Recent results from proton intermittency analysis in nucleus-nucleus collisions from NA61/SHINE at CERN SPS

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grant no. 2014/14/E/ST2/00018
1. QCD Phase Diagram and Critical Phenomena

2. Method of intermittency analysis

3. Previously released results at 150/158A GeV/c

4. New results on Ar+Sc at 150A GeV/c

5. Summary and outlook
Objective: Detection / existence of the QCD Critical Point (CP)

- Look for observables tailored for the CP; Scan phase diagram by varying energy and size of collision system.

Critical Observables; the Order Parameter (OP)

Event-by-event (global) fluctuations:
- Variance, skewness, kurtosis - sensitive to experimental acceptance

Local:
- Density fluctuations of OP in transverse space (stochastic fractal)

Chiral condensate
\[ \sigma(x) = \langle \bar{q}(x)q(x) \rangle \]

Net baryon density
\[ n_B(x) \]

*\[Y. Hatta and M. A. Stephanov, PRL 91, 102003 (2003)\]
Self-similar density fluctuations near the CP

Critical Point \xrightarrow{\text{divergent correlation}} Universality Class & space dimensionality

\rightarrow \text{dictate}

Critical exponents (power-law) \rightarrow \text{Correlations in configuration space}

\rightarrow \text{Correlations in momentum space}

\rightarrow \text{3D-Ising, infinite size system}

\rightarrow \text{Baryons:}

\sigma\text{-field: }
\langle n_{\sigma}(k)n_{\sigma}(k') \rangle \sim |k - k'|^{-4/3},
\ n_{\sigma}(k) = \sigma^2(k)

Baryons:
\langle n_B(k)n_B(k') \rangle \sim |k - k'|^{-5/3},
\ n_B = \text{net baryon density at midrapidity}

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Observing power-law fluctuations

Experimental observation of local, power-law distributed fluctuations

\[\Rightarrow\]

Intermittency in transverse momentum space (net protons at mid-rapidity)

(Critical opalescence in ion collisions*)

- Net proton density carries the same critical fluctuations as the net baryon density, and can be substituted for it.
  
  [Y. Hatta and M. A. Stephanov, PRL 91, 102003 (2003)]

- Furthermore, antiprotons can be dropped to the extent that their multiplicity is much lower than of protons, and proton density analyzed.

Transverse momentum space is partitioned into $M^2$ cells

Calculate second factorial moments $F_2(M)$ as a function of cell size $\Leftrightarrow$ number of cells $M$:

$$F_2(M) \equiv \frac{\left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^2},$$

where $\langle \ldots \rangle$ denotes averaging over events.
Subtracting the background from factorial moments

- Experimental data is noisy $\Rightarrow$ a background of non-critical pairs must be subtracted at the level of factorial moments.
- Intermittency will be revealed at the level of subtracted moments $\Delta F_2(M)$.

**Partitioning of pairs into critical/background**

\[
\langle n(n-1) \rangle = \langle n_c(n_c-1) \rangle + \langle n_b(n_b-1) \rangle + 2\langle n_bn_c \rangle
\]

- critical
- background
- cross term

\[
\Delta F_2(M) = F_2^{(d)}(M) - \lambda(M)^2 \cdot F_2^{(b)}(M) - 2 \cdot \lambda(M) \cdot (1 - \lambda(M)) f_{bc}
\]

- correlator
- data
- background
- ratio $\frac{\langle n \rangle_b}{\langle n \rangle_d}$

- The cross term can be neglected under certain conditions (non-trivial! Justified by Critical Monte Carlo* simulations)

Scaling of factorial moments – Subtracting mixed events

For $\lambda \lesssim 1$ (background domination), two approximations can be applied:

1. Cross term can be neglected
2. Non-critical background moments can be approximated by (uncorrelated) mixed event moments; then,

$$\Delta F_2(M) \simeq \Delta F_2^{(e)}(M) \equiv F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

For a critical system, $\Delta F_2$ scales with cell size (number of cells, $M$) as:

$$\Delta F_2(M) \sim \left( M^2 \right)^{\varphi_2}$$

where $\varphi_2$ is the intermittency index.

