Centrality determination based on charged particle multiplicity

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Outline

- Introduction
- PHOBOS Glauber Monte Carlo (MC-Glauber)
- Methods of centrality determination based on charged particle multiplicity
  - MC-Glauber based (MC-Gl)
  - Bayesian inversion method (Γ-fit)
- Comparison of the centrality determination for different models
- Centrality framework performance in MPD
- Summary

Motivation

Evolution of matter produced in heavy-ion collisions depend on its initial geometry

Centrality procedure maps initial geometry parameters with measurable quantities

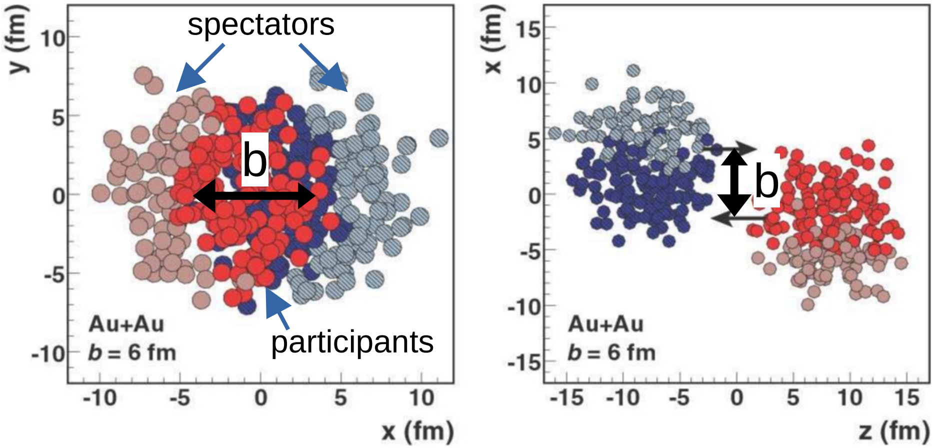
This allows comparison of the future MPD results with the data from other experiments (STAR BES, NA49/NA61 scans) and theoretical models

Collision geometry

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

  Energy of the spectators

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

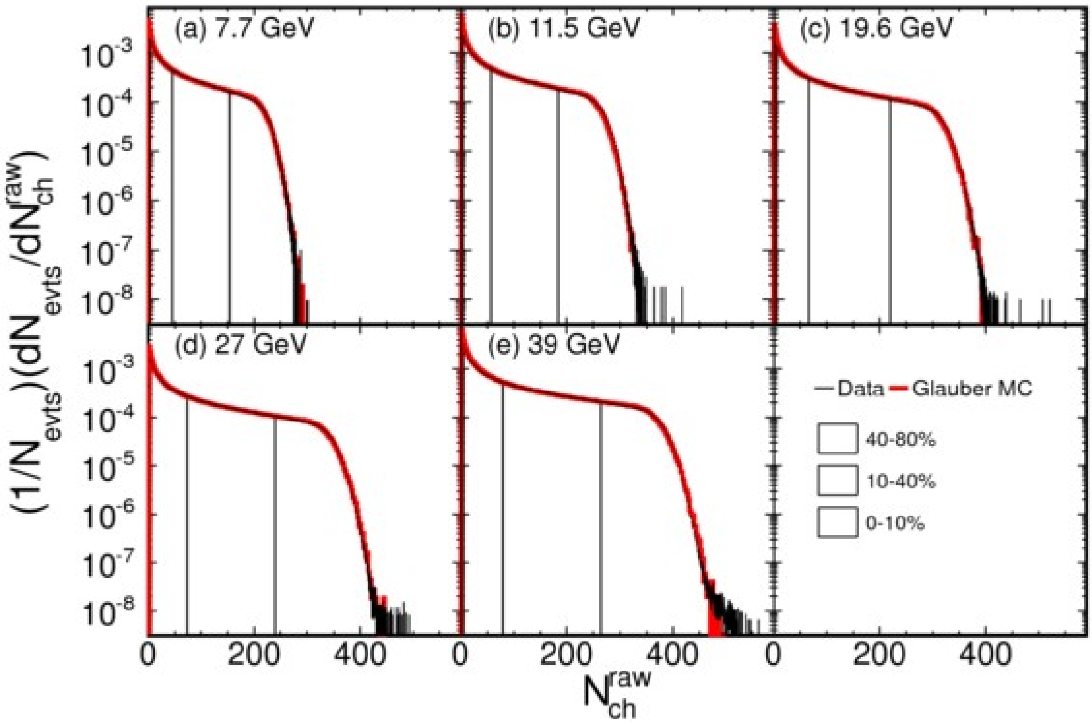


Centrality in STAR experiment

- Uncorrected primary (|DCA| < 2 cm) charged particle multiplicity distribution in TPC (|η|<0.5)
- Comparison with MC Glauber simulations
- Fitted using two-component model:

$$\left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} = n_{pp}\left[(1-x)N_{part}/2 + xN_{coll}\right]$$

Phys. Rev. C 86 (2012) 54908



Different centrality estimators are needed in MPD (NICA) for detailed studies and comparisons with existing experimental results

Centrality frameworks: links

- Glauber-based centrality framework (MC-Gl):
  - Git link: https://github.com/FlowNICA/CentralityFramework
  - Manual: https://github.com/FlowNICA/CentralityFramework/blob/master/Documentation/CentralityFrameworkManual_Glauber.pdf
- The Bayesian inversion method (Γ-fit):
  - Git link: https://github.com/Dim23/GammaFit
  - Manual: https://github.com/Dim23/GammaFit/blob/master/Readme.pdf
- Draft of analysis note: https://github.com/FlowNICA/CentralityFramework/blob/master/Documentation/Centrality_AnalysisNote.pdf

PHOBOS Glauber Monte Carlo (MC-Glauber)

Input for the model

- Nuclear density distribution (Woods-Saxon):

$$\rho(r)=\frac{\rho_0}{1+\exp\left(\frac{r-R}{a}\right)}$$

R – nuclear radius
a – skin-depth

  - Au+Au
    - R = 6.55 fm, a = 0.523 fm
  - Bi+Bi
    - R = 6.75 fm, a = 0.468 fm

- Inelastic NN cross section σ_{NN}
  - σ_{NN}=29.3 mb for $\sqrt{s_{NN}}$=4.5 GeV
  - σ_{NN}=29.7 mb for $\sqrt{s_{NN}}$=7.7 GeV
  - σ_{NN}=30.8 mb for $\sqrt{s_{NN}}$=9.46 GeV
  - σ_{NN}=31.2 mb for $\sqrt{s_{NN}}$=11.5 GeV

Output from the model

- **TNtuple** with model parameters:
  - Impact parameter *b*
  - Number of participating in the collision nucleons N_{part}
  - Number of NN collisions N_{coll}
  - Participant eccentricity ε_n
  - etc.

C. Loizides, J. Nagle and P. Steinberg, SoftwareX 1-2 (2015) 13-18
Used improved version of the PHOBOS Glauber Monte Carlo software.
TGlauberMC-3.2 version from tglaubermc.hepforge.org:
https://tglaubermc.hepforge.org/downloads/

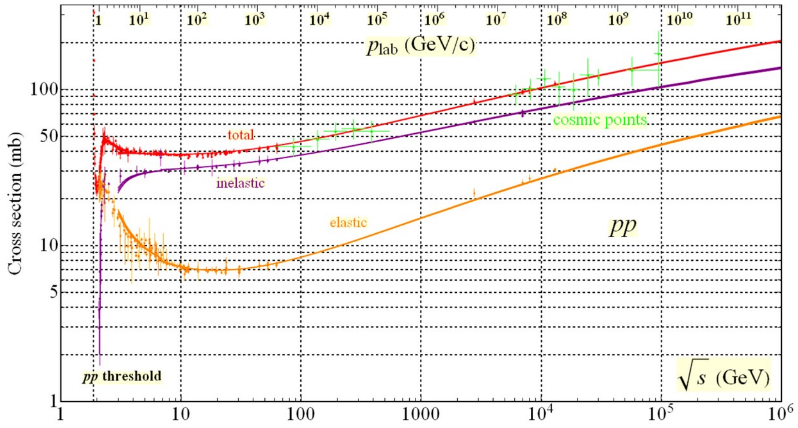
MC-Glauber configuration

Used TGlauberMC-3.2 version from tglaubermc.hepforge.org:
https://tglaubermc.hepforge.org/downloads/
One should manually set parametrization for ^{197}Au and ^{209}Bi in **runlauber_v3.2.C** (under the line number 1172):

```
else if (TString(name) == "Au3")
    {fN = 197; fR = 6.5541; fA = 0.523; fW = 0; fF = 1; fZ=79;}
else if (TString(name) == "Bi")
    {fN = 209; fR = 6.75; fA = 0.468; fW = 0; fF = 1; fZ=83;}
```

And set up inelastic NN cross section σ_{NN} – one can find it as the difference between the total and elastic cross sections for p+p collisions found here:
https://pdg.lbl.gov/2020/hadronic-xsections/hadron.html

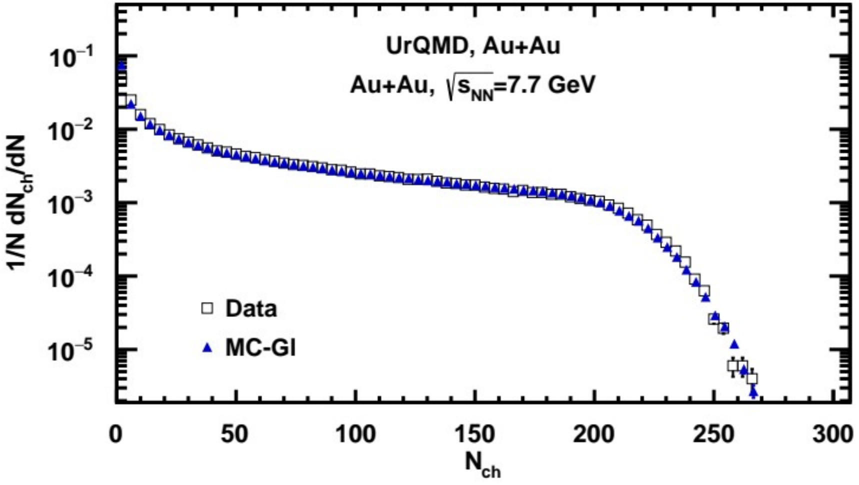
- σ_{NN}=29.3 mb for $\sqrt{s_{NN}}$=4.5 GeV
- σ_{NN}=29.7 mb for $\sqrt{s_{NN}}$=7.7 GeV
- σ_{NN}=30.8 mb for $\sqrt{s_{NN}}$=9.46 GeV
- σ_{NN}=31.2 mb for $\sqrt{s_{NN}}$=11.5 GeV



MC-Glauber based centrality framework

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

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

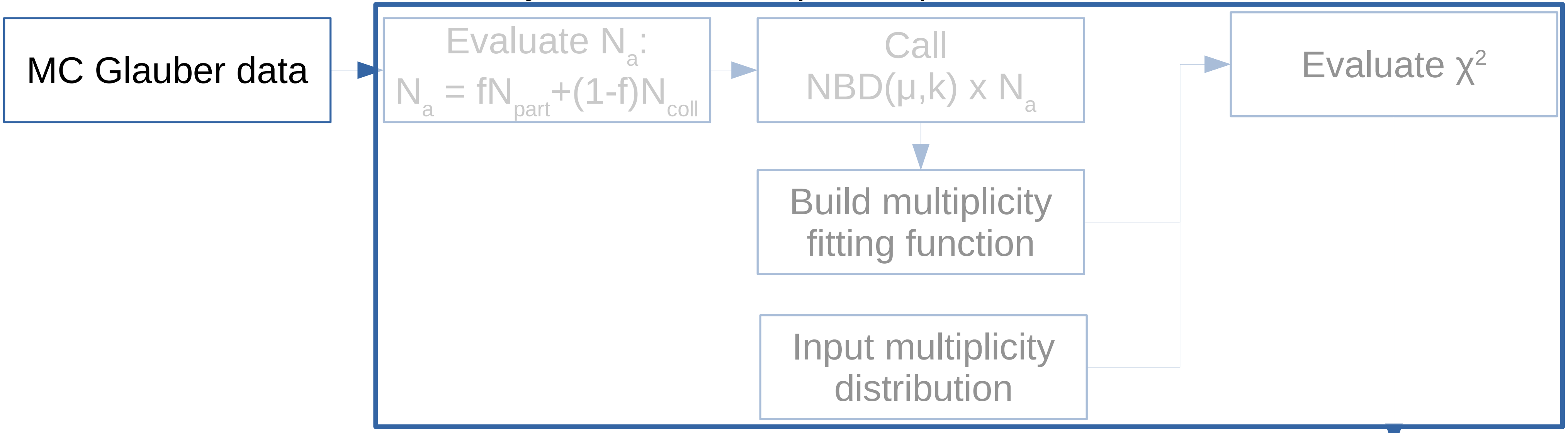
This centrality procedure was used in CBM, NA49, and NA61/SHINE:

- 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

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

Centrality framework software layout

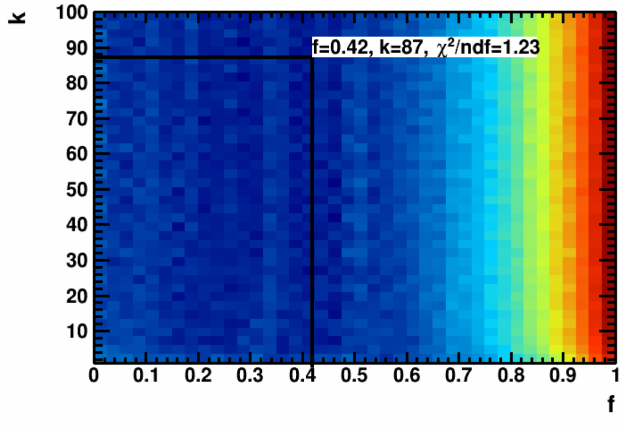
Main bash script (works via SGE on NICA cluster):
CentralityFramework/scripts/template/start.sh



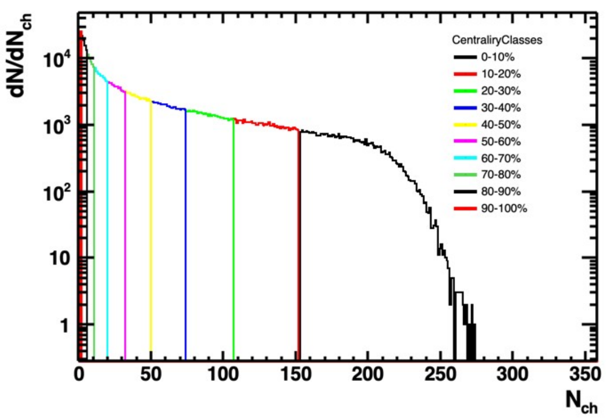
start.sh is an example of the executable script for the fit procedure.
It has 2 input file – see manual:

- **config.txt.template -** contains parameters for the framework
- **parameter.list** – contains a set of parameters for the fit procedure

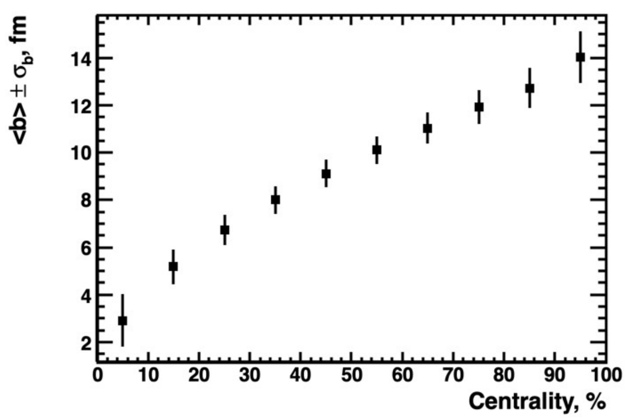
Final steps of the centrality determination analysis



Step 1
Find optimal fit:
Chi2.C



Step 2
Define centrality classes
HistoCut.C



Step 3
Map b,N_{part},N_{coll} with centrality
CentralityClasses.C

How to implement results in MDPROOT:

Resulting output file from CentralityClasses.C macro is called FINAL.root.
One can generate simple C++ function GetCentMult(Int_t mult):
CentralityFramework/Framework/printFinal.C

