Searching for the QCD critical point through power-law fluctuations of the proton density in heavy ion collisions

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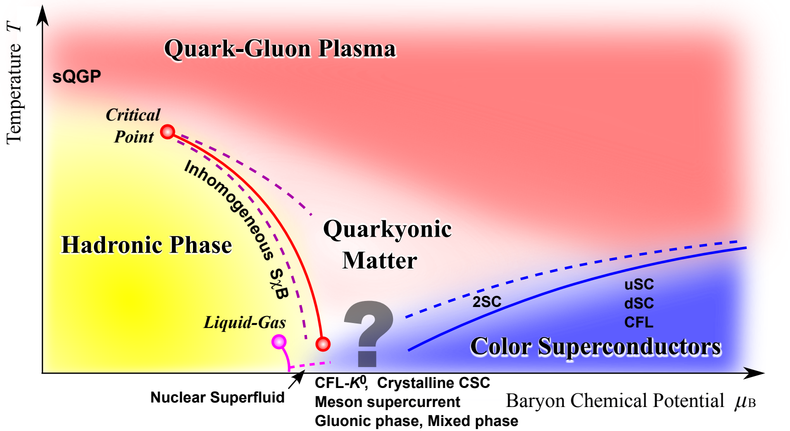
Phase diagram of QCD

- Objective: Detection / existence of the QCD Critical Point (CP)



K. Fukushima, T. Hatsuda, Rept. Prog. Phys. 74:014001 (2011)

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

Critical Observables; the Order Parameter (OP)

CP observables

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

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

Order parameter

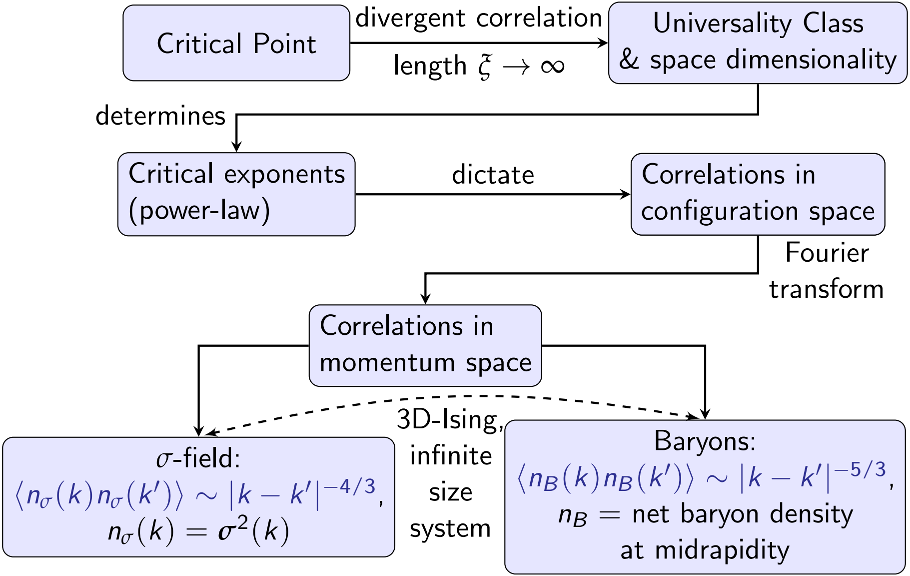
Chiral condensate
$\sigma(\boldsymbol{x}) = \langle \bar{q}(\boldsymbol{x}) q(\boldsymbol{x}) \rangle$

coupling $\Updownarrow$ induced critical fluctuations*

Net proton density
$n_B(\boldsymbol{x})$

*[Y. Hatta and M. A. Stephanov, PRL**91**, 102003 (2003)]

Self-similar density fluctuations near the CP



Observing power-law fluctuations

Experimental observation of local, power-law distributed fluctuations

$\Downarrow$

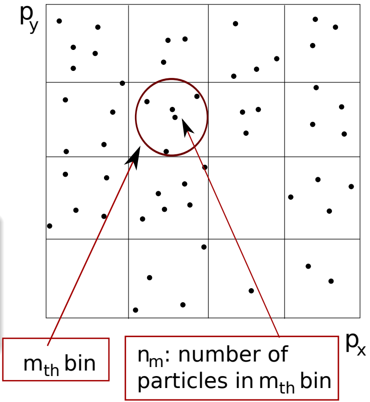
Intermittency in transverse momentum space (net protons at mid-rapidity)

(Critical opalescence in ion collisions*)

- 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:

$$F_2(M) \equiv \frac{\sum_m \langle n_m(n_m-1)\rangle}{\sum_m \langle n_m\rangle^2},$$

where $\langle \dots \rangle$ denotes averaging over events.



