Benchmark values for net proton number fluctuations

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Critical Point and the Onset of Deconfinement
Mon Repos, Corfu

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Motivation: net proton number fluctuations

- baryon number susceptibilities χ_i^B calculated on the lattice
- enhancement of susceptibilities near the critical point
- susceptibilities are measurable as cumulants of baryon number distribution
- B-number not measurable, since no neutrons are measured
- Conflict!
  - susceptibilities are calculated in grand-canonical ensemble
  - cumulants are measured in real collisions which conserve B, have limited acceptance, and measure (almost) only protons
- many papers devoted to these subjects
- 100% detector efficiency assumed in this work
- New in this work:
  - rapidity distribution of wounded vs. produced (anti)baryons
  - isospin memory in wounded nucleons

Our approach: Monte Carlo simulation

- baryon number is conserved
- only protons and neutrons (and their antiparticles) in the simulations
- only a (fluctuating) part of incoming nucleons participate
- isospin of individual wounded nucleons is kept
- wounded nucleons have double-Gaussian rapidity distribution
  protons from this source fluctuate due to:
  - fluctuations of number of wounded nucleons
  - random number of protons out of wounded nucleons, track isospin
  - limited acceptance out of the whole rapidity distribution
- additionally produced $B\bar{B}$-pairs flat in rapidity
  (net) protons from this source fluctuate due to:
  - Poissonian fluctuations of $B\bar{B}$ pairs with mean proportional to N_{wound}
  - random number of protons and antiprotons ($p = 1/2$)
  - limited acceptance out of the whole rapidity distribution

$\Rightarrow$ **composition wounded/produced protons depends on energy, centrality, and rapidity window**

Rapidity distribution of wounded nucleons

$$\frac{dN_w}{dy}(y) = \frac{N_w}{2\sqrt{2\pi\sigma_y^2}}\left\{\exp\left(-\frac{(y-y_m)^2}{2\sigma_y^2}\right) + \exp\left(-\frac{(y+y_m)^2}{2\sigma_y^2}\right)\right\}$$

Parameter settings:

- $\sigma_y = 0.8$
- obtain y_m from

$$N_{p-\bar{p}} = \frac{Z}{A}\int_{-y_b}^{y_b}\frac{dN_w}{dy}\,dy$$

where
$N_{p-\bar{p}}$ in $|y| < y_b = 0.25$
is taken from STAR:
PRC**79** (2009) 034909,
PRC**96** (2017) 044904

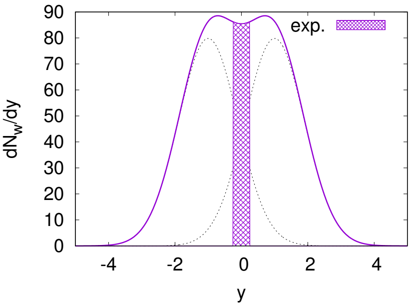


Illustration for: $y_m = 1$, $dy = 0.8$

Rapidity distribution of produced $N\bar{N}$ pairs

$$\frac{dN_{B\bar{B}}}{dy} = N_{B\bar{B}} \frac{C}{1 + \exp\left(\frac{|y| - y_m}{a}\right)}$$

Parameter settings:

- $C = \left(2a \ln\left(e^{y_m/a} + 1\right)\right)^{-1}$
- $a = \sigma_y/10$
- obtain $N_{B\bar{B}}$ from

$$N_{\bar{p}} = \frac{1}{2}\int_{-y_b}^{y_b} \frac{dN_{B\bar{B}}}{dy}\, dy$$

where
$N_{\bar{p}}$ in $|y| < y_b = 0.25$
is taken from STAR:
PRC**79** (2009) 034909,
PRC**96** (2017) 044904

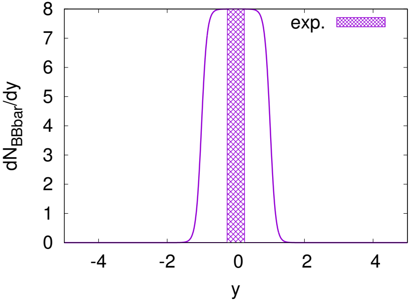


Illustration for: $y_m = 1,\ a = 0.08$

Other model faetures

Isospin determination

- Wounded nucleons remember their isospin. This feature can be turned off and on.
- Wounded proton number thus follows hypergeometric distribution.
- A produced nucleon becomes proton with probability $1/2$.

