# The effect of bias in centrality determination in flow measurements

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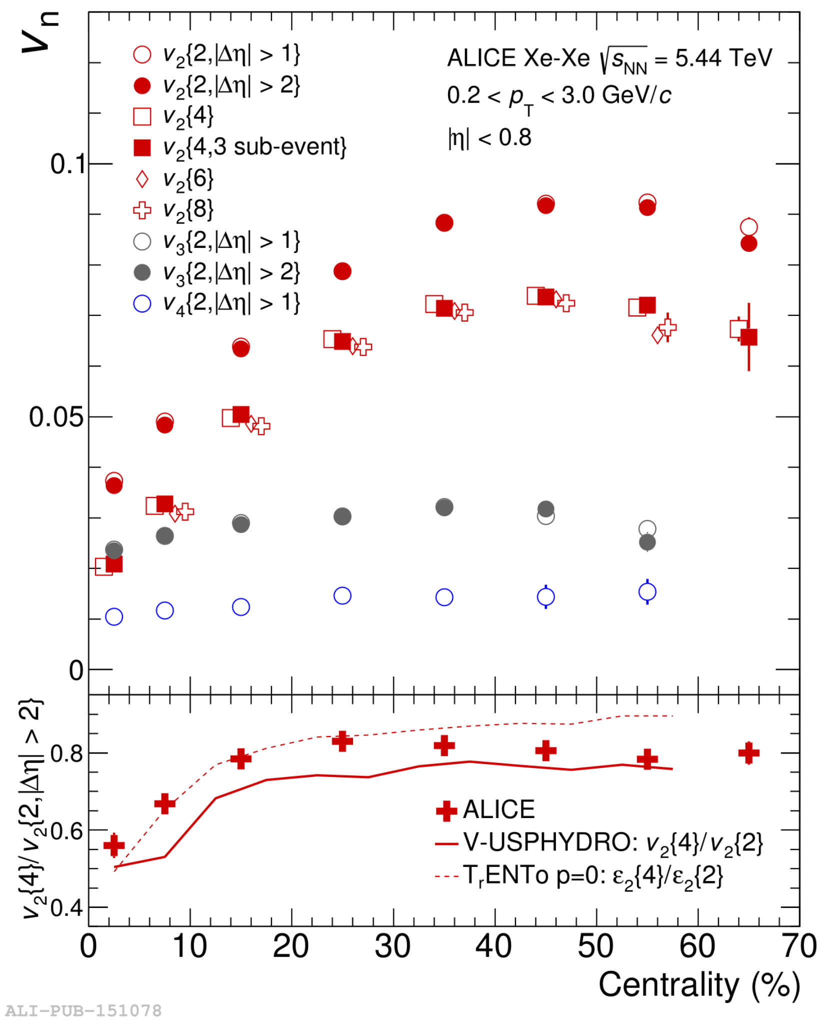
VII-th Collaboration Meeting of the MPD Experiment at the NICA Facility
23 April 2021

This work is supported by:
the RFBR according to the research project No. 18-02-40086 and No. 18-02-40065
the European Union‘s Horizon 2020 research and innovation program under grant agreement No. 871072

# Outline

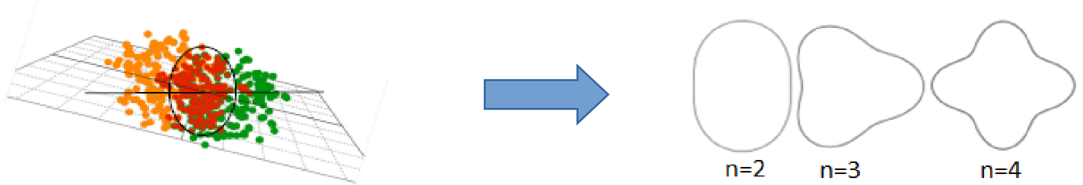
- Introduction
- Description of event plane  and Q-Cumulants methods for flow measurements
- Methods of centrality determination based on charged particle multiplicity
- The effect of bias in centrality determination for flow analysis:
  - comparison of different models and energies
  - performance study of $v_2$ of charged hadrons in MPD
- Summary and outlook

# Anisotropic flow in HIC




**Jacopo Margutti, et al., Nuclear Physics A 982, 367-370 (2019)**

Dependence of anisotropic flow on centrality



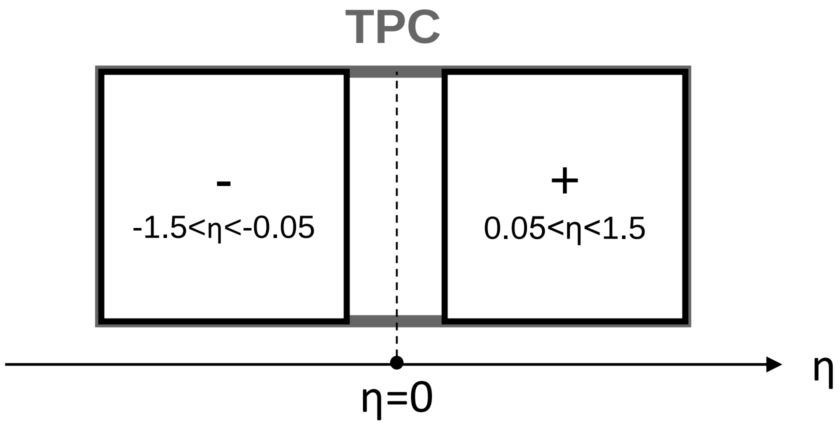

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]\right) \quad , v_2 = \langle \cos 2(\varphi - \Psi_n) \rangle$$

- Initial eccentricity (and its attendant fluctuations) $\varepsilon_n$ drives momentum anisotropy $v_n$ with specific viscous modulation
- $v_1$ - directed flow, $v_2$ - elliptic flow, $v_3$ - triangular flow
- $v_n$ ($p_T$, centrality):
  - sensitive to the early stages of collision
  - important constraint for transport properties: EoS, η/s, ζ/s, etc.

# The methods for flow measurements

**Event Plane:**

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




**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 estimate with direct cumulant method

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

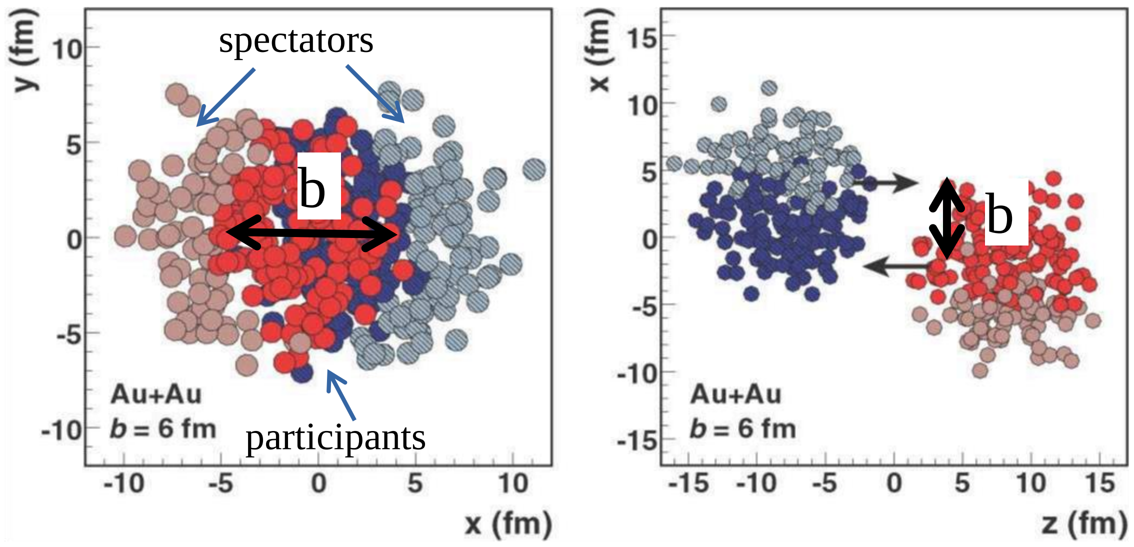
**Phys. Rev. C83:044913, 2011**

# Initial geometry of HIC

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

**Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243**

- **Collision geometry**
- **Models:**
  Impact parameter *b*
- **Measurable quantities (Experiment):**
  - Multiplicity or transverse energy of the produced particles
  - Energy of the spectators

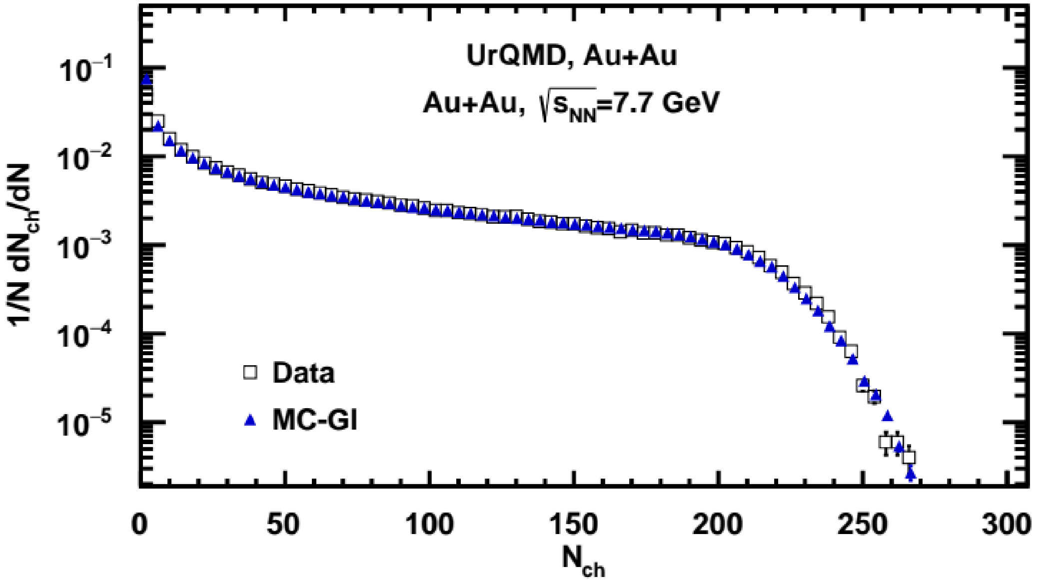


# MC-Glauber based centrality framework

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

Build multiplicity fitting function + Input multiplicity distribution → Evaluate $\chi^2$ → Minimize $\chi^2$ to find f, μ, k




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, I. Selyuzhenkov et al., J.Phys.Conf.Ser. 1690 (2020) 1, 012107**
- **V. Klochkov, I. Selyuzhenkov et al., EPJ Web Conf. 182 (2018) 02132**