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

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

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

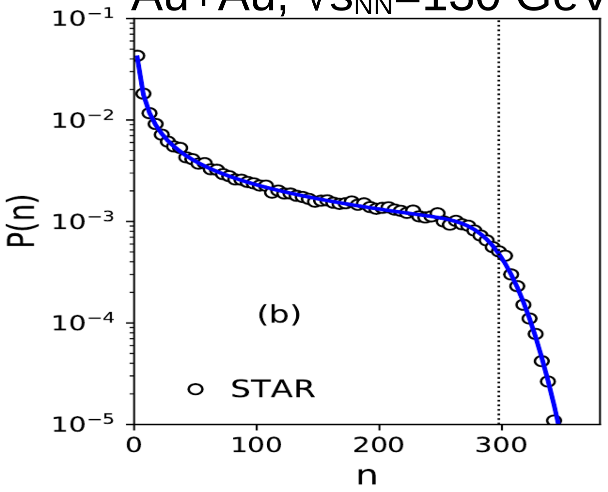
c_b – impact parameter based centrality

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

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

Implementation for STAR data:
Phys. Rev. C 97, 014905 (2018)

Au+Au, $\sqrt{s_{NN}}$=130 GeV



R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902
Implementation in MPD: https://github.com/Dim23/GammaFit

Γ-fit: parametrizations for the fit function

- Charged particle multiplicity distribution:

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

$$P(N_{ch}|c_b) = f\left(k(c_b), \theta(c_b), \sigma_{inel}\right)$$

σ_{inel} was used for 2 systems:

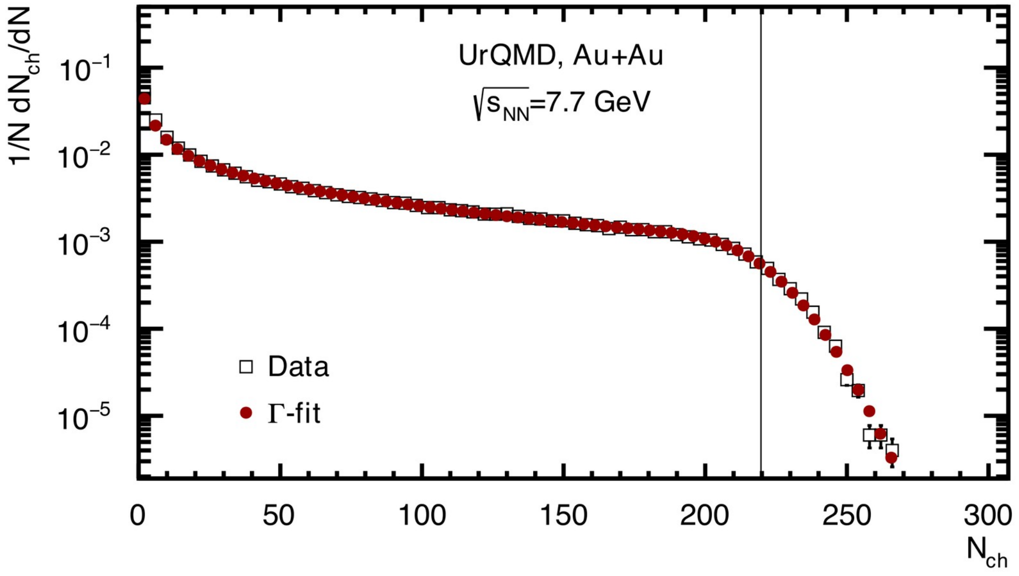
- Au+Au: σ_{inel} = 677 (±2%) fm^2
- Bi+Bi: σ_{inel} = 686 fm^2

Parameters for gamma-function approach:

$$k(c_b) = k_{max} \cdot \exp\left(-\sum_{i=1}^{3} a_i c_b^i\right), \quad \theta = const$$

$$\left(k(c_b)\,\theta \equiv \overline{N_{ch}}(c_b), \quad \sqrt{k(0)}\,\theta \equiv \sigma(0)\right)$$

Free parameters: k_{max}, θ, a_i.

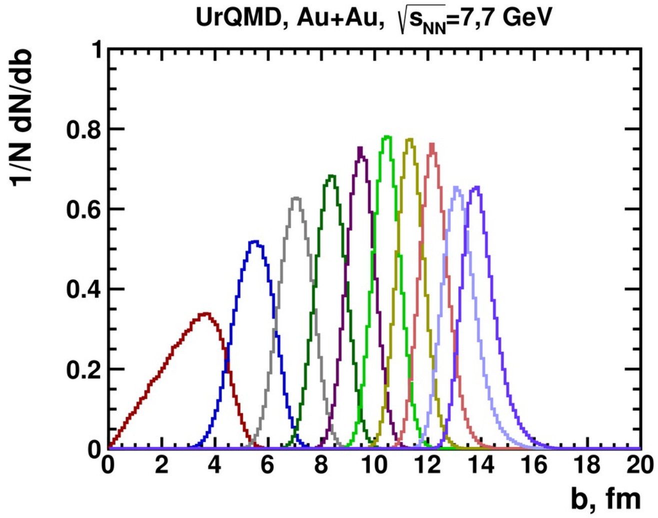


Reconstruction of *b*

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

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

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



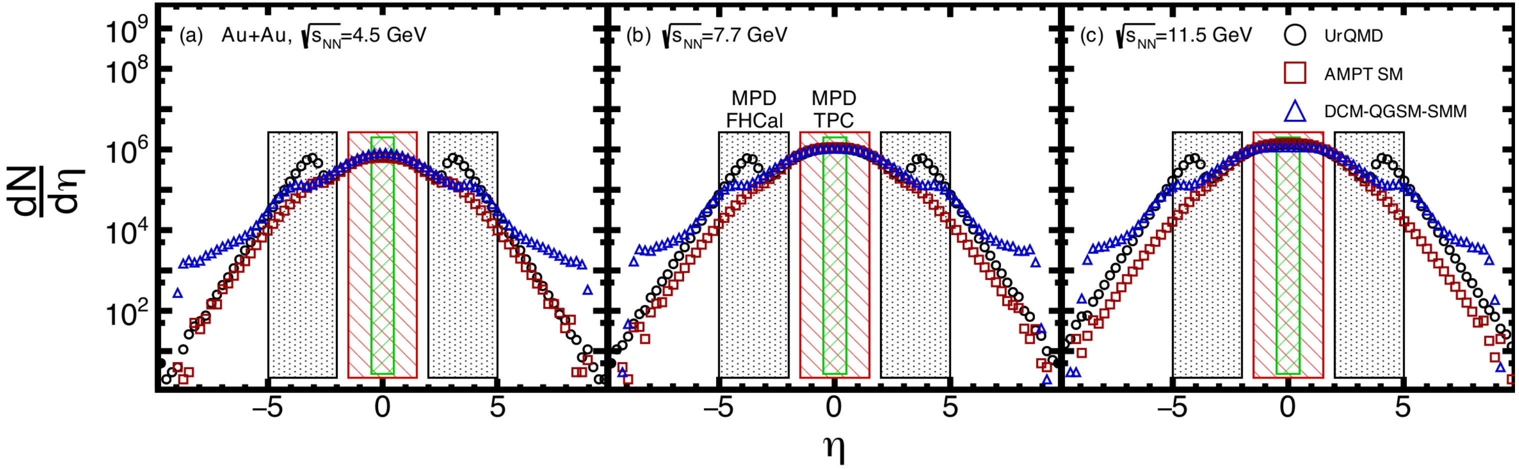
The Bayesian inversion method consists of 2 steps:

- Fit normalized multiplicity distribution with $P(N_{ch})$
- Construct $P(b|N_{ch})$ using Bayes' theorem with parameters from the fit

How to implement results in MDPROOT:
The whole procedure was done in GammaFit/GammaFit.C
One can generate simple C++ function GetCentMult(Int_t mult) from the output file GammaFit/printFinal.C

Comparison of the centrality determination for different models

Charged particle multiplicity at NICA energies



Models for event simulation:

- UrQMD ver. 3.4 in cascade mode
- AMPT ver. 1.26 with string melting mode ver. 2.26, σ_{part}=1.5 mb
- DCM-QGSM-SMM

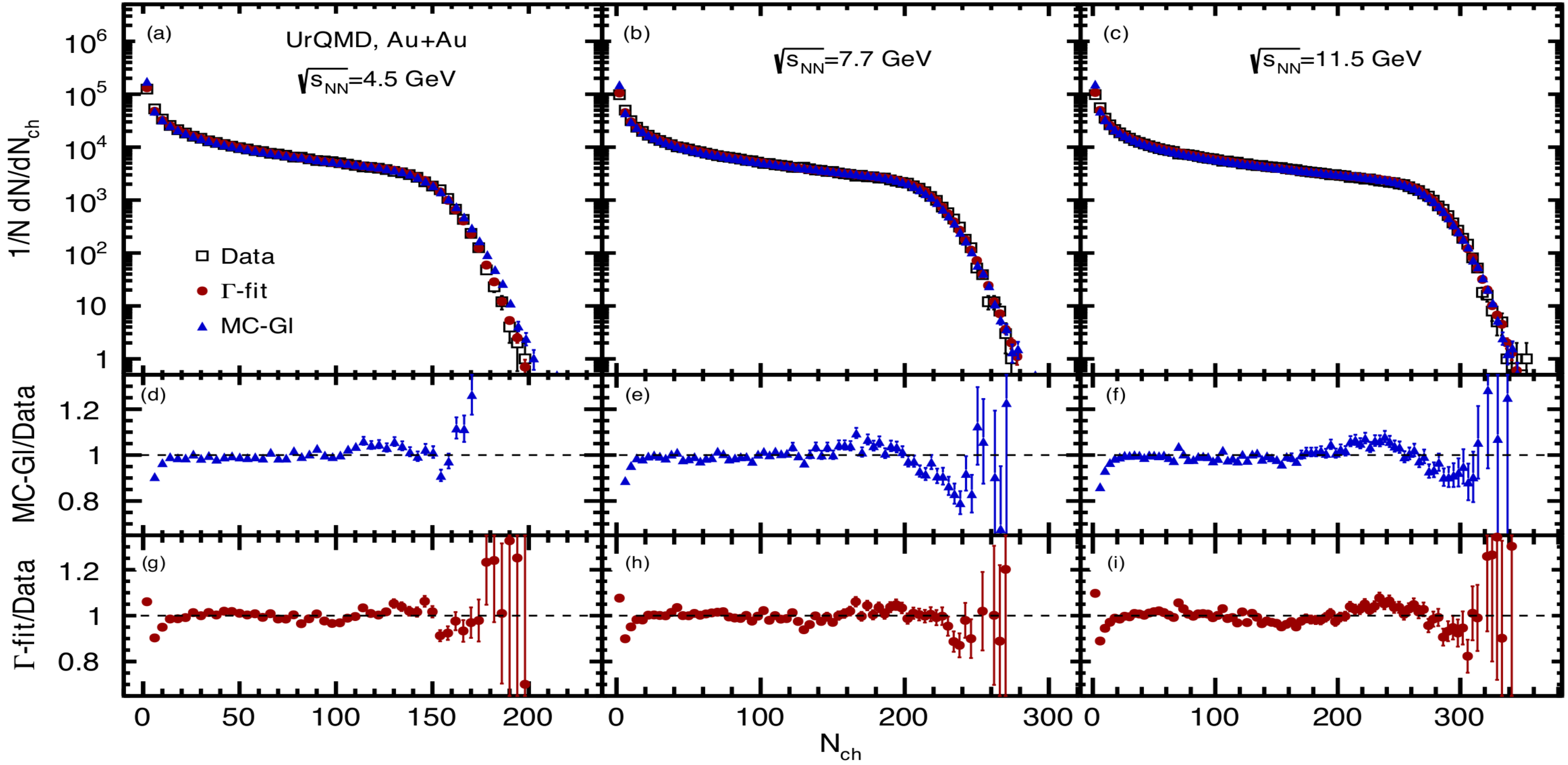
Simulated data sets:

- Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=4.5, 7.7, 11.5 GeV

Hadron selection:

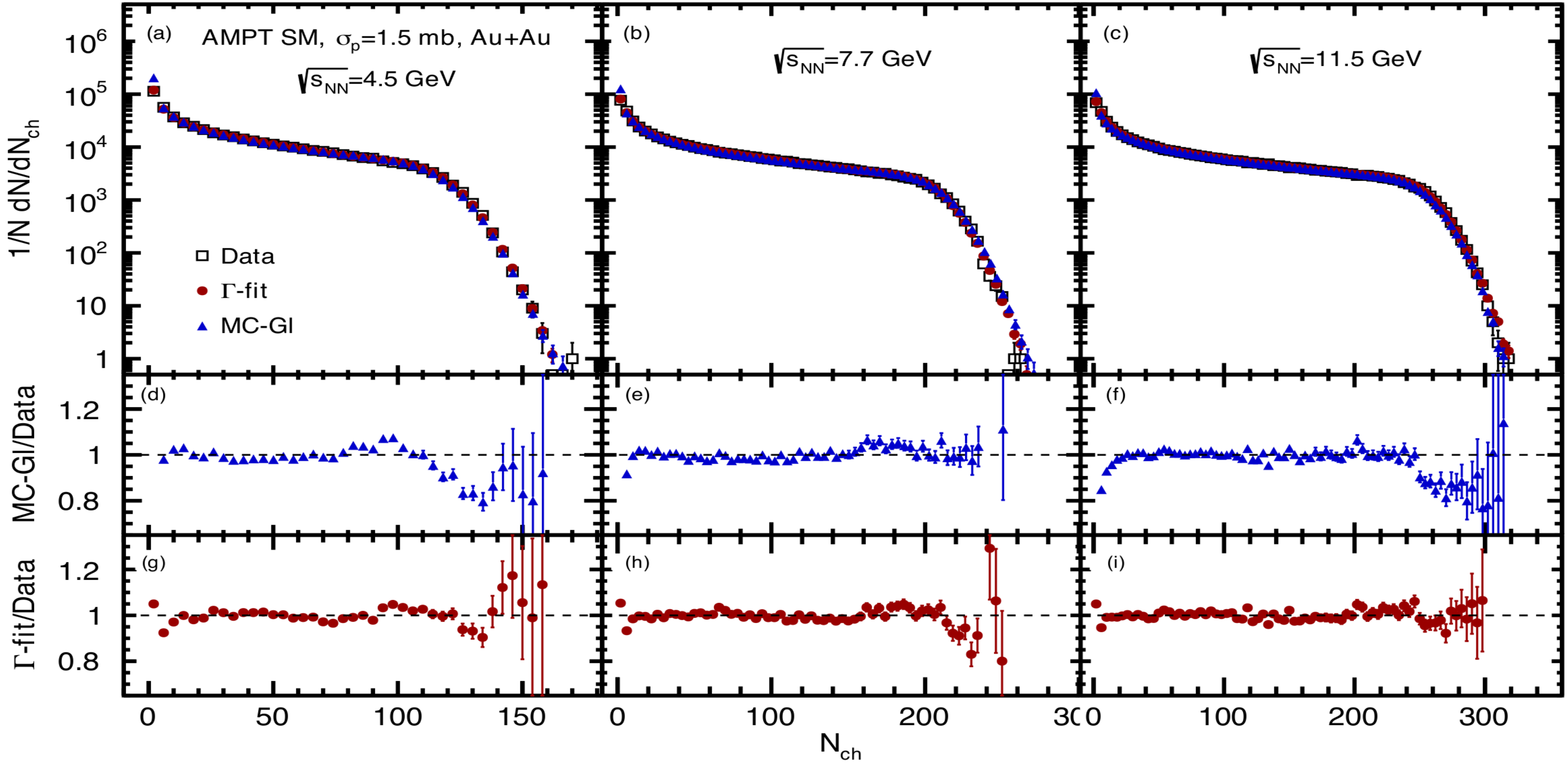
- $|\eta|<0.5$
- Charged particles only
- p_T>0.15 GeV/c

