Centrality determination in MPD using MC Glauber model

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Outline

- Introduction

- Fitting procedure using MC Glauber Centrality framework

- Comparison of the initial geometry parameters between models (UrQMD, SMASH, PHSD and MC Glauber)

- Comparison of the impact parameter distribution between MC Glauber used in Centrality framework and the new method proposed by R. Rogly and G. Giacalone

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
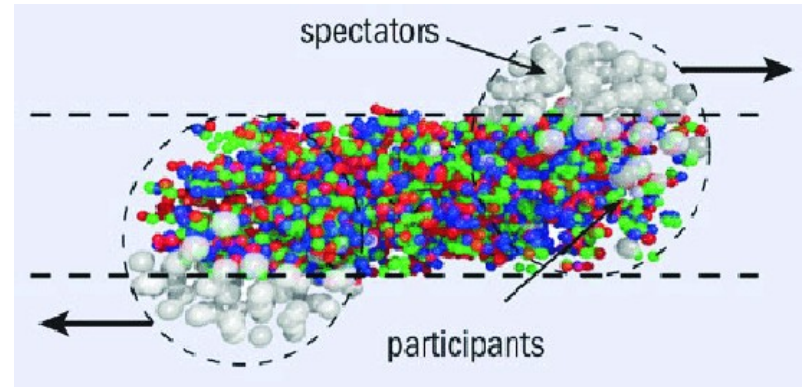
Application of the MC Glauber model in centrality determination in MPD experiment

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 [1]	4 weeks	Au+Au	160M 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
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

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 5

Centrality in STAR

- Uncorrected charged particle multiplicity distribution in TPC (|η|<0.5)

- Comparison with MC Glauber simulations

- Fitted using two-component model:

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

Similar centrality estimator is needed for comparisons with STAR
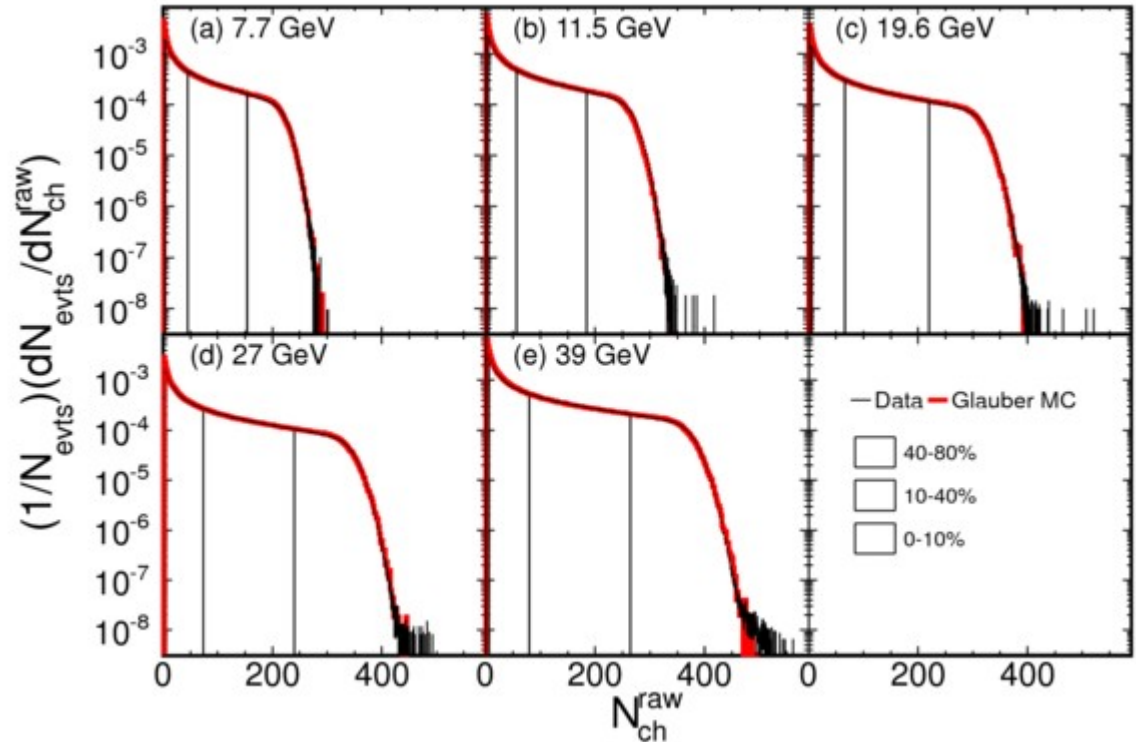
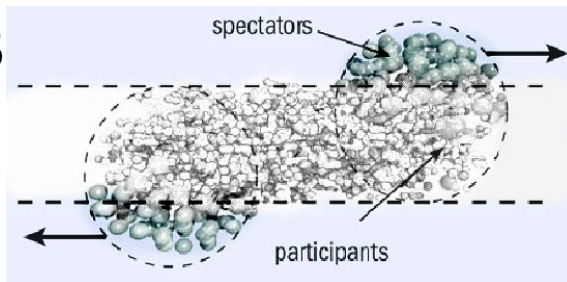Phys. Rev. C 86 (2012) 54908

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Centrality determination in MPD (NICA)

- Time Projection Chamber (TPC)

$|\eta|<1.5$
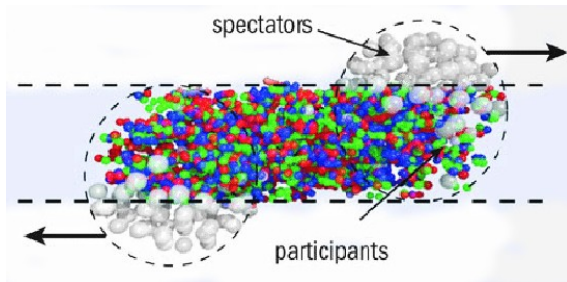
- Forward Hadron Calorimeter (FHCal)

$2<|\eta|<5$
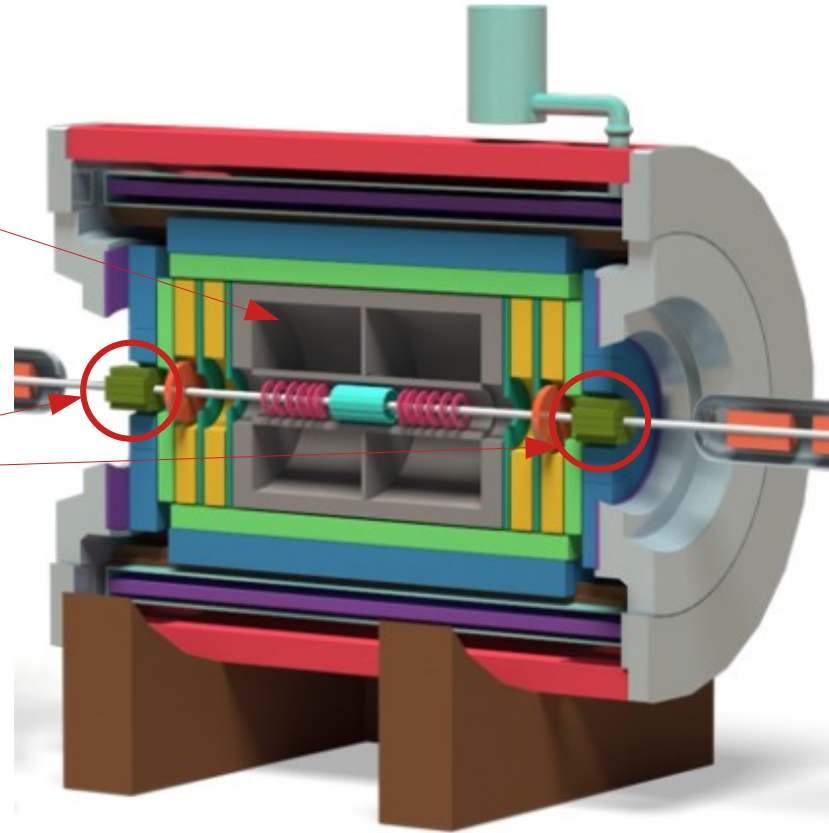
Charged particle multiplicity in MPD
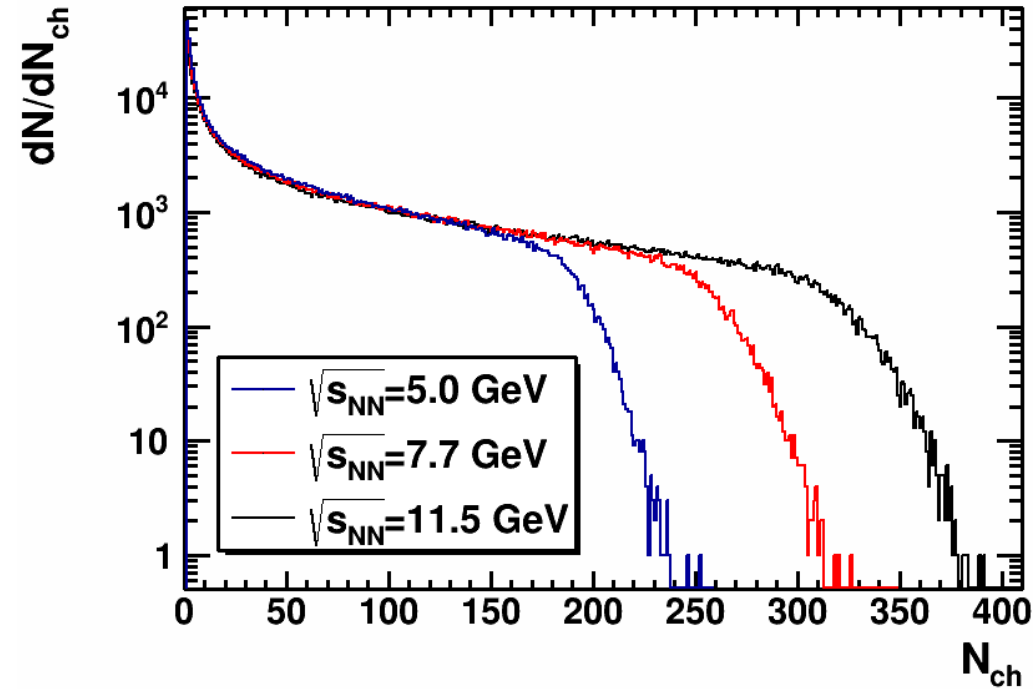
Reconstructed data:

- UrQMD 3.4 simulation
  - Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=5, 7.7, 11.5 GeV
- GEANT4 MPD detector simulation
- Reconstruction procedure:
  - Realistic tracking in TPC (Cluster Finder)

Used particle selection:

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

Integrating the CBM Centrality framework

```
┌─────────────────┐     ┌─────────────────────────────┐     ┌──────────────────┐          ┌──────────────────┐
│                 │     │      Evaluate $N_a$:        │     │      Call        │          │                  │
│ MC Glauber data │ ──▶ │ $N_a = fN_{part}+(1-f)N_{coll}$ │ ──▶ │ NBD(μ,k) x $N_a$ │     ──▶  │ Evaluate $\chi^2$ │
│                 │     │                             │     │                  │          │                  │
└─────────────────┘     └─────────────────────────────┘     └──────────────────┘          └──────────────────┘
                                                                      │                             │
                                                                      ▼                             ▼
                                                            ┌──────────────────┐          ┌──────────────────┐
                                                            │ Build multiplicity│         │ Minimize $\chi^2$ to find│
                                                            │ fitting function │          │      f, μ, k     │
                                                            └──────────────────┘          └──────────────────┘
┌──────────────────┐
│ Input multiplicity│
│   distribution   │
└──────────────────┘
```
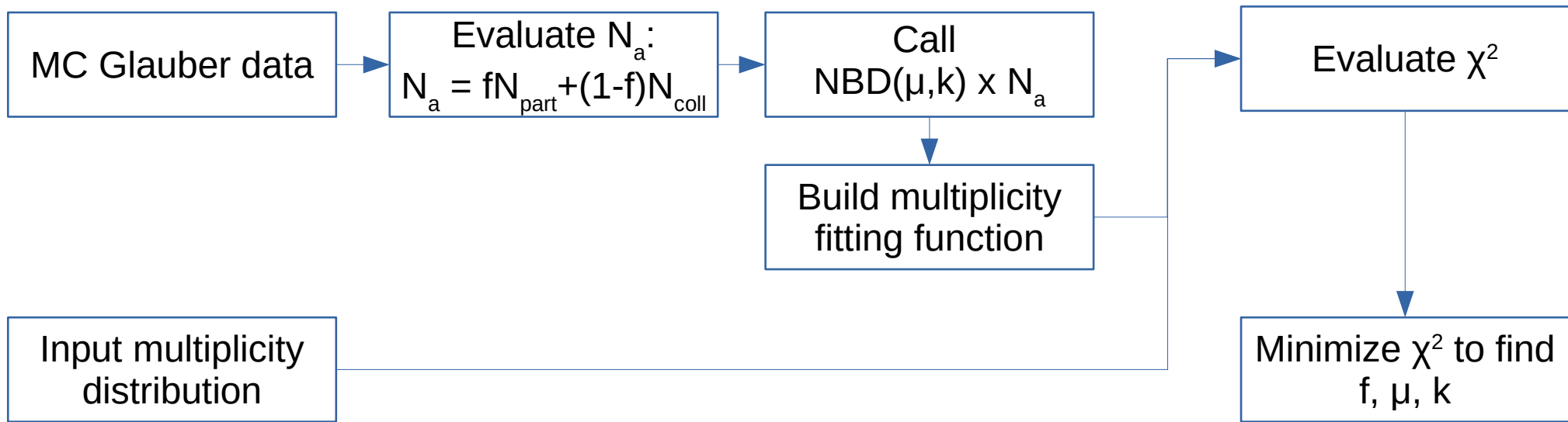

This centrality procedure was used in CBM, NA49, and NA61/SHINE:
     Acta Phys.Polon.Supp. 10 (2017) 919
     EPJ Web Conf. 182 (2018) 02132
Implemantation in MPD: https://github.com/IlyaSegal/NICA

Lubynets O., Selyuzhenkov I., Klochkov V. 33-rd CBM CM
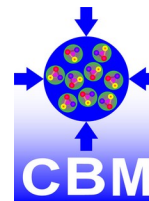
Glauber Model configuration

C. Loizides, J. Nagle and P. Steinberg, SoftwareX 1-2 (2015) 13-18
Used TGlauberMC-3.2 version from tglaubermc.hepforge.org

Input to the model

- Inelastic NN cross section

  – σ_{NN}=29.3 mb for $\sqrt{s_{NN}}$=5.0 GeV

  – σ_{NN}=29.7 mb for $\sqrt{s_{NN}}$=7.7 GeV

  – σ_{NN}=31.2 mb for $\sqrt{s_{NN}}$=11.5 GeV

- Colliding nuclei

  – "Au(197,79)"+"Au(197,79)"

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

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.

Centrality framework configuration

NBD Equation:

$$P_{\mu,k}(n) = \frac{\frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \cdot \left(\mu/k\right)^n}{\left(\mu/k + 1\right)^{n+k}}$$

Fitting function for charged particle multiplicity:

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

Normalization of the total number of events:

$$\frac{N_{ev}^{reco}}{N_{ev}^{MC\,Glauber}} = \frac{1}{10}$$

Parameter range:

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

Fitting region:

$$N_{ch} = \begin{cases} (10-235), & \sqrt{s_{NN}} = 5.\,GeV \\ (20-310), & \sqrt{s_{NN}} = 7.7\,GeV \\ (15-380), & \sqrt{s_{NN}} = 11.5\,GeV \end{cases}$$

Fit parameters f,k vs χ²
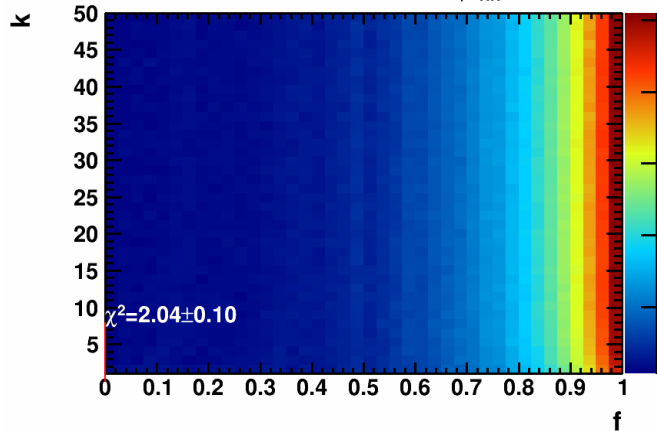
f=0, k=8, μ=0.23, χ²=2.04±0.10, M=(10,235)

f=0, k=14, μ=0.31, χ²=1.46±0.12, M=(20,310)

f=0.24, k=2, μ=0.71, χ²=1.24±0.06, M=(15,380)

χ² vs f,k for UrQMD, Au+Au, $\sqrt{s_{NN}}$=5.0 GeV

χ² vs f,k for UrQMD, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV

χ² vs f,k for UrQMD, Au+Au, $\sqrt{s_{NN}}$=11.5 GeV

χ²=2.04±0.10
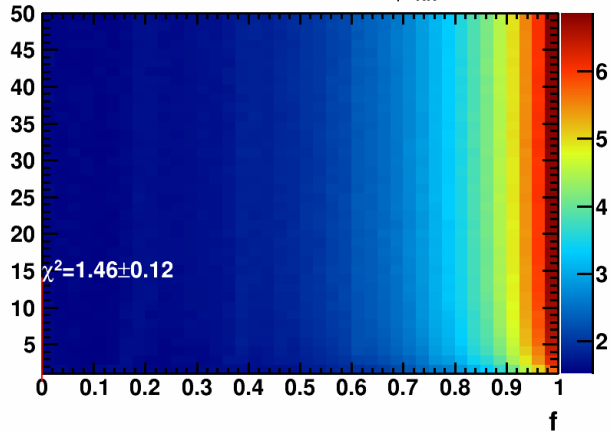
χ²=1.46±0.12

χ²=1.24±0.06

MC Glauber fit: $h^{\pm}$ multiplicity

f=0, k=14, μ=0.31, χ^2=1.46±0.12, M=(20,310)

UrQMD, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV
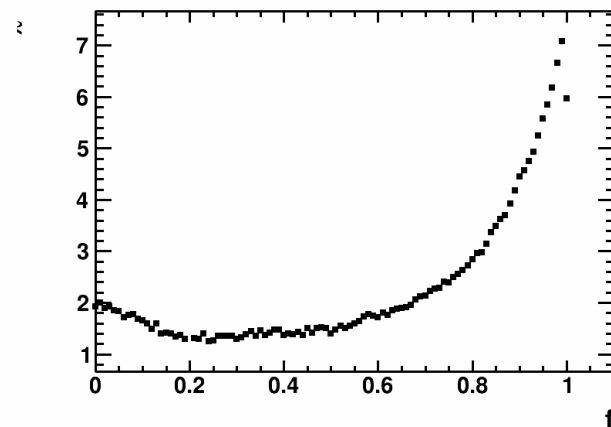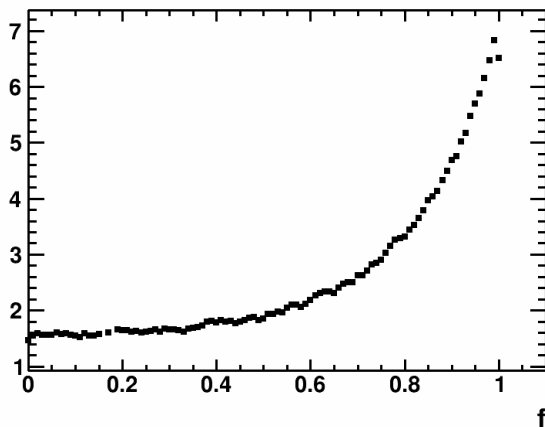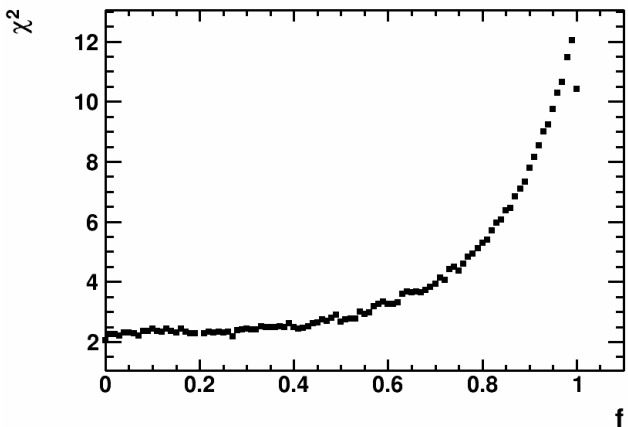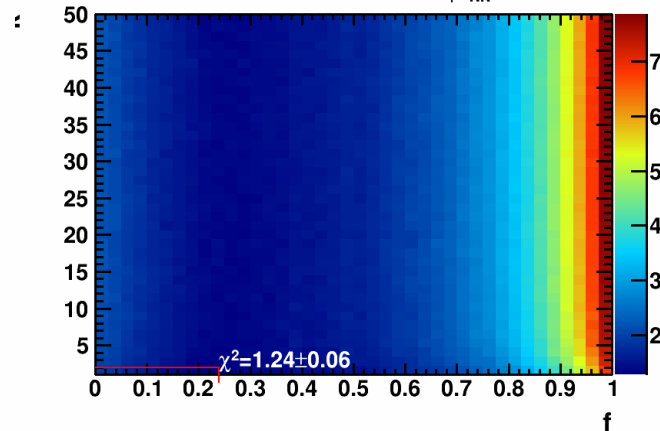
Glauber fit: f = 0.00; k = 14; M = [20,310]

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

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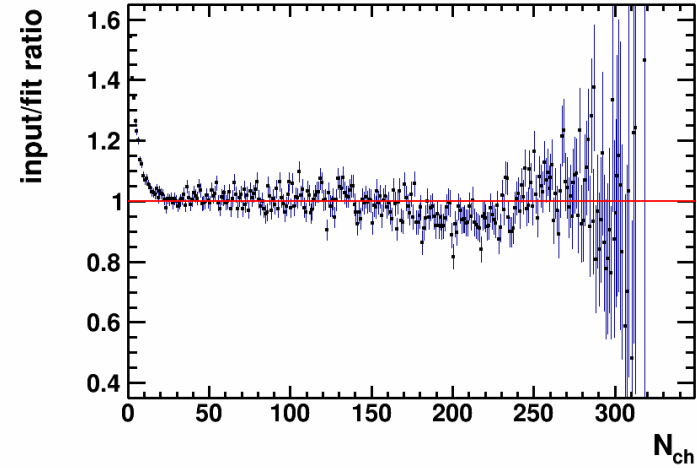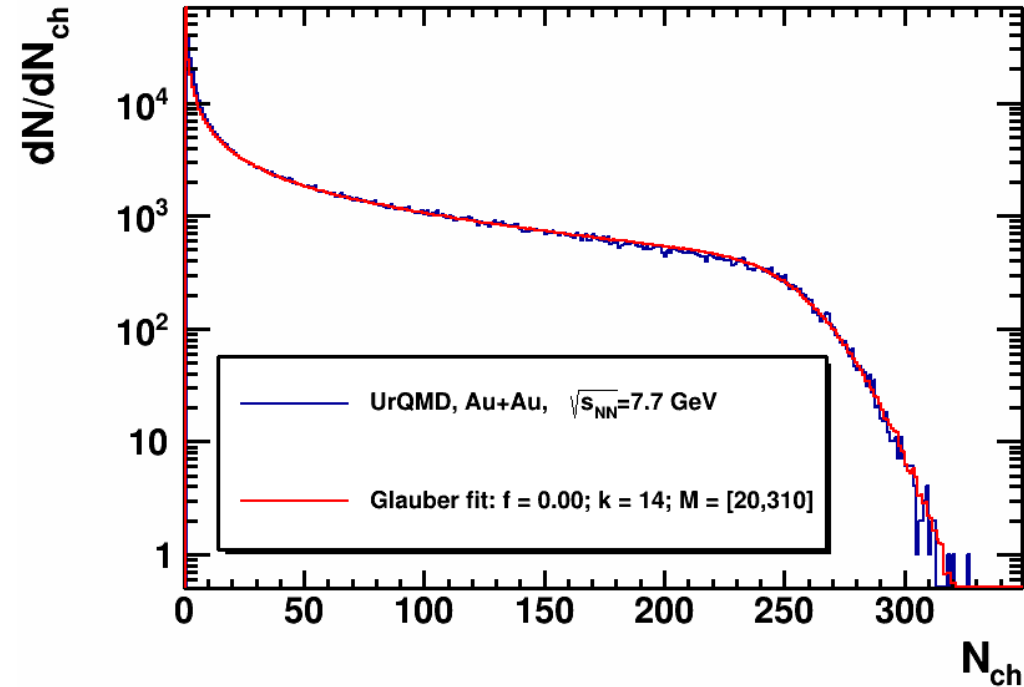
MC Glauber fit: $h^{\pm}$ multiplicity

f=0.24, k=2, μ=0.71, χ^2=1.24±0.06, M=(15,380)
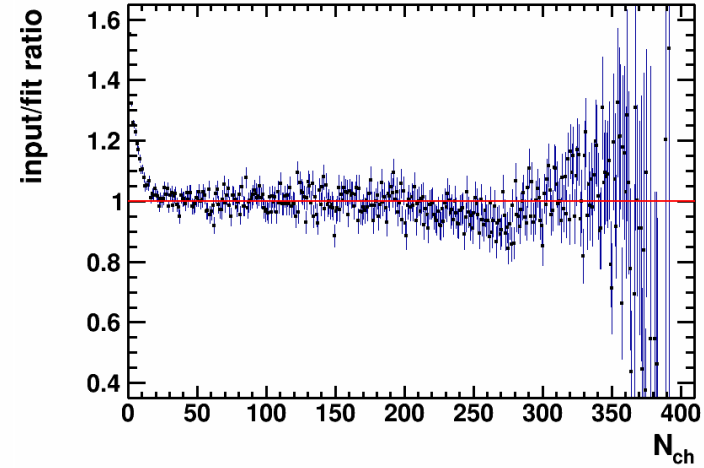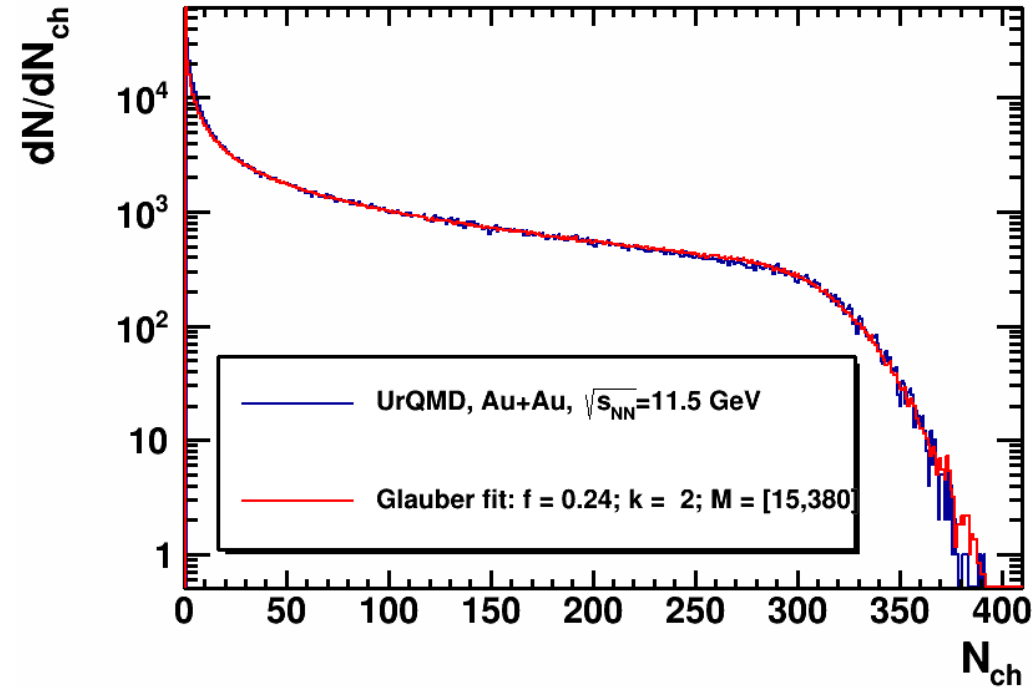
MC Glauber fit is in the good agreement with simulated input for the large multiplicity region

