The effect of different centrality determination on the elliptic flow measurements

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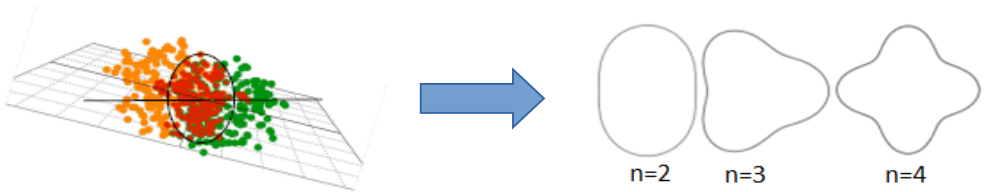
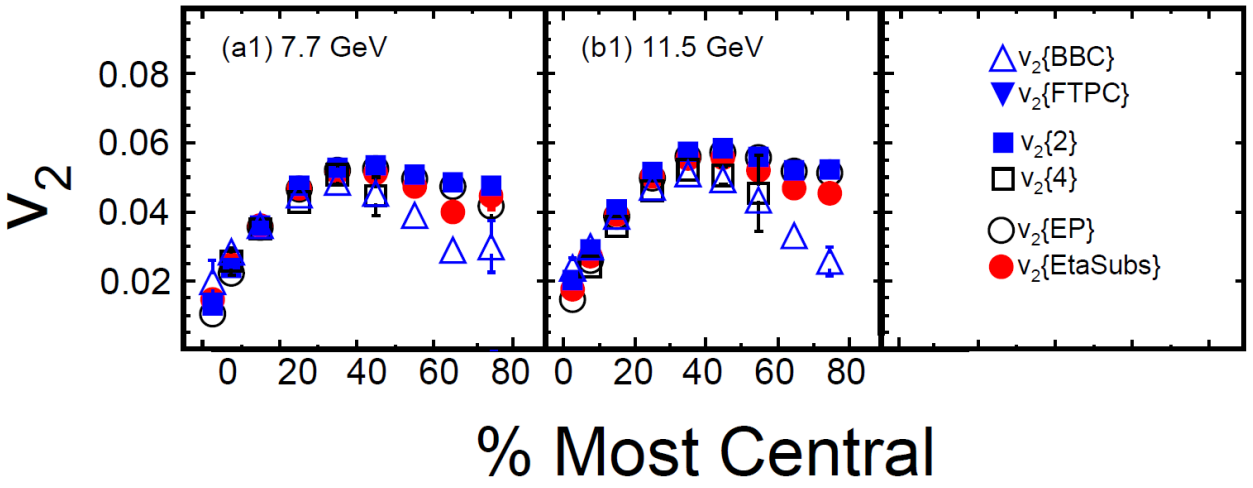
Initial geometry of HIC



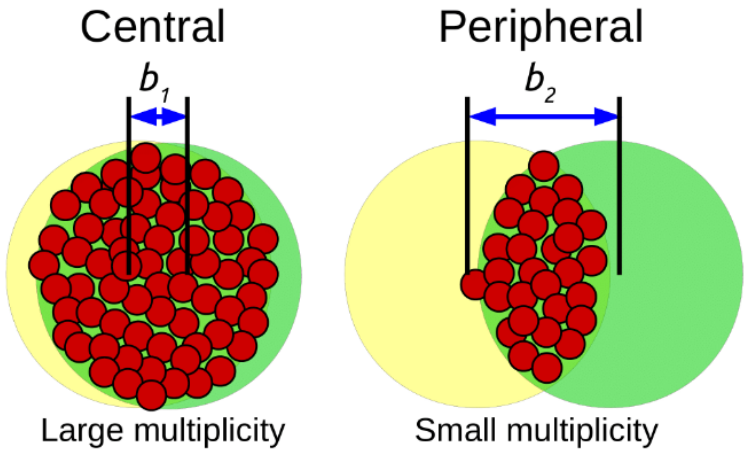
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right), \; v_2 = \left\langle \cos 2(\varphi - \Psi_n) \right\rangle$$



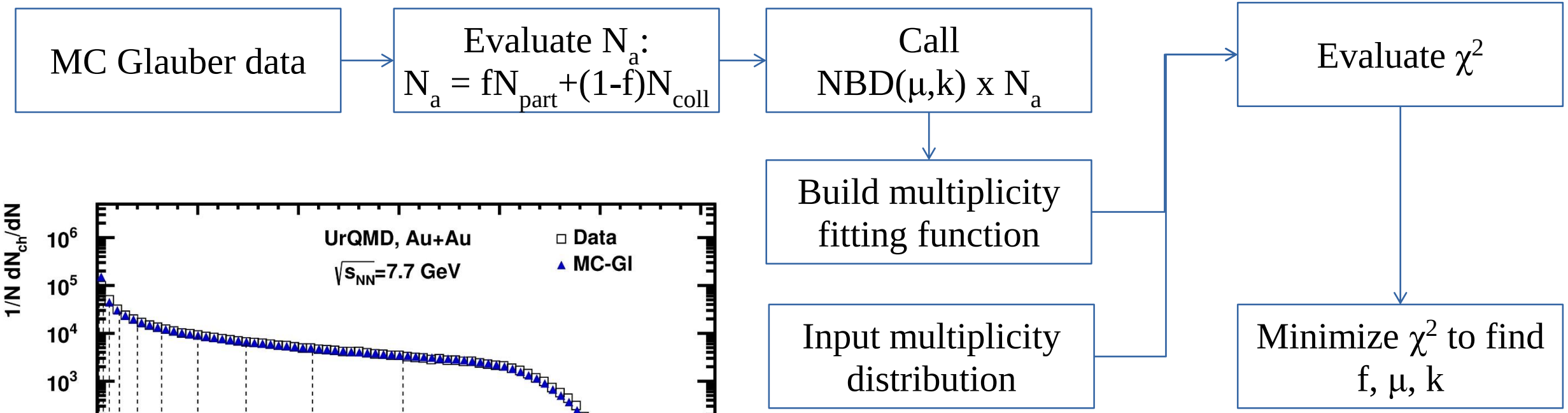
L. Adamczyk, et al., Phys. Rev. C 86, 054908 (2012)

Dependence of elliptic flow on 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 transverse energy of the produced particles)
- **This allows comparison of the future MPD results with the data from other experiments (STAR BES, NA49/NA61 scans) and theoretical models**



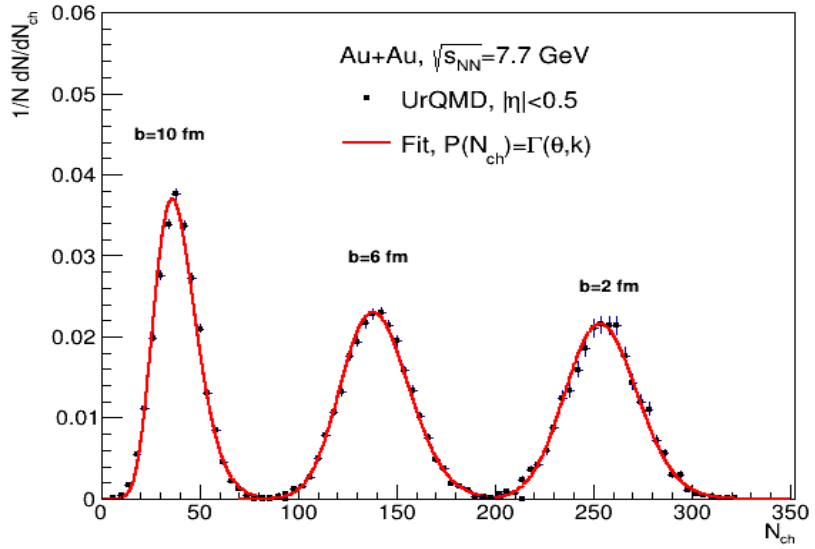
MC-Glauber based centrality framework

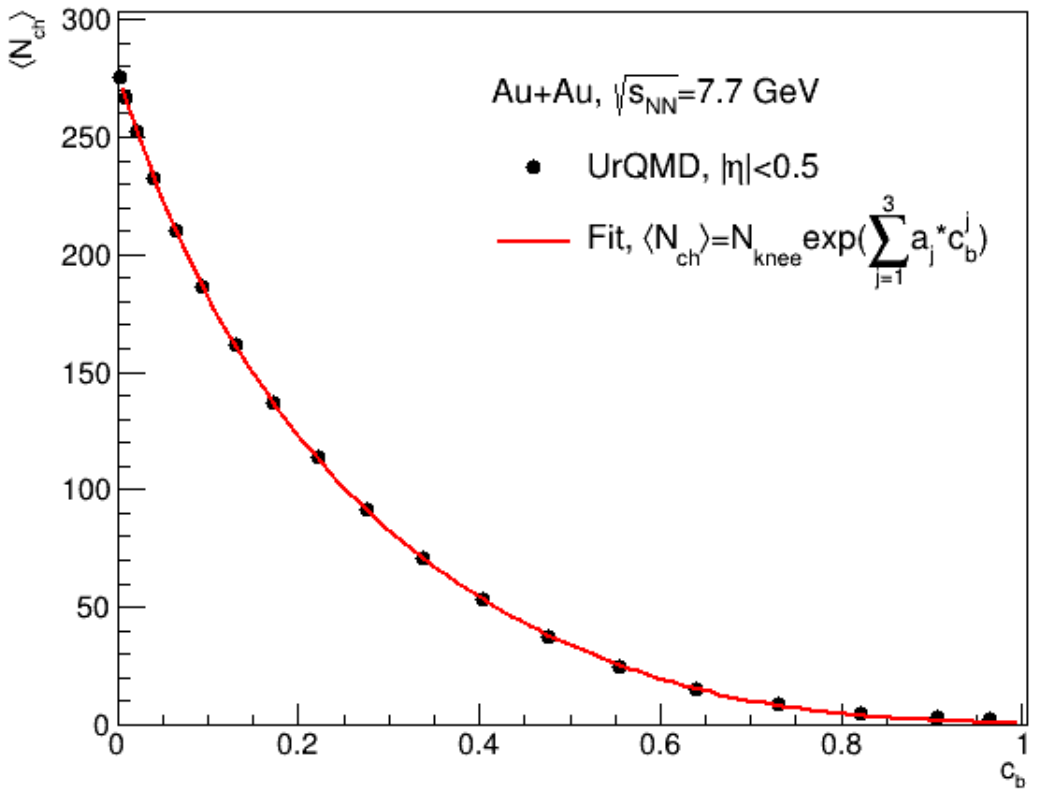


NBD – negative binomial distribution
Parameters of the fit:
- **f** – fraction of the production from the soft component
- **μ** – mean multiplicity value
- **k** – width of the multiplicity distribution, can be connected to the fluctuations

This centrality procedure was used in CBM, NA49, and NA61/SHINE:
I. Segal, et al., J.Phys.Conf.Ser. 1690 (2020) 1, 012107
Implemantation for MPD: https://github.com/FlowNICA/CentralityFramework
P. Parfenov, et al., Particles. 2021; 4(2):275-287

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





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

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

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

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

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

R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902

Five fit parameters N_{knee}, θ, a_j

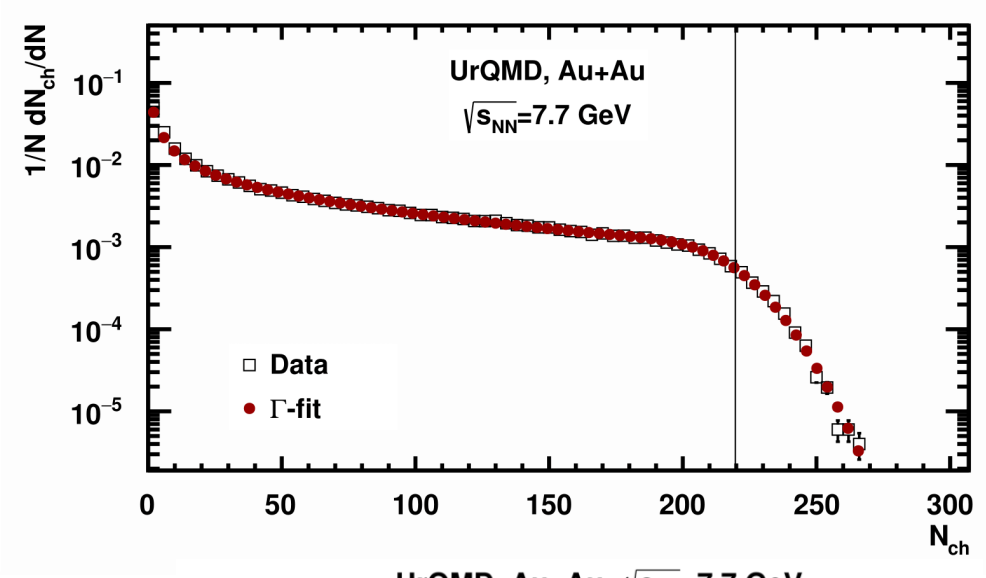
Implementation in MPD: https://github.com/Dim23/GammaFit

Reconstruction of *b*

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

$$P(b|N_{ch}) = \frac{P(N_{ch}|b)P(b)}{P(n)}$$

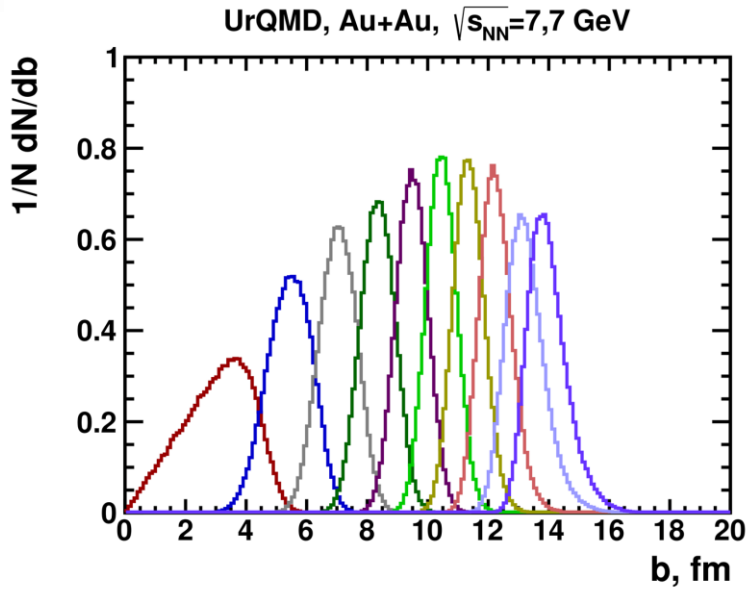
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(b|n)dn}{\int_{n_1}^{n_2} P(n)dn}$$



- **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



Results of fit for UrQMD model

Simulated data sets:

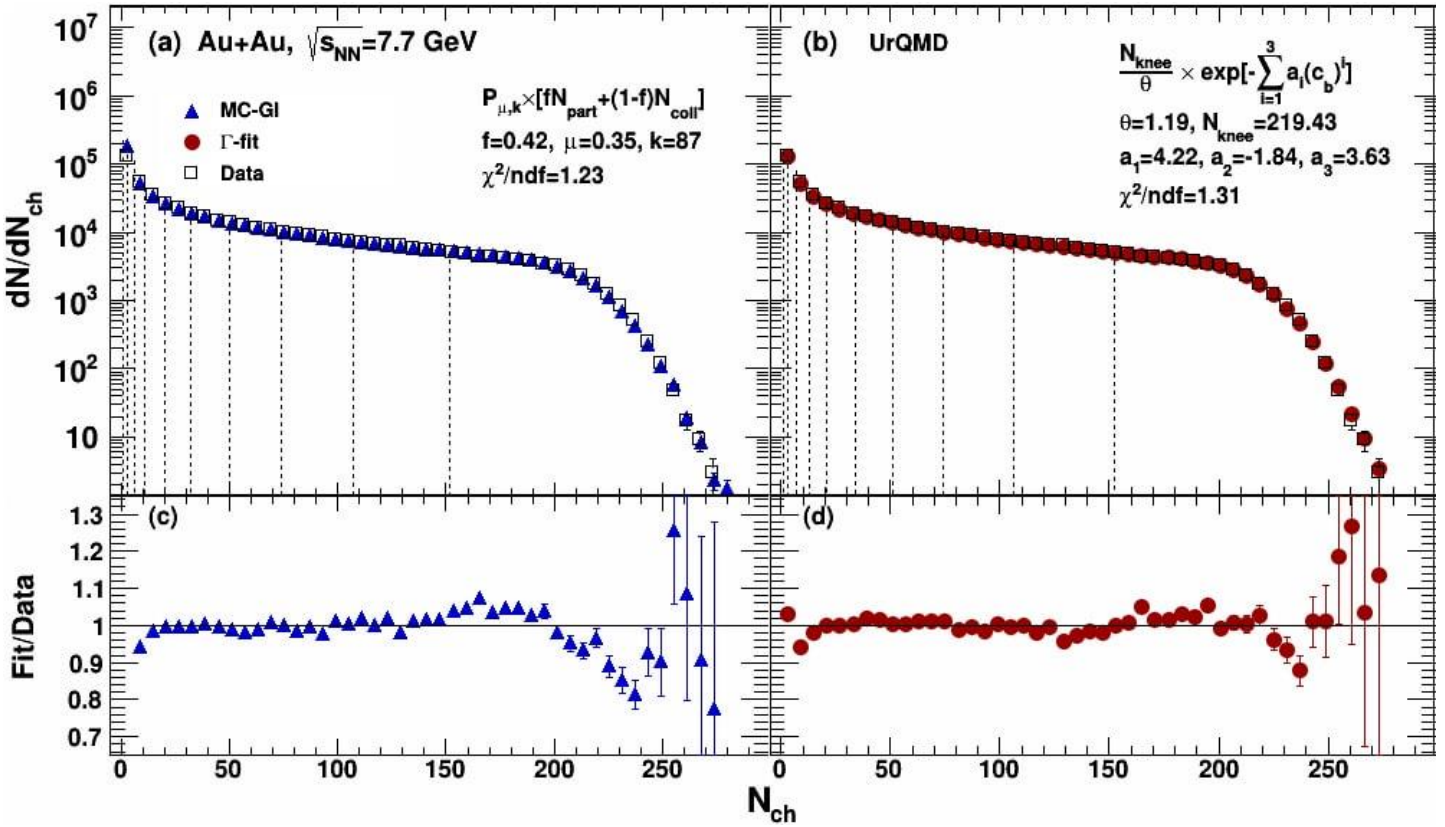
- Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=7.7 GeV

Hadron selection:

- Charged particles only
- $|\eta|<0.5$
- $p_T>0.15$ GeV/c

The model version:

- UrQMD ver. 3.4 in cascade mode



Good fit quality for both methods

Results of fit for AMPT SM model

Simulated data sets:

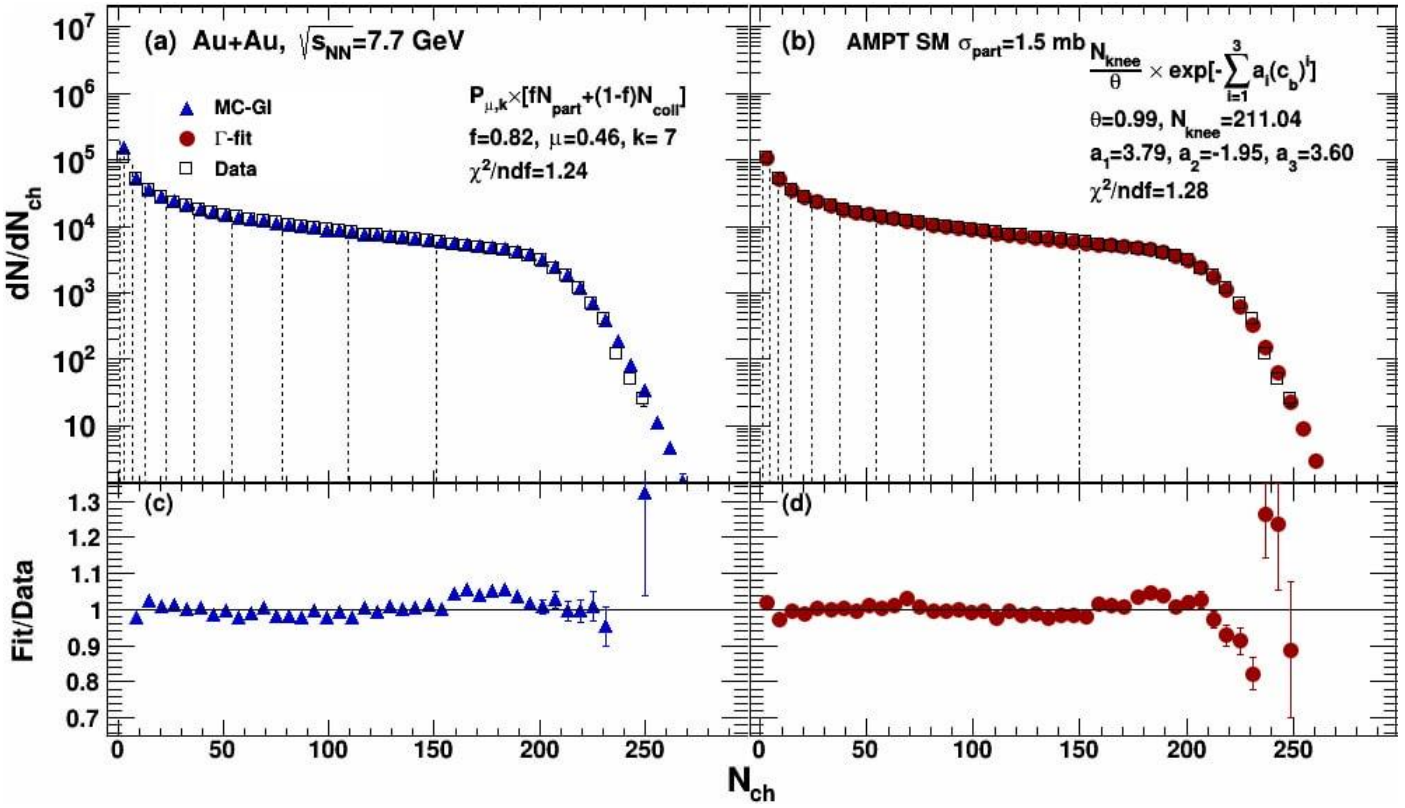
- Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=7.7 GeV

Hadron selection:

- Charged particles only
- $|\eta|<0.5$
- $p_T>0.15$ GeV/c

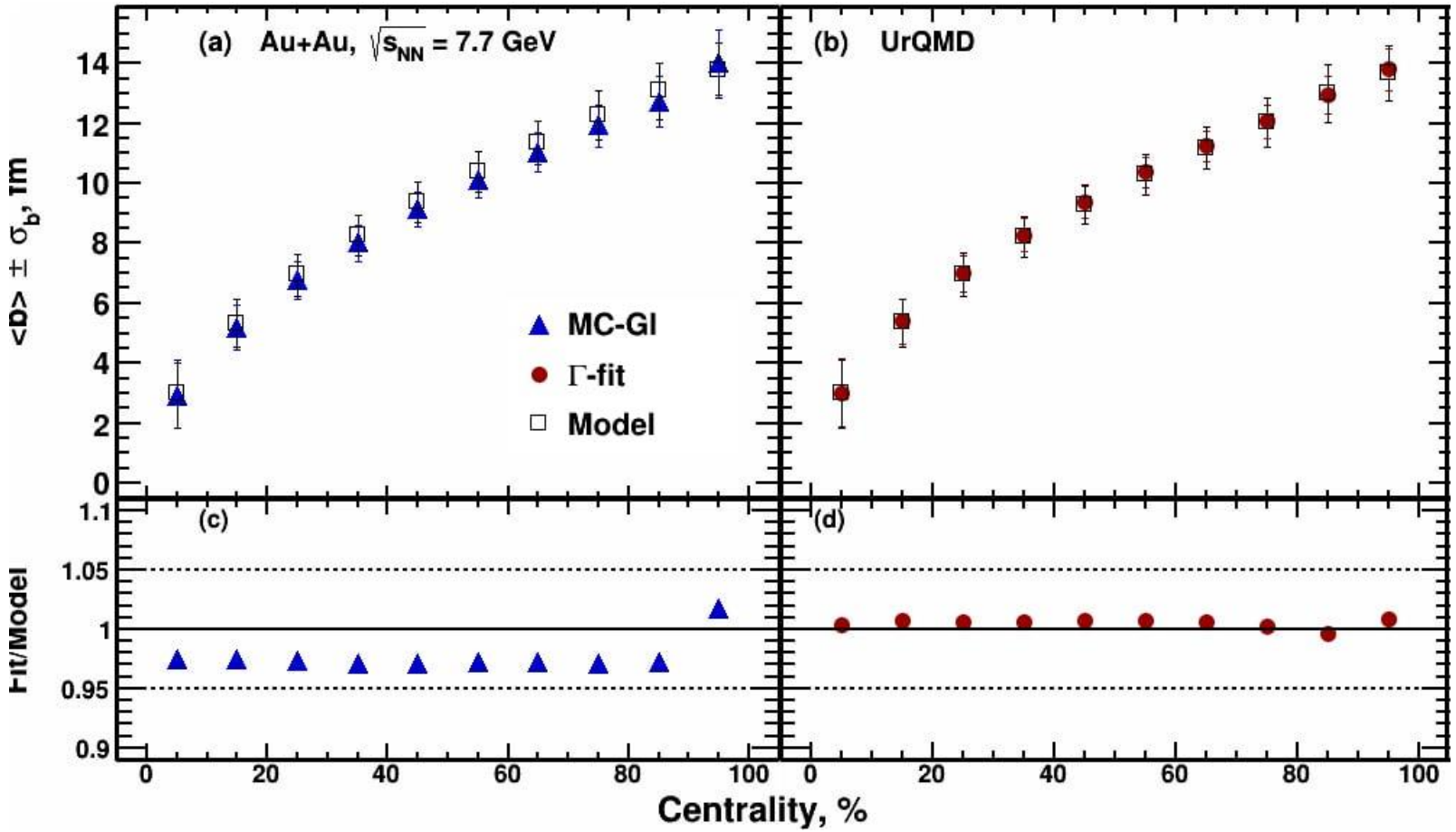
The model version:

- AMPT ver. 1.26 with string melting mode ver. 2.26, σ_{part}=1.5 mb



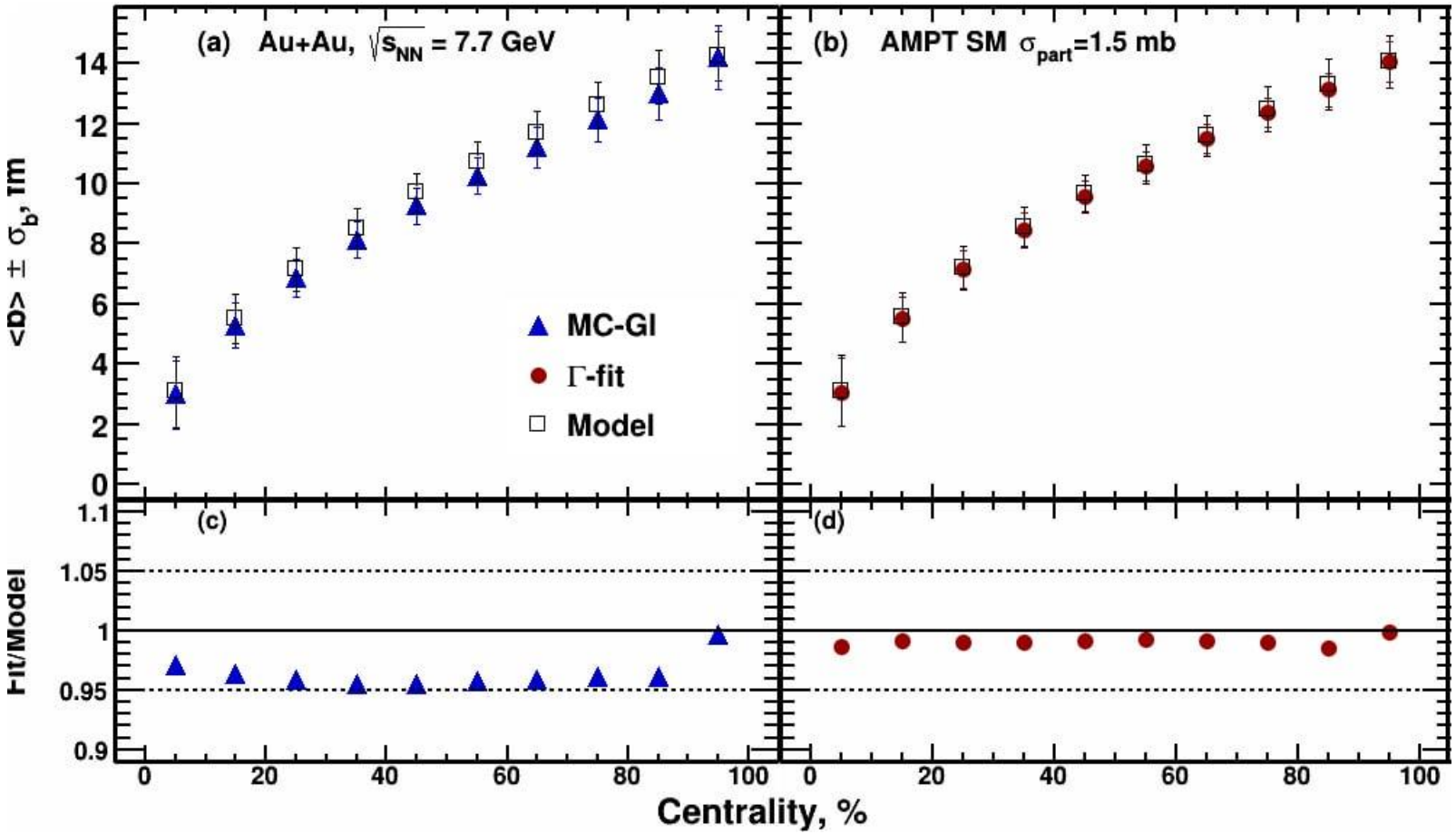
Good fit quality for both methods

Results of reconstruction of the impact parameter for the model UrQMD



The reconstructed values of the impact parameter are in good agreement with the results from the model

