Методы определения центральности в эксперименте BM@N

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Научная сессия секции ядерной физики ОФН РАН

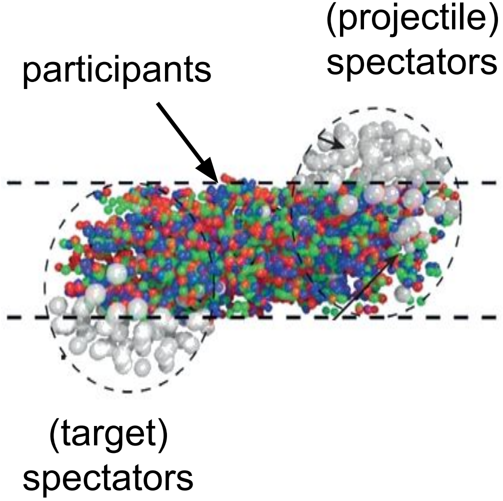
Motivation for centrality determination

- 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)

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

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



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

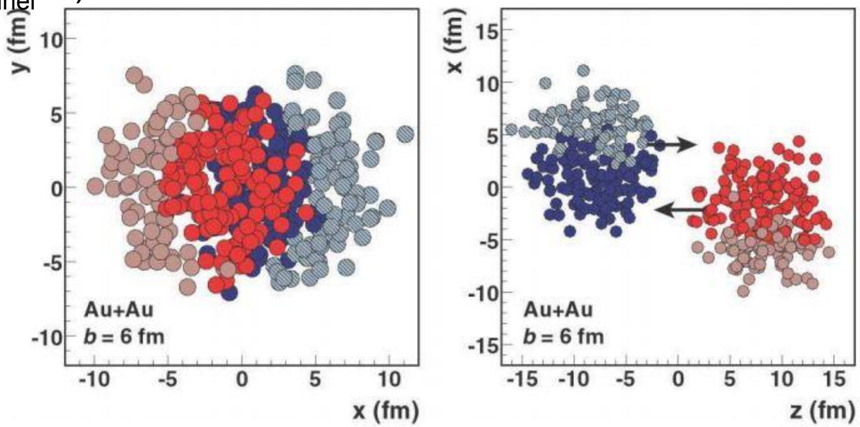
- Colliding nuclei
- Inelastic nucleon-nucleon cross section (σ^{NN}_{inel}) (depends on collision energy)
- Nuclear charge densities (Wood-Saxon distribution)

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

Geometry parameters

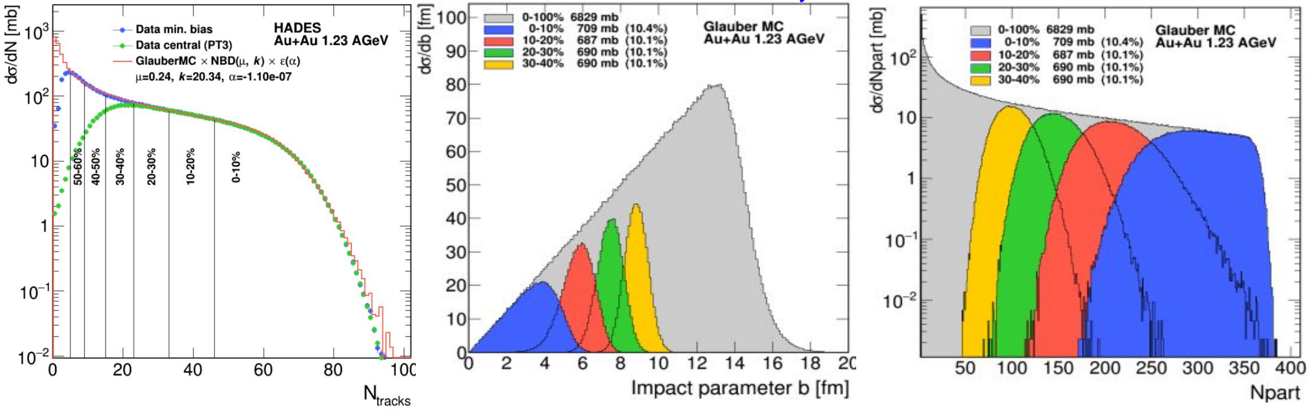
b – impact parameter
N_{part} – number of nucleons participating in the collision
N_{spec} – number of spectator nucleons in the collision
N_{coll} – number of binary NN collisions

Glauber Modeling in High Energy Nuclear Collisions: ARNPS57:205-243,2007



Centrality determination

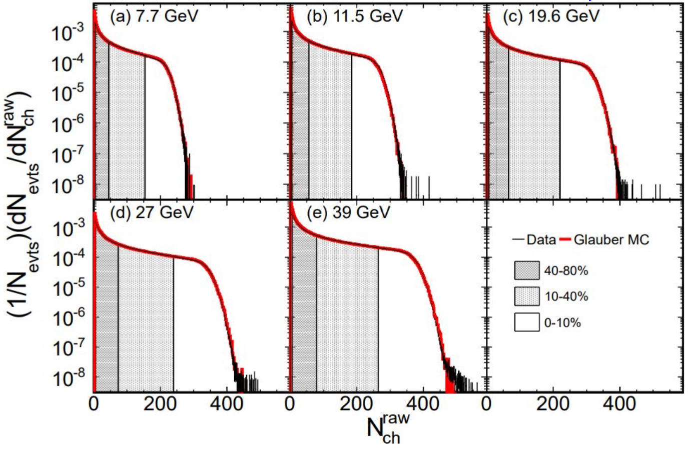
HADES, Au+Au 1.23A GeV



Eur. Phys. J. A (2018) 54: 85

Centrality Classes	$b_{\min}$	$b_{\max}$	$\langle b \rangle$
0 – 5 %	0.00	3.30	2.20
5 – 10 %	3.30	4.70	4.04
10 – 15 %	4.70	5.70	5.22
15 – 20 %	5.70	6.60	6.16
20 – 25 %	6.60	7.40	7.01
25 – 30 %	7.40	8.10	7.75
30 – 35 %	8.10	8.70	8.40
35 – 40 %	8.70	9.30	9.00
40 – 45 %	9.30	9.90	9.60
45 – 50 %	9.90	10.40	10.15
50 – 55 %	10.40	10.90	10.65
55 – 60 %	10.90	11.40	11.15

STAR, Au+Au, BES



Phys. Rev. C 86, 054908 (2012)

Centrality (%)	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
0-5%	337 ± 2	774 ± 28
5-10%	290 ± 6	629 ± 20
10-20%	226 ± 8	450 ± 22
20-30%	160 ± 10	283 ± 24
30-40%	110 ± 11	171 ± 23
40-50%	72 ± 10	96 ± 19
50-60%	45 ± 9	52 ± 13
60-70%	26 ± 7	25 ± 9
70-80%	14 ± 4	12 ± 5

Centrality determination based on multiplicity provides with:

- impact parameter (b)
- number of participating nucleons (N_{part})

Similar centrality estimator is needed for comparisons with STAR, HADES, etc.

Model dependence of b, N_{part}

The MC Glauber non-realistic $\mathbf{N_{part}}$ simulations at low energies:

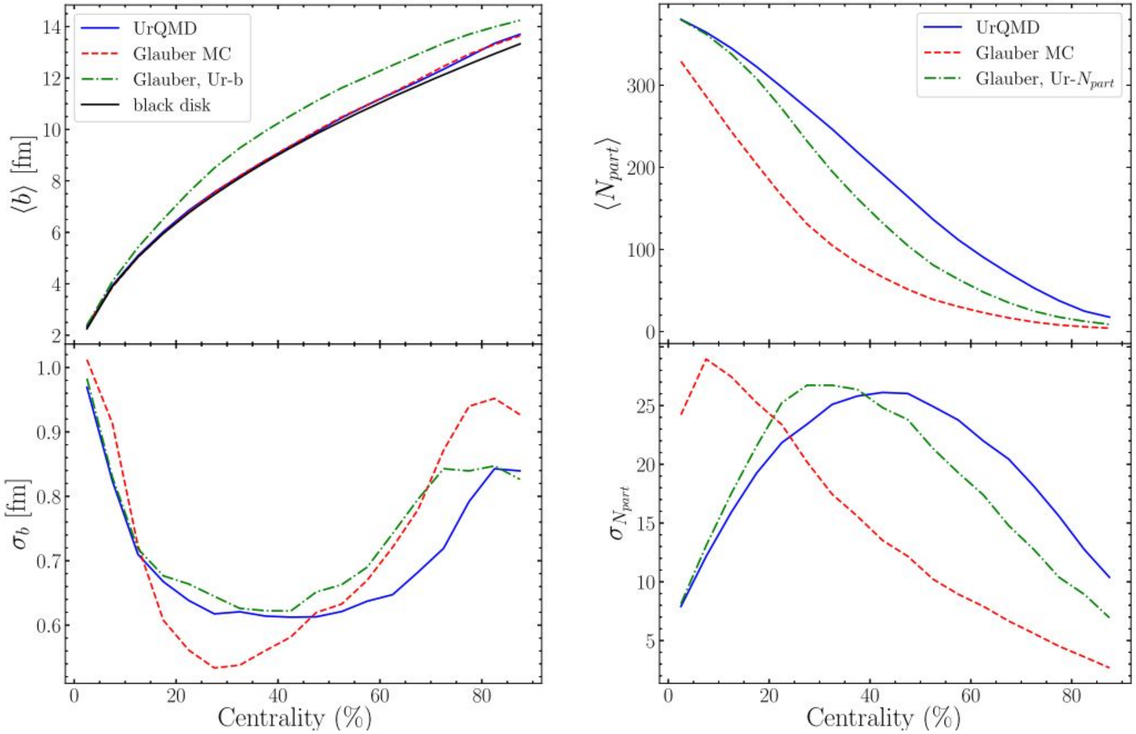
- elastic scatterings

Differences in of number of participant nucleons ($\mathbf{N_{part}}$) distributions from UrQMD and MC

The impact parameter (**b**) - model independent centrality estimator

Use MC Glauber for centrality determination

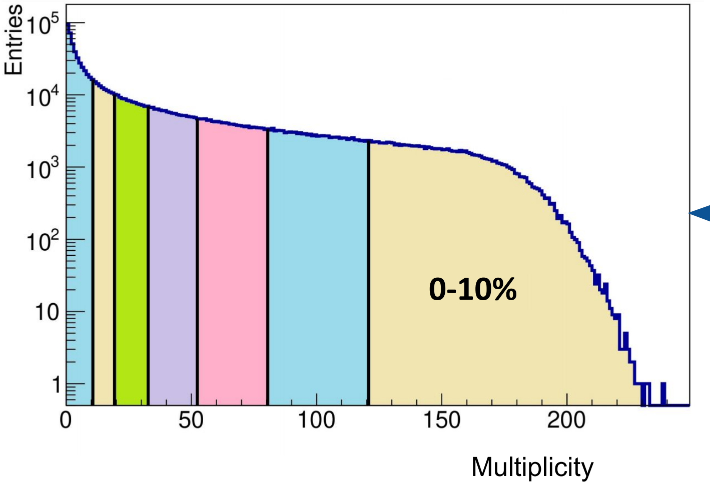
Eur. Phys. J. C 83, 792 (2023)

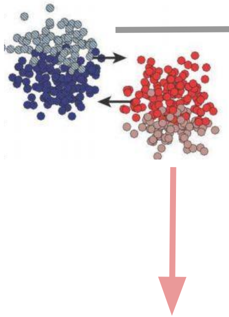


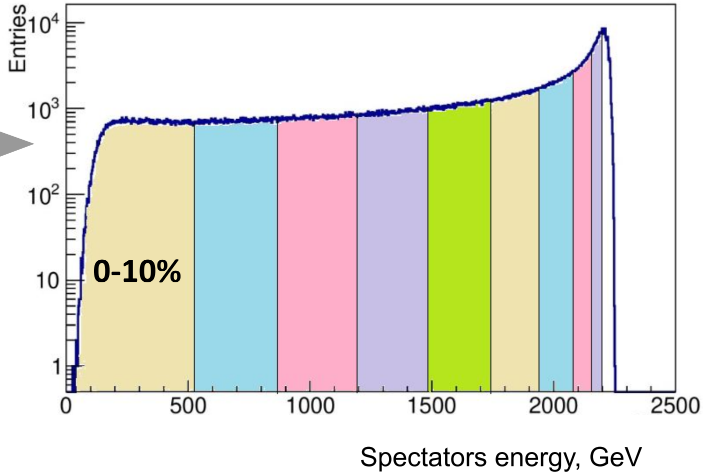
Types of centrality estimators

Produced charged particles

Spectators







(Target spectators not measured for fixed-target)

BM@N subsystems for centrality determination

SImulation:

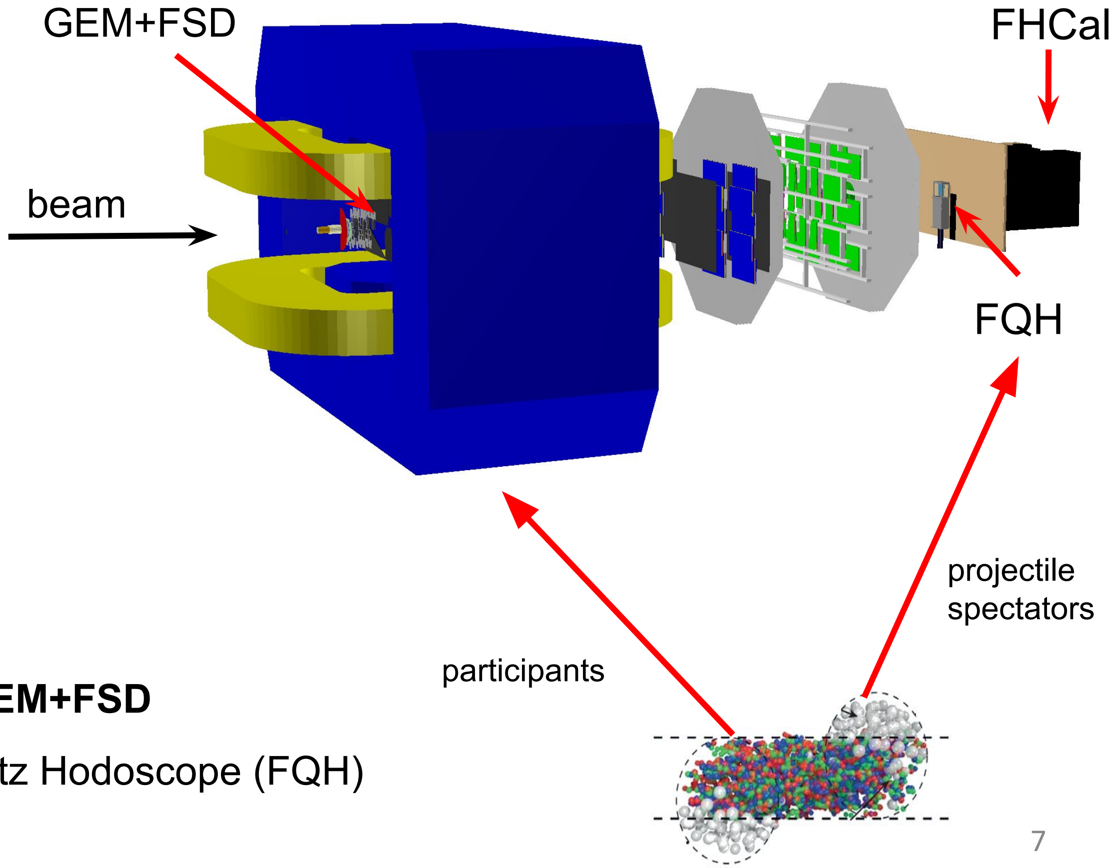
- Xe-Cs @4.0*A* GeV
- GEANT4 transport

Data:

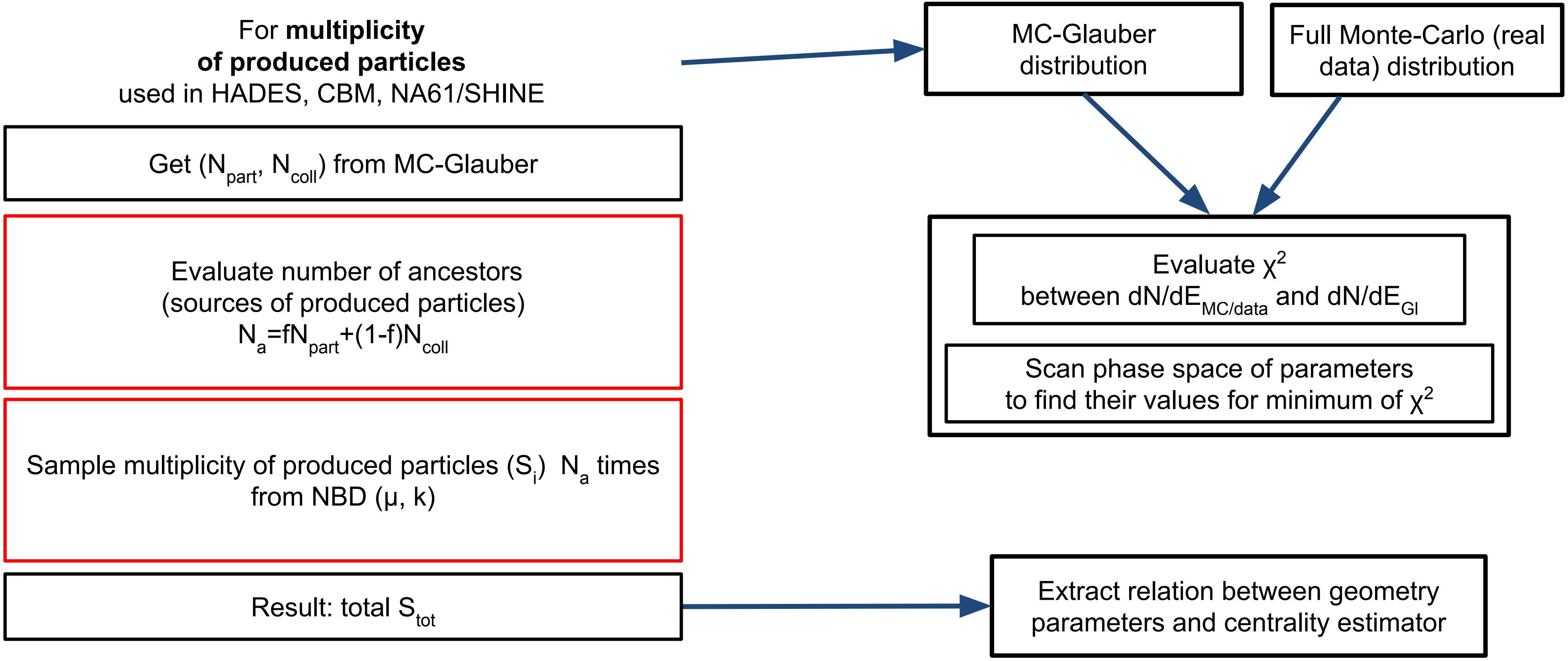
- run8 Xe-CsI @3.8*A* GeV
- Pile-up cut
- More than 1 track in vertex reconstruction

Subsystems

- Participants: **Tracking system GEM+FSD**
- Spectators: FHCal, Forward Quartz Hodoscope (FQH)

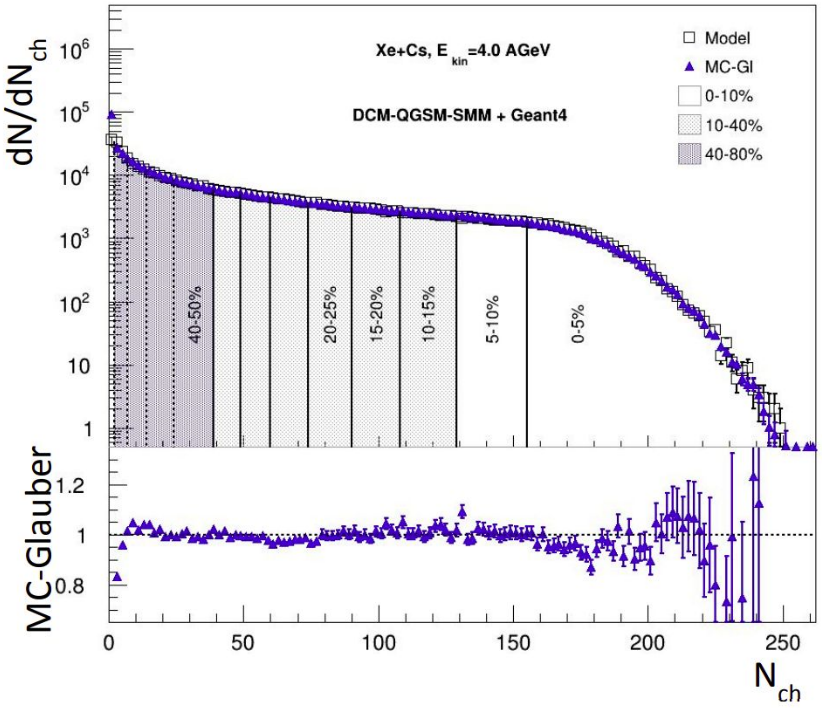


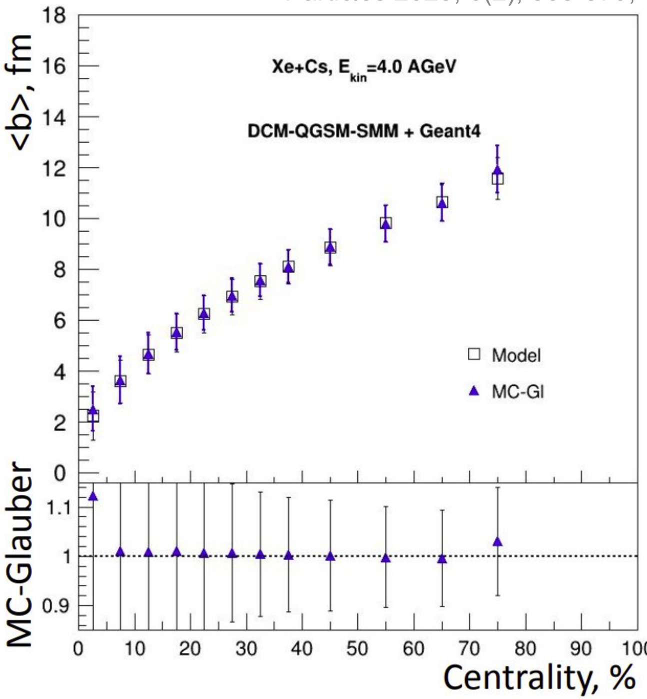
Centrality determination based on Monte-Carlo sampling of produced particles



MC-Glauber fit result Xe-Cs @ 4.0 AGeV

Particles 2023, 6(2), 568-579;





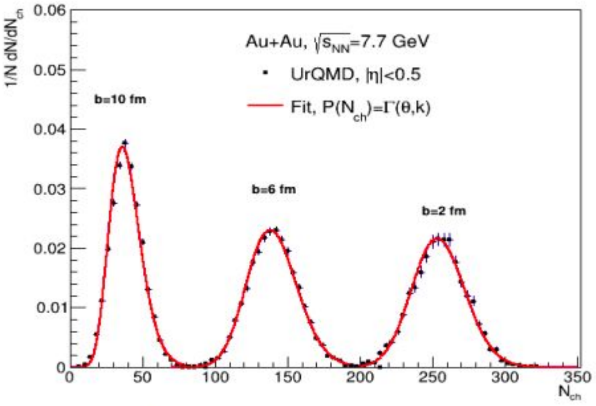
- Good agreement between Model data and fit
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM

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

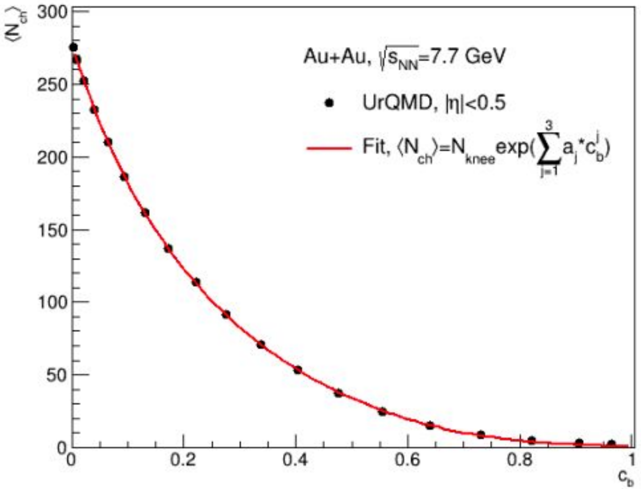
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

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

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

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

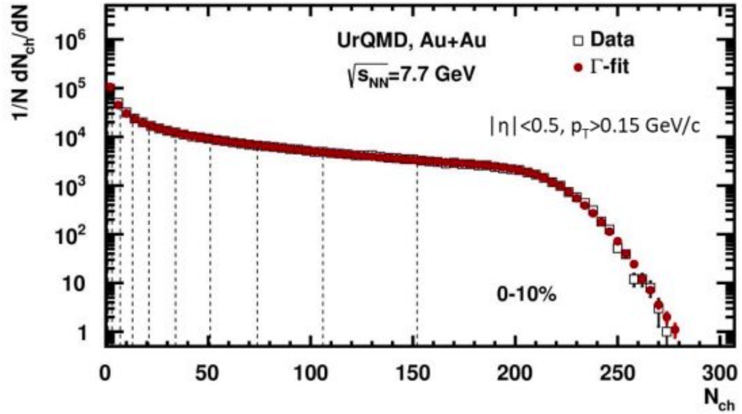
- Find probability of *b* for fixed range of N_{ch} using Bayes' theorem:

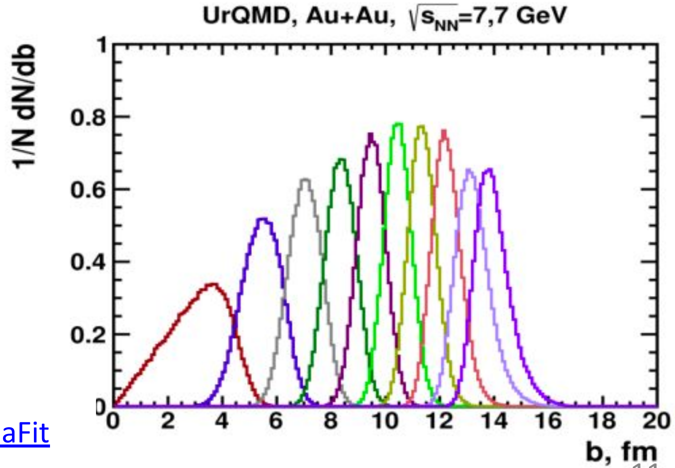
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(N_{ch}|b)dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$

- **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

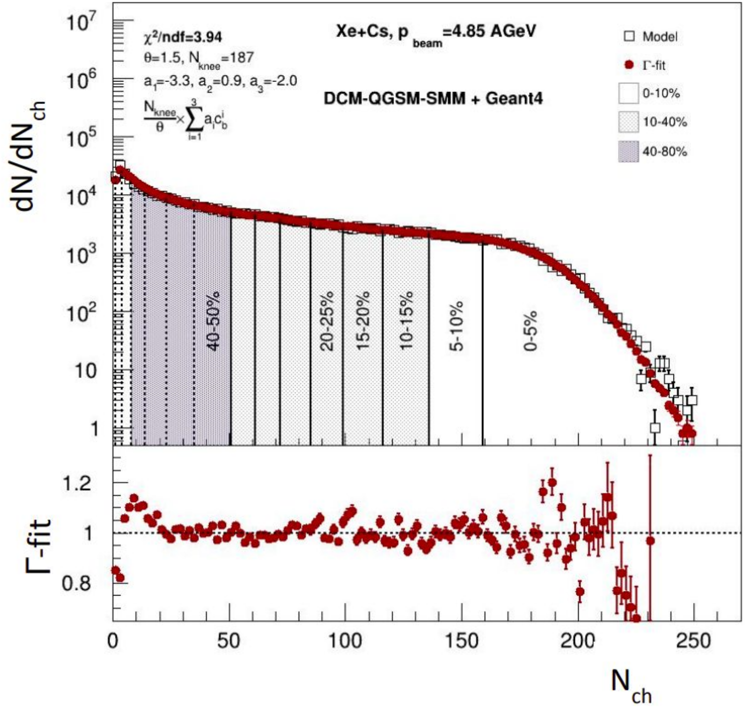


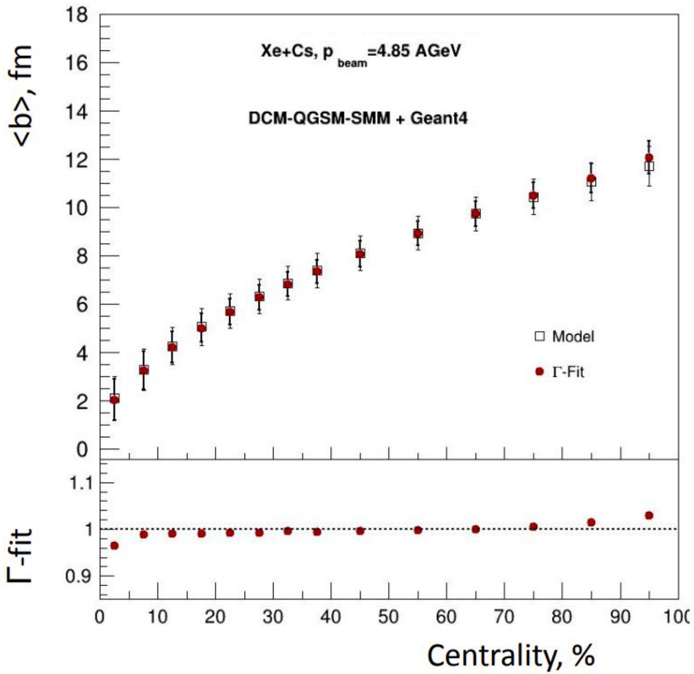


R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902
Implementation for MPD and BM@N by D. Idrisov: https://github.com/Dim23/GammaFit
Example of application in MPD: **P. Parfenov et al., Particles 4 (2021) 2, 275-287**

Γ-fit result Xe-Cs @ 4.0 AGeV

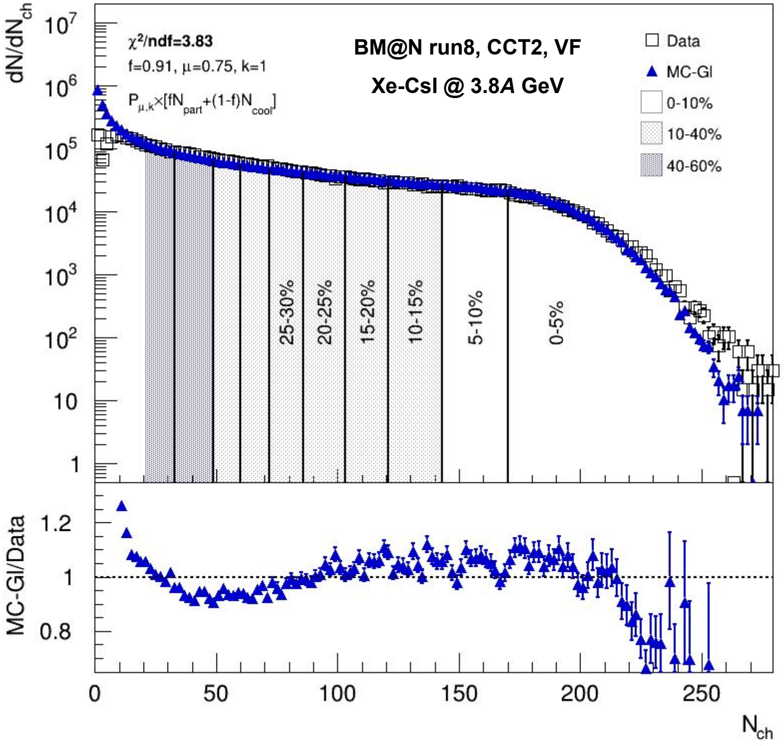
Particles 2023, 6(2), 568-579;

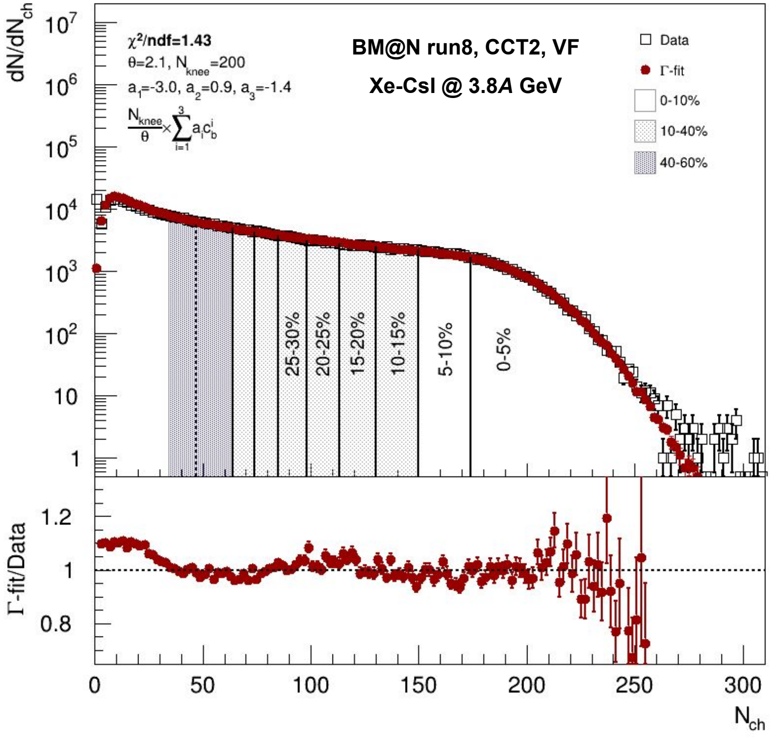




- Good agreement between Model data and fit
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM

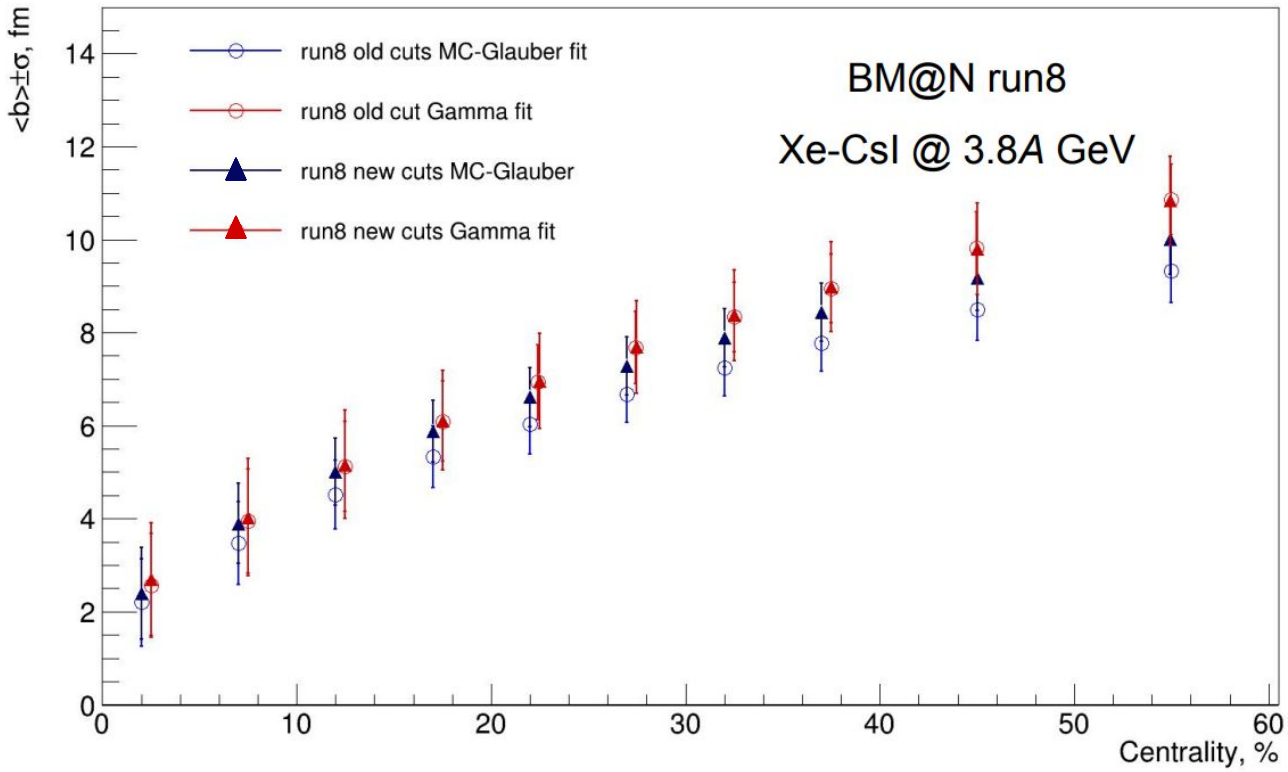
Result of centrality determination at Xe-CsI @ 3.8 AGeV





