N-N, PT-N and PT-PT fluctuations in nucleus-nucleus collisions at the NA61/SHINE experiment

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Motivation of the NA61/SHINE strong interaction programme

- Search for the critical point
- Study of properties of the onset of deconfinement
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Comprehensive scan with light and intermediate mass nuclei in beam momentum range 13A-150A GeV/c
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Comprehensive scan with light and intermediate mass nuclei in beam momentum range 13A-150A GeV/c

Data taking schedule:

- taken data (green)
- approved (red)
- proposed extension (gray)

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N-N, PT-N and PT-PT fluctuations in nucleus-nucleus collisions at the NA61/SHINE experiment
NA61/SHINE detector

- Located at CERN SPS
- Large acceptance hadron spectrometer – coverage of the full forward hemisphere, down to $p_T = 0$ GeV/$c$
- Performs measurements on hadron production in h+p, h+A, A+A at 13A - 150(8)A GeV/$c$
- Event selection in A+A collisions by measurements of forward energy with PSD
- Recent upgrades: vertex detector (open charm measurements), FTPC-1/2/3

NA61/SHINE in virtual reality: http://shine3d.web.cern.ch/shine3d/
Intensive fluctuation measure

A ratio of two extensive quantities \( \sim W \) - number of sources) is an intensive measure

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

- Independent of \( W \) in the Wounded Nucleon Model
- \( \omega[N] = 1 \) for the Poisson distribution
- \( \omega[N] = 0 \) in the absence of fluctuations

- should be sensitive to critical fluctuations (e.g. in classical van der Waals gas within GCE formulation)
- CP signal may be shadowed by volume fluctuations \( \omega[W] \)
- no traces of CP are seen in data at the moment (see next talk by A. Seryakov)

Vovchenko, et al., JPA 48: 305001
Strongly intensive fluctuation measures

Baseline of search for critical behaviour: quantities with trivial properties in the reference models (e.g. WNM or IB-GCE)

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

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

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

\( N \) - multiplicity of charged hadrons in an experimental acceptance

\( \omega[p_T] \) - scaled variance of inclusive \( p_T \) distribution

- Independent of \( \langle W \rangle \) and \( \omega[W] \) in the Wounded Nucleon Model
- \( \Delta[P_T, N] = \Sigma[P_T, N] = 1 \) for the independent particle production model
- \( \Delta[P_T, N] = \Sigma[P_T, N] = 1 \) for the ideal Boltzmann gas in both Grand Canonical Ensemble and Canonical Ensemble formulations
- \( \Delta[P_T, N] = \Sigma[P_T, N] = 0 \) in the absence of fluctuations
Strongly intensive fluctuation measures
Sensitivity to critical point

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

$$\Sigma[E^*, N]$$ and $$\Delta[E^*, N]$$ for nucleon system with van der Waals EOS in GCE formulation in vicinity of critical point, $$E^*$$ - excitation energy
$\Delta, \Sigma[P_T, N]$: energy vs. system size scan

Inelastic p+p vs. 0-5% $^7$Be+$^9$Be vs. 0-5% $^{40}$Ar+$^{45}$Sc

Systematic uncertainties due to experimental biases are under investigation (estimated to be smaller than 5%).

They are largely correlated between points for a given colliding system.

No prominent structures which could be related to the critical point are visible.
\[ \Delta, \Sigma[P_T, N]: \text{energy vs. system size scan} \]

Inelastic p+p vs. 0-5% \(^7\text{Be}+^9\text{Be}\) vs. 0-5% \(^{40}\text{Ar}+^{45}\text{Sc}\)

\[ \Delta[P_T, N] < 1 \]
\[ \Sigma[P_T, N] \geq 1 \]

Explanations?
- Bose-Einstein statistics of pion gas
- Negative \(M(p_T)\) vs. \(N\) correlation leads to the same inequalities.

No prominent structures which could be related to the critical point are visible.
Analysis extension: choice of phase-space

$^7$Be+$^9$Be at 150A GeV/c

Sketch of pseudorapidity (lab) spectrum of charged hadrons with proposed windows

Rapidity width dependence studies will allow to probe different baryochemical potentials ($\frac{\bar{\rho}}{\rho} = e^{-(2\mu_B)/T}$) - extension of the phase diagram scan!

Rapidity spectra of $p$ and $\bar{p}$ in inelastic $p+p$ interactions at SPS energies

9 intervals considered:

from $\eta^{lab} \in (4.6; 5.2)$ up to $\eta^{lab} \in (3; 5.2)$

The lower cut: poor azimuthal angle acceptance and stronger electron contamination at backward rapidities.

The upper cut: to reduce effects of spectators.