Results of reconstruction of the impact parameter for the model AMPT SM

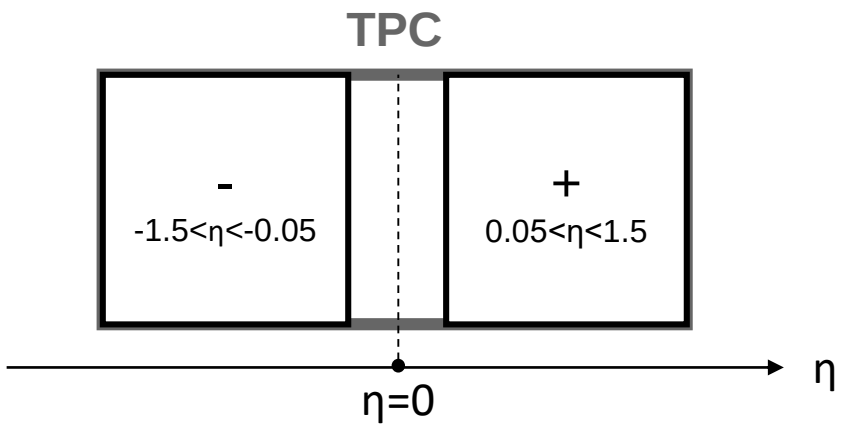


The results of the reconstruction of the impact parameter obtained using the MC-Glauber method in agreement with the model results within 5%

The methods for flow measurements

Event Plane:

$$v_2^{EP}\{TPC\} = \frac{\left\langle \cos\left[2\left(\varphi - \Psi_{2,\eta^{\pm}}\right)\right]\right\rangle}{R_2^{EP}\left\{\Psi_{2,TPC}\right\}} \quad (1)$$



Q-cumulants:

2 and 4 particle azimuthal correlations

$$\left\langle v_n^2 \right\rangle \simeq \left\langle e^{in(\varphi_1 - \varphi_2)} \right\rangle \quad (2)$$

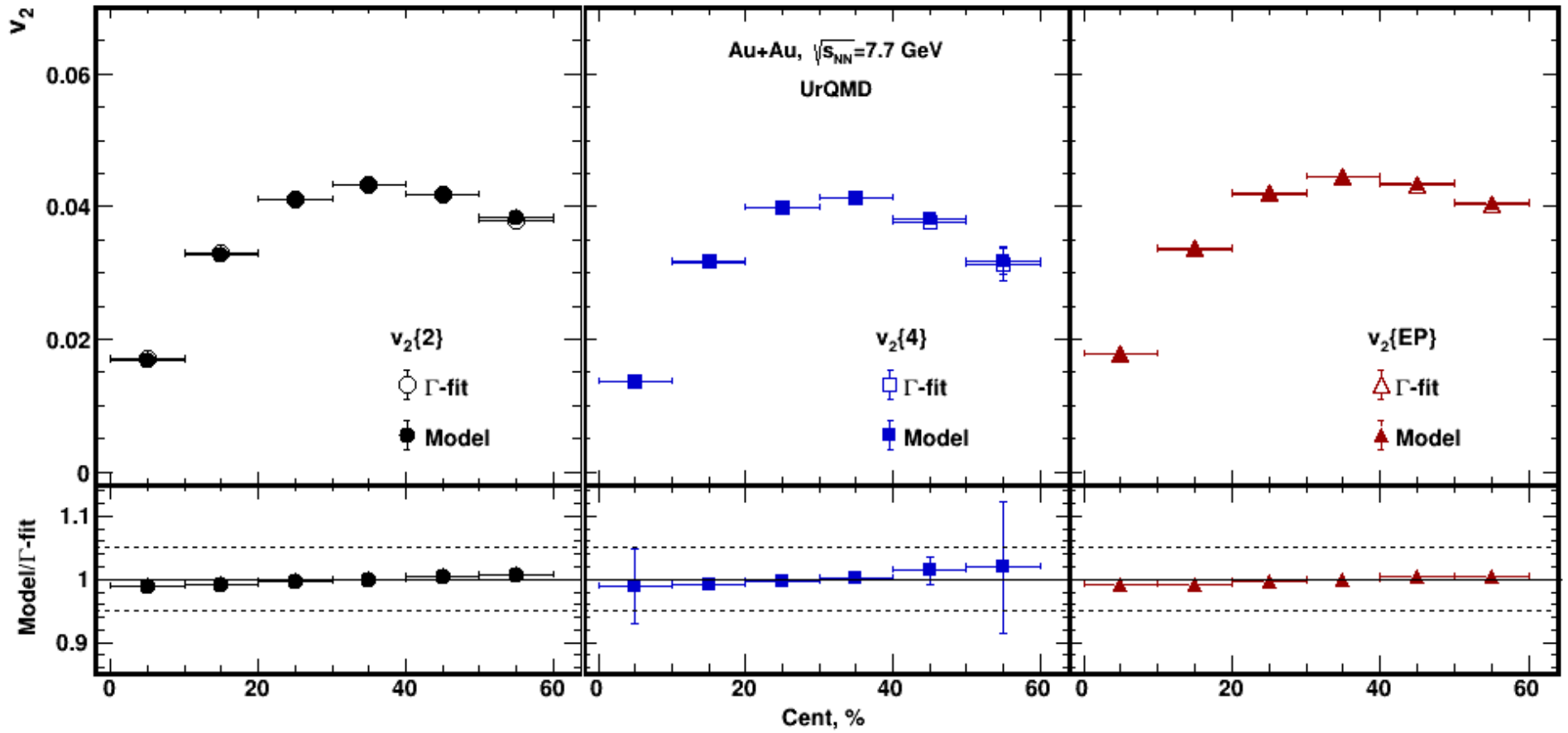
$$\left\langle v_n^4 \right\rangle \simeq \left\langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \right\rangle - 2 \cdot \left\langle e^{in(\varphi_1 - \varphi_3)} \right\rangle \left\langle e^{in(\varphi_2 - \varphi_4)} \right\rangle \quad (3)$$

Elliptic flow measurements with direct cumulant method

$$\left\langle v_n^2 \right\rangle = \frac{|Q_n|^2 - M}{M(M-1)} \quad (4) \text{ where } \quad Q_n = \sum_{i=1}^{M} e^{in\varphi_i} \quad (5)$$

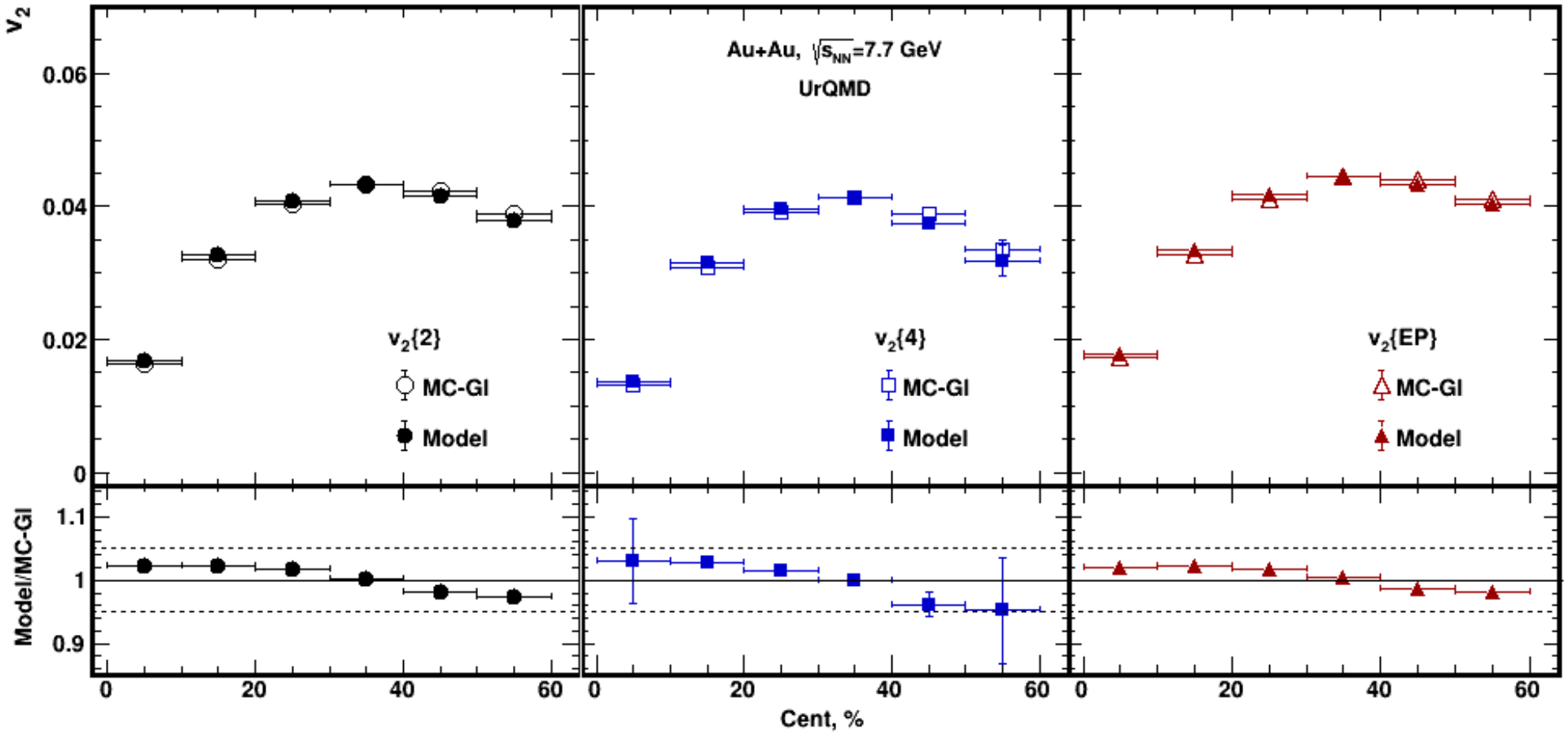
Phys. Rev. C83:044913, 2011

The effect of the bias in centrality determination in flow measurements for UrQMD model (Γ-fit)



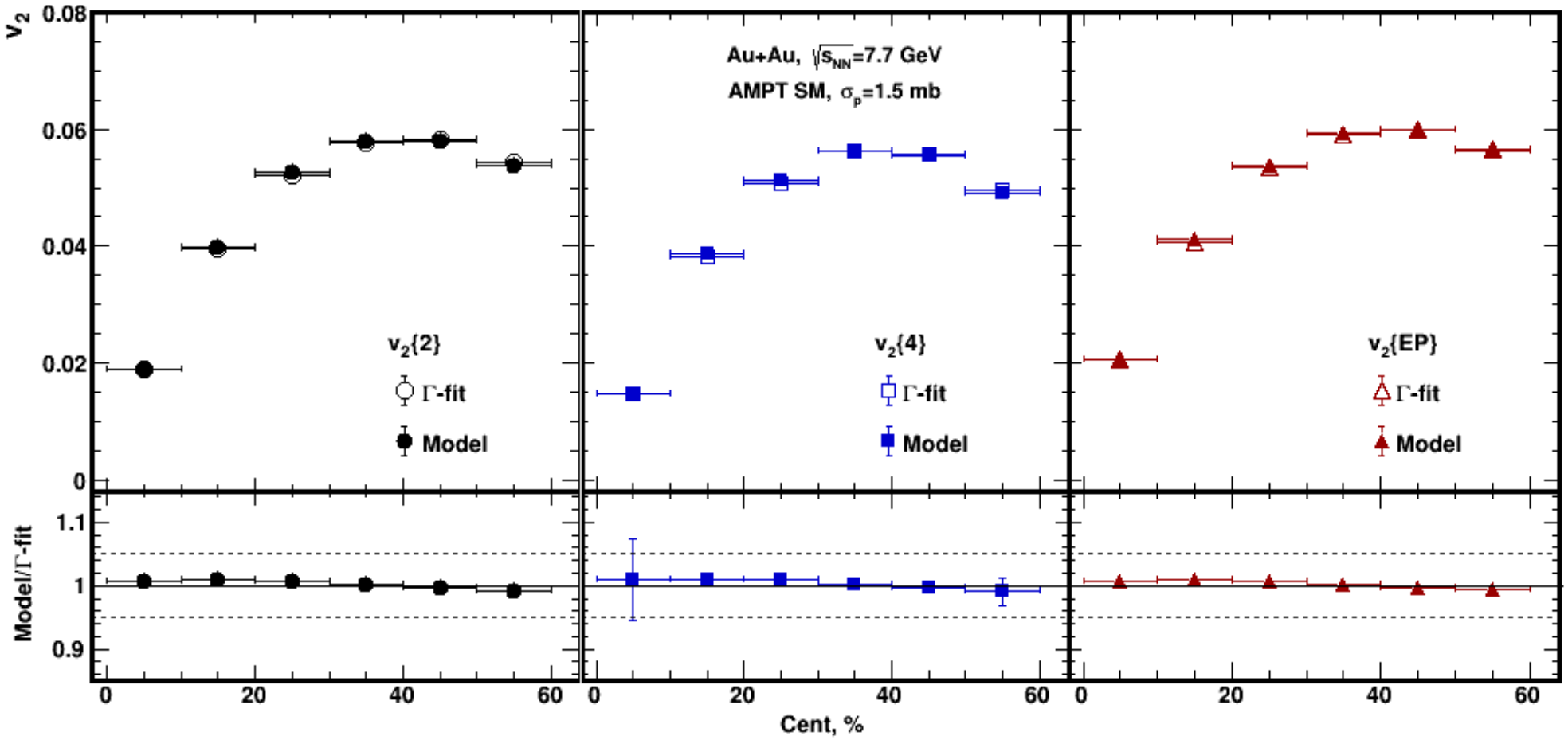
The effect of the bias caused by different centrality determination methods is within 1-2%.

