Recent results from NA61/SHINE

from the strong interaction programme

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SPbSU, Laboratory of Ultra-High Energy Physics

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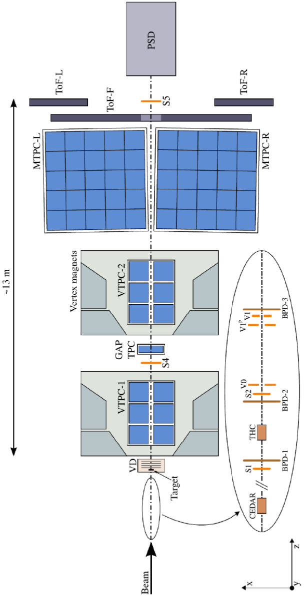
NA61/SHINE experiment

- Large acceptance hadron spectrometer located at the CERN SPS
- High momentum resolution: $\frac{\sigma(p)}{p^2} \approx 10^{-4}\ (\mathrm{GeV/c})^{-1}$ (at full $B = 9$ T m)
- ToF walls resolution: $\sigma(\mathrm{tof}) \approx 60$ ps
- Good particle identification: $\frac{\sigma(dE/dx)}{dE/dx} \approx 0.04$, $\sigma(m_{inv}) \approx 5$ MeV
- Under testing: Vertex Detector (for open charm measurement) - talk by G. Feofilov on Thursday

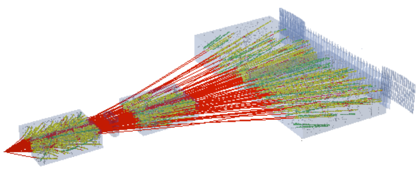


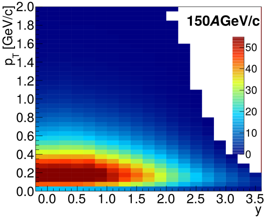
Proposal: CERN-SPSC-2006-034, SPSC-P-330 (November 3, 2006)

NA61/SHINE facility paper: JINST 9 (2014) P06005

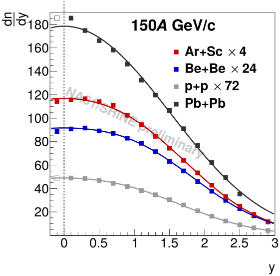
NA61/SHINE highlights

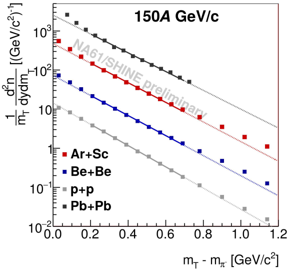
π^- spectra in Ar+Sc collisions at 150A GeV/c





$d^2n/dp_T dy$ of π^- from the h^- method





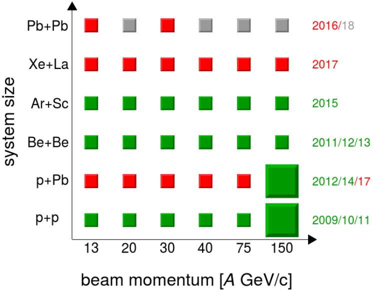
Be+Be, Ar+Sc: NA61 preliminary (0-5% of most central events)

Pb+Pb(7%) by NA49: PR C66, 054902, 2002

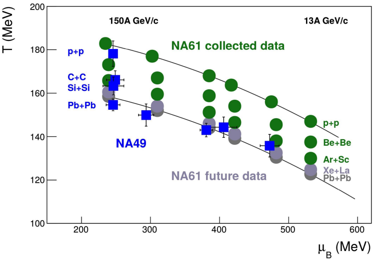
inelastic p+p by NA61: EPJ C74, 2794, 2014

Motivation of the NA61/SHINE strong interaction programme

- Study of the onset of deconfinement
- Search for the critical point of strongly interacting matter



$$\sqrt{s_{NN}} = 5.1 - 16.8/17.3 \text{ GeV}$$

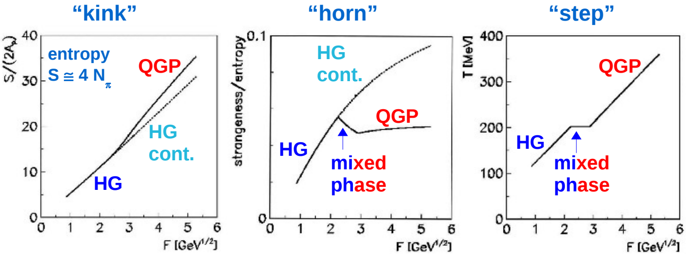


Estimated (NA49) and expected (NA61) chemical freeze-out points according to PR C73, 044905, 2006

Onset of deconfinement signals

Statistical Model of the Early Stage (SMES)

