Proton number fluctuations due to mundane effects

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1. Motivation: net-proton number fluctuations

- baryon number susceptibilities χ^B_i can be calculated on the lattice
- enhancement of susceptibilities near the critical point
- susceptibilities are (in principle) measurable as cumulants of baryon number distribution
- Problems with the measurement:
  - susceptibilities are calculated in grand-canonical ensemble, however cumulants are measured in real collisions which conserve *B*
  - baryon number involved in the collision fluctuates due to centrality fluctuations
  - baryon number is not measurable, net-proton number is used as proxy (e.g. since no neutrons are measured)

2. Features of this model: Monte Carlo simulation

- conservation of the baryon number based on the number of particiapants (wounded nucleons), which fluctuates e-by-e
- rapidity distribution of wounded vs. produced (anti)baryons
- wounded nucleons (may) remember their isospin
- only protons and neutrons (and their antiparticles) in the simulations
- Two sorts of nucleons (and antinucleons) in the final state:
  - originally wounded nucleons
  - produced as nucleon-antinucleon pairs
- Glauber Monte Carlo
  - we use GLISSANDO 2 [1]
  - centrality is determined based on deposited energy measure

3. Rapidity distribution of wounded nucleons

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

- $\sigma_y = 0.8$
- y_m set to reproduce

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

- $y_b = 0.25$
- data on net-proton number taken from [2,3]

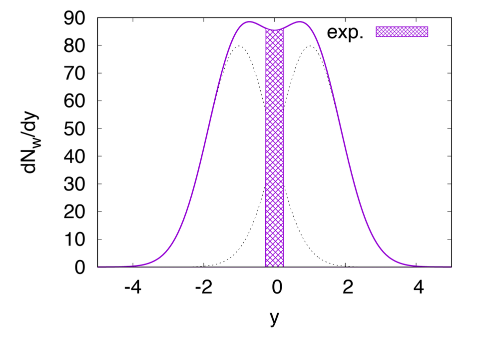


Illustration for: $y_m = 1$, $\sigma_y = 0.8$

4. Rapidity distribution of produced nucleon pairs

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

- *C* is normalization to 1
- N_{BBbar} set to reproduce the observed number of antiprotons

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

- $y_b = 0.25$
- data on antiproton numbers taken from [2,3]

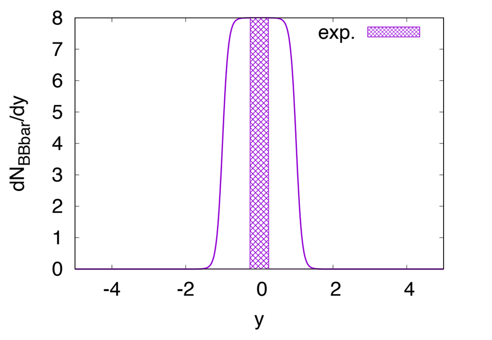


Illustration for: $y_m = 1$, $a = 0.08$

5. Details of Glauber MC simulation

- Centrality is determined according to the multiplicity

$$M \propto \frac{1-\alpha}{2}N_w + \alpha N_{bin}$$
$$\alpha(\sqrt{s_{NN}}) = \alpha_0 + \alpha_1 \ln\sqrt{s_{NN}}$$

- The number of NNbar pairs fluctuates according to Poissonian with the mean proportional to N_w

$$\mu_{N\bar{N}} = \frac{dN_{\bar{p}}}{dy}y_m\frac{N_w}{\langle N_w\rangle}$$

where dN_{pbar}/dy is measured for given energy and centrality, and $\langle N_w \rangle$ is mean number of wounded nucleons at given centrality

6. Model parameters for different energies

$\sqrt{s_{NN}}$ [GeV]	α	y_m	$N_{B\bar{B}}$
7.7	0.110	0.519	0.8265
11.5	0.114	0.770	4.4790
19.6	0.120	1.019	16.946
27	0.123	1.128	27.1070
39	0.127	1.308	44.4262
62.4	0.132	1.384	75.2842
200	0.145	1.665	177.794

