Transverse momentum and multiplicity fluctuations in Ar+Sc collisions at CERN SPS from NA61/SHINE

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Critical Point and Onset of Deconfinement 2016
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Outline

- Introduction: motivation, definitions
- Analysis details
- Preliminary results on P_T vs. N fluctuations:

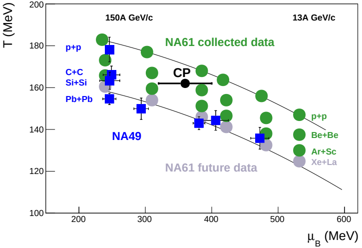
  • for forward energy selected ^{40}Ar+^{45}Sc collisions and particles produced in strong and EM processes within the NA61/SHINE acceptance at $\sqrt{s_{NN}} = 6.12, 7.62, 8.76, 11.94, 16.83$ GeV

  • Comparison with the EPOS1.99 model

  • Comparison with the NA61/SHINE data on inelastic p+p interactions and forward energy selected ^{7}Be+^{9}Be collisions

  • Comparison with the NA49 data on p+p, C+C, Si+Si and Pb+Pb collisions
- Conclusions

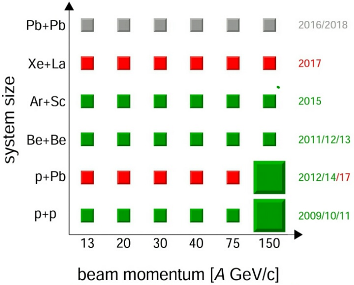
Motivation of the NA61/SHINE strong interaction programme



Estimated (NA49) and expected (NA61) chemical freeze-out points F. Becattini, *et al.*, PRC **73**:044905

Comprehensive scan with light and intermediate mass nuclei in energy range 13*A*-158*A* GeV

Data taking schedule and its proposed extension (in gray)



Strongly intensive fluctuation measures

We consider fluctuation quantities with trivial properties in the reference models (e.g. WNM or IB-GCE)

Two families of strongly intensive quantities

$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right)$$
$$\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left(\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2cov(P_T, N)\right)$$
$$\text{where } P_T = \sum_{i=1}^{N} p_{Ti}$$

N - multiplicity of charged hadrons in an experimental acceptance

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

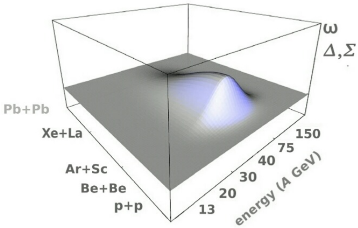
M.Gorenstein, M.Gazdzicki, PRC **84**:014904

M.Gorenstein, *et al.*, PRC **88** 2:024907

Strongly intensive fluctuation measures

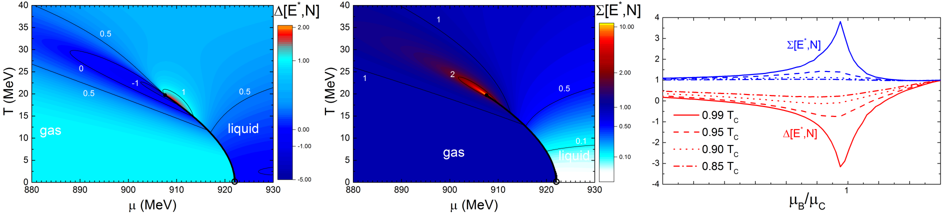
Sensitivity to critical point

Analysis of SI fluctuation measures is expected to give more insight into CP location



SI quantities for nucleon system with van der Waals EOS in GCE formulation in vicinity of CP

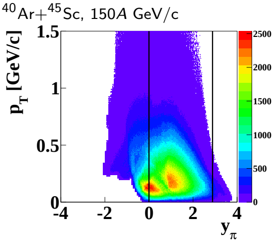
Energy of the particles corresponds to P_T

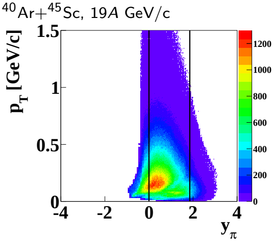


V. Vovchenko talk at CPOD2016

Analysis

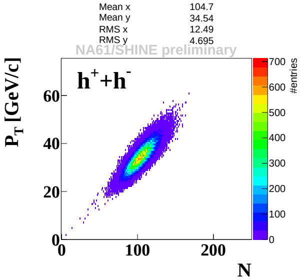
- Event selection criteria:
  - good beam quality
  - no off-time beam particles
  - good main vertex fit
  - centrality selected by forward energy
- Track selection criteria:
  - sufficient number of points inside TPCs
  - track trajectory points to interaction point
  - not electron or positron
  -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

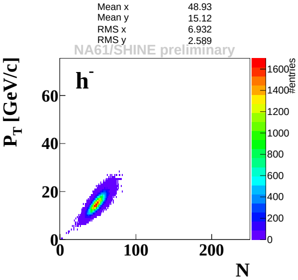


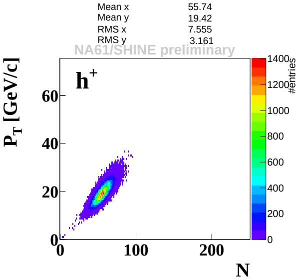


Examples of uncorrected N vs. P_T distributions

^{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

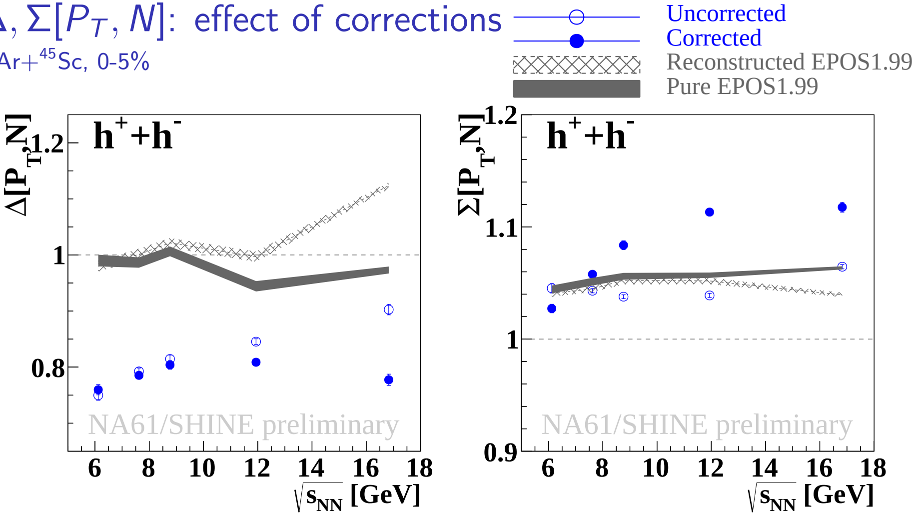
- MC used for corrections: EPOS1.99 model (version CRMC 1.5.3), GEANT3.21. The simulated data were analysed within the NA61/SHINE acceptance.
- Corrections for losses due to event and track selections, trigger biases, detector inefficiencies, secondary interactions and feed-down from weak decays for ^{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.

