Feasibility studies of conserved charge fluctuations in Au-Au collisions with CBM

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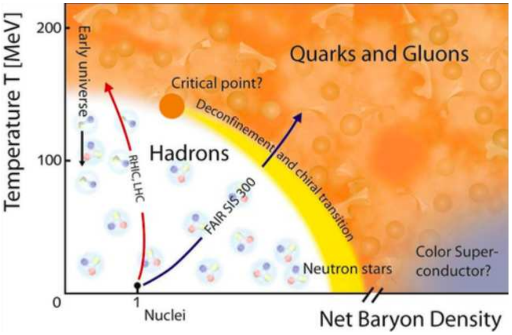
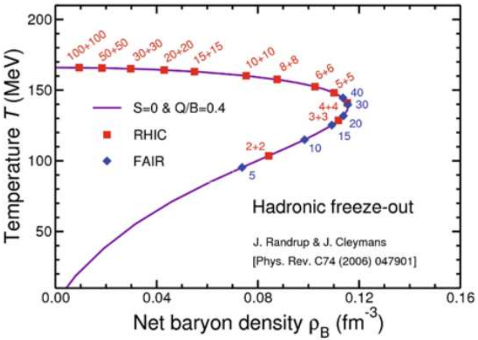
Outline

- Introduction
- CBM experiment
- Analysis details
- Results
  - Net-proton cumulants
  - Net-charge cumulants
- Summary

QCD phase diagram





- Study QCD phase diagram at high net-baryon density
  - At high net-baryon density and low temperature, first order phase transition is expected which will end at a critical point (CP)
  - CBM program supplements the Beam Energy Scan Program at RHIC, NA61 at SPS, NICA at JINR

Ref: CBM: EPJA 53, 60 (2017); PRC 74, 047901 (2006)

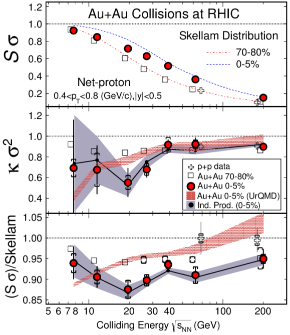
Observables for CP search

Cumulants

$$C_1 = \langle N_q \rangle, \quad C_2 = \left\langle (\delta N_q)^2 \right\rangle, \quad C_3 = \left\langle (\delta N_q)^3 \right\rangle,$$
$$C_4 = \left\langle (\delta N_q)^4 \right\rangle - 3 \left\langle (\delta N_q)^2 \right\rangle^2$$

$N_q = N_{q^+} - N_{q^-}$ and $\delta N_q = N_q - \langle N_q \rangle$
q can be any conserved quantum number

(net-baryon, net-charge, net-strangeness etc.)



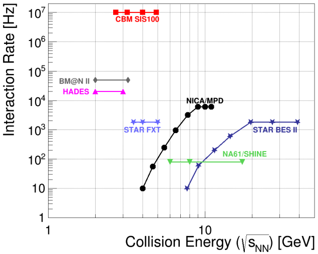
Mean, variance, skewness, kurtosis

$$M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{\sigma^3}, \quad \kappa = \frac{C_4}{\sigma^4}$$

- ⋆ Higher moments of conserved quantities are sensitive to correlation length
  $\left\langle (\delta N_q)^2 \right\rangle \sim \zeta^2 \qquad \left\langle (\delta N_q)^3 \right\rangle \sim \zeta^{4.5} \qquad \left\langle (\delta N_q)^4 \right\rangle \sim \zeta^7$
- ⋆ Non-monotonic variations of $S\sigma = C_3/C_2$, $\kappa\sigma^2 = C_4/C_2$ with beam energy are believed to be good signatures of CP

Ref: STAR: PRL 112, 032302 (2014); PRL 102, 032301 (2009)

CBM experiment



- ⋆ Fixed target experiment
- ⋆ SIS 100: Au + Au collision, $\sqrt{s_{NN}} = 2.7 - 4.9$ GeV
- ⋆ High interaction rate
- ⋆ High statistics data
- ⋆ Density in the center of the fireball expected to exceed few times greater than density of nucleus

Challenges of higher moments measurements at CBM

⋆ Particle identification

⋆ Non-trivial variations of efficiency $\times$ acceptance with p_T and rapidity (proper method of corrections needed)

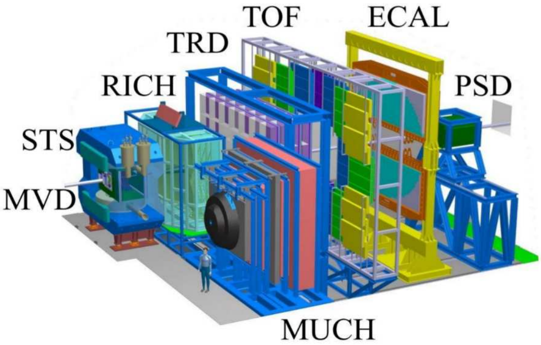
⋆ Proper vertex identification in multiple collisions

