Centrality determination in heavy-ion collisions at the NICA energy range.

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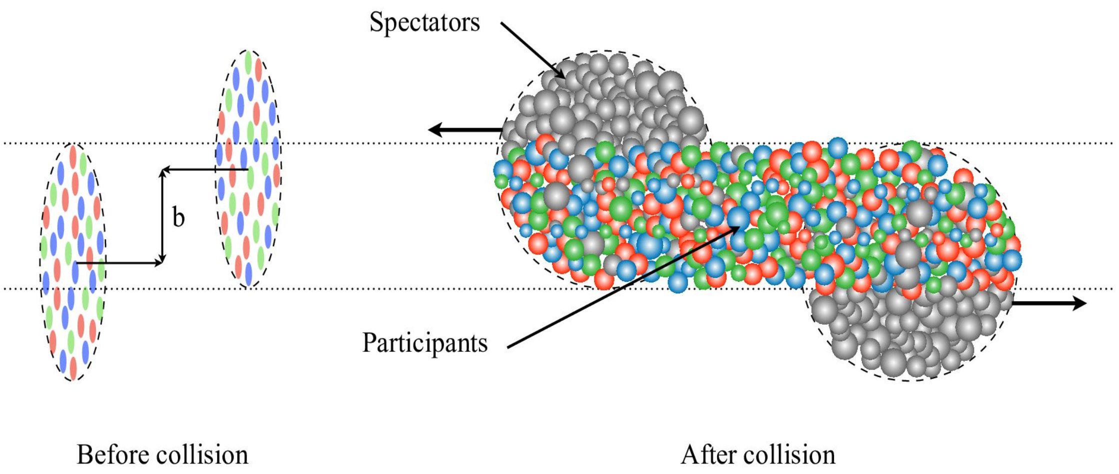
Motivation for centrality determination

- Evolution of matter produced in heavy-ion collisions depends on its initial geometry
- Impact parameters (**b**) - one of the important collision parameters
  - impossible to measure experimentally
- **Goal of centrality determination:** map (on average) the collision geometry parameters to experimental observables (centrality estimators)

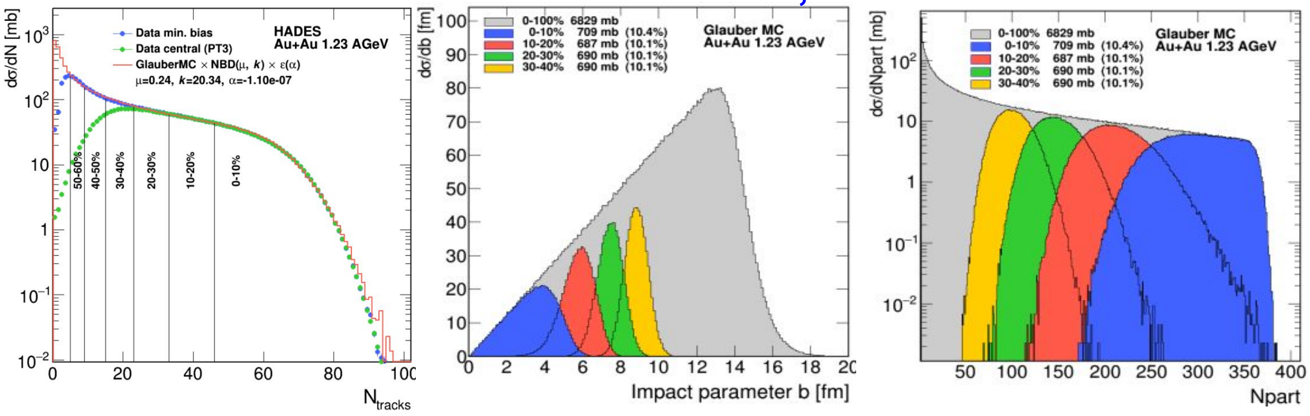
Centrality class S_1-S_2:
group of events corresponding to a given fraction (in %) of the total cross section:

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



Centrality determination

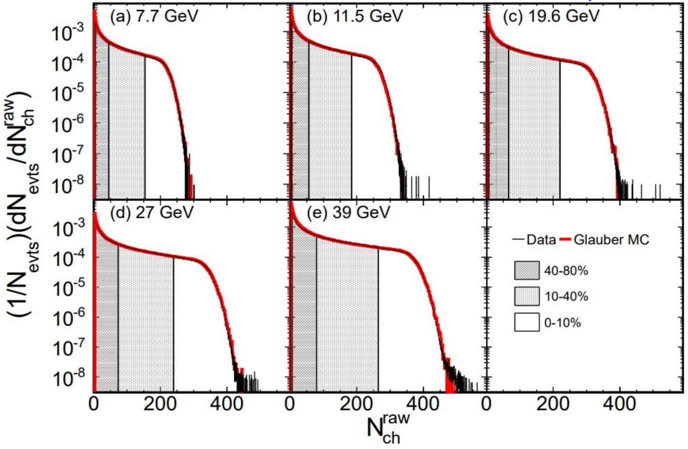
HADES, Au+Au 1.23A GeV



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

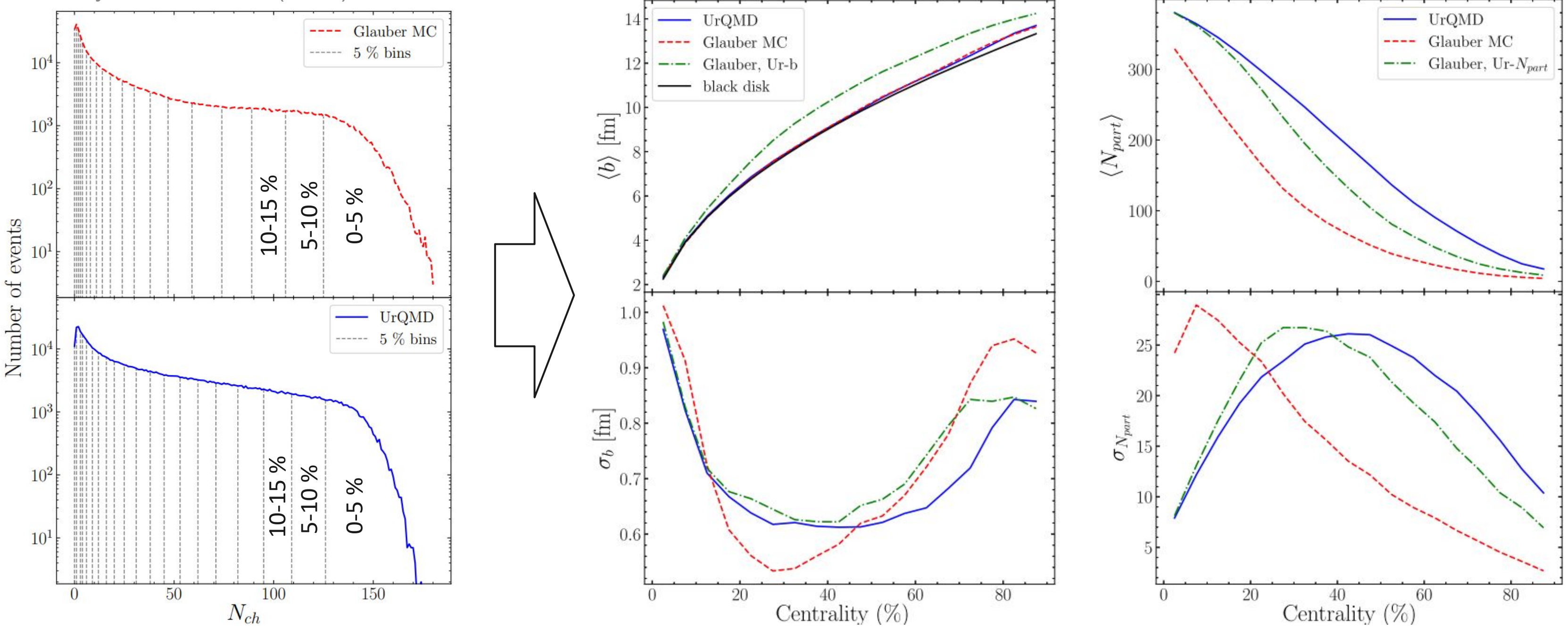
Centrality determination based on multiplicity provides with:

- 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}

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



- MC-Glauber x NBD multiplicity fitting procedure is standard method for centrality determination
- The MC-Glauber non-realistic $\mathbf{N}_{\mathbf{part}}$ simulations at low energies
- Differences in of number of participant nucleons ($\mathbf{N}_{\mathbf{part}}$) distributions from UrQMD and MC
- The impact parameter (**b**) - model independent centrality estimator

The BM@N and MPD experiments

SImulation:

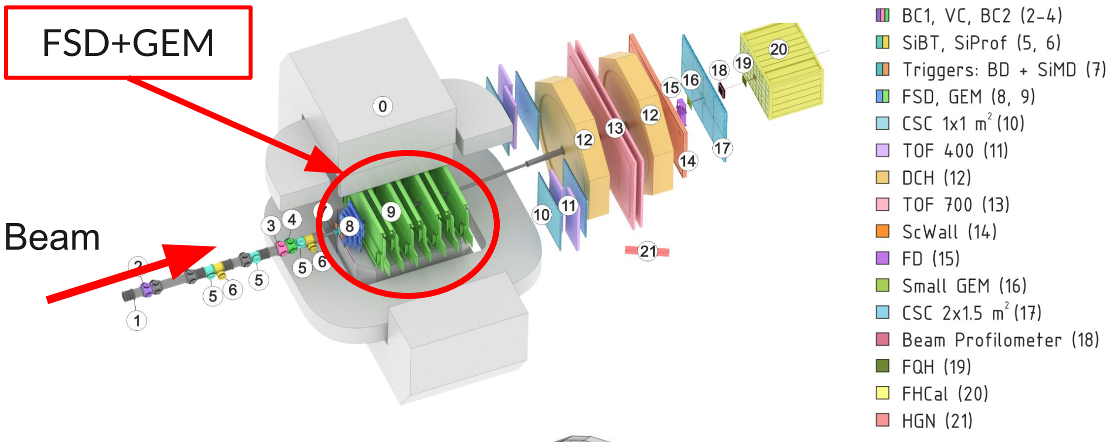
- DCM-QGSM-SMM, Xe-Cs
- GEANT4 transport

Data:

- run8 Xe-CsI @3.8*A* GeV

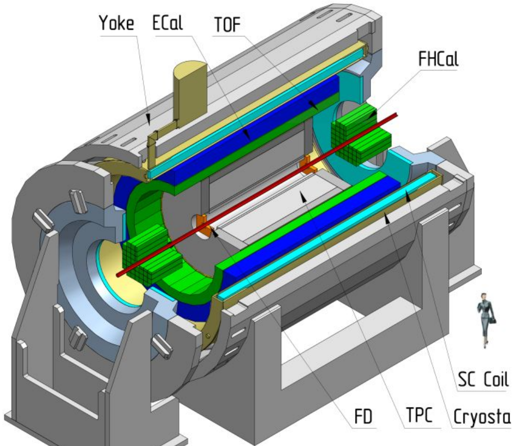
Multiplicity of charged particles from tracking system FSD+GEM

arXiv:2312.17573



SImulation:

- Au+Au, UrQMD, $\sqrt{s_{NN}}$ = 5, 7.7, 11.5, 19.6, 27, 39 GeV
- Used particle selection:
  $|\eta|<0.5$, $p_T>0.1$ GeV/c



MPD Collaboration, Eur. Phys. J. A 58, 140 (2022)

Centrality determination based on Monte-Carlo sampling of produced particles

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

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

Evaluate number of ancestors (sources of produced particles)
$N_a = \mathbf{f} N_{part} + (1-\mathbf{f}) N_{coll}$

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

Multiplicities from two collision events are randomly superimposed with the probability **p** (“pileup” events)

Result: total S_{tot}

MC-Glauber distribution

Full Monte-Carlo (real data) distribution

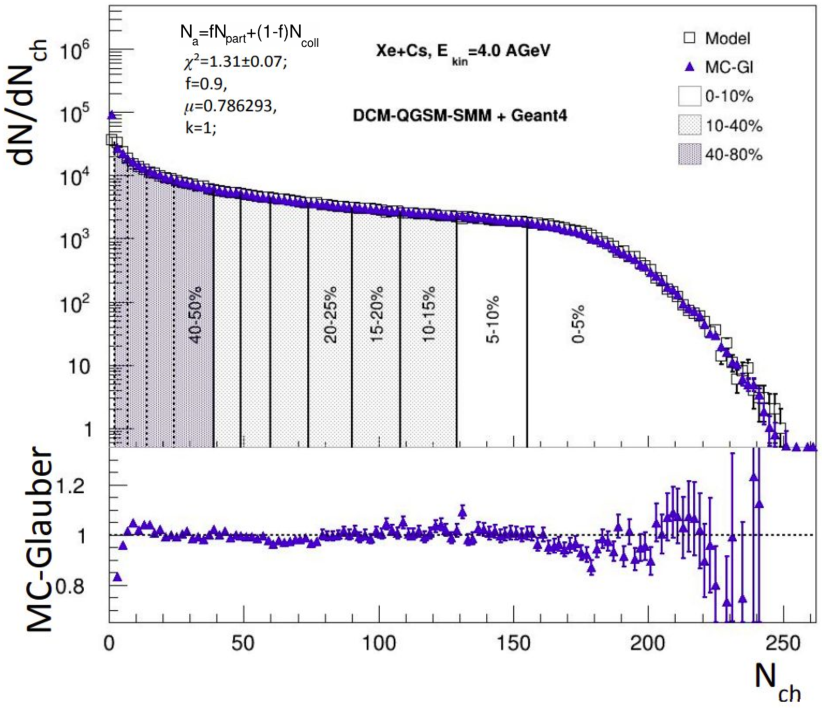
Evaluate χ^2 between $N/dN_{MC/data}$ and N/dN_{Gl}

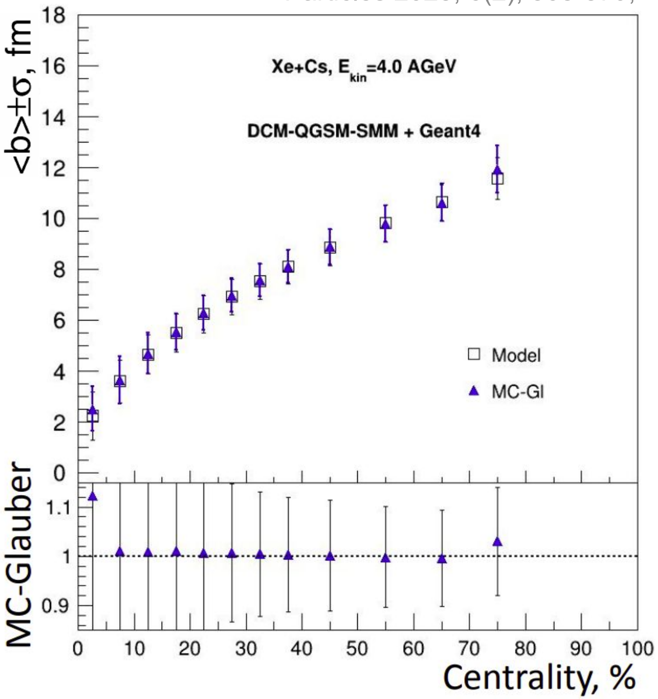
Scan phase space of parameters to find their values for minimum of χ^2

Extract relation between geometry parameters and centrality estimator

MC-Glauber fit result Xe-Cs

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)

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

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

$$\frac{\sigma^2}{\langle N_{ch} \rangle} = \theta \simeq const, \; k = \frac{\langle N_{ch} \rangle}{\theta}$$