$\Delta, \Sigma[P_T, N]$: effect of corrections

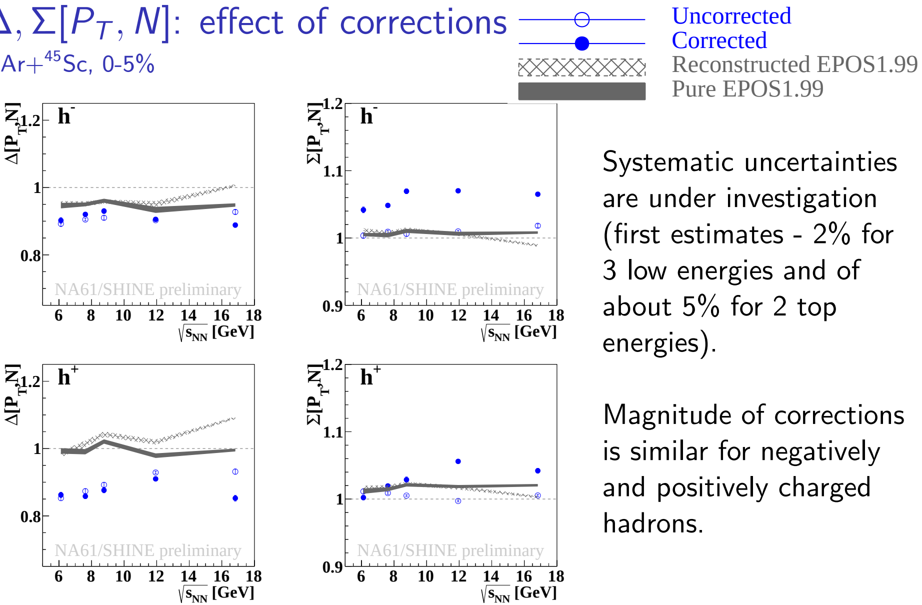
^{40}Ar+^{45}Sc, 0-5%



The correction changes uncorrected data by no more than 10%.
Systematic uncertainties are under investigation (first estimates - 2% for 3 low energies and of about 5% for 2 top energies).

$\Delta, \Sigma[P_T, N]$: effect of corrections

^{40}Ar+^{45}Sc, 0-5%



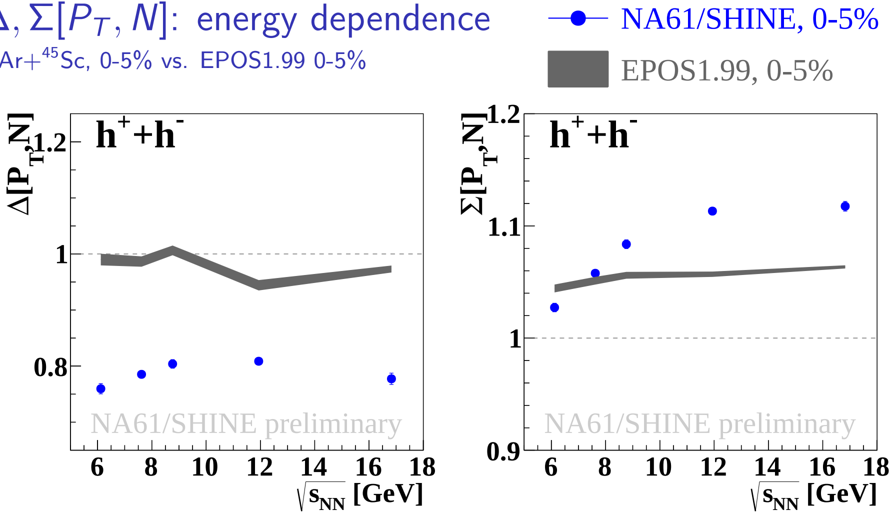
Systematic uncertainties are under investigation (first estimates - 2% for 3 low energies and of about 5% for 2 top energies).

Magnitude of corrections is similar for negatively and positively charged hadrons.

Preliminary results

$\Delta, \Sigma[P_T, N]$: energy dependence

^{40}Ar+^{45}Sc, 0-5% vs. EPOS1.99 0-5%

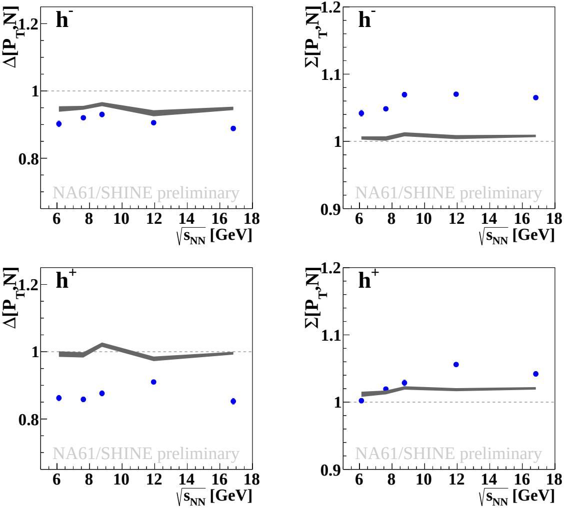


Weak and smooth energy dependence of $\Delta[P_T, N]$ and $\Sigma[P_T, N]$, no evidence of anomalies related to CP.

The EPOS1.99 model overestimates $\Delta[P_T, N]$.

