Anomalous kaon correlations measured in Pb-Pb collisions at the LHC as evidence for the melting and refreezing of the QCD vacuum

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

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

- $\nu_{\mathrm{dyn}}(A, B) = R_{AA} + R_{BB} - 2R_{AB}$ 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 $\nu_{\mathrm{dyn}} = 0$.

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

- 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 $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

ALICE Collaboration *

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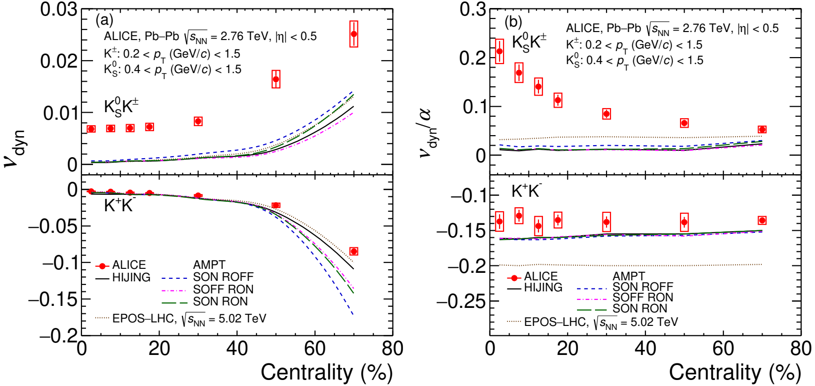
ABSTRACT

We present the first measurement of event-by-event fluctuations in the kaon sector in Pb – Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ 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 $\nu_{\mathrm{dyn}}[\mathrm{K}^+, \mathrm{K}^-]$ exhibits a scaling approximately in inverse proportion of the charged particle multiplicity, $\nu_{\mathrm{dyn}}[\mathrm{K}^0_{\mathrm{S}}, \mathrm{K}^\pm]$ features a significant deviation from such scaling. Within uncertainties, the value of $\nu_{\mathrm{dyn}}[\mathrm{K}^0_{\mathrm{S}}, \mathrm{K}^\pm]$ 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 $\nu_{\mathrm{dyn}}(K^+, K^-)$ exhibits a scaling approximately in inverse proportion of the charged particle multiplicity, $\nu_{\mathrm{dyn}}(K^0_S, K^\pm)$ 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).

• 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.

Isospin fluctuations from condensates

- Putting this together we have

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

- 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.

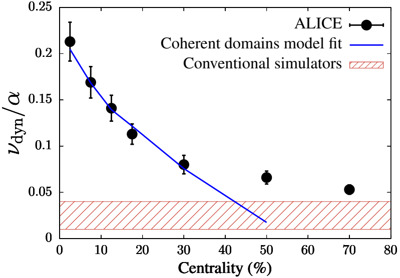
Proper time elapsed in fm/c beginning at impact and ending at the indicated temperature using the hydrodynamic code MUSIC with IP Glasma initial conditions

Centrality	$T = 160$ MeV	$T = 150$ MeV	$T = 140$ MeV
0-5 %	11.96	13.67	15.33
5-10 %	11.24	12.88	14.79
10-15 %	10.62	12.18	14.24
15-20 %	10.21	11.92	13.38
20-25 %	9.71	11.12	12.50
25-30 %	9.45	10.55	12.29
30-35 %	8.87	10.09	11.51
35-40 %	8.28	9.21	10.93
40-45 %	7.64	9.01	10.23
45-50 %	7.28	7.91	9.34

Fit to the 5 most central bins

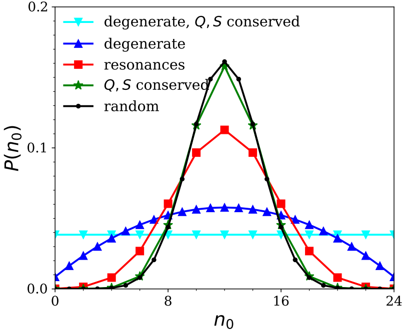
$$b = 0.1044 \pm 0.0380$$
$$\frac{b^2}{a} = 0.2187 \pm 0.0458$$

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.



- Probability distribution of neutral fraction of kaons in a degenerate state is flat.
- Above result holds when $I_3 = 0$ irrespective of whether overall isospin is unconstrained or constrained to be in isosinglet. This result also holds when the isospin state is disoriented as in DCC
- Condensates with degenerate kaons have identical neutral fractions whether isospin is constrained or not.