7. Definitions

Central moments

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

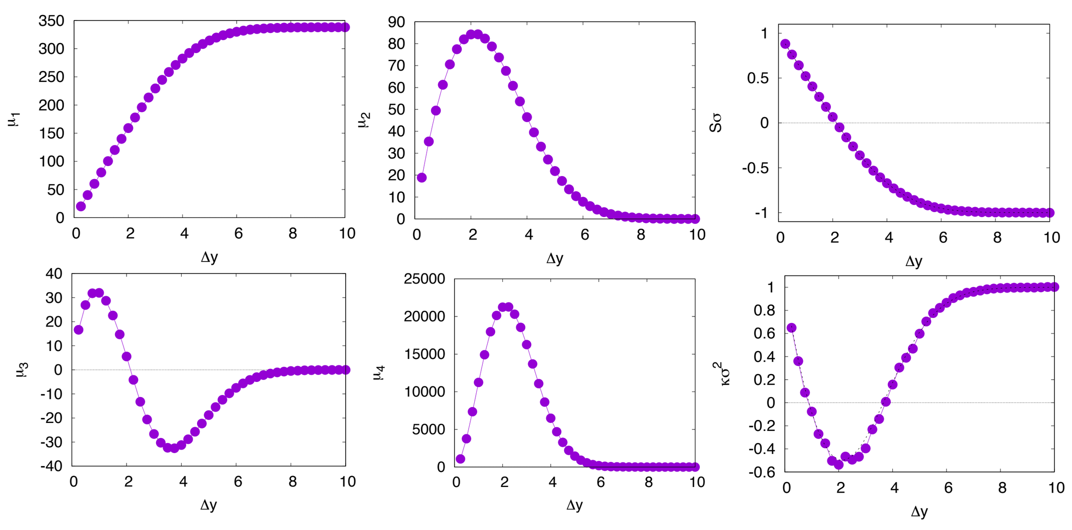
Scaled skewness and kurtosis

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

8. Basic exercise: baryon number conservation

Moments of *B* number distribution depending on rapidity bin width around central rapidity – reproduced by binomial distribution.

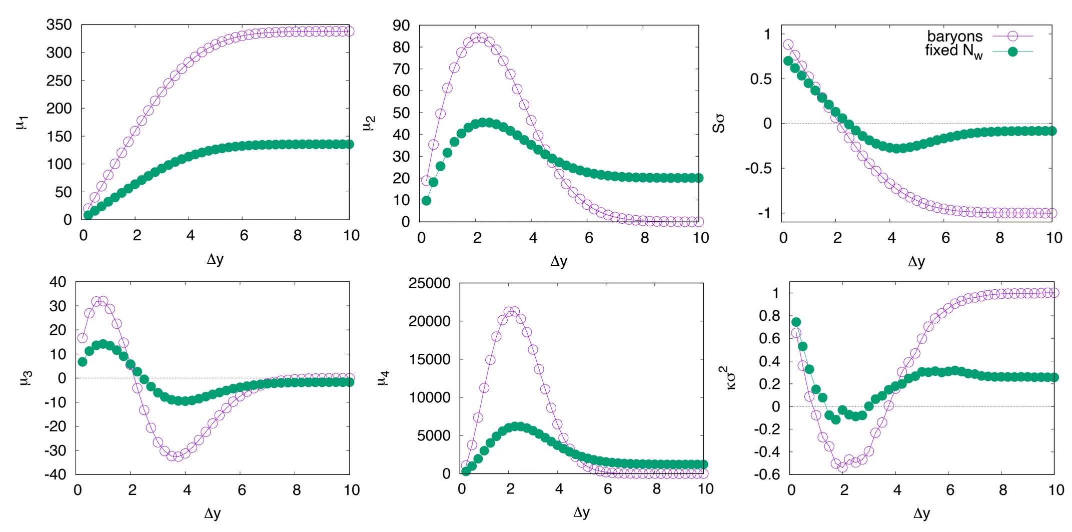
$\sqrt{s_{NN}} = 19.6$ GeV, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, $N_w = 338$
5×10^7 events