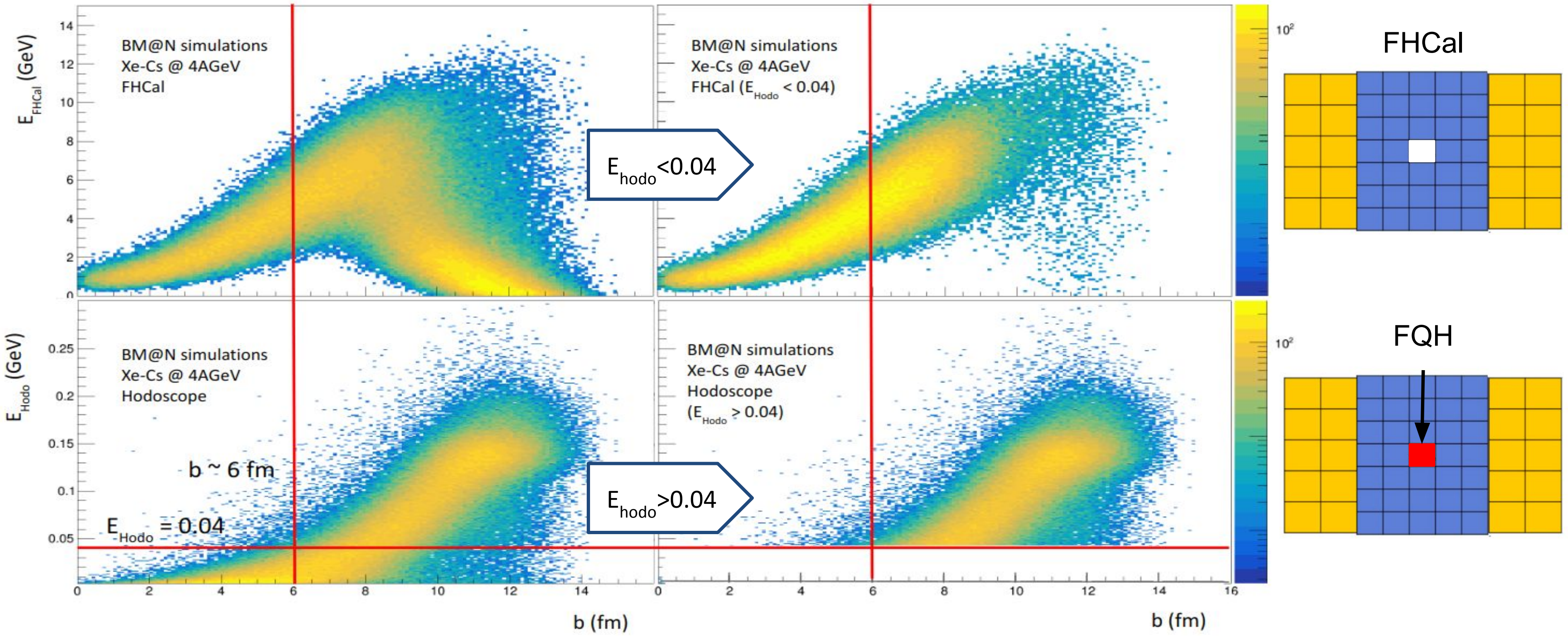
- Centrality determination methods were applied on experimental Xe-CsI data
- Good agreement between data and fit for both methods
- New centrality classes is used in analysis (see talk by M.Mamaev)

Comparison between impact parameter distributions



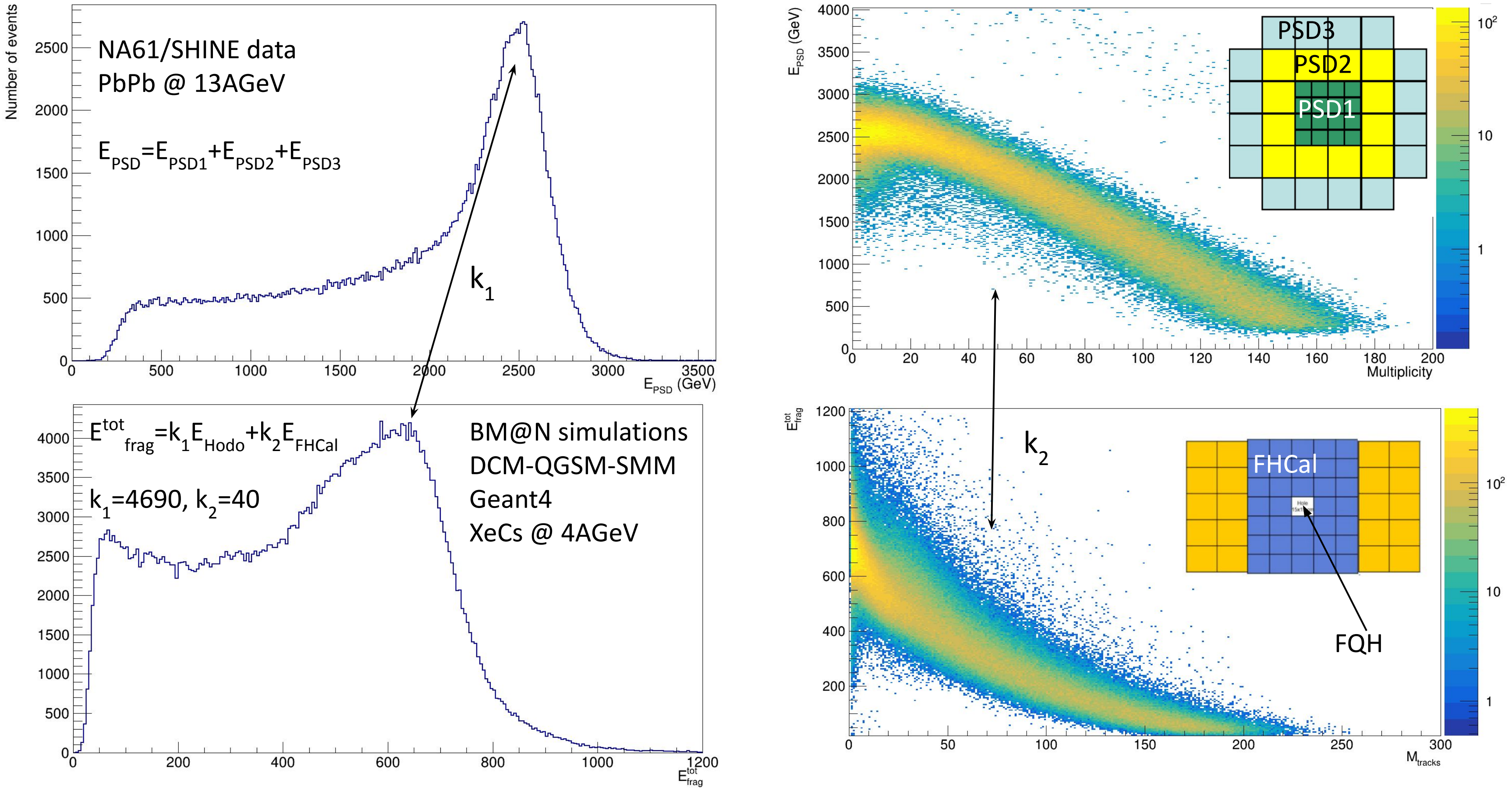
Γ-fit and MC-Glauber are good agreement

Possibilities of spectators fragments as estimators



- Physical threshold of switching between estimators could be Hodoscope signal E_{Hodo}=0.04 (corresponding to b~6fm)
- 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



Use FHCal and quartz hodoscope (FQH) as two parts of one detector.

Summary

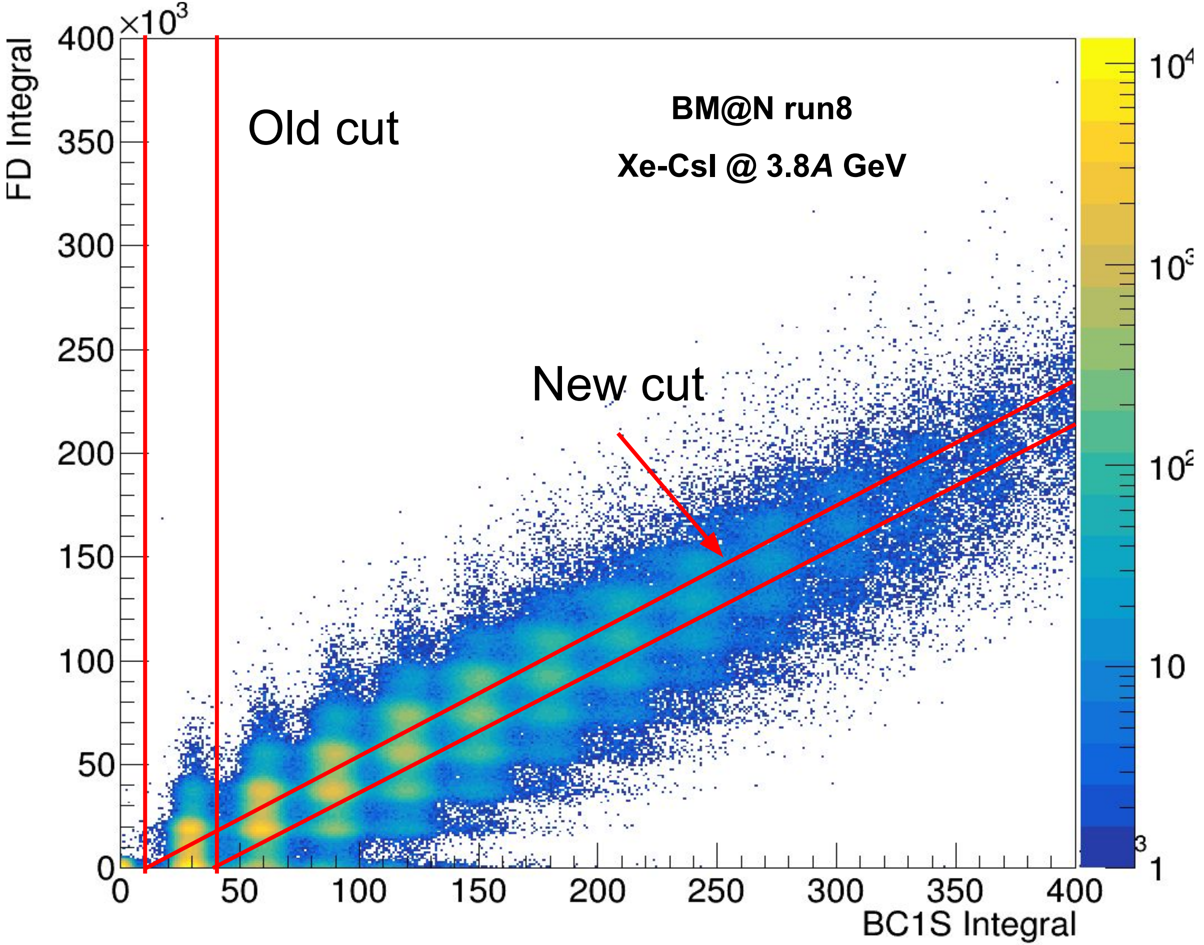
- Methods of centrality determination are presented:
  - MC Glauber for multiplicity of produced particles
  - The Bayesian inversion method for multiplicity
- Relation between impact parameter and centrality classes is extracted
- Possibilities of using of forward detectors for centrality determination was studied

Work in progress:

- Combination of forward detectors can be used to avoid effects due to the beam hole in FHCal

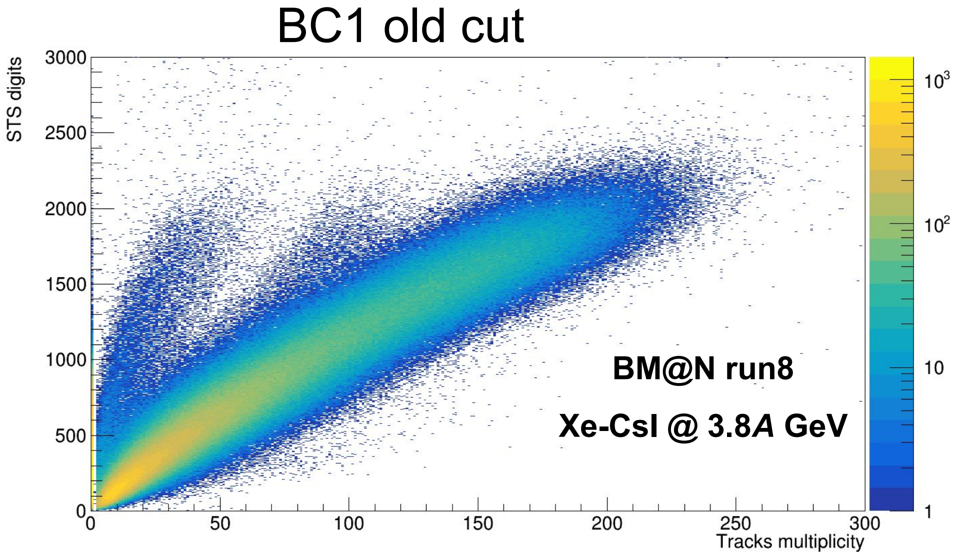
Backup

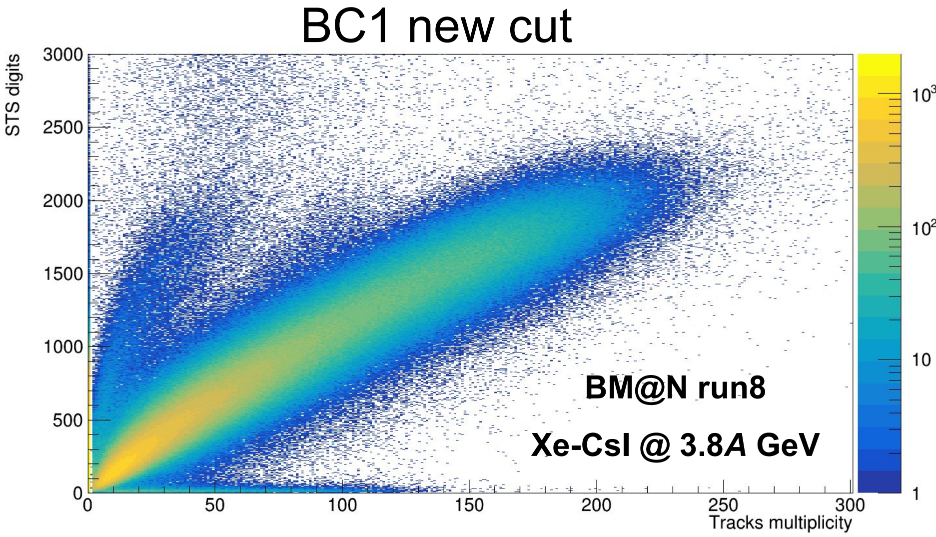
BC1 Integral cut improvement



- Suggestions by S.Sedykh:
- New cut saves all events where only one collision occurs
- Difference: 23% ⟶ 43% of all events

