Clusters and higher moments of proton number fluctuations

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Critical Point and the Onset of Deconfinement
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Outline

1. (Net) Proton number fluctuations and the influence of deuterons
2. Production mechanism of deuterons and their scaled moments

Part 1: Proton number fluctuations

- particle number fluctuations are sensitive to the phase transition
- higher-order cumulants are sensitive to the vicinity of the critical point
- however, cumulants can be influenced:
  - conservation laws
  - final state hadronic interactions
  - acceptance effects
  - efficiency effects
  - ...
- proton number serves as proxy for baryon number in measurements
- How well is the baryon number (multiplicity) distribution represented by proton number?

The influence of deuteron formation

- deuterons are formed after the fireball breakup
- some of the originally produced protons are eaten up by deuterons
- deuteron numbers scales with n_p^2 – non-linear coupling to proton number
- therefore, if proton number in an event is high, many protons disappear in deuterons
- this must be seen in higher moments of multiplicity distributions

The measures

n_p is the number of protons
$\langle \cdots \rangle$ = averaging over events

variance

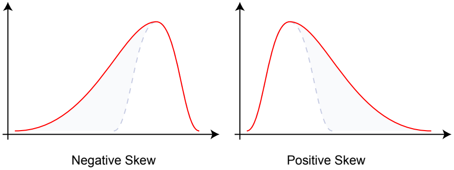
$$\sigma^2 = \langle (n_p - \langle n_p \rangle)^2 \rangle$$

skewness

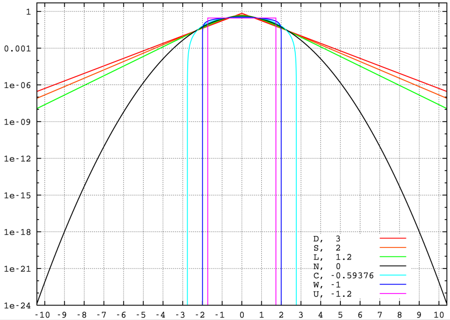
$$S = \frac{\langle (n_p - \langle n_p \rangle)^3 \rangle}{\sigma^3}$$

kurtosis

$$\kappa = \frac{\langle (n_p - \langle n_p \rangle)^4 \rangle}{\sigma^4} - 3$$



kurtosis measures the tails:



Underlying distributions of protons and deuterons

- initial proton number distribution Poissonian

$$P_i(n_i) = \lambda_p^{n_i} \frac{e^{-\lambda_p}}{n_i!}$$

NB: n_i is not measurable – it still includes protons which go into deuterons

- average number of deuterons is proportional to n_i^2

$$\lambda_d = B n_i^2$$

- number of deuterons fluctuates according to Poisson distribution

$$P_d(n_d|n_i) = \lambda_d^{n_d} \frac{e^{-\lambda_d}}{n_d!} = (B n_i^2)^{n_d} \frac{e^{-B n_i^2}}{n_d!}$$

The observed distributions of protons and deuterons

- the observed number of deuterons is distributed as

$$P_d(n_d) = \sum_{n_i \geq n_d} P_d(n_d|n_i) P_i(n_i)$$

- the measured proton number is obtained after subtracting protons in deuterons $n_p = n_i - n_d$
- observed proton number distribution

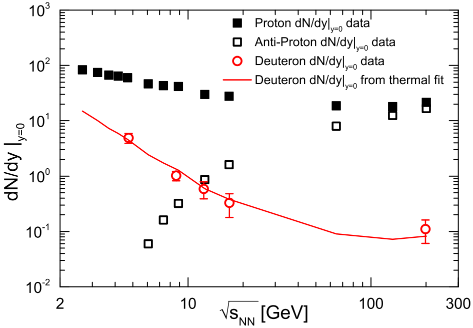
$$P(n_p) = \sum_{n_i \geq n_p} P_i(n_i) P_d(n_i - n_p|n_i)$$

Parameters fixed by observables

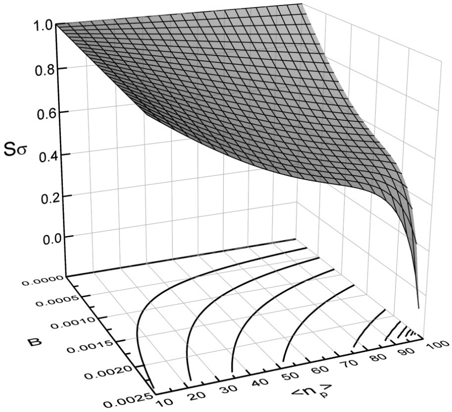
- parameters are:
  - mean initial proton number λ_p
  - coalescence factor B
- can be fixed with the help of observed multiplicities:
  - $\langle n_p \rangle = \sum_{n_p} n_p \, P(n_p)$
  - $\langle n_d \rangle = \sum_{n_d} n_d \, P(n_d)$