$\Delta, \Sigma[P_T, N]$: energy dependence

^{40}Ar+^{45}Sc, 0-5% vs. EPOS1.99 0-5%

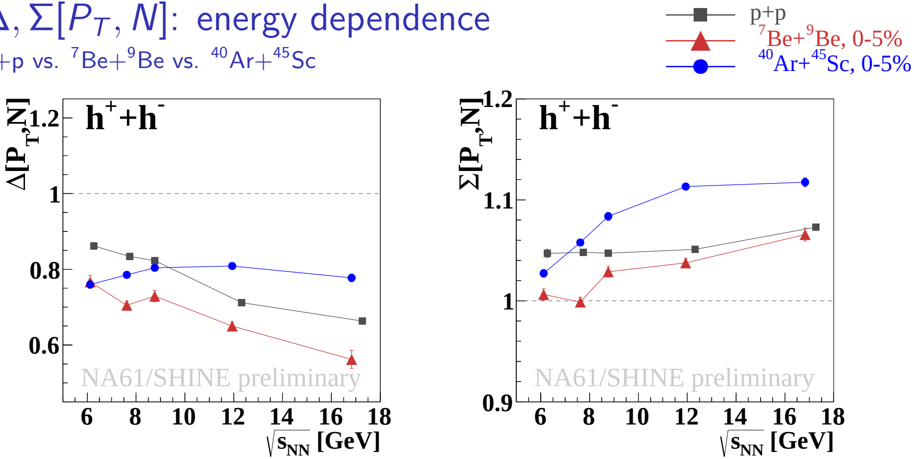


Weak and smooth energy dependence of $\Delta[P_T, N]$ and $\Sigma[P_T, N]$, no evidence of anomalies related to CP.

EPOS describes better $\Delta[P_T, N]$ for negatively charged hadrons and $\Sigma[P_T, N]$ for positively charged hadrons.

$\Delta, \Sigma[P_T, N]$: energy dependence

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

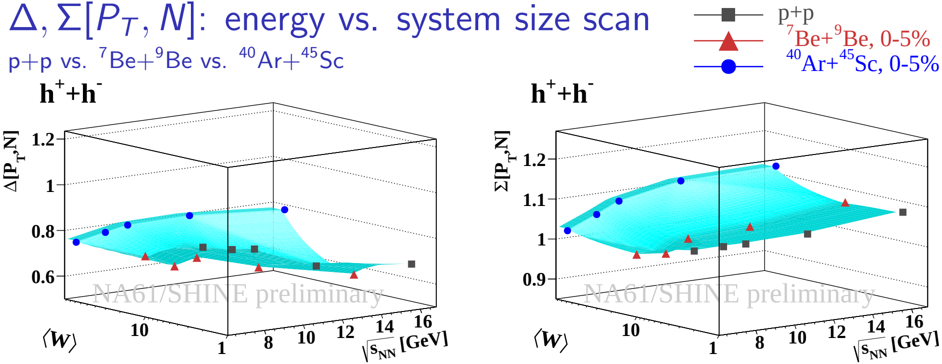


Systematic uncertainties are under investigation (first estimates - 2% for 3 low energies and of about 5% for 2 top energies)

No prominent structures which could be related to 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



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

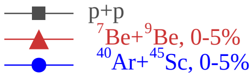
Mean number of wounded nucleons $\langle W \rangle$ estimated using the GLISSANDO model.

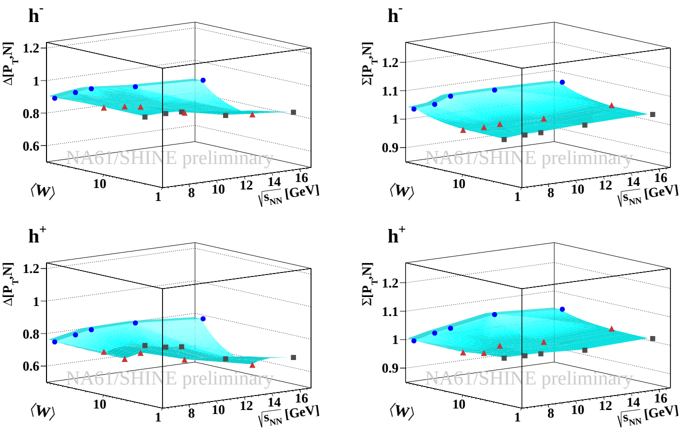
Statistical uncertainties are less than 1% for all points and not drawn. Systematic uncertainties are under investigation (first estimates - 2% for 3 low energies and of about 5% for 2 top energies).

W. Broniowski, M. Rybczynski, PRC **81**: 064909

$\Delta, \Sigma[P_T, N]$: 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

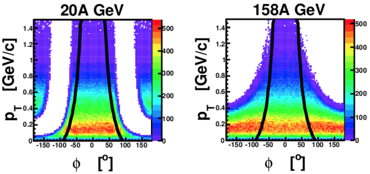
No prominent structures which could be related to CP are visible.

Comparison with Pb+Pb results from NA49

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

In NA49:

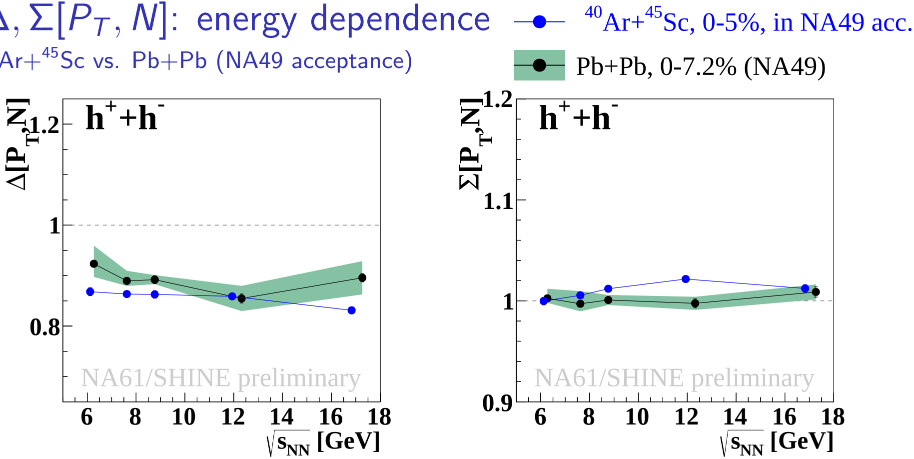
- because of high density of tracks, analysis was limited to forward-rapidity region ($1.1 < y_\pi < 2.6$)
- to exclude elastically scattered or diffractively produced protons, analysis was limited in proton rapidity ($y_p < y_{beam} - 0.5$)
- $0.005 < p_T < 1.5$ GeV/c
- common azimuthal acceptance for all energies (only for energy dependence analysis)



