

Holmganga: CLASH Workshop 2023

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Correlation/Fluctuation techniques are the main tools for:

- Studying the nature of phase transition
- Probing the QCD critical point.

ALI-PREL-495743

- ALI-PREL-495747
- Scaled V_{dyn} [+,-] shows increasing correlations with increasing multiplicity for all systems,
- net-charge fluctuations are strongly dominated by resonance contributions.

Lattice QCD meets experiment tor or the electrical charged charged

Thermodynamic susceptibilities (response of a thermalized system 1.2 to changes in external conditions): **conserved charge fluctuations** carriers of charm quantum numbers at low and high temperatures at low and high temperatures as well a

• Lattice QCD calculations: Taylor expansion of the QCD pressure: $\begin{bmatrix} 0.8 \end{bmatrix}$ l**ations.** Taylor expar

 \overline{a} and the intervals with electric charge are \overline{a} **HRG vs. QCD** Deviations from the Baseline: Jaryon-namker fluctuations

Zing
አæ∎ P. Braun-Munzinger, A. Rustamov, J. Stachel

Cumulants Higher orders <u>Nucturations</u> in OCD shueve e Nuck **Cumulants** er fluctuations in QCD always smaller than in PIRG for –130 –130

. (2)

0

 χ_4^B/χ_2^B

 $T_{\text{pc}} = 156.5(1.5) \text{ MeV}$

140

cont. extr. \blacksquare

150

150

160

170

 $\mu_B=0$ $0.69(3)$ $0.50(2)$

T [MeV]

HotQCD preliminary

190

180

170

160

HRG

 \overline{a}

<u>ia</u>

Net-proton fluctuations at LHC energies

ALICE collaboration, arXiv: 2206.03343

• 3rd order: data agree with Skellam baseline "0"

- **due to Baryon number conservation.**
- long-range correlations (Δη about ±2.5) originating from earlier in time.

Lattice meets experiment: fluctuation of conserved quantities

Probing the QCD Critical Point

Moments of Net-proton STAR: PRL 130, 82301 (2023)

What other observables can be used to get a better handle on the locaton of the critical point?

- Net-proton kurtosis ratio shows non-monotonic behavior as a function of collision energy.
- At 3 GeV, the fluctuations are driven by baryon number conservation (matter hadron dominated).
- Higher order moments can pin-point the nature of phase transition (cross-over).

<u>Isothermal compressibility Equation of State and Heat capacity</u>

\mathbf{r} is in in \mathbf{r} in \mathbf{r} in \mathbf{r} distribution of \mathbf{Q} distributions. **Equation of State**

a advantage by statistical fluctuations, which is a statistical fluctuations, which is a statistical fluctuatio $\frac{1}{\tau}$ 11 aat aartaa b 11 neal capacity results to the set of \sim