The effect of bias in centrality determination in flow measurements for UrQMD model(MC-Glauber)



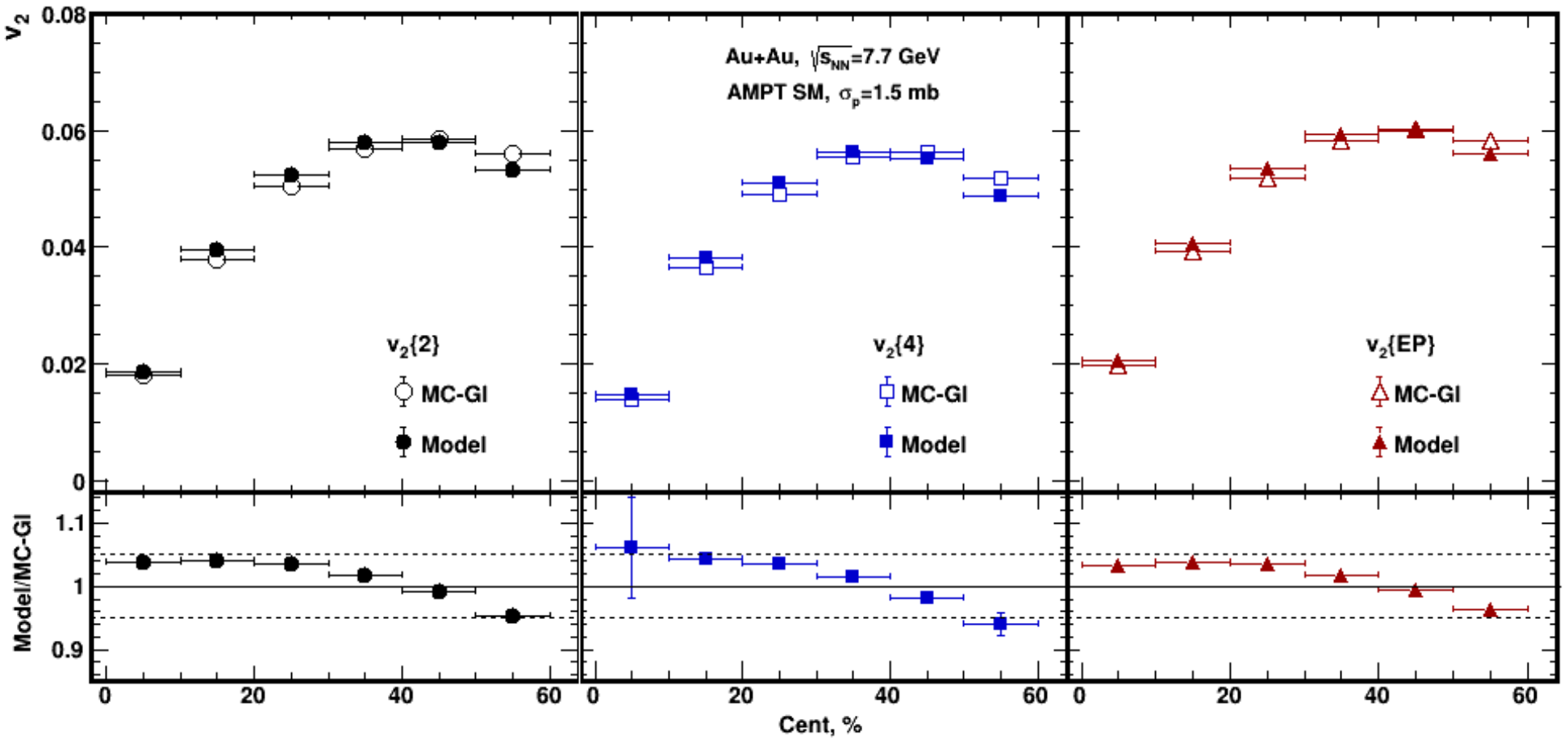
The effect of the bias caused by different centrality determination methods is within 4%.

The effect of bias in centrality determination in flow measurements for AMPT model(Γ-fit)



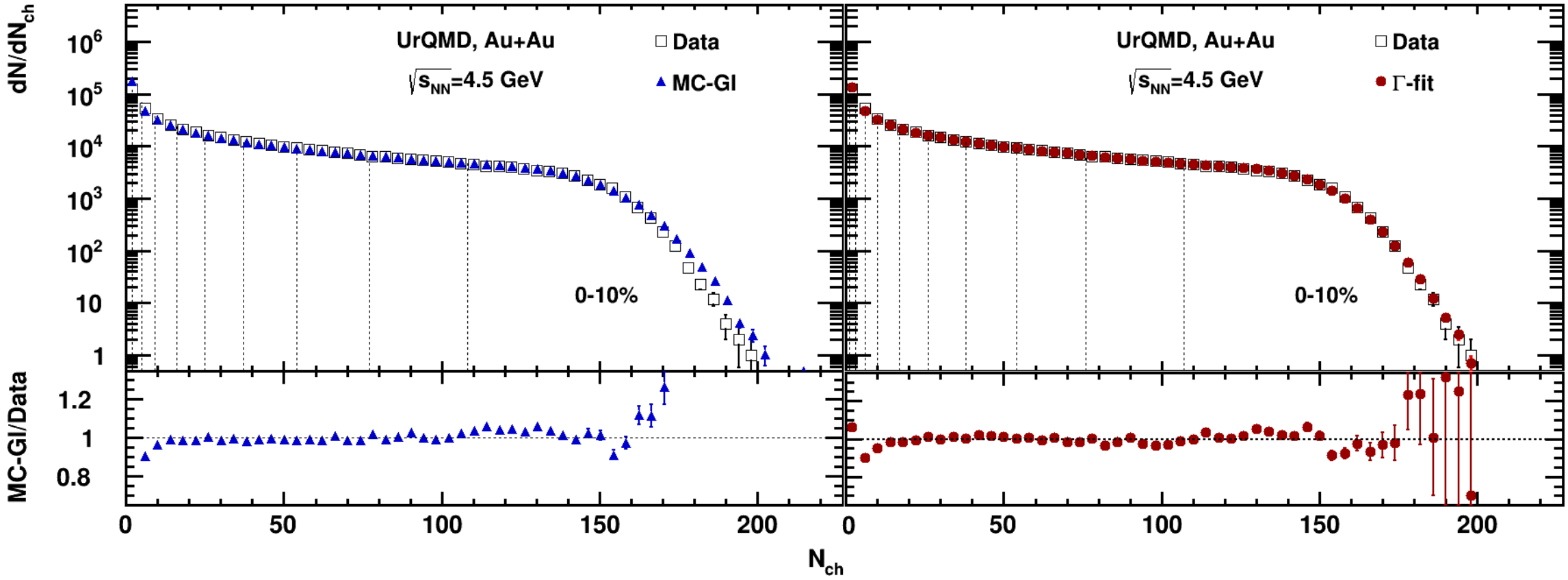
The effect of the bias caused by different centrality determination methods is within 1-2%.

The effect of bias in centrality determination in flow measurements for AMPT model(MC-Glauber)



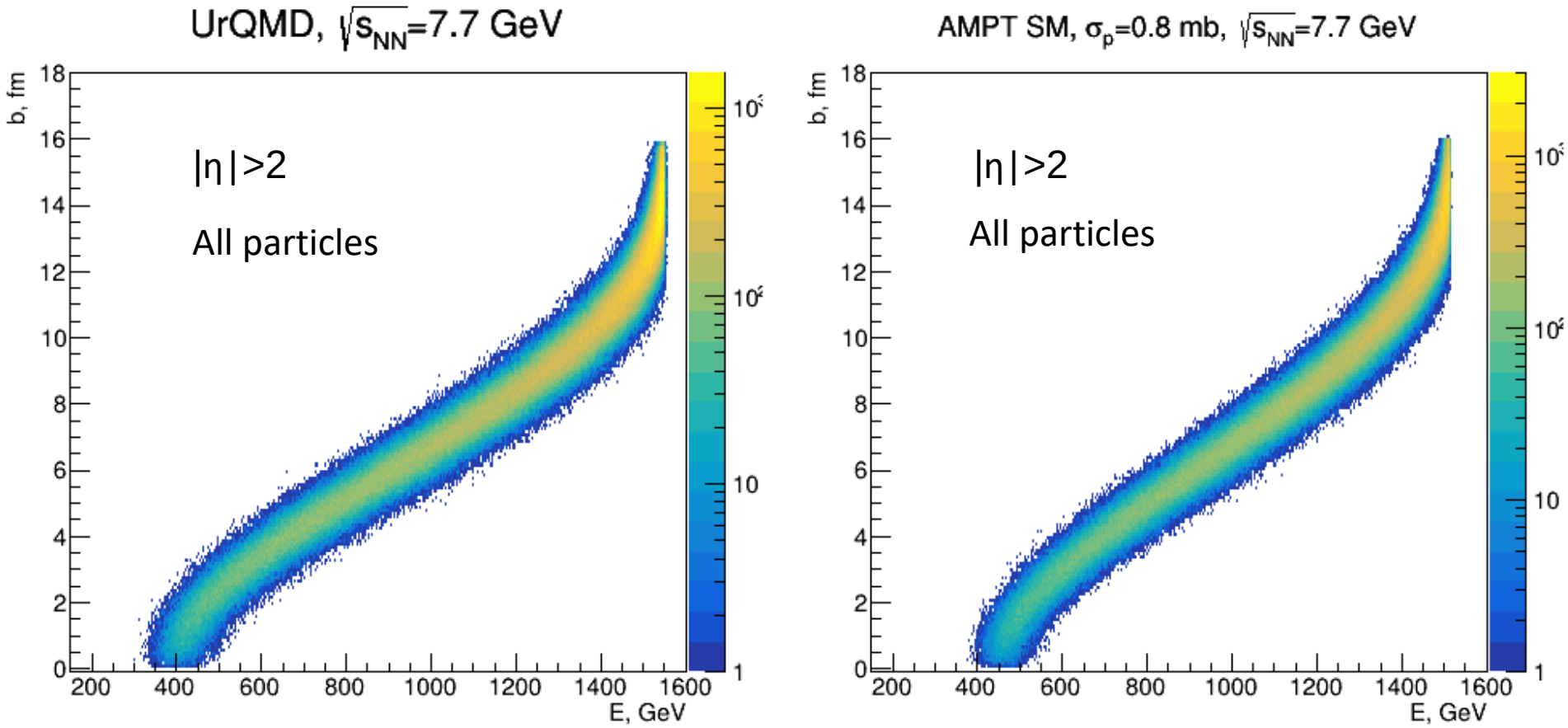
The effect of the bias caused by different centrality determination methods is within 5%.

Results of fit for UrQMD model at $\sqrt{s_{NN}}$ =4.5 GeV



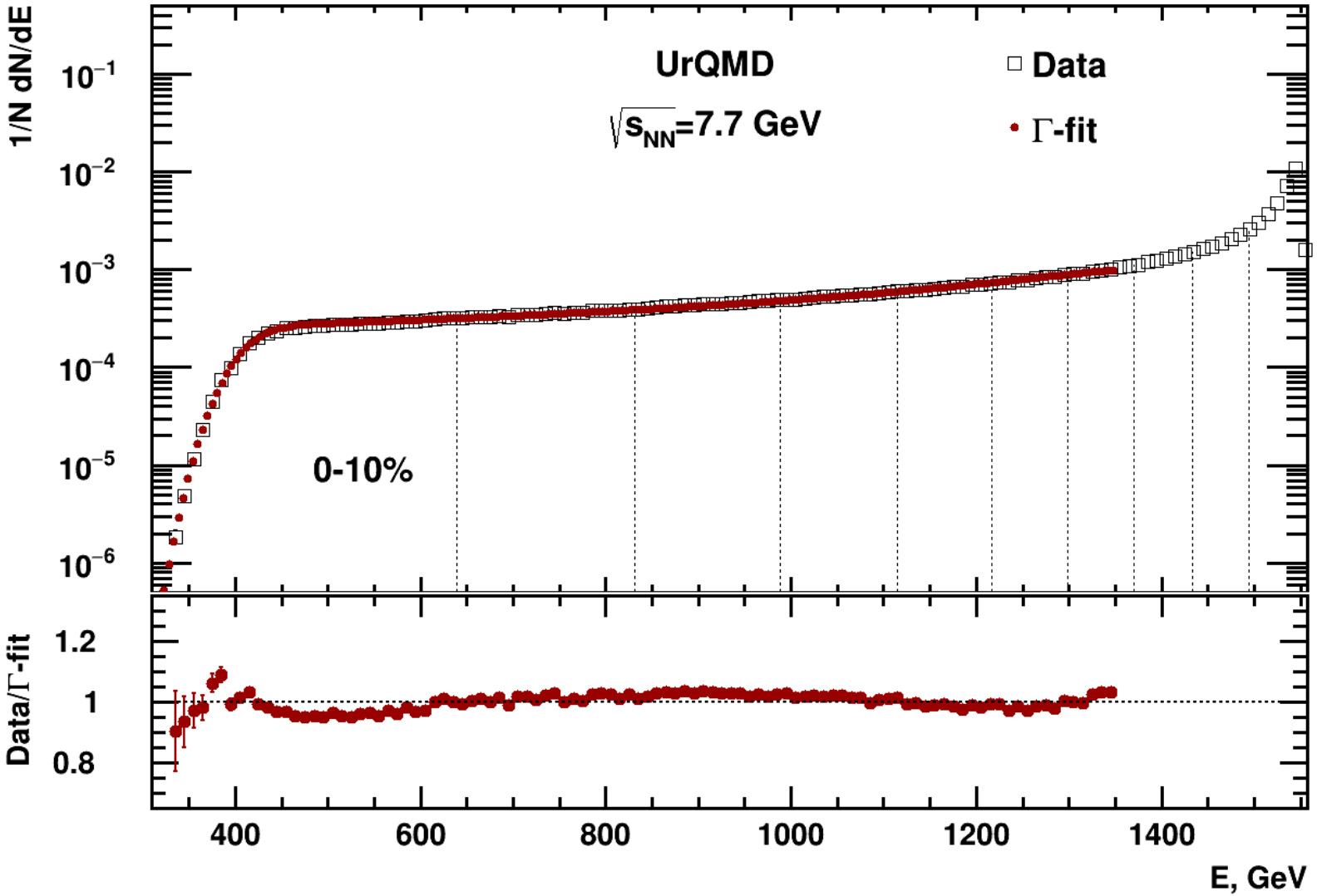
At lower energies, the quality of the fit for MC-Glauber decreases

