Search for the critical point of strongly interacting matter in the NA61/SHINE experiment at CERN SPS

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N02

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IFJ PAN NO2 seminar

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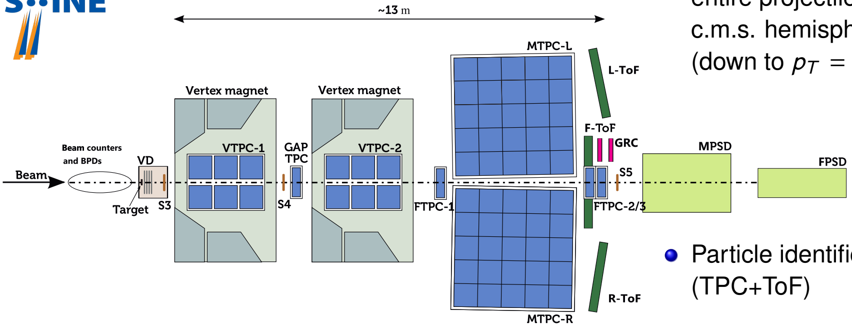
IFJ PAN, Kraków, Poland

Outline

The NA61/SHINE experiment – detector

NA61/SHINE
at CERN SPS

⟹ Multipurpose fixed-target spectrometer with unique capabilities



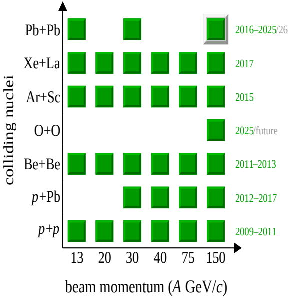
- Coverage of the entire projectile c.m.s. hemisphere (down to $p_T = 0$)
- Particle identification (TPC+ToF)

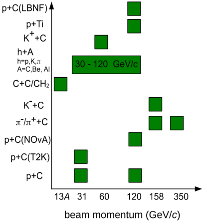
- Spectra and total multiplicities: $\pi^{\pm}$, $K^{\pm}$, K_s^0, K^*, ϕ, p, $\bar{p}$, Λ, Ξ, $\bar{\Xi}$ ...
- Heavy quarks: D^0 and $\bar{D}^0$
- **Correlations, fluctuations, intermittency...**

NA61/SHINE – Research program $\sqrt{s_{NN}}$ = 5-17/27 GeV

Strong interactions

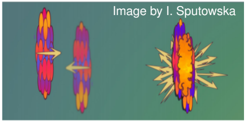
- study the onset of deconfinement
- **search for the critical point**
- measurement of open charm
- measurements of violation of isospin symmetry in multiparticle production

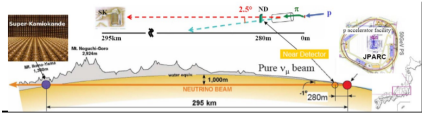


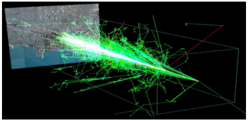


Neutrino and cosmic-ray physics

- measurements for neutrino programs (J-PARC, Fermilab)
- measurements for cosmic-ray physics (Pierre-Auger, Telescope Array, IceTop)



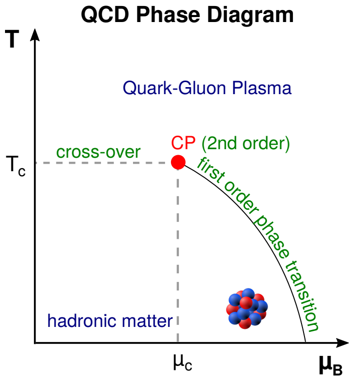


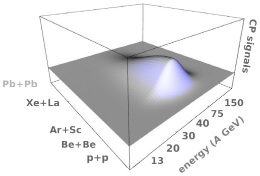


The NA61/SHINE search for the critical point

The NA61/SHINE critical point search

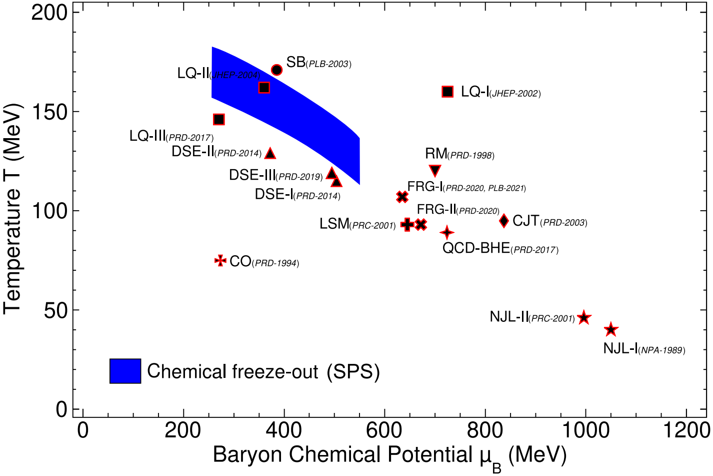
- **Critical point (CP)** — a hypothetical end point of **first order** phase transition line (QGP-HM) that has properties of **second order** phase transition
- **2nd order** phase transition → **scale invariance** → **power-law form** of **correlation function**
- Expectations for **enhanced fluctuations and correlations**





- **Scan** in the **experimentally controlled parameters** (collision energy, nuclear mass number, centrality). The conjecture is that, by varying them, we vary **freeze-out conditions** (T, μ_B)

Critical point predictions



[T. Czopowicz, CPOD 2024, Berkeley, California]

Predictions on the CP existence and its location are **varying** and **model-dependent**.