Additional graphic cut

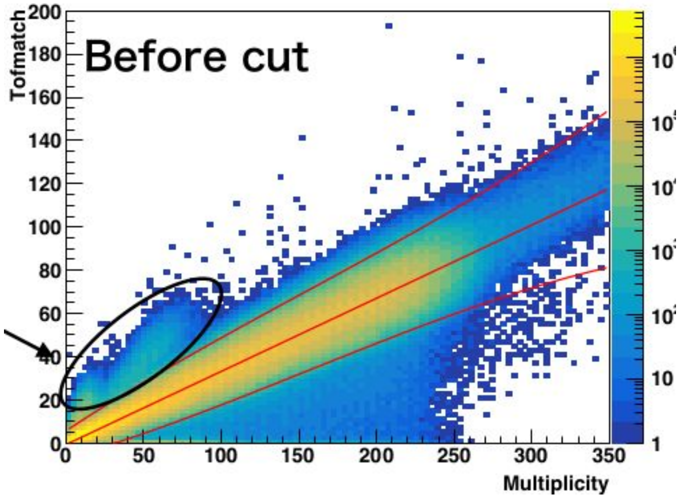


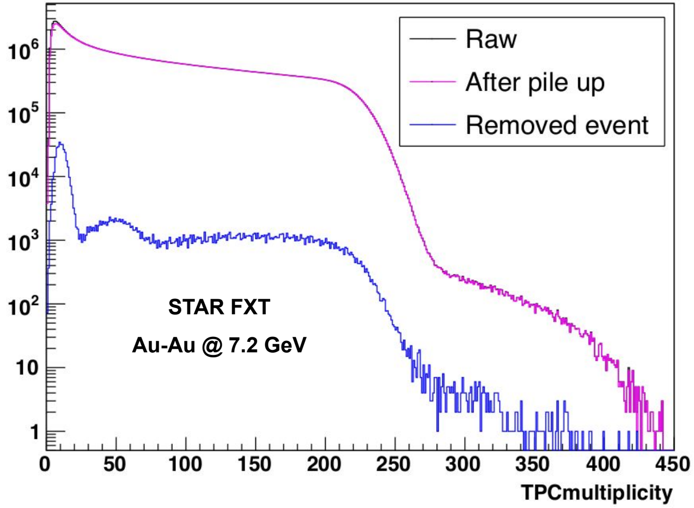


- There are some additional structures of events with unusual behaviour which may affect physical results

- Those events can be declined using graphic cut

Additional graphic cut

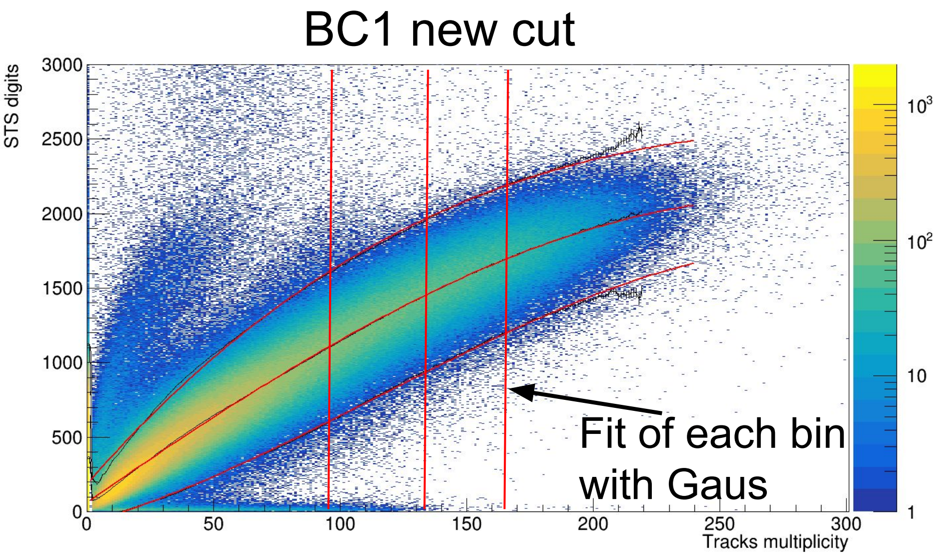


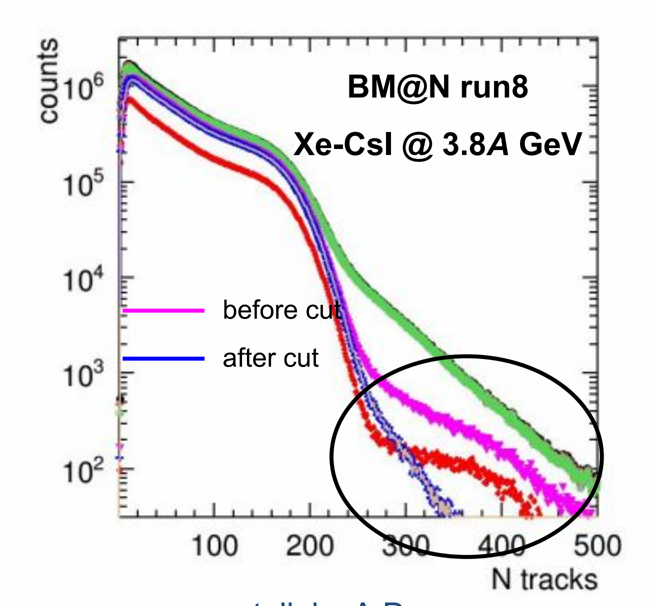


results from STAR by K.Okubo

- In the STAR’s case number of tracks matched with TOF were used to reject events with unusual behaviour

Additional graphic cut





see talk by A.Demanov

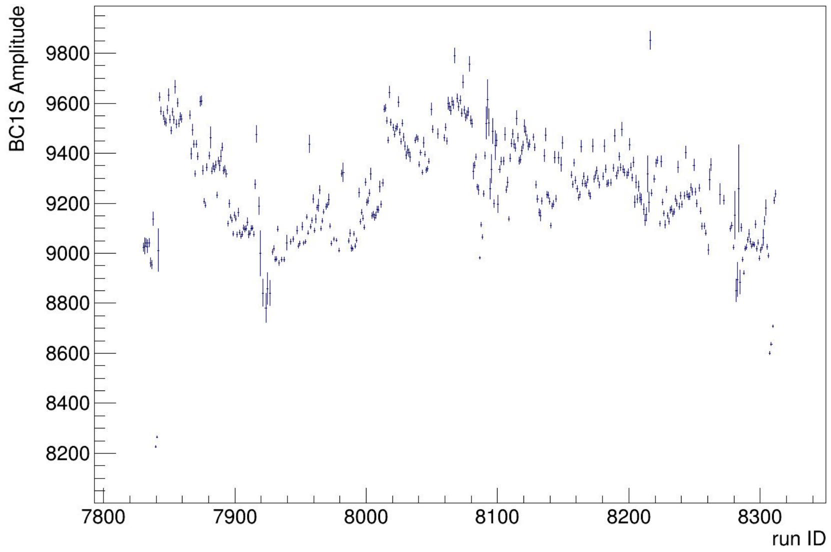
- Graphic cut was performed to throw out all events with unusual behaviour:

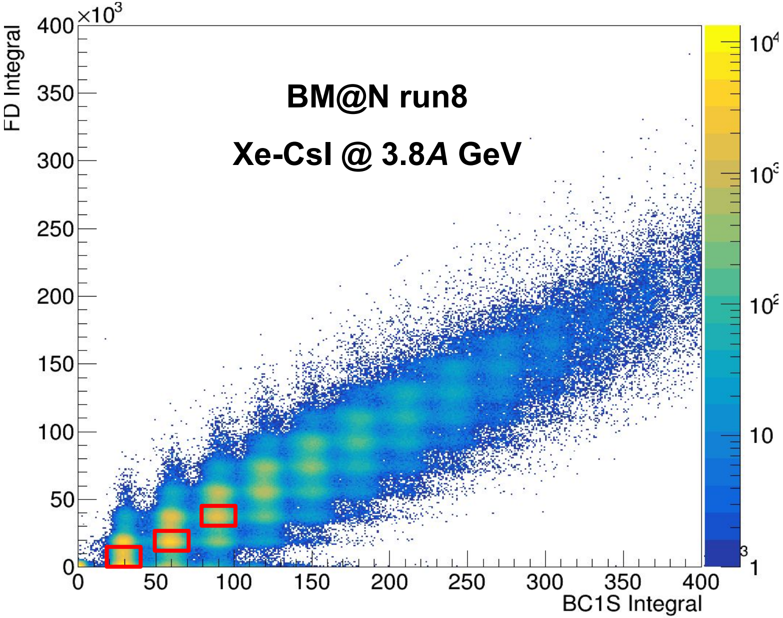
  $STS_{max}(N_{tracks})$=4.6e-05*N^3-0.052*N^2+19.4*N+188 (mean+3σ)

  $STS_{min}(N_{tracks})$=-9.6e-05*N^3+0.033*N^2+4.8*N-74 (mean-3σ)

- Difference: 23% ⟶ 41% of all events

Future improvements





- Calibrate BC1 Amplitude over all runs to improve FD vs BC1 Integrals correlation
- Use areas of each peak instead of line on this correlation

- Finally, we should adjust before/after protection window for physics analysis

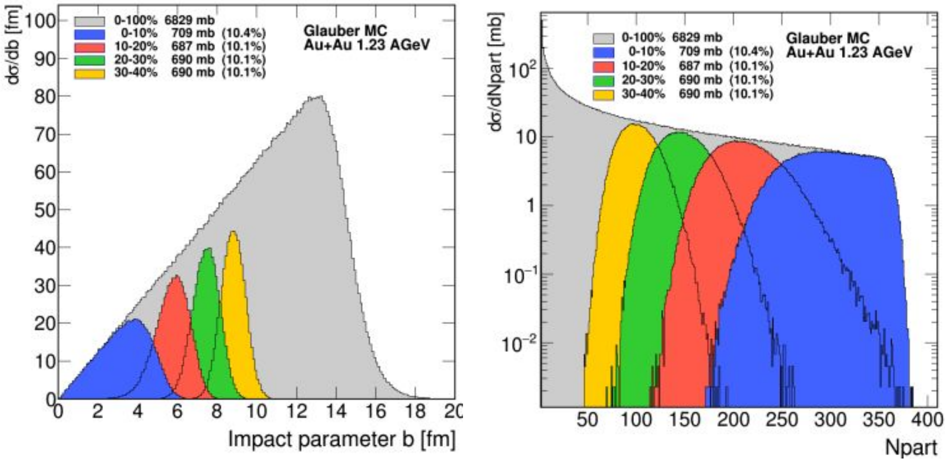
Centrality determination

HADES, Au+Au 1.23A GeV

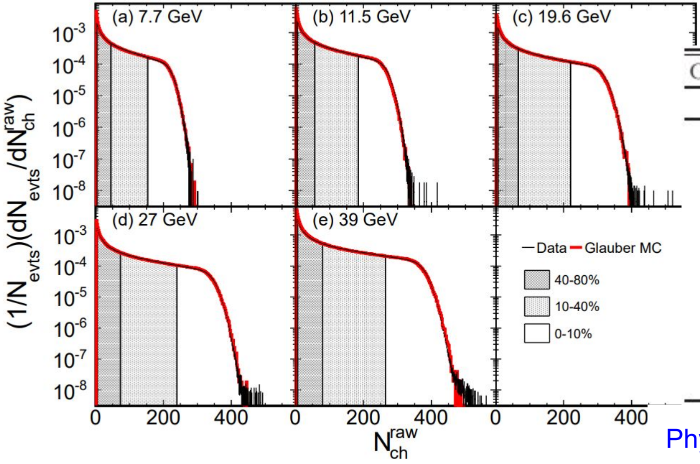
Centrality determination based on multiplicity provides with:

- impact parameter (b)
- number of participating nucleons (N_{part})

Similar centrality estimator is needed for comparisons with STAR, HADES, etc.