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

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

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

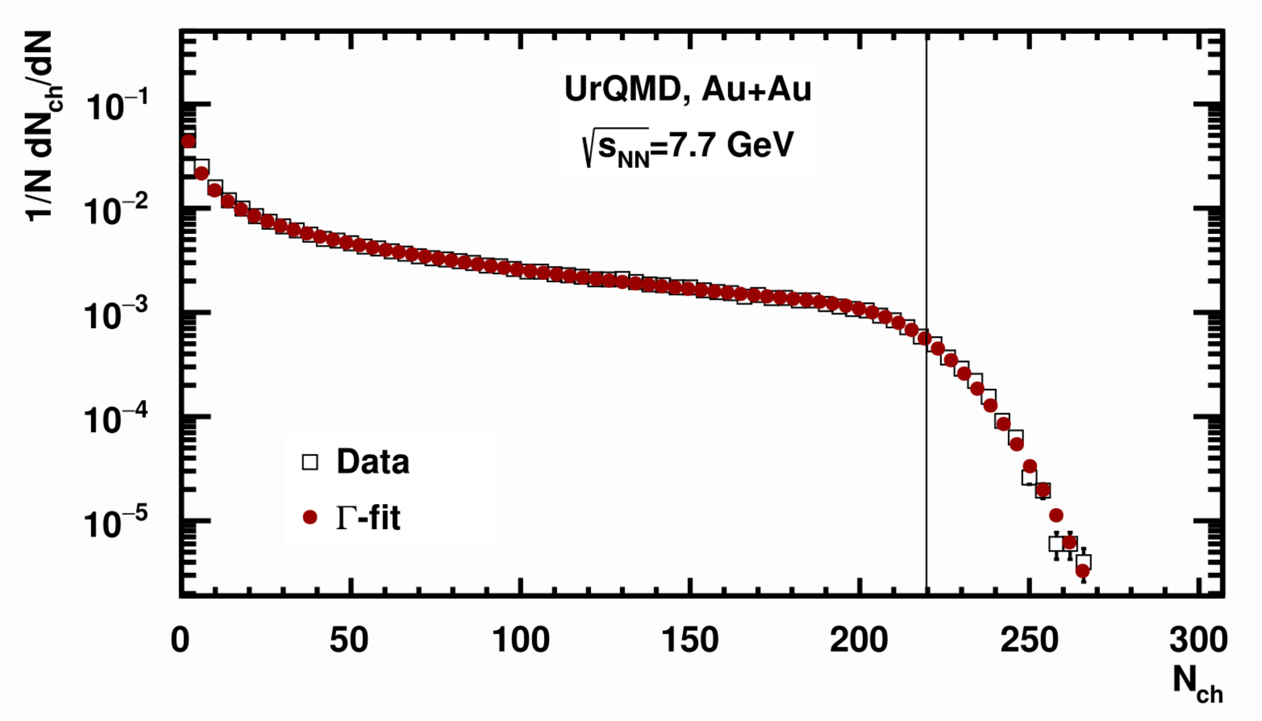
$$P(N_{ch}|c_b) = \frac{1}{\Gamma\big(k(c_b)\big)\theta^k} N_{ch}^{k(c_b)-1} \mathrm{e}^{-n/\theta}$$

$c_b$ – impact parameter based centrality

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

$\sigma_{inel}$ – geometrical inelastic NN cross section

$P_{inel}(b)$ – probability of inelastic NN collision ($P_{inel}(b)\approx 1$)




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

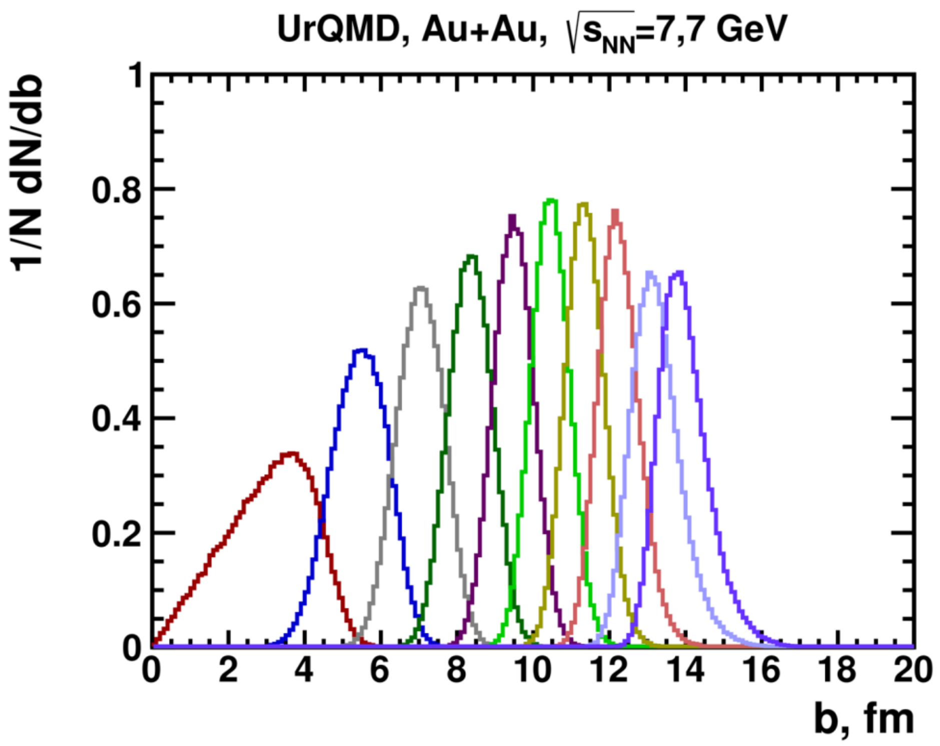
Implementation in MPD: [https://github.com/Dim23/GammaFit](https://github.com/Dim23/GammaFit)