B vs N$_{ch}$ & N$_{ch}$ centrality classes
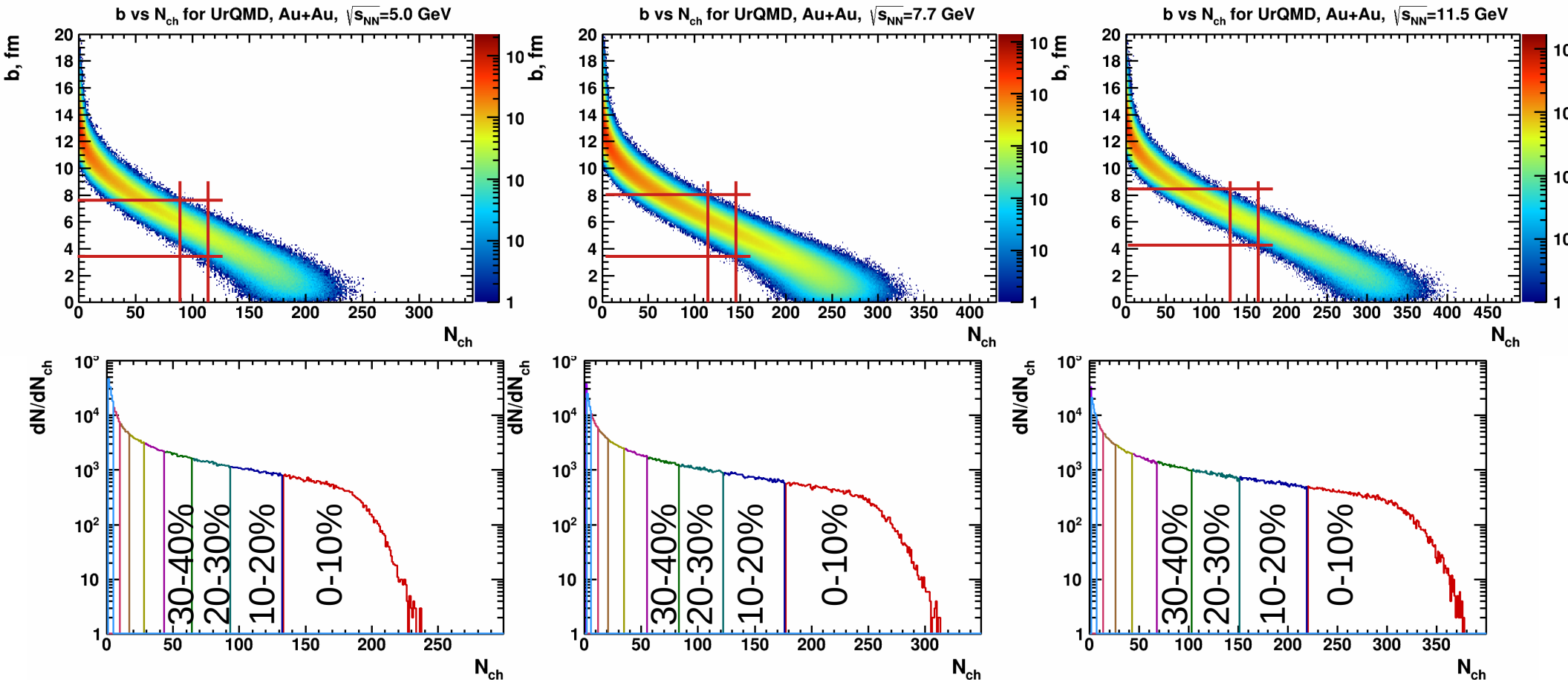
b vs N$_{ch}$ for UrQMD, Au+Au, $\sqrt{s_{NN}}$=5.0 GeV

b vs N$_{ch}$ for UrQMD, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV

b vs N$_{ch}$ for UrQMD, Au+Au, $\sqrt{s_{NN}}$=11.5 GeV

Events in multiplicities M ± ΔM have impact parameter in range b ± σ$_b$

b distribution in centrality classes

N$_{part}$ distribution in centrality classes

$\sqrt{s_{NN}}$=5 GeV

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

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

Legend:
- 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%

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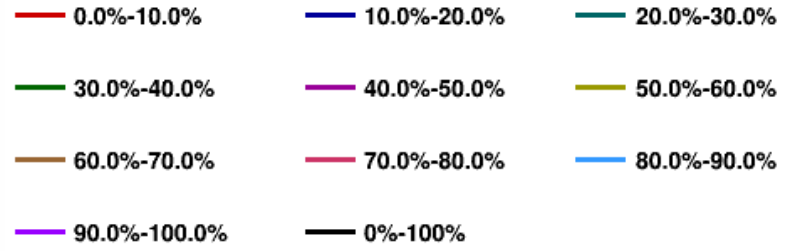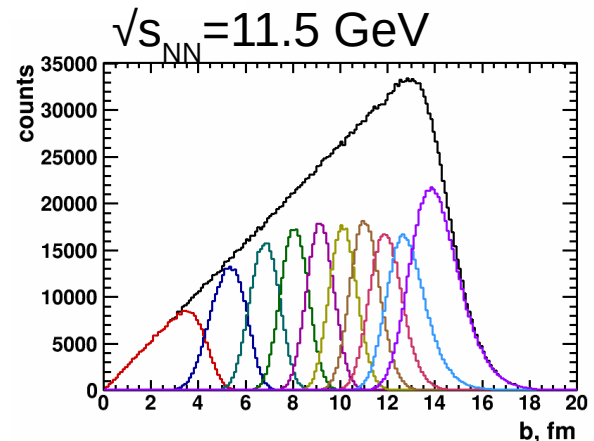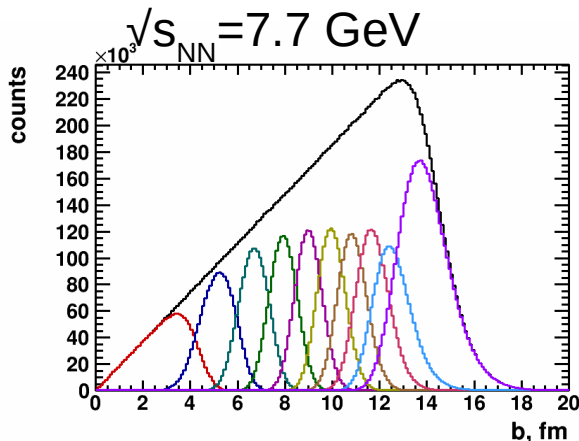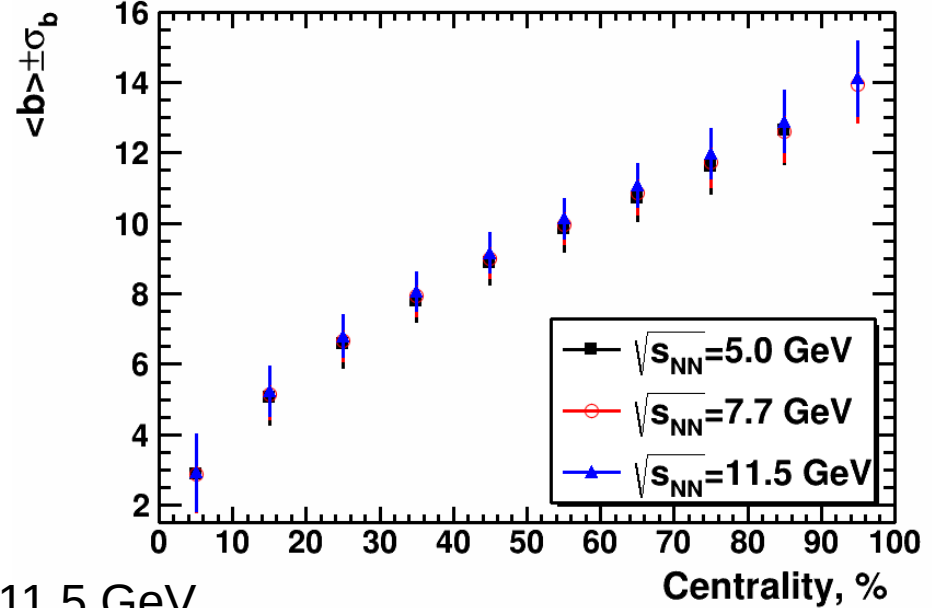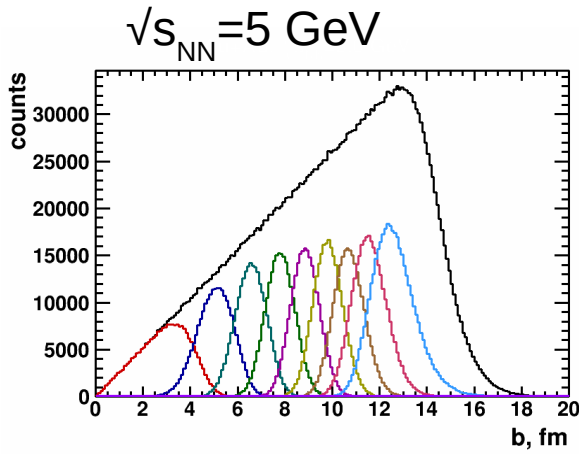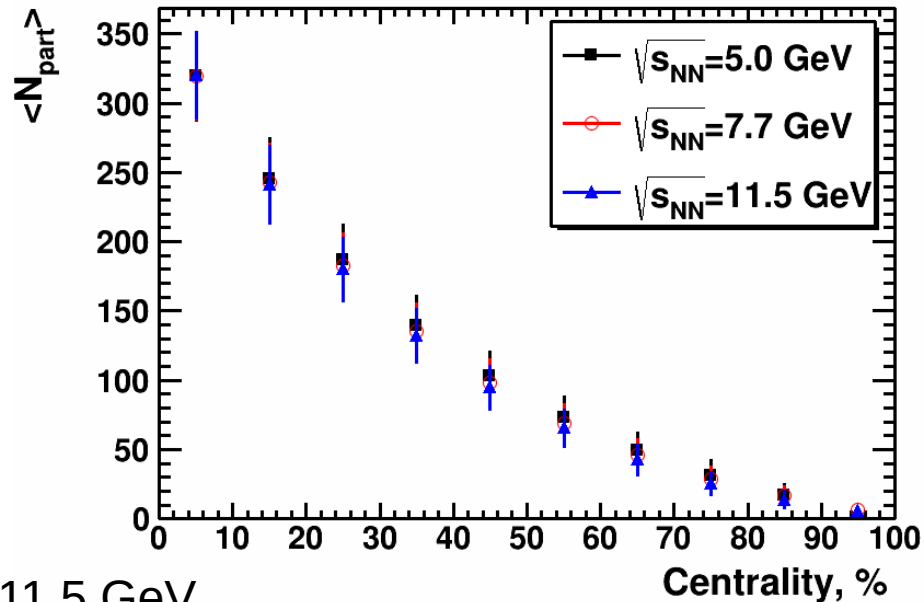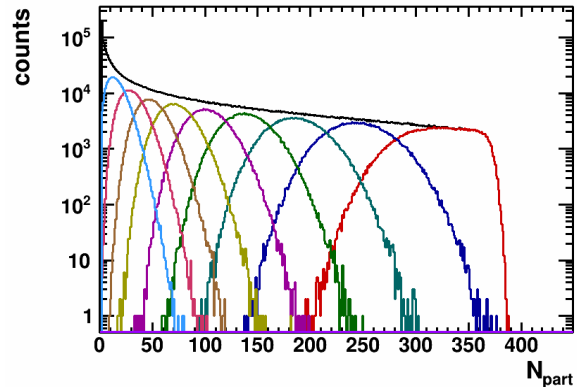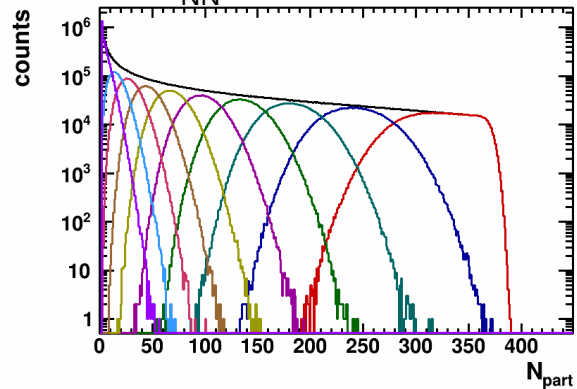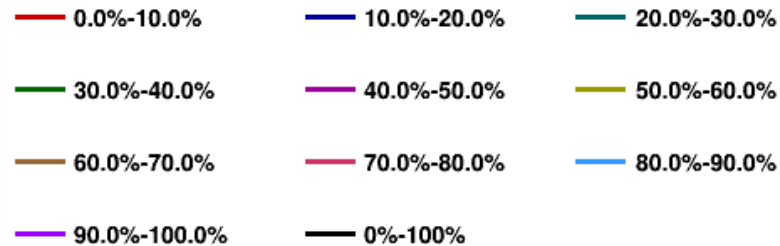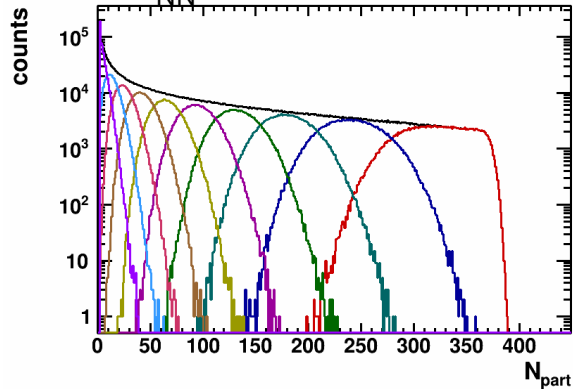
N$_{coll}$ distribution in centrality classes

√s$_{NN}$=5 GeV
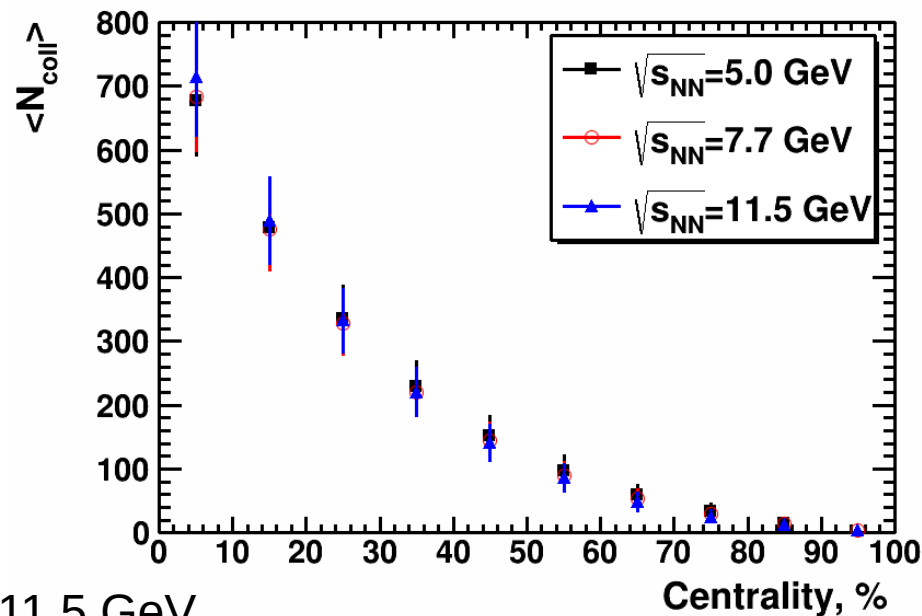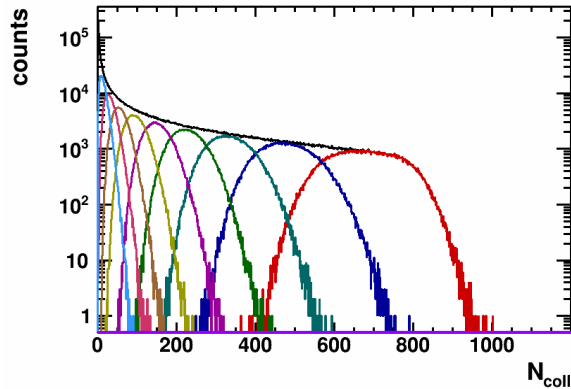
√s$_{NN}$=7.7 GeV
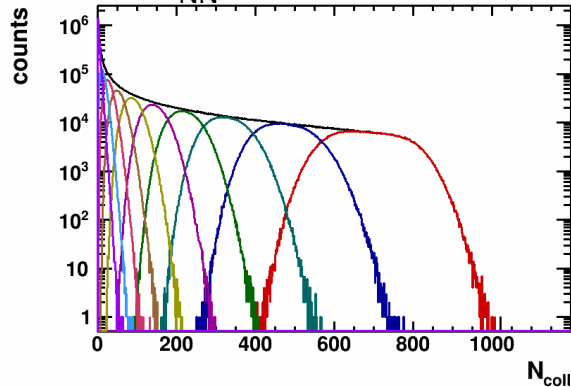
√s$_{NN}$=11.5 GeV
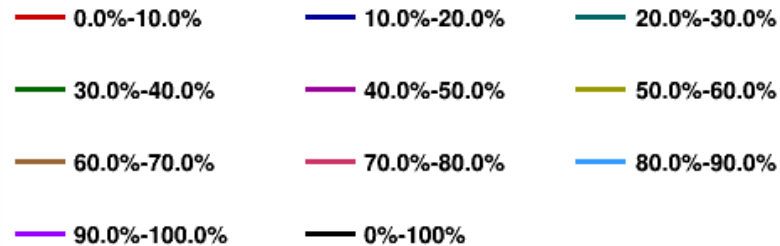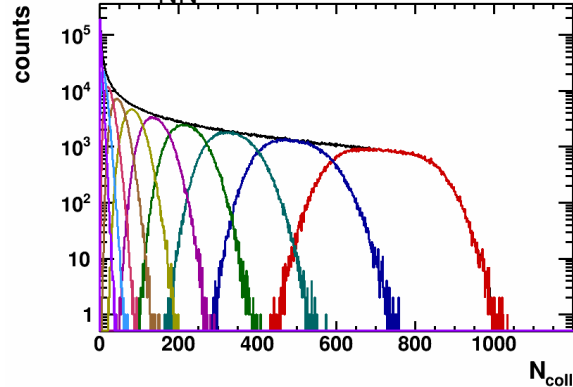
Comparison of the UrQMD, PHSD, SMASH and MC Glauber parameters

Generated vs reconstructed UrQMD
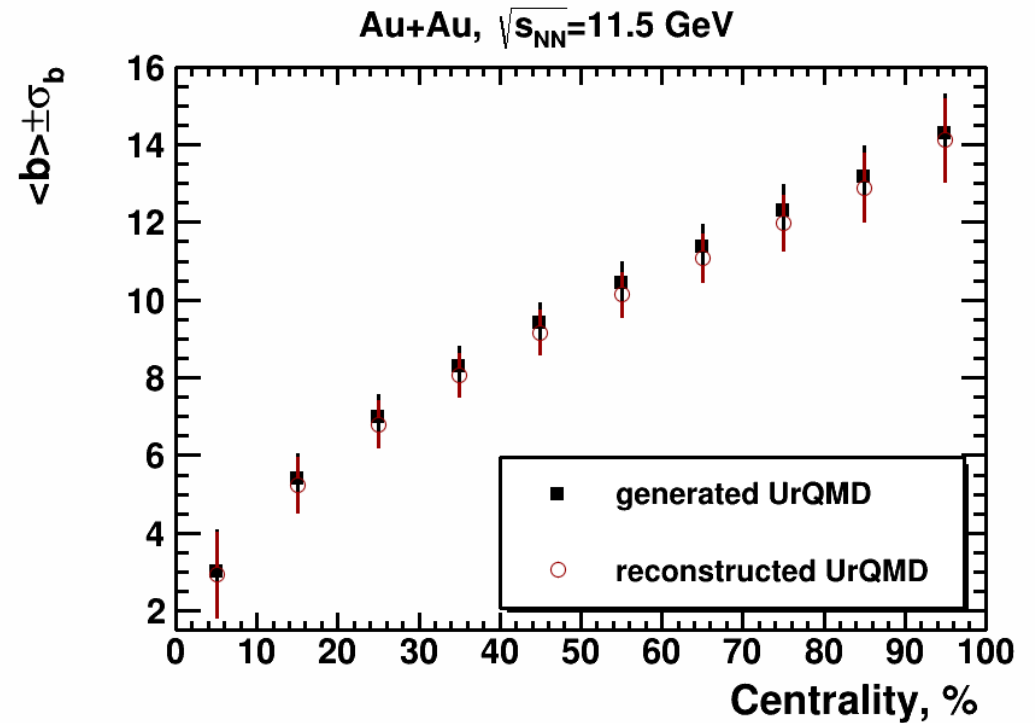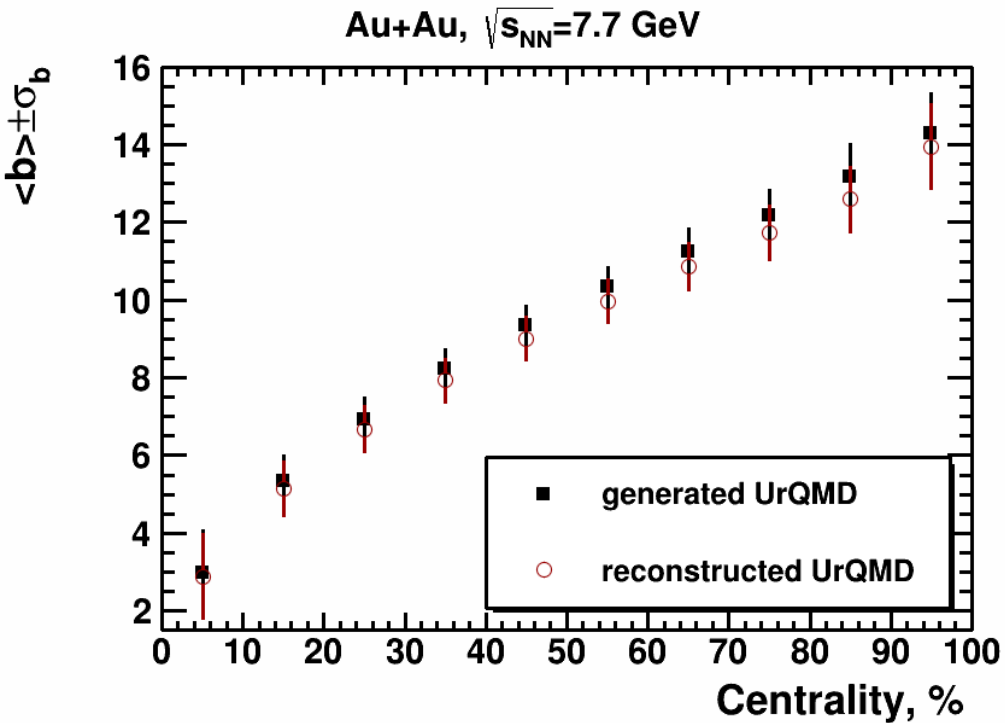
Reasonable agreement between reconstructed data and pure model

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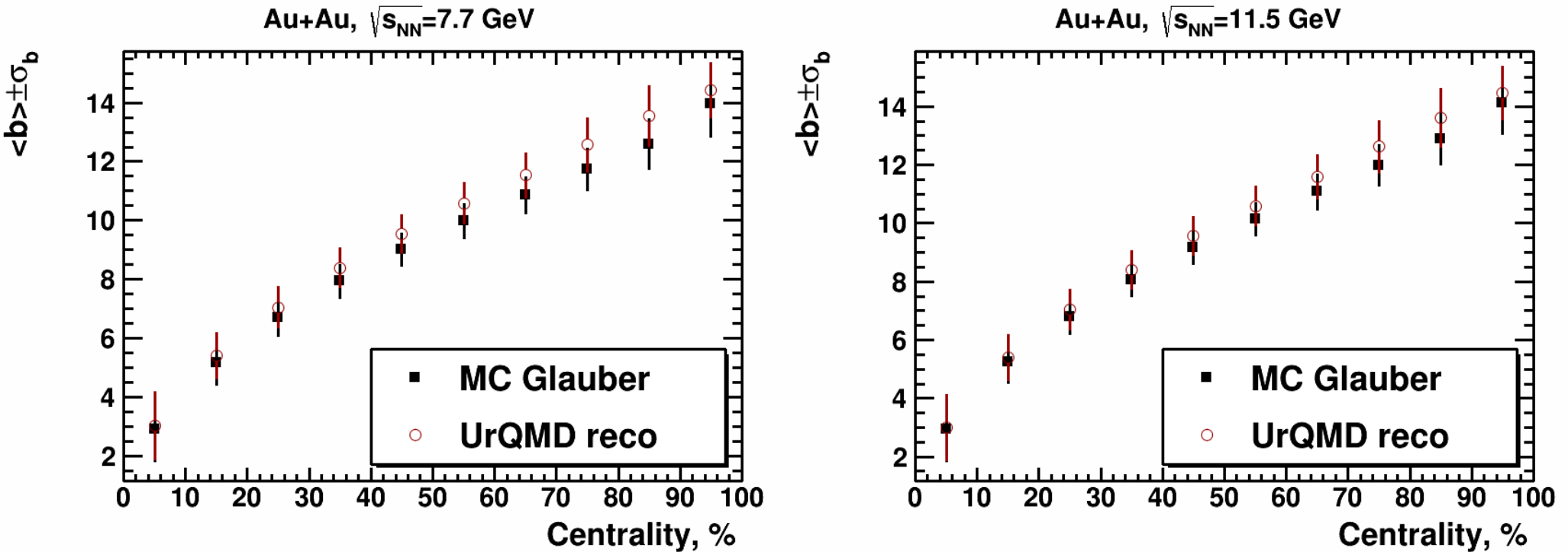
Reasonable agreement between MC Glauber and UrQMD

b vs centrality: Glauber vs PHSD
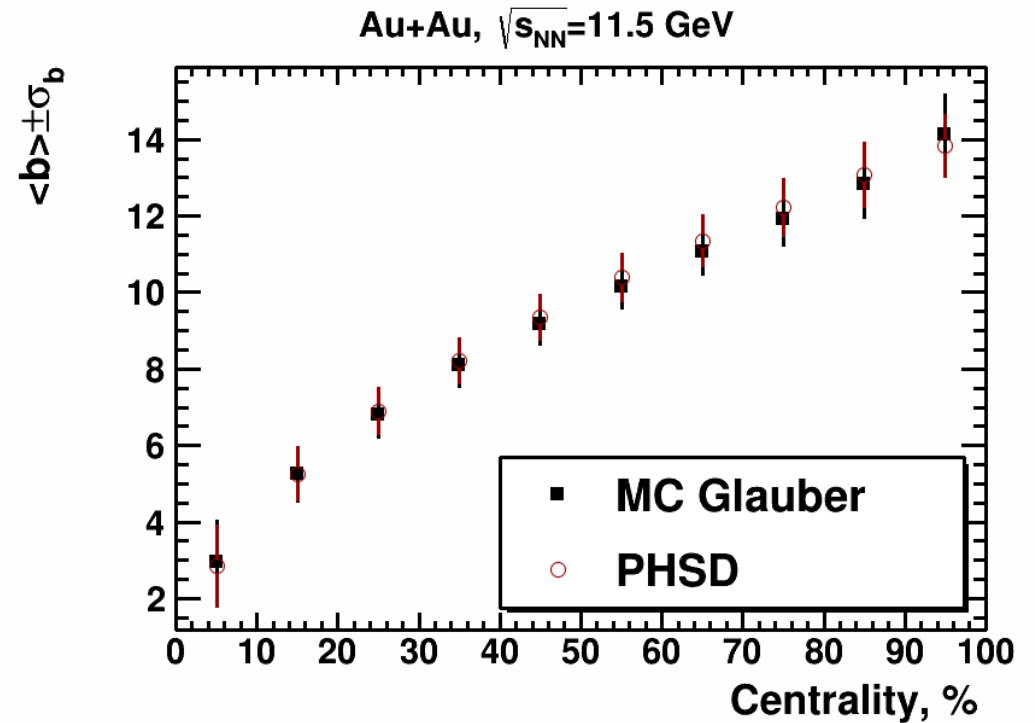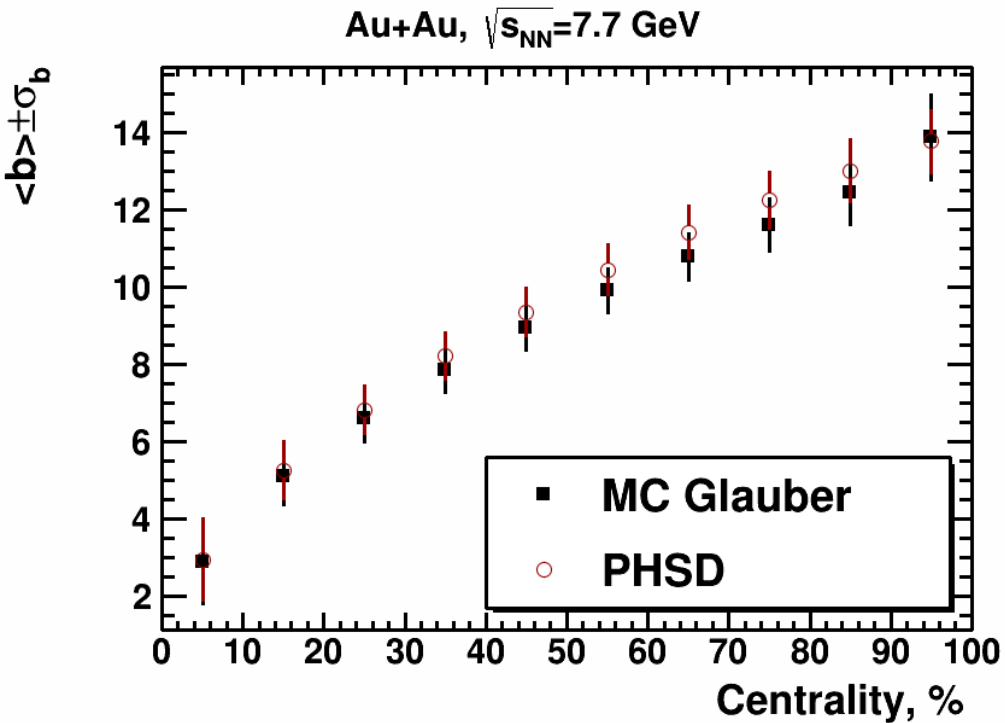
b vs centrality: all models

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

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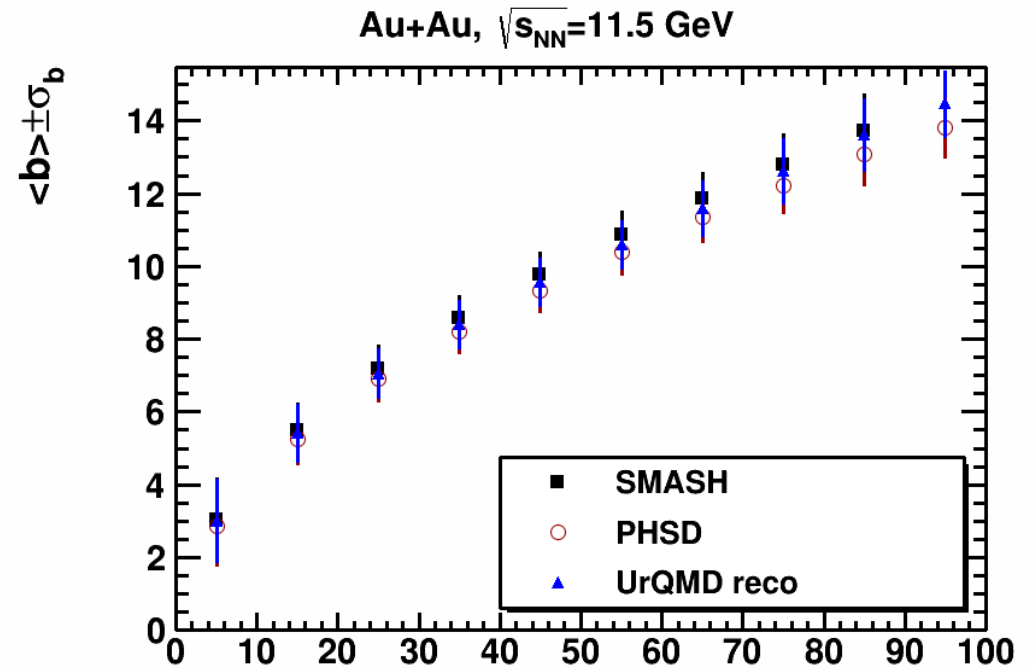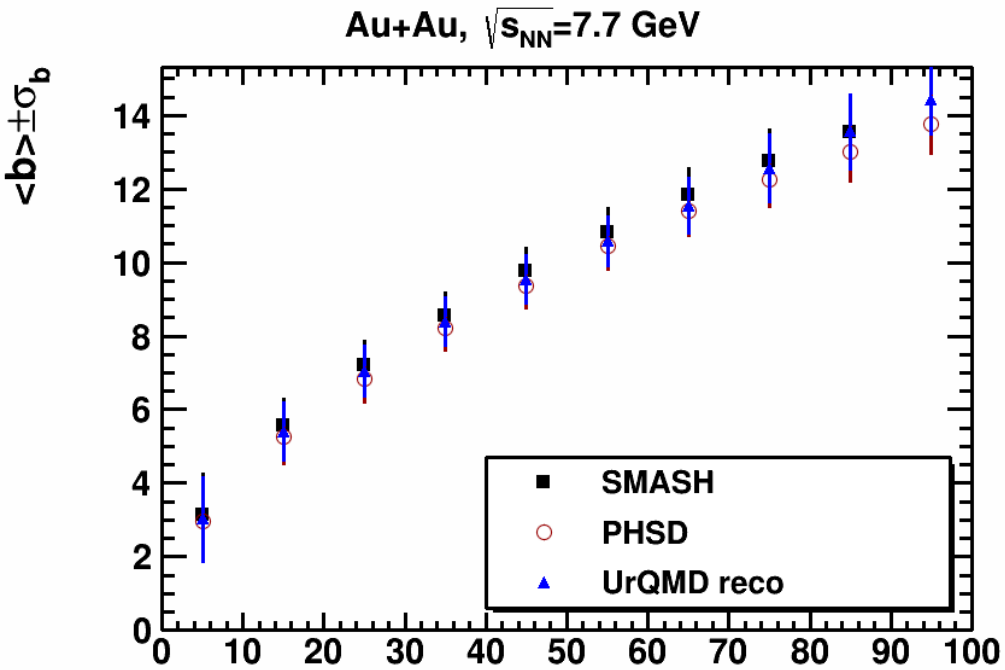
N$_{part}$ vs b: all models