Theoretical prediction for $\varphi_2$

$$\varphi_2^{(p)} = \frac{5}{6} \left( 0.833 \ldots \right)$$

net baryons (protons)

Bootstrap method used to calculate statistical uncertainties

Bootstrap samples of events created by sampling of events with replacement

$\Delta F_2(M)$ calculated for each bootstrap sample; variance of sample values provides statistical error of $\Delta F_2(M)$


Distribution of $\varphi_2$ values, $P(\varphi_2)$, and confidence intervals for $\varphi_2$ obtained by fitting individual bootstrap samples


Systematic uncertainties arise from:

- Misidentification of protons & detector effects (e.g. acceptance)
- The fact that $F_2(M)$ are correlated for different bin sizes $M$
- Selection of $M$-range to fit for power-law

Bin correlations are partially handled by the bootstrap $\varphi_2$ distribution

Other systematic uncertainties are estimated by varying proton and $M$-range selection
3 sets of NA49 collision systems were analysed, at 158A GeV/c

Factorial moments of proton transverse momenta analyzed at mid-rapidity

Fragmentation beams used for C and Si ("C"=C,N ; "Si"=Si,Al,P) – components were merged to enhance statistics

Fit with $\Delta F_2^{(e)}(M; C, \phi_2) = e^C \cdot (M^2)^{\phi_2}$, for $M^2 \geq 6000$

No intermittency detected in the “C”+C, Pb+Pb datasets.
Evidence for intermittency in “Si” + Si – but large statistical errors.

Bootstrap distribution of $\phi_2$ values is highly asymmetric due to closeness of $F_2^{(d)}(M)$ to $F_2^{(m)}(M)$.

Based on CMC simulation, we estimate a fraction of $\sim 1\%$ critical protons are present in the sample.

Estimated intermittency index: $\phi_{2,B} = 0.96^{+0.38}_{-0.25}$ (stat.) $\pm 0.16$ (syst.)

$F_2(M)$ of data and mixed events overlap $\Rightarrow$

Subtracted moments $\Delta F_2(M)$ fluctuate around zero $\Rightarrow$

No intermittency effect is observed.

Preliminary analysis with CMC simulation indicates an upper limit of $\sim 0.3\%$ critical protons

[PoS(CPOD2017) 054]
First released results of preliminary analysis in Ar+Sc at 150A GeV/c – CPOD 2018.

Intermittency analysis process:

- Proton selection via particle energy loss $dE/dx$
- Removal of split tracks – $q_{inv}$ distribution & cut of proton pairs
- Probe $\Delta p_T$ distribution of proton pairs for power-law like behaviour in the limit of small $p_T$ differences
- Calculate factorial moments $F_2(M), \Delta F_2(M)$ for selected protons
- Calculate intermittency index $\phi_2$ (when possible) & estimate its statistical uncertainty

Results were obtained for:

- 0-5%, 5-10% and 10-15% centrality bins
- 80%, 85% and 90% minimum proton purity selections
Proton selection

Employ $p_{\text{tot}}$ region where Bethe-Bloch bands do not overlap ($3.98 \text{ GeV/c} \leq p_{\text{tot}} \leq 126 \text{ GeV/c}$)

Fit $dE/dx$ distribution with 4-gaussian sum for $\alpha = \pi, K, p, e$ – Bins: $p_{\text{tot}}, p_T$

30 Bins in $\log_{10}(p_{\text{tot}})$: $10^{0.6} \rightarrow 10^{2.1}$ GeV/c

20 Bins in $p_T$: $0.0 \rightarrow 2.0$ GeV/c

Proton purity: probability for a track to be a proton, $P_p = p / (\pi + K + p + e)$

Additional cut along Bethe-Blochs (avoid low-reliability region between p and K curves)
Events may contain **split tracks**: sections of the same track erroneously identified as a **pair of tracks** that are close in momentum space.