*[F.K. Diakonos, N.G. Antoniou and G. Mavromanolakis, PoS (CPOD2006) 010, Florence]

Subtracting the background from factorial moments

- Experimental data is noisy $\Rightarrow$ a background of uncorrelated/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

$$\langle n(n-1)\rangle = \underbrace{\langle n_c(n_c-1)\rangle}_{\text{critical}} + \underbrace{\langle n_b(n_b-1)\rangle}_{\text{background}} + \underbrace{2\langle n_b n_c\rangle}_{\text{mixed term}}$$

$$\underbrace{\Delta F_2(M)}_{\text{correlator}} = \underbrace{F_2^{(d)}(M)}_{\text{data}} - \lambda(M)^2\,\underbrace{F_2^{(b)}(M)}_{\text{background}} - 2\,\underbrace{\lambda(M)}_{\text{ratio } \frac{<n>_b}{<n>_d}}\,(1-\lambda(M))\,f_{bc}$$

- The mixed term can be neglected for dominant background (non-trivial! Justified by CMC simulations)

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, ΔF_2 scales with cell size (number of cells, M) as:

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

where φ_2 is the intermittency index.

Theoretical predictions for φ_2

universality class, effective actions

$$\varphi_{2,cr}^{(\sigma)} = \frac{2}{3}\ (0.66\ldots)$$

sigmas (neutral isoscalar dipions)

[N. G. Antoniou **et al**, Nucl. Phys. A **693**, 799 (2001)]

$$\varphi_{2,cr}^{(p)} = \frac{5}{6}\ (0.833\ldots)$$

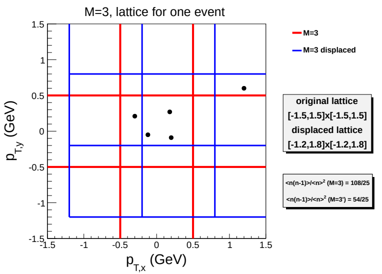
net baryons (protons)

[N. G. Antoniou, F. K. Diakonos, A. S. Kapoyannis, K. S. Kousouris, Phys. Rev. Lett. **97**, 032002 (2006)]

Statistical & systematic error handling in $F_2(M)$

- $F_2(M)$ averaged over many lattice positions
  $\Downarrow$
  smoothing of bin boundary effect

Displaced lattice — a simple example

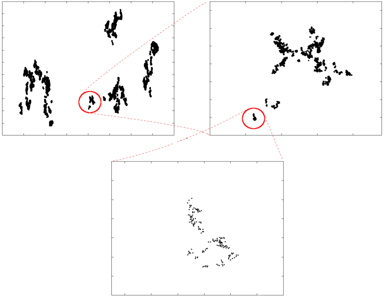


- Variations of original sample of events produced by resampling (bootstrap) method $\Rightarrow$ sampling of events with replacement
- $\Delta F_2(M)$ calculated for each bootstrap sample; variance of sample values provides statistical error of $\Delta F_2(M)$
  [W.J. Metzger, *"Estimating the Uncertainties of Factorial Moments"*, HEN-455 (2004).]
- Distribution of φ_2 values, $P(\varphi_2)$, and confidence intervals for φ_2 obtained by fitting individual bootstrap samples
  [B. Efron, *The Annals of Statistics* **7**,1 (1979)]

Critical Monte Carlo (CMC) algorithm for baryons

- Simplified version of CMC* code:
  - Only protons produced
  - One cluster per event, produced by random Lévy walk: $\tilde{d}_F^{(B,2)} = 1/3 \Rightarrow \phi_2 = 5/6$
  - 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.

Lévy walk example



Input parameters

Parameter	p_{min} (MeV)	p_{max} (MeV)	λ_{Poisson}	T_c (MeV)
Value	$0.1 \rightarrow 1$	$800 \rightarrow 1200$	$\langle p \rangle_{\text{non-empty}}$	163

* [Antoniou, Diakonos, Kapoyannis and Kousouris, Phys. Rev. Lett. 97, 032002 (2006).]

NA49 analysed data sets & cuts

- Published in [T. Anticic *et al.*, Eur. Phys. J. C 75:587 (2015), arXiv:1208.5292v5]

A	**"C"+C***	**"Si"+Si***	**Pb+Pb**
# Bootstrap Samples	1000		
Rapidity range	$-0.75 \leq y_{CM} \leq 0.75$		
# lattice positions	11 (2×5 + central)		
Lattice range (GeV)	$[-1.529, 1.471] \to [-1.471, 1.529]$		
Beam Energy ($\sqrt{s_{NN}}$)	158 A GeV (17.3 GeV)		
Centrality range	$0 \to 12\%$		$0 \to 10\%$
Proton purity	$> 80\%$		$> 90\%$
# events	148 060	165 941	329 789
$\langle p_{data} \rangle$ (after cuts)	1.6 ± 0.9	3.1 ± 1.7	9.12 ± 3.15