Glauber Monte Carlo

- we use GLISSANDO 2
  [M. Rybczyński *et al.*, Comp. Phys. Commun. **185** (2014) 1759]
- centrality is determined based on deposited energy measure (analogically to experiment)

Definitions

Central moments

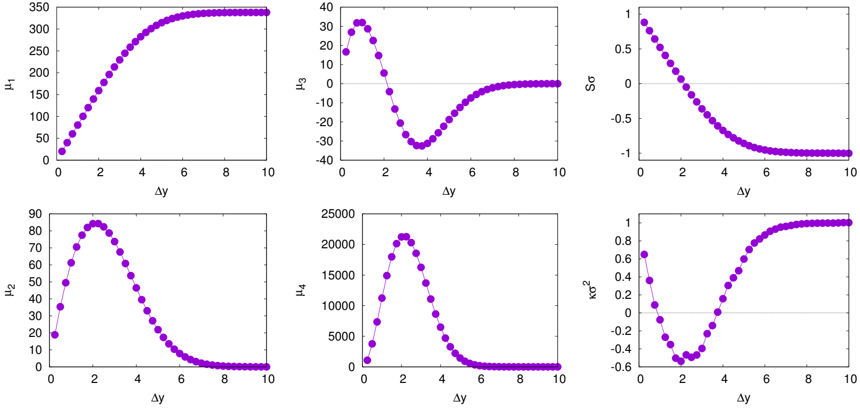
$$
\begin{aligned}
\mu_1 &= \langle n \rangle = \bar{n} \\
\mu_2 &= \langle (n - \bar{n})^2 \rangle = \sigma^2 \\
\mu_3 &= \langle (n - \bar{n})^3 \rangle \\
\mu_4 &= \langle (n - \bar{n})^4 \rangle
\end{aligned}
$$

Scaled skewness and kurtosis

$$
\begin{aligned}
S\sigma &= \frac{\mu_3}{\mu_2} = \frac{\chi_3}{\chi_2} \\
\kappa\sigma^2 &= \frac{\mu_4}{\mu_2} - 3\mu_2 = \frac{\chi_4}{\chi_2} \\
\frac{\kappa\sigma^4}{\bar{n}} &= \frac{\mu_4 - 3\mu_2^2}{\mu_1} = \frac{\chi_4}{\chi_1}
\end{aligned}
$$

Exercise: Baryon number conservation

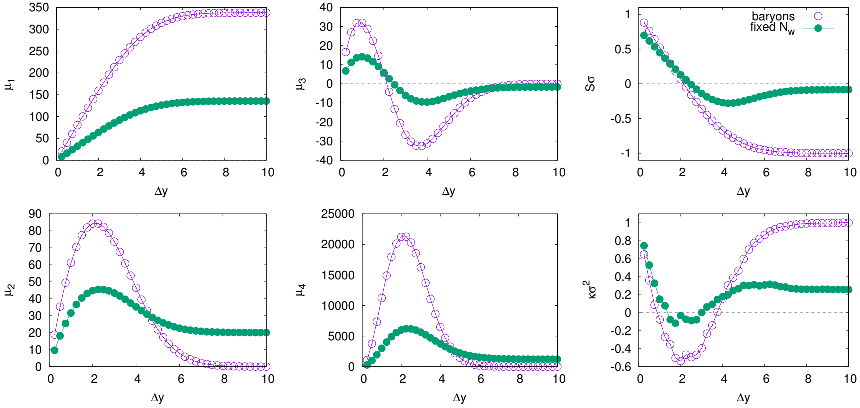
Moments of baryon number distribution around midrapidity.



$N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 5×10^7 events

Net proton number: dependence on rapidity window width

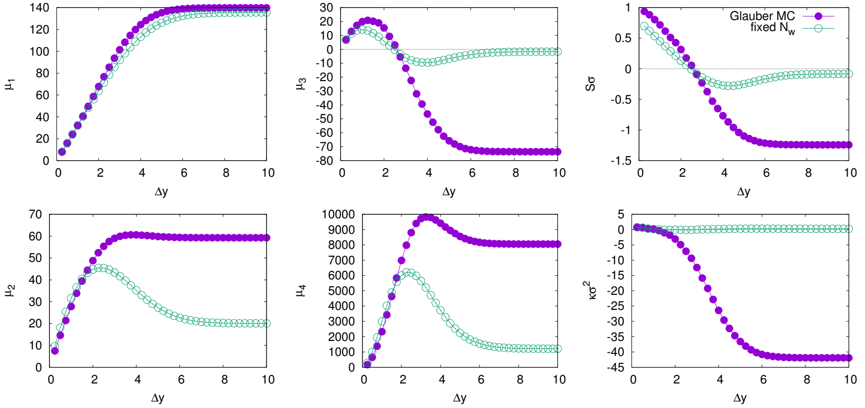
Moments of net proton number distribution around midrapidity.