Eccentricity ε_n

B. Schenke, et al.
PRC 89, 064908 (2014)
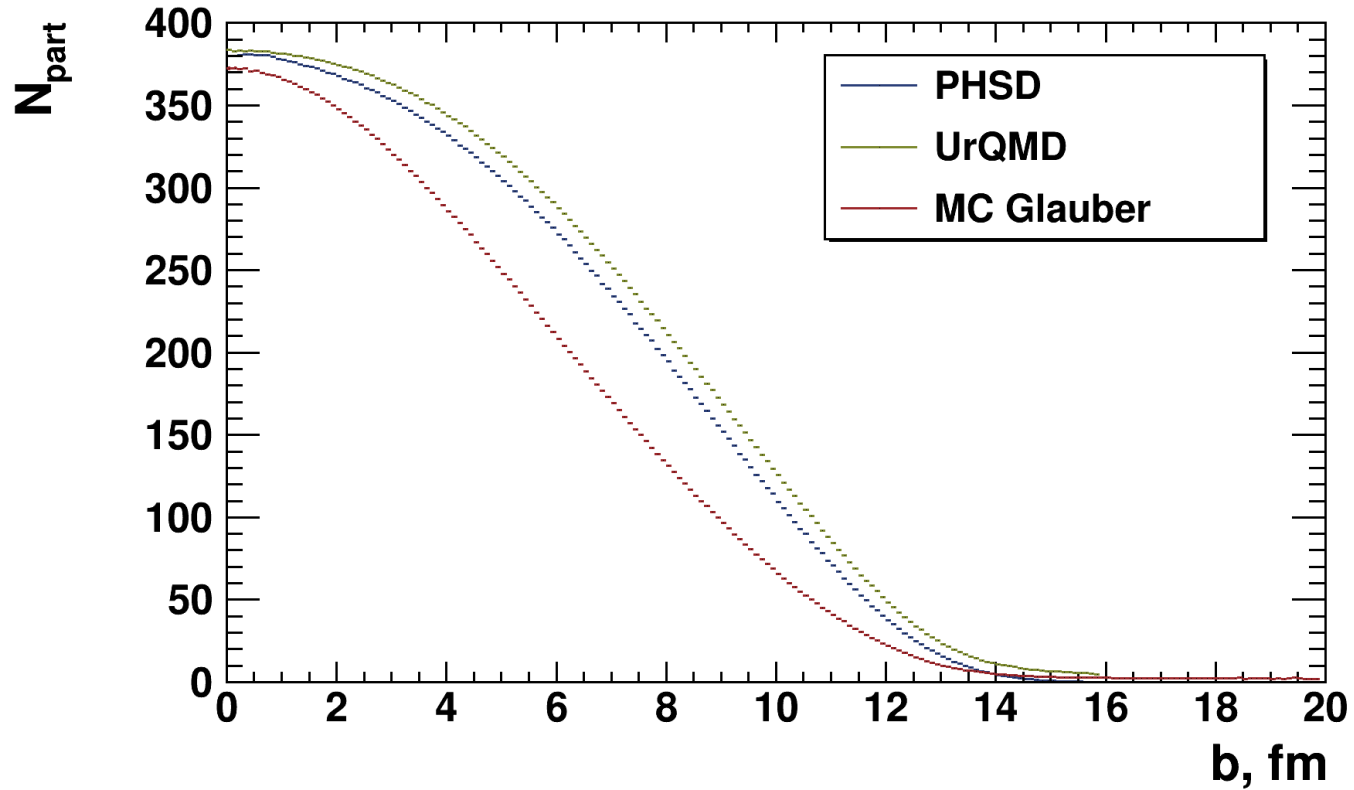
- Eccentricity characterizes initial-state spatial anisotropy

- In MC Glauber, ε_n defined as a ε_{part} in the center-of-mass system of the participant nuclei (Phys.Rev. C81 (2010) 054905):

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

- ε_2 is system dependent

- ε_3 is system independent

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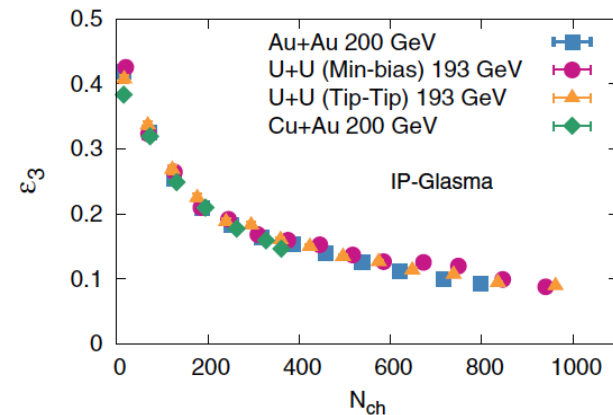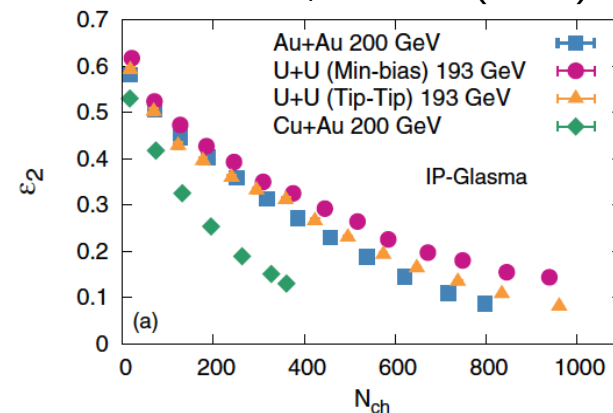
Eccentricity: Comparison w/ UrQMD
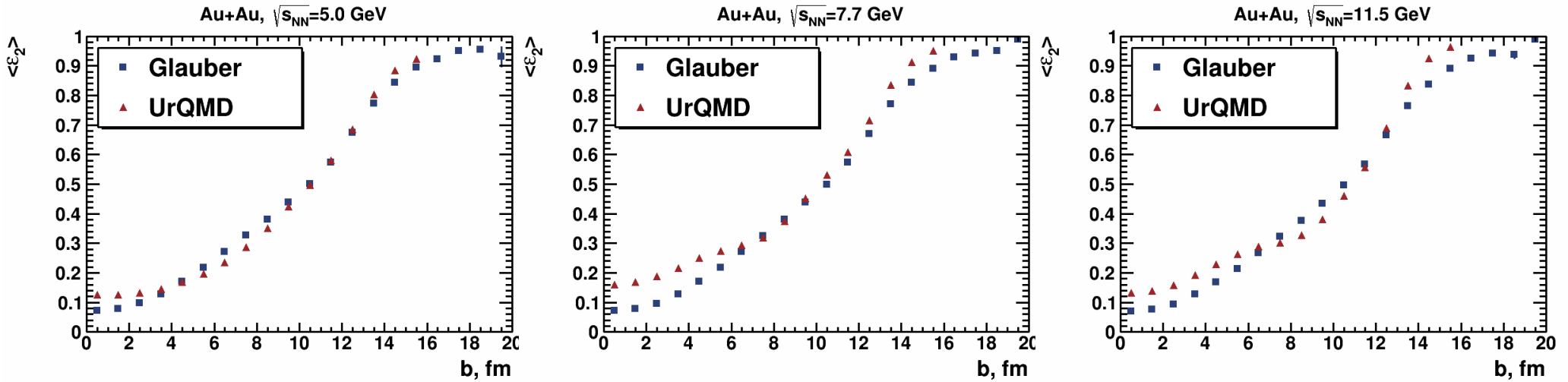
Notable difference between MC Glauber and UrQMD eccentricities

ε_3: Comparison w/ UrQMD
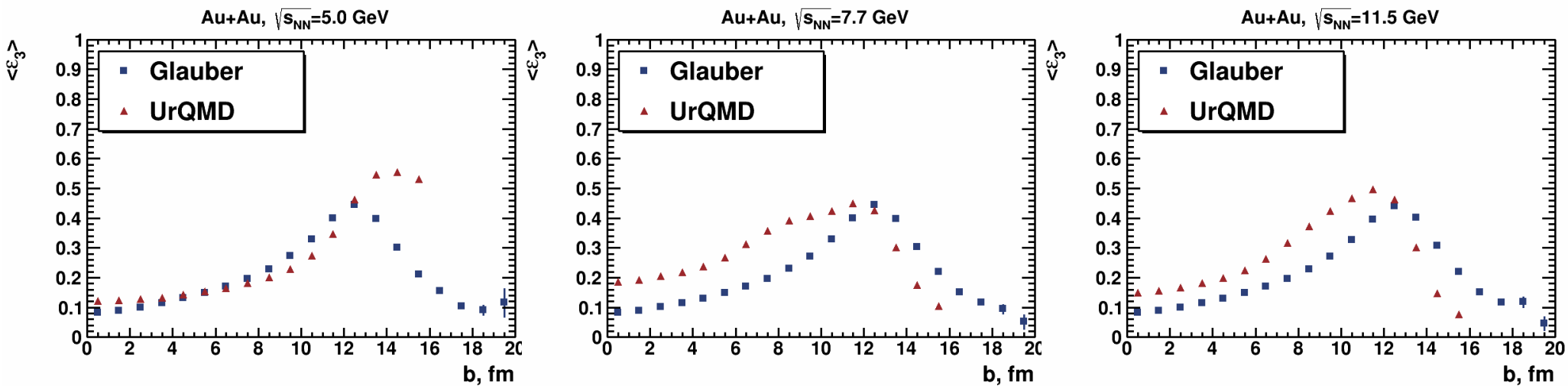
Notable difference between MC Glauber and UrQMD

ε_n: UrQMD at different $\sqrt{s}_{NN}$
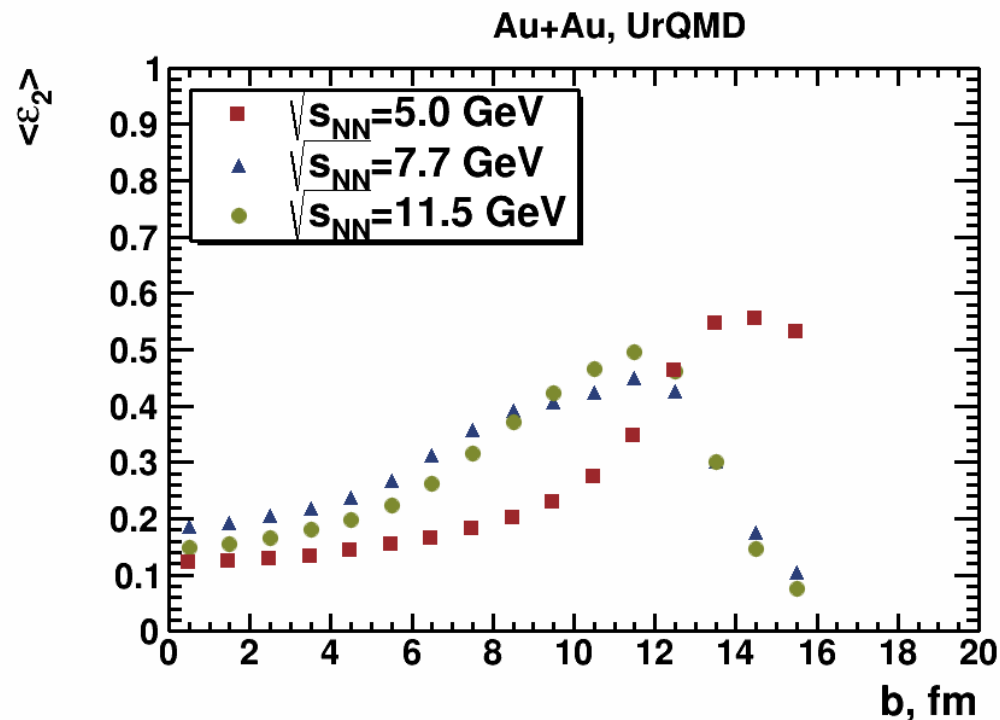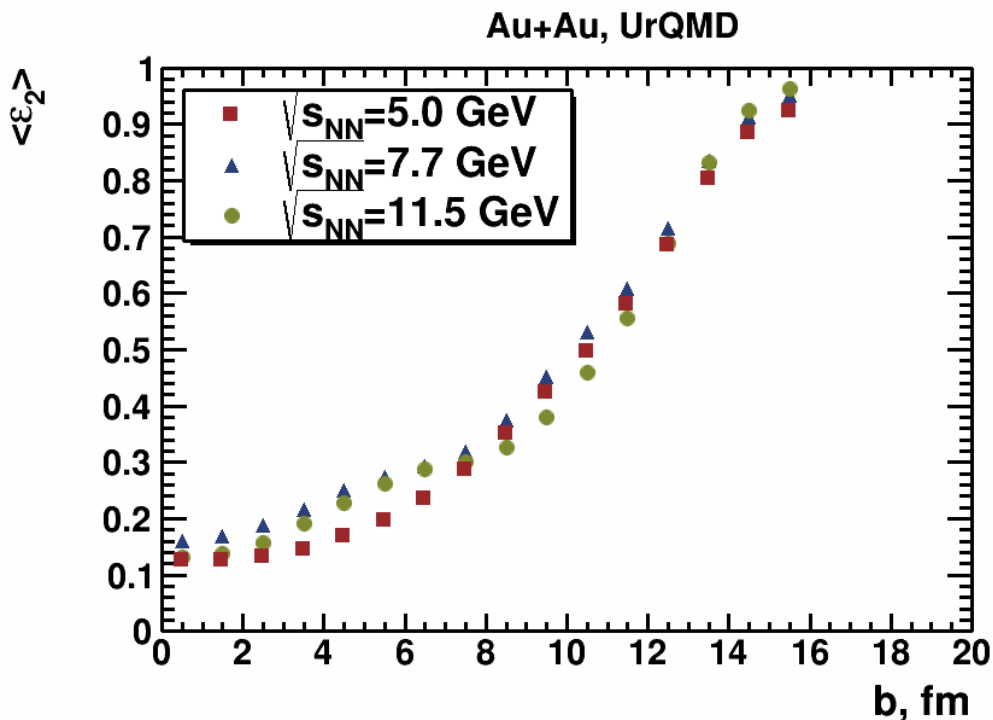
Notible difference for ε_3 at $\sqrt{s}_{NN}$= 5 GeV for UrQMD

ε_n: MC Glauber at different $\sqrt{s_{NN}}$
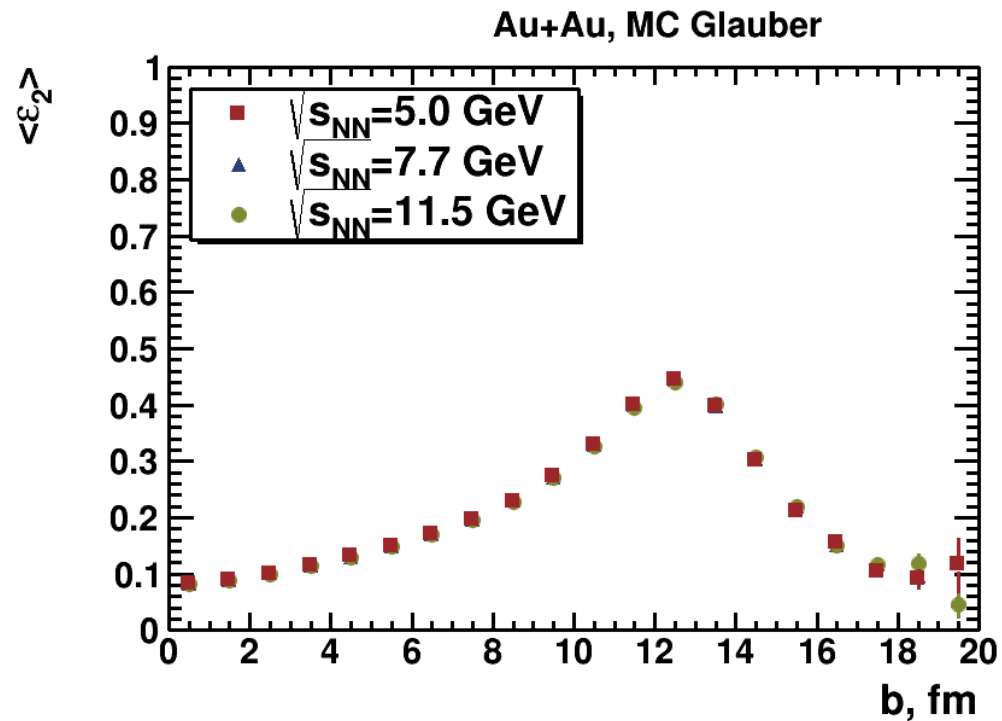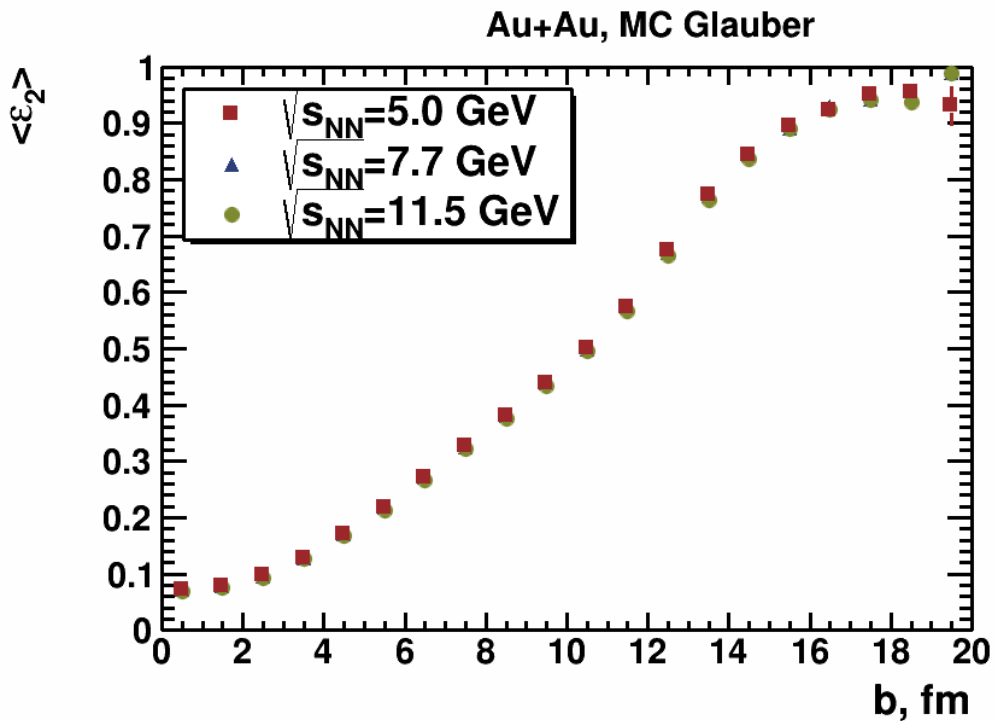
No notible difference for ε_3 for MC Glauber

Eccentricity comparison: ε_2

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

Glauber
UrQMD
PHSD

$\langle \varepsilon_2 \rangle$

b, fm

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

MC Glauber
UrQMD
PHSD

ε_2

Centrality, %
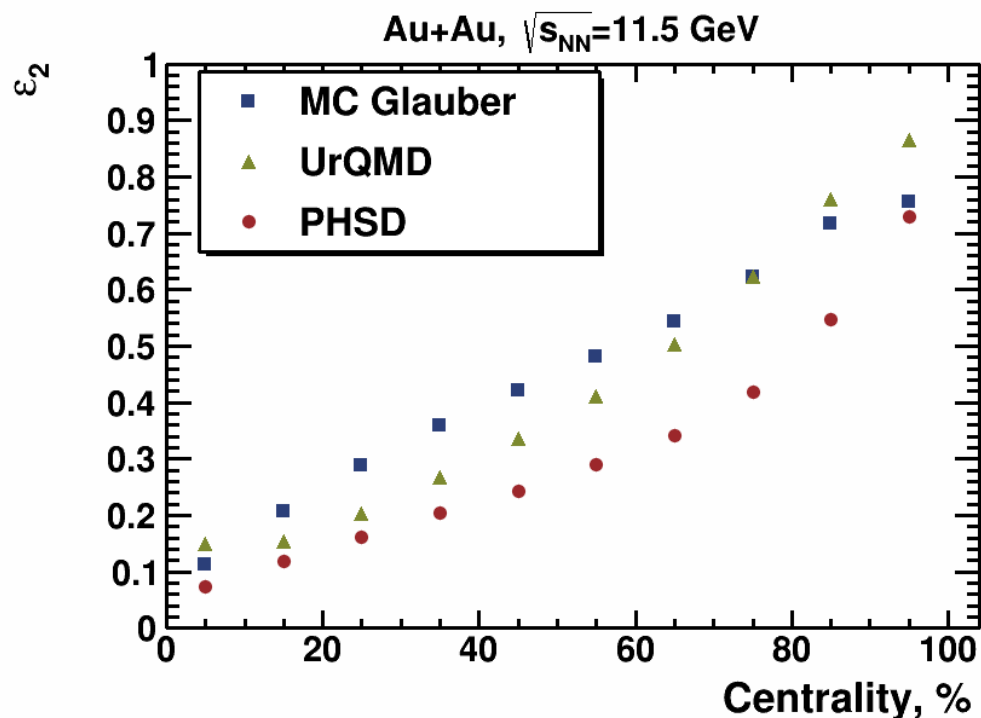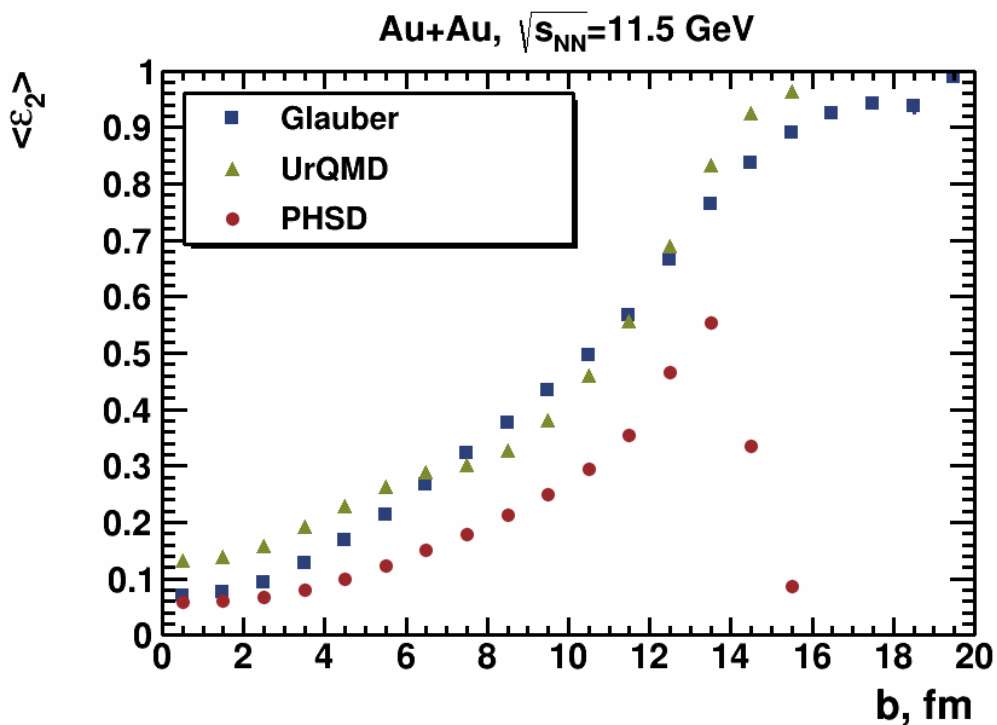
Eccentricity comparison: ε_3
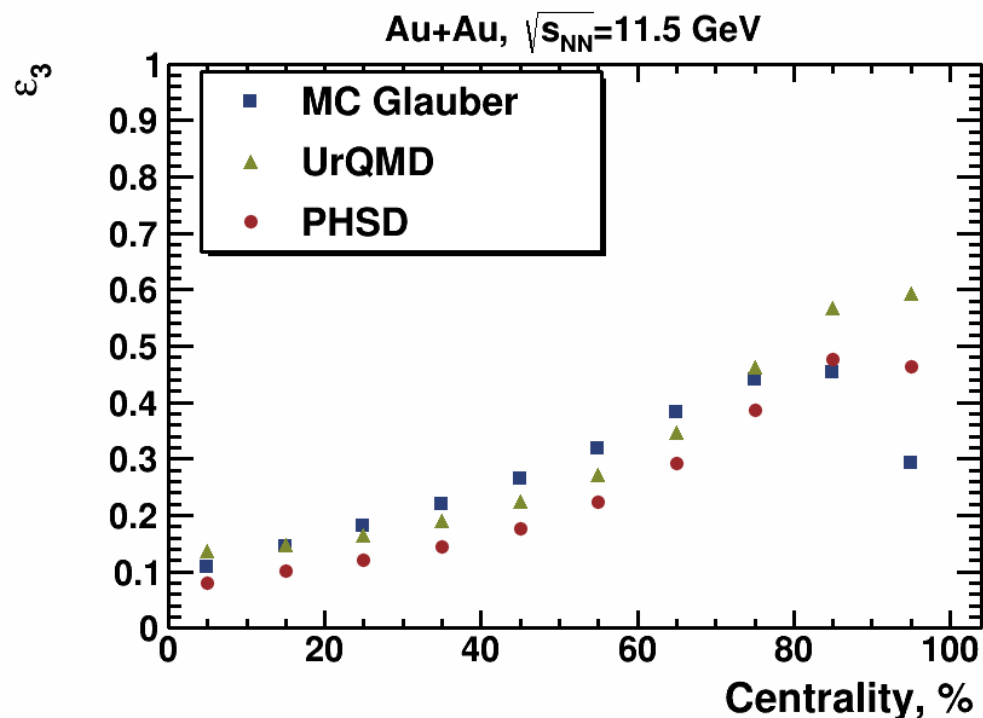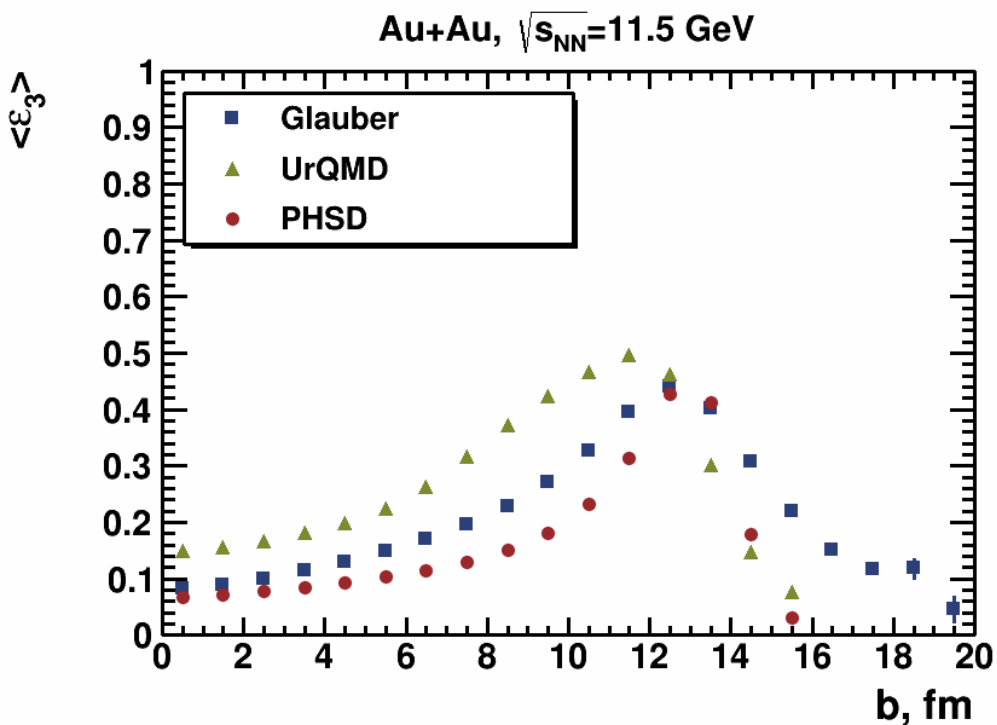
Reconstructing the impact parameter of nucleus-nucleus collisions

based on the work of R. Rogly and G. Giacalone

N$_{ch}$ to *b* correlation

Probability of N_{ch} for fixed b:

-Gaussian approach
(Phys.Rev. C97 (2018) no.1, 014905):

$$P(N_{ch}|c_b) = \frac{1}{\sigma(c_b)} \exp\left(\frac{-(N_{ch} - \overline{N_{ch}})^2}{2\,\sigma(c_b)^2}\right)$$

-Approach using gamma distribution
(Phys.Rev. C98 (2018) no.2, 024902):

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

where c_b − centrality defined from impact parameter:

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

Phys.Rev. C97 (2018) no.1, 014905

Phys.Rev. C98 (2018) no.2, 024902

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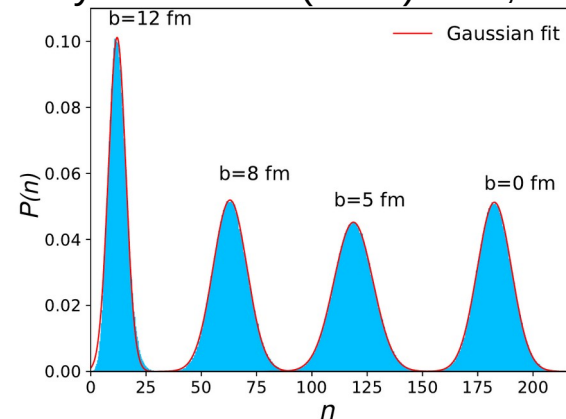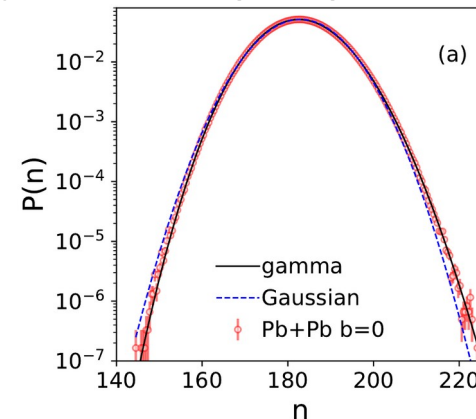
Fit function

Probability function for multiplicity distribution:

$$P(N_{ch}) = \int\limits_{0}^{1} P(N_{ch}|c_b)\,dc_b$$

Parameters for Gaussian approach:

$$\overline{N_{ch}}(c_b) = N_{knee}\cdot\exp\left(-\sum_{i=1}^{3} a_i c_b^i\right), \quad \sigma(c_b) = \sigma(0)\sqrt{\frac{\overline{N_{ch}(c_b)}}{N_{ch}(0)}}$$

Free parameters: $N_{knee}, \sigma(0), a_i$.

Parameters for gamma-function approach:

$$k(c_b) = k_{max}\cdot\exp\left(-\sum_{i=1}^{4} a_i c_b^i\right), \quad \theta = const \quad \left(k(c_b)\,\theta \equiv \overline{N_{ch}}(c_b), \quad \sqrt{k(0)}\,\theta \equiv \sigma(0)\right)$$

Free parameters: k_{max}, θ, a_i.