The energy dependence on the impact parameter



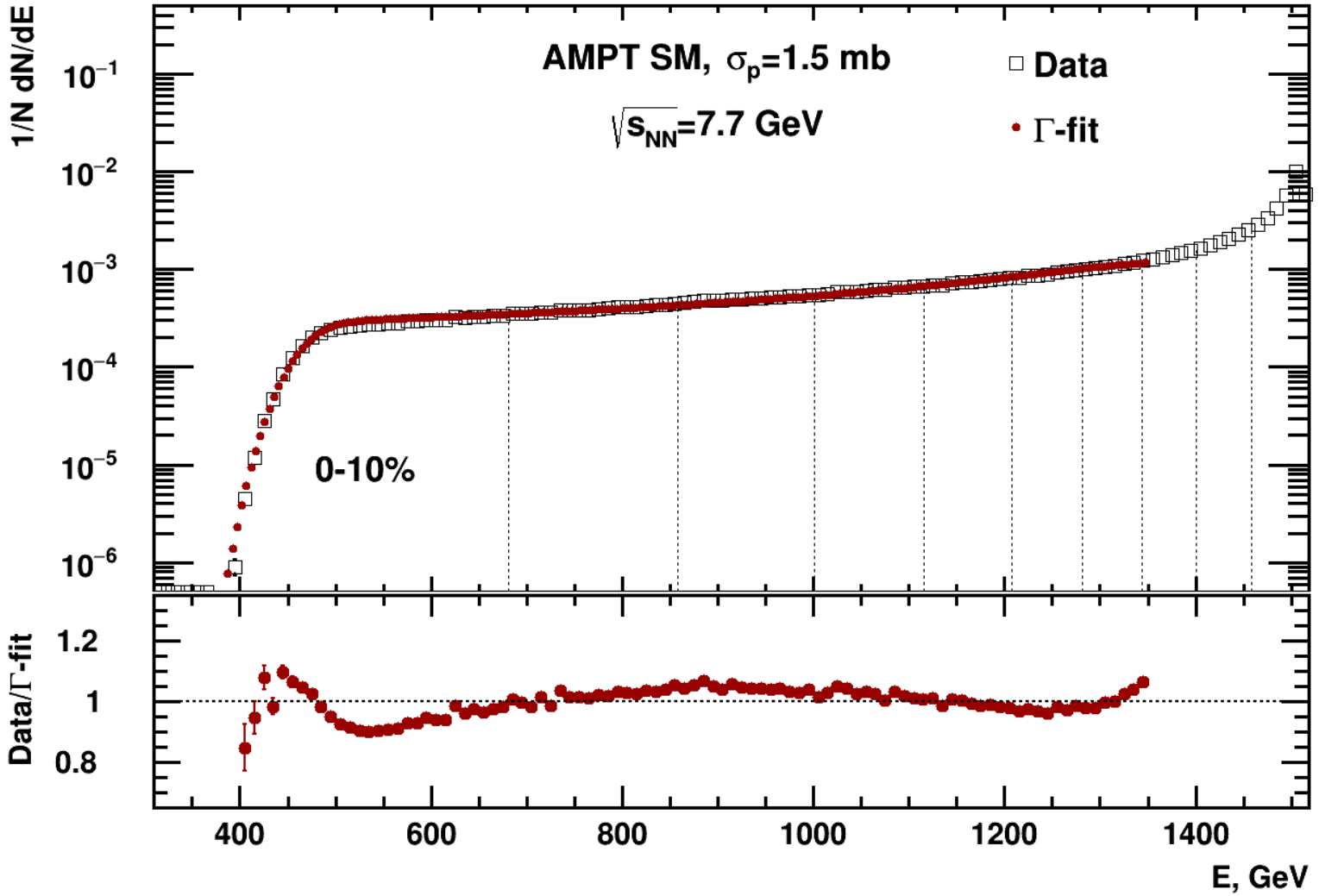
There is a correlation between the impact parameter and the total energy in the forward rapidity region

Results of fitting the energy distribution in the UrQMD model



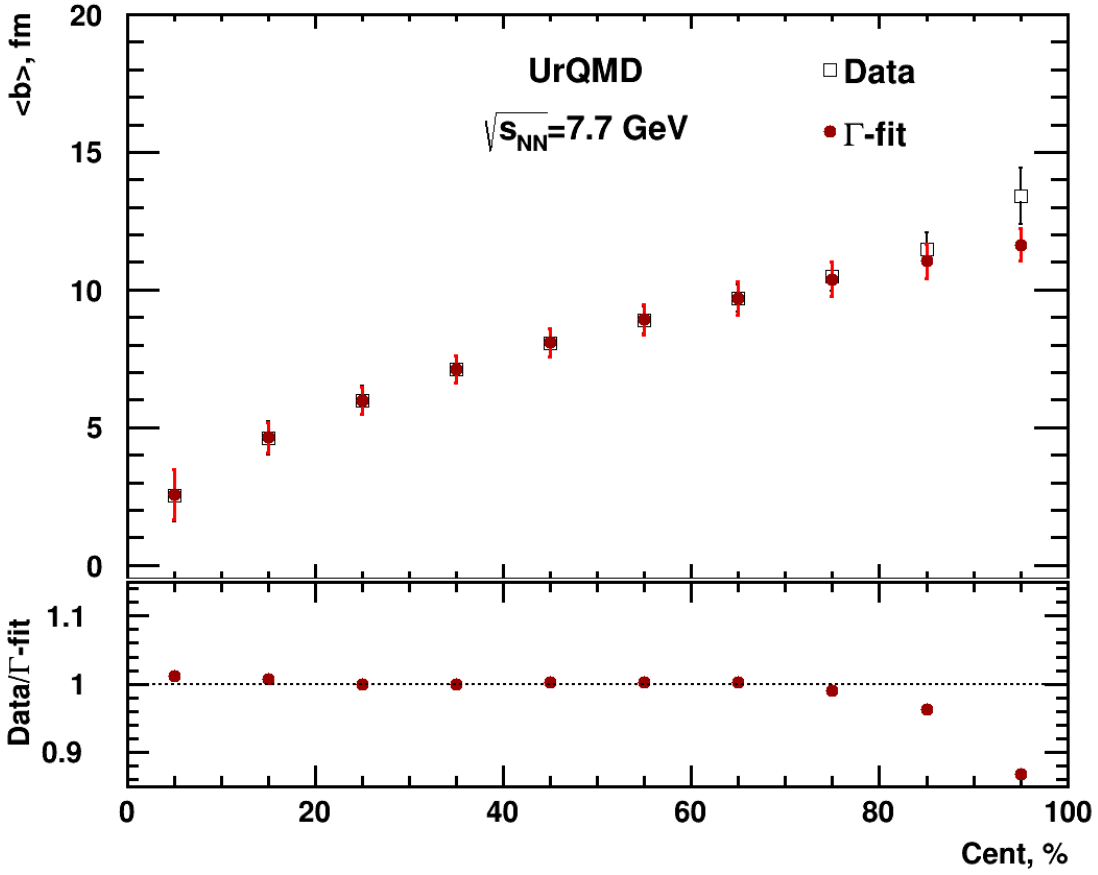
Good fit quality of energy dependence

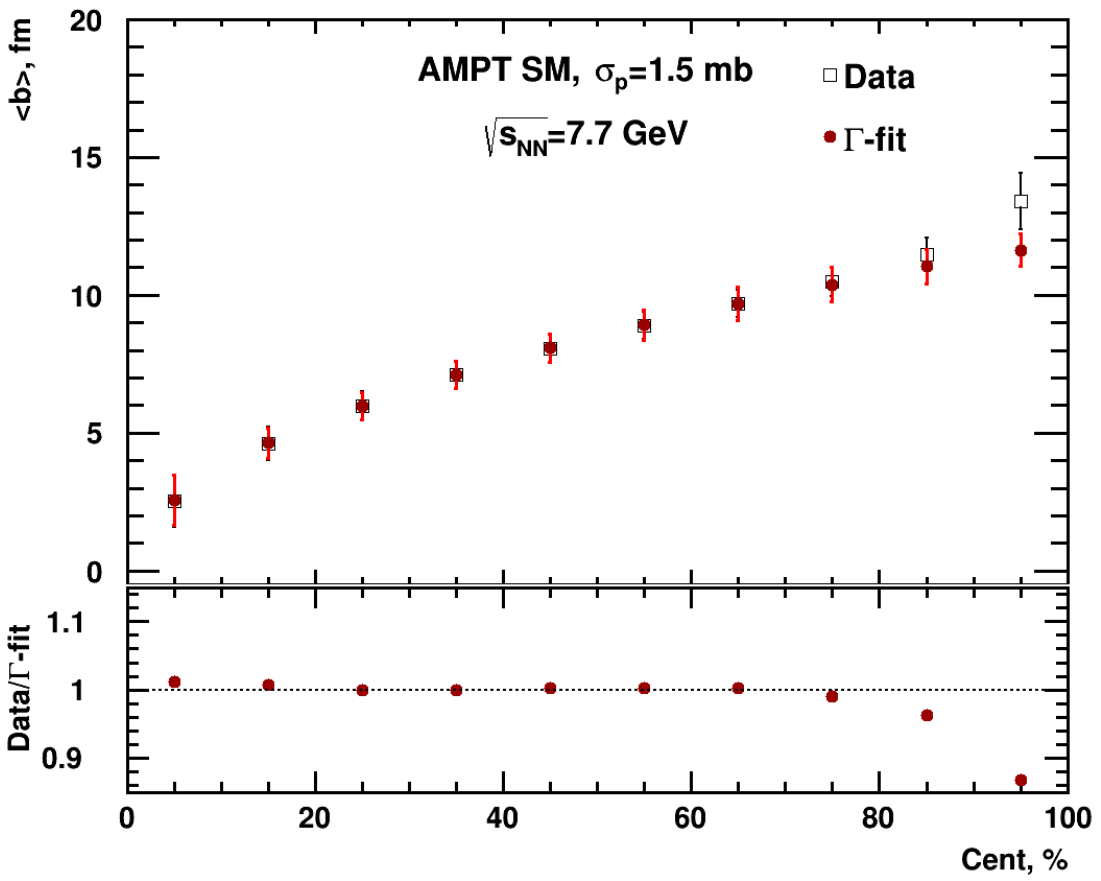
Results of fitting the energy distribution in the AMPT model



Good fit quality of energy dependence

Results of reconstruction of the impact parameter from the energy distribution





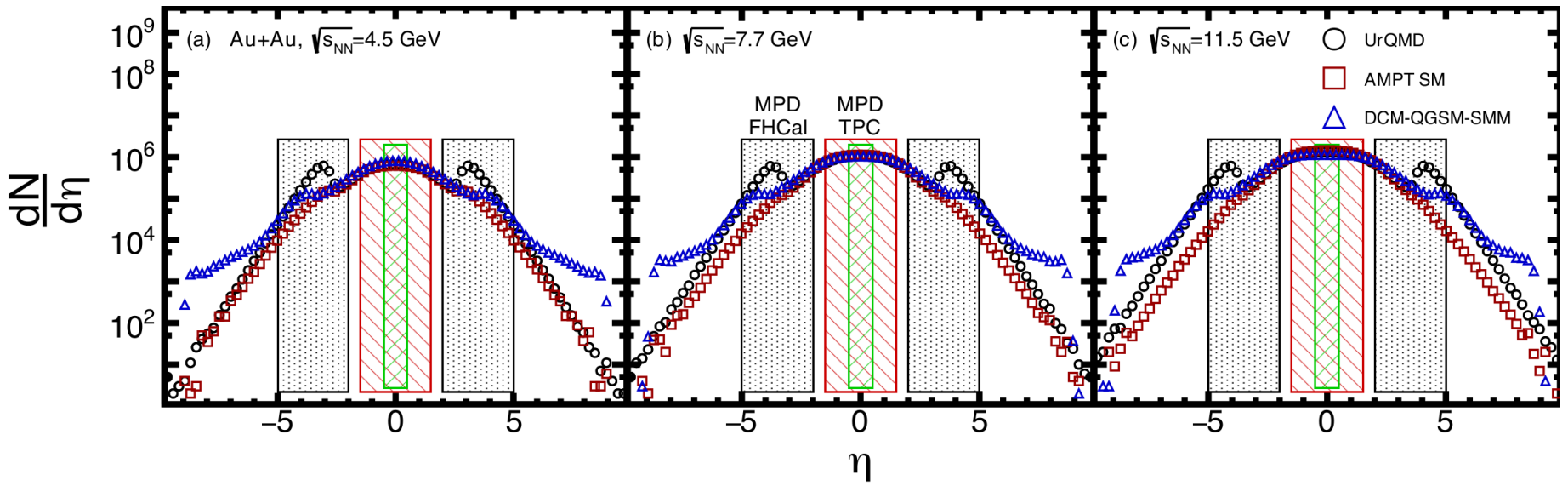
The reconstructed impact parameter is in good agreement with model data

Summary and outlook

- Fitted functions from both methods reproduce charged particle multiplicity.
    - The reconstructed impact parameter are in good agreement with model data.
- The effect of the elliptic flow measurement bias caused by the difference in centrality determination is within 1-2% for Γ-fit and 1-5% for MC-Glauber methods.
- The Γ-fit method can be used for centrality determination based on the distribution of the total energy in the forward rapidity region.
- To perform detailed study on the centrality determination based on the deposited energy in the forward calorimeters in MPD, models with fragment simulation are required (DCM-QGSM-SMM, PHQMD).

Thank you for your attention!

Models and statistics



Au+Au, min. bias

- UrQMD ver. 3.4 in cascade mode:
  - $\sqrt{s_{NN}}$ = 11.5 GeV: 50M
  - $\sqrt{s_{NN}}$ = 7.7 GeV: 88M
  - $\sqrt{s_{NN}}$ = 4.5 GeV: 115M
- AMPT SM, ver. 1.26 with string melting mode ver. 2.26, σ_{part}=1.5 mb:
  - $\sqrt{s_{NN}}$ = 11.5 GeV: 60M
  - $\sqrt{s_{NN}}$ = 7.7 GeV: 42M
  - $\sqrt{s_{NN}}$ = 4.5 GeV: 80M
- DCM-QGSM-SMM:
  - $\sqrt{s_{NN}}$ = 11.5 GeV: 10M
  - $\sqrt{s_{NN}}$ = 7.7 GeV: 10M
  - $\sqrt{s_{NN}}$ = 4.5 GeV: 10M

Comparison of fit results

Models

- UrQMD ver. 3.4 in cascade mode
- AMPT SM, ver. 1.26 with string melting mode ver. 2.26, σpart=1.5 mb:
- DCM-QGSM-SMM