Gazdzicki, Gorenstein, Acta Phys. Polon. B30, 2705, 1999



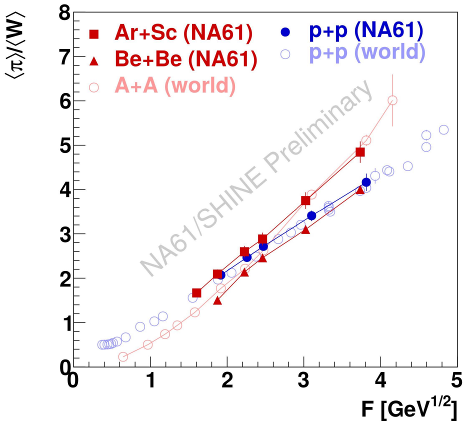
Fermi variable

$$F \equiv \left[\frac{\left(\sqrt{s_{NN}} - 2m_N\right)^3}{\sqrt{s_{NN}}} \right]^{1/4}$$

$$F \simeq \sqrt{\sqrt{s_{NN}}}$$

- 1st order phase transition to QGP between top AGS and top SPS energies $\sqrt{s_{NN}} \approx 7$ GeV
- Number of internal degrees of freedom (ndf) increases as HG→QGP (activation of partonic degrees of freedom)
- Total entropy and total strangeness are the same before and after hadronization (cannot decrease as QGP→HG)
- Mass of strangeness carriers decreases as HG→QGP ($m_{\Lambda,K}, \ldots > m_s$)
- Constant temperature and pressure in mixed phase

π multiplicity - kink



Wounded Nucleon Model (Bialas et al, NPB 111, 461 (1976)):

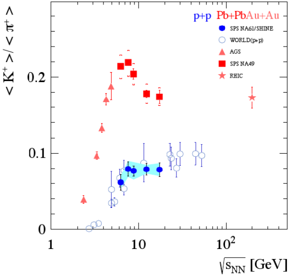
$$\frac{\langle \pi \rangle}{\langle W \rangle}(AA) = \frac{\langle \pi \rangle}{2}(pp)$$

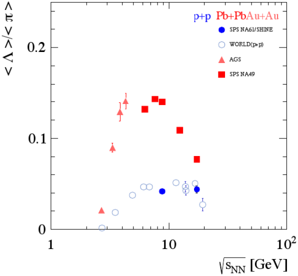
Data: EPJC74:2794; PLB 726, 610 (2013); PRL 109, 252301 (2012)

- $\langle \pi \rangle$ multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p collisions (kink)
- p+p and Pb+Pb dependences cross at about 40*A* GeV
- For high SPS energies Ar+Sc follows the Pb+Pb trend; for low SPS energies Ar+Sc follows the p+p tendency
- The situation is opposite for Be+Be
- Results suffer from model dependence of estimating $\langle W \rangle$

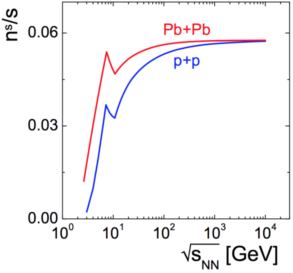
Strangeness/π - horn

p+p vs. Au+Au vs. Pb+Pb





arXiv:1502.05650



The NA61/SHINE results from inelastic p+p collisions exhibit rapid changes like observed in central Pb+Pb interactions

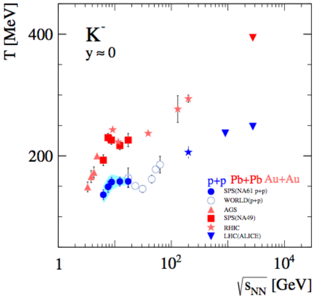
Do we see onset of deconfinement in p+p?

Strict strangeness conservation (CE) leads to horn-like structures even in p+p

NA61/SHINE: 2014 CERN-SPSC-2014-031 ; SPSC-SR-145
ZP C65, 215 (1995); ZP C71, 55 (1996); PRC 72,014908 (2005); EPJC 71, 1655 (2011), PRL 109, 252301 (2012)

K inverse slope parameter T - step

p+p vs. Au+Au vs. Pb+Pb



Transverse mass spectra $\frac{1}{m_T}\frac{dn}{dm_T} = Cexp(-\frac{m_T}{T})$ fits close to mid-rapidity

The NA61/SHINE results from inelastic p+p collisions exhibit rapid changes like observed in central Pb+Pb interactions

Do we see onset of deconfinement in p+p?

NA61/SHINE: CERN-SPSC-2014-031 ; SPSC-SR-145
PRC 69, 044903 (2004); PRC 79, 034909 (2009); PLB 736, 196 (2014); EPJC 71, 1655 (2011)

Strongly intensive fluctuation measures

We consider fluctuation quantities with trivial properties in the reference models (e.g. Wounded Nucleon Model - WNM)

Two families of strongly intensive quantities

$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right)$$

$$\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2cov(P_T, N)\right)$$

where $P_T = \sum_{i=1}^{N} p_{Ti}$

N - multiplicity of charged hadrons in an experimental acceptance

$$\omega[x] = Var(x)/\langle x\rangle$$

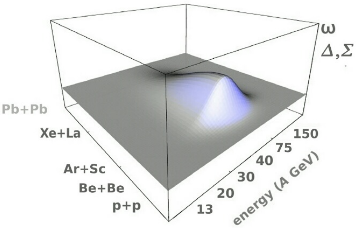
- Independent of $\langle V\rangle$ and $\omega[V]$ in WNM
- $\Delta[P_T, N] = \Sigma[P_T, N] = 1$ for the independent particle production model
- $\Delta[P_T, N] = \Sigma[P_T, N] = 0$ in the absence of fluctuations

