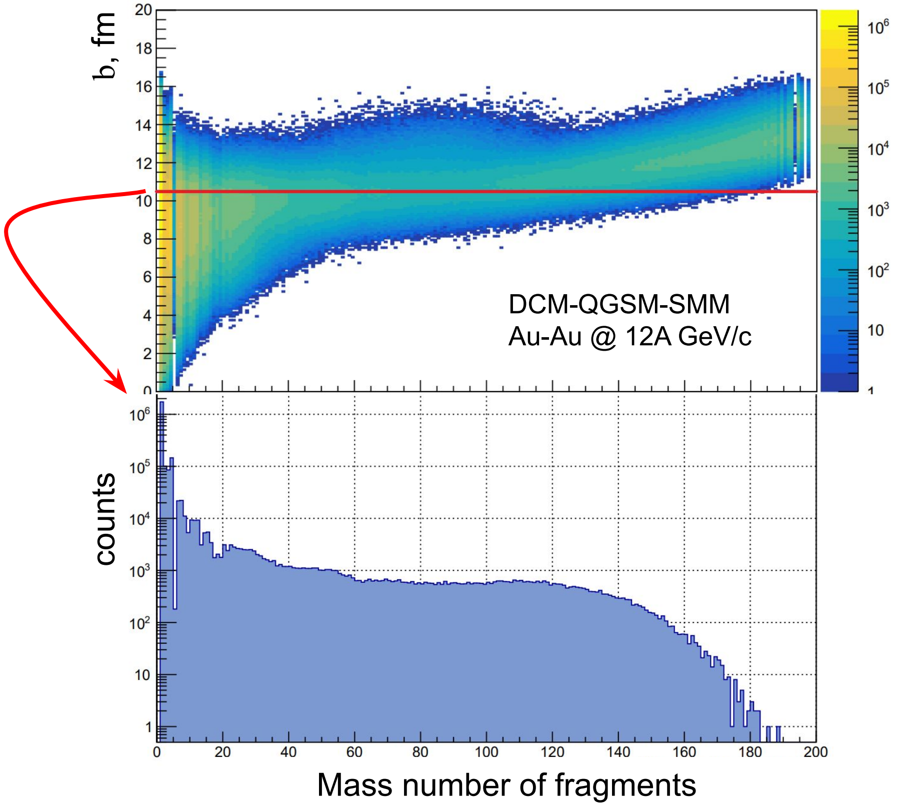
Sample number of spectator nucleons ($N_{spec,Gl}$) and impact parameter (b) from Glauber Model

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 PSD energy, $E_{PSD}\{(E,Y)_{Frag}\}$



Complicated shape of the distribution of impact parameter and fragment's mass reflects the fragments formation process

Note: for a full procedure the geometry (b, N_{spec}) will be sampled from MC-Glauber model not directly from DCM-QGSM-SMM as shown here

Sampling distribution of b vs. mass number of fragments

Sample number of spectator nucleons ($N_{spec,Gl}$) and impact parameter (b) from Glauber Model

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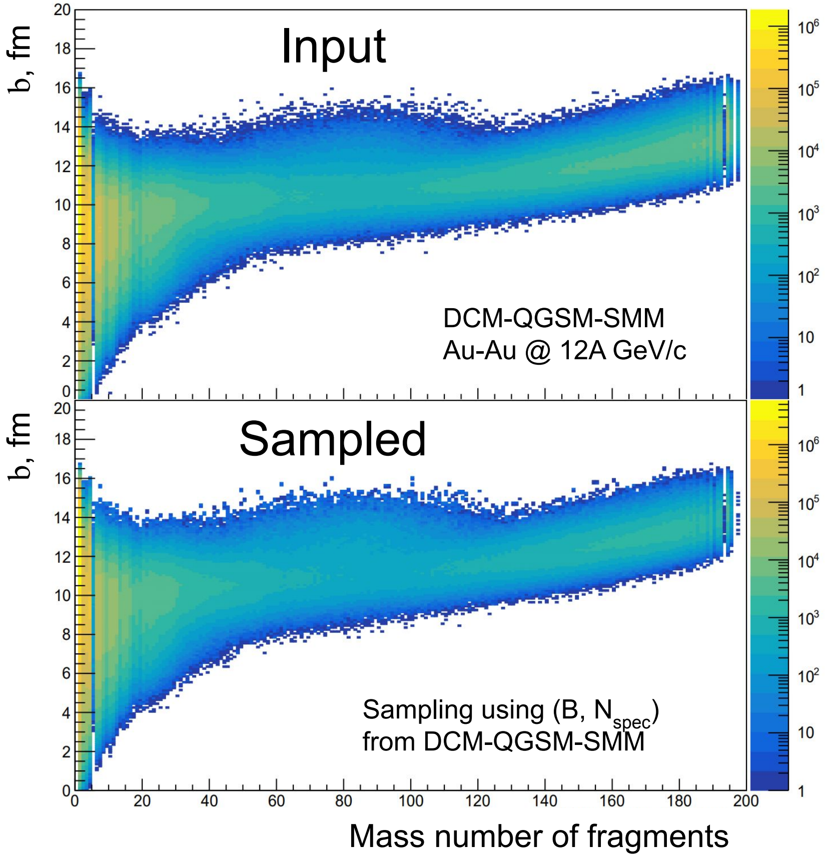


Sampled (lower) mass number distribution of fragments reproduces corresponding input distribution (upper) from the DCM-QGSM-SMM model

Population of fragments with energy and rapidity

Sample number of spectator nucleons ($N_{spec,Gl}$) and impact parameter (b) from Glauber Model