# 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

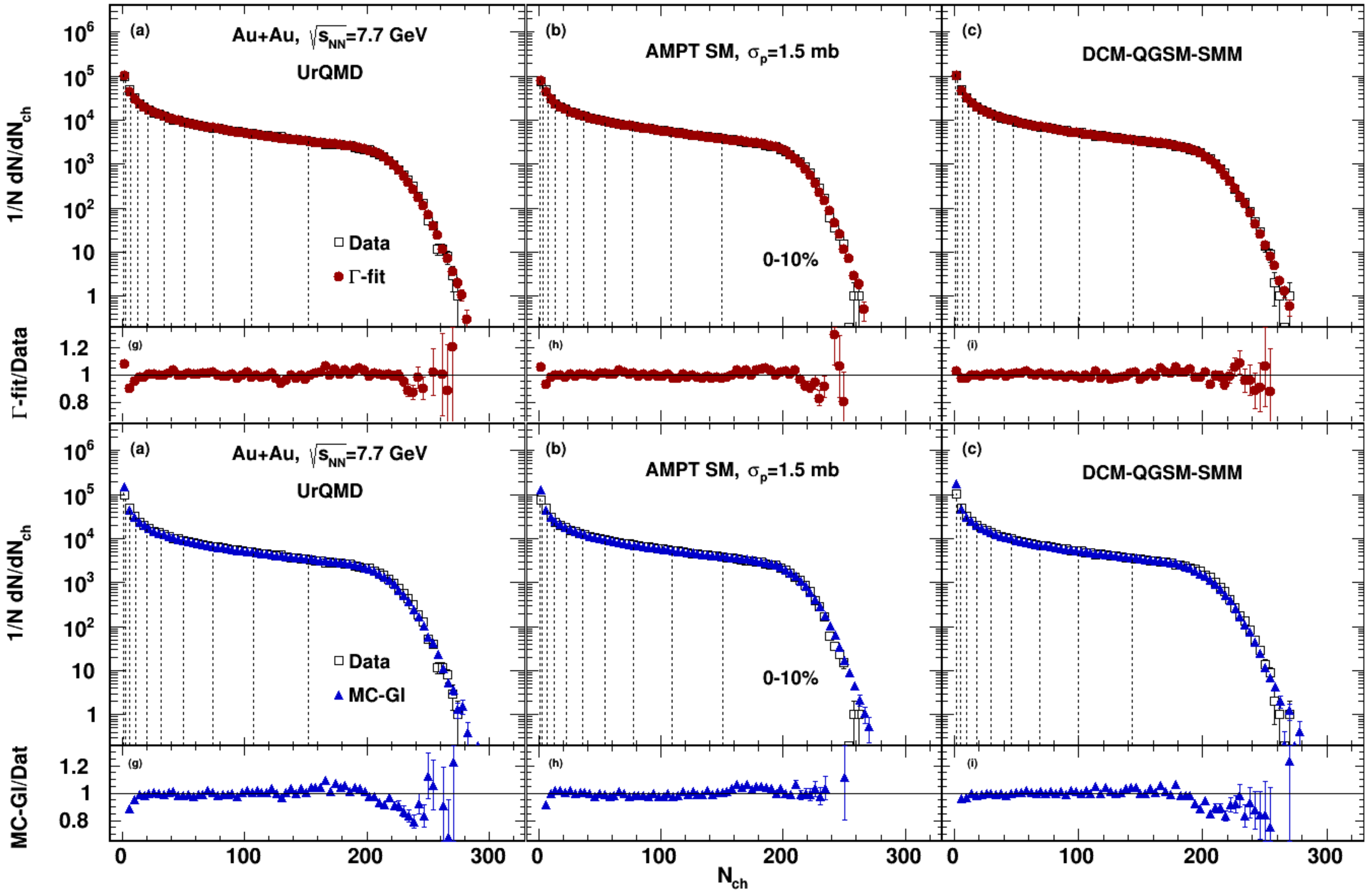
**Simulated data sets:**

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

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

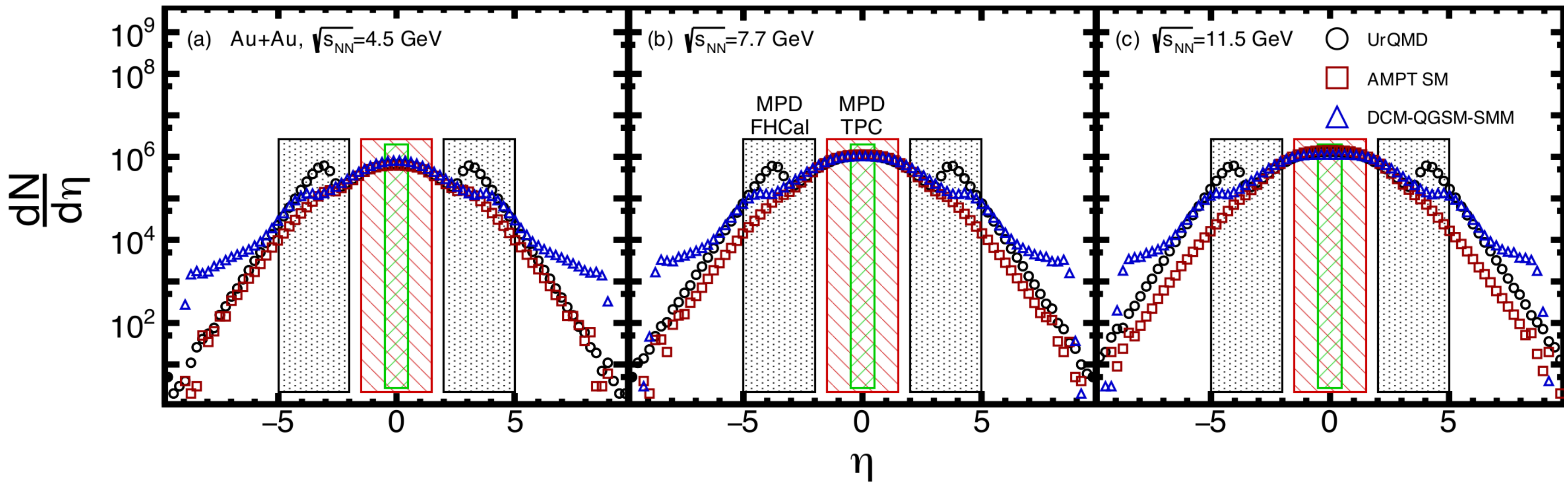
**Hadron selection:**

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




Good fit quality for both methods

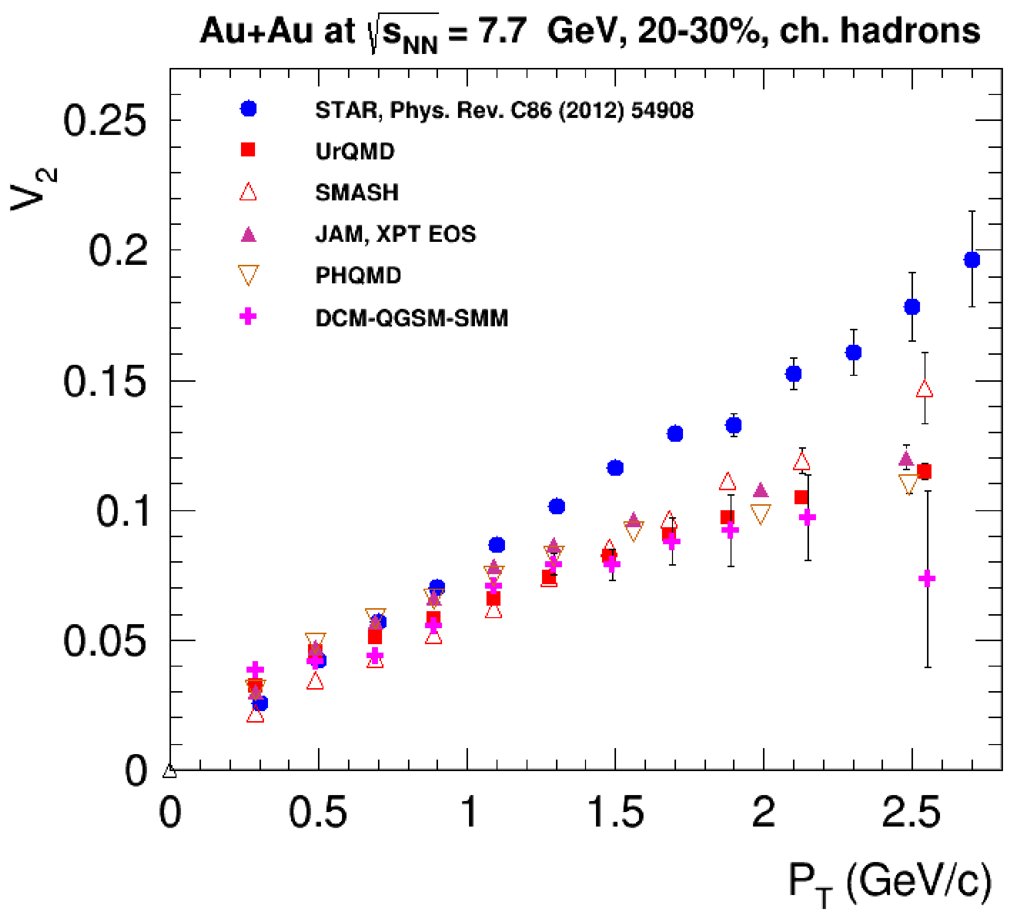
# Models and statistics

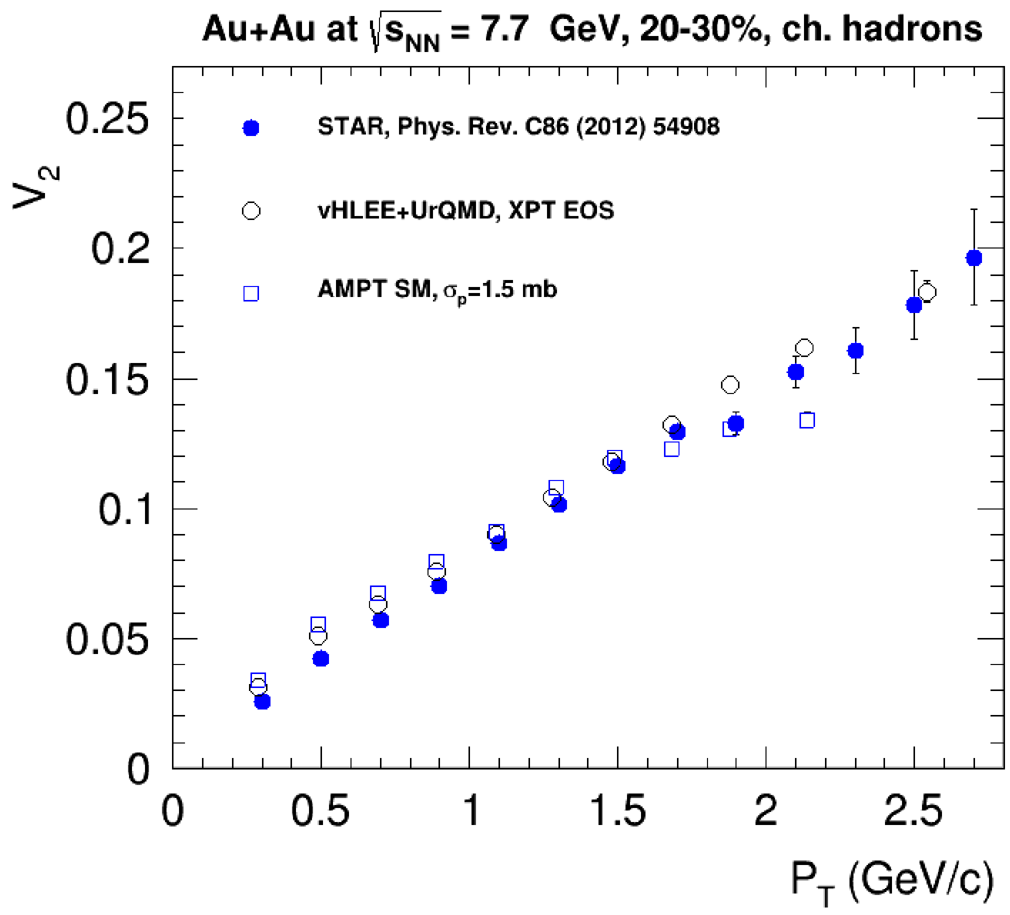



**Au+Au, min. bias**

- 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, $\sigma_{part}$=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