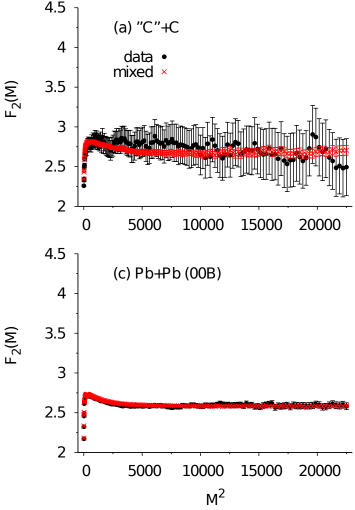
* Beam Components: "C" = C,N, "Si" = Si,Al,P

- Standard NA49 event/track cuts [T. Anticic *et al*, PR**C 81**, 149 (2010)].
- q_{inv} cut to remove split tracks, F-D effects and Coulomb repulsion
- Mid-rapidity selected because of approximately constant proton density in rapidity in this region (also avoids nucleons in the corona).

[N.G. Antoniou, F.K. Diakonos, A.S. Kapoyannis and K.S. Kousouris, PRL.**97**, 032002 (2006)]

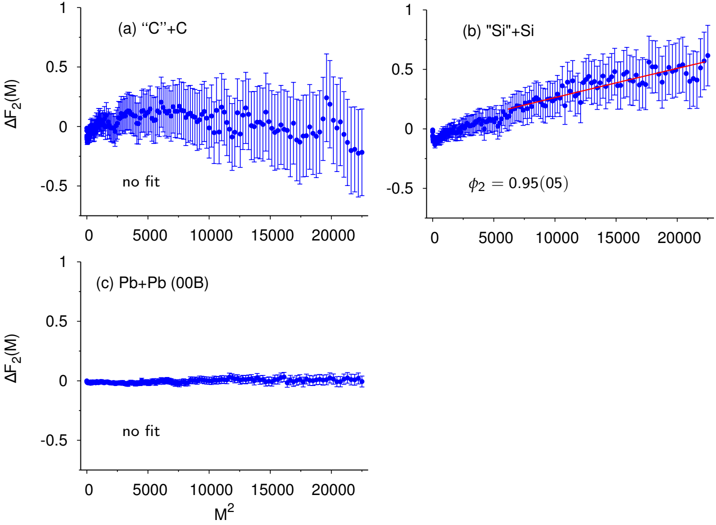
Analysis results - $F_2(M)$ for protons

- Evidence for intermittent behaviour in “Si”+Si – but large statistical errors.



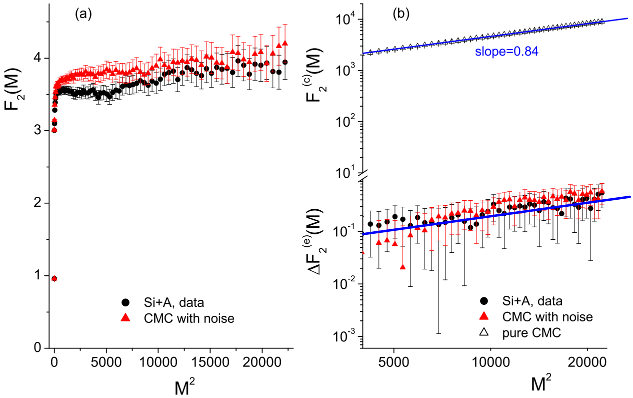
Analysis results - $\Delta F_2(M)$ for protons

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



Noisy CMC (baryons) – estimating the level of background

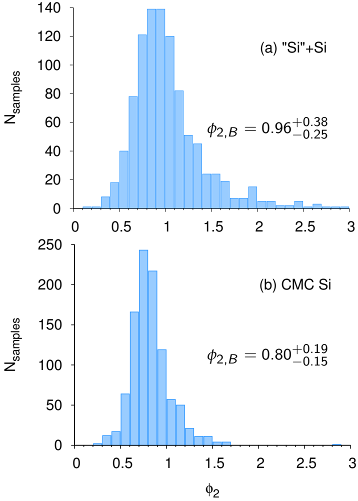
- $F_2(M)$ of noisy CMC approximates "Si"+Si for $\lambda \approx 0.99$
- Correlator $\Delta F_2^{(e)}(M)$ has slope $\phi_2 = 0.80^{+0.19}_{-0.15}$, very close to $\phi_2 = 0.84$ of pure $F_2^{(c)}(M)$



- $\Delta F_2^{(e)}(M)$ 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.

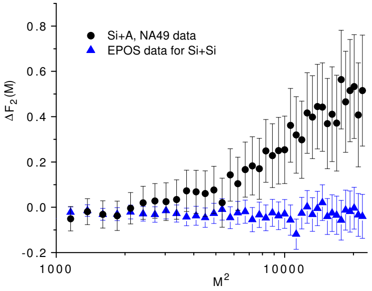
Analysis results - φ_2 bootstrap distribution

- Distributions are highly asymmetric due to closeness of $F_2^{(d)}(M)$ to $F_2^{(m)}(M)$.



