Prospects for centrality determination in run8

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for the BM@N Collaboration

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BM@N Analysis & Software Meeting

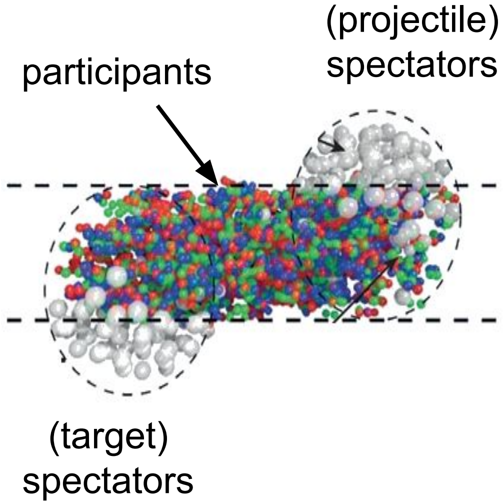
Motivation for centrality determination

- 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:

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



BM@N subsystems for centrality determination

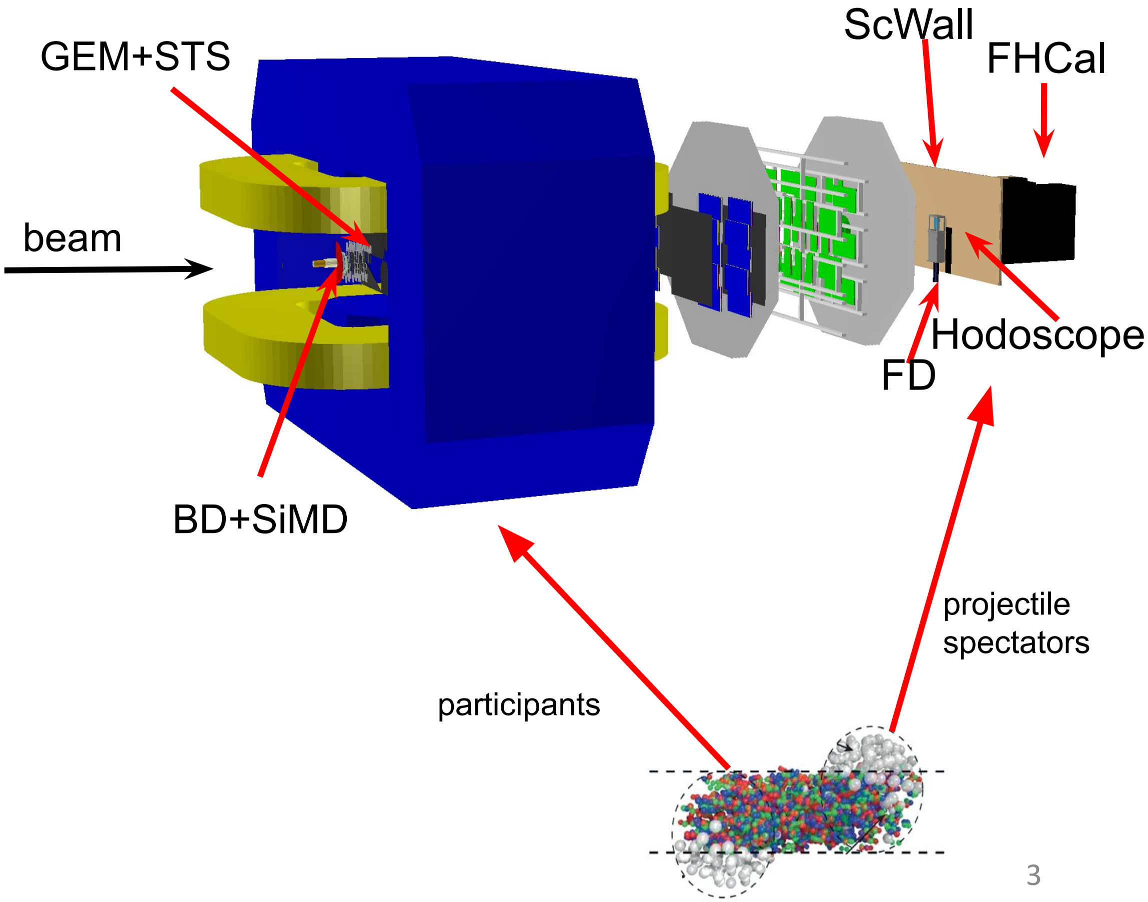
Data:

- run8 Xe-CsI @3.8*A* GeV

  @3*A* GeV
- MBT / CCT2
- Tracking: L1 / Vertex finder
- 10^4 < BC1Integral < $4*10^4$
- vtxChi2/vtxNdf > 0.1

Subsystems

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



Centrality determination based on Monte-Carlo sampling of produced particles

For **multiplicity of produced particles**
used in HADES, CBM, BM@N, NA61/SHINE

Get (N_{part}, N_{coll}) from MC-Glauber

Calculate $N_a = fN_{part} + (1-f)N_{coll}$

Sample multiplicity of produced particles (S_i) N_a times from NBD (μ, k)

Result: total S_{tot}

MC-Glauber distribution

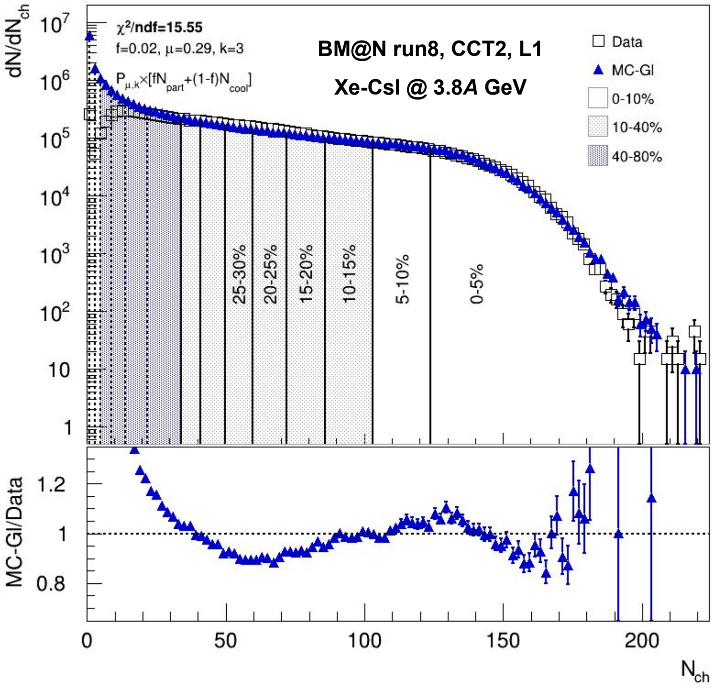
Full Monte-Carlo (real data) distribution

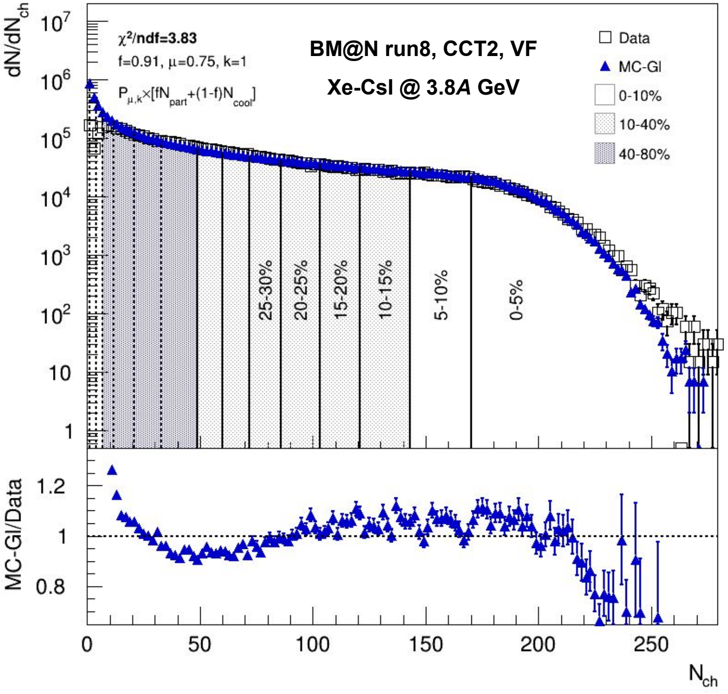
Evaluate χ^2
between $dN/dE_{MC/data}$ and dN/dE_{Gl}

