Centrality determination in MPD using MC Glauber model

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Motivation

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

Goal: map collision geometry to the measurable quantities
Comparison with existing data (RHIC BES, NA49/NA61 scans)

- **Collision geometry:** impact parameter, number of participating nucleons, number of binary NN collisions, etc.
- **Measurable quantities:** multiplicity of the produced charged particles, energy of the spectators
STAR BES-II program

<table>
<thead>
<tr>
<th>Beam Energy (GeV/nucleon)</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Run Time</th>
<th>Species</th>
<th>Number Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.8</td>
<td>19.6</td>
<td>4.5 weeks</td>
<td>Au+Au</td>
<td>400M MB</td>
</tr>
<tr>
<td>7.3</td>
<td>14.5</td>
<td>5.5 weeks</td>
<td>Au+Au</td>
<td>300M MB</td>
</tr>
<tr>
<td>5.75</td>
<td>11.5</td>
<td>5 weeks</td>
<td>Au+Au</td>
<td>230M MB</td>
</tr>
<tr>
<td>4.6</td>
<td>9.1 $^1$</td>
<td>4 weeks</td>
<td>Au+Au</td>
<td>160M MB</td>
</tr>
<tr>
<td>9.8</td>
<td>4.5 (FXT)</td>
<td>2 days</td>
<td>Au+Au</td>
<td>100M MB</td>
</tr>
<tr>
<td>7.3</td>
<td>3.9 (FXT)</td>
<td>2 days</td>
<td>Au+Au</td>
<td>100M MB</td>
</tr>
<tr>
<td>5.75</td>
<td>3.5 (FXT)</td>
<td>2 days</td>
<td>Au+Au</td>
<td>100M MB</td>
</tr>
<tr>
<td>31.2</td>
<td>7.7 (FXT)</td>
<td>2 days</td>
<td>Au+Au</td>
<td>100M MB</td>
</tr>
<tr>
<td>19.5</td>
<td>6.2 (FXT)</td>
<td>2 days</td>
<td>Au+Au</td>
<td>100M MB</td>
</tr>
<tr>
<td>13.5</td>
<td>5.2 (FXT)</td>
<td>2 days</td>
<td>Au+Au</td>
<td>100M MB</td>
</tr>
</tbody>
</table>

Many measurements at NICA energy range will be done during STAR BES-II
Will require comparison of the future MPD measurements with the RHIC/SPS
Centrality in STAR

- Uncorrected charged particle multiplicity distribution in TPC ($|\eta|<0.5$)
- Comparison with MC Glauber simulations
- Fitted using two-component model:
  
  \[ \frac{dN_{ch}}{d\eta} \bigg|_{\eta=0} = n_{pp} \left[ (1-x) N_{part}/2 + x N_{coll} \right] \]

Similar centrality estimator is needed for comparisons with STAR

Centrality determination in MPD (NICA)

- Time Projection Chamber (TPC)  
  $|\eta|<1.5$

- Forward Hadron Calorimeter (FHCaI)  
  $2<|\eta|<5$
Charged particle multiplicity in MPD

Reconstructed data:
- UrQMD 3.4 simulation
  - Au+Au, $N_{ev}=500k$, $\sqrt{s_{NN}}=7.7, 11.5 \text{ GeV}$
- GEANT4 MPD detector simulation
- Reconstruction procedure:
  - Realistic tracking in TPC (Cluster Finder)

Used particle selection:
- $|\eta|<0.5$
- $p_T>0.15 \text{ GeV/c}$
Integrating the CBM Centrality framework

MC Glauber data

Evaluate \( N_a \):
\[
N_a = f N_{\text{part}} + (1-f) N_{\text{coll}}
\]

Call
\[
\text{NBD}(\mu, k) \times N_a
\]

Build multiplicity fitting function

Evaluate \( \chi^2 \)

Minimize \( \chi^2 \) to find \( f, \mu, k \)