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

Mean multiplicity as a function of c_b can be defined as follows:

$$\langle N_{ch} \rangle = N_{knee} \exp\left(\sum_{j=1}^{3} a_j c_b^j \right)$$

N_{knee}, θ, a_j - 5 parameters

Fit function for N_{ch} distribution: $P(N_{ch}) = \int_0^1 P(N_{ch}|c_b)dc_b$

b-distribution for a given N_{ch} range: $P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(N_{ch}|b)dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$

2 main steps of the method:

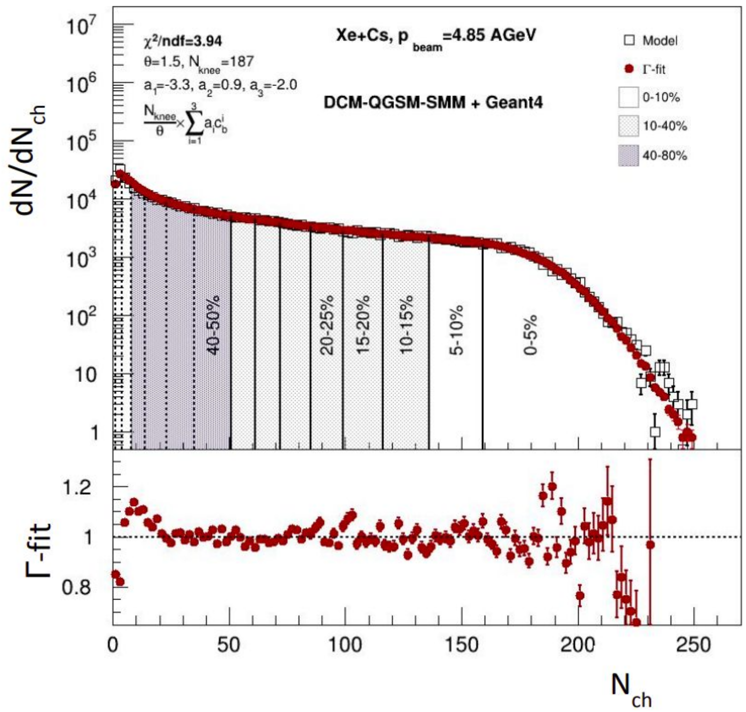
Fit experimental (model) distribution with P(N)

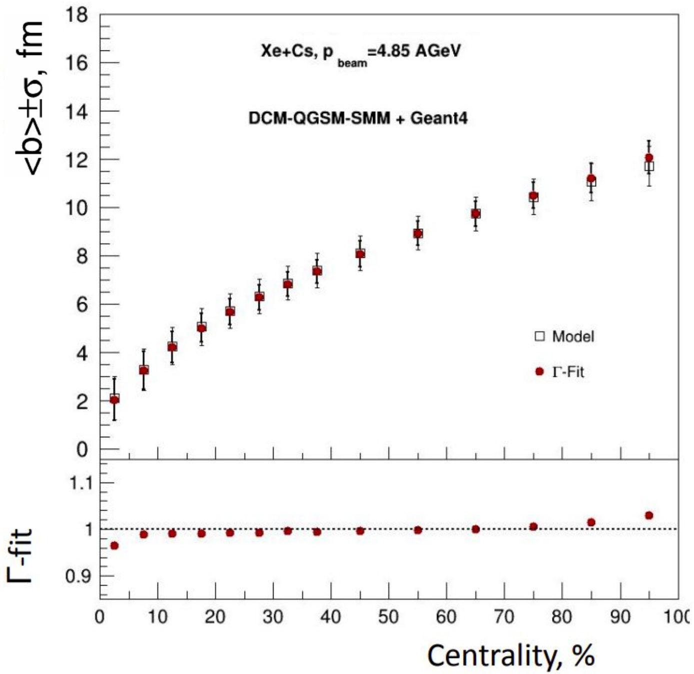
↓

Construct P(b|N) using Bayes' theorem:
P(b|N) = P(b)P(N|b)/P(N)

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

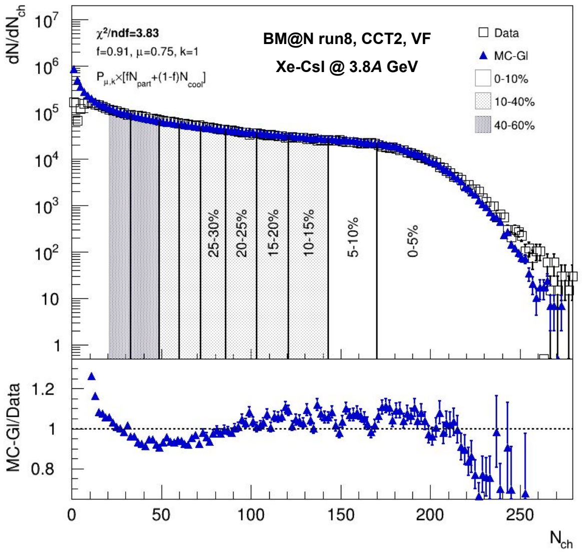
Γ-fit result Xe-Cs

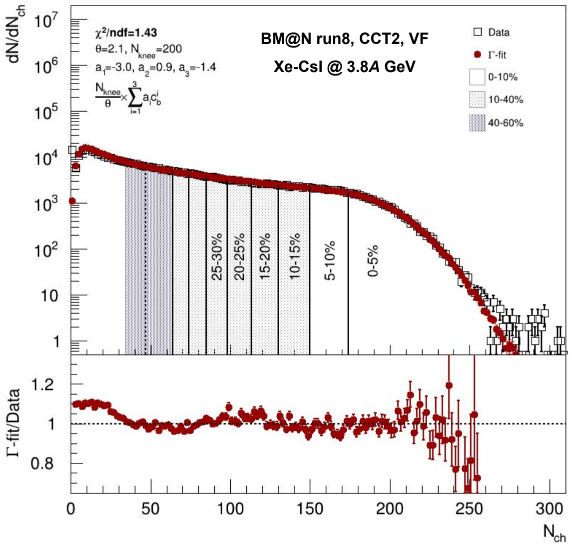


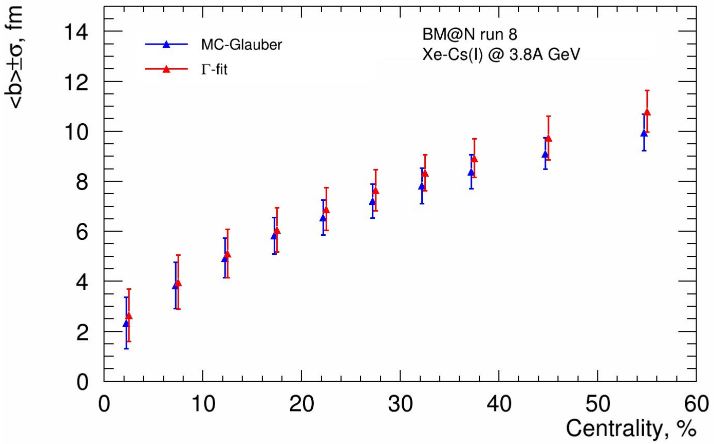


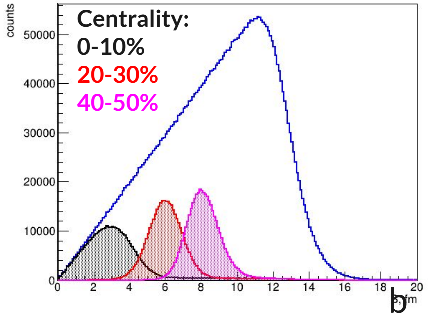
- Good agreement between model data and fit
- Impact parameter distributions in different centrality classes reproduces ones from DCM-QGSM-SMM

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
- For Γ-fit, all centrality classes are comparable