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

$\Delta, \Sigma[P_T, N]$: energy dependence

^{40}Ar+^{45}Sc vs. Pb+Pb (NA49 acceptance)



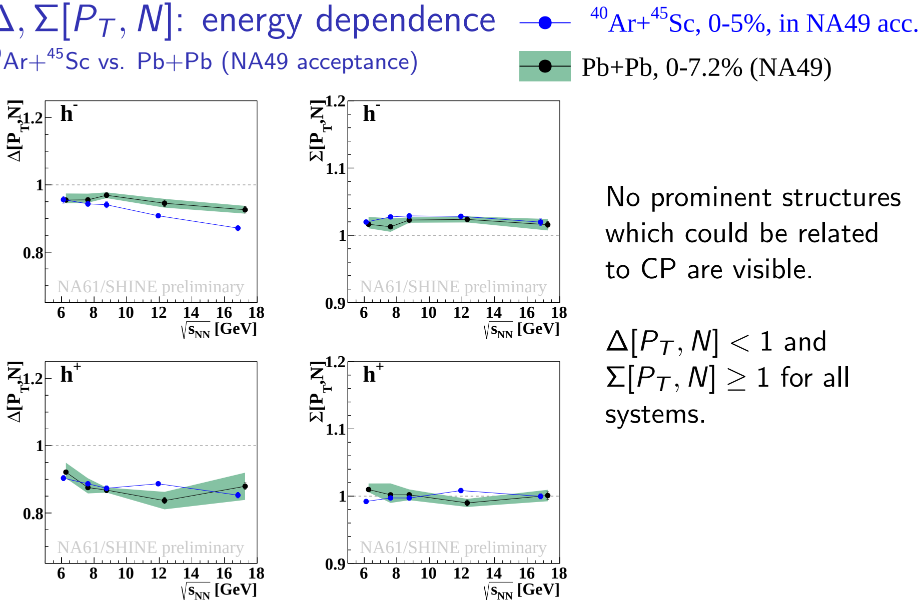
Results for ^{40}Ar+^{45}Sc collisions are very close to Pb+Pb. No prominent structures which could be related to CP are visible.

$\Delta[P_T, N] < 1$ and $\Sigma[P_T, N]$ is consistent with 1 for both systems.

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

$\Delta, \Sigma[P_T, N]$: energy dependence

^{40}Ar+^{45}Sc vs. Pb+Pb (NA49 acceptance)



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

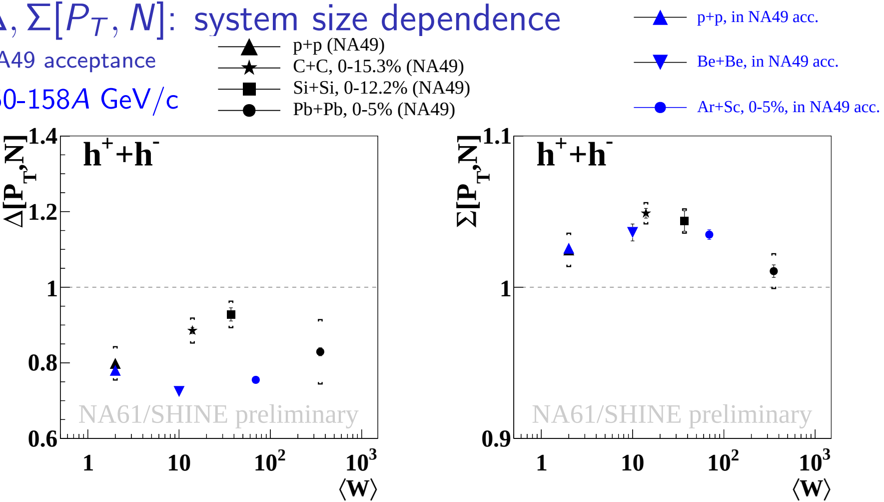
$\Delta[P_T, N] < 1$ and $\Sigma[P_T, N] \geq 1$ for all systems.

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

$\Delta, \Sigma[P_T, N]$: system size dependence

NA49 acceptance

150-158A GeV/c



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

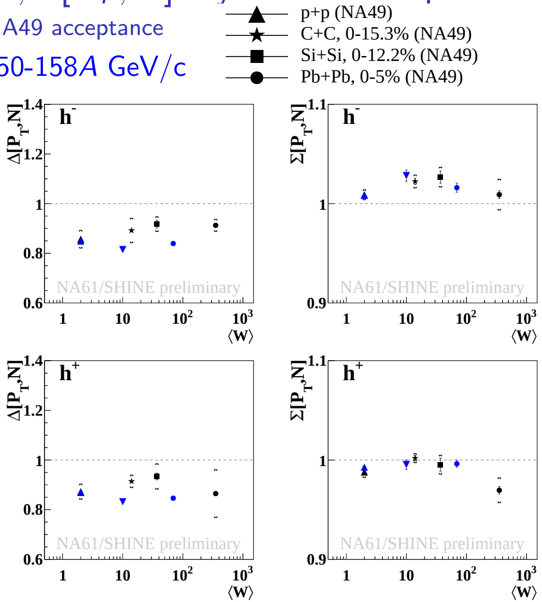
$\Delta[P_T, N]$ is more sensitive to centrality selection than $\Sigma[P_T, N]$.

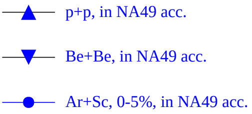
T. Anticic, *et al.* (NA49 Collaboration), PRC **92** no.4:044905

$\Delta, \Sigma[P_T, N]$: system size dependence

NA49 acceptance

150-158A GeV/c





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

$\Delta[P_T, N]$ for less central collisions (C+C, Si+Si) deviates stronger from other measurements than $\Sigma[P_T, N]$.