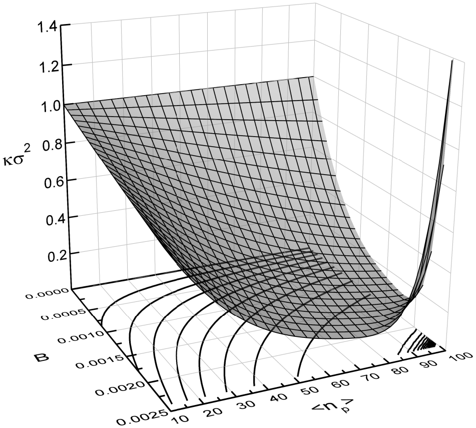
parametrisation of the mean deuteron/proton ratio

$$\frac{d}{p} = 0.8 \left[\frac{\sqrt{s_{NN}}}{1\,\mathrm{GeV}} \right]^{-1.55} + 0.0036$$

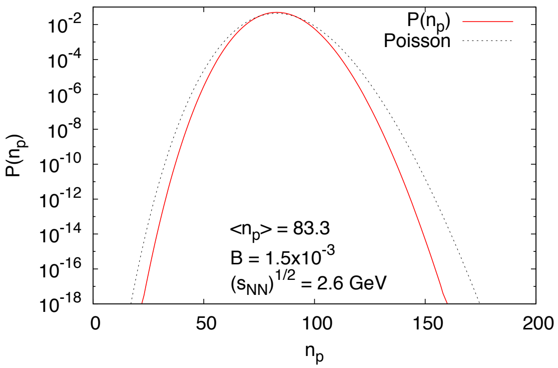


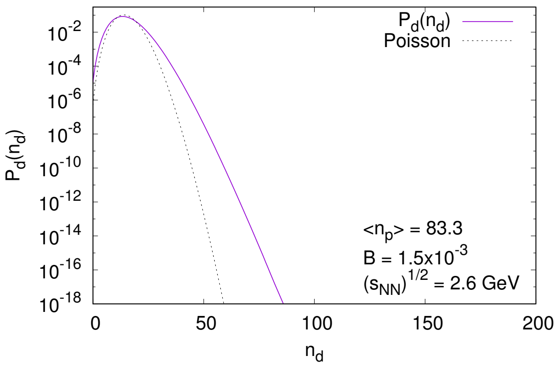
Skewness and kurtosis after subtraction of deuterons





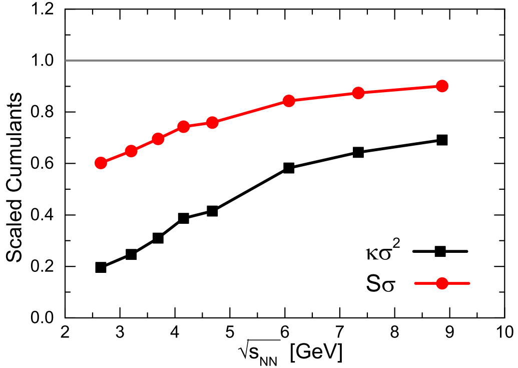
Example: distributions of p and d for $\langle n_p \rangle = 83.3$ and $B = 1.5 \times 10^{-3}$



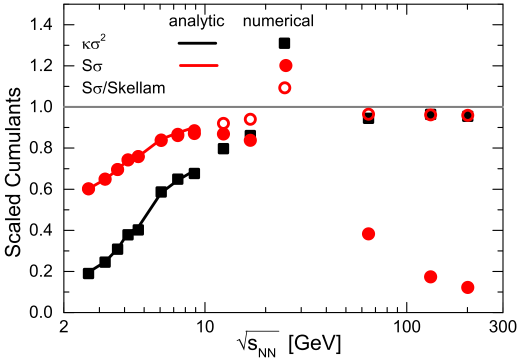


Results for scaled cumulants as functions of $\sqrt{s_{NN}}$

low energy: no antiprotons



higher energy:
also antiprotons fluctuate



Formation of deuterons has an important impact on proton number fluctuations.