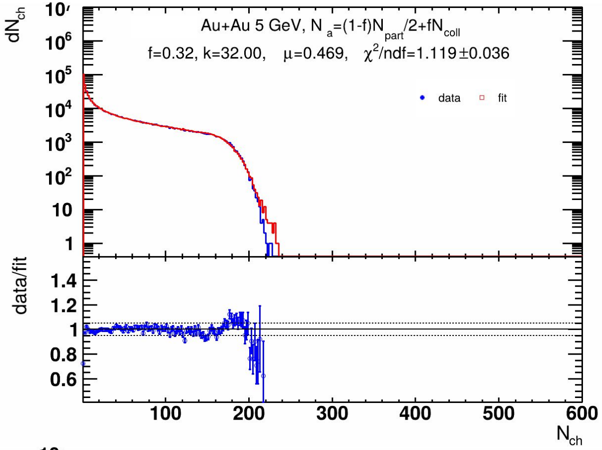
UrQMD, Au+Au, $\sqrt{s_{NN}}$= 5–39 GeV

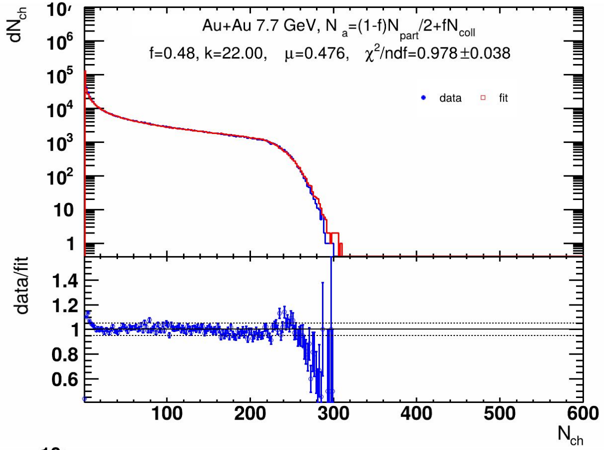
SImulation:

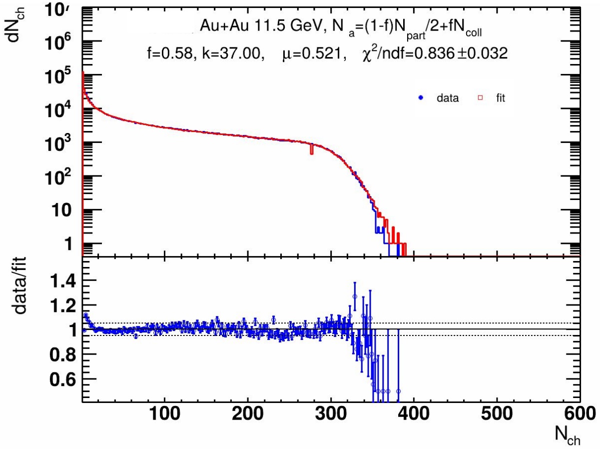
UrQMD, Au+Au, $\sqrt{s_{NN}}$ = 5, 7.7, 11.5, 19.6, 27, 39 GeV

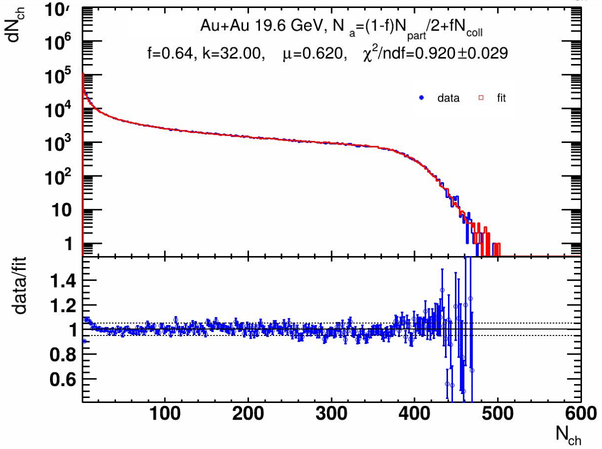
Used particle selection:

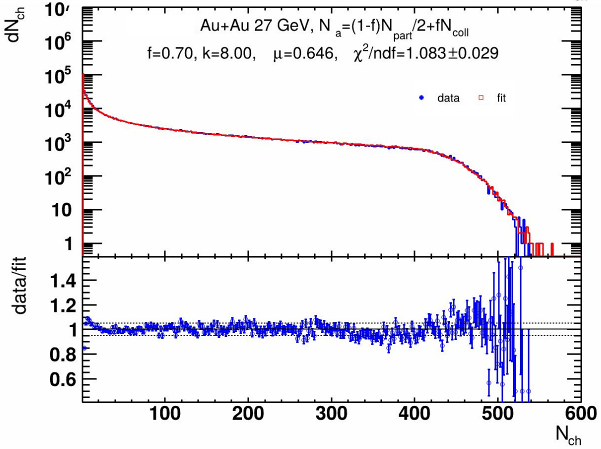
$|\eta|<0.5$, $p_T>0.1$ GeV/c







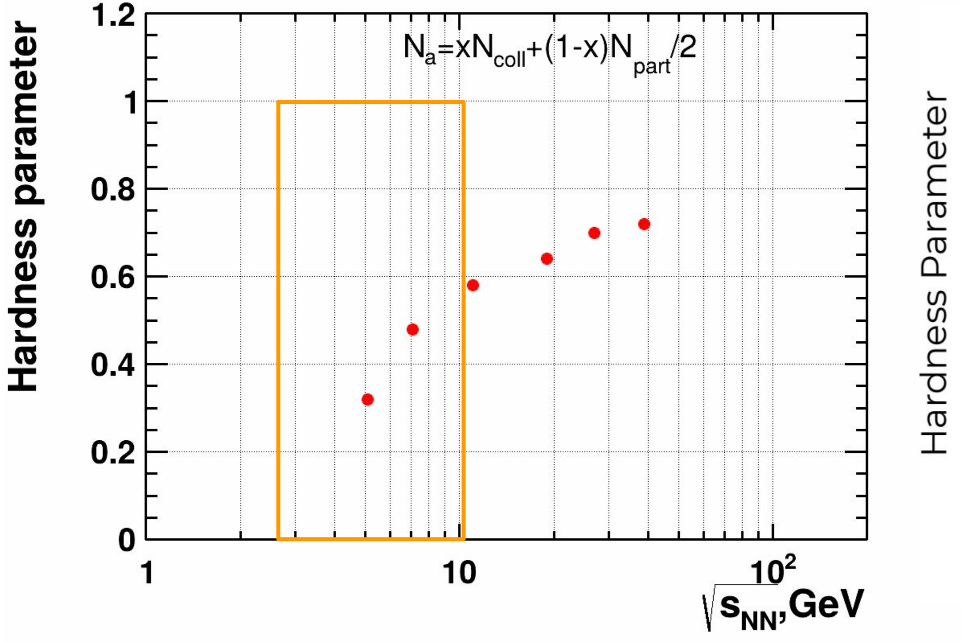


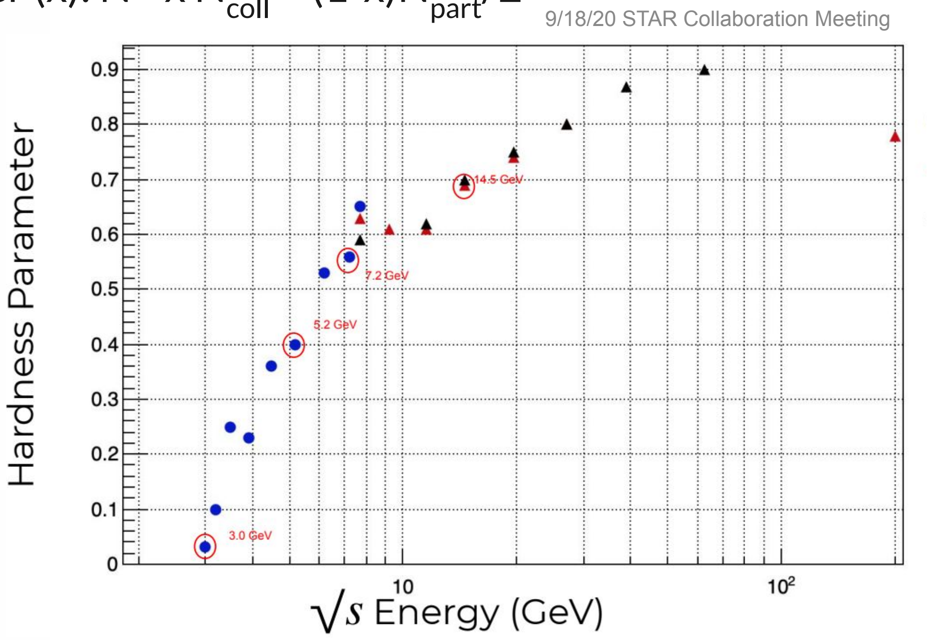


Good agreement between data and fit for all energies

Hardness vs. Energy

Crude Hardness parameter (x): $N = x\,N_{coll} + (1-x)N_{part}/2$

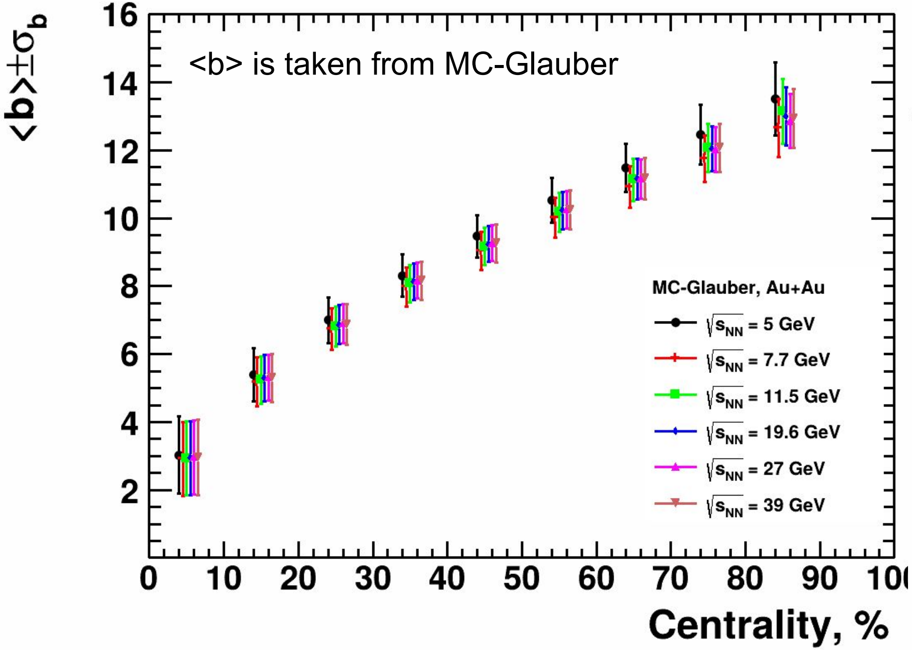


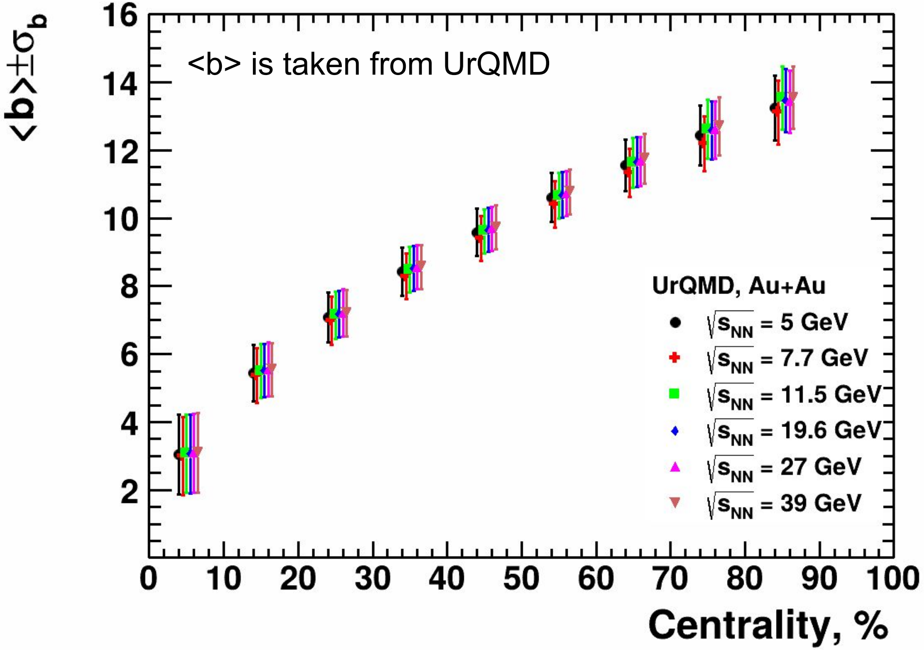


- Hardness parameter which determines Ncoll/Npart contributions to multiplicity
- Trend in Hardness vs. $\sqrt{s_{NN}}$ in UrQMD model is similar to the trend in STAR
- Strong dependence of x at low energies

<b>(cent) vs. Energy

centrality bin: 0-10, 10-20, 20-30, ...

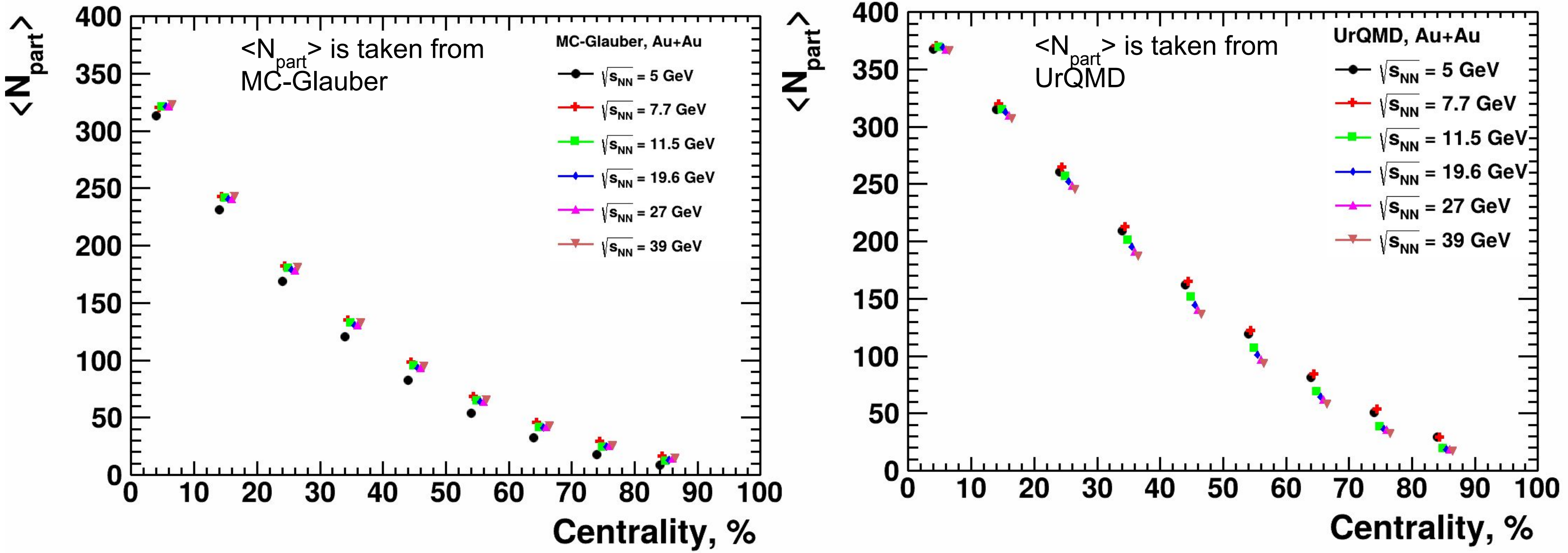




- The <b> in each centrality bin does not depend on energy
- At 5 GeV the MC-Glauber data show a deviation from other energy points

<Npart>(cent) vs. Energy

centrality bin: 0-10, 10-20, 20-30, ...