- **Three cuts** to root them out:
  1. Ratio of points / potential points in a track (removes most)
  2. Minimum track distance in the detector (pair cut)
  3. \( q_{inv} \) cut (pair cut, physics-significant)

- \( q_{inv} \) distribution of track pairs probed in order to root the rest out:
  \[
  q_{inv}(p_i, p_j) \equiv \frac{1}{2} \sqrt{-(p_i - p_j)^2}, \quad p_i : \text{4-momentum of } i^{th} \text{ track.}
  \]

- We calculate the ratio of \( q_{inv}^{data} / q_{inv}^{mixed} \).
Split tracks & the $q_{inv}$ cut

- **A peak** at low $q_{inv}$ (below 20 MeV/c) indicates a possible split track contamination that must be removed.

- Anti-correlations due to F-D effects and Coulomb repulsion must be removed before intermittency analysis $\Rightarrow$ “dip” in low $q_{inv}$, peak predicted around 20 MeV/c [Koonin, PLB 70, 43-47 (1977)]

- Universal cutoff of $q_{inv} > 7$ MeV/c applied to all sets before analysis.

![Graphs showing ratio data/mix vs $q_{inv}$ for different centrality and purity settings.](image-url)
\( \Delta p_T \) distributions: NA61 data vs EPOS

- Ar+Sc at 150A GeV/c: \( \Delta p_T = \frac{1}{2} \sqrt{(p_{X_1} - p_{X_2})^2 + (p_{\gamma_1} - p_{\gamma_2})^2} \)

  distributions of protons selected for intermittency analysis

\[ \begin{align*}
\text{NA61 data} & \quad \text{Ar+Sc NA61, cent.10-15%, pur.90\%, } \Delta p_T \text{ Ratio} \\
& \quad \text{Significant peak at } \Delta p_T \to 0 \\
\text{EPOS} & \quad \text{Ar+Sc EPOS, cent.10-15%, pur.90\%, } \Delta p_T \text{ Ratio} \\
& \quad \text{Flat distribution}
\end{align*} \]

- In NA61 data, we see strong correlations in \( \Delta p_T \to 0 \) ⇒ indication of intermittent behaviour
Δp_T distributions & $F_2(M)$: NA61 data vs EPOS

NA61 data

Ar+Sc NA61, cent.10-15%, pur.90%, Δp_T Ratio

NA61 data

EPOS

Ar+Sc EPOS, cent.10-15%, pur.90%, Δp_T Ratio

Ar+Sc NA61, cent.10-15%, pur > 90%

Ar+Sc EPOS, cent.10-15%, pur > 90%

$F_2(M)$ vs $M^2$
NA61/SHINE: Ar+Sc at 150A GeV/c: $F_2(M)$

NA61/SHINE preliminary

NA61/SHINE intermittency analysis

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NA61/SHINE: Ar+Sc at 150A GeV/c: $\Delta F_2(M)$

NA61/SHINE preliminary

$\phi^2, B = 0.37^{+0.08}_{-0.07}$

$\phi^2, B = 0.72^{+0.21}_{-0.21}$

$\phi^2, B = 0.53^{+0.07}_{-0.07}$

$\phi^2, B = 0.25^{+0.07}_{-0.11}$

$\phi^2, B = 0.31^{+0.09}_{-0.11}$

$\phi^2, B = 0.52^{+0.06}_{-0.06}$

$\phi^2, B = 0.22^{+0.05}_{-0.07}$

$\phi^2, B = 0.36^{+0.07}_{-0.08}$

$\phi^2, B = 0.50^{+0.05}_{-0.05}$

NA61/SHINE intermittency analysis

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NA61/SHINE: Ar+Sc at 150A GeV/c: $\phi_2$ bootstrap dist.