[Pandav, Mallick, Mohanty, Prog.Part.Nucl.Phys. 125 (2022) 103960]

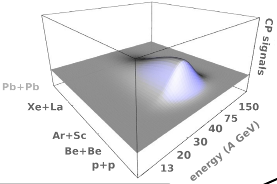
[Becattini, Manninen, Gazdzicki, Phys. Rev.C73 2006]

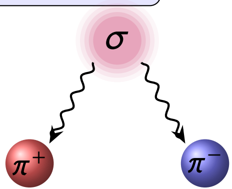
Critical Observables & the Order Parameter (OP)

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

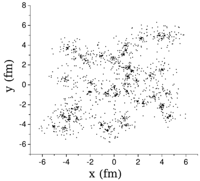
A quantity that:

- is **= 0** in **disordered** phase (QGP)
- is **≠ 0** in **ordered** phase (hadrons)

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

coupling ⇕ induced critical fluctuations*

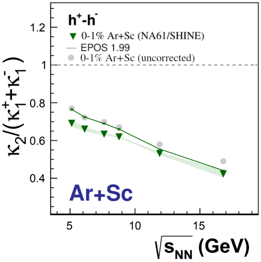
Net baryon density
$n_B(\boldsymbol{x})$



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

Net-electric charge ($h^+ - h^-$) fluctuations – Ar+Sc

[NA61/SHINE, EPJC 85 (2025) 918]



- Fluctuations captured by **ratios of cumulants**
  - $\kappa_2/(\kappa_1^+ + \kappa_1^-)$, κ_3/κ_1 , κ_4/κ_2 **(net-charge: $h^+ - h^-$)**
- **Reference values**: 0 – no fluctuations, 1 – "trivial" Poisson/Skellam distribution

$$N = \text{multiplicity}$$

$$\delta N = N - \langle N \rangle$$

$$S = \text{skewness}$$

$$K = \text{kurtosis}$$

$$\kappa_1 = \langle N \rangle$$

$$\kappa_2 = \left\langle \delta N^2 \right\rangle \equiv \sigma^2$$

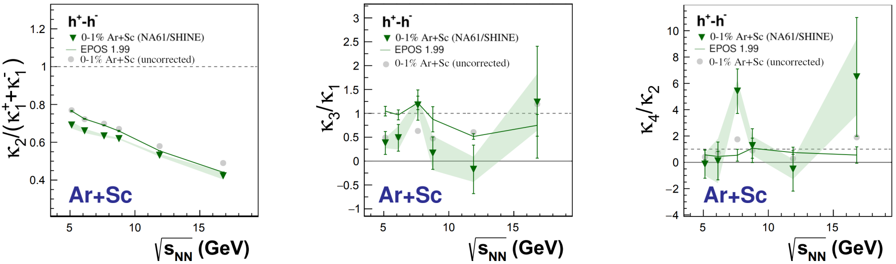
$$\kappa_3 = \left\langle \delta N^3 \right\rangle \equiv S\sigma^3$$

$$\kappa_4 = \left\langle \delta N^4 \right\rangle - 3 \left\langle \delta N^2 \right\rangle^2 \equiv K\sigma^4$$

$$\langle \delta N^n \rangle \equiv \left\langle (N - \langle N \rangle)^n \right\rangle$$

Net-electric charge ($h^+ - h^-$) fluctuations – Ar+Sc

[NA61/SHINE, EPJC 85 (2025) 918]



- **EPOS 1.99 reproduces the magnitude** of the signal observed in the data
- **Largest deviations: κ_3/κ_1, κ_4/κ_2** at **mid-SPS energies** (7–12 GeV)
- gray points – results from uncorrected distributions (statistical uncertainties are not indicated)
- **Hint of non-monotonic behaviour** at mid-SPS energies, but **large statistical uncertainties**

$$\langle \delta N^n \rangle \equiv \left\langle (N - \langle N \rangle)^n \right\rangle$$

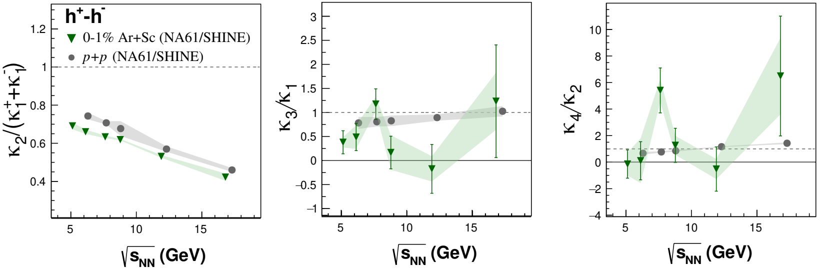
$$\kappa_1 = \langle N \rangle, \ \kappa_2 = \left\langle \delta N^2 \right\rangle \equiv \sigma^2$$

$$\kappa_3 = \left\langle \delta N^3 \right\rangle \equiv S\sigma^3$$

$$\kappa_4 = \left\langle \delta N^4 \right\rangle - 3 \left\langle \delta N^2 \right\rangle^2 \equiv K\sigma^4$$

Net-electric charge fluctuations – Ar+Sc *vs* *p+p* collisions

[NA61/SHINE, EPJC 85 (2025) 918]