A. Bialas et al., NPB 111: 461 (1976)
M.Gorenstein, M.Gazdzicki, PRC 84: 014904
M.Gorenstein, *et al.*, PRC 88, 2:024907

Strongly intensive fluctuation measures

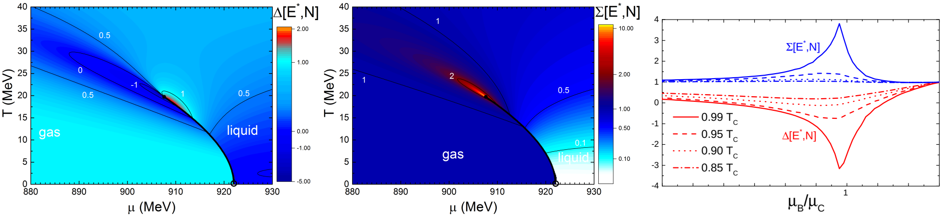
Sensitivity to critical point - CP

Analysis of strongly intensive fluctuation measures is expected to give more insight into the CP location



Δ and Σ for nucleon system with van der Waals EOS in GCE formulation in vicinity of CP

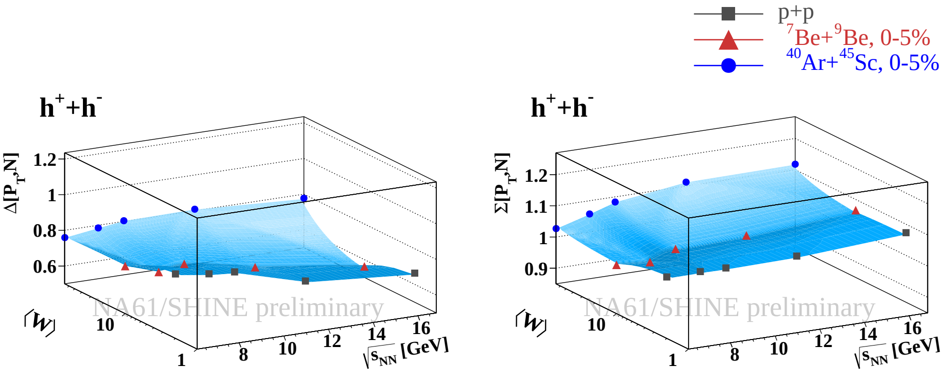
Energy of the particles corresponds to P_T



V. Vovchenko, CPOD2016

$\Delta, \Sigma[P_T, N]$: energy vs. system size scan

$0 < y_\pi < y_{beam}$, $p_T < 1.5$ GeV/c, NA61/SHINE acceptance

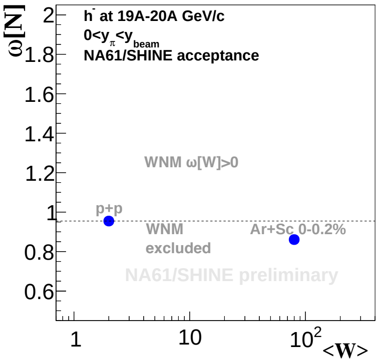


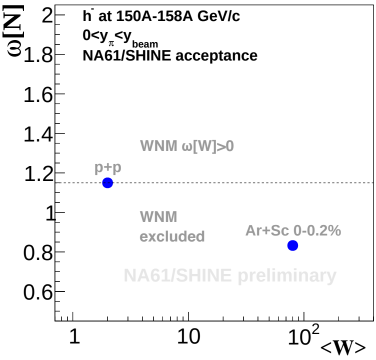
No prominent structures which could be related to the CP are visible.

Number of wounded nucleons $\langle W \rangle$ from the GLISSANDO model W. Broniowski, M. Rybczynski, PRC **81**: 064909.

Scaled variance of negatively charged particles

$0 < y_\pi < y_{beam}$, $p_T < 1.5$ GeV/c, NA61/SHINE acceptance





In WNM: $\omega[N] = \omega^*[N] + \langle N\rangle/\langle W\rangle \cdot \omega[W]$

$\omega^*[N]$ - scaled variance calculated for any fixed value of W (i.e. $= \omega[N]_{pp}$)

$\omega[W]$ - fluctuations in W

Thus in WNM $\omega[N]_{AA} \geq \omega[N]_{pp}$, what contradicts NA61 data

Higher moments of net electric charge

Relation with the correlation length

N: e-by-e net charge

Mean: $M = \langle N \rangle$

St. dev.: $\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$

Skewness: $S = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$

Kurtosis: $k = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$

$$\langle (N - \langle N \rangle)^2 \rangle \approx \xi^2$$
$$\langle (N - \langle N \rangle)^3 \rangle \approx \xi^{4.5}$$
$$\langle (N - \langle N \rangle)^4 \rangle \approx \xi^7$$

Volume independent combinations of the various moments:

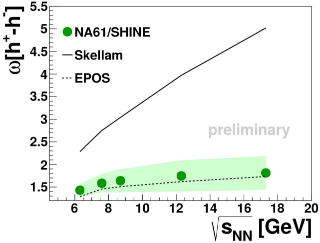
$$\omega[N] = \frac{\sigma^2}{M} = \frac{\chi^{(2)}}{\chi^{(1)}},\ S\sigma = \frac{\chi^{(3)}}{\chi^{(2)}},\ S\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}$$

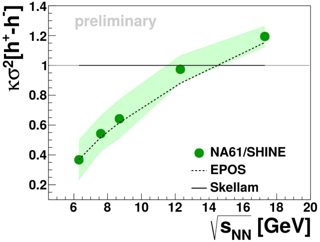
The signature of non-monotonicity of these observables is expected if there is a nearby critical point in QCD phase transition.

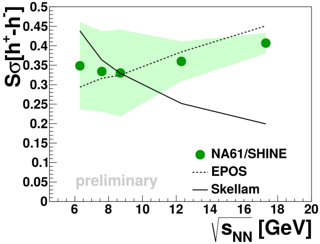
Athanasiou et al., PRD82 (2010) 074008, Stephanov, PRL 107, 052301(2011), Karsch et al., PLB 695, 136 (2011).

Fluctuations of net-charge in inelastic p+p interactions

$p_T < 1.5$ GeV/c, NA61/SHINE acceptance







- No non-monotonic behavior suggesting CP
- EPOS model describes data on net-charge fluctuations
- Results do not agree with independent particle production (Skellam), difference may come from multi-charged particles and quantum statistics

P. Braun-Munzinger et al., Nucl.Phys. A880 48-64 (2012)

Summary

- Data taking for the system size − energy scan is well advanced: data for p+p, ^{7}Be+^{9}Be and ^{40}Ar+^{45}Sc collisions have already been recorded.
- Preliminary results on 4π pion multiplicities were shown in the form of kink plot.
- Even in p+p the energy dependence of $\langle K^+\rangle/\langle\pi^+\rangle$ and kaons inverse slope parameter T exhibits rapid changes in the SPS energy range.
- Preliminary results on transverse momentum and multiplicity fluctuations in p+p, Be+Be and Ar+Sc collisions were presented in $0 < y_\pi < y_{beam}$. The energy dependence does not show any non-monotonic behaviour as expected for CP. Scaled variance for Ar+Sc collisions is surprisingly smaller than for p+p.
- Results on higher order moments of net-charge distribution in inelastic p+p interactions were shown. The trends of all measures are reproduced by EPOS and do not agree with independent particle production (Skellam).

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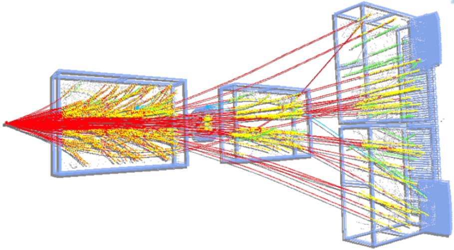
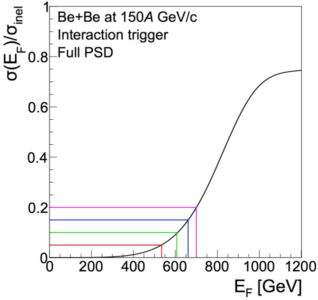
Thank You!

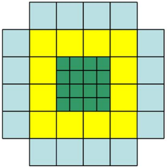


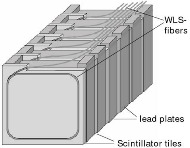
Back-up

PSD detector. Centrality determination.

PSD (Projectile Spectator Detector) is located on the beam axis and measures the forward energy E_F related to the non-interacting nucleons of the beam nucleus



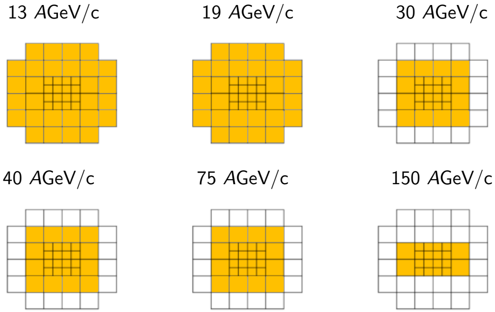




Cuts on E_F allows to select different centrality classes

Centrality determination

Due to the differences in magnetic field, PSD position and Fermi motion for various energies, different set of modules is chosen to calculate the E_F:



The module sets are chosen on the basis of corelations between energy and multiplicity for each module.

