Overview of experimental critical point search

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Strangeness in Quark Matter
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Experimental search for the critical point at SQM 2019

- Dmytro Oliinychenko, *Snowballs from hell: light nuclei production in HI collisions*
- Mesut Arslandok, *Higher moments of net-particle fluctuations in Pb-Pb collisions from ALICE*
- Sukanya Sombun, *Higher order net-proton number cumulants dependence on the centrality definition and other spurious effects*
- Ashish Pandav, *Measurement of higher moments of net particle distributions in Au+Au collisions at* $\sqrt{s_{NN}} = 54.4$ *GeV at RHIC*
- Rene Bellwied, *Fluctuations of net* Λ *distributions in Au+Au collisions measured as a function of collision energy with the STAR detector at RHIC*
- Alice Ohlson, *Correlations and fluctuations*

Outline

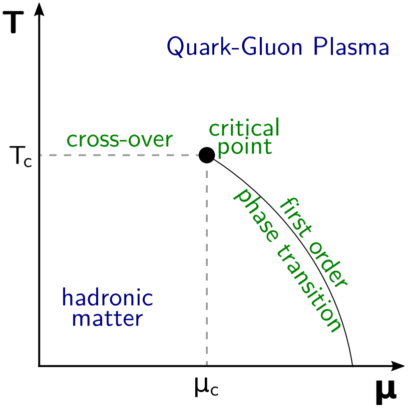
1. **Critical point search strategies**
2. **Biasing effects**
3. **Experimental measures**
4. **Experimental results**
5. **Summary**

❶ Critical point search strategies

- Critical point of QGP
- Exploring the phase diagram with heavy-ion collisions

Critical point of QGP

Critical point search strategies



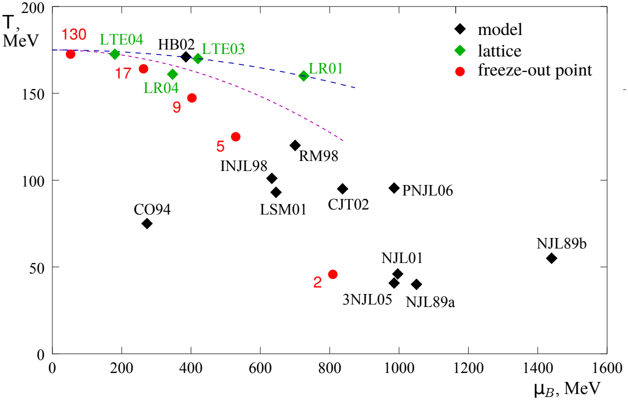
Critical point (CP) – a hypothetical end point of first order phase transition line (QGP-HM) that has properties of second order phase transition.

2nd order phase transition $\longrightarrow$ scale invariance $\longrightarrow$ power-law form of correlation function.
These expectations are for fluctuations and correlations in the configuration space which are expected to be projected to the momentum space via quantum statistics and/or collective flow.

Asakawa, Yazaki NPA 504 (1989) 668
Barducci, Casalbuoni, De Curtis, Gatto, Pettini, PLB 231 (1989) 463

Critical point of QGP

Critical point search strategies



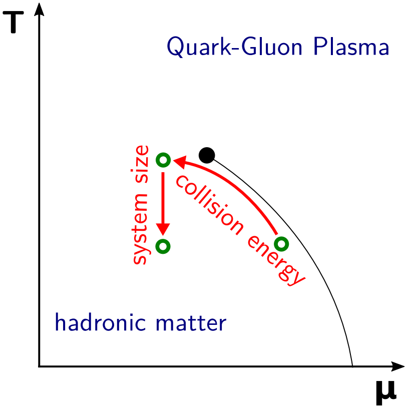
The main signal of the CP is anomaly in fluctuations in a narrow domain of the phase diagram.

However predictions on the CP existence, its location and what and how should fluctuate are model-dependent.

Stephanov, PoS LAT2006 (2006) 024

Exploring the phase diagram with heavy-ion collisions

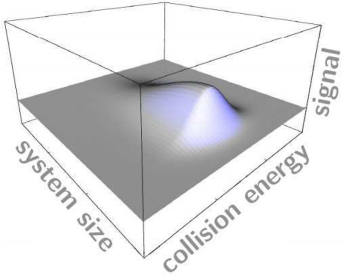
Critical point search strategies



Search for the critical end point in heavy-ion collisions is performed by a scan in the parameters controlled in laboratory (collision energy and nuclear mass number, centrality).