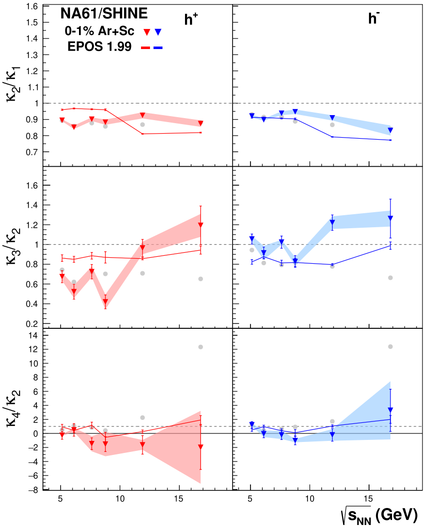


- **Hint of non-monotonic behavior** in **central Ar+Sc** for κ_3/κ_1 **and** κ_4/κ_2 is not seen in *p+p*
- **Largest difference** between systems visible in case of κ_3/κ_1 **and** κ_4/κ_2 at **mid-SPS** energies; **magnitude** of signal is comparable to *p+p*

- Fluctuations captured by **ratios of cumulants**
  - κ_2/κ_1 , κ_3/κ_2 , κ_4/κ_2 **(multiplicity)**
- **Comparison** with **EPOS 1.99**
- **Model reproduces** the **magnitude of the signal** in the data
- $\boldsymbol{\kappa_2/\kappa_1, \kappa_3/\kappa_2}$ – **deviation** between model & data
- $\boldsymbol{\kappa_4/\kappa_2}$ – **agreement** with model
- gray points – results from uncorrected distributions

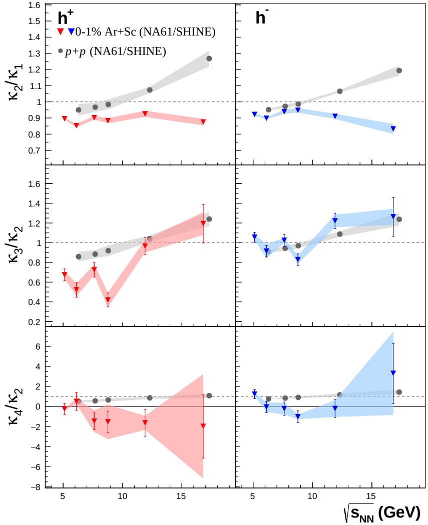
  (statistical uncertainties not indicated)

[NA61/SHINE, EPJC 85 (2025) 918]



Multiplicity fluctuations – ratios of cumulants (p+p, Ar+Sc)

[NA61/SHINE, EPJC 85 (2025) 918]



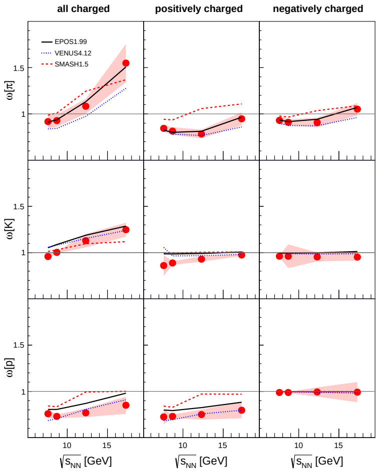
System size dependence:

- κ_2/κ_1 **systematic deviation** at **top energies**
- κ_3/κ_2 **difference** at **lowest energies**
- κ_4/κ_2 some differences, **large uncertainties**

Multiplicity fluctuations in $p+p$ collisions

- **Multiplicity fluctuations** of identified π, K, p studied in inelastic $p+p$ collisions at **SPS**

[NA61/SHINE, EPJ C 81 (2021) 384]



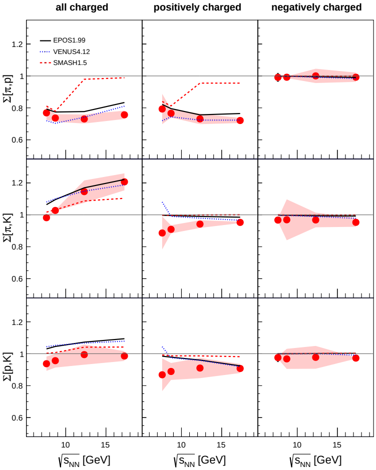
- **Collision energy** dependence of **scaled variance $\omega[A]$**,

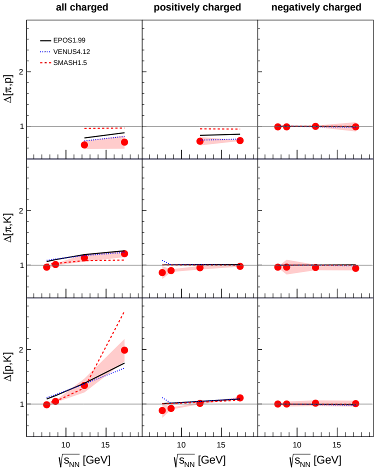
$$\omega[A] = \frac{Var[A]}{\langle N_A \rangle}$$

  is presented for **identified π, K, p**
- **Results** for **positively, negatively and all charged** are presented separately
- **Comparison with models: EPOS, SMASH, VENUS**
- **Red bands**: systematic uncertainties

Multiplicity fluctuations in *p+p* – SI quantities

- **Strongly intensive (SI)** quantities $\Sigma[A,B], \Delta[A,B]$: **independent** of **volume & volume fluctuations** (see also IFJ PAN seminar by **I. Sputowska**, Dec 4th, 2025)