NA61/SHINE preliminary

- Ar+Sc NA61, cent. 0-5%, pur > 80% $\phi_2$ C.I. (0.298, 0.372, 0.450)
- Ar+Sc NA61, cent. 5-10%, pur > 80% $\phi_2$ C.I. (0.511, 0.724, 0.930)
- Ar+Sc NA61, cent. 10-15%, pur > 80% $\phi_2$ C.I. (0.460, 0.525, 0.593)
- Ar+Sc NA61, cent. 0-5%, pur > 85% $\phi_2$ C.I. (0.135, 0.245, 0.318)
- Ar+Sc NA61, cent. 5-10%, pur > 85% $\phi_2$ C.I. (0.203, 0.312, 0.404)
- Ar+Sc NA61, cent. 10-15%, pur > 85% $\phi_2$ C.I. (0.457, 0.515, 0.577)
- Ar+Sc NA61, cent. 0-5%, pur > 90% $\phi_2$ C.I. (0.144, 0.215, 0.266)
- Ar+Sc NA61, cent. 5-10%, pur > 90% $\phi_2$ C.I. (0.283, 0.360, 0.427)
- Ar+Sc NA61, cent. 10-15%, pur > 90% $\phi_2$ C.I. (0.449, 0.496, 0.545)
Ar+Sc EPOS: $F_2(M)$, $\Delta F_2(M)$, $\phi_2$ bootstrap distribution

NA61/SHINE preliminary
Indication of intermittency effect in middle-central NA61/SHINE Ar+Sc collisions

First possible evidence of CP signal in NA61/SHINE

Effect quality increases with increased proton purity selection, up to 90% proton purity; EPOS does not reproduce observed effect.
Expanding the analysis to other NA61/SHINE systems (Xe+La, Pb+Pb) and SPS energies (Ar+Sc) will hopefully lead to a more reliable interpretation of the observed intermittency signal in terms of the critical point.
Thank you!
Acknowledgements

This work was supported by the National Science Centre, Poland under grant no. 2014/14/E/ST2/00018.
Scaling of factorial moments – Subtracting mixed events

For $\lambda \lesssim 1$ (background domination), $\Delta F_2(M)$ can be approximated by:

$$\Delta F_2^{(e)}(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

For a critical system, $\Delta F_2$ scales with cell size (number of cells, $M$) as:

$$\Delta F_2(M) \sim (M^2)^{\varphi_2}$$

where $\varphi_2$ is the intermittency index.

Theoretical predictions for $\varphi_2$

\[
\begin{align*}
\varphi_{2,cr}^{(\sigma)} &= \frac{2}{3} \ (0.66\ldots) \\
\text{sigmas (neutral isoscalar dipions)} \\
\varphi_{2,cr}^{(p)} &= \frac{5}{6} \ (0.833\ldots) \\
\text{net baryons (protons)}
\end{align*}
\]

Critical Monte Carlo (CMC) algorithm for baryons

- Simplified version of CMC* code:
  - Only protons produced
  - One cluster per event, produced by random Lévy walk:
    \[ \bar{d}_{F}^{(B,2)} = 1/3 \Rightarrow \phi_2 = 5/6 \]
  - Lower / upper bounds of Lévy walks \( p_{\min,\max} \) plugged in.
  - Cluster center exponential in \( p_T \), slope adjusted by \( T_c \) parameter.
  - Poissonian proton multiplicity distribution.

**Input parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( p_{\min} ) (MeV)</th>
<th>( p_{\max} ) (MeV)</th>
<th>( \lambda_{\text{Poisson}} )</th>
<th>( T_c ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.1 ( \rightarrow ) 1</td>
<td>800 ( \rightarrow ) 1200</td>
<td>( \langle p \rangle_{\text{non-empty}} )</td>
<td>163</td>
</tr>
</tbody>
</table>

NA61/SHINE data analysis – $^{40}Ar + ^{45}Sc$ at 150A GeV/c

- NA49 analysis encourages us to look for intermittency in medium-sized nuclei, in the NA61 experiment.

- Intermittency analysis requires:
  - Large event statistics $\Rightarrow \sim 100K$ events min., ideally $\sim 1M$ events.
  - Reliable particle ID $\Rightarrow$ proton purity should be $\sim 80\% - 90\%$.
  - Central collisions.
  - Adequate mean proton multiplicity in midrapidity ($\geq 2$)

- A preliminary analysis for Be+Be data at 150A GeV/c was previously performed [PoS(CPOD2017) 054]; no intermittency signal was observed.