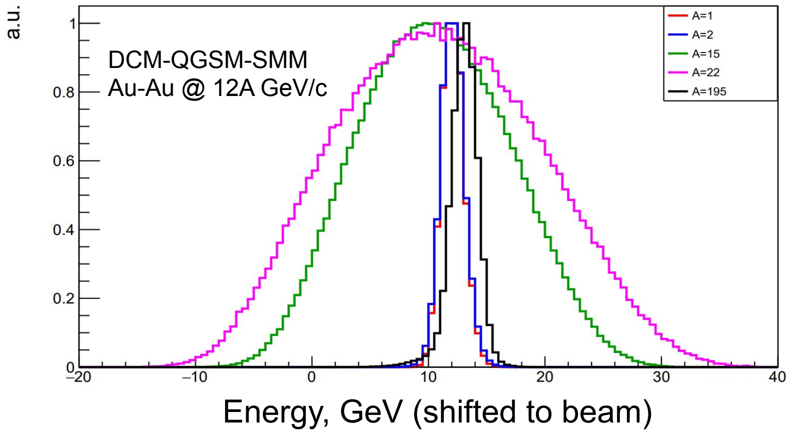
Sample number of bound spectator nucleons ΣA_{Frag} according to fragmentation model from number of free spectator nucleons in MC-Glauber $N_{spec,Gl}$

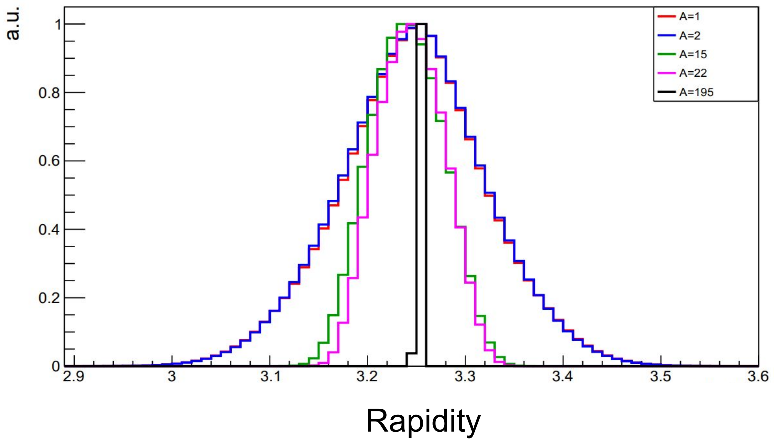
Sample a mass number distribution of fragments, $A_{Frag}(\Sigma A_{Frag}, b)$

Sample energy & rapidity distribution of fragments $(E,Y)_{Frag}\{A_{frag}, E_{lab}\}$

Calculate PSD energy, $E_{PSD}\{(E,Y)_{Frag}\}$

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





Sampled distribution of fragments: energy

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, $A_{Frag}(\Sigma A_{Frag}, b)$

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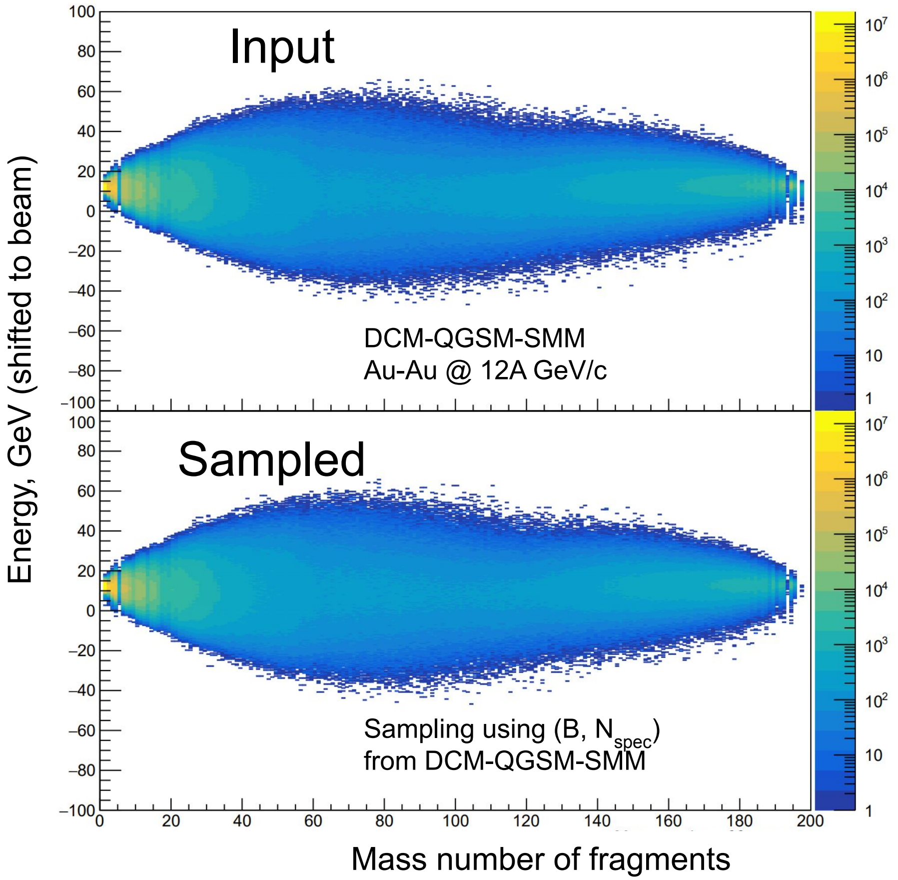

- Shape of the energy distribution vs. mass number can be easily parameterized
- Sampled distribution corresponds to the original from DCM-QGSM-SMM model

