Comparison of methods for determining centrality in nucleus-nucleus collisions in the BM@N experiment

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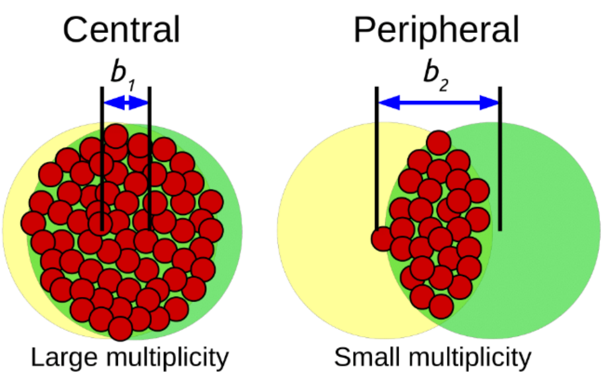
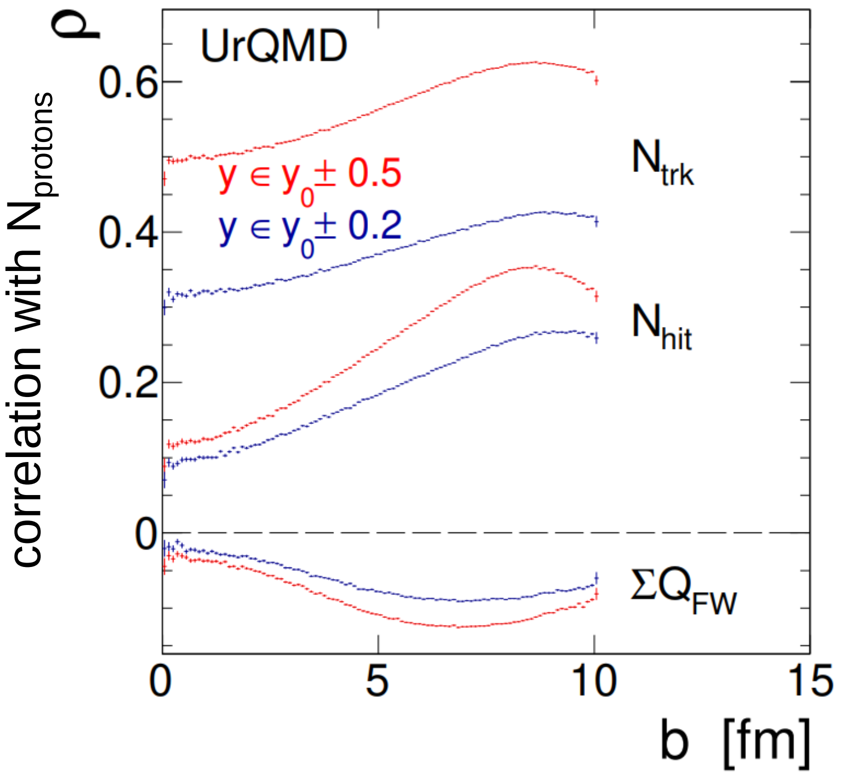
Centrality

- Evolution of matter produced in heavy-ion collisions depend on its initial geometry
- Centrality procedure maps initial geometry parameters with measurable quantities (multiplicity or energy of the spectators)
- **This allows comparison of the future BMAN results with the data from other experiments (STAR BES, NA49/NA61 scans) and theoretical models**

$$c(b) = \frac{\int_0^b \frac{d\sigma}{db'} db'}{\int_0^\infty \frac{d\sigma}{db'} db'} = \frac{1}{\sigma_{A-A}} \int_0^b \frac{d\sigma}{db'} db'$$





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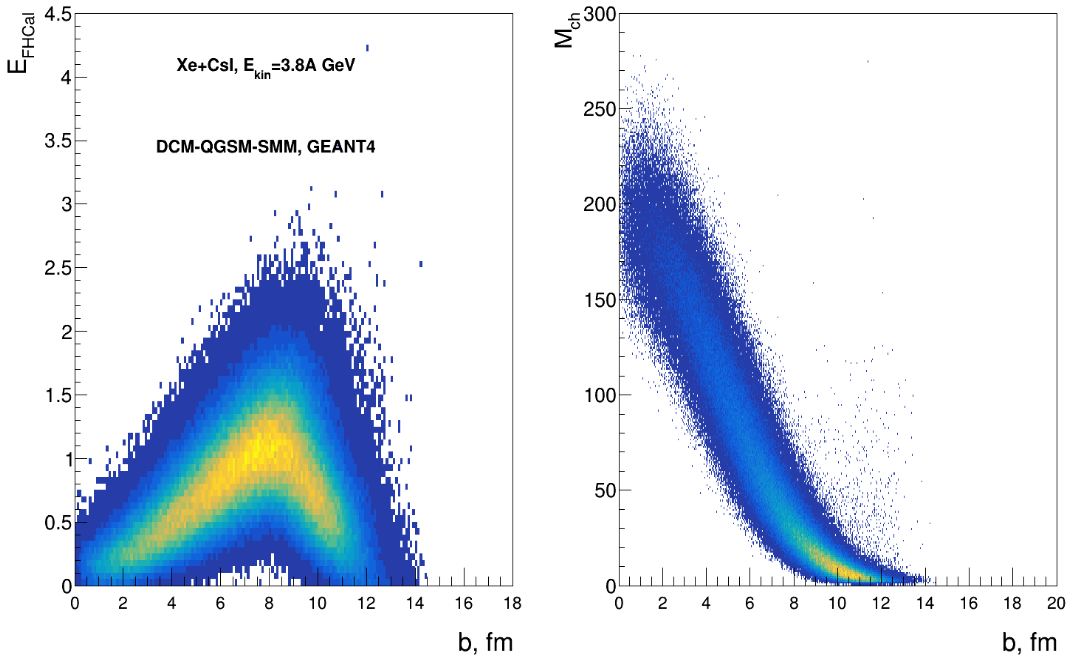
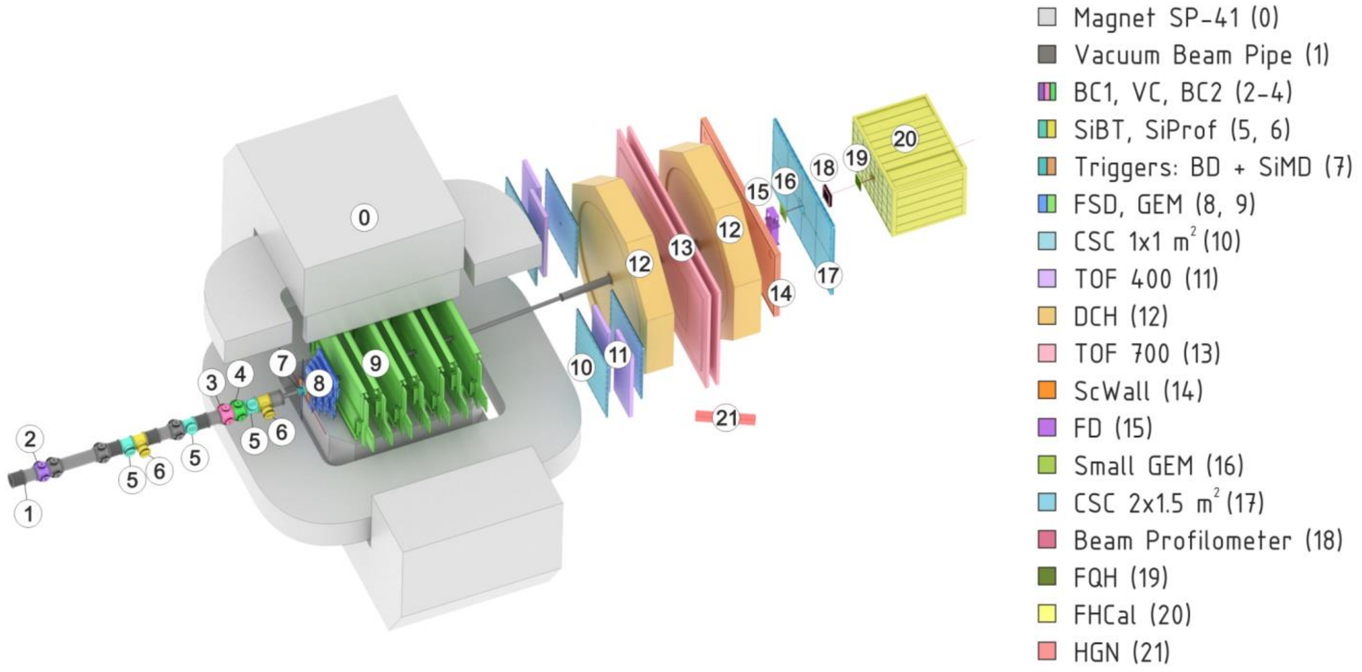
- A number of produced protons is stronger correlated with the number of produced particles (track & RPC+TOF hits) than with the total charge of spectator fragments (FW)
- to suppress self-correlation biases, it is necessary to use spectators fragments for centrality estimation

