Anomalous kaon correlations in Pb-Pb collisions at the LHC: melting and refreezing of the QCD vacuum

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$\nu_{\rm dyn}(A,B)$

- $\nu_{\rm dyn}(A,B)$ measures how particles of type A and B are correlated.

- $\nu_{\rm dyn}(A,B) = R_{AA} + R_{BB} - 2R_{AB}$ where

$$R_{AB} = \frac{\langle N_A N_B\rangle - \langle N_A\rangle\langle N_B\rangle - \langle N_A\rangle\delta_{AB}}{\langle N_A\rangle\langle N_B\rangle}$$

- For uncorrelated particles $R_{AA} = R_{BB} = R_{AB} = 0$ and consequently $\nu_{\rm dyn} = 0$.

- If $\nu_{\rm dyn} > 0$ detection of one particle biases the next particle to be of the same type. It is the opposite for $\nu_{\rm dyn} < 0$.

- It is considered a relatively robust observable.

S. Gavin and J. I. Kapusta, Phys. Rev. C **65**, 054910 (2002)

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Neutral to charged kaon yield fluctuations in Pb – Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration *

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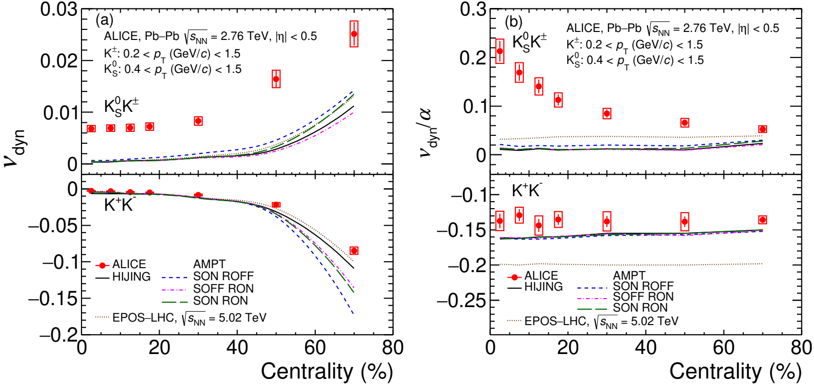
ABSTRACT

We present the first measurement of event-by-event fluctuations in the kaon sector in Pb – Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the LHC. The robust fluctuation correlator ν_{dyn} is used to evaluate the magnitude of fluctuations of the relative yields of neutral and charged kaons, as well as the relative yields of charged kaons, as a function of collision centrality and selected kinematic ranges. While the correlator $\nu_{dyn}[K^+, K^-]$ exhibits a scaling approximately in inverse proportion of the charged particle multiplicity, $\nu_{dyn}[K^0_S, K^\pm]$ features a significant deviation from such scaling. Within uncertainties, the value of $\nu_{dyn}[K^0_S, K^\pm]$ is independent of the selected transverse momentum interval, while it exhibits a pseudorapidity dependence. The results are compared with HIJING, AMPT and EPOS–LHC predictions, and are further discussed in the context of the possible production of disoriented chiral condensates in central Pb – Pb collisions.

While the correlator $\nu_{\rm dyn}(K^+, K^-)$ exhibits a scaling approximately in inverse proportion of the charged particle multiplicity, $\nu_{\rm dyn}(K^0_S, K^\pm)$ features a significant deviation from such scaling.

Models cannot reproduce the neutral-charged correlations



$$\alpha \equiv \frac{1}{N_{K^0_S}} + \frac{1}{N_{K^\pm}} \approx \frac{6}{N_K^{tot}}$$

Isospin fluctuations from condensates

• Suppose we have multiple domains of condensates which give rise to flat neutral kaon fractions $P(f) = 1$. This is the case for DCC with three flavors J. Schaffner-Bielich and J. Randrup, Phys. Rev. C **59**, 3329 (1999) and also for kaons in an electrically neutral degenerate quantum state.

• If the number of domains N_d is greater than 2 or 3 then

$$\nu_{\rm dyn} = 4\beta_K \left(\frac{\beta_K}{3N_d} - \frac{1}{N_K^{tot}} \right)$$

where β_K is the fraction of all kaons that come from condensate domains.

• The relation is derived by folding the distributions of kaons from condensates and thermal/random sources. For multiple condensate sources, $P(f)$ approaches a Gaussian by the Central Limit Theorem.

S. Gavin and J. I. Kapusta, Phys. Rev. C **65**, 054910 (2002)

Isospin fluctuations from condensates

• The fraction β_K can be estimated from the energy of condensation

$$\beta_K = \frac{\epsilon_\zeta V_d}{m_K N_K^{tot}}$$

where ϵ_ζ is the energy density available from condensation and V_d is the sum total volume of all condensates.