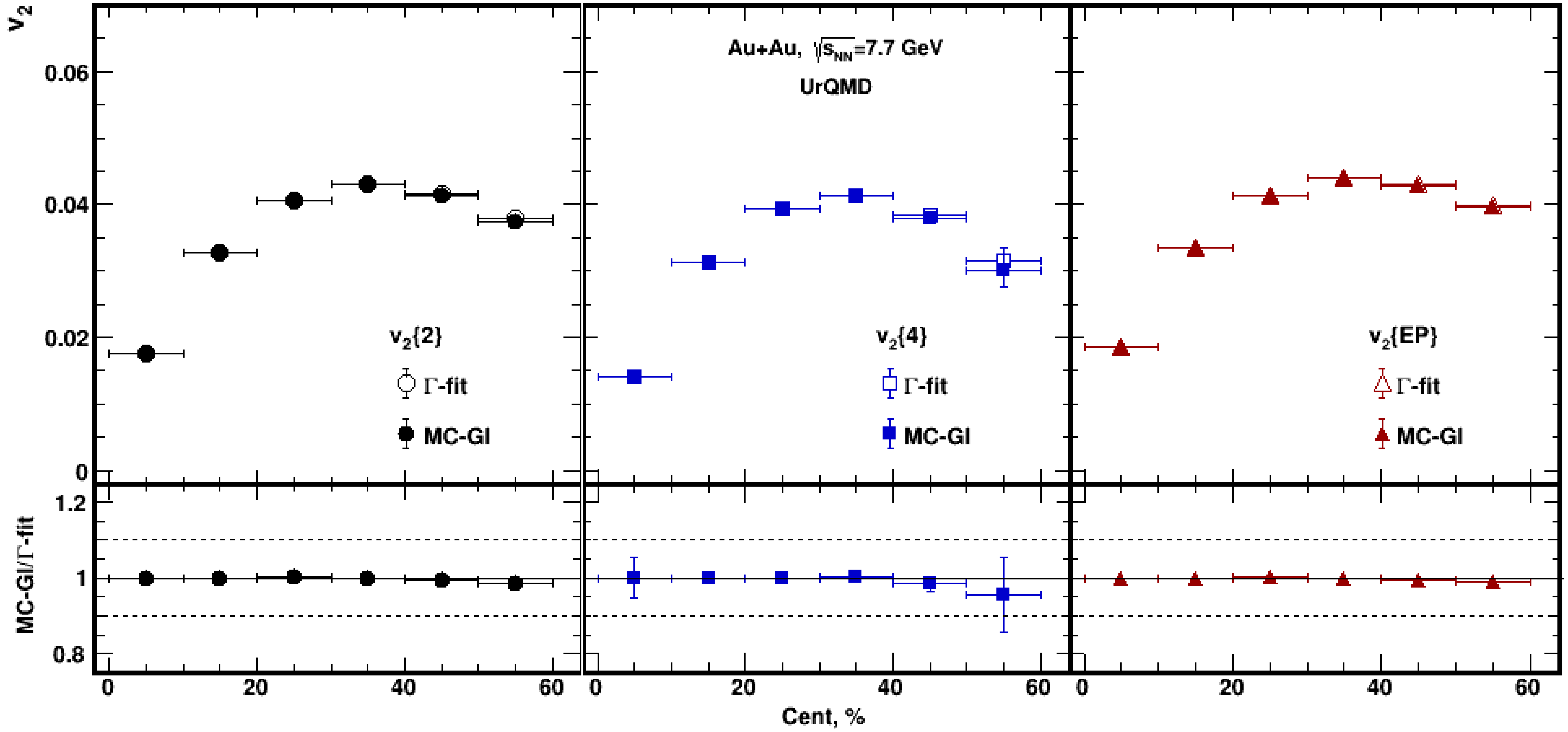
# Elliptic flow in UrQMD and AMPT



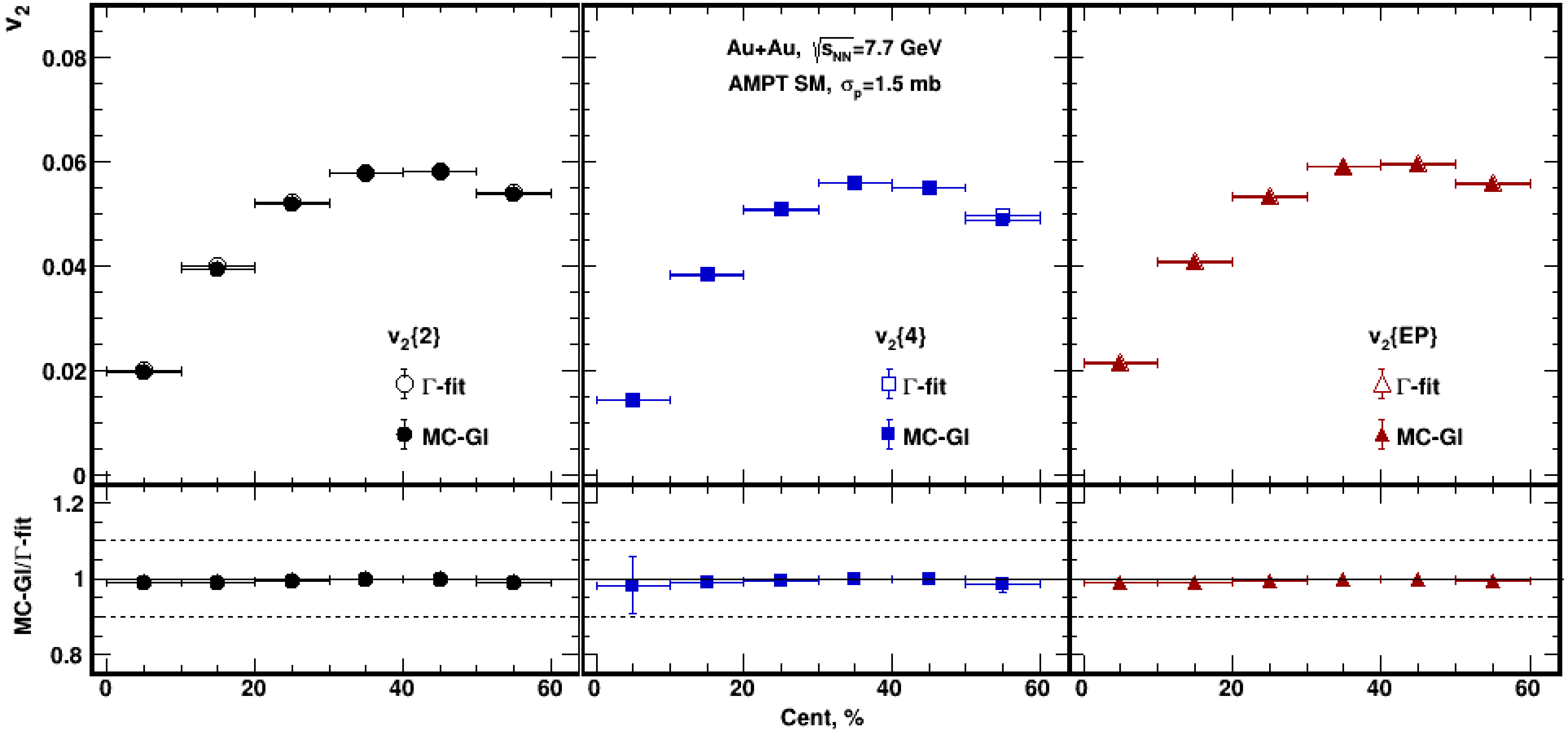

At $\sqrt{s_{NN}} \geq$ 7.7 GeV pure string/hadronic cascade models underestimate $v_2$ – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…)