- We now expand on it with our preliminary analysis in Ar+Sc at 150A GeV/c.

- Simulation through EPOS* (detector effects included) would suggest:

$$\left. \frac{dN_p}{dy} \right|_{|y_{CM}| \leq 0.75, p_T \leq 1.5} \sim 1.6 - 2$$

for $\sim 0 - 15\%$ centrality; adequate for an intermittency analysis.

- We perform a 2D scan in proton purity (80-90%) and centrality of collisions

$^{40} Ar + ^{45} Sc$ – data set overview

- **Production used:** Ar_Sc_150_15/026_17c_v1r8p0_pA_slc6_phys_PP (miniSHOE, unofficial)
- **Runs:** 20328 - 20345, 20368 - 20380
- **Bad runs rejected** – almost 2/3rds of total!
- **miniSHOE files** with Potential Point information provided by B. Maksiak – not an official production yet
- **SHINE code to select events** (primary vertex charged particles)
- **Event & Track cuts** based on Maciej Lewicki’s and Michal Naskret’s $h^-$ analysis.
- **Non-bias event cuts:** used Andrey Seryakov’s NonBiasEventCutsArSc class.
- **0%-20% most central events in 5% bin intervals** selected via cut in energy sum of PSD selected modules (based on Andrey Seryakov’s Moscow meeting presentation on centrality determination).
### EPOS – proton $p_T$ statistics

| Centrality | #events   | $\langle p \rangle | p_T | \leq 1.5 $ GeV, $ | y_{CM} | \leq 0.75 $ Non-empty | With empty | $\Delta p_{x,y}$ |
|------------|-----------|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0- 5%      | 293,412   | 3.06 ± 1.60         | 2.89 ± 1.70     | 0.35 - 0.43     |
| 5-10%      | 252,362   | 2.72 ± 1.45         | 2.49 ± 1.58     | 0.35 - 0.43     |
| 10-15%     | 274,072   | 2.45 ± 1.33         | 2.16 ± 1.48     | 0.35 - 0.43     |

### $^{40}Ar + ^{45}Sc$ NA61 data – proton $p_T$ statistics

| Centrality | #events   | $\langle p \rangle | p_T | \leq 1.5 $ GeV, $ | y_{CM} | \leq 0.75 $ Non-empty | With empty | $\Delta p_{x,y}$ |
|------------|-----------|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0- 5%      | 144,362   | 3.44 ± 1.79         | 3.30 ± 1.89     | 0.46 - 0.58     |
| 5-10%      | 148,199   | 3.00 ± 1.61         | 2.79 ± 1.73     | 0.46 - 0.58     |
| 10-15%     | 142,900   | 2.81 ± 1.53         | 2.58 ± 1.66     | 0.45 - 0.57     |
$p_{x,y}$ spectra comparison – NA61 vs EPOS (0 – 15%)
Event & Track cuts

**Event cuts**
- Target IN/OUT,
- BPD status,
- WFA particles (4.5 $\mu$s),
- WFA interaction (25 $\mu$s),
- BPD3X(Y) charge,
- S5 (0 $\rightarrow$ 170),
- T2 trigger (eAll),
- Vertex track fitted to the main vertex,
- Vertex fit quality = ePerfect,
- Fitted vertex position $-580 \pm 10$ cm,
- PSD Module Energy Sum cut (inner/outer),
- Centrality 0-20% (based on PSD)
- $n_{\text{TracksFit}}/n_{\text{TracksAll}} > 0.25$ if $n_{\text{TracksFit}} \leq 50$ (Andrey)

