Disoriented Isospin Condensates as source of anomalous kaon correlations at LHC

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Kaon correlations from ALICE

ALICE collaboration reported a surprising measurement in 2022

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

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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.

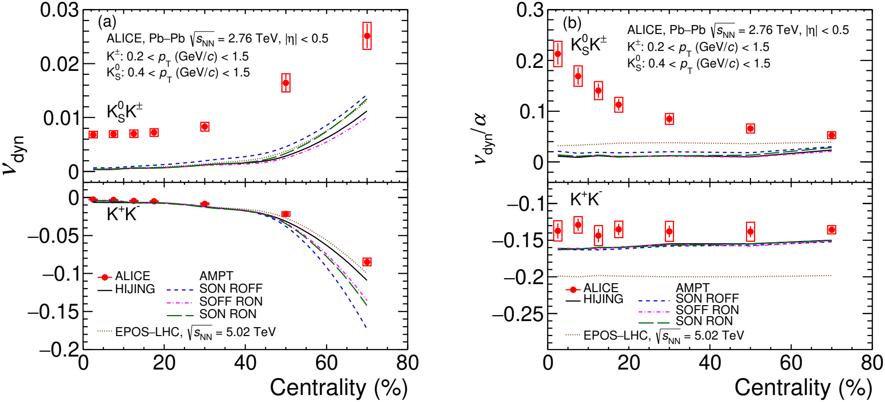
ν_{dyn}

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

- ν_{dyn}[A,B] measures how detection of particles of type A or B is correlated with itself than with the other type
- Specifically
$$\nu_{\mathrm{dyn}}[A, B] = R_{AA} + R_{BB} - 2R_{AB}$$
where R_{AB} are robust covariences
$$R_{AB} = \frac{\langle N_A N_B \rangle - \langle N_A \rangle \langle N_B \rangle - \langle N_A \rangle \delta_{AB}}{\langle N_A \rangle \langle N_B \rangle}$$
- 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 opposite for $\nu_{\mathrm{dyn}} < 0$

$\nu_{\rm dyn}$

ALICE Collaboration, Phys. Lett. B 832, 137242 (2022)
R. Nayak, S. Dash, B. Nandi and C. Pruneau, Phys. Rev. C 101, 054904 (2020)

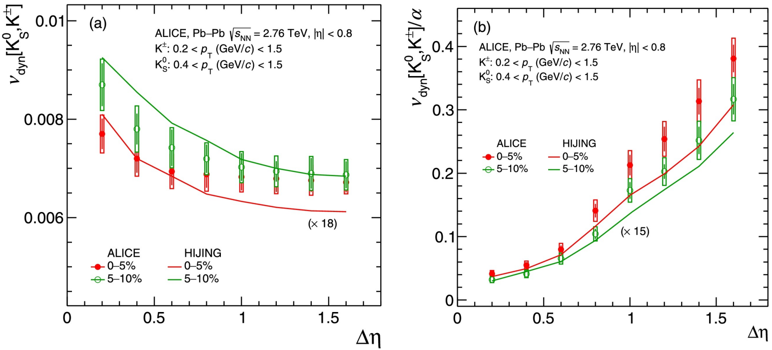


$$\alpha \equiv \frac{1}{N_{K^0_S}} + \frac{1}{N_{K^\pm}} \approx \frac{6}{N_K^{tot}}$$

$\nu_{\rm dyn}$

ALICE Collaboration, Phys. Lett. B 832, 137242 (2022)
R. Nayak, S. Dash, B. Nandi and C. Pruneau, Phys. Rev. C 101, 054904 (2020)

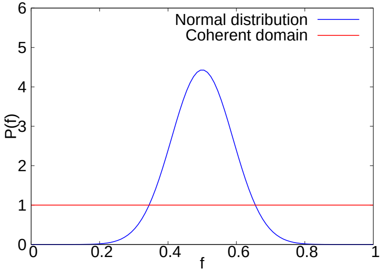
- They also extend over a unit in rapidity



ν_{dyn}

- The measured ν_{dyn} has three distinct anomalies
  1. It is unusually large
  2. Scaled ν_{dyn} grows with multiplicity
  3. Correlations stretch over a unit in rapidity
- The systems appears to have an unusual neutral kaon fraction over large volumes

Coherent domains seem unavoidable



Isospin fluctuations from coherent domains

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

- Suppose we have domains of condensates (not necessarily disoriented) which give rise to coherent emission i.e. have flat neutral kaon fractions
- If the number of domains is > 2, $\nu_{\rm dyn}[K_S^0, K^{\pm}]$ is given by

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

  where β_K is he fraction of all kaons that come from condensate domains, N_d is the number of such domains
- The relation is derived from folding the distributions of kaons from condensates and thermal sources. For multiple condensate sources, $P(f)$ again approaches a Gaussian by the Central Limit Theorem

Isospin fluctuations from coherent domains

- β_K can be estimated from the energy of condensation

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

  ϵ_ζ is the energy density available from condensation and V_d is the total volume of all condensates put together