9. Basic exercise: net-protons vs. net baryons

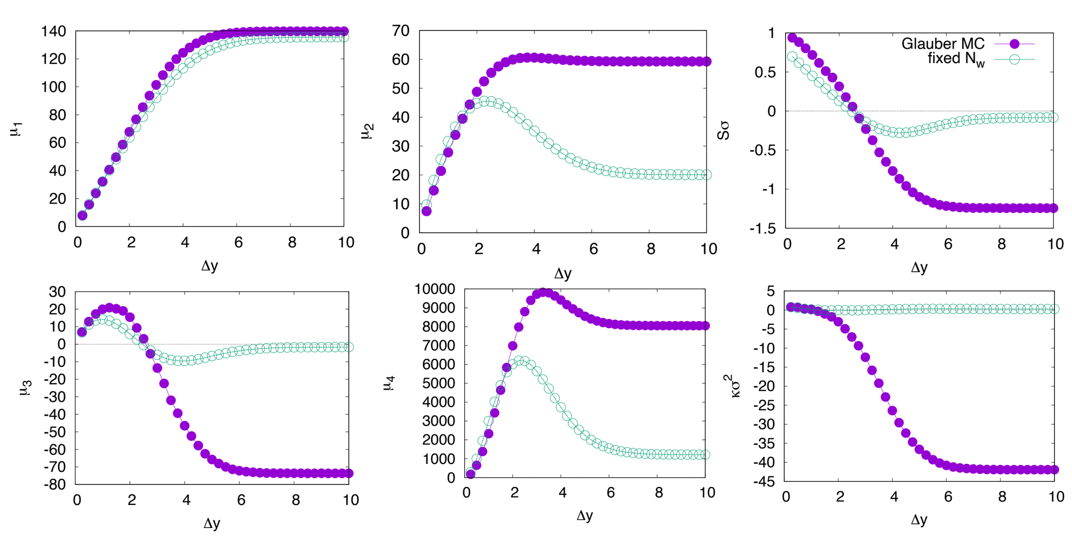
Fluctuations of net baryon number compared to net-proton number

$\sqrt{s_{NN}} = 19.6$ GeV, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, $N_w = 338$
5×10^7 events



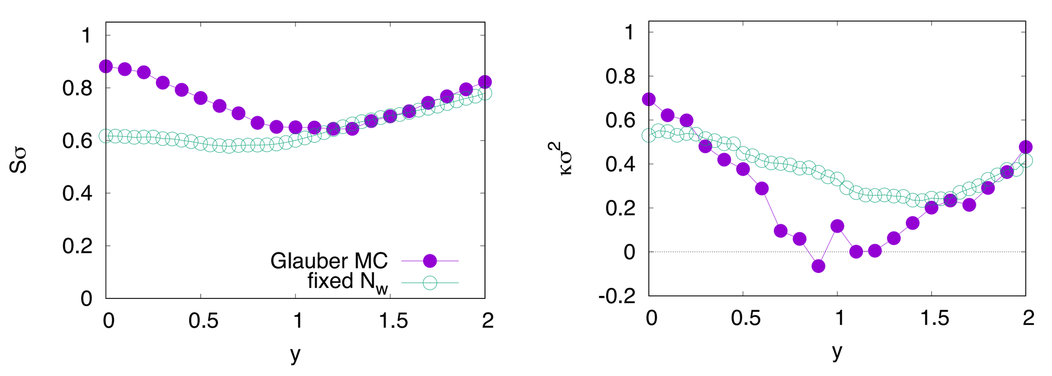
10. Basic exercise: net protons + fluctuating N_w

Comparison: fixed number of wounded nucleons vs. fluctuating N_w
$\sqrt{s_{NN}} = 19.6$ GeV, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, $N_w = 338$
5×10^7 events, Glauber MC 1.2×10^6 events



11. Results: net-proton number as function of *y*

Brewer et al [4]: search for critical point by looking at the rapidity dependence of cumulants, because μ_B depends on rapidity.
Here: non-critical dependence of the moments on rapidity.

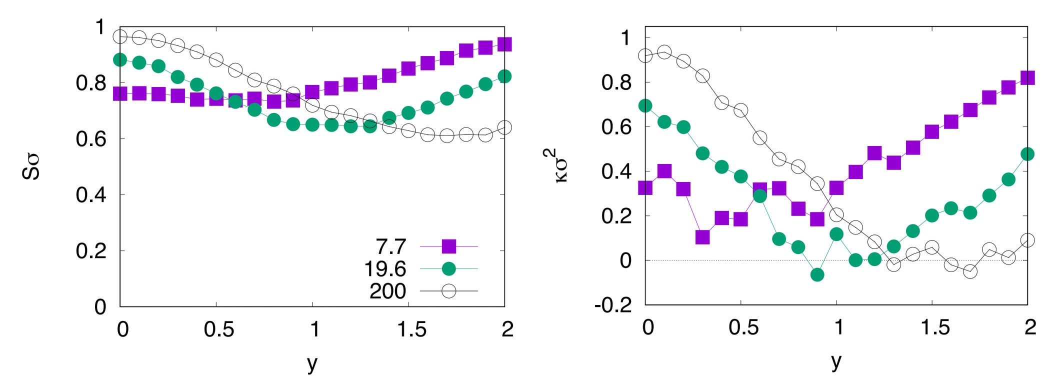


$\sqrt{s_{NN}} = 19.6$ GeV, $N_{B\bar{B}} = 16.94$, $y_m = 1.019$, $N_w = 338$
Glauber MC 1.2×10^6 events, $\Delta y = 0.5$

12. Rapidity dependence for different energies

As panel 11, but for different energies.