• It is reasonable to assume that N_d scales with the total kaon multiplicity N_K^{tot} and V_d scales with N_d and with the lifetime τ_{av} of the fireball

$$\begin{aligned} N_d &= a N_K^{tot} \\ V_d &= v_0 N_K^{tot} \left(\frac{\tau_{av}}{10\tau_0} \right) \end{aligned}$$

• The initial time for hydrodynamic evolution is $\tau_0 = 0.4$ fm/c.

• Putting this together we have

$$\beta_K = b\left(\frac{\tau_{av}}{10\tau_0}\right)$$
$$b = \frac{\epsilon\zeta v_0}{m_K}$$

• This results in a two parameter formula for $\nu_{\rm dyn}/\alpha$

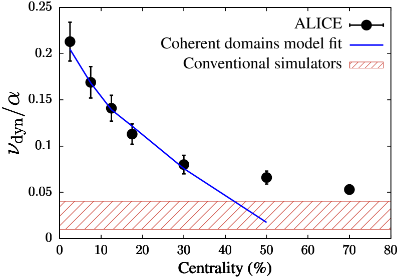
$$\frac{\nu_{\rm dyn}}{\alpha} = \frac{2}{3}b\left(\frac{\tau_{av}}{10\tau_0}\right)\left[\frac{b}{3a}\left(\frac{\tau_{av}}{10\tau_0}\right) - 1\right]$$

• We obtain τ_{av} as a function of centrality from realistic hydrodynamic simulations of heavy-ion collisions using MUSIC with IP Glasma initial conditions.

Fit to the 5 most central bins

$$b = 0.1044 \pm 0.0380$$
$$\frac{b^2}{a} = 0.2187 \pm 0.0458$$

For reference energy density $\epsilon_\zeta = 25$ MeV/fm^3. Only V_d changes with ϵ_ζ.



Centrality	N_d	V_d(fm^3)	β_K
0-5 %	9.32	1120	0.302
5-10 %	7.29	821	0.283
10-15 %	6.02	640	0.267
15-20 %	4.67	476	0.256
20-40 %	2.88	258	0.225
40-60 %	1.20	82	0.172

Average domain size ranges from 86 fm^3 for 20-40% centrality to 120 fm^3 for 0-5% centrality.

Disordered Isospin Condensates

• It is always assumed that $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$. What if their relative magnitudes fluctuated at finite temperature? This means fluctuations between an isosinglet $\langle \bar{u}u \rangle + \langle \bar{d}d \rangle$ and an isotriplet $\langle \bar{u}u \rangle - \langle \bar{d}d \rangle$. The lowest vacuum excitation of the latter is the neutral member of the $a_0(980)$ isotriplet meson.

• If the domain happened to be totally $\langle \bar{u}u \rangle$ then, when it loses energy due to cooling, combination with strange quarks and anti-quarks results in charged kaons. If the domain happened to be totally $\langle \bar{d}d \rangle$ then combination with strange quarks and anti-quarks results in neutral kaons.

• If the distribution in the relative proportion of the two condensates was flat then we essentially recover the previous phenomenology.

• In addition, quarks and anti-quarks are most likely strongly correlated already before chemical freezeout.

The field potential U is expressed in terms of the 3×3 bosonic field matrix M as

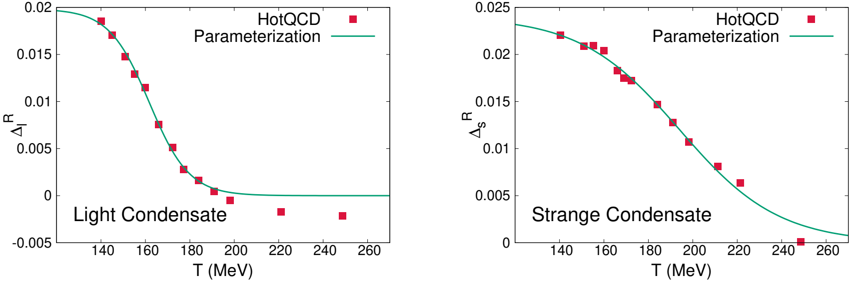
$$\begin{aligned} U(M) &= -\frac{1}{2}\mu^2 \mathrm{Tr}(MM^\dagger) + \lambda \mathrm{Tr}(MM^\dagger MM^\dagger) + \lambda' [\mathrm{Tr}(MM^\dagger)]^2 \\ &- c(\det M + \det M^\dagger) - \frac{c'}{\sqrt{2}} \mathrm{Tr}(\mathcal{M}^\dagger M + M^\dagger \mathcal{M}) \end{aligned}$$