STAR, Au+Au, BES



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Phys. Rev. C 86, 054908 (2012)

Centrality Classes	b_{min}	b_{max}	$\langle b \rangle$	$\langle N_{part} \rangle$	RMS(N_{part})
0 – 5 %	0.00	3.30	2.20	331.3	19.4
5 – 10 %	3.30	4.70	4.04	275.6	16.4
10 – 15 %	4.70	5.70	5.22	231.9	13.7
15 – 20 %	5.70	6.60	6.16	195.5	13.0
20 – 25 %	6.60	7.40	7.01	163.3	12.2
25 – 30 %	7.40	8.10	7.75	135.8	11.4
30 – 35 %	8.10	8.70	8.40	113.2	10.6
35 – 40 %	8.70	9.30	9.00	93.7	10.5
40 – 45 %	9.30	9.90	9.60	75.5	10.1
45 – 50 %	9.90	10.40	10.15	60.4	9.4
50 – 55 %	10.40	10.90	10.65	48.0	8.9
55 – 60 %	10.90	11.40	11.15	36.9	8.3

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Centrality determination based on Monte-Carlo sampling of spectators

For **spectators energy from hadron calorimeters**
tested based on NA61/SHINE results

Get (N_{spec}) from MC-Glauber

Calculate total mass of fragments
$A_{tot}=A^{1-f}N_{spec}$
(based on the result of DCM-QGSM-SMM model)

Sample hadron calorimeter response (S_i) A_{tot} times from Gauss(μ,k)

Mixing of produced particles contribution based on Monte-Carlo events

Result: total S_{tot}

MC-Glauber distribution

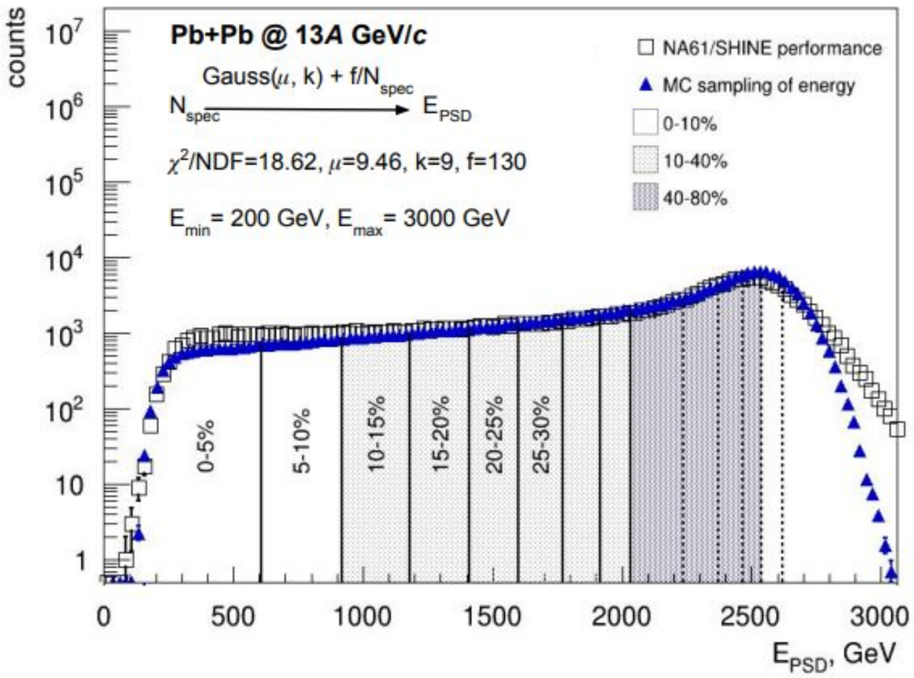
Full Monte-Carlo (real data) distribution

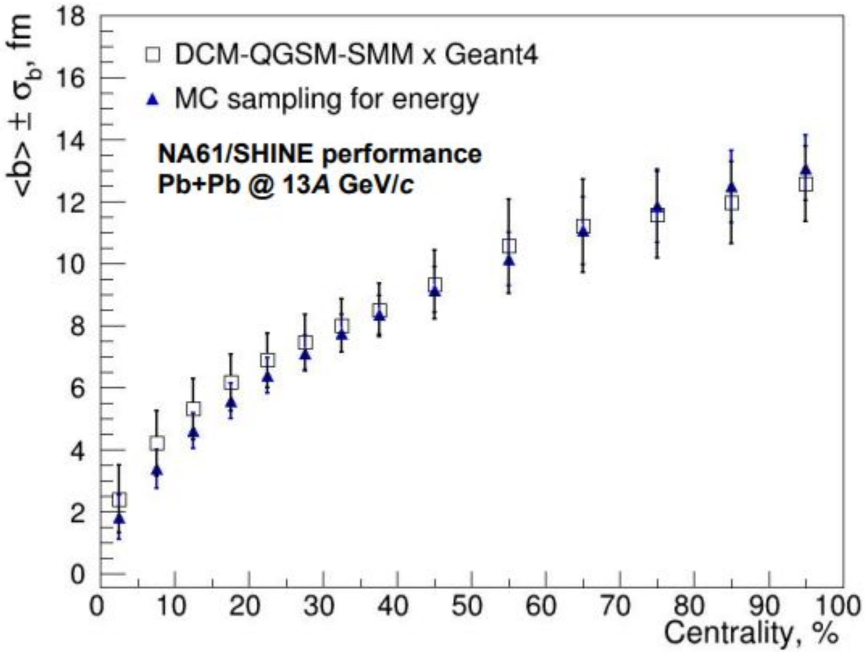
Evaluate χ^2
between $dN/dE_{MC/data}$ and dN/dE_{Gl}

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

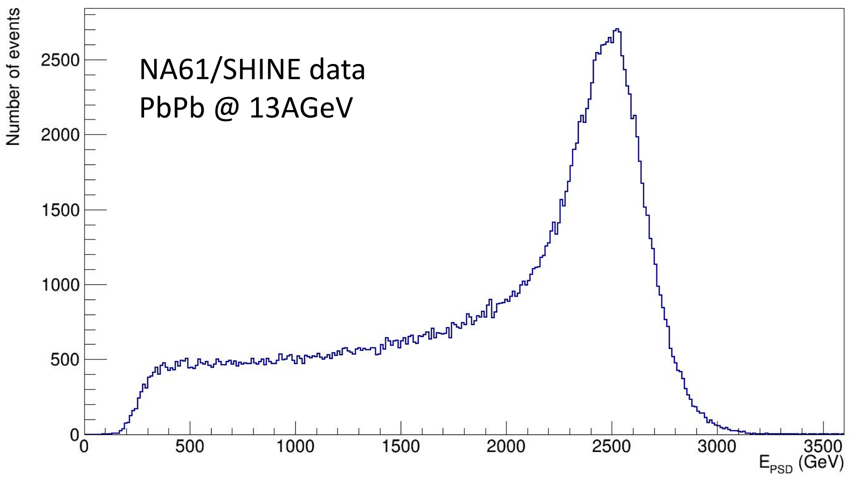


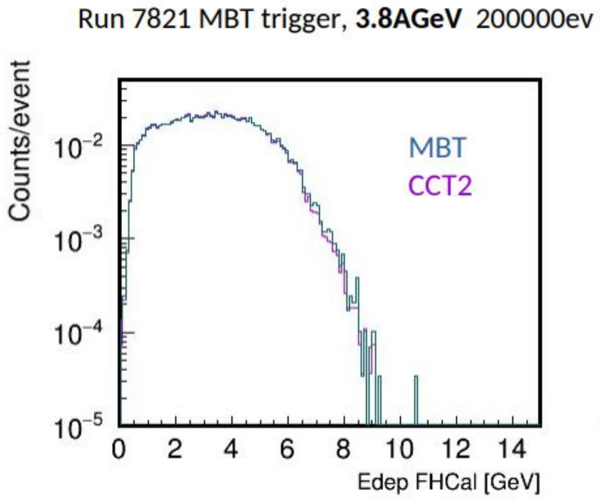


see for more details Segal I. Particles. 2023; 6(2):568-579.

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

How to reconstruct “real” energy of spectators?





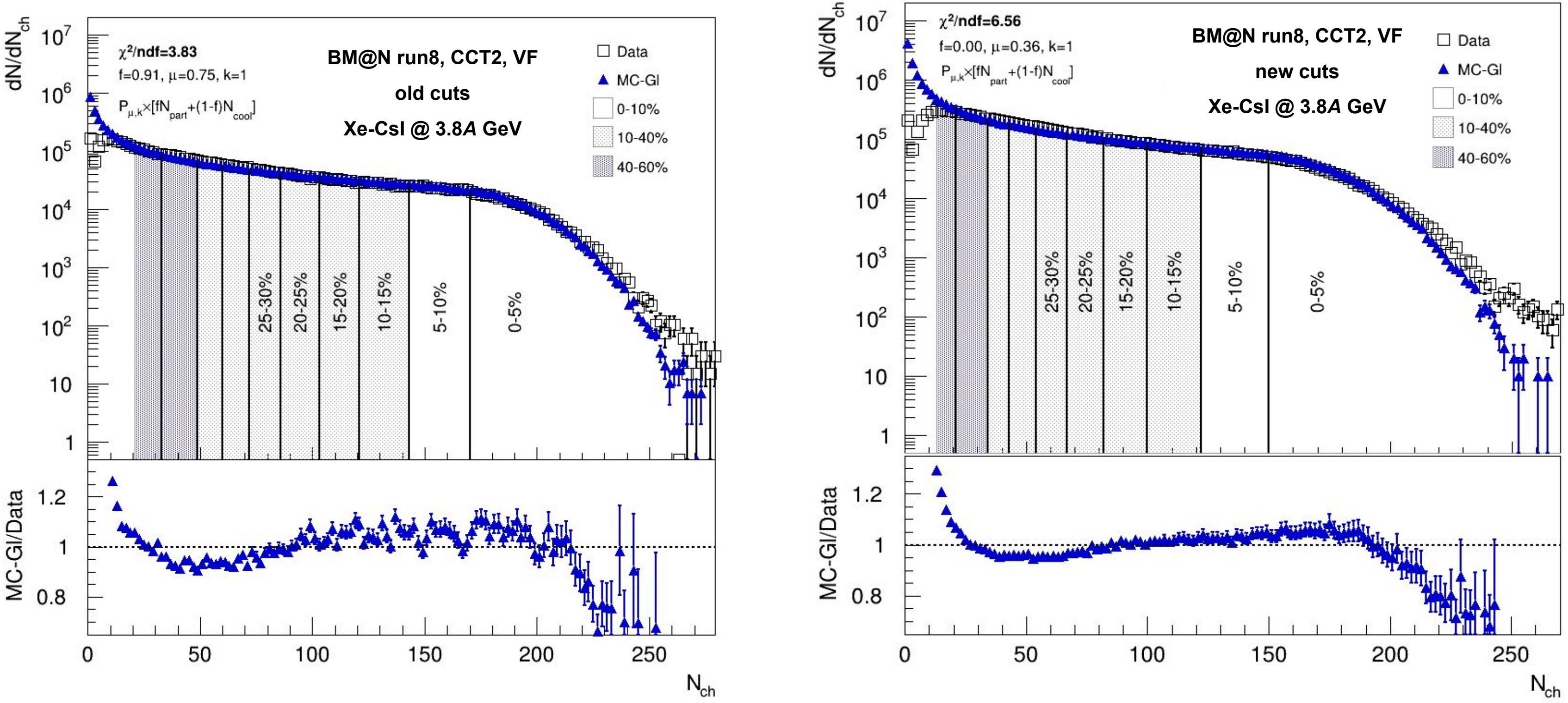
by N.Karpushkin
at 10th BM@N CM

- In the NA61/SHINE experiment the peak of PSD energy distribution is located at E_{beam} * A_{Pb}~2700 GeV
- In our case we don’t see range of energies in FHCal corresponding to collision energy and colliding system
- Is it possible to reconstruct “real” energy of spectators using E_{dep}?
- If so is there any way to do so for Hodoscope?