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

Extract relation between geometry parameters and centrality estimator

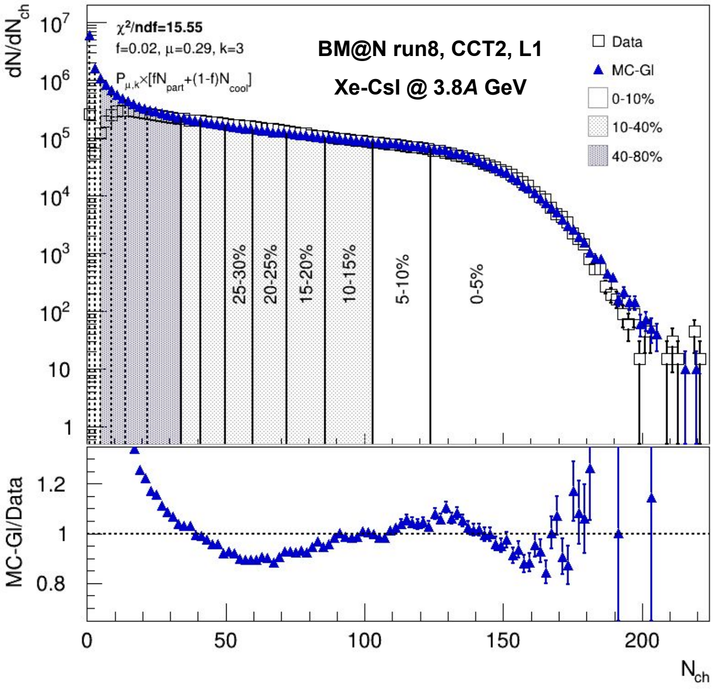
Comparison between tracking algorithms (E_{kin}=3.8 GeV)

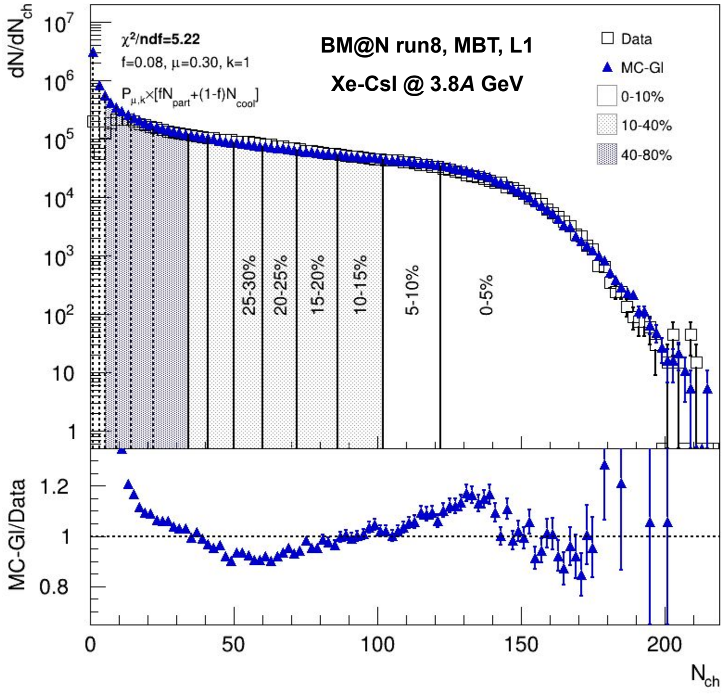




- Vertex Finder provides more even distribution
- Multiplicities for VF is larger than for L1 (ghost tracks?)

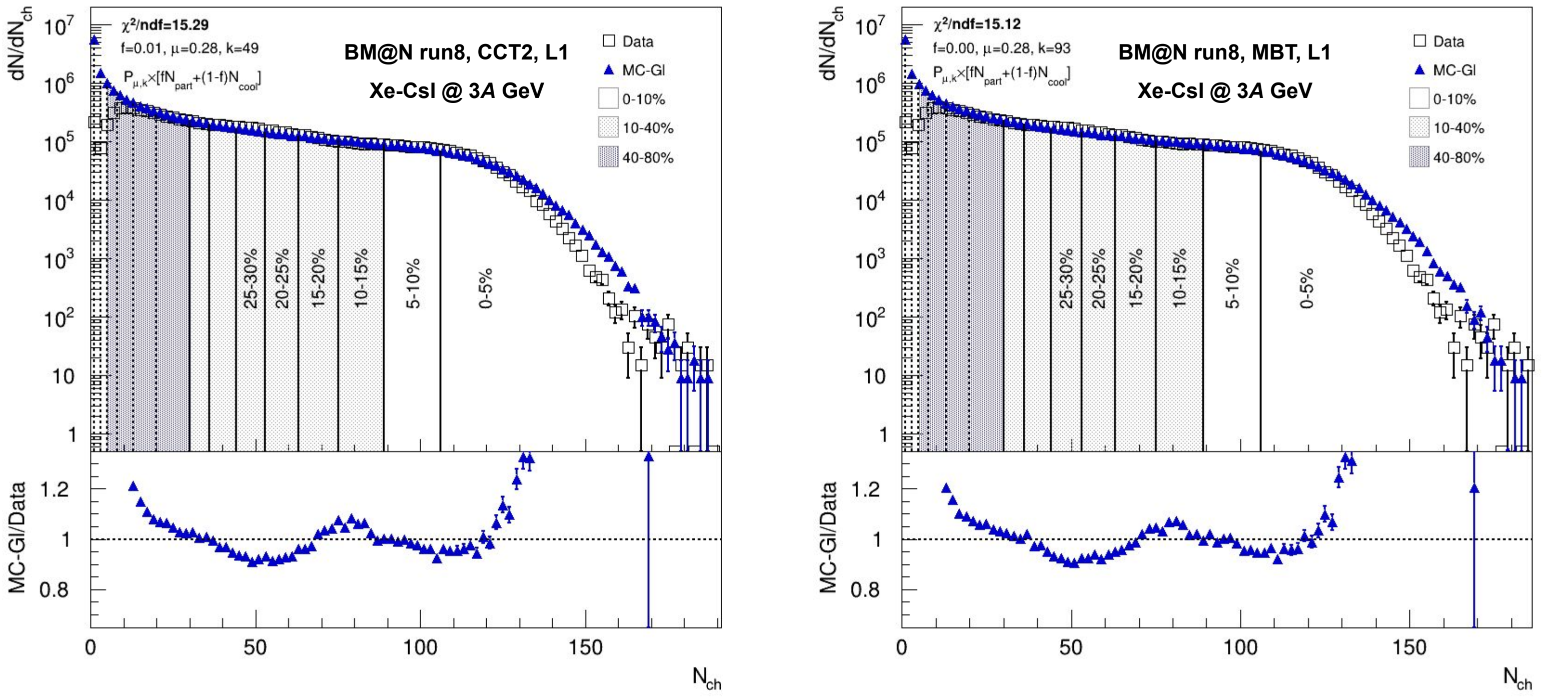
Comparison between triggers (E_{kin}=3.8 GeV)





- Fit result is better for MBT
- CCT2 record events up to ~60%, while MBT up to ~70%
- For centralities larger than 70% both triggers ineffective

Comparison between triggers (E_{kin}=3GeV)



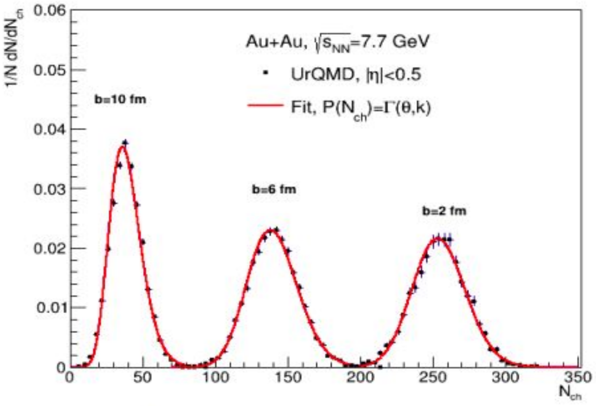
- In case of lower energies this method also applicable but fit should be improved