This centrality procedure was used in CBM, NA49, and NA61/SHINE:
EPJ Web Conf. 182 (2018) 02132
Implementantion in MPD: https://github.com/IlyaSegal/NICA
Lubynets O., Selyuzhenkov I., Klochkov V. 33-rd CBM CM
Glauber Model configuration

Used TGlauberMC-3.2 version from tglaufermc.hepforge.org

Input to the model

- Inelastic NN cross section
  - $\sigma_{NN}=29.7$ mb for $\sqrt{s}_{NN}=7.7$ GeV
  - $\sigma_{NN}=31.2$ mb for $\sqrt{s}_{NN}=11.5$ GeV
- Colliding nuclei
  - “Au(197,79)”+”Au(197,79)”

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 $\varepsilon_n$
  - etc.

In progress: comparison MC Glauber with GLISSANDO arXiv:1901.04484 [nucl-th]
Centrality framework configuration

NBD Equation:

\[ P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1) \Gamma(k)} \left( \frac{\mu}{k} \right)^n \left( \frac{\mu}{k} + 1 \right)^{n+k} \]

Fitting function for charged particle multiplicity:

\[ N_{ch}(f, \mu, k) = P_{\mu,k}(n) \cdot [f N_{part} + (1-f) N_{coll}] \]

Normalization of the total number of events:

\[ \frac{N_{reco}^{ev}}{N_{ev}^{MC\ Glauber}} = \frac{1}{10} \]

Parameter range:

\[ f = (0 - 1), \ f_{step} = 0.01 \]
\[ k = (0 - 50), \ k_{step} = 1 \]

Fitting region:

\[ N_{ch} = \begin{cases} (20 - 310), & \sqrt{s_{NN}} = 7.7 \text{ GeV} \\ (15 - 380), & \sqrt{s_{NN}} = 11.5 \text{ GeV} \end{cases} \]
Fit parameters $f, k$ vs $\chi^2$

- $f=0$, $k=14$, $\mu=0.31$, $\chi^2=1.46\pm0.12$, $M=(20,310)$

- $f=0.24$, $k=2$, $\mu=0.71$, $\chi^2=1.24\pm0.06$, $M=(15,380)$
MC Glauber fit: $h^\pm$ multiplicity

MC Glauber fit is in the good agreement with simulated input for the large multiplicity region

$f=0$, $k=14$, $\mu=0.31$, $\chi^2=1.46\pm0.12$, $M=(20,310)$
MC Glauber fit: \( h^\pm \) multiplicity

\[ f=0.24, k=2, \mu=0.71, \chi^2=1.24\pm0.06, M=(15,380) \]
b vs. multiplicity correlation

Events in multiplicities $M \pm \Delta M$ have impact parameter in range $b \pm \sigma_b$
$N_{ch}$ distribution in centrality classes

$\sqrt{s_{NN}} = 7.7$ GeV

$\sqrt{s_{NN}} = 11.5$ GeV
b distribution in centrality classes

\[ \sqrt{s_{\text{NN}}} = 7.7 \text{ GeV} \]

\[ \sqrt{s_{\text{NN}}} = 11.5 \text{ GeV} \]
$N_{\text{part}}$ distribution in centrality classes
$N_{\text{coll}}$ distribution in centrality classes
Comparison of the UrQMD, PHSD, SMASH & MC Glauber parameters
b vs centrality: MC Glauber vs UrQMD

Reasonable agreement between MC Glauber and UrQMD
b vs centrality: MC Glauber vs PHSD

Reasonable agreement between MC Glauber and PHSD
b vs centrality: different models

Reasonable agreement between UrQMD, PHSD and SMASH

Au+Au, $\sqrt{s_{NN}}=7.7$ GeV

Au+Au, $\sqrt{s_{NN}}=11.5$ GeV
$N_{\text{part}}$ vs $b$: all models

- PHSD
- UrQMD
- MC Glauber
Eccentricity $\varepsilon_n$

- Eccentricity characterizes initial-state spatial anisotropy
- In MC Glauber, $\varepsilon_n$ defined as a $\varepsilon_{\text{part}}$ in the center-of-mass system of the participant nuclei (Phys. Rev. C81 (2010) 054905):

$$\varepsilon_n = \sqrt{\frac{\langle r^2 \cos(n \varphi) \rangle^2 + \langle r^2 \sin(n \varphi) \rangle^2}{\langle r^2 \rangle}}$$