Effect of bound nucleons and spectator interaction

- 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 $N_{spec,Gl}$
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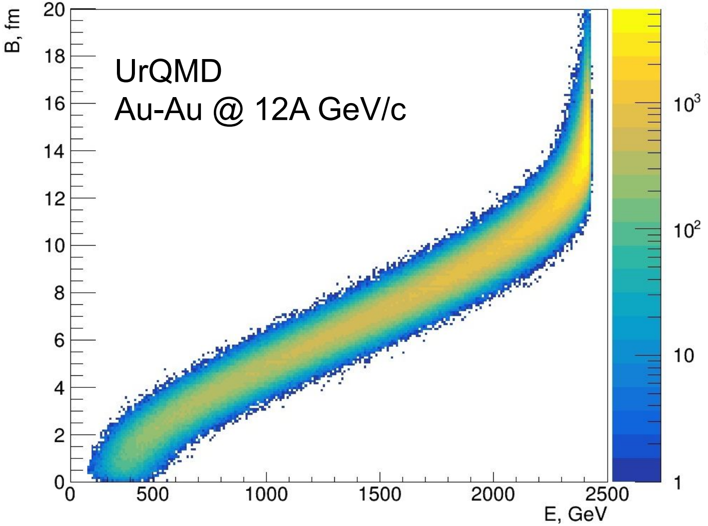
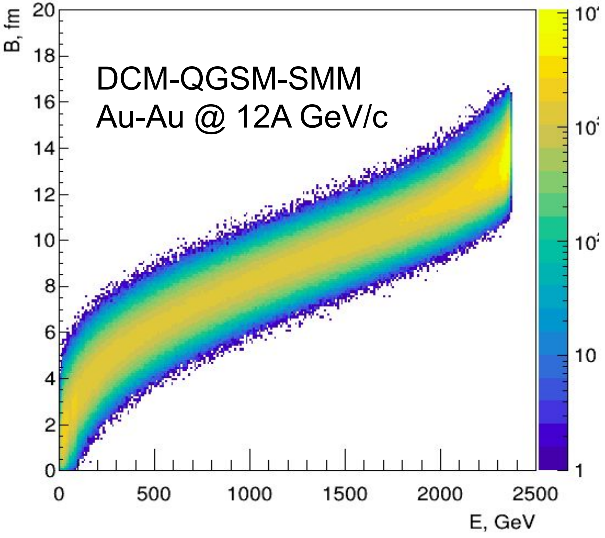
free nucleons



nucleons bound in fragments



- Widening of distribution of total energy of nuclear fragments for a certain value of b
- Decrease in the number of peripheral events with b value close to the size of nuclei
- Increase in the number of central collisions with a small number of spectator nucleons

Effect of bound nucleons and spectator interaction

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 $N_{spec,Gl}$

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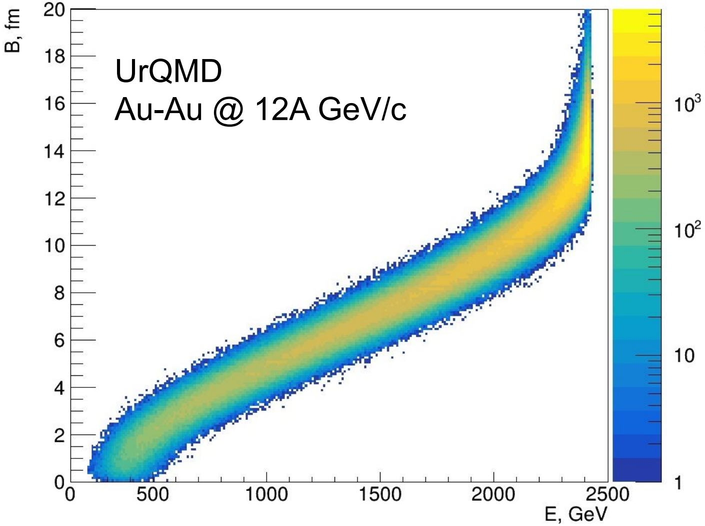
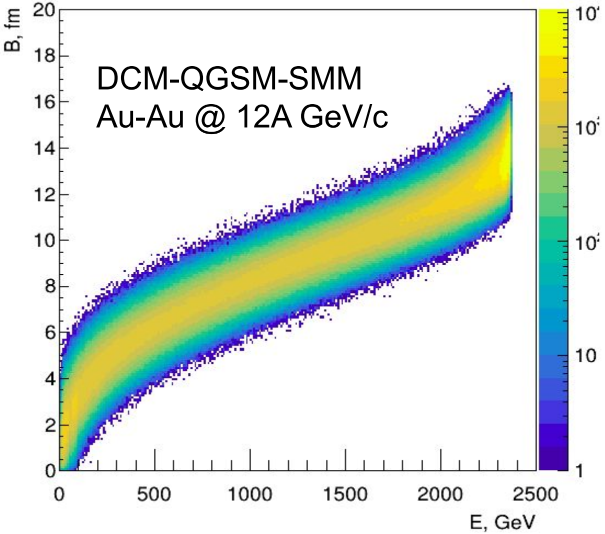
free nucleons



nucleons bound in fragments



Implementation in progress

1. Write to a file initial positions of nucleons generated by the DCM-QGSM-SMM
2. Change initial positions of nucleons in MC-Glauber model using positions from previous step
3. Run MC-Glauber model with changed positions of nucleons
4. Extract number of spectators using result of MC-Glauber model ($N_{spec,Gl}$)
5. Map $N_{spec,Gl}$ with number of spectators known from DCM-SMM-QGSM (ΣA_{Frag})

Summary

Procedure for centrality determination in CBM based on the MC-Glauber model
in a combination with the energy of spectator fragments is proposed and is being developed:

- Implemented sampling of the fragment’s mass number distribution
  and population of fragments with energy and rapidity
- Tuned results on the spectator production implemented in the DCM-QGSM-SMM model

In progress

- Incorporate effects of bound nucleons and spectators interaction
- Extract relation between PSD energy and (N_{part}, N_{coll}, b) using GEANT4 for CBM response simulations
- Investigate the effect on centrality determination due to the fragment loss in beam hole of the CBM PSD