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

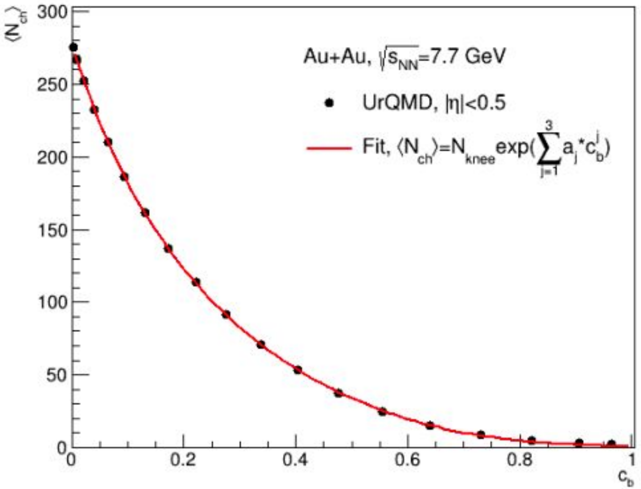
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

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

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

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

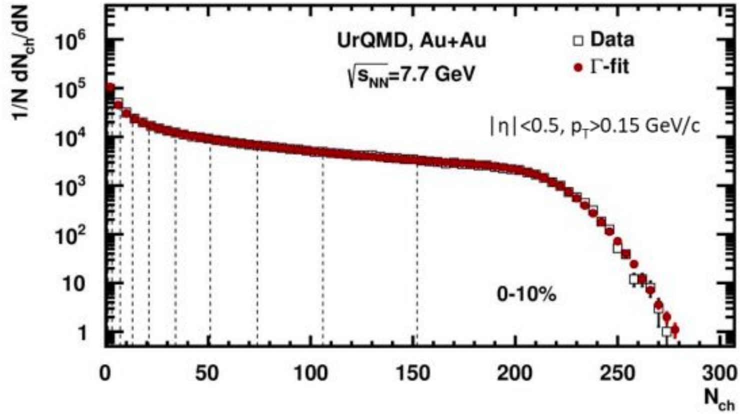
- Find probability of *b* for fixed range of N_{ch} using Bayes' theorem:

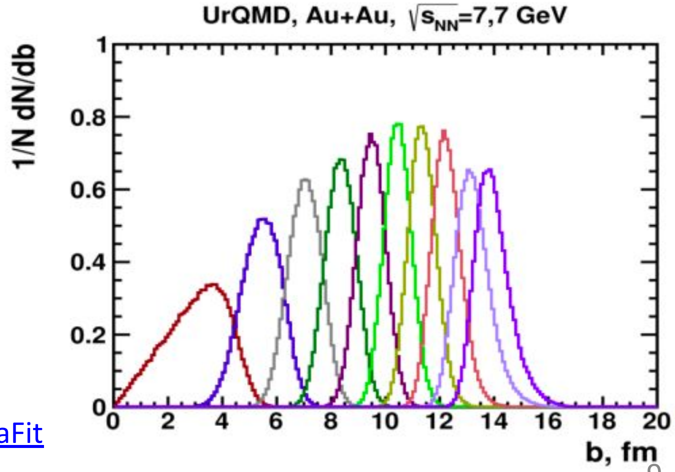
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(b|N_{ch})dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$

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

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

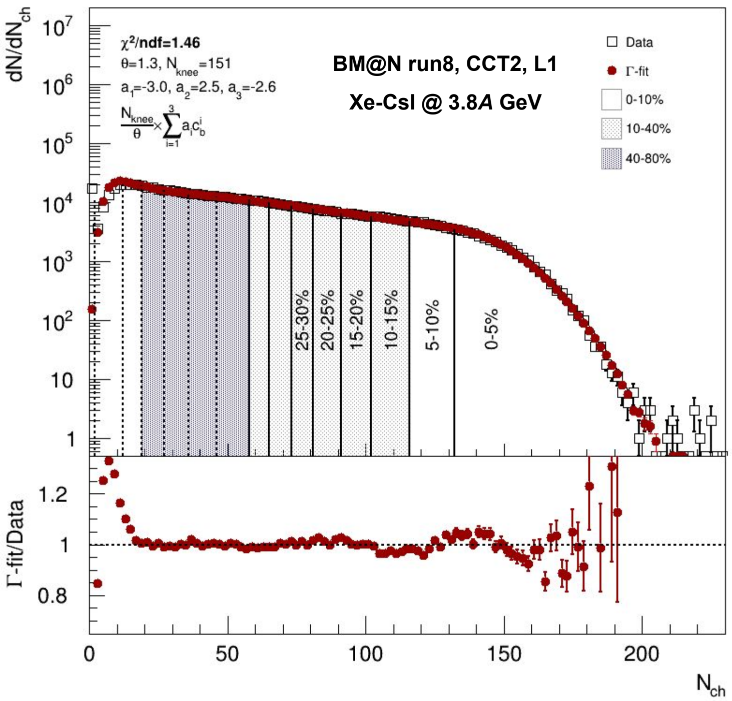
–Construct $P(b|N_{ch})$ using Bayes' theorem with parameters from the fit

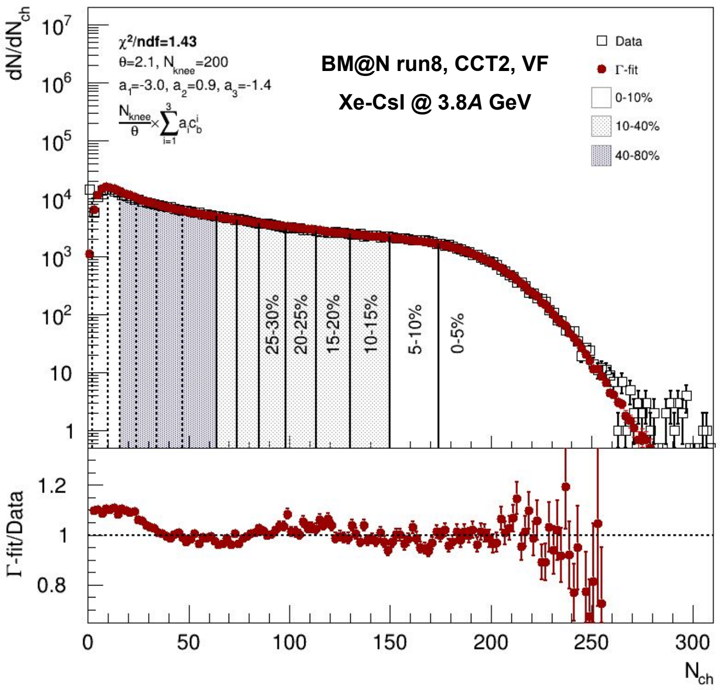




R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902
Implementation for MPD and BM@N by D. Idrisov: https://github.com/Dim23/GammaFit
Example of application in MPD: **P. Parfenov et al., Particles 4 (2021) 2, 275-287**

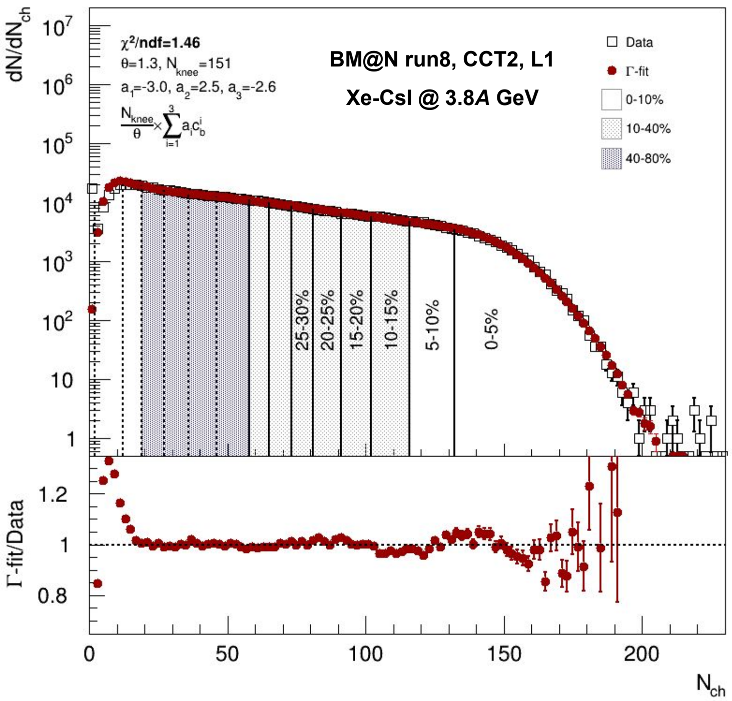
Comparison between tracking algorithms (E_{kin}=3.8 GeV)