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

Conclusions - 1

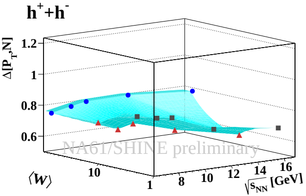
- Preliminary results on P_T vs. N fluctuations for forward energy selected ^{40}Ar+^{45}Sc collisions with particles produced in strong and EM processes within the NA61/SHINE acceptance at $\sqrt{s_{NN}} = 6.12, 7.62, 8.76, 11.94, 16.83$ GeV were reported

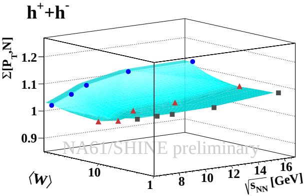
- Uncorrected and corrected measurements of strongly intensive quantities $\Delta[P_T, N]$ and $\Sigma[P_T, N]$ were shown

- The results were compared with 1) the NA61/SHINE data on p+p and ^{7}Be+^{9}Be collisions 2) the NA49 data on p+p, C+C, Si+Si and Pb+Pb collisions 3) the predictions of the EPOS1.99 model

Conclusions - 2

- No clear indications of CP in strongly intensive P_T vs. N fluctuation measures were observed
- Analyses more sensitive to CP (intermittency, higher moments, identified particle ratio fluctuations etc.) of the NA61/SHINE are in progress
- See dedicated NA61/SHINE talks on higher moments by M. Mackowiak-Pawlowska and on intermittency by N. Davis on Friday





Waiting for p+Pb, Xe+La and Pb+Pb...

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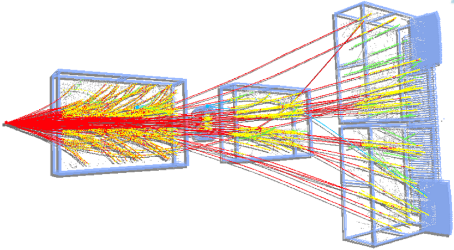
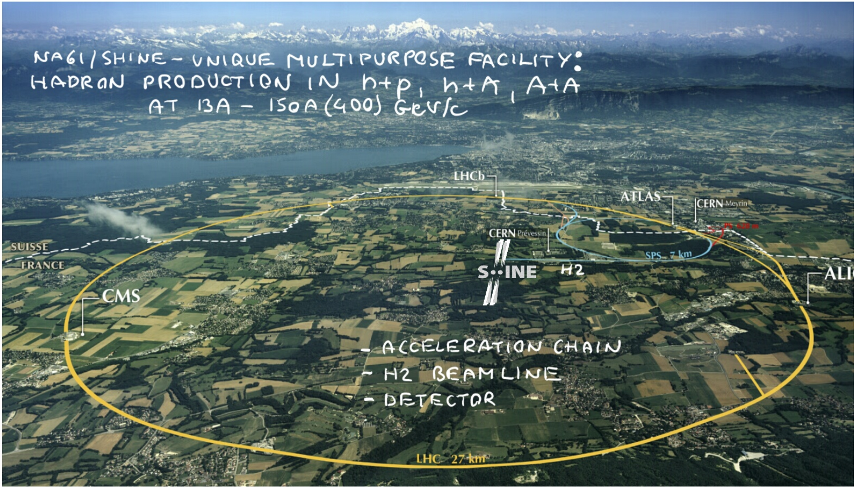
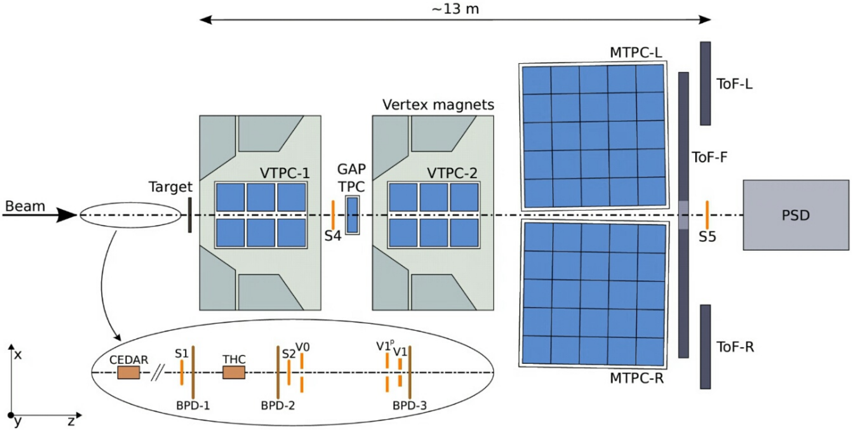
Thank You!

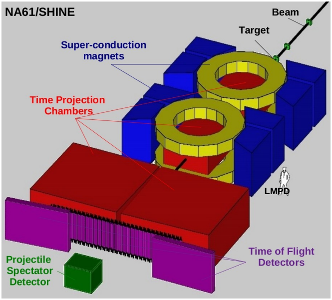


Back-up

DETECTOR


NA61/SHINE – UNIQUE MULTIPURPOSE FACILITY:
HADRON PRODUCTION IN h+p, h+A, A+A
AT 13A – 150A (400) GeV/c
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
S••INE
H2
SPS 7 km
CMS
- ACCELERATION CHAIN
- H2 BEAMLINE
- DETECTOR
LHC 27 km

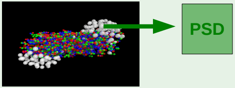

~13 m
MTPC-L
ToF-L
Vertex magnets
ToF-F
GAP
TPC
VTPC-1
VTPC-2
Target
Beam
S4
S5
PSD
x
y
z
CEDAR
S1
THC
S2
V0
V1^{p}
V1
BPD-1
BPD-2
BPD-3
ToF-R
MTPC-R



- Large acceptance: ≈ 50%
- High momentum resolution: $\sigma(p)/p^2 \approx 10^{-4} (\mathrm{GeV}/c)^{-1}$ (at full B=9 T•m)
- ToF walls resolution: ToF-L/R: $\sigma(t) \approx 60$ ps; ToF-F: $\sigma(t) \approx 120$ ps
- Good particle identification: $\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$; $\sigma(m_{inv}) \approx 5$ MeV
- High detector efficiency: > 95%
- Event rate: 70 events/sec

- Four large volume **Time Projection Chambers (TPCs)**: VTPC-1, VTPC-2 (inside superconducting magnets), MTPC-L, MTPC-R; measurement of dE/dx and p. **Time of Flight (ToF)** detector walls.

- **Projectile Spectator Detector (PSD)** for centrality measurement (energy of projectile spectators) and determination of reaction plane; **resolution of 1 nucleon (!)** in the studied energy range (important for fluctuation analysis).