$N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 2×10^7 events

Dependence on Δy: fixed N_w vs. Glauber MC

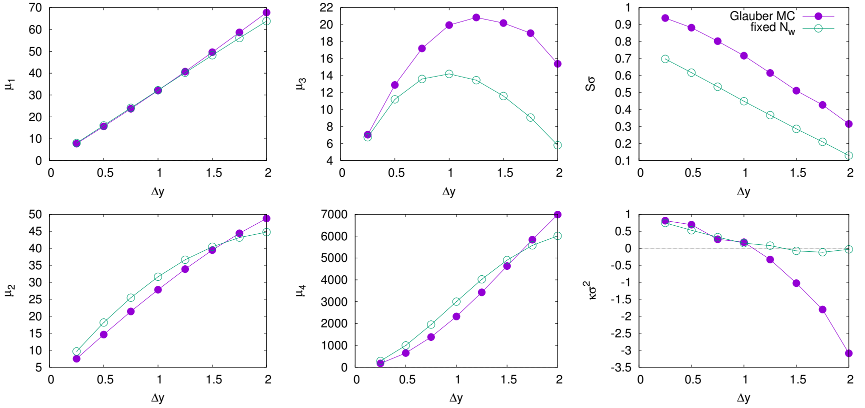
Moments of $p - \bar{p}$ distribution around $y = 0$



$N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 2×10^7 events,
Glauber MC: 1.2×10^6 events

Dependence on Δy: fixed N_w vs. Glauber MC

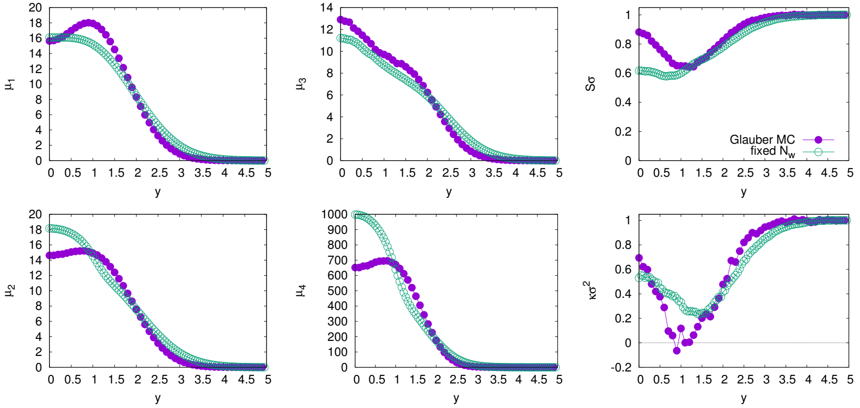
Moments of $p - \bar{p}$ distribution around $y = 0$: zoom into detector coverage



$N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 2×10^7 events,
Glauber MC: 1.2×10^6 events

Net proton number: dependence on rapidity

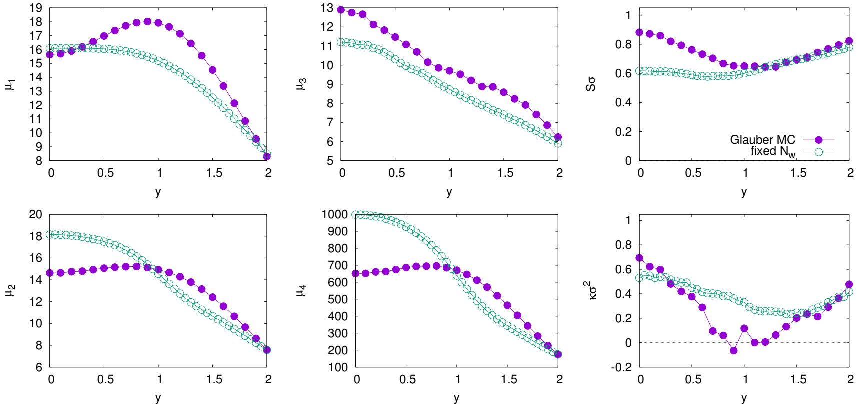
Moments of $p - \bar{p}$ distribution for $\Delta y = 0.5$



$N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 2×10^7 events,
Glauber MC: 1.2×10^6 events