- CMC model with a dominant background can reproduce the spread of ϕ_2 values observed in the "Si"+Si dataset
- The spread is partly artificial due to pathological fits (negative $\Delta F_2(M)$ values in some bootstrap samples)

Can jets "fake" intermittency effect?



*[K. Werner, F. Liu, and T. Pierog, Phys. Rev. C 74, 044902 (2006)]

- EPOS event generator* includes high-p_T jets $\Rightarrow$ possible spurious intermittency by non-critical protons.
- We simulate 630K Si+Si EPOS events:
  1. Z=14, A=28, for both beam and target
  2. $b_{max} = 2.6$ fm (12% most central)
  3. $\sqrt{s_{NN}} = 17.3$ GeV
  4. Rapidity cuts as in NA49 data
- Intermittency analysis (data & mixed events) repeated for EPOS.
- EPOS clearly cannot account for intermittency presence $\Rightarrow \Delta F_2(M)$ fluctuates around zero.

Onwards to NA61 analysis...

- 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 $\sim 80\%, 90\%$.
  - In general, $5 \rightarrow 10\%$ most central collisions.
  - Adequate mean proton multiplicity in midrapidity (≥ 2)
- Two candidate NA61 systems – Be+Be @ 150 GeV & Ar+Sc @ 150 GeV.
- What follows is a feasibility study for Be+Be & Ar+Sc – no actual data intermittency analysis at this stage.

Overview of $^7Be + ^9Be$, $^{40}Ar + ^{45}Sc$ @ 150 GeV

Be+Be:

- Mean proton multiplicity density per event, in mid-rapidity – pilot analysis of NA61 data suggests:

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

rather low $\Rightarrow \geq 1.5 \rightarrow 2$ needed

Ar+Sc:

- Analysis of NA61 data in progress.
- Simulation through EPOS would suggest:

$$\left.\frac{dN_p}{dy}\right|_{|y_{CM}|\leq 0.75,\, p_T\leq 1.5} \sim 4$$

for $b_{max} \sim 3.5 \Leftrightarrow \sim 10\%$ centrality; adequate for an intermittency analysis

Simulating Be+Be – EPOS & CMC

- EPOS Simulation parameters:
  1. ^{7}Be (beam) + ^{9}Be (target)
  2. Beam energy: $150A\ GeV$ (target rest frame) $\Leftrightarrow \sqrt{s_{NN}} = 16.8\ GeV$
  3. Central collisions $\Rightarrow b_{\max} = 2.0\ fm$
  4. Total number of simulated events: 200K

EPOS – proton p_T statistics

$b_{\max}$	#events	$\langle p \rangle_{\lvert p_T \rvert \le 1.5\ GeV,\ \lvert y_{CM} \rvert \le 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
1.0	50,093	1.48 ± 0.74	0.78 ± 0.92	0.43

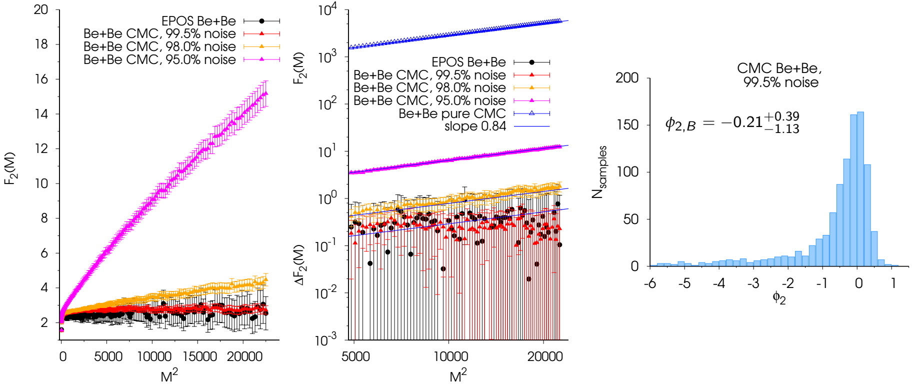
CMC simulation parameters

Parameter	$p_{\min}$ (MeV)	$p_{\max}$ (MeV)	λ_{Poisson}	T_c (MeV)
Value	0.85	1200	0.76	163

- $\langle p \rangle$ in mid-rapidity remains low, except for very central collisions

Noisy CMC, Be+Be – estimating the level of background

- $F_2(M)$ of noisy CMC approximates Be+Be EPOS for $\lambda \approx 0.995$
- Correlator $\Delta F_2^{(e)}(M)$ has slope $\phi_2 = -0.21^{+0.39}_{-1.13} \rightarrow$ fluctuates around zero.