Ref: CBM overview talk at QM2019 by Viktor Klochkov; EPJA 53, 60 (2017); The CBM Physics Book, Lect. Notes Phys. 814, Springer 2011; PRC 75 (2007) 034902

Simulation details

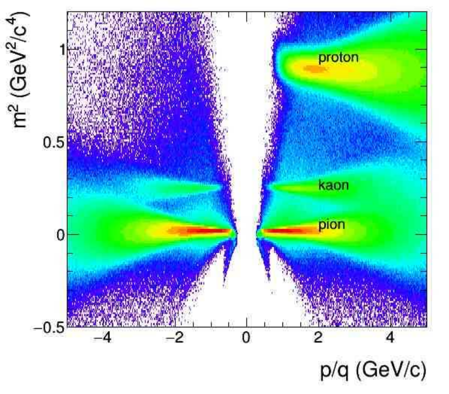
- ⋆ Event generators: UrQMD
- ⋆ Collision: Au+Au
- ⋆ Energy: E_{lab} = 10 AGeV ($\sqrt{s_{NN}} = 4.72$ GeV)
- ⋆ Events: 5 M (minimum bias)

Detectors used:
MVD, STS, RICH, TOF
MVD: Vertex information
STS: Momentum information
RICH: Electron identification
TOF: Hadron identification
Detector acceptance:
$1.5 < \eta < 3.8$ $(25^\circ > \theta > 2.5^\circ)$

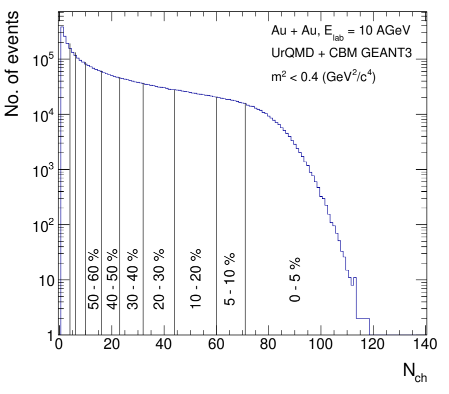


sis100 setup

Particle identification using TOF



Centrality selection using STS

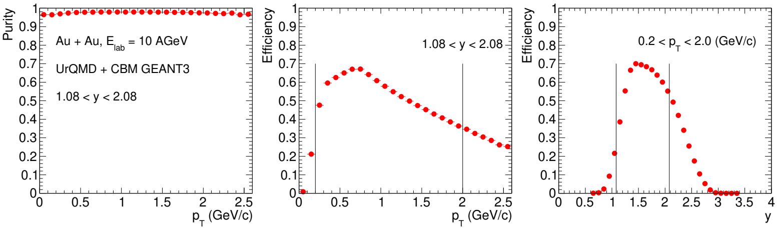


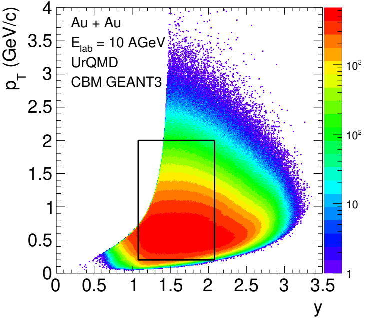
(Multiplicities are uncorrected for efficiency and acceptance)

- ⋆ Clean particle identification for bulk properties studies
- ⋆ To remove auto correlation in net-proton study, charge particles selected excluding $p, \bar{p}$

Proton (anti-proton) selection

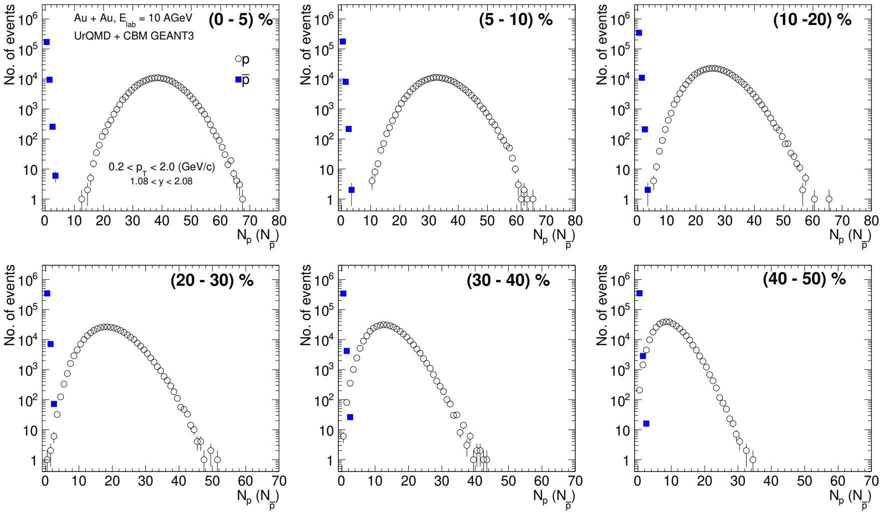
Mass square cut:
$0.6 < m^2 < 1.2$ GeV^2/c^4
Rapidity acceptance:
$\Delta y = 1$ ($y_{mid} = 1.58$)
p_T acceptance:
$0.2 < p_T < 2$ GeV/c