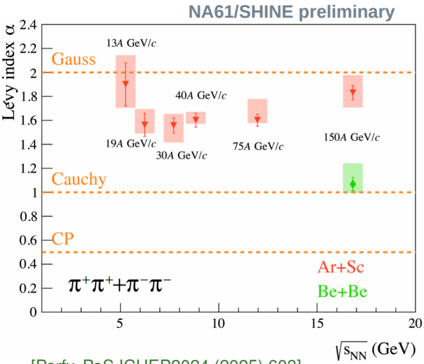


[NA61/SHINE, EPJ C 81 (2021) 384]

$$\Sigma[A,B] = \frac{1}{\langle N_B\rangle + \langle N_A\rangle}\left[\langle N_B\rangle\omega[A] + \langle N_A\rangle\omega[B] - 2\Big(\langle N_A N_B\rangle - \langle N_A\rangle\langle N_B\rangle\Big)\right]$$

$$\Delta[A,B] = \frac{1}{\langle N_B\rangle - \langle N_A\rangle}\Big[\langle N_B\rangle\omega[A] - \langle N_A\rangle\omega[B]\Big]$$

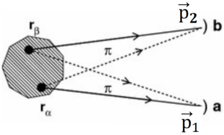
Bose-Einstein (HBT) correlations (femtoscopy)



[Porfy, PoS ICHEP2024 (2025) 603]

Ar+Sc, 0-10% central, NA61/SHINE preliminary

Be+Be, 0-20% central, NA61/SHINE, EPJC 83 (2023) 919
+ later estimate of sys. uncertainty



Correlation function from Lévy source:

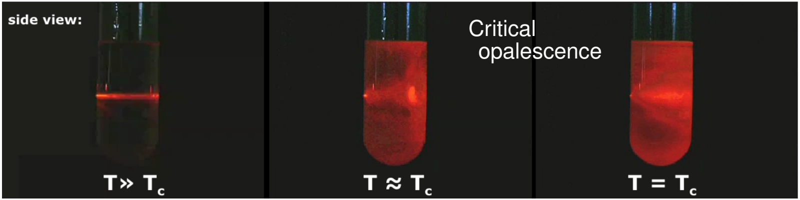
$$C(q) = 1 + \lambda e^{-(qR)^\alpha}$$
$$q = |\vec{p}_1 - \vec{p}_2|$$

- Bose-Einstein correlations (femtoscopy) reveal the **space-time structure** of hadron production
- The Lévy parameter α describes the **shape of the source** and is **sensitive to the system freezing out at the CP**

[Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828 (2006) 525]

- The new Ar+Sc results are close to Gaussian, and **far from the CP**; slight **non-monotonic behaviour** as a function of **collision energy**

Observing power-law fluctuations through intermittency



[Csorgo, Tamas, PoS CPOD2009 (2009) 035]

Experimental observation of local, power-law distributed fluctuations of net baryon density

⇓

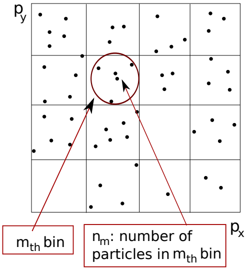
Intermittency in transverse momentum space
(Critical opalescence in ion collisions)

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

- 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 ignored (their multiplicity is negligible compared to protons), so we can analyze just the proton density.

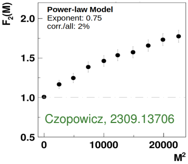
Proton intermittency – scaled factorial moments $F_r(M)$

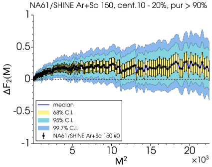


- When the system **freezes out at CP**, the **scaled factorial moments $F_r(M)$** are expected to follow a **power-law** behaviour:

$$F_r(M) \sim \left(M^2\right)^{\varphi_r}$$

- For **protons** and $r = 2$, $\varphi_2 = 5/6$ is expected
- Either **correlated**[1] or **statistically independent data points**[2] can be used





- **Cumulative variables**[3] or **mixed-event moment subtraction**[4] handle **baseline correlations**

$$F_r(M) \equiv \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^r}$$

M^2 – number of bins; $\langle\ldots\rangle$ – averaging over events

[Białas, Peschanski, NPB 273 (1986) 703]
[Wosiek, APPB 19 (1988) 863]
[Asakawa, Yazaki, NPA 504 (1989) 668]
[Barducci et al., PLB 231 (1989) 463]
[Satz, NPB 326 (1989) 613]
[Antoniou et al., PRL 97 (2006) 032002]
1 [Davis, APP.Supp. 13 (2020) 637]
2 [NA61/SHINE, EPJC 83 (2023) 881]
3 [Białas, Gazdzicki, PLB 252 (1990) 483]
4 [NA49, EPJC 75 (2015) 587]

Background subtraction – the correlator $\Delta F_2(M)$

- Background of **non-critical pairs** must be **subtracted** from experimental data;

Partitioning of pairs into critical/background

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

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

- If **$\lambda(M) \lesssim 1$ (dominant background)** $\Rightarrow$ **cross term negligible** & **$F_2^{(b)}(M) \sim F_2^{\text{mix}}(M)$** (**Critical Monte Carlo*** **simulations**), **then:**