By changing them, we change freeze-out conditions (T, μ_B).

The experimental search for the critical point requires a two-dimensional scan in collision energy and size of the colliding nuclei (centrality).



Biasing effects (and how to minimize them)

Physics:

- volume fluctuations

  fix: select central events, use strongly intensive quantities
- conservation laws

  fix: limit acceptance, use non-conserved quantities
- formation and decay of resonances

  fix: use quantities weakly influenced by resonance decays as suggested by models

Measurement:

- detector efficiency should be large to avoid model-dependent corrections
- incomplete particle identification

  fix: use Identity or PSET identification methods
- limited acceptance makes it difficult to compare different results

Kitazawa, PRC 93 (2016) 044911
Gorenstein, PRC 84 (2011) 024902
Bzdak, Koch, PRC 86 (2012) 044904
Bzdak, Koch, PRC 91 (2015) 027901
Rustamov, Gorenstein, PRC 86 (2012) 044906
Nonaka, Kitazawa, Esumi, PRC 95 (2017) 064912
Gazdzicki, Gorenstein, Mackowiak-Pawlowska, Rustamov, arXiv:1903.08103

Extensive quantities

Experimental measures

A quantity proportional to W (WNM) or V in (IB-GCE) is called an extensive quantity. The most popular are particle number (multiplicity) distribution P(N) cumulants:

- $\kappa_1 = \langle N \rangle$
- $\kappa_2 = \left\langle (\delta N)^2 \right\rangle = \sigma^2$
- $\kappa_3 = \left\langle (\delta N)^3 \right\rangle = S\sigma^3$
- $\kappa_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N)^2 \right\rangle^2 = \kappa\sigma^4$

These multiplicity cumulants characterize the shape of multiplicity distribution and quantify fluctuations.

WNM – Wounded Nucleon Model ($\langle N_{A+B} \rangle = \langle W_{A+B} \rangle / 2 \cdot \langle N_{N+N} \rangle$)

IB-GCE – Ideal Boltzmann Grand Canonical Ensamble

Bialas, Bleszynski Czyz, NPB 111 461 (1976)

Intensive quantities

Experimental measures

Ratio of any two extensive quantities is independent of W (WNM) or V (IB-GCE). It is an intensive quantity.
For example:

$$\langle A\rangle / \langle B\rangle = W \cdot \langle a\rangle / W \cdot \langle b\rangle = \langle a\rangle / \langle b\rangle$$

where A and B are any extensive event quantities, i.e. $\langle \mathrm{A}\rangle \sim \mathrm{W}$, $\langle \mathrm{B}\rangle \sim \mathrm{W}$ and $\langle \mathrm{a}\rangle = \langle \mathrm{A}\rangle$ and $\langle \mathrm{b}\rangle = \langle \mathrm{B}\rangle$ for $\mathrm{W} = 1$.

Popular examples:

- $\frac{\kappa_2}{\kappa_1} = \omega[\mathrm{N}] = \frac{\sigma^2[\mathrm{N}]}{\langle \mathrm{N}\rangle} = \frac{\mathrm{W} \cdot \sigma^2[\mathrm{n}]}{\mathrm{W} \cdot \langle \mathrm{n}\rangle} = \omega[\mathrm{n}]$ (scaled variance)
- $\frac{\kappa_3}{\kappa_2} = \mathrm{S}\sigma$
- $\frac{\kappa_4}{\kappa_2} = \kappa\sigma^2$

Strongly intensive quantities

Experimental measures

For an event sample with varying W, cumulants are not extensive quantities any more. For example:

$$\kappa_2 = \sigma^2[N] = \sigma^2[n]\langle W\rangle + \langle n\rangle^2\sigma^2[W]$$

But having two extensive event quantities, one can construct quantities that are independent of P(W)!

Popular examples:

- $\langle K\rangle / \langle \pi\rangle$
- $\Delta[N, P_T] = \frac{1}{C}(\omega[N]\langle P_T\rangle - \omega[P_T]\langle N\rangle)$
- $\Sigma[N, P_T] = \frac{1}{C}(\omega[N]\langle P_T\rangle + \omega[B]\langle N\rangle - 2(\langle NP_T\rangle - \langle P_T\rangle\langle N\rangle)$

where $P_T = \sum_{i=1}^{N} p_{T,i}$ and C is any extensive quantity (e.g.$\langle N\rangle$).