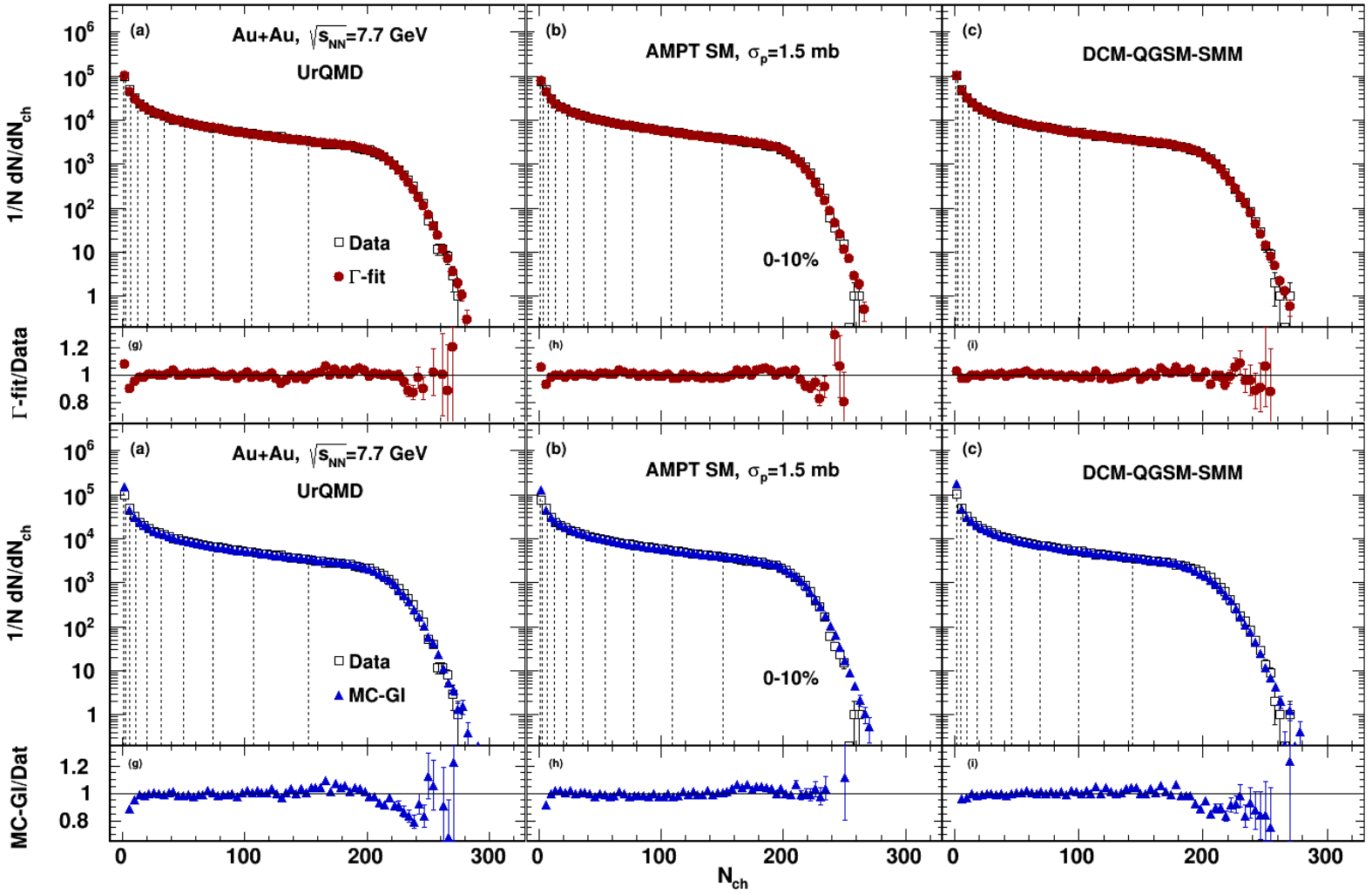
Simulated data sets:

- Au+Au, N_{ev}=500k,

$\sqrt{s_{NN}}$=4.5, 7.7, 11.5 GeV

Hadron selection:

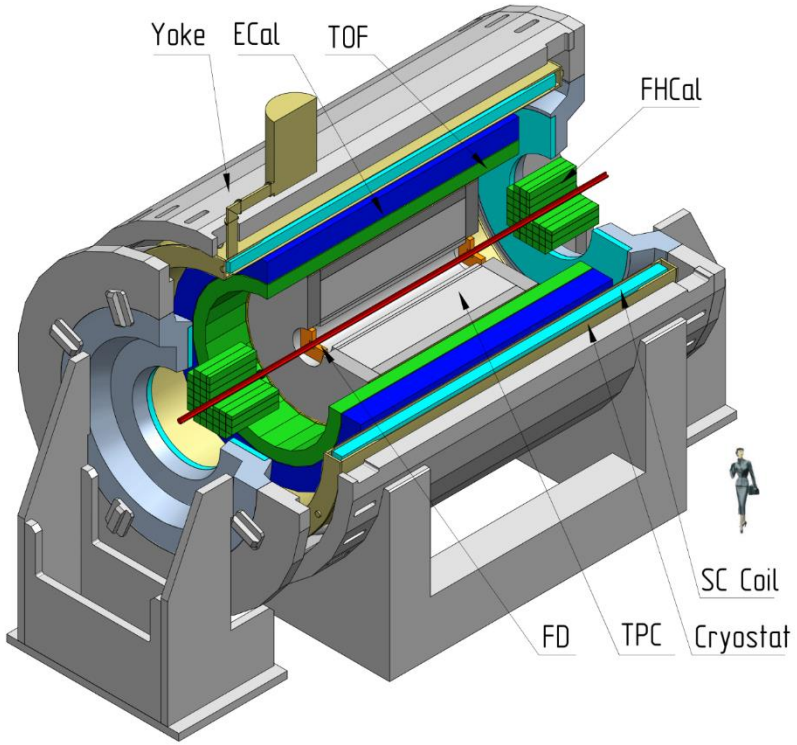
- |η|<0.5
- Charged particles only
- p_T>0.15 GeV/c



Fitted functions from both methods reproduce charged particle multiplicity

MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis

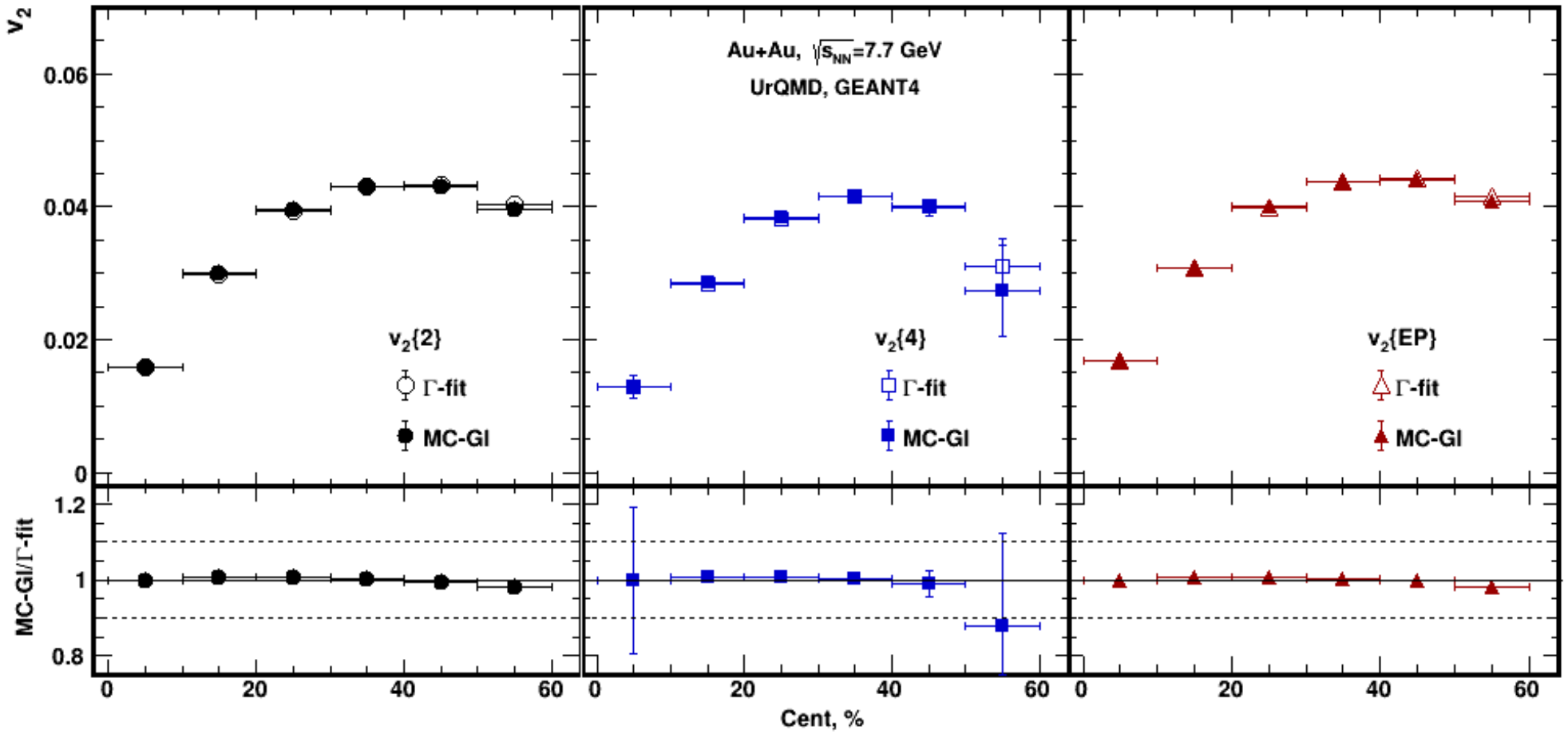


Multi-Purpose Detector (MPD) Stage 1

- **Centrality determination:** Multiplicity of produced charged particles in TPC
- **Event plane determination:** TPC
- **Track selection:**
  - Primary tracks
  - $N_{TPC\ hits} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  - $|\eta| < 1.5$
  - PID based on PDG code

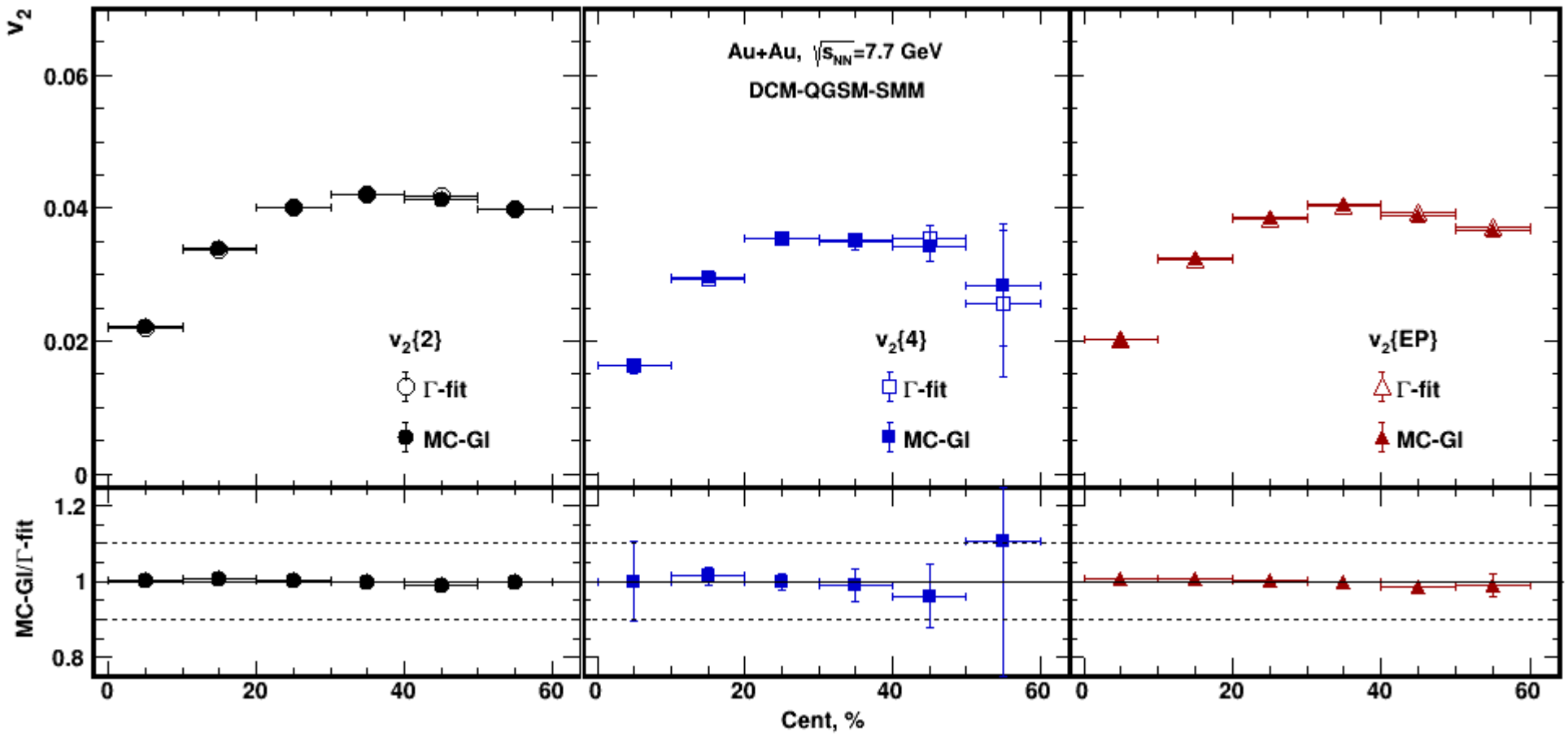
-5<η<-2 **FHCal** | -1.5<η<1.5 **TPC** 0.2< p_T<3 GeV/c | 2<η<5 **FHCal**

The effect of bias in centrality determination in MPD



Agreement within statistical errors for all methods

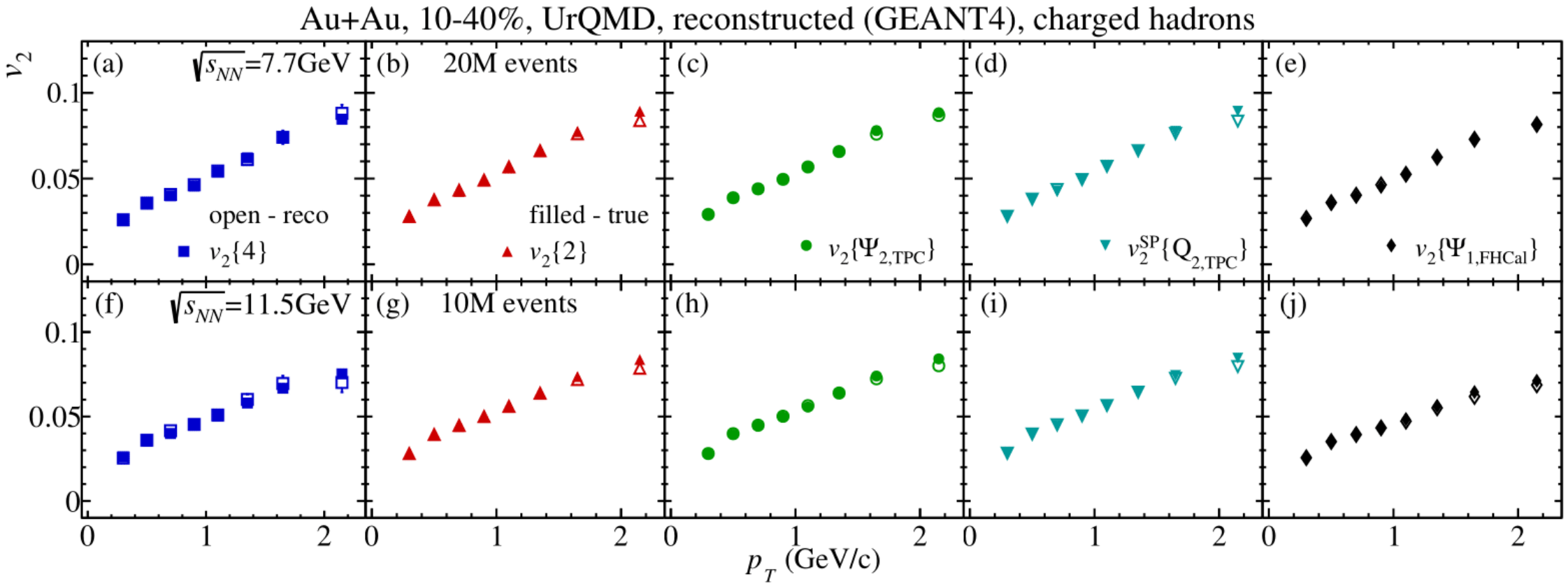
The effect of bias in centrality determination in flow measurements for DCM-QGSM-SMM model