Net proton number: dependence on rapidity

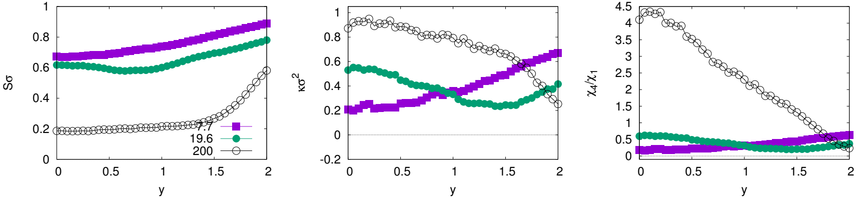
Moments of $p - \bar{p}$ distribution for $\Delta y = 0.5$: zoom into detector coverage



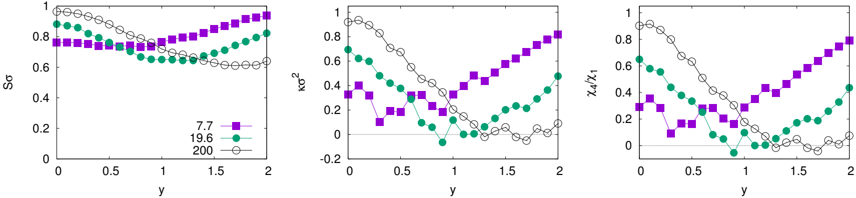
$N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 2×10^7 events,
Glauber MC: 1.2×10^6 events

Dependence on rapidity for different collision energies

Fixed $N_w = 338$, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, 2×10^7 events,

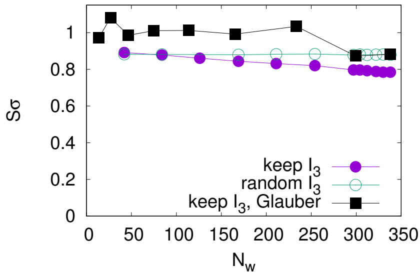


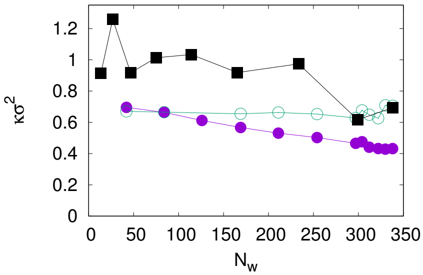
Glauber MC, 1.2×10^6 events



Net proton number: dependence on centrality

$\sqrt{s_{NN}} = 19.6$ GeV: $y_m = 1.019$, $N_{B\bar{B}}/N_w = 0.050$
Statistics: 2×10^7 for fixed N_w, $\sim 5 \times 10^5$ for Glauber MC

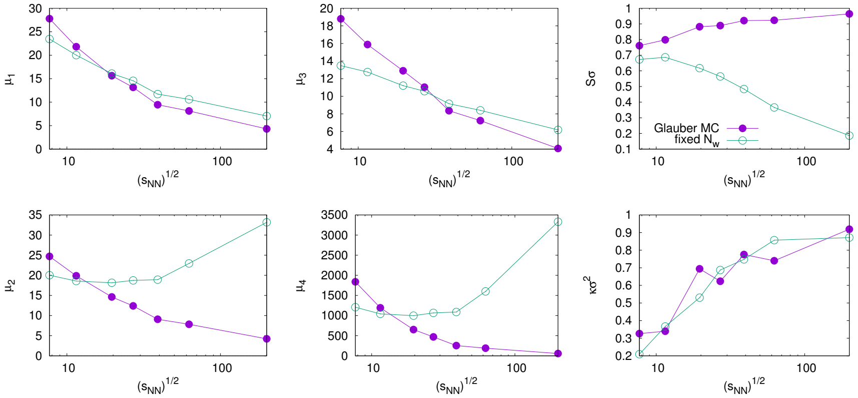




$S\sigma$ and $\kappa\sigma^2$ are lowered towards more central events of wounded protons nucleons remember their isospin.

Net proton number: dependence on collision energy

rapidity bin $\Delta y = 0.5$ around $y = 0$
Statistics: 2×10^7 events for fixed N_w, 1.2×10^6 events for Glauber MC



The importance of produced $B\bar{B}$ pairs grows with increasing energy.

Conclusions

A “minimal” model for proton number fluctuations:

- rapidity dependent composition through two components: wounded nucleons and produced $B\bar{B}$ pairs
- possible “isospin memory” of wounded nucleons
- Glauber MC (GLISSANDO 2)

Findings:

- rapidity dependence of $\kappa\sigma^2$ with $\sqrt{s_{NN}}$-dependent minimum
- isospin effect: decrease of $S\sigma$ and $\kappa\sigma^2$ with higher centrality
- baryon number conservation: decrease of $S\sigma$ and $\kappa\sigma^2$ with lower energies