Centrality determination in BM@N

DCM-QGSM-SMM → GEANT4 → Reconstruction → Centrality determination



Dependence of energy in FHCal and track multiplicity on the impact parameter



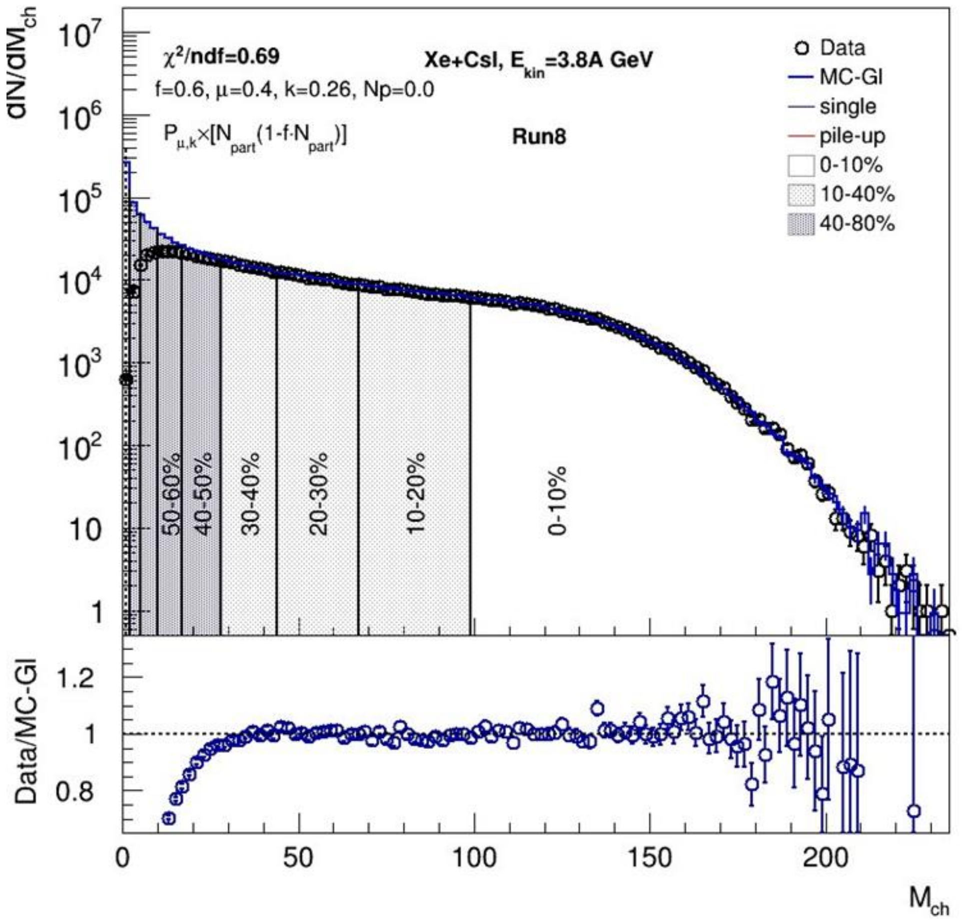
BM@N setup overview

MC-Glauber based centrality framework

MC Glauber data → Evaluate N_a: $N_a = fN_{part} + (1-f)N_{coll}$ → Call $NBD(\mu,k) \times N_a$ → Build multiplicity fitting function

Input multiplicity distribution

Evaluate χ^2 → Minimize χ^2 to find f, μ, k



NBD – negative binomial distribution

Parameters of the fit:

- **f** – the fraction of multiplicity from the soft component
- **μ** – mean multiplicity value
- **k** – width of the multiplicity distribution, can be connected to the fluctuations

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

The Bayesian inversion method (Γ-fit): DCM-QSM-SMM based

- The fluctuation kernel for multiplicity at fixed impact parameter is Gamma distr.:

$$P(M \mid c_b) = \frac{1}{\Gamma(k(c_b))\theta^2} M^{k(c_b)-1} e^{-M/\theta}$$

$$c_b = \int_0^b P(b')db'$$ – centrality based on impact parameter

$$\theta = \frac{D(M)}{\langle M \rangle}, \quad k = \frac{\langle M \rangle}{\theta}$$

$\langle M \rangle, D(M)$ – average and variance of Multiplicty

$$P(M) = \int_0^1 P(M \mid c_b)dc_b$$

$$\langle M \rangle = m_1 \cdot \langle M' \rangle$$

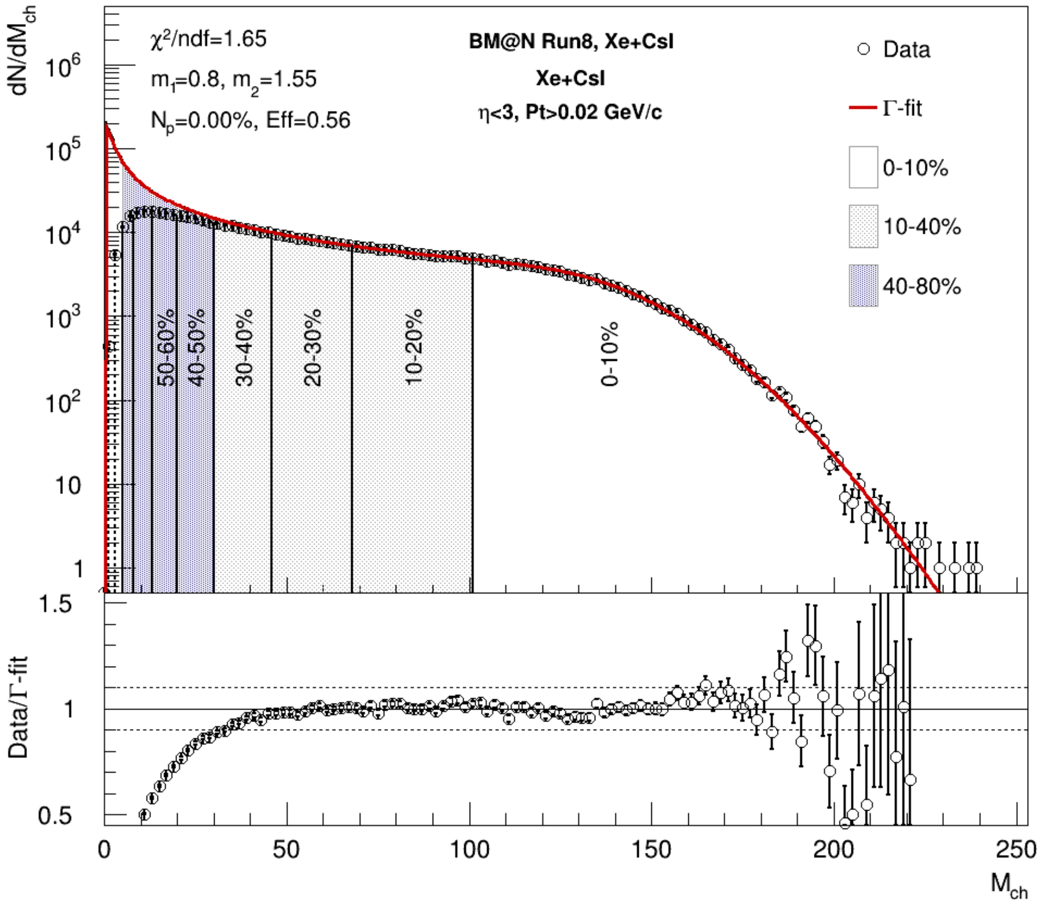
$$D(M) = m_1^2 \cdot D(M') + m_1 \cdot m_2 \langle M' \rangle$$