Simulating Ar+Sc – EPOS & CMC

- Simulation parameters:
  1. ^{40}Ar (beam) + ^{45}Sc (target)
  2. Beam energy: $150A\ GeV$ (target rest frame) $\Leftrightarrow \sqrt{s_{NN}} = 16.8\ GeV$
  3. Central collisions $\Rightarrow b_{\max} = 3.5\ fm$
  4. Total number of simulated events: 100K

EPOS – proton p_T statistics

$b_{\max}$	#events	$\langle p \rangle_{\lvert p_T\rvert \leq 1.5\ GeV,\ \lvert y_{CM}\rvert \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
3.5	100,000	5.3 ± 2.5	5.3 ± 2.4	0.490

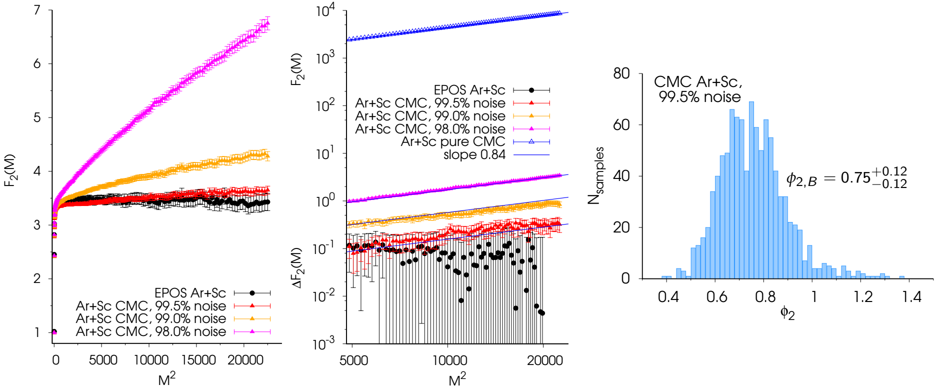
CMC simulation parameters

Parameter	$p_{\min}$ (MeV)	$p_{\max}$ (MeV)	λ_{Poisson}	T_c (MeV)
Value	0.41	1200	5.3	163

- $\langle p \rangle$ in mid-rapidity acceptable for $b_{max} \leq 3.5$

Noisy CMC, Ar+Sc – estimating the level of background

- $F_2(M)$ of noisy CMC approximates Ar+Sc EPOS for $\lambda \approx 0.995$
- Correlator $\Delta F_2^{(e)}(M)$ has slope $\phi_2 = 0.75^{+0.12}_{-0.12}$



Summary and outlook

Intermittency analysis in transverse momentum space of NA49 data for central "C"+C, "Si"+Si and Pb+Pb collisions has been performed.

- For protons at midrapidity we find significant power-law fluctuations in "Si"+Si at 158A GeV. No significant intermittent behaviour is observed in "C"+C and low-intensity Pb+Pb (00B) data sets.
- The **intermittency index ϕ_2** for the **Si system overlaps with the critical QCD prediction**.

Summary and outlook

- Study of self-similar (power-law) fluctuations of the net baryon density provides us with a promising set of observables for detecting the location of the QCD critical point.
- **First experimental evidence** for the **approach to the vicinity of the critical point**.
- Analysis favors a CP close to the freeze-out conditions of the "Si"+Si system

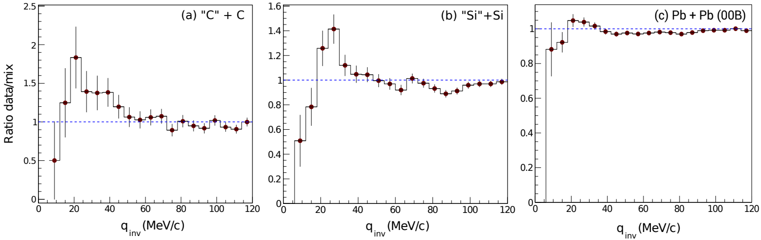
  [T. Anticic *et al.* (NA49 Collaboration), Eur. Phys. J. C 75:587 (2015), arXiv:1208.5292v5]
- Preliminary study of light nuclei collisions in NA61 experiment indicates that an intermittency analysis is feasible for (at least) the Ar+Sc system at maximum SPS energy. Performing a systematic intermittency analysis in this system size region (Be+Be, Ar+Sc, Xe+La) will hopefully lead to an **accurate determination of the critical point location**.

Thank you!