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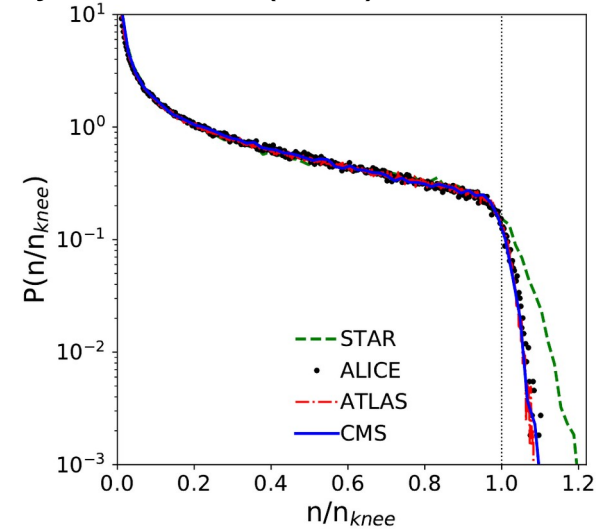
Reconstruction of *b*

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

$$P(b|N_{ch}) = \frac{P(N_{ch}|b)P(b)}{P(n)} = \frac{P(N_{ch}|c_b)\frac{2\pi b}{\sigma_{inel}}P_{inel}(b)}{P(n)} = \frac{2\pi b}{\sigma_{inel}P(n)}P(N_{ch}|b),$$

where $P_{inel}(b) \simeq 1$, $\sigma_{inel} = 685\,fm^2$, $c_b \simeq \frac{\pi b^2}{\sigma_{inel}}$

Experimental centrality:

$$c(N_{ch}) = \int_{N_{ch}}^{\infty} P(N'_{ch})\,dN'_{ch}$$

Main steps to reconstruct *b* from N$_{ch}$:

- Fit normalized multiplicity distribution with P(N$_{ch}$)

- Define centrality c(N$_{ch}$)

- Construct P(*b*|N$_{ch}$) using Bayes' theorem using parameters from the fit

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Gaussian approach: fitting procedure

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

χ^2 / ndf	502.6 / 408
p0	22.3 $\pm$ 0.3527
p1	373.6 $\pm$ 0.4615
p2	4.238 $\pm$ 0.02696
p3	$-$1.871 $\pm$ 0.1047
p4	3.743 $\pm$ 0.1154

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

χ^2 / ndf	627.2 / 510
p0	26.73 $\pm$ 0.4445
p1	460.7 $\pm$ 0.5576
p2	4.245 $\pm$ 0.02586
p3	$-$1.937 $\pm$ 0.09623
p4	3.806 $\pm$ 0.1016
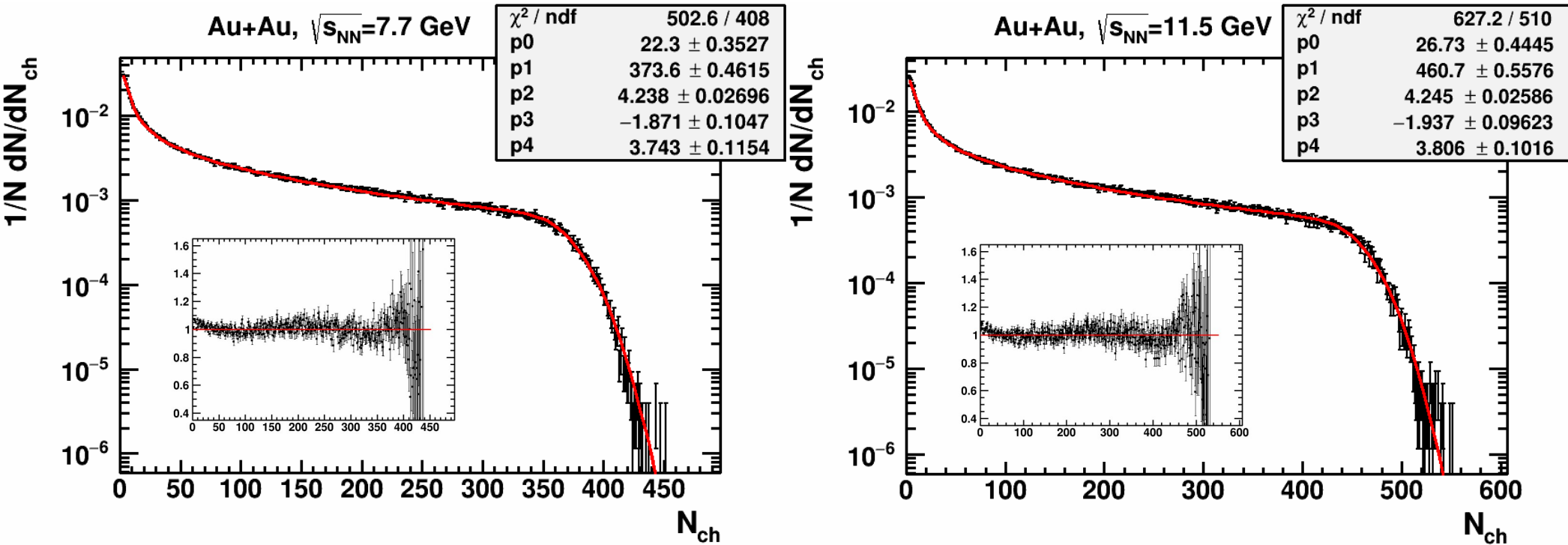
Fit reproduces charge particle multiplicity from pure UrQMD

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Gaussian approach: *b* distribution

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

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

b, fm

b, fm
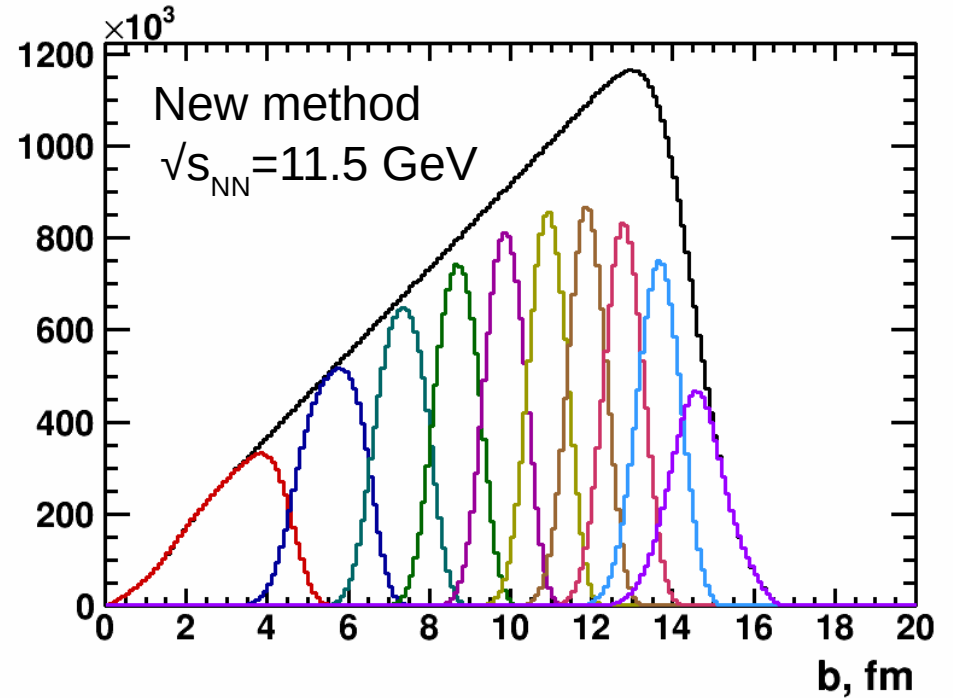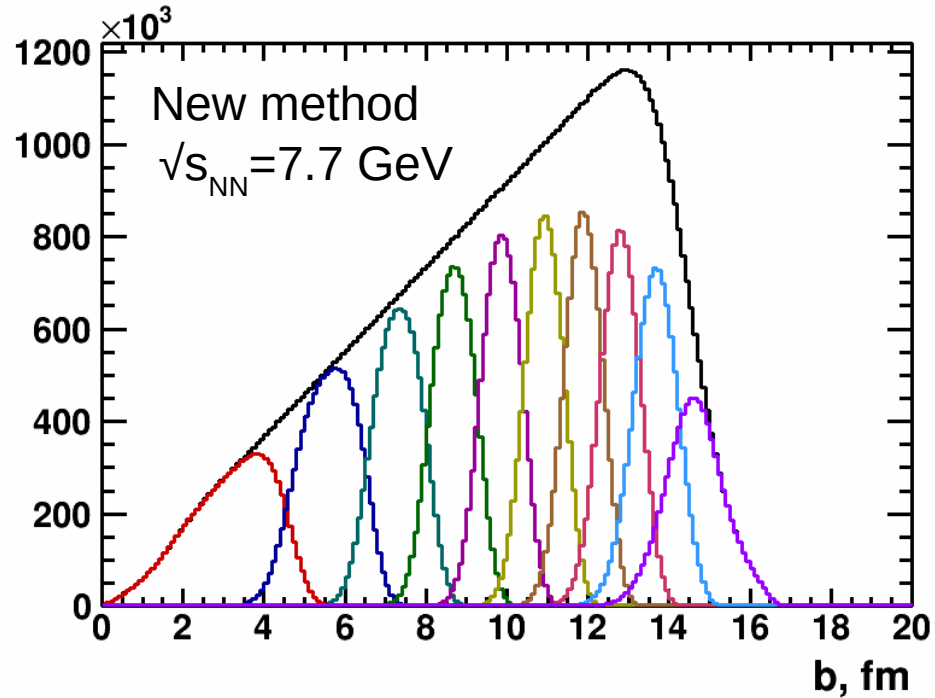
b vs centrality: method comparison
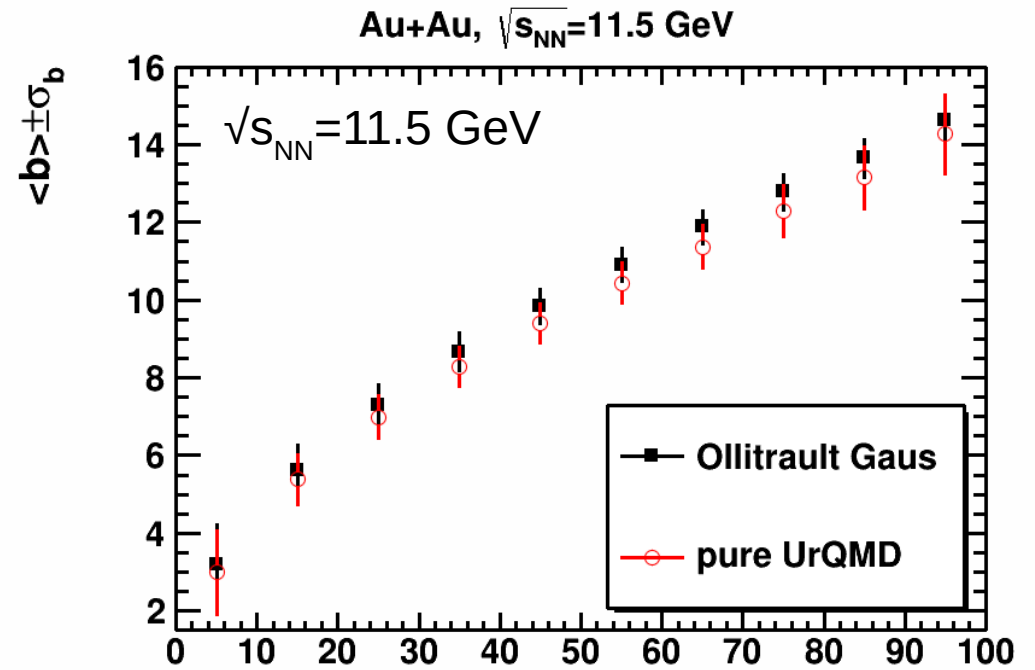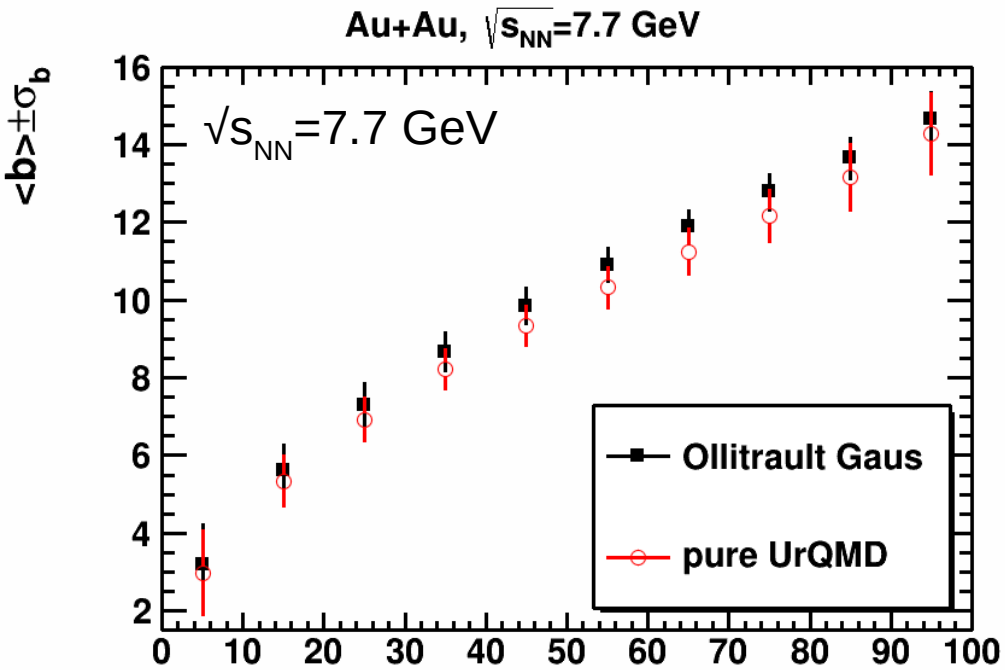
Reasonable agreement between two methods

Γ-function approach: fitting procedure

√s_NN=7.7 GeV

√s_NN=11.5 GeV
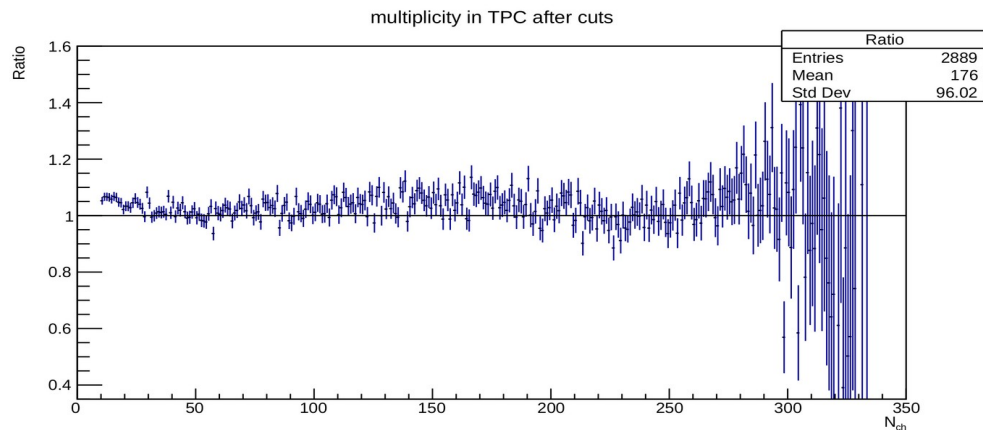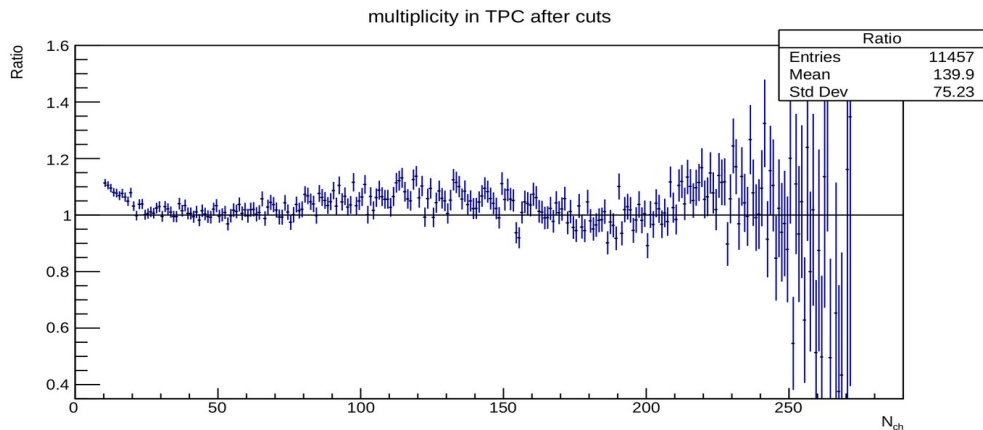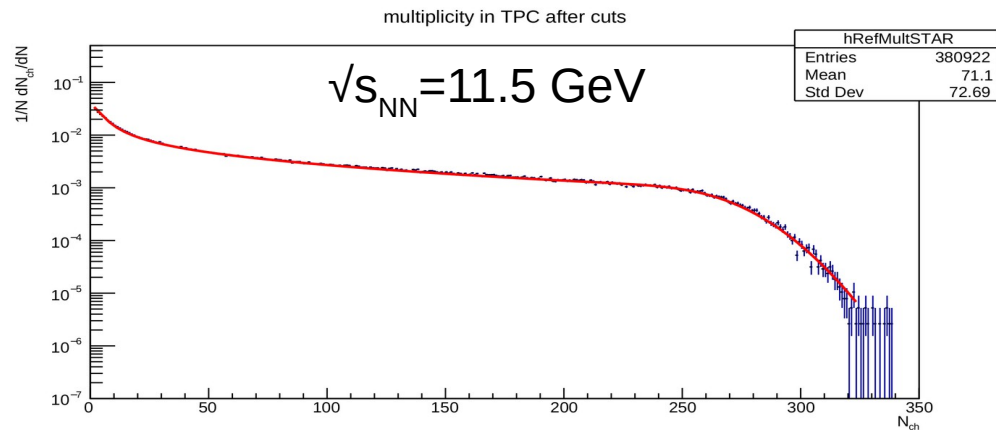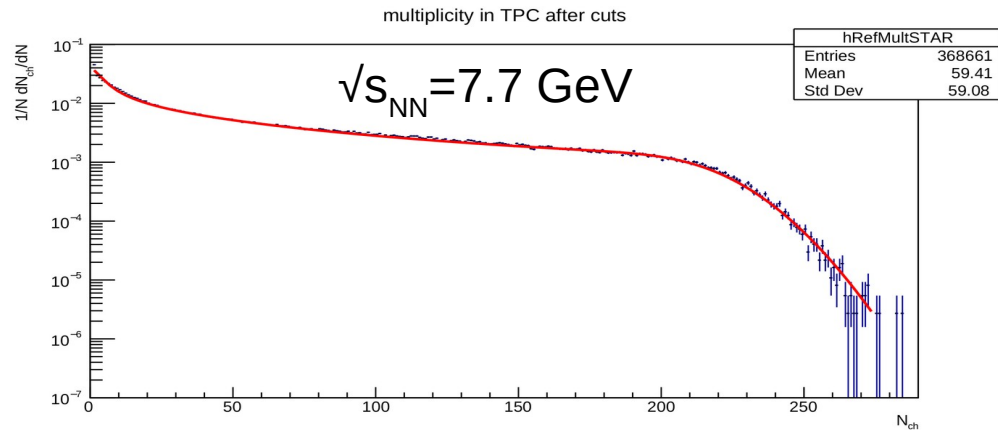
Fit reproduces charge particle multiplicity from reco UrQMD

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Γ-function approach: *b* distribution

√s$_{NN}$=7.7 GeV

Legend:
- 0-10%
- 10-20%
- 20-30%
- 30-40%
- 40-50%
- 50-60%
- 60-70%
- 70-80%
- 80-90%
- 90-100%

b, fm

√s$_{NN}$=11.5 GeV

b, fm
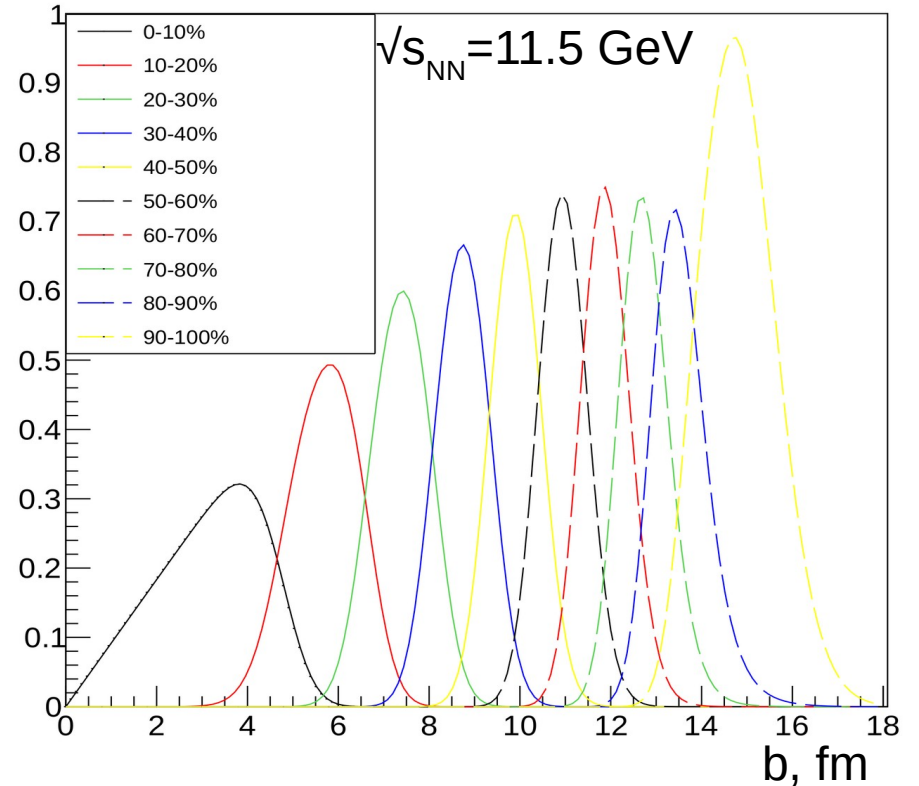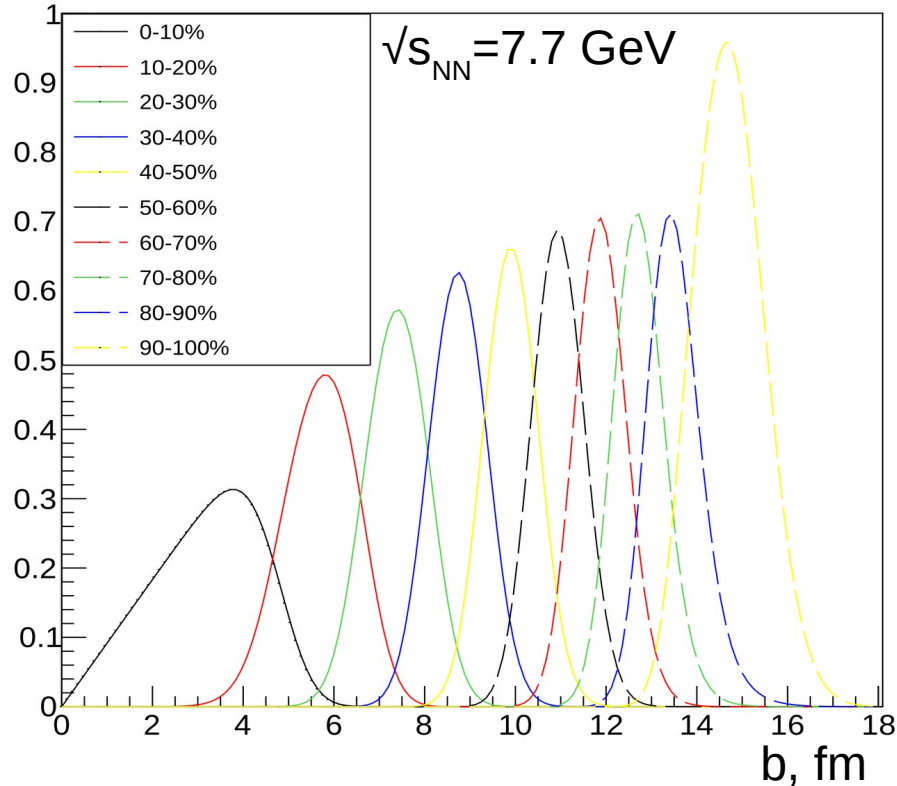
Comparison with method based on MC Glauber is in progress

Summary and next steps

- MC-Glauber based procedure for centrality determination is established
  - UrQMD at 3 energies ($\sqrt{s_{NN}}$=5, 7.7, 11.5 GeV) are under study

- Fit reproduces charged particle multiplicity with chosen parameters

- Extracted relation between model parameters (b, N_{part}, N_{coll}) and multiplicity centrality classes
  - Impact parameter from MC Glauber and UrQMD in given centrality classes are in reasonable agreement

- Comparison of the ε_n between MC Glauber and UrQMD and for different $\sqrt{s_{NN}}$ shows notable difference

- First comparison with the new method proposed by J. Ollitrault shows reasonable agreement with standard method based on MC-Glauber
  - Comparison with the new improved method based on Gamma function is in progress

- Systematic study and analysis note are under preparation

Thank you for your attention!

Backup

MC Glauber fit: $h^{\pm}$ multiplicity

f=0, k=8, μ=0.23, χ^2=2.04±0.10, M=(10,235)
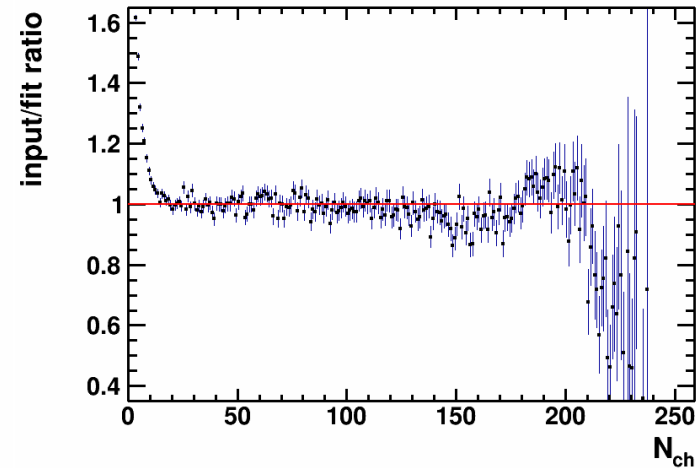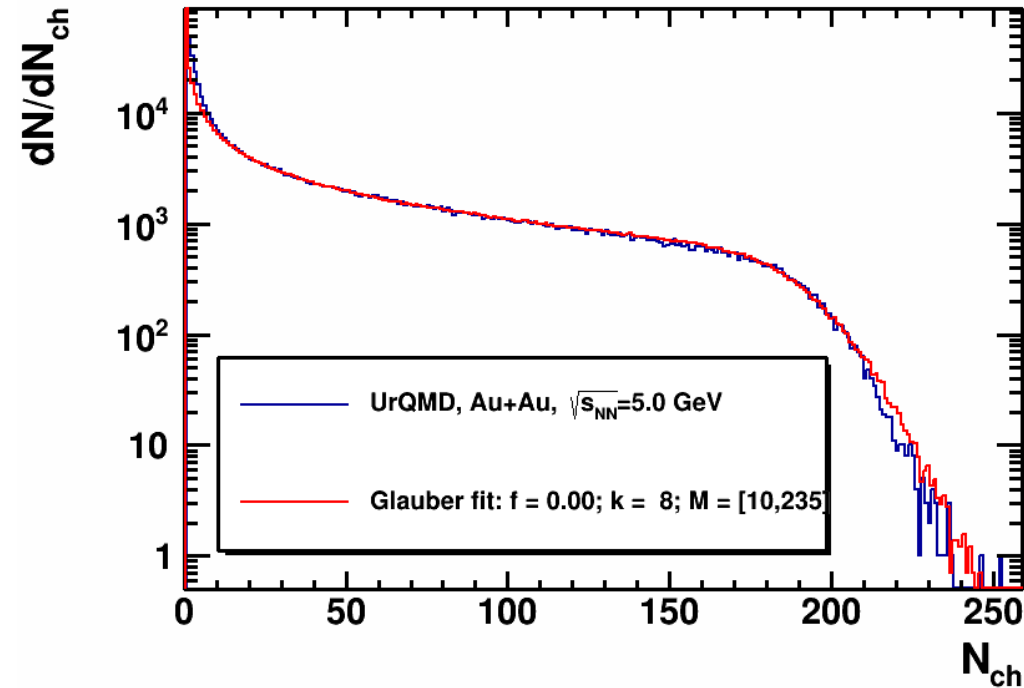
MC Glauber fit deviates from UrQMD data for large multiplicity region