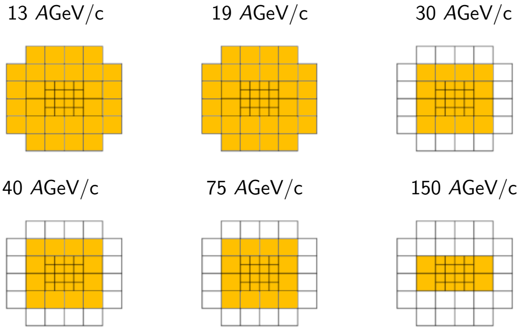
- **Helium beam pipes** inside VTPC-1 and VTPC-2 (to reduce δ-electrons).

- **Z-detector** (measures ion charge for on-line selection of secondary ions, **A-detector** (measures mass composition of secondary ion beam).

- Low Momentum Particle Detector (**LMPD**) for centrality determination in p+A; measures target nucleus spectators.

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.

Statistics

^{40}Ar+^{45}Sc: $0-5\%$, $0 < y_{\pi} < y_{beam}$

Event stats	19	30	40	75	150
Total	2.1M	3.1M	1.9M	4.1M	2.8M
Selected	0.1M	0.2M	0.1M	0.5M	0.1M

Track stats	19	30	40	75	150
Total	22M	54M	35M	156M	55M
Selected	5M	11M	8M	37M	15M

$[P_T, N]$ fluctuations

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

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

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

Here:

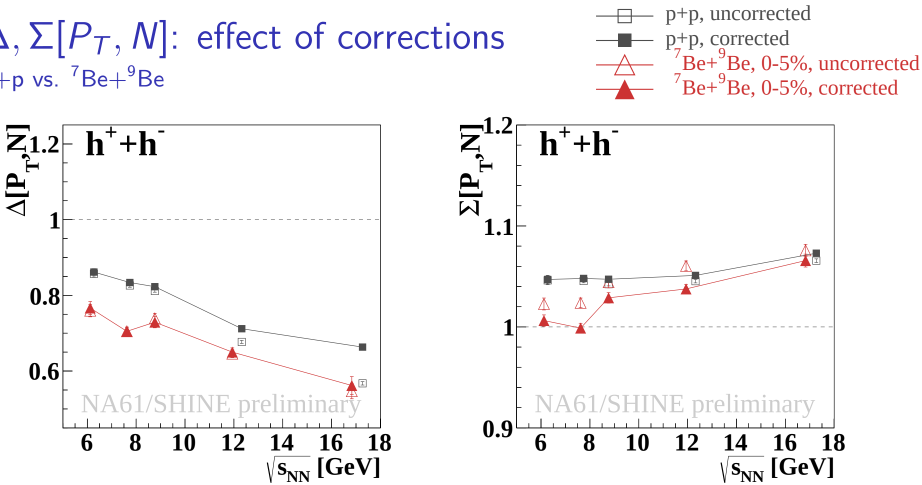
$\omega[P_T] = \frac{\langle P_T^2 \rangle - \langle P_T \rangle^2}{\langle P_T \rangle}$, $\langle \rangle$ - average over all events

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

$\omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}}$, $\bar{\cdot}$ - average over all particles

$\Delta, \Sigma[P_T, N]$: effect of corrections

p+p vs. ^{7}Be+^{9}Be

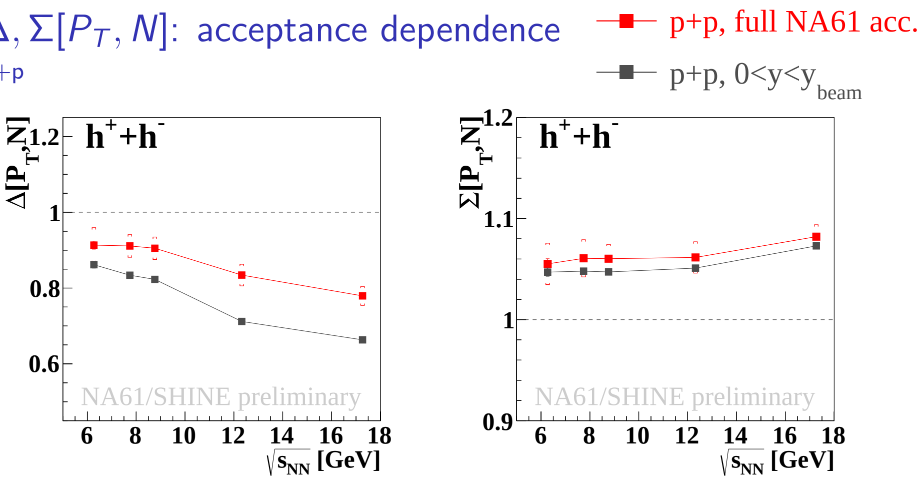


Corrections are larger for $\Delta[P_T, N]$ in p+p and for $\Sigma[P_T, N]$ in ^{7}Be+^{9}Be

SI fluctuation measures do not change their energy dependence after corrections

$\Delta, \Sigma[P_T, N]$: acceptance dependence

p+p



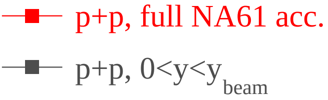
Full acc. - A. Aduszkiewicz, *et al.* (NA61/SHINE Collaboration), arXiv:1510.00163[hep-ex]

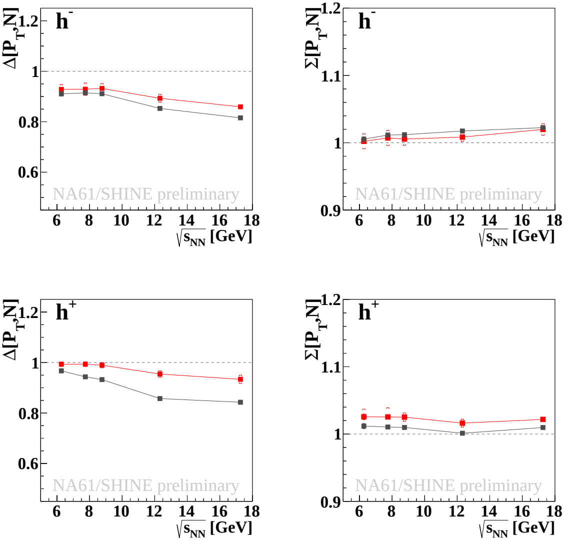
Energy dependence trend is the same for full and limited acceptance.

Systematic uncertainties for limited acceptance are expected to be of about uncertainties for full acceptance.