Back Up Slides

Split tracks; the q_{inv} cut in analysed datasets

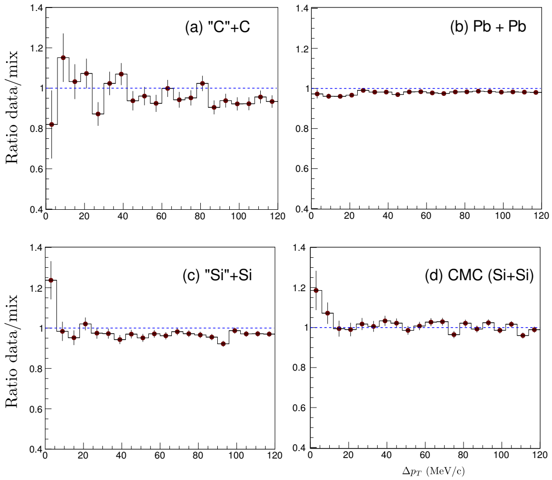
- Split tracks can create false positive for intermittency $\Rightarrow$ must be reduced or removed.
- q_{inv}-test – distribution of track pairs: $q_{inv}(p_i, p_j) \equiv \frac{1}{2}\sqrt{-(p_i - p_j)^2}$, p_i : 4-momentum of i^{th} track.
- Calculate ratio $q_{inv}^{data} / q_{inv}^{mixed}$ $\Rightarrow$ peak at low q_{inv} (below 20 MeV/c): possible split track contamination.



- 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.

NA49 analysis – Δp_T distributions

- We measure correlations in relative p_T of protons via $\Delta p_T = 1/2\sqrt{(p_{X_1} - p_{X_2})^2 + (p_{Y_1} - p_{Y_2})^2}$

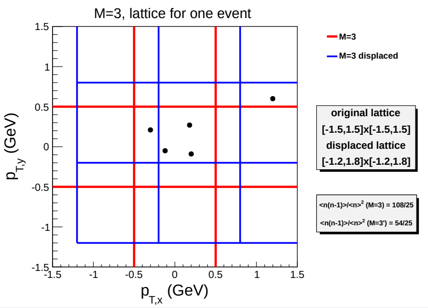


- Strong correlations for $\Delta p_T \to 0$ indicate power-law scaling of the density-density correlation function $\Rightarrow$ intermittency presence
- We find a strong peak in the "Si"+Si dataset
- A similar peak is seen in the Δp_T profile of simulated CMC protons with the characteristics of "Si"+Si.

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.

Displaced lattice — a simple example



Improved confidence intervals for ϕ_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) $\Rightarrow$
  - 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 $\Delta F_2(M)$.

[W.J. Metzger, *"Estimating the Uncertainties of Factorial Moments"*, HEN-455 (2004).]

- Furthermore, we can obtain a distribution $P(\varphi_2)$ of φ_2 values. Each bootstrap sample of $\Delta F_2(M)$ is fit with a power-law:

$$\Delta F_2(M; \mathcal{C}, \varphi_2) = e^{\mathcal{C}} \cdot (M^2)^{\varphi_2}$$

and we can extract a confidence interval for φ_2 from the distribution of values. [B. Efron, *The Annals of Statistics* **7**,1 (1979)]

Event & track cuts for Si+A

Event cuts:

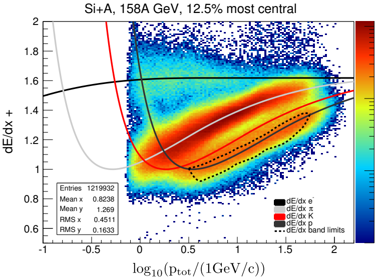
- Iflag $= 0$, chi$^2 > 0$
- Beam charge cuts (Al,Si,P)
- Vertex cuts:
  - -0.4 cm $\leq V_x \leq 0.4$ cm
  - -0.5 cm $\leq V_y \leq 0.5$ cm
  - -580.3 cm $\leq V_z \leq -578.7$ cm

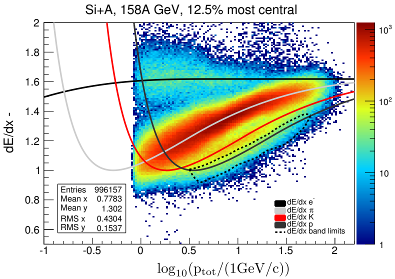
Track cuts:

- Iflag $= 0$
- Npoints ≥ 30 (for the whole detector)
- Ratio $\frac{\text{Npoints}}{\text{NMaxPoints}} \geq 0.5$
- ZFirst ≤ 200
- Impact parameters: $|B_x| \leq 2$, $|B_y| \leq 1$
- dE/dx cuts for particle identification
- p_{tot} cuts (via dE/dx cut)
- rapidity cut

NA49 analysis – applied cuts and particle ID

- Cuts based on the standard set of event & track cuts used in NA49 experiment [Anticic et al., PRC,83:054906 (2011)]
- Beam components merged for analysis in "Si"+Si, "C"+C
- Quality cuts to minimize split track effect
- Proton identification through cuts in particle energy loss dE/dx vs p_{TOT}:
    - Inclusive dE/dx distribution fitted in 10 bands of $\log[p_{TOT}/1\mathrm{GeV/c}]$
    - Fit with 4 gaussian sum for $\alpha = \pi, K, p, e$
    - Probability for a track with energy loss x_i of being a proton:
      $P = f^{\mathrm{p}}(x_i, p_i)/(f^{\pi}(x_i, p_i) + f^{\mathrm{K}}(x_i, p_i) + f^{\mathrm{p}}(x_i, p_i) + f^{\mathrm{e}}(x_i, p_i))$





Split tracks & the q_{inv} cut

- 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.