Fit of N_{ch}: UrQMD



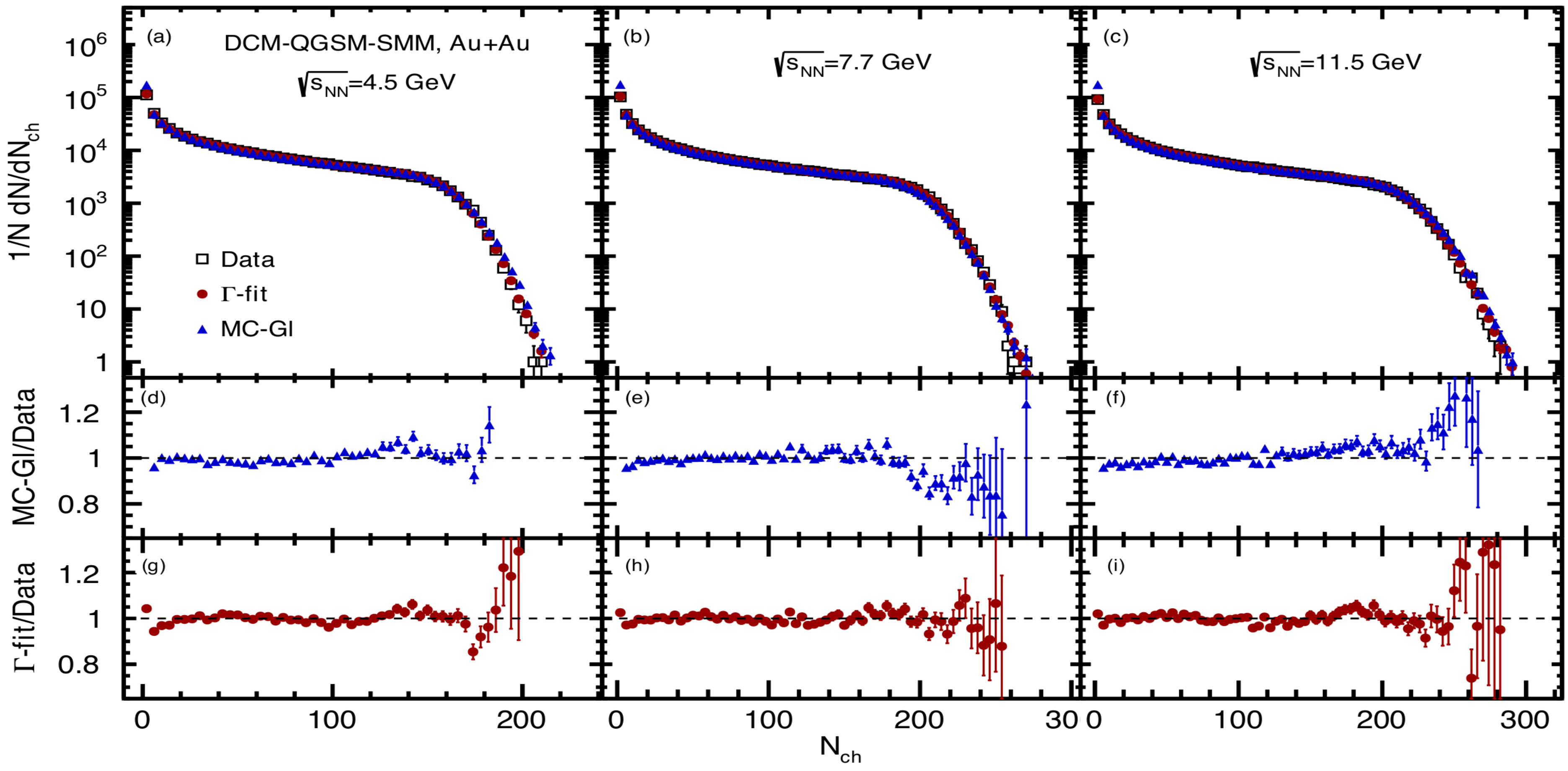
Good fit quality for both methods

Fit of N_{ch}: AMPT SM, σ_p=1.5 mb



Good fit quality for both methods

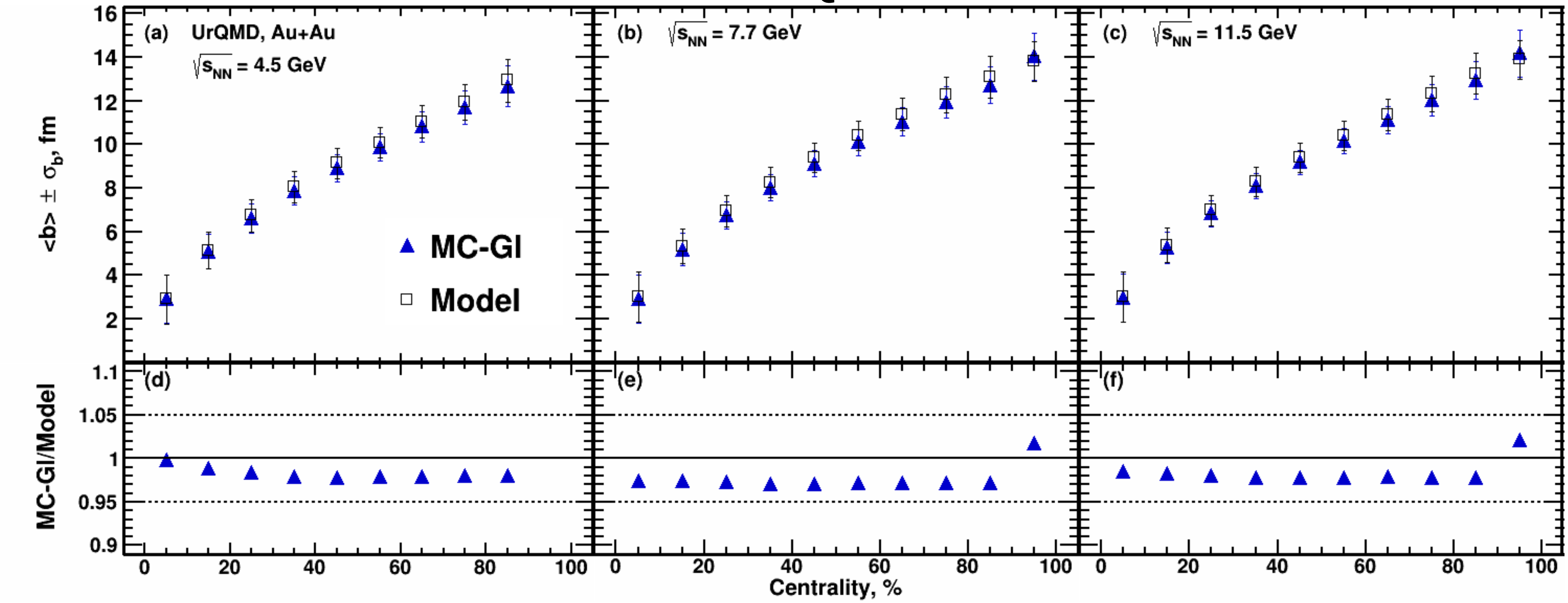
Fit of N_{ch}: DCM-QGSM-SMM



Good fit quality for both methods

<b> vs Centrality: MC-Glauber

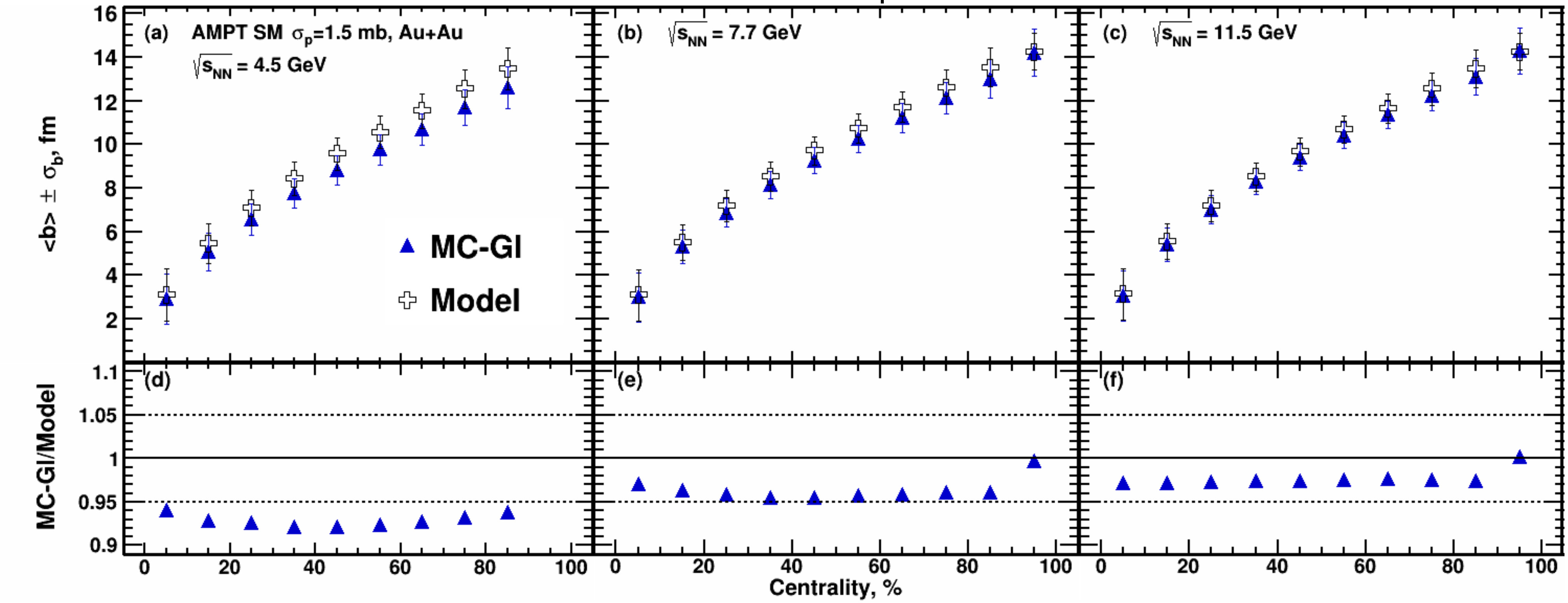
UrQMD



Agreement within 1-4%

<b> vs Centrality: MC-Glauber

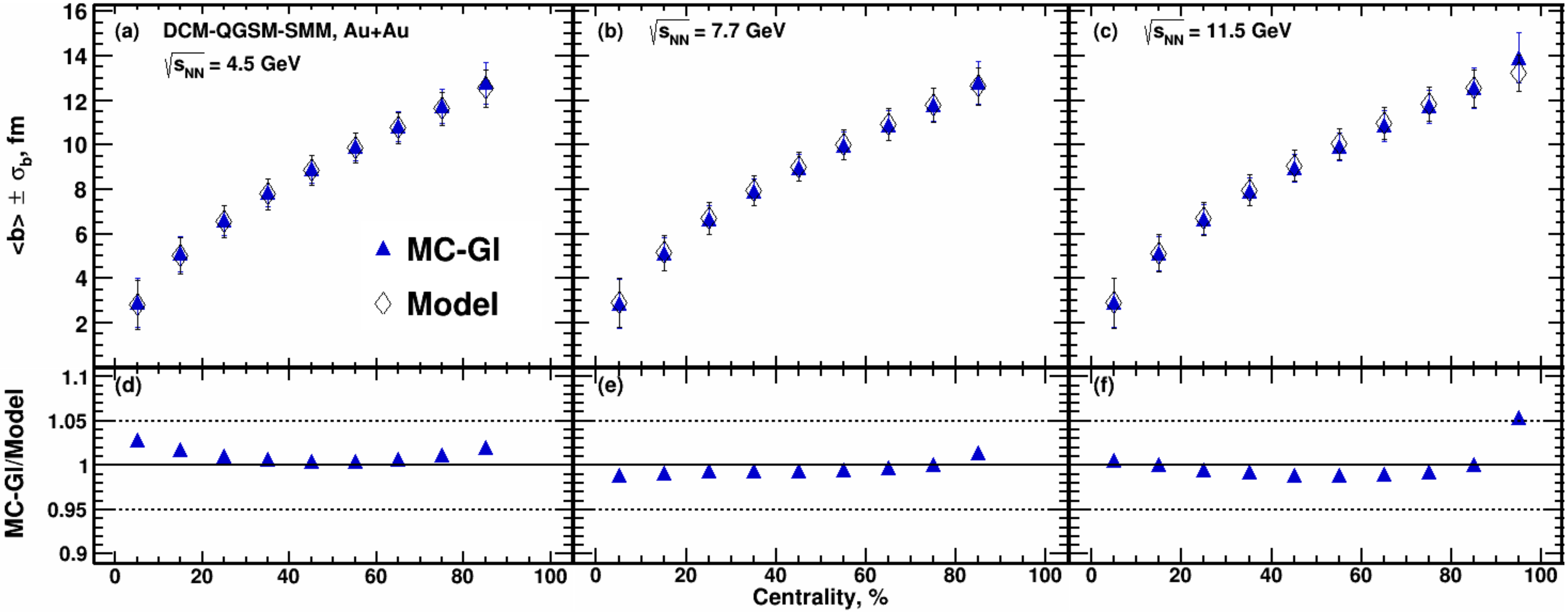
AMPT SM, σ_p=1.5 mb



Agreement within 1-10%

<b> vs Centrality: MC-Glauber

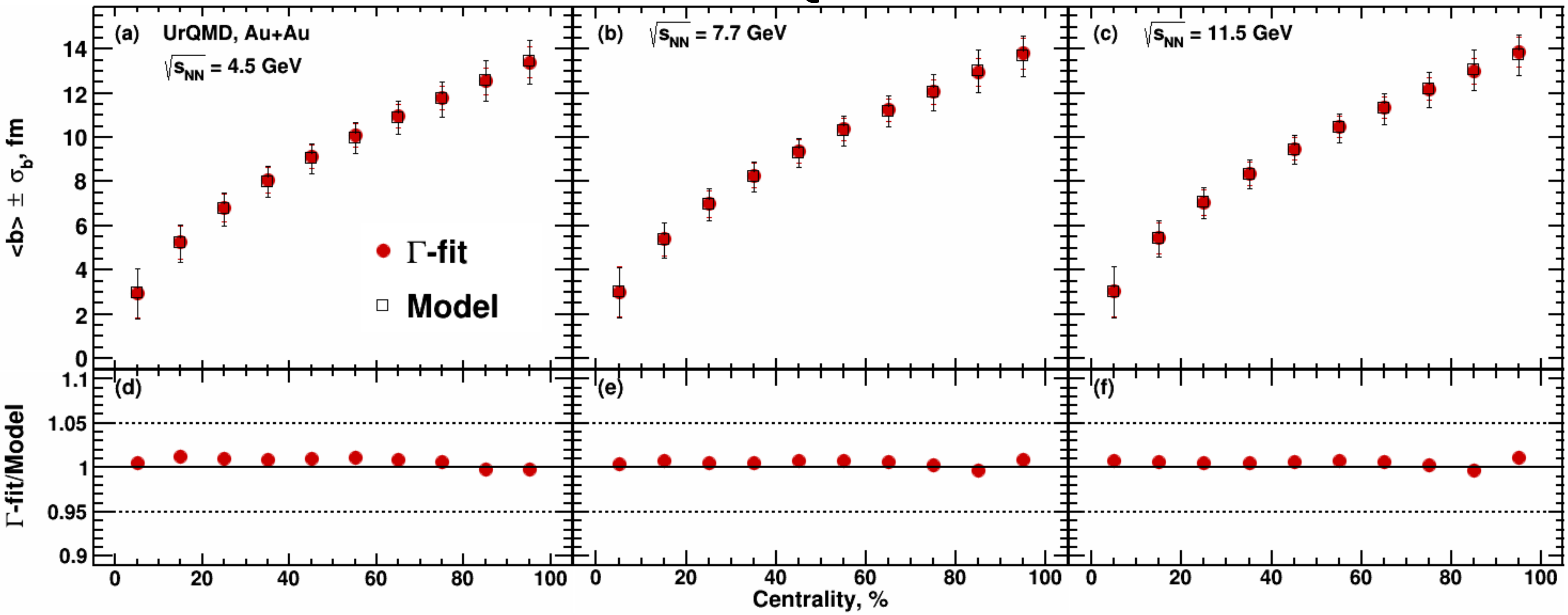
DCM-QGSM-SMM



Agreement within 1-4%

<b> vs Centrality: Γ-fit

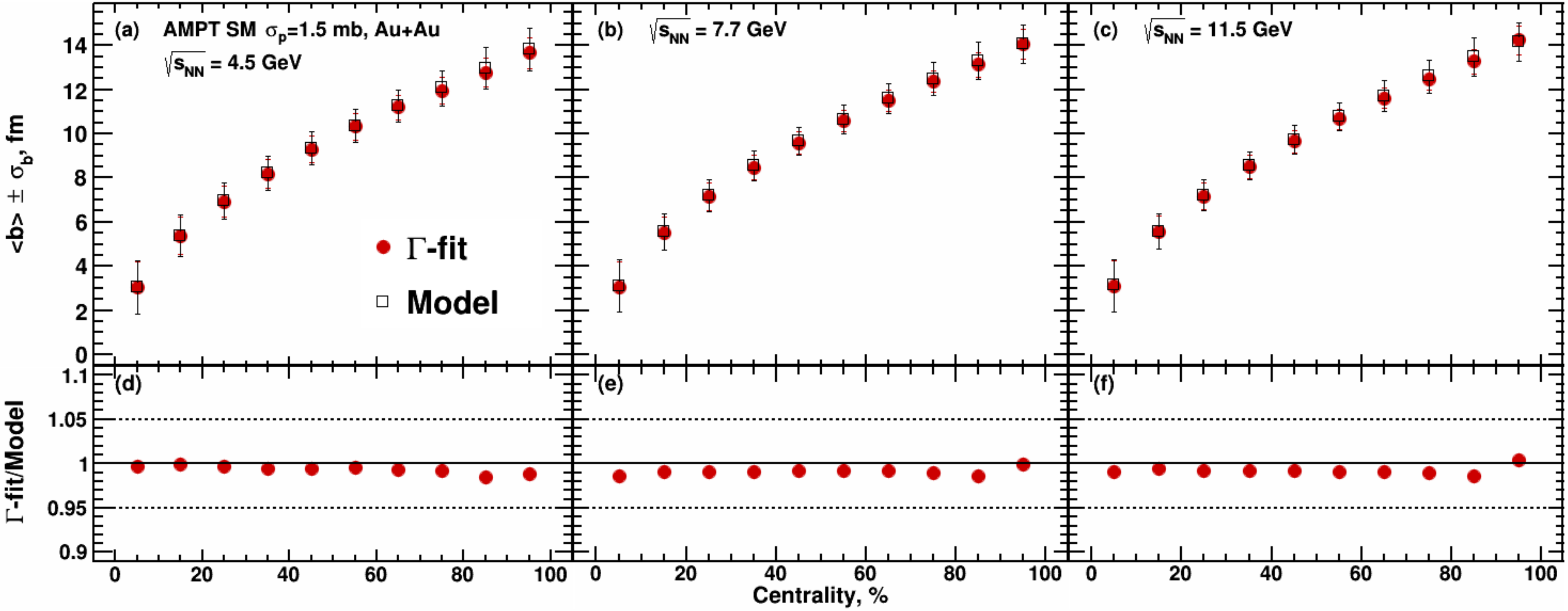
UrQMD



Agreement within 1-3%

<b> vs Centrality: Γ-fit

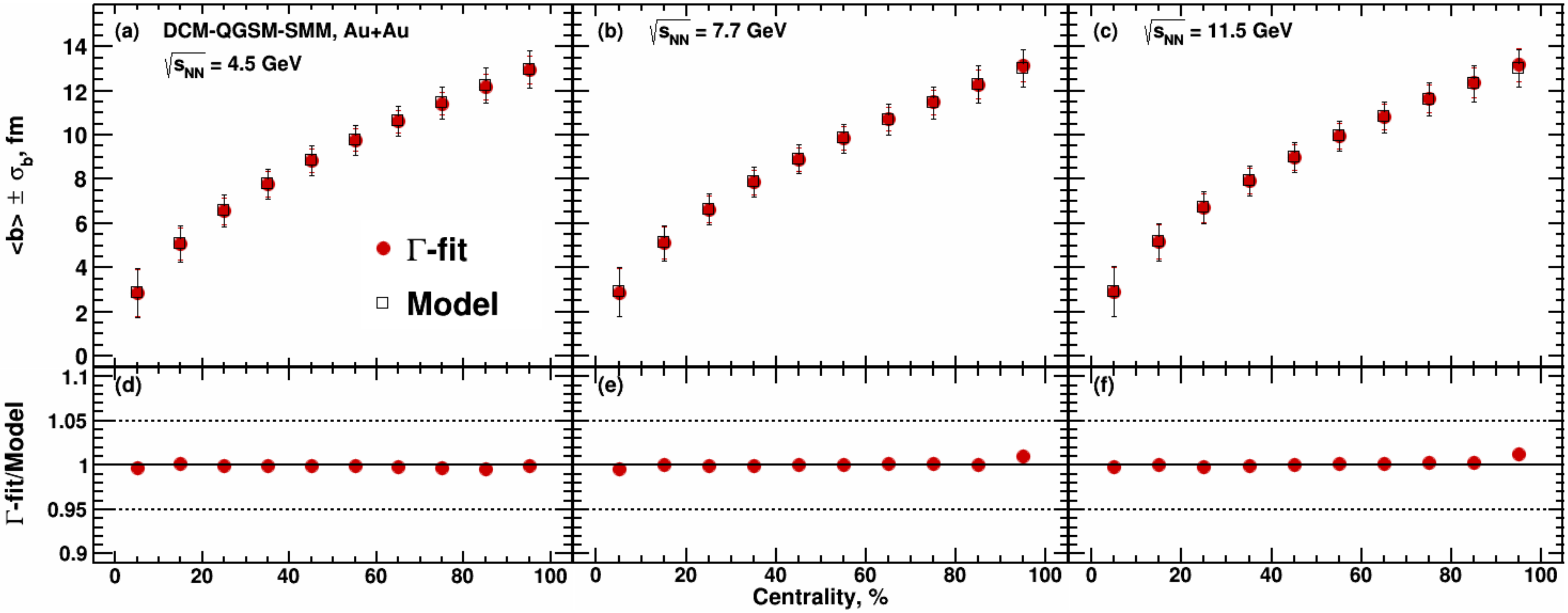
AMPT SM, σ_p=1.5 mb



Agreement within 1-2%

<b> vs Centrality: Γ-fit

DCM-QGSM-SMM



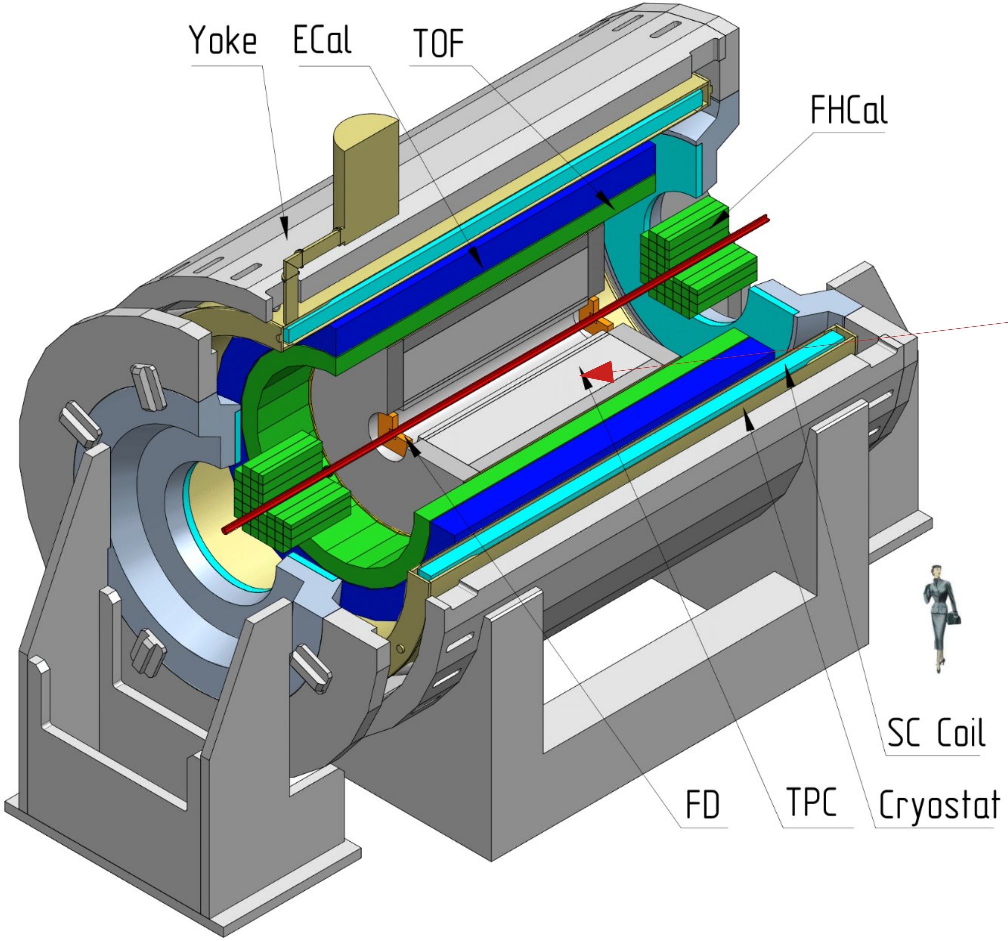
Agreement within 1-2%

Model comparison: Conclusion

- Γ-fit method:
  - Shows better agreement for centrality dependence of <b>