Gazdzicki, Gorenstein, PRC 84 (2011) 014904
Gazdzicki, Gorenstein, Mackowiak-Pawlowska, PRC 88 (2013) 024907

Short-range correlations

Experimental measures

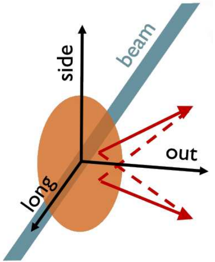
Quantum statistics leads to short-range correlations in momentum space, which are sensitive to particle correlations in configuration space (e.g. of CP origin).

Popular measure:
Momentum difference in LCMS, $\mathbf{q}$, is decomposed into three components:
q_{long} – momentum difference along the beam
q_{out} – parallel to the pair transverse momentum vector $\mathbf{k}_t = (\mathbf{p}_{T,1} + \mathbf{p}_{T,2})/2$
q_{side} – perpendicular to q_{out} and q_{long}

The two-particle correlation function C is often approximated by a three-dimensional Gauss function:

$$C(\mathbf{q}) \cong 1 + \lambda \cdot exp\left(-R^2_{long} q^2_{long} - R^2_{out} q^2_{out} - R^2_{side} q^2_{side}\right)$$

where λ describes the correlation strength and $R_{out}, R_{side}, R_{long}$ denote Gaussian HBT radii.



Short-range correlations

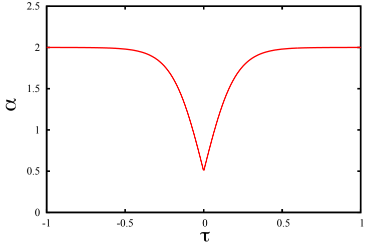
Experimental measures

A more general idea – Lévy-shaped source (1-D):

$$C(q) \cong 1 + \lambda \cdot e^{(-qR)^{\alpha}}$$

where $q = |p_1 - p_2|_{LCMS}$, λ describes correlation length, R determines the length of homogenity and Lévy exponent α determines source shape:

- $\alpha = 2$
  Gaussian, predicted from simple hydro
- $\alpha < 2$
  anomalous diffusion, generalized central limit theorem
- $\alpha = 0.5$
  conjectured value at the critical point



Csorgo, Hegyi, Novak, Zajc, AIP Conf.Proc. 828 (2006) 525

Fluctuations as a function of momentum bin size

Experimental measures

Momentum space is partitioned into M bins.
Second factorial moment is calculated as a function of cell size (number of cells, M):

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

At the second order phase transition the system is a simple fractal and the factorial moment exhibits a power law dependence on M:

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

Prediction for critical point: $\varphi_2 = 5/6$.

Wosiek, APPB 19 (1988) 863
Bialas, Hwa, PLB 253 (1991) 436
Bialas, Peschanski, NPB 273 (1986) 703
Antoniou, Diakonos, Kapoyannis, Kousouris, PRL 97 (2006) 032002

Fluctuations as a function of momentum bin size

Experimental measures

However, to cancel the $F_2(M)$ dependence on the single particle inclusive momentum distribution, one needs a uniform distribution of particles in bins. One can either subtract $F_2(M)$ for mixed events:

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

or use cumulative quantities, e.g.

$$Q_x = \int_{x_{min}}^{x} \rho(x)\mathrm{d}x \Big/ \int_{x_{min}}^{x_{max}} \rho(x)\mathrm{d}x$$

Bialas, Gazdzicki, PLB 252 (1990) 483

Light nuclei production

Experimental measures

Based on coalescence model, particle ratios of light nuclei are sensitive to the nucleon density fluctuations at kinetic freeze-out and thus to CP.
In the vicinity of the critical point or the first order phase transition, density fluctuation becomes larger.

Neutron density fluctuation can be expressed by proton, triton and deuteron yields:

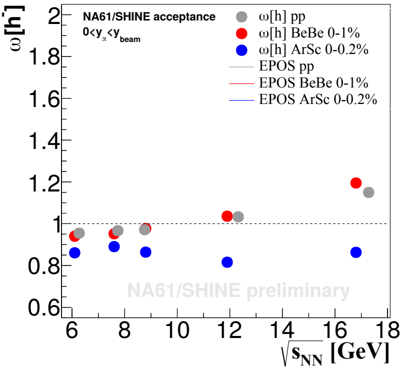
$$\Delta n = \frac{\left\langle (\delta n)^2 \right\rangle}{\langle n \rangle} \approx \frac{1}{2\sqrt{3}} \frac{N_p \cdot N_t}{N_d^2} - 1$$