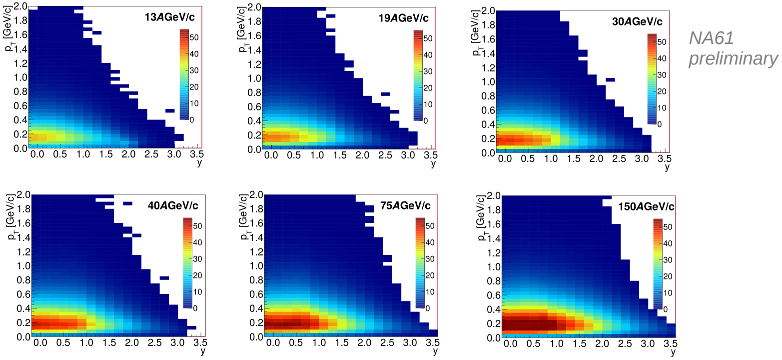
Analysis methods

- h^- analysis based on the fact that the majority of negatively charged particles are π^- mesons. Contribution of the other particles is subtracted using Monte-Carlo models
- dE/dx analysis uses TPC energy loss information to identify particles

h⁻ analysis method – majority of negatively charged particles are π^- mesons. Contribution ($\approx$10%) of other particles (K^-, anti-p) is subtracted using EPOS 1.99

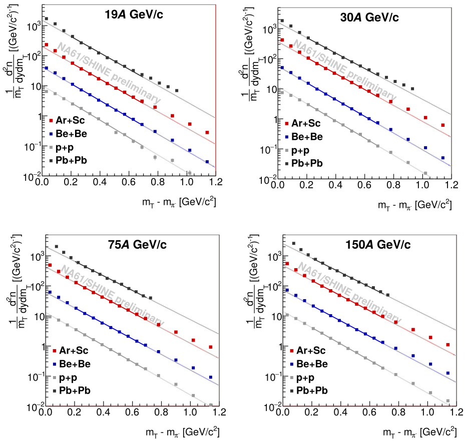
Precise large statistics results in full p_T and wide rapidity range in all SPS energies

- The results are corrected for particles from weak decays (feed-down) and the detector effects using MC simulations
- Out of target interactions are subtracted using events recorded with removed target



Double differential spectra $d^2n/(dp_T dy)$ of negatively charged pions in rapidity and transverse momentum for central (0-5%) Ar+Sc collisions

Transverse mass spectra of π^- mesons in Ar+Sc - comparison to p+p, Be+Be, Pb+Pb



m_T spectra at mid-rapidity

Be+Be, Ar+Sc: 0-5% central

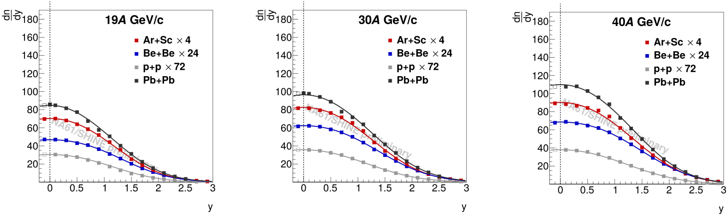
Be+Be, Ar+Sc: *NA61 preliminary*

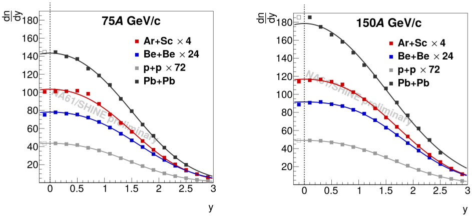
- p+p spectra are exponential
- Convex shape of Pb+Pb, Ar+Sc and Be+Be spectra

$$\frac{d^2 n}{dy\, dm_T} = A\, m_T \exp\left(\frac{-m_T}{T}\right)$$
$$0.2 < m_T - m_\pi < 0.7 \quad \mathrm{GeV/c^2}$$

Pb+Pb (7%; 5%) measured by NA49: PR C66, 054902, 2002; PR C77, 024903, 2008
Inelastic p+p measured by NA61: EPJ C74, 2794, 2014

Rapidity spectra of π^- mesons in Ar+Sc – comparison to p+p, Be+Be, Pb+Pb



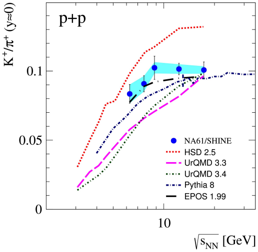


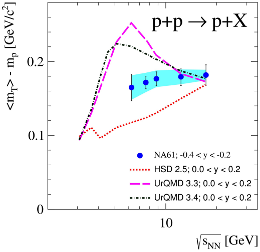
Lines to guide the eye

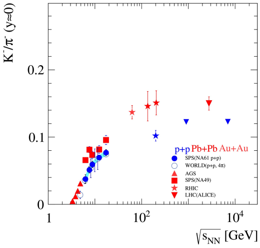
Be+Be, Ar+Sc: NA61 preliminary

Be+Be, Ar+Sc:
0-5% central

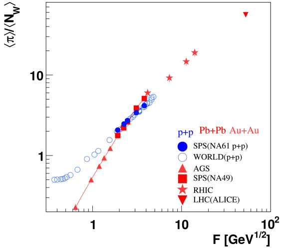
Pb+Pb (7%; 5%) measured by NA49: PR C66, 054902, 2002; PR C77, 024903, 2008
Inelastic p+p measured by NA61: EPJ C74, 2794, 2014