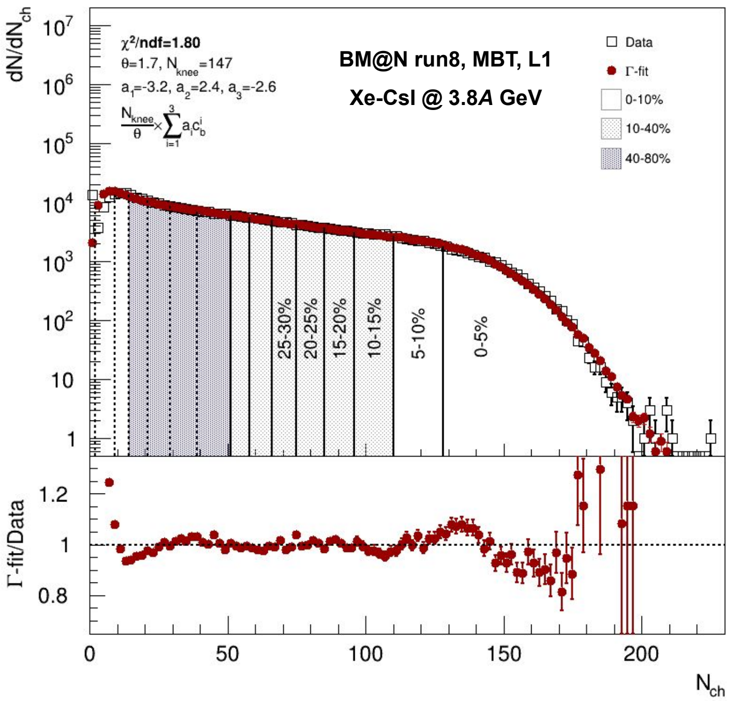




- For both VF and L1 results are comparable

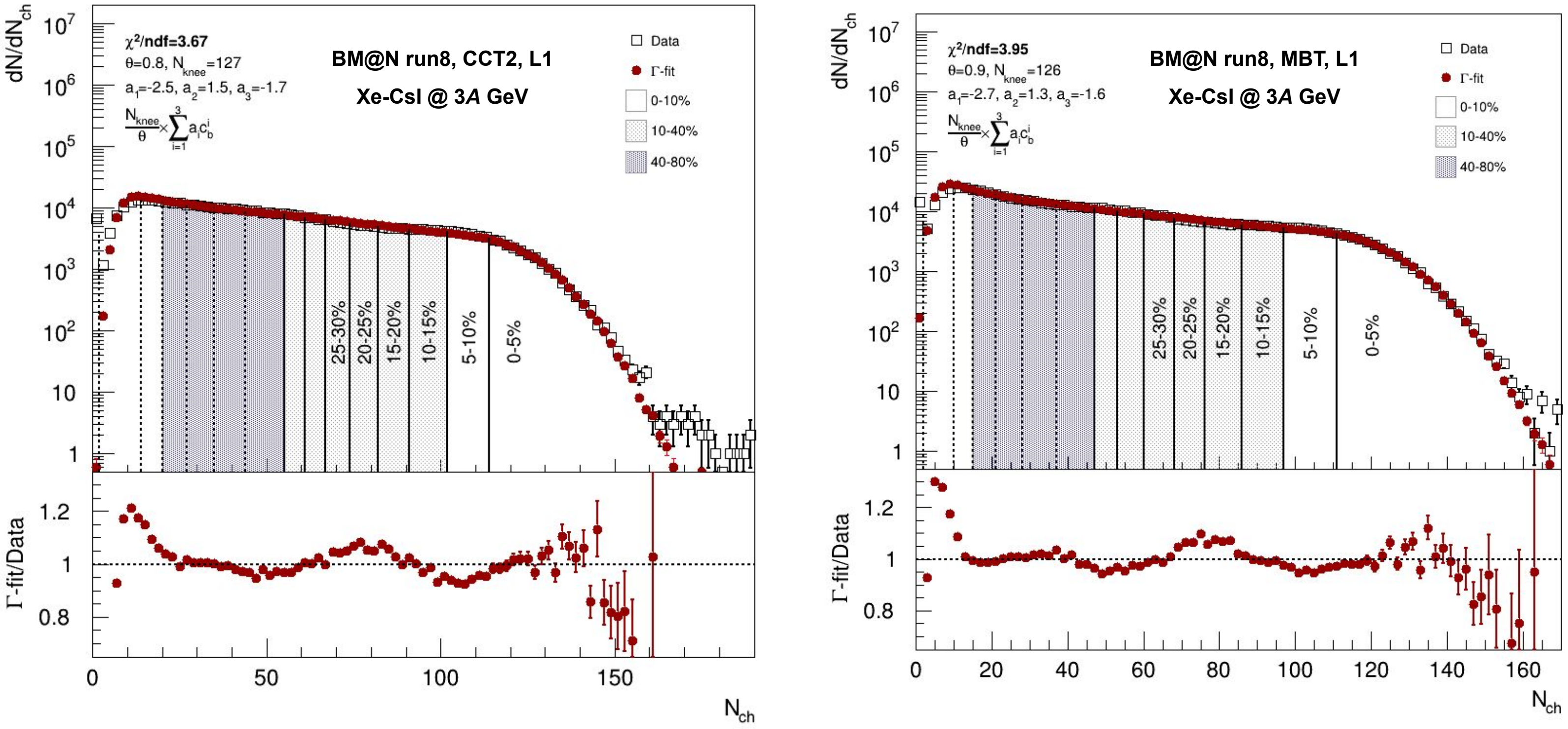
Comparison between triggers (E_{kin}=3.8 GeV)





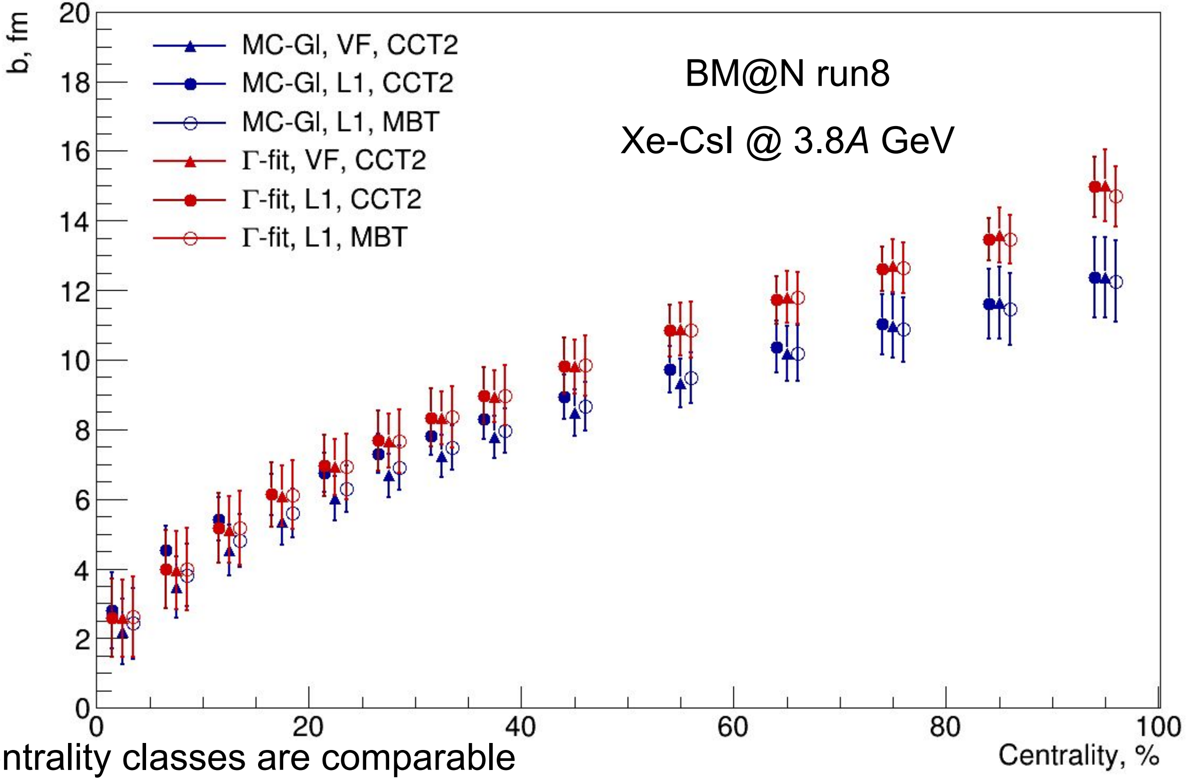
- Γ-fit provides better results
- Detectors efficiency for the peripheral events should be taken into account