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

Intermittency **restored** in **$\Delta F_2(M)$**:

$$\Delta F_2(M) \sim (M^2)^{\varphi_2}, \; M \gg 1$$

$\Rightarrow$

φ_2: intermittency index

Theoretical prediction* for φ_2

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

*[Antoniou *et al*, PRL **97**, 032002 (2006)]

Independent bin analysis with cumulative variables

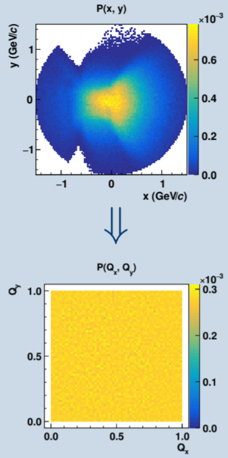
- In **standard** NA61/SHINE intermittency analysis, we use **independent bins**
  → for each M, we calculate $F_2(M)$ from an independent subsample of events

- **Disadvantage:** we **break up statistics**, and can only **calculate $F_2(M)$** for **a handful of bins**
- Furthermore, we use **cumulative coordinates:**
  [Bialas, Gazdzicki, PLB 252 (1990) 483]

$$Q_x(x) = \int_{min}^{x} P(x)dx \Big/ \int_{min}^{max} P(x)dx;$$

$$Q_y(x,y) = \int_{ymin}^{y} P(x,y)dy \Big/ P(x)$$

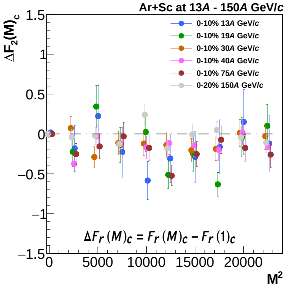
→ transform any distribution into **uniform** one $(0,1)$

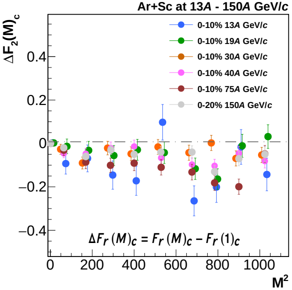


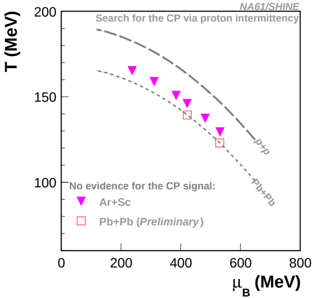
(example for 0-5% Ar+Sc at 150A GeV/c)

SHINE Ar+Sc independent bin proton intermittency

- **No signal** indicating the **critical point** in **cumulative independent bin** analysis







$$1^2 \leq M^2 \leq 150^2$$

$$1^2 \leq M^2 \leq 32^2$$

↖ ↗

number of subdivisions in
cumulative transverse momentum space

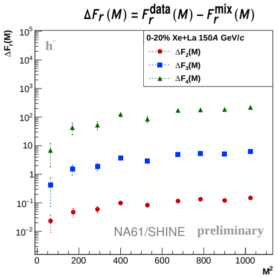
Beam momentum to $\sqrt{s_{NN}}$ key

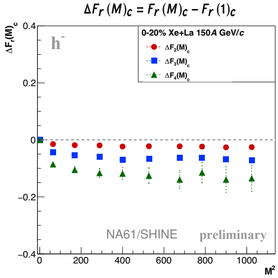
p_{lab} (A GeV/c)	$\sqrt{s_{NN}}$ (GeV)
13	5.1
19	6.1
30	7.6
40	8.8
75	11.9
150	16.8

[NA61/SHINE, EPJC 83 (2023) 881; EPJC 84 (2024) 741]

Intermittency of negatively charged hadrons

[V. Reyna, NA61/SHINE, CPOD 2024]

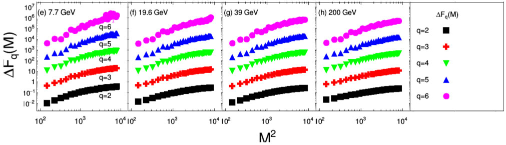




0 – 20% Xe+La, $\sqrt{s_{NN}} = 16.8$ GeV

1. **"Standard"** analysis (**binning** in p_x & p_y)
   - A characteristic hierarchy emerges: increase of $\Delta F_r(M)$ with M, and with **moment order** r
   - Qualitatively similar to **STAR** results on charged hadrons [STAR, PLB 845, 2023, 138165]
2. Analysis made with the **cumulative** (p_x, p_y) transformation [Białas, Gazdzicki, PLB 252 (1990) 483]
   - **No indication** of power-law scaling
   - Effect shown in 1 attributed to **short-range correlations (HBT)** [V. Reyna, NA61/SHINE, CPOD 2024]

→ Demonstrates the importance of elimination of **spurious** (baseline) effects!