The v_2 are in good agreement for all methods

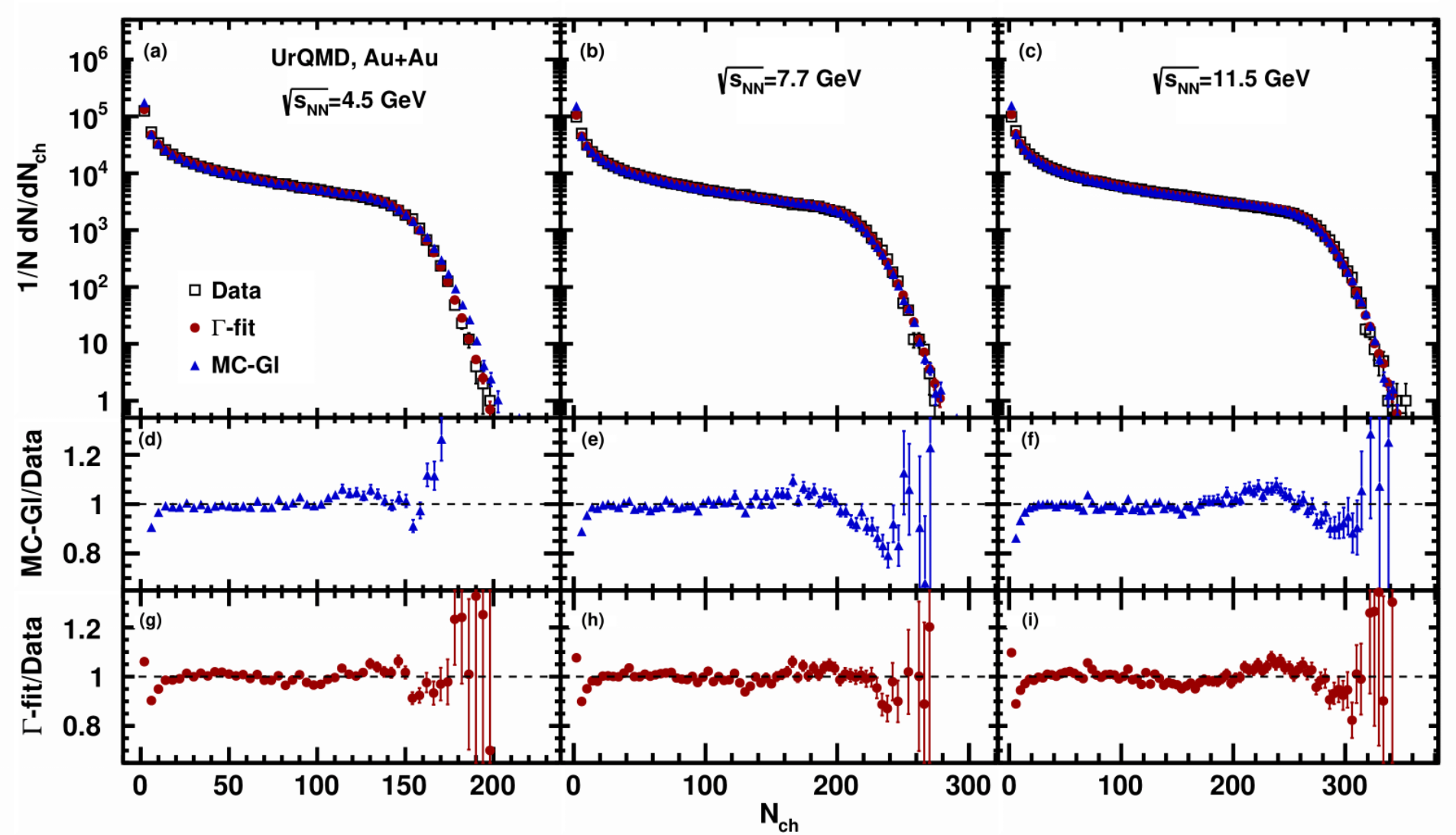
Performance of v_2 of charged hadrons in MPD

Vinh Ba Luong, Dim Idrisov et al 2103.05064 [nucl-ex]



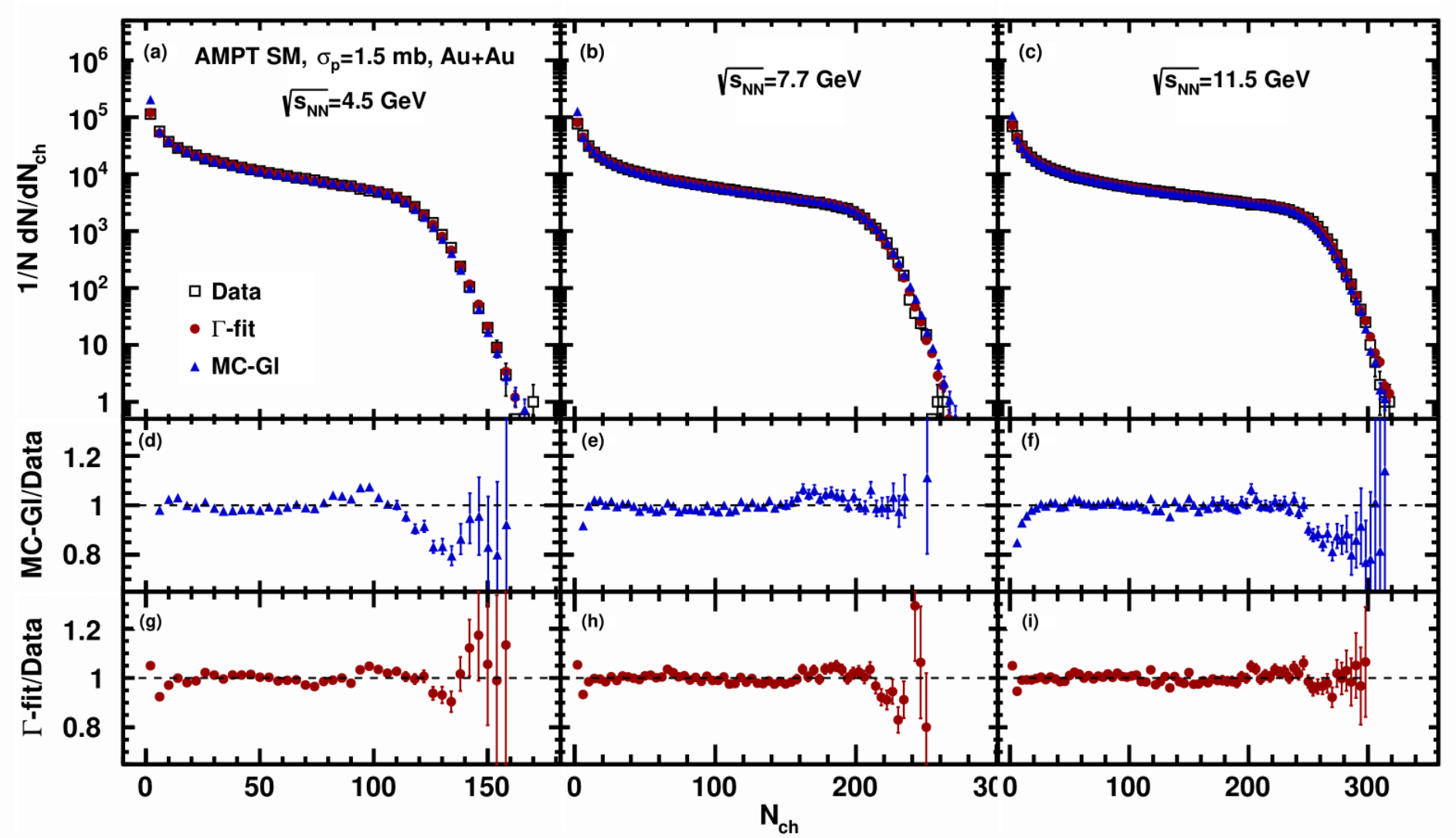
Reconstructed and generated v_2 of charged hadrons have a good agreement for all methods

Fit of N_{ch}: UrQMD



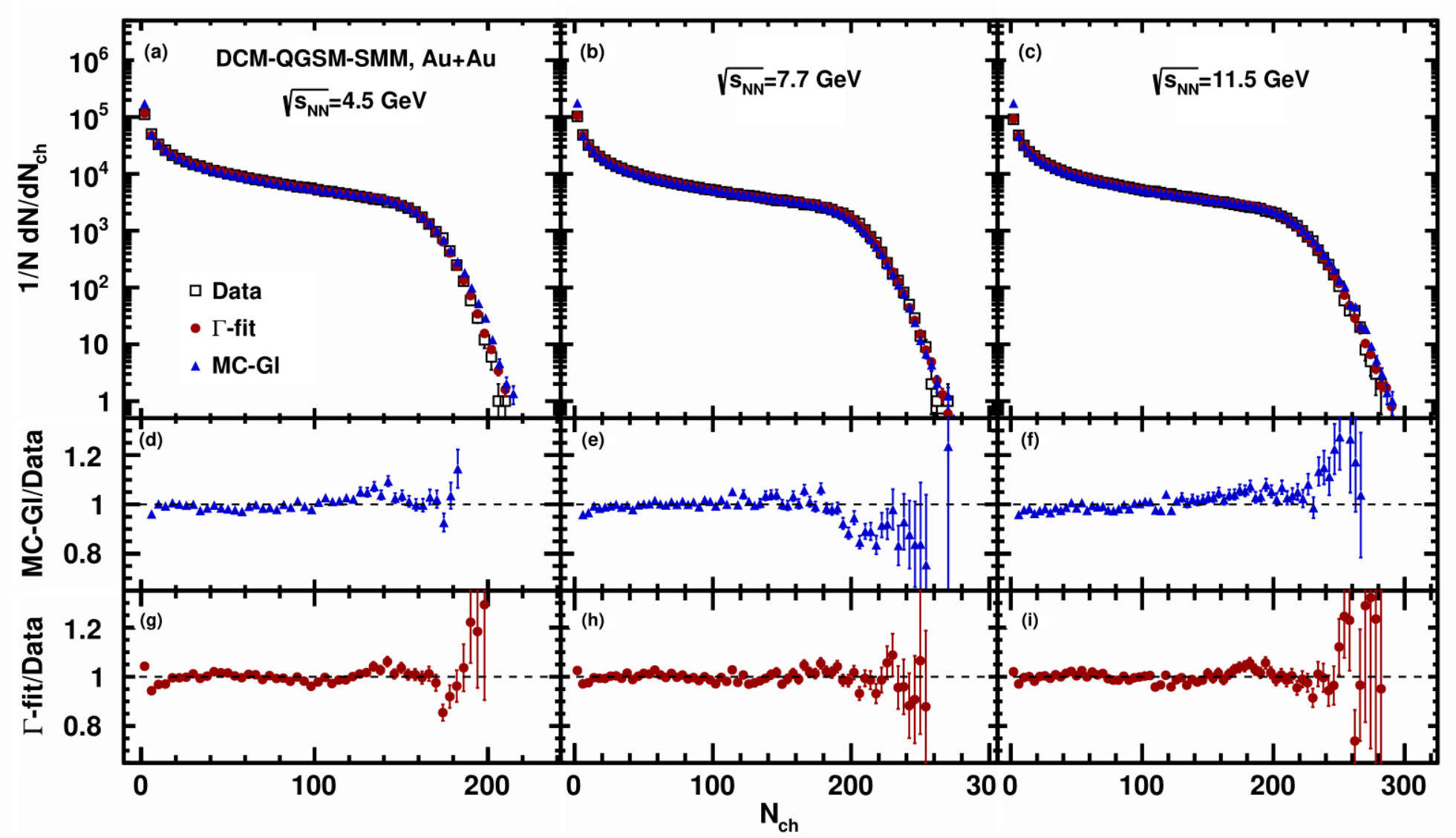
Good fit quality for both methods

Fit of N_{ch}: AMPT SM, σ_p=1.5 mb



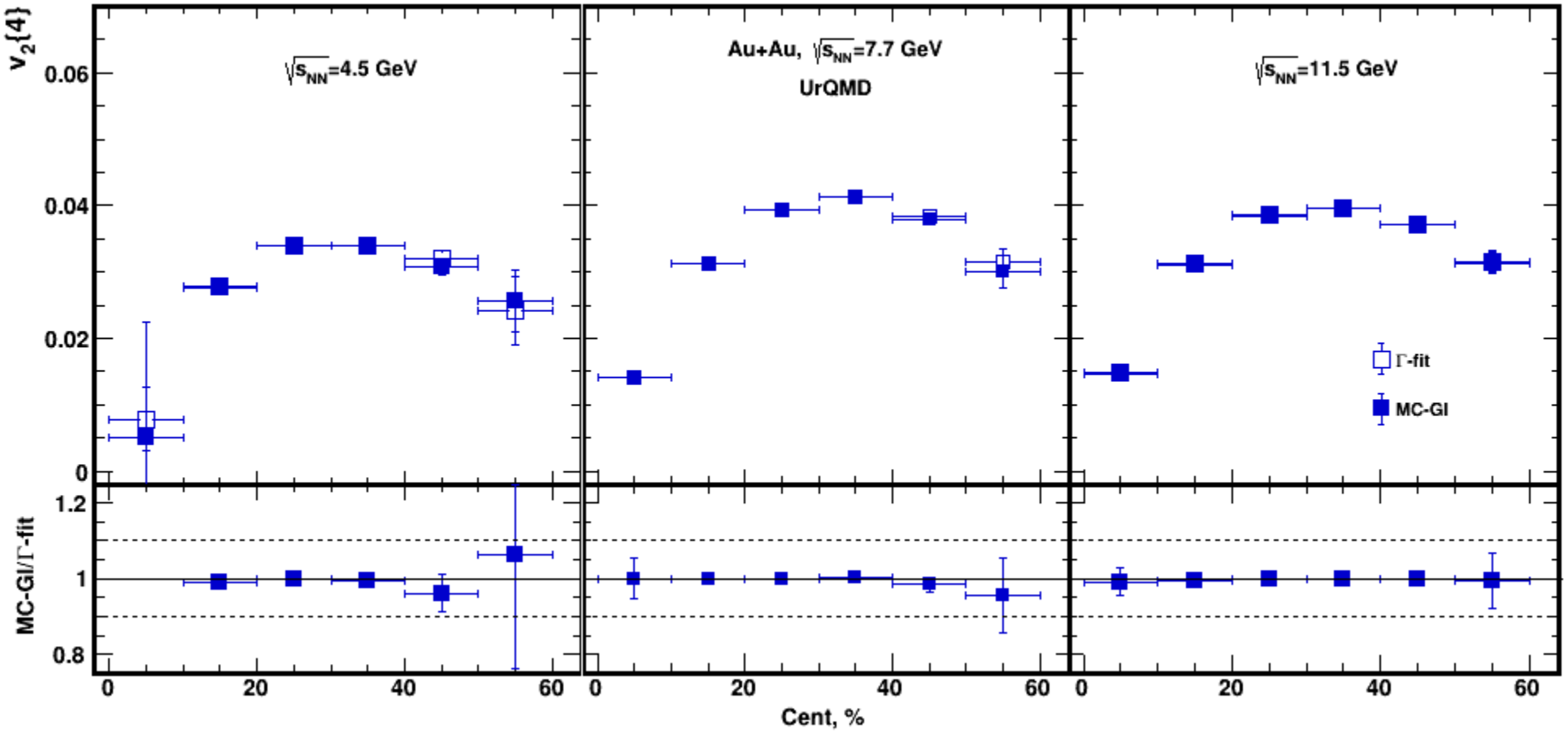
Good fit quality for both methods

Fit of N_{ch}: DCM-QGSM-SMM



Good fit quality for both methods

The effect of bias in centrality determination in flow measurements for UrQMD model at NICA energies