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



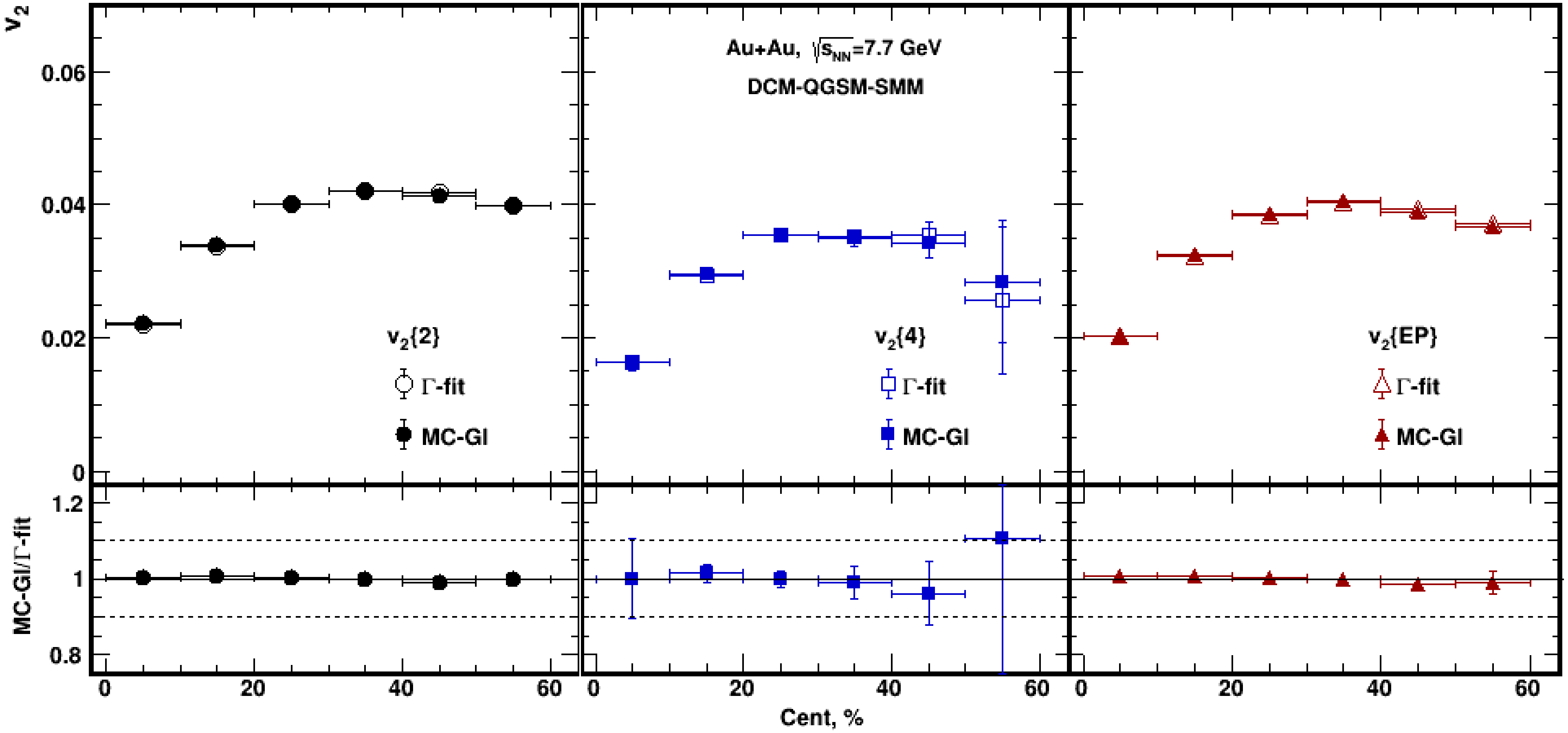

The $v_2$ are in good agreement for all methods

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



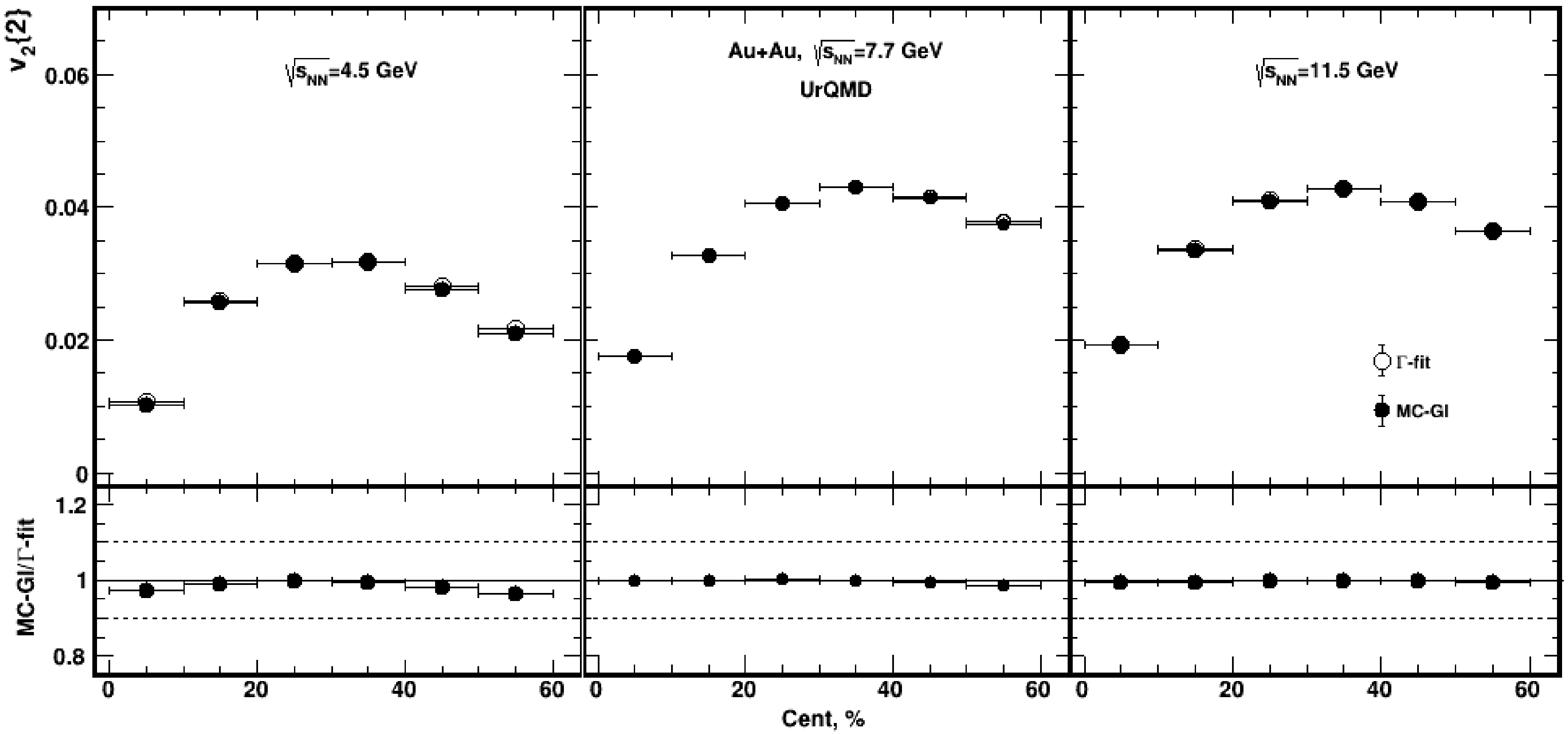

The $v_2$ are in good agreement for all methods

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



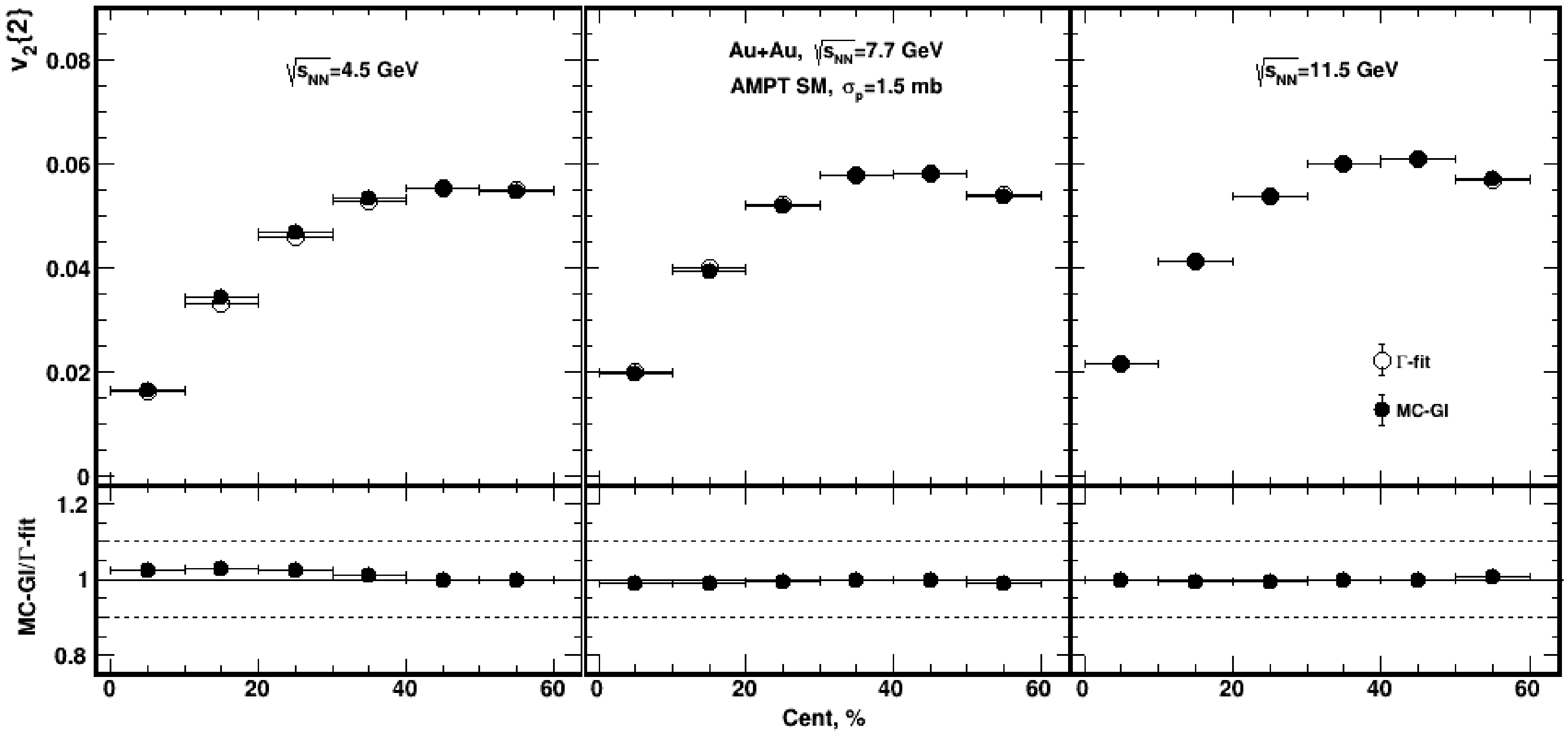

The $v_2$ are in good agreement for all methods

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



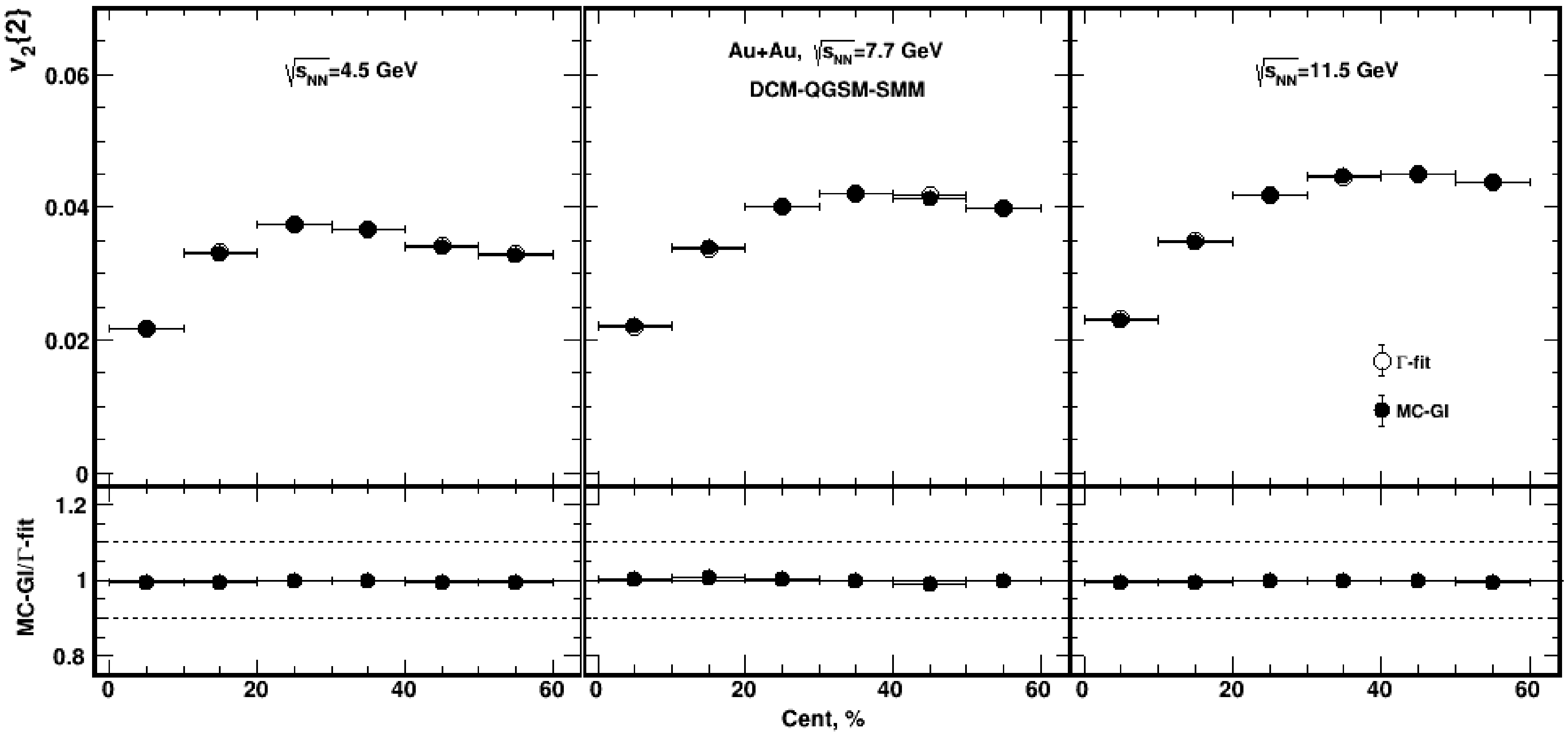

- Difference for $v_2\{2\}$ at 4.5 GeV using different centrality estimators is within 1-4%.
- Better agreement at higher energies.

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




- Difference for $v_2\{2\}$ at 4.5 GeV using different centrality estimators is within 1-4%.
- Better agreement at higher energies.

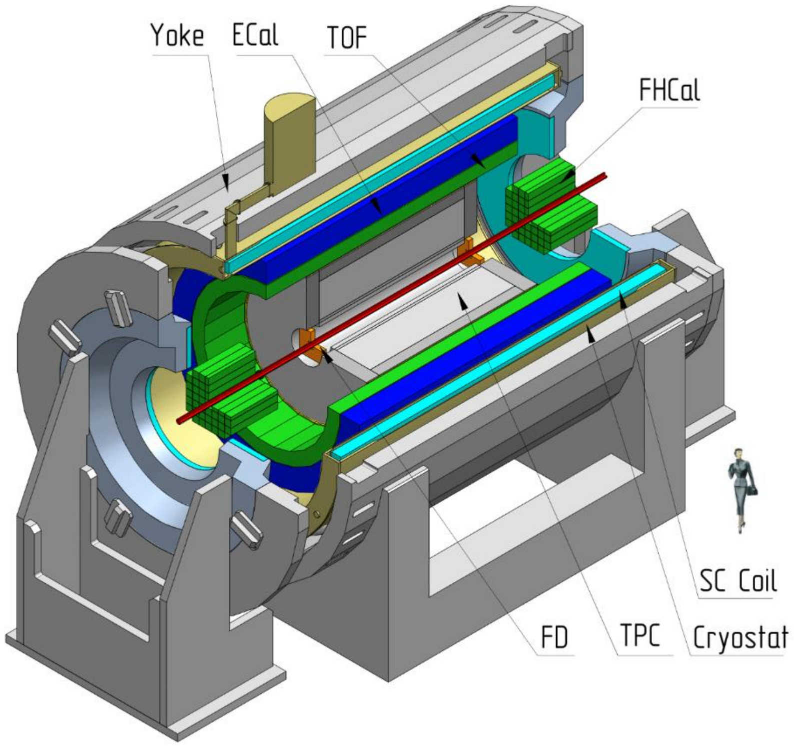
# The effect of bias in centrality determination in flow measurements for DCM-QGSM-SMM model at NICA energies