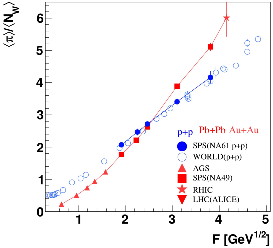






arXiv:1510.08239;
arXiv:1512.05938





$\langle\pi\rangle = 3/2(\langle\pi^-\rangle + \langle\pi^+\rangle)$

For p+p: $\langle\pi^+\rangle = \langle\pi^-\rangle + 2/3$

Phys. Atom. Nucl. 64, 1841, 2001

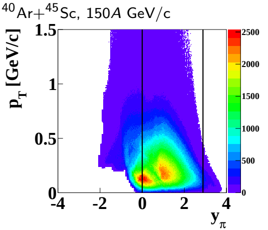
$\langle\pi\rangle_{p+p} = 3\langle\pi^-\rangle_{p+p} + 1$

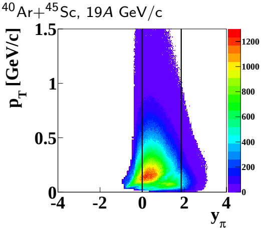
$\langle\pi\rangle_{Ar+Sc} = 3\langle\pi^-\rangle_{Ar+Sc}$

$\langle\pi\rangle_{Be+Be} = 3\langle\pi^-\rangle_{Be+Be}$

Analysis

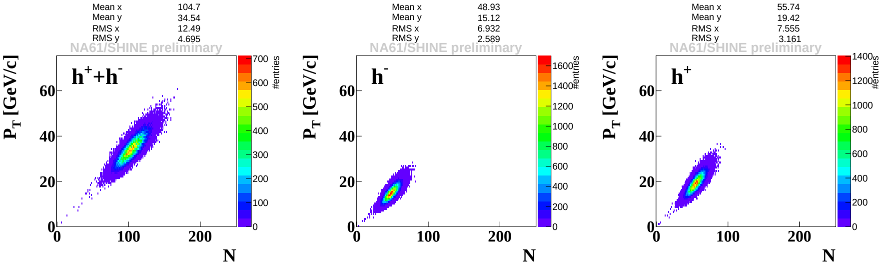
- Event selection criteria:
  - good beam quality
  - no off-time beam particles
  - good main vertex fit
  - centrality selected by forward energy
- Track selection criteria:
  - sufficient number of points inside TPCs
  - track trajectory points to interaction point
  - not electron or positron
  - $p_T < 1.5$ GeV/c
  - $0 < y_\pi < y_{beam}$ (due to poor azimuthal angle acceptance and stronger electron contamination at backward rapidities)
  - NA61/SHINE acceptance map





Examples of uncorrected N vs. P_T distributions

^{40}Ar+^{45}Sc at 150A GeV/c, $0-5\%$



N, P_T and $P_{T,2} = \sum_{i=1}^{N} p_{Ti}^2$ are measured for each event.

$P_{T,2}$ is needed to calculate the scaled variance of the inclusive p_T distribution $\omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}}$ using only event quantities.

Corrections

K. Werner, *et al.*, PRC **74**:044902

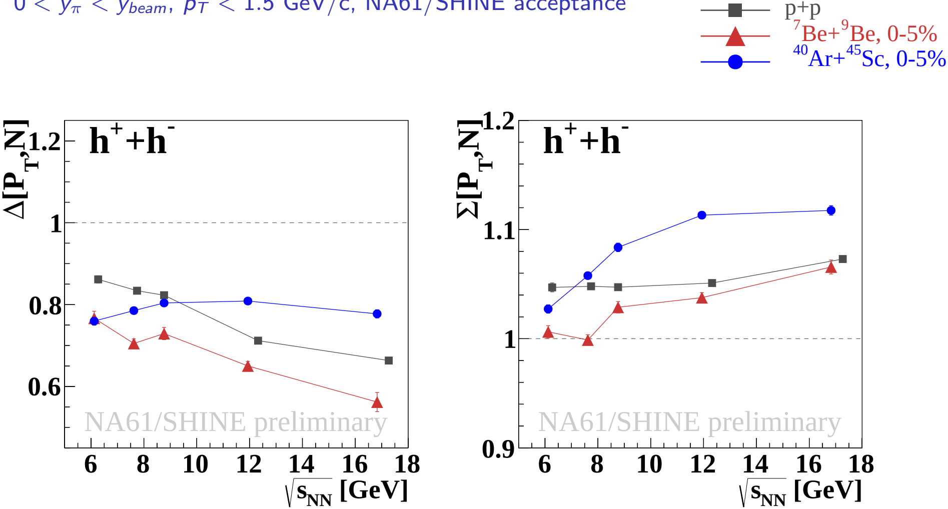
- MC used for corrections: EPOS1.99 model (version CRMC 1.5.3), GEANT3.21. The simulated data were analysed within the NA61/SHINE acceptance.
- Corrections for losses due to event and track selections, trigger biases, detector inefficiencies, secondary interactions and feed-down from weak decays for ^{40}Ar+^{45}Sc were performed on the level of the first and second moments of measured observables.
- Correction factors for $\langle N \rangle$, $\langle N^2 \rangle$, $\langle P_T \rangle$, $\langle P_T^2 \rangle$, $\langle N \cdot P_T \rangle$ and $\langle P_{T,2} \rangle$ were calculated as ratios of the corresponding moments for pure to reconstructed MC for positively, negatively and all charged hadrons, separately.