$\frac{\bar{p}}{p}$ changes significantly with rapidity

NA61, arXiv:1705.02467 [nucl-ex]
\( \Delta[\Delta P_T, N] \): pseudorapidity width dependence

\( ^7\text{Be} + ^9\text{Be} \) at 150\text{A GeV}/c

To estimate magnitude of experimental biases differences between pure and reconstructed Monte Carlo simulations were studied.

This difference was estimated to be less than 5\% for all data points.

Corrections are not performed.
$\Delta[P_T, N]:$ pseudorapidity width dependence  
$^7$Be+$^9$Be at 150A GeV/c

$\Delta[P_T, N] < 1$ and is monotonically decreasing with the width of the pseudorapidity interval

Data are in disagreement with the non-trivial dependence from the EPOS1.99 model

Huge discrepancy with models for p+p interactions for full acceptance as well!
$\Sigma[P_T, N]$: pseudorapidity width dependence

$^7\text{Be} + ^9\text{Be}$ at 150A GeV/c

$\Sigma[P_T, N]$ > 1 and is monotonically increasing with the width of the pseudorapidity interval

$\Sigma[P_T, N]$ approaches 1 for small width of the pseudorapidity interval (close to Poisson limit)

Good description of this dependence by the EPOS1.99 model
Forward-backward correlations

Causality requires appearance of long-range pseudorapidity correlations at early stages of evolution. Long-range correlations originate from fluctuations in the number of particle sources (many other effects like jets, flow, resonance decays, etc may affect these correlations).

Strength of correlations is quantified by the correlation coefficient:

\[ b(B, F) = \frac{\langle BF \rangle - \langle B \rangle \langle F \rangle}{\langle F^2 \rangle - \langle F \rangle^2} \]

- \( B \) - an observable in “backward” \( \eta \) window (e.g. \( N_B \))
- \( F \) - an observable in “forward” \( \eta \) window (e.g. \( N_F \))

Sensitivity to the number of sources makes correlation coefficient to be not strongly intensive, i.e. to be centrality dependent.
Strongly intensive fluctuation measures: two windows case

For extensive observables in two separated pseudorapidity intervals $F$ and $B$ one can introduce new strongly intensive quantities:

\[
\Sigma [N_F, N_B] = \langle N_B \rangle \omega [N_F] + \langle N_F \rangle \omega [N_B] - 2 \text{cov} (N_F, N_B) / \left( \langle N_B \rangle + \langle N_F \rangle \right)
\]

Similar expressions can be given for $N_F, P_{TB}$ fluctuations $\Rightarrow$ $N_F, P_{TB}$ fluctuations $\Rightarrow$ $P_{TF}, P_{TB}$ fluctuations

Sketch of pseudorapidity (lab) spectrum of charged hadrons with proposed windows

7 pairs of intervals considered:

$\eta^\text{lab}_B$ moves from (3; 3.5) up to (4.2; 4.7)

$\eta^\text{lab}_F \in (4.7; 5.2)$
Strongly intensive fluctuation measures: two windows case

$\Sigma [N_F, N_B]$ can be calculated in the model of independent quark gluon strings

Estimations for $p+p$ collisions at LHC energies show growth of $\Sigma [N_F, N_B]$ with separation between windows

Predictions are based only on string decay features, no influence of volume fluctuations
$\Sigma[N_F, N_B]$: pseudorapidity separation dependence

$^7$Be+$^9$Be at 150A GeV/c

$\Sigma[N_F, N_B]$ is growing with separation between windows

Behaviour is similar to predictions of string model for p+p collisions at LHC energies

Dominating role of short-range correlations (from a single string)?

Trend is reproduced by EPOS1.99
$\Sigma[N_F, P_{TB}]$ and $\Sigma[P_{TF}, P_{TB}]$

$^7\text{Be}+^9\text{Be}$ at 150$A$ GeV/$c$

$\Sigma[N_F, P_{TB}] > 1$ and $\Sigma[P_{TF}, P_{TB}] > 1$

$\Sigma[N_F, P_{TB}]$ and $\Sigma[P_{TF}, P_{TB}]$ are growing with separation between windows

Trend is reproduced by EPOS1.99
Conclusions

• Results on system size vs. energy dependence of \([P_T, N]\) fluctuations for particles produced in strong and EM processes within the NA61/SHINE acceptance were reported – **no indications** of the critical point of strongly interacting matter so far.

• New results on pseudorapidity dependence of \([P_T, N]\) fluctuations for forward energy selected \(^7\text{Be}+^9\text{Be}\) collisions at 150\(A\) GeV/c – \(\Delta[P_T, N]\) pseudorapidity dependence is **in disagreement** with EPOS1.99.