- ⟨N_{part}⟩is energy-independent in MC-Glauber but shows weak dependence in UrQMD.
- At 5 GeV the MC-Glauber data show a deviation from other energy points

Summary

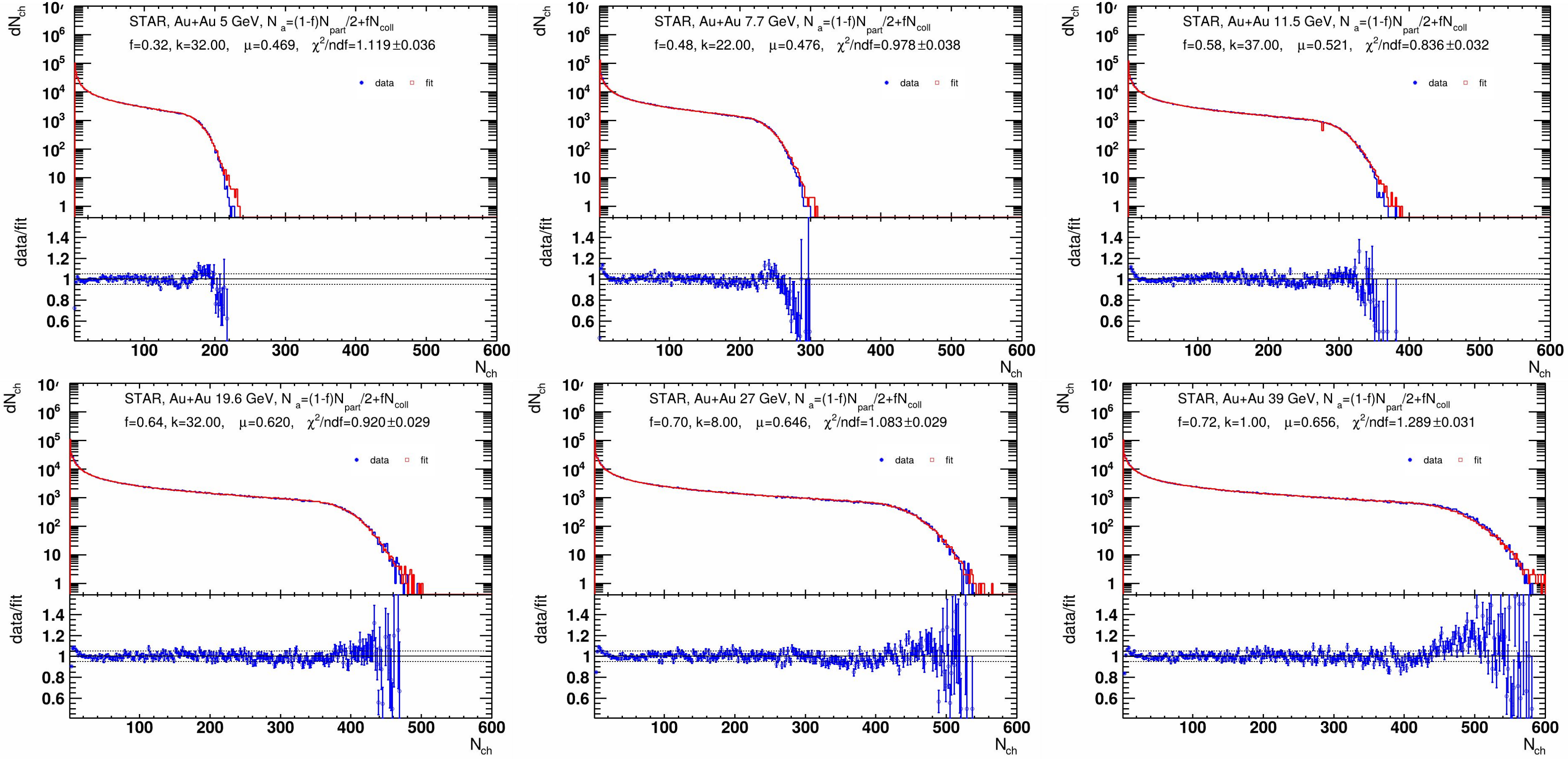
- The MC-Glauber and the Bayesian inversion method reproduce charged particle multiplicity for fixed-target experiment at BM@N
- Relation between impact parameter and centrality classes is extracted
- Impact parameter (b) from MC Glauber and UrQMD in given centrality classes are in reasonable agreement (Au+Au, UrQMD, 5-39 GeV)
- Systematic study of hardness vs $\sqrt{s_{NN}}$ in UrQMD (Au+Au, 5-39 GeV)
  - Trend in Hardness vs. $\sqrt{s_{NN}}$ is similar to the trend in STAR
  - Strong dependence at low energies

Future plans:

- Consider other collision systems and other models

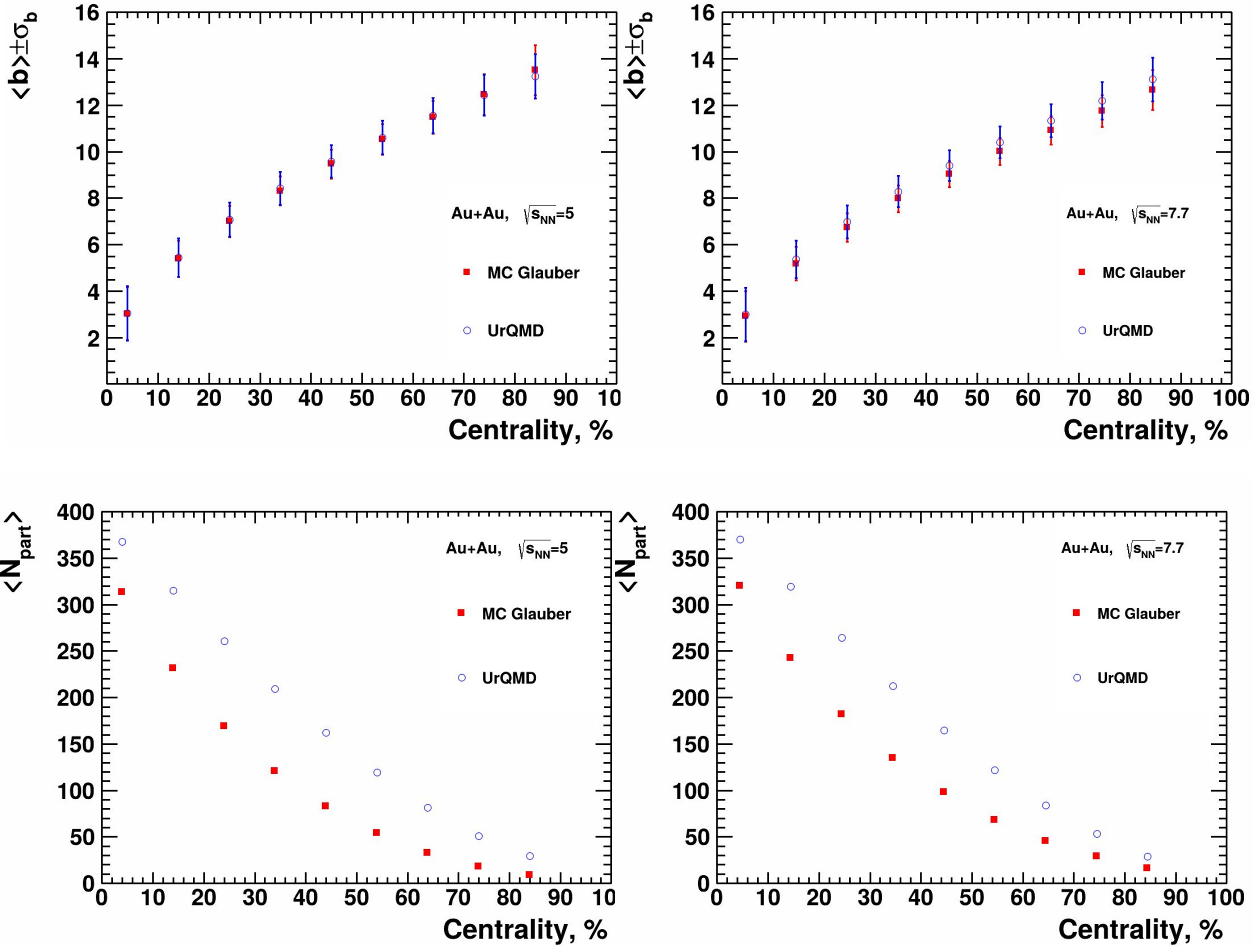
Thank you for your attention!