- $\varepsilon_2$ is system dependent
- $\varepsilon_3$ is system independent
Eccentricity: Comparison w/ UrQMD

Notable difference between MC Glauber and UrQMD eccentricities
$\varepsilon_3$: Comparison w/ UrQMD

Notable difference between MC Glauber and UrQMD
Summary and next steps

- MC-Glauber based procedure for centrality determination is established
  - UrQMD at two energies ($\sqrt{s_{NN}}=7.7, 11.5$ GeV) are under study
- Fit reproduces charged particle multiplicity with chosen parameters
- Extracted relation between model parameters ($b$, $N_{\text{part}}$, $N_{\text{coll}}$) and multiplicity centrality classes
  - Impact parameter from MC Glauber and UrQMD in given centrality classes are in reasonable agreement
- Comparison of the $\varepsilon_n$ between MC Glauber and UrQMD shows notable difference
- Comparison between MC Glauber and other models: PHSD, PHQMD, SMASH, JAM - work in progress.
- Systematic study and analysis note are under preparation.
Thank you for your attention!
Backup
$h^\pm$ multiplicity

Au+Au, $\sqrt{s_{NN}}=7.7$ GeV

$\sqrt{s_{NN}}=7.7$ GeV

$\sqrt{s_{NN}}=11.5$ GeV

Au+Au, $\sqrt{s_{NN}}=11.5$ GeV
<b> vs centrality: comparison between models
b vs centrality: Glauber vs SMASH

Au+Au, $\sqrt{s_{NN}} = 7.7$ GeV

Au+Au, $\sqrt{s_{NN}} = 11.5$ GeV

- MC Glauber
- SMASH
b vs centrality: all models

$Au+Au, \sqrt{s_{NN}}=7.7$ GeV

$Au+Au, \sqrt{s_{NN}}=11.5$ GeV

- SMASH
- PHSD
- UrQMD reco
Eccentricity: comparison with STAR

Good agreement with the published data
Initial state comparison:
\[ \sqrt{s_{NN}} = 7.7 \text{ GeV} \]
MC Glauber vs PHSD: $b, N_{\text{part}}$
MC Glauber vs PHSD: $\varepsilon_n$
Initial state comparison:
\[ \sqrt{s_{_{NN}}} = 11.5 \text{ GeV} \]
MC Glauber vs PHSD: $b$, $N_{\text{part}}$
MC Glauber vs PHSD: $\varepsilon_n$
MC Glauber vs UrQMD: $b$, $N_{\text{part}}$
MC Glauber vs UrQMD: $\varepsilon_n$
MC Glauber vs pure UrQMD
Fit parameters $f, k$ vs $\chi^2$

$f=0.49$, $k=46$, $\mu=0.61$, $\chi^2=1.29\pm0.06$, $M=(35,445)$
Fit parameters $f,k$ vs $\chi^2$

$f=0.45$, $k=29$, $\mu=0.71$, $\chi^2=1.24\pm0.05$, $M=(40,540)$
MC Glauber fit: $h^\pm$ multiplicity

$\sqrt{s_{NN}} = 7.7$ GeV

$\sqrt{s_{NN}} = 11.5$ GeV
b-multiplicity correlation

Events in multiplicities $M \pm \Delta M$ have impact parameter in range $b \pm \sigma_b$
b distribution in centrality classes

\[ \sqrt{s_{NN}} = 7.7 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 11.5 \text{ GeV} \]
Multiplicity distribution in centrality classes

\( \sqrt{s_{NN}} = 7.7 \text{ GeV} \)