$\langle M'(c_b) \rangle$, $D(M'(c_b))$ – average value and var. of energy/mult. from the rec. model data

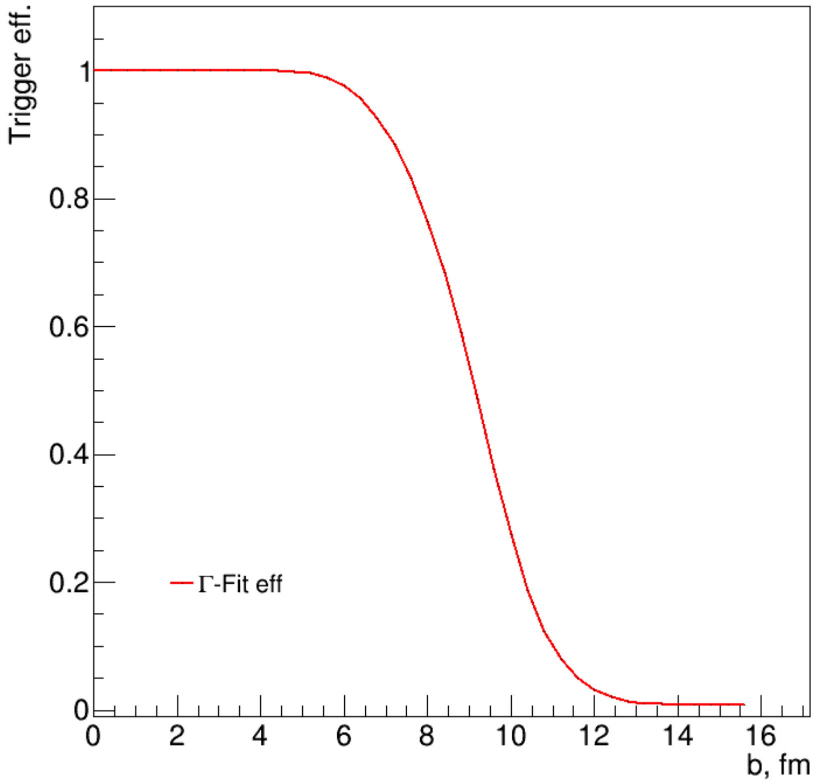
- can be approximated by polynomials or exponential polynomial