Comparison with simulated C+C – PHSD

- Simulation parameters:
  1. ^{12}C (beam) + ^{12}C (target)
  2. Beam energy: $150A\ GeV$ (target rest frame)
  3. Minimum bias $\Rightarrow b_{\text{max}} \sim 6\ fm$
  4. Total number of simulated events: 100K
- Centrality selection by cut on minimum # of wounded nucleons:

$n_{\text{wounded}}^{\text{min}}$	#events	$\langle p \rangle_{\lvert p_T \rvert \leq 1.5\ GeV, \lvert y_{CM} \rvert \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
13	11684	1.50 ± 0.80	0.85 ± 0.95	0.48
14	10003	1.54 ± 0.80	0.90 ± 1.00	0.485
15	8245	1.57 ± 0.80	0.95 ± 0.99	0.48
16	6524	1.60 ± 0.80	0.99 ± 1.00	0.48
17	5008	1.63 ± 0.85	1.06 ± 1.03	0.48
18	3534	1.70 ± 0.90	1.11 ± 1.11	0.48

- NA49 "C"+C @ 158 GeV: $\langle p \rangle = 1.6 \pm 0.9 \Rightarrow$ close to 10% most central C+C PHSD

Simulating non-critical Be+Be – PHSD*

- Simulation parameters:
  1. ^{7}Be (beam) + ^{9}Be (target)
  2. Beam energy: $150A\ GeV$ (target rest frame)
  3. Minimum bias $\Rightarrow b_{\text{max}} \sim 6\ fm$
  4. Total number of simulated events: 74600
- Centrality selection by cut on minimum # of wounded nucleons:

$n_{\text{wounded}}^{\text{min}}$	#events	$\langle p \rangle_{\lvert p_T \rvert \leq 1.5\ GeV,\ \lvert y_{CM} \rvert \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
10	2632	1.36 ± 0.62	0.61 ± 0.80	0.48
11	1879	1.39 ± 0.64	0.65 ± 0.82	0.47
12	1219	1.42 ± 0.66	0.69 ± 0.85	0.48
13	710	1.46 ± 0.68	0.76 ± 0.88	0.47
14	358	1.48 ± 0.70	0.82 ± 0.90	0.44 - 0.48
15	108	1.50 ± 0.70	0.84 ± 0.91	0.43 - 0.49
16	21	1.52 ± 0.79	0.78 ± 0.95	0.40 - 0.53

PHSD data provided by Dr. Vitalii Ozvenchuk

*[Cassing W. and Bratkovskaya E. L., Nucl. Phys. A **831** 215 (2009)]

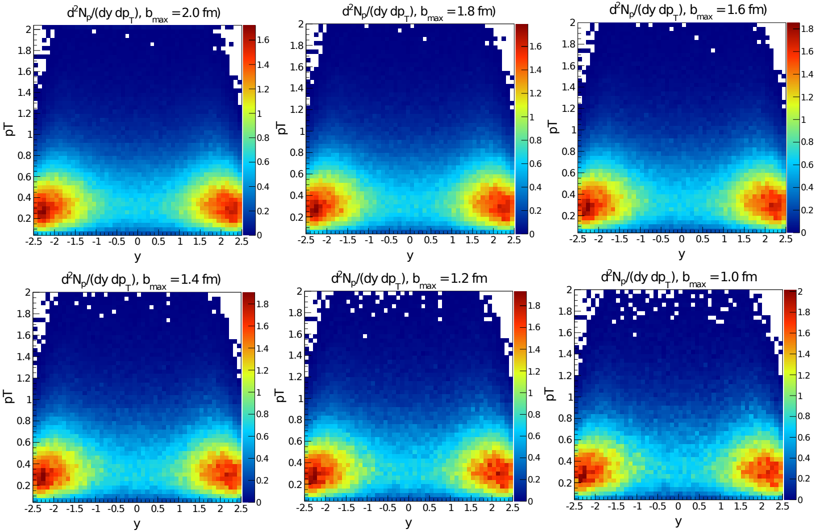
Simulating non-critical Be+Be – EPOS

- Simulation parameters:
  1. ^7Be (beam) + ^9Be (target)
  2. Beam energy: $150A\ GeV$ (target rest frame) $\Leftrightarrow \sqrt{s_{NN}} = 16.8\ GeV$
  3. Central collisions $\Rightarrow b_{\max} = 2.0\ fm$
  4. Total number of simulated events: 200K