\( \sqrt{s_{NN}} = 11.5 \text{ GeV} \)
Centrality classes: Npart

Au+Au, $\sqrt{s_{NN}} = 7.7$ GeV

Au+Au, $\sqrt{s_{NN}} = 11.5$ GeV
Centrality classes: Ncoll

Au+Au, $\sqrt{s_{NN}}=7.7$ GeV

Au+Au, $\sqrt{s_{NN}}=11.5$ GeV
Centrality classes: Ncoll
Centrality framework results for UrQMD reco with pion multiplicity
Charged particle multiplicity in MPD

Reconstructed data:
- UrQMD 3.4 simulation
  - Au+Au, \( N_{\text{ev}} = 500k \), \( \sqrt{s_{\text{NN}}} = 7.7, 11.5 \text{ GeV} \)
- GEANT4 MPD detector simulation
- Reconstruction procedure:
  - Realistic tracking in TPC (Cluster Finder)

Used particle selection:
- Only charged pions
- \(|\eta| < 0.5\)
- \(p_T > 0.15 \text{ GeV/c}\)
Fit parameters $f,k$ vs $\chi^2$

- $f=0$, $k=42$, $\mu=0.24$, $\chi^2=1.39\pm0.1$, $M=(10,240)$
- $f=0.01$, $k=43$, $\mu=0.3$, $\chi^2=1.17\pm0.07$, $M=(10,320)$
MC Glauber fit: $\pi^\pm$ multiplicity

f=0, k=42, $\mu=0.24$, $\chi^2=1.39\pm0.1$, $M=(10,240)$

MC Glauber fit is in the good agreement with simulated input for the large multiplicity region
MC Glauber fit: $\pi^\pm$ multiplicity

$f=0.01$, $k=43$, $\mu=0.3$, $\chi^2=1.17\pm0.07$, $M=(10,320)$

MC Glauber fit is in the good agreement with simulated input for the large multiplicity region.
b vs. multiplicity correlation

Events in multiplicities $M \pm \Delta M$ have impact parameter in range $b \pm \sigma_b$
$N_{\text{ch}}$ distribution in centrality classes

\[ \sqrt{s_{\text{NN}}} = 7.7 \text{ GeV} \]

\[ \sqrt{s_{\text{NN}}} = 11.5 \text{ GeV} \]
b distribution in centrality classes

\[ \sqrt{s_{NN}} = 7.7 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 11.5 \text{ GeV} \]

No 90-100% centrality bin. Investigating.
$N_{\text{part}}$ distribution in centrality classes

![Graphs showing $N_{\text{part}}$ distribution in different centrality classes.](Image)

- $\sqrt{s_{\text{NN}}}=7.7$ GeV
- $\sqrt{s_{\text{NN}}}=11.5$ GeV

Centrality, %

- 0.0%-10.0%
- 10.0%-20.0%
- 20.0%-30.0%
- 30.0%-40.0%
- 40.0%-50.0%
- 50.0%-60.0%
- 60.0%-70.0%
- 70.0%-80.0%
- 80.0%-90.0%
- 90.0%-100.0%
- 0%-100%
$N_{\text{coll}}$ distribution in centrality classes
Centrality framework results for PHSD
Charged particle multiplicity in PHSD

Generated data:
- PHSD v4.0 simulation
  - Au+Au, $N_{ev} = 500k$, $\sqrt{s_{NN}} = 7.7, 11.5 \text{ GeV}$

Used particle selection:
- $|\eta| < 0.5$
- $p_T > 0.15 \text{ GeV/c}$
Fit parameters $f, k$ vs $\chi^2$

$f=0, k=24, \mu=0.27, \chi^2=1.75\pm0.09, M=(10,265)$

$f=0.34, k=21, \mu=0.39, \chi^2=1.47\pm0.08, M=(10,320)$
MC Glauber fit: $h^\pm$ multiplicity

$f=0$, $k=24$, $\mu=0.27$, $\chi^2=1.75\pm0.09$, $M=(10,265)$

MC Glauber fit is in the good agreement with simulated input for the large multiplicity region
MC Glauber fit: $h^\pm$ multiplicity

f=0.34, k=21, $\mu=0.39$, $\chi^2=1.47\pm0.08$, M=(10,320)