- Let's assume that N_d scales with kaon multiplicity and V_d scales with N_d and the lifetime of the fireball

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

Isospin fluctuations from coherent domains

- Putting this together we have

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

- And a two parameter formula for $\nu_{\rm dyn}/\alpha$

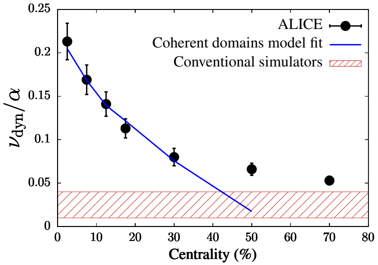
$$\frac{\nu_{\rm dyn}}{\alpha} = \frac{2}{3}b\left(\frac{\tau_{av}}{10\tau_0}\right)\left[\frac{b}{3a}\left(\frac{\tau_{av}}{10\tau_0}\right) - 1\right]$$

- We obtain τ_{av} as a function of centrality from realistic hydrodynamic simulations of heavy-ion collisions

Isospin fluctuations from coherent domains

We performed fit for 5 central points

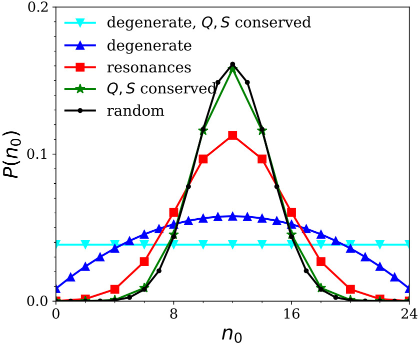
$$
\begin{aligned}
b &= 0.1044 \pm 0.0380 \\
\frac{b^2}{a} &= 0.2187 \pm 0.0458
\end{aligned}
$$



For reference energy density $\epsilon_\zeta = 25$ MeV/fm^3, only V_d changes

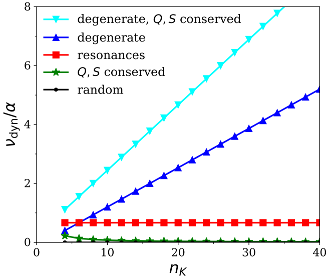
Centrality	N_d	V_d(fm^3)	β_K
0-5 %	9.32	1120	0.302
5-10 %	7.29	821	0.283
10-15 %	6.02	640	0.267
15-20 %	4.67	476	0.256
20-40 %	2.88	258	0.225
40-60 %	1.20	82	0.172

Simple kaon systems



- 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 is also holds when the isospin state is disoriented as in DCC

Simple kaon systems

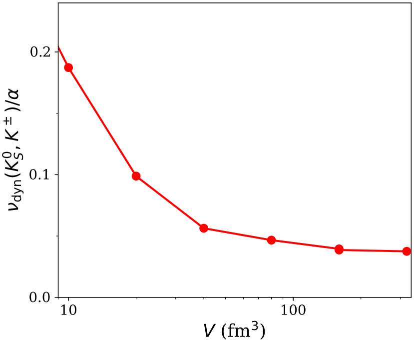


- These values of $\nu_{\rm dyn}/\alpha$ are for a single domain in isolation and not what is measured in experiments
- These needs to be folded with other domains and thermal kaons to calculate experimental observables
- Only large number of degenerate kaons can explain the data.

Hadron Gas Model

S. Pratt and R. Steinhorst, Phys. Rev. C 102, 064906 (2020)

- We set up a box at a given temperature and fill it with hadrons of many species consistent with canonical ensemble. They are then allowed to decay
- ν_{dyn} decreases with increasing volumes. It is consistent with data for very small volumes, which are not relevant for heavy-ion collisions



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

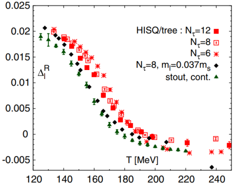
$$
\begin{aligned}
U(M) &= -\frac{q}{2}\mu^2 \mathrm{Tr}(MM^\dagger) + \lambda \mathrm{Tr}(MM^\dagger MM^\dagger) + \lambda' [\mathrm{Tr}(MM^\dagger)]^2 - c(\det M + \det M^\dagger) \\
&- f_\pi m_\pi^2 \sigma - \left(\sqrt{2} f_K m_K^2 - \frac{1}{\sqrt{2}} f_\pi m_\pi^2\right)\zeta
\end{aligned}
$$

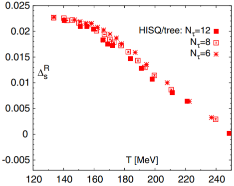
σ meson is a $\bar{u}u + \bar{d}d$ scalar and the ζ meson is an $\bar{s}s$ scalar. Assuming only those two condense, we have

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

Energy of Condensation

- In high temperature limit, in absence of condensation $\sigma = \zeta = 0$. We also have vacuum values of $\sigma_{\text{vac}} = f_\pi$ and $\zeta_{\text{vac}} = \sqrt{2} f_K - \frac{1}{\sqrt{2}} f_\pi$
- We get σ and ζ value at chiral symmetry restoration temperature from lattice