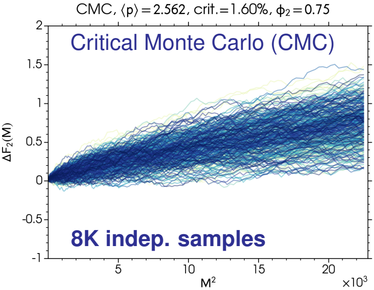
[STAR, PLB 845 (2023) 138165]

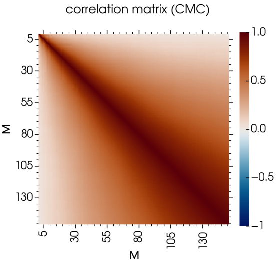
Methodological progress in intermittency analysis

- [Davis, PLB 868 (2025) 139697]

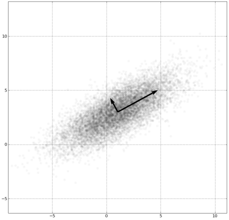
Methodological progress: M-bin correlation handling (PCA)

- In **intermittency**, ***$F_r(M)$* values** for different ***M*-bin sizes** are **correlated** if the **same events** are used for **all *M*-bins**; this **invalidates** fitting & model comparison
- **Independent points** can be used, but **point uncertainties increase!**



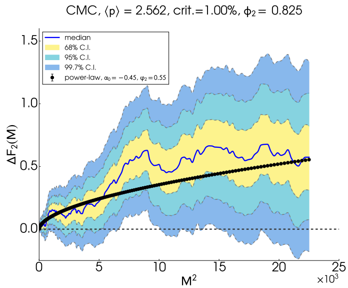


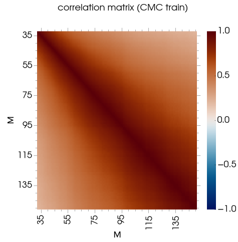
- An alternative is to **untangle correlations!**

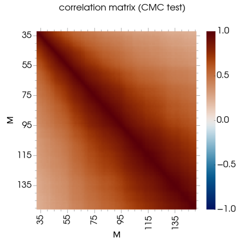


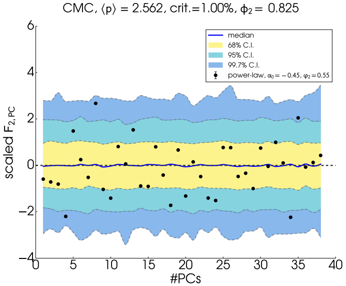
- We can do this via **Principal Component Analysis (PCA)**: **center and scale** sample points in ***M*-space**, then **rotate** the axes to make **independent linear combinations** of ***M*-bins**. Finally, keep **only a few** significant components

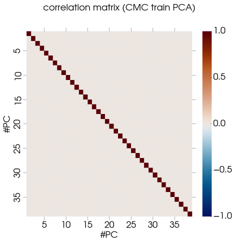
Performing a scan in power-laws with PCA (CMC “data”)

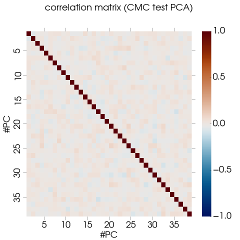




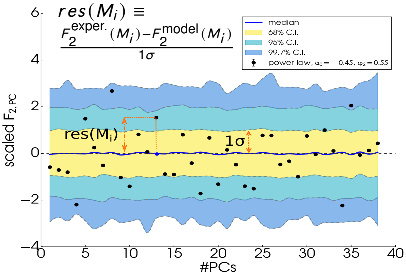


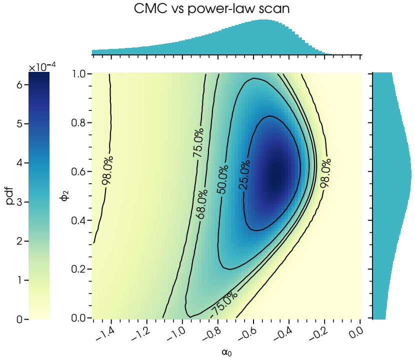






- **Original data sample** becomes **PC baseline**; **all power-laws** compared to it





Power-law model

$$\Delta F_2(M) \equiv 10^{\alpha_0} \left(\frac{M^2}{10^4}\right)^{\varphi_2}$$

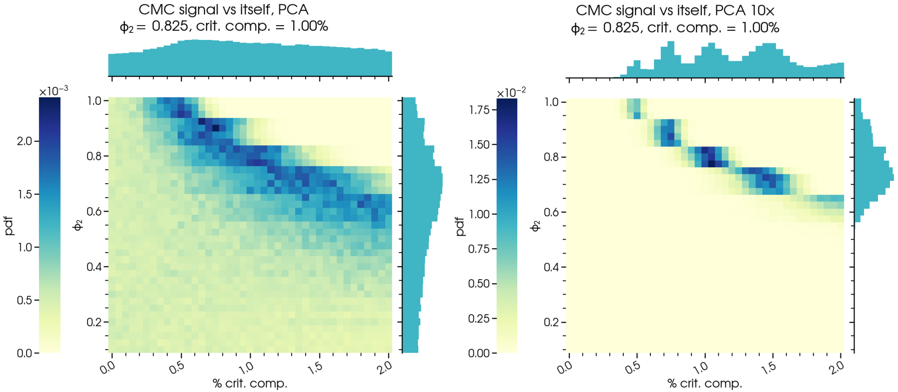
α_0 : power-law strength,
φ_2: power-law exponent

$$\chi^2 = \sum_i res^2(M_i) \Rightarrow \text{Model Weight} \sim e^{-\frac{\chi^2}{2}}$$

- **Scan in power-law parameters** $\Rightarrow$ **best-fitting power-laws** to the data
- **Percentage of critical protons** can be estimated by **power-law strength α_0**
- **PCA transformation** ensures **valid model weighting**

The role of event statistics

- **Event statistics** (number of analyzed events) **greatly affects** the **precision** of the method!



