Recent results on fluctuations from the NA61/SHINE strong interactions program

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New results on fluctuations from the NA61/SHINE

This presentation shows results on:

- **transverse momentum and multiplicity fluctuations in Ar+Sc**
- **multiplicity fluctuations in Ar+Sc**
- **higher order moments of net-charge and multiplicity distribution of negatively charged hadrons in p+p interactions**:
  - net-charge defined as a difference between positively and negatively charged hadron multiplicities in a given event
  - net-charge fluctuations can be under some assumptions compared to QCD calculations
  - negatively charged hadrons were selected as they are the least affected by resonance decays

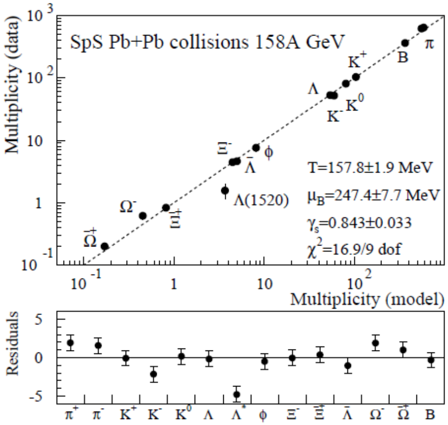
Motivation

Studies of fluctuations and correlations open new possibilities to investigate properties of strongly interacting matter:

- **test models** (statistical vs dynamical) of strong interactions
- **study properties of the phase transition**

http://www.nova-pen.pl

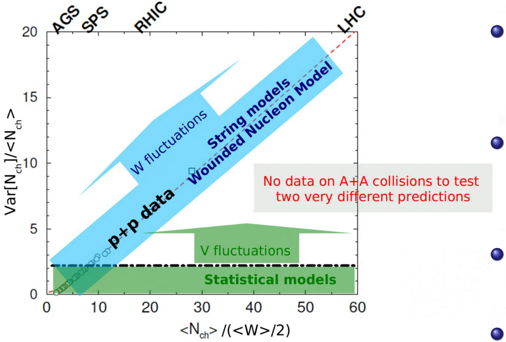
Test models (statistical vs dynamical) of strong interactions



F.Becattini, arXiv:0901.3643

- statistical models are very successful in describing elementary and HIC data on first moments
- contrary to string models they do not require many parameters
- string models also describe data at the price of using many parameters but allow to include restricted detector acceptance, etc.

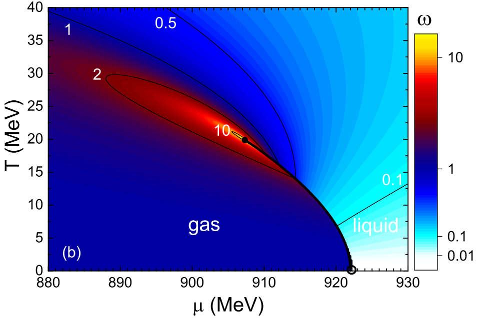
Test models (statistical vs dynamical) of strong interactions

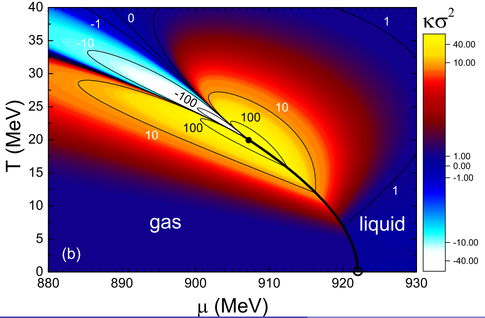


https://indico.cern.ch/event/520685/

- first moments of various particle types do not allow to distinguish between different types of models
- already for second moments fluctuations are very different in string and statistical models
- for higher order moments such differences are probably equally visible
- very little is known how fluctuations behave in A+A collisions

Study properties of the phase transition





Higher order moments are more sensitive to the phase transition

GCE calculation within the Van der Waals model of nuclear matter.

V. Vovchenko et al., Phys.Rev. C92, 054901

Extensive and intensive measures

In grand canonical ensemble mean, variance and in general cumulants (denoted with index c) of a multiplicity distribution are extensive quantities ($\sim V$).

Intensive

A ratio of two extensive quantities is an intensive measure e.g.:

$$\omega[A] = \frac{\langle A^2 \rangle - \langle A \rangle^2}{\langle A \rangle},$$

where A stands for an event quantity.