  - But: requires information about total multiplicity integral
- MC-Glauber method:
  - Shows worse agreement for <b>
  - But: automatically approximates multiplicity dependence in the peripheral region

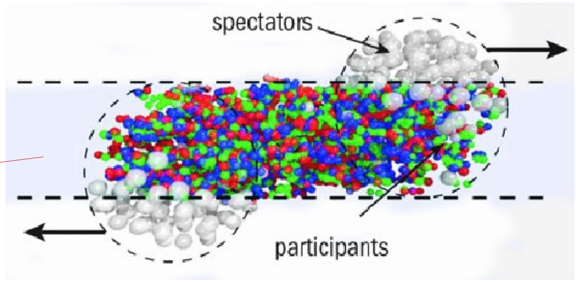
Centrality framework performance in MPD

Centrality determination performance in MPD



- Multiplicity of produced charged particles in Time Projection Chamber (TPC)

  $|\eta|<1.5$

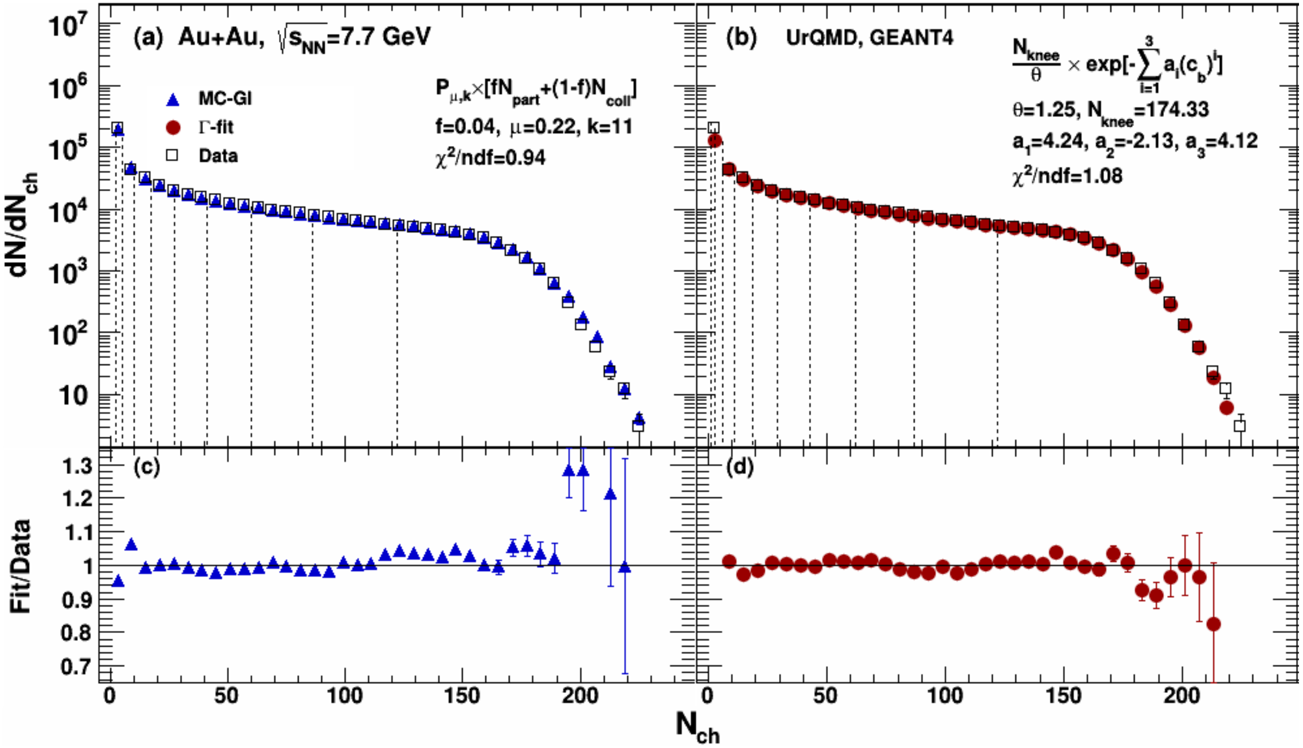


Official productions were used:

- Request 9, PWG3, UrQMD, GEANT4
  - Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=7.7 GeV
- Request 5, PWG4, UrQMD, GEANT4
  - Bi+Bi, N_{ev}=500k, $\sqrt{s_{NN}}$=9.46 GeV
- Request 7, PWG4, PHQMD, GEANT3
  - Bi+Bi, N_{ev}=500k, $\sqrt{s_{NN}}$=9 GeV

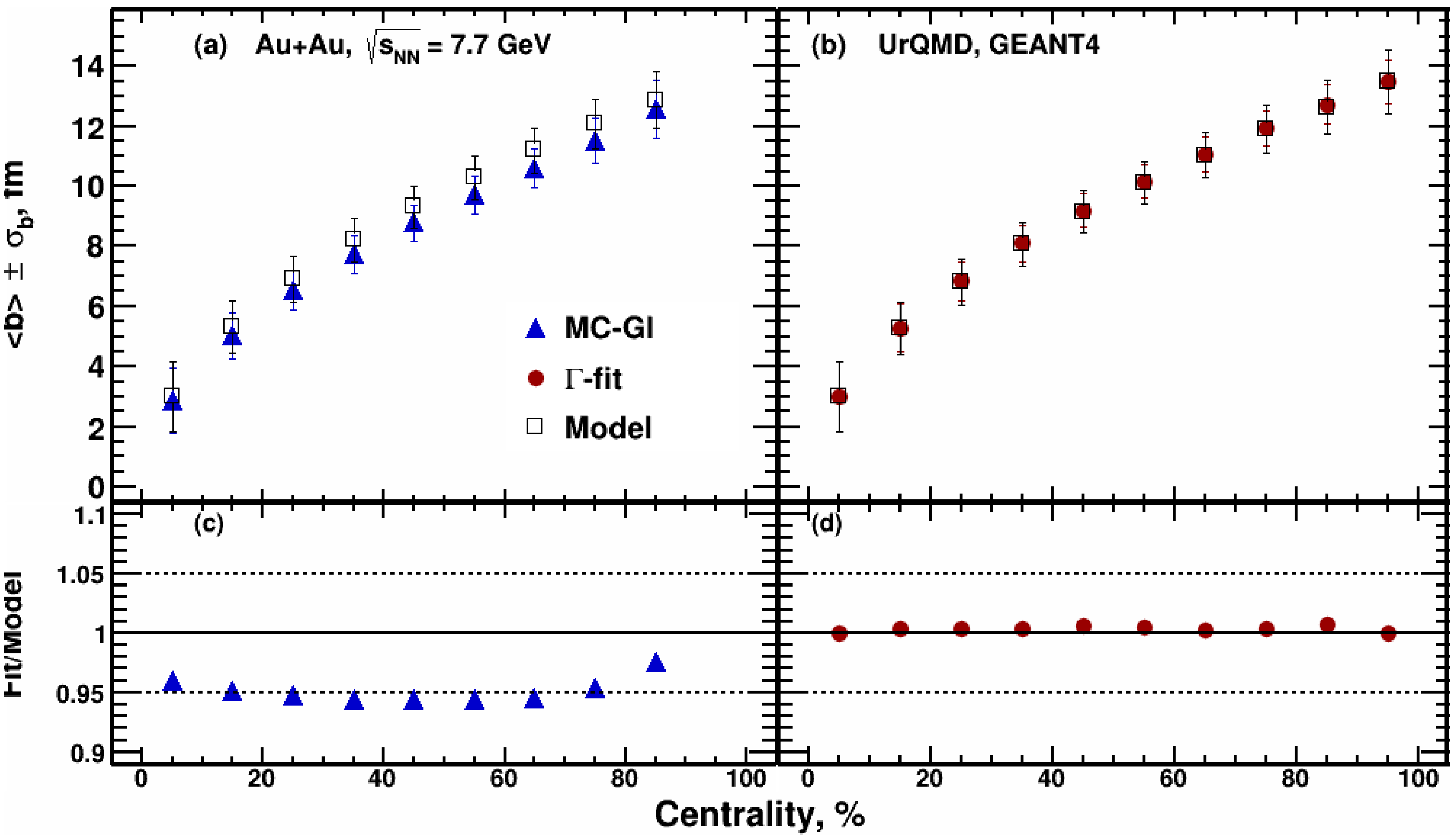
Requested data set I

- PWG3 production (request 9):
  - UrQMD, GEANT4, Au+Au, $\sqrt{s_{NN}}$= 7.7 GeV
  - N_{ev}=500k
- Hadron selection:
  - $|\eta|<0.5$
  - p_T>0.15 GeV/c
  - N_{hits} > 16
  - Primary track selection (|DCA| < 0.5 cm)