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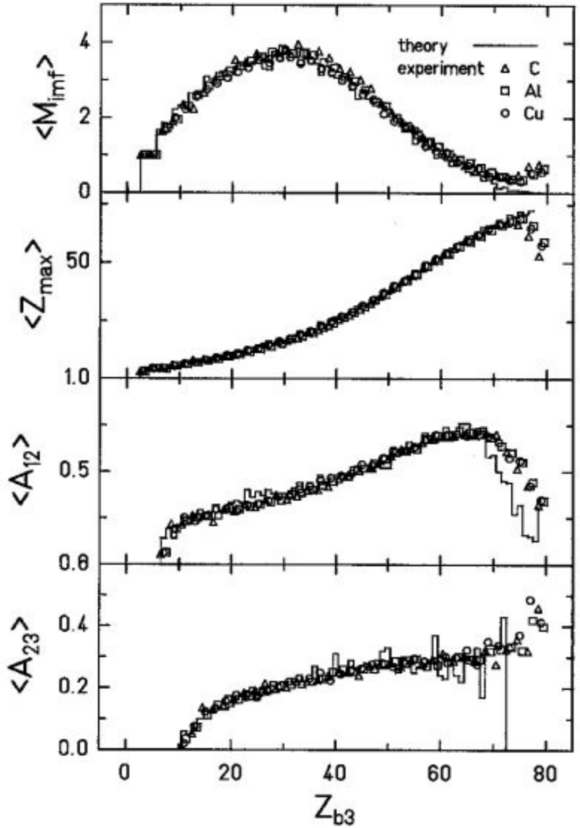
of the Russian Academic Excellence Project (contract no. 02.a03.21.0005, 27.08.2013)

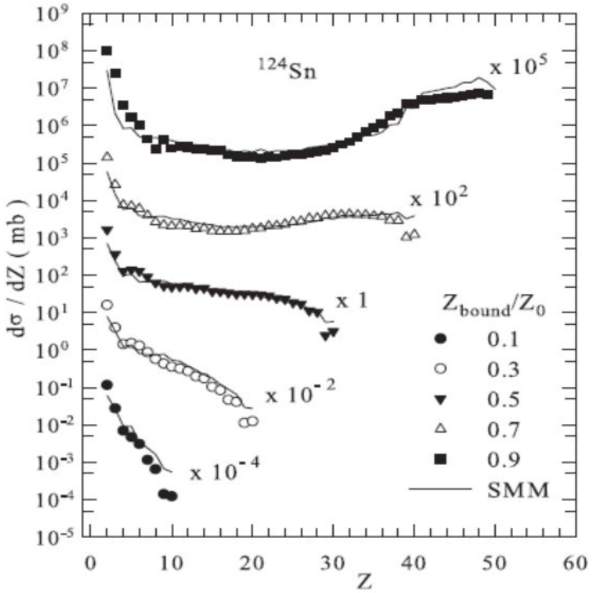
Backup

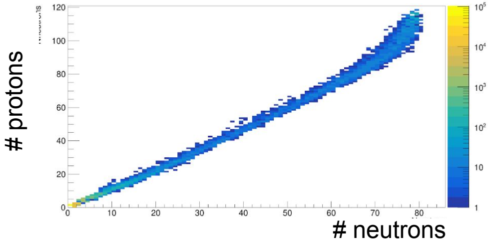
SMM description of the ALADIN's fragmentation data

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

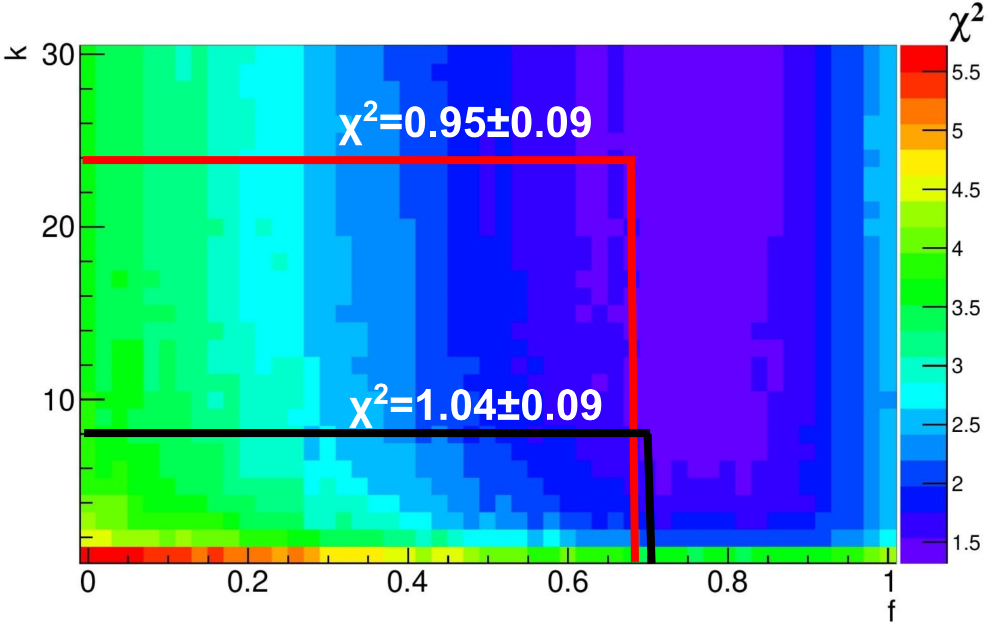


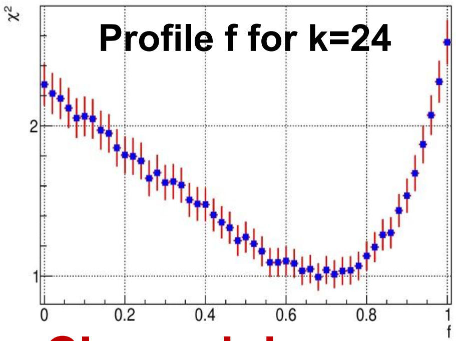
R.Ogul et al. PRC 83, 024608 (2011)