Fit results: experimental data

$$P_{eff}(b) = \int_0^{M_{max}} P_{eff}(M) P(M \mid b) dM$$

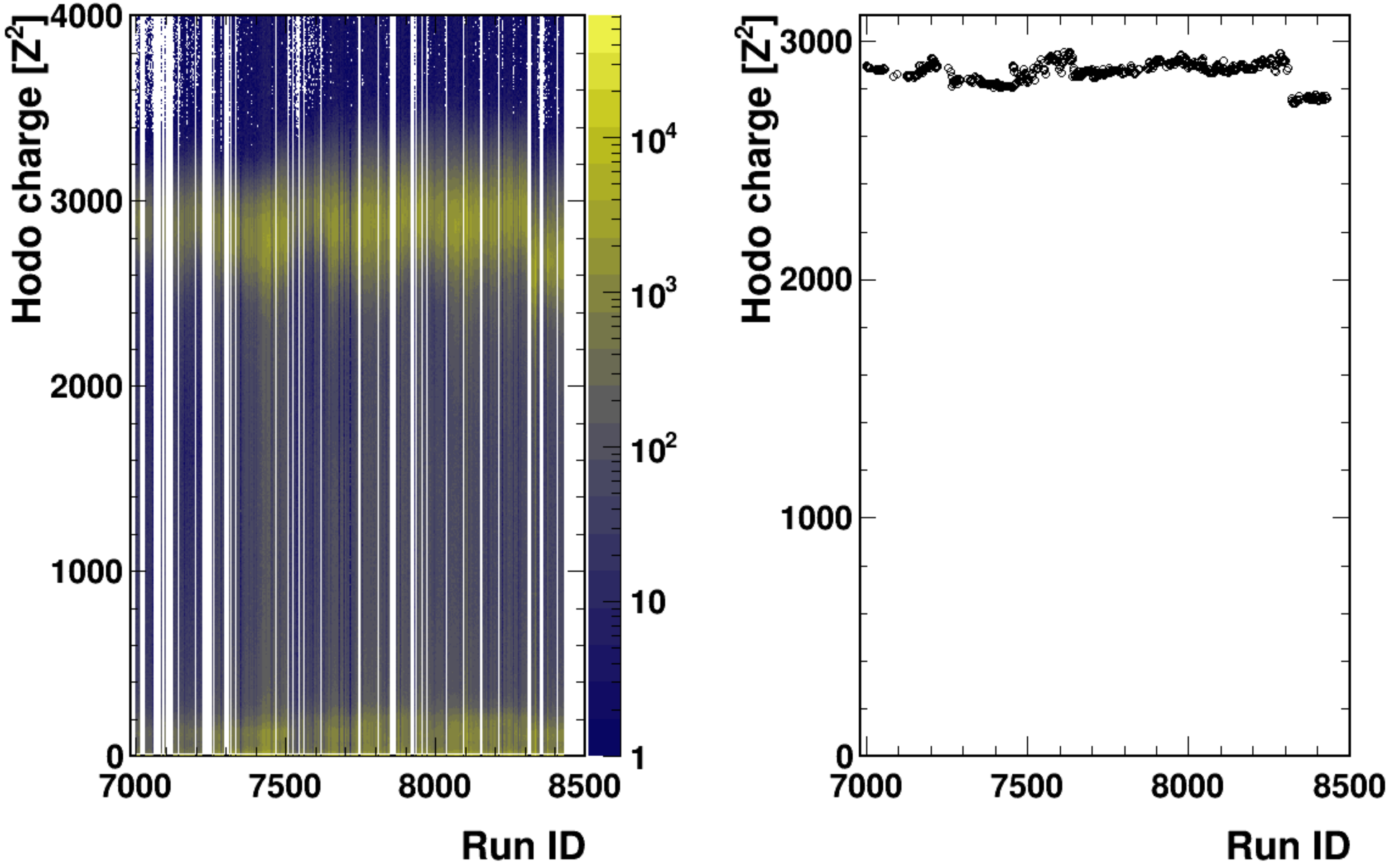


Good agreement with fit



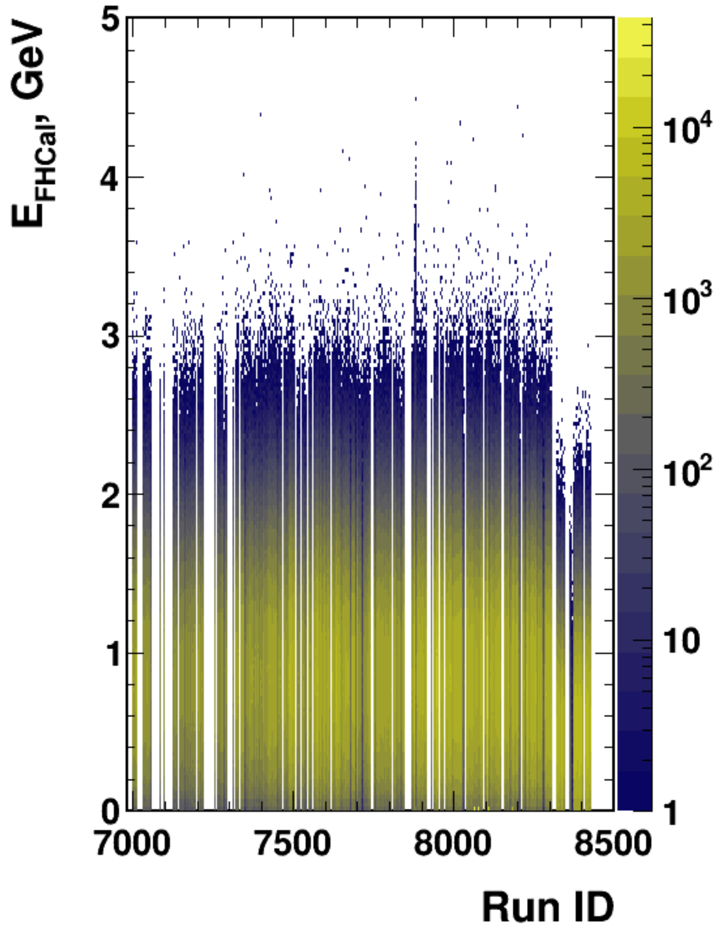
Convoluted trigger efficiency can be calculated using Bayes' theorem

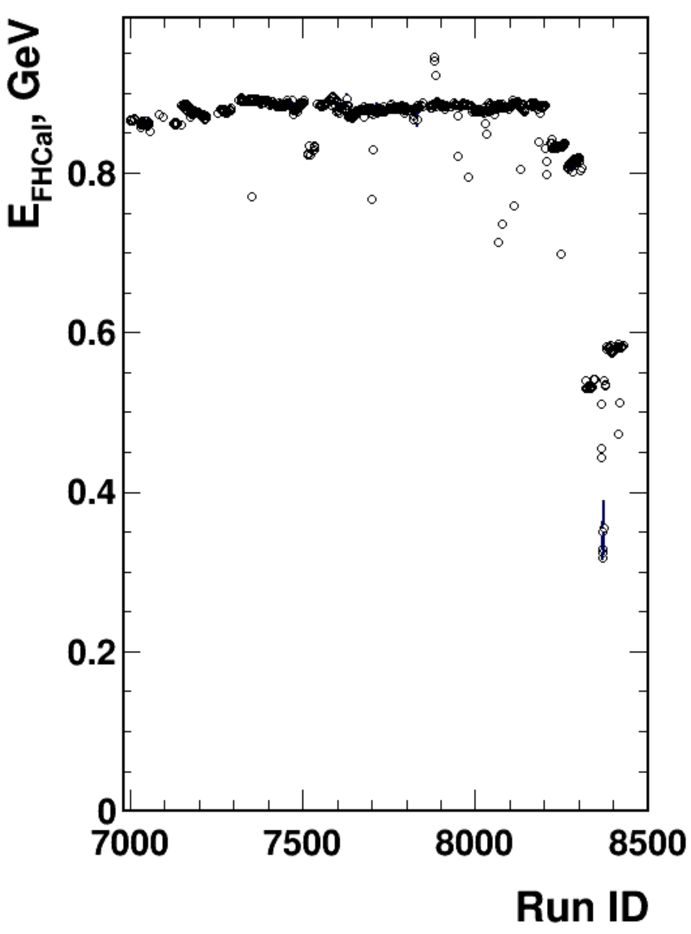
Signal of Hodoscope vs Run ID



The average signal value for the xenon ion in the hodoscope is weakly dependent on the Run ID

Signal of Hodoscope vs Run ID





The average signal value in the FHCal is weakly dependent on the Run ID, but some modules require calibration

The Bayesian inversion method (Γ-fit): 2D fit

- The fluctuation kernel for energy and multiplicity at fixed impact parameter can be describe by 2D Gamma distr.:

$$P(E,M\,|\,c_b) = G_{2D}(E,M,\langle E\rangle,\langle M\rangle,D(E),D(M),R)$$

$\langle E\rangle, D(E)$ – average value and variance of energy

$R(E,M)$ – Pirson correlation coefficient

$$P(E,M) = \int_0^1 P(E,M\,|\,c_b)\,dc_b$$

$$R(E,M) = \frac{\varepsilon_1^2 m_1^2}{\varepsilon_2 m_2} R(E',M')$$

$\varepsilon_1, \varepsilon_2, m_1, m_2$ - fit parameters

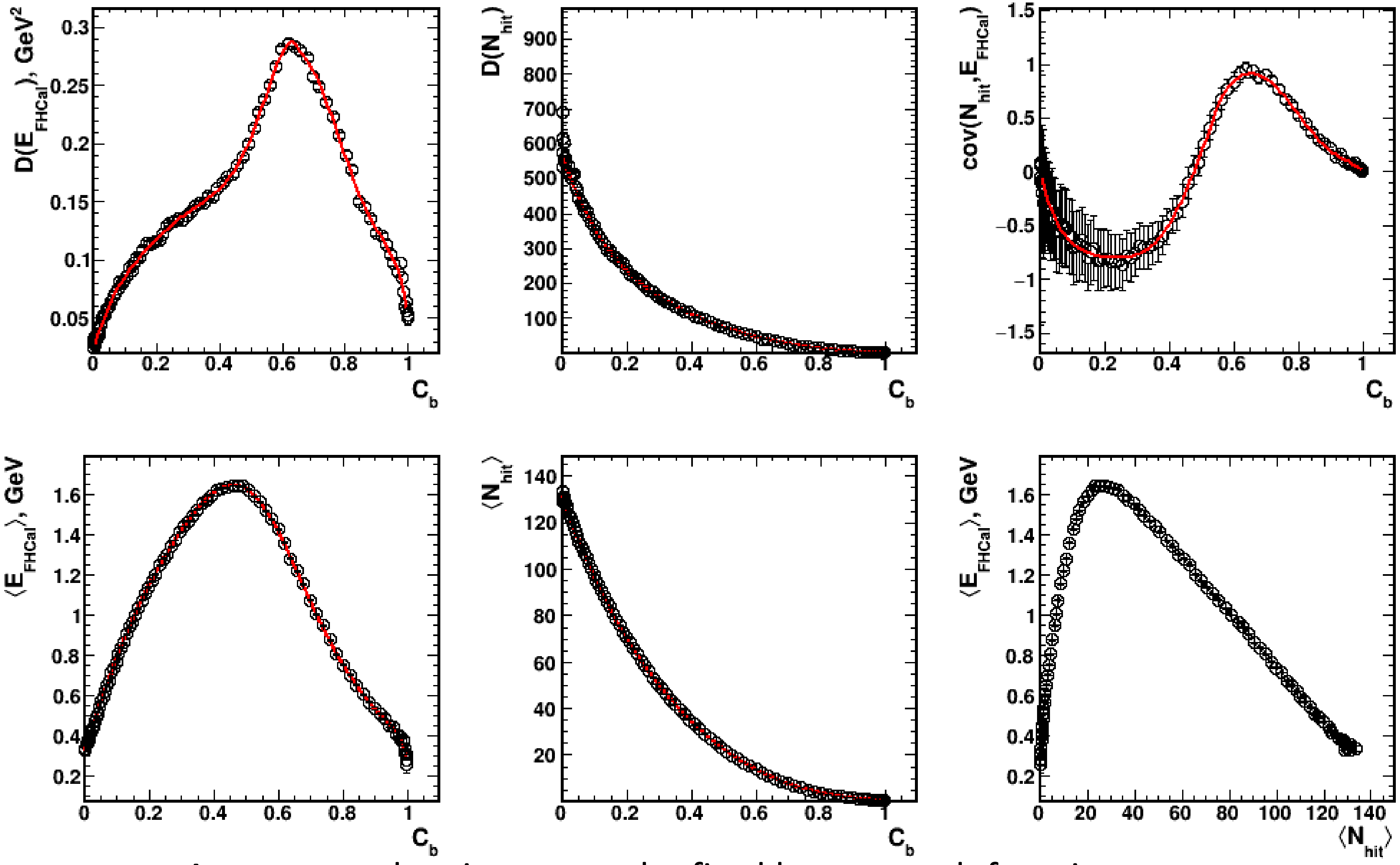
$\langle E'(c_b)\rangle$ – average value and var. of energy/mult.