$\Delta, \Sigma[P_T, N]$: acceptance dependence

p+p





$\Delta[P_T, N]$ and $\Sigma[P_T, N]$ changes due to acceptance are more pronounced for positively charged hadrons.

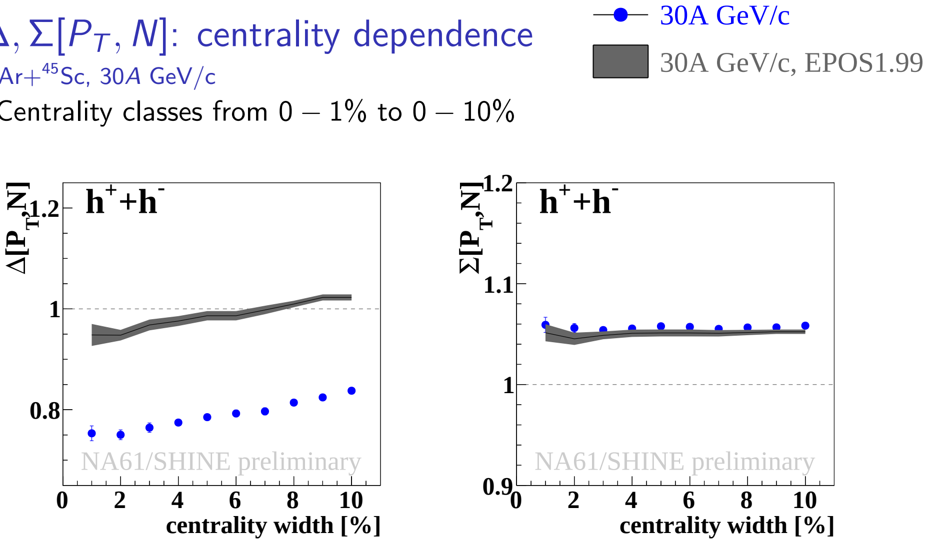
It can be indication of stronger Δ^{++} resonance decay contribution for full acceptance case.

Full acc. - A. Aduszkiewicz, *et al.* (NA61/SHINE Collaboration), arXiv:1510.00163[hep-ex]

$\Delta, \Sigma[P_T, N]$: centrality dependence

$^{40}Ar+^{45}Sc$, 30A GeV/c

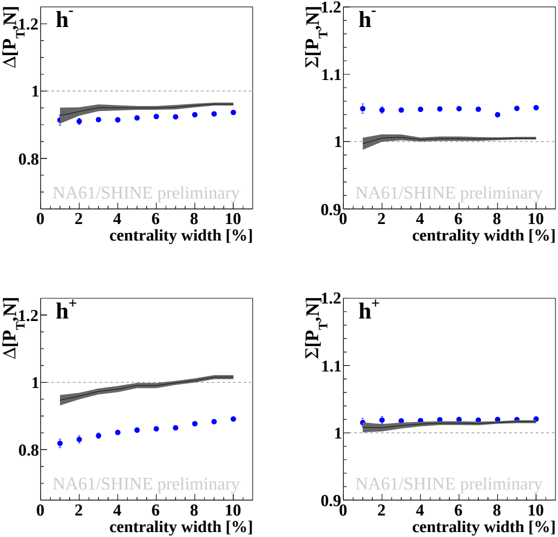
Centrality classes from $0-1\%$ to $0-10\%$



$\Sigma[P_T, N]$ is less centrality dependent than $\Delta[P_T, N]$ both in data and in the EPOS1.99 model.

$\Delta, \Sigma[P_T, N]$: centrality dependence

$^{40}Ar+^{45}Sc$, 30A GeV/c

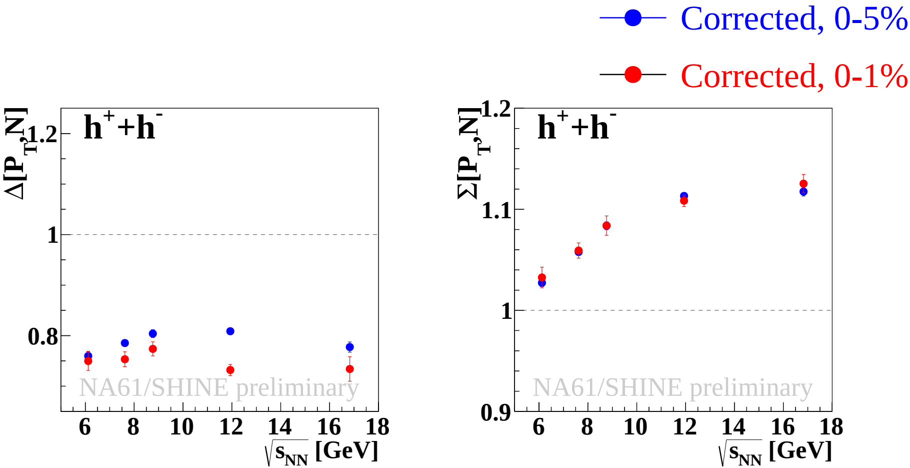


The EPOS1.99 model describes better $\Delta[P_T, N]$ for negatively charged hadrons and $\Sigma[P_T, N]$ for positively charged hadrons

$\Sigma[P_T, N]$ is less centrality dependent than $\Delta[P_T, N]$ for negatively and positively charged hadrons.

$\Delta, \Sigma[P_T, N]$: energy dependence for 2 centrality classes

^{40}Ar+^{45}Sc



$\Sigma[P_T, N]$ is less centrality dependent than $\Delta[P_T, N]$.