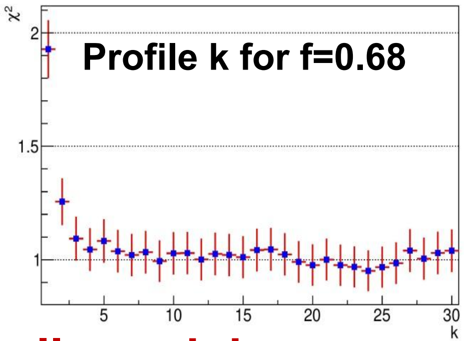
Self-consistency check





Clear minimum

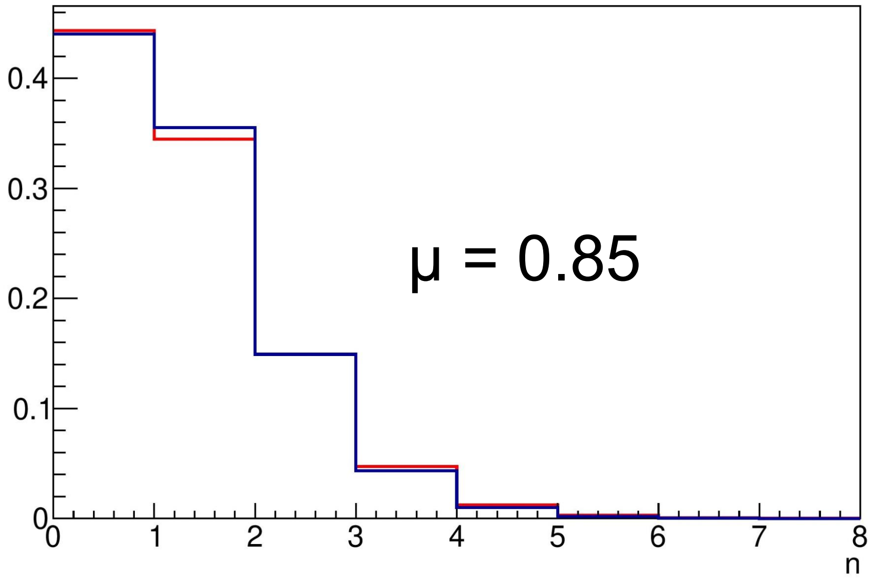
Scan the phase space of (f, k) to find a value of μ with minimal χ^2