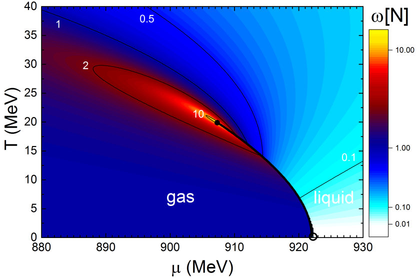
Sun, Chen, Ko, Xu, PLB 774 (2017) 103
Shuryak, Torres-Rincon, NPA 982 (2019) 831

1. Critical point search strategies
2. Biasing effects
3. Experimental measures
4. **Experimental results**
    - Fluctuations in large momentum bins
        - Multiplicity fluctuations
        - Multiplicity-transverse momentum fluctuations
        - Net-proton fluctuations
        - Net-kaon and net-charge fluctuations
    - Short-range correlations
    - Fluctuations as a function of momentum bin size
    - Light nuclei production
5. Summary

Multiplicity fluctuations

Experimental results: Fluctuations in large momentum bins



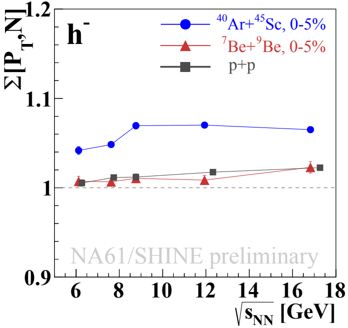


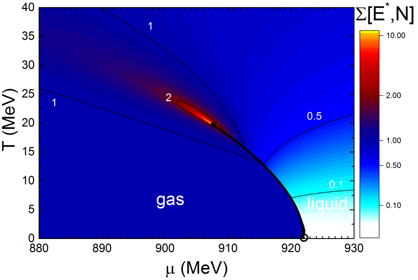
No prominent structures that could be related to the critical point are observed so far...

NA61/SHINE: PoS CPOD2017 (2018) 012
Vovchenko, Anchishkin, Gorenstein, Poberezhnyuk, Stoecker, Acta Phys.Polon.Supp. 10 (2017) 753

Multiplicity-transverse momentum fluctuations

Experimental results: Fluctuations in large momentum bins



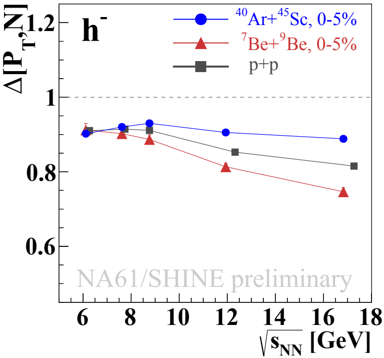


No prominent structures that could be related to the critical point are observed so far...

NA61/SHINE: Acta Phys.Polon.Supp. 10 (2017) 449
Vovchenko, Anchishkin, Gorenstein, Poberezhnyuk, Stoecker, Acta Phys.Polon.Supp. 10 (2017) 753

Multiplicity-transverse momentum fluctuations

Experimental results: Fluctuations in large momentum bins



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NA61/SHINE: Acta Phys.Polon.Supp. 10 (2017) 449

Multiplicity-transverse momentum fluctuations

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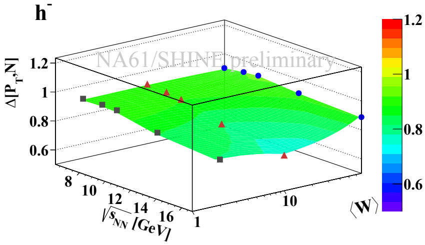
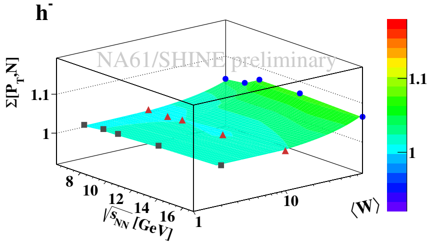


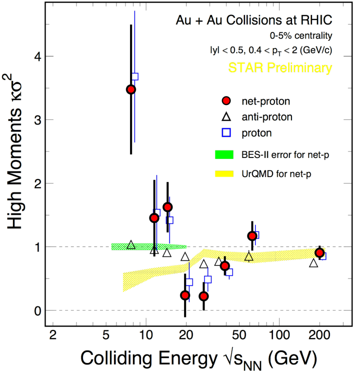


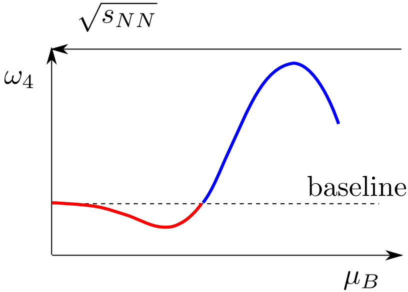
No prominent structures that could be related to the critical point are observed so far...