Overview of centrality determination methods

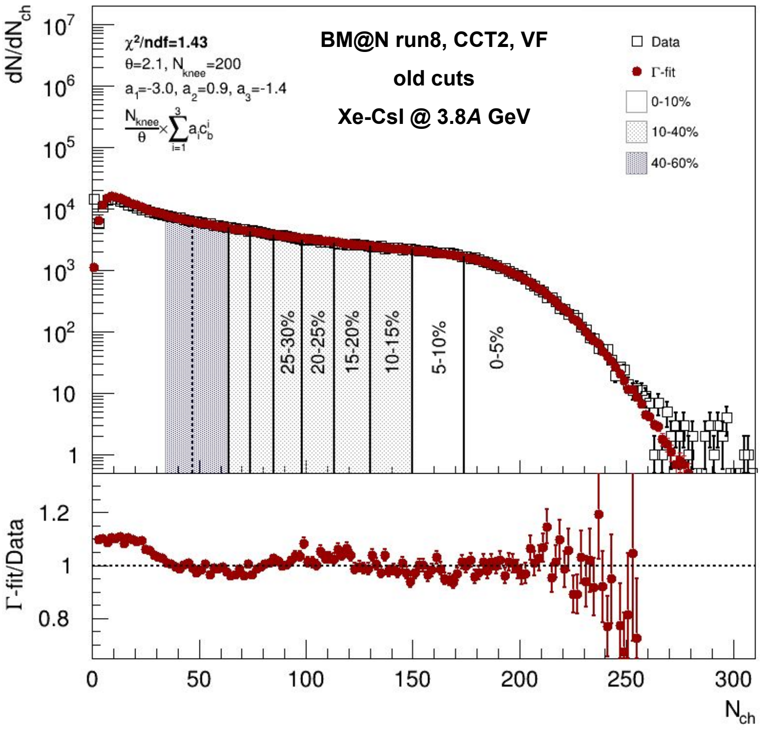
Method type	MC-Glauber based	Model independent (e.g. Γ-fit method)	Based on ML
Used in	STAR, ALICE, HADES, CBM, MPD, etc.	ALICE, CMS, ATLAS J. Y. Ollitrault et al. Phys.Rev. C 98 (2018) 024902	Becoming popular Fupeng L. et al. J.Phys.G 47 (2020) 11, 115104
Advantages	Commonly used, well established procedure	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

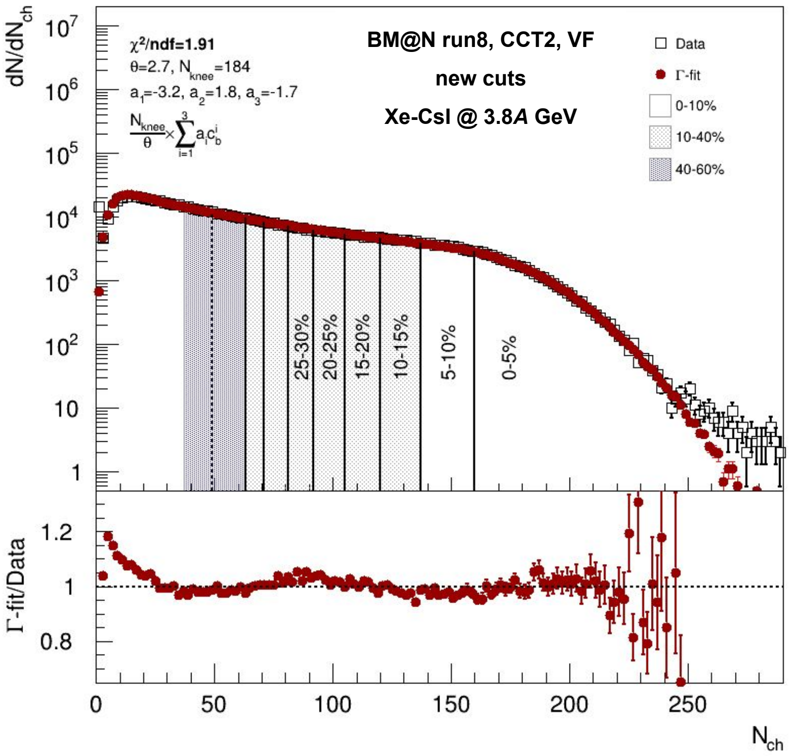
Comparison with older results (E_{kin}=3.8 GeV)



- Glauber fit improved in comparison with previous results
- CCT2 has good efficiency up to 60% centrality
- New centrality classes is used in analysis (see talk by M.Mamaev)

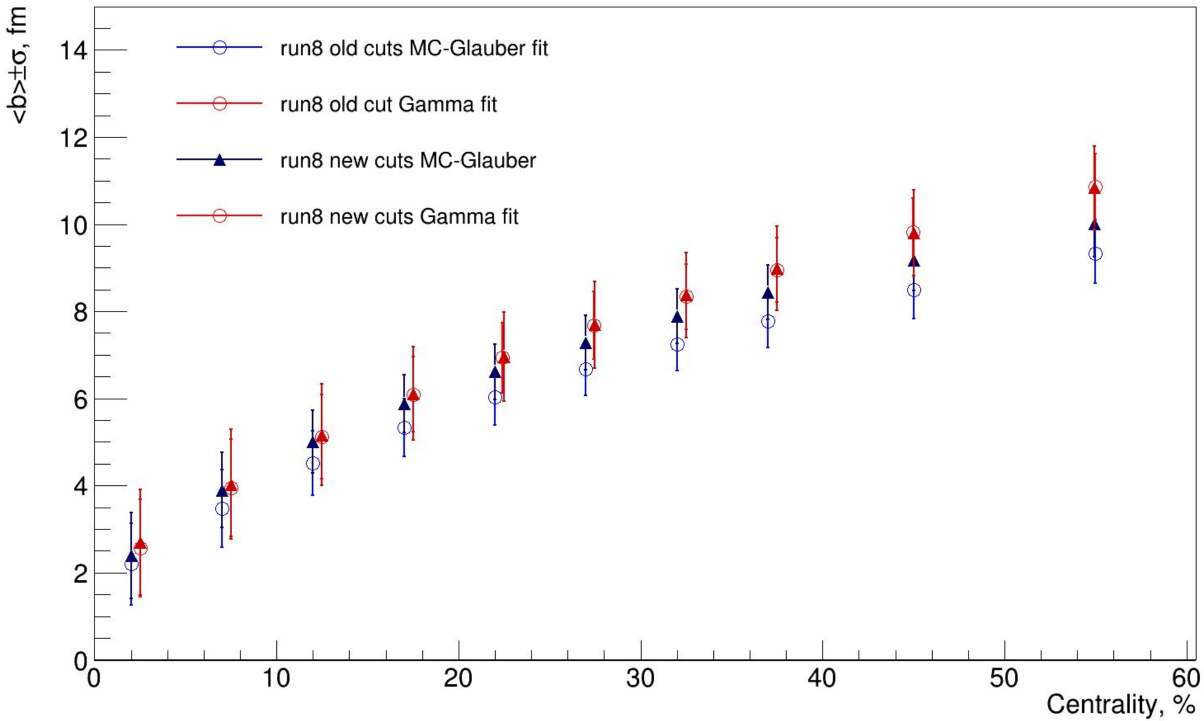
Comparison with older results (E_{kin}=3.8 GeV)





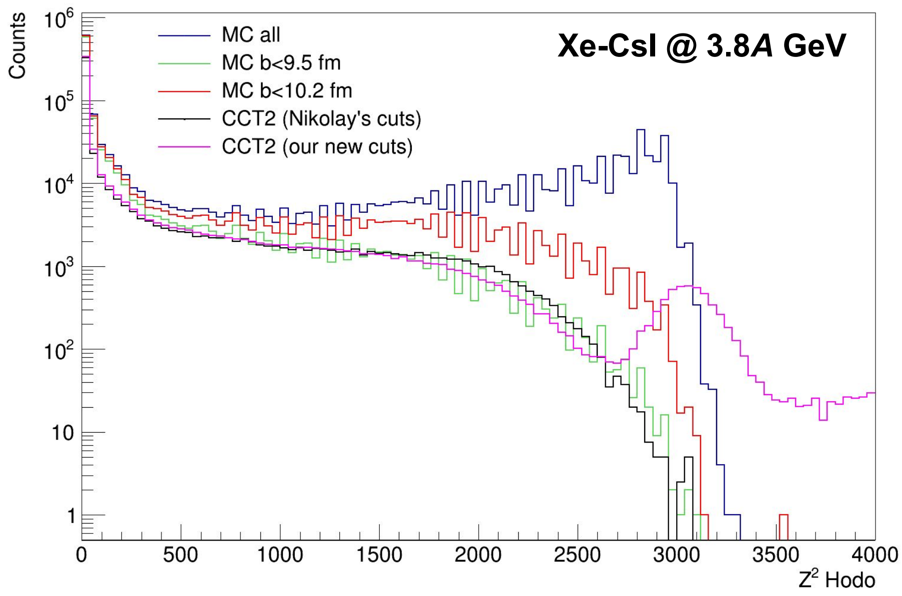
- For the new cuts fit also a little bit better
- These classes can be used during physics analysis
- Trigger efficiency at the peripheral events should be taken into account

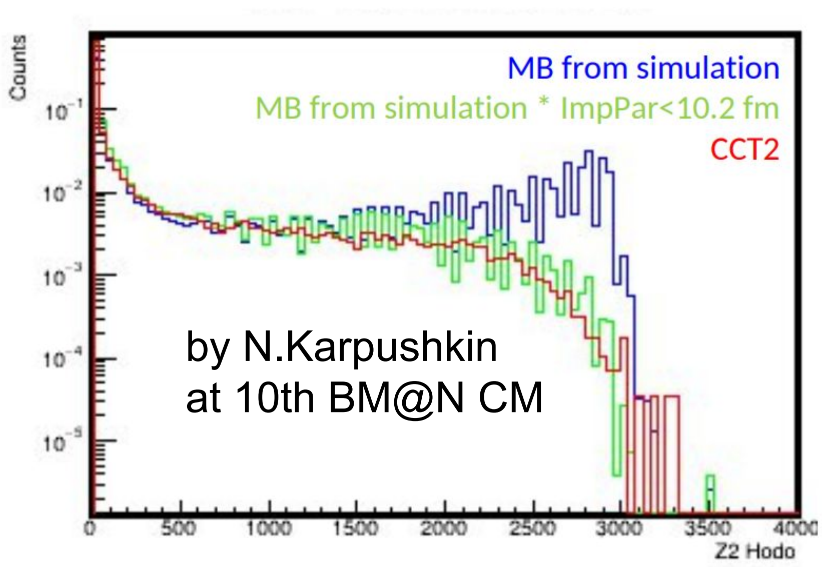
Comparison between impact parameter distributions



- For Γ-fit all centrality classes are comparable
- Γ-fit and MC-Glauber fit are now in more agreement with each other

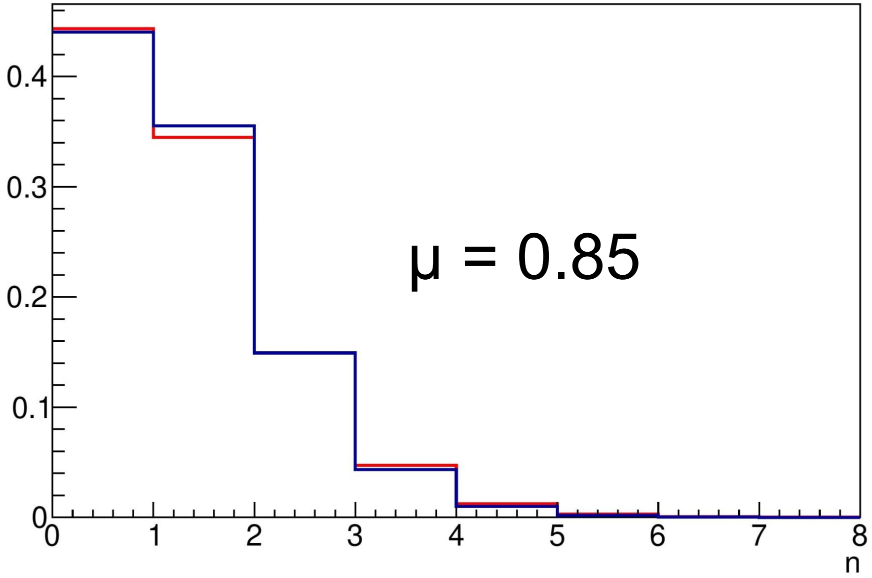
Estimation of trigger efficiency





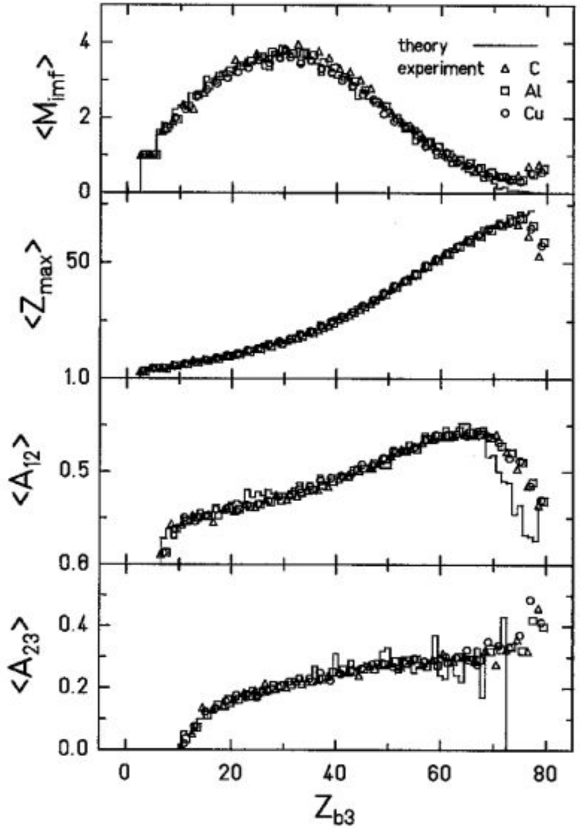
- Results do not agree with Nikolay's results from the last CM
- Looks like CCT2 trigger has good efficiency for the events with up to 60% centrality