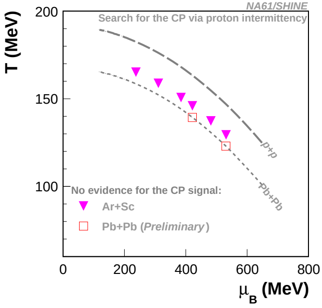
- **Model simulations** indicate that a $\sim$ **10× increase** in event statistics for **SHINE** could detect **as weak as a 1%** critical component signal! The **upgraded NA61/SHINE detector** is expected to provide **sufficient data** for this
  – see: [NA61/SHINE, CERN-SPSC-2023-022]

Summary (1) Experimental results

- Overall: **no signal** indicating approach to **critical point** (as of yet?)

- **Final results** on **net-charge fluctuations** in 1% most central Ar+Sc; **hint of non-monotonic signal**, but **large statistical uncertainties**
- **HBT analyses:** Obtained exponents from the Lévy-shaped source fit in Be+Be and Ar+Sc collisions ⟶ **far from the values predicted for the critical point**
- Results on the dependence of **proton scaled factorial moments** of multiplicity distribution on cumulative momentum bin size, analyzed using independent data points show **no indication of a power-law increase**
- **No indication of a power-law increase** in **negatively charged hadron factorial moments** in Xe+La ($\sqrt{s_{NN}}$ = 16.8 GeV) when **cumulative p_T bins** are used
- Our **hope** could reside in **better methods** ⇒ see **next slide!**

Status of NA61/SHINE CP search via proton intermittency



Points indicate analyzed reactions with no evidence for CP. They are placed at T - μ_B values calculated based on Becattini, Manninen, Gazdzicki, PRC 73 (2006) 044905

Summary (2) Progress on intermittency methodology

- **Intermittency analysis:** the long-standing **bin-by-bin correlation problem** now **effectively solved**; the **Principal Component Analysis (PCA)** allows a **direct handling** of **factorial moment bin correlations**, using **the full event statistics** [Davis, PLB 868 (2025) 139697]

- Other Collaborations pursuing intermittency analyses **(STAR, ALICE, CBM)** could **benefit** from utilizing **PCA** for model parameter estimation, instead of traditional methods

- A $\sim$ **10× increase** in event statistics for **SHINE** could detect **as weak as a 1%** critical component signal. The **upgraded NA61/SHINE detector** is expected to provide **sufficient data**

Thank You!

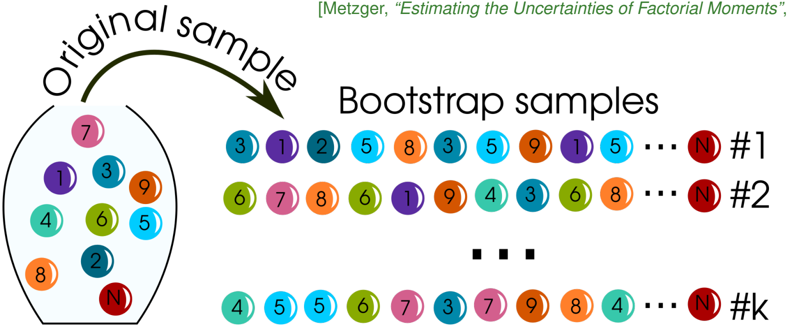
Backup Slides

Backup Slides Outline

Intermittency analysis tools: the bootstrap

- Random **sampling** of events, **with replacement**, from the original set of events
- *k* bootstrap samples ($k \sim 1000$) of the **same number of events** as the original sample
- Each **statistic** ($\Delta F_2(M)$, ϕ_2) **calculated for bootstrap** samples as for the **original** [Efron, *The Annals of Statistics* 7,1 (1979)]
- **Variance of bootstrap values** estimates **standard error** of **statistic**

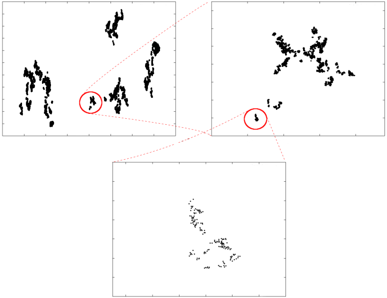
[Metzger, *"Estimating the Uncertainties of Factorial Moments"*, HEN-455 (2004)]



Critical Monte Carlo (CMC) algorithm for baryons

- Simplified version of CMC* code:
  - Only **protons** produced
  - **One cluster** per event, produced by sampling random Lévy walk of **adjustable dimension d_F**, e.g.: $d_F^B = 1/3 \Rightarrow \phi_2 = 1 - d_F^B/2 = 5/6$
  - **Lower / upper bounds** of Lévy walks $p_{\text{min,max}}$ plugged in
  - Cluster center **adjustable** to **experimental set mean proton p_T** per event
  - **Poissonian** proton multiplicity distribution

Lévy walk example



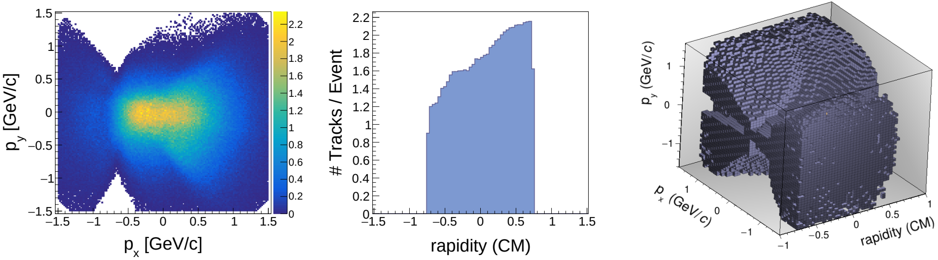
Input parameters (example)