$h^{\pm}$ multiplicity

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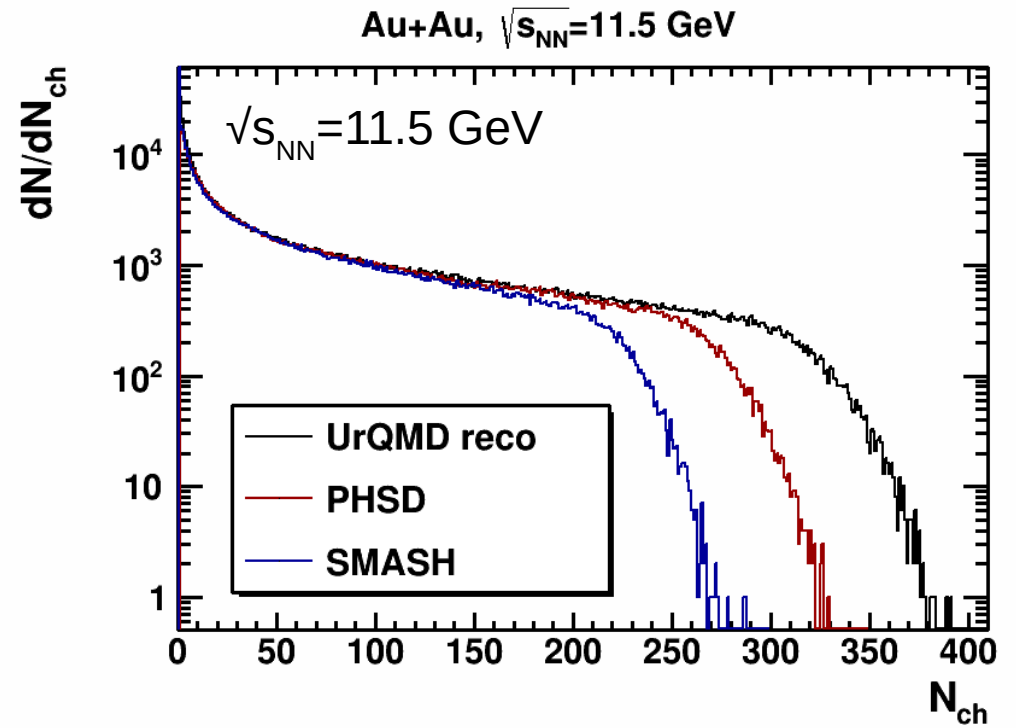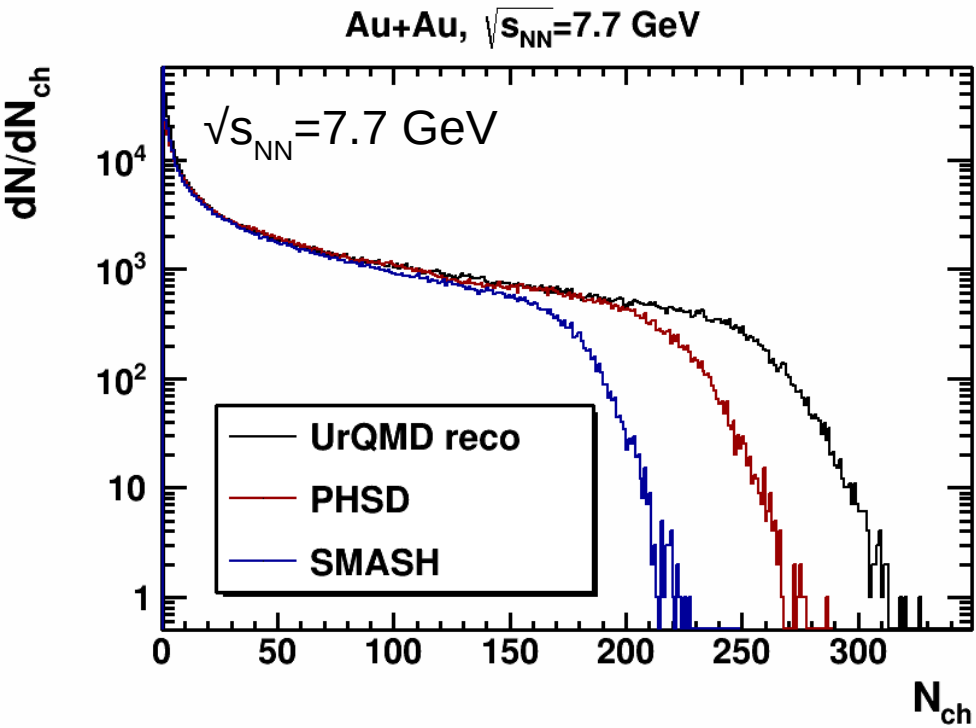
\<b\> vs centrality: comparison between models

b vs centrality: Glauber vs UrQMD
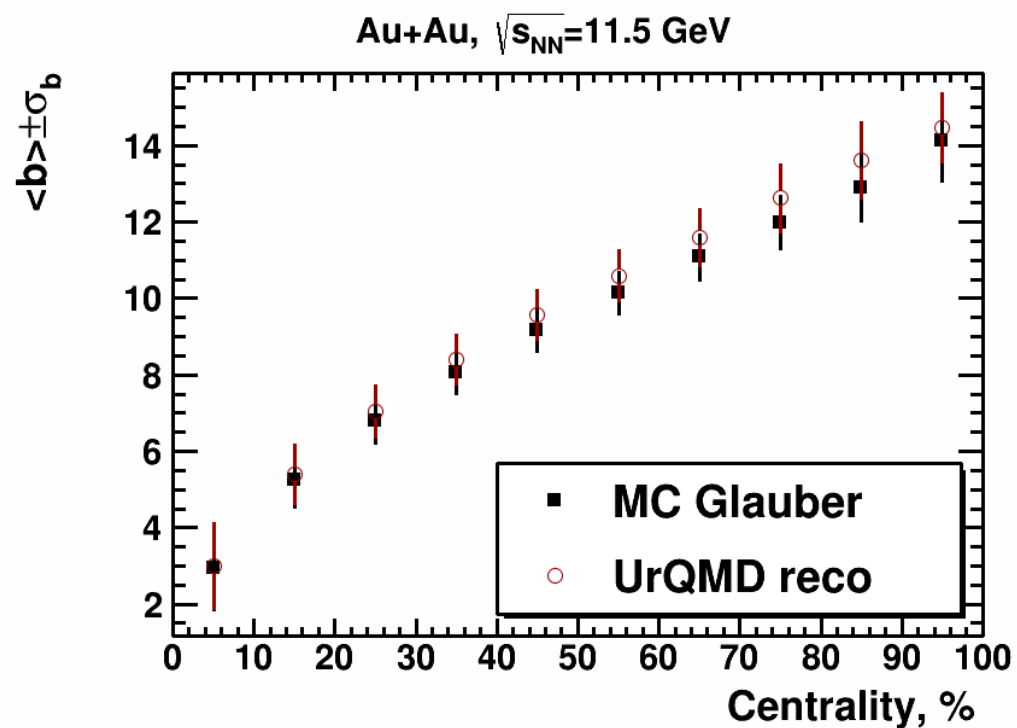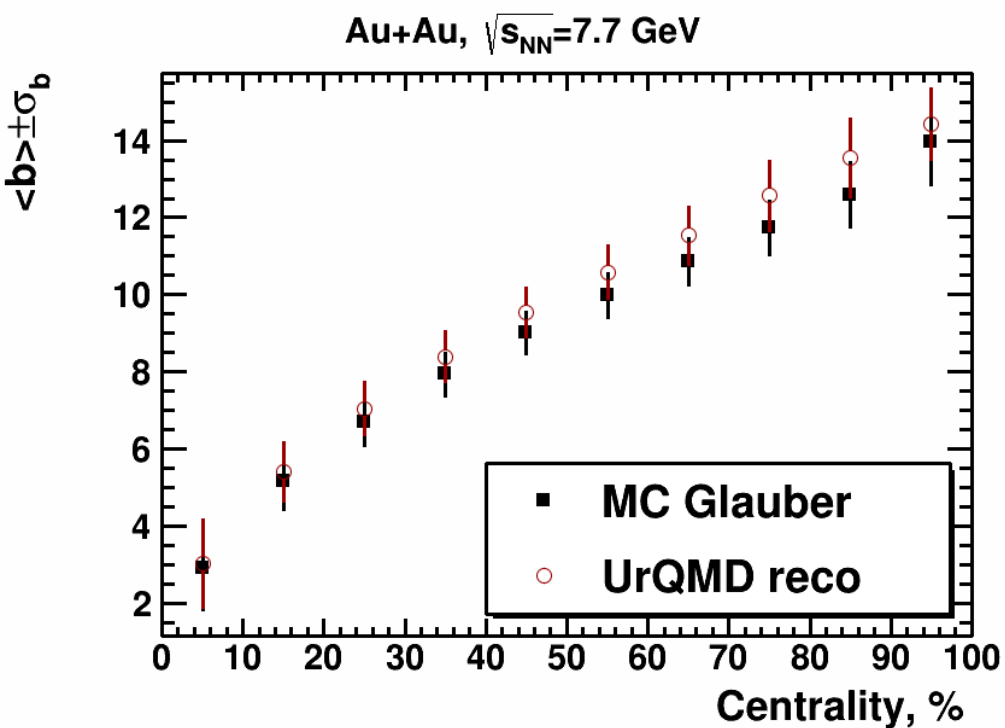
b vs centrality: Glauber vs SMASH

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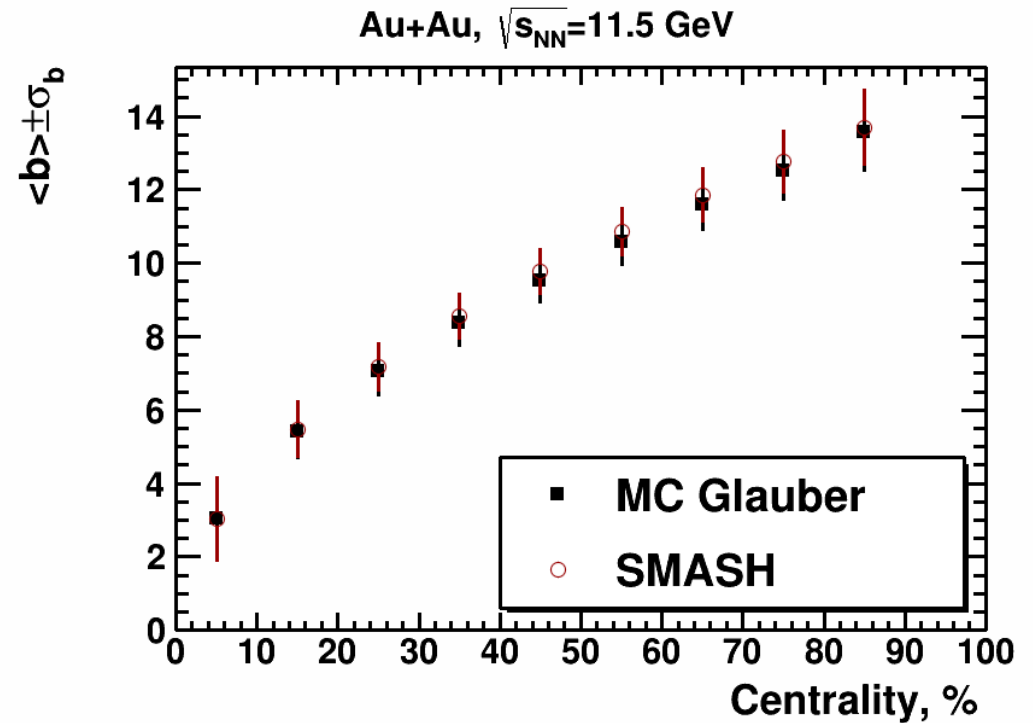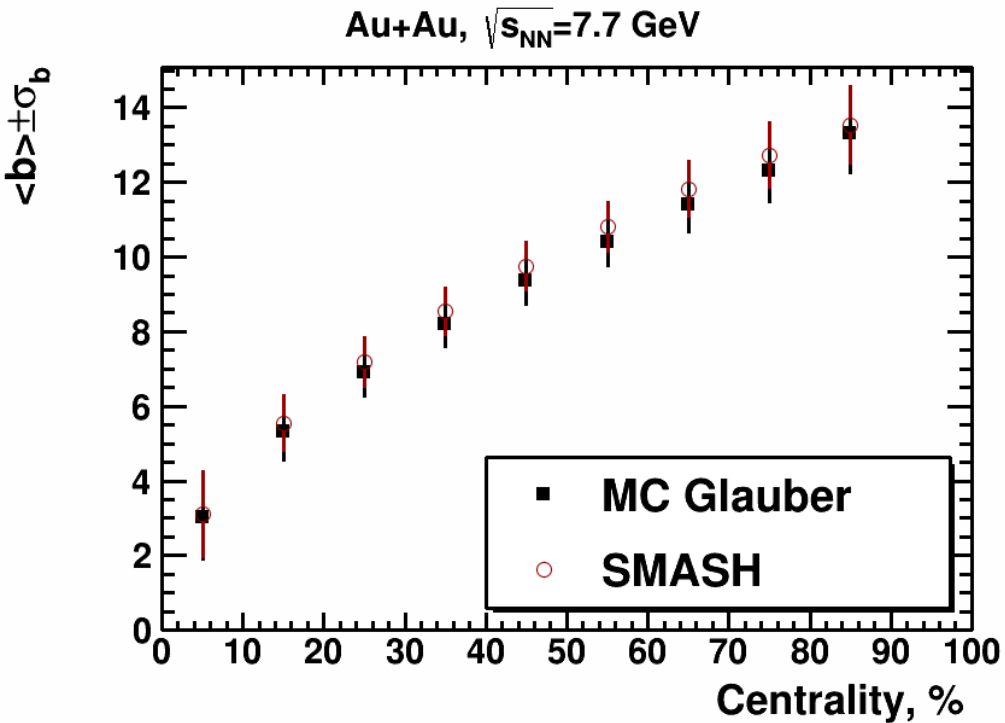
Eccentricity: comparison with STAR
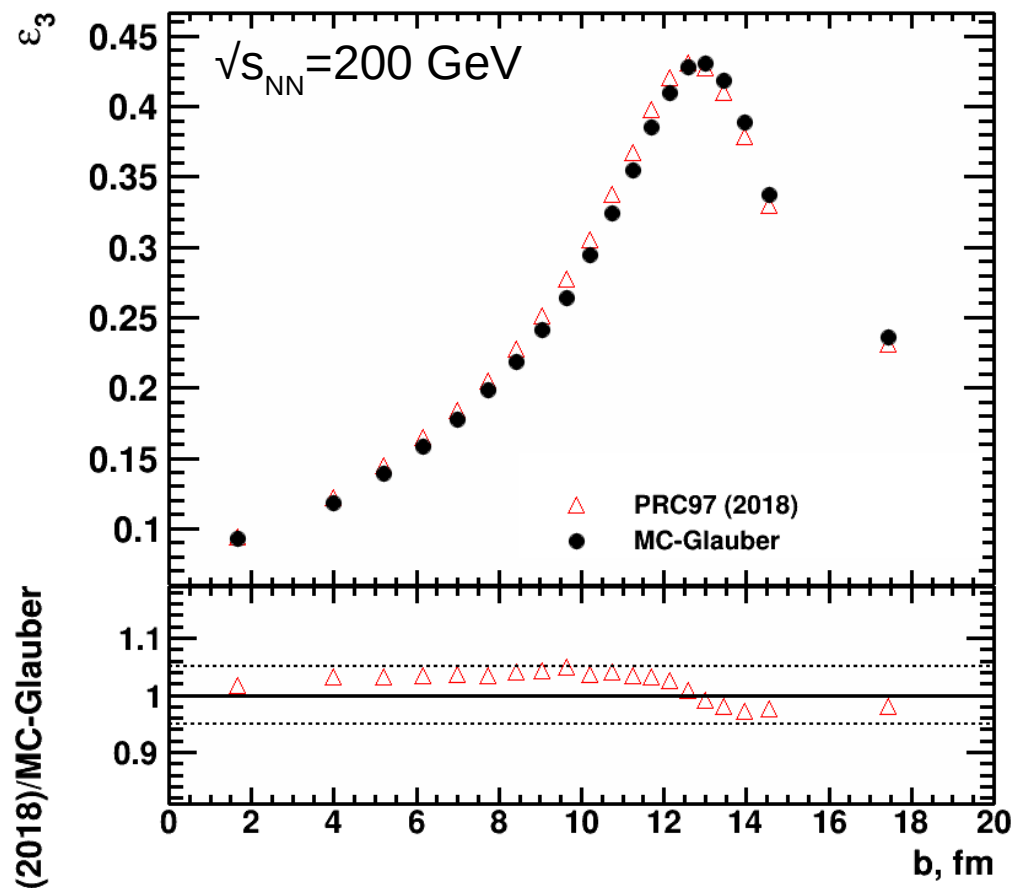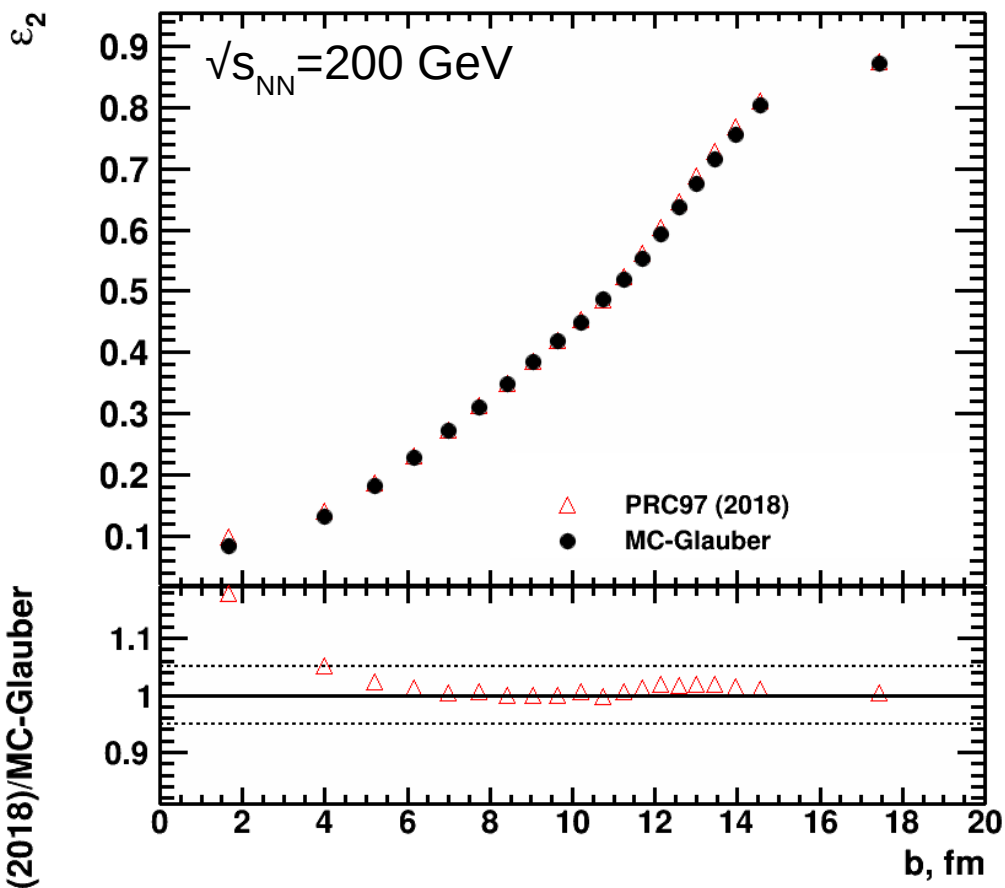
Good agreement with the published data

Initial state comparison:
$\sqrt{s_{NN}}$=7.7 GeV

MC Glauber vs PHSD: b, N_{part}
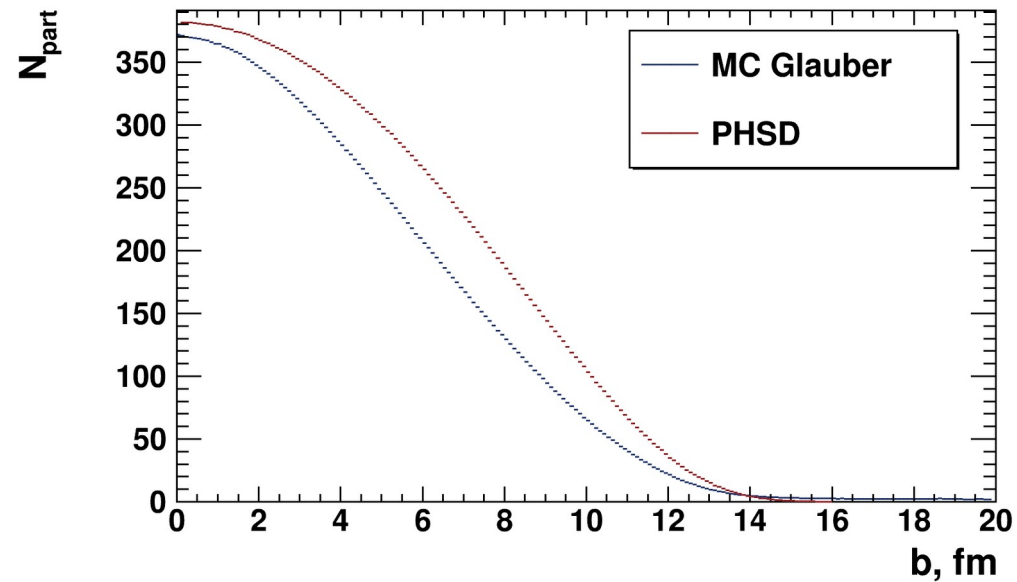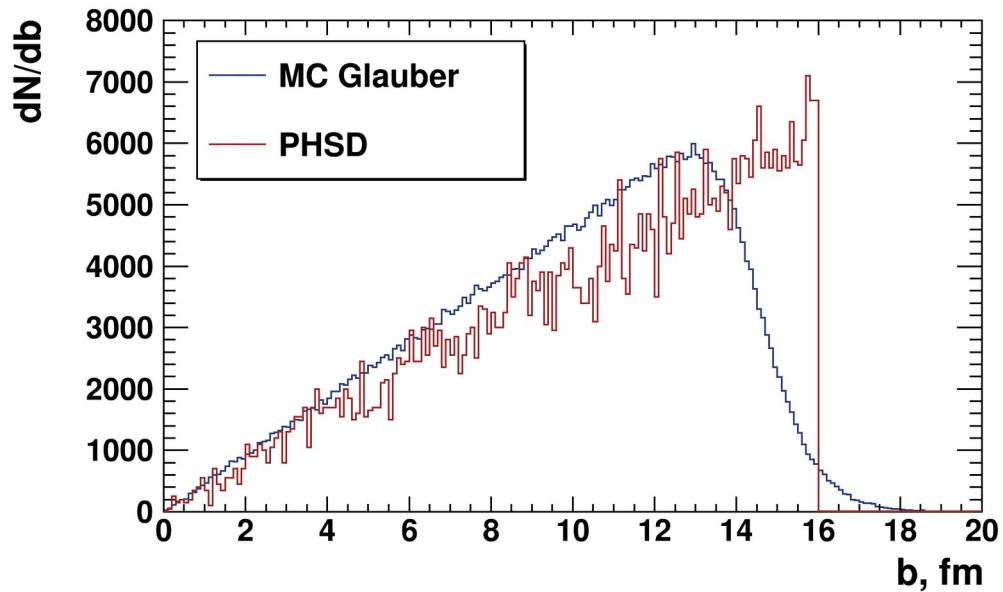
MC Glauber vs PHSD: ε_n
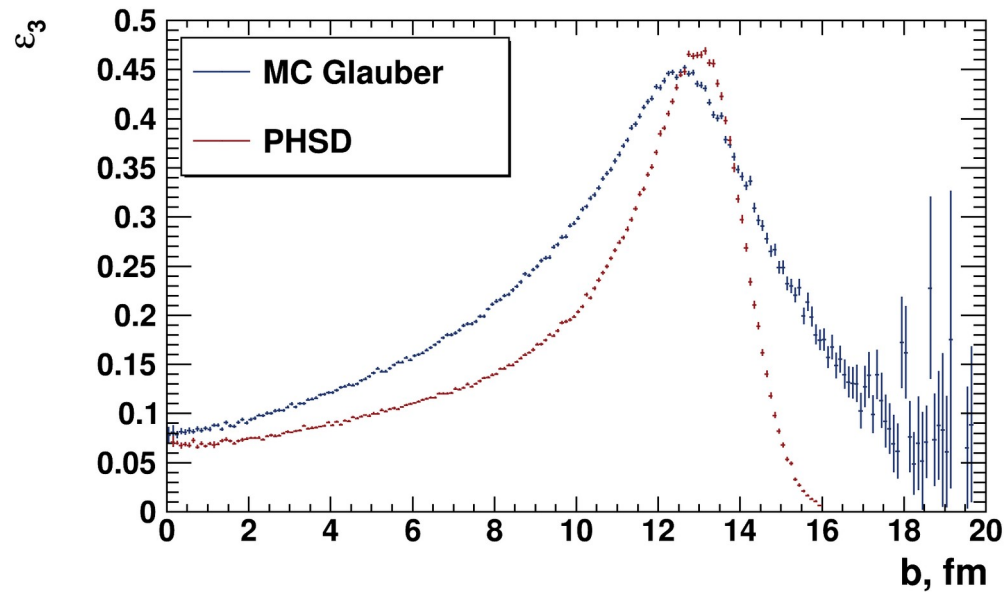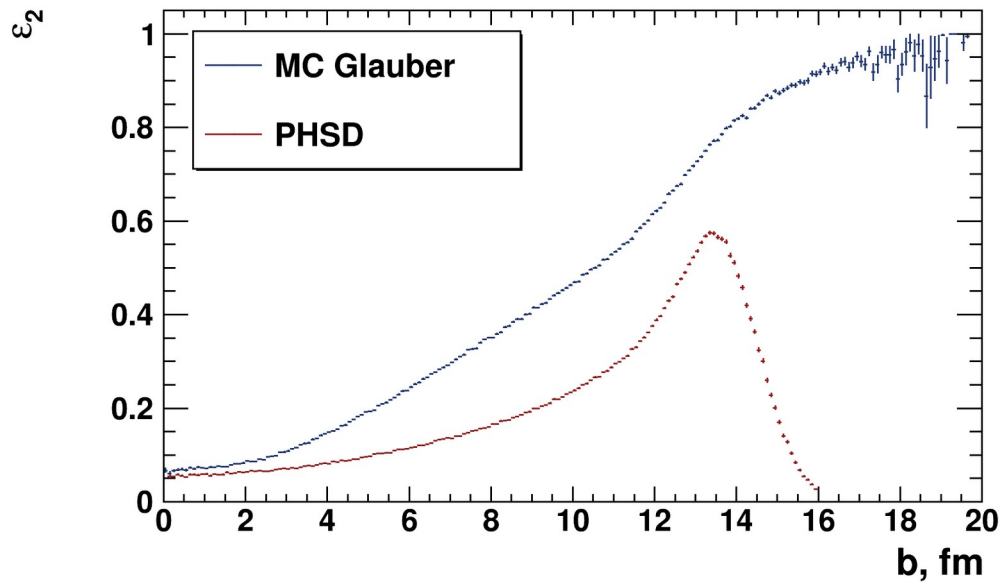
Initial state comparison: $\sqrt{s_{NN}}=11.5$ GeV

MC Glauber vs PHSD: b, N_{part}
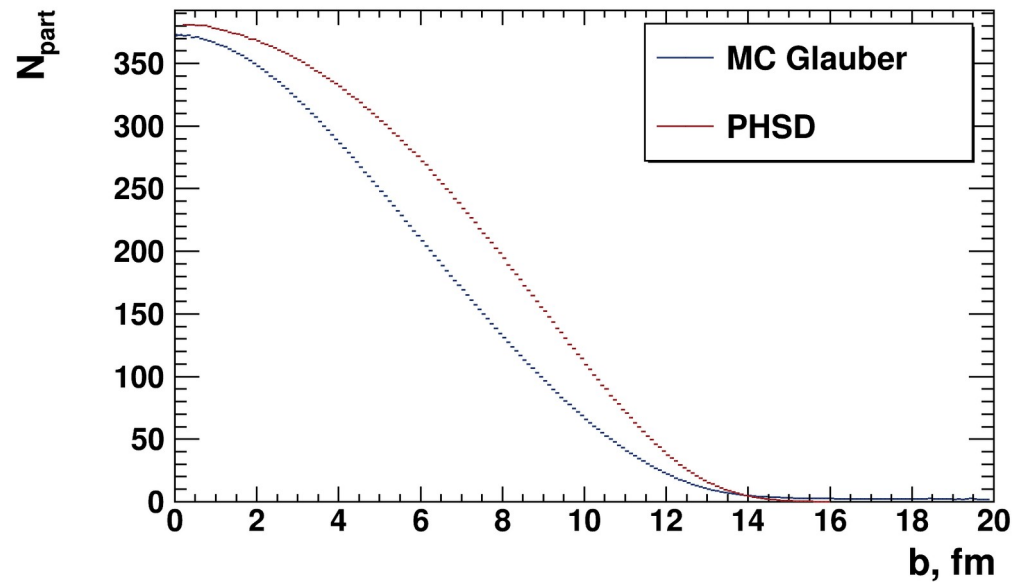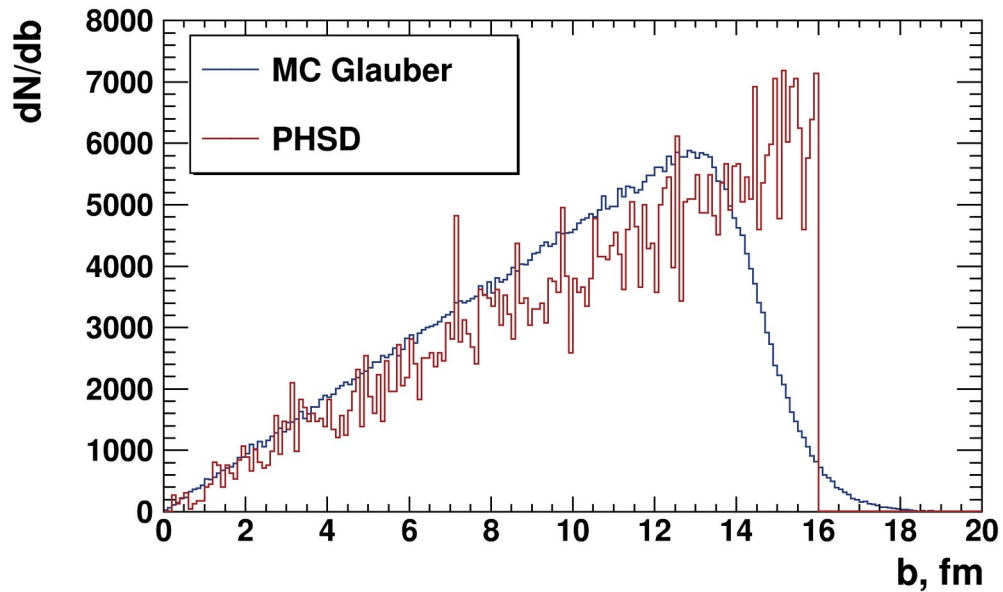
MC Glauber vs PHSD: ε_n
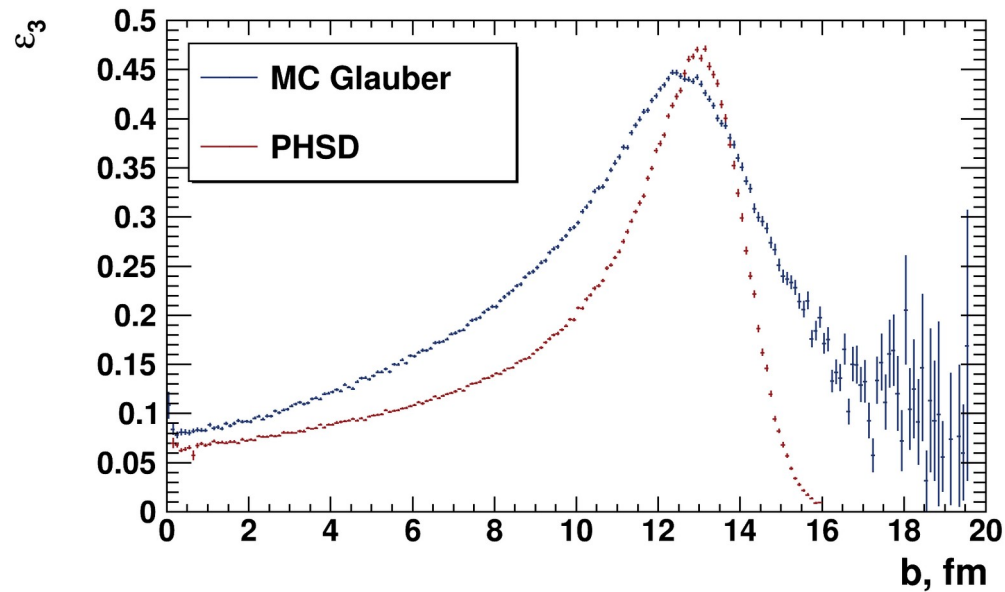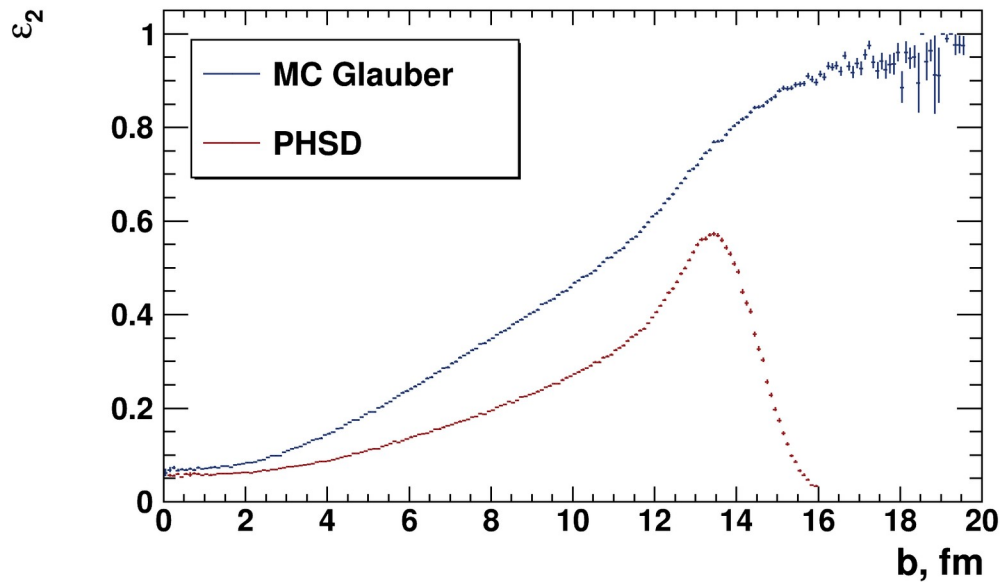
MC Glauber vs UrQMD: b, N$_{part}$
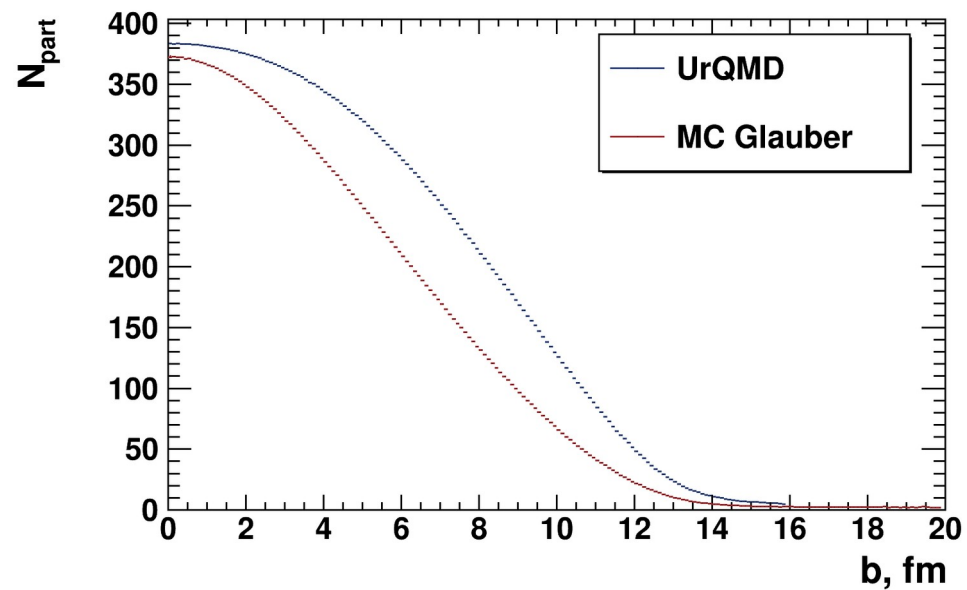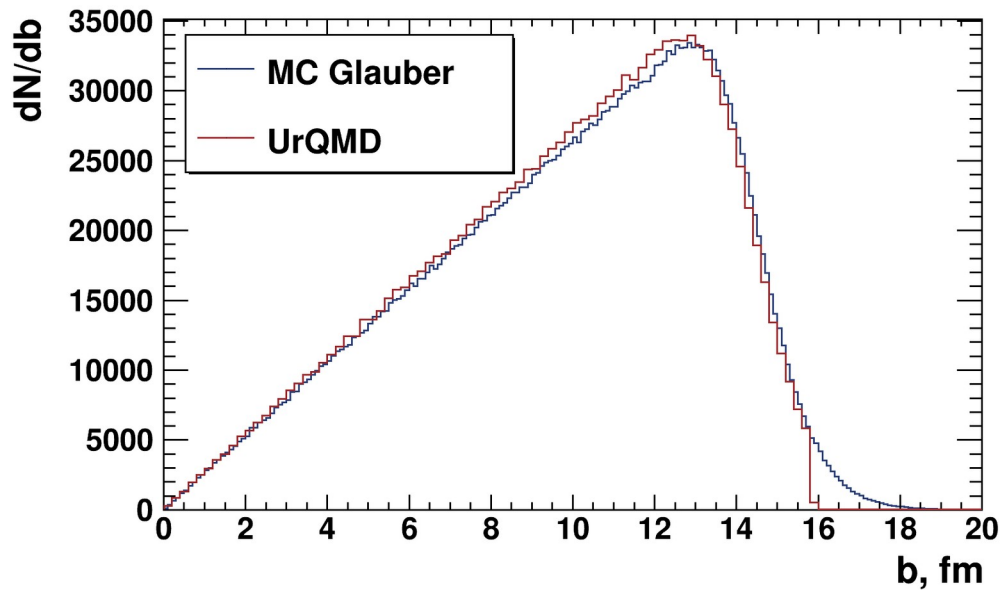
MC Glauber vs UrQMD: ε_n
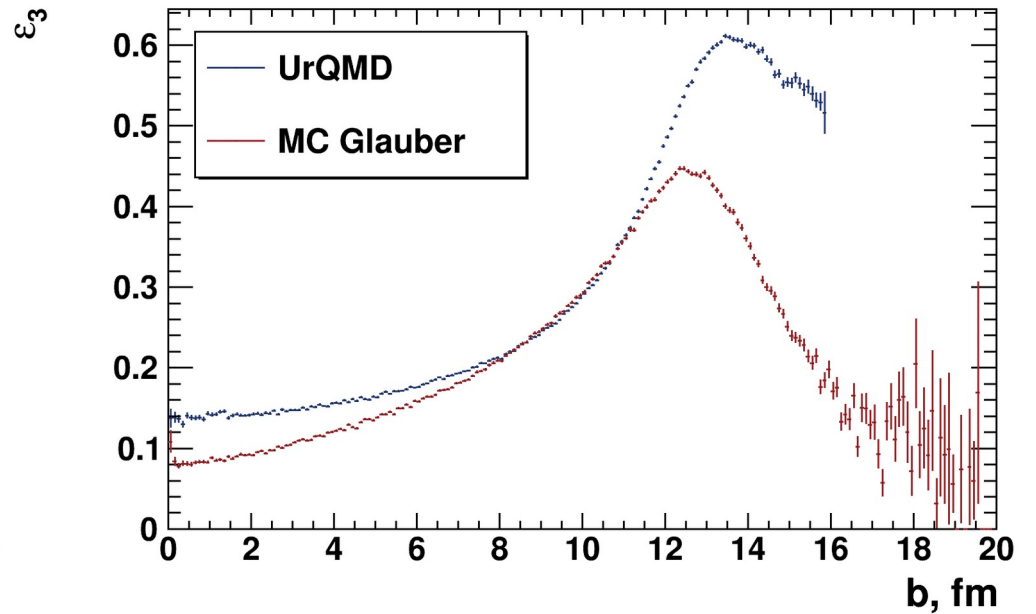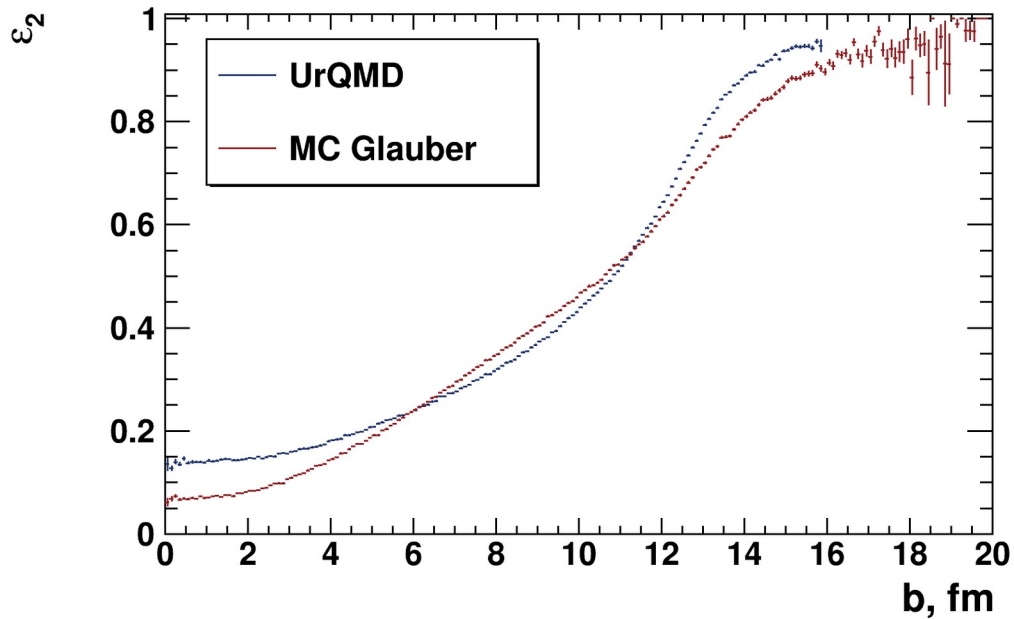
MC Glauber vs pure UrQMD