$D(E'(c_b))$ from the rec. model data

$$\langle E\rangle = \varepsilon_1 \langle E'(c_b)\rangle, \quad D(E) = \varepsilon_2 D(E'(c_b))$$
$$\langle M\rangle = m_1 \langle M'\rangle, \quad D(M) = m_1^2 D(M') + m_2 \langle M'\rangle$$

$\langle E'(c_b)\rangle, \quad D(E'(c_b))$ - can be approximated by polynomials

Dependence of the average value and variance on centrality



Averages and variances can be fited by a smooth function.

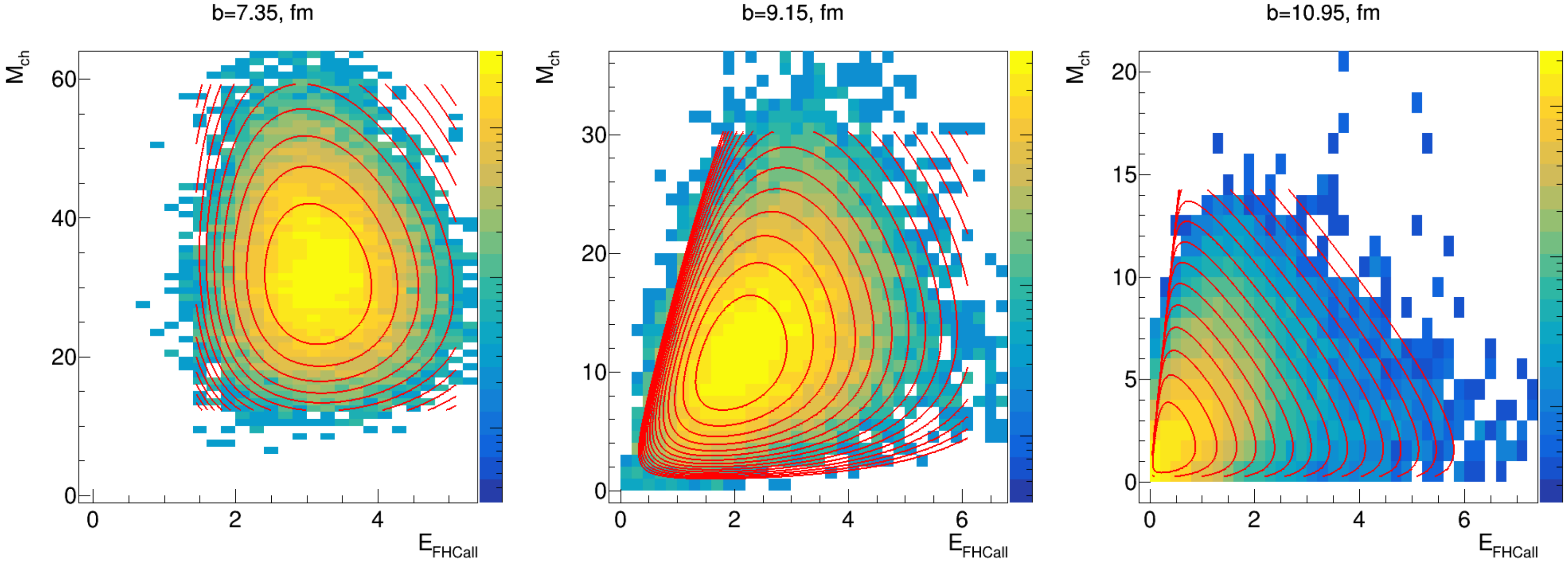
The fluctuation of energy and multiplicity at fixed impact parameter

It is possible to find such a rotation angle of the system that $\operatorname{cov}(x, y) = 0$

$$x = \cos(\alpha)E + \sin(\alpha)M,$$
$$y = -\sin(\alpha)E + \cos(\alpha)M$$

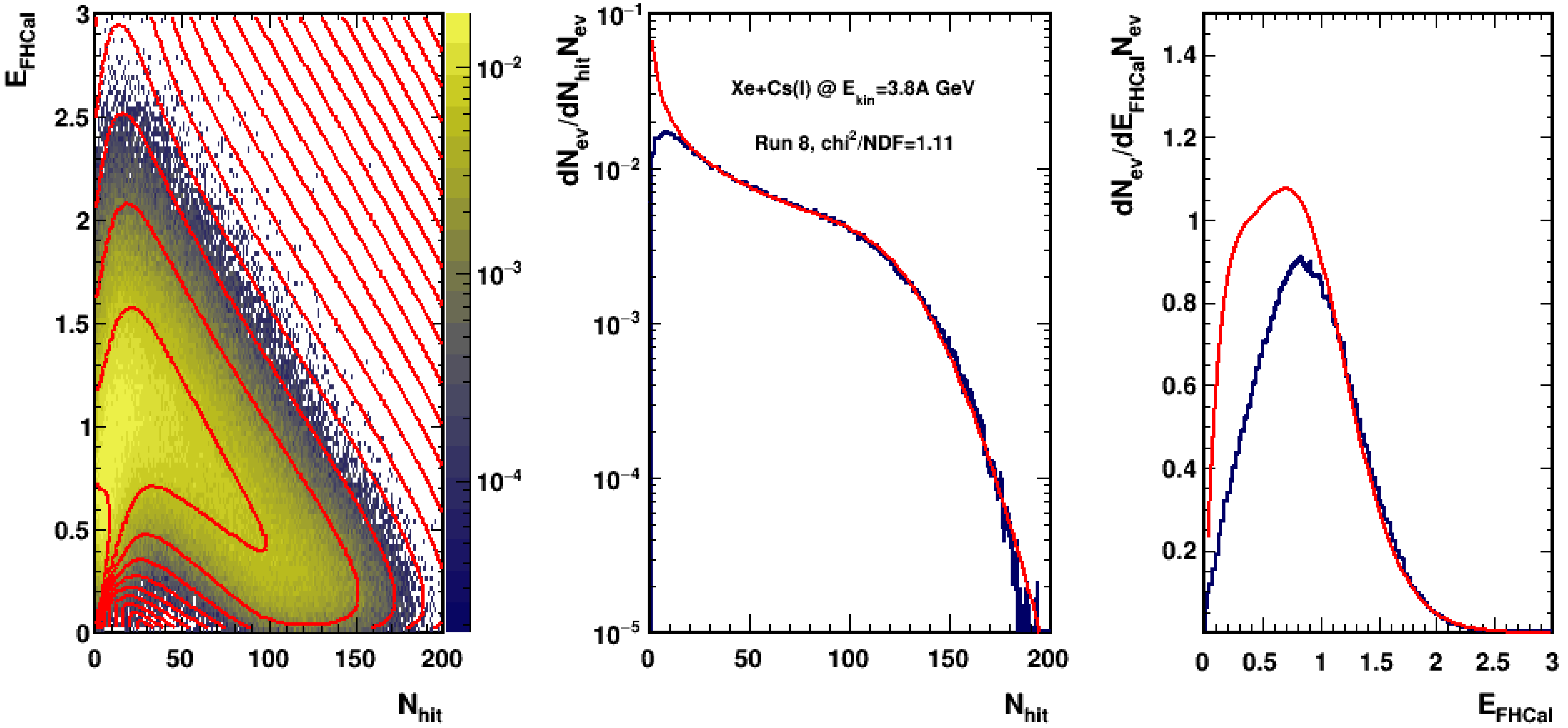
$$\alpha = \arctan\left(\frac{2\sqrt{D(E)D(M)}R(E,M)}{D(E) - D(M)}\right)$$

$$G_{2D}(E_{FH}, M_{ch}, \langle E\rangle, \langle M\rangle, D(E), D(M), R) = G(x, \theta_x, k_x)\cdot G(y, \theta_y, k_y)$$