- independent of V
- depends on fluctuations of V
- $\omega = 1$ for Poisson distribution

In IB-GCE $\omega_i = \frac{Var(a)}{\langle a \rangle} + \langle a \rangle \frac{Var(V)}{\langle V \rangle}$, where a - are particles produced for fixed volume

Strongly intensive

Special combination of extensive quantities can be a strongly intensive measure e.g.:

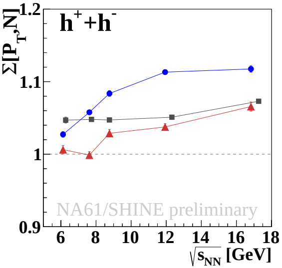
$$\Delta[A, B] = \frac{1}{C_\Delta} \left[\langle B \rangle \omega_A - \langle A \rangle \omega_B \right]$$

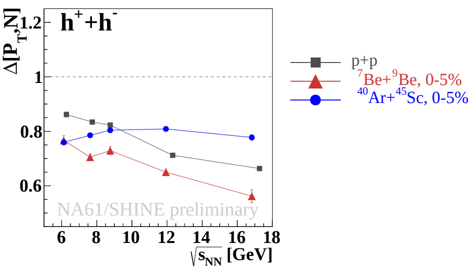
$$\Sigma[A, B] = \frac{1}{C_\Sigma} \left[\langle B \rangle \omega_A + \langle A \rangle \omega_B - 2\big(\langle AB \rangle - \langle A \rangle \langle B \rangle \big) \right]$$

- independent of V and fluctuations of V
- normalization chosen such that $\Delta[A, B] = \Sigma[A, B] = 1$ for independent particle model and both quantities are dimensionless
- $\Delta[A, B] = \Sigma[A, B] = 0$ in the absence of fluctuations

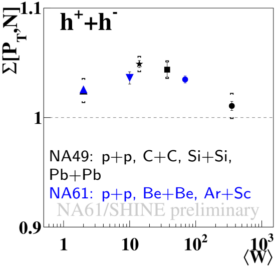
Transverse momentum and multiplicity fluctuations

NA61 acceptance:



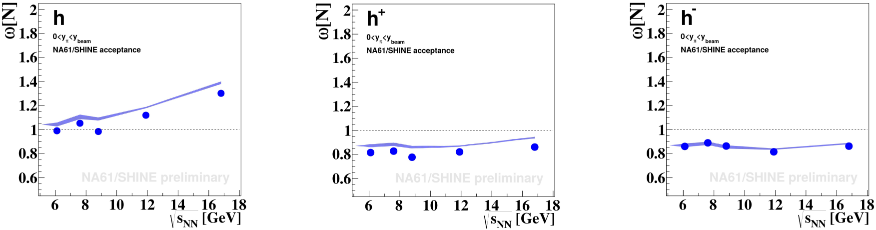


NA49 acceptance (PRC92,044905):

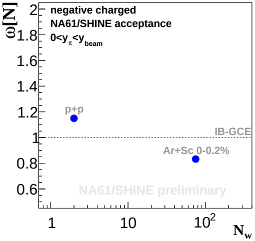


- for details see E. Andronov for NA61/SHINE (arXiv:1610.05569)
- $\Delta[P_T, N] < 0$ and $\Sigma[P_T, N] < 0$ for all energies and reactions
- No prominent structure which could be related to CP
- results consistent with the NA49 ones

Multiplicity fluctuations in Ar+Sc 0-0.2% most central



- for details see A. Seryakov for NA61/SHINE (CPOD 2016)
- No significant non-monotonic behaviour
- $\omega[N]_{p+p} > \omega_{[}N]_{Ar+Sc}$ (violation of statistical and wounded nucleon models predictions)
- NA61/SHINE results in agreement with EPOS model



Intensive measures of higher order fluctuations

For third and fourth cumulants there are several possibilities of intensive measures. Two, most popular are:

$$\frac{\langle N^3 \rangle_c}{Var[N]}, \quad \frac{\langle N^4 \rangle_c}{Var[N]},$$

where $\langle N^3 \rangle_c$ and $\langle N^4 \rangle_c$ are third and fourth cumulants of a multiplicity distribution. Described in terms of skewness S and kurtosis κ as:

$$S = \frac{\langle N^3 \rangle_c}{(Var[N])^{3/2}} = \frac{\langle N^3 \rangle_c}{\sigma^3}, \quad \kappa = \frac{\langle N^4 \rangle_c}{Var[N]} = \frac{\langle N^4 \rangle_c}{\sigma^4},$$

where σ^2 is the variance of N distribution ($Var[N] = \langle N^2 \rangle_c$). Then

$$S\sigma = \frac{\langle N^3 \rangle_c}{Var[N]}, \quad \kappa\sigma^2 = \frac{\langle N^4 \rangle_c}{Var[N]}.$$