NA61/SHINE: Acta Phys.Polon.Supp. 10 (2017) 449

Net-proton fluctuations

Experimental results: Fluctuations in large momentum bins



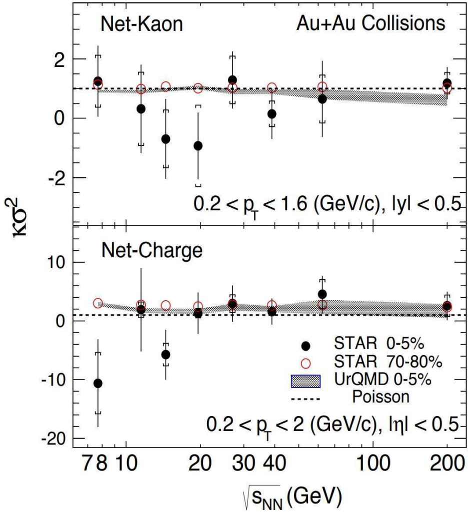


Observation of non-monotonic energy dependence of fourth order net-proton fluctuation.

STAR: PRL 112 (2014) 032302
Stephanov, PRL 107, 052301

Net-kaon and net-charge fluctuations

Experimental results: Fluctuations in large momentum bins



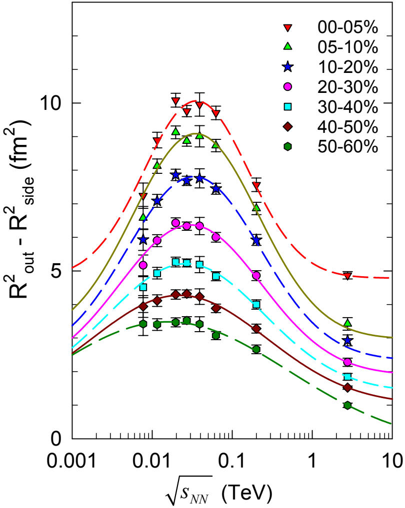
Within errors, the results on net-kaon and net-charge show flat energy dependence.

No prominent structures that could be related to the critical point are observed so far...

STAR: PLB 785 (2018) 551
PRL 113 (2014) 092301

Short-range correlations

Experimental results



Data taken from:
STAR: Phys. Rev. C 92, 014904 (2015)
ALICE: Phys.Lett. B696 (2011) 328

Clear non-monotonic energy dependence in Au+Au/Pb+Pb

Lacey, PRL 114 (2015) 142301

Short-range correlations

Experimental results

Finite size scaling analysis

$L = \overline{R}$

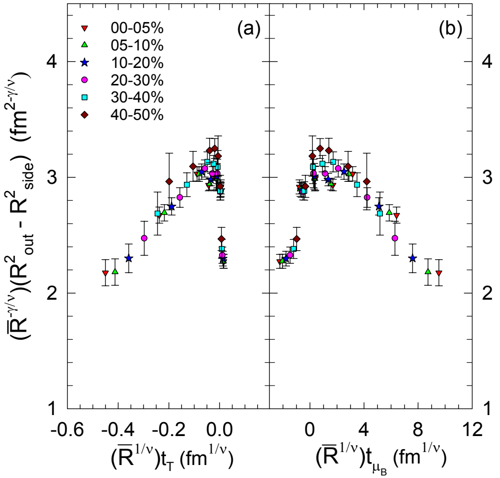
$1/\overline{R} = \sqrt{(1/\sigma_x)^2 + (1/\sigma_y)^2}$