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

$$\sigma_{160} \approx 0.25\sigma_{\text{vac}}$$
$$\zeta_{160} \approx 0.85\zeta_{\text{vac}}$$

- Plugging in the values,

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

Disoriented Isospin Condensate (DIC)

- It is always assumed that $\langle u\bar{u}\rangle = \langle d\bar{d}\rangle$. What if their relative magnitudes fluctuated at finite temperature? Nothing in QCD prohibits this
- This will be a fluctuation between the isosinglet $\langle u\bar{u}\rangle + \langle d\bar{d}\rangle$ and isotriplet $\langle u\bar{u}\rangle - \langle d\bar{d}\rangle$. The excitation of latter corresponds to triplet $a_0(980)$ meson
- If the condensate is all $\langle u\bar{u}\rangle$, then at the time of cooling it will combine with strange quarks to form charged kaons. Similarly all $\langle d\bar{d}\rangle$ will form neutral kaons
- This will lead to the same kaon neutral fraction phenomenology as above

Disoriented Isospin Condensates (DIC)

- Is it plausible? Thermodynamic energy cost can be calculated in the linear sigma model
- Scalar field matrix M has diagonal elements $(\sigma_u, \sigma_d, \zeta)$ (as opposed to (σ, σ, ζ)) where

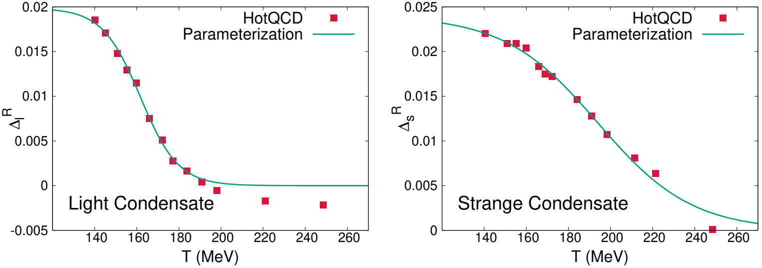
$$\begin{aligned}\sigma_u &= -\langle u\bar{u}\rangle/\sqrt{2}c' \\ \sigma_d &= -\langle d\bar{d}\rangle/\sqrt{2}c' \\ \zeta &= -\langle s\bar{s}\rangle/\sqrt{2}c'\end{aligned}$$

- We can calculate the energy associated with these fluctuations

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

Disoriented Isospin Condensates (DIC)

- We can paramterize the condensates

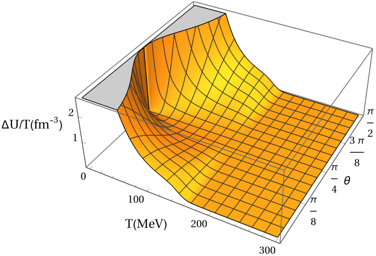


$$\frac{A}{e^{(T-T_0)/\Delta T}+1}$$

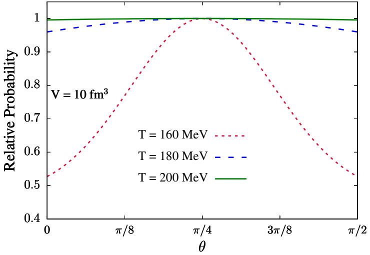
$$\begin{aligned} \text{Light}: \quad & A = 0.01984, T_0 = 161.7\text{MeV}, \Delta T = 9.009\text{MeV} \\ \text{Strange}: \quad & A = 0.02402, T_0 = 194.0\text{MeV}, \Delta T = 22.25\text{MeV} \end{aligned}$$

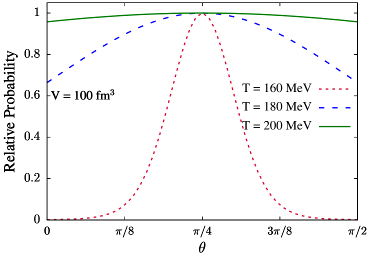
Energy cost of DIC

- Let us define $\sigma_u = \sigma \cos\theta$ and $\sigma_d = \sigma \sin\theta$. The $\theta = \pi/4$ corresponds to $\langle u\bar{u}\rangle = \langle d\bar{d}\rangle$



- We can also calculate the relative probability of such a state $= e^{-V\Delta U/T}$





Outlook

- It would be illuminating to see similar measurements at 5.02 TeV Pb+Pb collisions at LHC and at 200 GeV Au+Au collisions at RHIC. More differential measurement in rapidities and azimuthal angles are needed
- Maybe Lattice QCD can provide guidance
- Need a theory for evolution of DIC fluctuations in conjunction with the hydrodynamic medium
- Are we seeing the melting and refreezing of the QCD vacuum?

Summary

- ALICE has measured isospin correlations in the kaon sector which are anomalously large, have anomalous centrality dependence and extend to over a unit in rapidity
- 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
- The DIC would show similar anomaly in particles rich in $u/\bar{u}$ vs those rich in $d/\bar{d}$, like Ξ^0 and Ξ^- and is a testable, verifiable and refutable idea.