MC Glauber fit is in the good agreement with simulated input for the large multiplicity region.
Events in multiplicities $M \pm \Delta M$ have impact parameter in range $b \pm \sigma_b$
$N_{\text{ch}}$ distribution in centrality classes

\[ \sqrt{s_{NN}} = 7.7 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 11.5 \text{ GeV} \]
$\sqrt{s_{NN}} = 7.7 \text{ GeV}$

$\sqrt{s_{NN}} = 11.5 \text{ GeV}$

$b$ distribution in centrality classes

$\langle b \rangle \pm \sigma_b$
$N_{\text{part}}$ distribution in centrality classes

- $\sqrt{s_{\text{NN}}}=7.7$ GeV
- $\sqrt{s_{\text{NN}}}=11.5$ GeV

Centrality, %
$N_{\text{coll}}$ distribution in centrality classes
Centrality framework results for SMASH
Charged particle multiplicity in SMASH

Generated data:
- SMASH v1.6 simulation
  - Au+Au, \( N_{ev}=500k \), \( \sqrt{s_{NN}}=7.7, 11.5 \) GeV

Used particle selection:
- \( |\eta|<0.5 \)
- \( p_T>0.15 \) GeV/c
Fit parameters $f, k$ vs $\chi^2$

$F=0.23$, $k=35$, $\mu=0.24$, $\chi^2=1.11\pm0.08$, $M=(5,225)$

$f=0.5$, $k=24$, $\mu=0.36$, $\chi^2=1.21\pm0.1$, $M=(10,265)$
MC Glauber fit: $h^\pm$ multiplicity

F=0.23, k=35, $\mu=0.24$, $\chi^2=1.11\pm0.08$, M=(5,225)

MC Glauber fit is deviate from SMASH data for large multiplicity region
MC Glauber fit: $h^{\pm}$ multiplicity

MC Glauber fit is in the good agreement with simulated input for the large multiplicity region.

$f=0.5$, $k=24$, $\mu=0.36$, $\chi^2=1.21\pm0.1$, $M=(10,265)$
Events in multiplicities $M \pm \Delta M$ have impact parameter in range $b \pm \sigma_b$
$N_{ch}$ distribution in centrality classes

\[ \sqrt{s_{NN}} = 7.7 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 11.5 \text{ GeV} \]
b distribution in centrality classes

$\sqrt{s_{NN}} = 7.7\ GeV$

$\sqrt{s_{NN}} = 11.5\ GeV$

No 90-100% centrality bin. Investigating.
$N_{\text{part}}$ distribution in centrality classes

\begin{align*}
\text{Counts} & \text{:} & 10^0 & 10^1 & 10^2 & 10^3 & 10^4 & 10^5 \\
N_{\text{part}} & \text{:} & 0 & 50 & 100 & 150 & 200 & 250 & 300 & 350 & 400
\end{align*}

\begin{align*}
\text{Counts} & \text{:} & 10^0 & 10^1 & 10^2 & 10^3 & 10^4 & 10^5 \\
N_{\text{part}} & \text{:} & 0 & 50 & 100 & 150 & 200 & 250 & 300 & 350 & 400
\end{align*}

\begin{align*}
\langle N_{\text{part}} \rangle & \text{:} & 350 & 300 & 250 & 200 & 150 & 100 & 50 & 0 \\
\text{Centrality, } \% & \text{:} & 0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100
\end{align*}

- $\sqrt{s_{\text{NN}}}=7.7$ GeV
- $\sqrt{s_{\text{NN}}}=11.5$ GeV

Centrality Classes:

- 0.0\%-10.0\%
- 10.0\%-20.0\%
- 20.0\%-30.0\%
- 30.0\%-40.0\%
- 40.0\%-50.0\%
- 50.0\%-60.0\%
- 60.0\%-70.0\%
- 70.0\%-80.0\%
- 80.0\%-90.0\%
- 90.0\%-100.0\%
- 0\%-100\%
$N_{\text{coll}}$ distribution in centrality classes