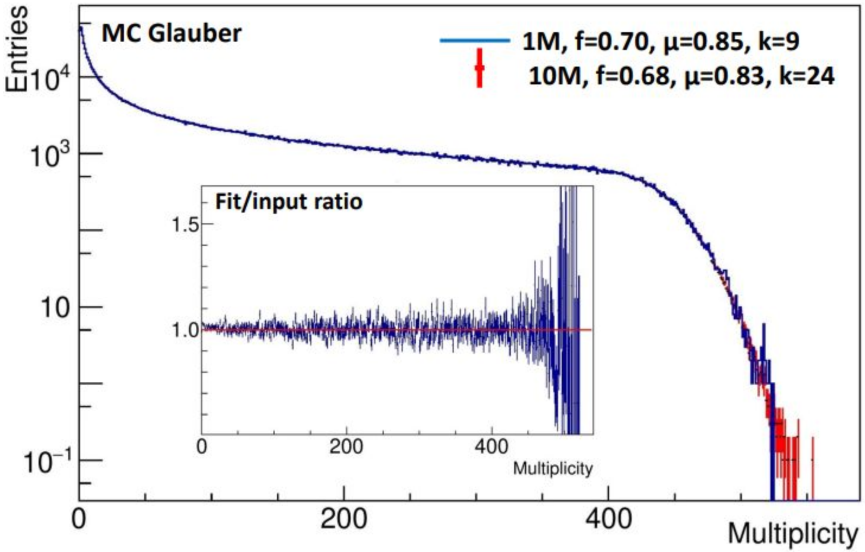


Shallow minimum

Input:	fit:
f=0.70, μ=0.85, k=9	f=0.68, μ=0.83, k=24

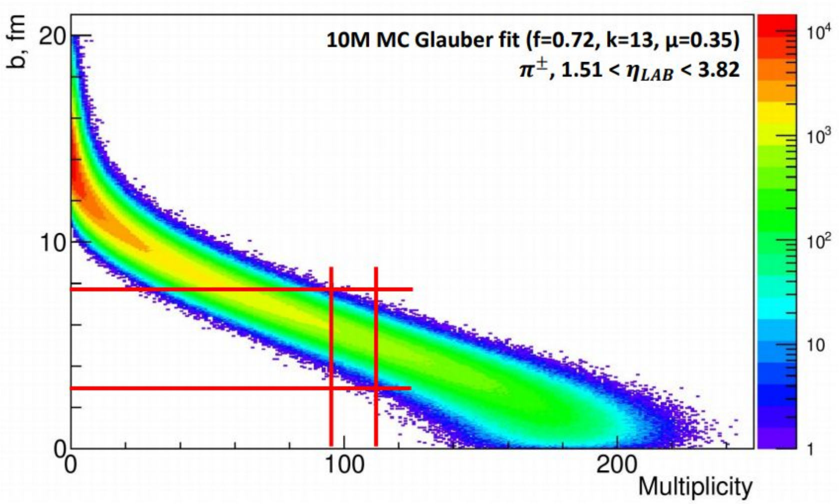
NBD at different values of k

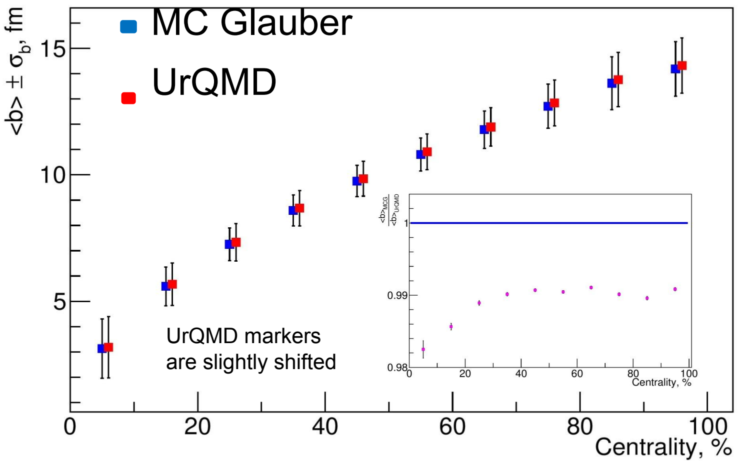




MC Glauber fit results are in good agreement with simulated input

Centrality determination using STS multiplicity





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

Mass number distribution of fragments for one event

Sample number of spectator nucleons (N_{spec}) and impact parameter (b) from Glauber Model

Sample a mass number distribution of fragments, $A(N_{spec}, b)$

Sample energy & rapidity distribution of fragments $(E,Y)_{frag}\{A(N_{spec}, b), E_{lab}\}$

Calculate PSD energy, $E_{PSD}\{(E,Y)_{frag}\}$

Procedure to sample distribution for a given event

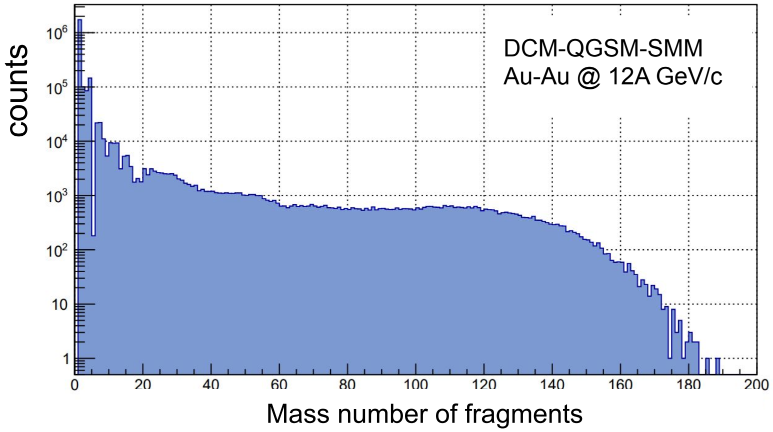
1.a. Generated a fragment mass number A_1

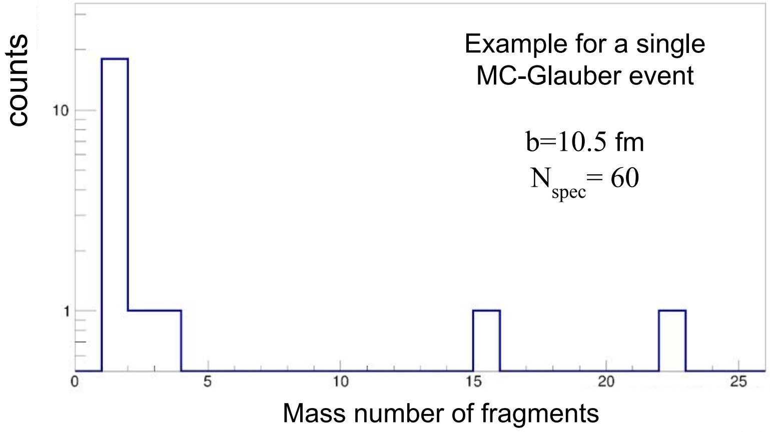
b. if $\{ N_{spec} < A_1 \}$ { then skip and do step #1.a again }

else $\{ N'_{spec} = N_{spec} - A_1 \}$

2.Repeat step #1 while $N_{spec'} > 0$

3.Result: $N_{spec} = A_1 + A_2 + \ldots A_N$





Sampled distribution of fragments: rapidity

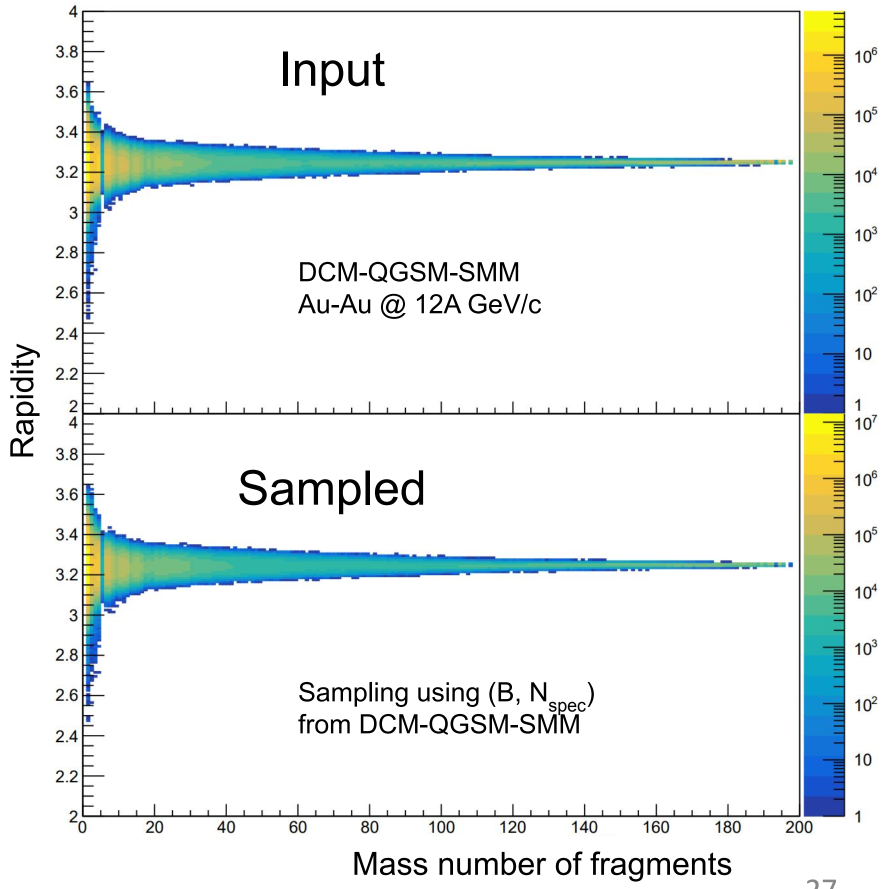
Sample number of spectator nucleons (N_{spec}) and impact parameter (b) from Glauber Model