Fit parameters f,k vs χ²
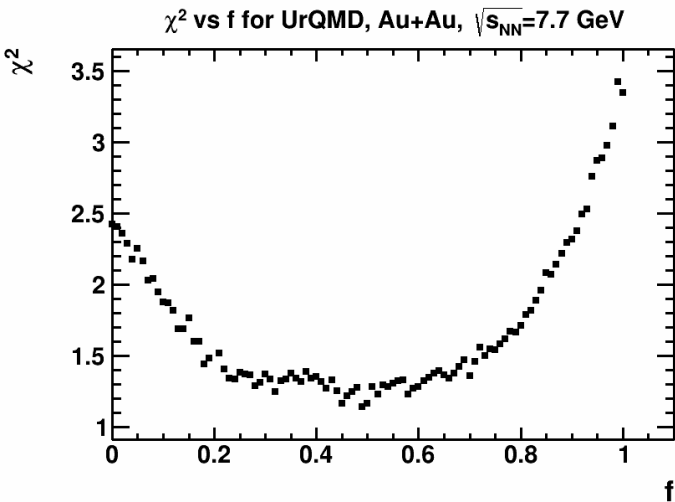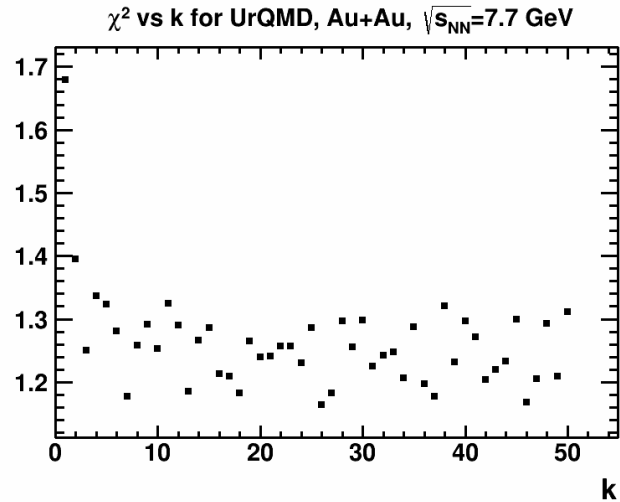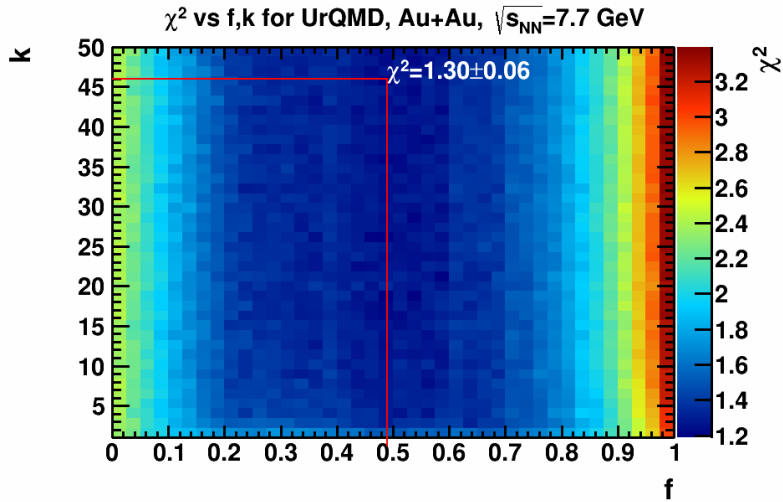
f=0.49, k=46, μ=0.61, χ²=1.29±0.06, M=(35,445)

Fit parameters f,k vs χ²

χ² vs f,k for UrQMD, Au+Au, $\sqrt{s_{NN}}$=11.5 GeV
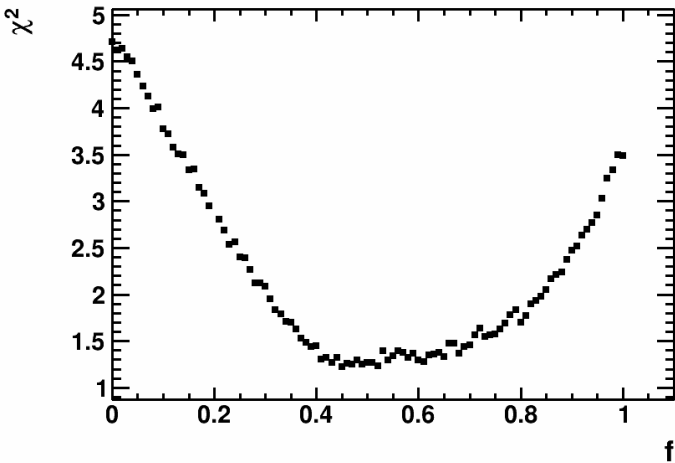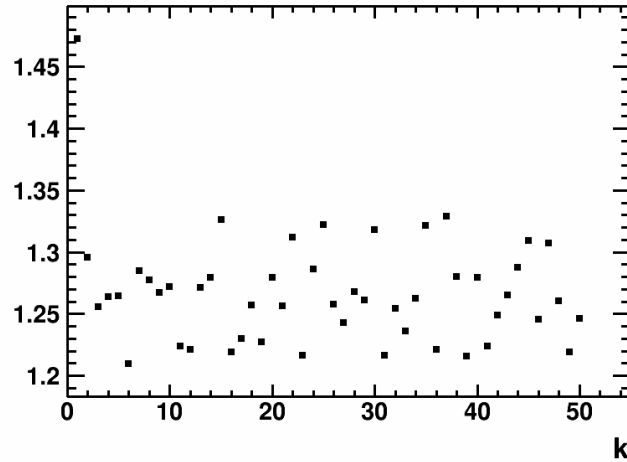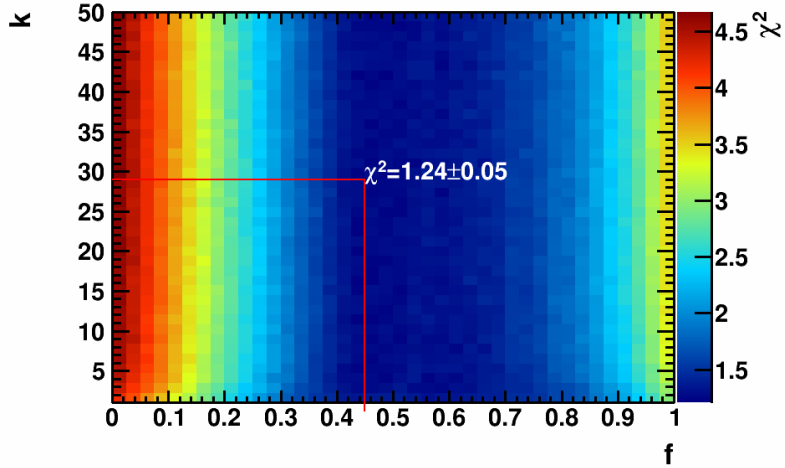
χ²=1.24±0.05

f=0.45, k=29, μ=0.71, χ²=1.24±0.05, M=(40,540)

MC Glauber fit: $h^{\pm}$ multiplicity

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

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

Glauber fit: f = 0.49; k = 46; M = [35,445]

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

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

Glauber fit: f = 0.47; k = 9; M = [40,515]
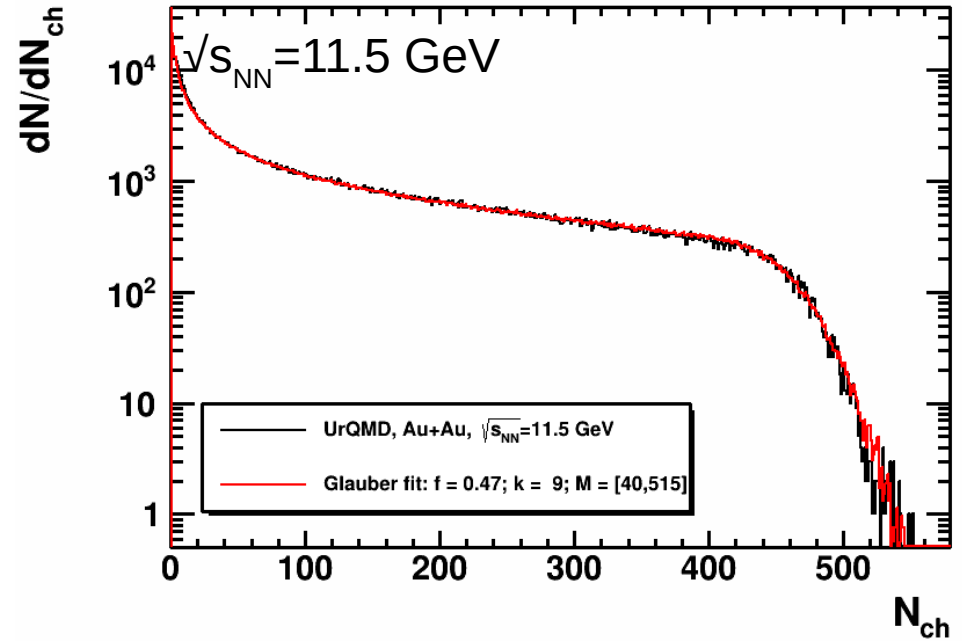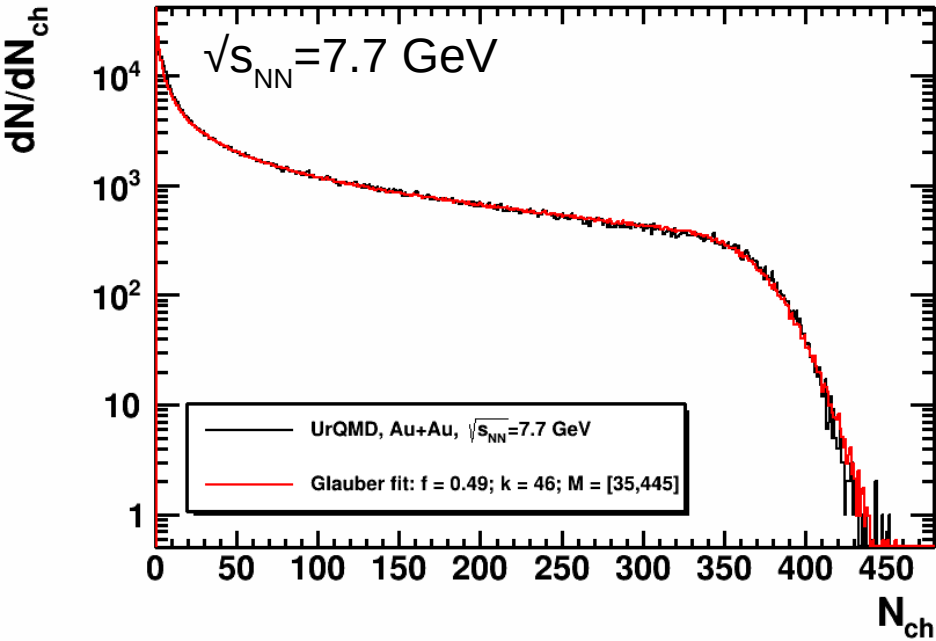
b-multiplicity correlation

Events in multiplicities M ± ΔM have impact parameter in range b ± σ_b

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b distribution in centrality classes

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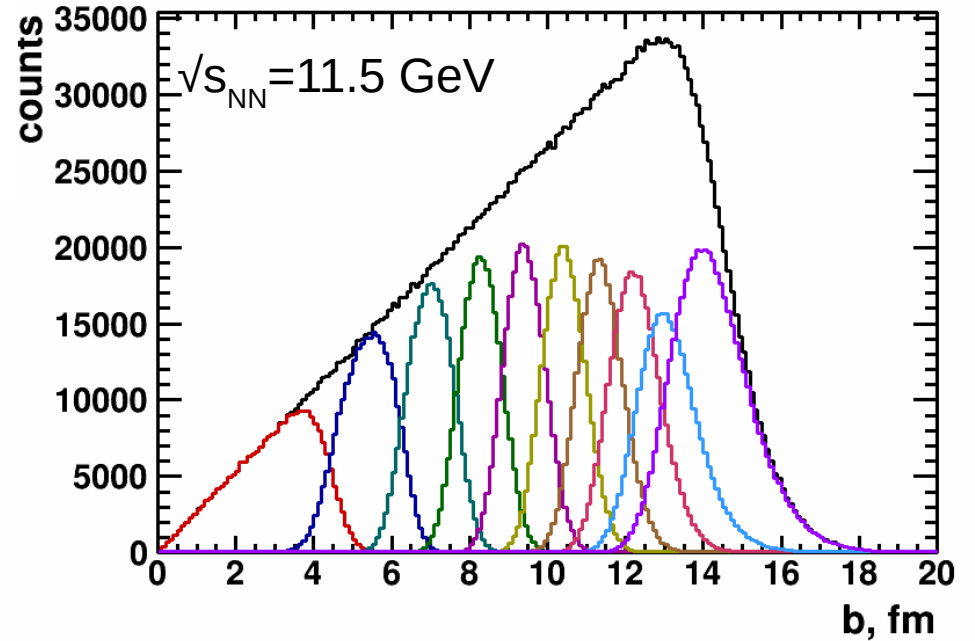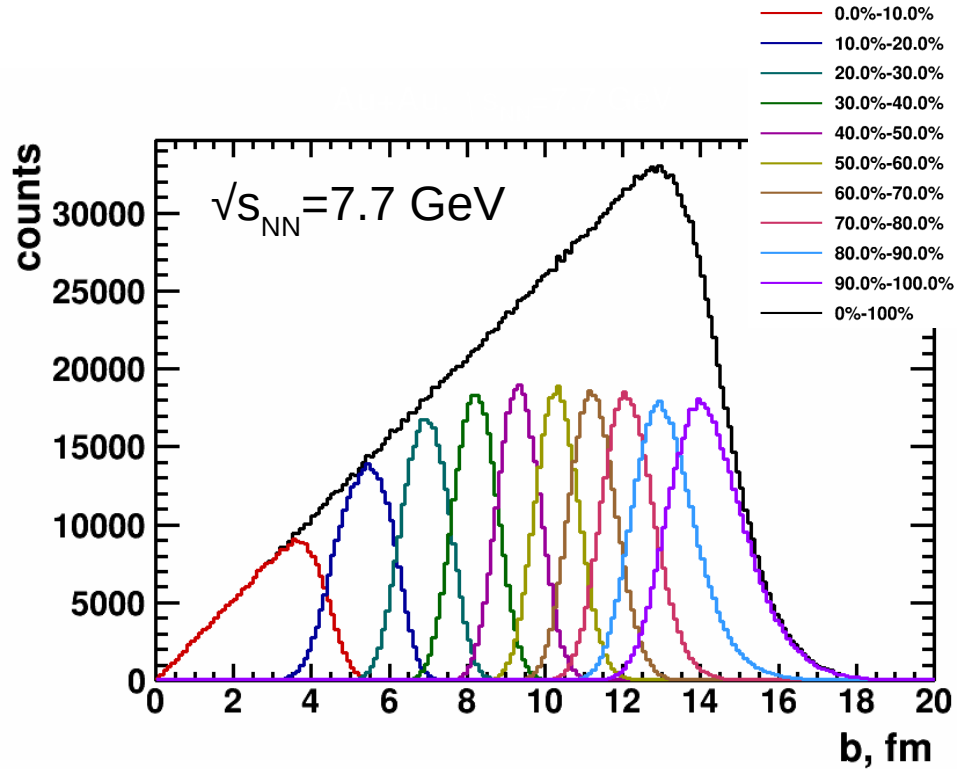
Multiplicity distribution in centrality classes
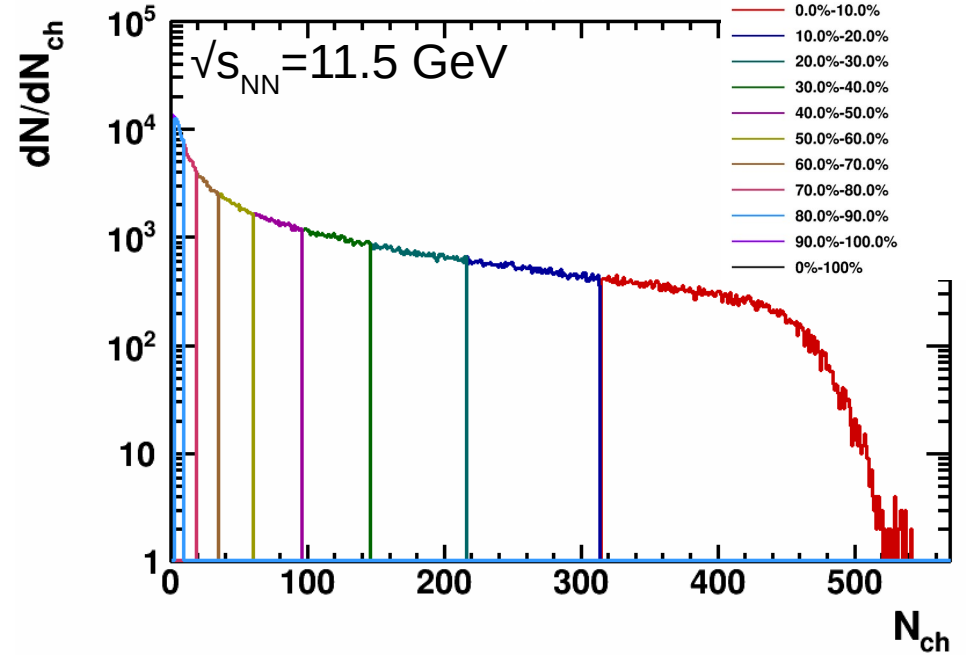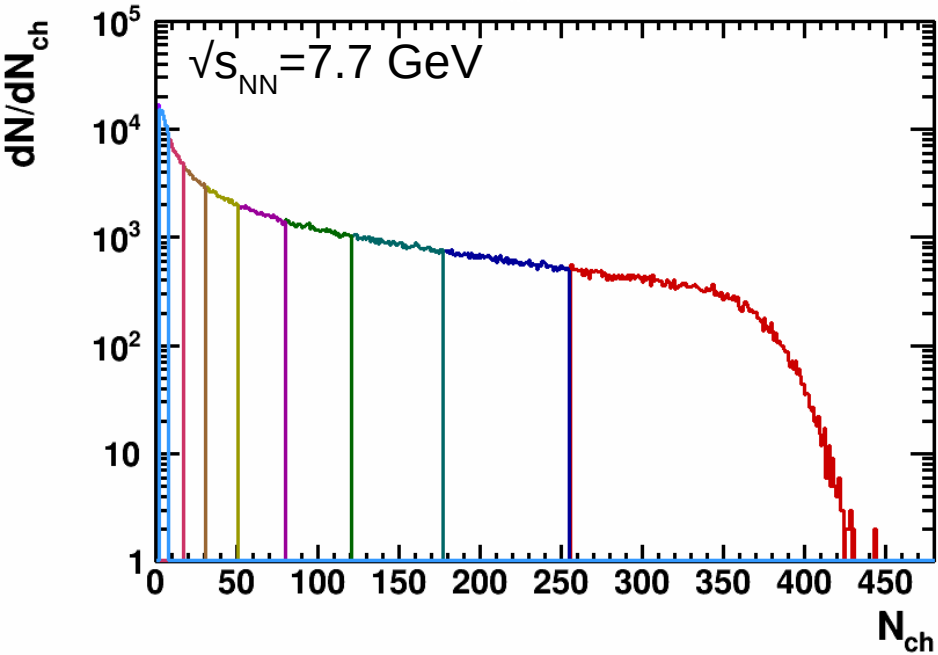
Centrality classes: Npart
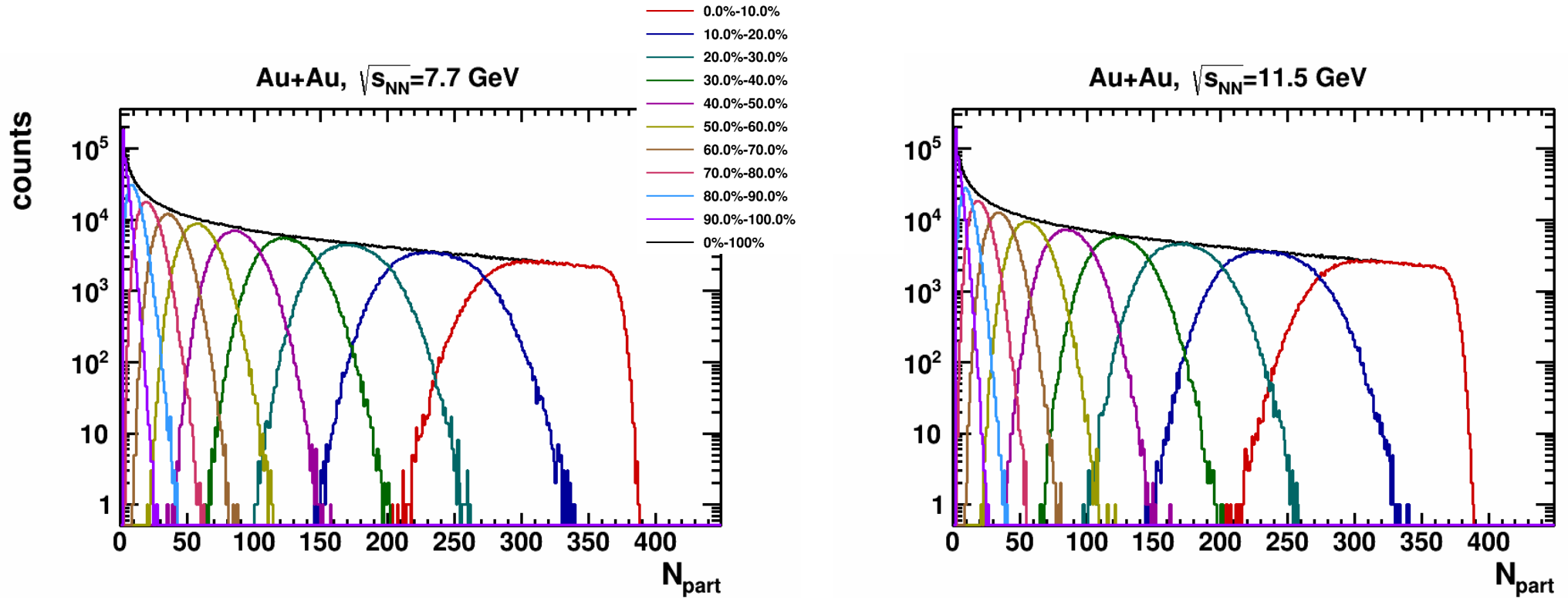
Centrality classes: Ncoll
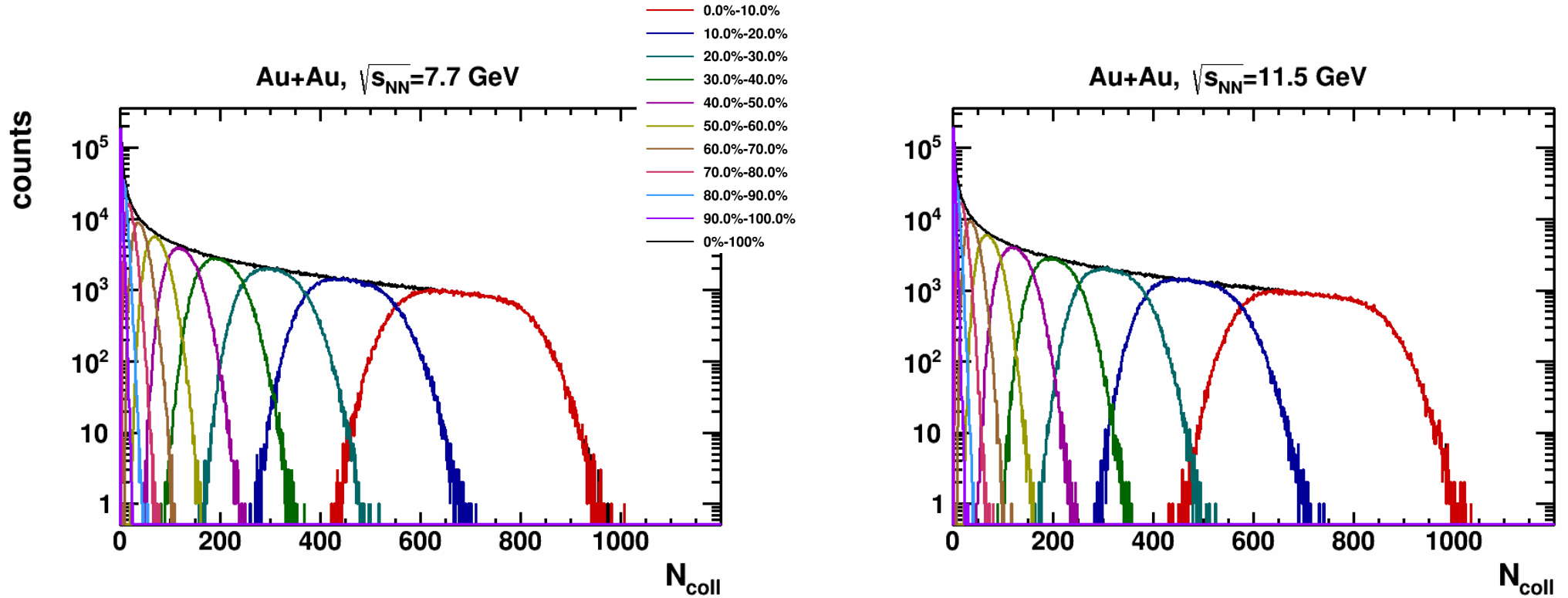
Centrality classes: Ncoll
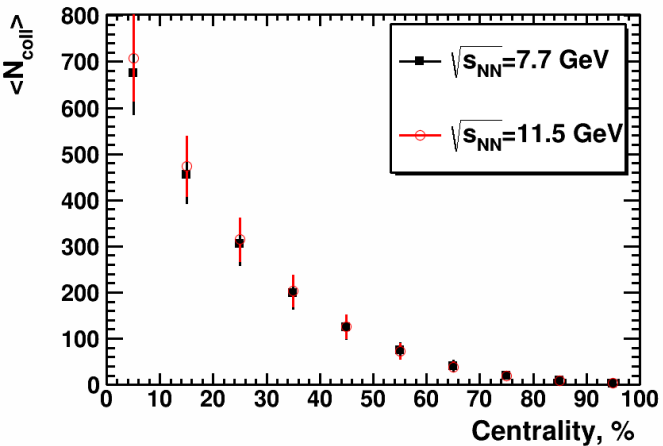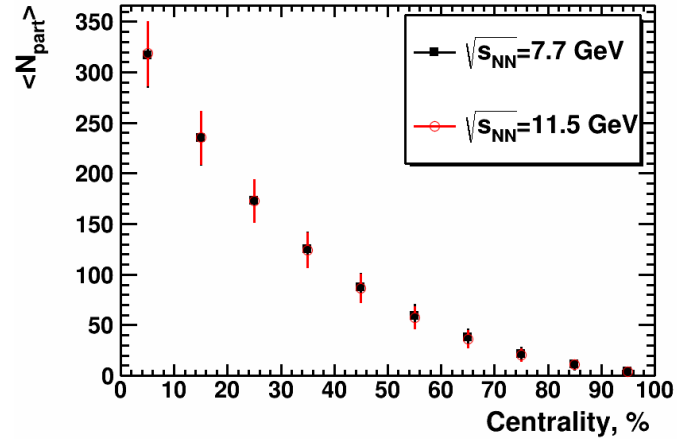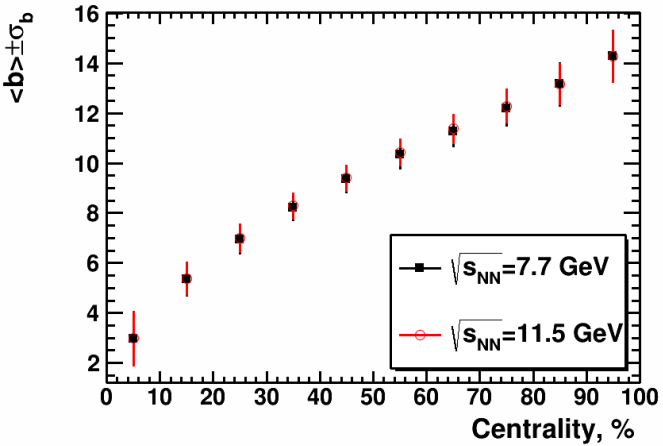
Centrality framework results for UrQMD reco with pion multiplicity