**Track cuts**
- Track status,
- Charge $\pm 1$,
- Impact point $[\pm 4 \text{cm}; \pm 2 \text{cm}]$,
- Total number of clusters $\geq 30$,
- VTPCs clusters $\geq 15$,
- NO GTPC clusters,
- $dE/dx$ clusters $\geq 30$,
- $0.5 \leq \frac{\# \text{Points}}{\# \text{Potential Points}} \leq 1.0$
- TTD cut $> 2$ cm
- $dE/dx \leq 1.8$ ($dE/dx$ fit issue)
- proton selection (scan)
- $3.98$ GeV/c $\leq p_{\text{tot}} \leq 126$ GeV/c
  (for $dE/dx$ proton ID – scan)
Production used: Simulation/Ar_Sc_150_15/
15_011_v14e_v1r2p0_pA_slc6_phys/EPOS_with_potential_points/

An estimated $\sim 300K$ simulated events per 5% centrality bin.

Potential Point information included for limited events subset.

SHINE code to select events (primary vertex charged particles)

Event & Track cuts (hastily) adapted to match Ar+Sc @150 data analysis (where applicable).

No PSD simulation – centrality selection based on $\#$ of forward spectators, $nFSpec = 40$ –

simEvent.GetPrimaryInteraction().GetProjectileParticipants() (see Andrey Seryakov’s centrality determination information on twiki).
Event & Track cuts – EPOS

**Event cuts**
- Target IN/OUT,
- BPD status,
- Vertex track fitted to the main vertex,
- Vertex fit quality = ePerfect,
- Fitted vertex position $-580 \pm 10$ cm,
- Centrality 10% (based on nFSpec)

**Track cuts**
- Track status,
- Charge $\pm 1$,
- Impact point $[\pm 4 \text{ cm}; \pm 2 \text{ cm}]$,
- Total number of clusters $\geq 30$,
- VTPCs clusters $\geq 15$,
- NO GTPC clusters,
- TTD cut $> 2$ cm,
- proton selection – matching closest simTrack,
- $3.98 \text{ GeV/c} \leq p_{tot} \leq 126 \text{ GeV/c}$ (to match effect of dE/dx $p_{tot}$ cut),
- acceptance cut
Centrality selection via \# forward spectators

- A **probabilistic selection** based on nFSpec percentiles used to select centrality bin.

![cBin vs nFSpectators (5% intervals)](image)

- A **discrepancy** observed in multiplicity distribution between data (above) & EPOS (below).
- **Acceptance cut** fixes the problem.
All Event cuts – statistics

- # events
- Target IN
- BPD Status
- WFA S1
- WFA T4
- BPD3 Charge
- S5 ADC
- T2 triggers
- Fitted vtx status ePerfect
- PSD Module Energy
- Centrality
- Vtx has good position
- TracksRatio

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Track cuts – statistics

- # tracks: 1.7e+09
- # tracks: 8.2e+07
- # tracks: 8.2e+07
- # tracks: 7.6e+07
- # tracks: 5.6e+07
- # tracks: 5.0e+07
- # tracks: 4.7e+07
- # tracks: 4.7e+07
- # tracks: 4.7e+07
- # tracks: 2.2e+06

- Good track
- Good charge
- Impact Parameter
- # TOT clusters > 30
- # VTPC clusters > 15 || # GapTPC clusters > 1000000
- 0.5 < nPointRatio < 1
- # dEdx clusters > 30
- dEdx < 1.8
- Proton Purity > 0.90 (via dE/dx)
Cuts (plots)

- **run_number**
  - Entries: 351463
  - Mean: $2.036 \times 10^4$
  - RMS: 18.52

- **nTracksCharged**
  - Entries: 351463
  - Mean: 90.78
  - RMS: 13.59

- **PSD Energy [1-16]**
  - Entries: 351463
  - Mean: 1383
  - RMS: 270.1 [GeV]

- **PSD Energy [17-44]**
  - Entries: 351463
  - Mean: 1622
  - RMS: 250.4 [GeV]
Cuts (plots)

PSD energy, mods: 1-16,21,22,27,28

Entries 660291
Mean 2301
RMS 420.9 [GeV]

PSD energy, mods: 1-16,21,22,27,28

Entries 2054319
Mean 0.8102
RMS 0.08466

NPratio
0.5
0.6
0.7
0.8
0.9
1 1.1

Entries 351463
Mean -579.8
RMS 0.2736 [cm]