Comparison between triggers (E_{kin}=3 GeV)



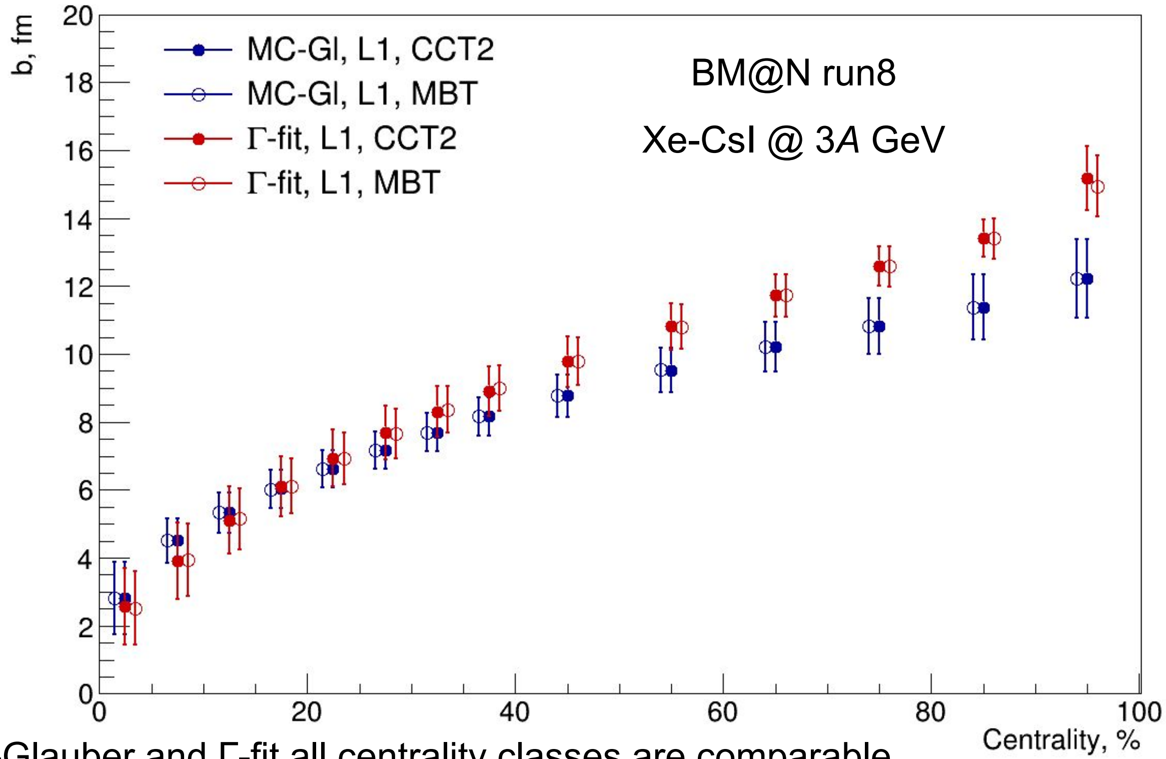
- In case of lower energies this method also applicable

Comparison between impact parameter distributions



- For Γ-fit all centrality classes are comparable
- For MC-Glauber fit is unstable for the most central events
- There huge difference between Γ-fit and MC-Glauber methods in the most peripheral events since Γ-fit does not take into account detectors efficiency

Comparison between impact parameter distributions



- For both MC-Glauber and Γ-fit all centrality classes are comparable
- There huge difference between Γ-fit and MC-Glauber methods in the most peripheral events since Γ-fit does not take into account detectors efficiency

Summary

- MC-Glauber and Γ-fit fitting procedures is applied for centrality determination for BM@N run8 data
- Relation between impact parameter and centrality classes is extracted
- Comparisons between different triggers and tracking algorithms are provided
- Both methods can be used for centrality determination, but should be improved:
  - for Γ-fit detector, efficiency should be taken into account
  - for MC-Glauber, stability of the fit should be investigated

Work in progress

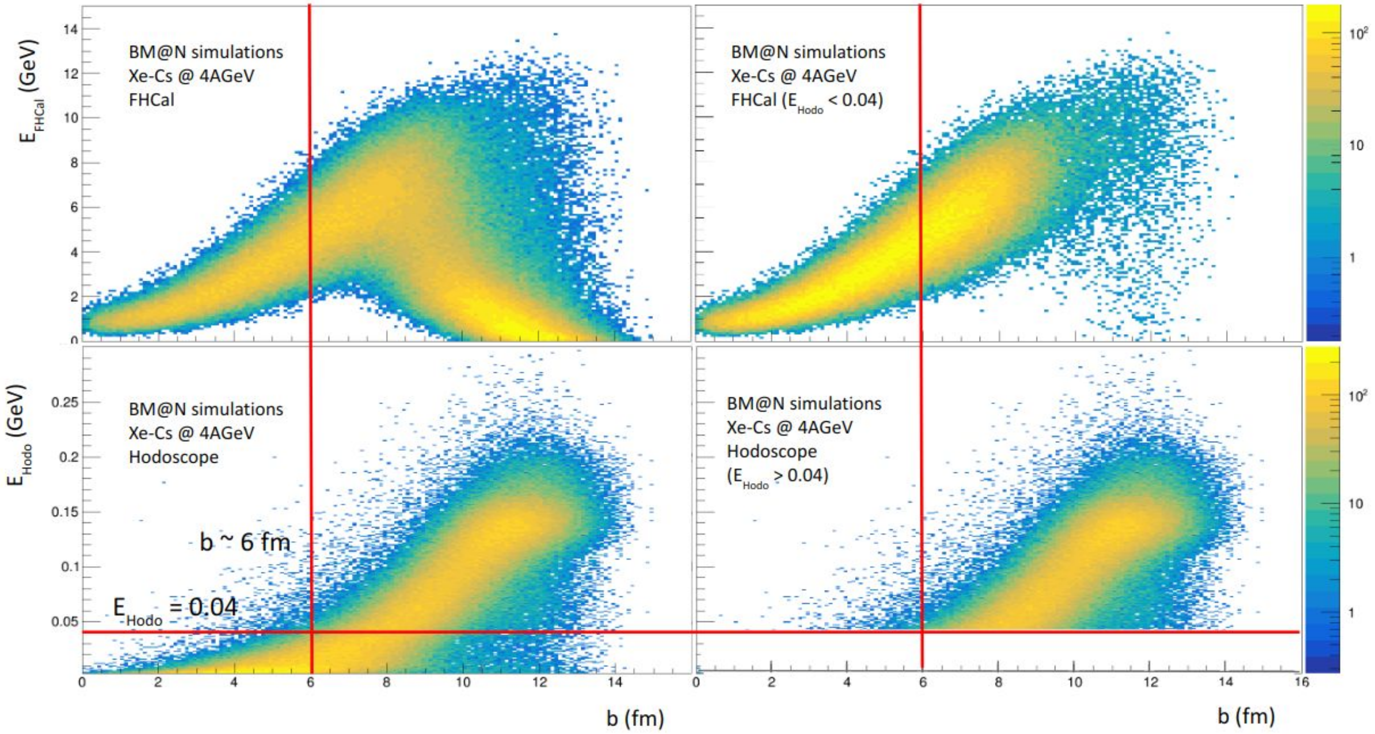
- Investigate possibilities of using spectators observables for centrality determination
- Corresponding procedures were discussed during previous CB
- Problems with minimum bias events (statistics, background)
  were discussed during BERDS meeting (July 19^{th}) and should be investigated

Backup

Overview of centrality determination methods

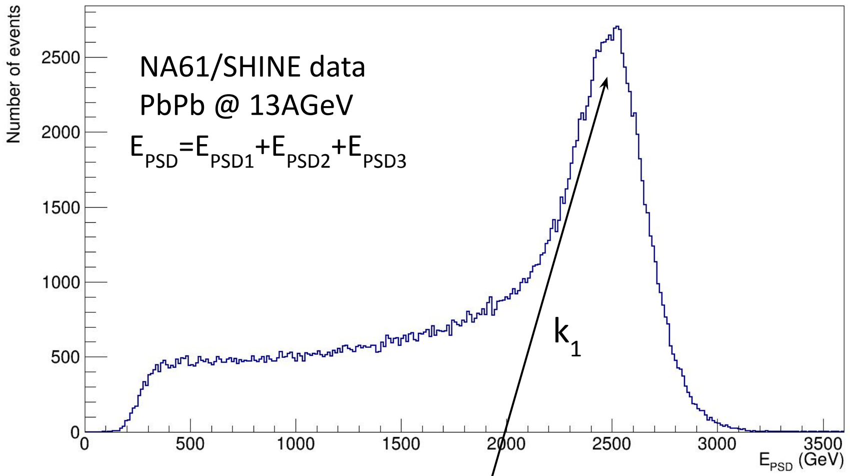
Method type	MC-Glauber based	Model independent (e.g. Γ-fit method)	Based on ML
Used in	STAR, ALICE, HADES, CBM, MPD, etc.	ALICE, CMS, ATLAS J. Y. Ollitrault et al. Phys.Rev. C 98 (2018) 024902	Becoming popular Fupeng L. et al. J.Phys.G 47 (2020) 11, 115104
Advantages	Commonly used, well established procedure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