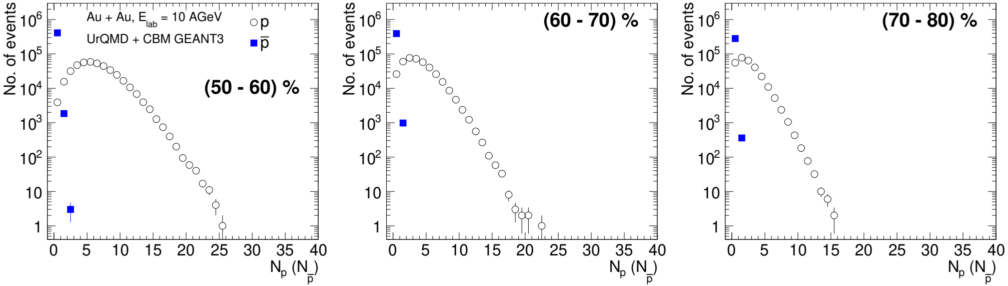
- ⋆ Purity > 96 %
- ⋆ Efficiency decreases at high p_T due to the detector acceptance
- ⋆ Efficiency for 0-5 % and 70 -80 % centralities are $\simeq$ 62 % and $\simeq$ 46 %

Proton (anti-proton) multiplicity distributions



Uncorrected distributions for efficiency and acceptance

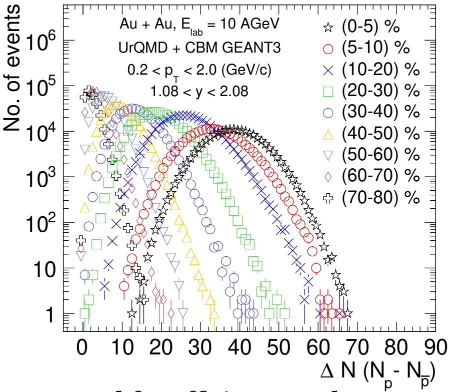
Proton (anti-proton) multiplicity distributions



(Uncorrected distributions for efficiency and acceptance)

- ⋆ Proton multiplicities follow negative binomial distribution
- ⋆ Number of $\bar{p}$ is very less compared to p
  ($\bar{p}/p = 7.8 \times 10^{-5}$ (0 -5 %), $\bar{p}/p = 2.5 \times 10^{-4}$ (70 - 80 %) from UrQMD)
- ⋆ Proton distributions are skewed more to the right side of the mean

Net-proton multiplicity distributions

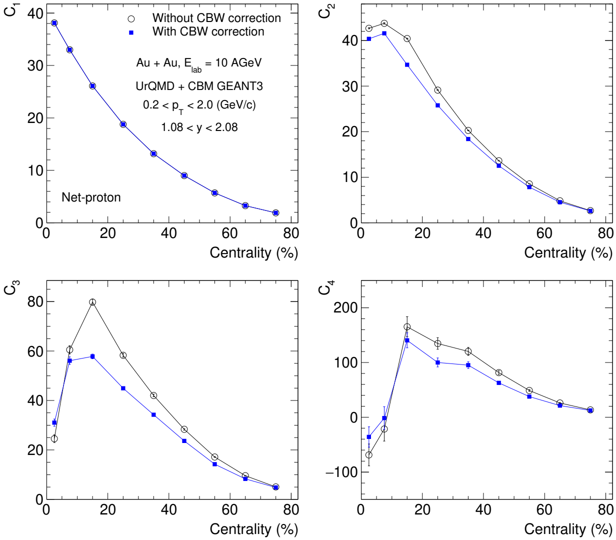


Uncorrected for efficiency and acceptance

Centrality (%)	N_{ch} ($m^2 < 0.4\ GeV^2/c^4$)
0-5	$N_{ch} \geq 71$
5-10	$60 \leq N_{ch} < 71$
10-20	$44 \leq N_{ch} < 60$
20-30	$32 \leq N_{ch} < 44$
30-40	$23 \leq N_{ch} < 32$
40-50	$16 \leq N_{ch} < 23$
50-60	$10 \leq N_{ch} < 16$
60-70	$6 \leq N_{ch} < 10$
70-80	$4 \leq N_{ch} < 6$