Write $M = \mathrm{diag}(\sigma_u, \sigma_d, \zeta)$ with $\sigma_u = -\langle \bar{u}u \rangle / \sqrt{2}c'$, $\sigma_d = -\langle \bar{d}d \rangle / \sqrt{2}c'$, and $\zeta = -\langle \bar{s}s \rangle / \sqrt{2}c'$. Then

$$\begin{aligned} U(M) &= -\frac{1}{2}\mu^2 (\sigma_u^2 + \sigma_d^2 + \zeta^2) + \lambda' (\sigma_u^2 + \sigma_d^2 + \zeta^2)^2 \\ &+ \lambda(\sigma_u^4 + \sigma_d^4 + \zeta^4) - 2c\sigma_u \sigma_d \zeta \\ &- \sqrt{2}c'(m_u \sigma_u + m_d \sigma_d + m_s \zeta) \end{aligned}$$

If $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$ then $\sigma_u = \sigma_d = \sigma / \sqrt{2}$, otherwise write $\sigma_u = \sigma \, \cos\theta$ and $\sigma_d = \sigma \, \sin\theta$ with $0 \leq \theta \leq \pi/2$. We take the temperature dependence of σ and ζ from lattice calculations.

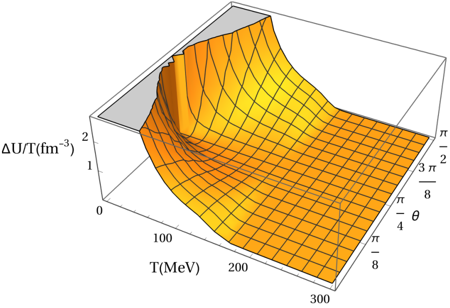
Parameterizing condensates



$$\frac{A}{e^{(T-T_0)/\Delta T}+1}$$

Light: $A = 0.01984$, $T_0 = 161.7$ MeV, $\Delta T = 9.009$ MeV

Strange: $A = 0.02402$, $T_0 = 194.0$ MeV, $\Delta T = 22.25$ MeV



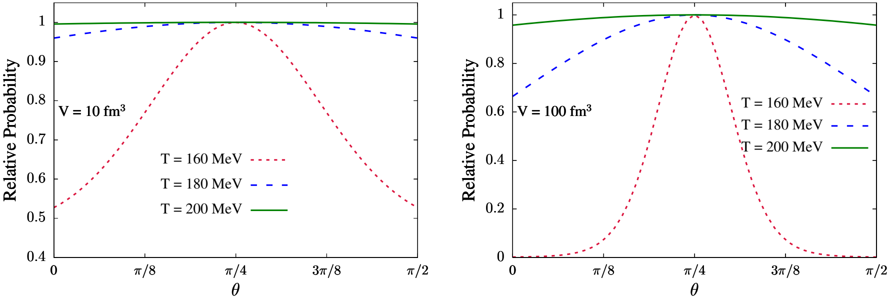
$$\begin{aligned}\Delta U(T,\theta) &= \frac{1}{2}\lambda\left[1-\sin^2(2\theta)\right]\sigma^4 \\ &+ c(T)\left[1-\sin(2\theta)\right]\sigma^2\zeta \\ &+ f_\pi m_\pi^2\left[1-\frac{\cos\theta+\sin\theta}{\sqrt{2}}\right]\sigma\end{aligned}$$

Axial U(1) symmetry is approximately restored at high temperature. From instanton calculations[1] we take $c(T) = c(0)/(1 + 1.2\pi^2\bar{\rho}^2T^2)^7$ with $\bar{\rho} = 0.33$ fm and $c(0) = 1.732$ GeV.

[1] J. I. Kapusta, E. Rrapaj and S. Rudaz, Phys. Rev. C **101**, 031901 (2020)

Relative probabilities

$$\text{Relative probability} = e^{-V\Delta U/T}$$



Summary

• ALICE has measured isospin correlations in the kaon sector which are anomalously large.

• These measurements cannot be explained by any known means without invoking kaon condensation (least likely), Disoriented Chiral Condensates (less likely), or Disoriented Isospin Condensates (most likely).

• DCC involve disorientation in the strange quark sector while DIC involve disorientation in the light quark sector.

• It would be illuminating to see similar measurements at $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb collisions at LHC and at $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC. More differential measurement in rapidities and azimuthal angles are needed.

• Can lattice QCD contribute?

• Are we seeing the melting and refreezing of the QCD vacuum?

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