$b_{\max}$	#events	$\langle p \rangle_{\lvert p_T \rvert \leq 1.5\ GeV, \lvert y_{CM} \rvert \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
2.0	200,000	1.41 ± 0.69	0.66 ± 0.85	0.42
1.8	162,231	1.43 ± 0.70	0.69 ± 0.87	0.42
1.6	128,216	1.44 ± 0.71	0.72 ± 0.88	0.42
1.4	98,137	1.46 ± 0.73	0.74 ± 0.90	0.42-0.43
1.2	72,267	1.47 ± 0.73	0.76 ± 0.91	0.42-0.43
1.0	50,093	1.48 ± 0.74	0.78 ± 0.92	0.43

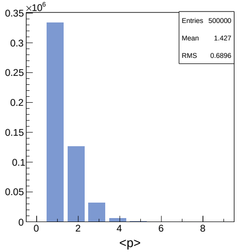
Simulating non-critical Be+Be – EPOS, y vs pT

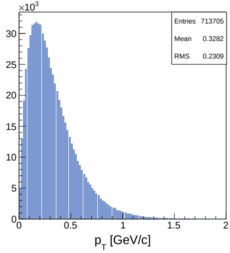
- $\langle p \rangle$ in mid-rapidity remains low, except for very central collisions

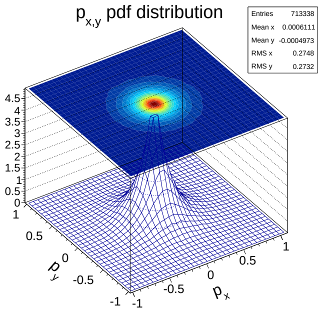


Simulating critical Be+Be – CMC baryon

Parameter	p_{min} (MeV)	p_{max} (MeV)	λ_{Poisson}	T_c (MeV)
Value	0.85	1200	0.76	163







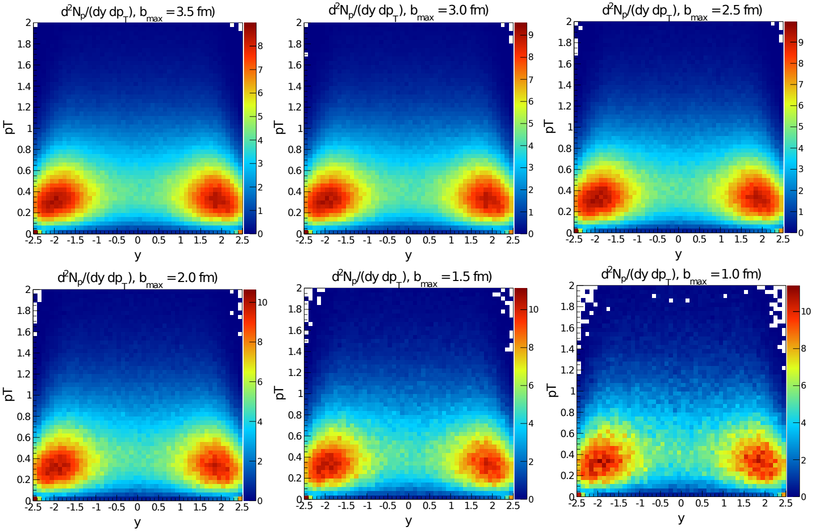
Simulating non-critical Ar+Sc – EPOS

- Simulation parameters:
  1. ^{40}Ar (beam) $+$ ^{45}Sc (target)
  2. Beam energy: $150A\ GeV$ (target rest frame) $\Leftrightarrow \sqrt{s_{NN}} = 16.8\ GeV$
  3. Central collisions $\Rightarrow b_{\max} = 3.5\ fm$
  4. Total number of simulated events: 100K

$b_{\max}$	#events	$\langle p \rangle_{\lvert p_T \rvert \leq 1.5\ GeV, \lvert y_{CM} \rvert \leq 0.75}$ Non-empty	With empty	$\Delta p_{x,y}$
3.5	100,000	5.3 ± 2.5	5.3 ± 2.4	0.490
3.0	73,452	5.6 ± 2.5	5.7 ± 2.5	0.495
2.5	50,891	5.9 ± 2.5	6.0 ± 2.5	0.495
2.0	32,591	6.2 ± 2.5	6.2 ± 2.5	0.500
1.5	18,345	6.4 ± 2.6	6.5 ± 2.6	0.500
1.0	8,285	6.6 ± 2.6	6.5 ± 2.6	0.500
0.5	2,032	6.7 ± 2.7	6.8 ± 2.7	0.500

Simulating non-critical Ar+Sc – EPOS, y vs pT

- $\langle p \rangle$ in mid-rapidity acceptable for $b_{max} \leq 3.5$



Simulating critical Ar+Sc – CMC baryon

Parameter	p_{min} (MeV)	p_{max} (MeV)	λ_{Poisson}	T_c (MeV)
Value	0.41	1200	5.3	163