Charged particle multiplicity in MPD
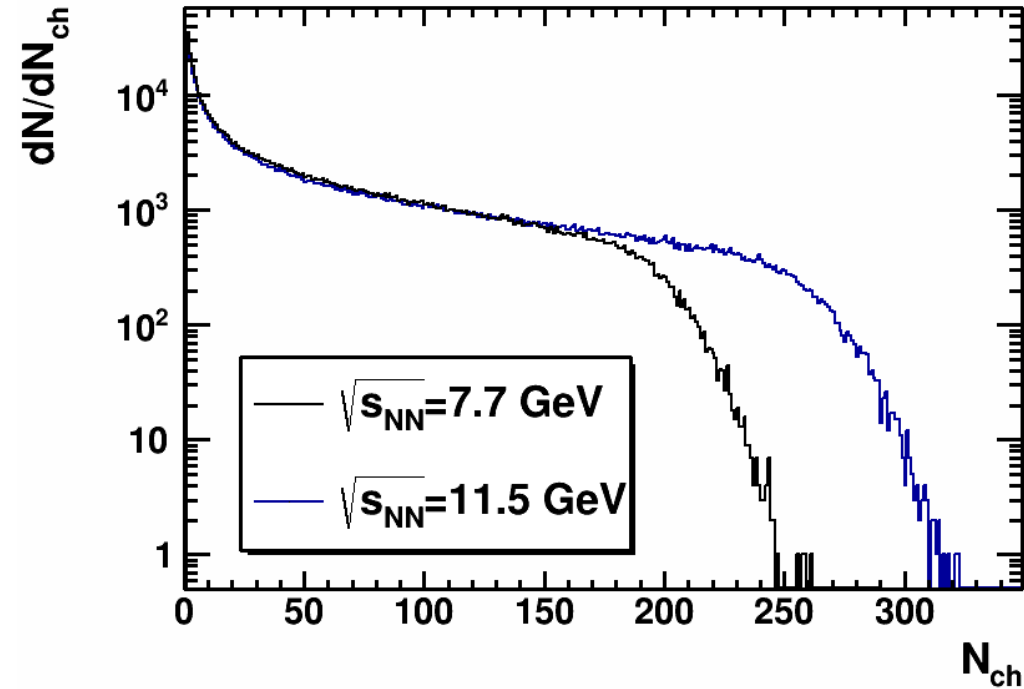
Reconstructed data:

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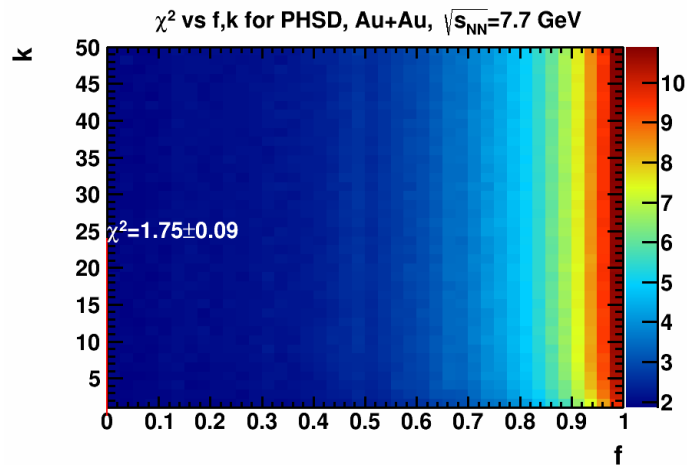 - Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=7.7, 11.5 GeV
- GEANT4 MPD detector simulation
- Reconstruction procedure:
  - Realistic tracking in TPC (Cluster Finder)

Used particle selection:

- Only charged pions
- $|\eta|$<0.5
- p_T>0.15 GeV/c

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Fit parameters f,k vs χ²

f=0, k=42, μ=0.24, χ²=1.39±0.1, M=(10,240)

f=0.01, k=43, μ=0.3, χ²=1.17±0.07, M=(10,320)

χ² vs f,k for UrQMD, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV

χ²=1.75±0.09

χ² vs f,k for UrQMD, Au+Au, $\sqrt{s_{NN}}$=11.5 GeV

χ²=1.47±0.08

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MC Glauber fit: $\pi^{\pm}$ multiplicity

f=0, k=42, μ=0.24, χ^2=1.39±0.1, M=(10,240)

UrQMD, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV
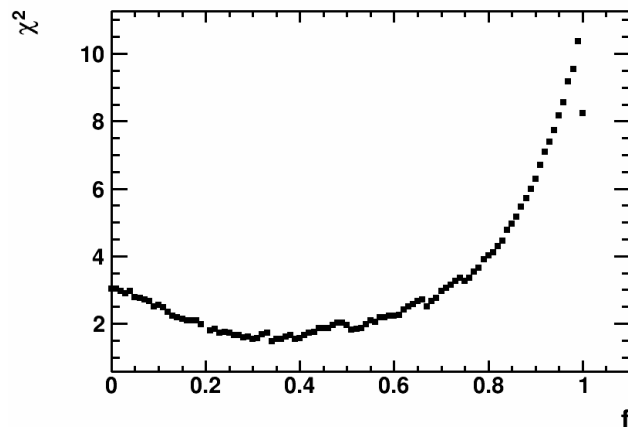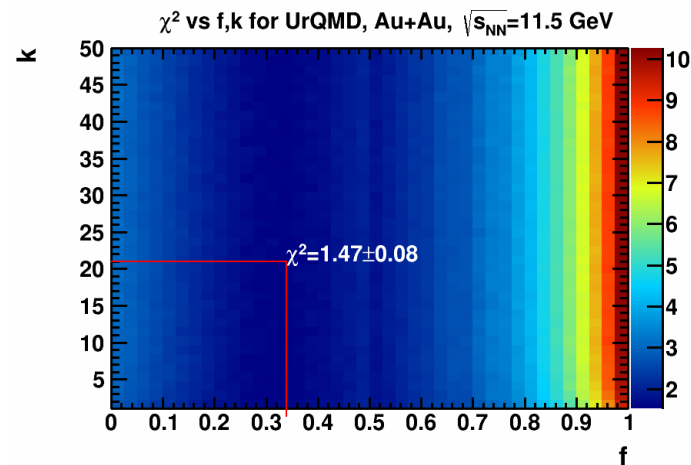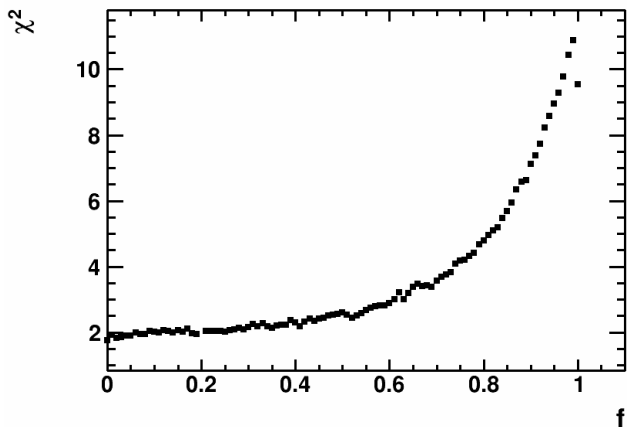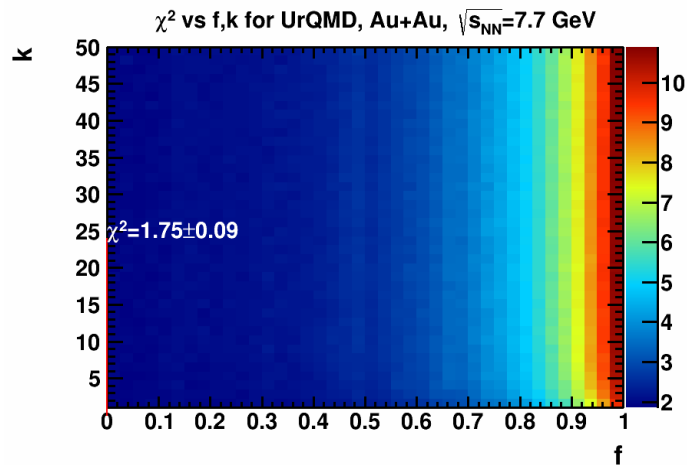
Glauber fit: f = 0.00; k = 42; M = [10,240]

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

MC Glauber fit: $\pi^{\pm}$ multiplicity
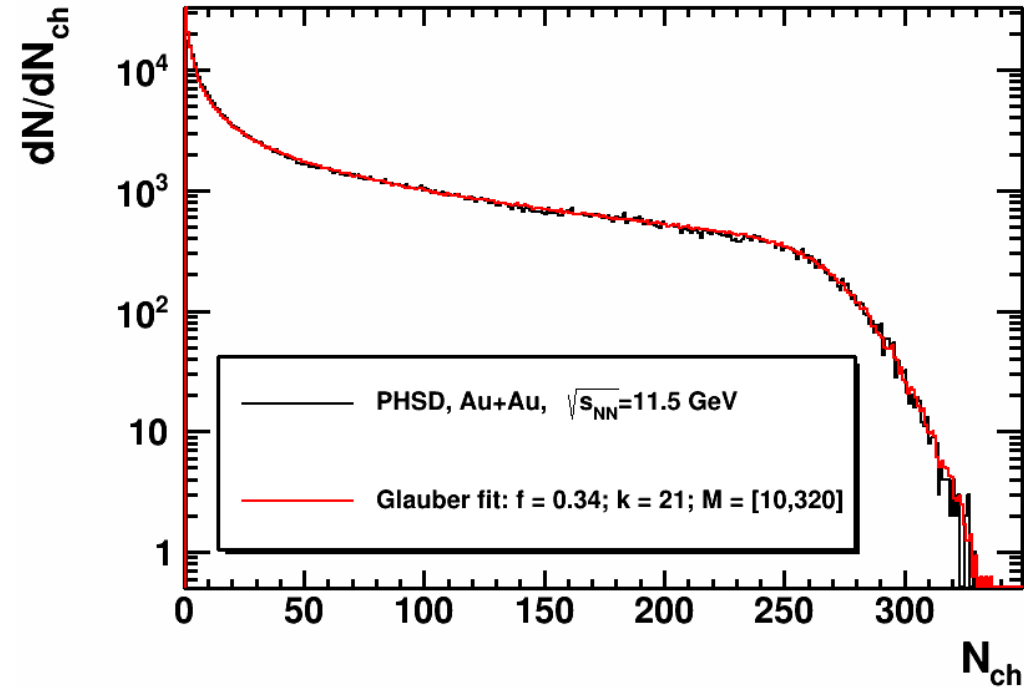
f=0.01, k=43, μ=0.3, χ^2=1.17±0.07, M=(10,320)

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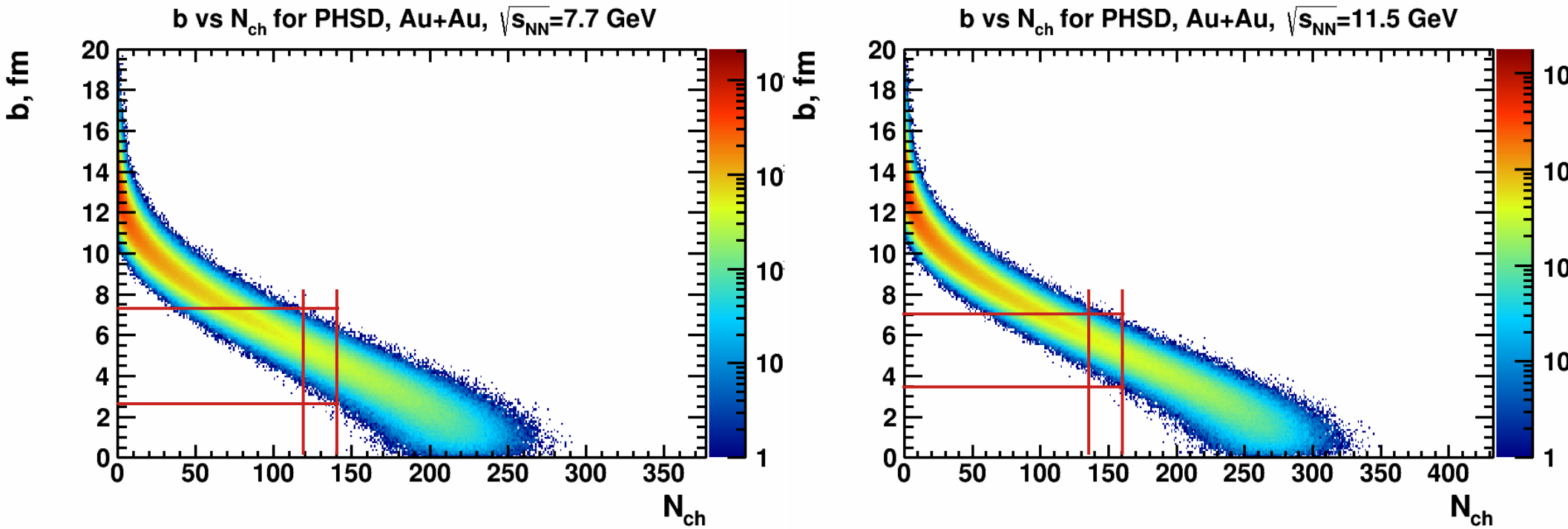
b vs. multiplicity correlation

Events in multiplicities M ± ΔM have impact parameter in range b ± σ_b

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N$_{ch}$ distribution in centrality classes

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

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

b distribution in centrality classes



No 90-100% centrality bin.

Investigating.

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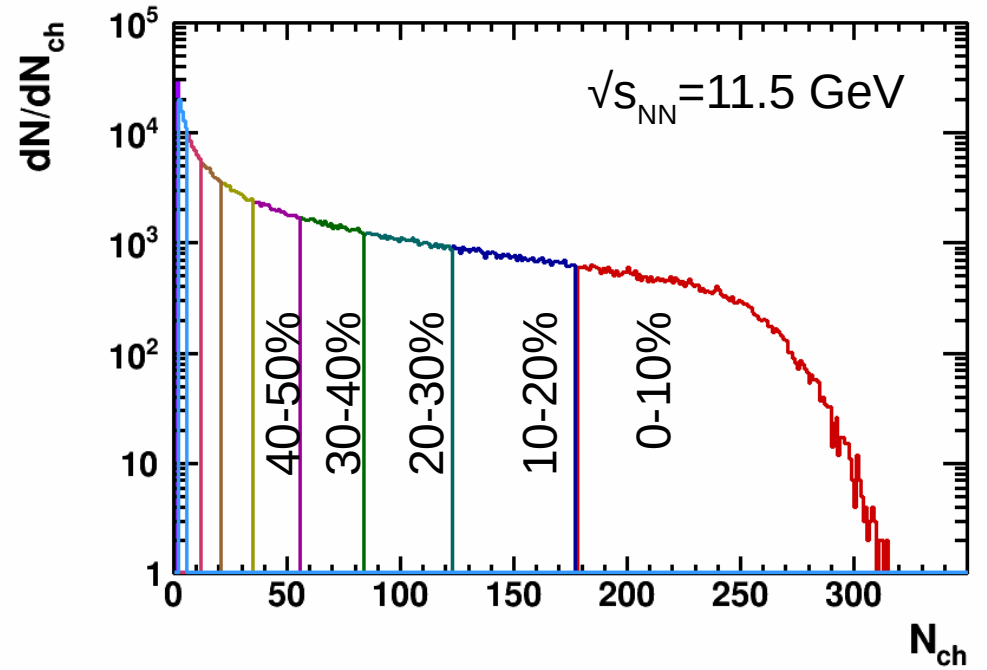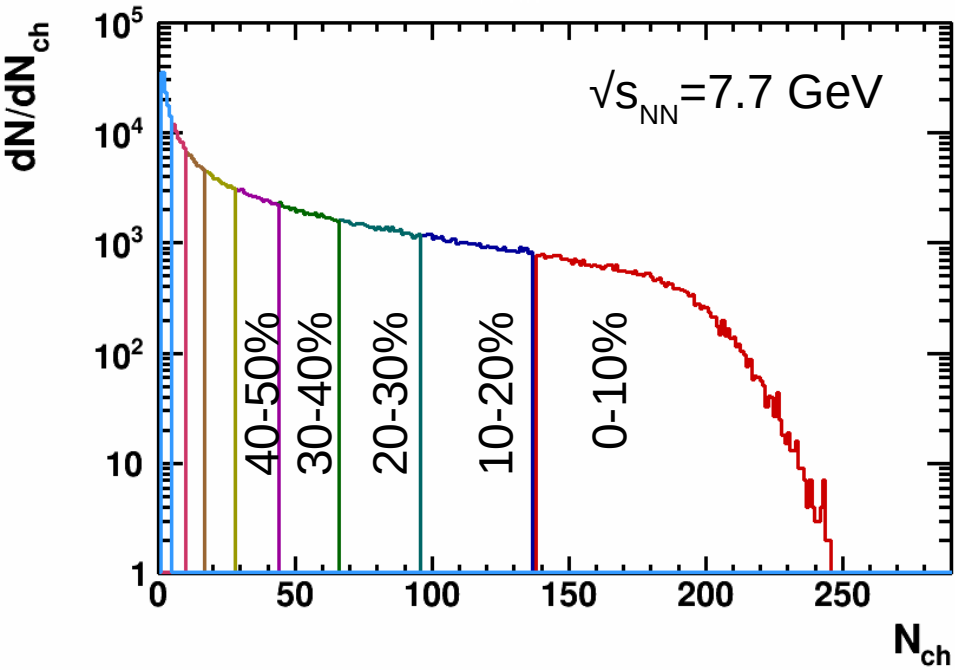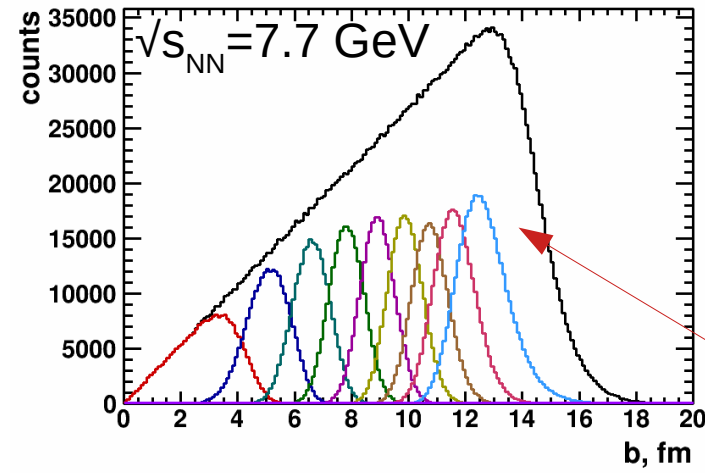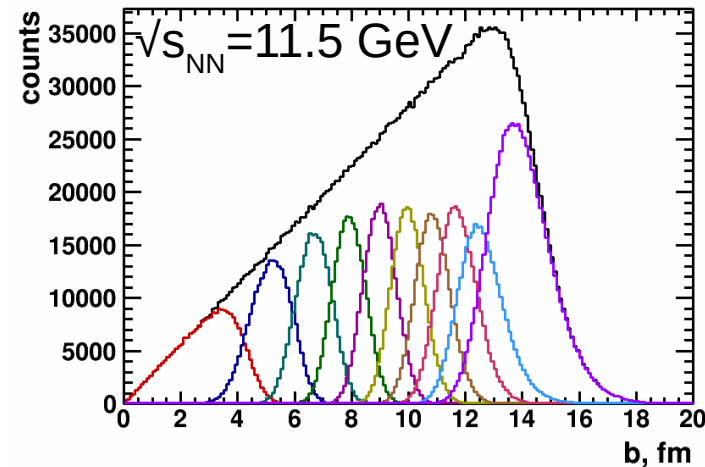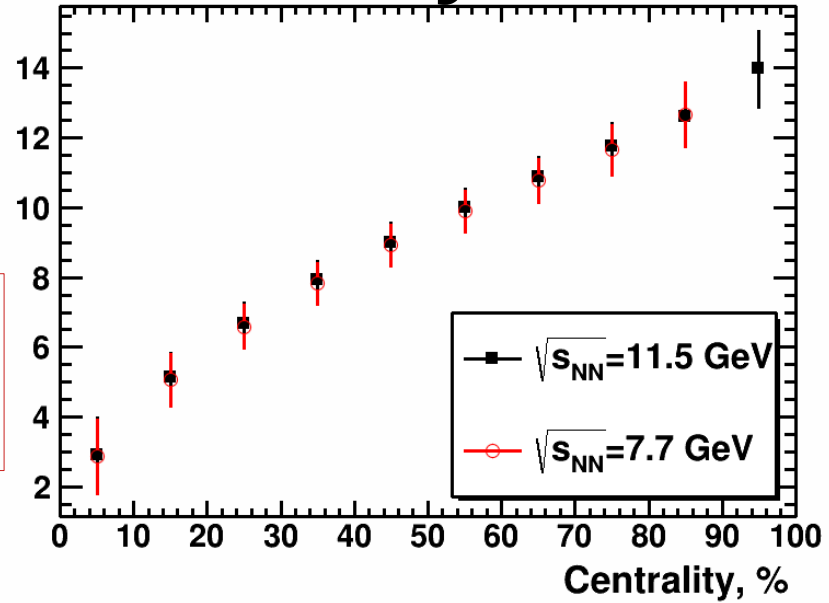
N$_{part}$ distribution in centrality classes

N$_{coll}$ 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 GeV

Used particle selection:

- |η|<0.5
- p_T>0.15 GeV/c

Fit parameters f,k vs χ^2

f=0, k=24, μ=0.27, χ^2=1.75±0.09, M=(10,265)

f=0.34, k=21, μ=0.39, χ^2=1.47±0.08, M=(10,320)
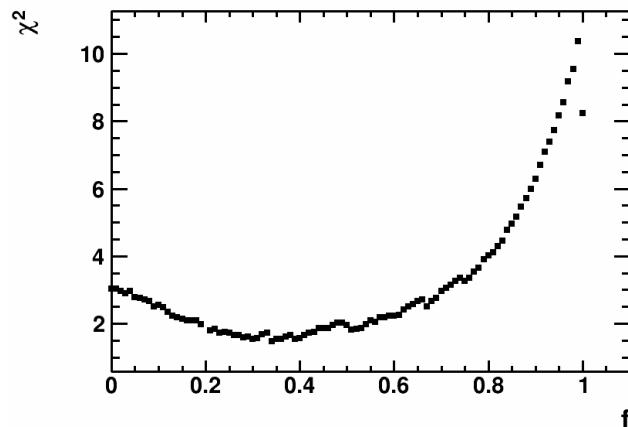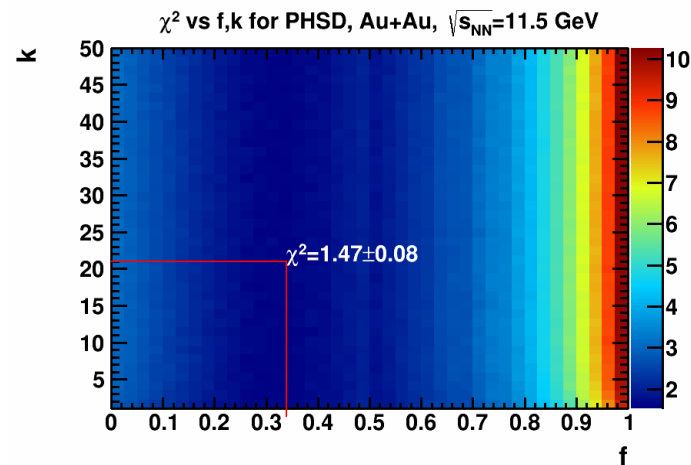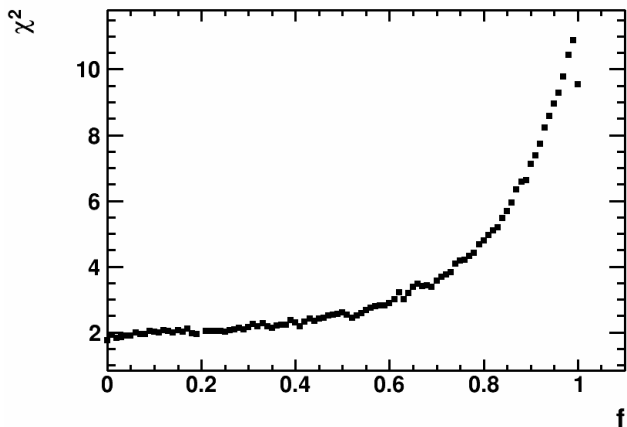
χ^2 vs f,k for PHSD, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV

χ^2=1.75±0.09

χ^2 vs f,k for PHSD, Au+Au, $\sqrt{s_{NN}}$=11.5 GeV

χ^2=1.47±0.08

MC Glauber fit: $h^\pm$ multiplicity

f=0, k=24, μ=0.27, χ^2=1.75±0.09, M=(10,265)

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

Glauber fit: f = 0.00; k = 24; 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, μ=0.39, χ^2=1.47±0.08, 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 ± ΔM have impact parameter in range b ± σ_b