The $v_2\{2\}$ are in good agreement for all energies

# MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis



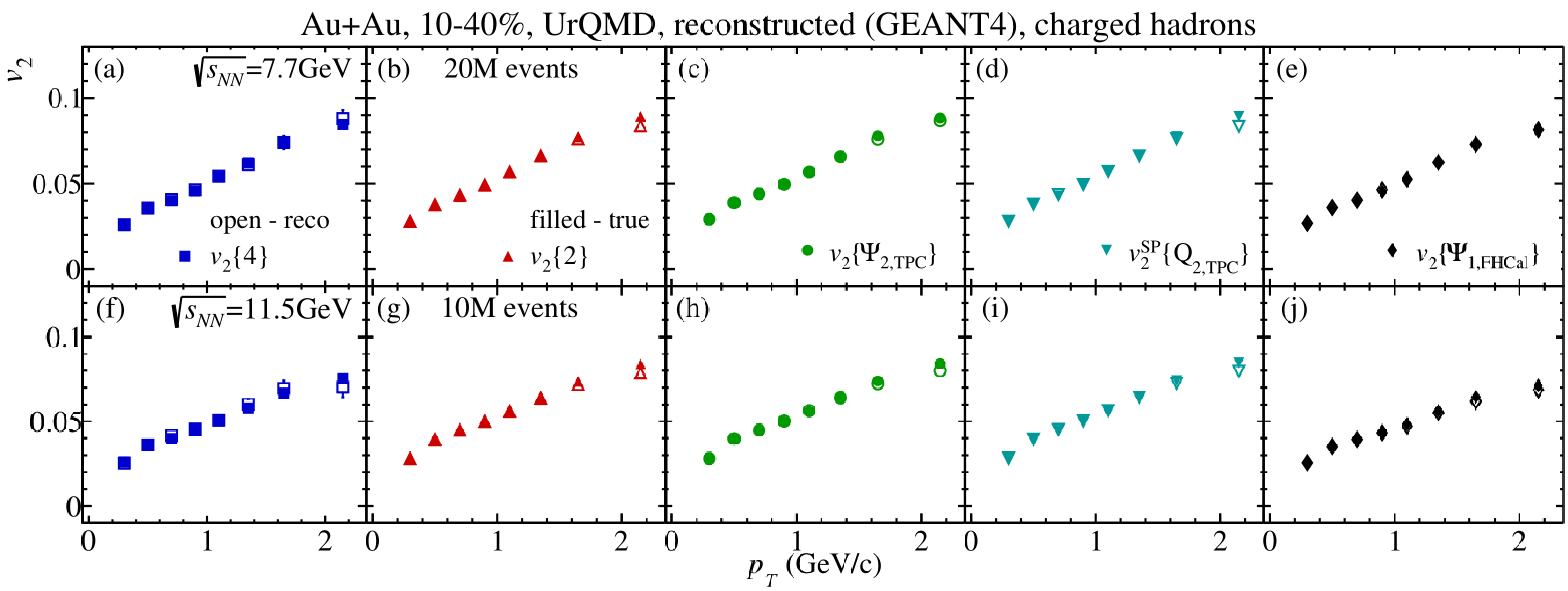

Multi-Purpose Detector (MPD) Stage 1

- **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

| $-5<\eta<-2$ | $-1.5<\eta<1.5$ | $2<\eta<5$ |
|---|---|---|
| **FHCal** | **TPC** $0.2< p_T<3$ GeV/c | **FHCal** |

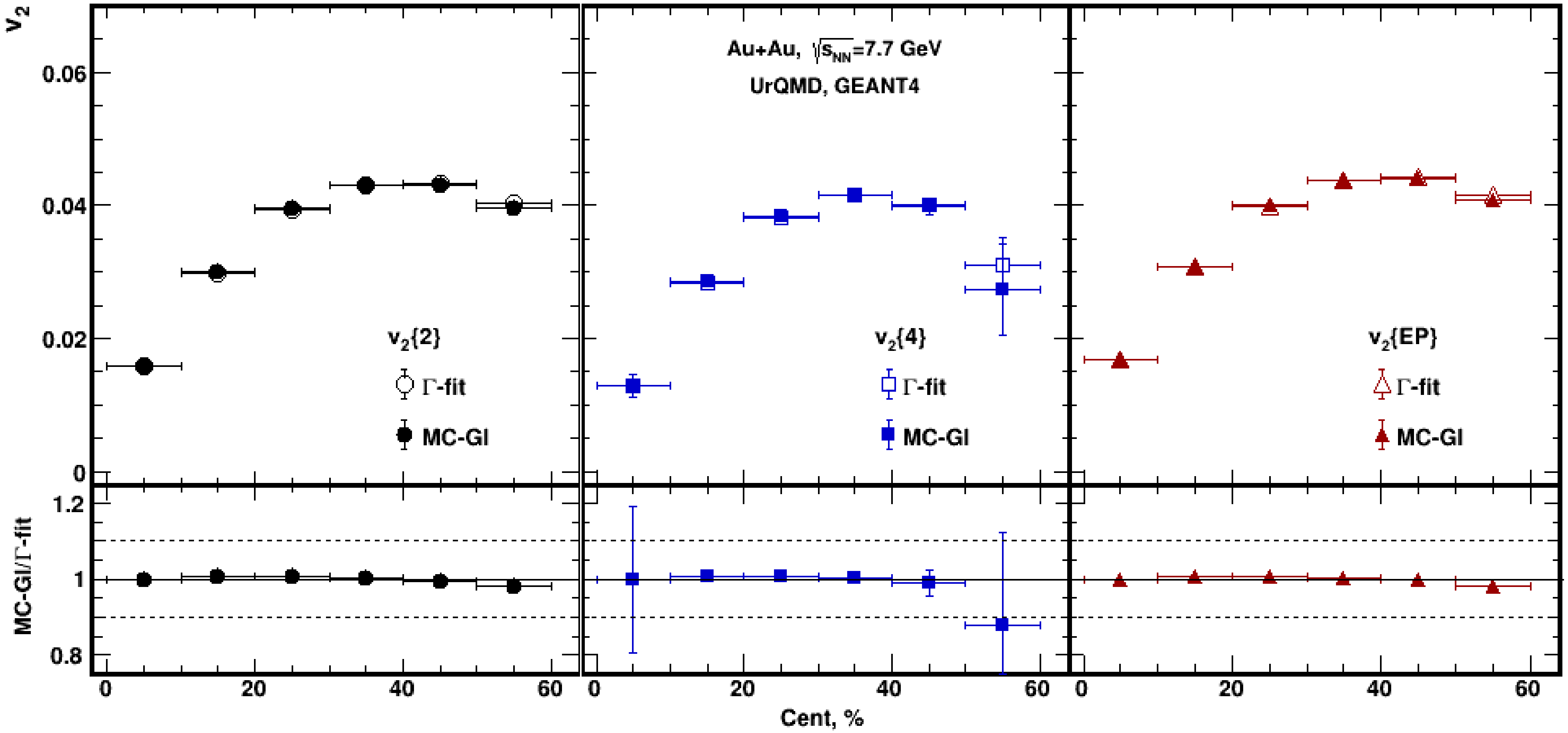
# Performance of $v_2$ of charged hadrons in MPD

**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**

# The effect of bias in centrality determination in MPD




Agreement within statistical errors for all methods

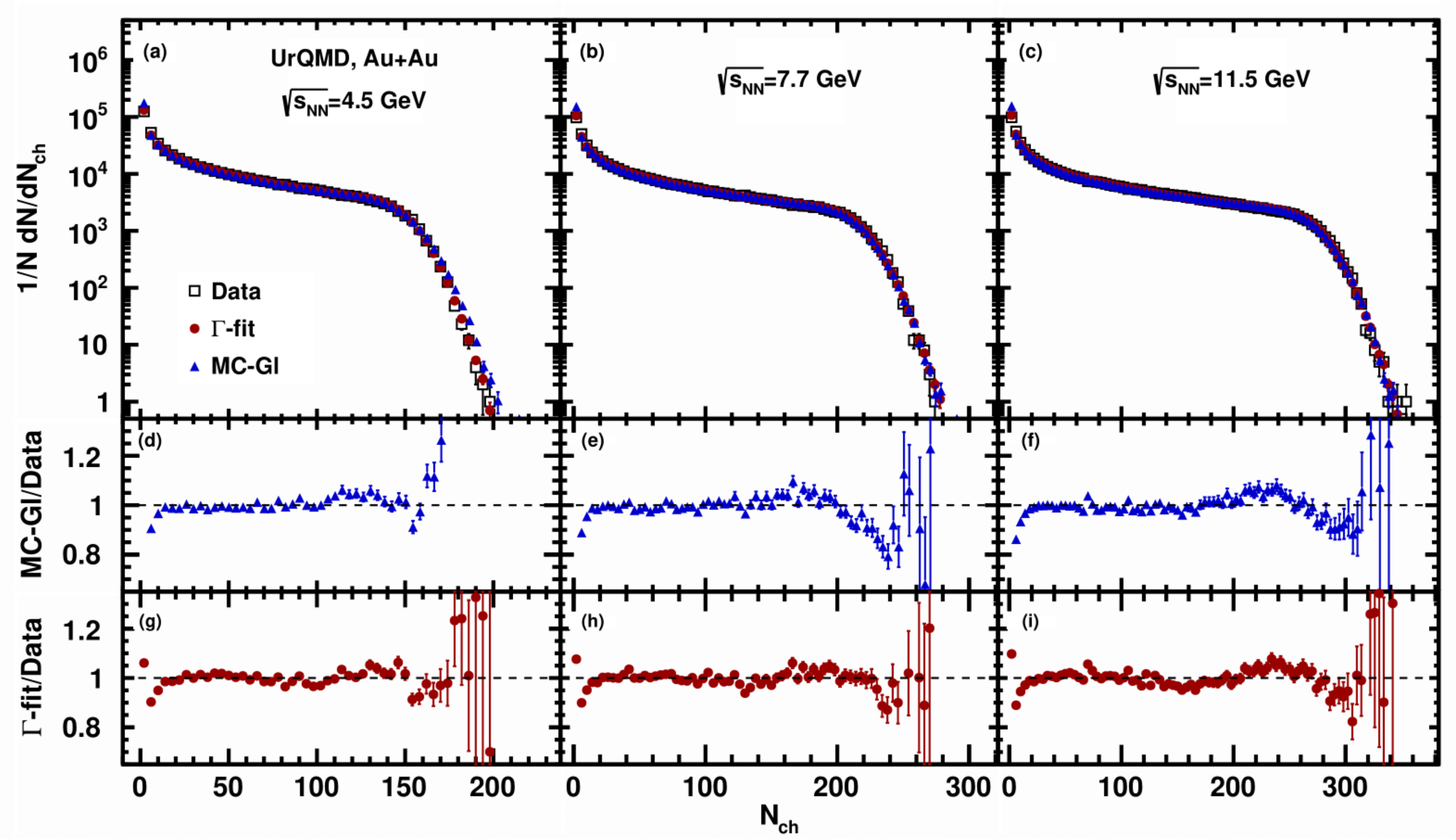
# Summary and outlook

- The effect of bias in centrality determination for flow analysis for models:
  - Fitted functions from both methods reproduce charged particle multiplicity
  - Comparison of $v_2$ using two centrality estimators shows a good agreement for all models (UrQMD, AMPT, DCM-QGSM-SMM)
  - The effect of bias in centrality determination is most expressed for the UrQMD and AMPT model at $\sqrt{s_{NN}}$ = 4.5 GeV
- The results from the reconstructed data obtained using the two methods for determining centrality are in good agreement.
- Make comparison of $v_2$ measurements using the centrality determination based on FHCal