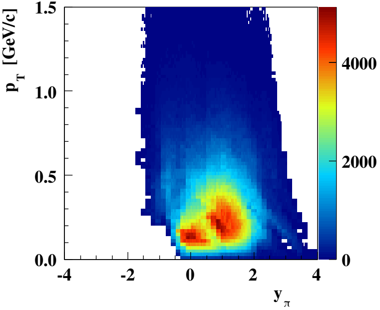
Data

Preliminary results were obtained from p+p data collected in 2009.

$\sqrt{s_{NN}}$ [GeV]	6.3	7.6	8.7	12.3	17.3
Events	0.2M	0.9M	3.0M	1.7M	1.6M

Corrected results refer to **inelastic interactions and particles produced in strong and EM** processes within the analysis acceptance.
Analysis acceptance is the same as for multiplicity and transverse momentum fluctuations analysis (CERN-PH-EP-2015-273).

158 GeV/c



Note: azimuthal acceptance depends on y, p_T and energy. Rapidity was calculated assuming pion mass to all particles.

Statistical and systematic uncertainties

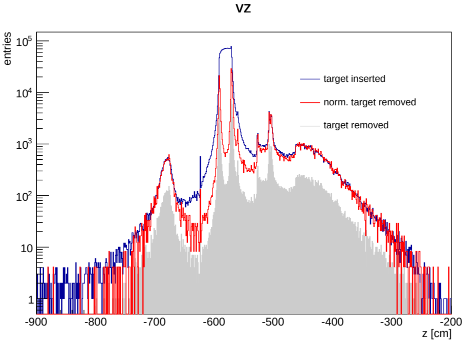
- Statistical uncertainties were calculated using sub-sample method
  Statistical uncertainties are smaller than marker's size in presented plots.
- Systematic uncertainties were estimated by varying event and track selection criteria
  Systematic uncertainties are shown with a band.

Corrections

Multiplicity distributions are corrected for

- off-target interactions
- detector effects
- event selection (trigger bias and analysis procedure)
- track selection within the analysis acceptance
- contribution of weak decays
- secondary interactions

Example of vertex z distribution



In order to estimate off-target interactions NA61/SHINE takes data with *target inserted* and *removed*.

Scaling factor between *removed* and *inserted target* is obtained in region far from target. It is defined as

$$\epsilon = \left.\frac{N^I_{ev}}{N^R_{ev}}\right|_{z>-450\ \mathrm{cm}}.$$

Correction for off-target interactions and simulation based correction

1. Off-target correction:
   Corrected multiplicity distribution is obtained by subtracting scaled *target removed* multiplicity distribution from *target inserted* one.
2. Simulation-based correction:
   - The correction was calculated using the EPOS 1.99 model as tables of correction factors in bins of N for negatively charged hadrons and net-charge distributions, separately.
   - Each entry of the table is the ratio of generated to reconstructed N (c_i).

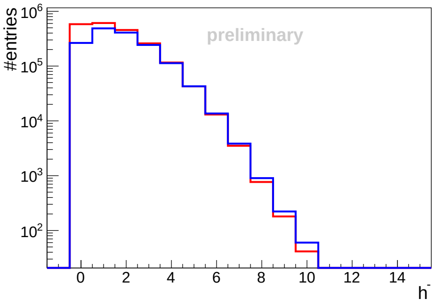
   Corrected multiplicity distribution is obtained by multiplying multiplicity distribution by table of correction factors

Moments are obtained from the corrected multiplicity distribution

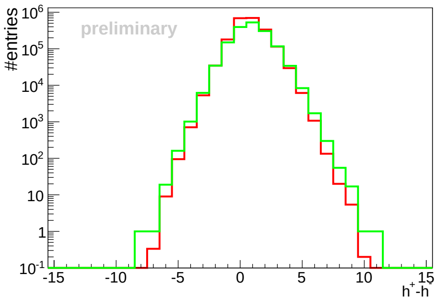
EPOS, K. Werner et al. Phys. Rev. C74, 044902