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N$_{ch}$ distribution in centrality classes
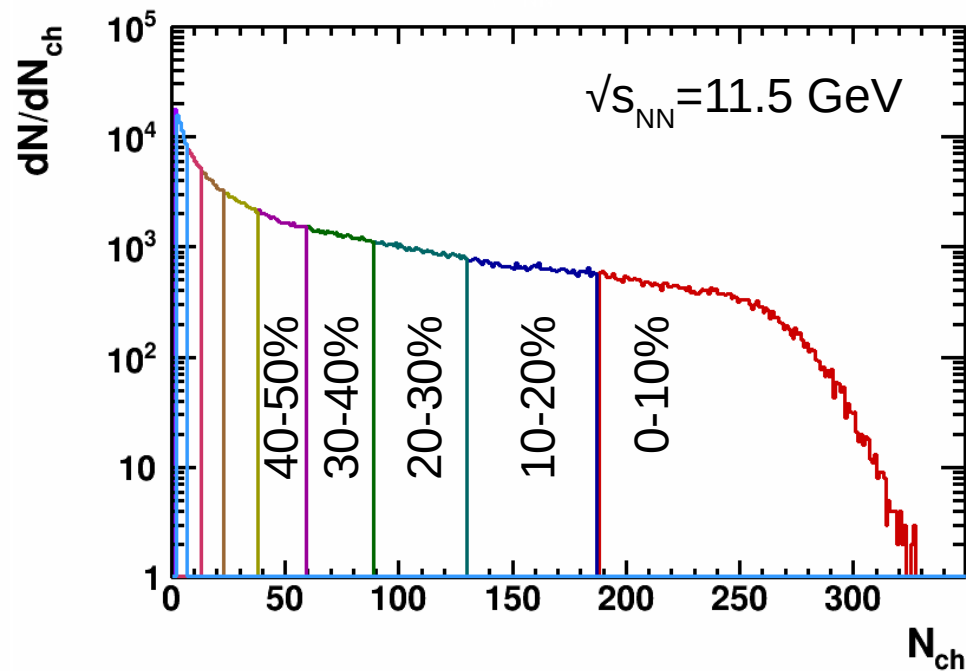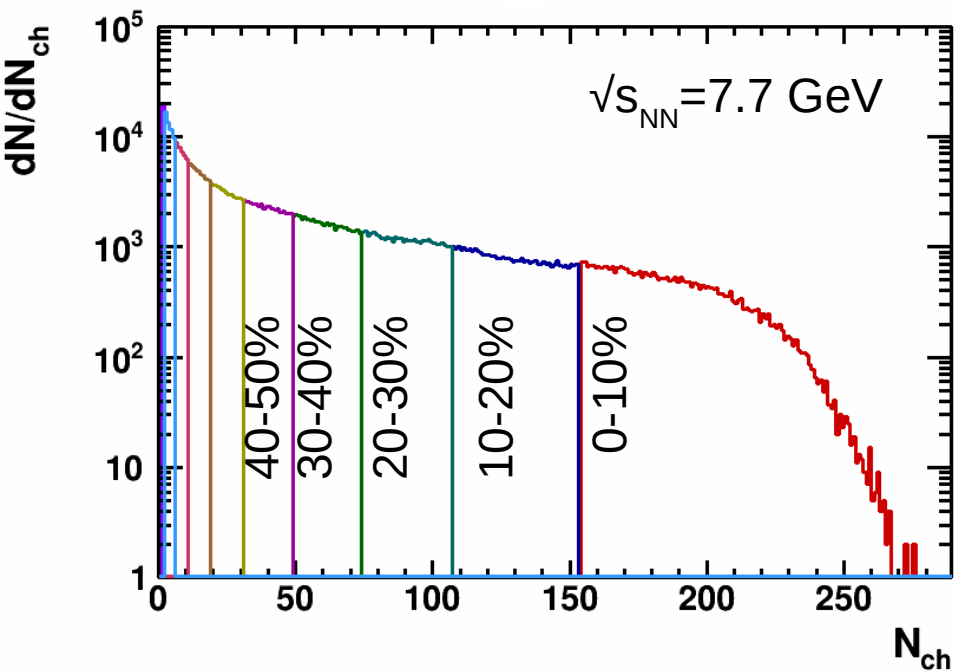
b distribution in centrality classes
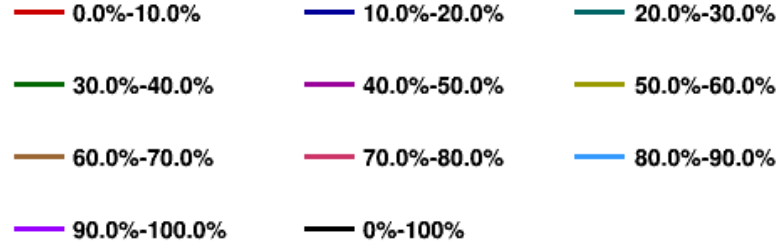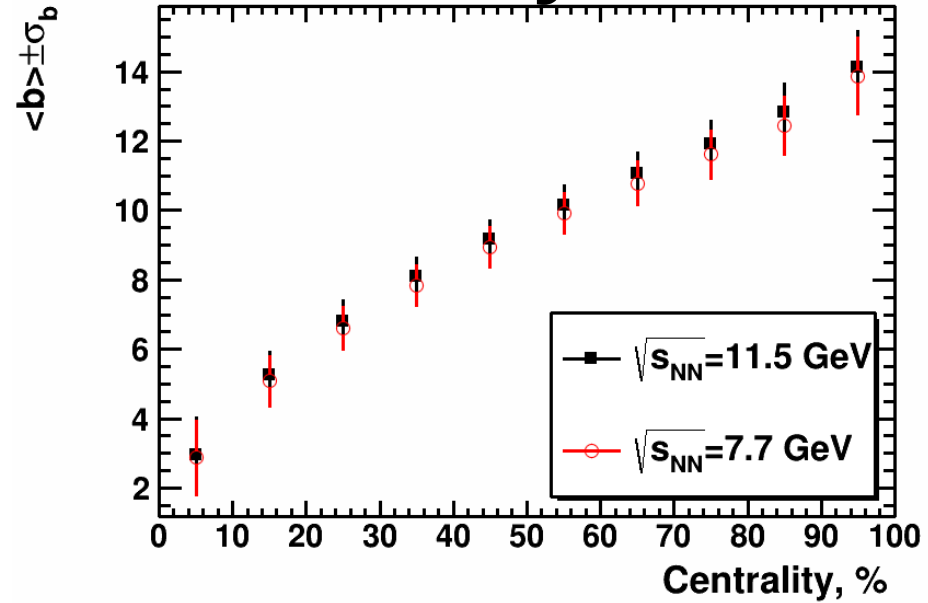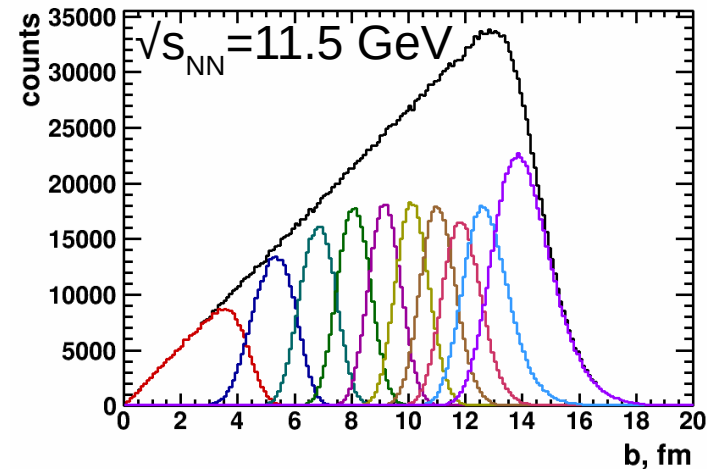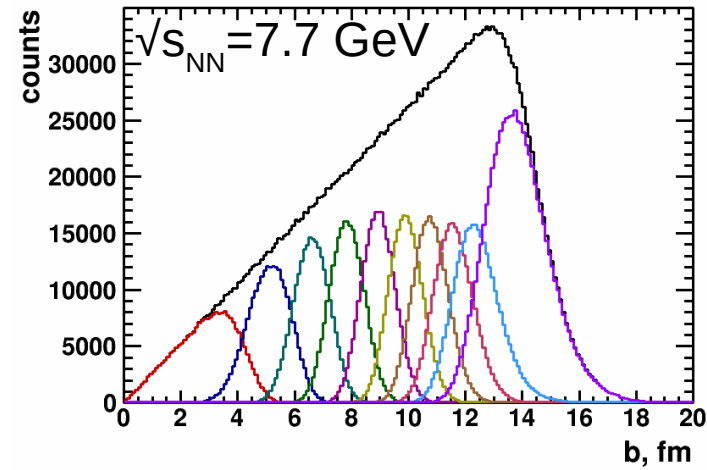
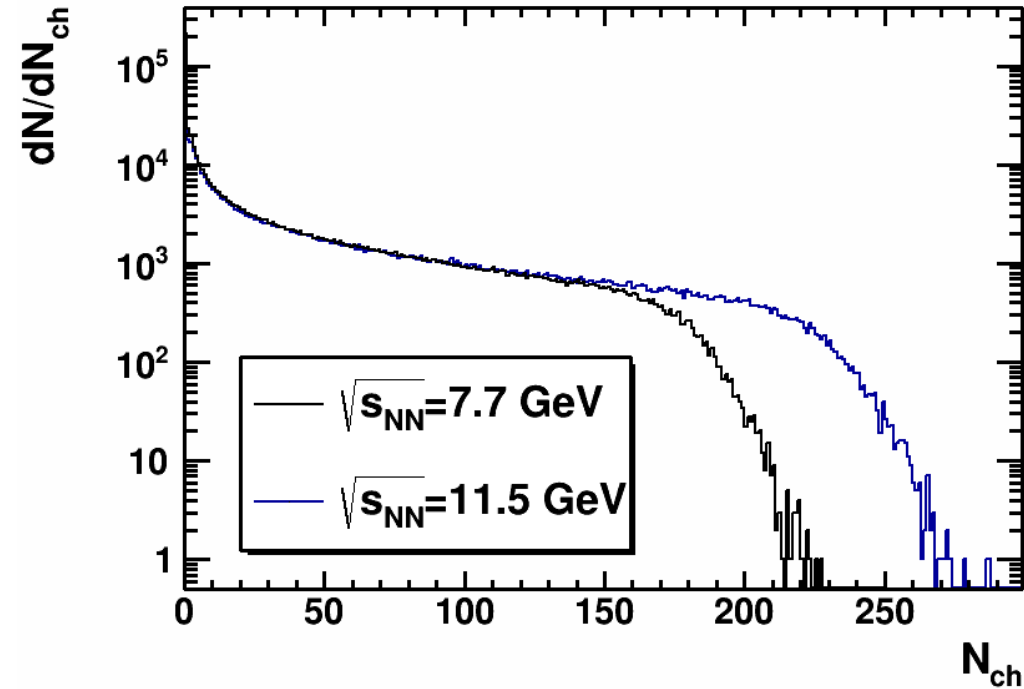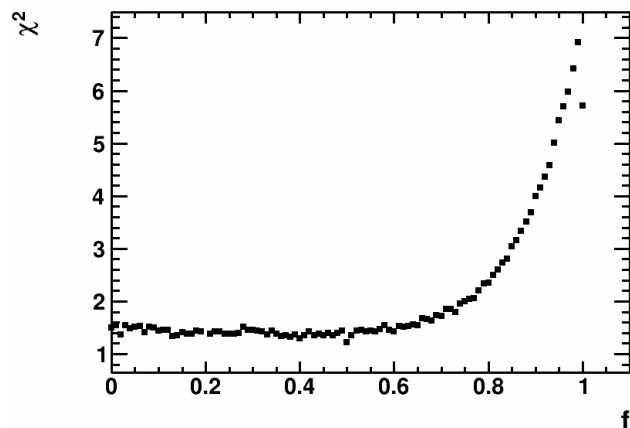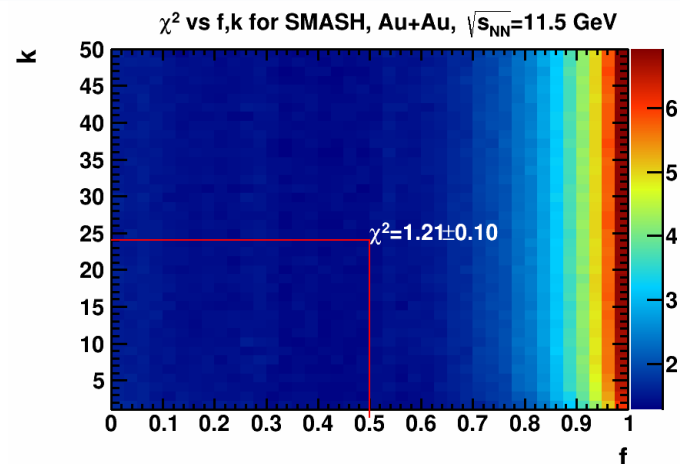# N$_{part}$ distribution in centrality classes
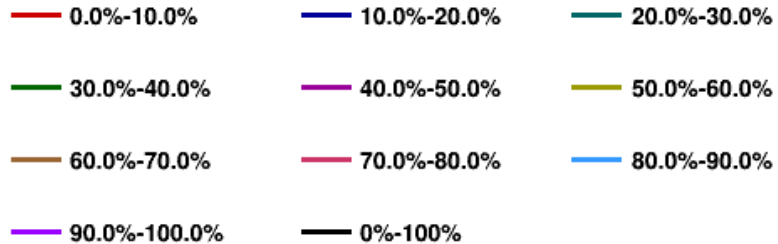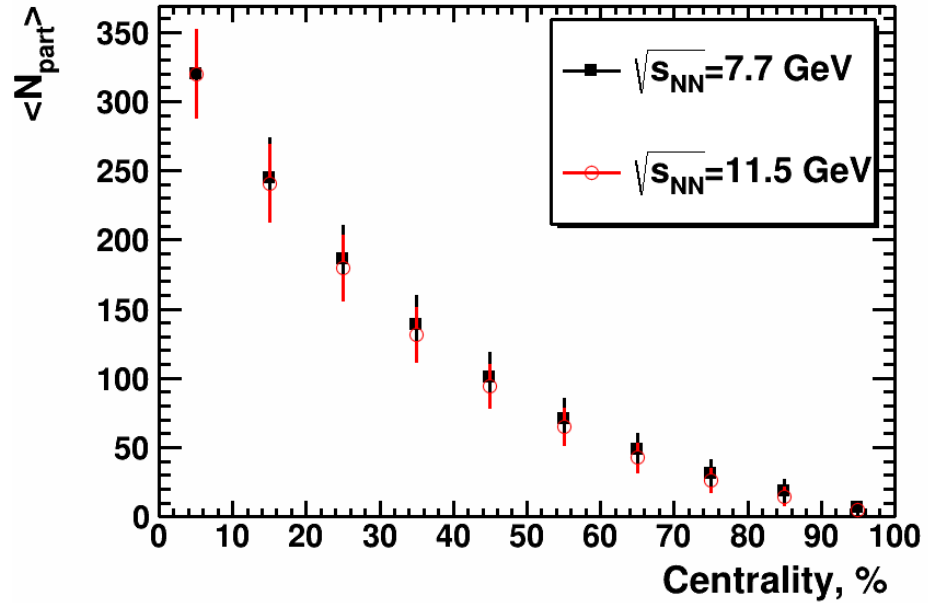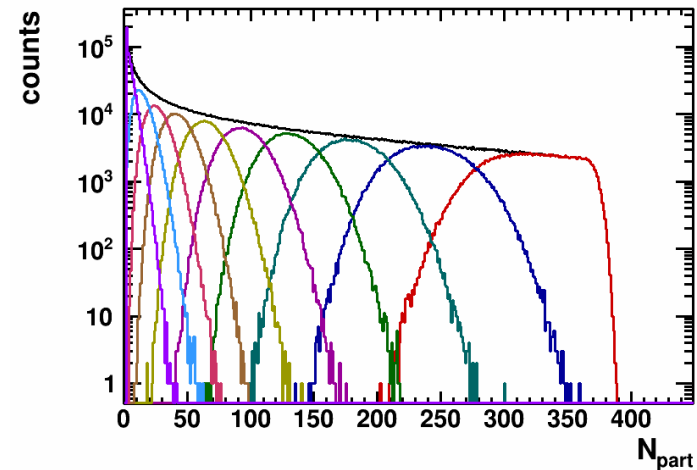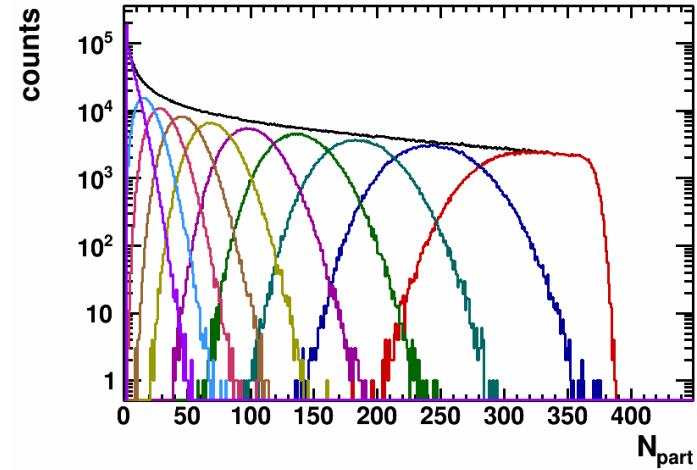
N$_{coll}$ distribution in centrality classes
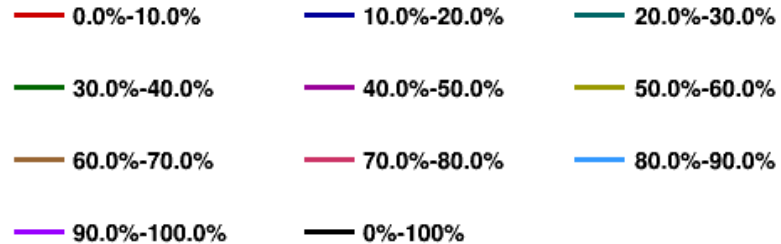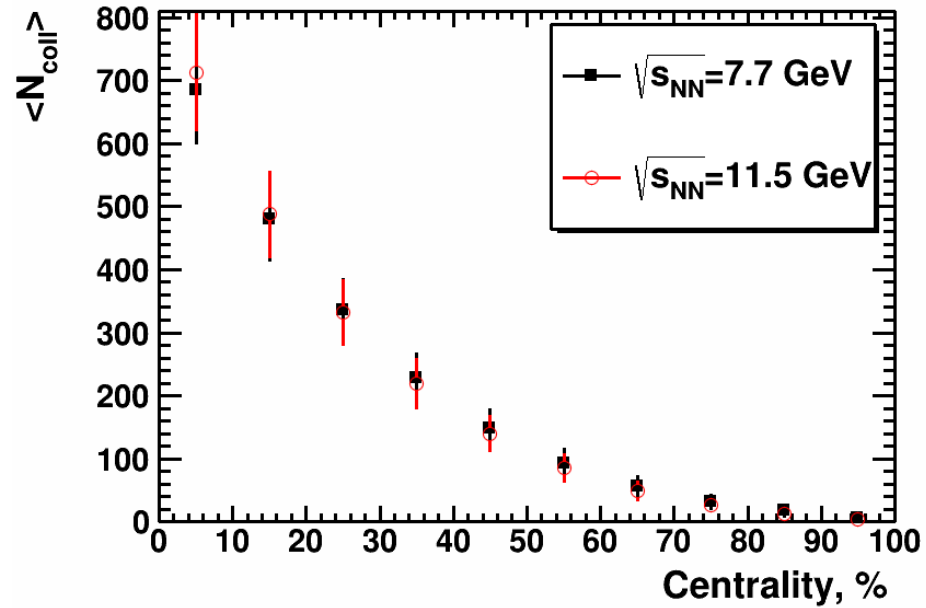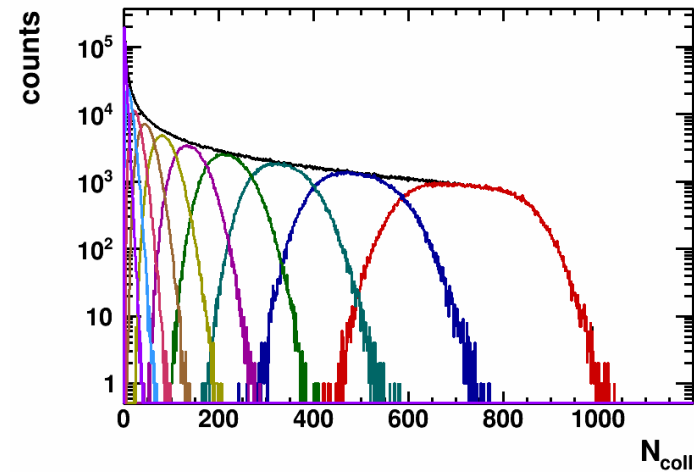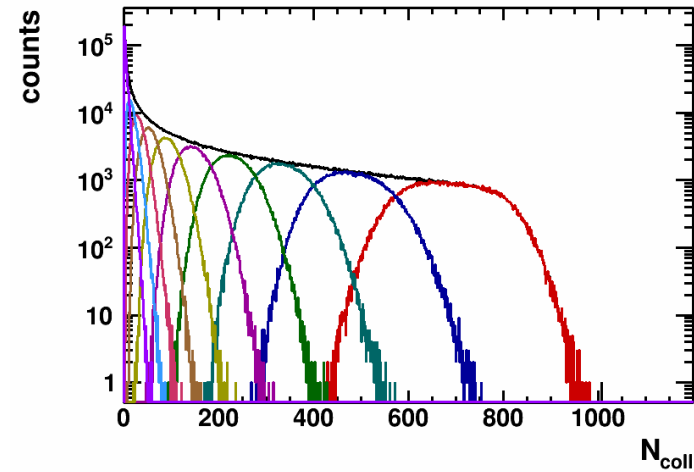
Centrality framework results for SMASH

Charged particle multiplicity in SMASH

Generated data:

- SMASH v1.6 simulation
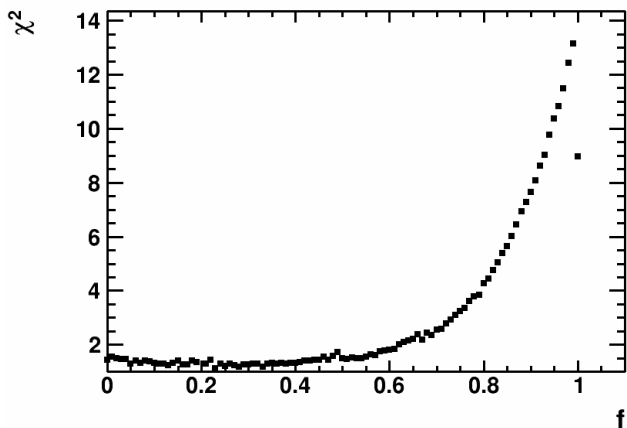 - Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=7.7, 11.5 GeV

Used particle selection:

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

Fit parameters f,k vs χ²

F=0.23, k=35, μ=0.24, χ²=1.11±0.08, M=(5,225)

f=0.5, k=24, μ=0.36, χ²=1.21±0.1, M=(10,265)

MC Glauber fit: $h^\pm$ multiplicity

F=0.23, k=35, μ=0.24, χ^2=1.11±0.08, M=(5,225)

SMASH, Au+Au, $\sqrt{s_{NN}}$=7.7 GeV
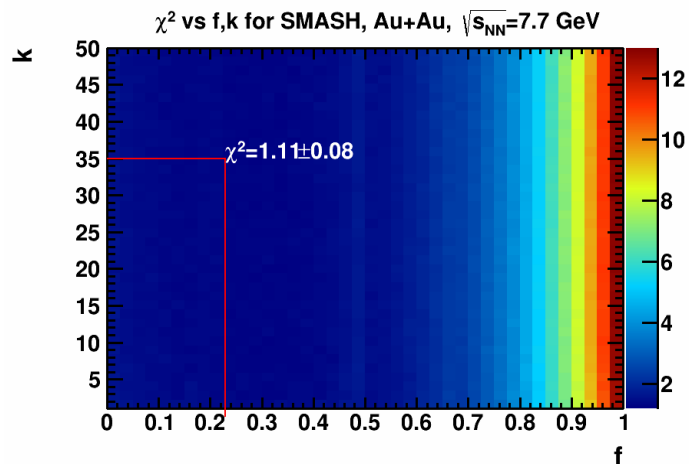
Glauber fit: f = 0.23; k = 35; M = [5,225]

MC Glauber fit is deviate from SMASH data for large multiplicity region

MC Glauber fit: $h^\pm$ multiplicity
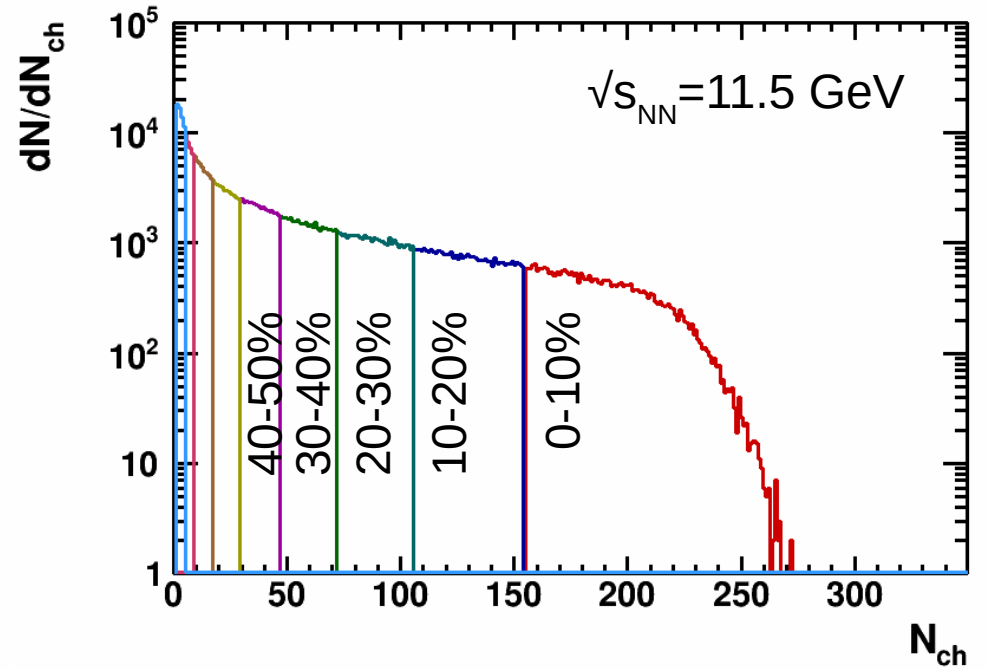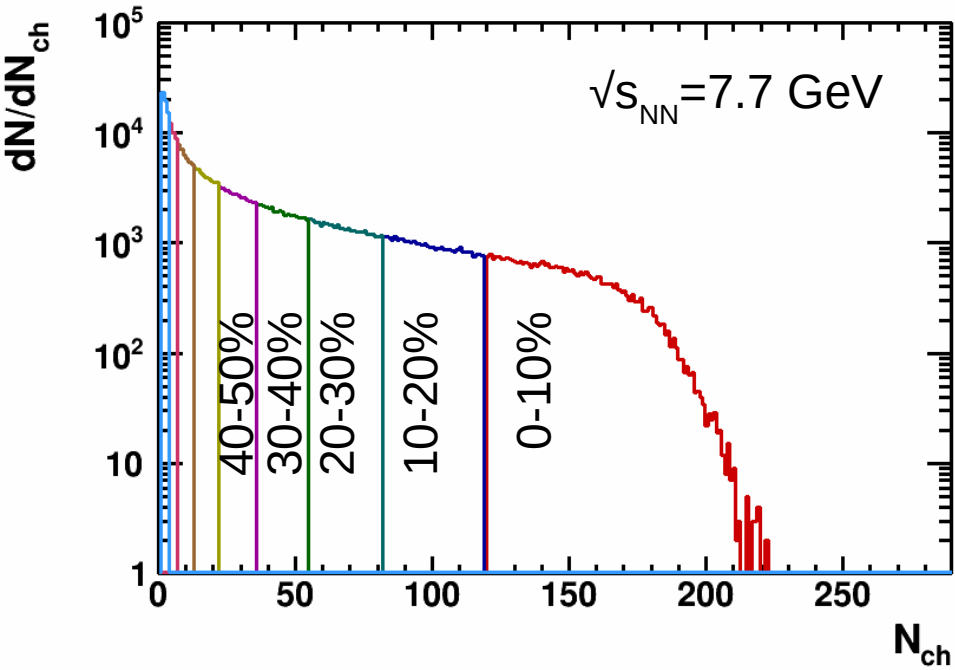
f=0.5, k=24, μ=0.36, χ^2=1.21±0.1, M=(10,265)

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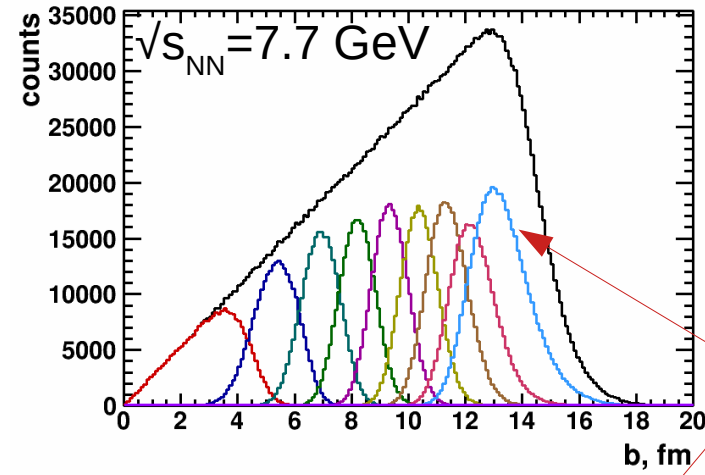
b vs. multiplicity correlation

Events in multiplicities M ± ΔM have impact parameter in range b ± σ_b
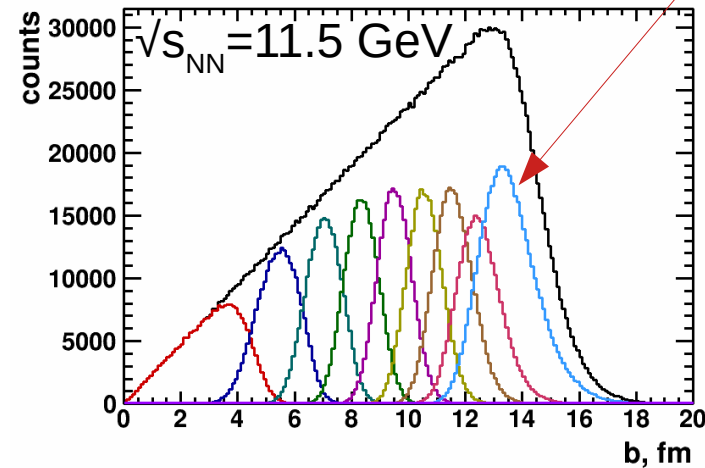
N$_{ch}$ distribution in centrality classes
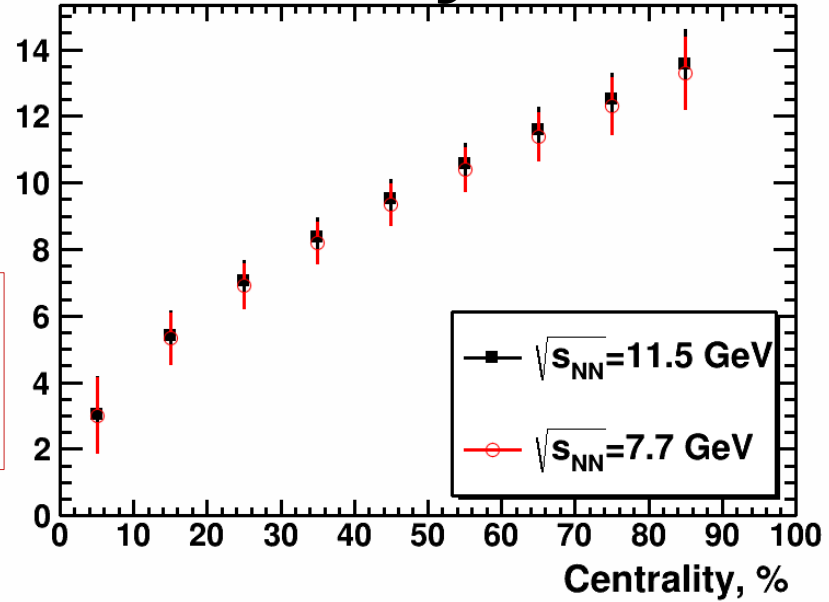
b distribution in centrality classes

No 90-100% centrality bin.

Investigating.
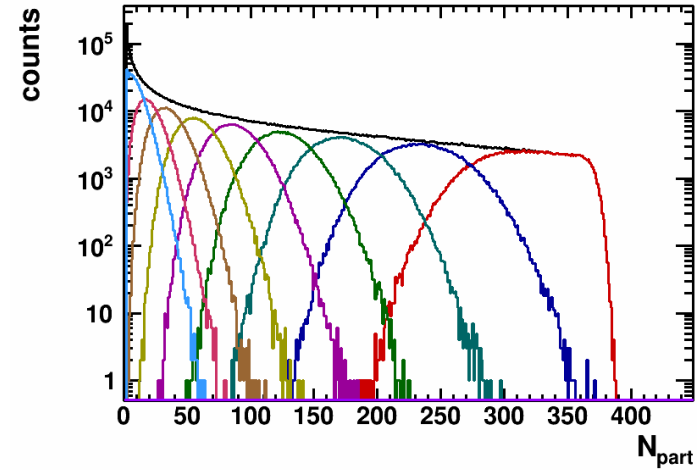
N$_{part}$ distribution in centrality classes

N$_{coll}$ distribution in centrality classes