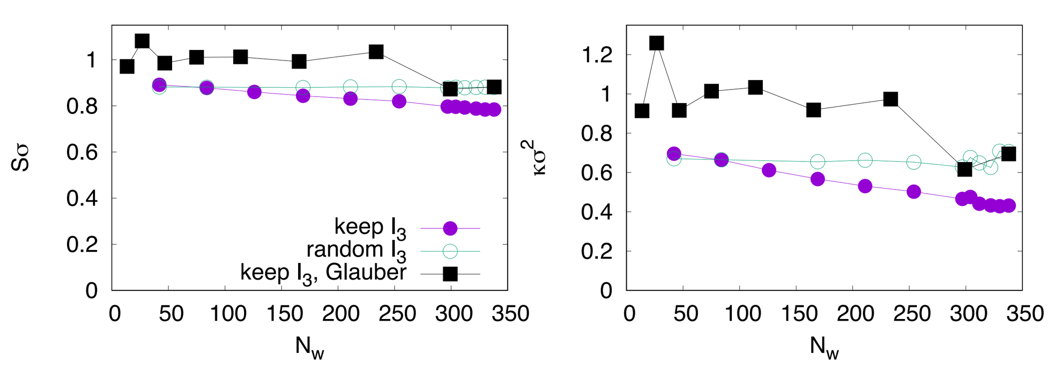
Glauber MC, 1.2×10^6 events



The minimum corresponds with the width of the rapidity distribution.

13. Centrality dependence

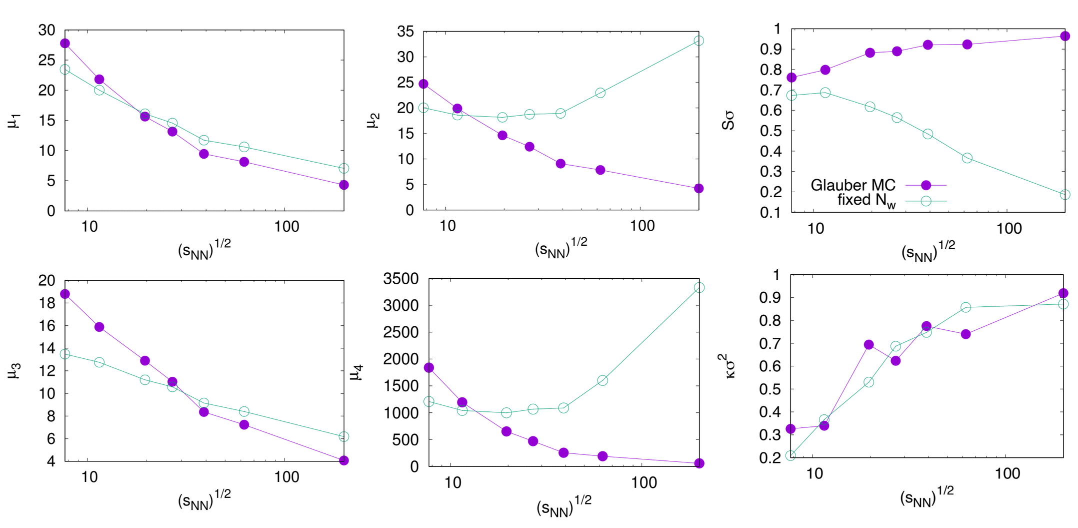
$\sqrt{s_{NN}} = 19.6$ GeV, $y_m = 1.019$, $N_{B\bar{B}}/N_w = 0.050$
Statistics: 2×10^7 for fixed N_w, ~ 5×10^5 for Glauber MC



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

14. Collision energy dependence of net protons

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



The importance of produced BBbar pairs grows with energy.

15. Conclusions

A "minimal" model for proton number fluctuations:
- rapidity dependent composition through two components: wounded nucleons and produced BBbar pairs
- Glauber MC (GLISSANDO 2)
- General formalism recently published by Braun-Munzinger *et al.* [5]

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

References

[1] M. Rybczyński et al., Comp. Phys. Commun. 185 (2014) 1759
[2] STAR collab., Phys. Rev. C 79 (2009) 034909
[3] STAR collab., Phys. Rev. C 96 (2017) 044904
[4] J. Brewer *et al.*, Phys. Rev. C 98 (2018) 061901
[5] P. Braun-Munzinger *et al.*, arXiv:2007.02463