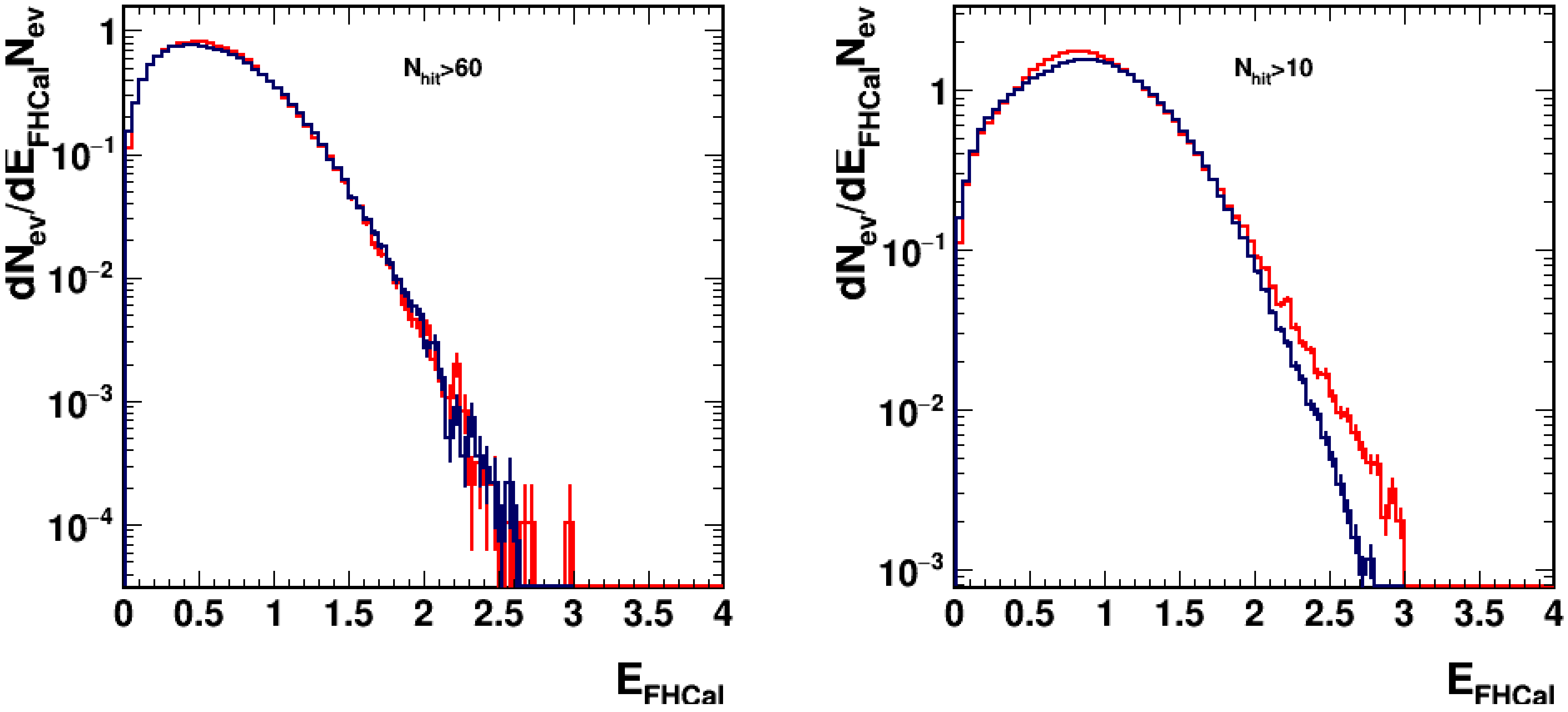
The distribution of energy and multiplicity at a fixed impact parameter is well described by the gamma distribution

2D fit results



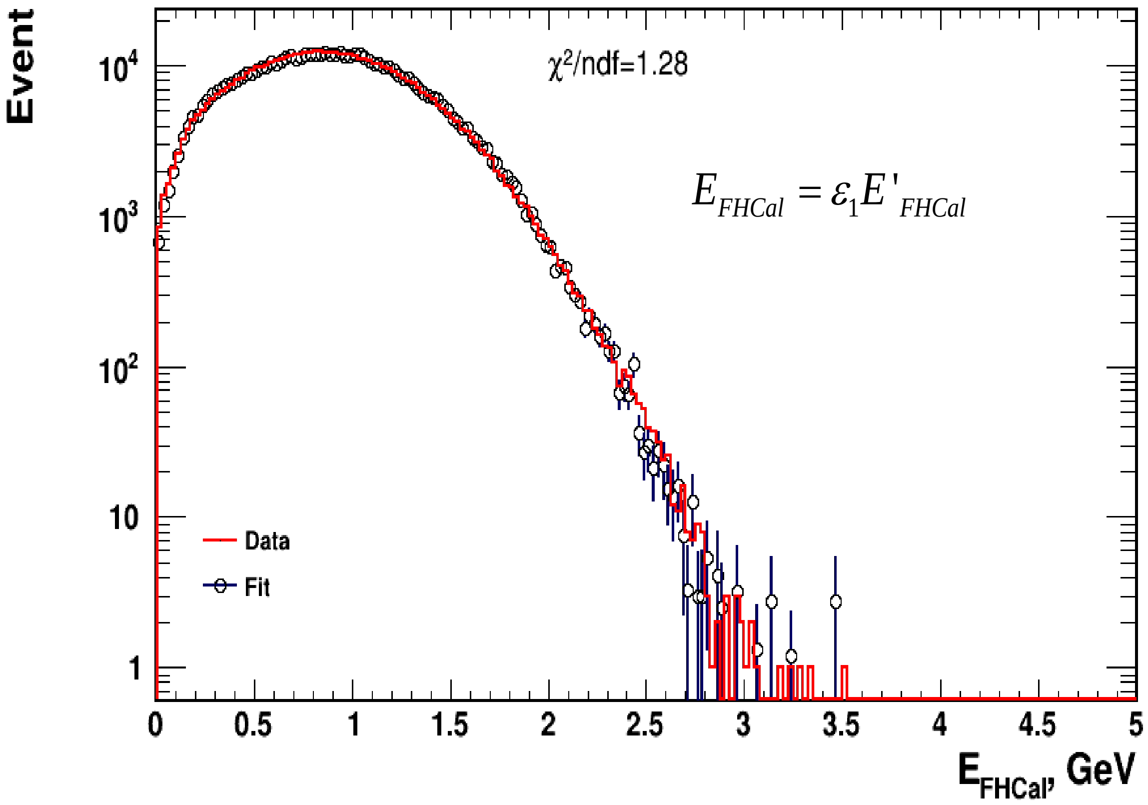
The fit function qualitatively reproduces the multiplicity-energy correlation from FHCal