Note on errors

Statistical uncertainties were calculated using the sub-sample method. They are typically smaller than the marker size.

$\Delta, \Sigma[P_T, N]$: energy vs. system size scan

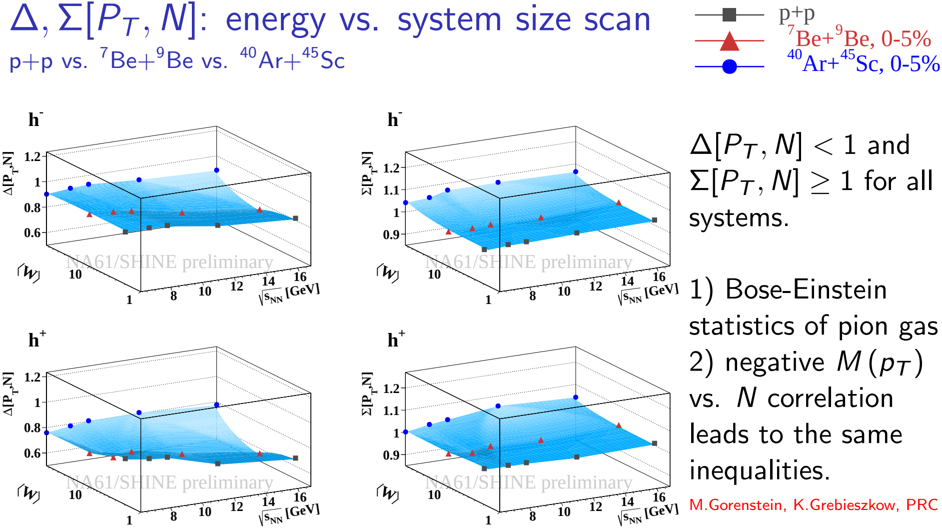
$0 < y_\pi < y_{beam}$, $p_T < 1.5$ GeV/c, NA61/SHINE acceptance



No prominent structures which could be related to the CP are visible.

$\Delta, \Sigma[P_T, N]$: energy vs. system size scan

p+p vs. ^{7}Be+^{9}Be vs. ^{40}Ar+^{45}Sc



$\Delta[P_T, N] < 1$ and $\Sigma[P_T, N] \geq 1$ for all systems.

1) Bose-Einstein statistics of pion gas
2) negative $M(p_T)$ vs. N correlation leads to the same inequalities.

M.Gorenstein, K.Grebieszkow, PRC **89**:034903

No prominent structures which could be related to the CP are visible.

Comparison with Pb+Pb results from NA49

To compare results of p_T fluctuations, NA49 cuts were applied to NA61/SHINE data.

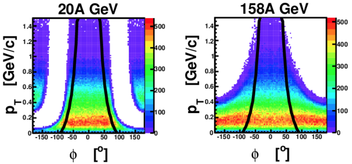
In NA49:

• because of high density of tracks, analysis was limited to forward-rapidity region $(1.1 < y_\pi < 2.6)$

• to exclude elastically scattered or diffractively produced protons, analysis was limited in proton rapidity $(y_p < y_{beam} - 0.5)$

• $0.005 < p_T < 1.5$ GeV/c

• common azimuthal acceptance for all energies (only for energy dependence analysis)



T. Anticic, *et al.* (NA49 Collaboration), PRC **92** no.4:044905

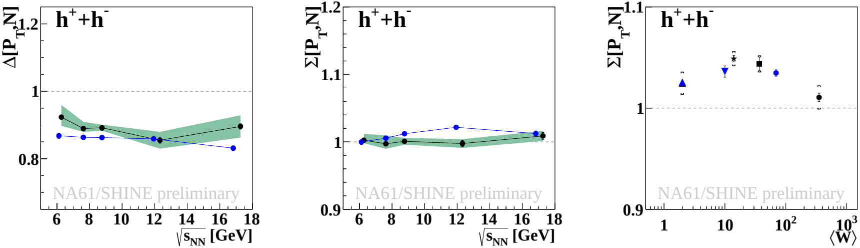
Comparison to NA49 A+A within NA49 acceptance

NA61 Ar+Sc, 0-5%

NA49 Pb+Pb, 0-7.2%

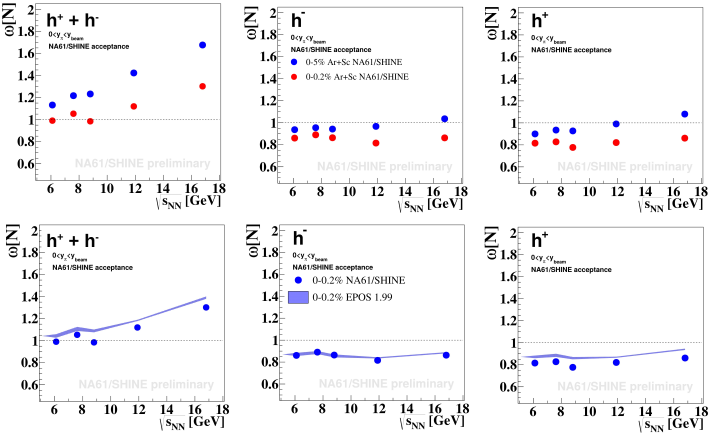
NA61: p+p, 0-5% Be+Be, 0-5% Ar+Sc

NA49: p+p, 0-15.3% C+C, 0-12.2% Si+Si, 0-5% Pb+Pb



- Energy scan: NA49 Pb+Pb and NA61 Ar+Sc results similar. No prominent structures which could be related to the CP are visible.
- System size dependence of $\Sigma[P_T, N]$ at 150/158A GeV/c: NA49 and NA61 points show consistent trends.