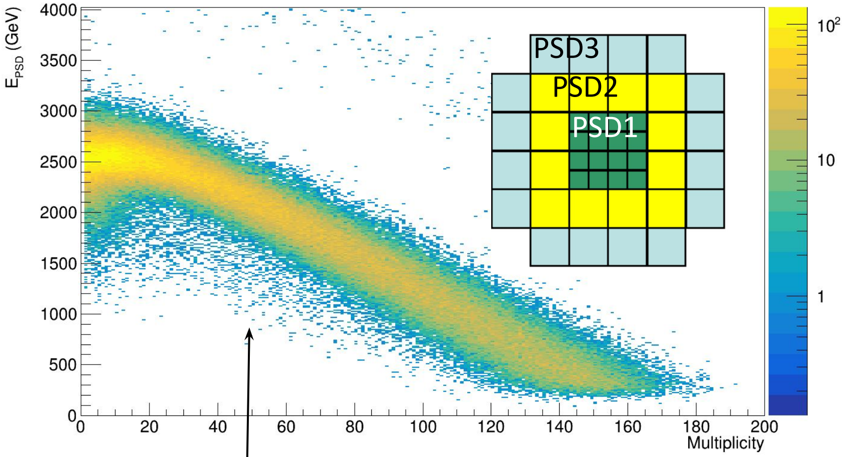
Possibilities of spectators fragments as estimators

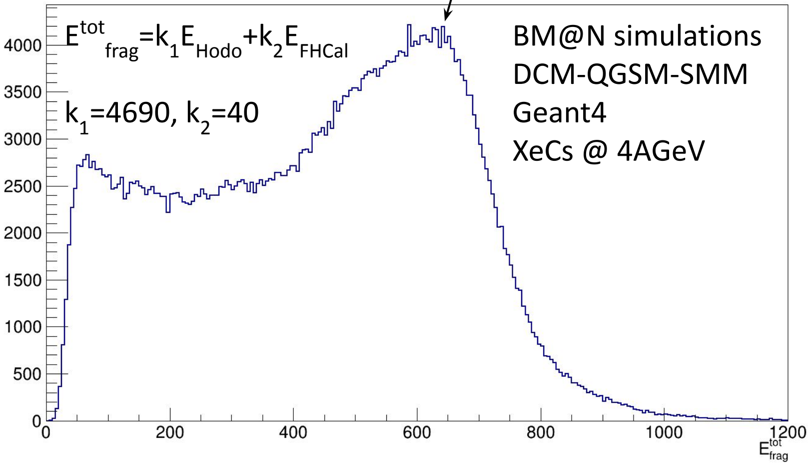


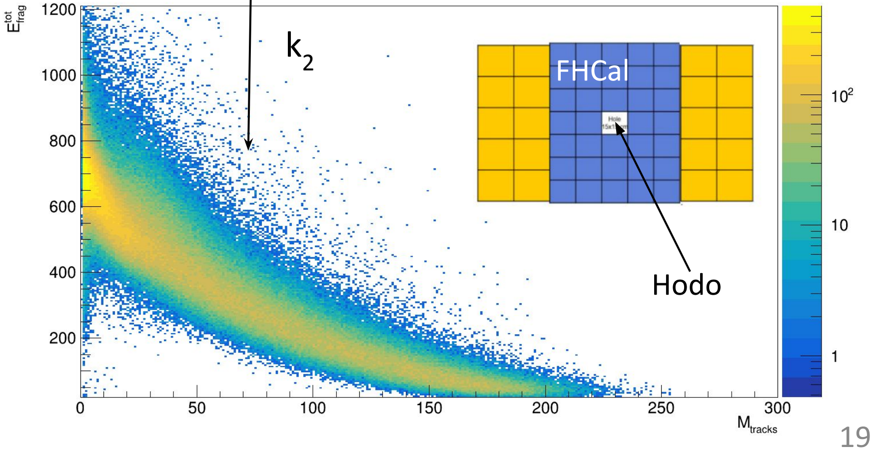
- Physical threshold of switching between estimators could be Hodoscope signal E_{Hodo} = 0.04 (corresponding to b ~ 6 fm)
- FHCal energy distribution improved and has more linear correlation with impact parameter (for range E_{Hodo} < 0.04)
- There is good correlation between Hodoscope charge and impact parameter (for range E_{Hodo} > 0.04)

Possibilities of spectators fragments as estimators









MC Glauber model

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

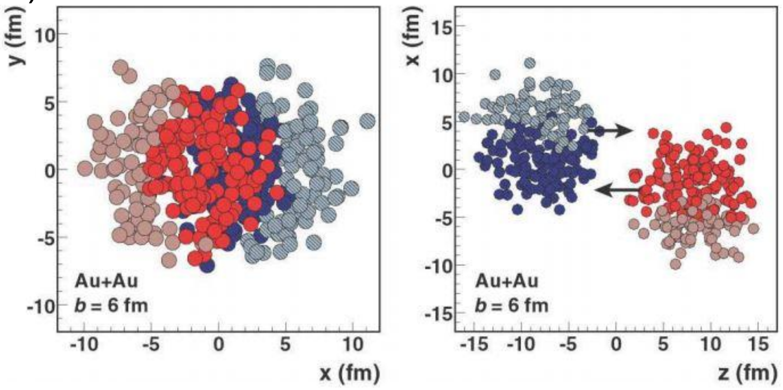
- Independent straight line trajectories of the nucleons
- A-A collision is treated as a sequence of independent binary NN collisions
- Monte-Carlo sampling of nucleons position for individual collisions

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

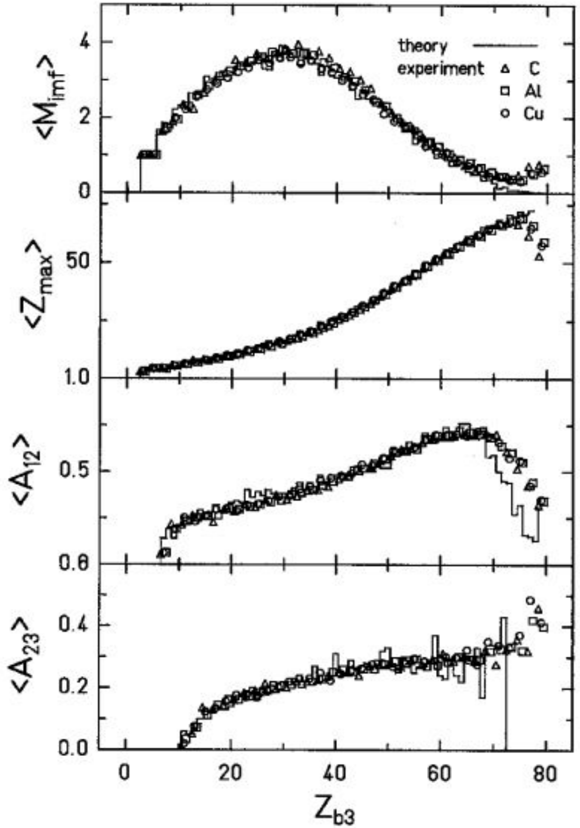
N_{part} – number of nucleons participating in the collision