Sample a mass number distribution of fragments, $A(N_{spec}, b)$

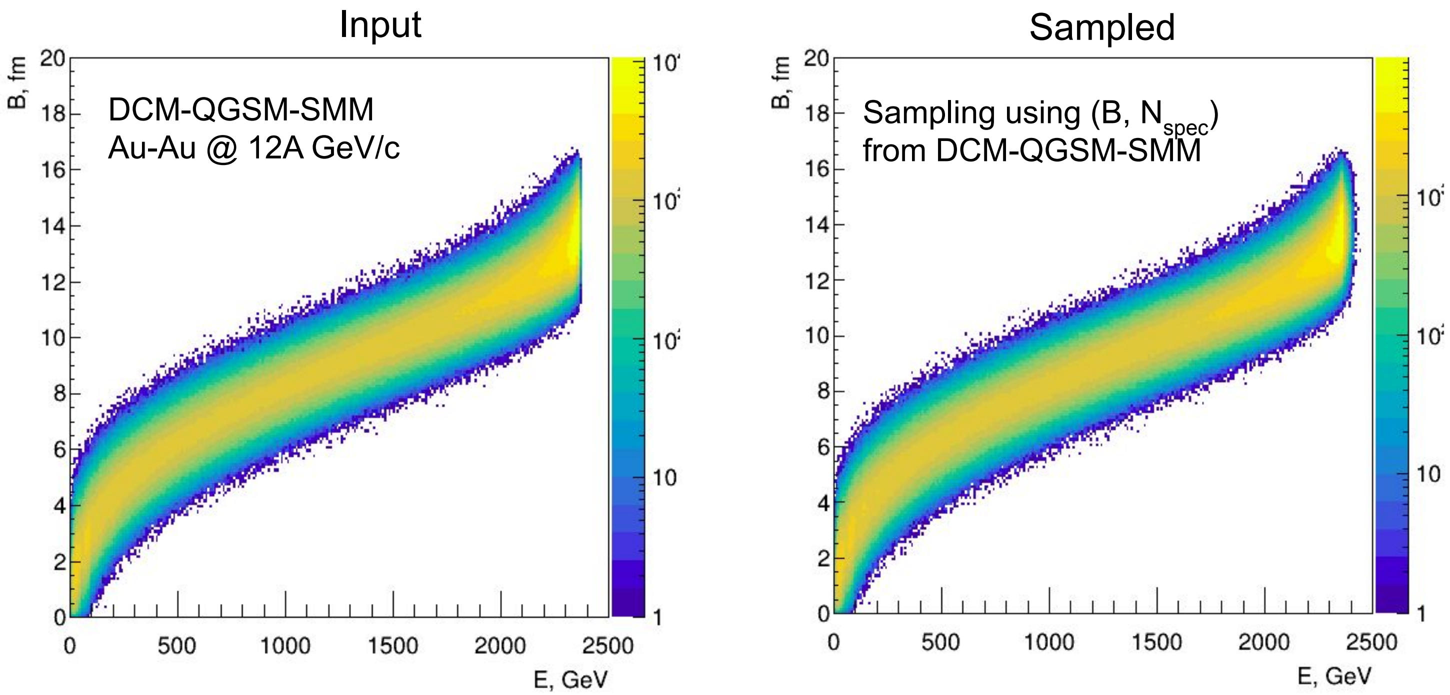
Sample energy & rapidity distribution of fragments $(E,Y)_{frag}\{A(N_{spec}, b), E_{lab}\}$

Calculate PSD energy, $E_{PSD}\{(E,Y)_{frag}\}$

- Shape of the rapidity distribution vs. mass number can be easily parameterized
- Same result: sampled distribution corresponds to that used as an input (upper)



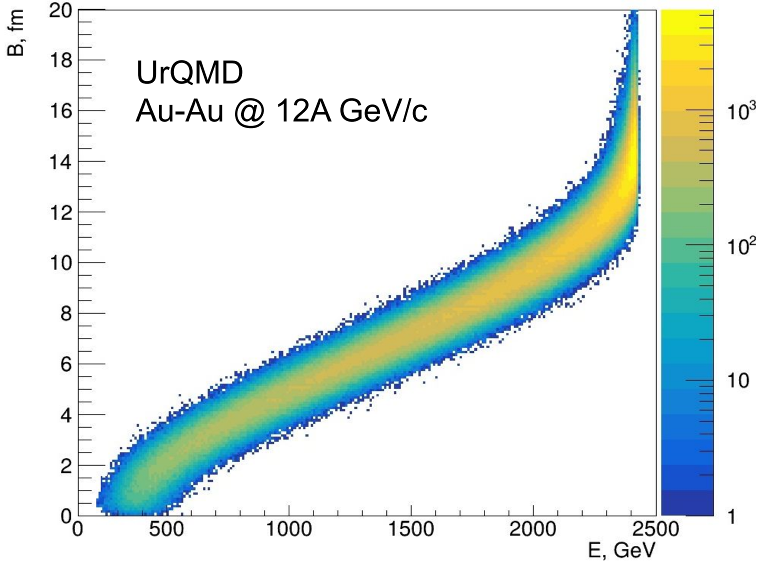
Spectators' energy VS impact parameter: **with** the fragmentation of nuclei