# Thanks for your attention!

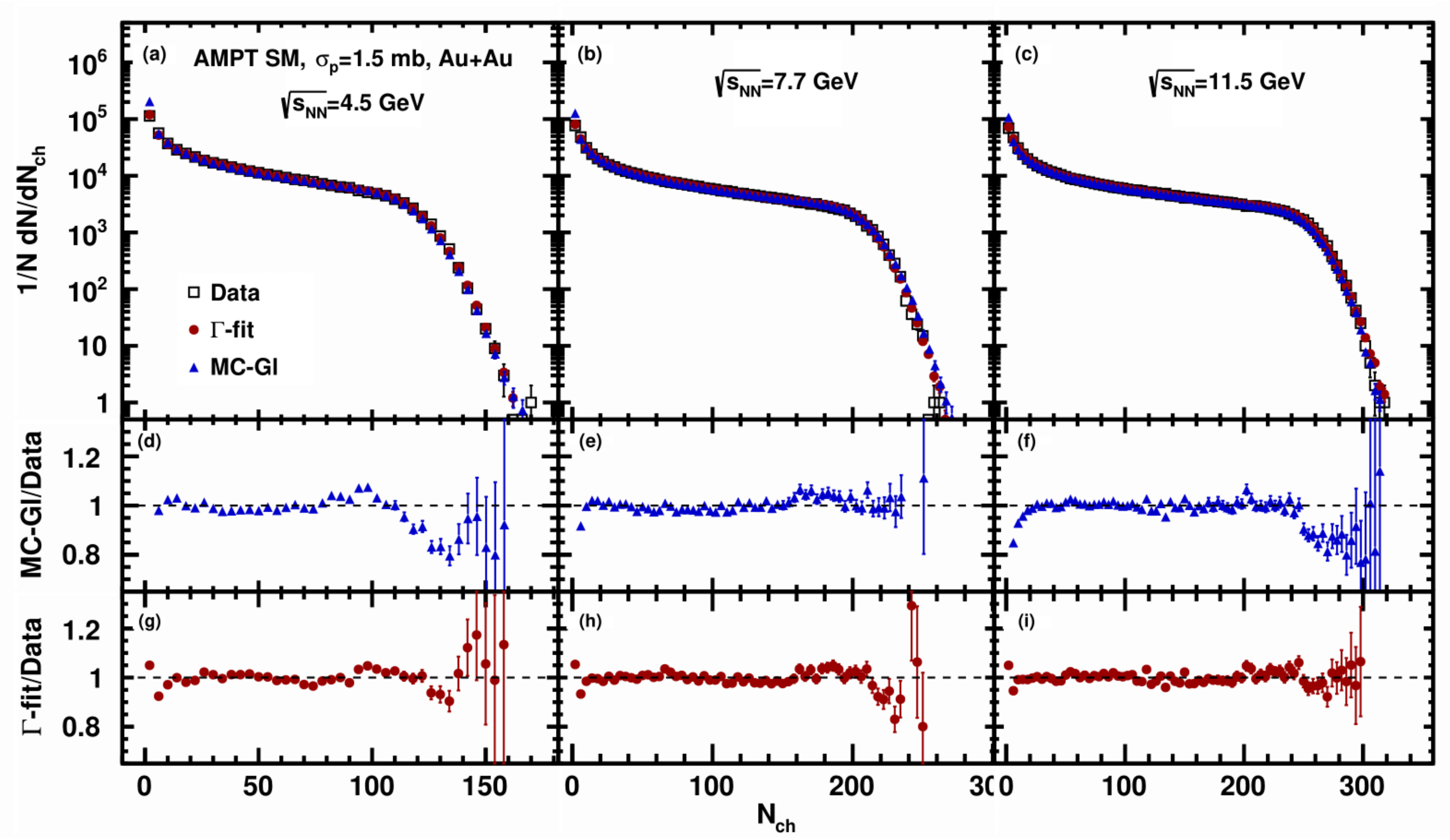
# Backup

# Fit of $N_{ch}$: UrQMD



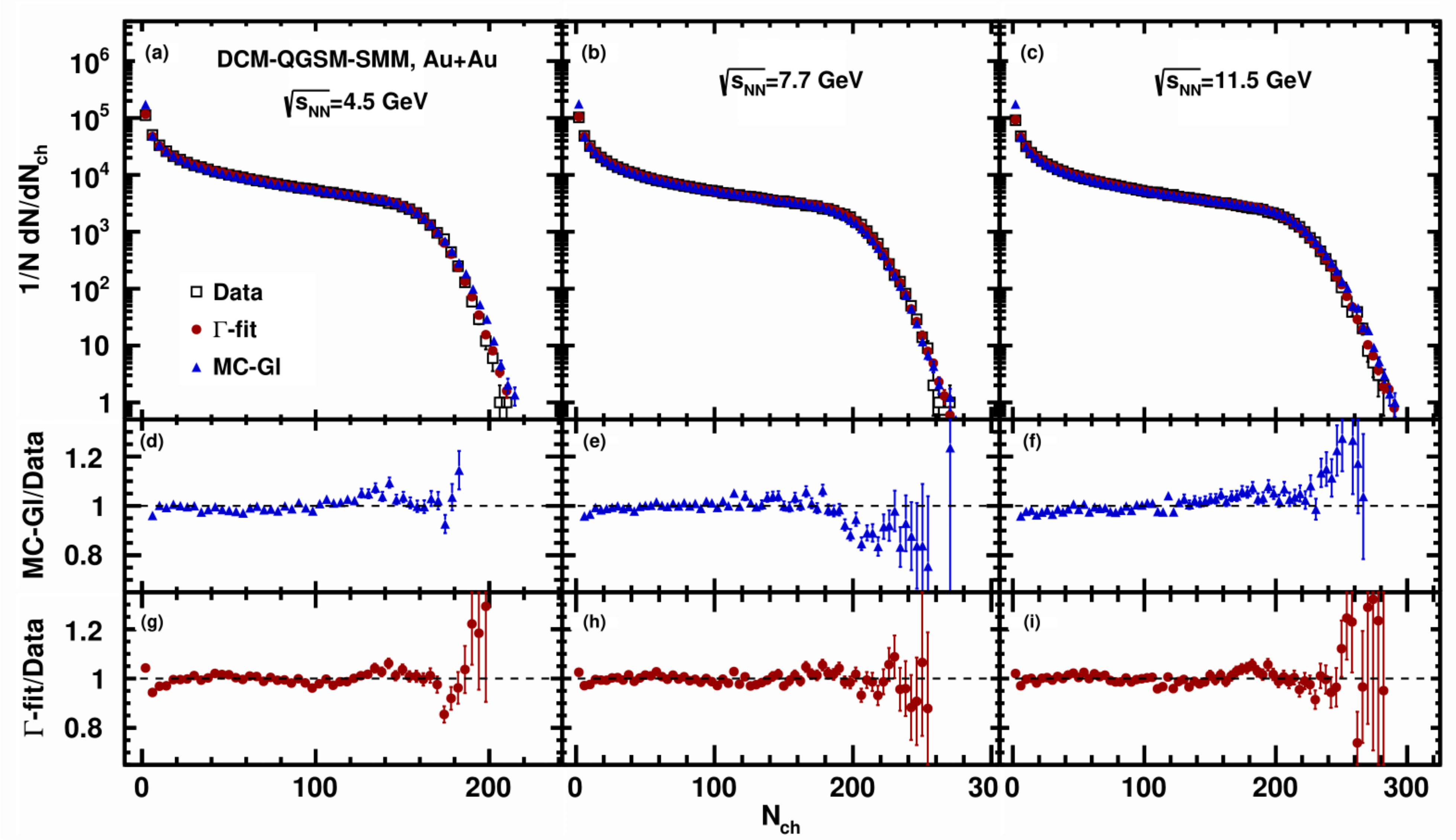

Good fit quality for both methods

# Fit of $N_{ch}$: AMPT SM, $\sigma_p$=1.5 mb



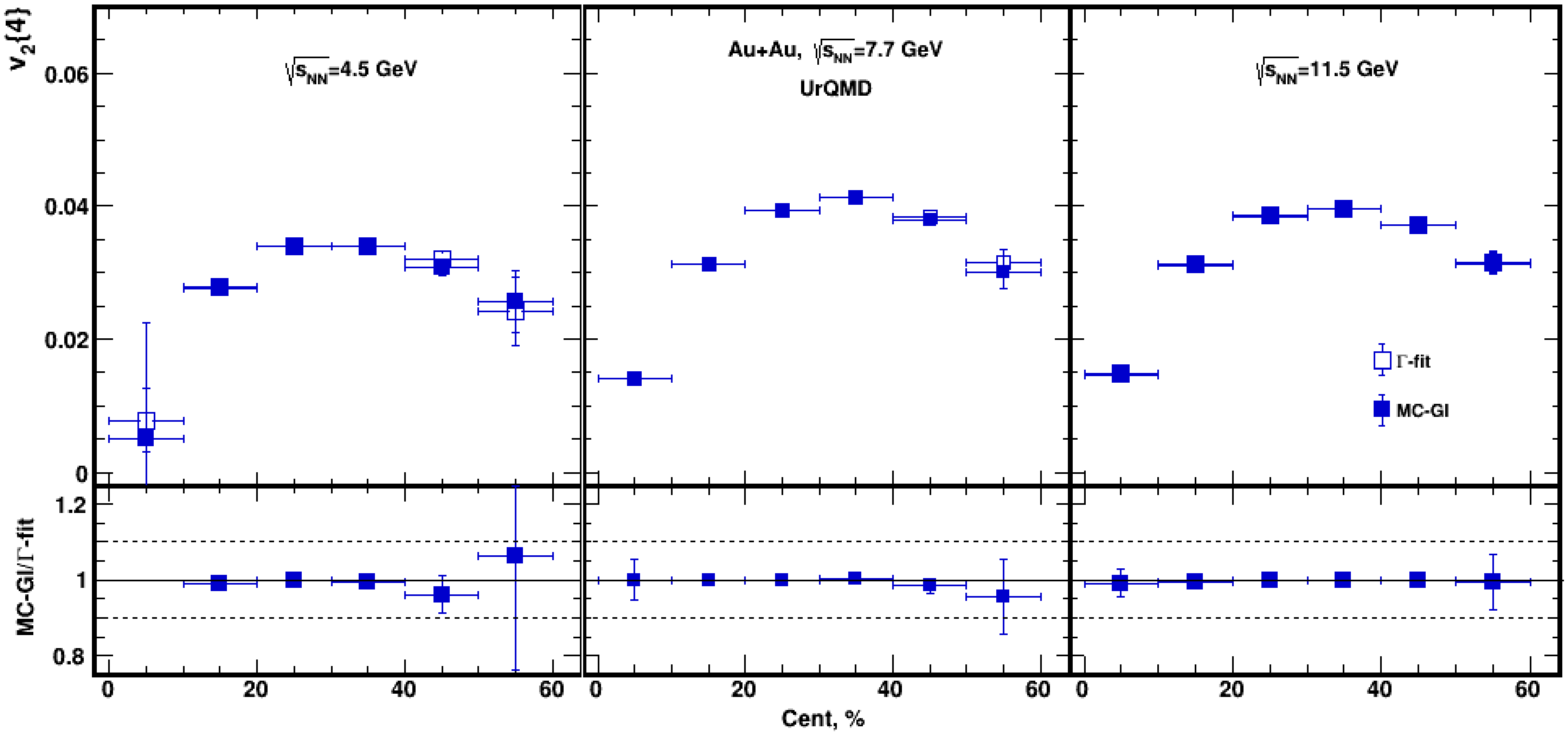

Good fit quality for both methods

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