σ_x, σ_y - widths of source

$t_T = \frac{T - T_C}{T_C}$

$t_{\mu_B} = \frac{\mu - \mu_C}{\mu_C}$

CP in Au+Au at $\sqrt{s_{NN}} = 47.5$ GeV
$T_C = 165$ MeV
$\mu_C = 95$ MeV

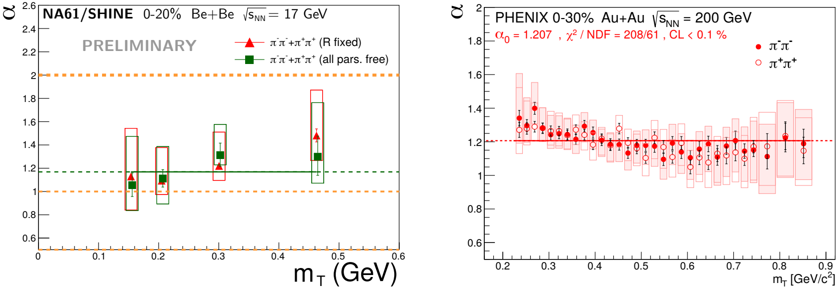


Lacey, PRL 114 (2015) 142301

Short-range correlations

Experimental results

Transverse mass dependence of Lévy exponent α



α(Be+Be at 17 GeV) $\approx$ α(Au+Au at 200 GeV) $\approx$ 1.2

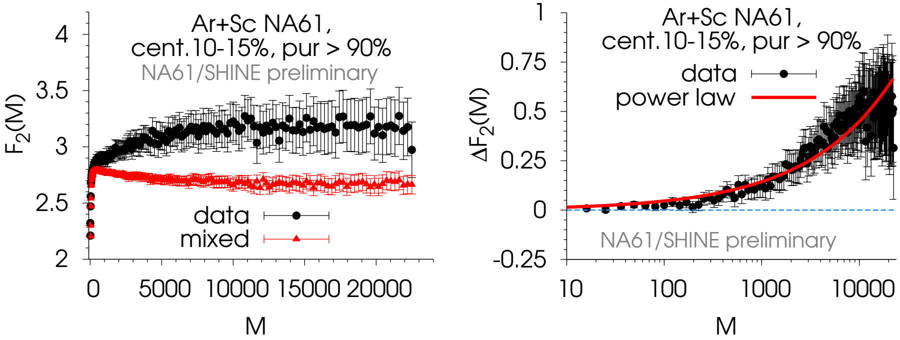
No indication of the critical point so far...

NA61/SHINE: Porfy, WPCF2019
PHENIX: PRC 97, 064911 (2018)

Fluctuations as a function of momentum bin size

Experimental results

Mid-rapidity protons at 17 GeV



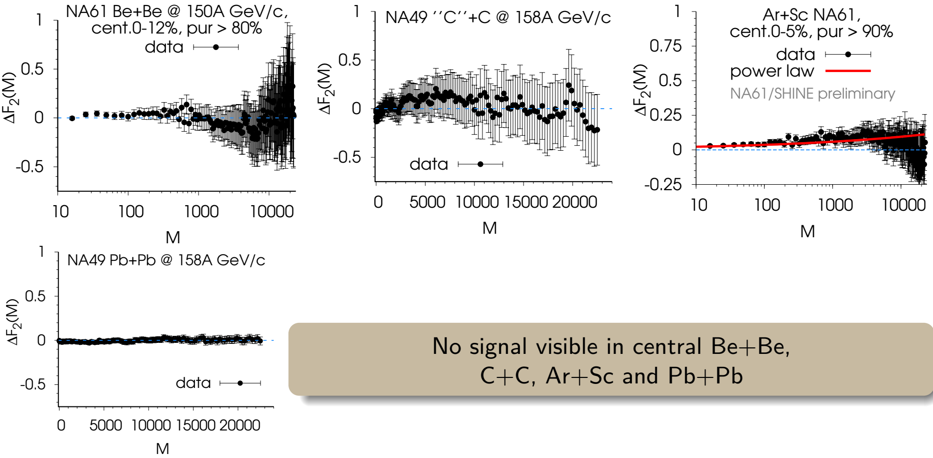
Note that points are strongly correlated.

NA61/SHINE: PoS(CPOD2017) 054

Fluctuations as a function of momentum bin size

Experimental results

ΔF_2 for mid-rapidity protons at 17 GeV



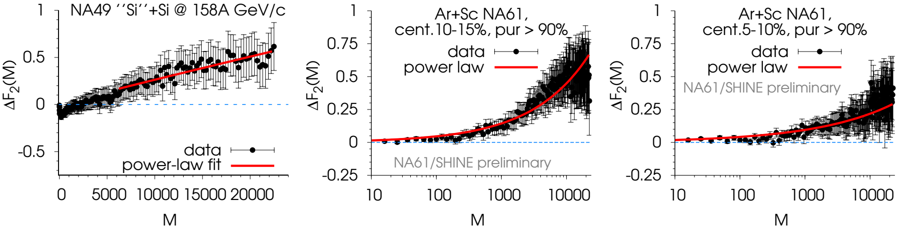
No signal visible in central Be+Be, C+C, Ar+Sc and Pb+Pb