Multiplicity fluctuations in Ar+Sc



p_T < 1.5 GeV/c

0 < y_π < y_{beam}

- Statistical uncertainties are included
- Systematic uncertainties are under investigation
- Results are corrected for non-target interactions, detector inefficiencies and trigger bias

- **ω[N]** is not a strongly intensive measure and it **depends on volume fluctuations**
  → values larger for 0-5% Ar+Sc than for 0-0.2% Ar+Sc
- **No significant non-monotonic behavior** observed
- Increase of ω[N] (for charged hadrons) with energy reflects increase of ω_{Nch} measured in full phase-space (see PR 351, 161, 2001)
- NA61 Ar+Sc results (0-0.2%) in **agreement with EPOS model**

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

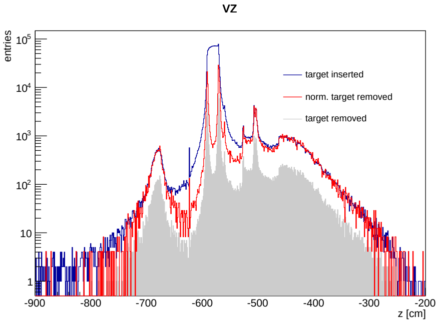
- Corrected results refer to inelastic interactions and particles produced in strong and EM processes within the analysis acceptance
- This analysis focuses on fluctuations of negatively charged hadrons and net-charge ($h^+ - h^-$) by calculating first, second, third and fourth moments of multiplicity distributions

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

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

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 tracks (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

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):

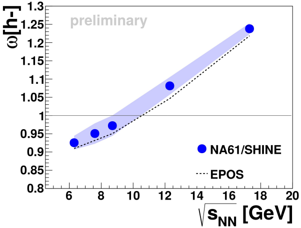
$$\langle h^+ - h^- \rangle = \langle h^+ \rangle - \langle h^- \rangle \tag{1}$$

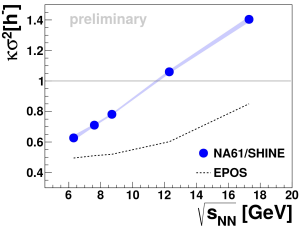
$$Var[h^+ - h^-] = \langle h^+ \rangle + \langle h^- \rangle \tag{2}$$

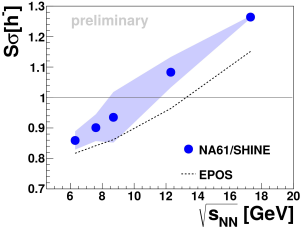
$$S[h^+ - h^-] = \frac{\langle h^+ \rangle - \langle h^- \rangle}{(\langle h^+ \rangle + \langle h^- \rangle)^{3/2}} \tag{3}$$

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

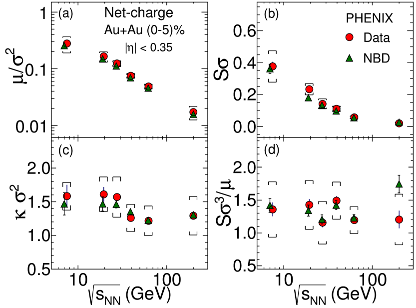
Fluctuations of negatively charged hadrons in inelastic p+p



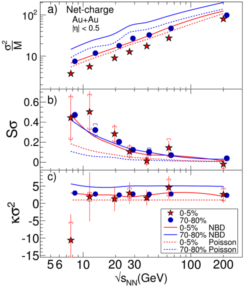




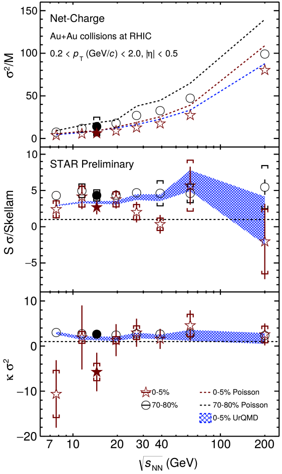
- In IB-GCE intensive quantities (ω, $S\sigma$, $\kappa\sigma^2$) should be 1
- All quantities rise with collision energy
- **No non-monotonic behavior** suggesting CP
- **Tendency reproduced by EPOS** but the magnitude of $\kappa\sigma^2$ is not reproduced



PHENIX, PR C93, 011901, 2016



STAR, PRL 113, 092301, 2014



Thader (for STAR), arXiv:1601.00951 (QM 2015)