NBD at different values of k

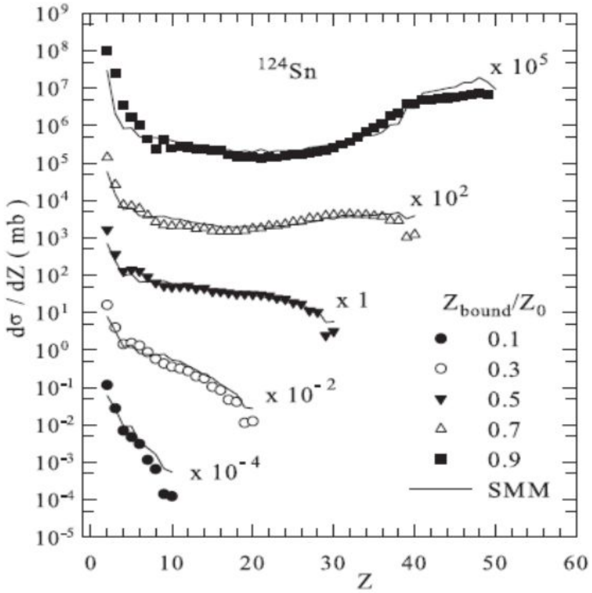


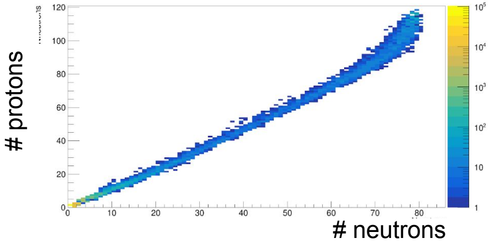
SMM description of the ALADIN's fragmentation data

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

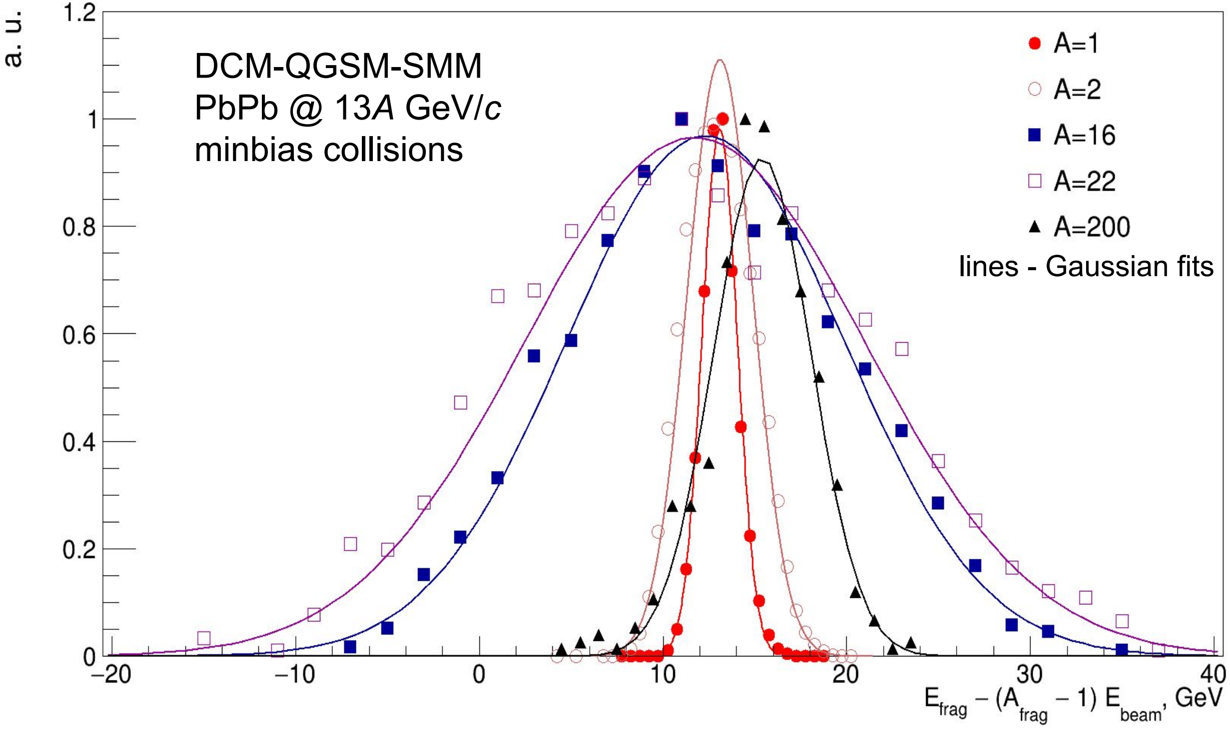


R.Ogul et al. PRC 83, 024608 (2011)





Gaussian approximation for fragments energy

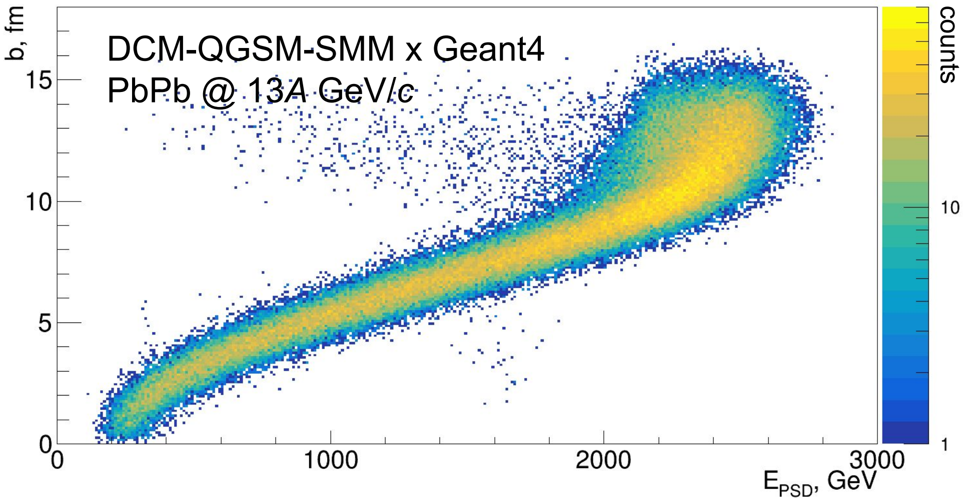


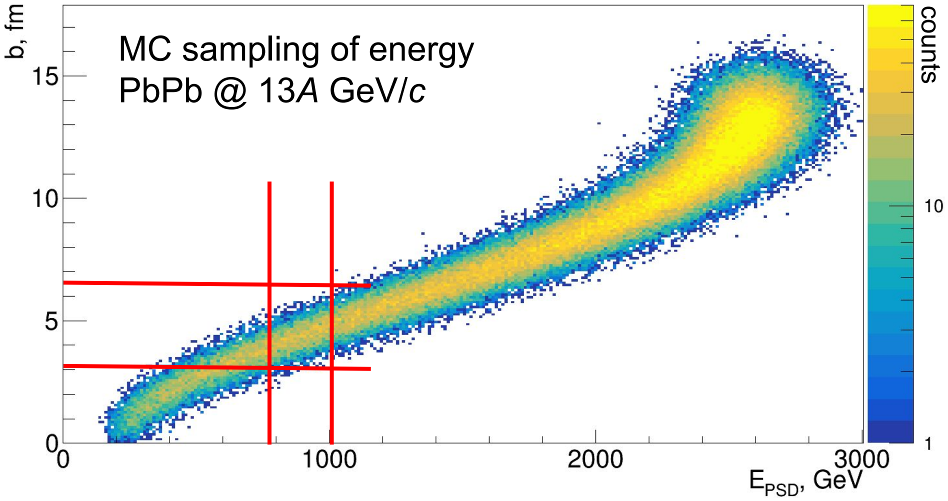
- Distribution of mass numbers of spectators fragments could be fitted by Gauss distribution
- Mean values equal to product of beam energy and fragment's mass
- Total spectators energy distribution is also Gauss:

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

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

Simplified MC sampling for hadron calorimeters

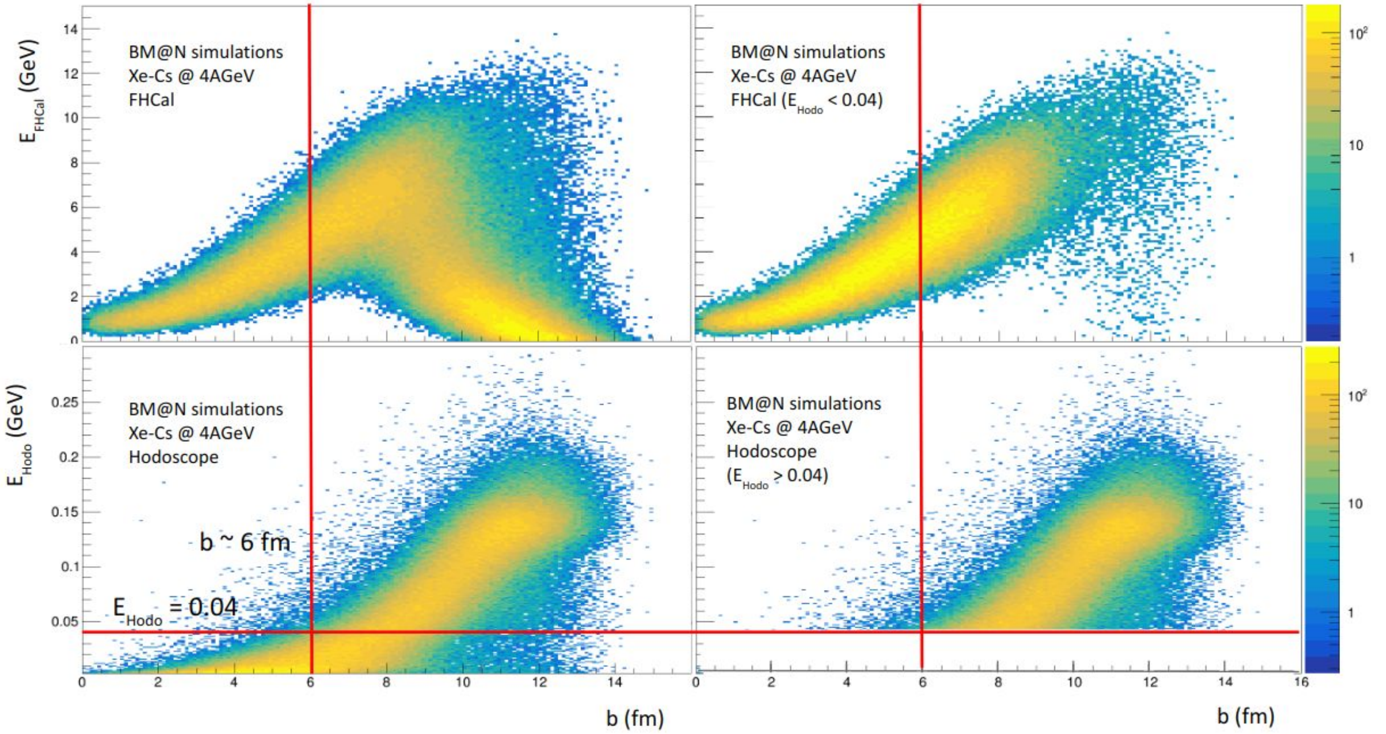




Segal I. Particles. 2023; 6(2):568-579.

- 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

Possibilities of spectators fragments as estimators



- Physical threshold of switching between estimators could be Hodoscope signal E_{Hodo}=0.04 (corresponding to b~6fm)
- 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)