NA49: EPJC 75 (2015) 587
NA61/SHINE: PoS(CPOD2017) 054

Fluctuations as a function of momentum bin size

Experimental results

ΔF_2 for mid-rapidity protons at 17 GeV

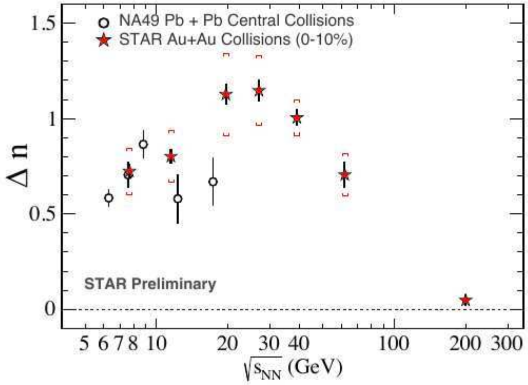


A deviation of ΔF_2 from zero seems apparent in central Si+Si and mid-central Ar+Sc

NA49: EPJC 75 (2015) 587
NA61/SHINE: PoS(CPOD2017) 054

Light nuclei production

Experimental results



$$\Delta n \approx \frac{1}{2\sqrt{3}} \frac{N_p \cdot N_t}{N_d^2} - 1$$

Data taken from:
NA49: PRC 94, 044906 (2016)
STAR: PRL 121, 032301 (2018)
NPA 967, 788

Δn shows a non-monotonic behavior on collision energy with a peak $\sqrt{s_{NN}} \approx 20$ GeV

STAR: Zhang, QM2018

Summary

4^{th} moment of net-proton dist.: $\approx$ 7 GeV (Au+Au)

Proton intermittency: $\approx$ 17 GeV (Si+Si and Ar+Sc)

Light ion production: $\approx$ 20 GeV (Au+Au)

Pion interferometry: $\approx$ 47 GeV (Au+Au)

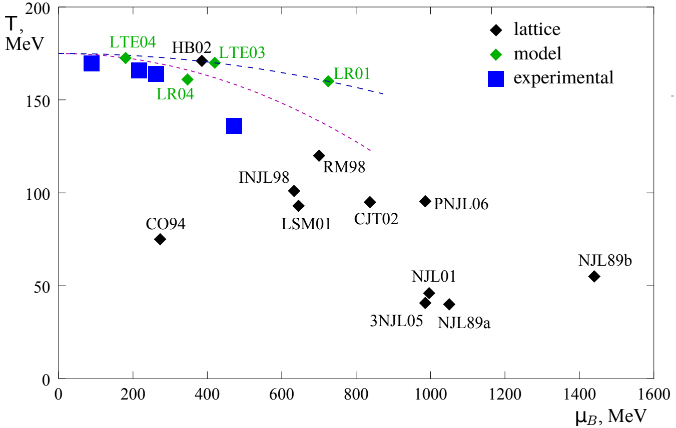
Summary

4th moment of net-proton dist.: ≈ 7 GeV (Au+Au)

Proton intermittency: ≈ 17 GeV (Si+Si and Ar+Sc)

Light ion production: ≈ 20 GeV (Au+Au)

Pion interferometry: ≈ 47 GeV (Au+Au)



Summary

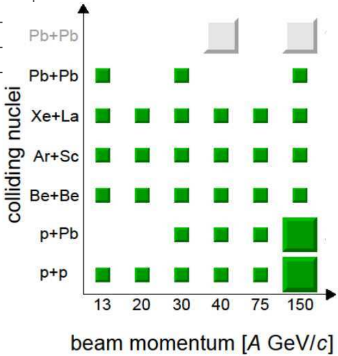
4^{th} moment of net-proton dist.: ≈ 7 GeV (Au+Au)

Proton intermittency: ≈ 17 GeV (Si+Si and Ar+Sc)

Light ion production: ≈ 20 GeV (Au+Au)

Pion interferometry: ≈ 47 GeV (Au+Au)

$\sqrt{s}$ (GeV)	Statistics(Millions) – BES-I	Statistics(Millions) – BES-II
7.7	~4	**~100**
9.1	-	**~160**
11.5	~12	**~230**
14.5	~ 20	**~300**
19.6	~36	**~400**
27	~70	**~500**



New, high-quality data is coming soon...