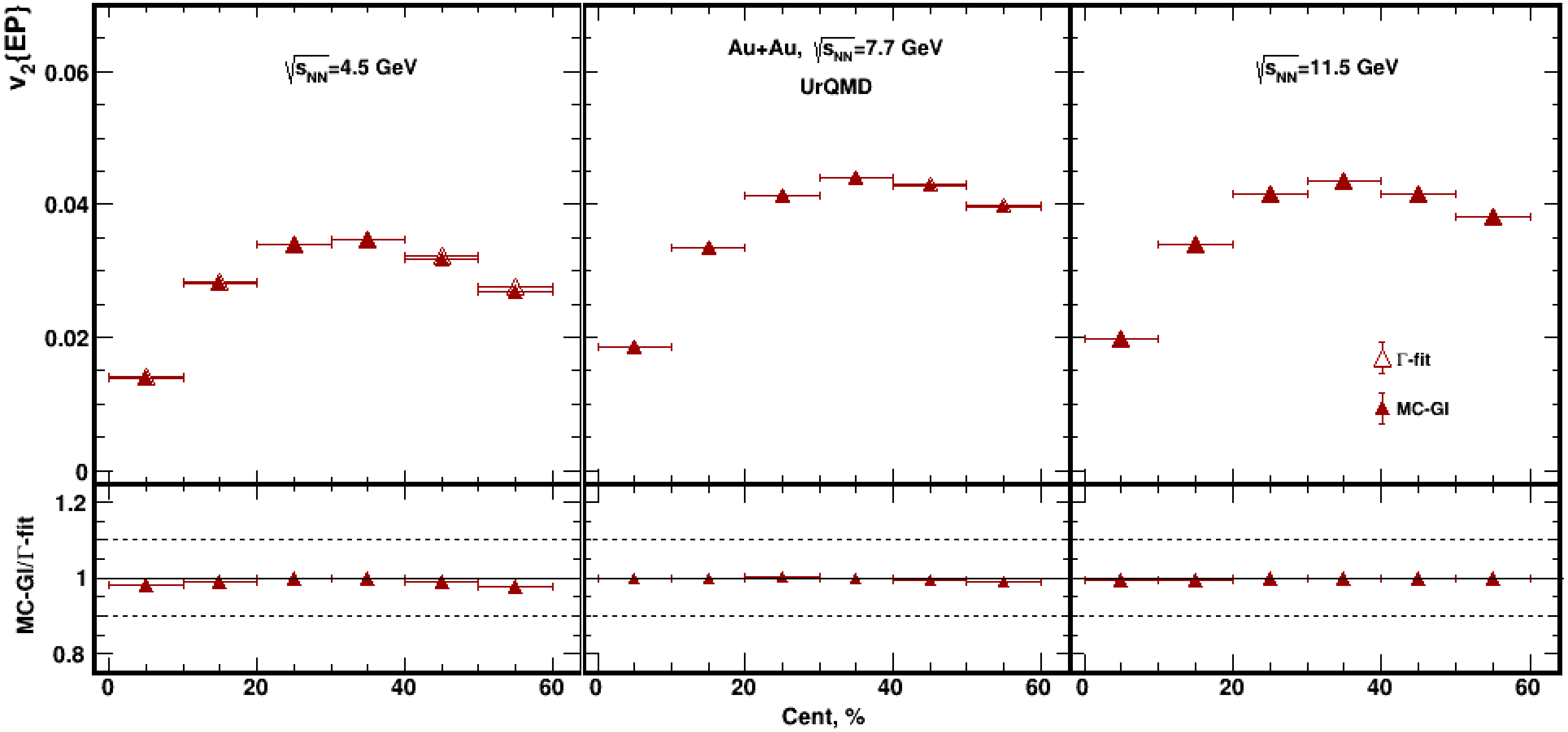

Good fit quality for both methods

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



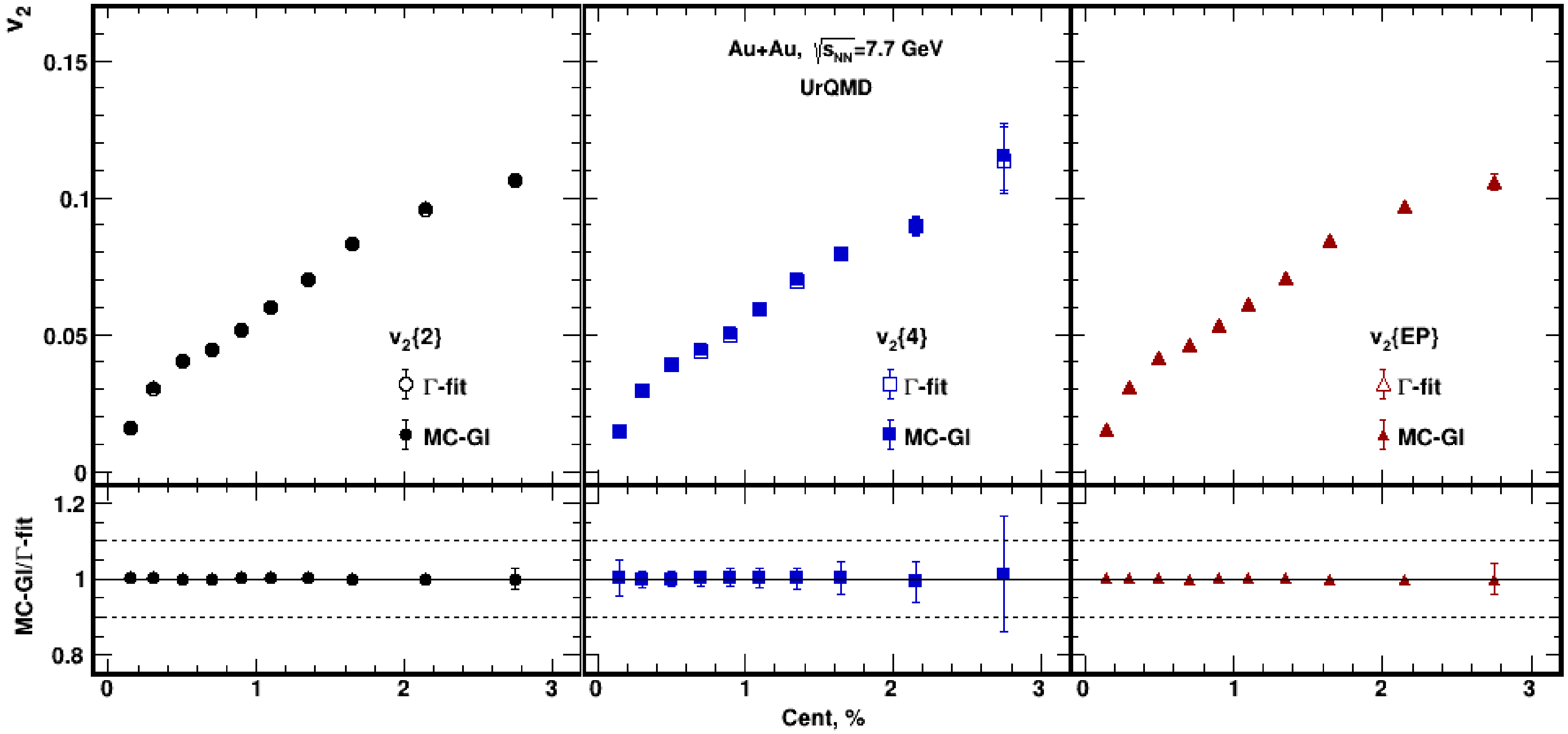

Agreement within 1-4%

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

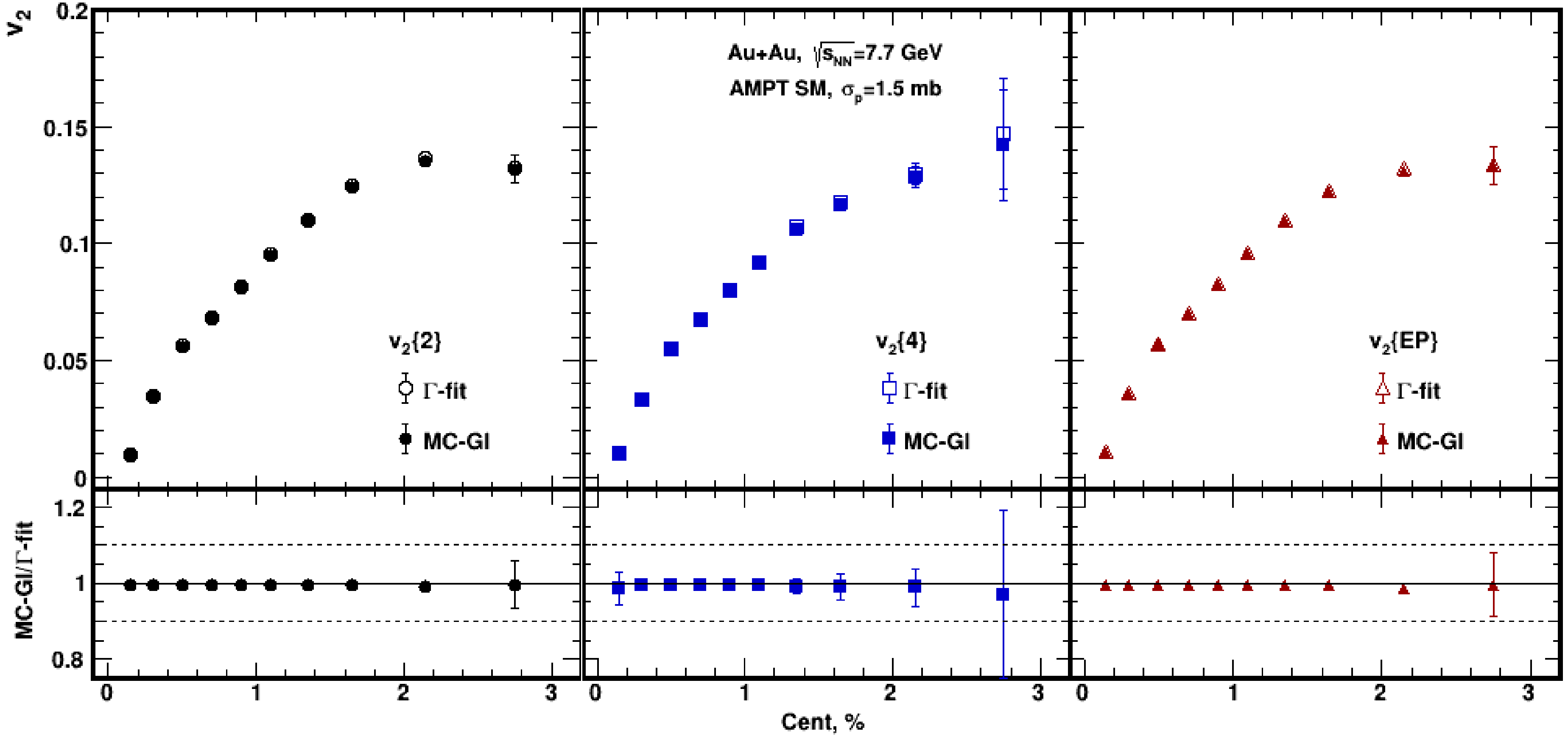



Agreement within 1-4%

# 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