Can we calculate the energy density available from condensation? First consider the 2 flavor Linear Sigma Model.

$$U(\sigma, \boldsymbol{\pi}) = \frac{\lambda}{4}\left(\sigma^2 + \boldsymbol{\pi}^2 - \frac{c^2}{\lambda}\right)^2 - f_\pi m_\pi^2 \sigma - \frac{c^4}{4\lambda}$$

- Minimizing the potential gives $\sigma_{\text{vac}} = f_\pi$ and masses $m_\pi^2 = \lambda\sigma_{\text{vac}}^2 - c^2$ and $m_\sigma^2 = 3\lambda\sigma_{\text{vac}}^2 - c^2$
- We use PDG values to get $m_\sigma = 450$ MeV. Then $c = 269.57$
- GMOR relations give the light quark condensate

$$m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

2+1 flavor Linear Sigma Model

J. Schaffner-Bielich and J. Randrup, Phys. Rev. C **59**, 3329 (1999)

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

$$\begin{aligned} U(M) &= -\frac{1}{2}\mu^2 \mathrm{Tr}(MM^\dagger) + \lambda \mathrm{Tr}(MM^\dagger MM^\dagger) + \lambda' [\mathrm{Tr}(MM^\dagger)]^2 \\ &- c(\det M + \det M^\dagger) - f_\pi m_\pi^2 \sigma - \left(\sqrt{2} f_K m_K^2 - \frac{1}{\sqrt{2}} f_\pi m_\pi^2\right)\zeta \end{aligned}$$

The σ meson is a $\bar{u}u + \bar{d}d$ scalar and the ζ meson is an $\bar{s}s$ scalar. Assuming only those two condense we have

$$\begin{aligned} U(\sigma,\zeta) &= -\frac{1}{2}\mu^2(\sigma^2+\zeta^2) + \frac{1}{2}\lambda(\sigma^4 + 2\zeta^4) + \lambda'(\sigma^2+\zeta^2)^2 - c\sigma^2\zeta - f_\pi m_\pi^2 \sigma \\ &- \left(\sqrt{2} f_K m_K^2 - \frac{1}{\sqrt{2}} f_\pi m_\pi^2\right)\zeta \end{aligned}$$

Extended 2+1 flavor Linear Sigma Model

Y. Kuroda, M. Harada, M. Matsuzaki, and D. Jido, Prog. Theor. Exp. Phys. 53D02 (2020)

- Explicit symmetry breaking from quark masses can be incorporated as

$$U_{\mathrm{SB}} = -\frac{c'}{\sqrt{2}}\mathrm{Tr}[\mathcal{M}^\dagger M + \mathcal{M} M^\dagger]$$

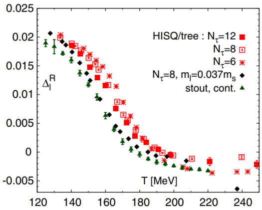
  where $\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s)$ is the diagonal quark mass matrix
- Recently it was shown that mass hierarchy of light scalar mesons can be explained by combining explicit symmetry breaking and the $U(1)_A$ anomaly

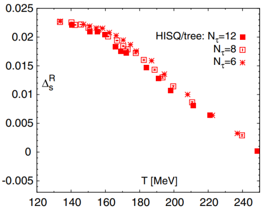
$$U_{\mathrm{SB-anom}} = -\frac{1}{2}c' k \left[\epsilon_{abc}\epsilon_{def}\mathcal{M}_{ad}M_{be}M_{cf} + \mathrm{h.c.}\right]$$

The point of this exercise was to get an estimate of the energy released in condensation. In the high temperature limit there is no condensation $\sigma = \zeta = 0$. We also know the vacuum values

$$\begin{aligned}\sigma_{\mathrm{vac}} &= f_\pi \\ \zeta_{\mathrm{vac}} &= \sqrt{2} f_K - \frac{1}{\sqrt{2}} f_\pi\end{aligned}$$

We can get the temperature dependence of σ and ζ from lattice.





HotQCD Collaboration, Phys. Rev. D **85**, 054503 (2012)

$$\begin{aligned}\sigma_{160} &\approx 0.25\sigma_{\mathrm{vac}} \\ \zeta_{160} &\approx 0.85\zeta_{\mathrm{vac}}\end{aligned}$$

Energies of condensation

Using these we have

$$\begin{aligned} U_{\mathrm{Ext}\ 2+1}(\sigma_{\mathrm{vac}}, \zeta_{\mathrm{vac}}) &= -222\ \mathrm{MeV/fm}^3 \\ U_{\mathrm{Ext}\ 2+1}(\sigma_{160}, \zeta_{160}) &= -193\ \mathrm{MeV/fm}^3 \\ \Delta U_{\mathrm{Ext}\ 2+1} &= 29\ \mathrm{MeV/fm}^3 \end{aligned}$$

$$\begin{aligned} U_{2+1}(\sigma_{\mathrm{vac}}, \zeta_{\mathrm{vac}}) &= -265\ \mathrm{MeV/fm}^3 \\ U_{2+1}(\sigma_{160}, \zeta_{160}) &= -234\ \mathrm{MeV/fm}^3 \\ \Delta U_{2+1} &= 31\ \mathrm{MeV/fm}^3 \end{aligned}$$

$$\begin{aligned} U_{2}(\sigma_{\mathrm{vac}}) &= -36\ \mathrm{MeV/fm}^3 \\ U_{2}(\sigma_{160}) &= -8\ \mathrm{MeV/fm}^3 \\ \Delta U_{2} &= 28\ \mathrm{MeV/fm}^3 \end{aligned}$$

Energies of condensation

• The difference in energy densities are remarkably consistent across models.