Thank You!

Additional slides

Limiting volume fluctuations with event selection

Additional slides

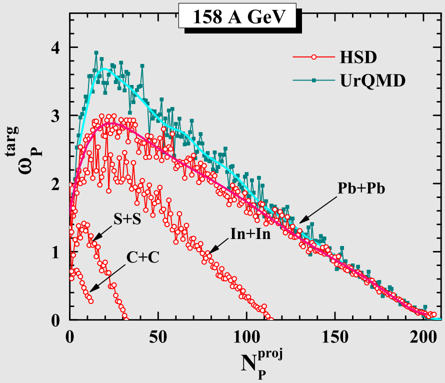
- In collider experiments' measurements of 'target' and 'projectile' spectators is possible under the same experimental conditions, but only free nucleon spectators can be measured. Fragments are lost in the beam pipe.
- In fixed-target experiments, all 'projectile' spectators can be measured but 'target' spectators are absorbed in the target material – can't be measured.

Possible strategy for fixed-target experiment:

- collisions of equal size nuclei
- select events with no projectile spectators

Limiting volume fluctuations with event selection

Additional slides



In symmetrical system, selecting events, in which all nucleons took part in the collisions ($N_P^{proj} = A$) reduces almost to zero target participants fluctuations (ω_P^{targ}).

Konchakovski, Lungwitz, Gorenstein, Bratkovskaya, PRC 78 (2008) 024906

Strongly intensive quantities

Additional slides

$$\left.\begin{array}{l}\langle A\rangle = \langle a\rangle \cdot \langle W\rangle \\ \langle B\rangle = \langle b\rangle \cdot \langle W\rangle\end{array}\right\} => \langle A\rangle \, / \, \langle B\rangle = \langle a\rangle \, / \, \langle b\rangle$$

If one subtract two variances:

$$\begin{array}{ll}\mathrm{Var}[A] = \mathrm{Var}[A]\,\langle W\rangle + \langle a\rangle^2\,\mathrm{Var}[W] & | \cdot \langle b\rangle \, / \, \langle a\rangle \\ \mathrm{Var}[B] = \mathrm{Var}[B]\,\langle W\rangle + \langle b\rangle^2\,\mathrm{Var}[W] & | \cdot \langle a\rangle \, / \, \langle b\rangle\end{array}$$

The dependence on Var[W] cancels out:

$$Var[A]\,\langle b\rangle \, / \, \langle a\rangle - Var[B]\,\langle a\rangle \, / \, \langle b\rangle = Var[A]\,\langle W\rangle\,\langle b\rangle \, / \, \langle a\rangle - Var[B]\,\langle W\rangle\,\langle a\rangle \, / \, \langle b\rangle$$

And that gives:

$$\omega[A]\,\langle B\rangle - \omega[B]\,\langle A\rangle = \langle W\rangle\,(\omega[a]\,\langle b\rangle - \omega[b]\,\langle a\rangle)$$

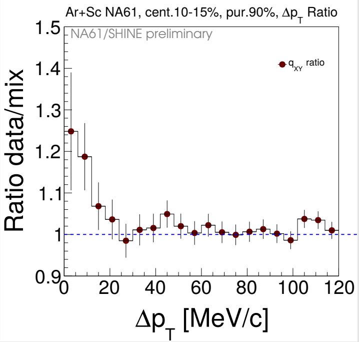
If one used covariance of A and B:

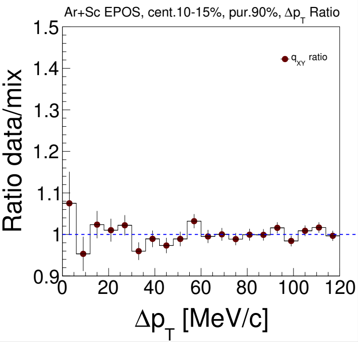
$$\omega[A]\,\langle B\rangle + \omega[B]\,\langle A\rangle - 2cov[A, B] = \langle W\rangle\,(\omega[a]\,\langle b\rangle + \omega[b]\,\langle a\rangle - 2cov[a, b])$$

Intermittency

Additional slides

Distributions of Δp_T for protons selected for intermittency analysis from Ar+Sc collisions at 150A GeV/c.





Strong correlations in $\Delta p_T \to 0$ in NA61/SHINE data may indicate intermittent behavior.

NA61/SHINE: PoS(CPOD2017) 054