Entrs 351463
Mean -579.8
RMS 0.2736 [cm]

Entries 2054319
Mean 0.1027
Mean y 0.05368
RMS x 0.5413
RMS y 0.2038

Entries 2054319
Mean 0.1027
Mean y 0.05368
RMS x 0.5413
RMS y 0.2038

Entries 2054319
Mean 0.1027
Mean y 0.05368
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RMS y 0.2038

Entries 2054319
Mean 0.1027
Mean y 0.05368
RMS x 0.5413
RMS y 0.2038
Avoid $p_{tot}$ region where Bethe-Bloch curves overlap (3.98 GeV/c $\leq p_{tot} \leq$ 126 GeV/c)

Using Hans Dembinski/Raul R Prado’s dE/dx fitting software – Bins: $p_{tot}$, $p_T$

Presented in Moscow meeting by Prado, Herve & Unger

30 Bins in $\log_{10}(p_{tot})$: $10^{0.6} \rightarrow 10^{2.1}$ GeV/c

20 Bins in $p_T$: 0.0 $\rightarrow$ 2.0 GeV/c

Preliminary p selection: 90% purity removing deuterons from the model

Cut along Bethe-Blochs: $BB_p + 0.15(BB_K - BB_p)$
Used $dE/dx$ spectra from Ar+Sc @150 data in the 6% - 18% centrality interval

For each track, assign a $dE/dx$ value based on particle species and phase space bin

Apply $dE/dx$ & purity cuts identical to NA61/SHINE data
Improving calculation of $F_2(M)$ via lattice averaging

- **Problem**: With low statistics/multiplicity, lattice boundaries may split pairs of neighboring points, affecting $F_2(M)$ values (see example below).

- **Solution**: Calculate moments several times on different, slightly displaced lattices (see example)

- **Average** corresponding $F_2(M)$ over all lattices. Errors can be estimated by variance over lattice positions.

- **Lattice displacement** is larger than experimental resolution, yet maximum displacement must be of the order of the finer binnings, so as to stay in the correct $p_T$ range.

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**Displaced lattice — a simple example**

![Displaced lattice diagram](image)

- $M=3$, lattice for one event
- $M=3$, displaced lattice

- $<n(n-1)/n> (M=3) = 108/25$
- $<n(n-1)/n> (M=3') = 54/25$

- $<n(n-1)/n> (M=3) = 108/25$
- $<n(n-1)/n> (M=3') = 54/25$
Improved confidence intervals for $\phi_2$ via resampling

- In order to estimate the statistical errors of $\Delta F_2(M)$, we need to produce variations of the original event sample. This, we can achieve by using the statistical method of resampling (bootstrapping) ⇒
  - Sample original events with replacement, producing new sets of the same statistics (# of events)
  - Calculate $\Delta F_2(M)$ for each bootstrap sample in the same manner as for the original.
  - The variance of sample values provides the statistical error of $\Delta F_2(M)$.


- Furthermore, we can obtain a distribution $P(\phi_2)$ of $\phi_2$ values. Each bootstrap sample of $\Delta F_2(M)$ is fit with a power-law:

$$\Delta F_2(M; C, \phi_2) = e^C \cdot (M^2)^{\phi_2}$$

and we can extract a confidence interval for $\phi_2$ from the distribution of values. [B. Efron, The Annals of Statistics 7,1 (1979)]
Split tracks; the $q_{inv}$ cut in analysed datasets

- Split tracks can create **false positive** for intermittency $\Rightarrow$ must be **reduced** or **removed**.

- $q_{inv}$-test – distribution of track pairs: $q_{inv}(p_i, p_j) \equiv \frac{1}{2} \sqrt{-(p_i - p_j)^2}$, $p_i$ : 4-momentum of $i^{th}$ track.

- Calculate ratio $\frac{q_{inv}^{data}}{q_{inv}^{mixed}}$ $\Rightarrow$ peak at low $q_{inv}$ (below 20 MeV/c): possible split track contamination.