• The relevant energy density of condensation could be significantly larger as lattice calculations show that strange quark condensate starts forming at 250 MeV and light quark condensate starts forming at 180 MeV.

• Heavy ion collisions produce rapidly expanding non-equilibrium systems. The condensation may be lagging behind expansion.

• Quarks and anti-quarks are most likely strongly correlated already before chemical freezeout.

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.

• As before the result depends on the energetics.

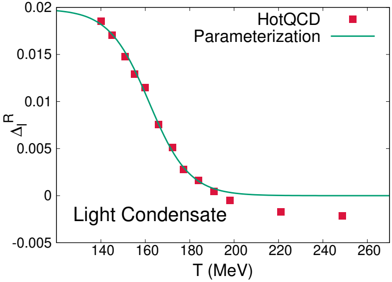
Consider the 2+1 Linear Sigma Model presented earlier except now the scalar field is $M = \mathrm{diag}(\sigma_u, \sigma_d, \zeta)$ with

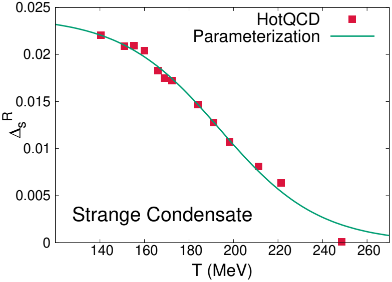
$$\begin{aligned}\sigma_u &= -\langle \bar{u}u \rangle / \sqrt{2}c' \\ \sigma_d &= -\langle \bar{d}d \rangle / \sqrt{2}c' \\ \zeta &= -\langle \bar{s}s \rangle / \sqrt{2}c'\end{aligned}$$

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

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

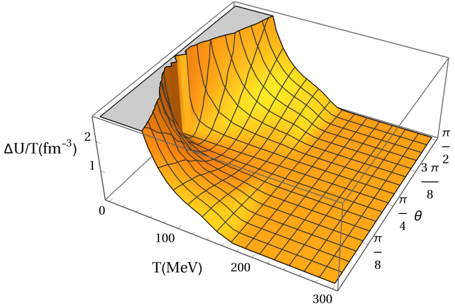




$$\frac{A}{e^{(T-T_0)/\Delta T}+1}$$

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

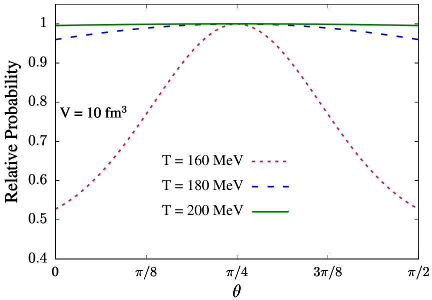


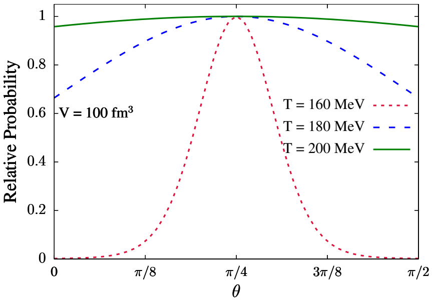
$$
\begin{aligned}
\Delta U(T,\theta) &= \frac{1}{2}\lambda\left[1-\sin^2(2\theta)\right]\sigma^4 \\
&+ c(T)\left[1-\sin(2\theta)\right]\sigma^2\zeta \\
&+ f_\pi m_\pi^2\left[1-\frac{\cos\theta+\sin\theta}{\sqrt{2}}\right]\sigma
\end{aligned}
$$

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)

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





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). There is no experimental support for the first two from Hanbury–Brown and Twiss interferometry or balance functions for kaons.

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

• We constructed a simple phenomenological model describing the observables and extracted the number and sizes of domains.

Outlook

• 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. These experiments probe the same region of the phase diagram, however they have different fireball lifetimes and volumes, kaon multiplicities and maximum temperatures reached.

• It will also be useful to see the same measurement in the pion sector, though that is challenging as π^0 is detected from $\pi^0 \to 2\gamma$ versus the measurement $K^0_S \to \pi^+\pi^-$.

• More differential measurement in rapidities and azimuthal angles are needed.

• We also need a more sophisticated model coupled with hydrodynamic calculations.

• Can lattice QCD contribute?

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

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