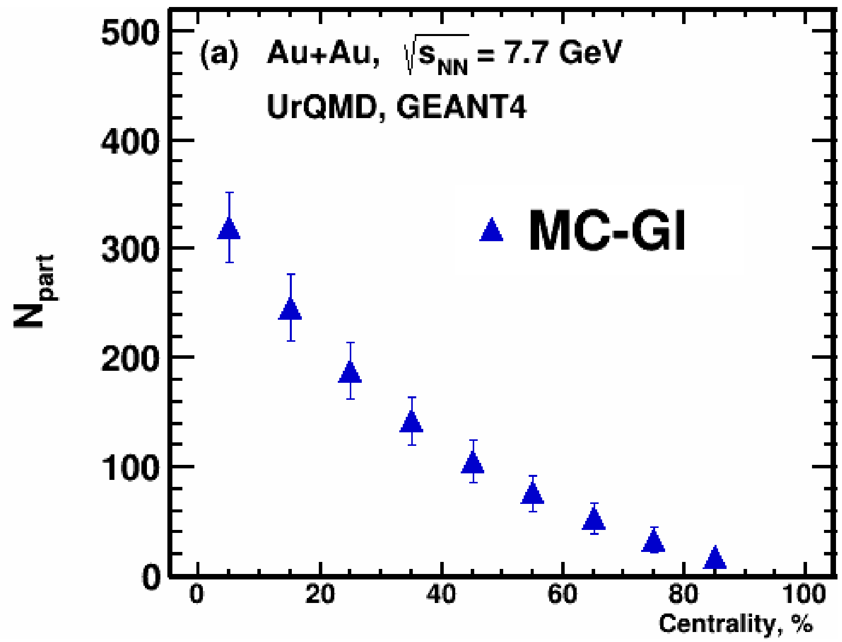


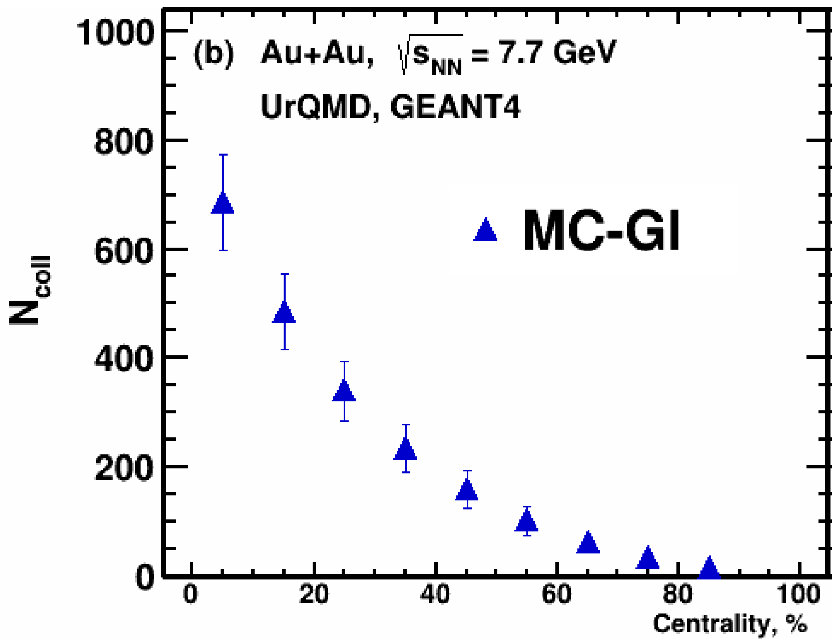
Good fit quality for both methods

<b> vs Centrality: MC-Glauber

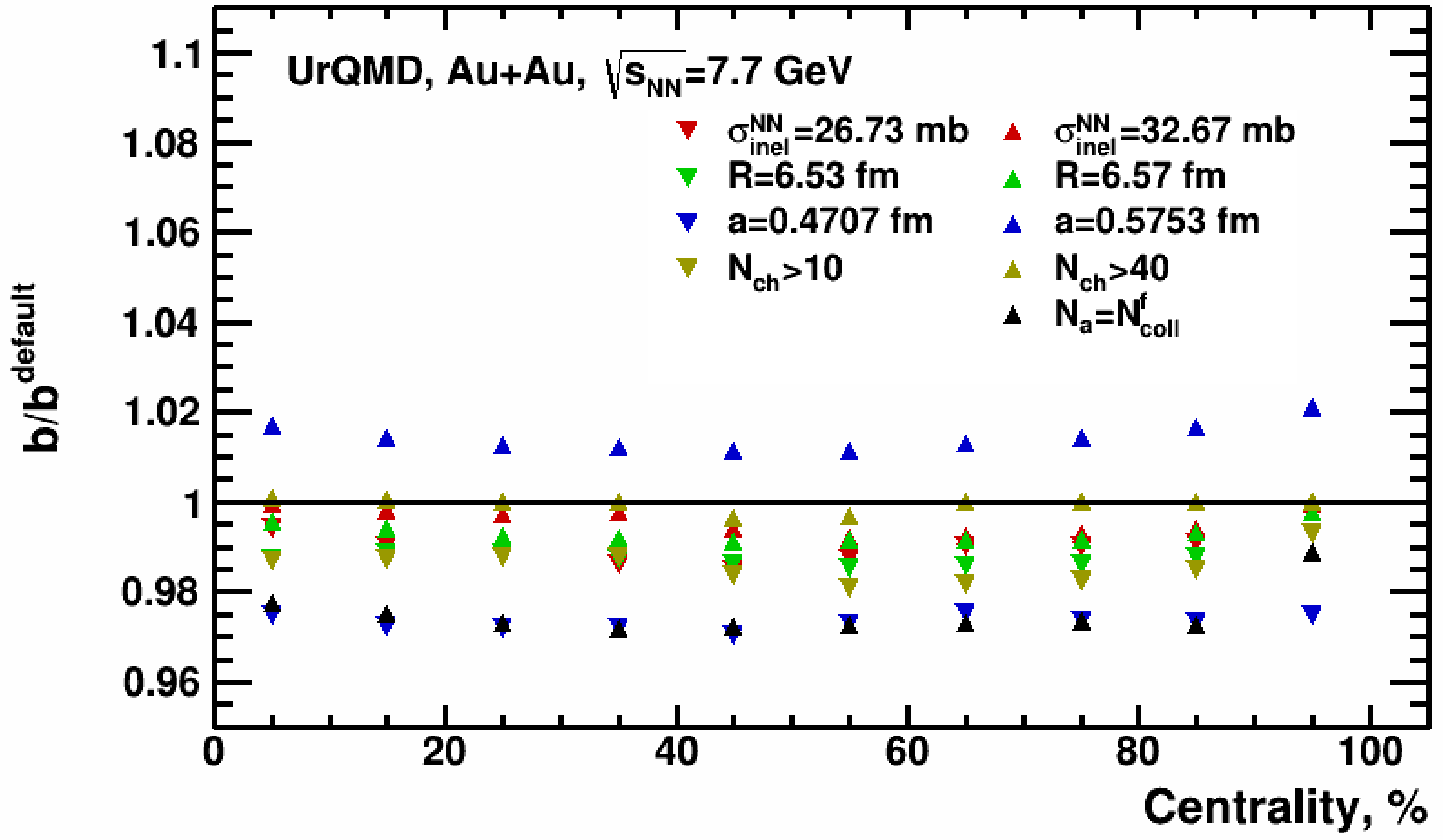


<N_{part}>, <N_{coll}> vs Centrality: MC-Glauber



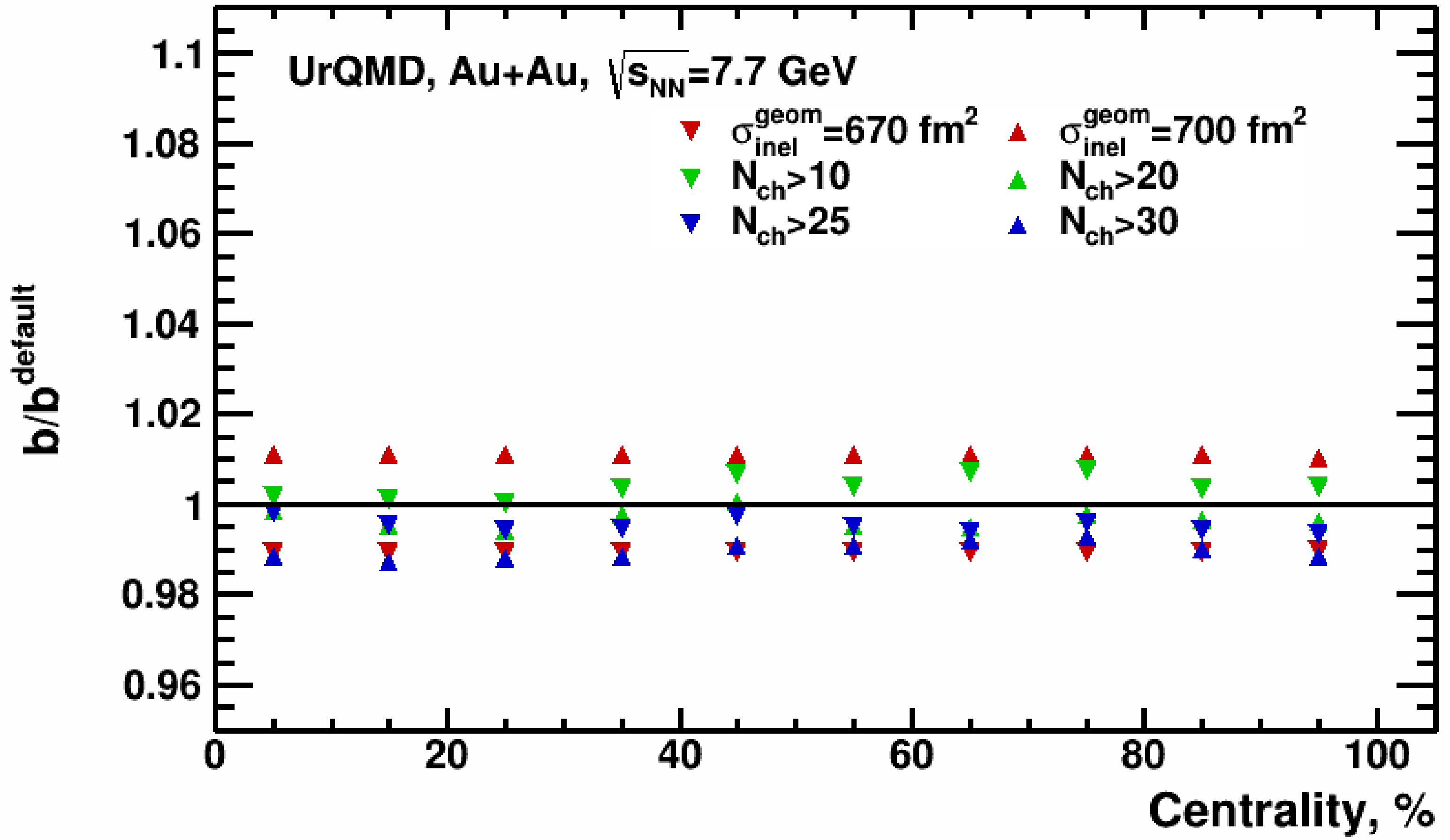


Systematics study: MC-Glauber



Systematic uncertainties for given parameter variations are within 1-3%

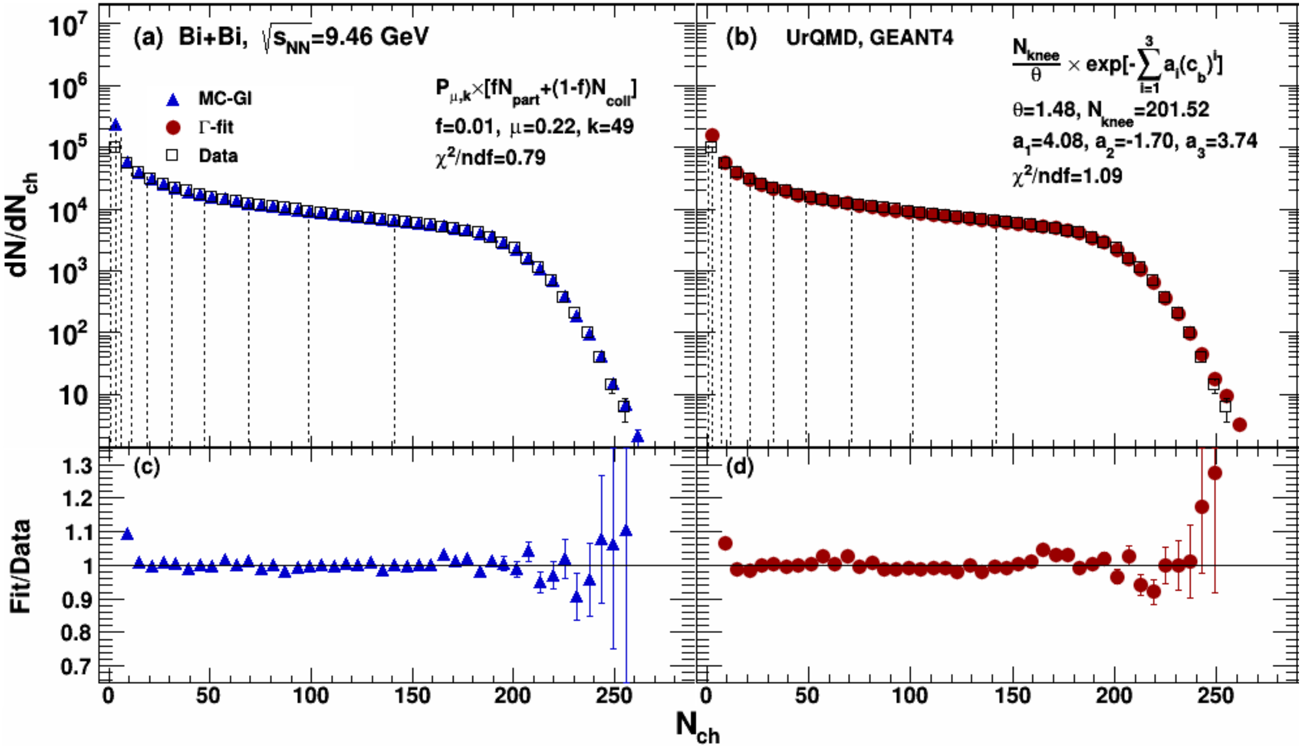
Systematics study: Γ-fit



Systematic uncertainties for given parameter variations are within 1-2%

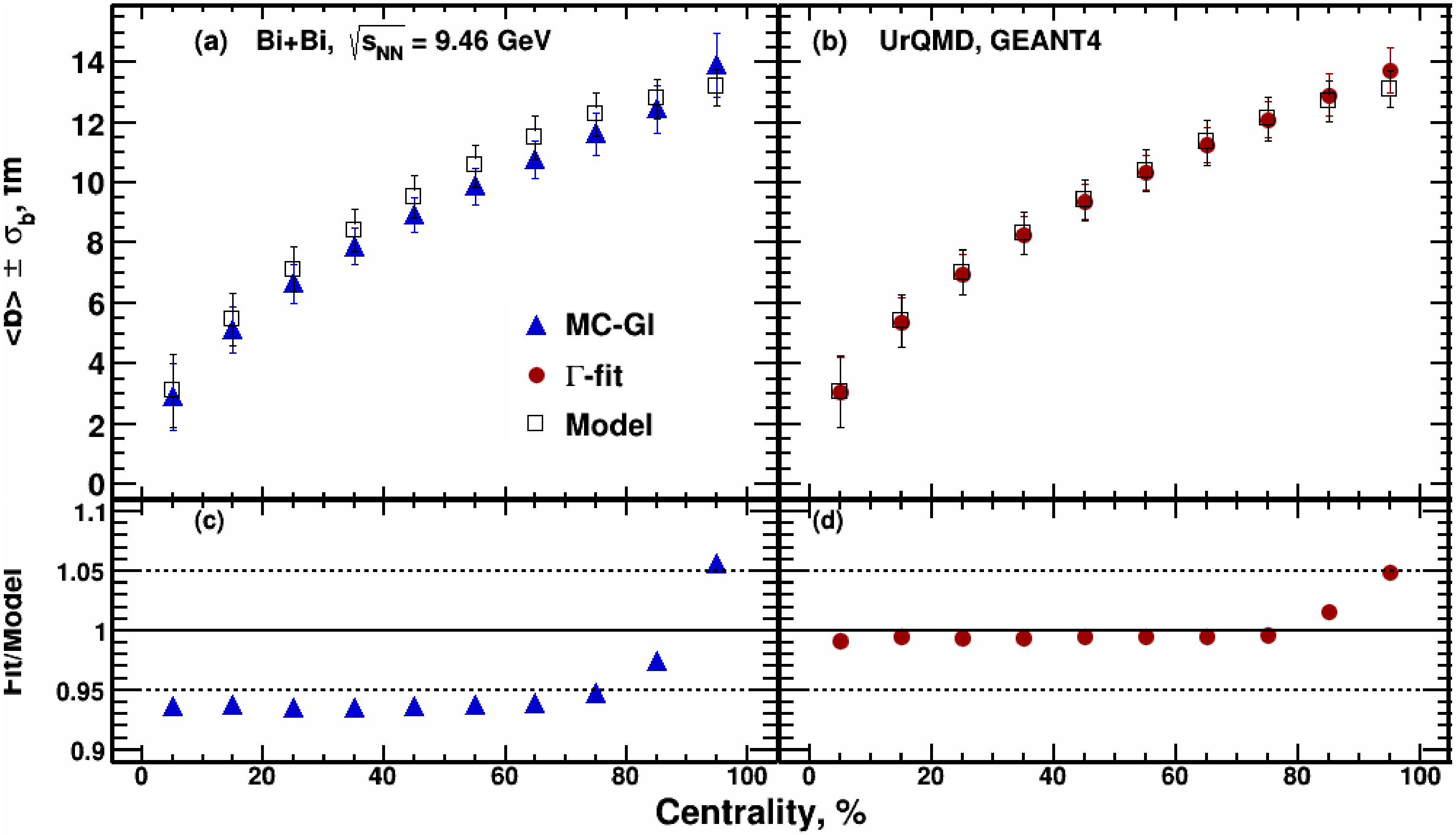
Requested data set II

- PWG4 production (request 5):
  - UrQMD, GEANT4, Bi+Bi, $\sqrt{s_{NN}}$= 9.46 GeV
  - N_{ev}=500k
- Hadron selection:
  - |η|<0.5
  - p_T>0.15 GeV/c
  - N_{hits} > 16
  - Primary track selection (|DCA| < 0.5 cm)