![Graphs showing data/mix ratio vs. $q_{inv}$ for different reactions](a) "C" + C (b) "Si"+Si (c) Pb + Pb (00B)

- Anti-correlations due to F-D effects and Coulomb repulsion must be removed before intermittency analysis $\Rightarrow$ “dip” in low $q_{inv}$, peak predicted around 20 MeV/c [Koonin, PLB 70, 43-47 (1977)]

- **Universal cutoff** of $q_{inv} > 25$ MeV/c applied to all sets before analysis.
We measure correlations in relative $p_T$ of protons via

$$\Delta p_T = \frac{1}{2} \sqrt{(p_{X1} - p_{X2})^2 + (p_{Y1} - p_{Y2})^2}$$

- Strong correlations for $\Delta p_T \to 0$ indicate power-law scaling of the density-difference correlation function $\Rightarrow$ intermittency presence
- We find a strong peak in the “Si”+Si dataset
- A similar peak is seen in the $\Delta p_T$ profile of simulated CMC protons with the characteristics of “Si”+Si.
Events may contain split tracks: sections of the same track erroneously identified as a pair of tracks that are close in momentum space.

Intermittency analysis is based on pairs distribution $\Rightarrow$ split tracks can create a false positive, and so must be reduced or removed.

Standard cuts remove part of split tracks. In order to estimate the residual contamination, we check the $q_{inv}$ distribution of track pairs:

$$q_{inv}(p_i, p_j) \equiv \frac{1}{2} \sqrt{- (p_i - p_j)^2},$$

$p_i$: 4-momentum of $i^{th}$ track.

We calculate the ratio of $q_{inv}^{data} / q_{inv}^{mixed}$. A peak at low $q_{inv}$ (below 20 MeV/c) indicates a possible split track contamination that must be removed.
Noisy CMC (baryons) – estimating the level of background

- \( F_2(M) \) of noisy CMC approximates “Si”+Si for \( \lambda \approx 0.99 \)
- \( \Delta F_2^{(e)}(M) \) reproduces critical behaviour of pure CMC, even though their moments differ by orders of magnitude!

Noisy CMC results show our approximation is reasonable for dominant background.
$q_{\text{inv}}$ proton distributions – NA61/SHINE

Ar+Sc NA61, cent.0-5%, pur.80%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.5-10%, pur.80%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.10-15%, pur.80%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.0-5%, pur.85%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.5-10%, pur.85%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.10-15%, pur.85%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.0-5%, pur.90%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.5-10%, pur.90%, $q_{\text{inv}}$ Ratio

Ar+Sc NA61, cent.10-15%, pur.90%, $q_{\text{inv}}$ Ratio
$\Delta p_T$ proton distributions – NA61/SHINE

Ar+Sc NA61, cent.0-5%, pur.80%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.5-10%, pur.80%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.10-15%, pur.80%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.0-5%, pur.85%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.5-10%, pur.85%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.10-15%, pur.85%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.0-5%, pur.90%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.5-10%, pur.90%, $\Delta p_T$ Ratio

Ar+Sc NA61, cent.10-15%, pur.90%, $\Delta p_T$ Ratio

N. Davis (IFJ PAN)
$q_{inv}$ & $\Delta p_T$ distributions – EPOS

Ar+Sc EPOS, cent.0-5%, pur.90%, $q_{inv}$ Ratio

Ar+Sc EPOS, cent.5-10%, pur.90%, $q_{inv}$ Ratio

Ar+Sc EPOS, cent.10-15%, pur.90%, $q_{inv}$ Ratio

Ar+Sc EPOS, cent.0-5%, pur.90%, $\Delta p_T$ Ratio

Ar+Sc EPOS, cent.5-10%, pur.90%, $\Delta p_T$ Ratio

Ar+Sc EPOS, cent.10-15%, pur.90%, $\Delta p_T$ Ratio

N. Davis (IFJ PAN)

NA61/SHINE intermittency analysis

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