Part 2: Thermal production vs coalescence of deutrons

- due to their fragility, deuterons can hardly exist in the dense hadronic system
- mean production numbers are well described by coalescence
- good description of data is also obtained with the help of Statistical model

Such models could be distinguished by fluctuations

- in Statistical model fluctuations of all species are Poissonian
- coalescence leads to non-Poissonian fluctuations of clusters (deuterons)

Deuteron number distribution

Model A: fully correlated proton and neutron numbers (as previously)

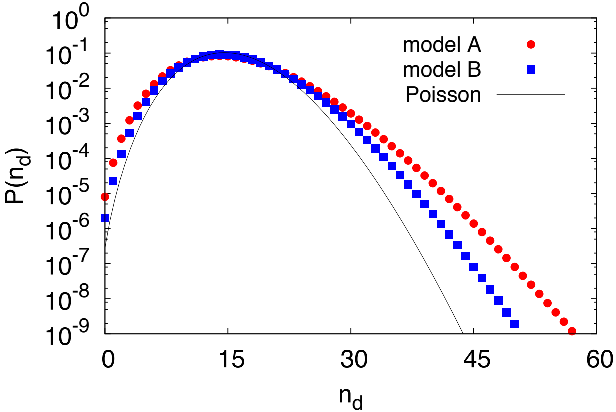
$$\begin{aligned}
\lambda_d &= B n_i^2 \\
P_d(n_d|n_i) &= \lambda_d^{n_d} \frac{e^{-\lambda_d}}{n_d!} = (B n_i^2)^{n_d} \frac{e^{-B n_i^2}}{n_d!} \\
P_d(n_d) &= \sum_{n_i \geq n_d} P_d(n_d|n_i) P_i(n_i)
\end{aligned}$$

Model B: independent proton number n_i and neutron number n_j

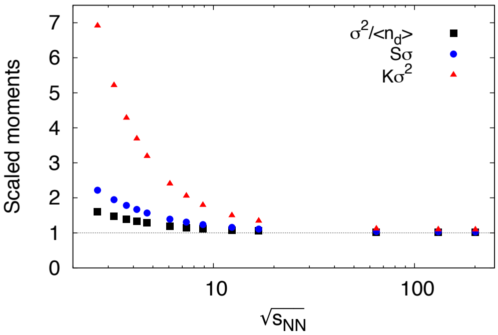
$$\begin{aligned}
\lambda_d &= B n_i n_j \\
P_d(n_d|n_i, n_j) &= \lambda_d^{n_d} \frac{e^{-\lambda_d}}{n_d!} = (B n_i n_j)^{n_d} \frac{e^{-B n_i n_j}}{n_d!} \\
P_d(n_d) &= \sum_{n_i, n_j \geq n_d} P_d(n_d|n_i, n_j) P_i(n_i) P(n_j)
\end{aligned}$$

An example of deuteron number distribution

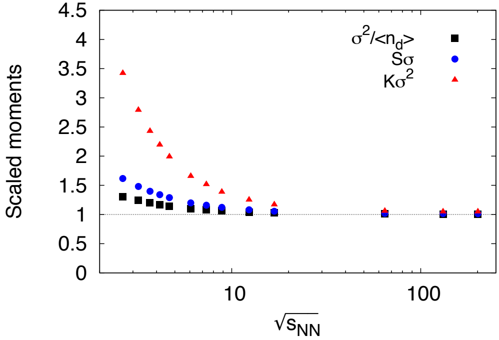
calculated for $\sqrt{s_{NN}} = 2.6\,\text{GeV}$
correlated p and n: $\sigma^2/\langle n_d\rangle = 1.609$, $S\sigma = 2.218$, $\kappa\sigma^2 = 6.915$
independent p and n: $\sigma^2/\langle n_d\rangle = 1.308$, $S\sigma = 1.616$, $\kappa\sigma^2 = 3.422$
Poissonian values are 1.



correlated p and n number



independent p and n number



Poissonian values (Statistical model) would be 1!

Higher moments in particular can clearly distinguish production by coalescence!

Summary

Deuteron formation has large influence on proton number fluctuations, especially at NICA/FAIR energies.

Z. Fecková, J. Steinheimer, B. Tomášik, M. Bleicher, Phys. Rev. C **92**, 064908 (2015)

Higher moments of deuteron number distribution can help to distinguish between statistical production and coalescence.

Z. Fecková, J. Steinheimer, B. Tomášik, M. Bleicher, Phys. Rev. C **93**, 054906 (2016)