Centrality dependence

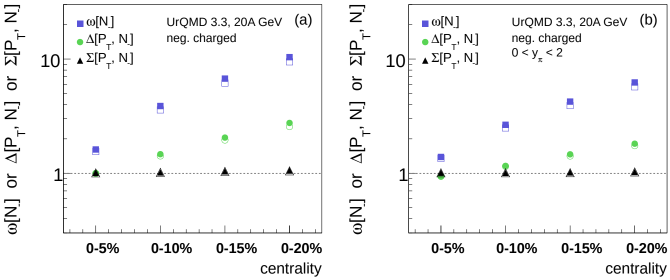
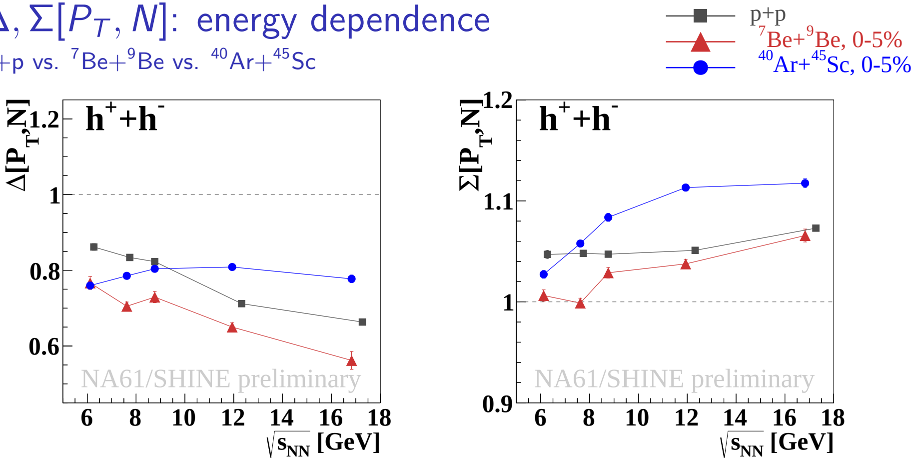


Figure 5: (Color online) The UrQMD results for the centrality dependence of $\omega[N_-]$ (*squares*), $\Delta[P_T, N_-]$ (*circles*), and $\Sigma[P_T, N_-]$ (*triangles*) in Pb+Pb collisions at $E_{lab} = 20$A GeV. A centrality selection is done with a restriction on the impact parameter b. (a): The full 4π detector acceptance. (b): Only particles with center of mass rapidity in the interval $1 < y_\pi < 2$ are accepted (pion mass was assumed for all particles). Open symbols correspond to the case when 10% of particles was randomly rejected.

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

$\Delta, \Sigma[P_T, N]$: energy dependence

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

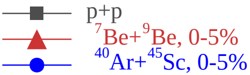


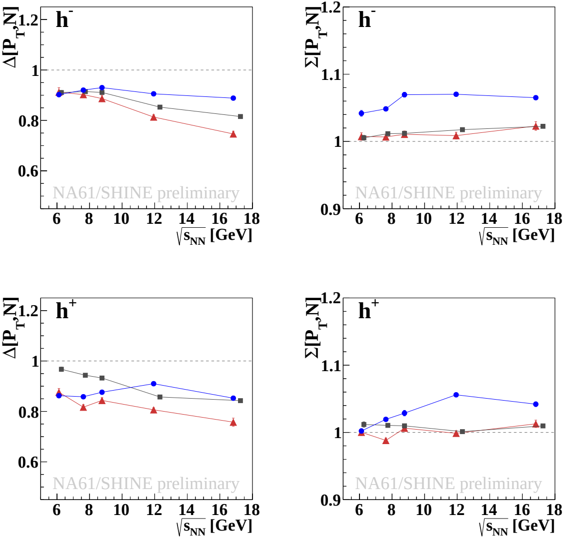
Systematic uncertainties are under investigation (first estimates - 2% for 3 low energies and of about 5% for 2 top energies)

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

$\Delta, \Sigma[P_T, N]$: energy dependence

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





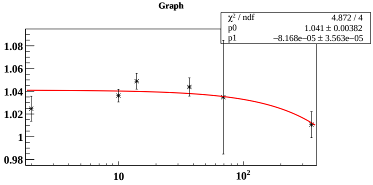
No prominent structures which could be related to CP are visible.

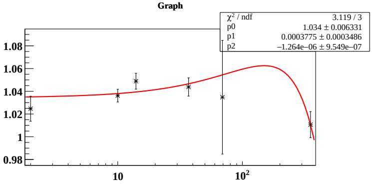
$\Delta[P_T, N] < 1$ and $\Sigma[P_T, N] \geq 1$ for all systems.

Systematic uncertainties are under investigation (first estimates - 2% for 3 low energies and of about 5% for 2 top energies)

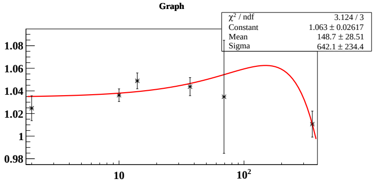
$\Sigma[P_T, N]$: system size dependence

Linear fit Parabolic fit





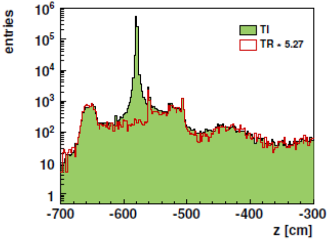
Gaussian fit



Corrections

Corrections for contamination from off-target interactions for ^{40}Ar+^{45}Sc were not applied, but with applied vertex position selection they are expected to be less than 1%.

Non-target interactions
In order to correct the data for non-target interactions, NA61/SHINE acquires data of both target-inserted and target-removed collisions. Then, in the analysis procedure, non-target interactions are subtracted.
Example of z position distribution of the fitted vertex for Be+Be at 150 GeV/c:



Obtaining $\langle W \rangle$

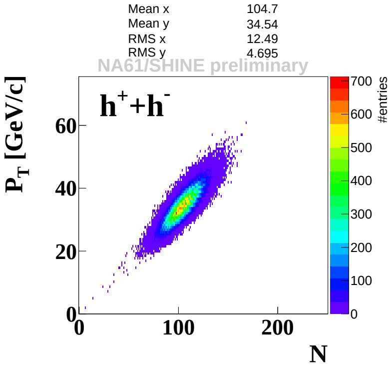
Glissando MC is based on Glauber model, whereas EPOS utilizes parton ladder model.

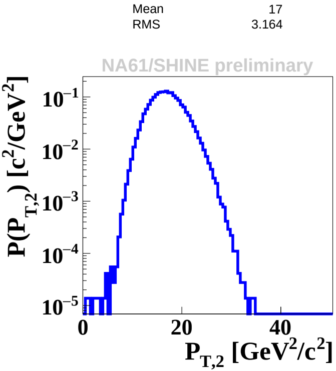
"...in our case the inelastic Nucleon-Nucleon cross-section in a nucleus is smaller than the corresponding pp cross-section leading to less binary collisions than in standard Glauber"

Tanguy Pierog, core EPOS developer

Examples of uncorrected N vs. P_T distributions

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





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.

Examples of uncorrected N vs. P_T distributions

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