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

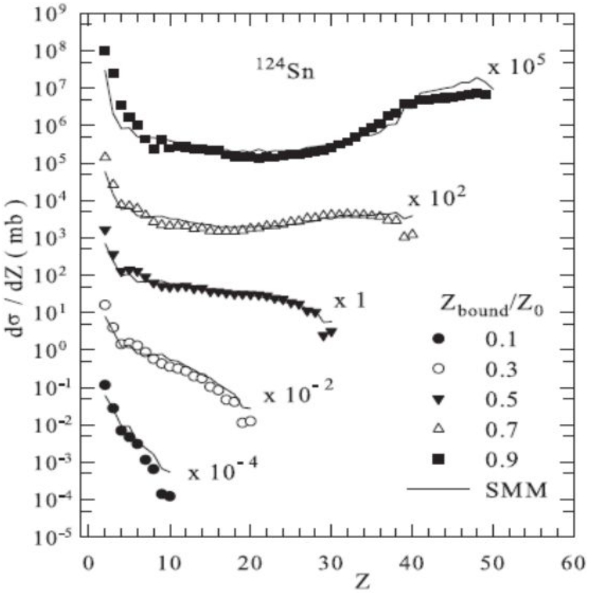
N_{coll} – number of binary NN collisions

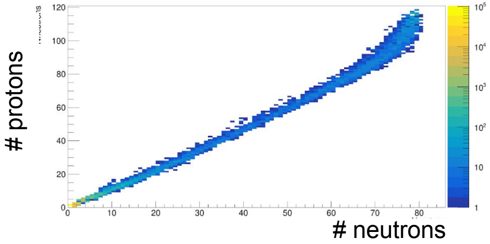
SMM description of the ALADIN's fragmentation data

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

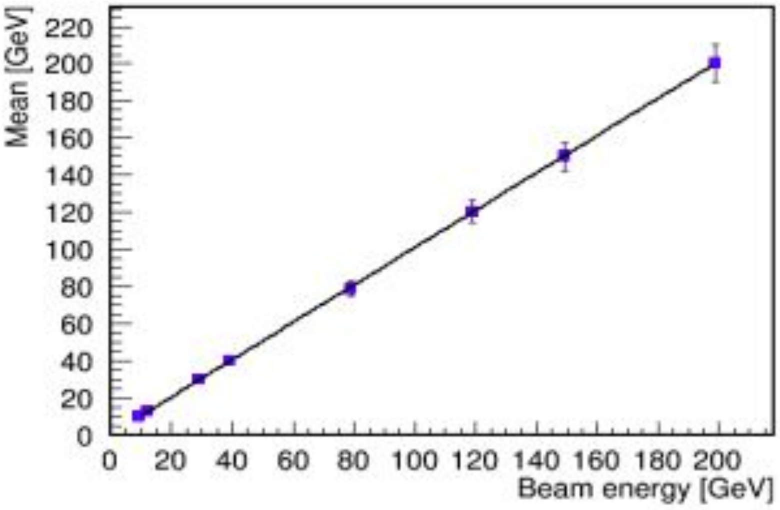


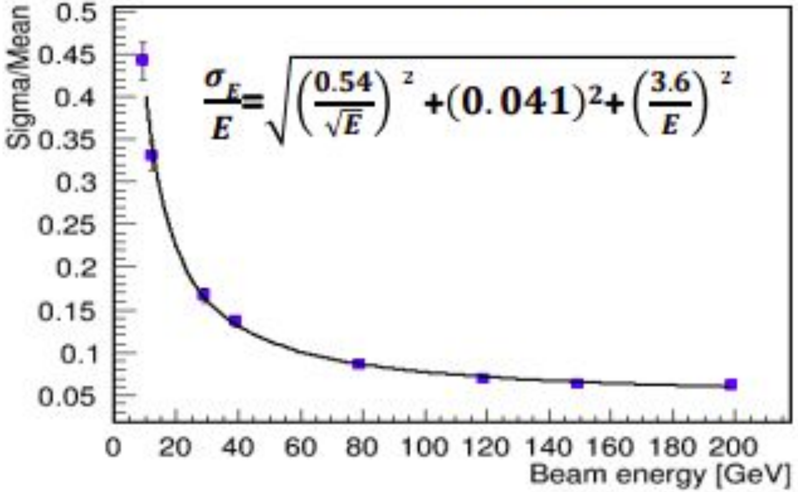
R.Ogul et al. PRC 83, 024608 (2011)