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N-N, PT-N and PT-PT fluctuations in nucleus-nucleus collisions at the NA61/SHINE experiment
Conclusions

- New results on $[N_F, N_B]$, $[N_F, P_{TB}]$ and $[P_{TF}, P_{TB}]$ fluctuations in forward energy selected $^7\text{Be} + ^9\text{Be}$ collisions at 150A GeV/$c$ were shown.

- First analysis of this kind at SPS energies.

- EPOS1.99 qualitatively reproduces the measured trend.

- Similar dependence seen in the quark gluon string model for $p+p$ collisions at LHC energies.
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Thank You!
Back-up
NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY:
HADRON PRODUCTION IN $p+p$, $p+A$, $A+A$
AT 13A - 150A (400) GeV/c

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N-N, PT-N and PT-PT fluctuations in nucleus-nucleus collisions at the NA61/SHINE experiment
NA61/SHINE Collaboration

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
  - University of Warsaw, Warsaw
  - WUT, Warsaw
  - Jagiellonian University, Kraków
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscow
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

∼150 physicists from ∼30 institutes
NA61/SHINE in 2021–2024

- Detector upgrade: 1 kHz readout, TOF, PSD, Large Acceptance Vertex Detector during Long Shutdown in 2019–2020
- High statistics beam momentum scan with Pb+Pb collisions for precise measurements of open charm and multi-strange hyperon production
- In parallel, NA61/SHINE performs measurements for long-baseline neutrino facilities at J-PARC and Fermilab; rich neutrino program is planned to be continued after 2020

Future NA61/SHINE will complement measurements at NICA, FAIR and J-PARC
NA61/SHINE conducts a reach neutrino physics program which is planned to be continued after 2020
**Centrality selection**

One needs to choose set of modules with dominating contribution of spectators and minimal contribution from the produced particles.

The proposed selection is data-driven and is based on correlations between energy and track multiplicity in TPC acceptance – negative correlation implies dominance of spectators in specific module.

Sketch of energy in the PSD modules and multiplicity correlations for $^7\text{Be}+^9\text{Be}$ collisions at 19A GeV/c
Centrality selection

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

Unexpectedly, for the same collision energy but for different colliding systems same modules show different behaviour.

Sketch of energy in the PSD modules and multiplicity correlations for $^7\text{Be}+^9\text{Be}$ and $^{40}\text{Ar}+^{45}\text{Sc}$ collisions at 19A GeV/c

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N-N, PT-N and PT-PT fluctuations in nucleus-nucleus collisions at the NA61/SHINE experiment
Strongly intensive fluctuation measures: two windows case

For observables in two separated pseudorapidity intervals $F$ and $B$ one can introduce new strongly intensive quantities:

1. $N_F, N_B$ fluctuations

$$\Sigma [N_F, N_B] = \frac{\langle N_B \rangle \omega [N_F] + \langle N_F \rangle \omega [N_B] - 2 \text{cov} (N_F, N_B)}{\langle N_B \rangle + \langle N_F \rangle}$$

2. $N_F, P_{TB}$ fluctuations

$$\Sigma [N_F, P_{TB}] = \frac{1}{\langle N_B \rangle + \langle N_F \rangle \cdot \langle \langle p_T \rangle \rangle_B + \langle N_F \rangle \omega [p_T]_B} \cdot \left[ \langle P_{TB} \rangle \omega [N_F] + \langle N_F \rangle \omega [P_{TB}] - 2 (\langle N_F P_{TB} \rangle - \langle N_F \rangle \langle P_{TB} \rangle) \right]$$

3. $P_{TF}, P_{TB}$ fluctuations

$$\Sigma [P_{TF}, P_{TB}] = \frac{1}{\langle P_{TB} \rangle \left( \langle \langle p_T \rangle \rangle_F + \omega [p_T]_F \right) + \langle P_{TF} \rangle \left( \langle \langle p_T \rangle \rangle_B + \omega [p_T]_B \right)} \cdot \left[ \langle P_{TB} \rangle \omega [P_{TF}] + \langle P_{TF} \rangle \omega [P_{TB}] - 2 (\langle P_{TF} P_{TB} \rangle - \langle P_{TF} \rangle \langle P_{TB} \rangle) \right]$$

Note the difference: $\langle \rangle$ - average over events; $\langle< . >>_B,F$ - average over tracks in backward/forward window.

Sketch of pseudorapidity (lab) spectrum of charged hadrons with proposed windows

7 pairs of intervals considered:

$\eta_{lab}^{lab}$ moves from $(3; 3.5)$ up to $(4.2; 4.7)$

$\eta_F^{lab} \in (4.7; 5.2)$
\[ \Sigma [P_T, N]: \text{pseudorapidity width dependence} \]

\[ ^7\text{Be}+^9\text{Be} \text{ at } 150\text{A GeV/c} \]

\[ \eta \text{lab} \]

\[ \Sigma [P_T, N] \]

To estimate magnitude of experimental biases differences between pure and reconstructed Monte Carlo simulations were studied.