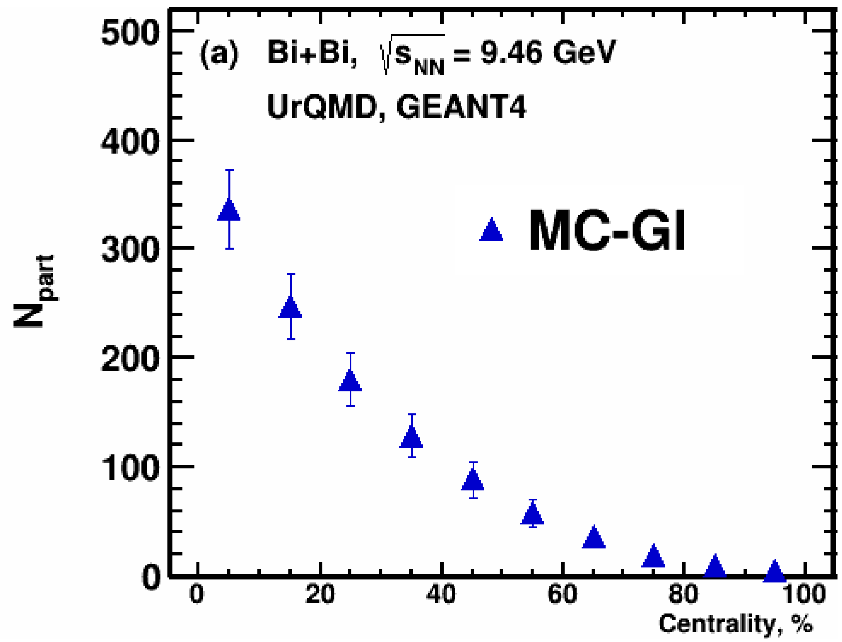


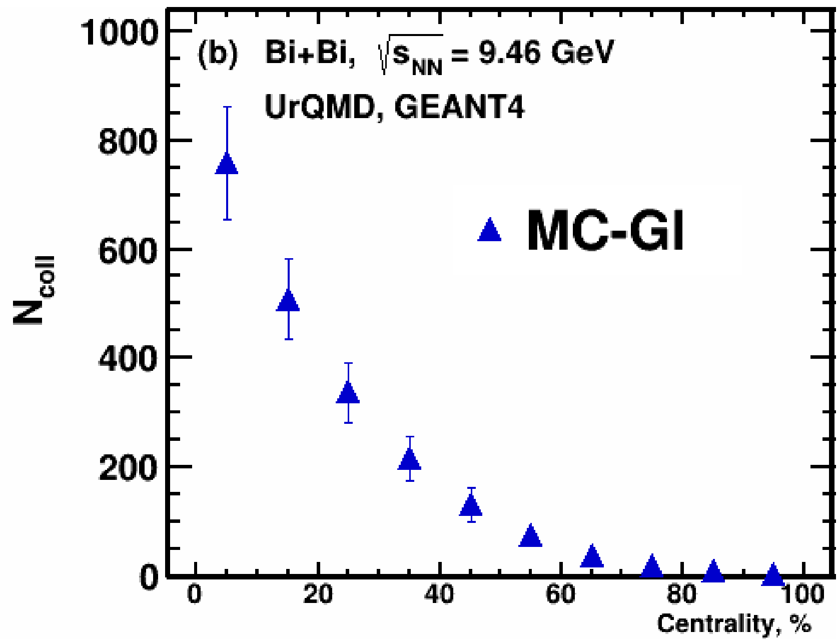
Good fit quality for both methods

<b> vs Centrality: MC-Glauber

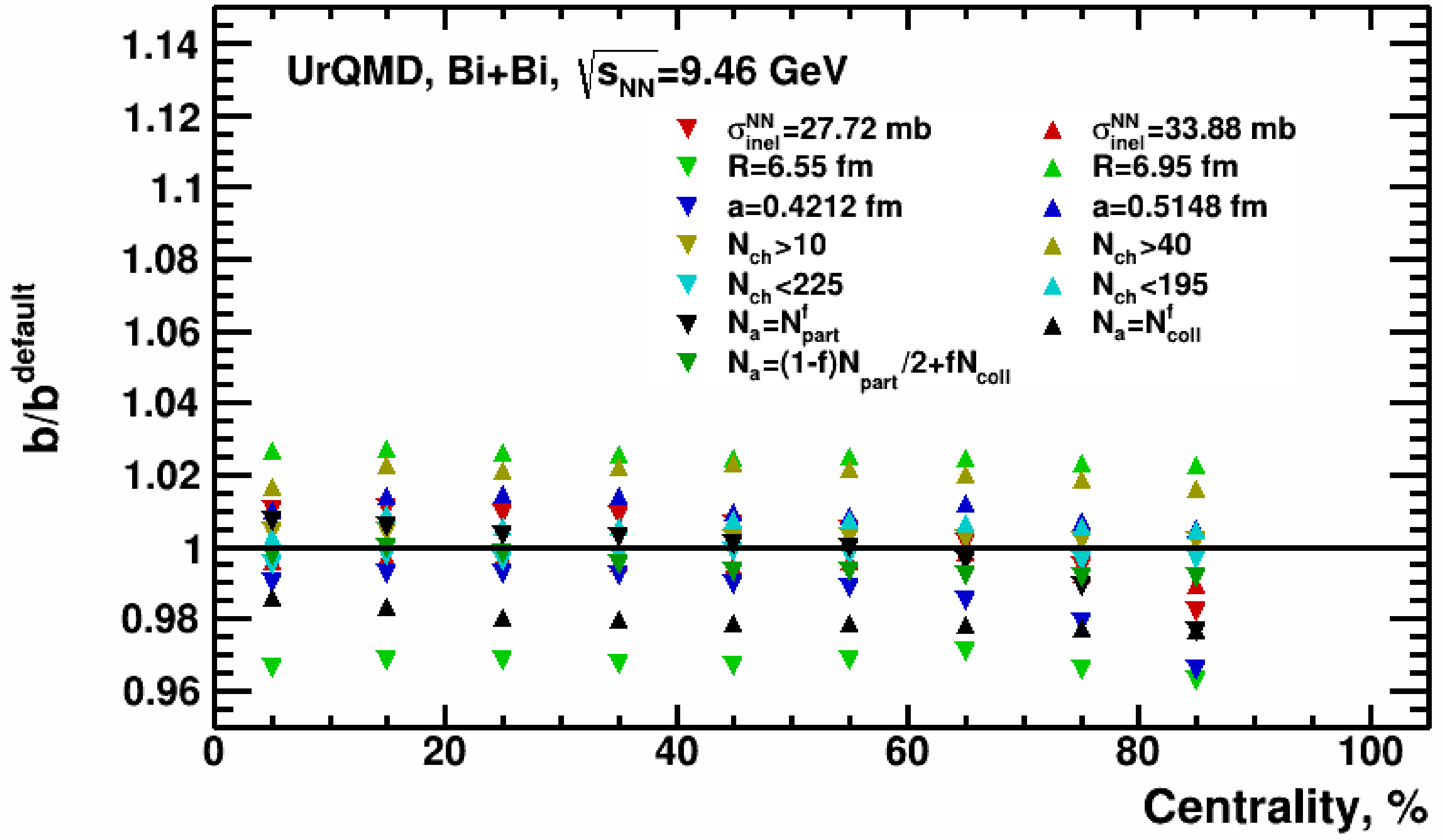


<N_{part}>, <N_{coll}> vs Centrality: MC-Glauber



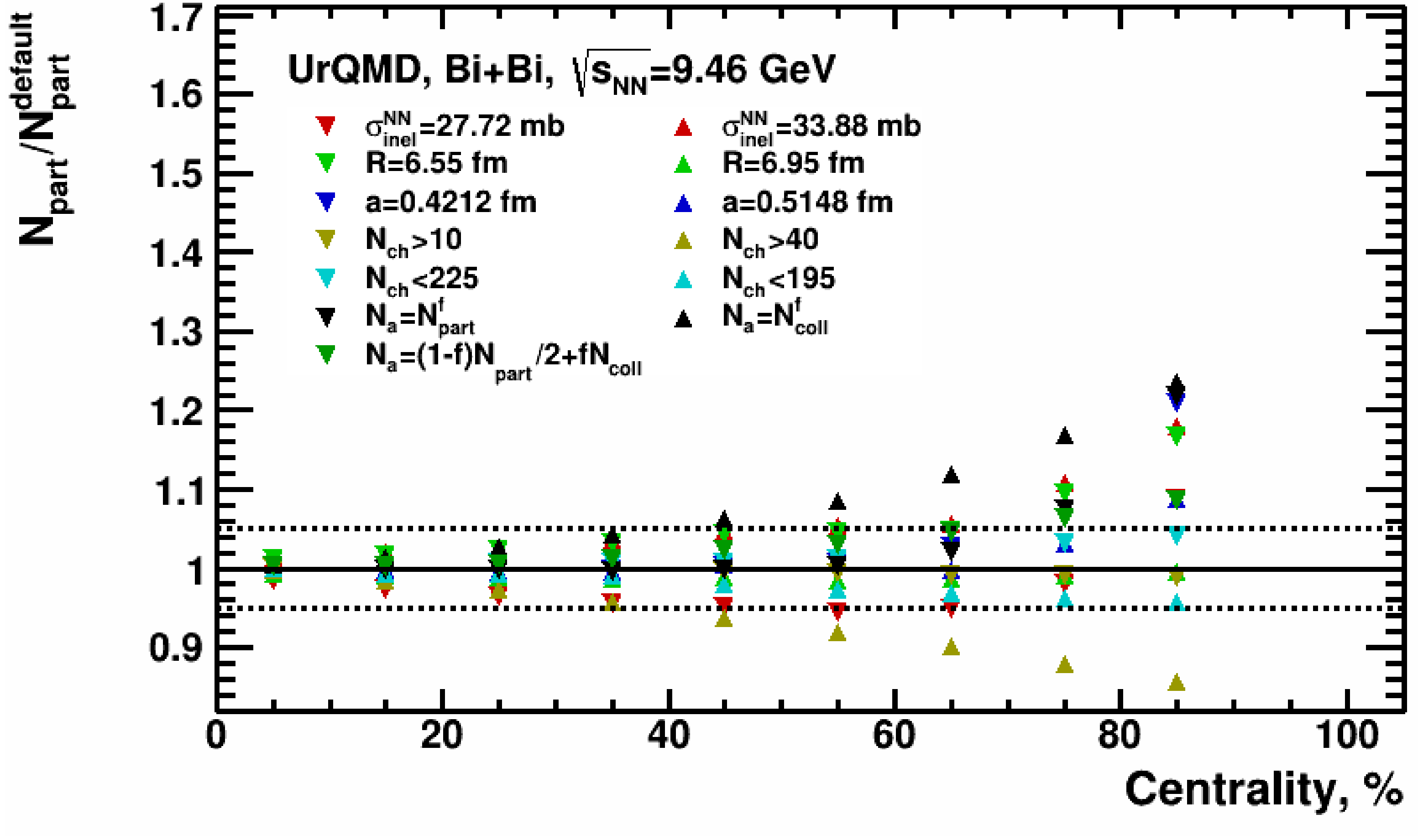


Systematics study: MC-Glauber

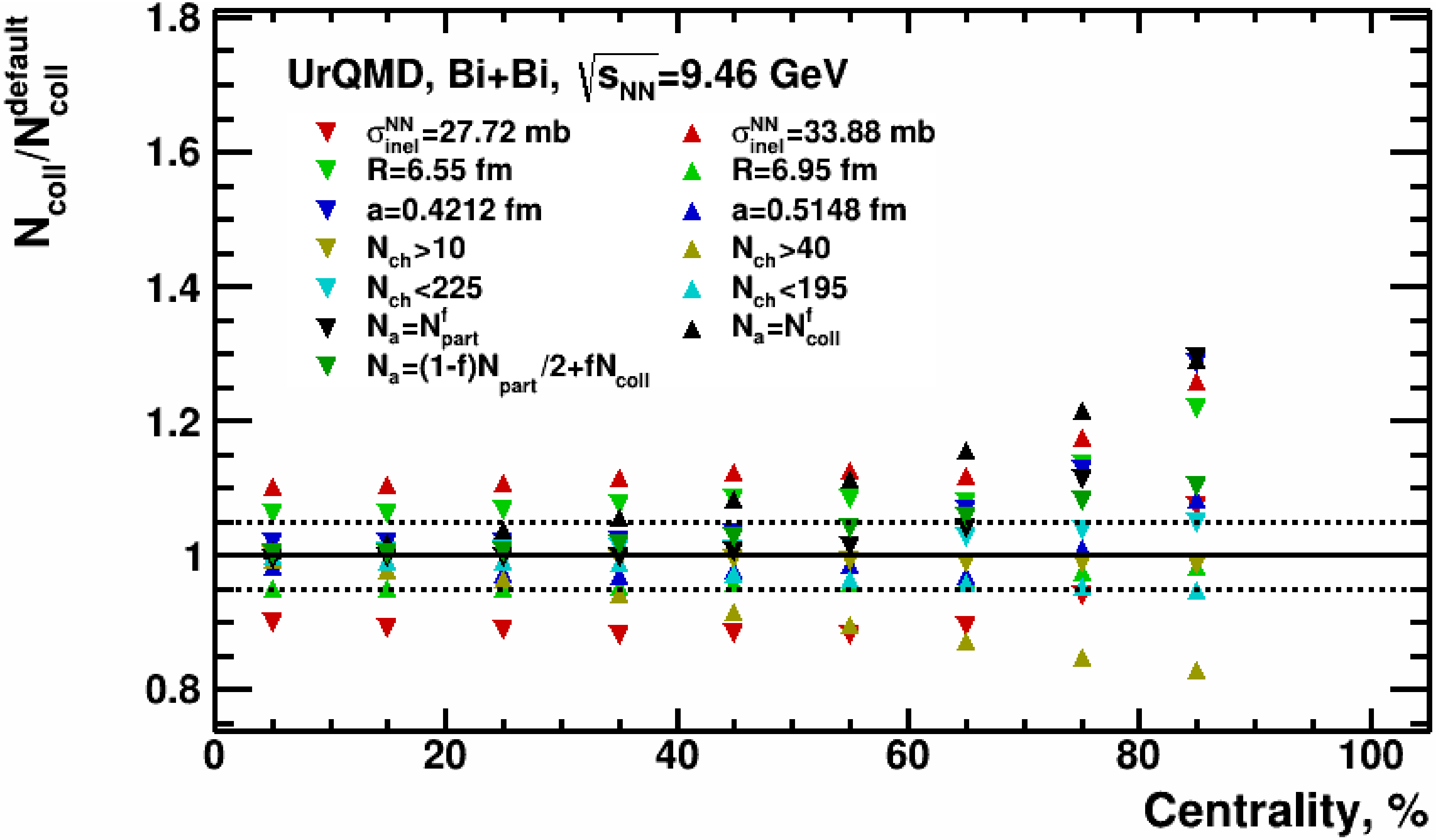


Systematic uncertainties for given parameter variations are within 1-4%

Systematics study: MC-Glauber

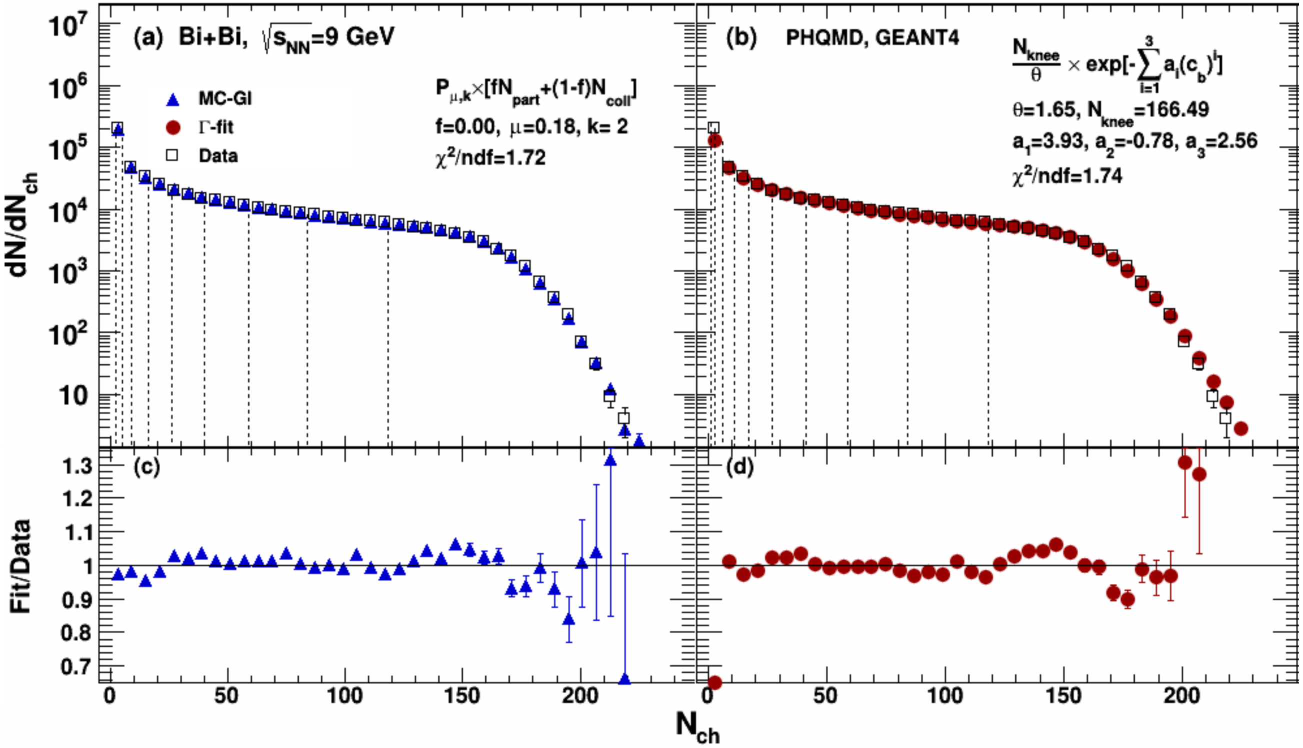


Systematics study: MC-Glauber