Example of corrected distributions for p+p at 158 GeV/c

Negatively charged hadrons:

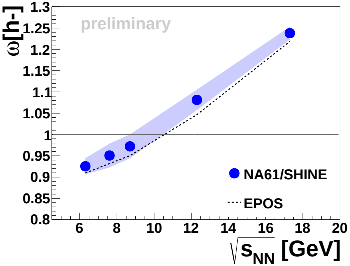


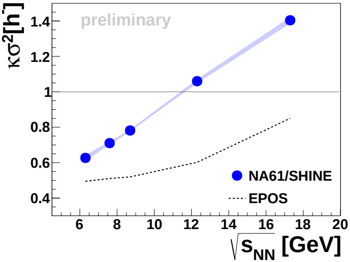
Net-charge:

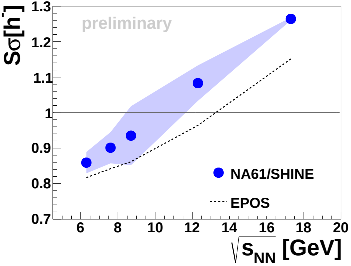


Raw distribution of negatively charged hadrons (**blue**) and net-charge (**green**) along with corrected distributions (**red**).

Results for negatively charged hadrons in p+p

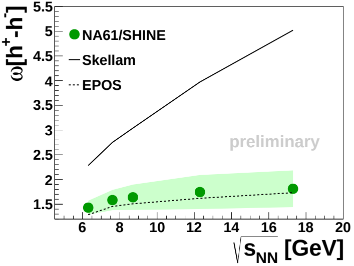


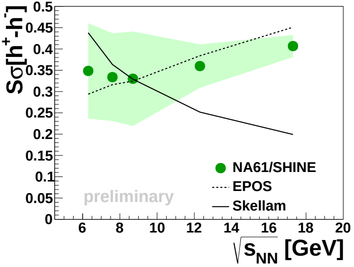


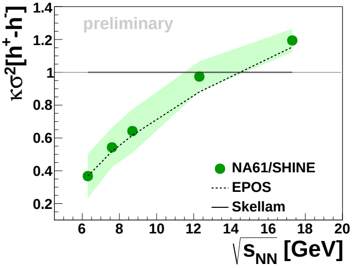


- all quantities rise with collision energy
- magnitude of $\kappa\sigma^2$ is not reproduced by EPOS 1.99 within the acceptance

Results for net-charge in p+p







- results do not agree with independent particle production (Skellam)
- EPOS 1.99 describes data

Summary

- **Fluctuations of transverse momentum and multiplicity fluctuations** as well as **multiplicity fluctuations** were presented
- The **energy dependence** of studied fluctuations **does not show** any non-monotonic behavior as expected for **CP**
- Values of studied quantities in **p+p, Be+Be and Ar+Sc are very close to each other**
- obtained **dependences do not agree** with predictions of **statistical models or wounded nucleon model** $(\omega[N]_{p+p} > \omega_{[}N]_{Ar+Sc})$
- EPOS model qualitatively describes all studied dependencies

Thank you.

Cuts

This is continuation of multiplicity and transverse momentum fluctuation analysis:

	standard cuts	loose cuts	tight cuts
T2 trigger	applied		
BPD	applied		
WFA beam	$< \pm 1\ \mu s$	no cut	$< \pm 5 \mu s$
fitted vertex z position	$\pm 10\ cm$	no cut	$\pm 10\ cm$
$p \approx p_{beam}$	applied		
total points	≥ 30	no cut	≥ 30
VTPC (GTPC) points	$\geq 15(5)$	$> 10(5)$	$\geq 30(7)$
$\lvert b_x \rvert$	$\leq 4\ cm$	no cut	$\leq 2\ cm$
$\lvert b_y \rvert$	$\leq 2\ cm$	no cut	$\leq 1\ cm$
p_T	$\leq 1.5\ GeV/c$		
$e^{\pm}$	applied		

Comparison with models - net charge

For negatively charged hadrons we expect Poisson distribution (independent particle production). Thus, our intensive quantities should be equal to 1 for negatively charge hadrons. Net-charge is a difference between positive and negative charge, so it is described by Skellam distribution (difference of two variables from Poisson distributions):