Agreement within 1-4%

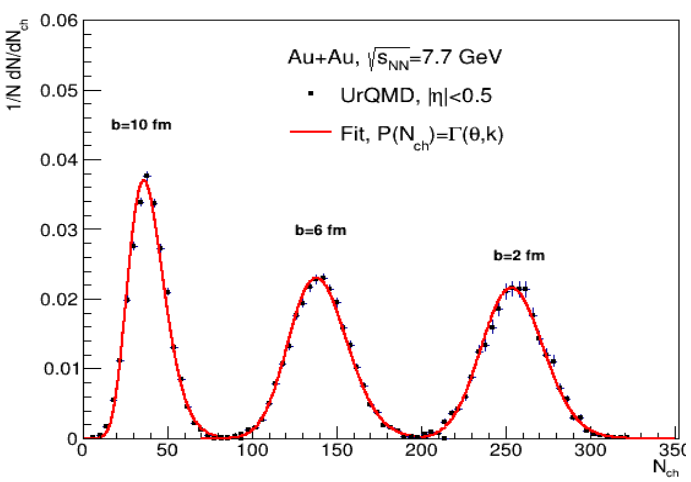
The Bayesian inversion method (Γ-fit): main assumptions

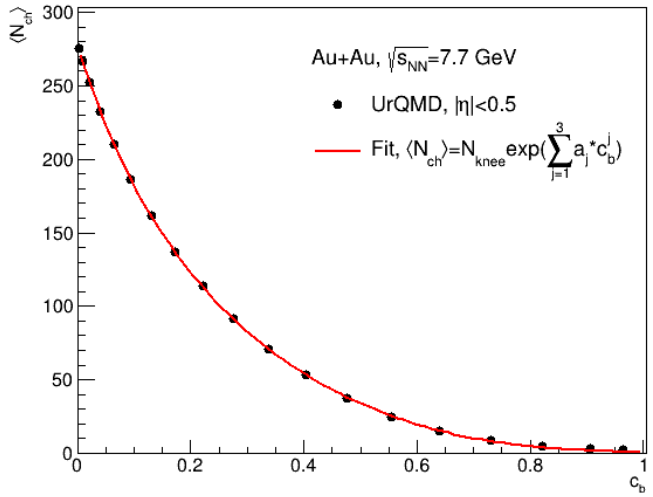
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

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

c_b – impact parameter based centrality

$$c_b = \frac{1}{\sigma_{inel}} \int_0^b P_{inel}(b') 2\pi b' db' \simeq \frac{\pi b^2}{\sigma_{inel}}$$





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

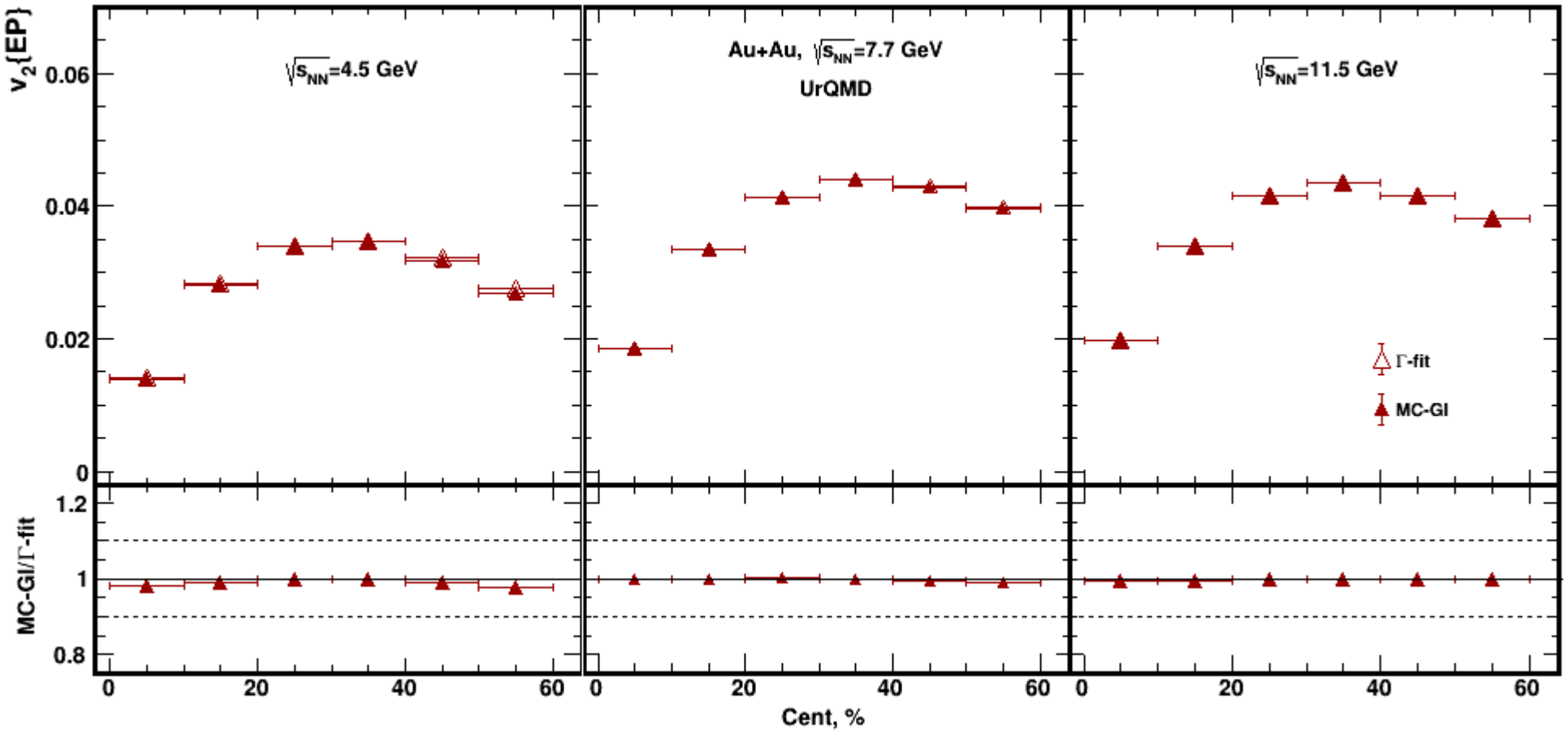
$$\langle N_{ch} \rangle = N_{knee} \exp\left(\sum_{j=1}^{3} a_j c_b^j \right), \quad k = \frac{\langle N_{ch} \rangle}{\theta}$$

R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902

Implementation in MPD: https://github.com/Dim23/GammaFit

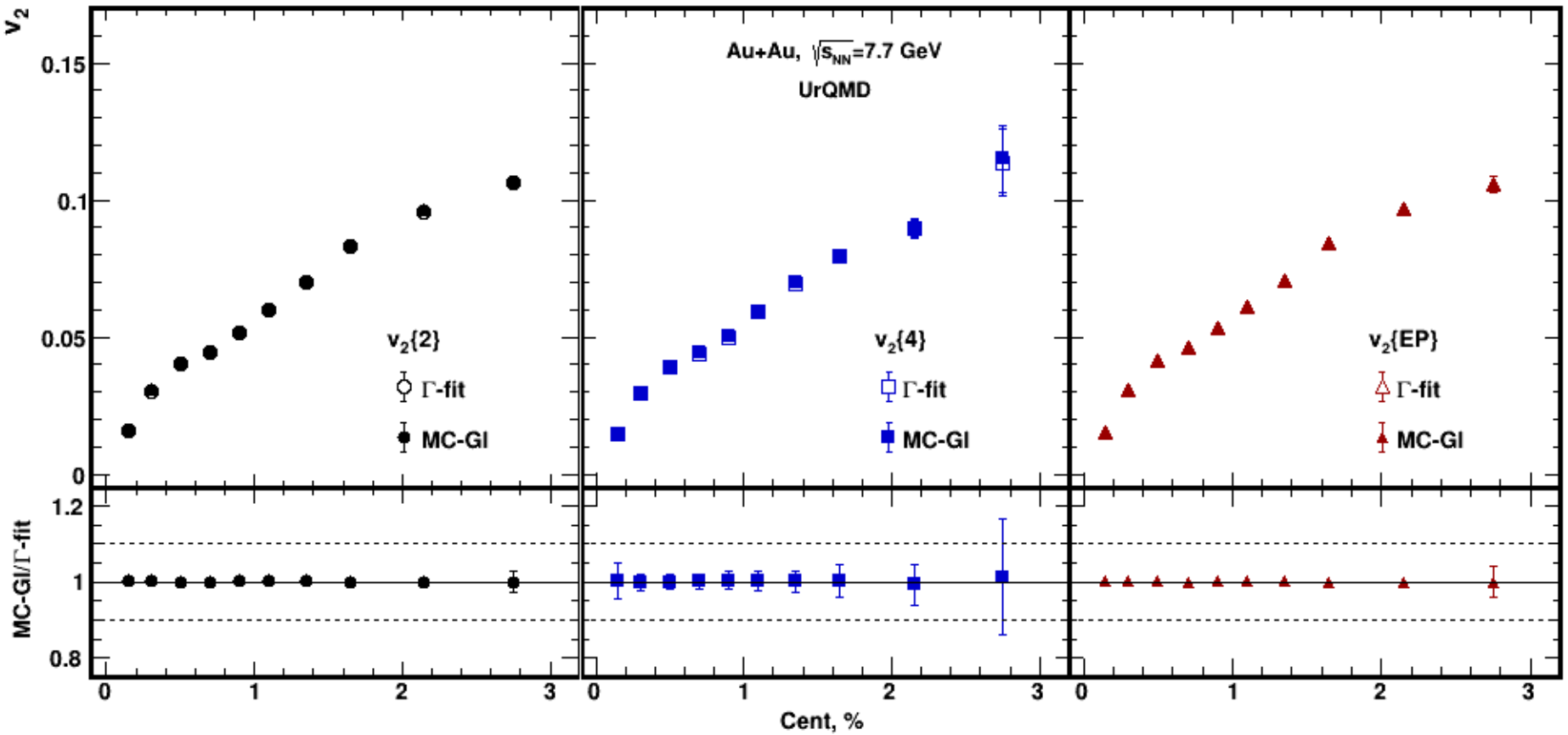
Five fit parameters N_{knee}, θ, a_j

The effect of bias in centrality determination in flow measurements for UrQMD model at NICA energies

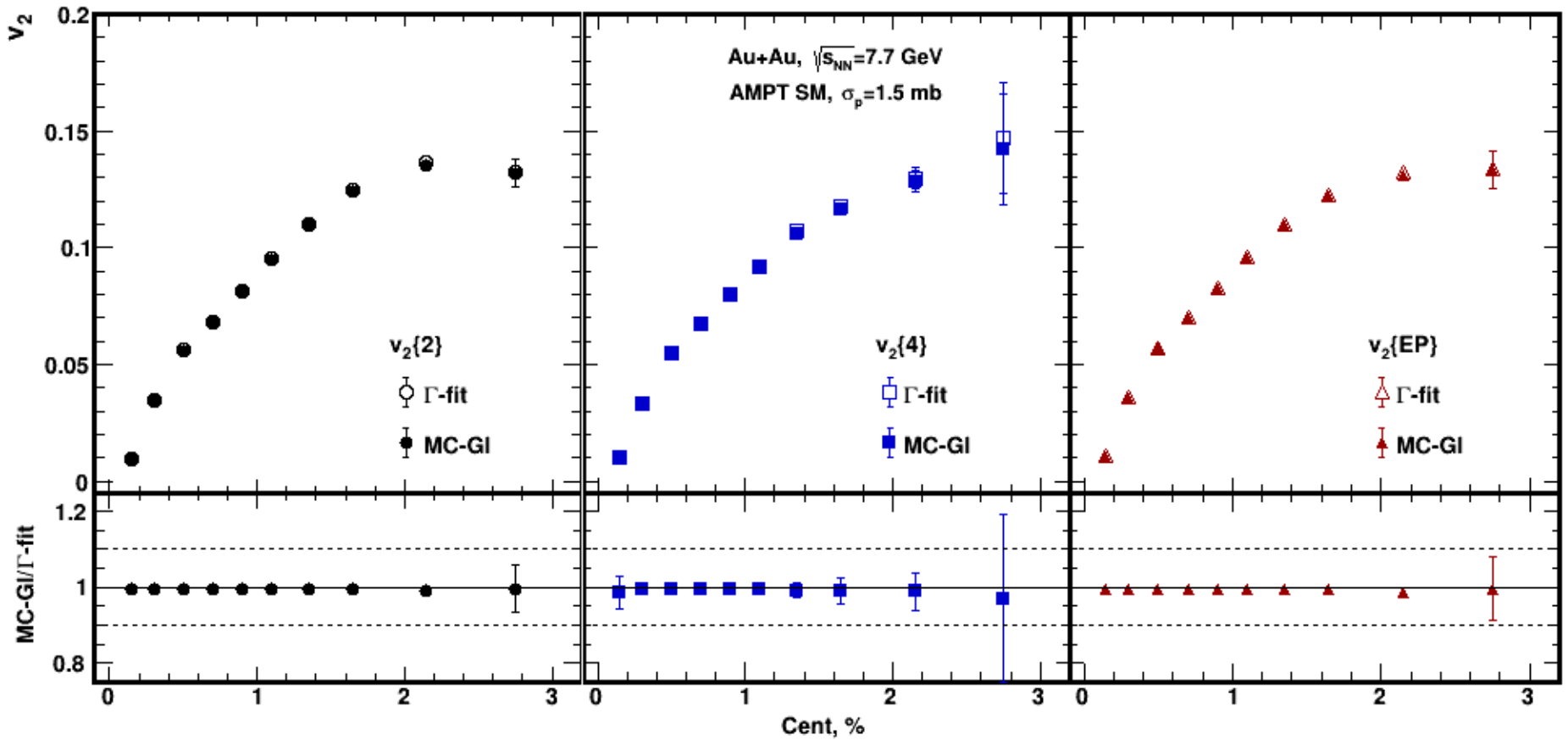


Agreement within 1-4%

The effect of bias in centrality determination in flow measurements for UrQMD model



The effect of bias in centrality determination in flow measurements for AMPT model



The effect of bias in centrality determination in flow measurements for UrQMD reconstructed data