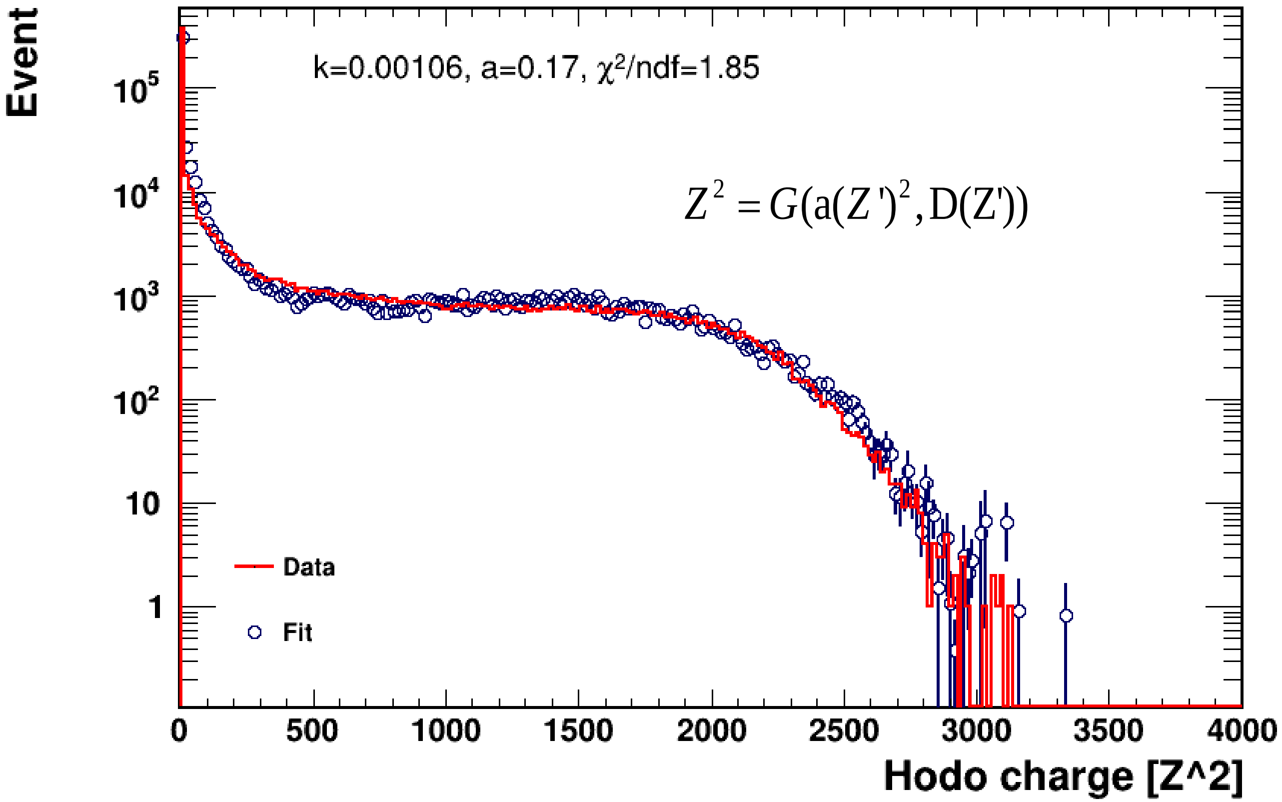
Energy distributions in FHCal



Good agreement between fit and data for the area below the anchorpoint

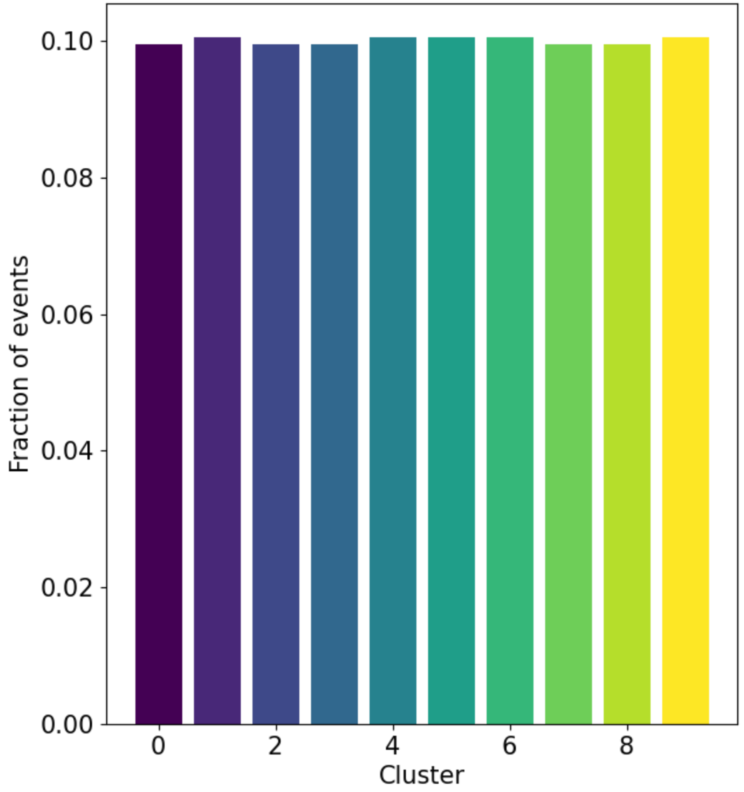
The results of the fit signals from the calorimeter and hodoscope