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

*[Antoniou, Diakonos, Kapoyannis and Kousouris, PRL 97, (2006) 032002]

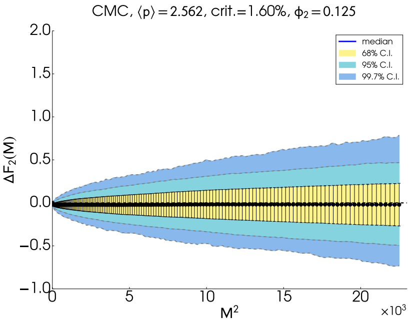
CMC – background simulation & detector effects

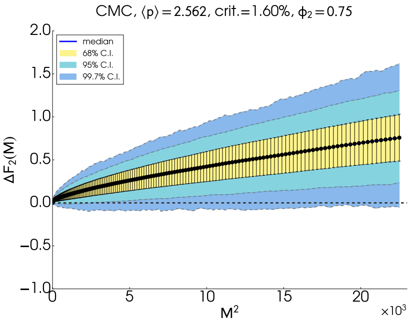
- **Non-critical background** simulation: **replace critical tracks** by **uncorrelated (random) tracks**, with **fixed probability:** $\mathcal{P}_{track} = 1 - \mathcal{P}_{crit}$, where $\mathcal{P}_{crit}$ is the **percentage** of **critical component**
- p_T **distribution** of background tracks **plugged in** to **match experimental data**
- y_{CM} **rapidity value** generated **orthogonal** to p_T, matching **experimental distribution**
- p_T, y_{CM}, **quality & acceptance cuts** applied, same as in **NA61/SHINE data**



CMC scan $\Delta F_2(M)$ – examples

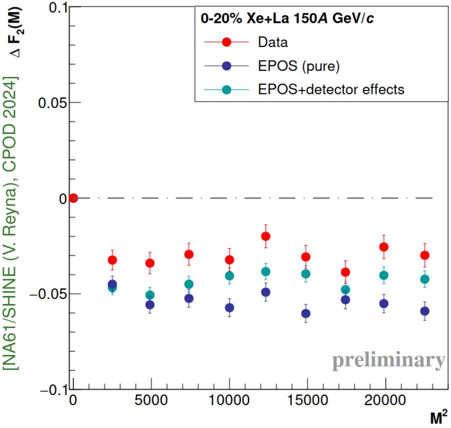
- Results shown for **CMC $\Delta F_2(M)$**, with **$\langle p \rangle = 2.562$**, corresponding to **NA61/SHINE Ar+Sc at 150A GeV/c, cent.10-20%**
- **2 settings**:
  1. **$\phi_2 = 0.125$, crit.% = 1.60%**
  2. **$\phi_2 = 0.750$, crit.% = 1.60%**
- For each setting, **~ 8K independent samples** of **~ 400K events** are generated; event statistics selected to **match NA61/SHINE data**





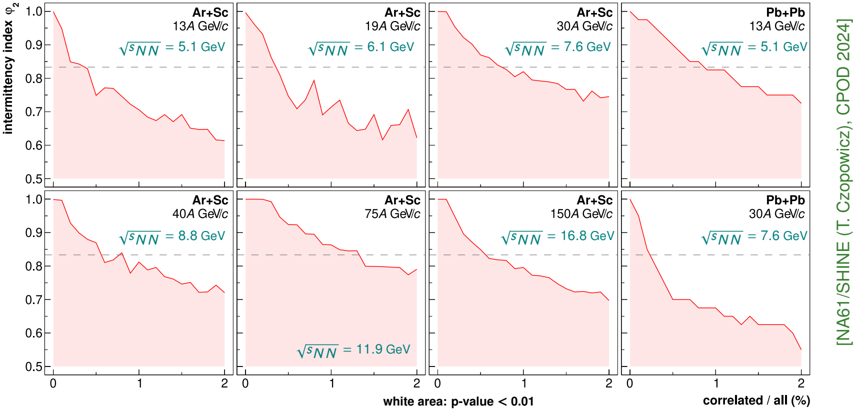
SHINE Xe + La negatively charged hadrons intermittency

- Intermittency analysis performed on **negatively charged hadrons (h^-)** in **SHINE Xe + La collisions at 150A GeV/c**; motivated by **corresponding STAR analysis** [STAR, PLB 845 (2023) 138165]



- Results after **cumulative transform** and **short-range correlation Δp_T** cut ($\Delta p_T < 100\,\text{MeV}/c$ **removed**) **do not show any signal** indicating the **critical point**
- Could the results of **STAR** (reported **increase of ΔF_2** with M) also be interpreted as due to **short-range correlations**?

Independent bin proton intermittency – exclusion plots



Exclusion plots for parameters of simple power-law model:

- power-law exponent ϕ in $|\Delta\vec{p}_T|$ correlation function $\rho\left(|\Delta\vec{p}_T|\right) = |\Delta\vec{p}_T|^{-\phi}$, $\varphi_2 = (\phi + 1)/2$
- fraction of correlated particles

Expected intermittency index: $\varphi_2 = 5/6$ (3D Ising universality class)