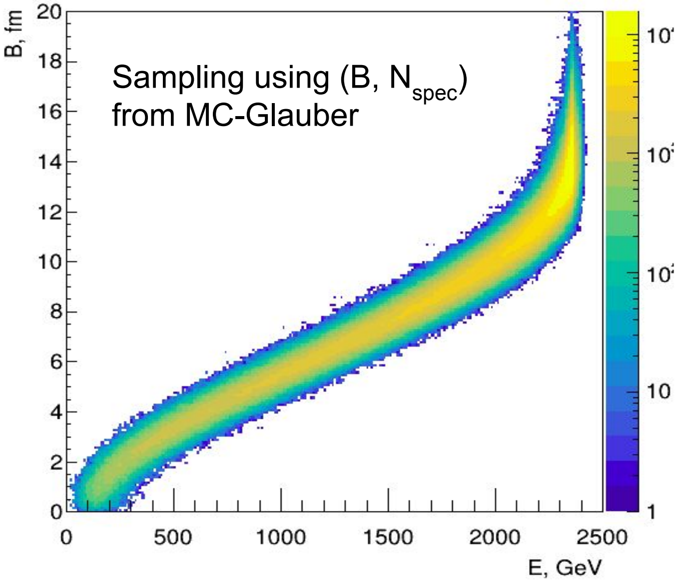
Developed procedure based on the MC-Glauber model reproduces relation from DCM-QGSM-SMM, which takes into account the process of fragmentation of projectile fragments and their interaction with produced particles

Spectators' energy VS impact parameter: **without** the fragmentation of nuclei

Input



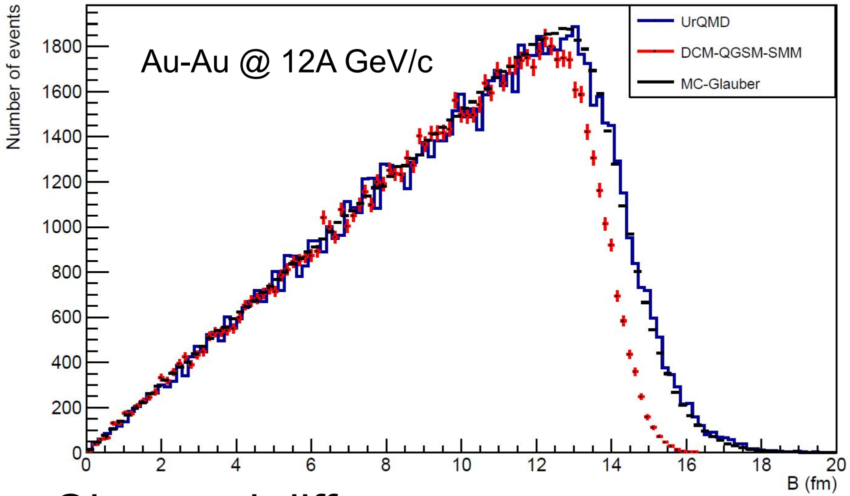
Sampled



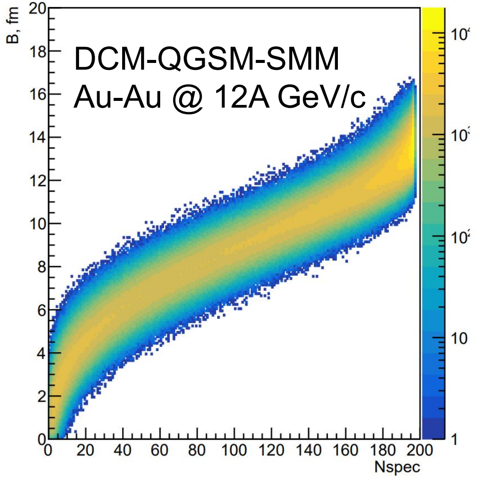
Reproduce distribution from UrQMD model, which takes into account only distribution of nucleons in the fragment, but not the process of fragmentation of nuclear fragments and their interaction with produced particles.

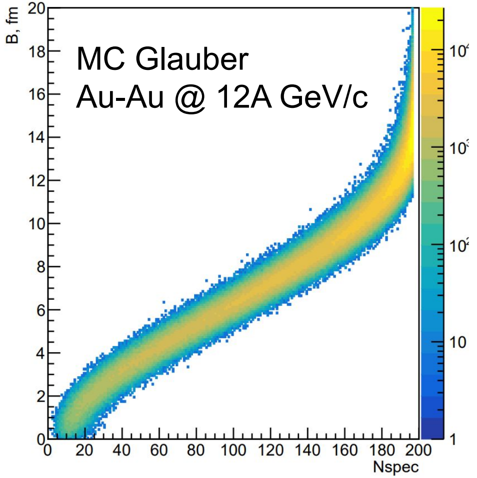
Differences between DCM-QGSM-SMM and MC Glauber

Impact parameter distribution



Correlation between impact parameter and number of spectator nucleons





Observed differences:

(a) shape of the tail for impact parameter distribution

(b) shape of the b vs. number of spectators N_{spec} (due to different definition of “spectators”)