UrQMD, Au+Au, $\sqrt{s_{NN}} = 5–39$ GeV

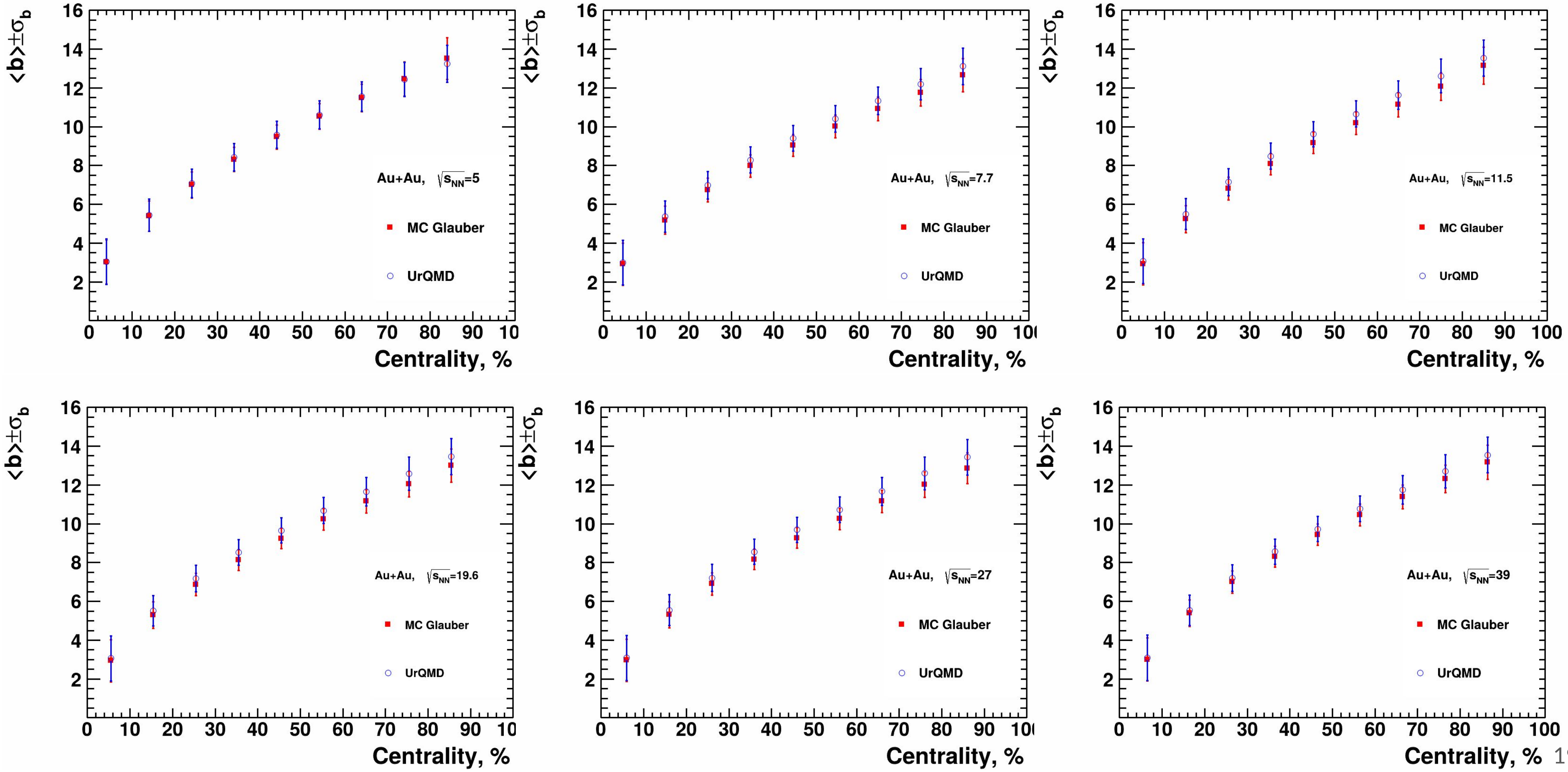


Good agreement between data and fit for all energies

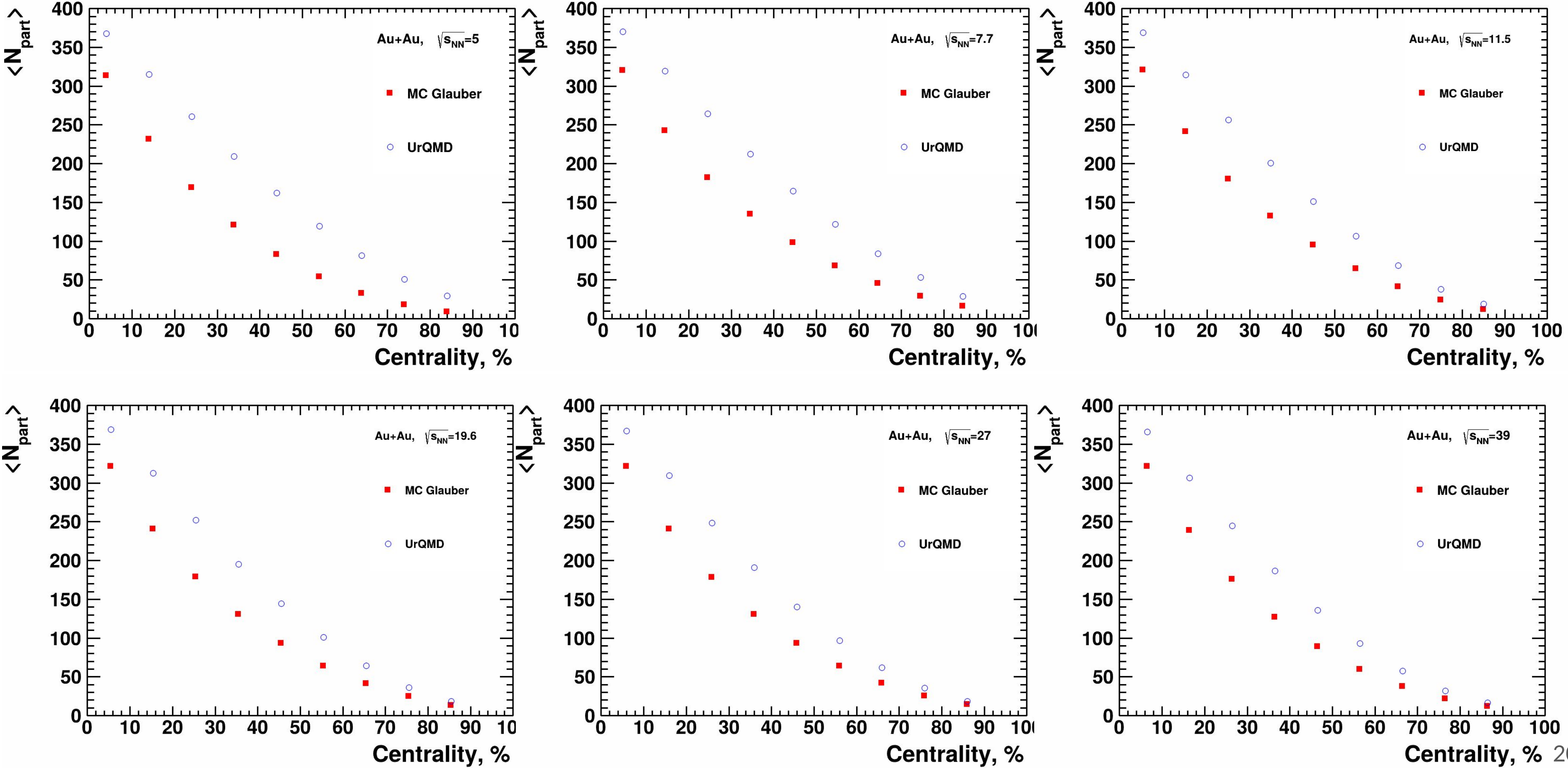
UrQMD, Au+Au, <b>: MC Glauber vs UrQMD



UrQMD, Au+Au, <b>: MC Glauber vs UrQMD



UrQMD, Au+Au, <Npart>: MC Glauber vs UrQMD

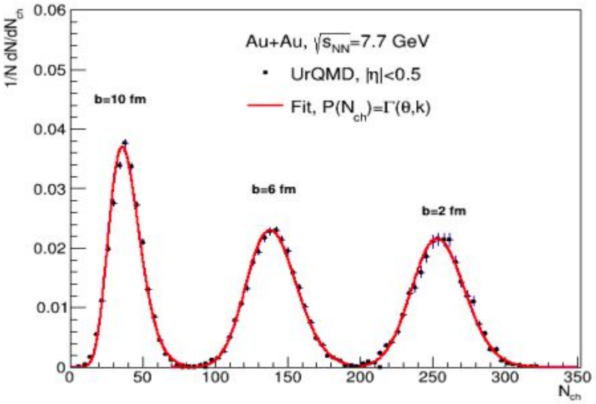


The Bayesian inversion method (Γ-fit): main assumptions

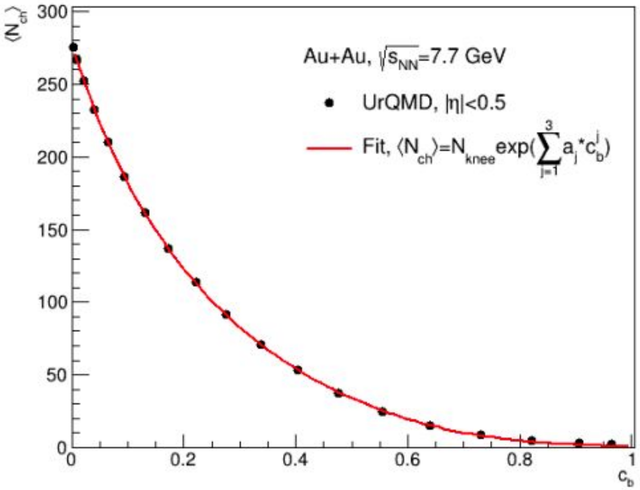
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

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

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

$$\frac{\sigma^2}{\langle N_{ch}\rangle} = \theta \simeq const$$

$$\langle N_{ch}\rangle = N_{knee}\exp\left(\sum_{j=1}^{3} a_j c_b^j\right)$$

$$, k = \frac{\langle N_{ch}\rangle}{\theta}$$

Five fit parameters N_{knee}, θ, a_j

Reconstruction of b

- Normalized multiplicity distribution $P(N_{ch})$