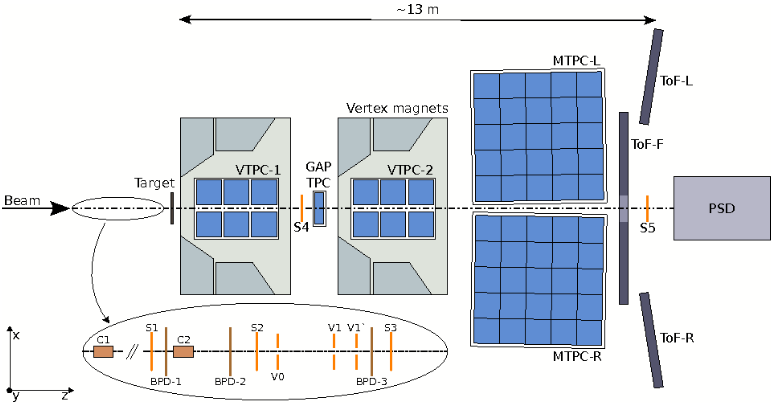
$$\langle h^+ - h^- \rangle = \langle h^+ \rangle - \langle h^- \rangle \tag{1}$$

$$Var[h^+ - h^-] = \langle h^+ \rangle + \langle h^- \rangle \tag{2}$$

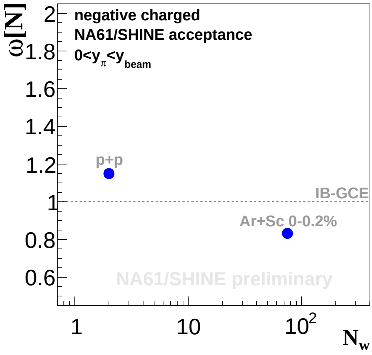
$$S[h^+ - h^-] = \frac{\langle h^+ \rangle - \langle h^- \rangle}{(\langle h^+ \rangle + \langle h^- \rangle)^{3/2}} \tag{3}$$

$$\kappa[h^+ - h^-] = \frac{1}{\langle h^+ \rangle + \langle h^- \rangle} \tag{4}$$

NA61/SHINE


~13 m
MTPC-L
ToF-L
Vertex magnets
ToF-F
VTPC-1
GAP
TPC
VTPC-2
Target
Beam
PSD
S4
S5
C1
C2
S1
S2
V1
V1`
S3
BPD-1
BPD-2
V0
BPD-3
ToF-R
MTPC-R
x
y
z

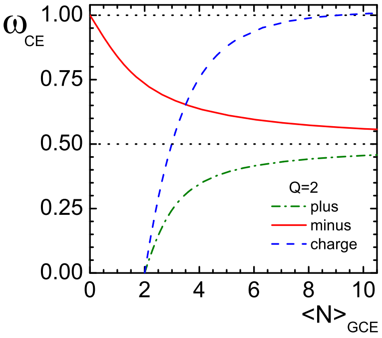
IB-GCE and the data



NA61/SHINE data at 158 and 150A GeV/c

In IB-GCE intensive quantities ω, $S\sigma$ and $\kappa\sigma^2$ should be 1.
In p+p $\omega[h^-] > 1$ - influence of KNO-G scaling?
The value of $\omega[h^-]$ in Ar+Sc is $<$1 - probably caused by conservation laws

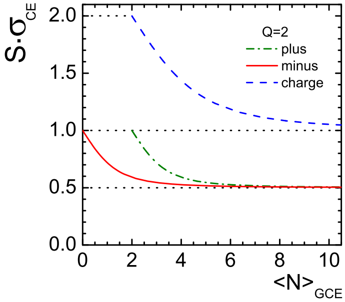
Canonical ensemble (CE) and the data

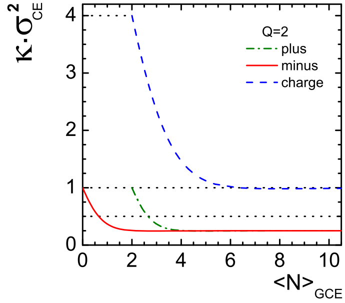


V. Begun, poster CPOD 2016

- Ideal gas of positive, negative and neutral particles with net-charge $= 2$ in CE
- In thermodynamical limit $\omega[N^-] \approx 0.5$.

CE and the data





V. Begun, poster CPOD 2016

- in p+p at $\sqrt{s_{NN}}$=17.3 GeV $S\sigma \approx 1.3$ and $\kappa\sigma^2 \approx 1.4$ which contradicts statistical models
- will we see suppression in A+A?