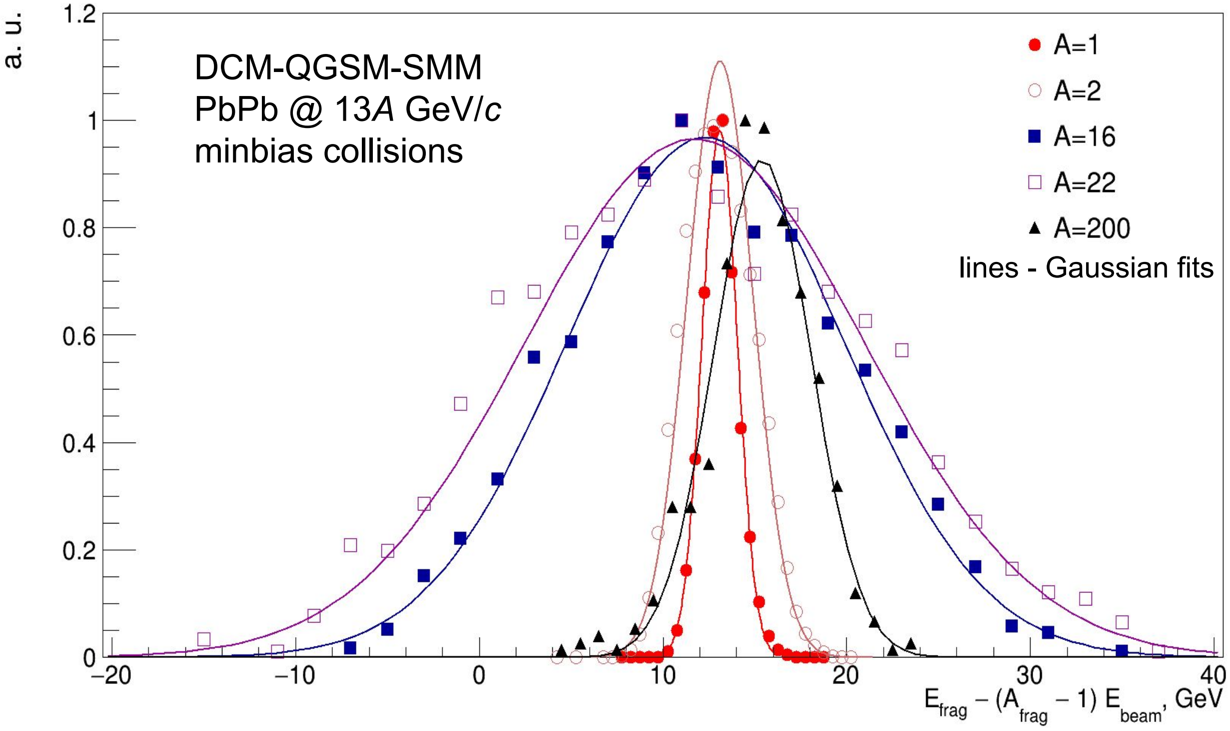
Respond of FHCal detector





- Mean of signal has linear dependency with beam energy

Gaussian approximation for fragments energy

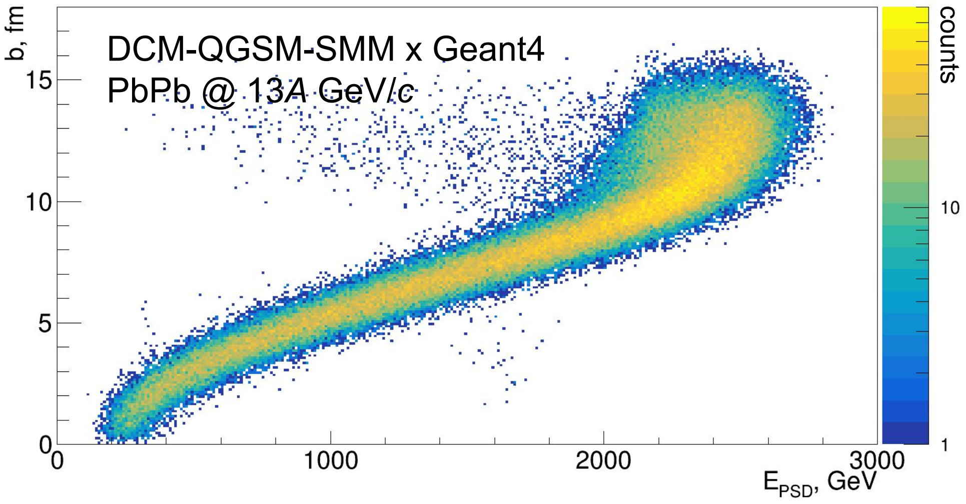


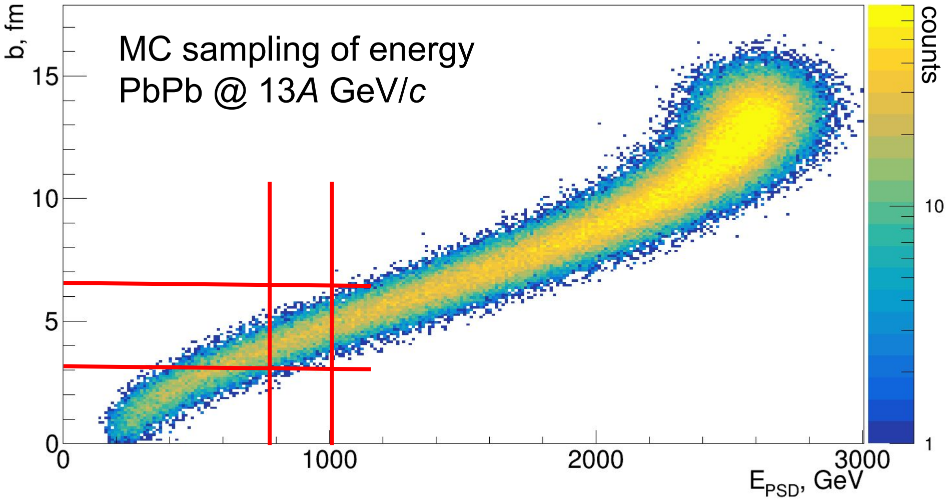
- Distribution of mass numbers of spectators fragments could be fitted by Gauss distribution
- Mean values equal to product of beam energy and fragment's mass
- Total spectators energy distribution is also Gauss:

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

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

Simplified MC sampling for hadron calorimeters

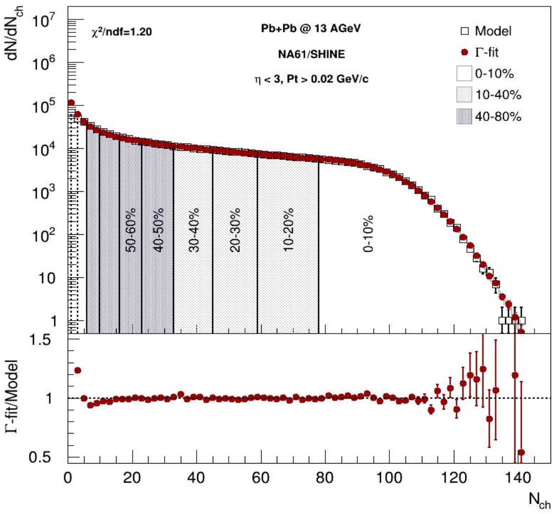


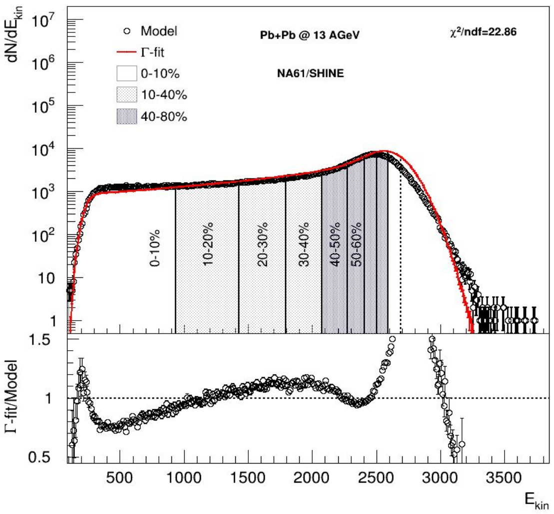


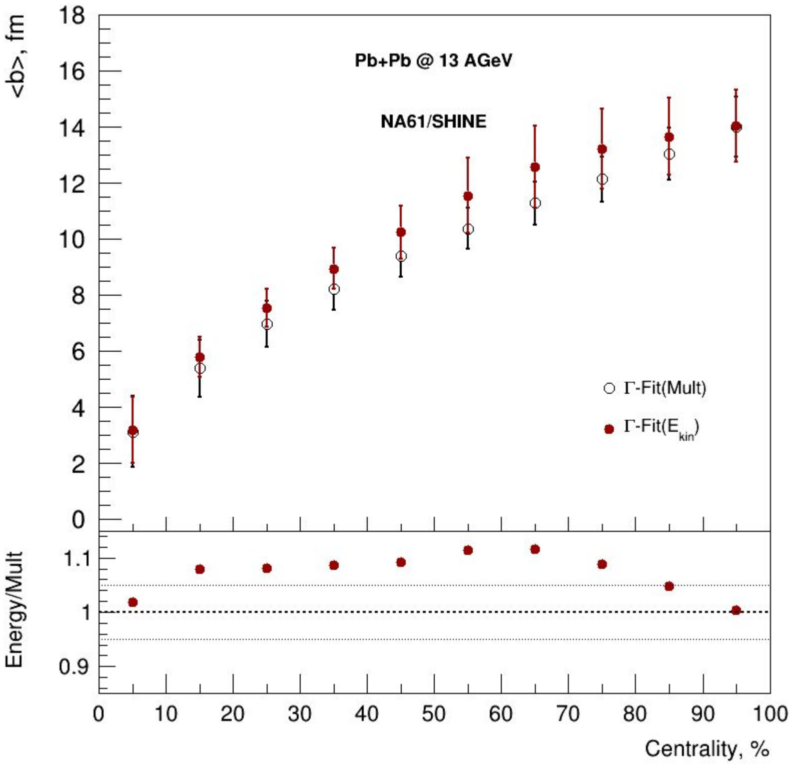
Segal I. Particles. 2023; 6(2):568-579.

- 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

Centrality determination using inverse Bayes approaches

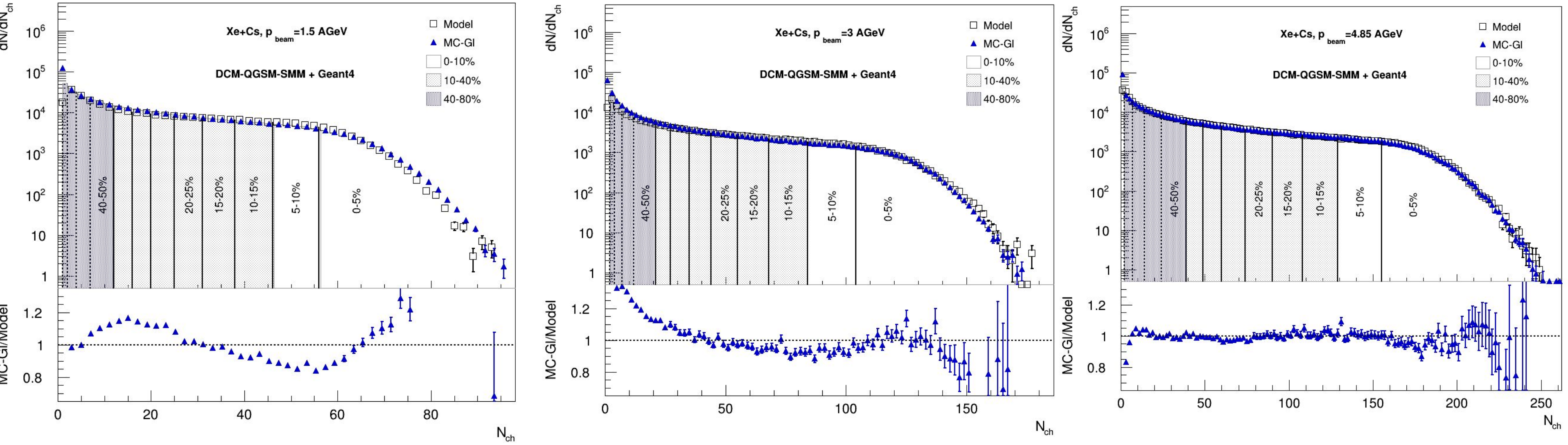






- Centrality determination based on spectator energy using inverse Bayes approach is being developed and tested on model (UrQMD, DCM-QGSM-SMM) and NA61/SHINE data
- Application of centrality determination based on spectator energy using MC-Glauber and inverse Bayes approaches is in progress
- Possible improvements are under investigation

Result of the fitting



NBD at different values of k