 \mathcal{L} top 10% central collisions are tabulated in \mathcal{L} T_{eff}
 T_{eff} \sqrt{AF} t eff the fluctuation of the fluctuation. The fluctuation of the width ℓ the width ℓ • S. Mrowczynski, Phys. Lett. B 430 (1998) 9 ^h*T*i²]*,* (3) $\sqrt{2}$ $\left(\frac{\partial E}{\partial T}\right)$ → Data
→ Mixed Event $C = \frac{\partial E}{\partial T}$ • M. Mukherjee, S. Basu, TN et al. PLB 784 (2018) 1-5 $\bigcap_{-1.0 \le n \le 1.0}^{\oplus \text{ Mixed Event}}$ 10^3 ' • A. Khuntia, R. Sahoo, TN et al. PRC 100 (2019) 014910 $-1.0 < \eta < 1.0$ $10²$ ∂*T* $\vert \cdot \cdot \cdot \vert \cdot \cdot \cdot \cdot \cdot \vert$ \setminus $\overline{}$ $10²$ *v***2** \sqrt{a} $\frac{1}{2}$ hTimes in temperature. This yields the variance in temperature. This yields the variance in temperature. The variance in temperature in temperature. The variance in temperature in temperature. The variance in te ² + (*Tstat* TABLE II: The event-by-event-by-event ^{Te}य distributions for central text of central text of central text of cen-20 GeV (*T*e↵) e
Le ¹²⁸ expression for *C*^v [2–4, 7, 25]:: $k_T = -\frac{1}{V}$ $\overline{1}$ $\left(\frac{\partial V}{\partial P}\right)$ ∂*V* $k_B T \langle N_{ch} \rangle_L$ $\left| \begin{array}{ccc} 1 & 1 & 1 \end{array} \right|$ *T dyn* $\begin{bmatrix}w_{\text{ch}} & - & V & \sqrt{1} & 0 \end{bmatrix}$ 10⁴ and **along** $\begin{bmatrix}w_{\text{ch}} & -w_{\text{ch}} & 0 \end{bmatrix}$ $=\frac{(\langle T^2 \rangle - \langle T \rangle^2)}{\langle T \rangle^2}$ e values are $\frac{1}{C} = \frac{(\langle T^2 \rangle - \langle T \rangle^2)}{\langle T \rangle^2}.$ *V* \setminus ∂*P* $\frac{\sqrt{1-\sqrt{2}}}{\sqrt{1-\sqrt{2}}}$. *T* with mean (¹⁰) and standard deviation (). The standard deviation (). The standard deviation (). The standard deviation (). The standard deviation () is a standard deviation (). The standard deviation (). The standard dev C_v $10²$ $\begin{array}{cc} \mathbf{C}_v & \langle I \rangle^2 \end{array}$ $\begin{array}{r} \text{SPS, RHIC data, UrQMD, EPOS & HRG \end{array}$ $\begin{array}{r} \begin{array}{c} \text{10}^2 \text{F} \\ \text{F} \end{array} \begin{array}{r} \text{62.4 GeV} \\ \text{N} \end{array}$ Counts $10²$ $\frac{1}{k}$ b2.4 GeV, $\frac{1}{k}$ ¹²⁹ Heat capacity thus can be estimated from the fluc-(GeV) (GeV) (GeV) (GeV) $\frac{1}{2}$ ture in energy or temperature. For a system in equation in equation (10⁴ $\begin{array}{c}\n\overline{}\Gamma$ (Data)
 Γ (Mixed) $\frac{1}{C} = \frac{(\Delta T_{\text{eff}}^{dyn})^2}{\langle T_{\text{kin}}\rangle^2}.$ 50 Experimental data $\begin{array}{ccc} 3 & 3.5566 \end{array}$
 $\begin{array}{ccc} 2 & 3.5666 \end{array}$ $\begin{array}{ccc} 2 & 3.5666 \end{array}$ $\frac{1}{C}$ 10^3 $\frac{1}{2}$ later by an equation of state of state $\frac{1}{2}$ and $\frac{$ $\frac{1}{\langle T_{\rm kin} \rangle^2}$. $\begin{bmatrix} \text{CC} \\ \text{EPOS} \end{bmatrix}$ 40 $\frac{1}{3}$ times in $C = \langle T_{\text{lim}} \rangle^2$ in $10²$ $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ and $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ and $\begin{bmatrix} 1 & 130 & \text{GeV} \\ 1 & 130 & \text{GeV} \end{bmatrix}$ ALICE: Eur. Phys. J. C (2021) 81:1012 ¹³⁴ behaviour. Energy being an extensive quantity, its k_T (fm³/GeV) $10 \leq$ 30 $\frac{1}{25}$ fluctuation has a component arising from the volume $\frac{1}{25}$ $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ \uparrow \up The heat capacity is capacity of the heat capacity of the heat capacity is calculated from equation of the second sec $2500 (a)$ \blacksquare 10^{4} 10^{3} 10^{2} 10^{3 **ALICE Role of radial flow fluctuation** 20 2000 Pb-Pb $\sqrt{s_{_{NN}}}$ = 2.76 TeV $\mathbf{Q} = \mathbf{I}$ Role of radial flow fluctuations \mathbf{I} 10^3 $\langle N_{_{\rm ch}} \rangle$ $0.2 < p < 2.0$ GeV/c 130 mixed 10⁰ mixed 10⁰ 1500 **1 in temperature fluctuation** 10^2 $|n|$ < 0.8 10 1000 $\frac{1}{3}$ as heat capacity per number of particles $\frac{1}{2}$ ²⁰⁰ data 1078.23 2.483⇥10⁴ 0.2677 0.00815 10 dividing *C* by number of charged particles in the system of charged particles in 500 0 $\frac{1}{10}$ $\frac{1}{100}$ $\frac{1}{$ T_{eff} (GeV) and T_{eff} and T_{\text 100 $8\frac{2}{\pi}$ **4 a** STAB AULAU O.5% 80 $\sqrt{s_{NN}}$ (GeV) \bullet STAR Au+Au 0-5% $\sigma_{\rm th}$ $7\frac{E}{\left[\frac{1}{2}\right]}$ construction at matter $\frac{1}{2}$ construction $\frac{1}{2}$ 60 7 **A**... HRG 40 ?] to obtain the specific heat. This is presented in HM 6 HM via QGM 20 TABLE II: The event-by-event *T*e↵ distributions for cen- $\frac{1}{2}$ o
 $\frac{1}{2}$ QGM $\bigcup_{i=1}^n \bigotimes_{i=1}^n \$ 5 AMPT ϵ address the non-physical 4 energies. The estimated **C/N** for the estimated **C**/N $\frac{1}{\sqrt{2}}$ **How to address the non-physical** \vec{c} $\frac{1}{2}$ function. The fit parameters that $\frac{1}{2}$ and $\frac{1}{2}$ 3 $\omega_{\rm ch}$ from the AMPT model using Fig. ?? is also shown **fluctuations (background)?** \bullet ALICE 2⊟ O HIJING \mathbf{g} in the figure in the data points are estimated by \mathbf{g} • L. Stodolsky, PRL 75, 1044 (1995)) ^p*s*NN Case ↵ *^µ* • S. Basu, TN et al PRC 94 (2016) 044901 AMPT-SM 1 $\frac{1}{\sqrt{2}}$ mated mate 100 150 200 250 300 350 50 $^{0-}_{10}$ 6 6 $\langle N_{\rm part} \rangle$ (GeV) 10^2 10^3 10^3 $\sqrt{S_{NN}}$ (GeV) $\sqrt{S_{NN}}$

Fluctuations of mean p_T

- $\langle p_{\tau} \rangle$ fluctuations result from fluctuations of the energy of the fluid when the hydrodynamic expansion starts.
- $\langle p_{\tau} \rangle$ is a proxy to the system temperature => measure of **temperature fluctuations** \Rightarrow **heat capacity**.
- Higher order: probes of QCD thermodynamics at higher *T*, achieved during the early stages of the collision.

 $10³$