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

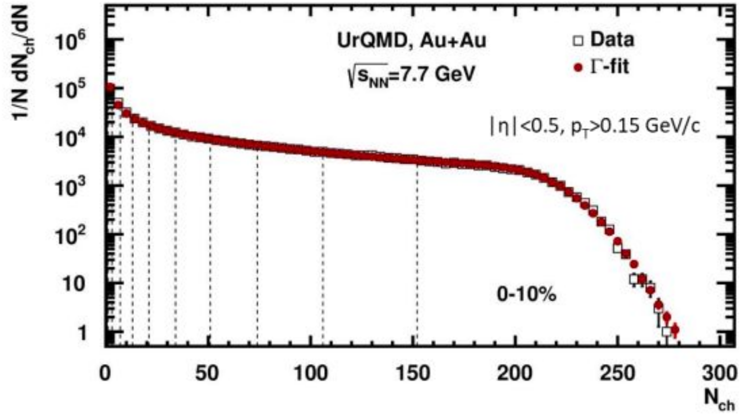
- Find probability of *b* for fixed range of N_{ch} using Bayes' theorem:

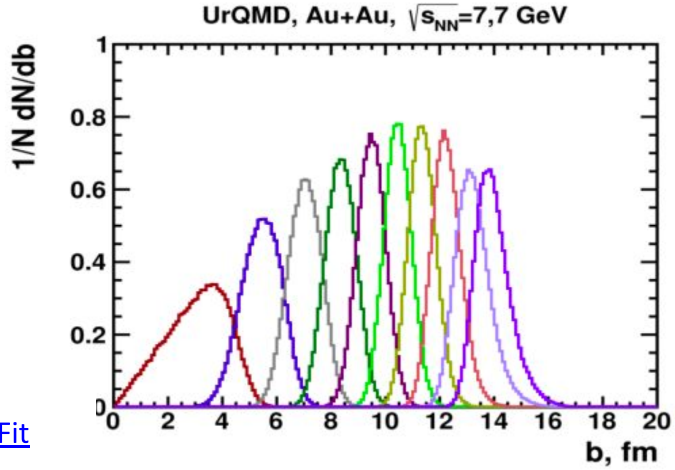
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P\,(N_{ch}|b)dN_{ch}}{\int_{n_1}^{n_2} P\,(N_{ch})dN_{ch}}$$

- **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



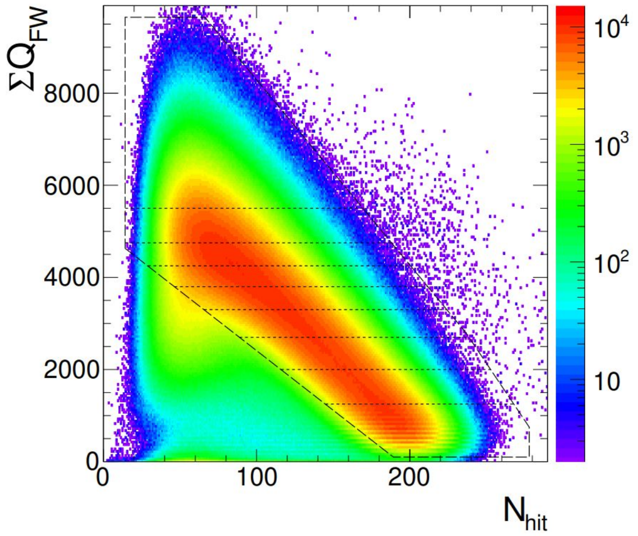


R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902
Implementation for MPD and BM@N by D. Idrisov: https://github.com/Dim23/GammaFit
Example of application in MPD: **P. Parfenov et al., Particles 4 (2021) 2, 275-287**

Why several alternative centrality estimators

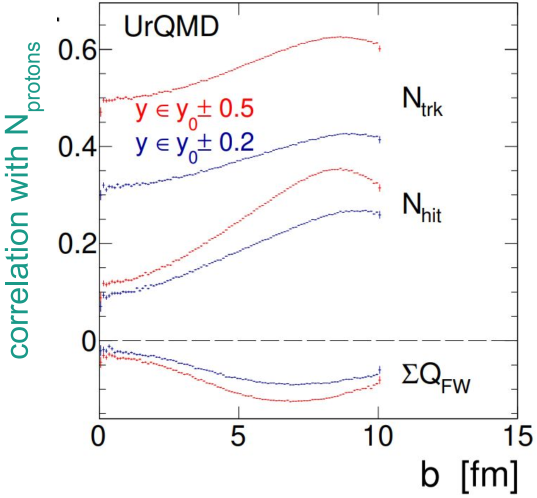
Anticorrelation between charge of the spectator fragments (FW) and particle multiplicity (hits)

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