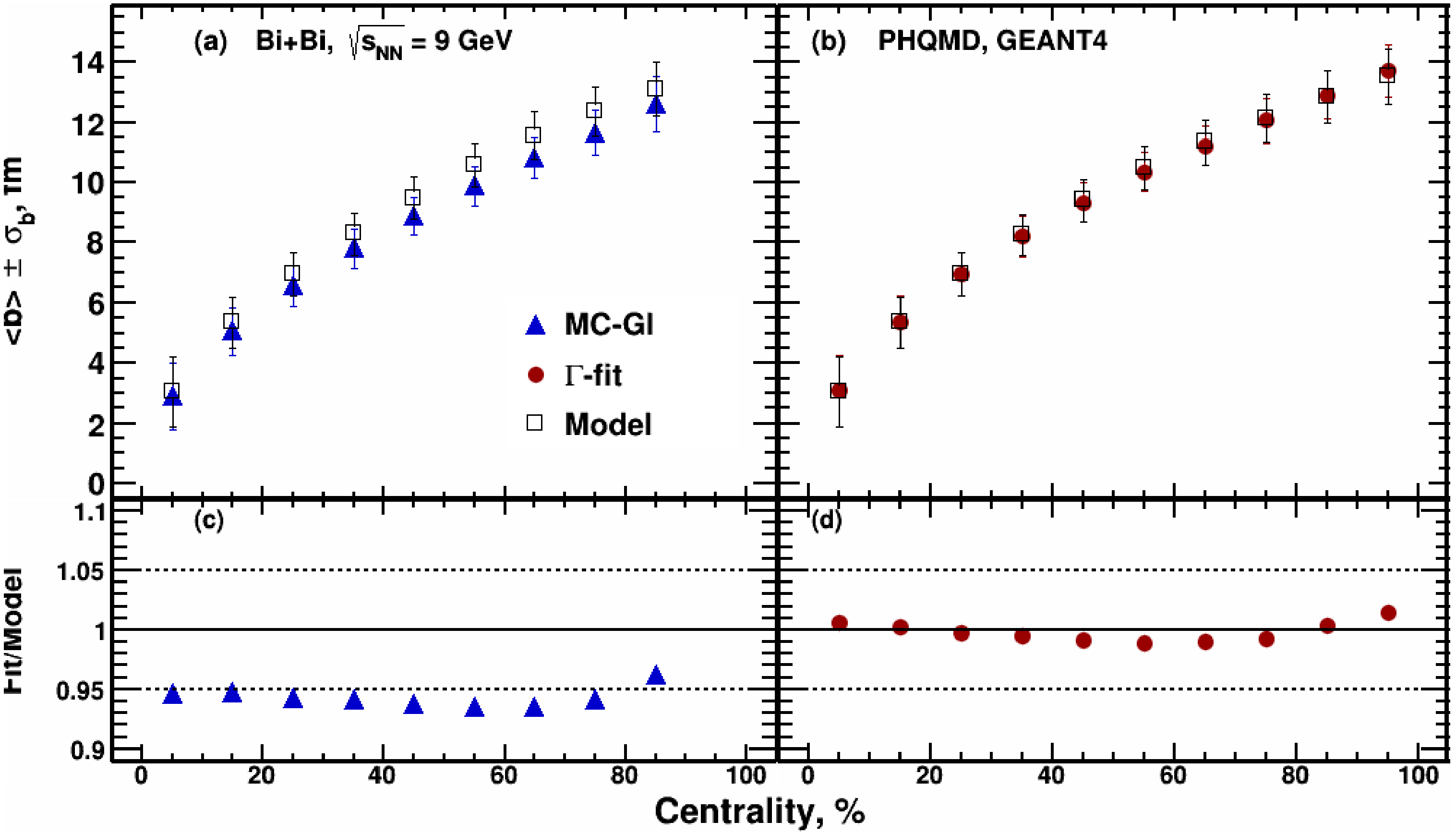
Requested data set III

- PWG2 production (request 7):
  - PHQMD, GEANT4, Bi+Bi, $\sqrt{s_{NN}}$= 9 GeV
  - N_{ev}=500k
- Hadron selection:
  - |η|<0.5
  - p_T>0.15 GeV/c
  - N_{hits} > 16
  - Primary track selection (|DCA| < 0.5 cm)

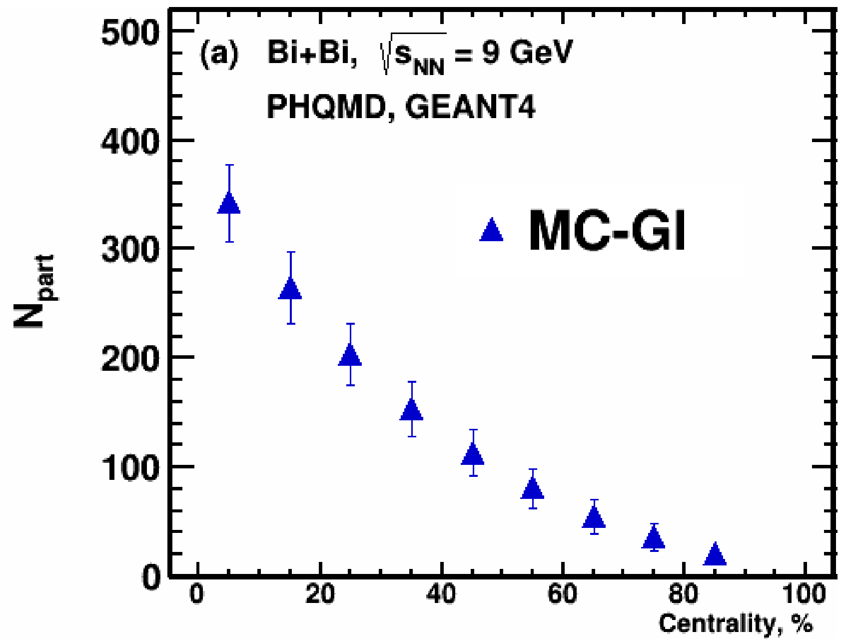


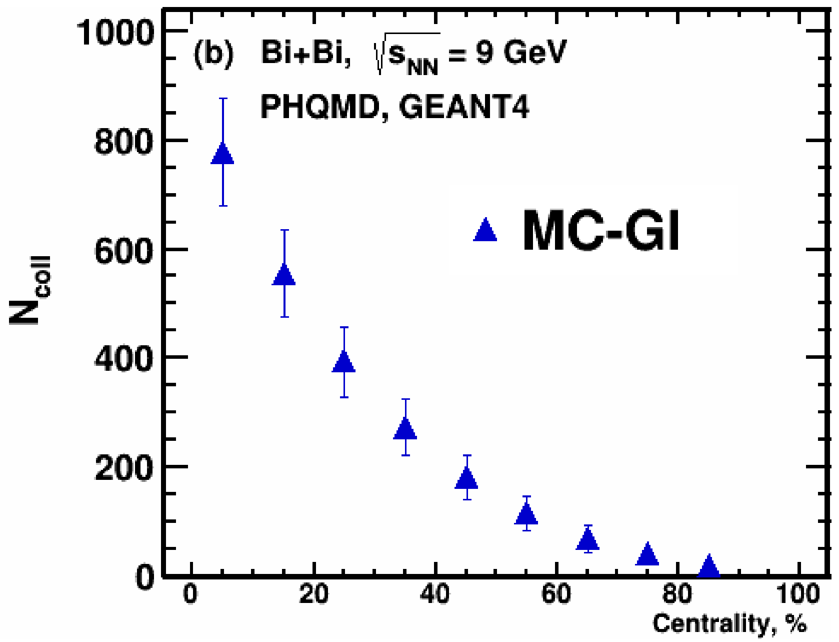
Good fit quality for both methods

<b> vs Centrality: MC-Glauber

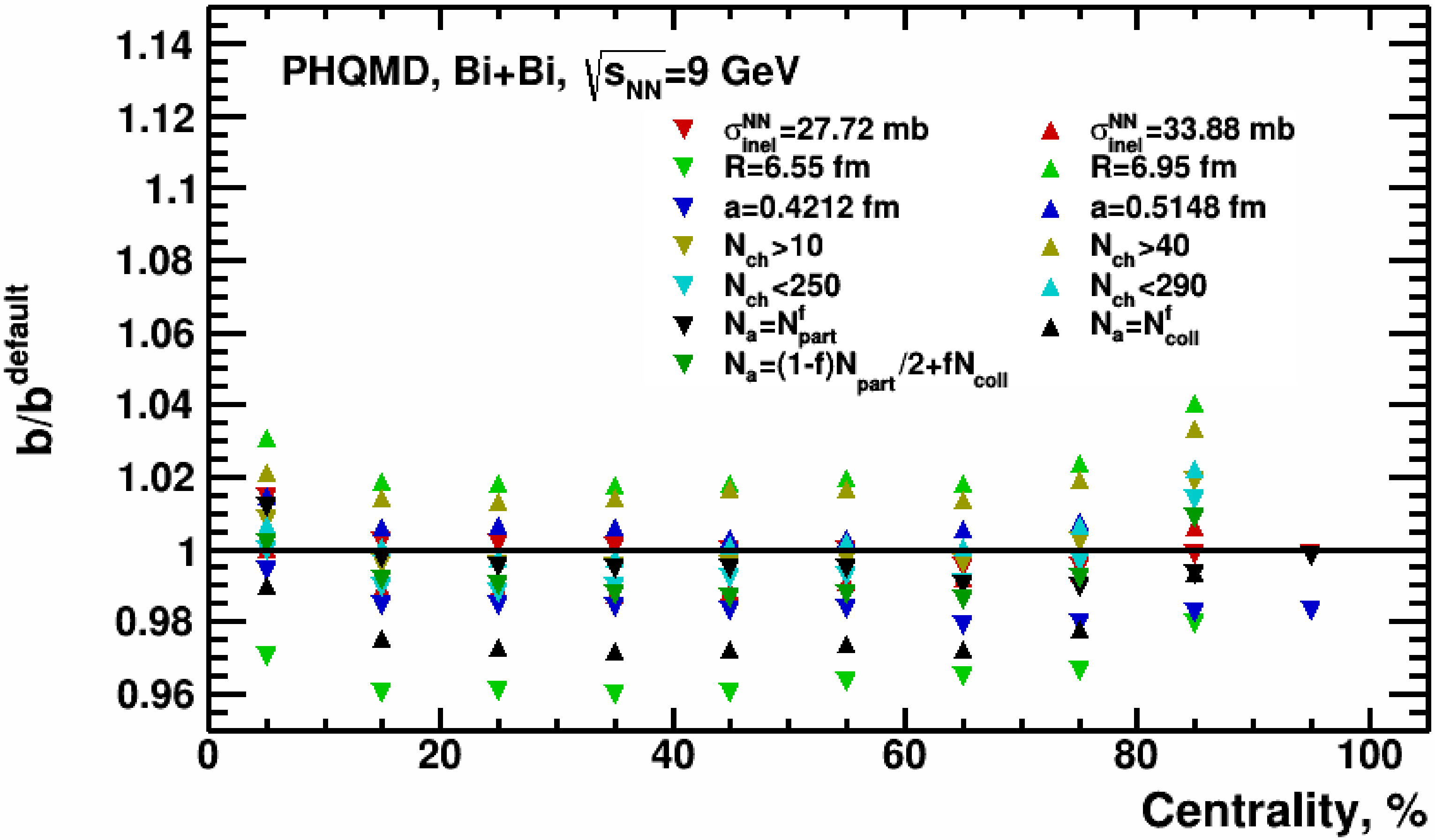


$\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ vs Centrality: MC-Glauber