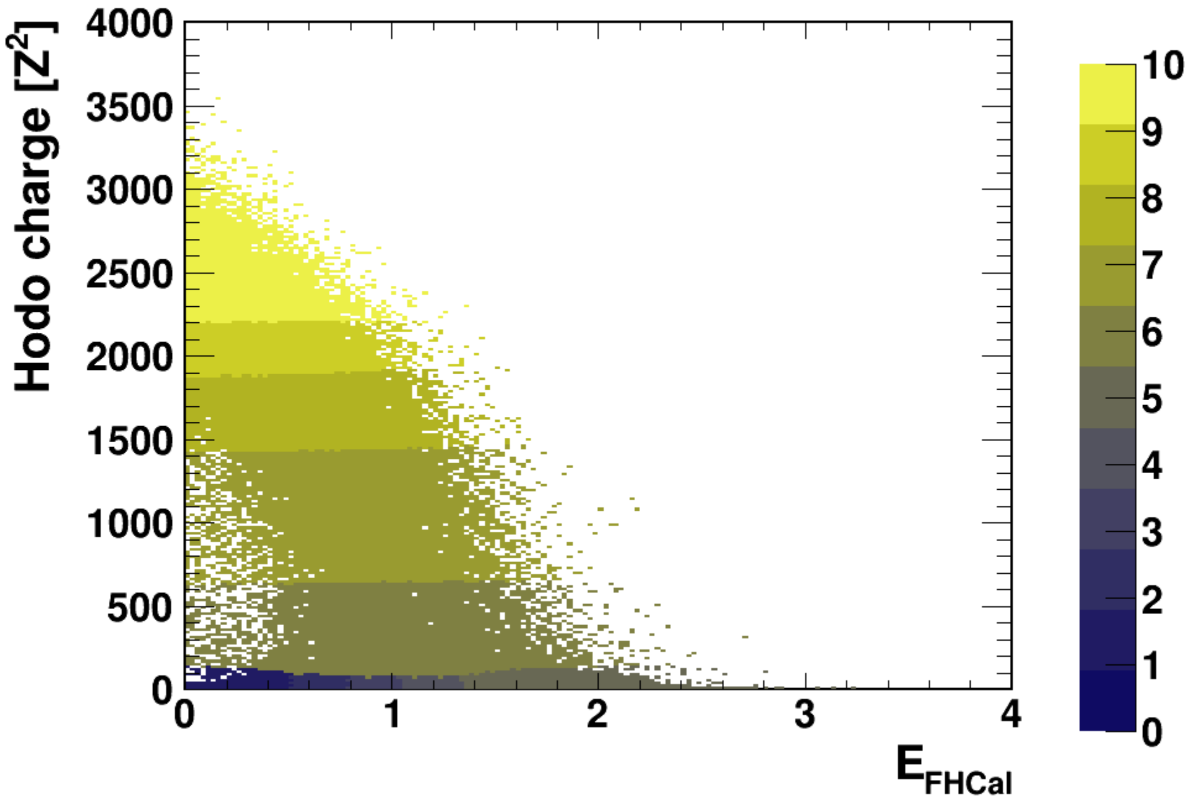




Good agreement of fit results

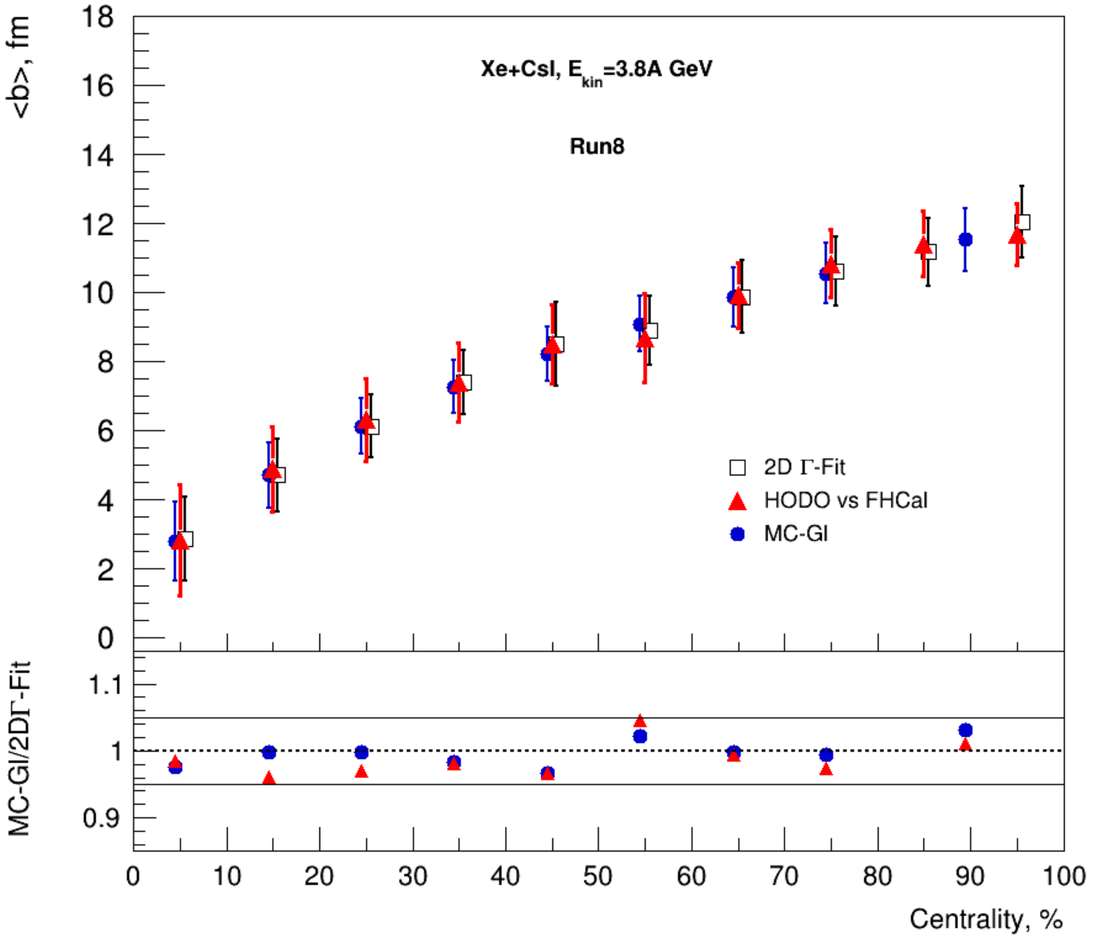
Centrality determination using an forward calorimeter and hodoscope

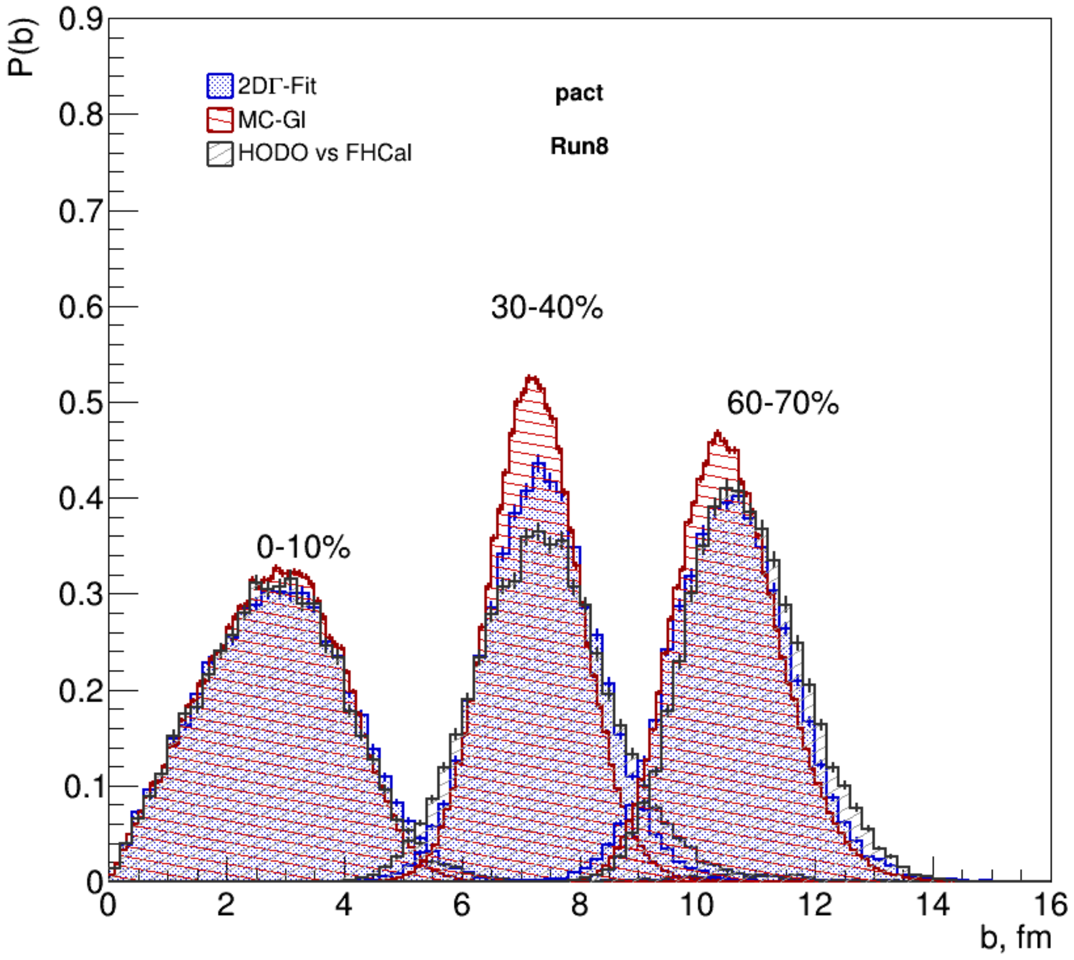




The K-means method allows to divide a two-dimensional distribution into centrality classes.
In order to correctly apply the class boundaries, it is necessary to match the simulation results with the experiment

Comparison with Glauber MC fit





There is agreement within 5%.

Summary and Outlook

- Both the Bayesian inversion and MC – Glauber methods provide consistent results
- The Bayesian inversion method was applied to the BM@N data:
    - Multiplicity-based and 2D approaches using Q^2_{Hodo} and E_{FHCal} describe experimental data reasonably well.
- In the future, it is planned to study systematics uncertainties using different models (DCM, UrQMD, etc.) and observables (GEM hit multiplicity, etc.)

Thank you for your attention!