This difference was estimated to be less than 5\% for all data points.

Corrections are not performed.
To estimate magnitude of experimental biases differences between pure and reconstructed Monte Carlo simulations were studied.

This difference was estimated to be less than 5% for all data points.

Corrections are not performed.
Statistics

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

|                  | 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

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

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

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

Here:

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

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

$$\omega[p_T] = \frac{p_T^2 - \langle p_T^2 \rangle}{p_T}, \overset{-}{\text{ - average over all particles}}$$
**Analysis details**

- In order to select properly measured central events one uses the following event selection criteria:
  - good beam quality
  - no off-time beam particles
  - good main vertex fit
  - centrality selected by forward energy (in simulations – selection is based on energy of all particles in the kinematic region corresponding to the selected modules)

- In order to select particles produced in strong and EM processes from the primary vertex one uses the following track selection criteria:
  - sufficient number of points inside TPCs
  - track trajectory points to interaction point
  - no electrons/positrons
  - \( p_T < 1.5 \) GeV/c
  - NA61/SHINE acceptance map
  - \( 0 < y^*_\pi < y_{beam} \) (due to poor azimuthal angle acceptance and stronger electron contamination at backward rapidities)
Examples of uncorrected $N$ vs. $P_T$ distributions

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

$h^+ + h^-$

Mean $x$: 104.7
Mean $y$: 34.54
RMS $x$: 12.49
RMS $y$: 4.695

$h^-$

Mean $x$: 48.93
Mean $y$: 15.12
RMS $x$: 6.932
RMS $y$: 2.589

$h^+$

Mean $x$: 55.74
Mean $y$: 19.42
RMS $x$: 7.555
RMS $y$: 3.161

$N$, $P_T$ 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 $\omega[p_T] = \frac{p_T^2 - \overline{p_T^2}}{\overline{p_T}}$ using only event quantities.
Corrections

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 $^{40}\text{Ar}+^{45}\text{Sc}$ 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 by dividing the data sets into 30 sub-samples. The statistical error is taken as the standard deviation of the sub-sample results divided by $\sqrt{30}$. They are typically smaller than a marker size.
The EPOS1.99 model overestimates $\Delta [P_T, N]$. The EPOS1.99 model results are close to 1 – the independent particle production model prediction.
$\Delta, \Sigma[PT, N]$: energy vs. system size scan
p+p vs. $^7\text{Be}+^9\text{Be}$ vs. $^{40}\text{Ar}+^{45}\text{Sc}$

Mean number of wounded nucleons $\langle W \rangle$ estimated using the GLISSANDO model Broniowski, Rybczynski, PRC 81: 064909.
Comparison with PbPb 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
Results for $^{40}\text{Ar}+^{45}\text{Sc}$ collisions are very close to Pb+Pb. No prominent structures which could be related to the CP are visible.

$\Delta[P_T, N] < 1$ and $\Sigma[P_T, N] \geq 1$ for both systems.
No prominent structures which could be related to the CP are visible. \( \Delta [P_T, N] \) is more sensitive to centrality selection than \( \Sigma [P_T, N] \).
$\Delta, \Sigma[P_T, N]$: centrality dependence

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

Centrality classes from 0 – 1% to 0 – 10%
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 $E_{lab} = 20A$ GeV. A centrality selection is done with a restriction on the impact parameter $b$. (a): The full $4\pi$ 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.
\[ \Delta, \Sigma [P_T, N]: \text{energy dependence} \]

\( p+p \) vs. \( ^7\text{Be}+^9\text{Be} \) vs. \( ^{40}\text{Ar}+^{45}\text{Sc} \)

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 the CP are visible.
Δ, Σ[PT, N]: energy dependence

p+p vs. 7Be+9Be vs. 40Ar+45Sc

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

Δ[PT, N] < 1 and Σ[PT, N] ≥ 1 for all systems.

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

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N-N, PT-N and PT-PT fluctuations in nucleus-nucleus collisions at the NA61/SHINE experiment
Corrections

Corrections for contamination from off-target interactions for $^{40}\text{Ar}+^{45}\text{Sc}$ 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:
Examples of uncorrected $N$ vs. $P_T$ distributions

$^{40}\text{Ar} + ^{45}\text{Sc}$ 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 $\omega[p_T] = \frac{p_T^2 - \overline{p_T}^2}{\overline{p_T}}$ using only event quantities.
Examples of uncorrected $N$ vs. $P_T$ distributions

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

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