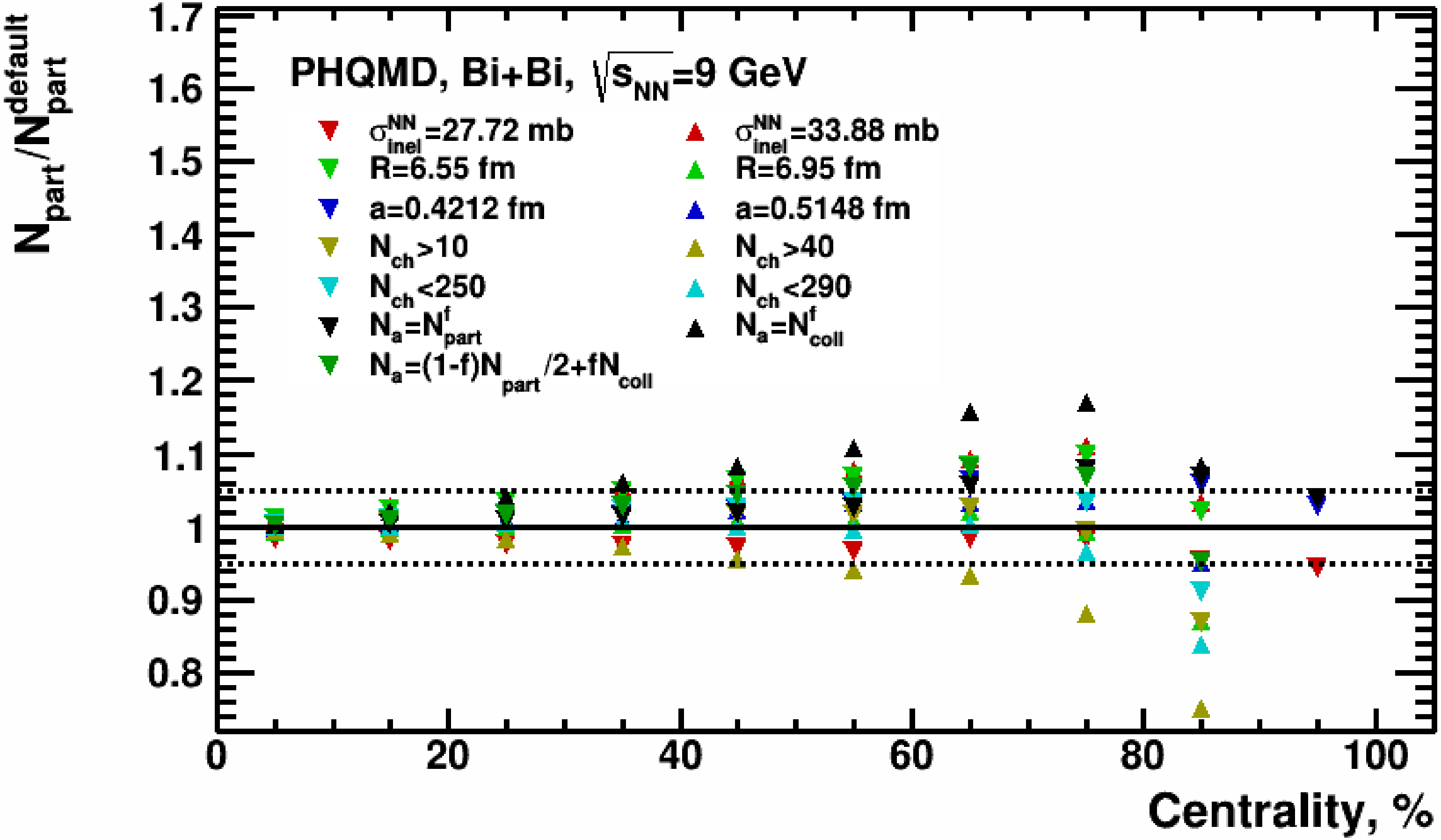


Systematics study: MC-Glauber

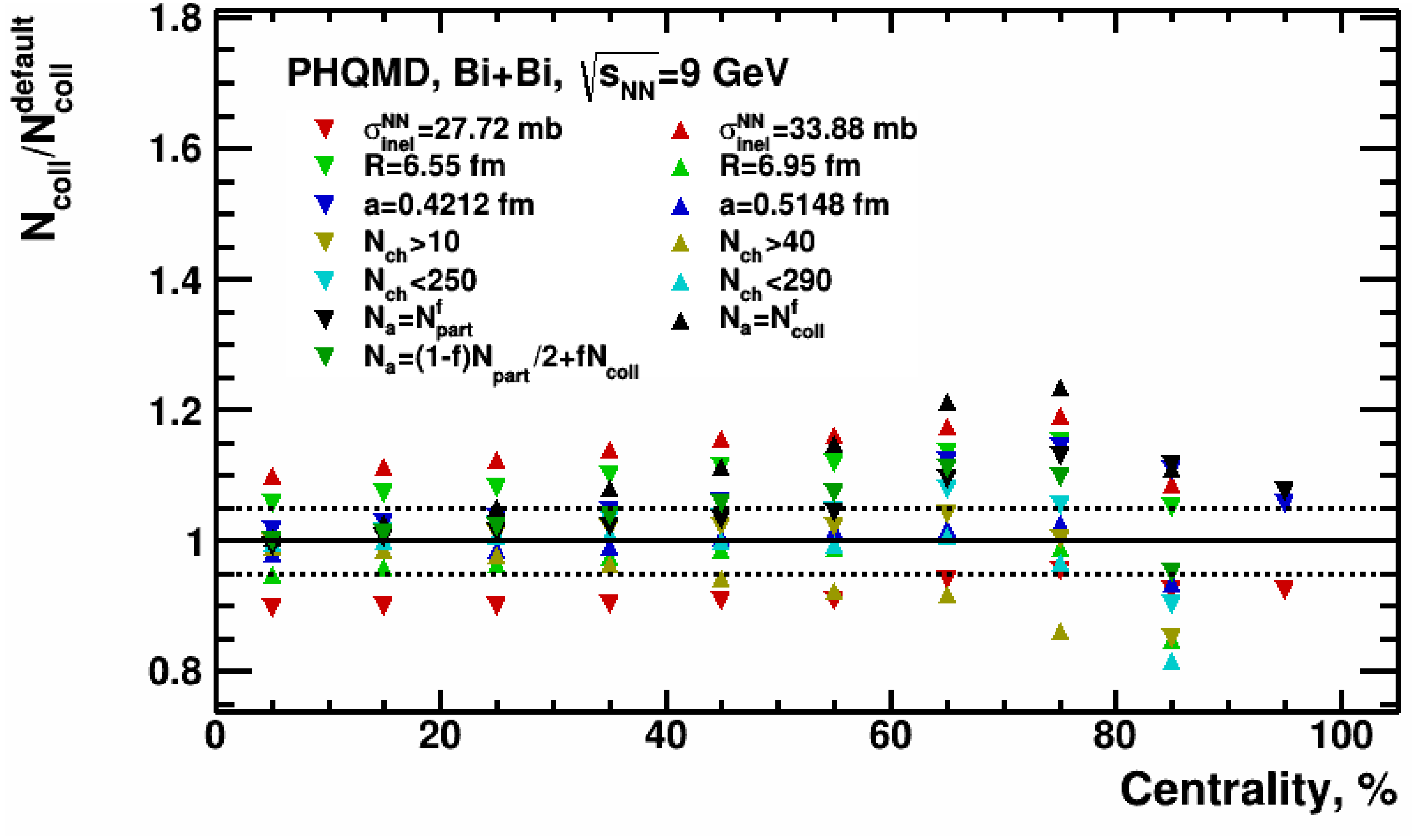


Systematic uncertainties for given parameter variations are within 1-4%

Systematics study: MC-Glauber



Systematics study: MC-Glauber



Summary and next steps

- Centrality determination for UrQMD, AMPT, DCM-QGSM-SMM:
  - Fitted functions from both methods reproduce charged particle multiplicity
  - Extracted relations between impact parameter and multiplicity centrality classes are in a reasonable agreement for both methods and for all given models
- Performance study was done for fully reconstructed data sets within MPDROOT framework:
  - Results are consistent with ones from the models
  - Used primary track selection based on DCA
  - Systematic study shows sensitivity for <b> within 1-3%

- Draft of the analysis note, code and manuals are provided with the code (see slide 6)

Thank you for your attention!

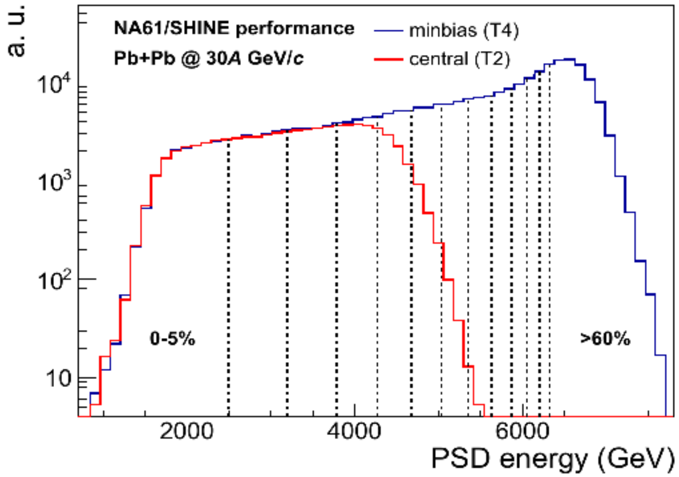
Backup

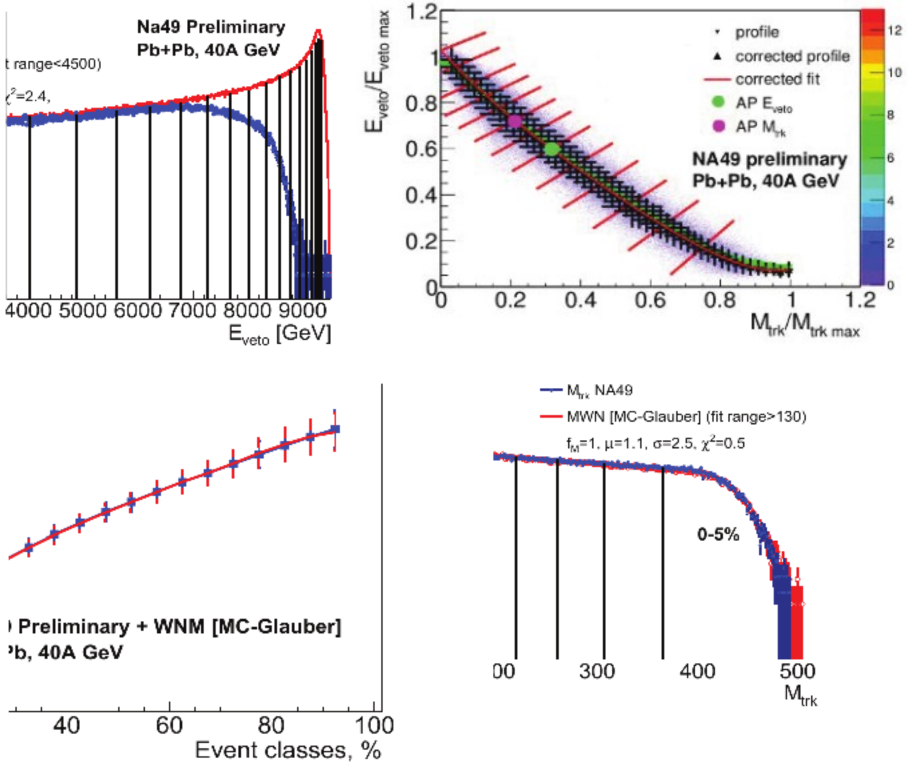
Centrality in NA49 & NA61/SHINE

KnE Energy & Physics, p. 275–279

Centrality Framework developed by V. Klochkov and I. Selyuzhenkov was used in both experiments

Nuclear Physics A 982, p. 439-442

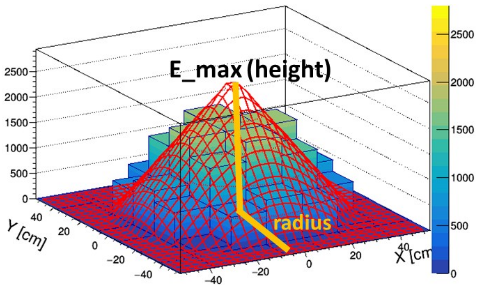


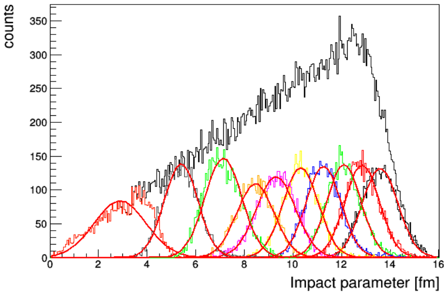


Both charged particle multiplicity and energy deposition can be used

Next step: comparison of centrality estimators

- Centrality determination based on energy deposition in FHCal is performed by the group from INR RAS (Troitsk, Moscow)
- It planned to compare different centrality estimators and their effect on the measurements (v_n)





For that study, production of reconstructed DCM-QGSM-SMM minbias events is requested:

5M events, GEANT4, Bi+Bi, $\sqrt{s_{NN}}$=4.5, 7.7, 11 GeV

BES programs

STAR BES-II program

Beam energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Number Events
9.8	19.6	4.5 weeks	Au+Au	400M MB
7.3	14.5	5.5 weeks	Au+Au	300M MB
5.75	11.5	5 weeks	Au+Au	230M MB
4.6	9.1	4 weeks	Au+Au	160M MB
31.2	7.7 (FXT)	2 days	Au+Au	100M MB
19.5	6.2 (FXT)	2 days	Au+Au	100M MB
13.5	5.2 (FXT)	2 days	Au+Au	100M MB
9.8	4.5 (FXT)	2 days	Au+Au	100M MB
7.3	3.9 (FXT)	2 days	Au+Au	100M MB
5.75	3.5 (FXT)	2 days	Au+Au	100M MB

Many new experimental results at NICA energy range ($\sqrt{s_{NN}}$=4-11 GeV) will be done during STAR (RHIC) and NA61/SHINE (SPS) BES

This will require comparison of the future MPD measurements with the RHIC/SPS

Simulating Glauber data

General usage of the **runlauber_v3.2.C**:

```
root -l
.L runlauber_v3.2.C+
runAndSaveNtuple(Nev, "Target", "Projectile", σNN)
.q
```

Recommended arguments:

- $N_{ev} = 5 \cdot 10^5$,
- “Target, Projectile” = “Au3” or “Bi”
- σ_{NN}:
  - σ_{NN}=29.3 mb for $\sqrt{s_{NN}}$=4.5 GeV
  - σ_{NN}=29.7 mb for $\sqrt{s_{NN}}$=7.7 GeV
  - σ_{NN}=30.8 mb for $\sqrt{s_{NN}}$=9.46 GeV
  - σ_{NN}=31.2 mb for $\sqrt{s_{NN}}$=11.5 GeV