- ⋆ Mean and variance decreases from central towards the peripheral collisions
- ⋆ Distributions are skewed more to the right side of the mean

C_n of net-proton vs centrality (%)



Centrality bin width correction

$$C_n = \sum_r w_r C_{n,r}$$
$$w_r = \frac{n_r}{\sum_r n_r}$$
$$\sum_r w_r = 1$$

sum is over multiplicity bins

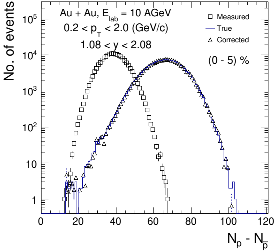
- CBWC done to suppress volume fluctuations
- Statistical error estimation is done using Delta theorem

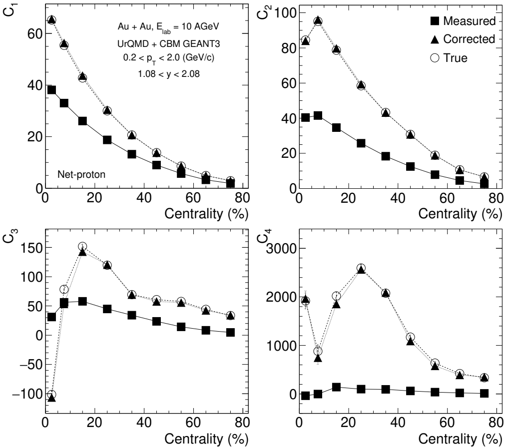
Ref: Advanced Theory of Statistics: Vol.1, London (1945); Asymptotic Theory of Statistics and Probability, Springer (2008); JPG 39, 025008 (2012); JPG 40, 105104 (2013)

Correction of cumulants of net-proton using Unfolding method

Algorithm used: RooUnfoldBayes
Relationship between measured and true distribution: $y = Rx$
y = measured, x = true, R = response matrix

⋆ 50 % events are used to construct R

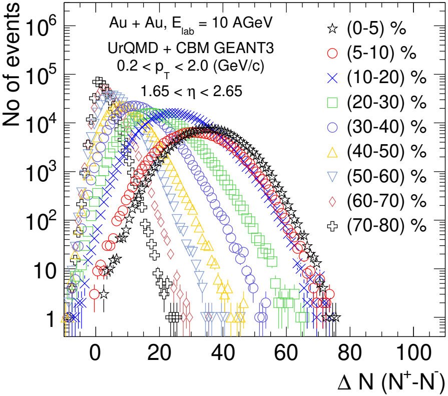




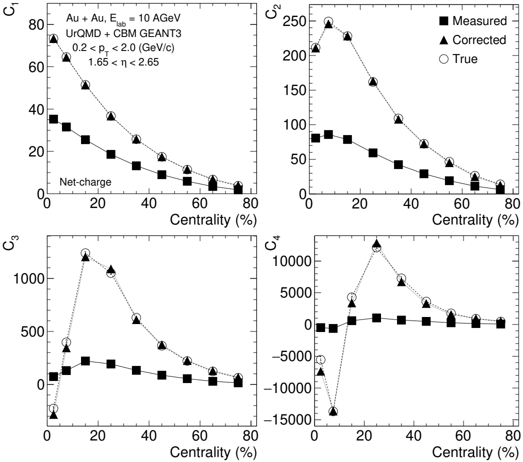
⋆We are able to get back cumulants of 'True', even if the efficiency is non-binomial and has non-trivial dependence on p_T and rapidity

Ref: NIMA 362, 487 (1995)

Net-charge multiplicity distributions and cumulants of net-charge



Uncorrected for efficiency and acceptance



- ⋆ We are able to get back cumulants of 'True', except C_4 in $0 - 5$ %
- ⋆ More statistics needed

Summary

- ⋆ Studied the feasibility of doing fluctuation analysis with conserved charges in Au+Au collisions at 10 AGeV with CBM detector using simulated events from UrQMD.
- ⋆ Clean proton identification with high purity is possible and hence one can study the net-proton (proxy for net-baryon) higher order moments using CBM detector.
- ⋆ Centrality selection using charged particles other than proton and anti-protons is possible.
- ⋆ Efficiency and detector effects were corrected for using unfolding techniques and original distributions and cummulants recovered. This shows that using the CBM detector, higher moments of net-proton and net-charge can be studied.

Outlook

- ⋆ Similar studies in other SIS100 energies
- ⋆ Look forward to data from CBM at SIS100 energies in the year 2025

Thank you